# Simulated frequency crowding constraints for modular quantum architecture design

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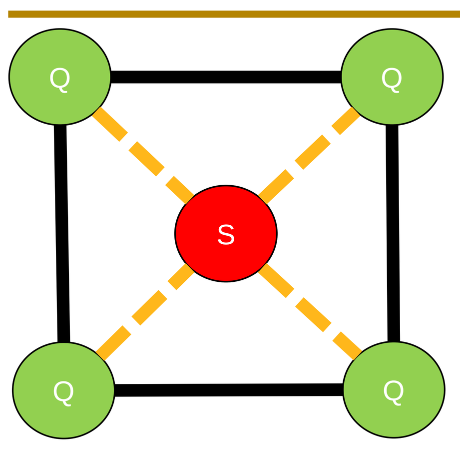
**Objective**: Use simulations to investigate *quantum architecture design tradeoffs* for (a) residual qubit couplings (spectators) and (b) frequency crowding requirements, for varying coupling strengths.



A modular unit couples all qubits via hybridization to a central SNAIL with strength $\lambda = \frac{g}{\Delta}$

Δ = frequency difference

$$H_L = w_s \hat{s}^\dagger \hat{s} + \sum_i \hat{q}_i^\dagger \hat{q}_i \quad H_{NL} = g_s(\hat{s} + \hat{s}^\dagger)^3 + \sum_i \frac{\alpha_i}{12}(\hat{q}_i + \hat{q}_i^\dagger)^4$$

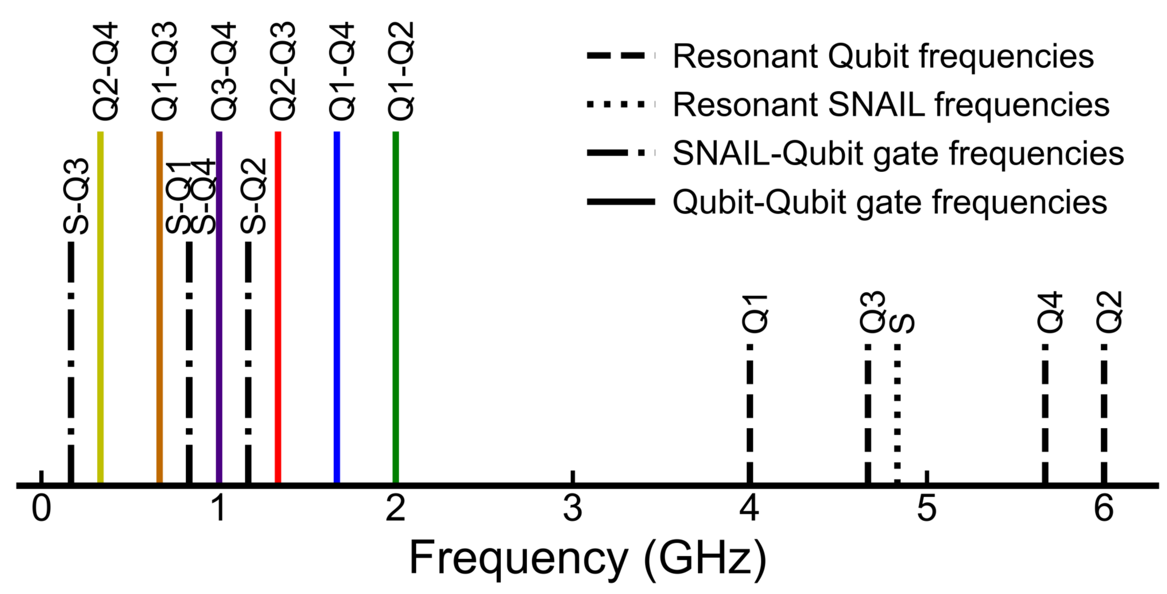
$$H_{coupling} = (\sum_i g_{s,q_i}(\hat{q}_i^\dagger \hat{s} + \hat{q}_i \hat{s}^\dagger)) + (\sum_i \sum_j g_{q_i,q_j}(\hat{q}_i^\dagger \hat{q}_j + \hat{q}_i \hat{q}_j^\dagger))$$

$$H_{pump} = [\epsilon(t)e^{-iw_p t} + \epsilon^*(t)e^{iw_p t}](\hat{s}^\dagger + \hat{s})$$

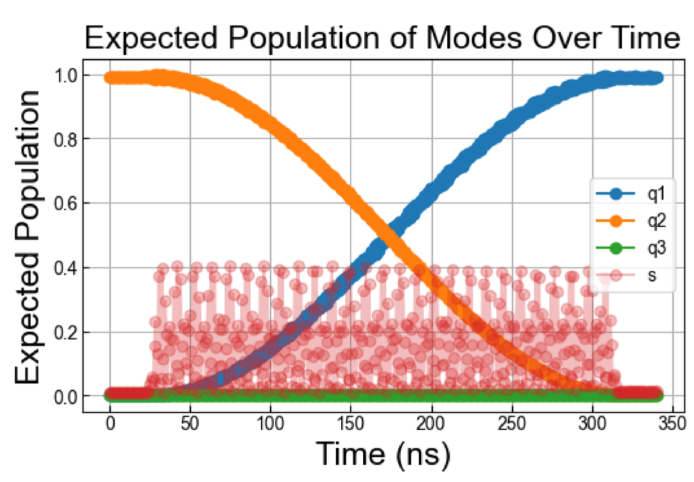
RWA ↓ Stiff pump ↓ Keeping slow oscillating terms and removing SNAIL-involved terms

$$H_{eff} = \sum_i \sum_j 6\lambda_{s,q_i}\lambda_{s,q_j} q_i q_j^\dagger [\eta e^{-i(w_i - w_j + w_p)t} + \eta^* e^{-i(w_i - w_j - w_p)t}]$$

Parametric interactions determined by differences in resonant mode frequencies




Frequency allocation for an ideal iSWAP




$$iSWAP = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

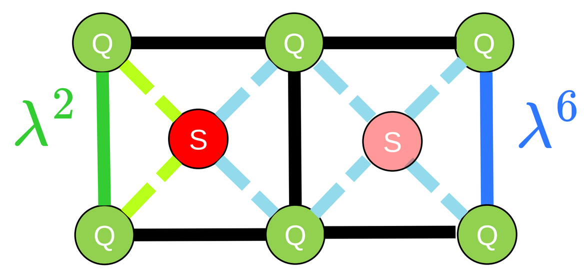
SNAIL drives iSWAP between qubit 1 and qubit 2

## Conclusions:

- Stronger hybridization (λ) makes faster gates but more noise from spectators
- Increase in λ from .1 to .3 resulted in decreasing fidelity gap for $\lambda^2 \rightarrow \lambda^4$ from **roughly 3 orders of magnitude to 2**
- Increased qubit density reduces SWAP overhead but with frequency crowding
- As gates become increasingly far from pumped SNAIL, fidelity grows from ~.3 to >.99 for intramodular vs intermodular gates

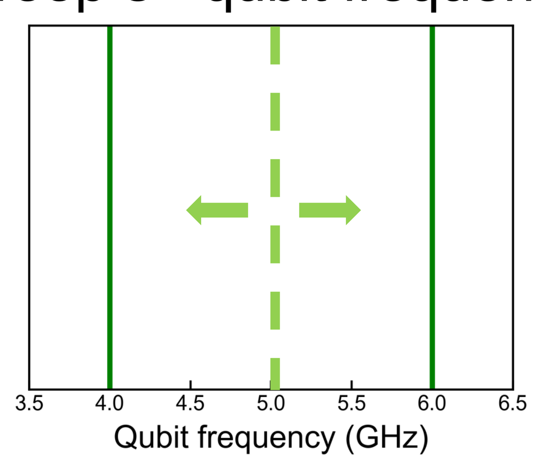
[1] Zhou, et al. **npj Quantum Inf.** (2023)
[2] Ding, et al **MICRO** (2020)
[3] Zajac, et al. ***arXiv:2108.11221*** (2021)
[4] Sete, et al **arXiv:2402.04238** (2024)

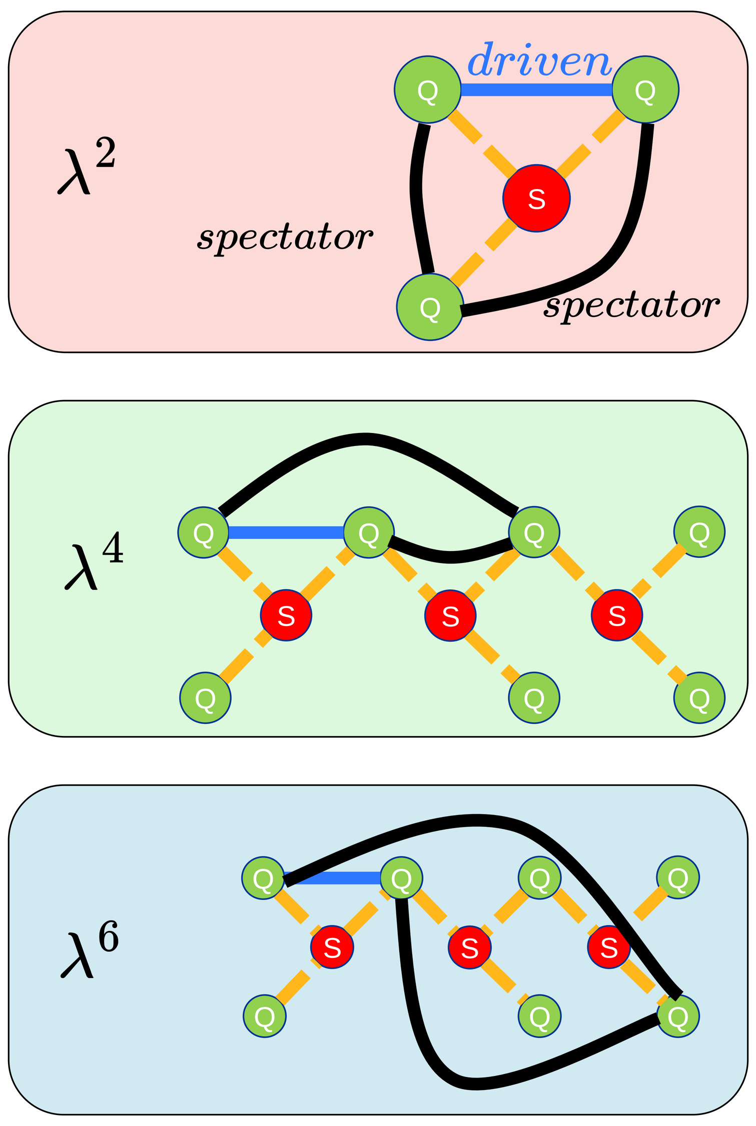
## Simulated qubit spectators:

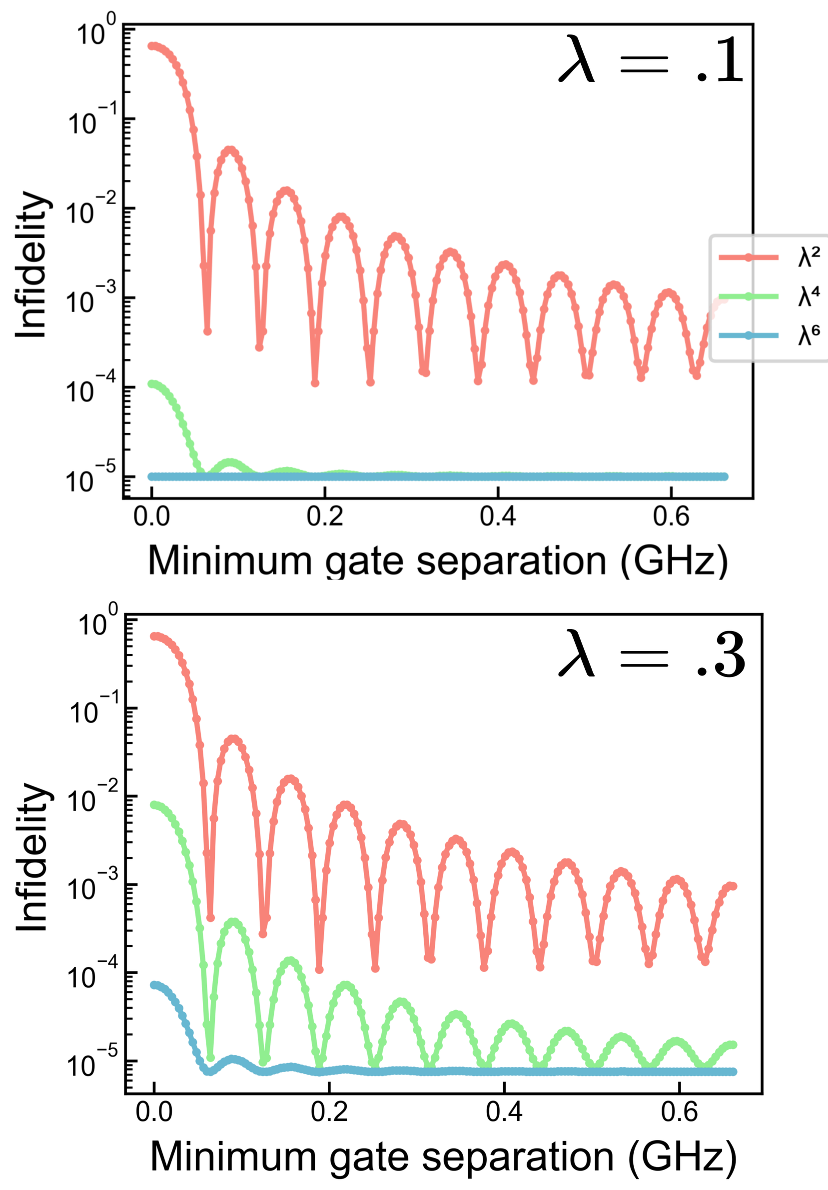



$\lambda^n$, n = total distance through hybridized modes

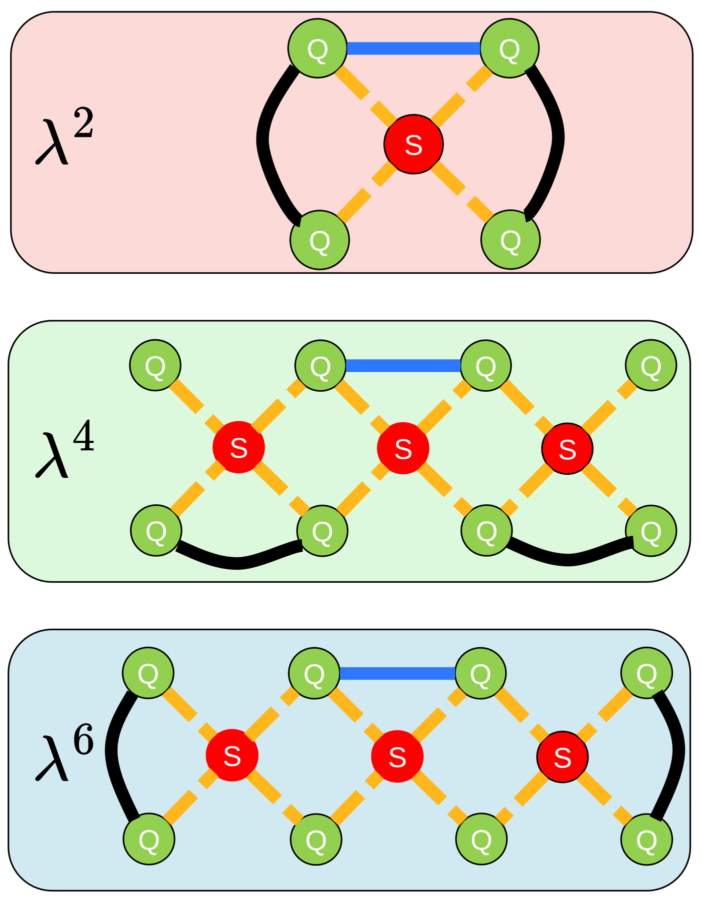
Sweep 3[rd] qubit frequency



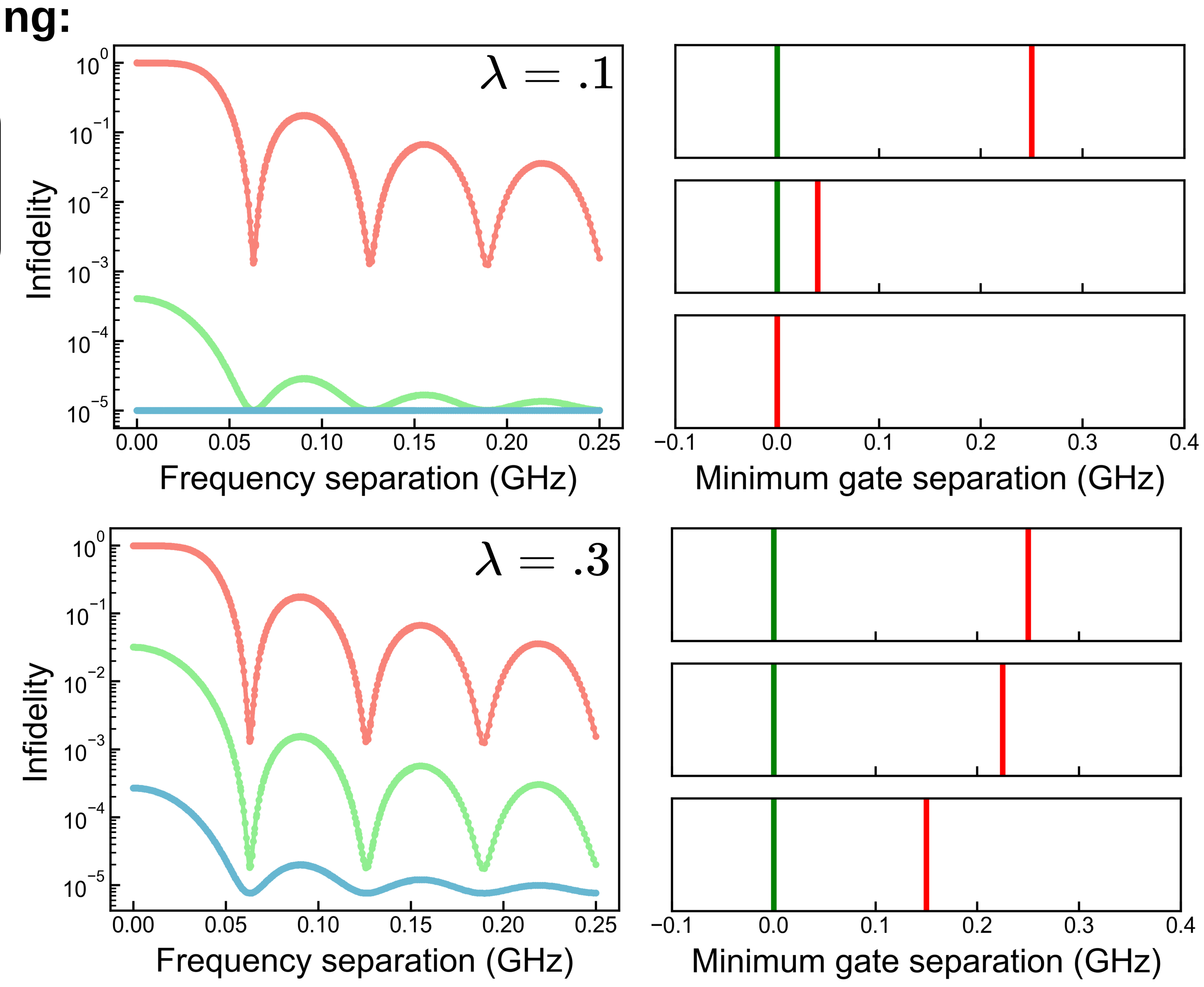




## Simulated gate crowding:



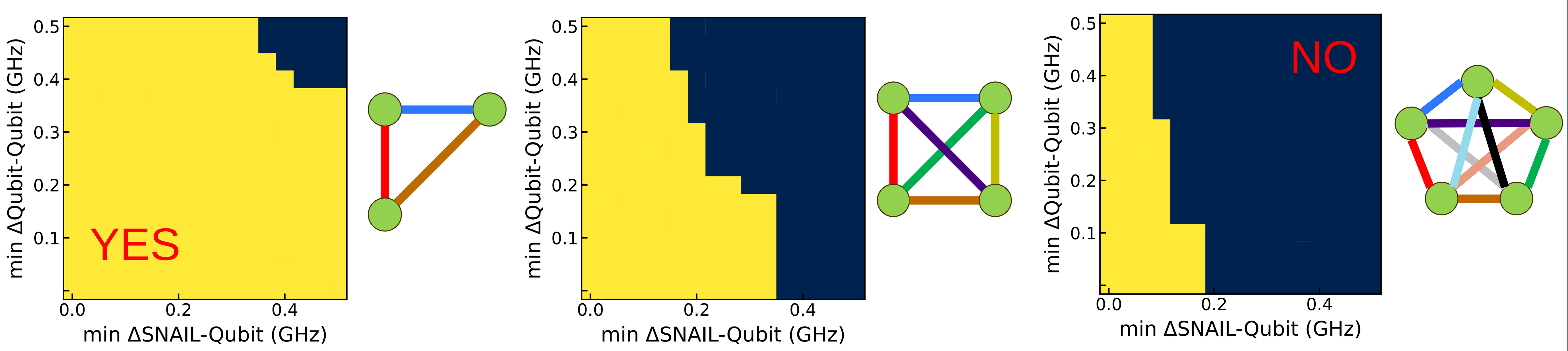

As hybridization (λ) increases, driven gate's radius of influence increases



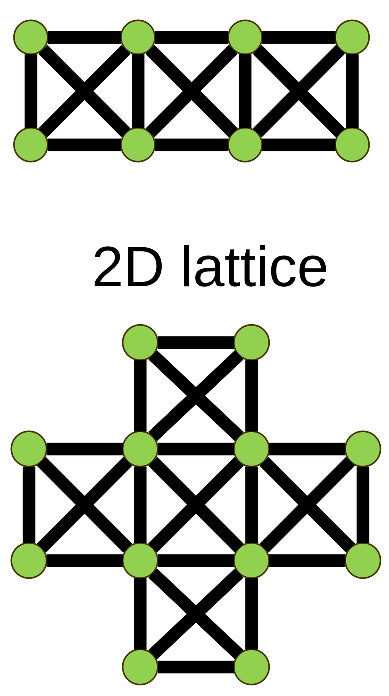

## Discrete frequency allocation:

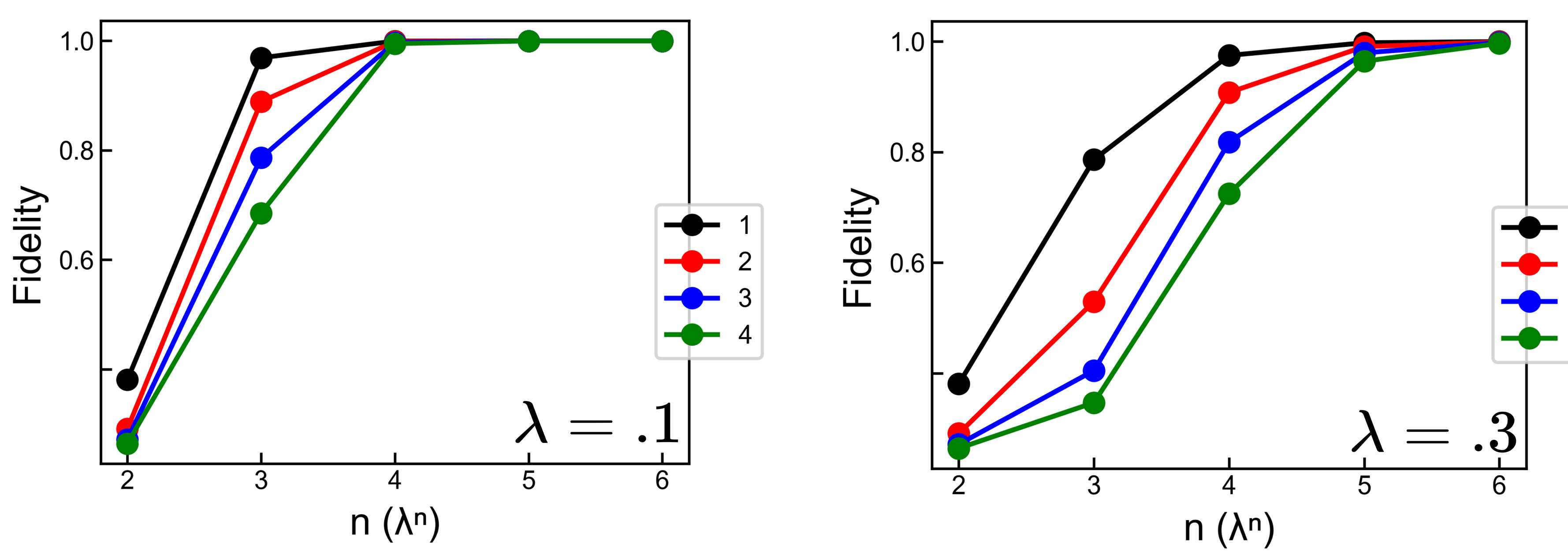
Frequency packing grows factorially with # qubits

### When is frequency allocation feasible?




### Separation required for high fidelity gates?




Interaction influence scales with number of neighboring modules