Fast Control of Multimode Cavities with Conditional Displacements

Eesh Gupta, S. Chakram, …

Flux transformers to introduce Static Magnetic Fields

Outline

Challenges in Cavity Control

Multimode Echoed Conditional Displacements

Alternative Schemes

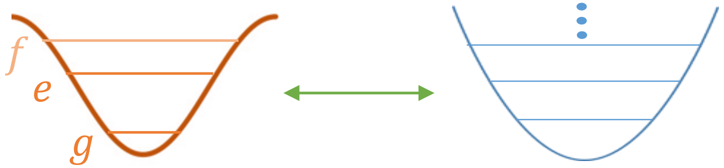
** Ma, Wen-Long, et al. *Science Bulletin* 66.17 (2021): 1789-1805.

Why 3D Cavities?

- High Coherence times compared to transmons *

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

- Simple decoherence processes and large Hilbert space -> hardware efficient for error correction



- Universal control achieved via coupling to transmons

<u>Goal</u>: Enact **high-speed** and **low-error** gates on cavity modes coupled to ancilla

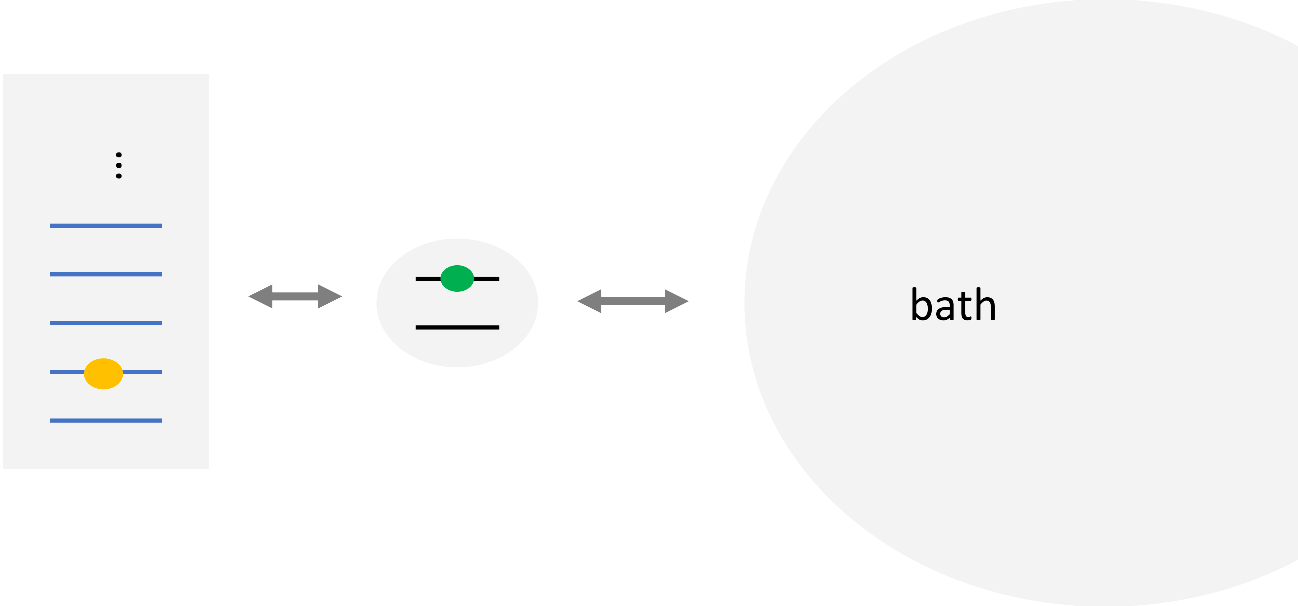
** Ma, Wen-Long, et al. *Science Bulletin* 66.17 (2021): 1789-1805.

Challenges in Cavity Control

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



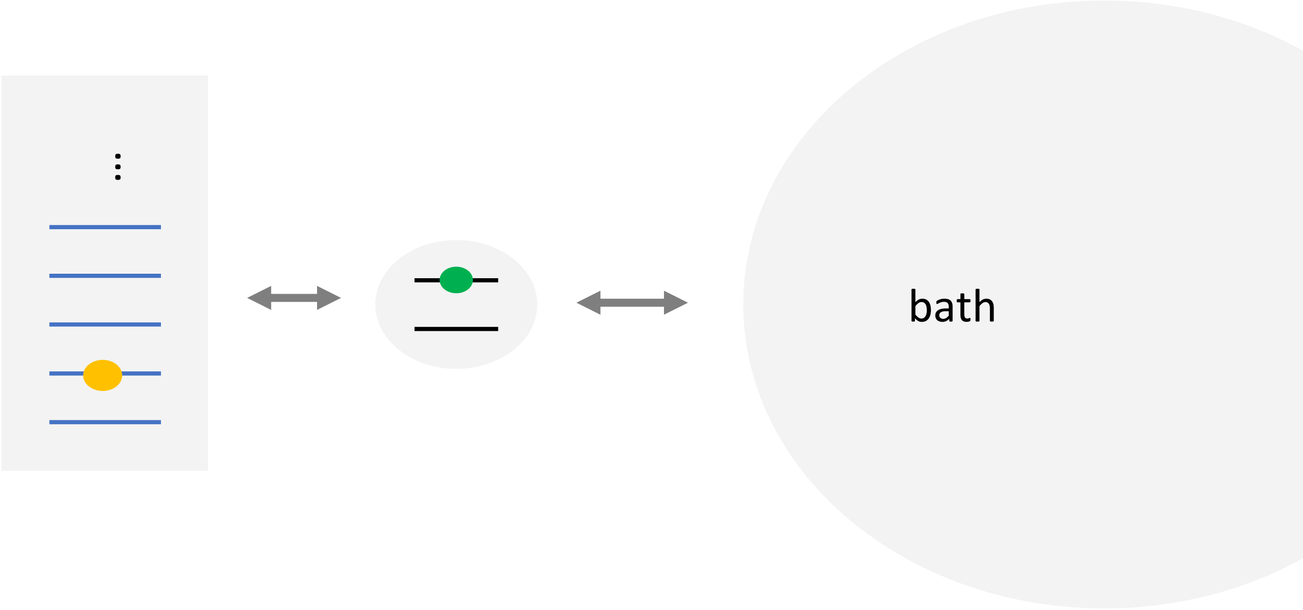
Eickbusch, A., Sivak, V., Ding, A.Z. et al. Nat. Phys. ***18****, 1464–1469 (2022)*

Challenges in Cavity Control

Can use finite-level ancilla for universal control

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)

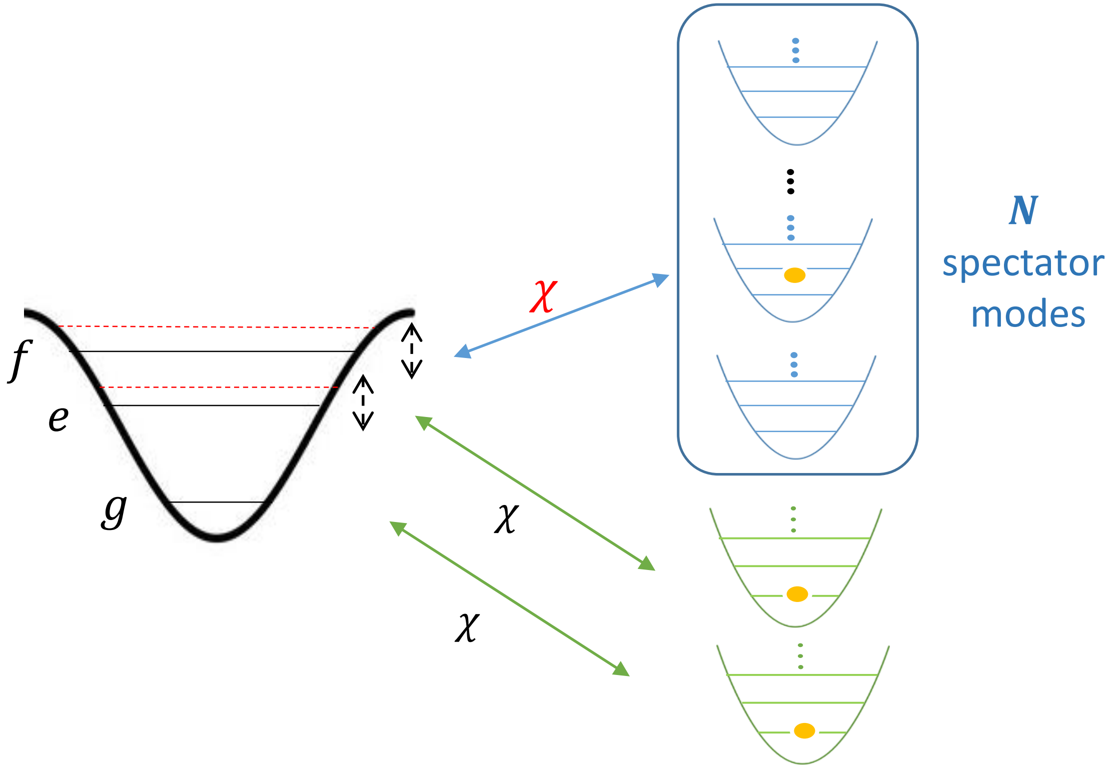
Conditional Displacement Gates

- Use Large Displacements to enhance effective interaction strength
- Weak $\chi/2\pi \sim 30$ kHz but strong $\chi\alpha_0/2\pi \sim 1$ MHz

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

Crosstalk Errors

- Dispersive shift causes frequency shifts in transmon from photons in spectator modes
- $\epsilon_{coh} = \dfrac{N\chi}{\chi\alpha_0} = \dfrac{N}{\alpha_0}$



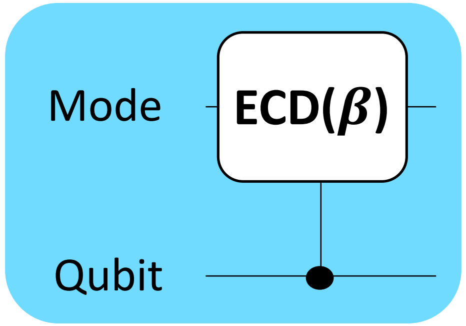
- Hacohen-Gourgy, S., Martin, L., Flurin, E. *et al.* *Nature* **538**, 491–494 (2016).
- Eickbusch, A., Sivak, V., Ding, A.Z. et al. *Nat. Phys.* 18, 1464–1469 (2022).

Echoed Conditional Gates

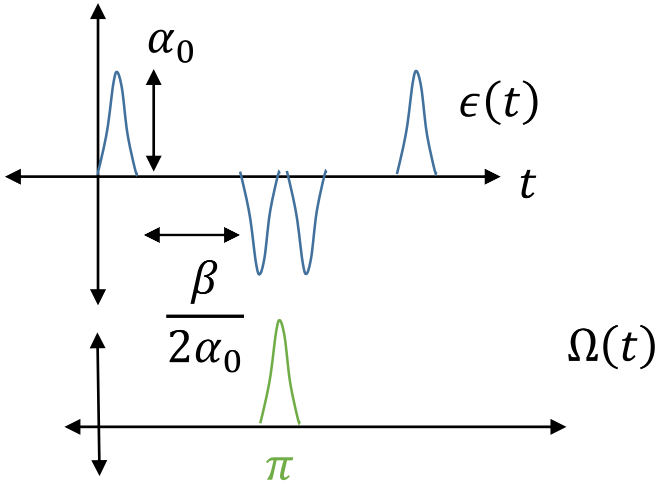
$$\chi(a^\dagger + \alpha^*)(a + \alpha)\sigma_z$$

$$=$$

$$\chi a^\dagger a \sigma_z \quad + \quad \boxed{\chi\,(\alpha a^\dagger + \alpha^* a)\,\sigma_z} \quad + \quad \chi|\alpha|^2\sigma_z$$



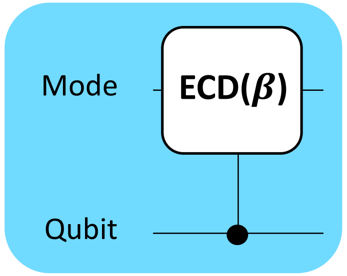
$$= \quad D\left(\frac{\beta}{2}\right)|e\rangle\langle g| + D\left(-\frac{\beta}{2}\right)|g\rangle\langle e| \quad =$$



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

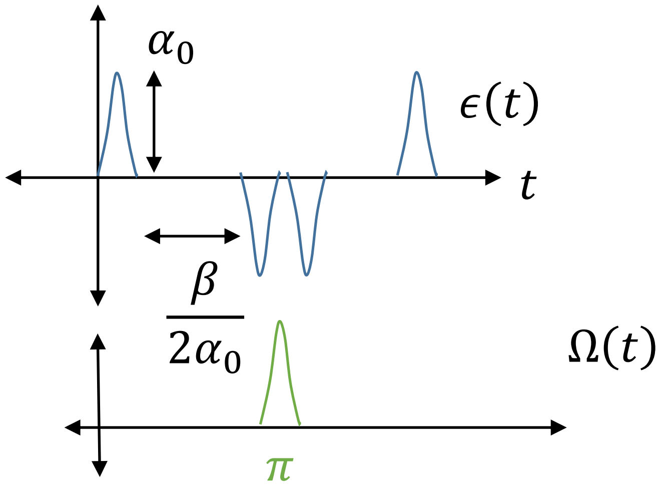
Echoed Conditional Displacements

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



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

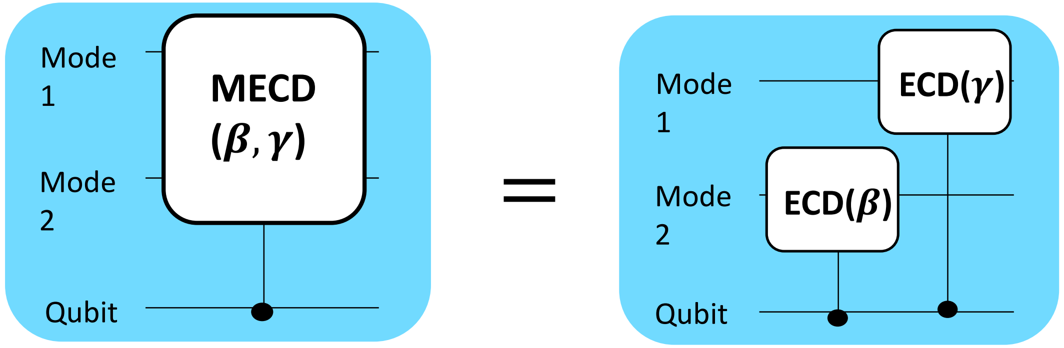
- Universal control of single mode coupled to qubit with gate set $\{ECD(\beta), R_\phi(\theta)\}$

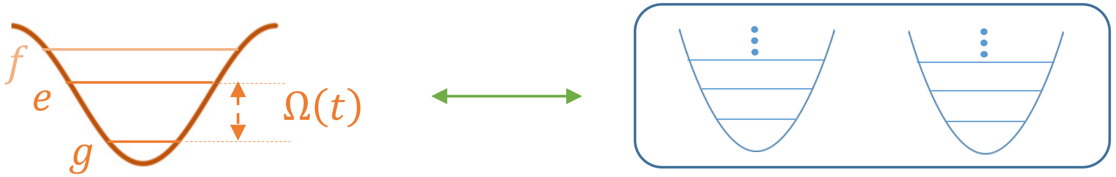


Eickbusch, A., Sivak, V., Ding, A.Z. et al. *Nat. Phys.* 18, 1464–1469 (2022)

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





$$H_{\text{had}} = \sum_{i=1.2} \chi_i \alpha_i (a_i^\dagger + a_i)\sigma_x + \Omega(t)\sigma_z$$

Jaynes Cummings Interaction

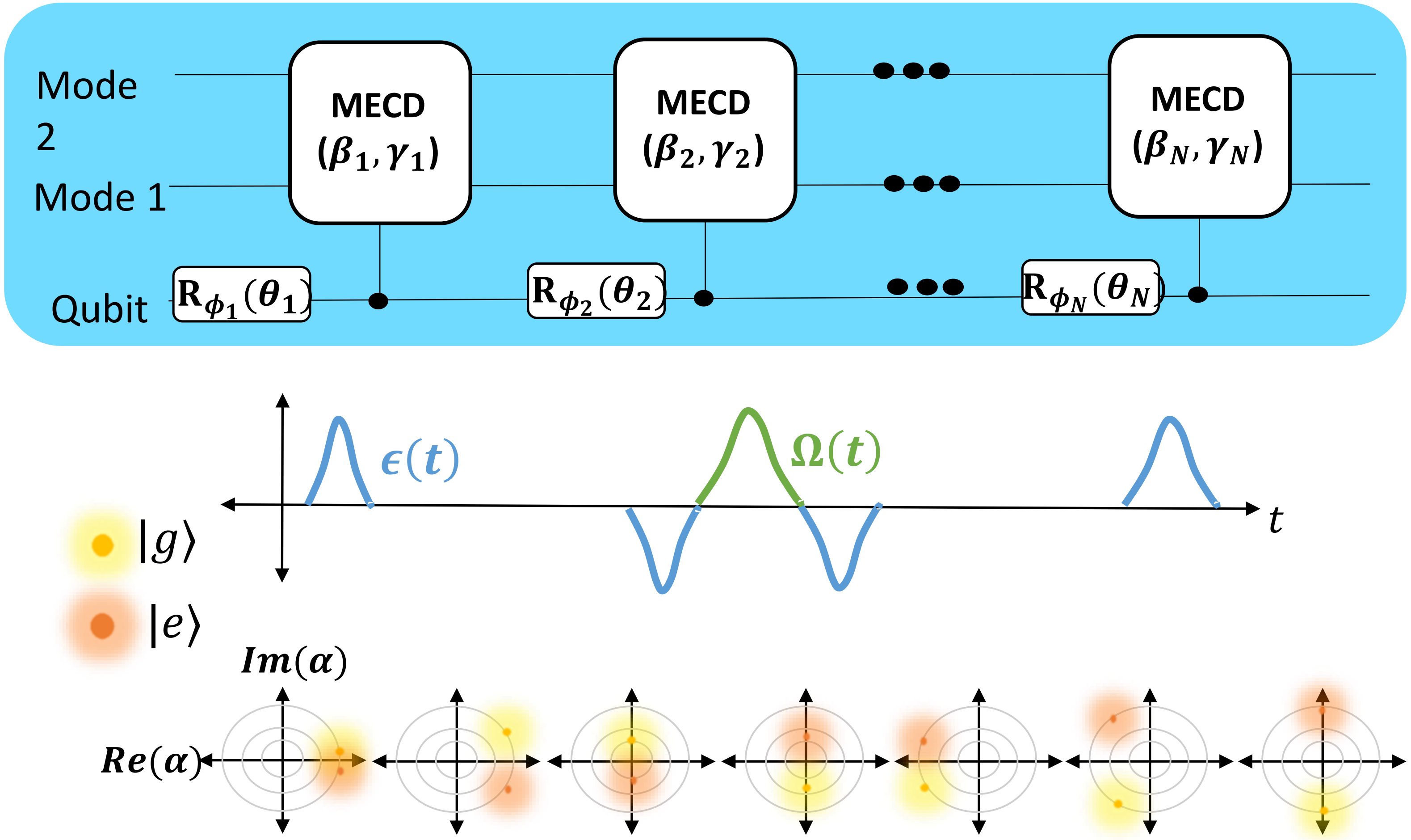
Tunable Qubit

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

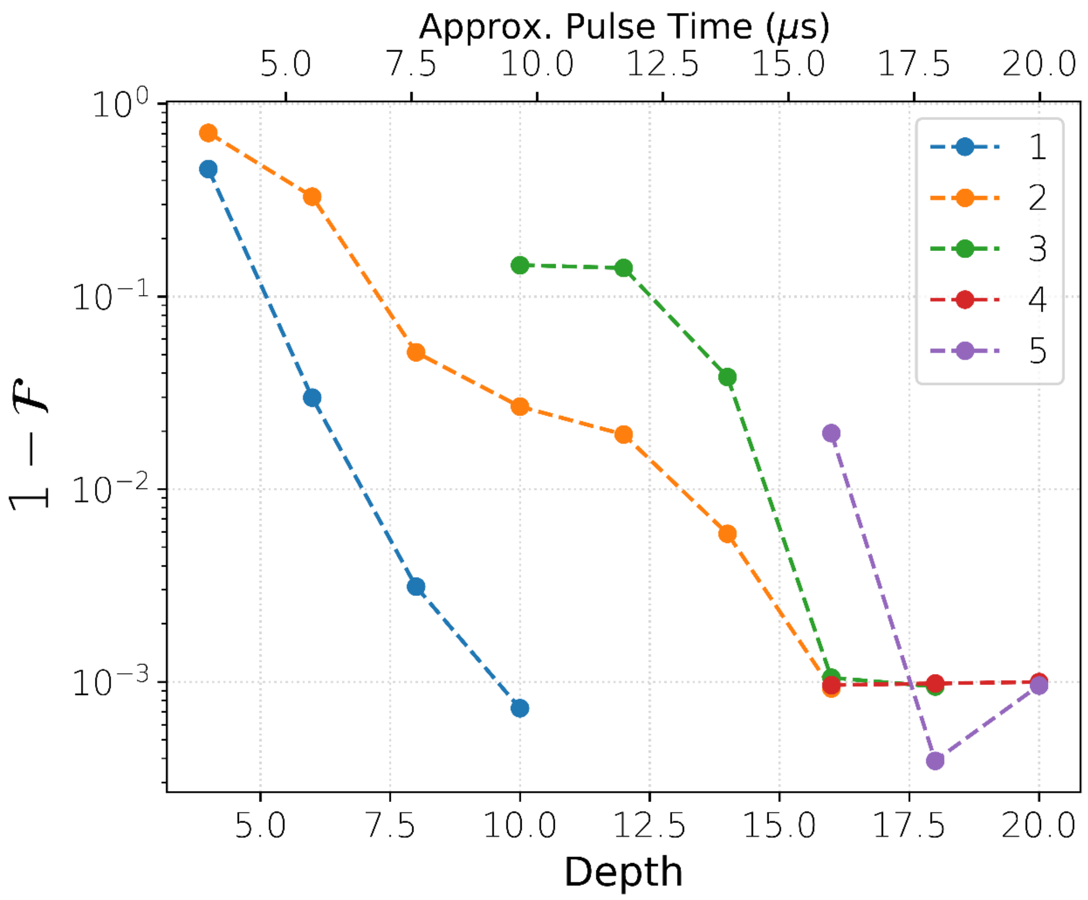
Workflow

Parameter Optimization

Pulse Optimization

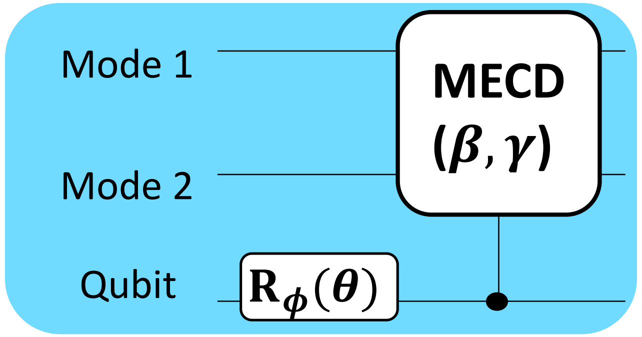


Two Mode ECD: State Transfer



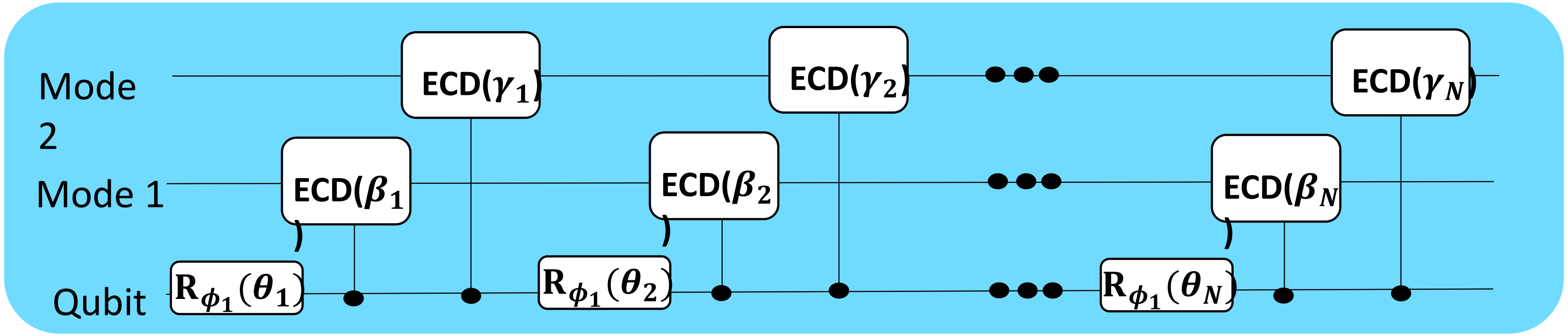
$$g \otimes |0n\rangle \rightarrow g \otimes |n0\rangle$$

1 layer/depth =

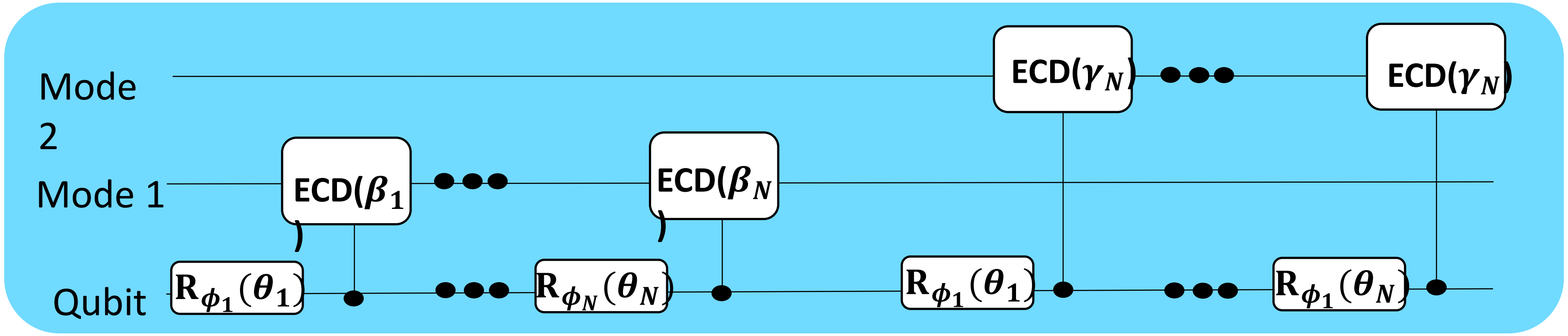


Two Mode ECD: State Transfer

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

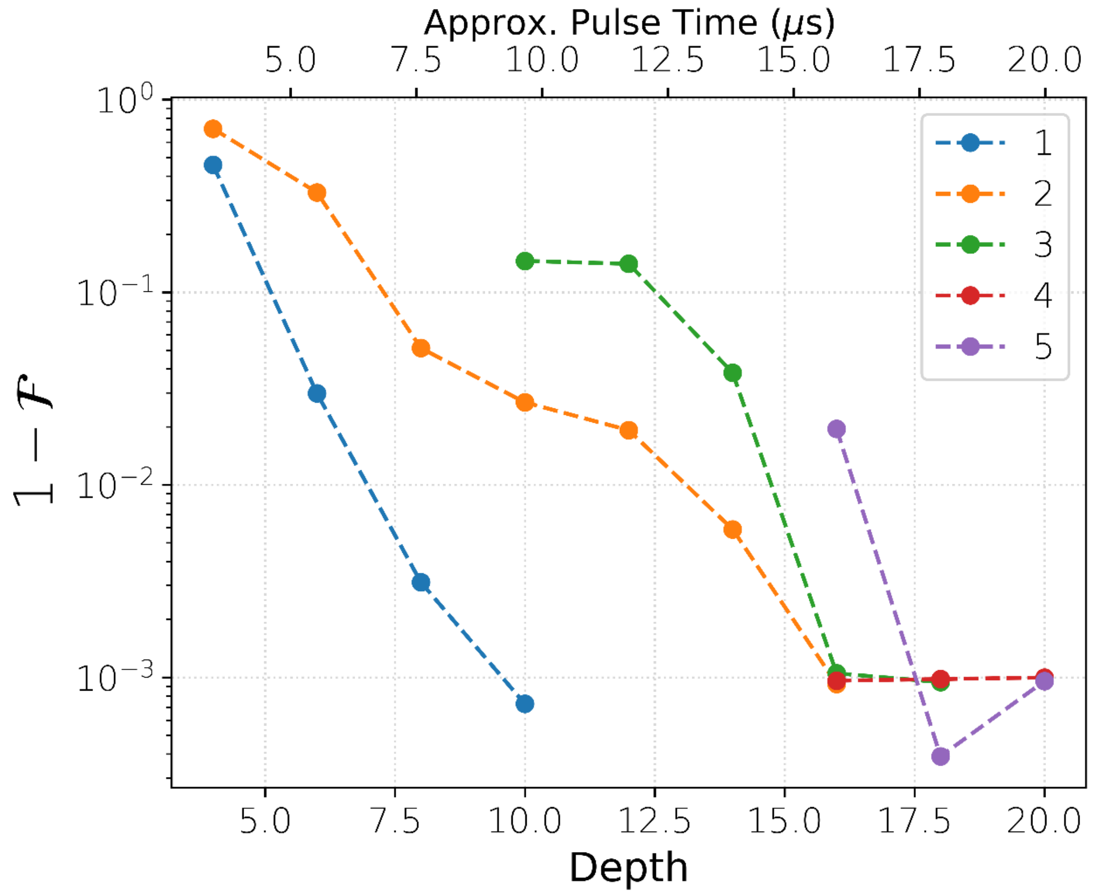


$$g \otimes (|n\rangle \to |0\rangle) \qquad g \otimes (|0\rangle \to |n\rangle)$$

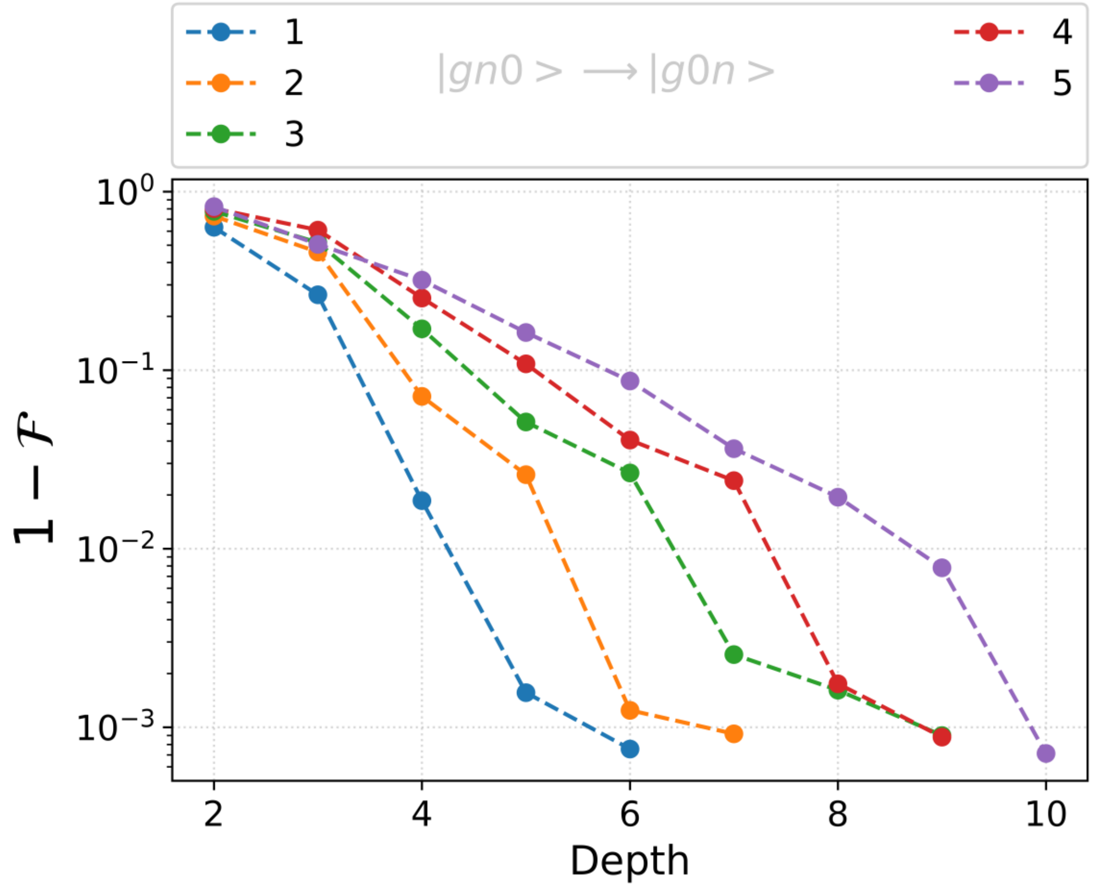


Two Mode ECD: State Transfer

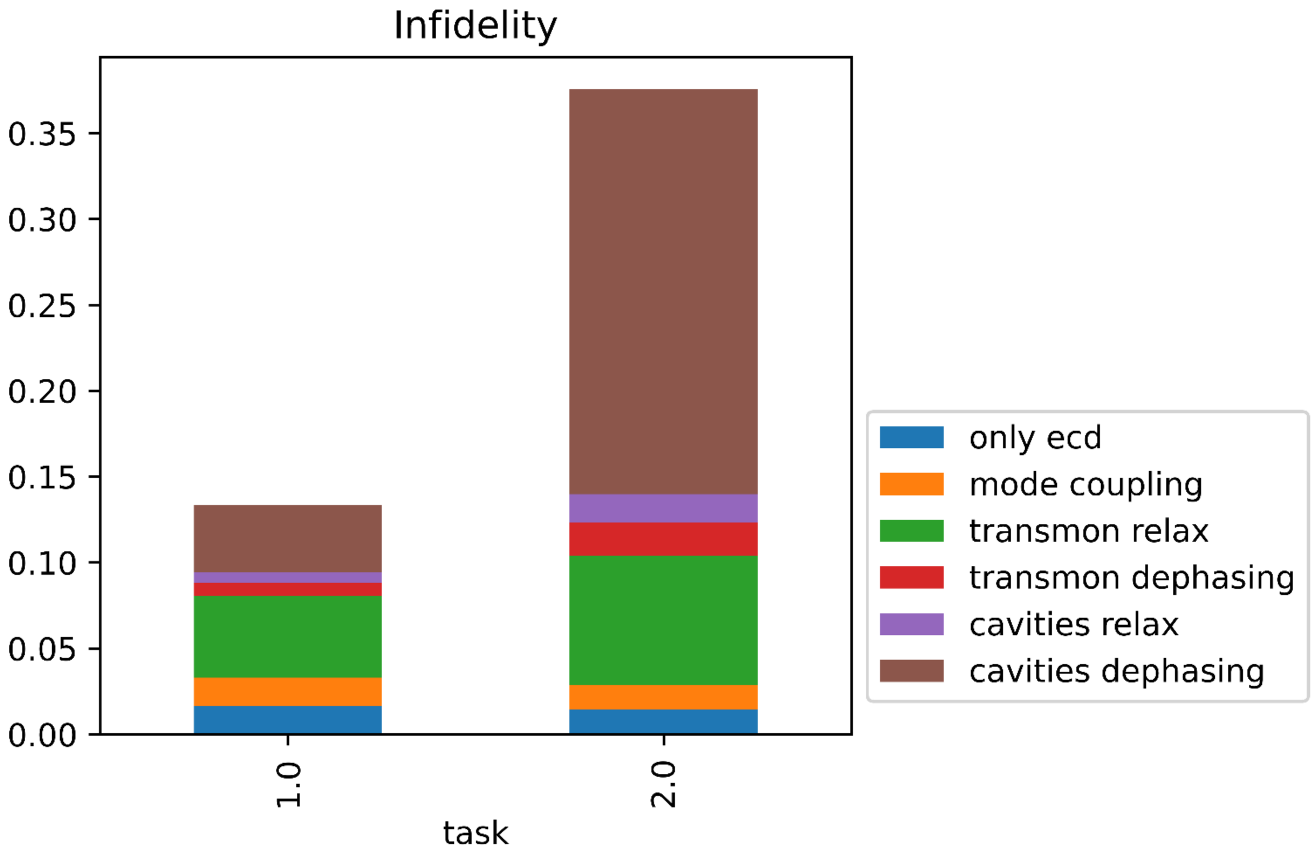
$$g \otimes (|n0\rangle \rightarrow |0n\rangle)$$



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



Multimode ECD: Error Budget

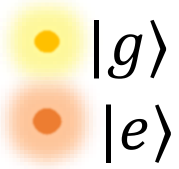


- $T_{1,q} = 85\ \mu s$
- $T_{2,q} = 98\ \mu s$
- $T_{1,c} = 2\ ms$
- $T_{\phi,c} = 150\ ms$ *

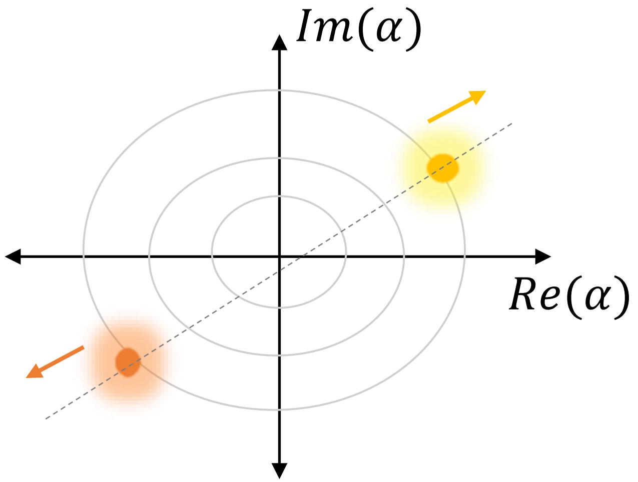
* *A. Eickbusch, ..., R. Schoelkopf, M. Devoret. ArXiv preprint arXiv:2111.06414 (2021)*

Circle Grape

- Qubit Drive Optimized
- Cavity mode always driven far from origin in phase space
- Cavity drives detuned

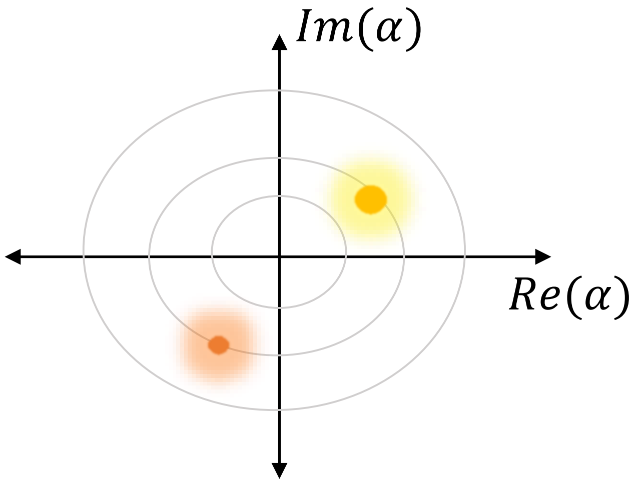


$$\mathrm{H} = \chi(\alpha a^{\dagger} + \alpha^{*} a)\sigma_z$$



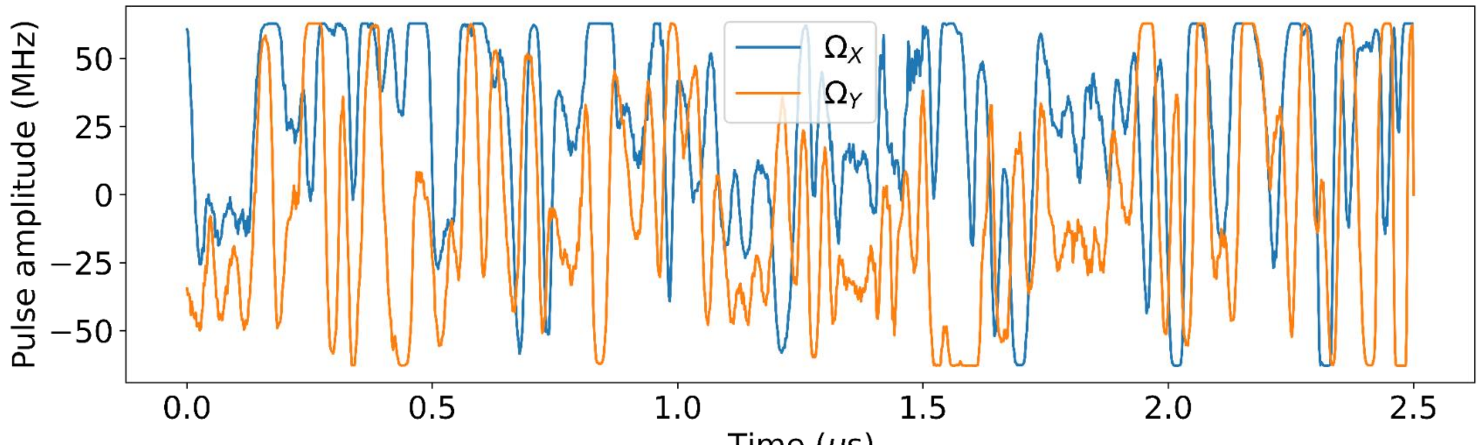
$$\mathrm{H} = \Delta_c a^{\dagger} a + \chi(\alpha a^{\dagger} + \alpha^{*} a)\sigma_z$$

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



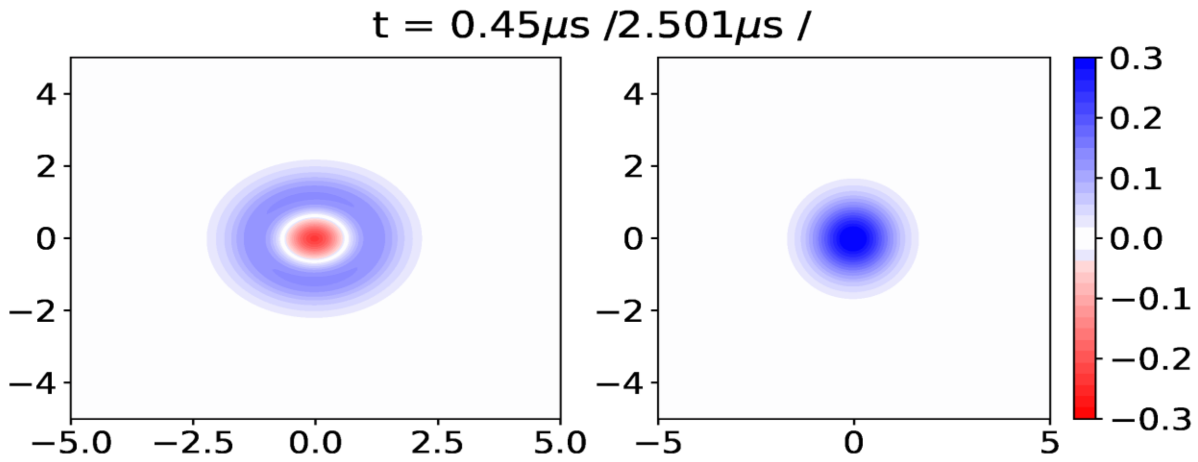
Elder S., et al. Bulletin of the American Physical Society 66 (2021)

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



Simulation Parameters

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



Sideband Drives Method

Since α oscillatory,

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

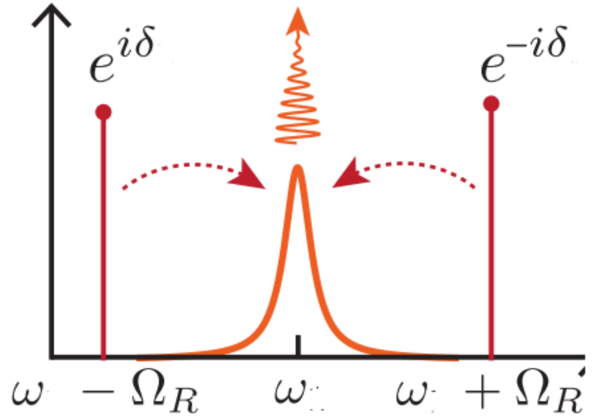
$\omega = 0$ $\quad$ $\omega = \Omega_R$ $\quad$ $\omega = 2\Omega_R$

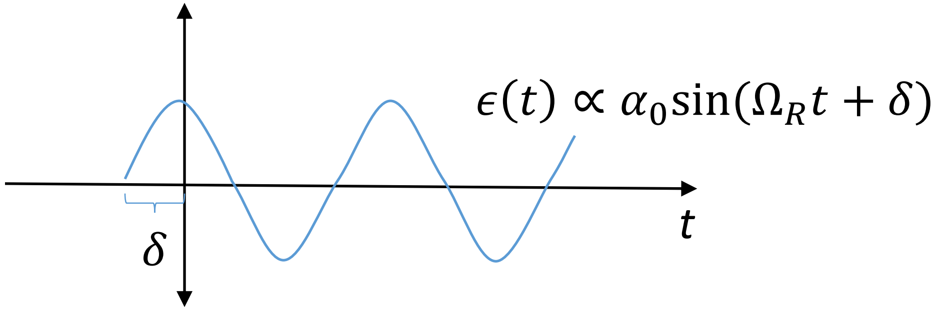
Frame Transformations:

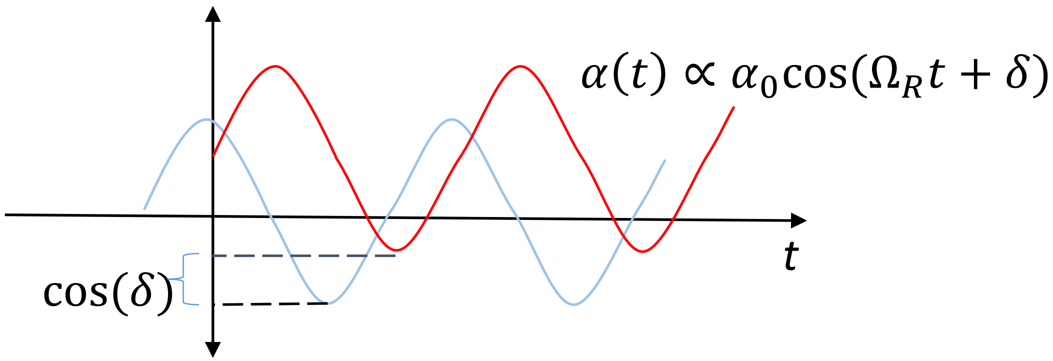
1. $\sigma_x \leftrightarrow \sigma_z$ $\longrightarrow$ $\Omega_R \sigma_z$
2. Rotating Frame of the qubit $\quad$ $\cancel{\Omega_R \sigma_z}$

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

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

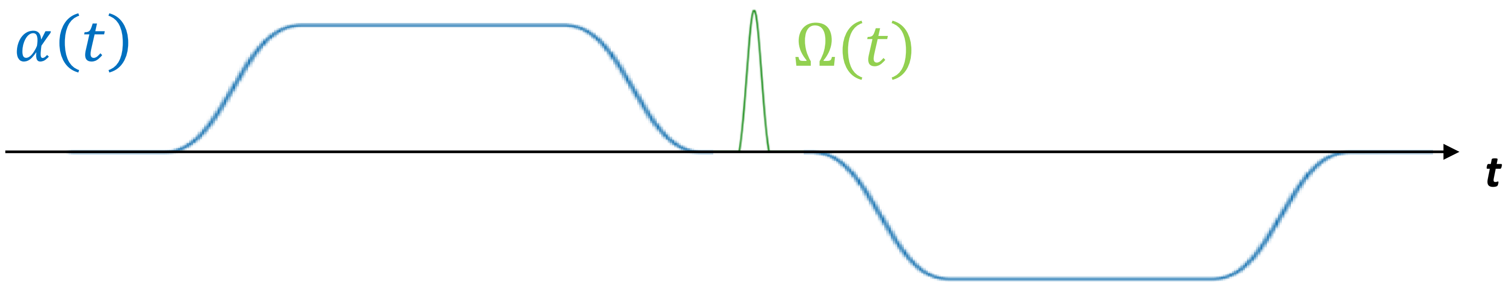






Shay Hacohen-Gourgy, …, Irfan Siddiqi. Nature 538-7626 (2016).

Echoing in ECD



$\chi a^+ a \sigma_z$ → Echo → $\chi a^+ a(-\sigma_z)$

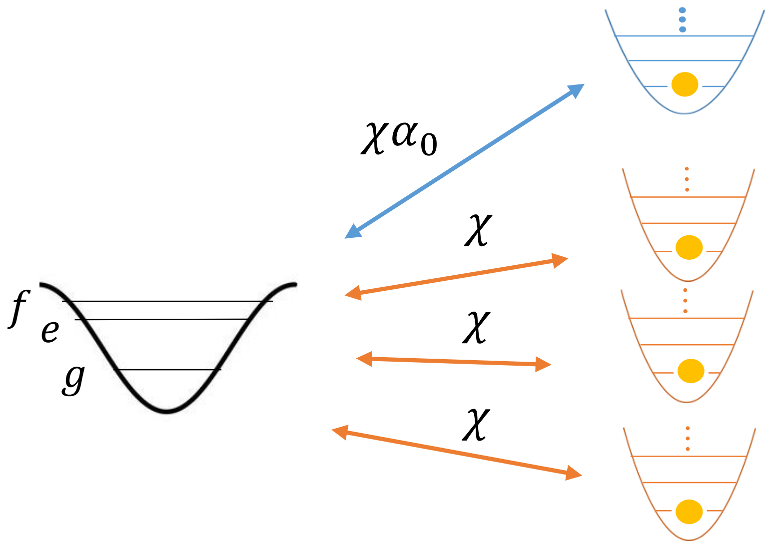
Not completely echoed out !

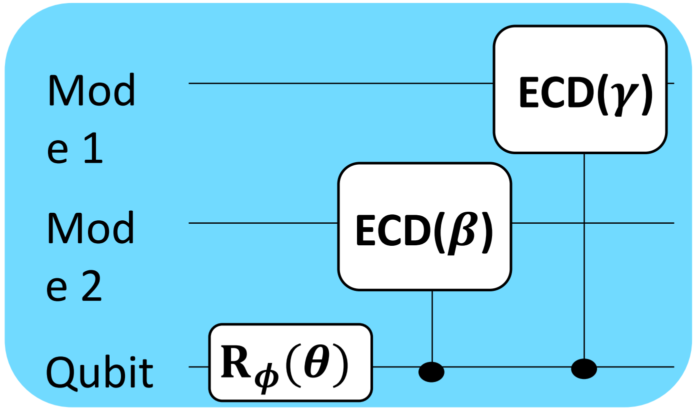
$\chi(\alpha a^+ + \alpha^* a)\sigma_z$ → $\chi(\alpha a^+ + \alpha^* a)\sigma_z$

$\chi|\alpha|^2\sigma_z$ → $\chi|\alpha|^2(-\sigma_z)$

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

Conclusions and Future Work

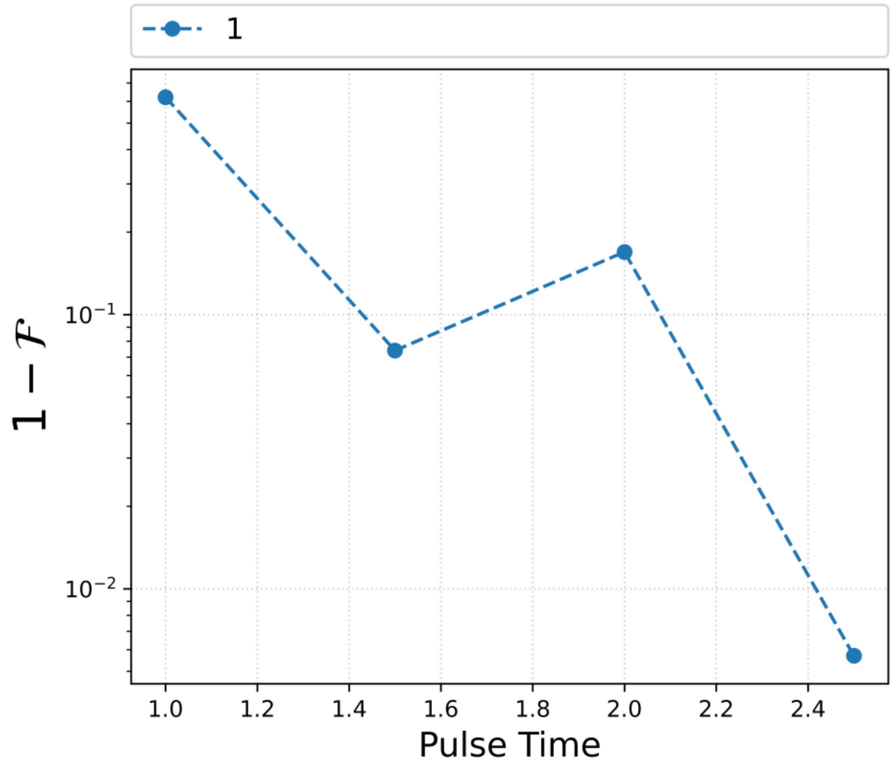




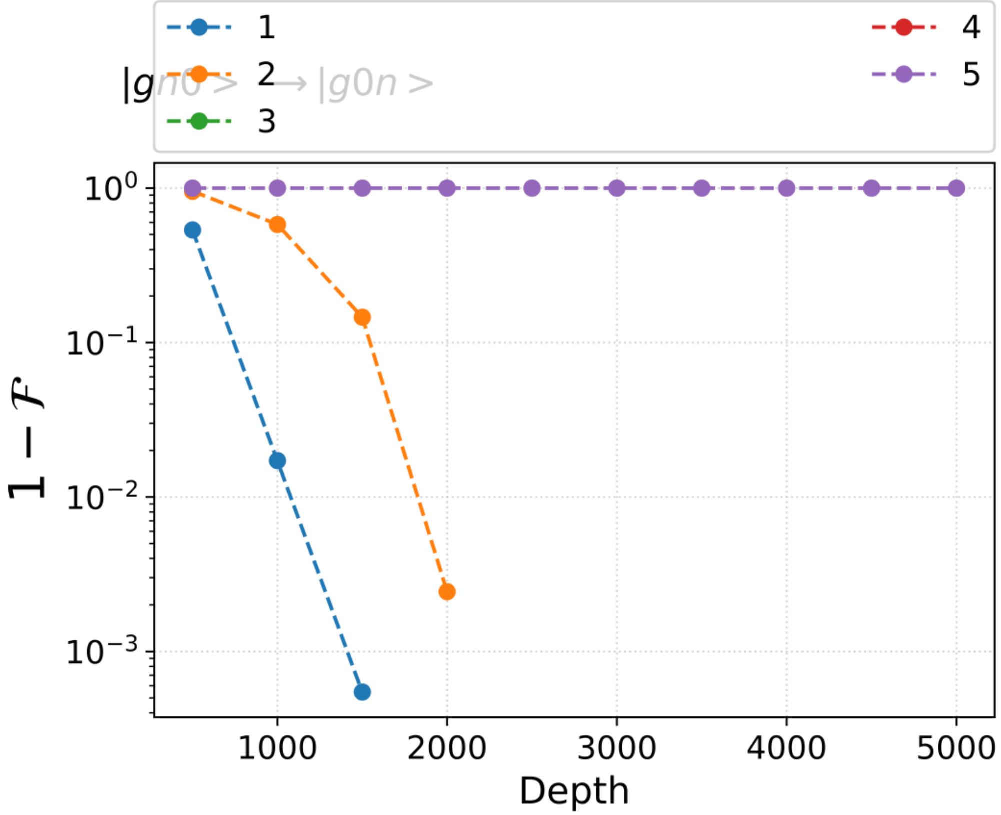
- Suppression of cross-talk errors
- Achieve >0.999 fidelity for fock state transfer using Double ECD
- Future Work:
  - Unite ECD with Sidebands scheme and CNOD

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

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

$$\downarrow$$

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

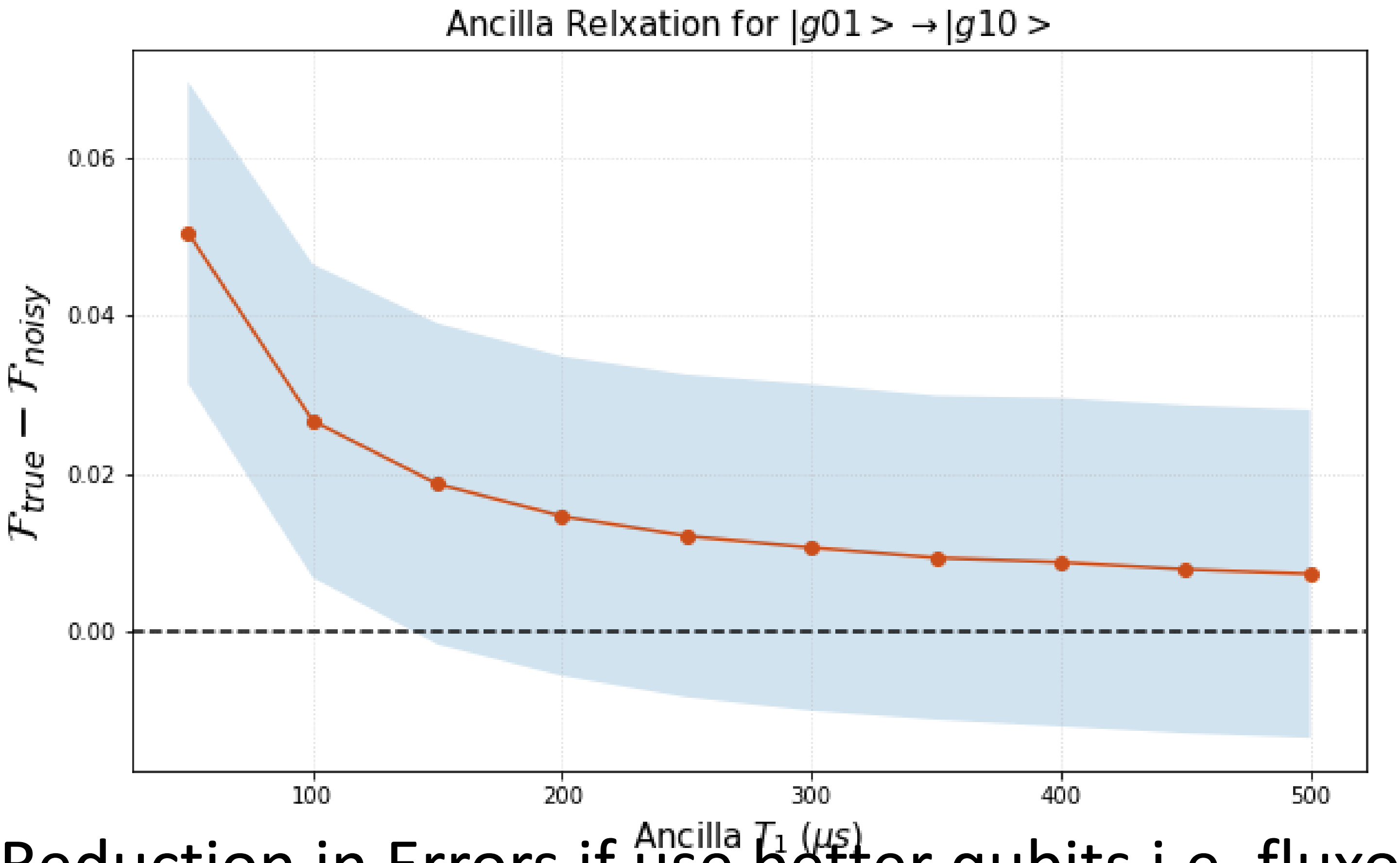
Sideband Drives

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

Echoed Cond. Displacements

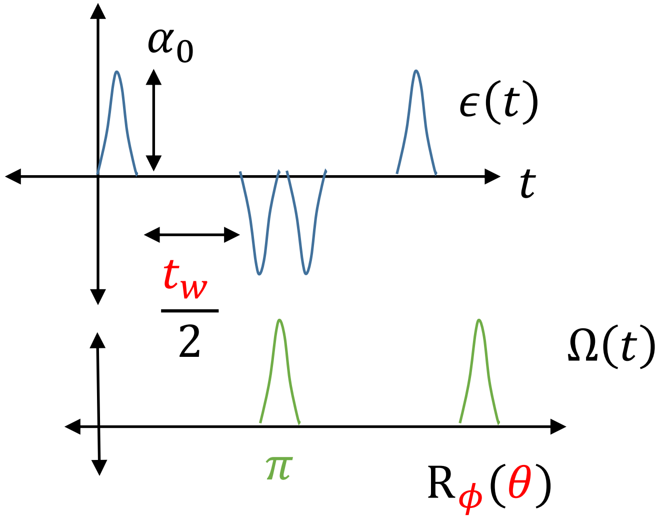
- Terms have different no. of α's but only a single σ_z
- **Clever flipping of α and $\boldsymbol{\sigma_z}$** can echo out unwanted terms

Transmon Relaxation



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

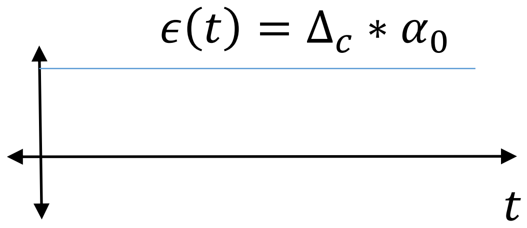
ECD



Optimizer

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

Circle Grape



Optimizer

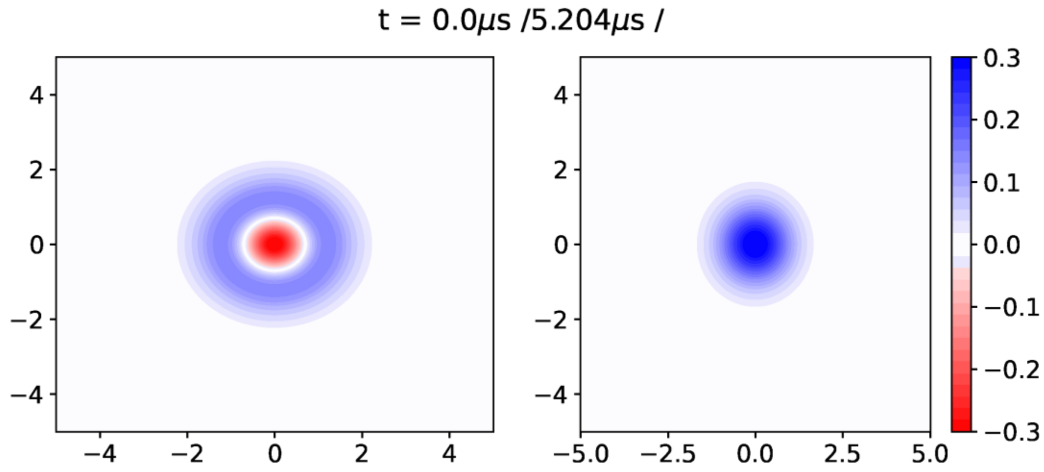
$\Omega_x(t), \Omega_y(t)$

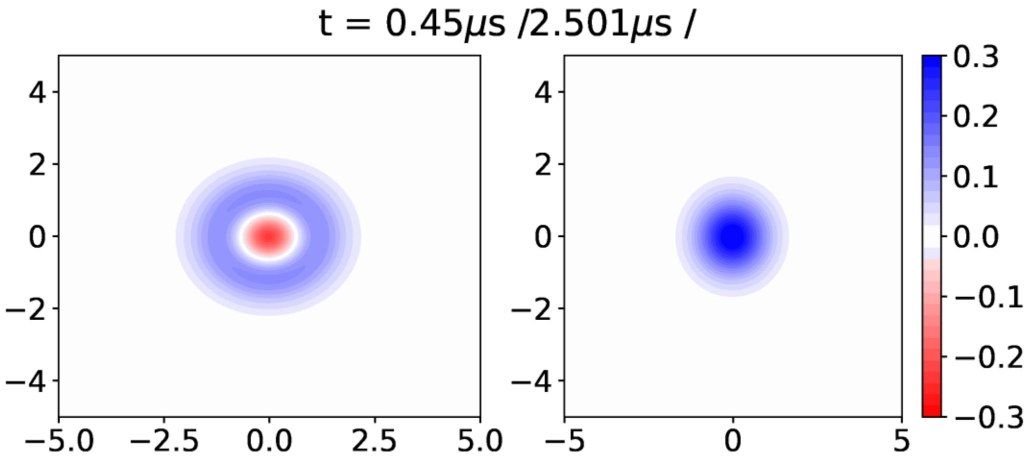
Comparing Grape and MECD

ECD

Circle Grape

Type equation here.





Motivation

- Goal: Enact gates on cavity modes

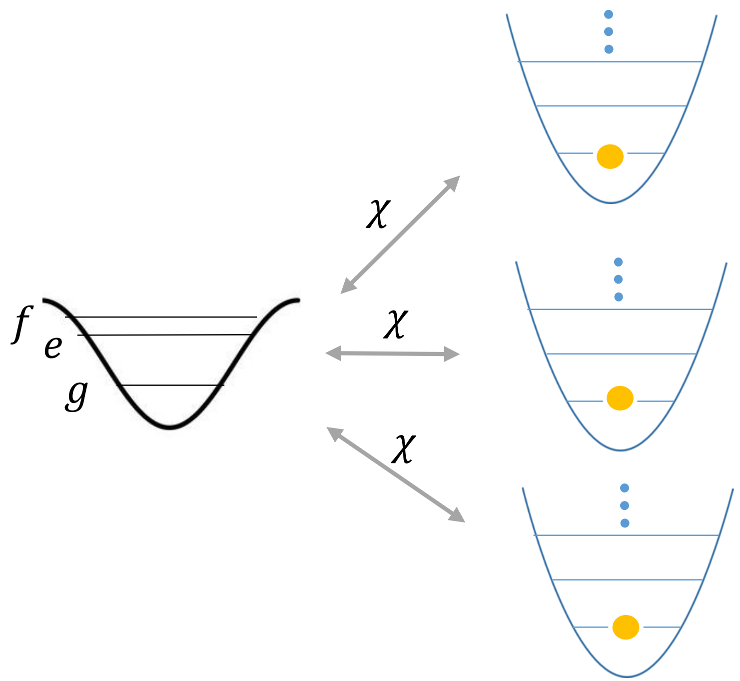
- Typical Schemes use $\chi a^\dagger a \sigma_z$

Increase χ for faster gates

- Coupling to the lossy ancilla reduces mode coherence

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

Decrease χ for better mode coherence



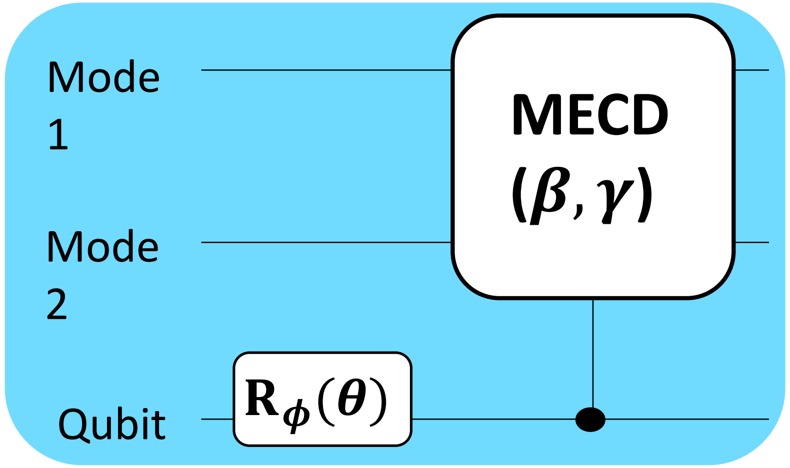
Circle Grape

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

Sent to Optimizer

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

Multimode ECD



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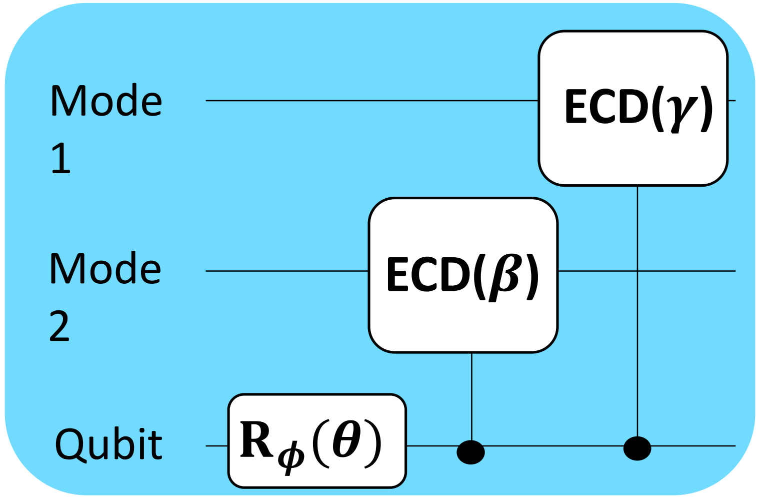
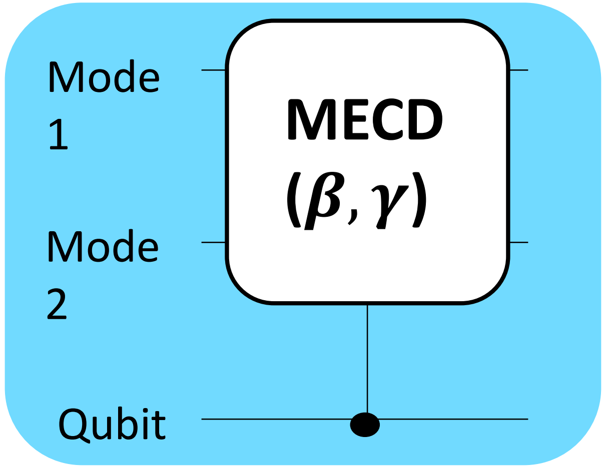


$$MECD(\beta,\gamma) = \begin{pmatrix} D_1\left(-\frac{\beta}{2}\right) D_2\left(\frac{\gamma}{2}\right) & 0 \\ 0 & D_1\left(\frac{\beta}{2}\right) D_2\left(-\frac{\gamma}{2}\right) \end{pmatrix}$$

Multimode ECD



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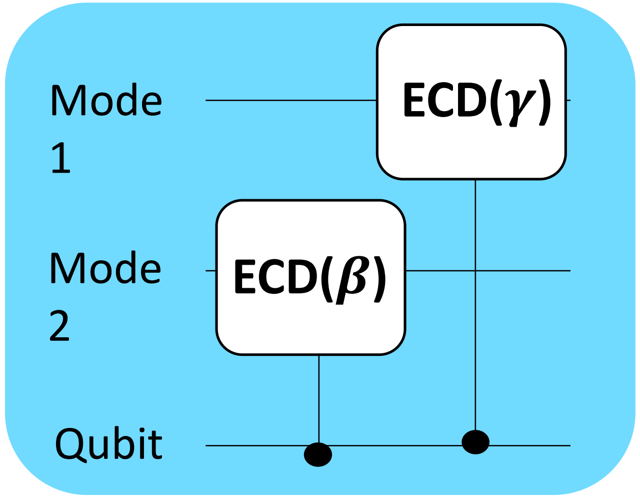
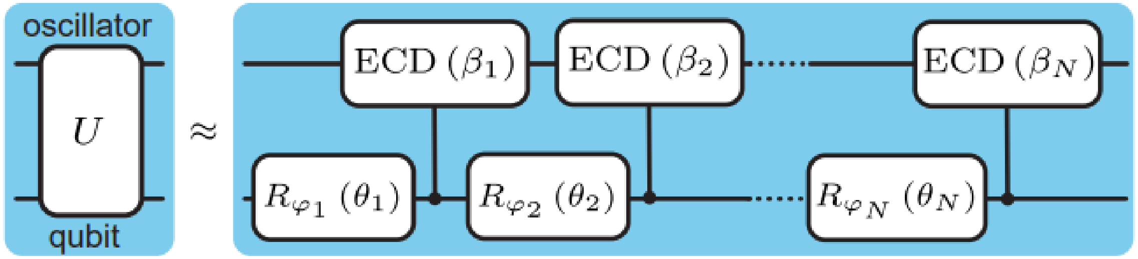


- Universal Control for Two Modes
- Asimultaneous drives to prevent heating of modes [1,2] and amplification of cross kerr terms

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

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

Parameter Optimization



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

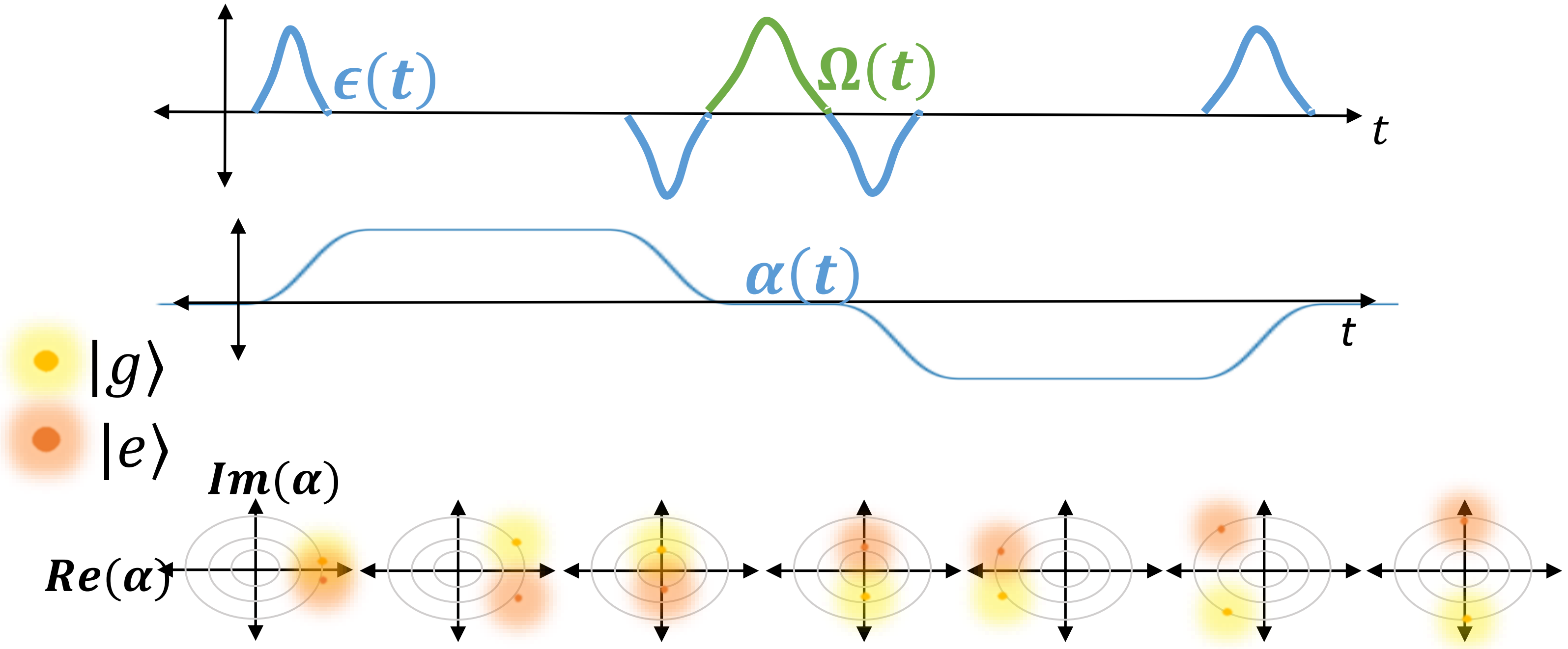
Pulse Optimization

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

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

Parameter Optimization

Pulse Optimization

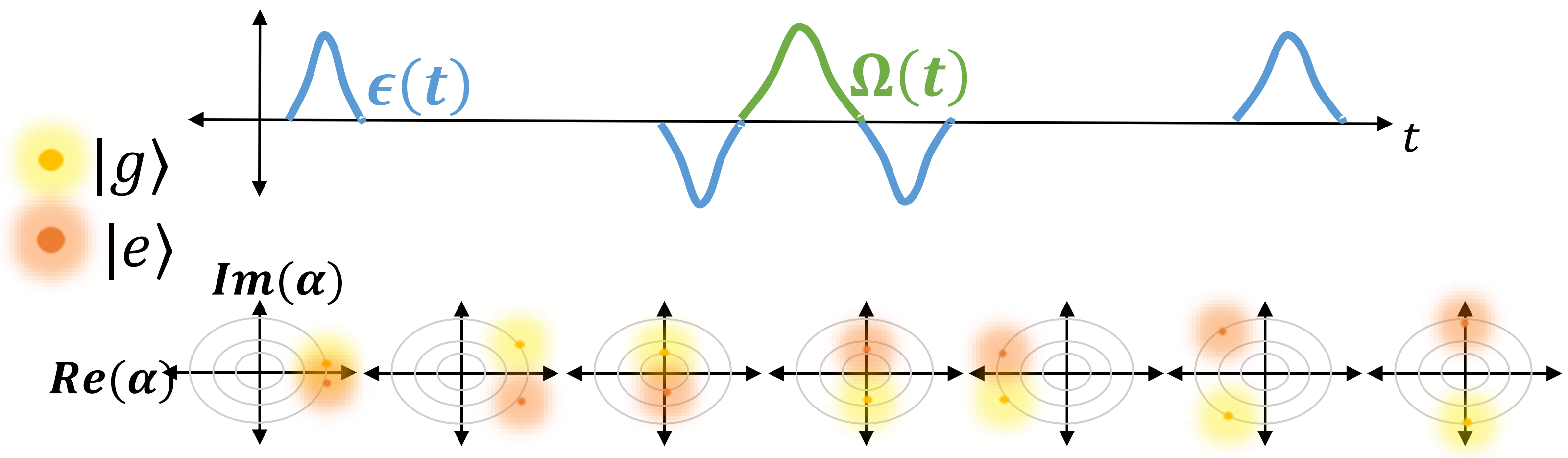


A. Eickbusch, ..., R. Schoelkopf, M. Devoret. *ArXiv preprint arXiv:2111.06414 (2021)*

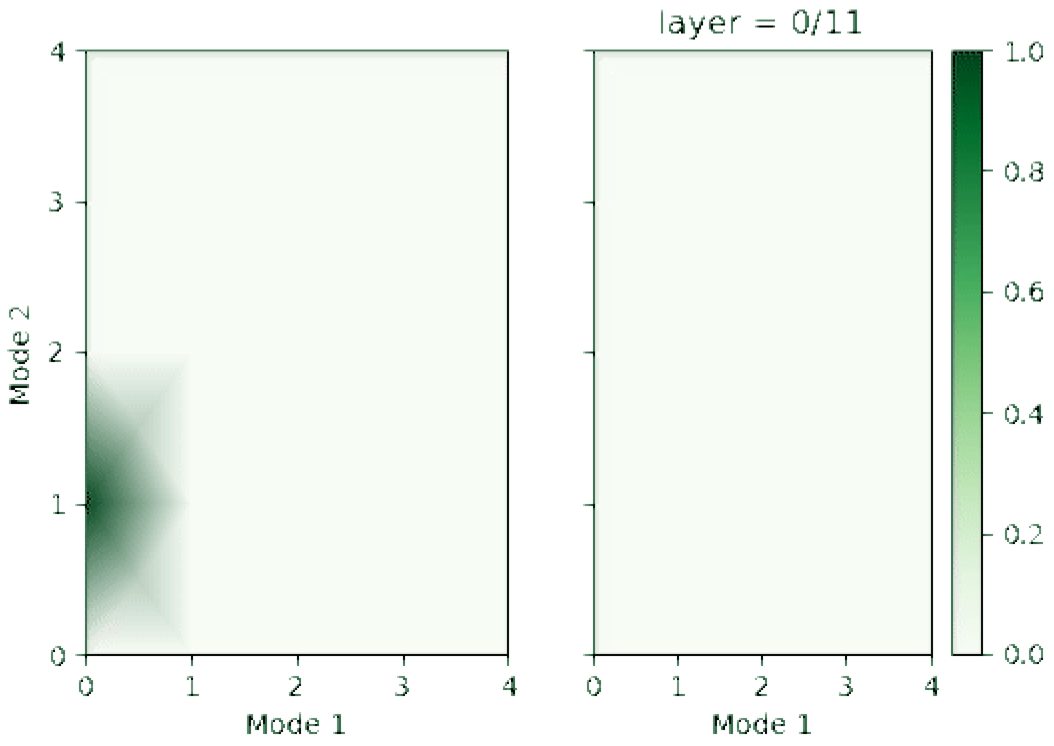
Two Mode ECD : Unwanted Cross Kerr Terms

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

Terms of form :	How to avoid :
$\chi_{ab}\boldsymbol{\alpha\beta}\, a^+ b^+$	α, β should not be simultaneously nonzero
$\chi_{ab}\lvert\boldsymbol{\alpha}\rvert^2 \boldsymbol{\beta}\, b^+$	Echoed out when β flips
$\chi_{ab}\lvert\boldsymbol{\alpha}\rvert^2 b^+ b$	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)



$\epsilon(t)$
$\Omega(t)$
t
$|g\rangle$
$|e\rangle$
$Im(\alpha)$
$Re(\alpha)$



layer = 0/11
Mode 2
Mode 1
Mode 1
0
1
2
3
4
0.0
0.2
0.4
0.6
0.8
1.0

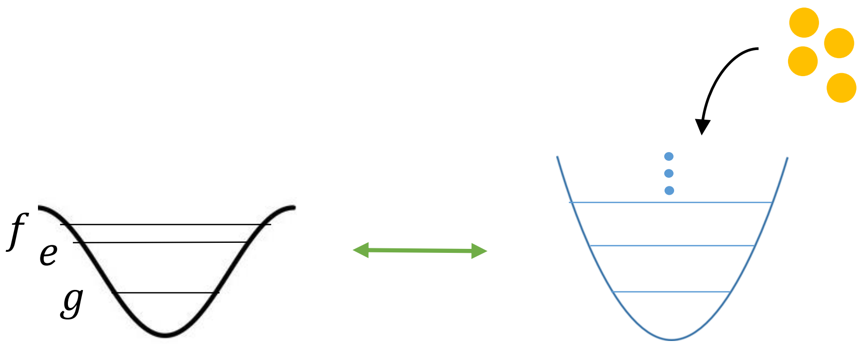
Large Displacements

Conditional Displacement Gates:

- Use Large Displacements to enhance effective interaction strength

$$\chi a^\dagger a \sigma_z \;\Rightarrow\; \boxed{\chi\left(\alpha_0 a^\dagger + \alpha_0^\star a\right)\sigma_z}$$

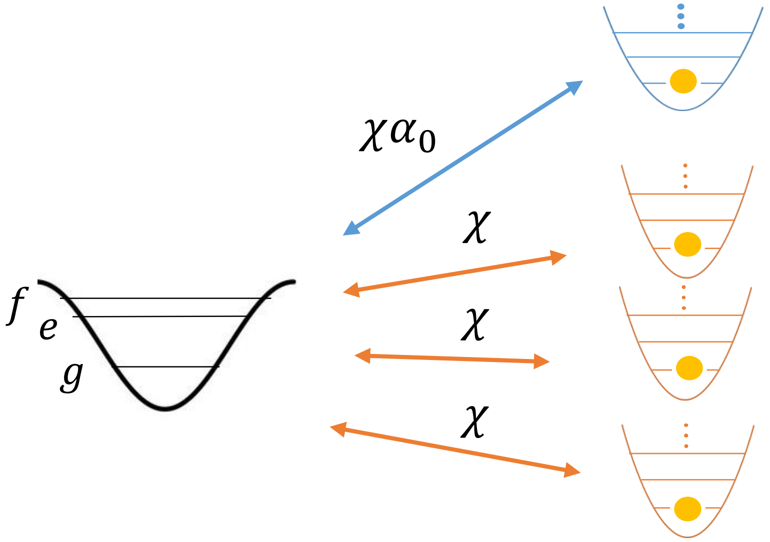
$$D(\alpha_0)$$



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).