Charge-Parity Switching Effects and Optimisation of Transmon Design Parameters

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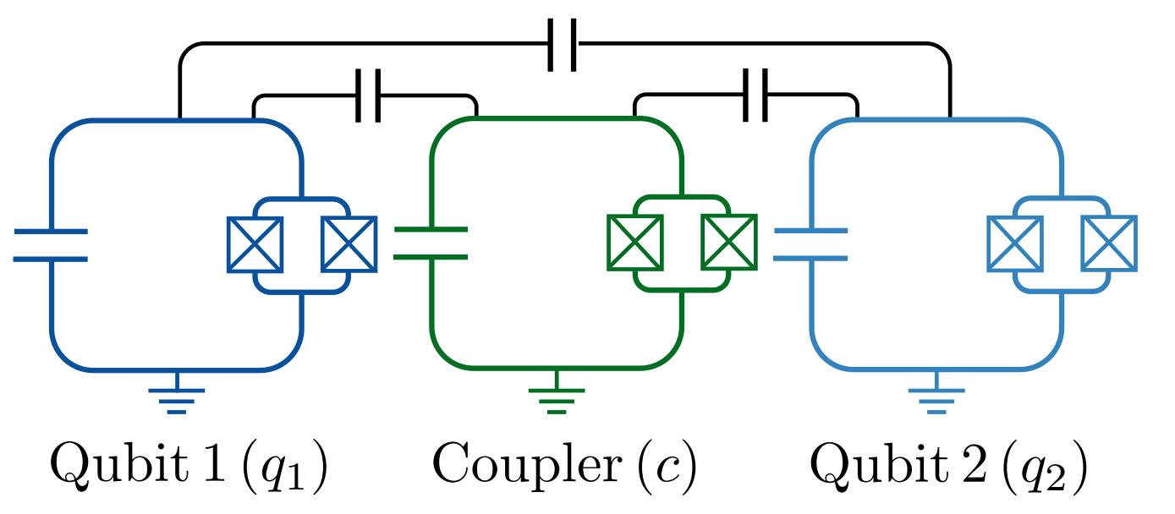
Overview

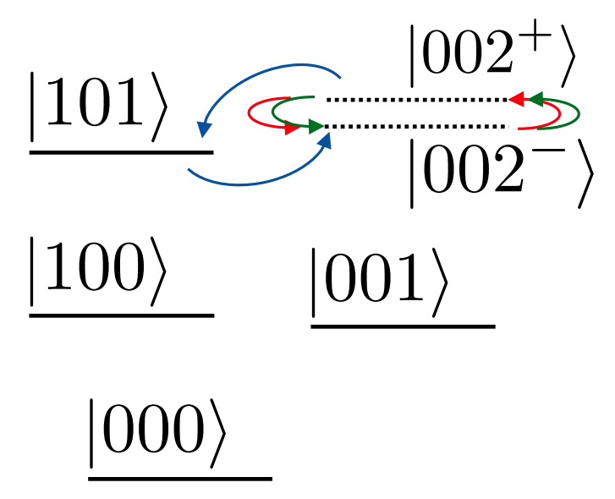
- A judicious selection of qubit design parameters plays a pivotal role in improving the performance of quantum processors.
- This requires a good understanding of the possible sources of error, beyond the coherence properties of the circuit.
- Therefore, we have analyzed the effect of charge–parity switches in the tunable coupler architecture.
- Combining this analysis with other error models enables us to optimal regions of transmon parameters [1].

Parity-Switching Errors

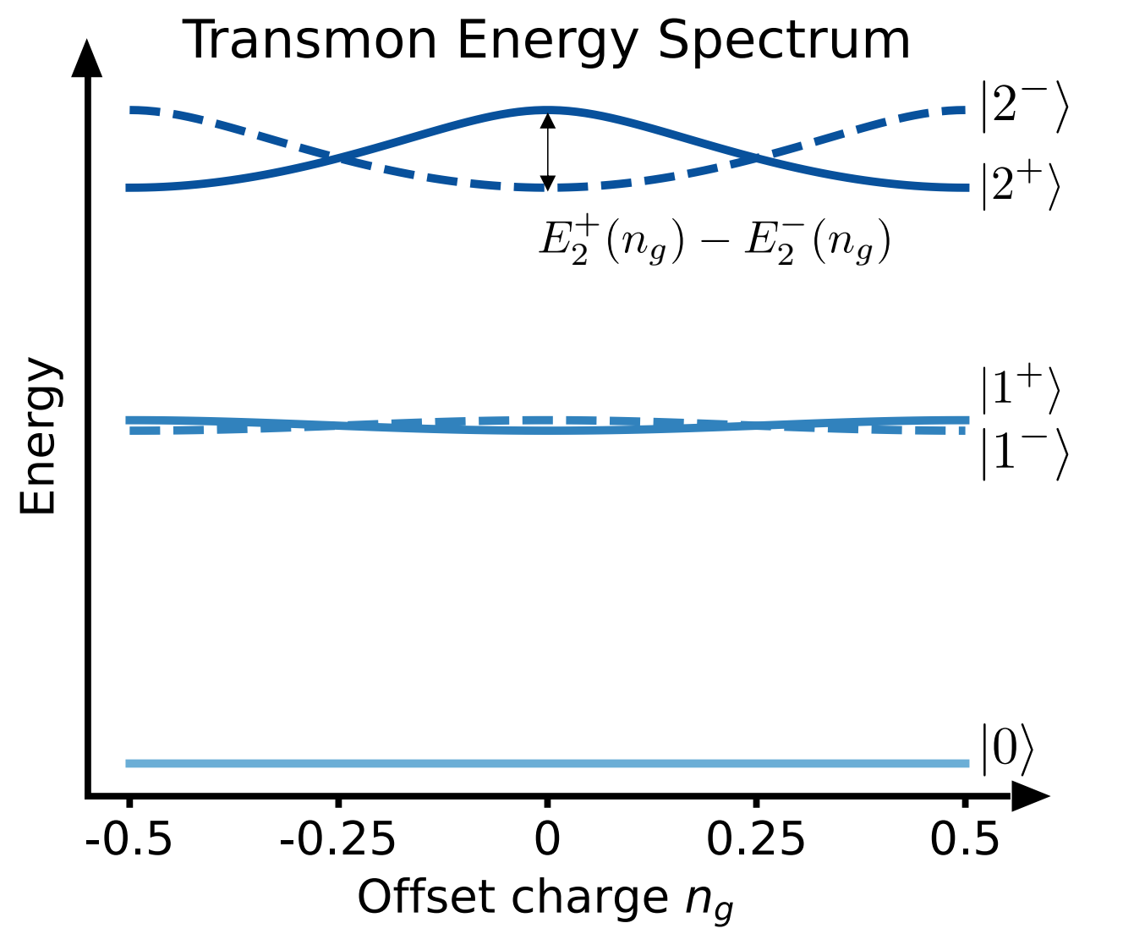
- Tunable coupler architecture [2].

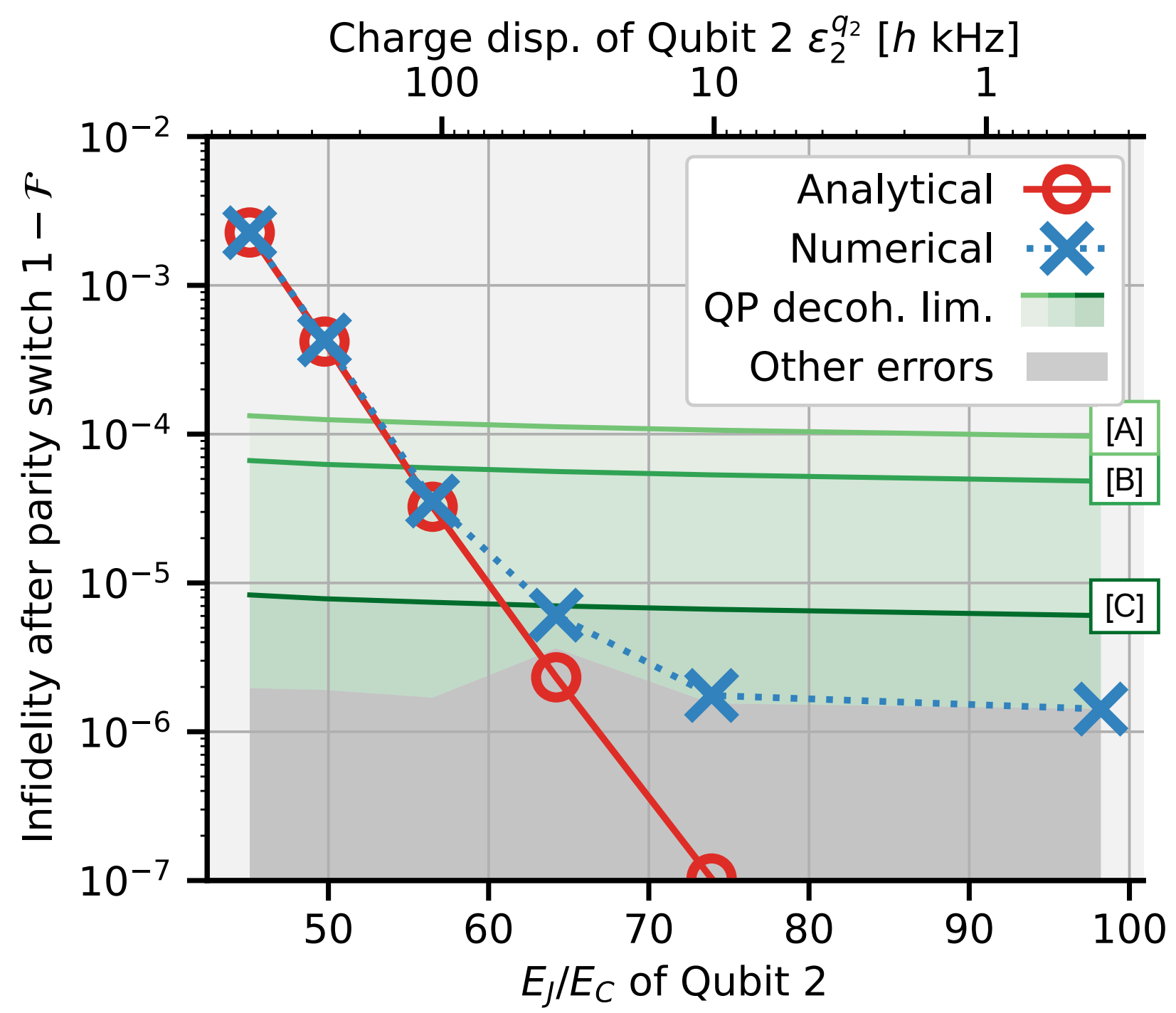


- Diabatic implementation



- Used in large-scale experiments [3].



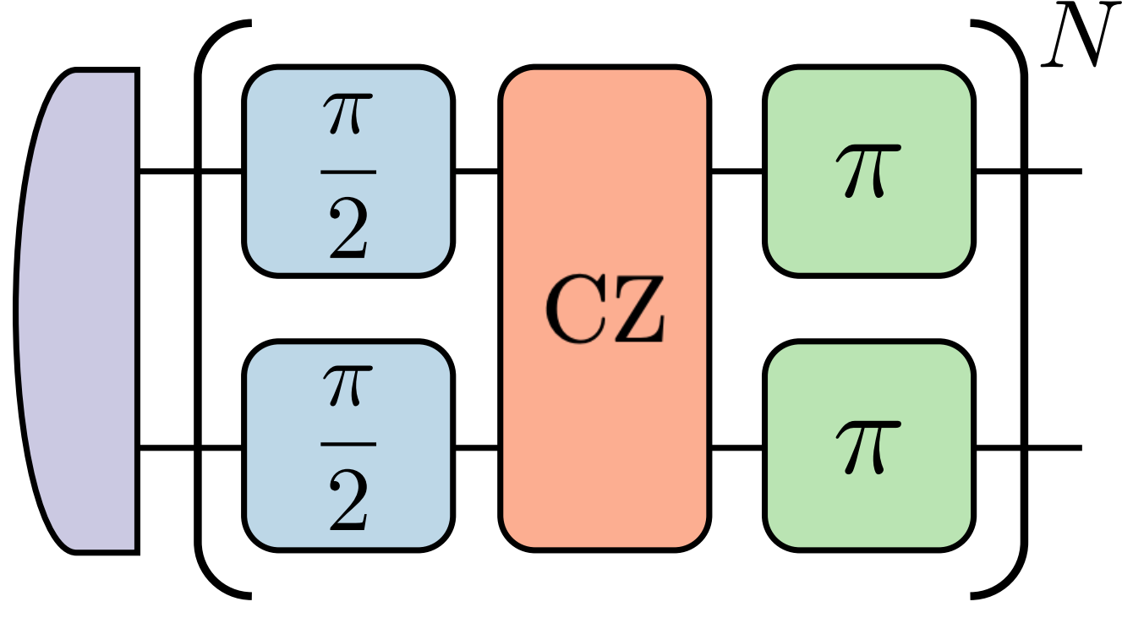


Parity-switching rate measured by:
[A] Kurter, C., *et al*. (2022), [B] Diamond, S., *et al*. (2022) and [C] Risté, D., *et al*. (2013).

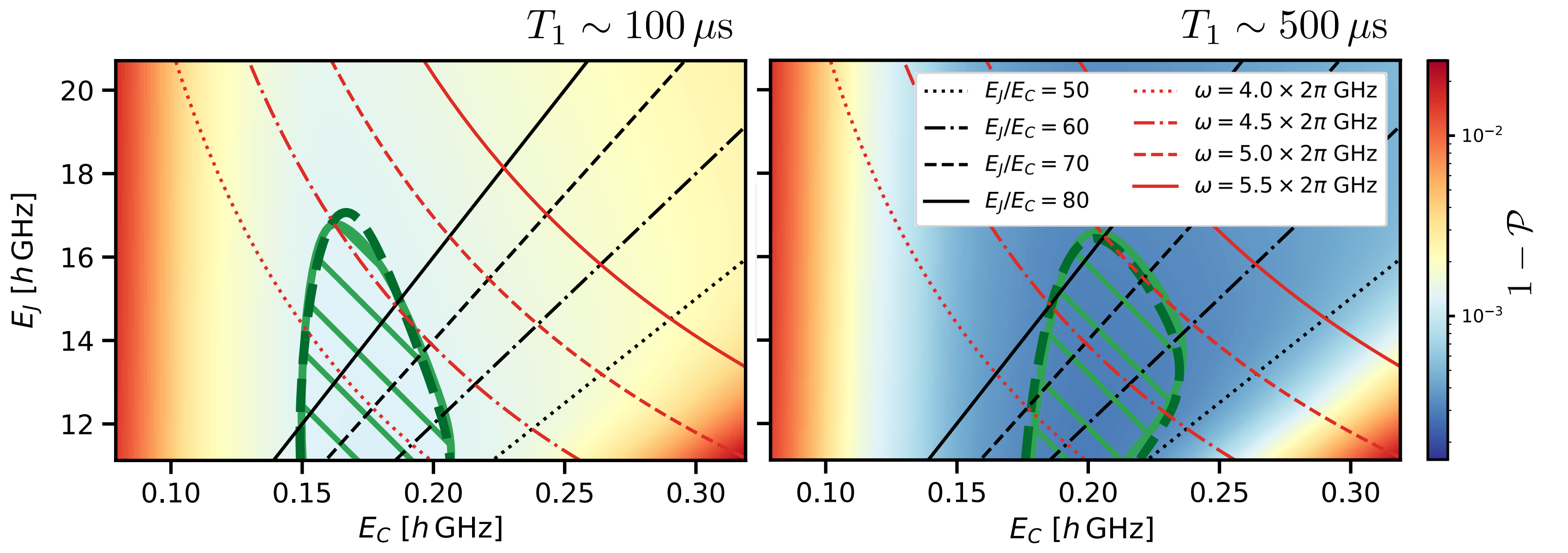
- Consider all possible errors [4]:

	Parameter scaling	Single-qubit gate infidelity	Two-qubit gate infidelity
Charge noise (T_1)	$\Gamma_1 = \frac{1}{T_1} \propto E_C^{3/2} E_J^{1/2}$	$\frac{1}{3}\Gamma_1 t_{\mathrm{SQG}}$	$\frac{2}{5}(\Gamma_1^{q_1}+\Gamma_1^{q_2})t_{\mathrm{TQG}}$
Flux noise (T_ϕ)	$\Gamma_\phi = \frac{1}{T_\phi} \propto E_C E_J$	$\frac{1}{6}\Gamma_\phi t_{\mathrm{SQG}}$	$\frac{1}{5}(\Gamma_\phi^{q_1}+\Gamma_\phi^{q_2})t_{\mathrm{TQG}}$
Leakage	$P_{\mathrm{leak.}} \propto E_C^{-\gamma}, 5 \lesssim \gamma \lesssim 6$	$\frac{1}{3}P_{\mathrm{leak.}}$	/
Parity Switch	$(\delta\phi)^2 \propto e^{-2\sqrt{8E_J/E_C}} E_C^{1/2} E_J^{7/2}$	/	$\frac{3}{80}\left(\frac{t_{\mathrm{TQG}}}{2\hbar}\varepsilon_2^{q_2}\right)^2$
Thermal excitation	$P_{\|1\rangle}/P_{\|0\rangle} = e^{-\beta(\sqrt{8E_J E_C}-E_C)}$	$P_{\|1\rangle}$	/

- Define a performance metric as a weighed infidelity sum, considering the frequency of each error source, e.g.

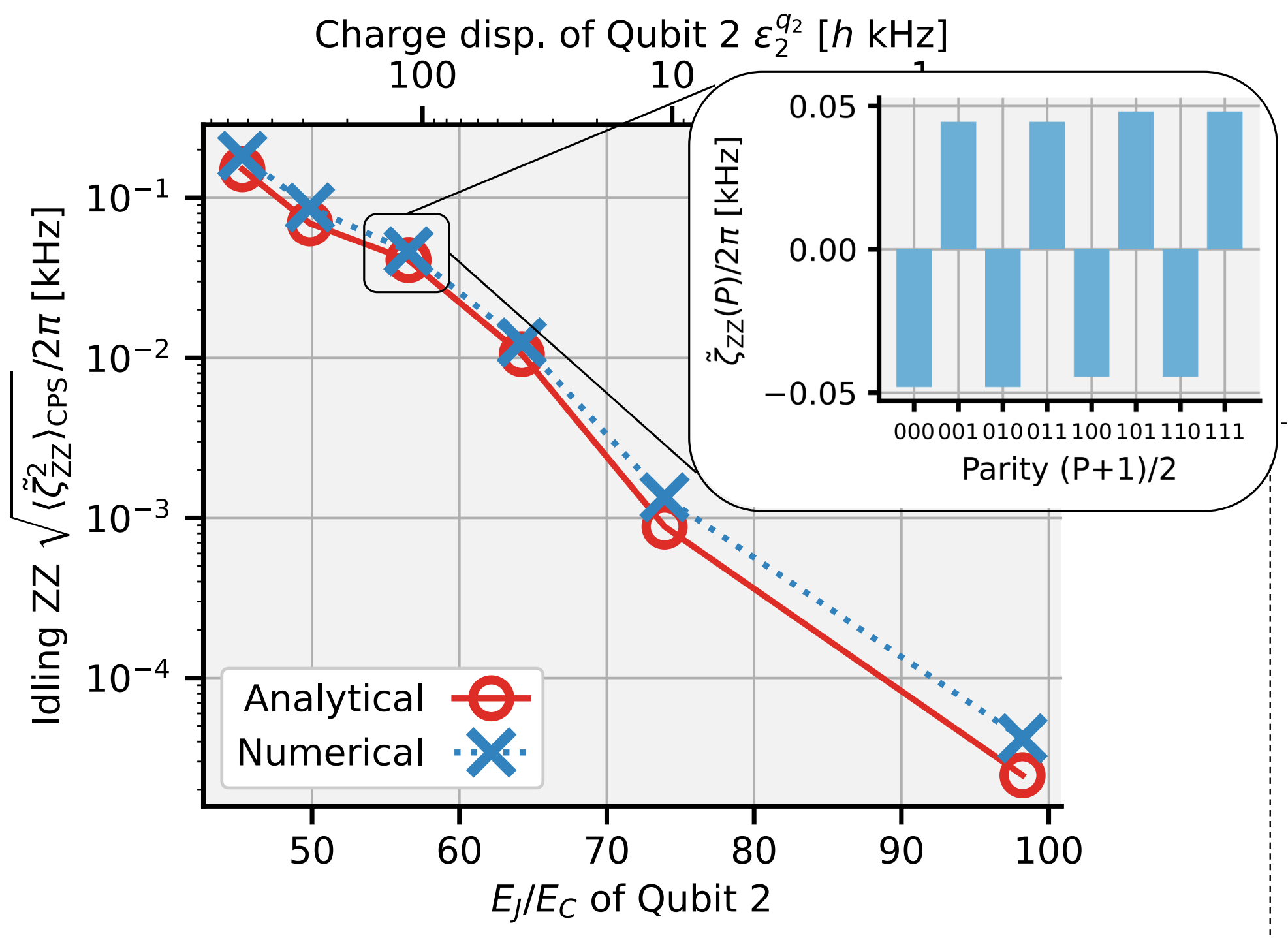


$$1-\mathcal{P} = \sum_{i=T_1,T_\phi,\mathrm{parity}} w_{\mathrm{TQG},i}(1-\mathcal{F}_{\mathrm{TQG},i}) + \sum_{i=q_1,q_2}\sum_{j=T_1,T_\phi,\mathrm{leak.}} w_{\mathrm{SQG},i,j}(1-\mathcal{F}_{\mathrm{SQG},i,j}) + \sum_{i=q_1,q_2} w_{\mathrm{SP},i}(1-\mathcal{F}_{\mathrm{SP},i}),$$



Residual Longitudinal Interaction

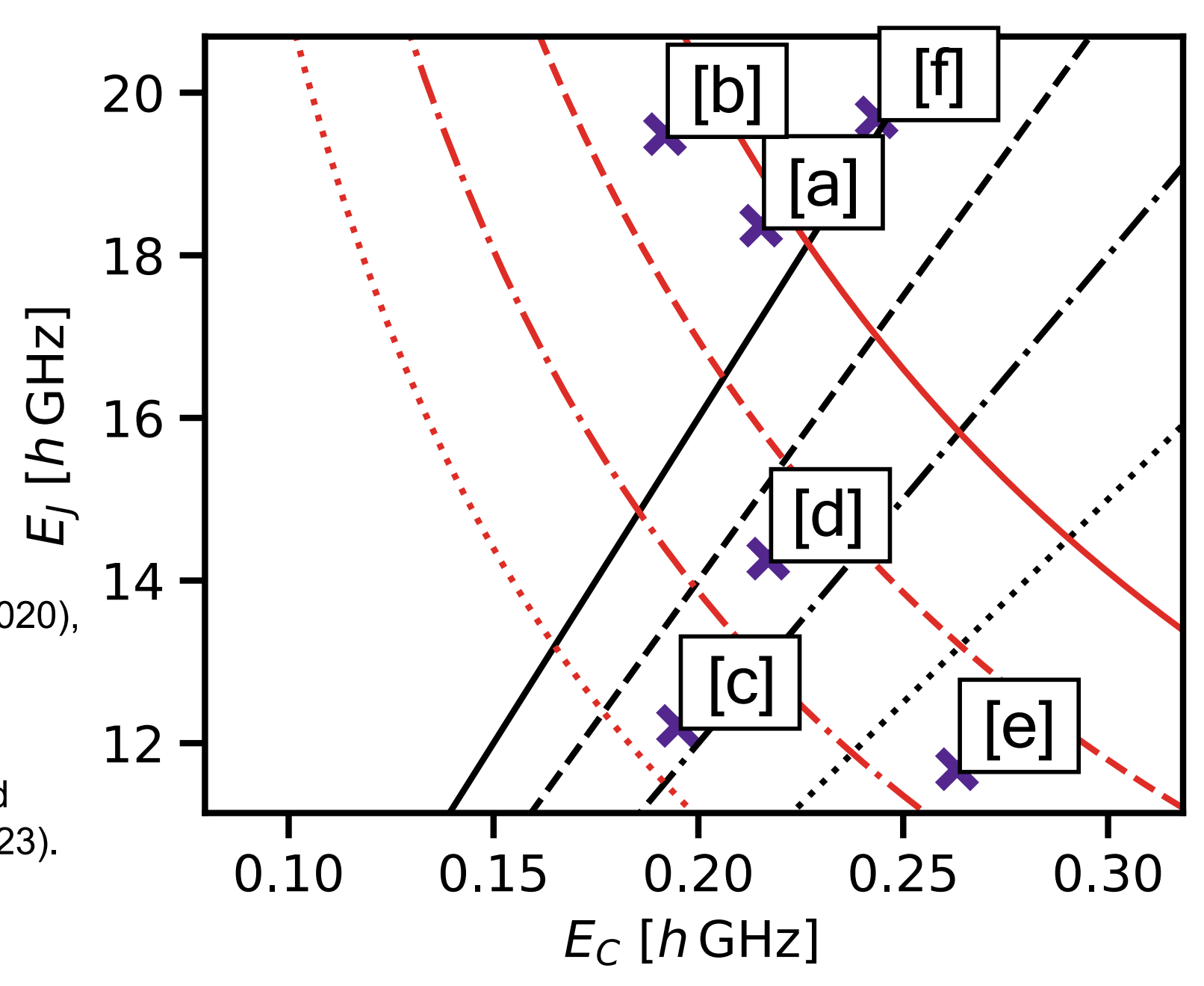
- The tunable coupler enables us to completely suppress the residual ZZ-interaction.
- This is no longer true due to stochastic parity switches.
- We define a parity-averaged coupling rate:



Optimal Transmon Parameters

- What is a good choice for E_J and E_C?
- Some examples from the literature*:

* Extracted assuming no higher harmonics are present in the JJ



[a] Collodo, M. C., et al. (2020),
[b] Xu, Y., et al. (2020),
[c] Sung, Y., et al. (2021),
[d] Wu, Y., et al. (2021),
[e] Xu, H., et al. (2021) and
[f] Google Quantum AI (2023).

Conclusions

- Charge-parity-switching errors can be the dominant QP-related error mechanism in diabatic CPHASE gates.
- Stochastic charge-parity switches will induce a residual ZZ-interaction between the qubits.
- Such effects should be considered when higher-excited states are employed.
- Good error modelling can be utilized to find optimal transmon parameter regimes, thus ensuring continuous improvement as coherence times increase.

References

[1] M. Papič, *et al.*, arXiv:2309.17168
[2] Y. Sung, *et al.*, Phys. Rev. X **11**, 021058 (2021)
[3] Google Quantum AI, Nature **614**, 676-681 (2023)
[4] M. Papič, *et al.*, arXiv:2305.08916