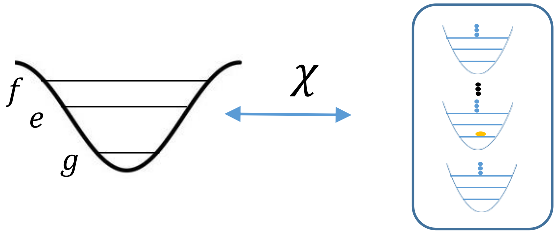
Fast Control of Multimode Cavities with Conditional Displacements

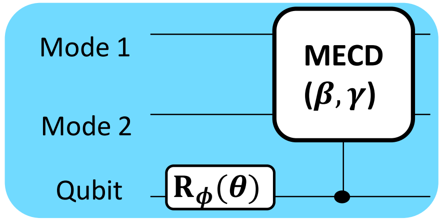
Eesh Gupta, S. Chakram, …

Outline

Challenges in Cavity Control



Multimode Conditional Displacements



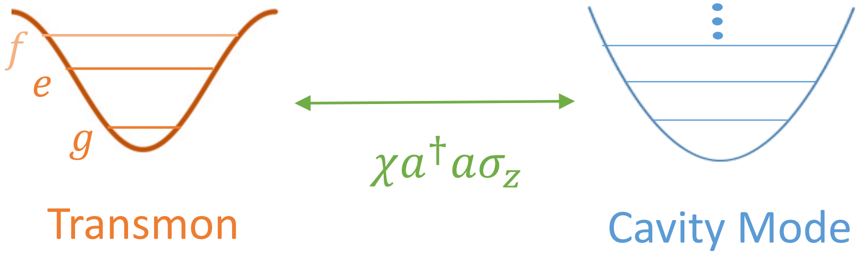
Alternative Schemes:
Circle Grape and Sideband Driving

3D Cavity QED

- High Coherence times compared to superconducting circuits [1,2]
  - $T_1 \sim 2$ ms for Al. Cavities [ref?]
  - $T_1 \sim 35$ ms $-$ 2 s for Nb. Cavities

[1] Romanenko, A., et al. *Physical Review Applied* 13.3 (2020): 034032.

- Infinitely large Hilbert Space and simple decoherence processes → hardware efficient error correction [2]
- Universal control via coupling to anharmonic systems [2]



<u>Goal</u>: Enact **high-speed** operations on cavity modes while **minimizing ancilla errors**

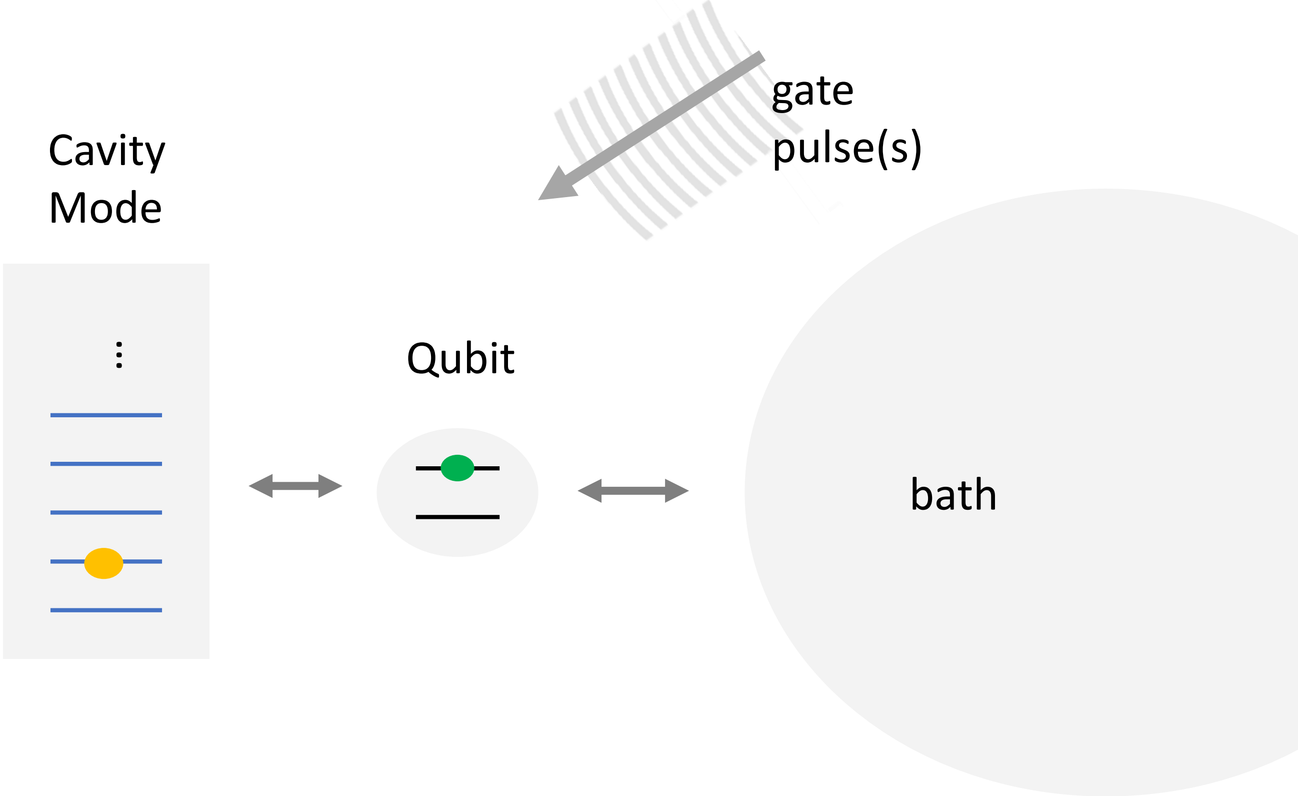
[2] Ma, Wen-Long, et al. *Science Bulletin* 66.17 (2021): 1789-1805.

Challenges in Cavity Control I

Coupling to lossy ancilla ⇨ source of error for high-Q cavities!

Transmon Relaxation

- Gate Errors dominated by ancilla coherence
- $\epsilon \sim \frac{\gamma_q}{\chi} = \frac{1}{(\chi T_q)}$
- Mitigate by strong $\chi \gg \gamma_q \sim 10$ kHz



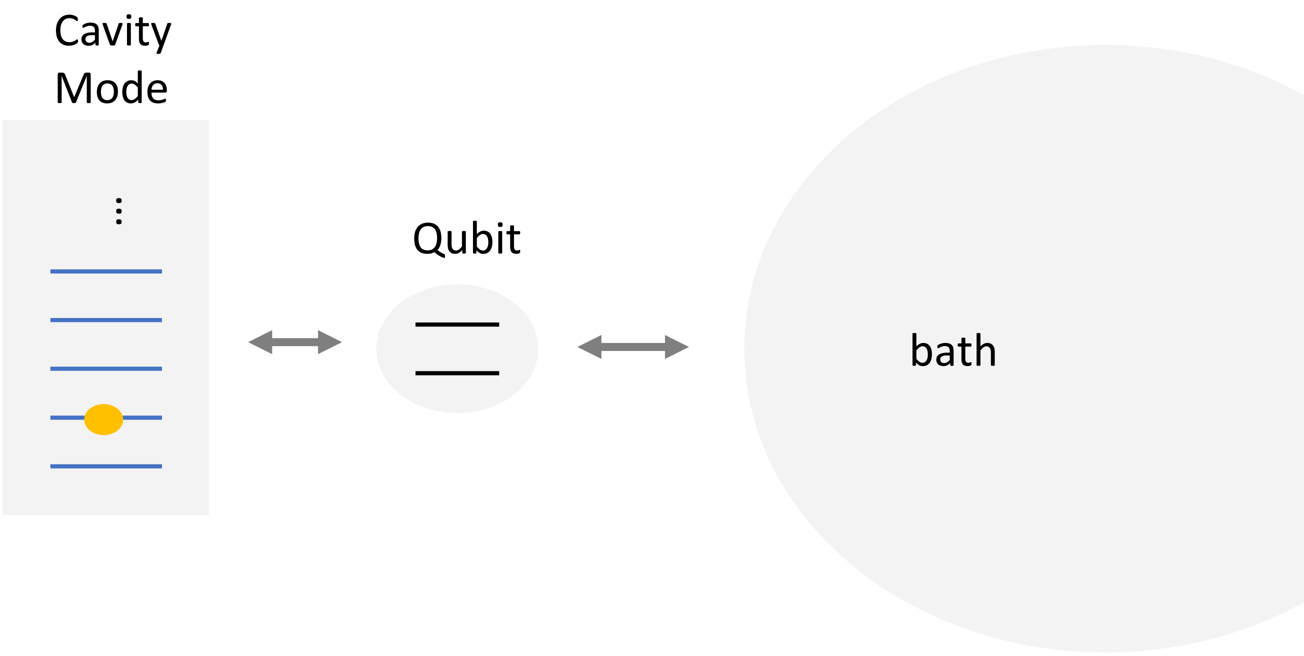
Eickbusch, A., Sivak, V., Ding, A.Z. et al. *Nat. Phys.* ***18***, 1464–1469 (2022)

Challenges in Cavity Control II

Coupling to lossy ancilla ➡ source of error for high-Q cavities!

Inverse Purcell Effect

- Coupling to lossy ancilla reduces mode coherence
- $T_1^{cav} \leq \frac{\Delta^2}{g^2} T_1^q \sim \frac{2\alpha}{\chi} \mathrm{T}_1^{\mathrm{q}}$
- Mitigate by weak $\chi \sim 10$ kHz



Boissonneault, M., et al. Physical Review A, 79(1), 013819.(2009)

Challenges in Cavity Control III

Coupling to lossy ancilla $\Rightarrow$ source of error for high-Q cavities!

Transmon Relaxation

Strong $\frac{\chi}{2\pi} \gg \gamma_q \sim 10$ kHz

Inverse Purcell Effect

Weak $\frac{\chi}{2\pi} \sim 10$ kHz

Conditional Displacement Gates

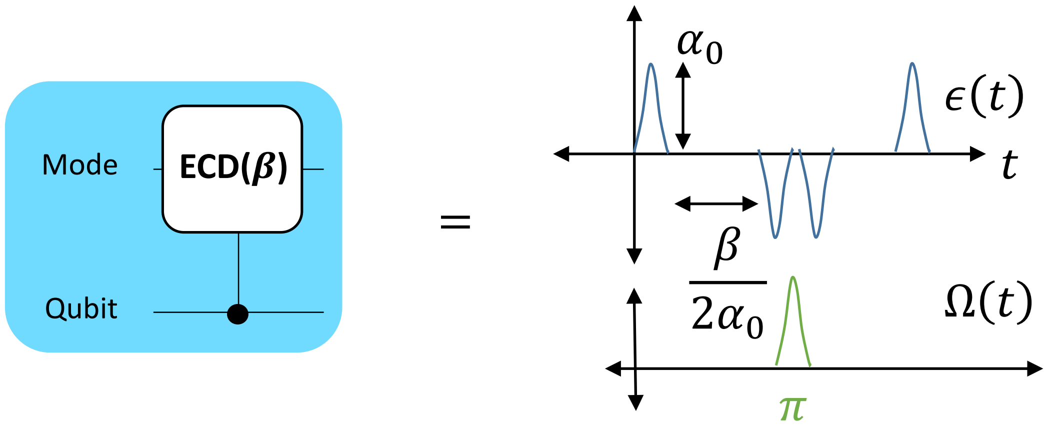
- large displacements of cavity mode to enhance gate speed

- Weak $\chi/2\pi \sim 30$ kHz but strong $\chi\alpha_0/2\pi \sim 1$ MHz

- Symmetric pulse sequences to isolate conditional displacement term in Hamiltonian.

- Universal control of single mode + qubit with $\{ECD(\beta),\ R_\phi(\theta)\}$

$$\chi a^\dagger a \sigma_z \xrightarrow[\alpha_0 \sim 30]{D(\alpha_0)} \boxed{\chi\,(\alpha_0 a^\dagger + \alpha_0^\star a)\,\sigma_z}$$



- Hacohen-Gourgy, S., Martin, L., Flurin, E. *et al.* *Nature* **538**, 491–494 (2016).
- Eickbusch, A., Sivak, V., Ding, A.Z. et al. *Nat. Phys.* 18, 1464–1469 (2022)

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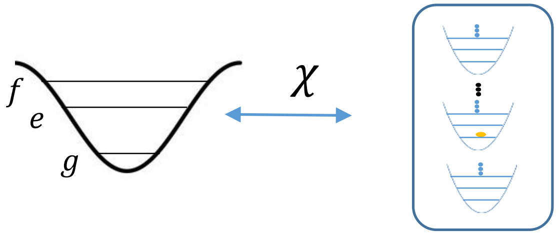
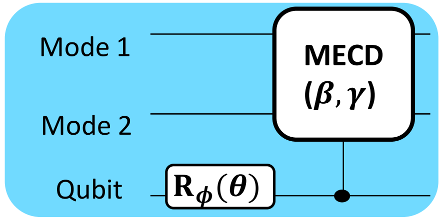
Challenges in Cavity Control



Multimode Conditional Displacements



Alternative Schemes:
Circle Grape and Sideband Driving

Coherent Errors

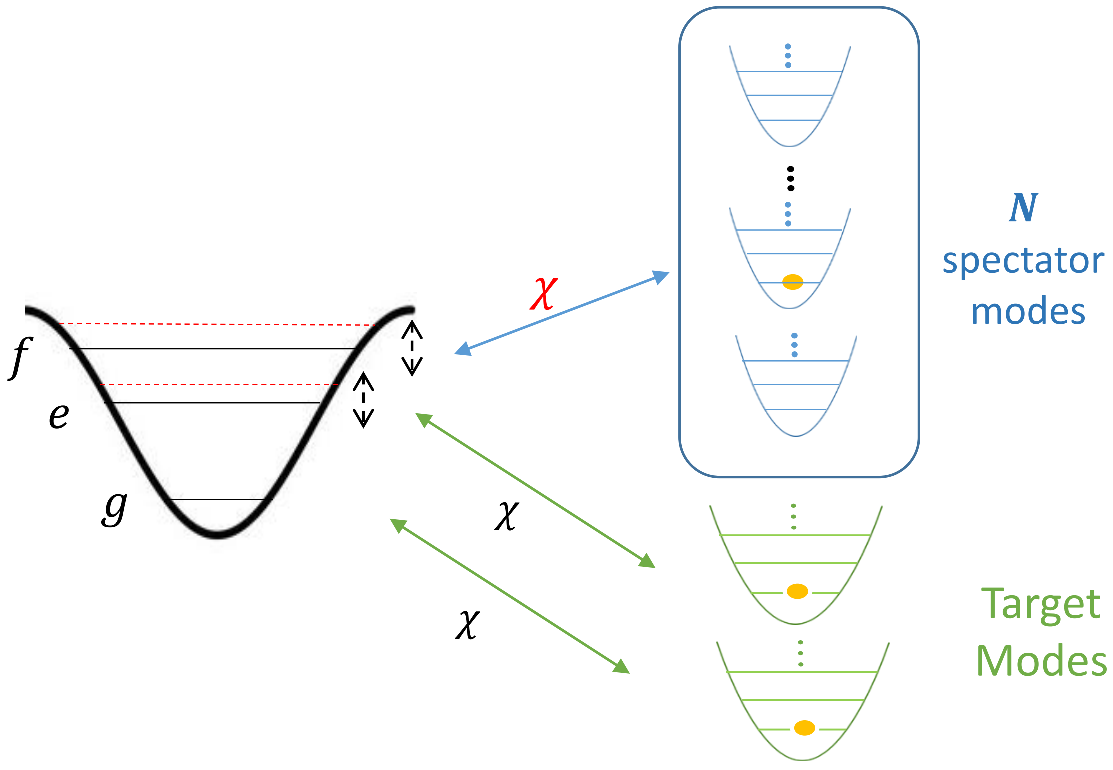
- Dispersive shift causes frequency shifts in transmon from photons in spectator modes

- Weaker χ and faster gate speeds mitigates this cross-talk error

- ϵ_{coh} = (Spurious Shifts)*(gate speed)

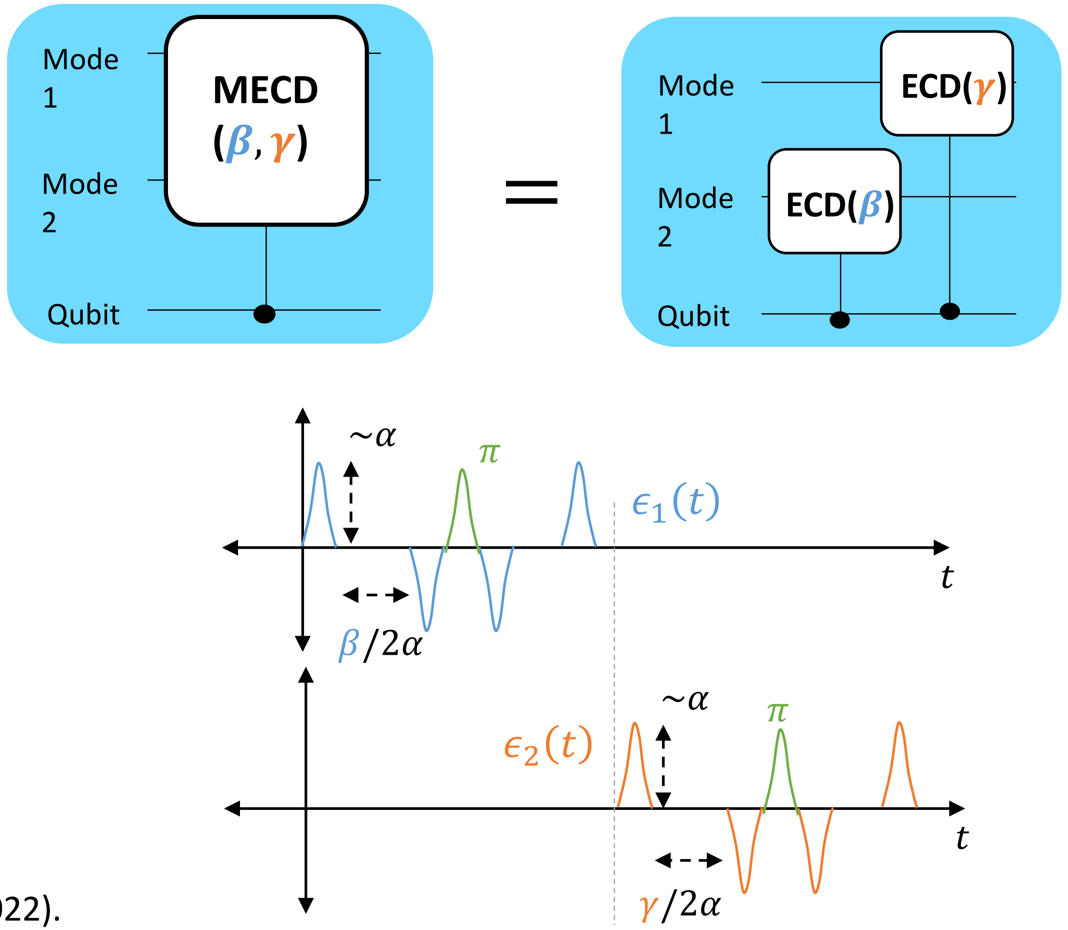
$$= \frac{N\chi}{\chi\alpha} = \frac{\boldsymbol{N}}{\boldsymbol{\alpha}} \sim 10\%$$

$N \sim 3$
$\alpha \sim 30$



Multimode ECD

- Sequentially acting ECD Gates on each mode
- Driving modes one at a time to avoid heating effects and amplifying cross kerr interaction [1, 2]
- Instead of enhanced cross kerr interaction, rely on JC-like interaction between ‘tunable qubit’ and modes



[1] Eickbusch, Alec , et al. W34. 00005. APS March Meeting (2022).
[2] Diringer, Asaf A., et al. *arXiv preprint arXiv:2301.09831* (2023).

Multimode ECD

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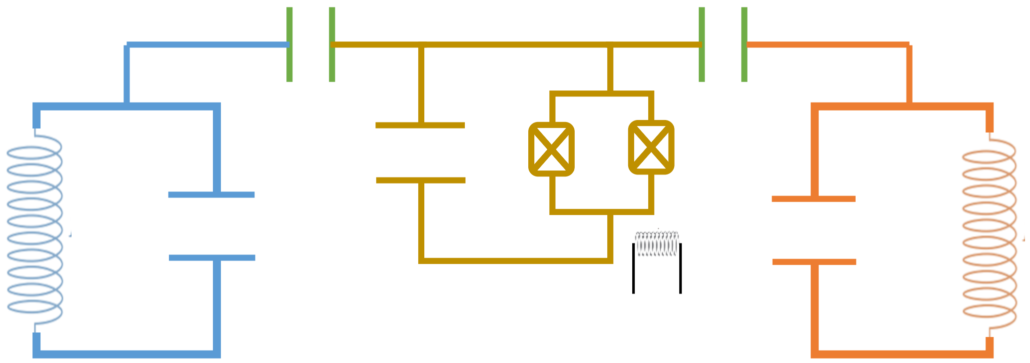
$$H_{\text{had}} = \underbrace{\sum_{i=1,2} \chi_i \alpha_i \left(a_i^\dagger + a_i\right)\sigma_x}_{\text{Jaynes Cummings}} + \underbrace{\Omega(t)\sigma_z}_{\text{Tunable Qubit}}$$



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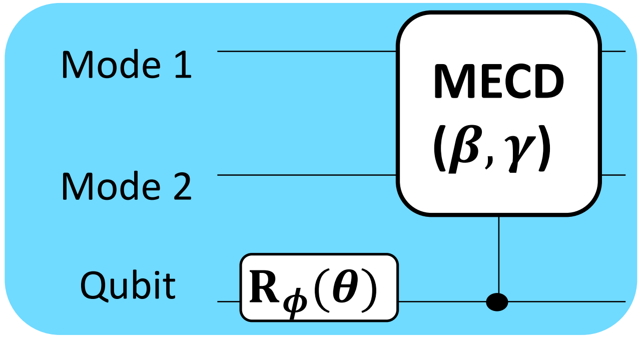
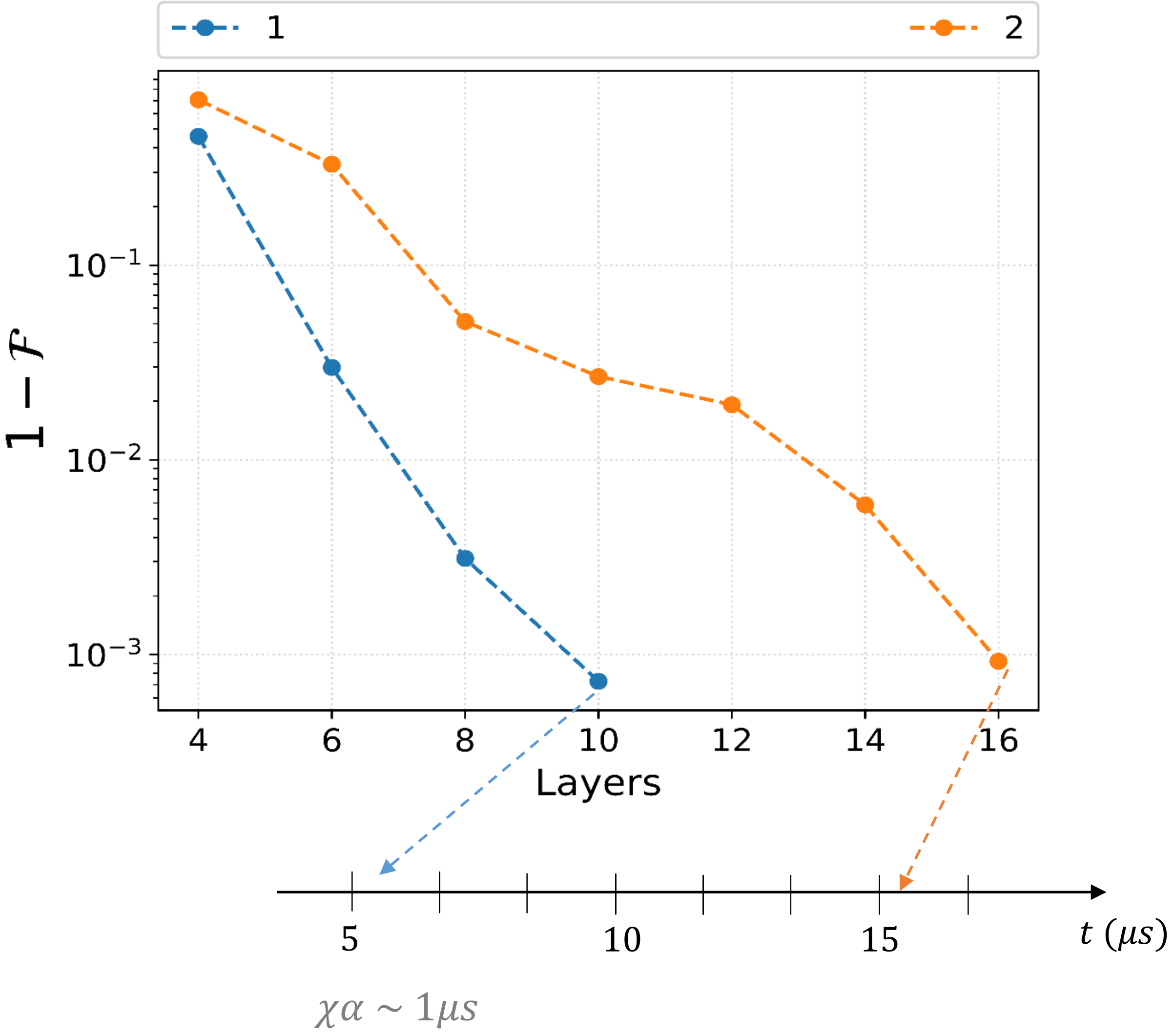
Multimode ECD: State Transfer I

- Task: $\mathrm{g} \otimes |n0\rangle \rightarrow \mathrm{g} \otimes |0n\rangle$

- Optimized Pulse Sequences with fidelity < 1e-3

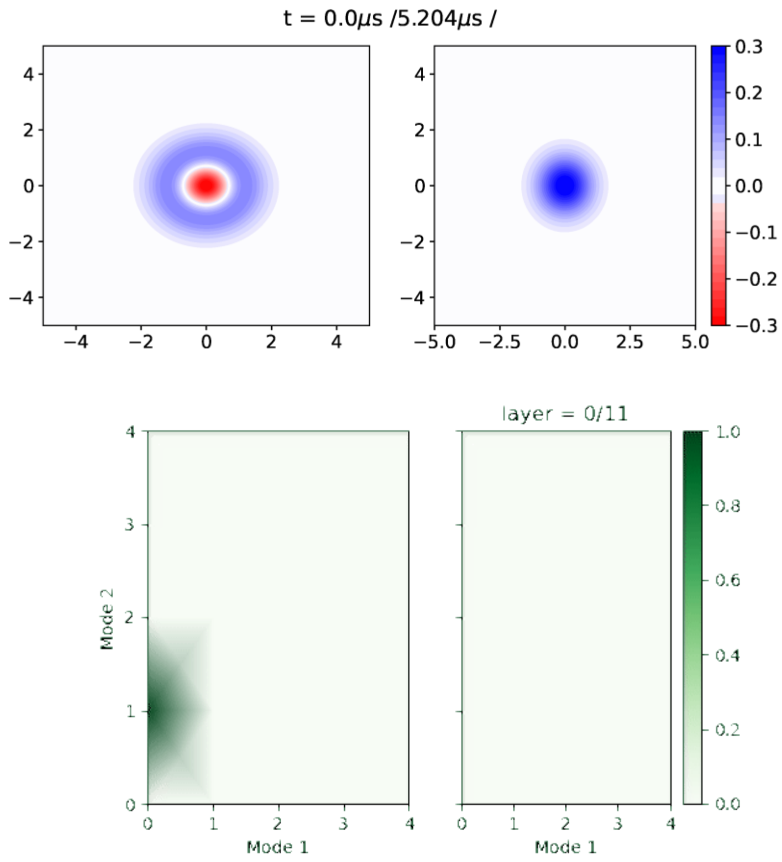
1 layer/depth =



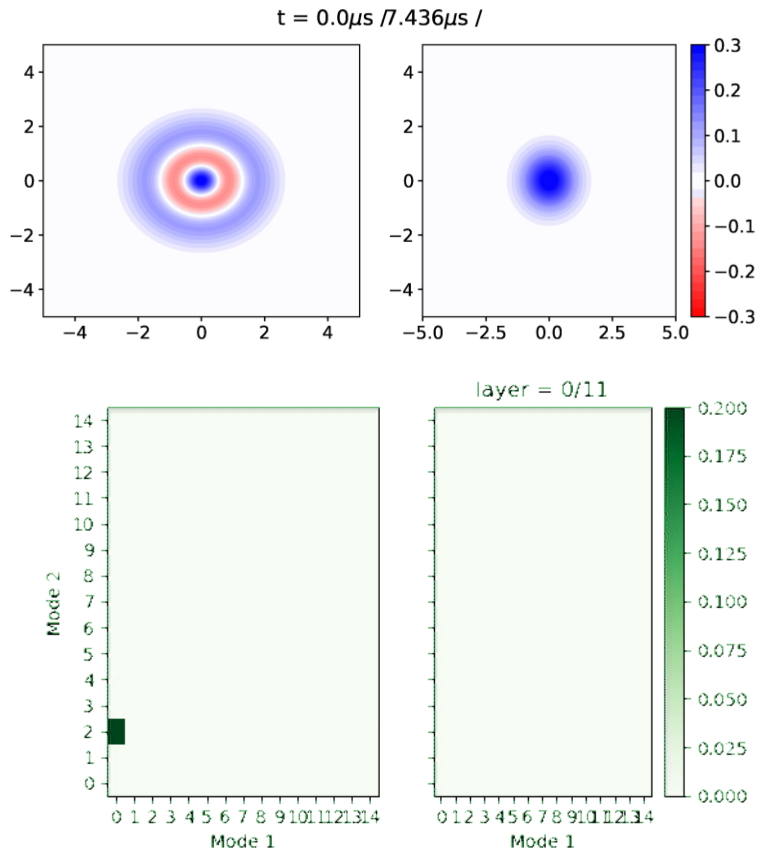


Multimode ECD: State Transfer II

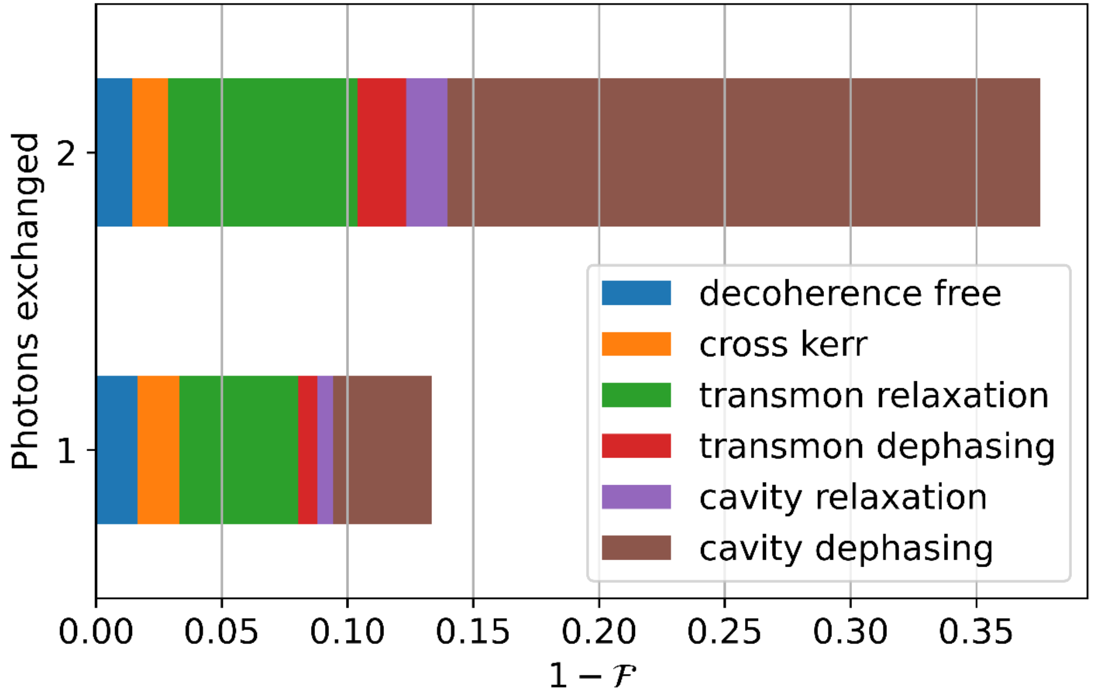
$g \otimes |10\rangle \rightarrow g \otimes |01\rangle$



$g \otimes |20\rangle \rightarrow g \otimes |02\rangle$



Multimode ECD: Error Budget



- $T_{1,q} = 85\ \mu s$
- $T_{2,q} = 98\ \mu s$
- $T_{1,c} = 2\ ms$
- $T_{\phi,c} = 150\ ms$ *

$$2\kappa_\phi D[a^\dagger a]\rho \xrightarrow[\textit{Displaced Frame}]{} \underbrace{2\kappa_\phi|\alpha|^2}_{\sim(83\ \mu s)^{-1}}\left(D[a]\tilde{\rho} + D[a^\dagger]\tilde{\rho}\right) + \ldots$$

*Eickbusch, A., Sivak, V., Ding, A.Z. et al. *Nat. Phys.* 18, 1464–1469 (2022)

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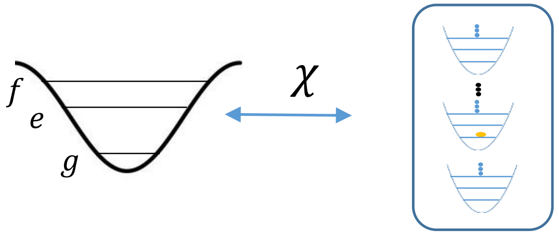

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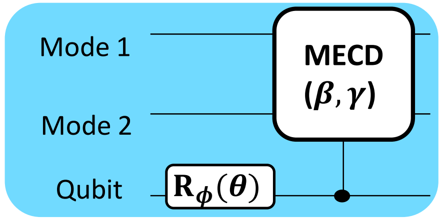


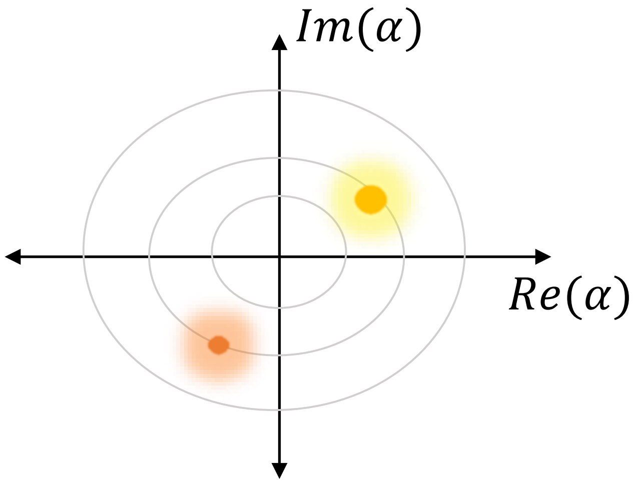
Alternative Schemes:
Circle Grape and Sideband Driving

Circle GRAPE

$|g\rangle$
$|e\rangle$

- Combines displacement enhanced $\chi\alpha$ technique with GRAPE [1,2]
- Detuning causes squeezed state to rotate in phase space
- Currently, only the qubit drive is optimized

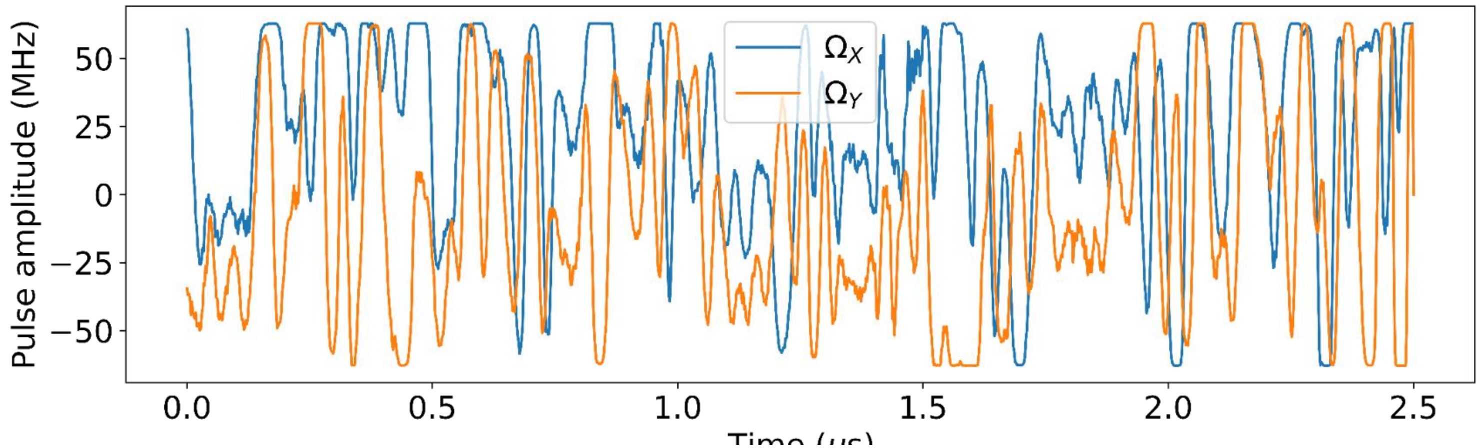
$$H = \sum_{i=1,2} \Delta_i a_i^\dagger a_i + \overbrace{\chi_i (a_i^\dagger + \alpha_i^*)(a_i + \alpha_i)\sigma_z}^{\text{Conditional Displacement}} + \underbrace{\Omega_x(t)\sigma_x + \Omega_y(t)\sigma_y}_{\text{Qubit Drive}}$$



[1] N. Khaneja et al. *Journal of Magnetic Resonance* 172, 29 (2005)

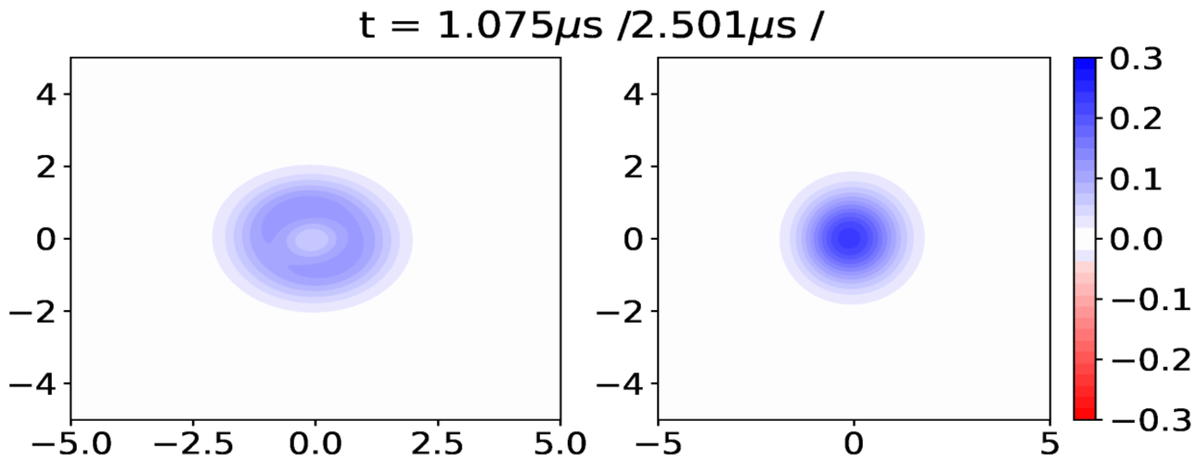
[2] Eickbusch, A., Elder, S., et al. In *APS March Meeting Abstracts* (Vol. 2021, pp. V31-005).

Example: $|g10\rangle \rightarrow |g01\rangle$



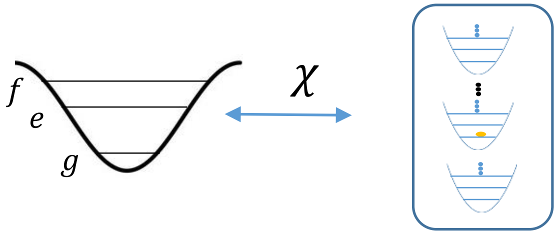
Simulation Parameters

- $\Delta_c = 2\pi \times 10$ Mhz
- $|\Omega| = 2\pi \ \times 10$ Mhz
- $\chi_1, \chi_2 = 2\pi \times 33$ kHz
- $\alpha_1, \alpha_2 = 30$



Conclusion

Challenges in Cavity Control



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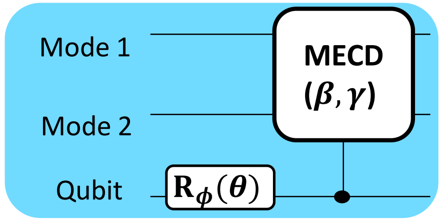

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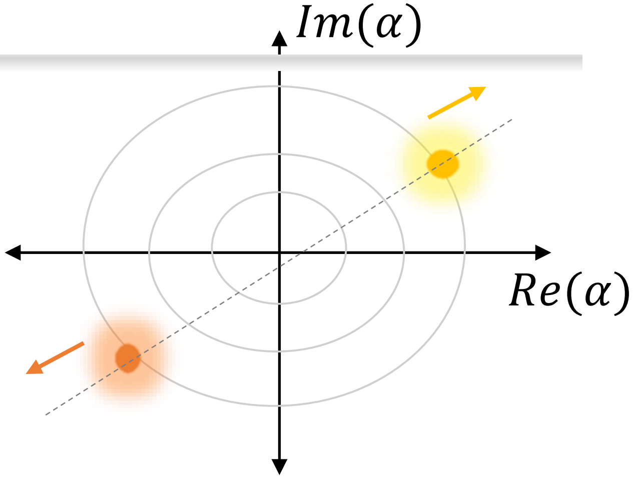
Circle Grape and Sideband Driving

$|g\rangle$

$|e\rangle$

$$H = \chi(\alpha a^\dagger + \alpha^* a)\sigma_z$$



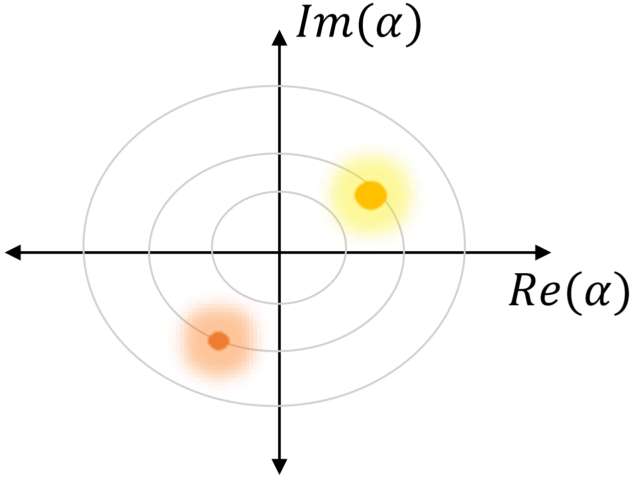
- Combines displacement enhanced $\chi\alpha$ technique with GRAPE algorithm

Circle GRAPE

- Cavity drives detuned

$$H = \Delta_c a^\dagger a + \chi(\alpha a^\dagger + \alpha^* a)\sigma_z$$

Rotate in circle because of detuning; is this a spiral?



Elder S., et al. Bulletin of the American Physical Society 66 (2021)