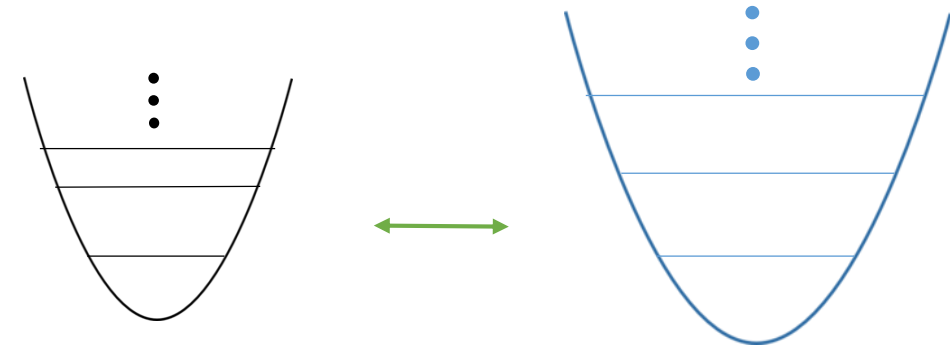


# Cross-talk Free Control of Multimode Cavities with Conditional Displacements

# 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

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



Increase  $\chi$  for faster gates

Decrease  $\chi$  for reducing error propagation

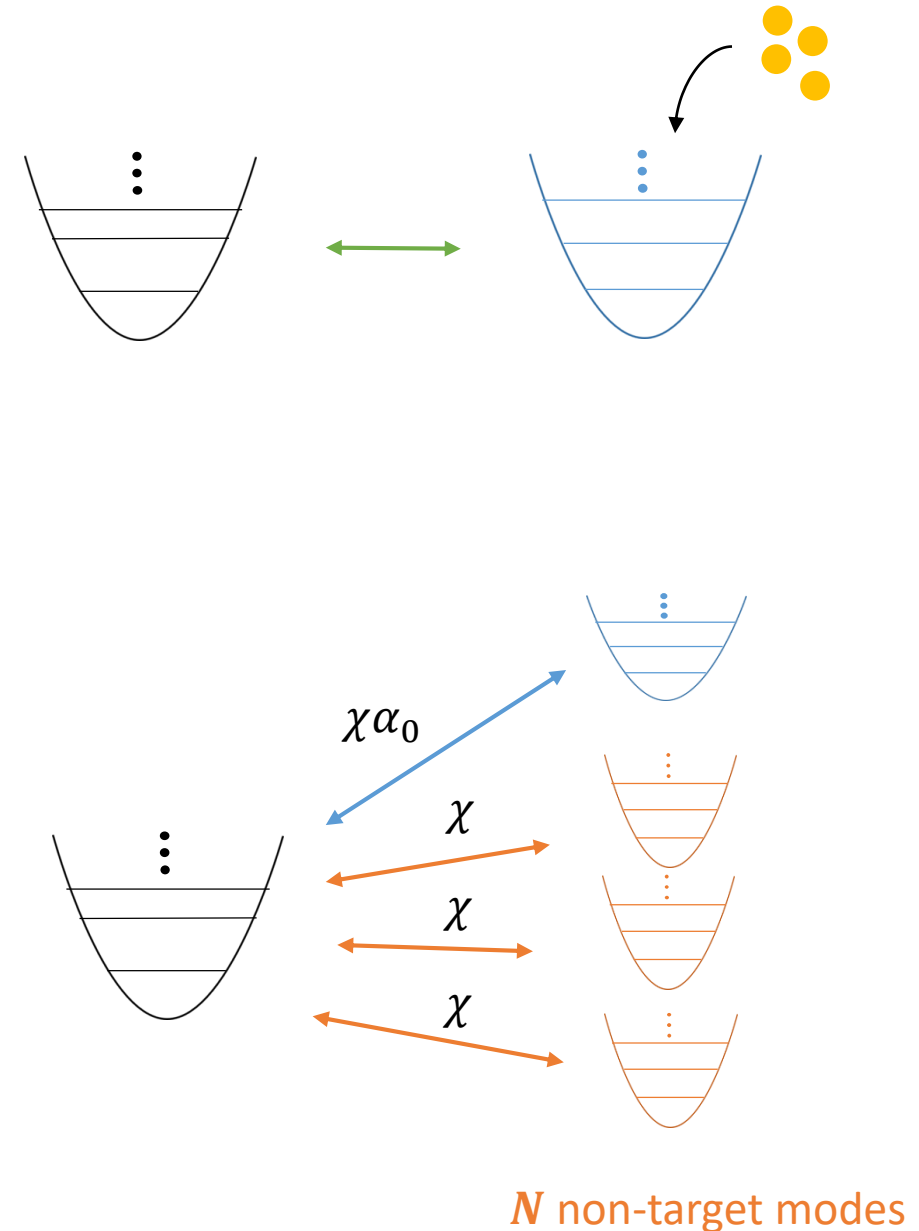
# Large Displacements

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

Advantage in Multimode Context:

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

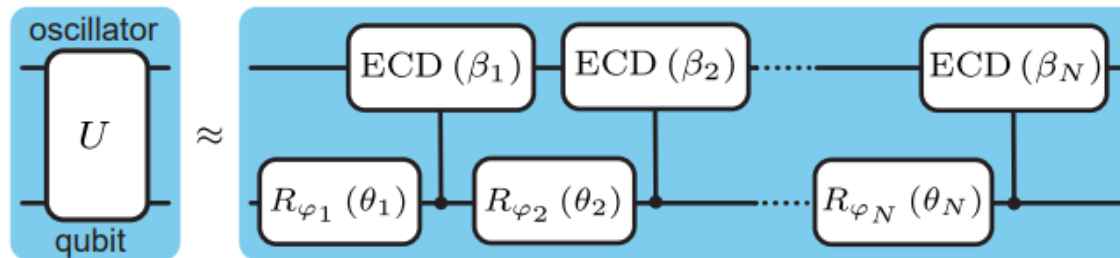
Coherent Errors:  $\epsilon_{coh} = \frac{N\chi}{g_{gate}} = \frac{N}{\alpha_0}$



- Hacoen-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



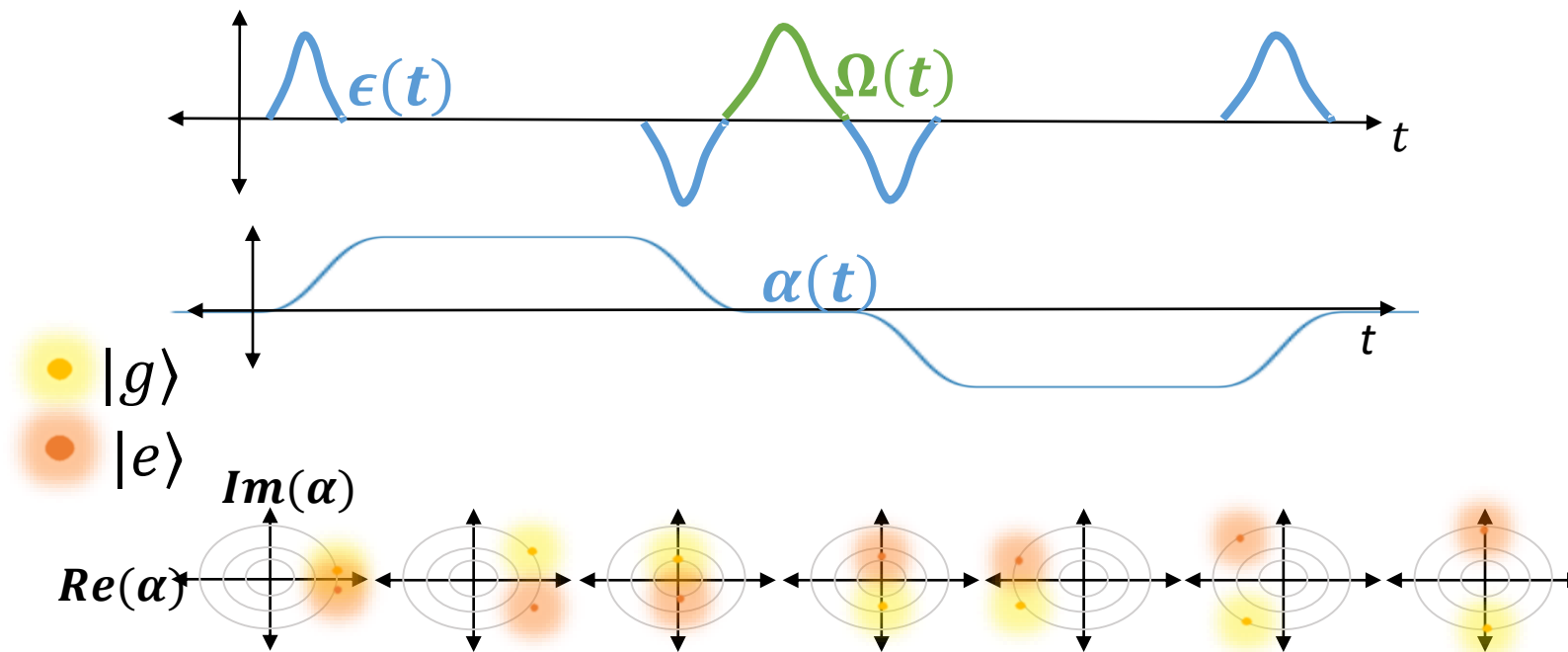
$$ECD(\beta) = D\left(\frac{\beta}{2}\right) |e\rangle\langle g| + D\left(-\frac{\beta}{2}\right) |g\rangle\langle e|$$

## Pulse Optimization

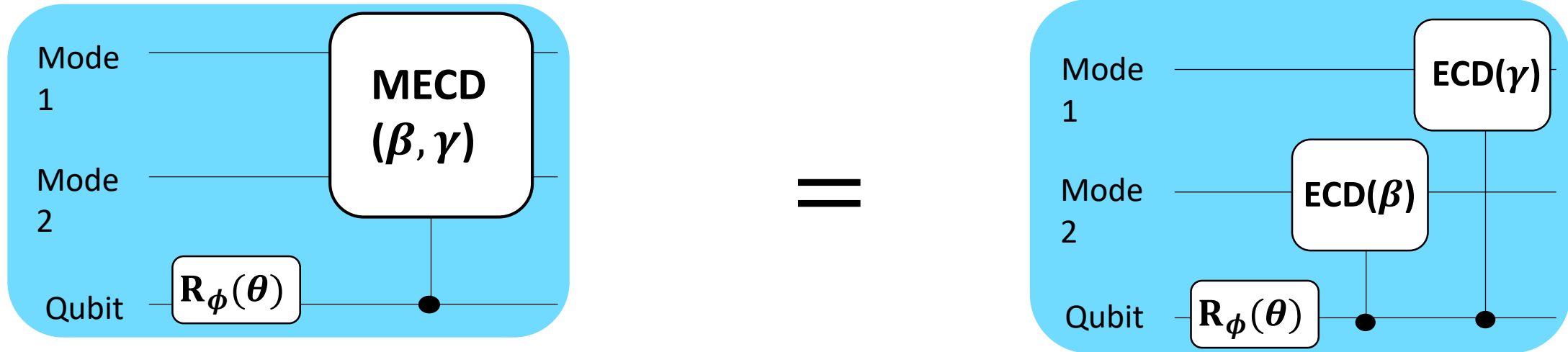
# Prev. Work: Echoed Cond. Disp.

## Parameter Optimization

### Pulse Optimization



# Multimode ECD



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

# 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 :

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

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

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

How to avoid :

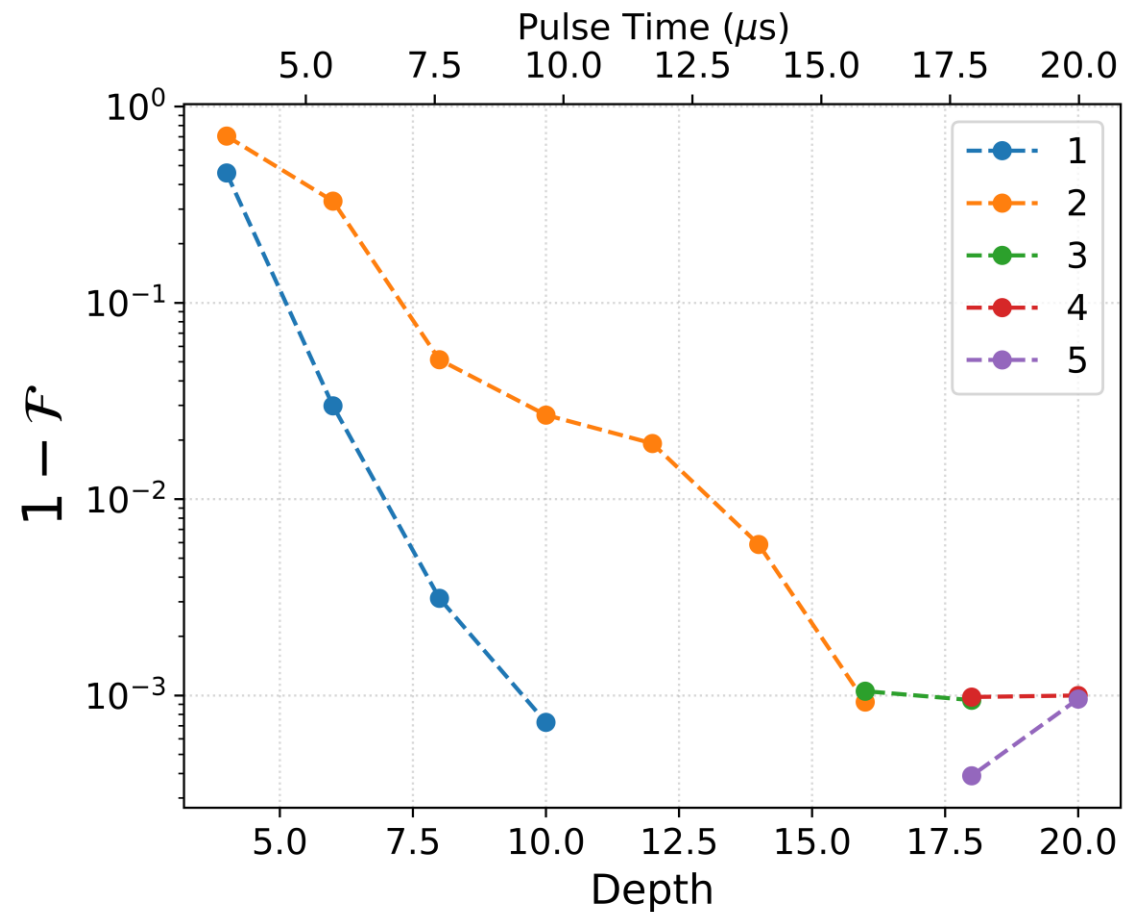
$\alpha, \beta$  should not be simultaneously nonzero

Echoed out when  $\beta$  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



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

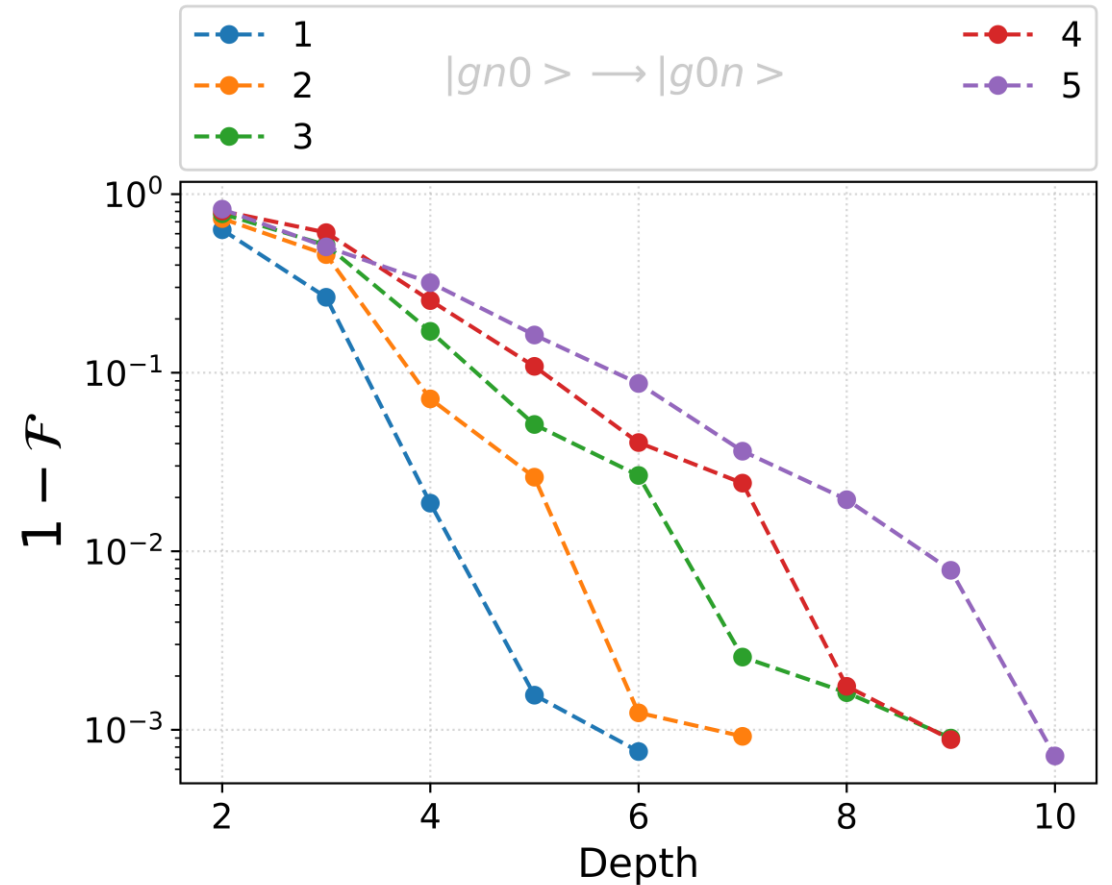
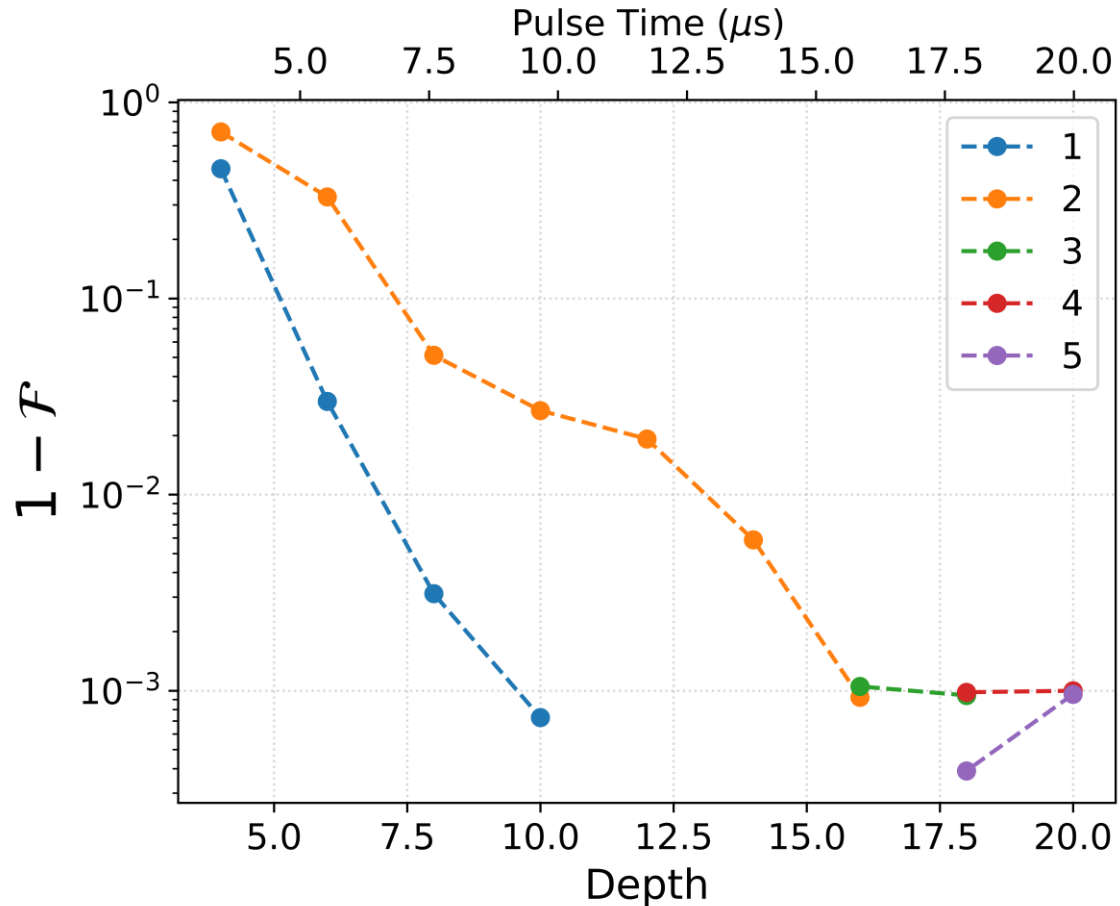


# Two Mode ECD: State Transfer

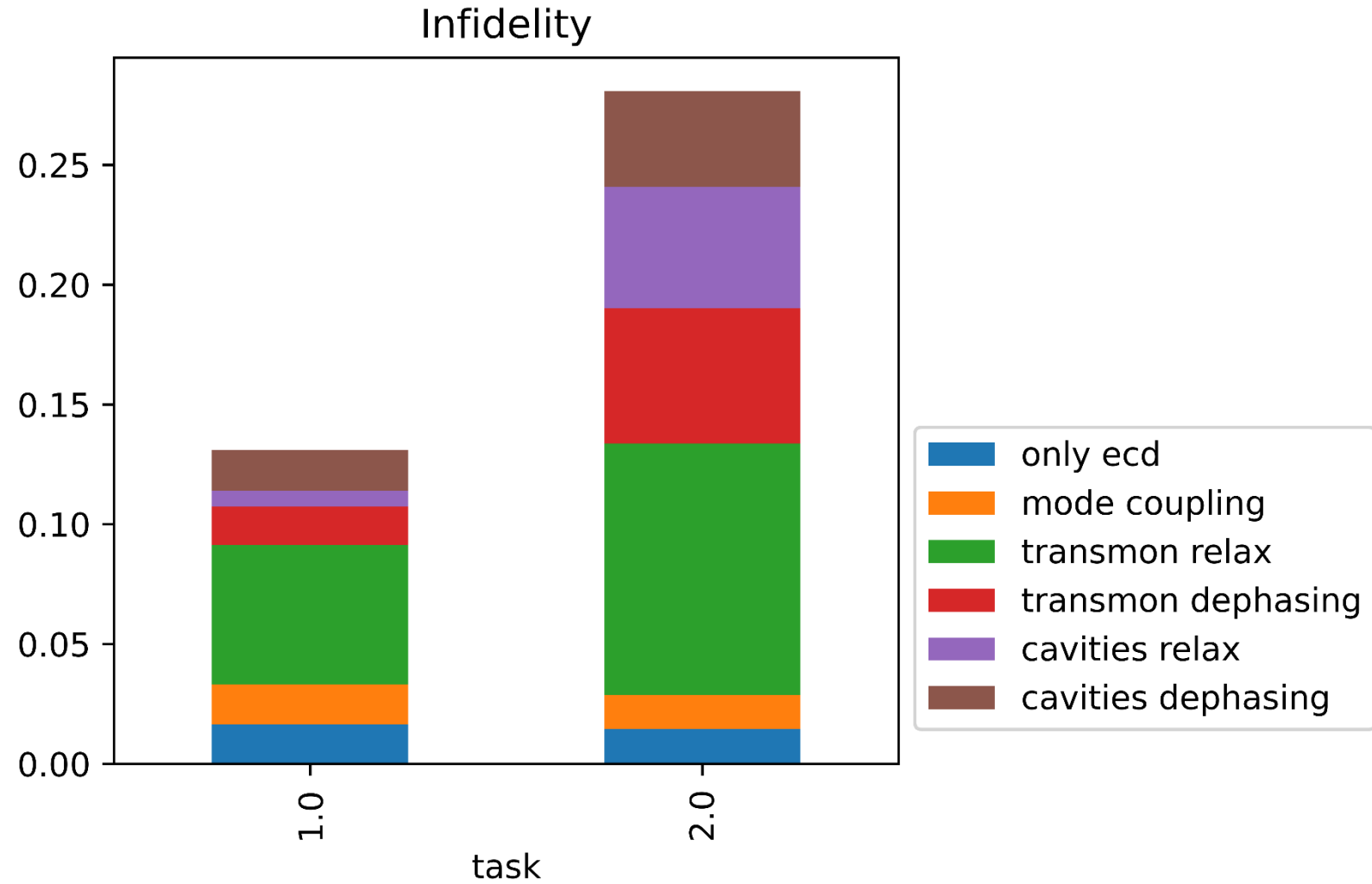
$$g \otimes (|n0\rangle \rightarrow |0n\rangle)$$

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

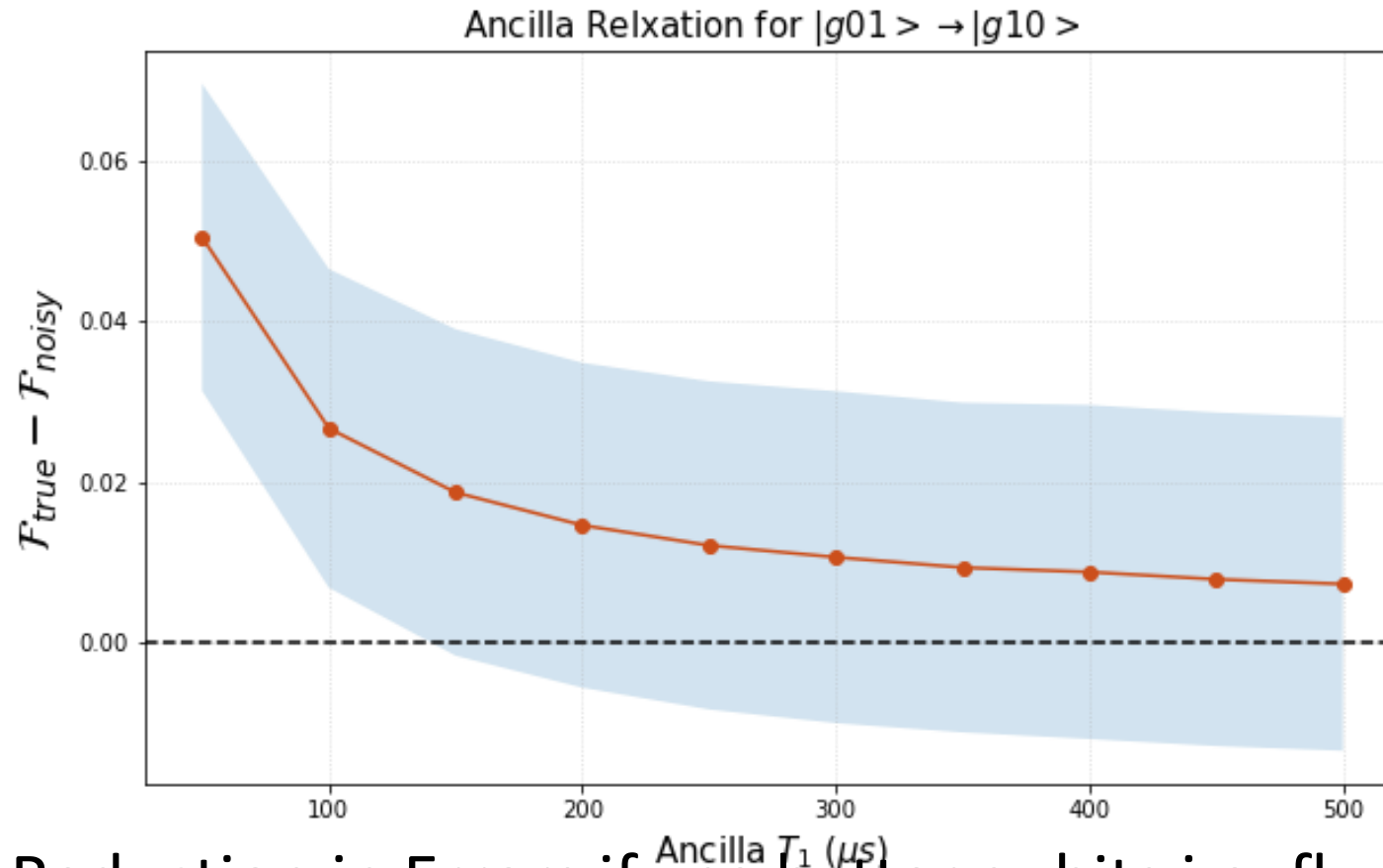
$$g \otimes (|n\rangle \rightarrow |0\rangle)$$



# Multimode ECD: Error Budget



# Transmon Relaxation

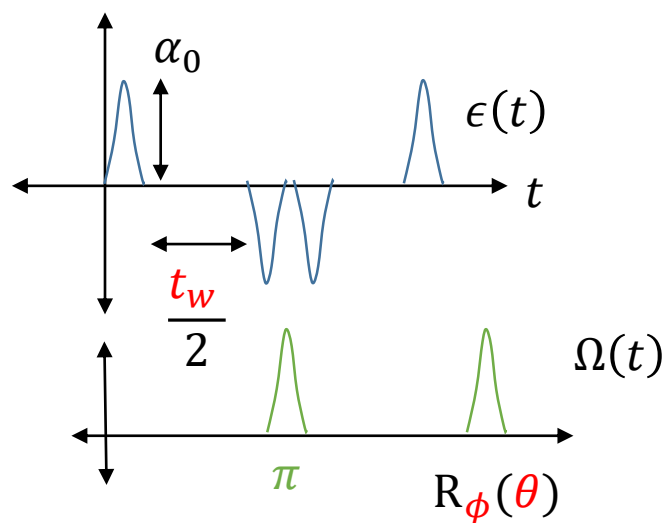


- Reduction in Errors if use better qubits i.e. fluxonium

# Circle Grape

- Rotates at detuning

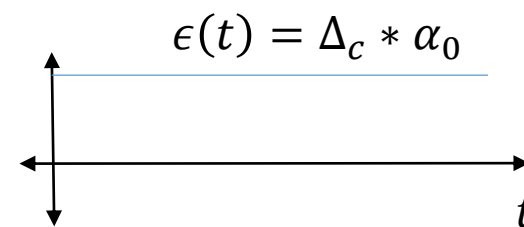
## ECD



Optimizer

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

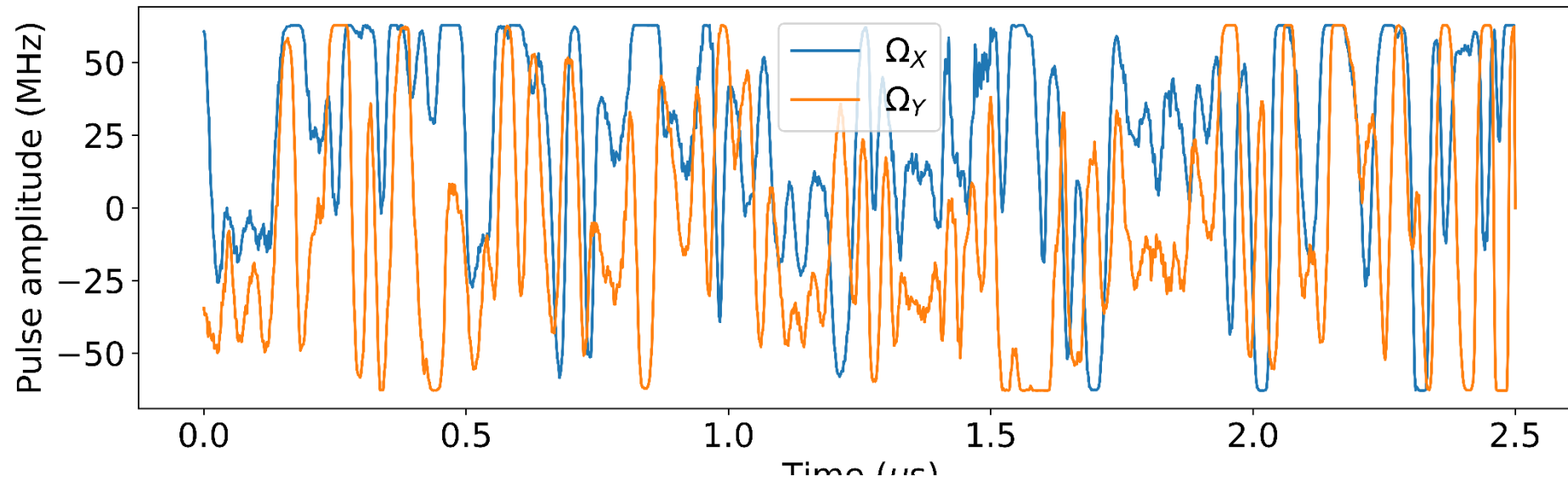
## Circle Grape



Optimizer

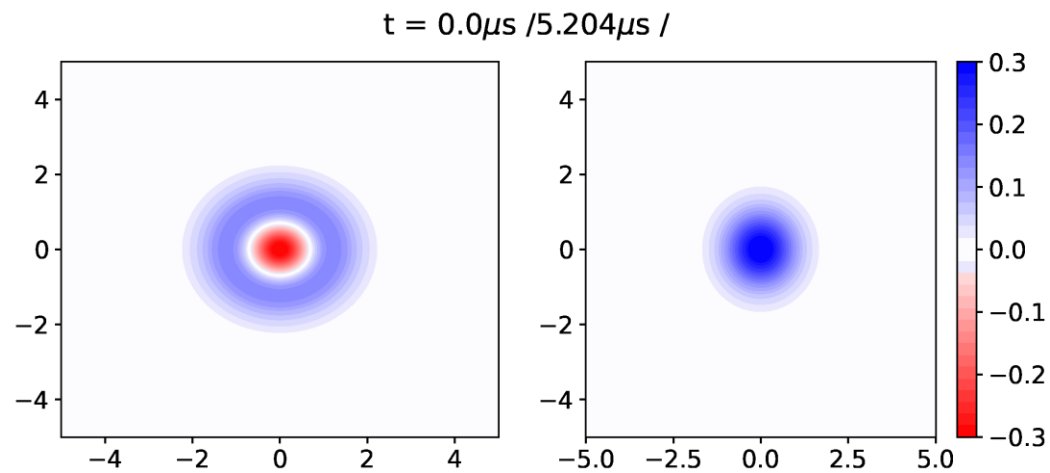
$$\Omega_x(t), \Omega_y(t)$$

# Circle Grape: g01 -> g10



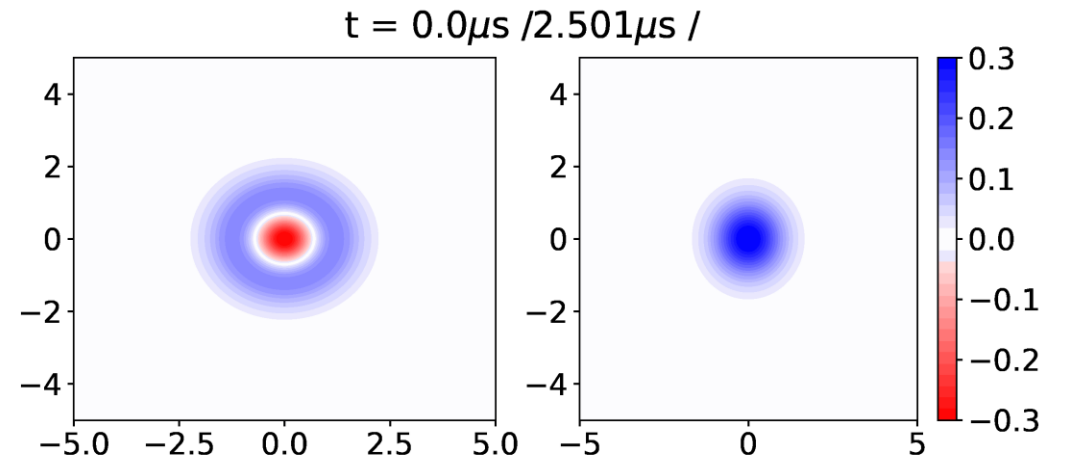
# Comparing Grape and MECD

ECD



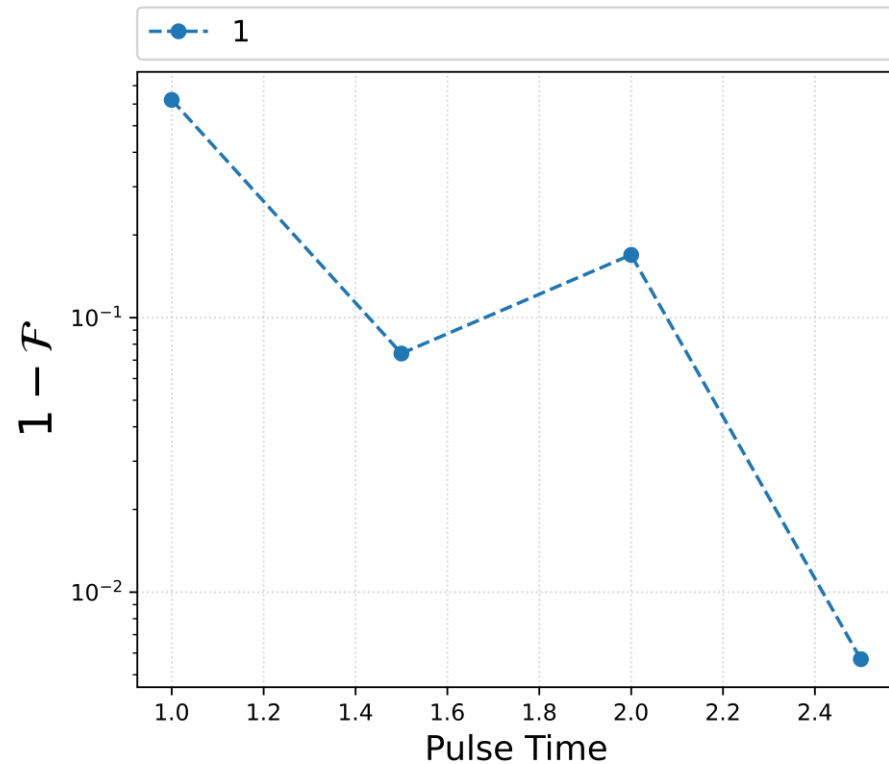
Circle Grape

Type equation here



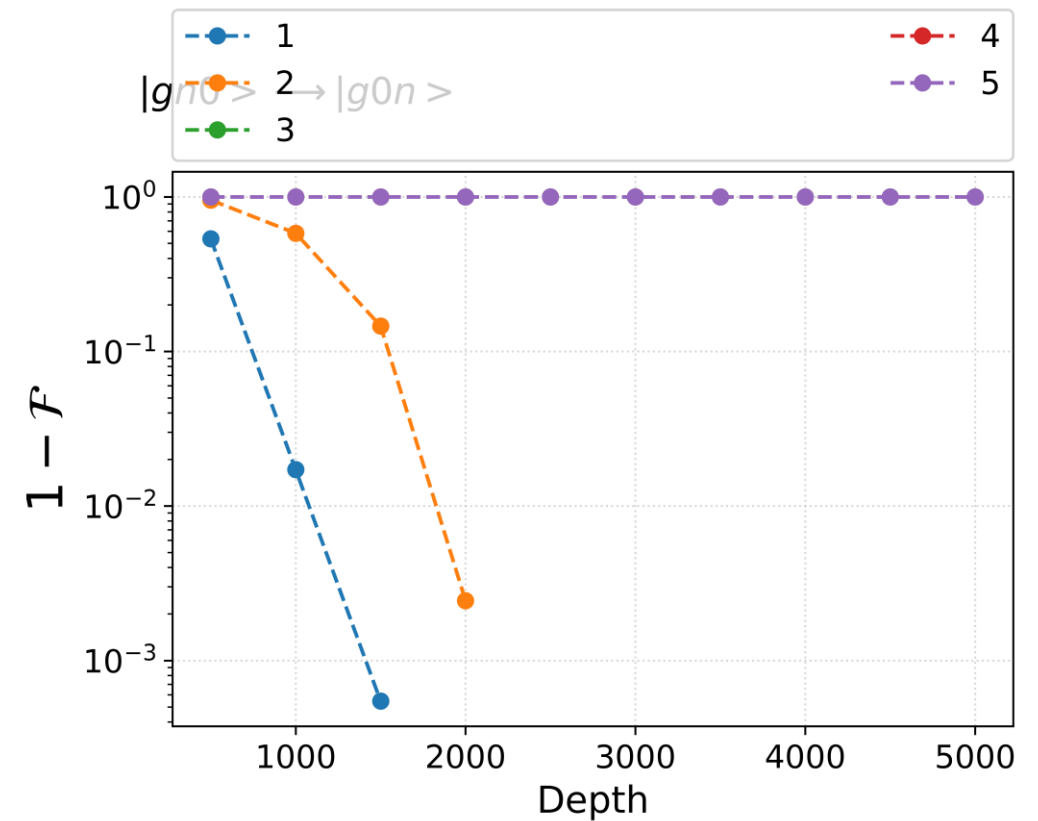
# Circle Grape Results

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



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

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





# 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

$$\begin{array}{c} \chi(a^\dagger + \alpha^*)(a + \alpha)\sigma_z \\ \downarrow \\ \chi a^\dagger a \sigma_z + \underbrace{\chi(\alpha a^\dagger + \alpha^* a)\sigma_z}_{\text{desired}} + \chi|\alpha|^2\sigma_z \end{array}$$

## 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  $\alpha$ 's but only a single  $\sigma_z$
- **Clever flipping of  $\alpha$  and  $\sigma_z$**  can echo out unwanted terms

# Sideband Drives

Since  $\alpha$  oscillatory,

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

$$\omega = 0$$

$$\omega = \Omega_R$$

$$\omega = 2\Omega_R$$

Frame Transformations:

$$1. \quad \sigma_x \leftrightarrow \sigma_z \quad \longrightarrow$$

$$\Omega_R \sigma_z$$

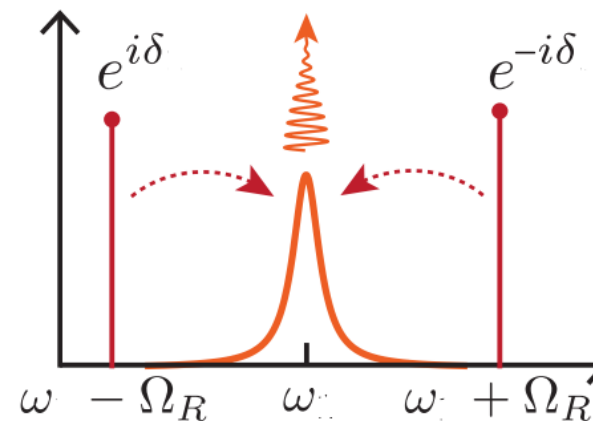
2. Rotating Frame of the qubit

$$\cancel{\Omega_R \sigma_z}$$

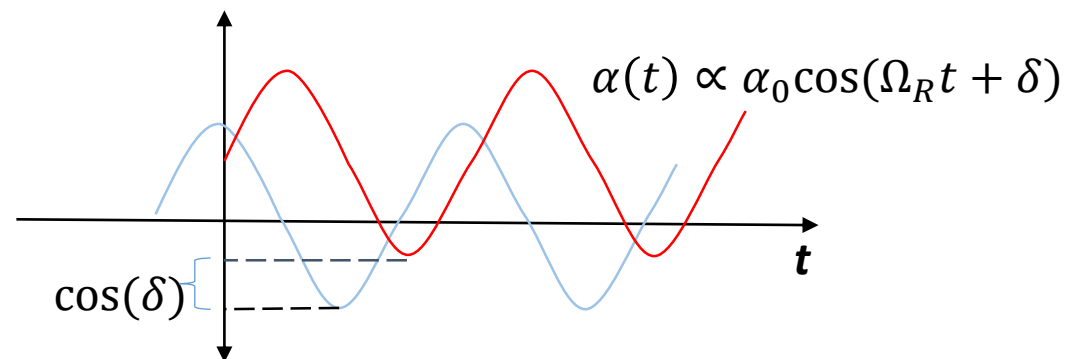
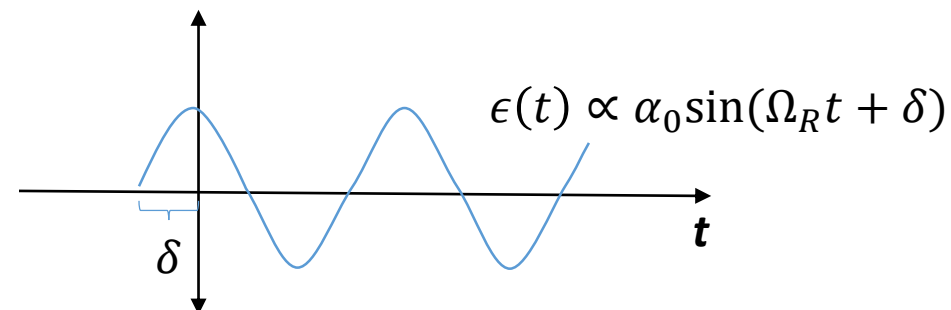
$$H = \chi \alpha_0 (a^\dagger + a) \otimes (\sigma_x \cos \delta + \sigma_y \sin \delta) + \dots$$

$$\omega = 0$$

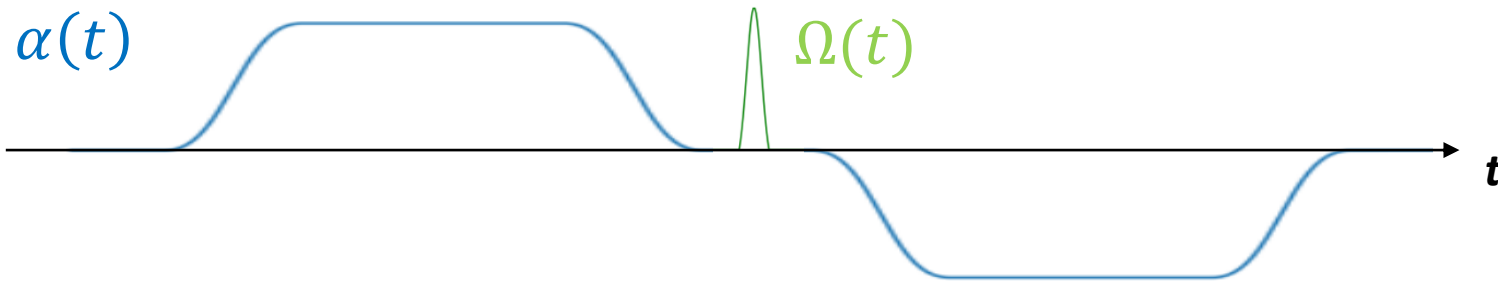
$$\omega \geq \Omega_R$$



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



# Prev. Work: Echoed Cond. Disp.



$$\begin{aligned} &\chi a^{\dagger} a \sigma_z \\ &\chi(\alpha a^{\dagger} + \alpha^* a) \sigma_z \\ &\chi |\alpha|^2 \sigma_z \end{aligned}$$

Echo  


$$\begin{aligned} &\chi a^{\dagger} a (-\sigma_z) \quad \text{Not completely echoed out !} \\ &\chi(\alpha a^{\dagger} + \alpha^* a) \sigma_z \\ &\chi |\alpha|^2 (-\sigma_z) \end{aligned}$$

# 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

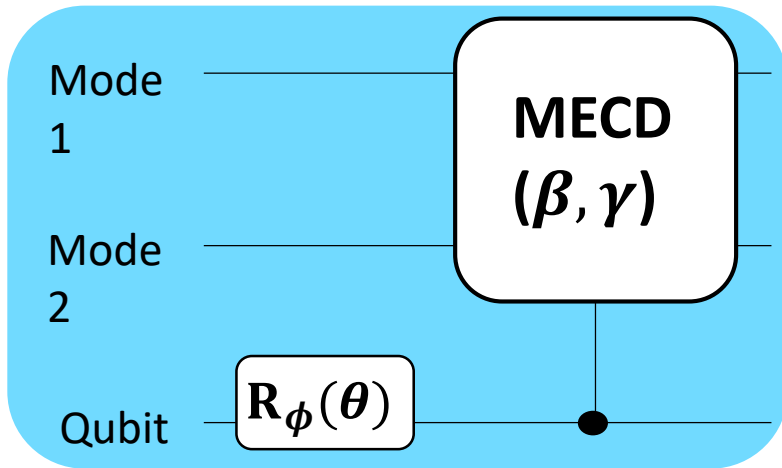
$$H = \chi a^\dagger a \sigma_z + \chi(\alpha_0 a^\dagger + \alpha_0^* a) \sigma_z + \chi |\alpha_0|^2 \sigma_z + \Omega(t) \sigma_x$$

Sent to Optimizer

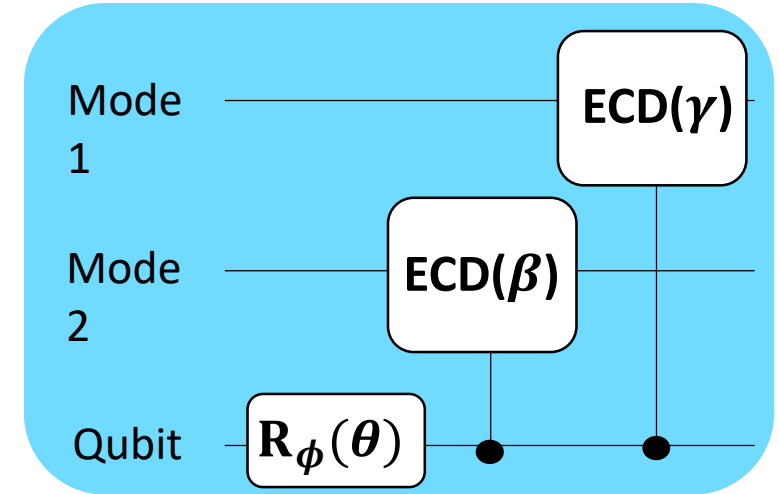


- Continuous version
- Currently uses simultaneous drives
- Phase Space Dynamics

# Multimode ECD



=



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



