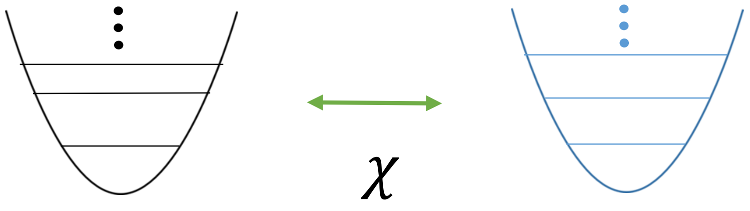
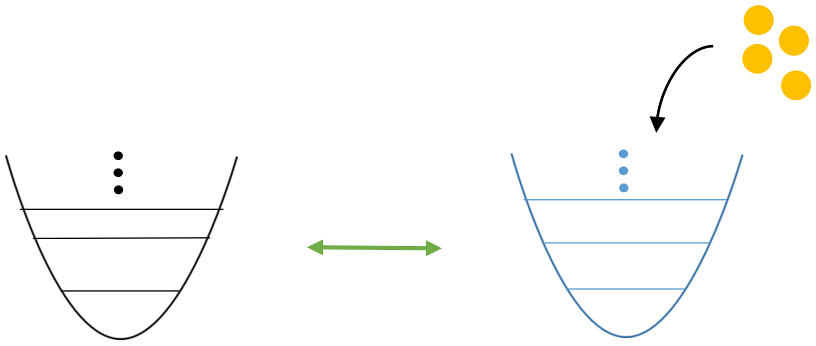
Cross-talk Free Control of Multimode Cavities with Conditional Displacements

Motivation

- Weak coupling -> slower gates but less error propagation
- Strong Coupling -> faster gates but more error propagation
- Maintain weak coupling but $\chi\alpha_0$ schemes enhance effective interaction strength



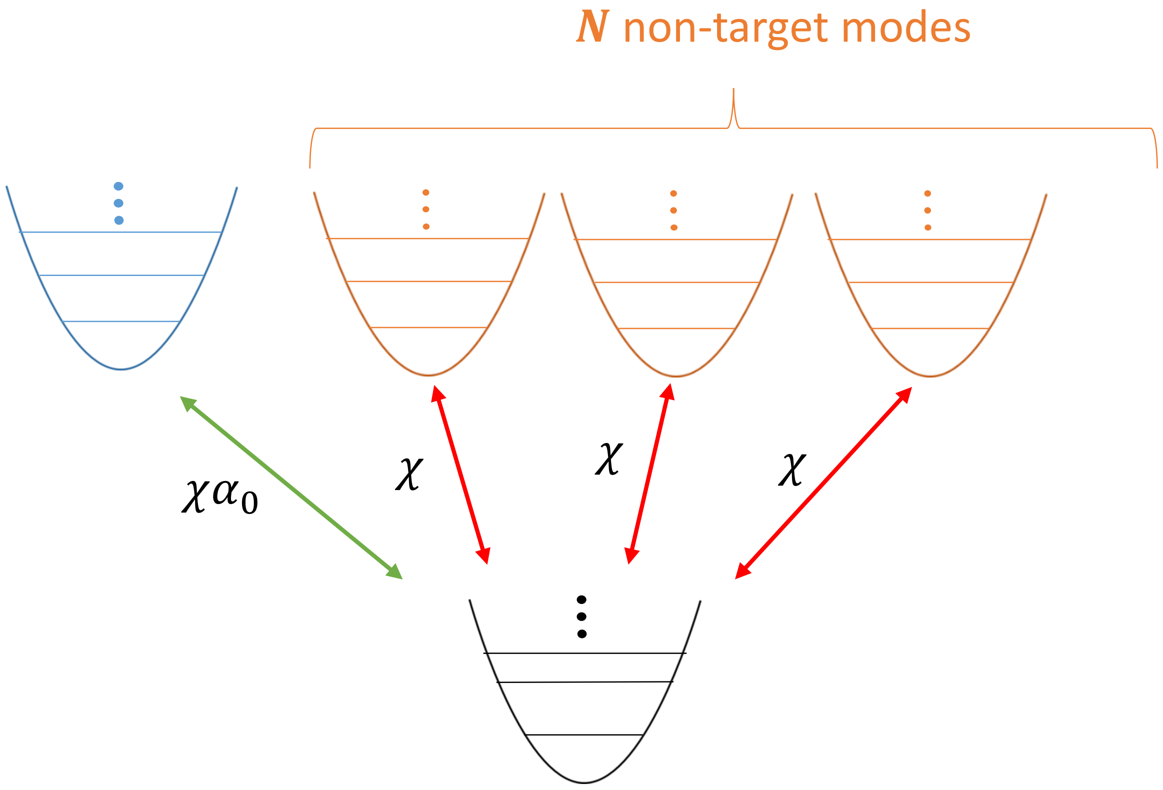


$$\chi_{eff} = \chi\alpha_0$$

Motivation

- Large displacement also increases contrast between interaction with target mode and that with non target modes.
- Gate Speed $g_{gate} = \chi\alpha_{max}$
- Coherent Errors: $\epsilon_{coh} = \frac{N\chi}{g_{gate}} = \frac{\boldsymbol{N}}{\boldsymbol{\alpha_{max}}}$

*assuming all chis's same



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

Parameter Optimization

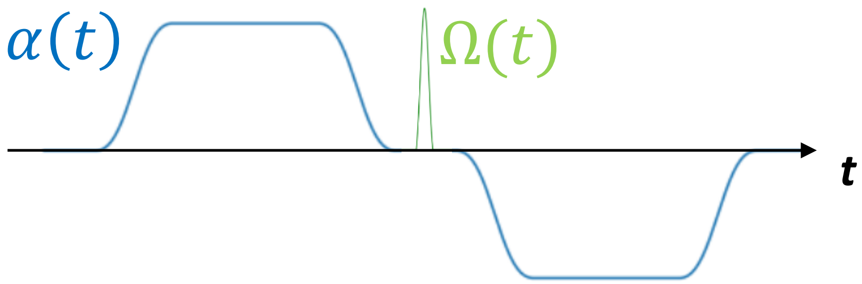
- Assume only $H = \chi(\alpha a^{+} + \alpha^{*} a)\sigma_z + \Omega\frac{\sigma_x}{2}$
- Optimize Sequences of Conditional Displacements ($\vec{\beta}$) followed by qubit rotations to realize desired operation

Pulse Optimization

- Echo out unwanted terms ($\chi|\alpha|^2\sigma_z$ and $\chi a^{+} a\sigma_z$) by constructing symmetric pulses for cavity drive.
- Use semi-classical phase space treajectory method to find pulses which realize target displacements $\vec{\beta}$

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

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



Not completely echoed out !

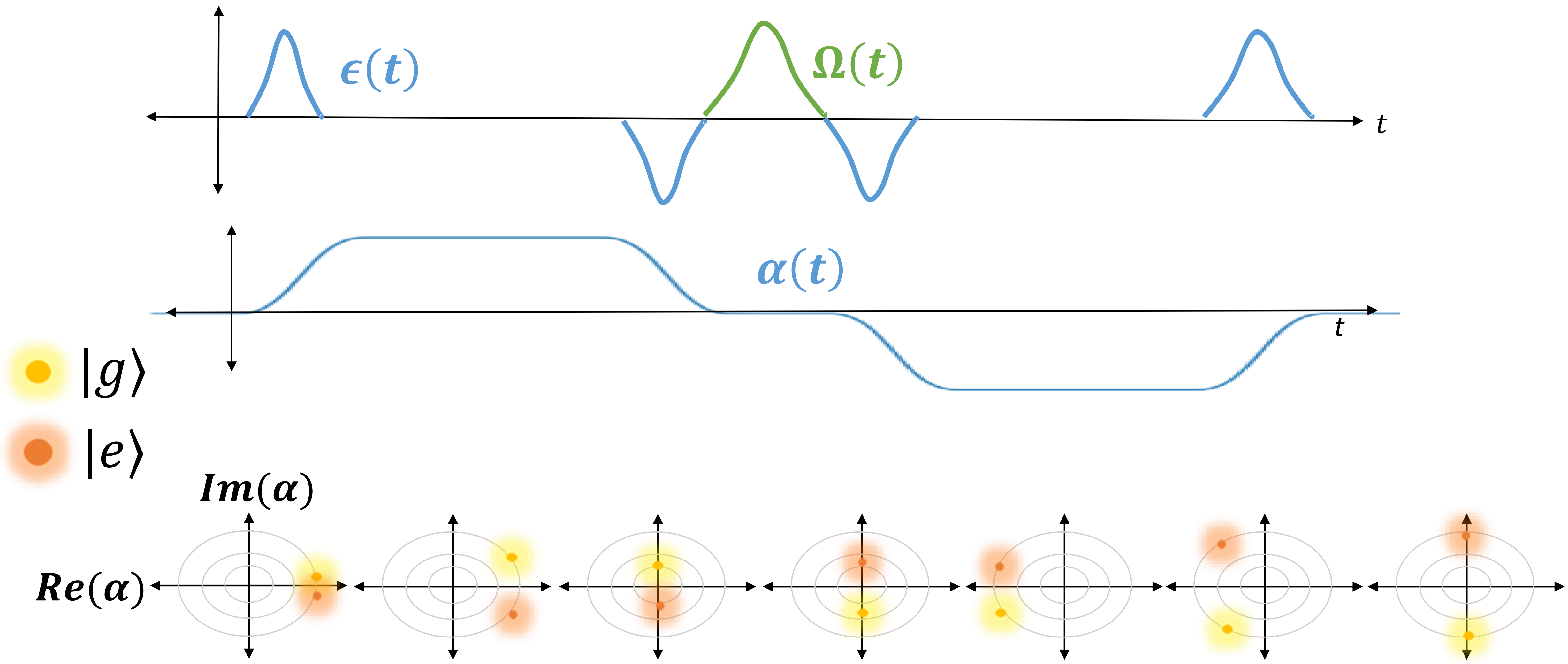
$$\chi a^{+} a \sigma_z \quad \xrightarrow{\text{Echo}} \quad -\chi a^{+} a \sigma_z$$

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

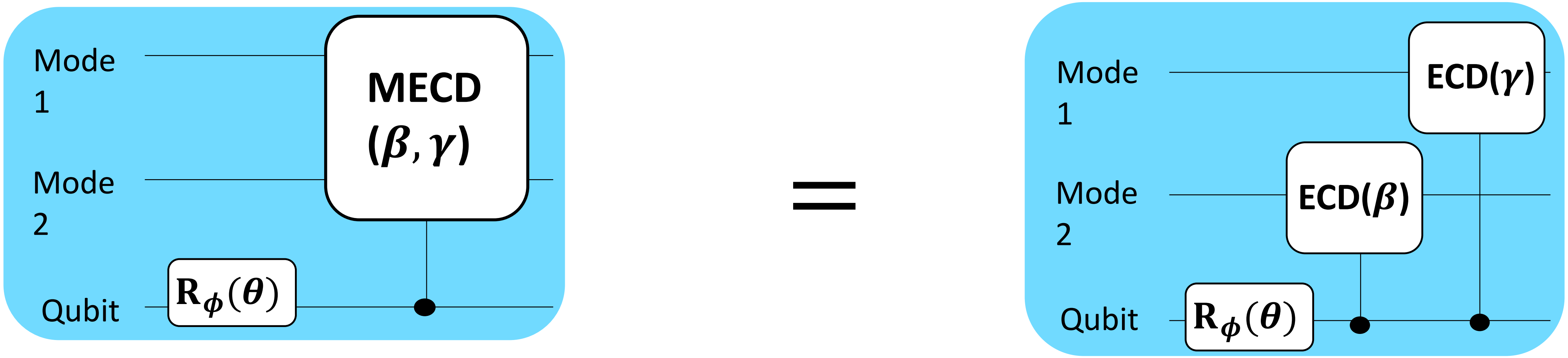
$$\chi|\alpha|^2\sigma_z \quad \longrightarrow \quad -\chi|\alpha|^2\sigma_z$$

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

Prev Work: ECD: Evolution in Phase Space



Multimode ECD



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

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

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

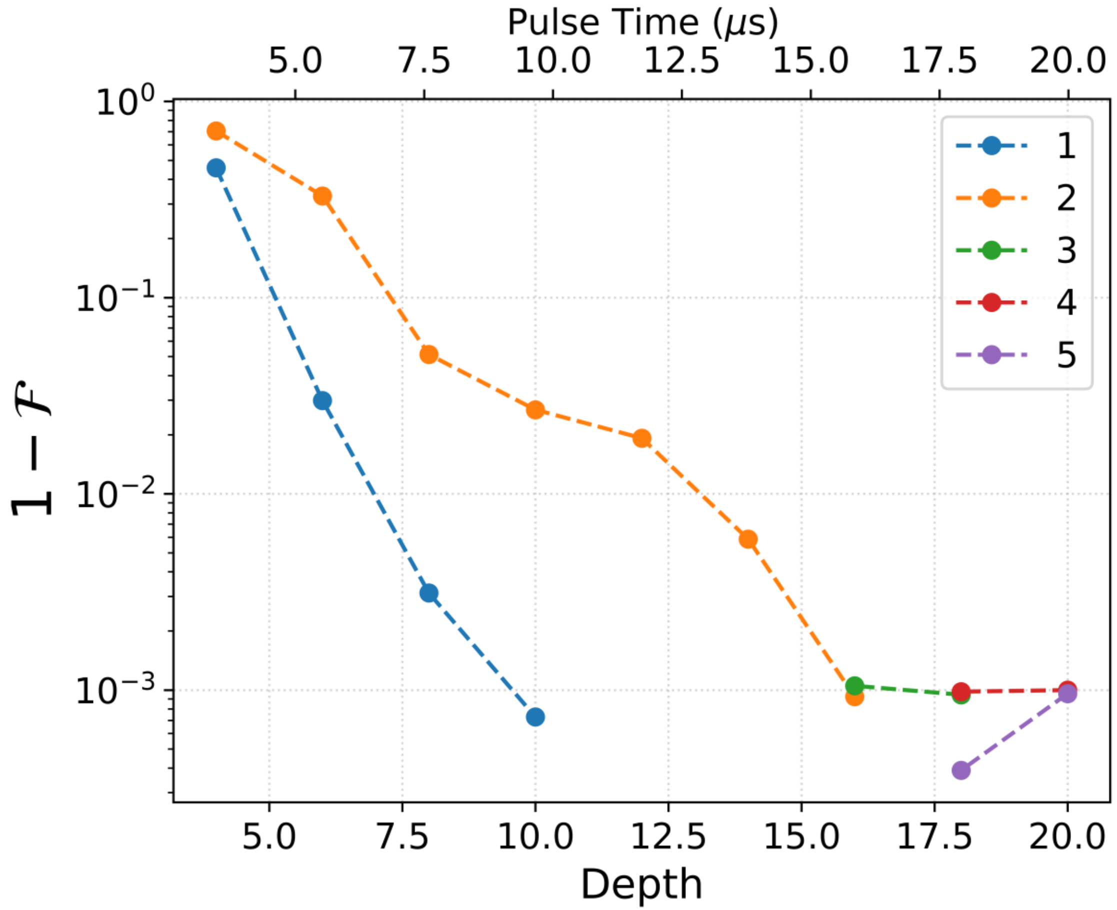
Echoed out when β flips

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!

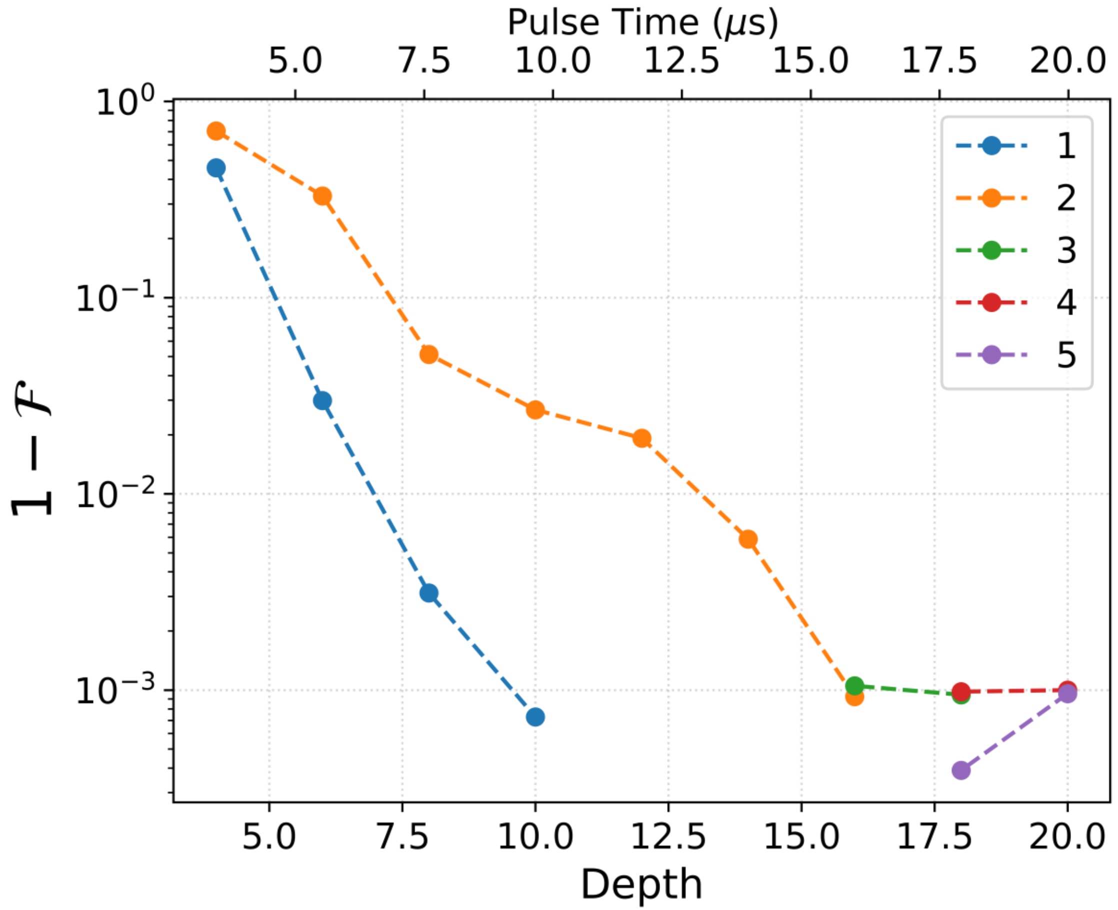
($\alpha' \leq 300$ MHz for transmons)

Two Mode ECD: State Transfer



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

Two Mode ECD: State Transfer

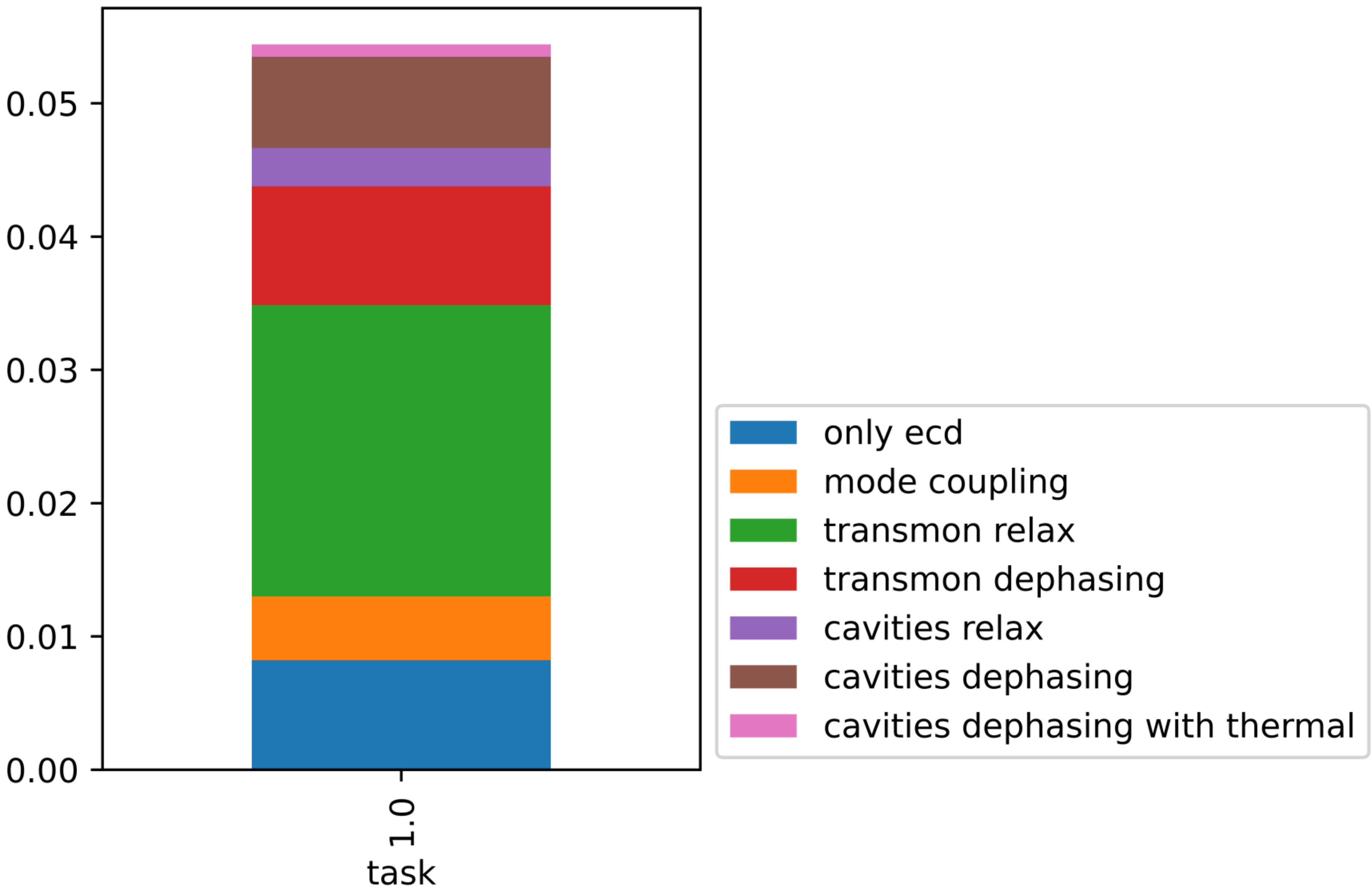


$$g \otimes (\,|n0\rangle \rightarrow |0n\rangle)$$

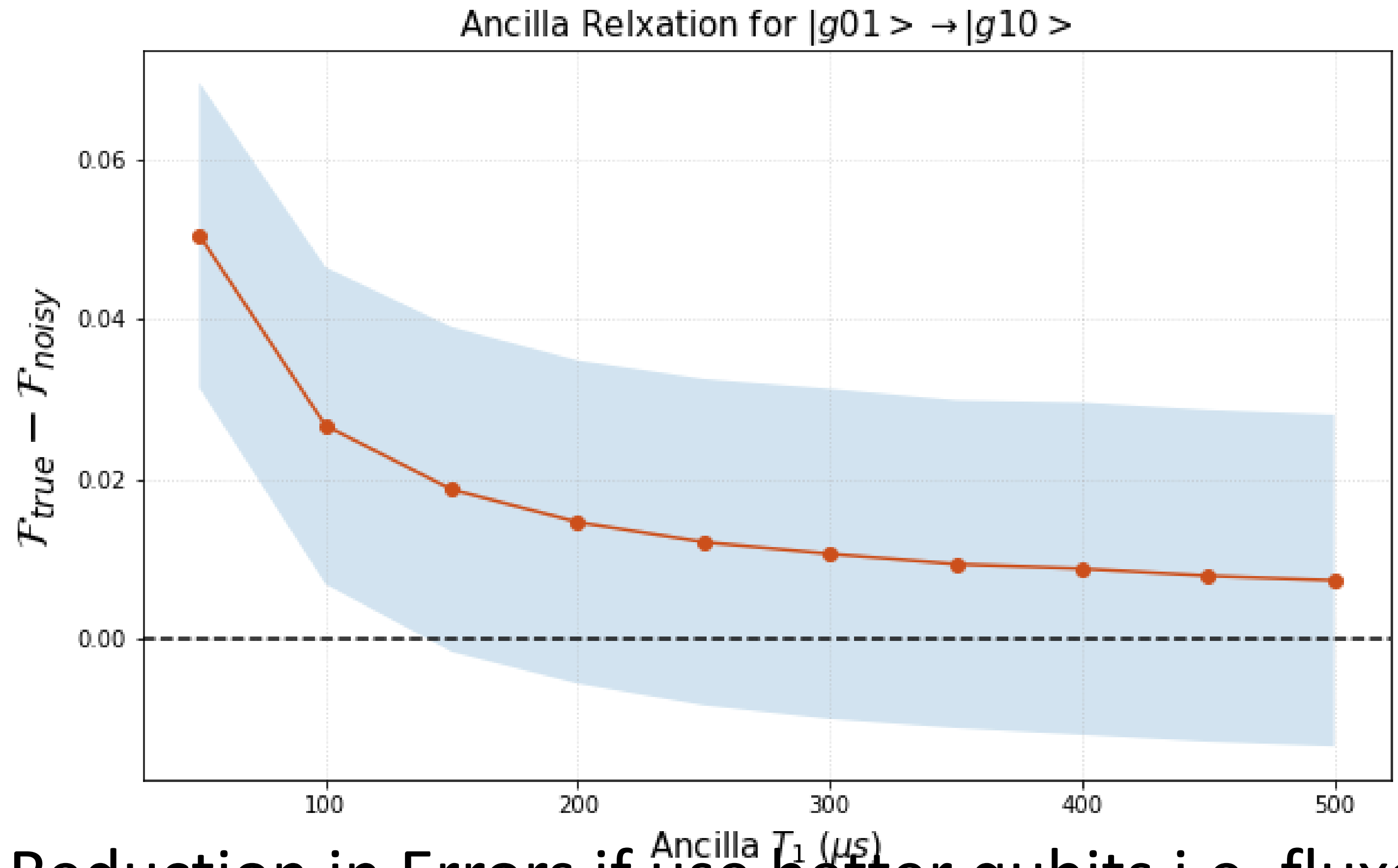
$$g \otimes (|0\rangle \rightarrow |n\rangle)$$

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

Multimode ECD: Error Budget



Transmon Relaxation



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

Circle Grape

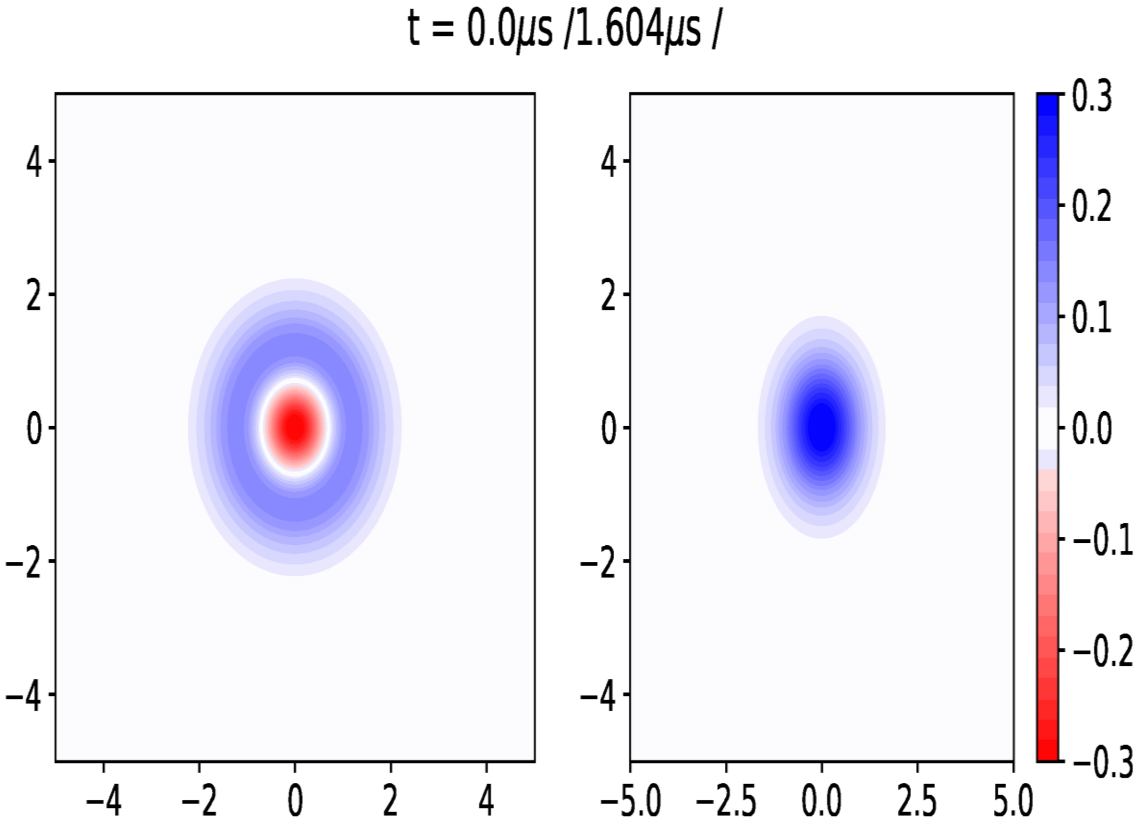
- Continuous version
- Currently uses simulatenous drives
- Phase Space Dynamics

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

Sent to Optimizer

Comparing Grape and MECD

ECD

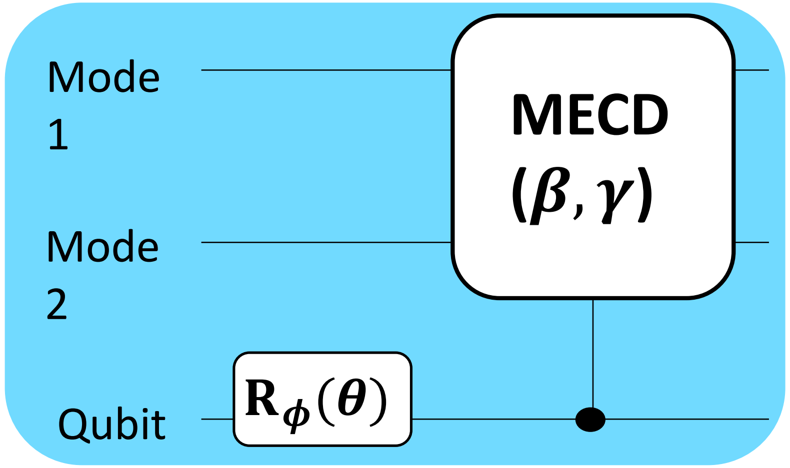


Circle Grape Results

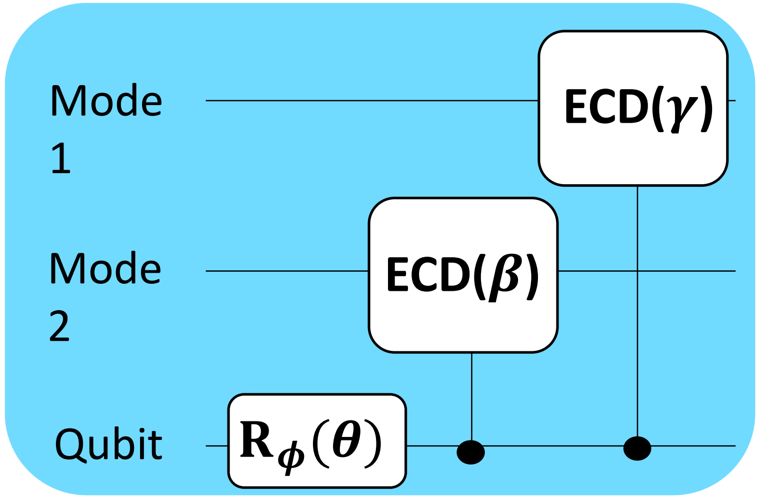
Conclusions and Future Work

- Suppression of cross-talk errors by chi alpha schemes
- Multimode schemes limited to 1/chi alphase instead of the squared for driving modes separately

Multimode ECD



=



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