Long-range two-qubit gates: hybrid qubit & quadrupolar

Phys. Rev. A 104, 032612 (2021)
Phys. Rev. Research 3 (1), 013171 (2021)

Outline

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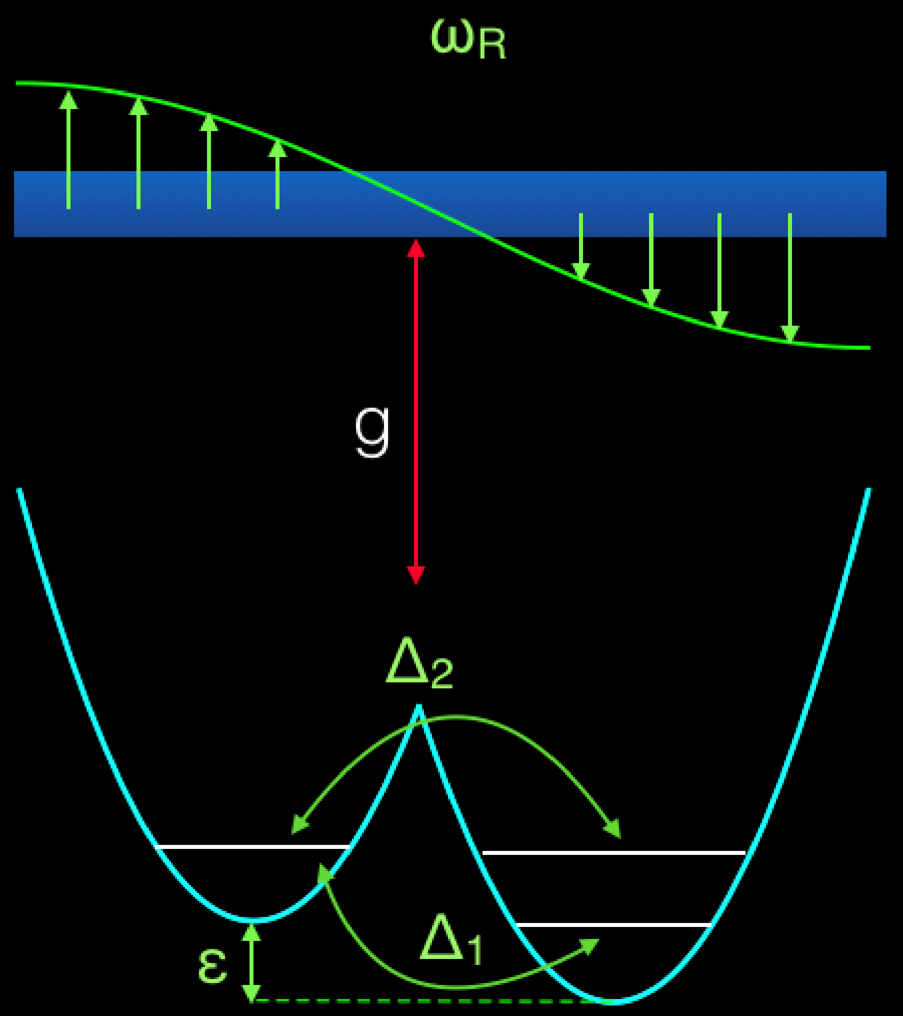


Background

Single-qubit gates with 99% fidelities are already achievable

See: Veldhorst et al. Nat. Nano **9**, 981-985 (2014)

Kawakami et al. PNAS October **18**, 2016 113 (42) 11738-11743

Takeda et al. Science Advances **2**, 8, e1600694

Yoneda et al. Nat. Nano **13**, 102-106 (2018)

Two-qubit gates based on exchange have been implemented. >90% achieved

See: Veldhorst et al. Nature **526**, 410-414 (2015)

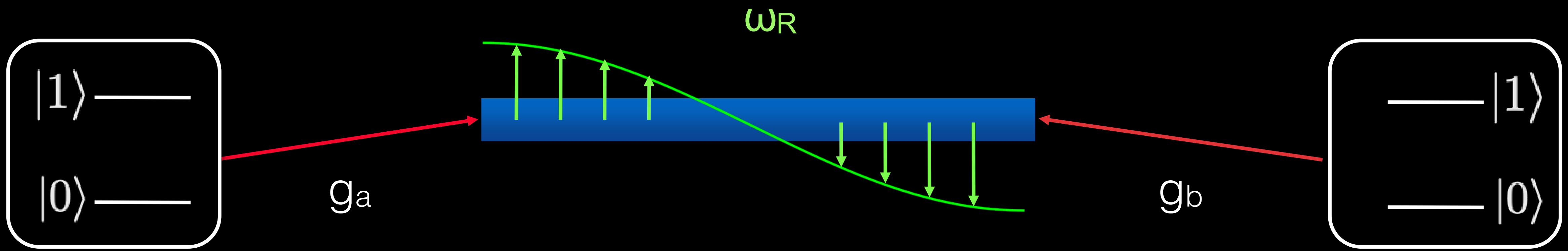
Zajac et al. Science **359**, 6374, 439-442 (2018)

Watson et al. Nature **555**, 633-637 (2018)

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

Xue et al. PRX **9**, 021011 (2019)

On the way towards long-range two-qubit gates



Spin-cQED architectures allow long-range coupling between qubits

Not limited by nearest neighbor interactions

Potential for hybrid quantum systems

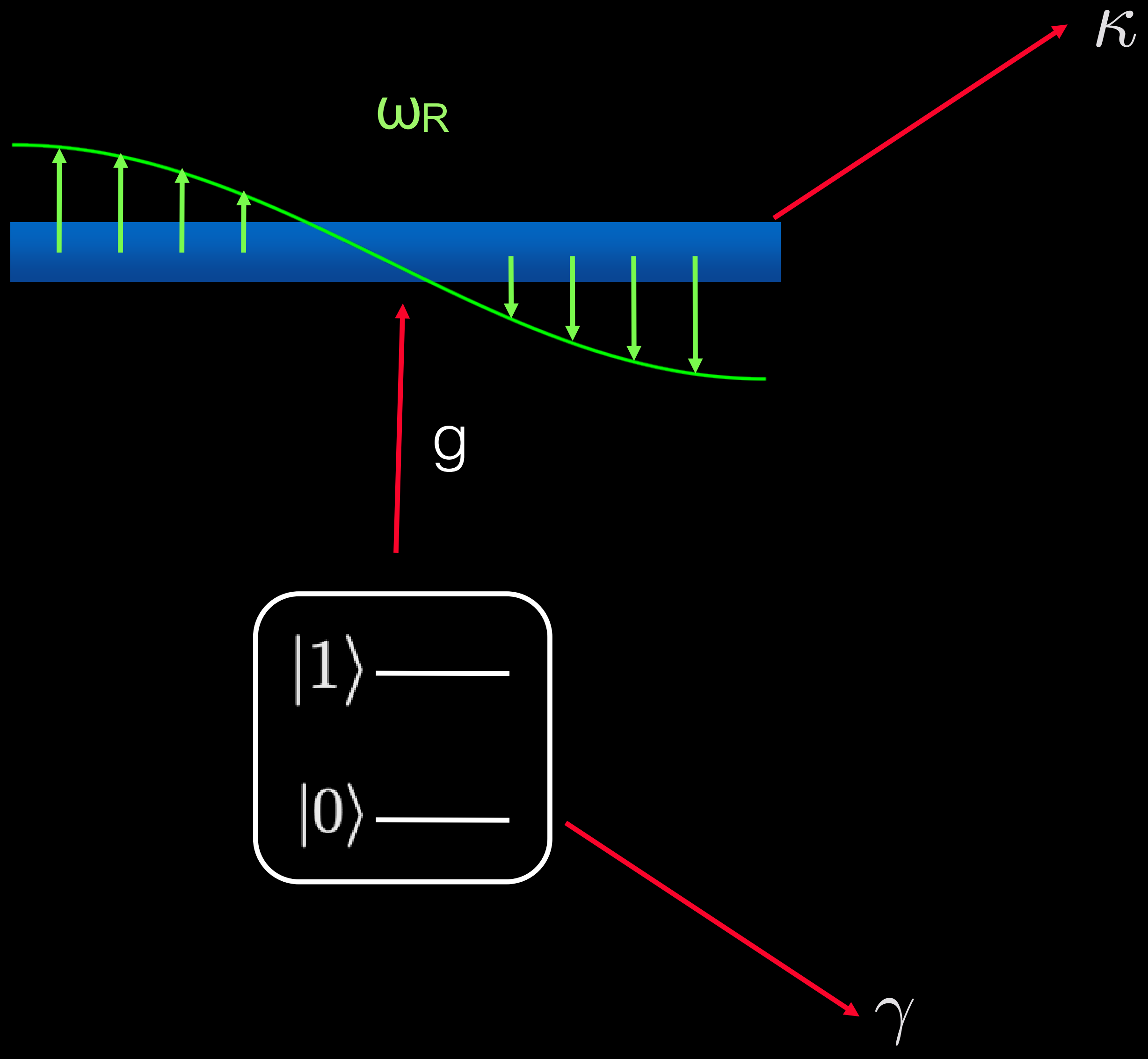
Coupling spin qubits with superconducting resonators

Strong coupling regime achieved with semiconductor qubits

See: Landig et al. Nature **560**, 179-184 (2018)

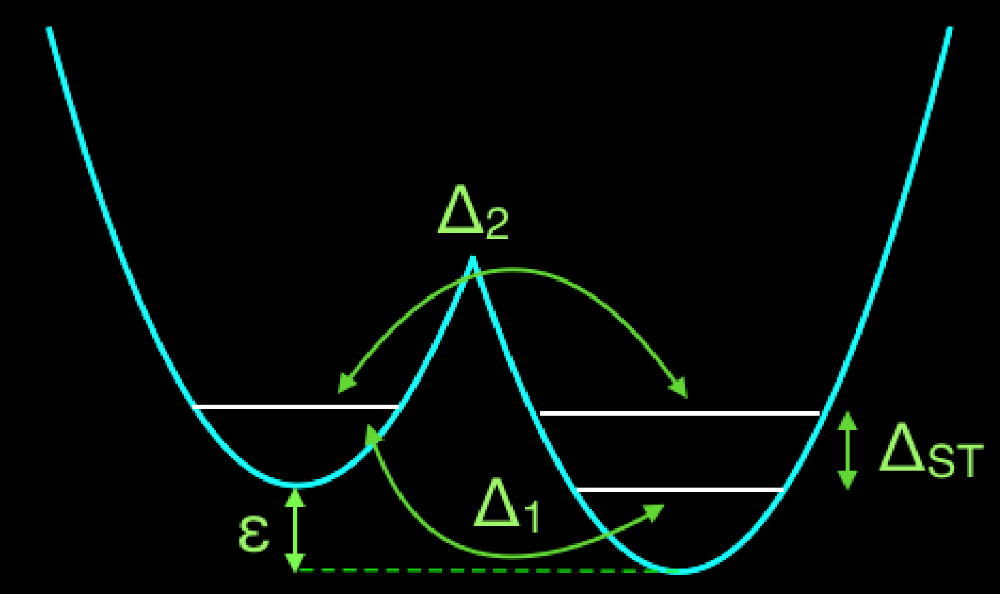
X. Mi et al. Nature **555**, 599-603 (2018)

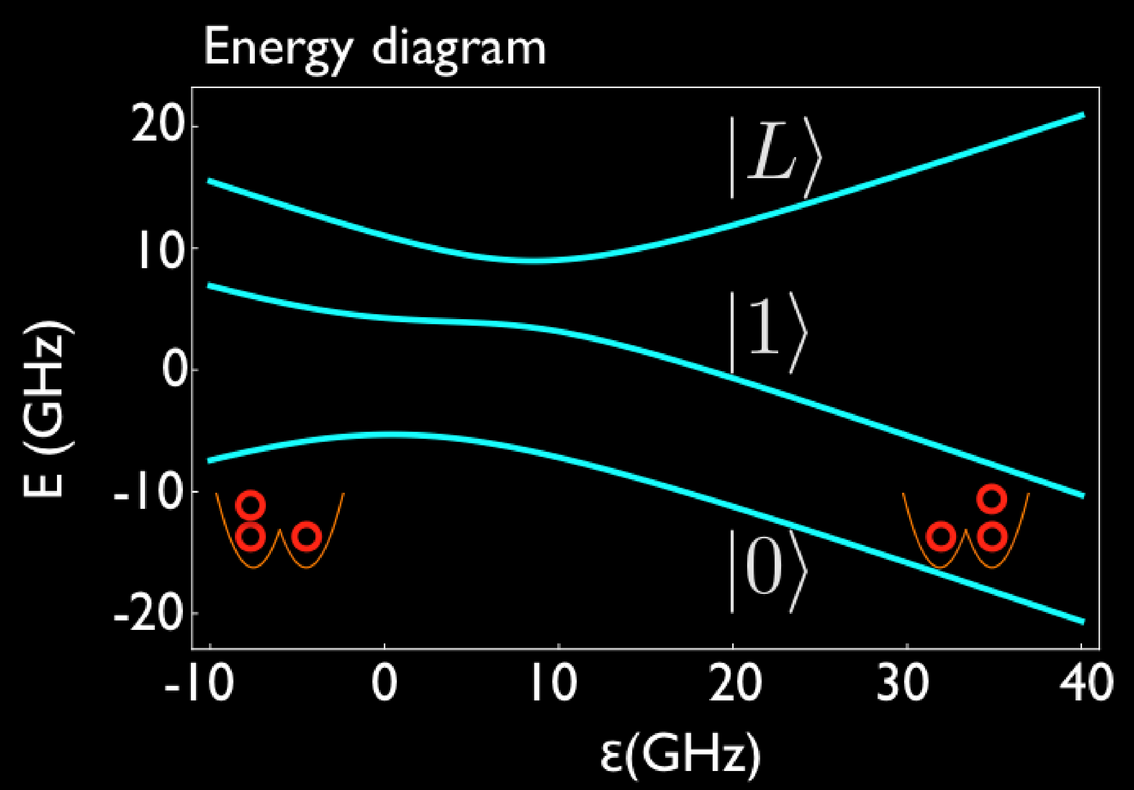
Samkharadze et al. Science 10.1126/science (2018)



Hybrid qubit

$$H = \begin{pmatrix} -\varepsilon/2 & 0 & \Delta_1 \\ 0 & -\varepsilon/2 + \Delta_{ST} & \Delta_2 \\ \Delta_1 & \Delta_2 & \varepsilon/2 \end{pmatrix}$$



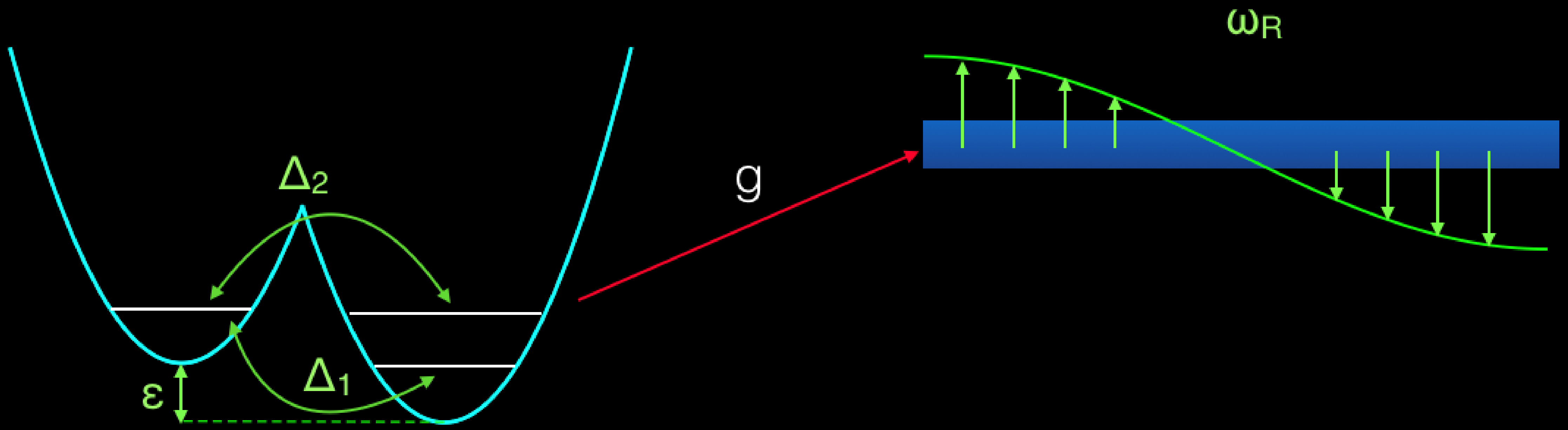


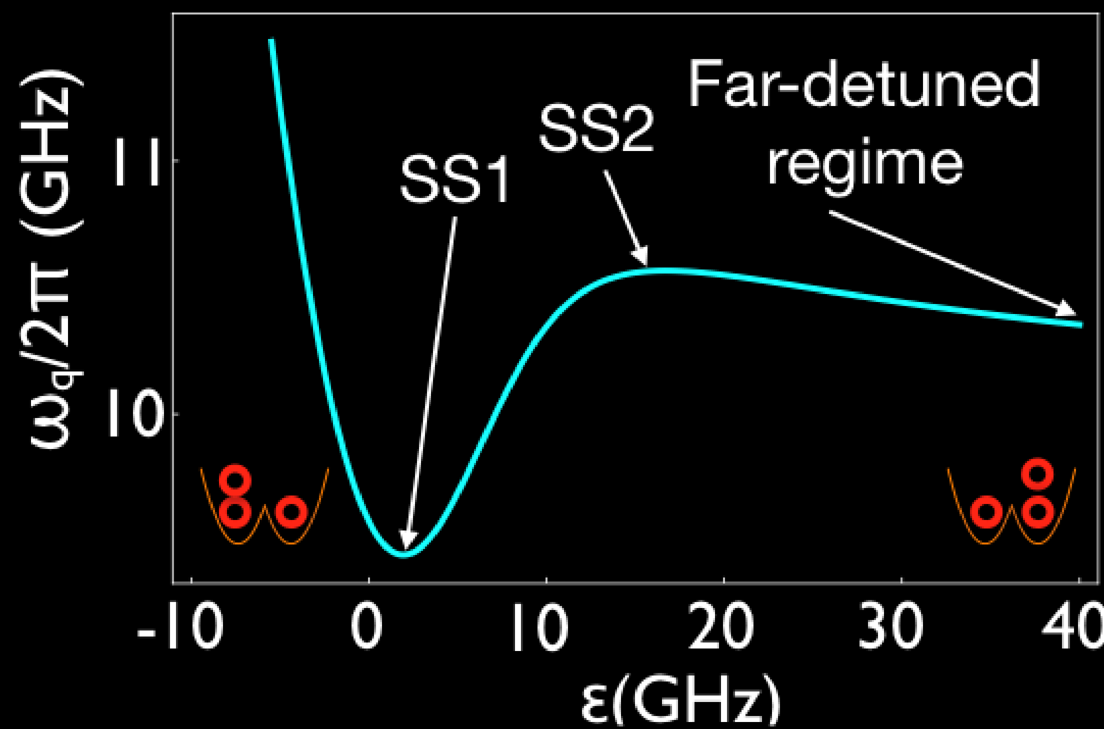
Two anticrossings related to the qubit parameters

Far-detuned regime

Dipolar coupling maximized near the 1st anticrossing

Strategy: Maximize g/γ

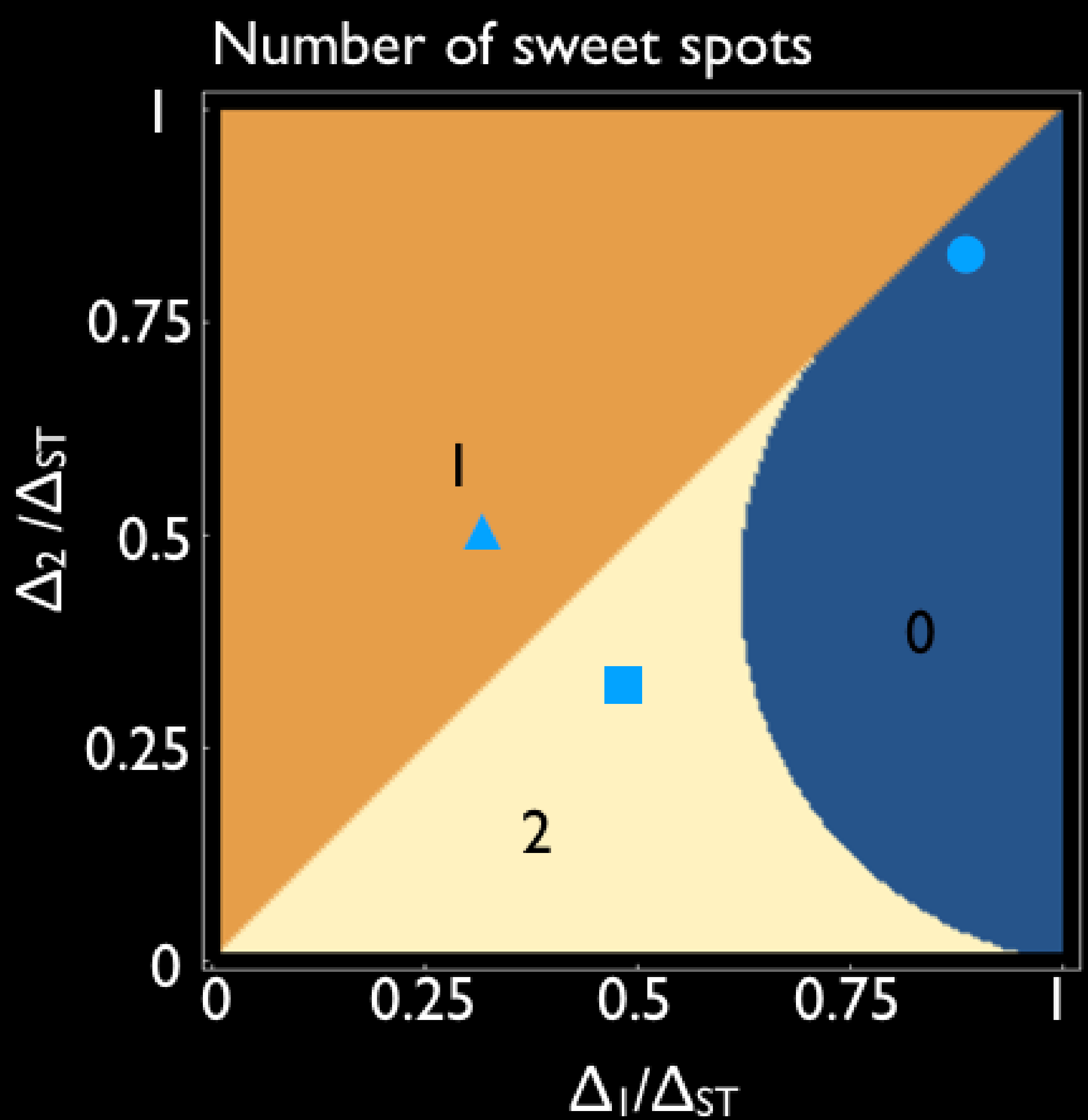


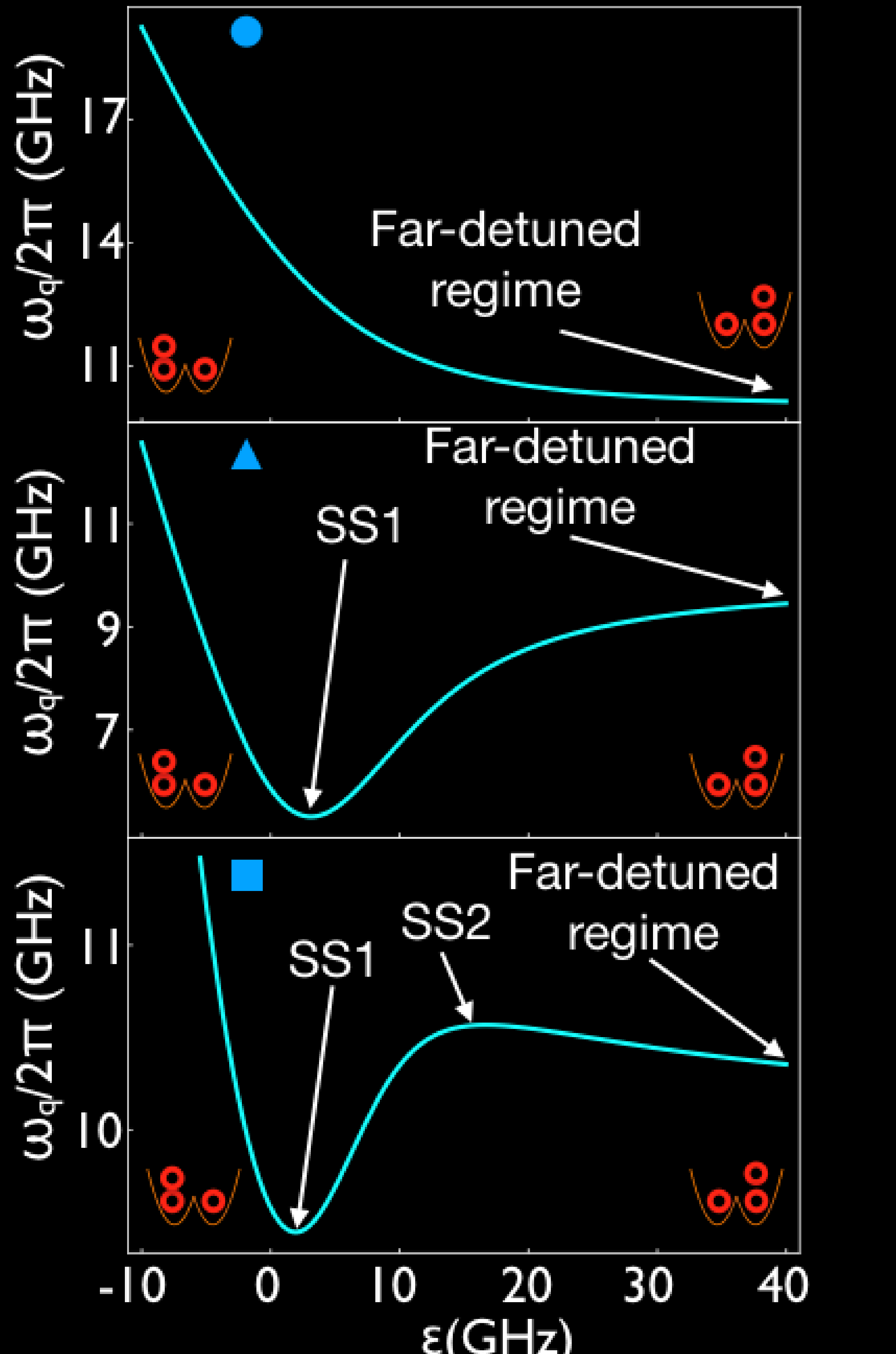


Achieving strong coupling requires $g/\gamma>1$

Strong coupling candidates: SSs, far-detuned regime

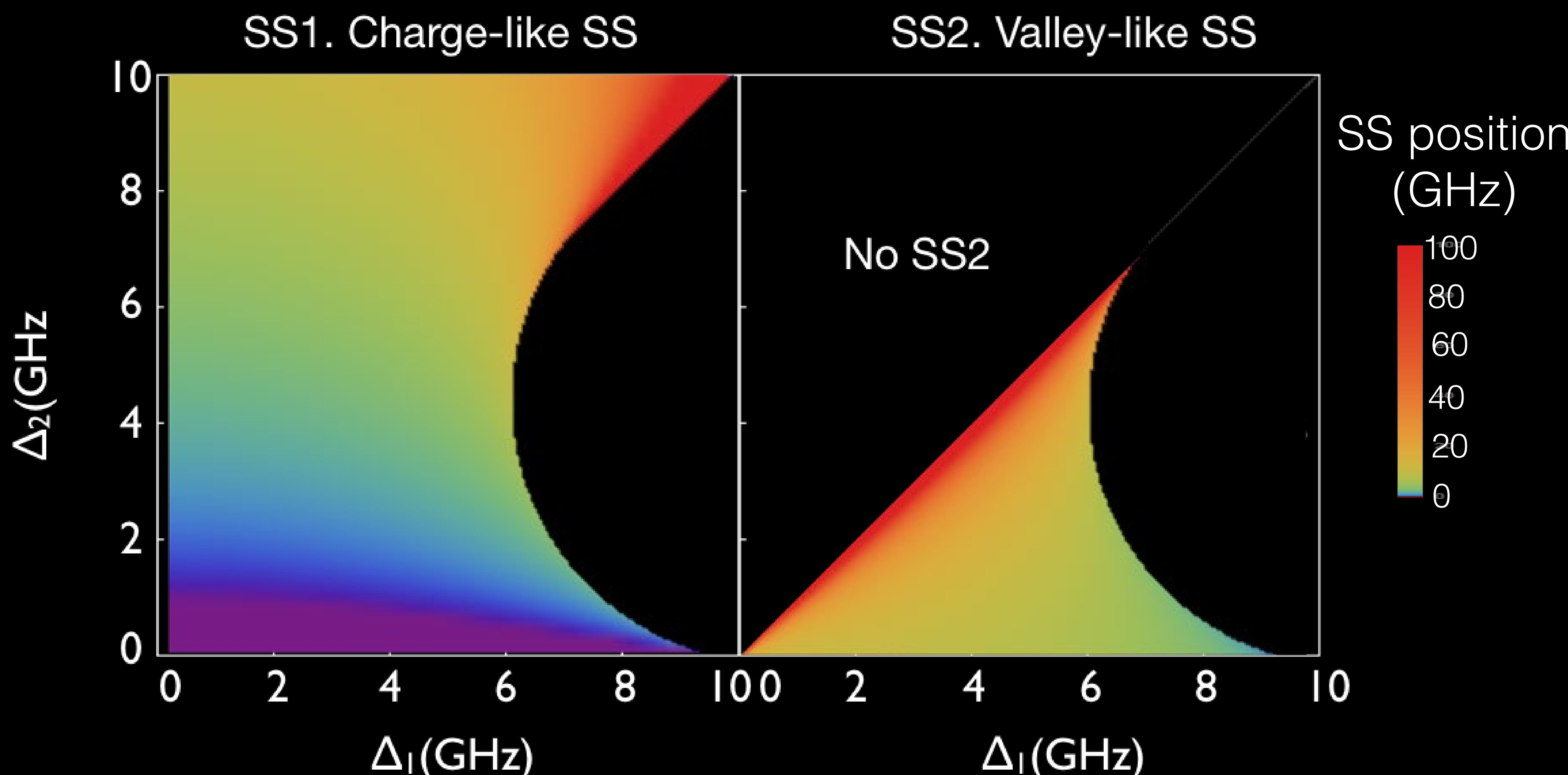
Basic properties of the HQ



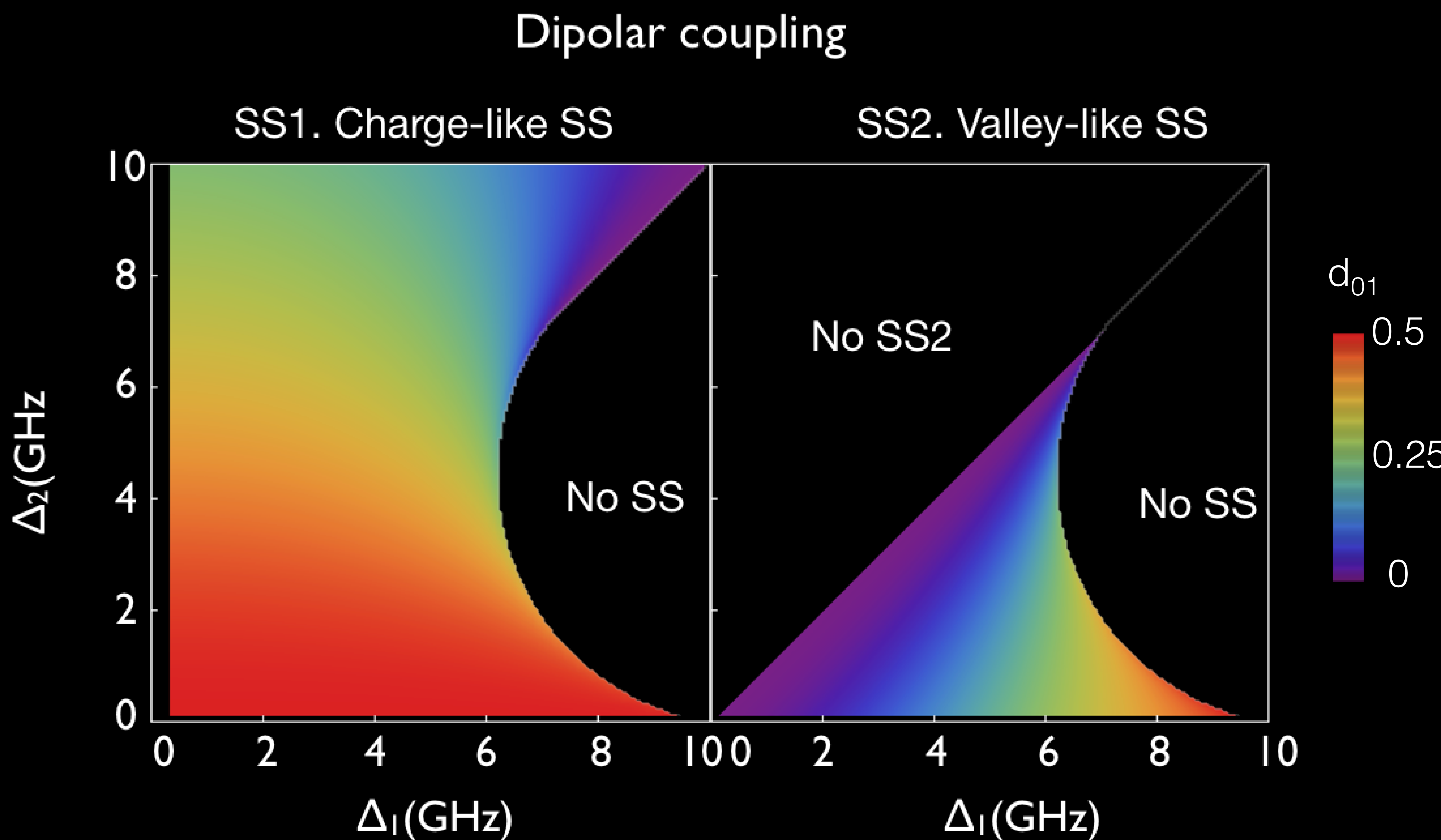


SS1: higher coupling, bad coherence
SS2: Smaller coupling with improved coherence
Far-detuned regime: Small coupling with good coherence

Sweet spot position.

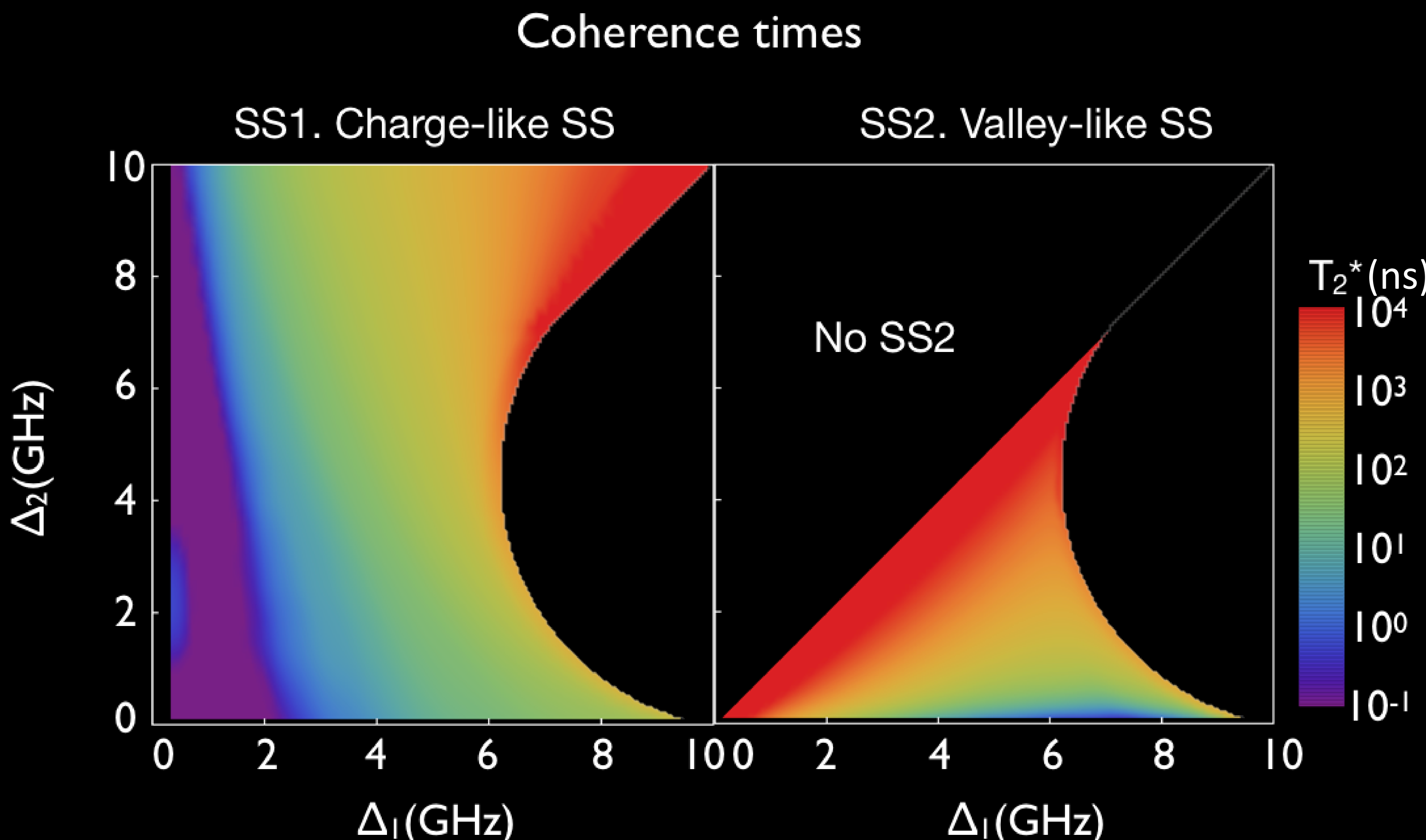


Sweet spot properties. VS=10 GHz

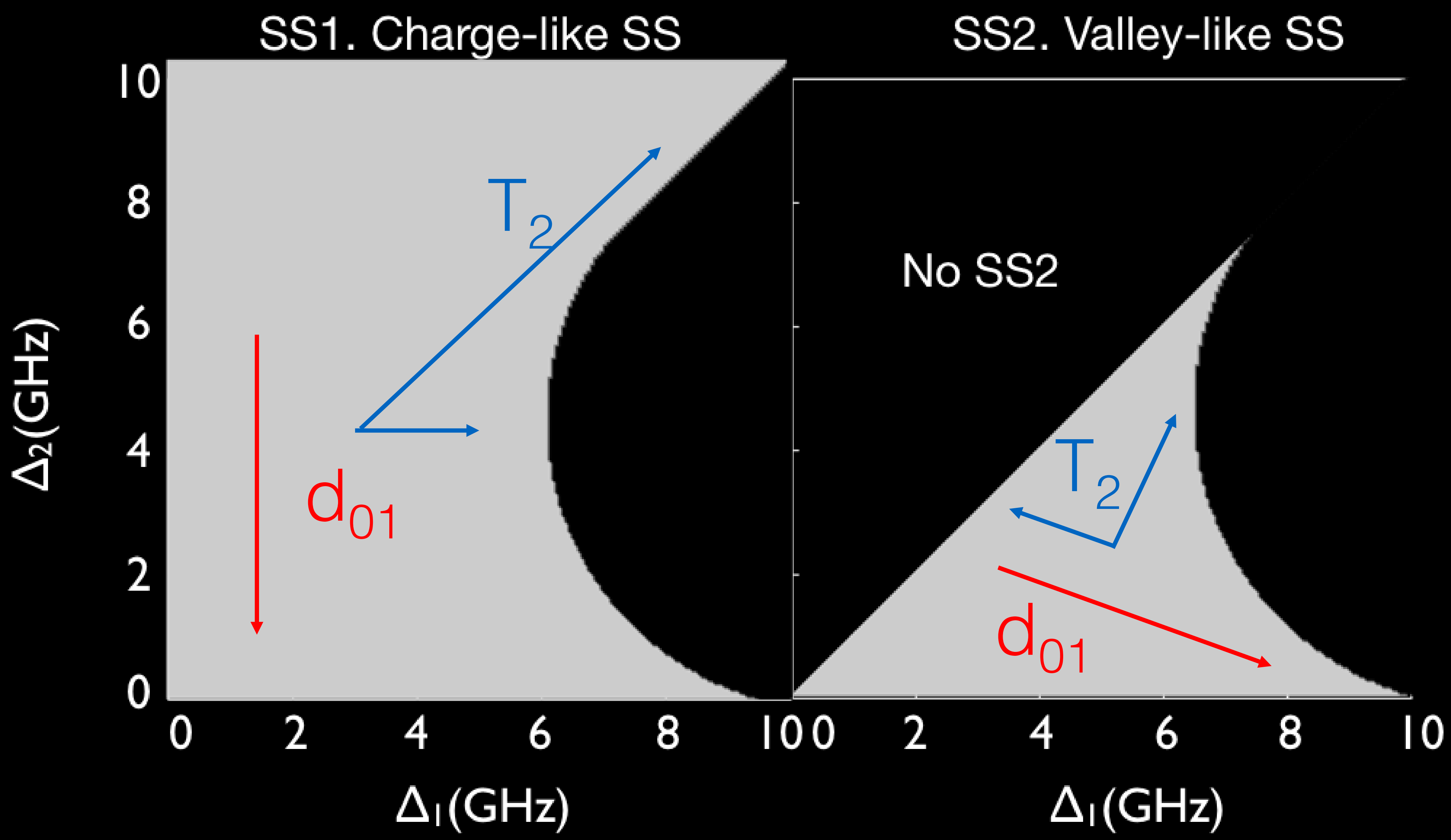


Sweet spot properties. VS=10 GHz

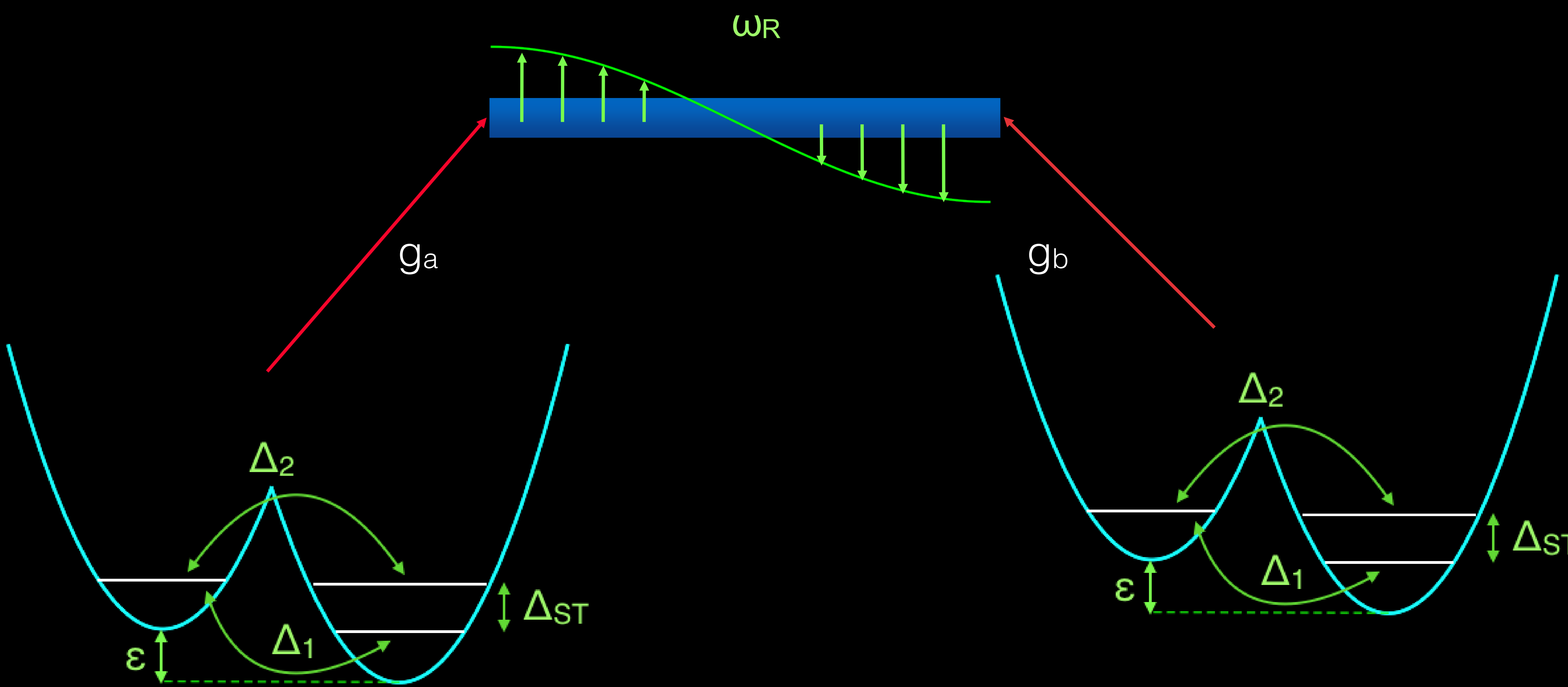
We estimate coherence times by simulating 1/f noise $\sigma_\varepsilon = 2\mu eV$



Overview of the sweet spot properties



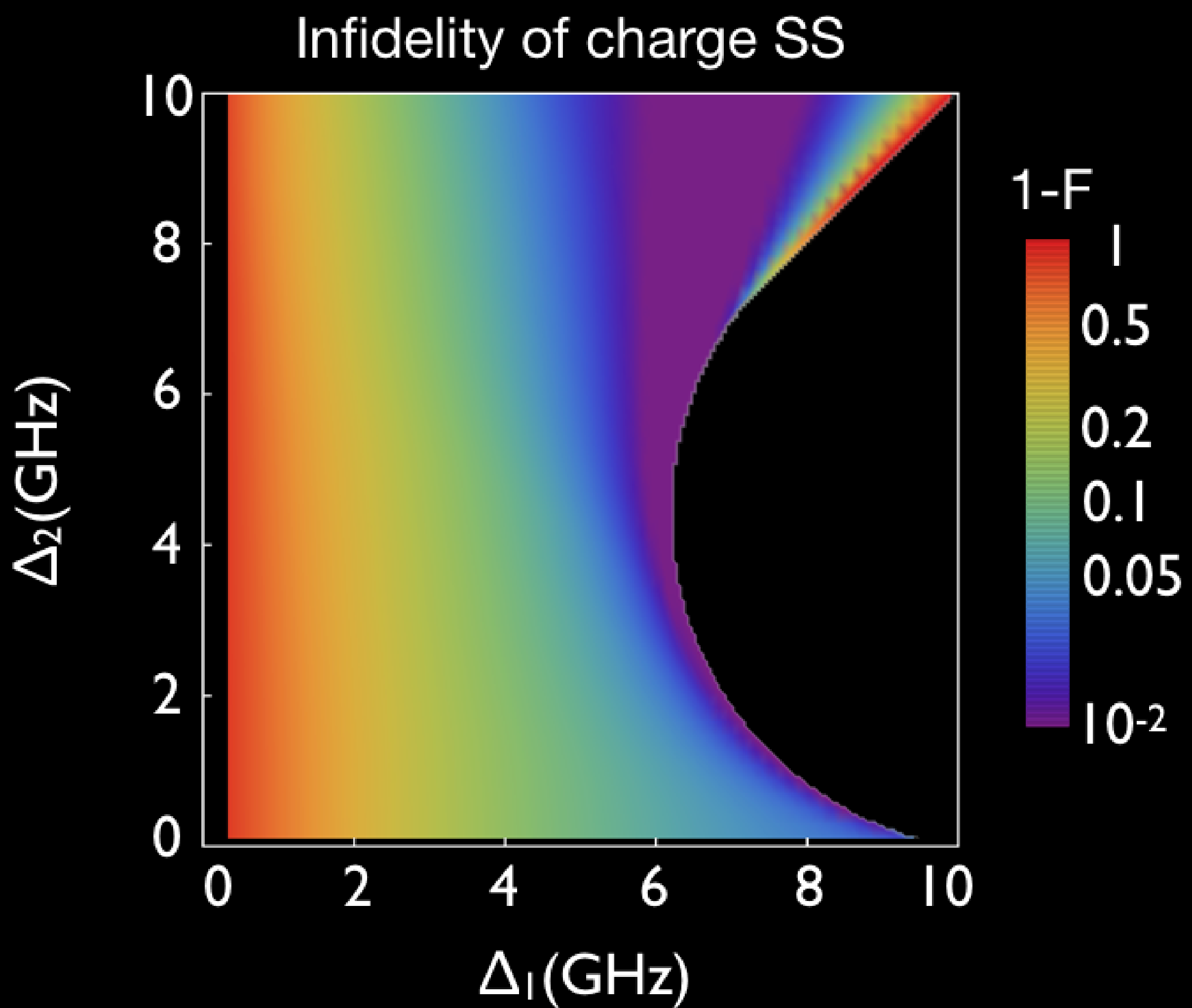
Coupling two hybrid-qubits through a resonator

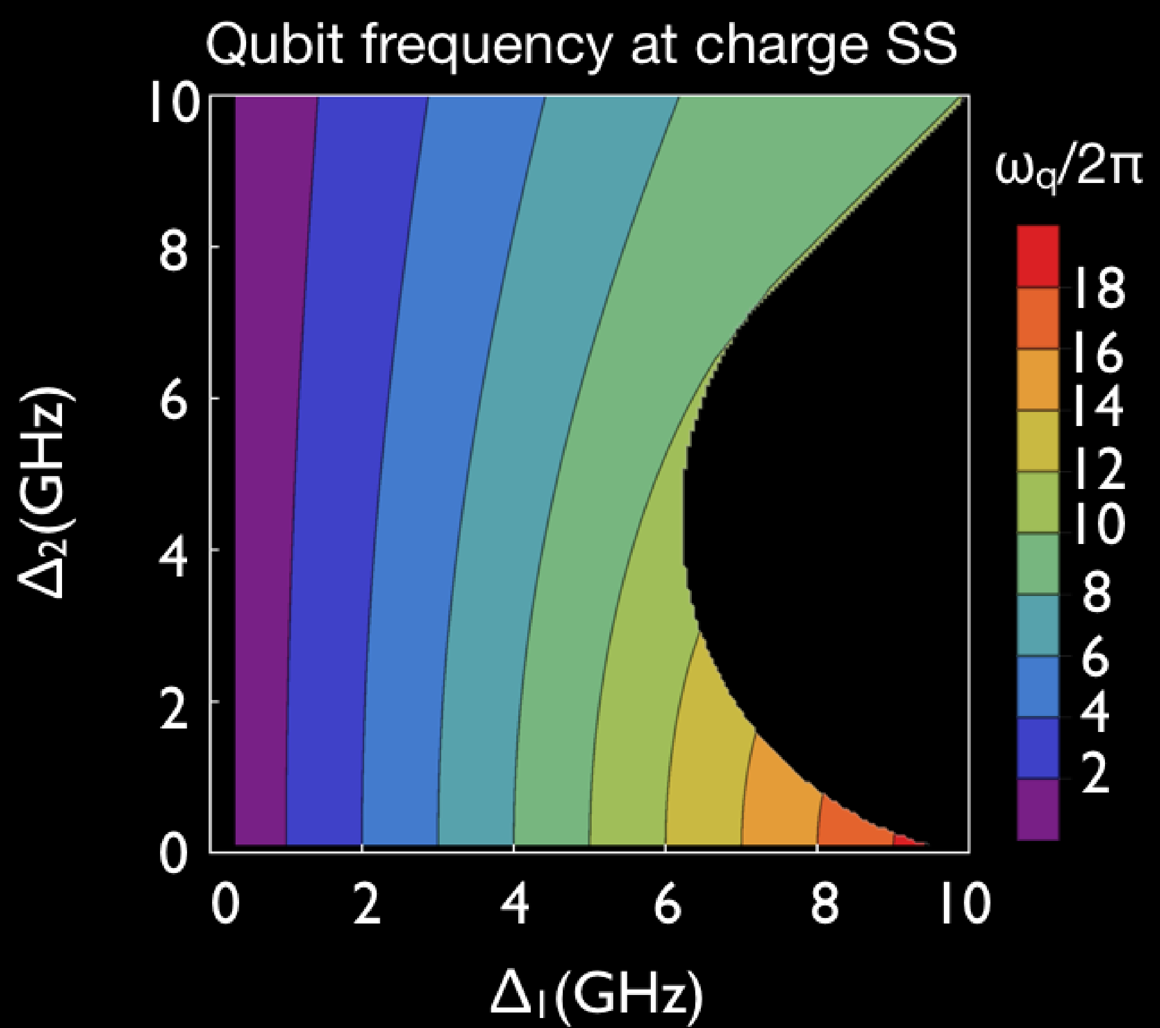


Upper bound two-qubit gate fidelities. Charge SS

Resonant operation with κ=0 gives the upper bound gate fidelities for a 01 <-> 10 operation

$$H = \omega_c a^\dagger a + \sum_{I=1,2} \frac{\omega_{q,i}}{2}\sigma_z^i + g_0 d_{01}^i (a + a^\dagger)\sigma_x^i$$

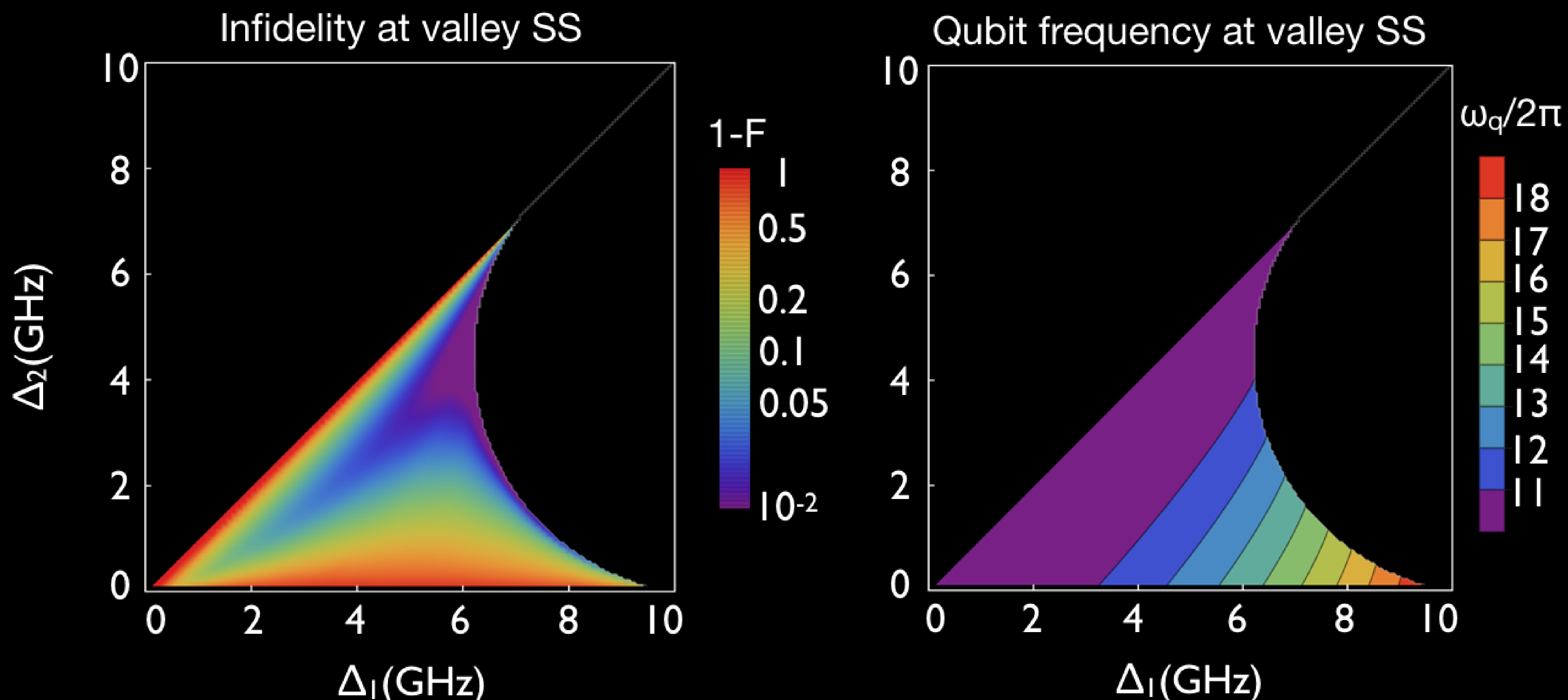




Upper bound two-qubit gate fidelities. Valley SS

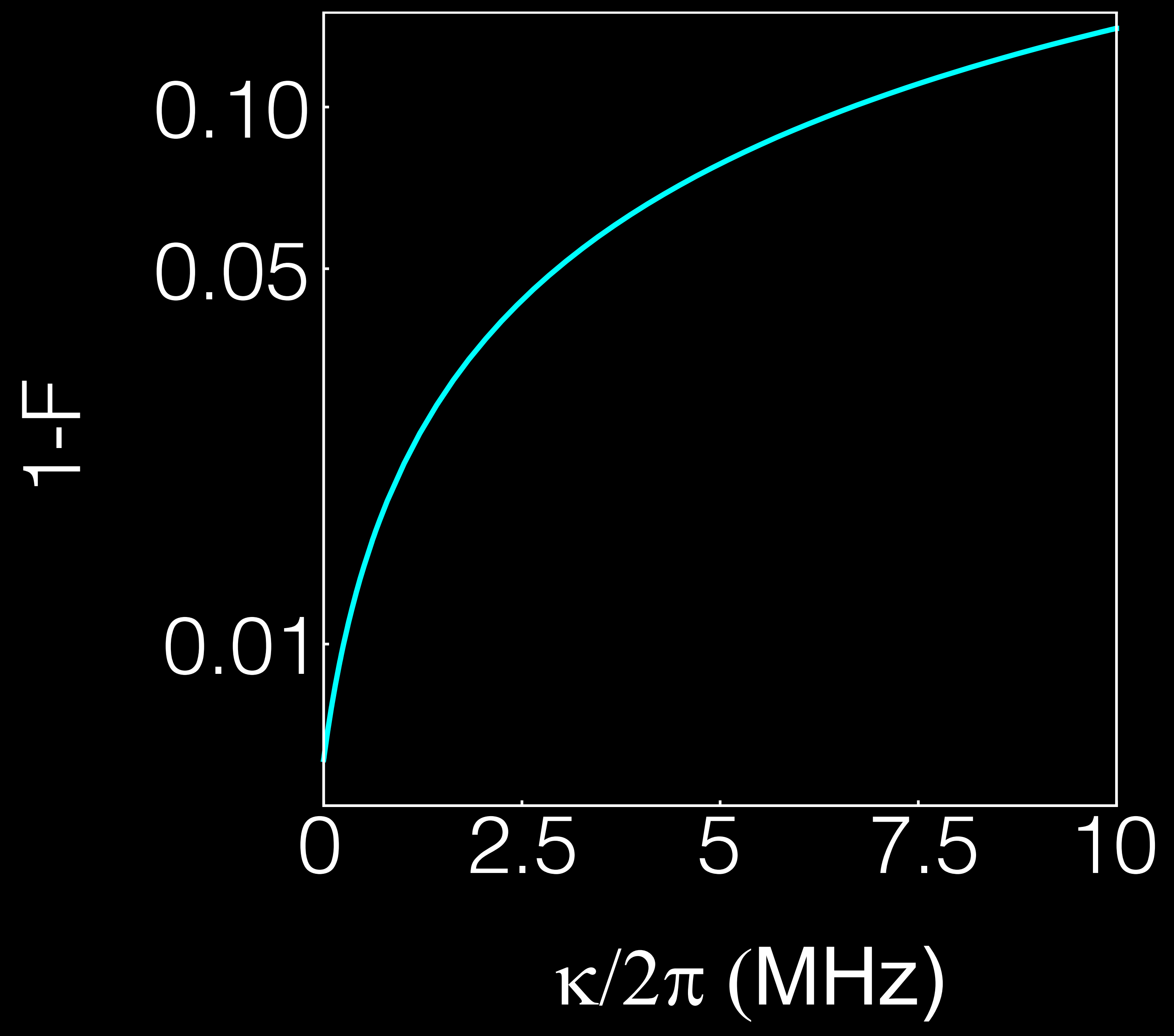
Resonant operation with κ=0 gives the upper bound gate fidelities for a 01 <-> 10 operation

$$H = \omega_c a^\dagger a + \sum_{I=1,2} \frac{\omega_{q,i}}{2}\sigma_z^i + g_0 d_{01}^i (a + a^\dagger)\sigma_x^i$$



Infidelity due to finite Q

Realistic resonators have finite decay rates (1-10 MHz)



SB transitions mediated by driving detuning and tunnel coupling

$$H = \omega_c a^\dagger a + \frac{\omega_{q,i}}{2}\sigma_z^i + g_0 d_{01}\sigma_x^i(a + a^\dagger) + d_{01}\delta\varepsilon\cos(\omega_{q,i}t + \phi)\sigma_x^i$$

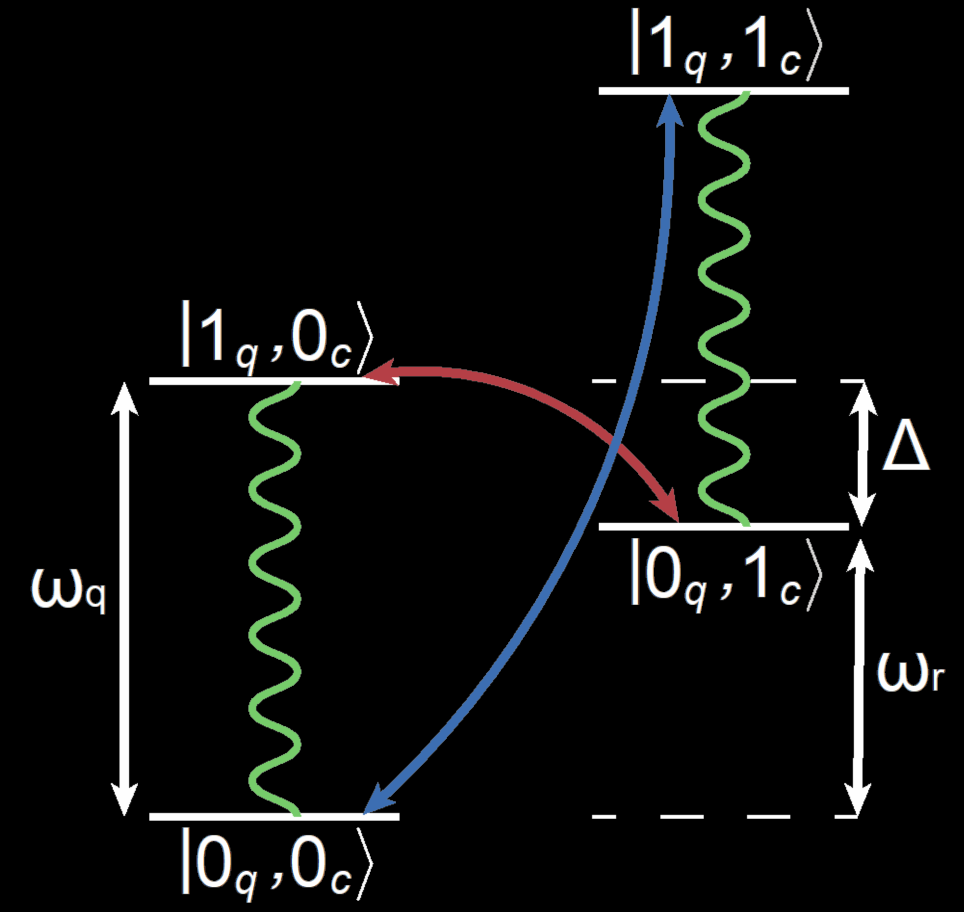
$$\downarrow$$

$$\omega_c - \omega_q = \pm d_{01}\delta\varepsilon$$

$$\downarrow$$

$$H_{S+} = \frac{g}{2}(e^{i\phi}\sigma^- a + e^{i\phi}\sigma^+ a^\dagger)$$

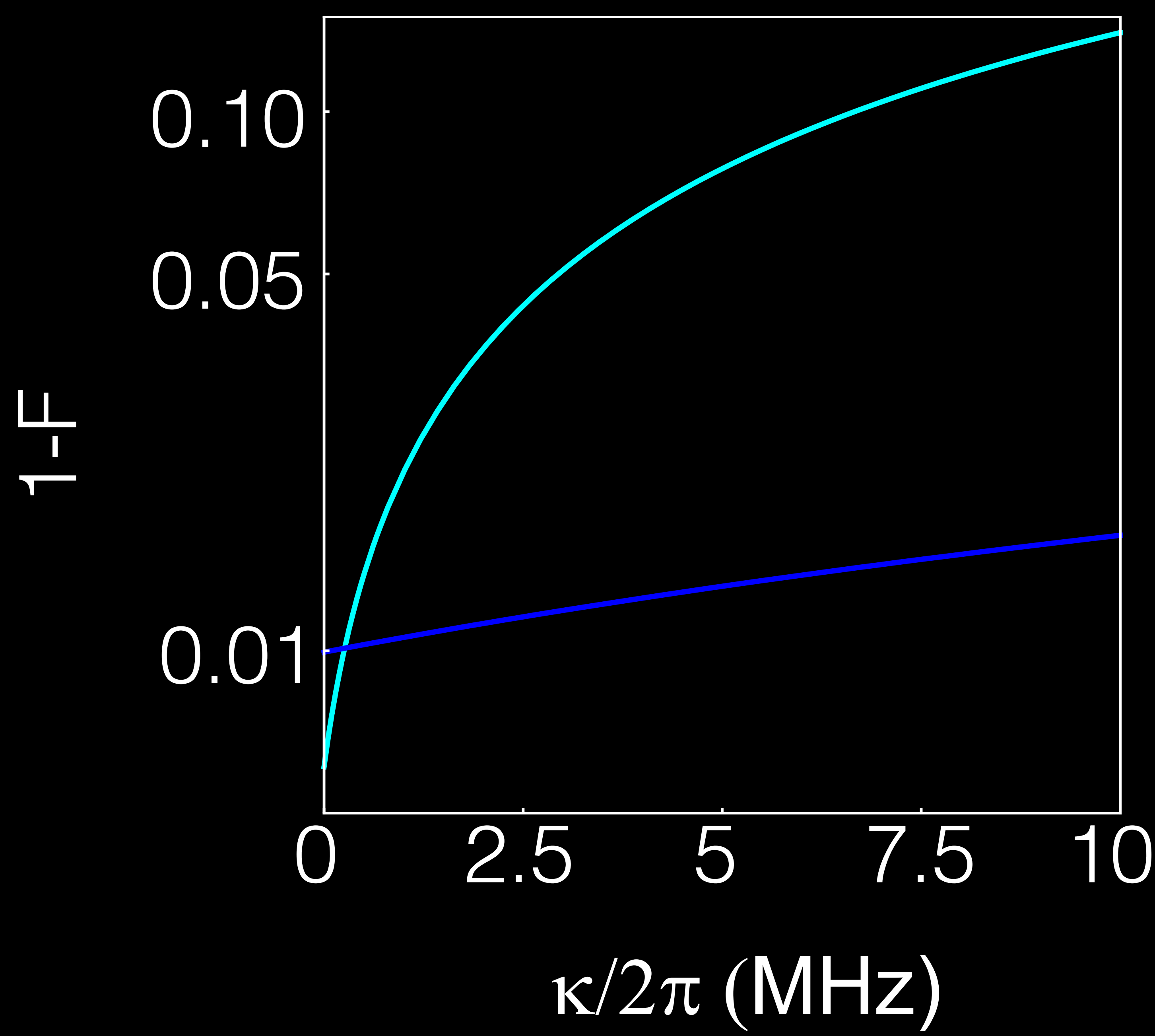
$$H_{S-} = \frac{g}{2}(e^{i\phi}\sigma^+ a + e^{i\phi}\sigma^- a^\dagger)$$



This method allows to work detuned away from resonance while keeping fast gates

$$U_{CZ} = R_{z,a}(\frac{\pi}{\sqrt{2}})S_a^+(\pi,\phi)S_a^-(\pi/2,0)S_a^-(\pi\sqrt{2},\pi/2)S_a^-(-\pi/2,0)R_{z,b}(\pi/\sqrt{2})S_a^+(\pi,\phi)$$

Sideband transition fidelities decay slower



Coupling a Charge quadrupole qubit to a SC resonator

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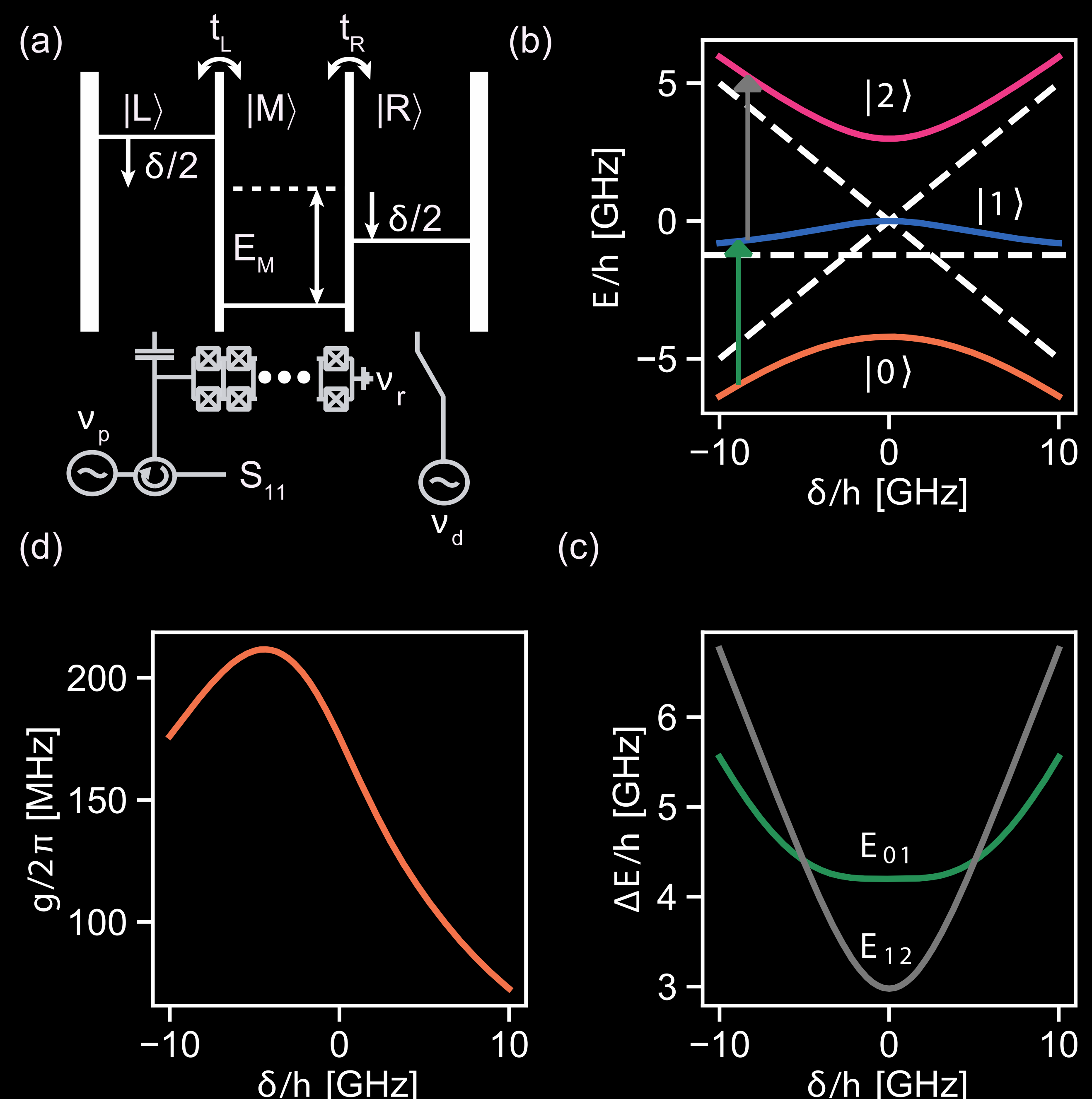
$$H = \begin{pmatrix} \delta/2 & t_L & 0 \\ t_L & E_M & t_R \\ 0 & t_R & -\delta/2 \end{pmatrix}$$

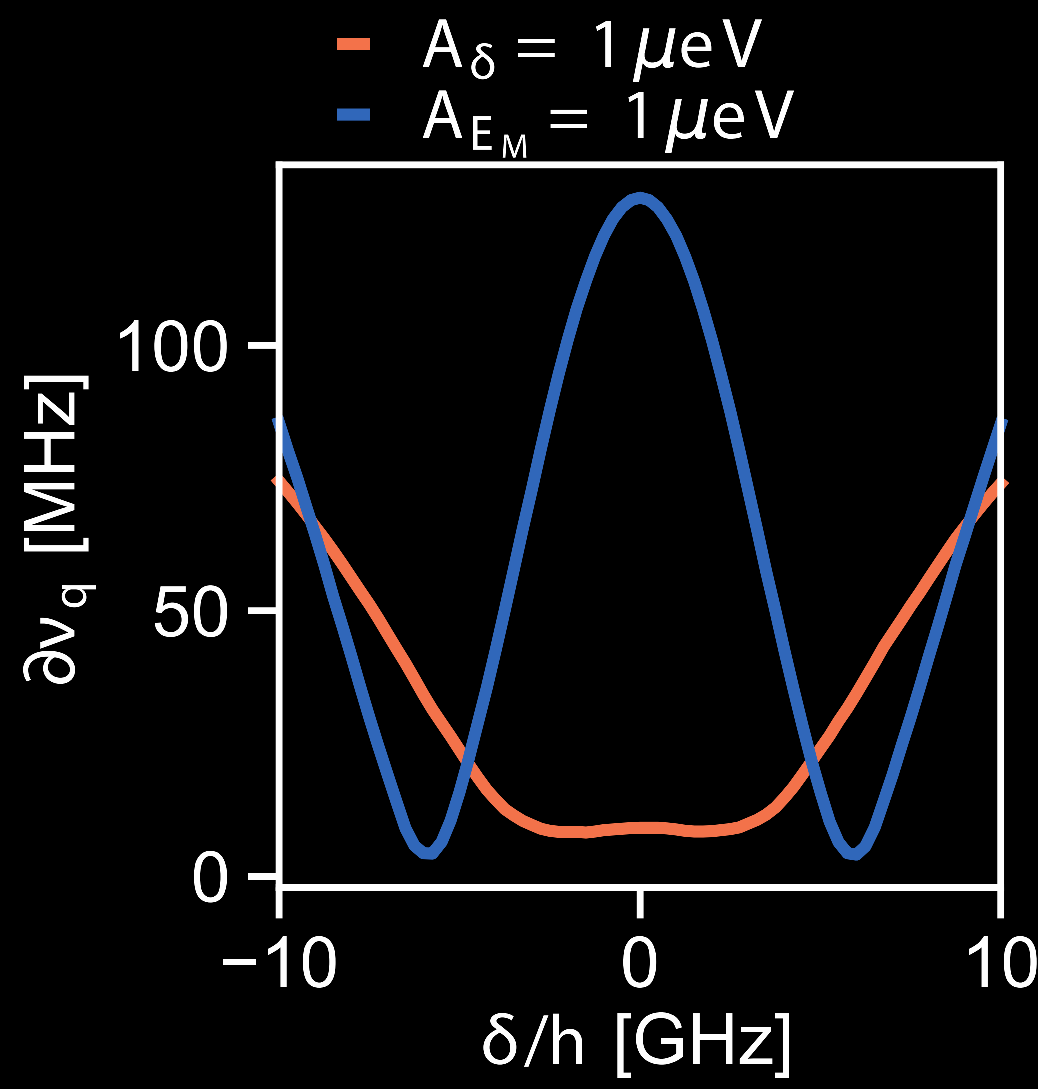


$$E_M^{\mathrm{Opt}} \approx -0.493t$$

At this optimal point, the qubit is in a 2nd order SS in dipolar detuning

Operating in the quad detuning vs dipolar detuning

If noise is dominated by long-range charged sources
dipolar noise dominates



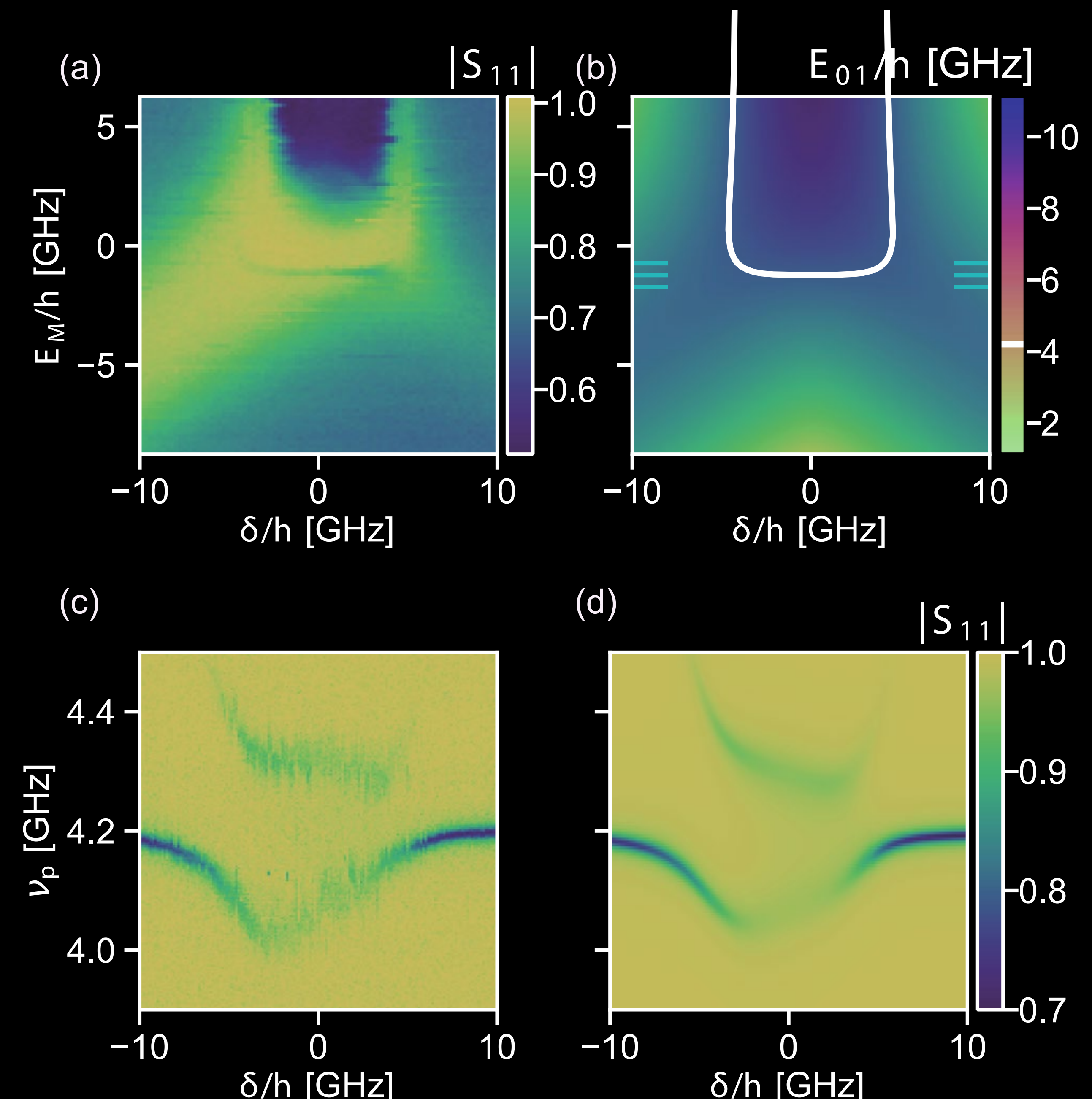
Experimental results and fitting

Fitting to IO theory yields

$g/2\pi = 203$ MHz

$\kappa_{int}/2\pi = 14$ MHz

$\kappa_{ext}/2\pi = 1.3$ MHz



Noise characterization

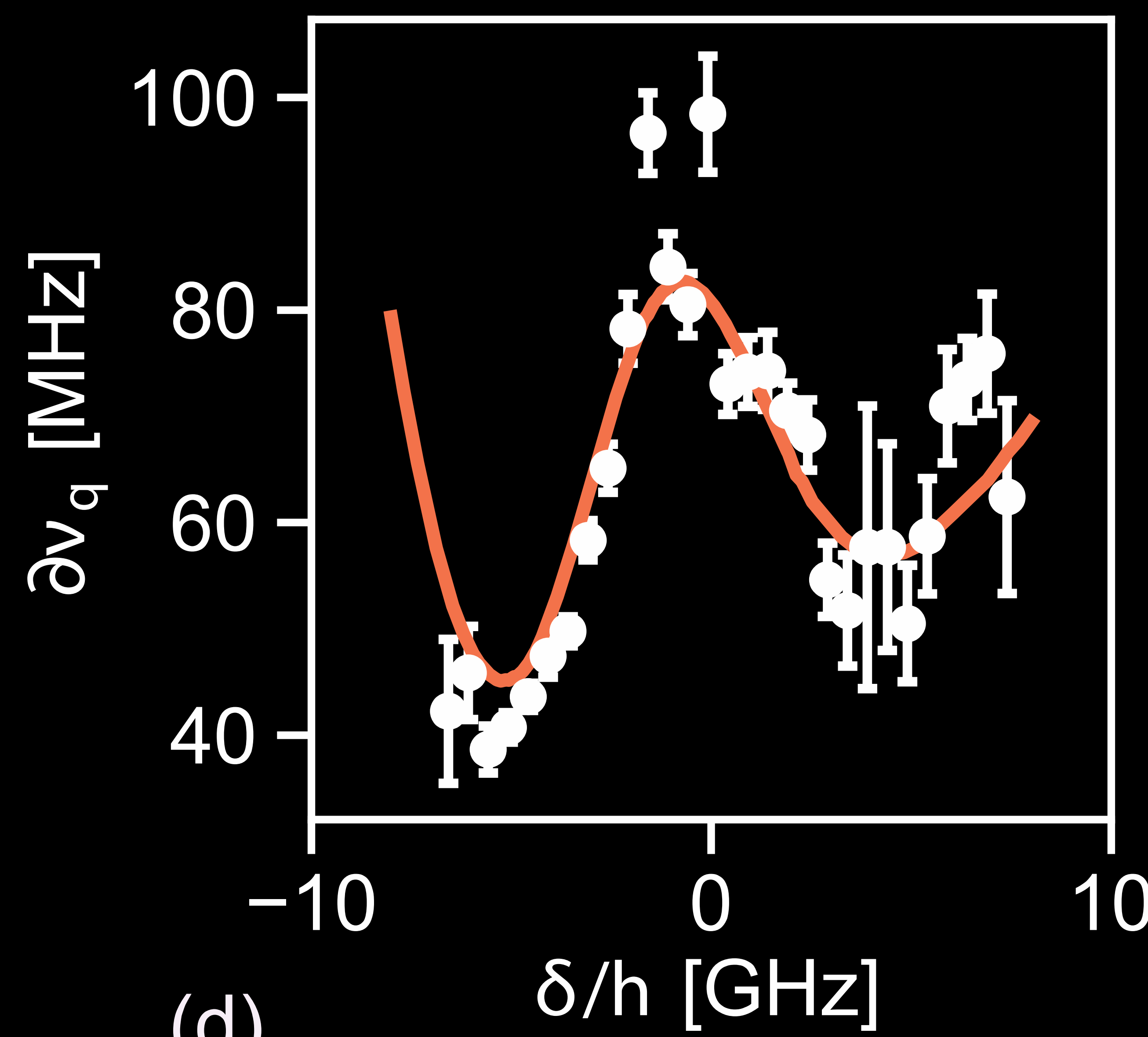
1/f noise simulations allow to fit the decoherence rate

A_{δ}=1.95 μeV

A_{EM}=0.935 μeV

ρ=-0.084

(b)



(d)

Conclusion

Superconducting resonators are a promising technology for long-range two-qubit gates

Coupling a HQ to a SCR imposes a frequency constraint.
Can be reduced by operating off-resonance

The CQ qubit allows to spatially characterize charge noise.
The experimental results seem to point towards close-range noise