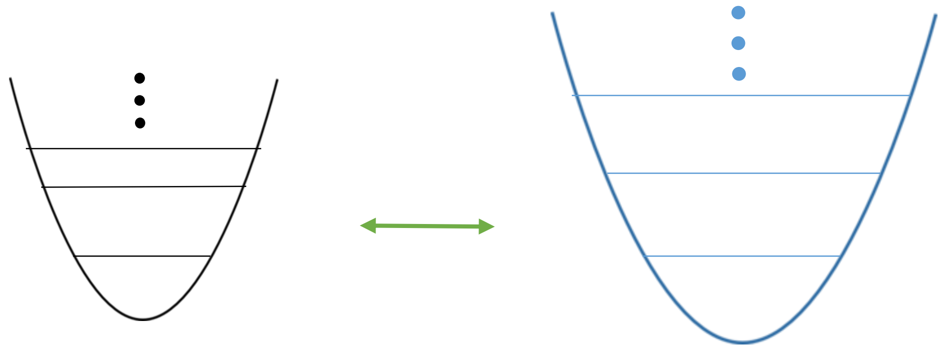
Cross-talk Free Control of Multimode Cavities with Conditional Displacements

Eesh Gupta, S. Chakram, …

Motivation

- Goal: Enact gates on cavity
- Typical Schemes (SNAP/GRAPE) use $\chi a^\dagger a \sigma_z$
- Coupling to the lossy ancilla reduces mode coherence

$$T_1^{cav} \leq \frac{\Delta^2}{g^2} T_1^q \sim \frac{2\alpha}{\chi} \mathrm{T}_1^{\mathrm{q}}$$

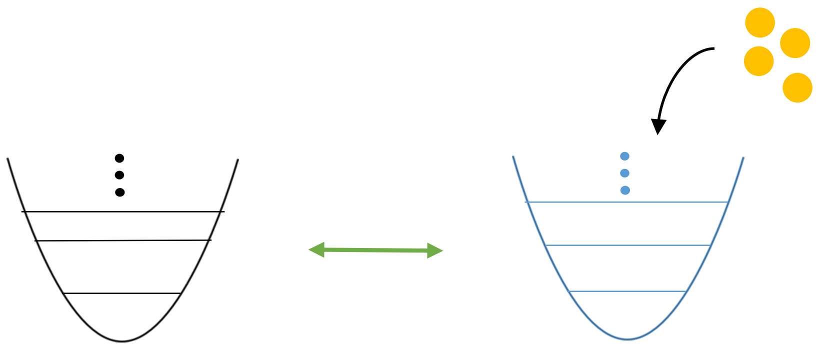


Increase χ for faster gates

Decrease χ for reducing error propagation

Large Displacements

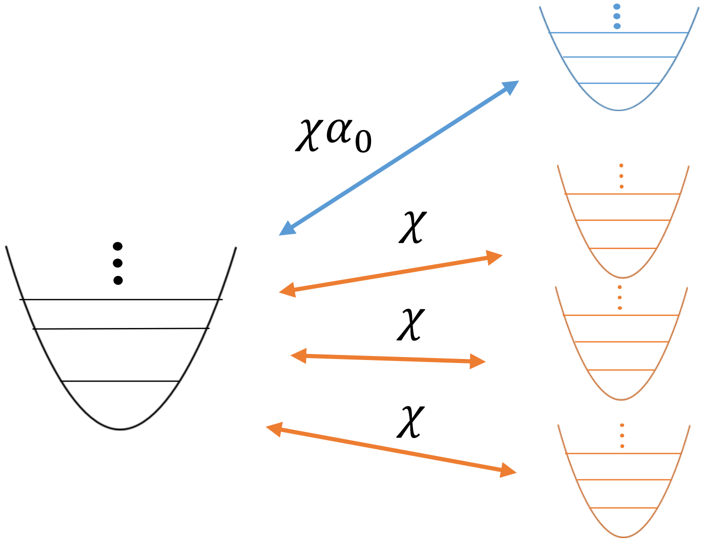
$$\chi a^\dagger a \sigma_z \xrightarrow[D(\alpha_0)]{} \chi \alpha_0 (a^\dagger + a)\, \sigma_z$$



Advantage in Multimode Context:

Gate Speed $g_{gate} = \chi \alpha_0$

Coherent Errors: $\epsilon_{coh} = \frac{N\chi}{g_{gate}} = \frac{\boldsymbol{N}}{\boldsymbol{\alpha_0}}$

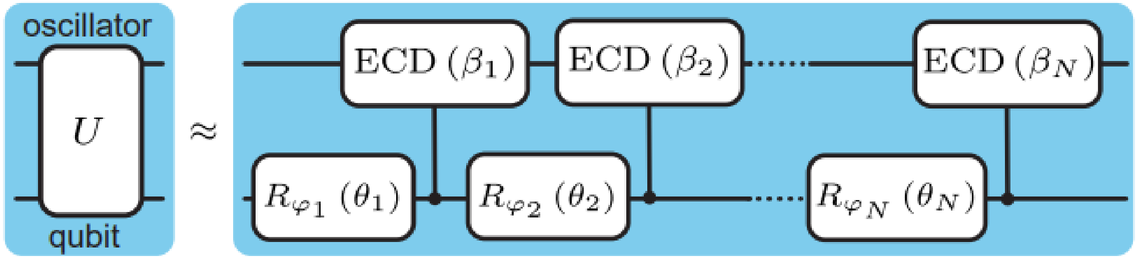


N non-target modes

- 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)

Prev. Work: **Echoed** Cond. Disp.

Parameter Optimization



$$ECD(\beta) = D\left(\frac{\beta}{2}\right)|e\rangle\langle g| + D\left(-\frac{\beta}{2}\right)|g\rangle\langle e|$$

Pulse Optimization

A. Eickbusch, ..., R. Schoelkopf, M. Devoret. ArXiv preprint arXiv:2111.06414 (2021)

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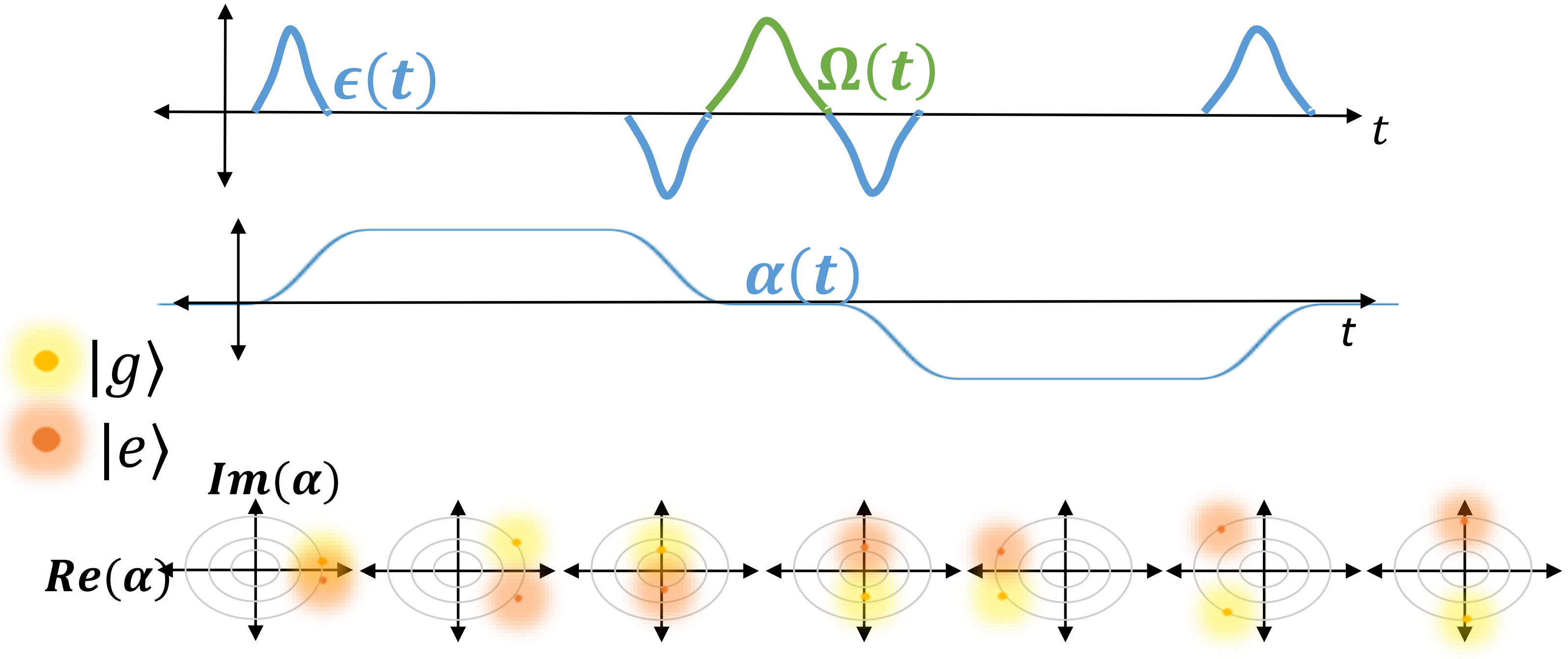
Parameter Optimization

Pulse Optimization



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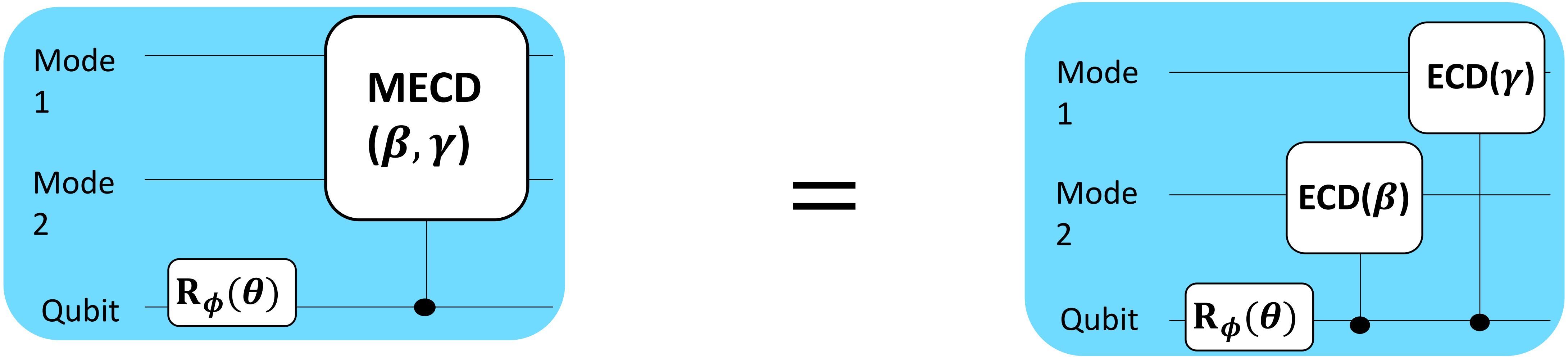
Multimode ECD



- Universal Control for Two Modes
- Not simultaneously driving each mode to prevent heating of modes [1,2]

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

Two Mode ECD : Unwanted Cross Kerr Terms

$$\chi_{ab} a^+ a\, b^+ b \xrightarrow{\text{Displaced Frame Transformation}} \chi_{ab}(a^+ + \alpha^*)(a+\alpha)(b^+ + \beta^*)(b+\beta)$$

Terms of form :

$\chi_{ab}\boldsymbol{\alpha\beta}\, a^+ b^+$

$\chi_{ab}|\boldsymbol{\alpha}|^2\boldsymbol{\beta}\, b^+$

$\chi_{ab}|\boldsymbol{\alpha}|^2 b^+ b$

How to avoid :

α, β should not be simultaneously nonzero

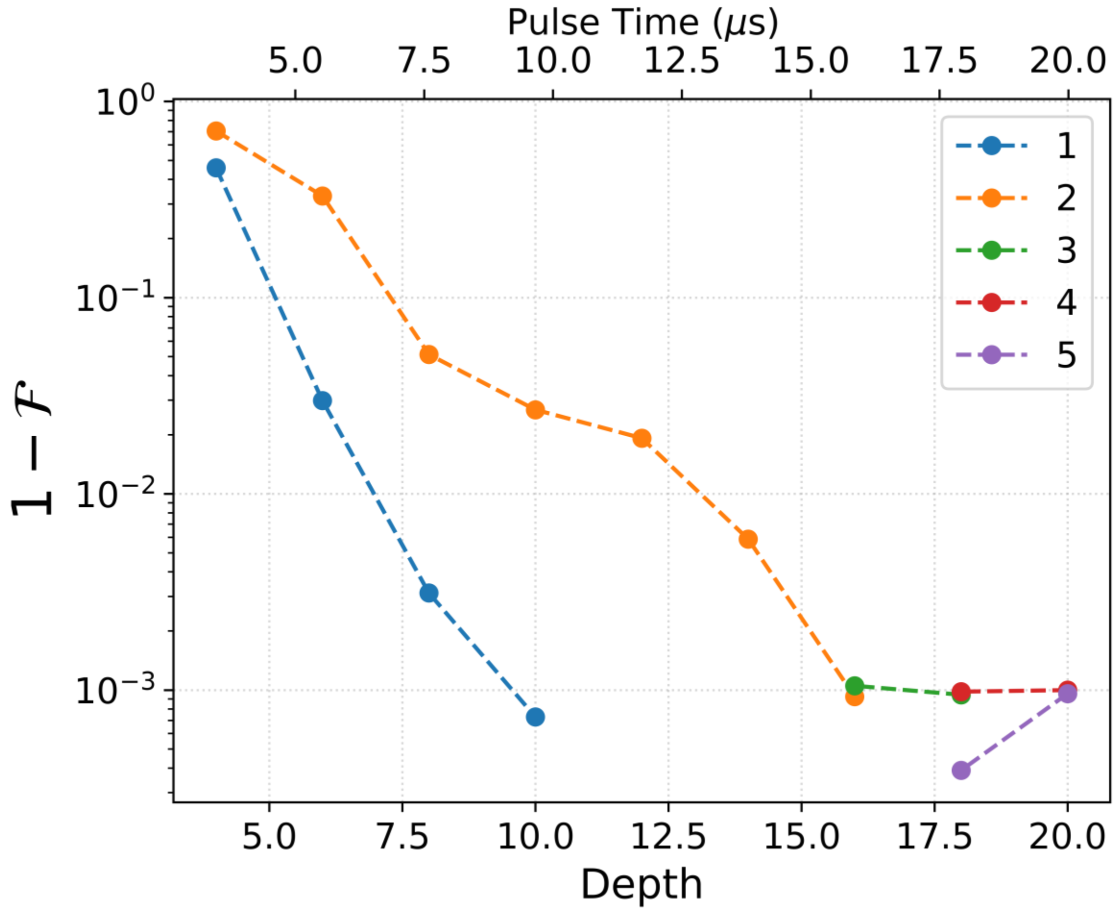
Echoed out when β flips

Make $\chi_{ab} \ll \chi_a, \chi_b \approx 10$ kHz

Note $\chi_{ab} = \sqrt{\kappa_a \kappa_b} = \frac{\chi_a \chi_b}{\alpha'} \approx 0.33$ Hz … good!

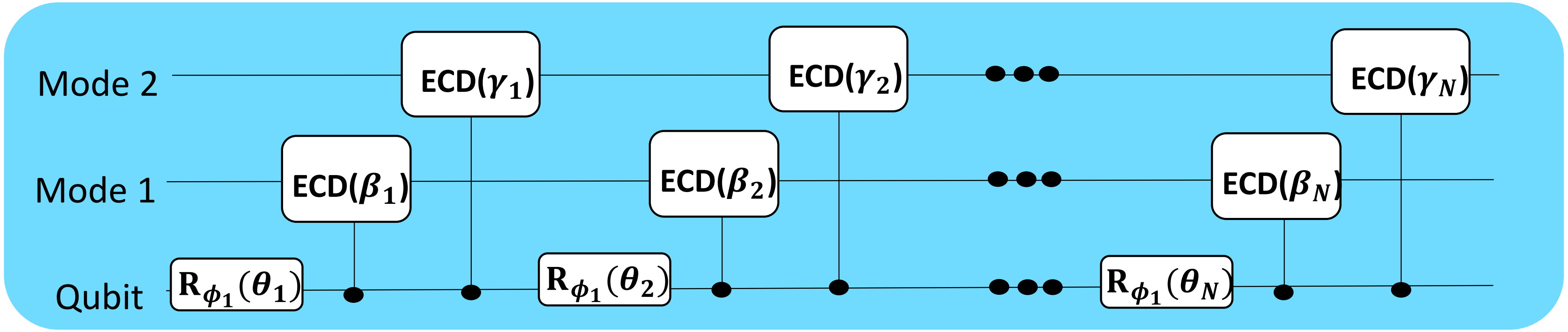
($\alpha' \leq 300$ MHz for transmons)

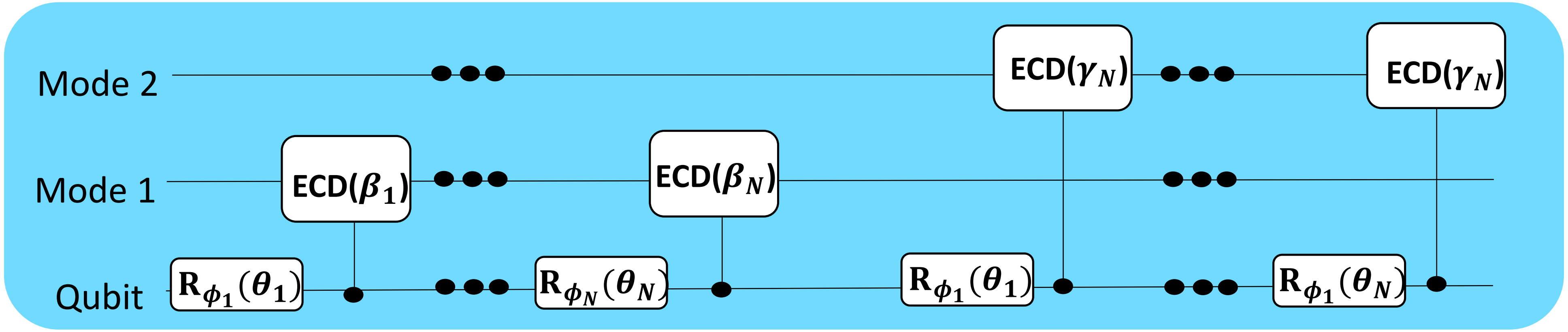
Two Mode ECD: State Transfer



$$g \otimes |0n\rangle \rightarrow g \otimes |n0\rangle$$

Two Mode ECD: State Transfer

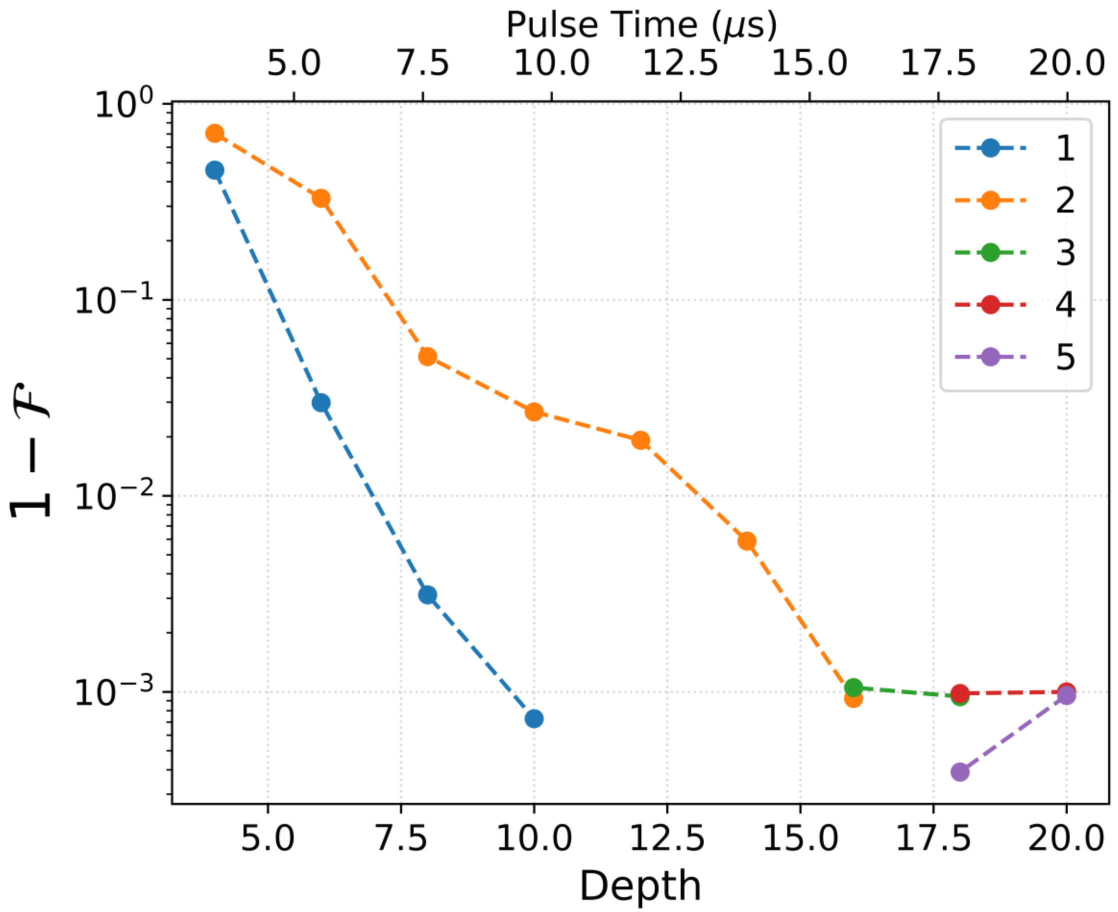


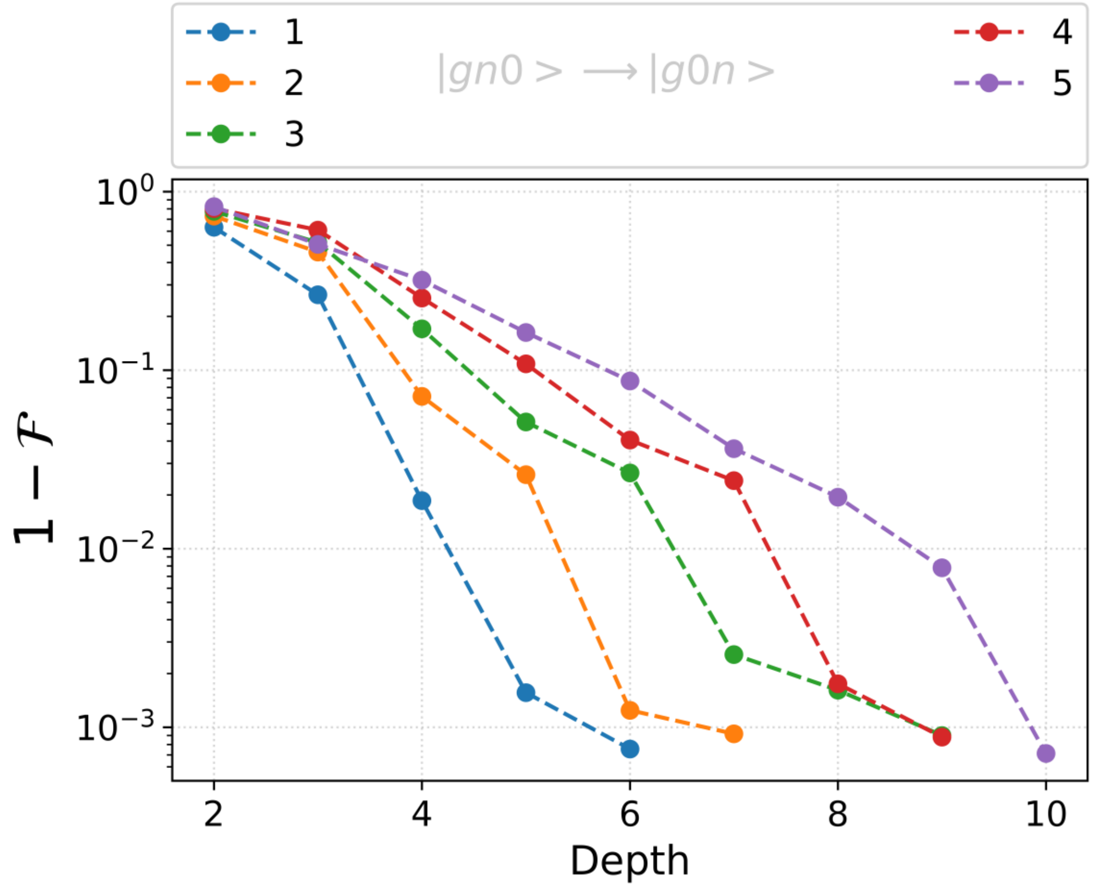


Two Mode ECD: State Transfer

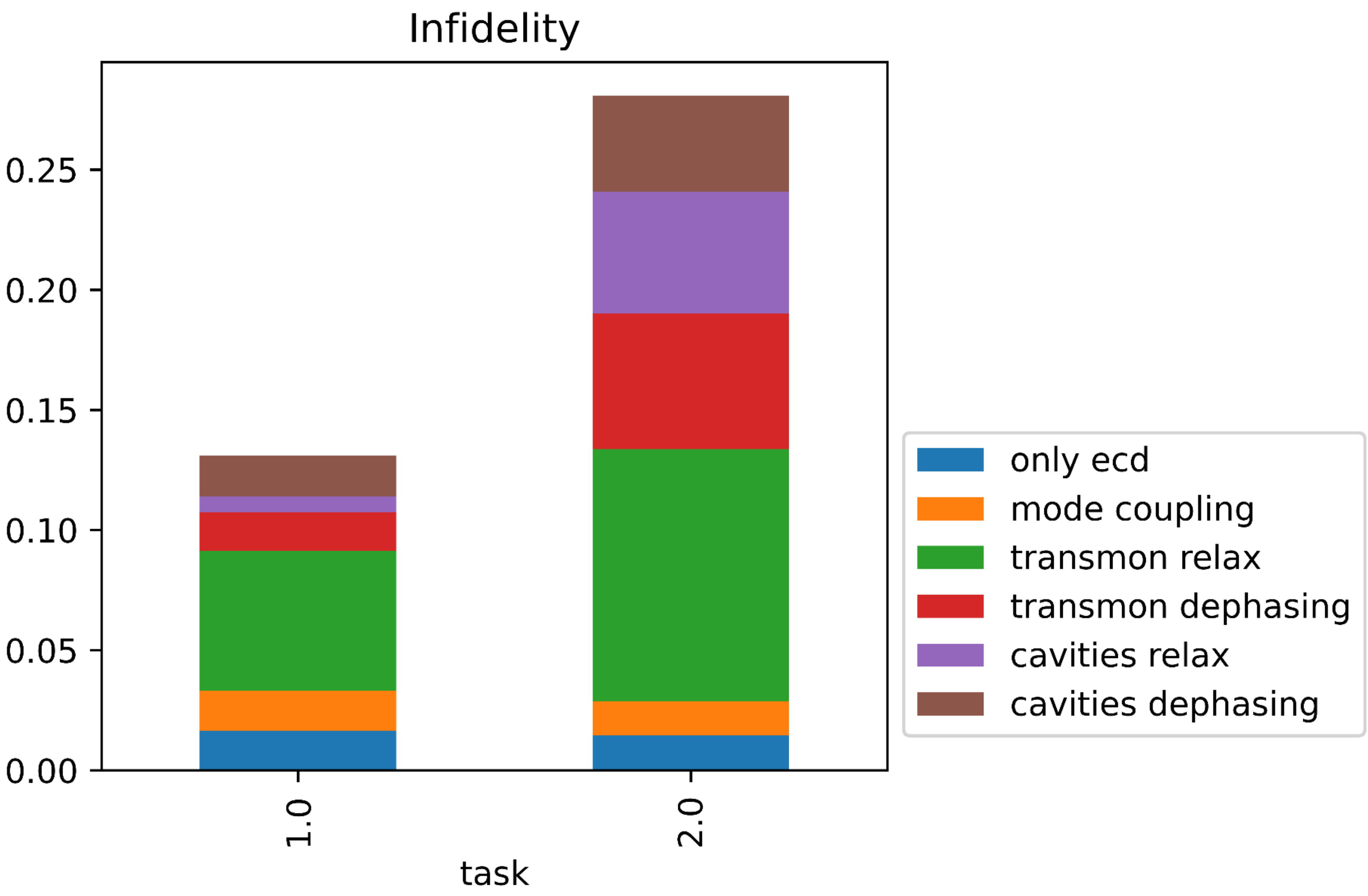
$$g \otimes (\,|n0\rangle \rightarrow |0n\rangle)$$

$$g \otimes (|0\rangle \rightarrow |n\rangle)$$
$$g \otimes (|n\rangle \rightarrow |0\rangle)$$

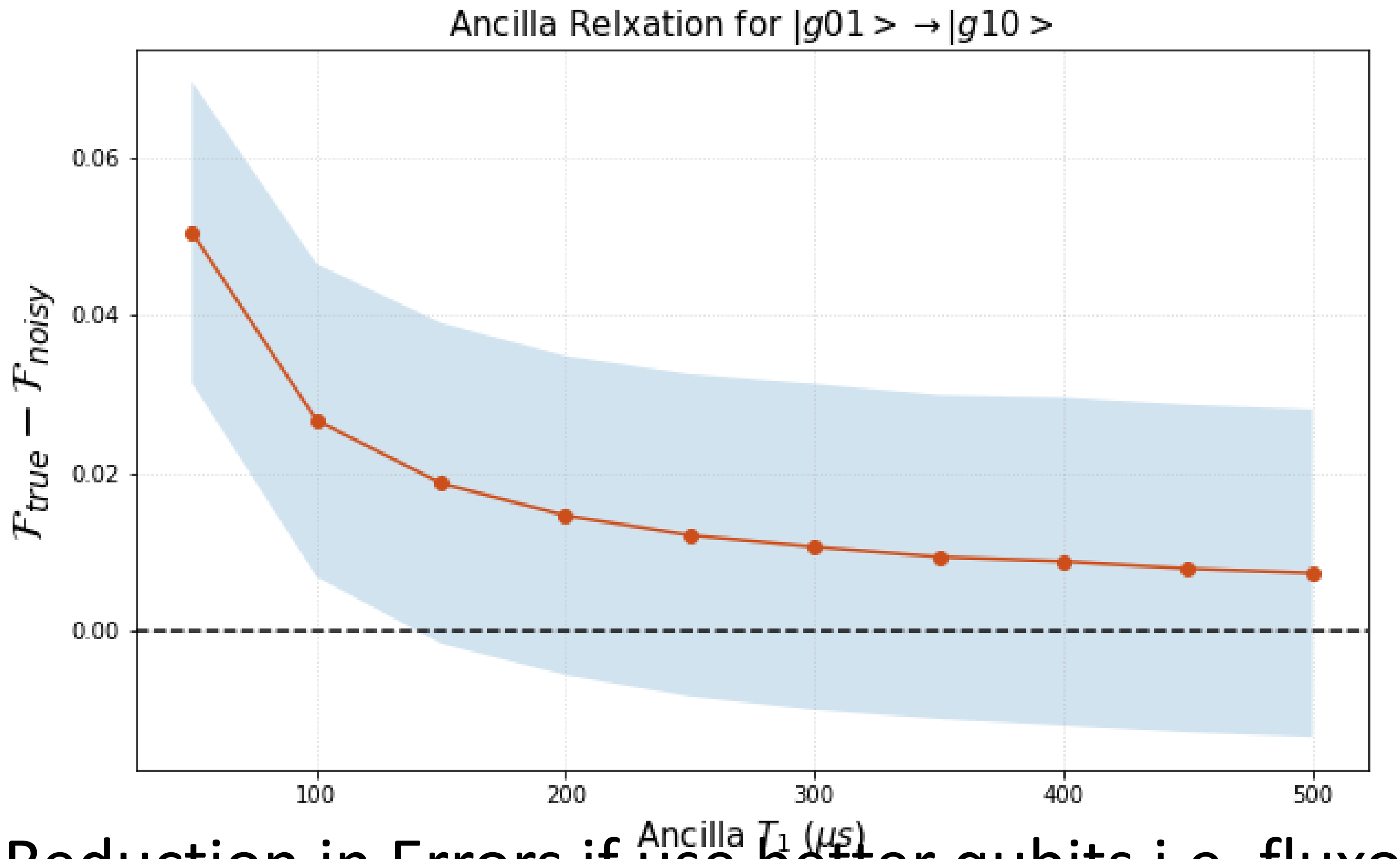




Multimode ECD: Error Budget



Transmon Relaxation

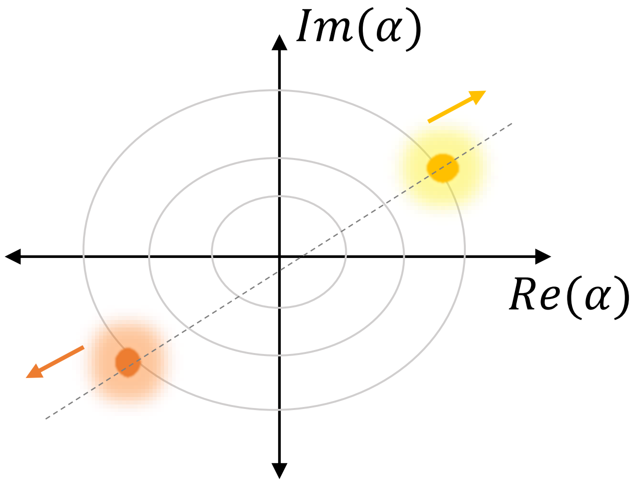


- Reduction in Errors if use better qubits i.e. fluxonium

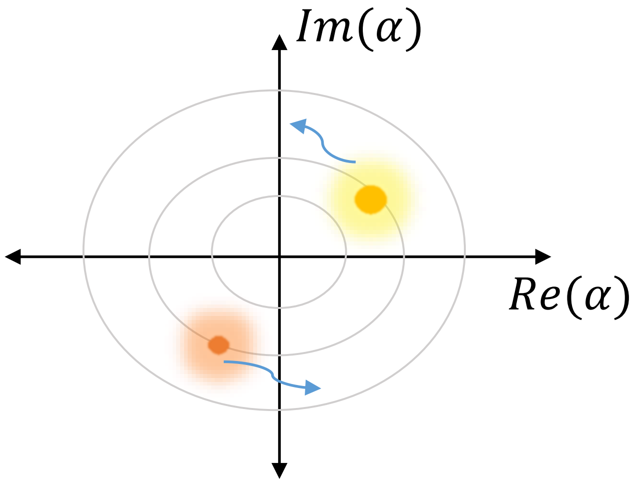
Circle Grape

- Continuously varying Qubit Drive (optimized)
- Includes detuning
- Simultaneously driving of the modes

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

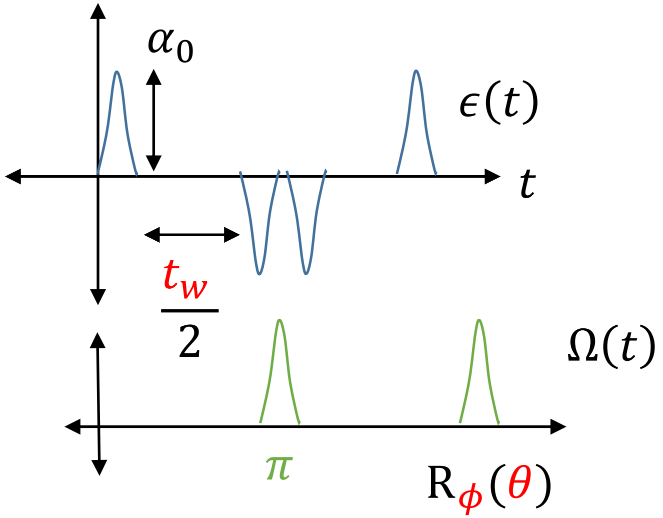


$$H = \Delta_c a^\dagger a + \chi(\alpha a^\dagger + \alpha^* a)\sigma_z$$



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

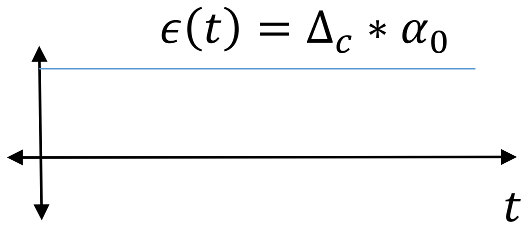
ECD



Optimizer

$\vec{\beta} = \alpha_0 \overrightarrow{t_w} \quad \vec{\phi}, \vec{\theta}$

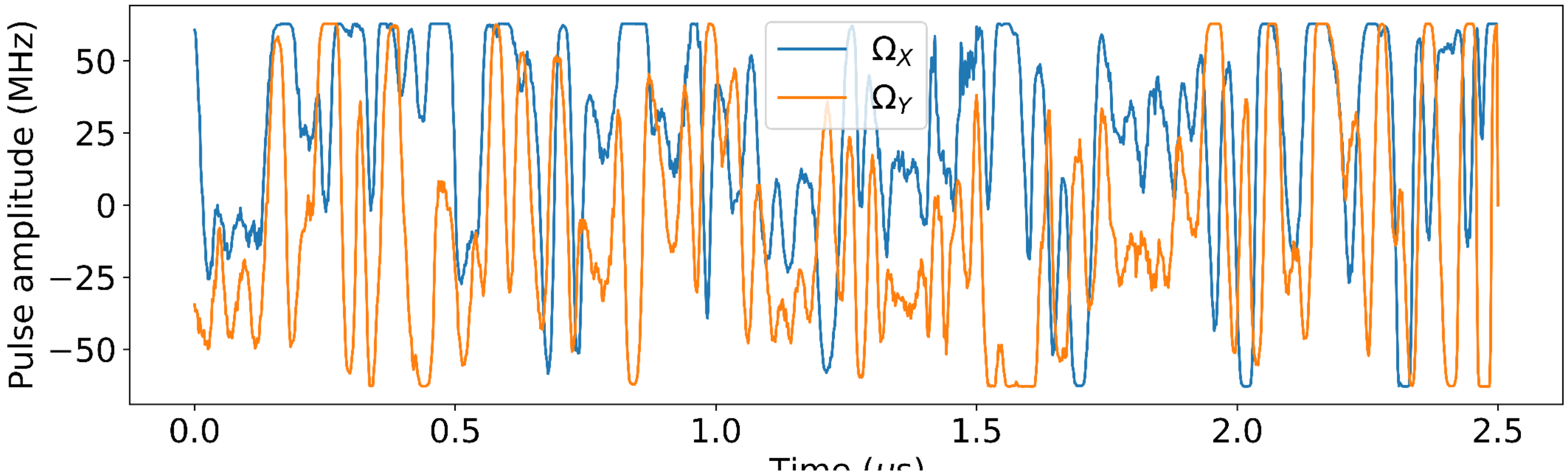
Circle Grape



Optimizer

$\Omega_x(t), \Omega_y(t)$

Circle Grape: g01 -> g10

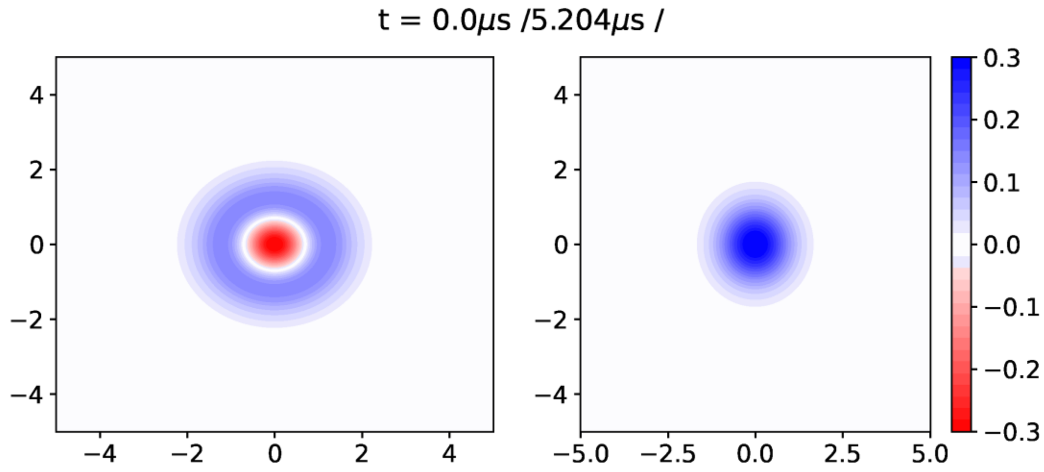


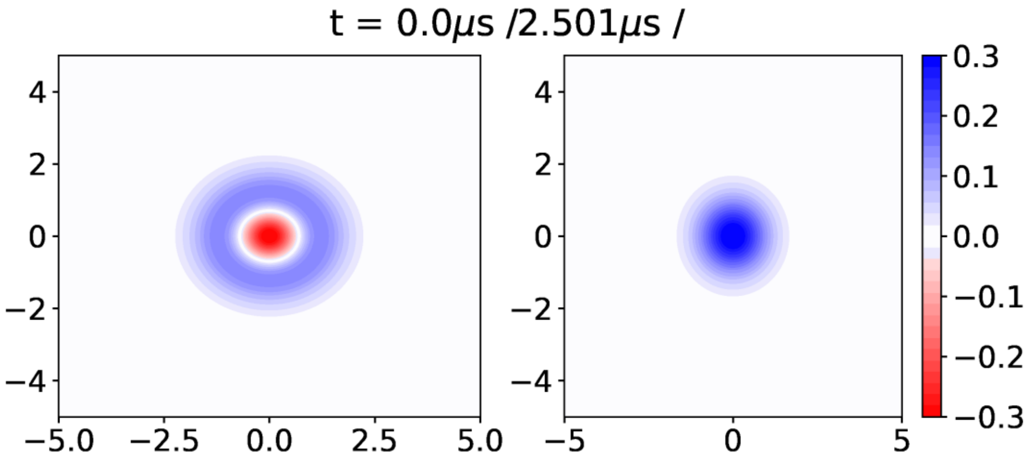
Comparing Grape and MECD

ECD

Circle Grape

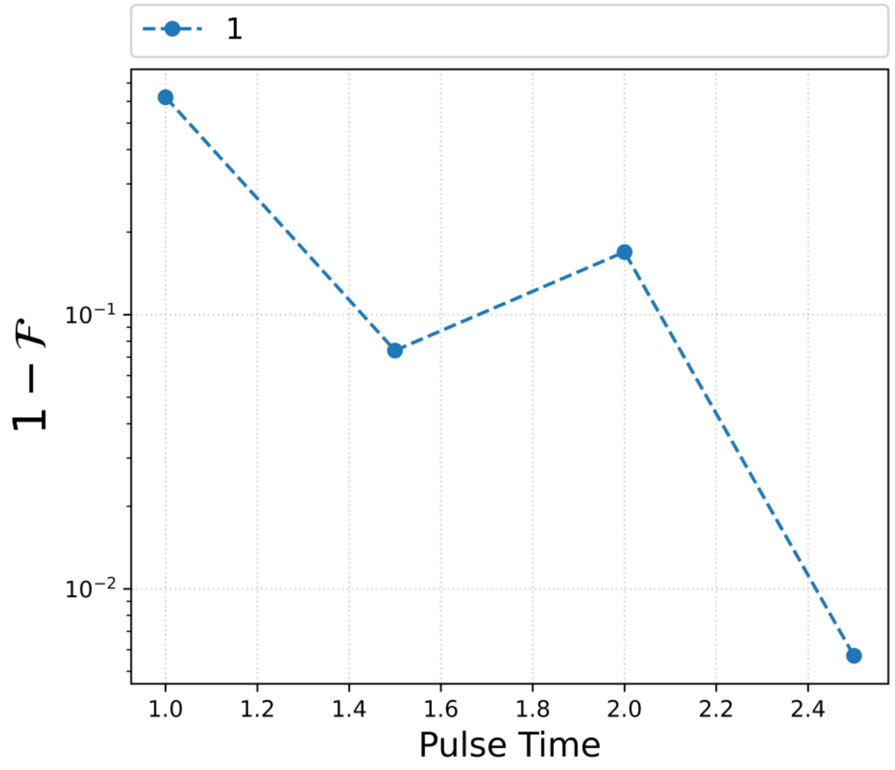
Type equation here





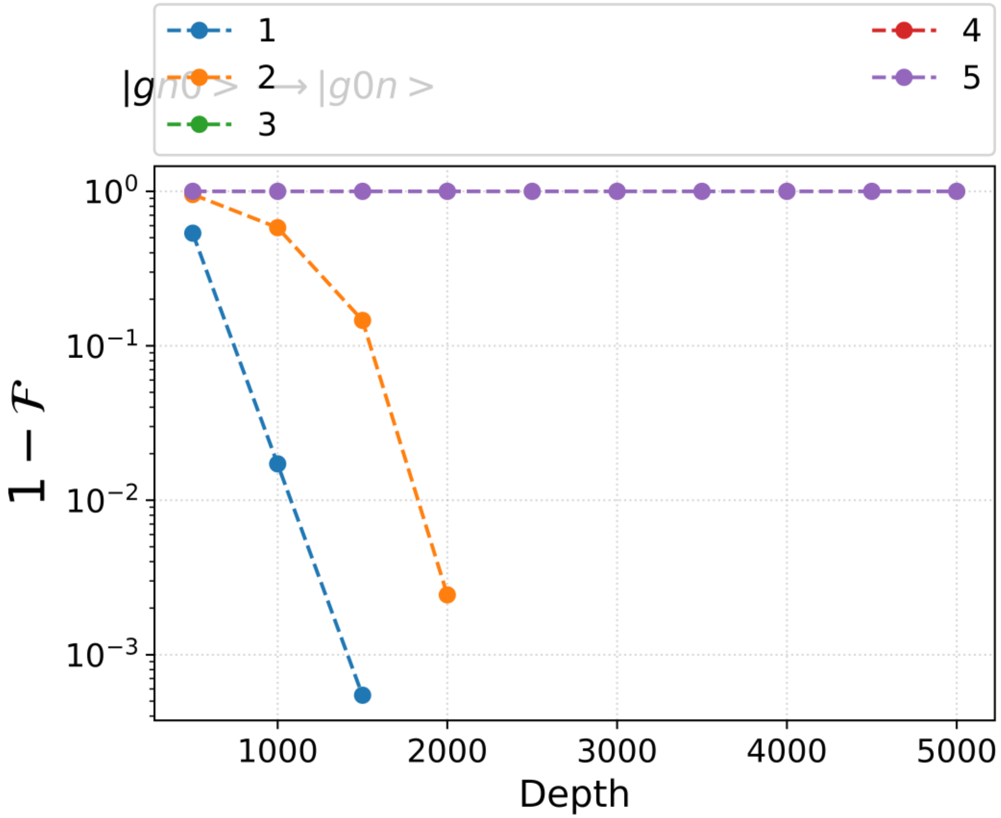
Circle Grape Results

$g \otimes (\,|n0\rangle \to |0n\rangle)$



$g \otimes (|0\rangle \to |n\rangle)$

$g \otimes (|n\rangle \to |0\rangle)$



Uniting with other schemes: Dealing with Unwanted Terms

The **displaced frame** transformation, however, divides the **initial ac-Stark shift** term into the following 3 terms

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

$$\downarrow$$

$$\chi a^\dagger a \sigma_z \quad + \quad \underbrace{\chi(\alpha a^\dagger + \alpha^* a)\sigma_z}_{\text{desired}} \quad + \quad \chi|\alpha|^2\sigma_z$$

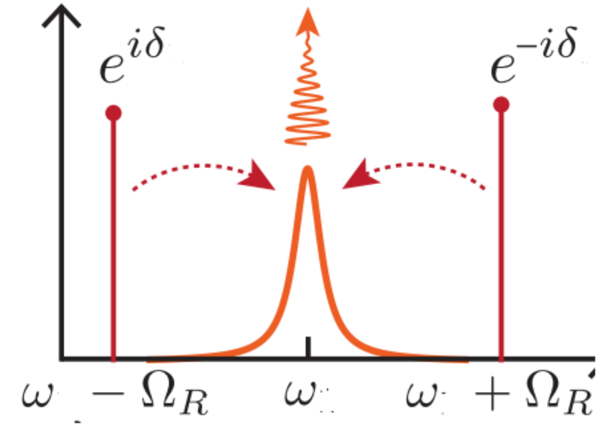
Sideband Drives

- Make terms **oscillate at different** frequencies
- Invoke RWA in a frame where only desired term is stationary

Echoed Cond. Displacements

- Terms have different no. of α's but only a single σ_z
- **Clever flipping of α and $\boldsymbol{\sigma_z}$** can echo out unwanted terms

Sideband Drives



https://arxiv.org/pdf/1608.06652.pdf

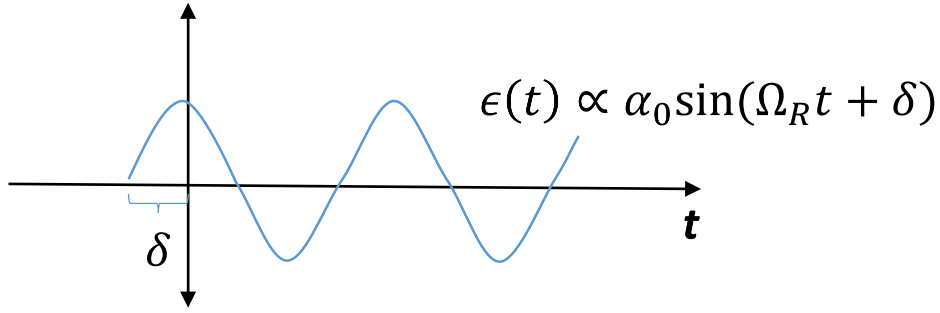
Since α oscillatory,

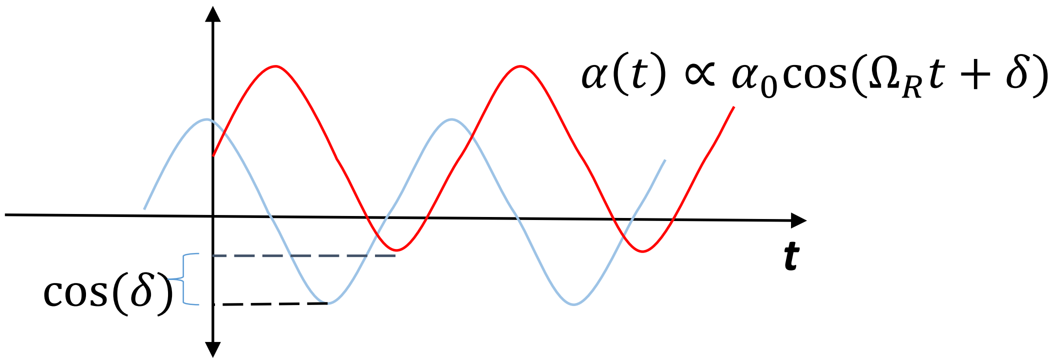
$$H = \chi a^{+} a \sigma_z + \chi(\alpha a^{+} + \alpha^{*} a)\sigma_z + \chi|\alpha|^2 \sigma_z + \Omega_R \sigma_x$$

$\omega = 0$ $\quad\quad$ $\omega = \Omega_R$ $\quad\quad$ $\omega = 2\Omega_R$

Frame Transformations:

1. $\sigma_x \leftrightarrow \sigma_z$ $\longrightarrow$ $\Omega_R \sigma_z$
2. Rotating Frame of the qubit $\quad$ $\cancel{\Omega_R \sigma_z}$





$$H = \chi \alpha_0 (a^{+} + a) \otimes (\sigma_x \cos\delta + \sigma_y \sin\delta) + \ldots$$

$\omega = 0$ $\quad\quad$ $\omega \geq \Omega_R$

Shay Hacohen-Gourgy, …, Irfan Siddiqi. Nature 538-7626 (2016).

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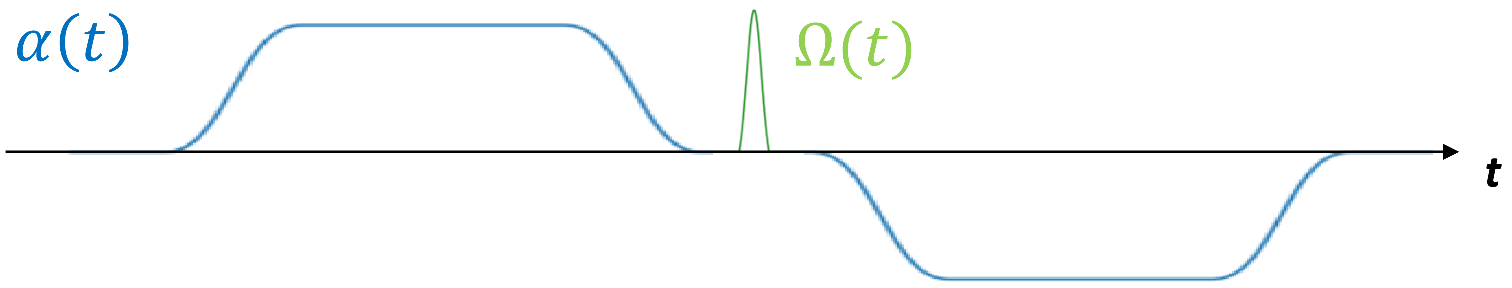


Not completely echoed out !

$$\chi a^{+} a \sigma_z \quad \xrightarrow{\text{Echo}} \quad \chi a^{+} a (-\sigma_z)$$

$$\chi(\alpha a^{+} + \alpha^{*} a)\sigma_z \quad \longrightarrow \quad \chi(\alpha a^{+} + \alpha^{*} a)\sigma_z$$

$$\chi|\alpha|^2 \sigma_z \quad \longrightarrow \quad \chi|\alpha|^2(-\sigma_z)$$

A. Eickbusch, ..., R. Schoelkopf, M. Devoret. ArXiv preprint arXiv:2111.06414 (2021)

Conclusions and Future Work

- Suppression of cross-talk errors by chi alpha schemes
- Achieve >0.999 fidelity for fock state transfer using Double ECD
- Speed Limit seems to be 1/chi * alpha

- Future Work:
  - Unite with other schemes

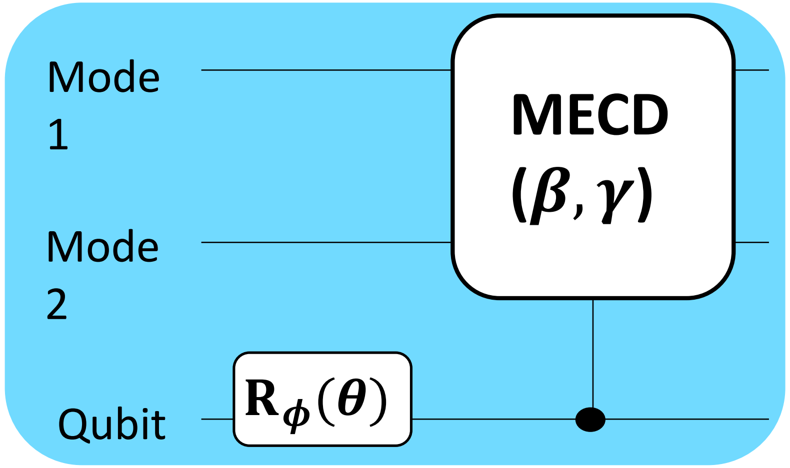
Circle Grape

$$H = \chi a^{+} a \sigma_z + \chi(\alpha_0 a^{+} + \alpha_0^* a)\sigma_z + \chi|\alpha_0|^2 \sigma_z + \Omega(t)\sigma_x$$

Sent to Optimizer

- Continuous version
- Currently uses simulatenous drives
- Phase Space Dynamics

Multimode ECD



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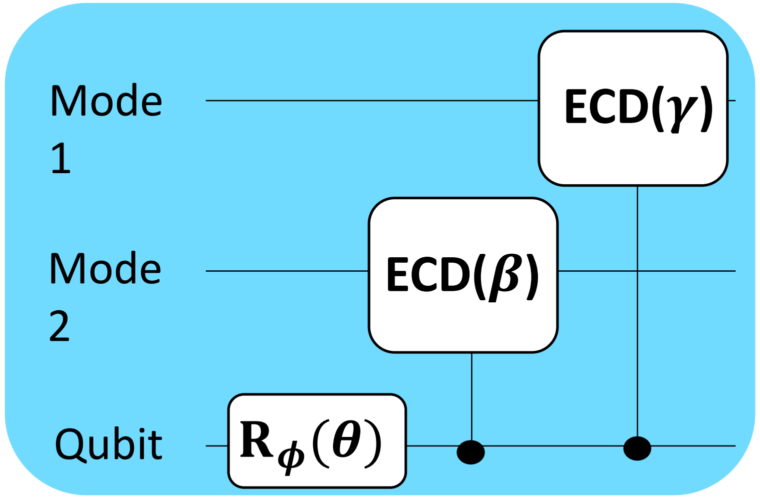

$$MECD(\beta,\gamma) = \begin{pmatrix} D_1\left(-\frac{\beta}{2}\right)D_2\left(\frac{\gamma}{2}\right) & 0 \\ 0 & D_1\left(\frac{\beta}{2}\right)D_2\left(-\frac{\gamma}{2}\right) \end{pmatrix}$$