Multimode Conditional Displacements

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Motivation

- SNAP Gates take time $\approx 2\pi/\chi$ where $\chi \approx$ MHz is dispersive coupling strength.
- Reducing Gate time $\rightarrow$ Increasing χ $\rightarrow$Reducing lifetime of cavity
- ECD Idea: Keep $\chi \approx 10$ kHz small; But enhance it by displacing cavity (α_0) far from origin
- Effective Gate time $1/\chi\alpha_0$ where $\alpha_0 \gg 1$

Achieving Conditional Displacements

Starting Point: $$H/\hbar = \omega_c a^\dagger a + \omega_q \frac{\sigma_z}{2} + \chi a^\dagger a \frac{\sigma_z}{2} + H_{drive}$$

Using **frame transformations**, our objective is to **isolate** the following term from the ac-Stark Shift

$$\tilde{H} = \chi(\alpha a^\dagger + \alpha^\star a)\sigma_i$$

where α is the displacement of the cavity mode. With such a term, we can realize a conditional displacement as follows

$$e^{-i(\chi(\alpha a^\dagger + \alpha^\star a)\sigma_i)t} \xleftrightarrow{\beta = -i\,\chi\alpha\,t} e^{(\beta a^\dagger - \beta^\star a)\sigma_i}$$

Dealing with Unwanted Terms I

1. Rotating Frames of oscillator and the qubit
2. Displacement transformation $D^{+}\big(\alpha(t)\big) = e^{\alpha^*(t)a - \alpha(t)a^{+}}$

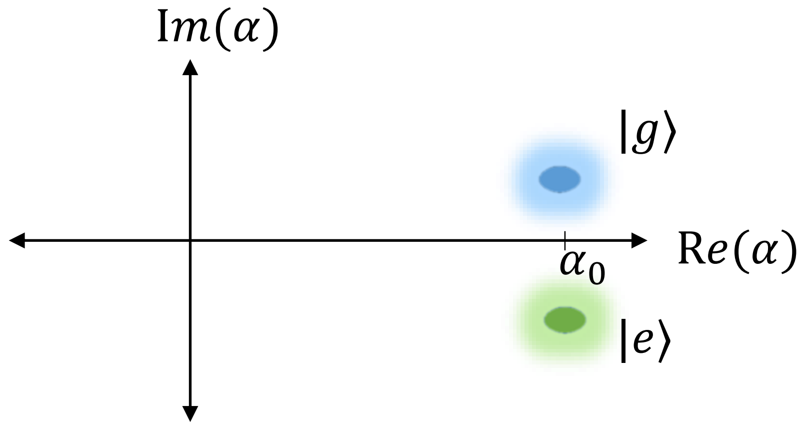
which renders $a \to a + \alpha(t)$

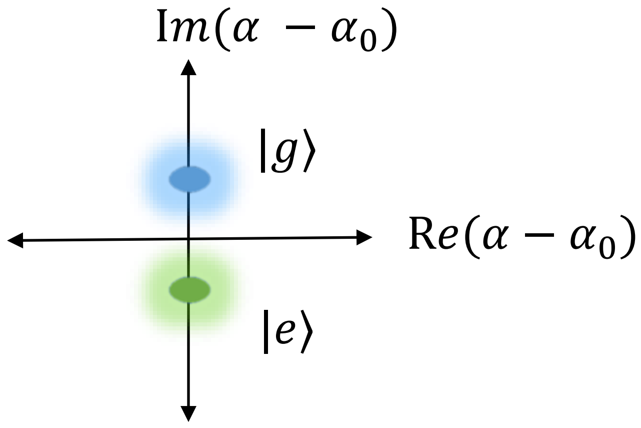
$$H_{disp} = D^{\dagger} H_{rot} D - i\dot{D}^{\dagger} D$$
$$= D^{\dagger} H_{rot} D + i(\dot{\alpha}^{\star} a - \dot{\alpha} a^{\dagger})$$

Cancel terms linear in $\boldsymbol{a}, \boldsymbol{a}^{+}$, such as the oscillator drive $\epsilon(t)a^{+} + \epsilon^*(t)a$, by picking the appropriate time dependent displacement frame

$$\boxed{\dot{\alpha} = -i\epsilon(t) \qquad \dot{\alpha}^* = i\epsilon^*(t)}$$

Implication: Disp. Frame Simulations





Lab Frame

- Large Displacement
- Number of photons $n = |\alpha_0|^2 \approx 900$
- Intractable simulations

Displaced Frame

- Size of Conditional Displacement ($|\alpha_g - \alpha_e| \leq 5$)
- Number of photons $n = |\alpha_g - \alpha_e|^2 \approx 25$
- Tractable simulations

Dealing with Unwanted Terms II

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

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

$$\downarrow$$

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

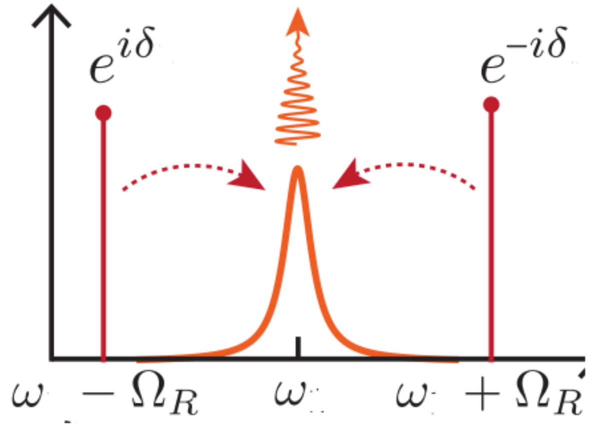
Sideband Drives

- 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

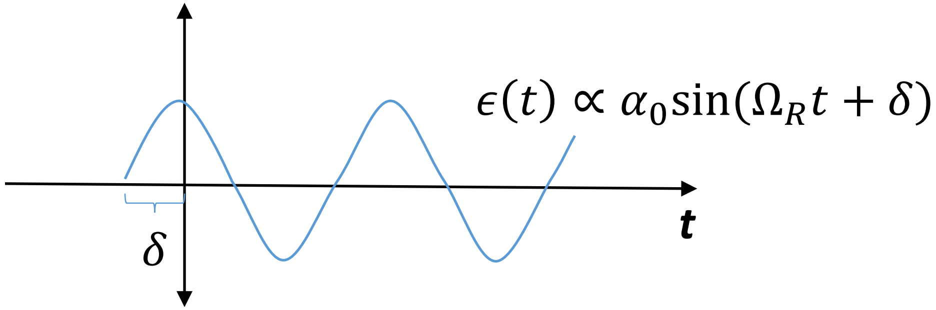


https://arxiv.org/pdf/1608.06652.pdf

Since α oscillatory,

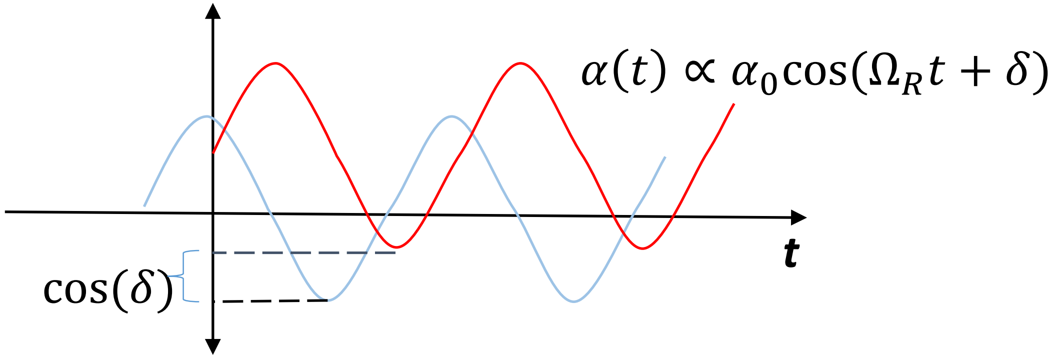
$$H = \chi a^{+} a \sigma_z + \chi(\alpha a^{+} + \alpha^{*} a)\sigma_z + \chi|\alpha|^2 \sigma_z + \Omega_R \sigma_x$$

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



Frame Transformations:

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

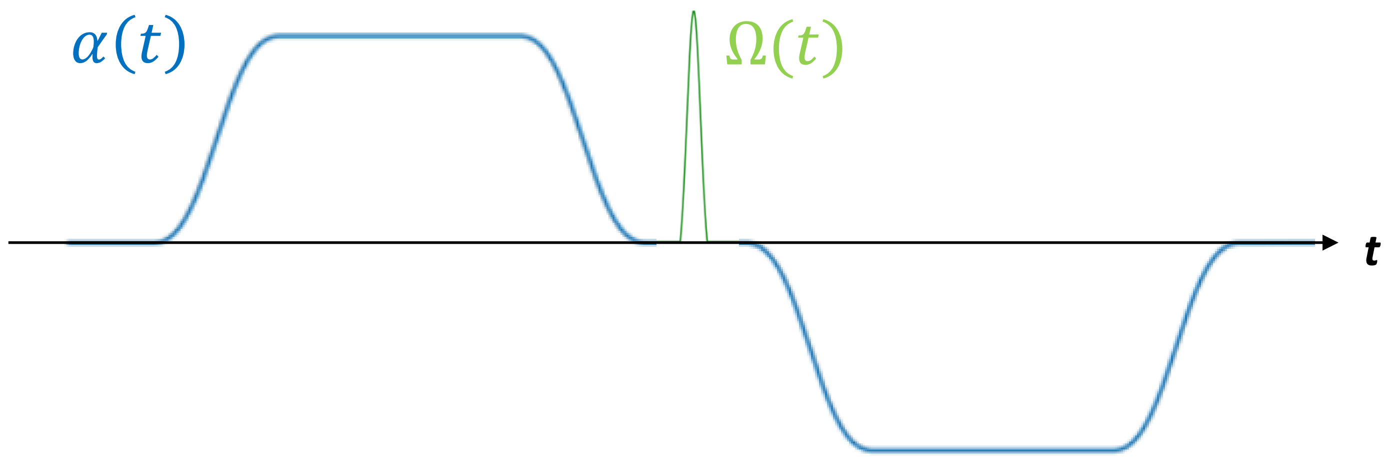


$$H = \chi \alpha_0 (a^{+} + a) \otimes (\sigma_x \cos\delta + \sigma_y \sin\delta) + \ldots$$

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

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

Echoed Cond. Disp.



$$\chi a^{+} a \sigma_z$$

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

$$\chi|\alpha|^2 \sigma_z$$

Echo

$$-\chi a^{+} a \sigma_z$$

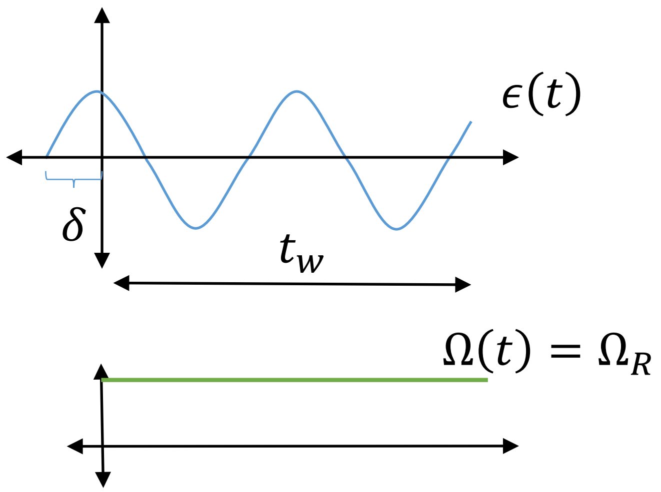
Not completely echoed out !

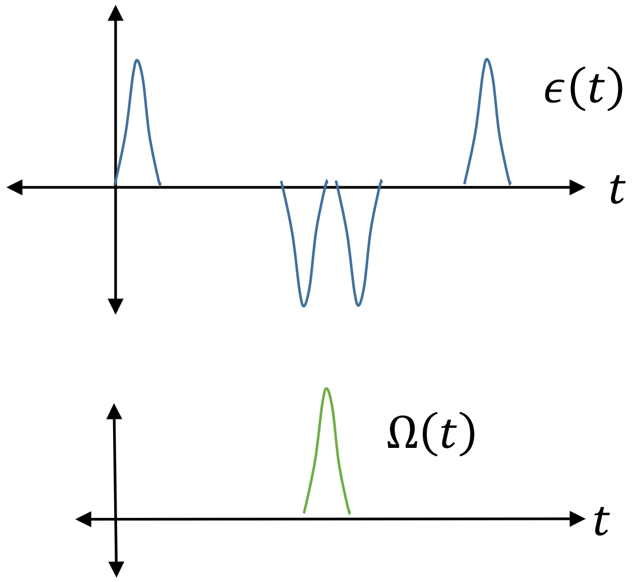
$$\chi(\alpha a^{+} + \alpha^{*} a)\sigma_z$$

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

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

Comparison





Sideband Drives

- Oscillating $\epsilon(t), \alpha(t)$
- Continuous Rabi Driving on the qubit
- Ridding unwanted terms via **RWA**: $e^{i\Omega t}$

Echoed Conditional Gates

- Single Oscillation of $\alpha(t)$
- Discrete Qubit pi pulses
- Ridding unwanted terms via **echoing**: Step Function

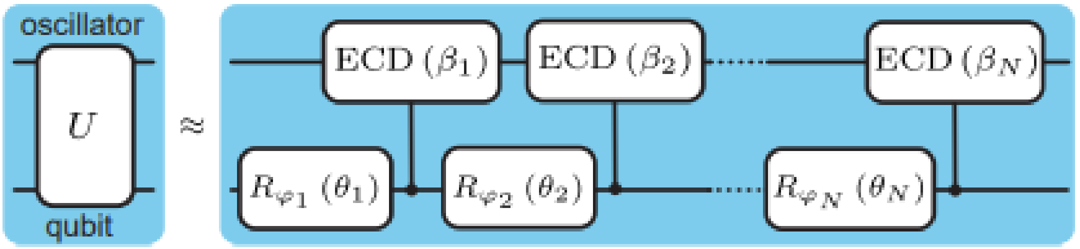
Implementation: Optimal Parameters

- ECD and Sideband Drives, by themselves, do not offer universal control of both oscillator and qubit
- Sol: Interleave parameterized qubit rotations between CD
- Gate times are dependent on # of layers to realize high fidelity gates

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

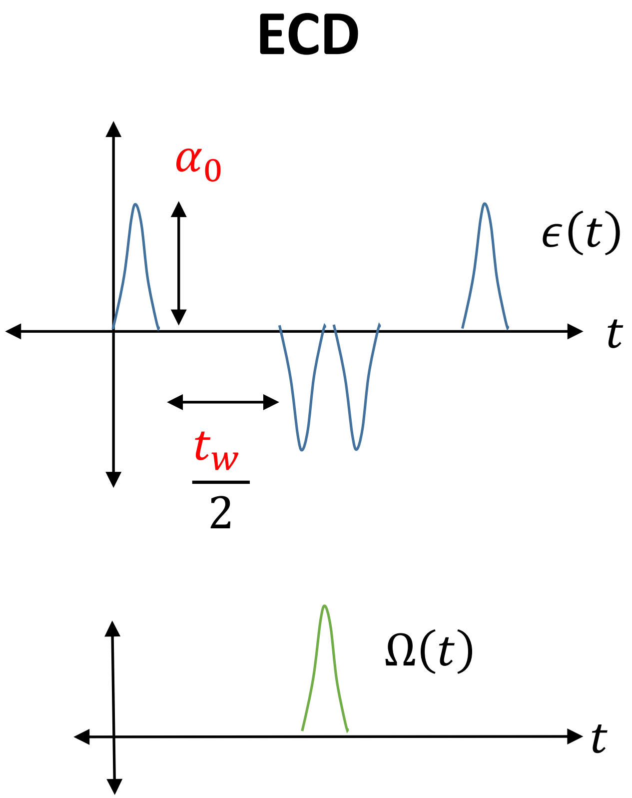
$$R_\phi(\theta) = e^{-i\left(\frac{\theta}{2}\right)(\cos\phi\sigma_x + \sin\phi\sigma_y)}$$

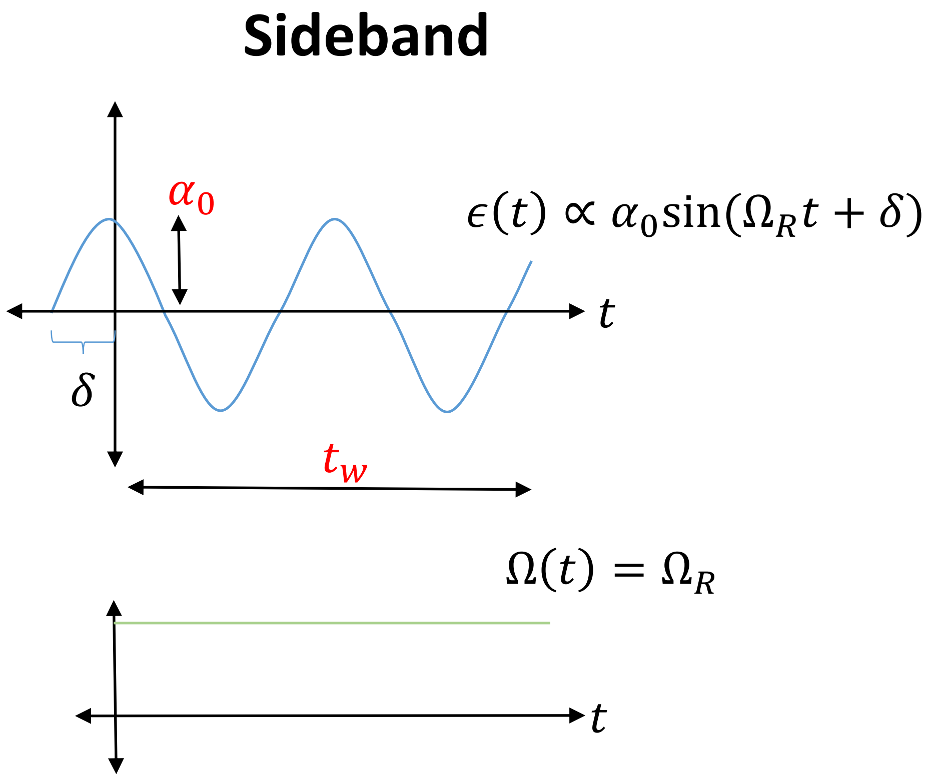
d



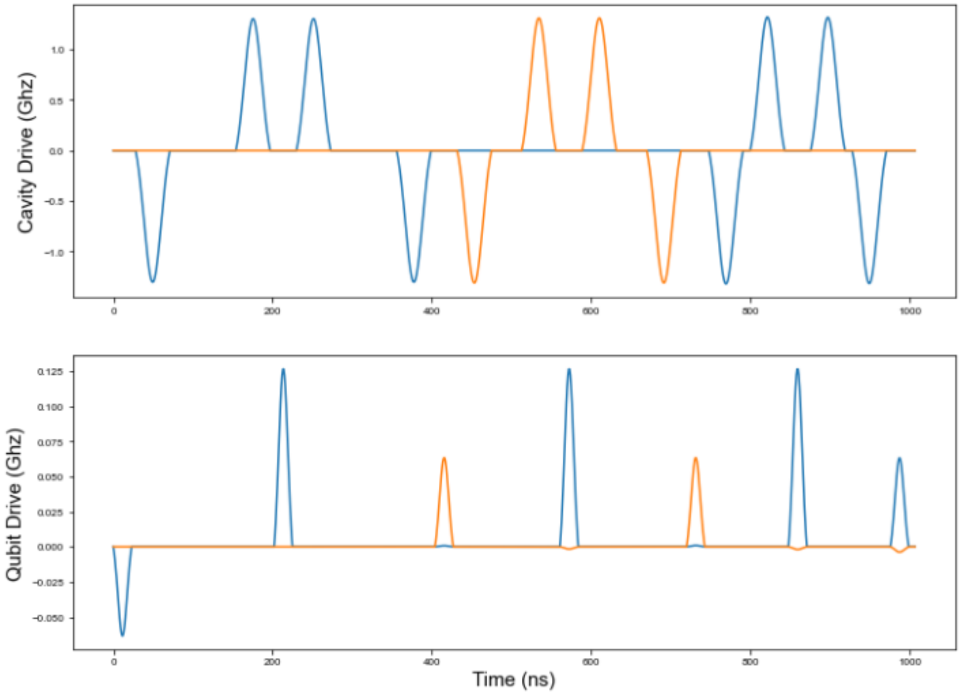
Implementation: Finding Pulses

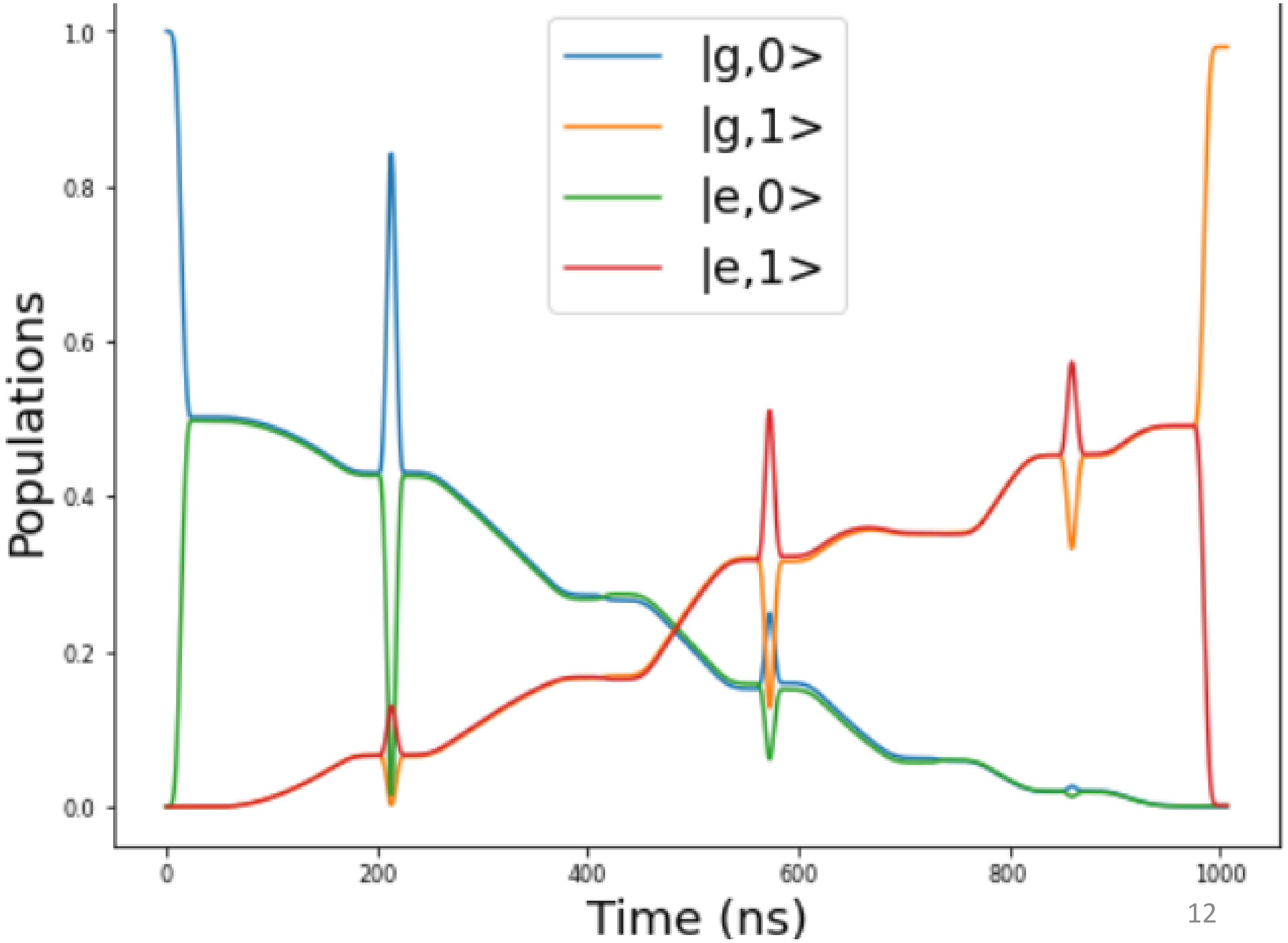
Task: find wait time t_w and scale intermediate displacement $\alpha_0$such that $\chi\alpha_0 t_w = \beta$



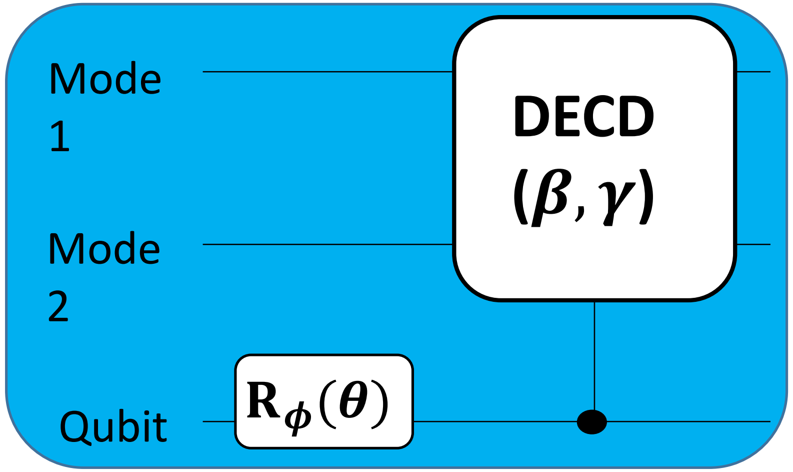


ECD: $|g0\rangle \rightarrow |g1\rangle$





Two Mode ECD



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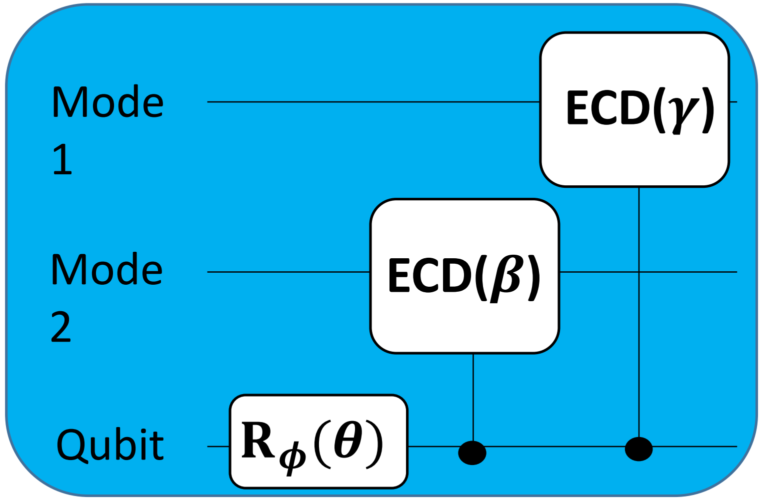
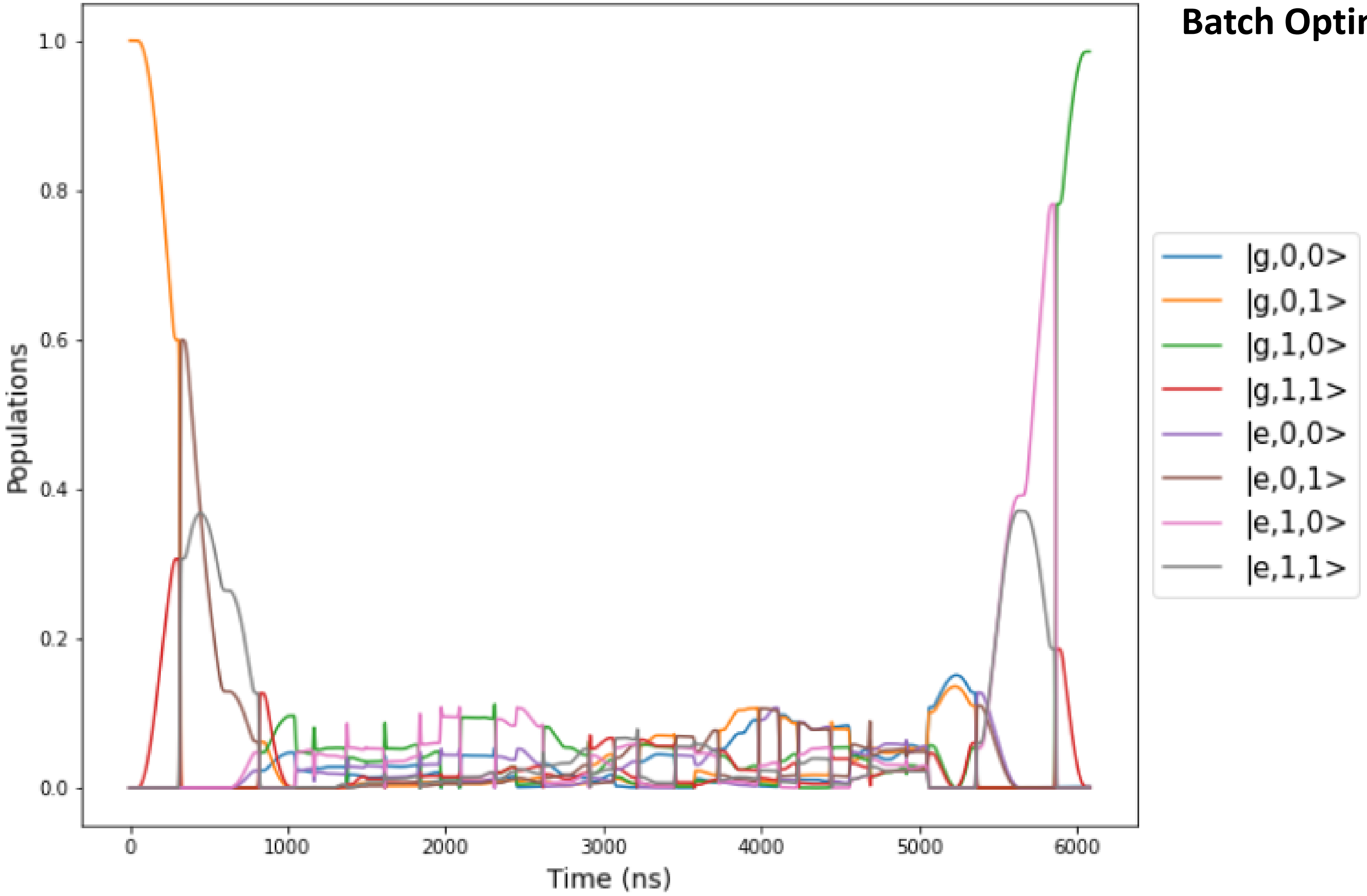


- Generalizing ECD gate to 2 modes
- Displacements on the two modes are not simultaneous (to avoid heating as observed in [*])

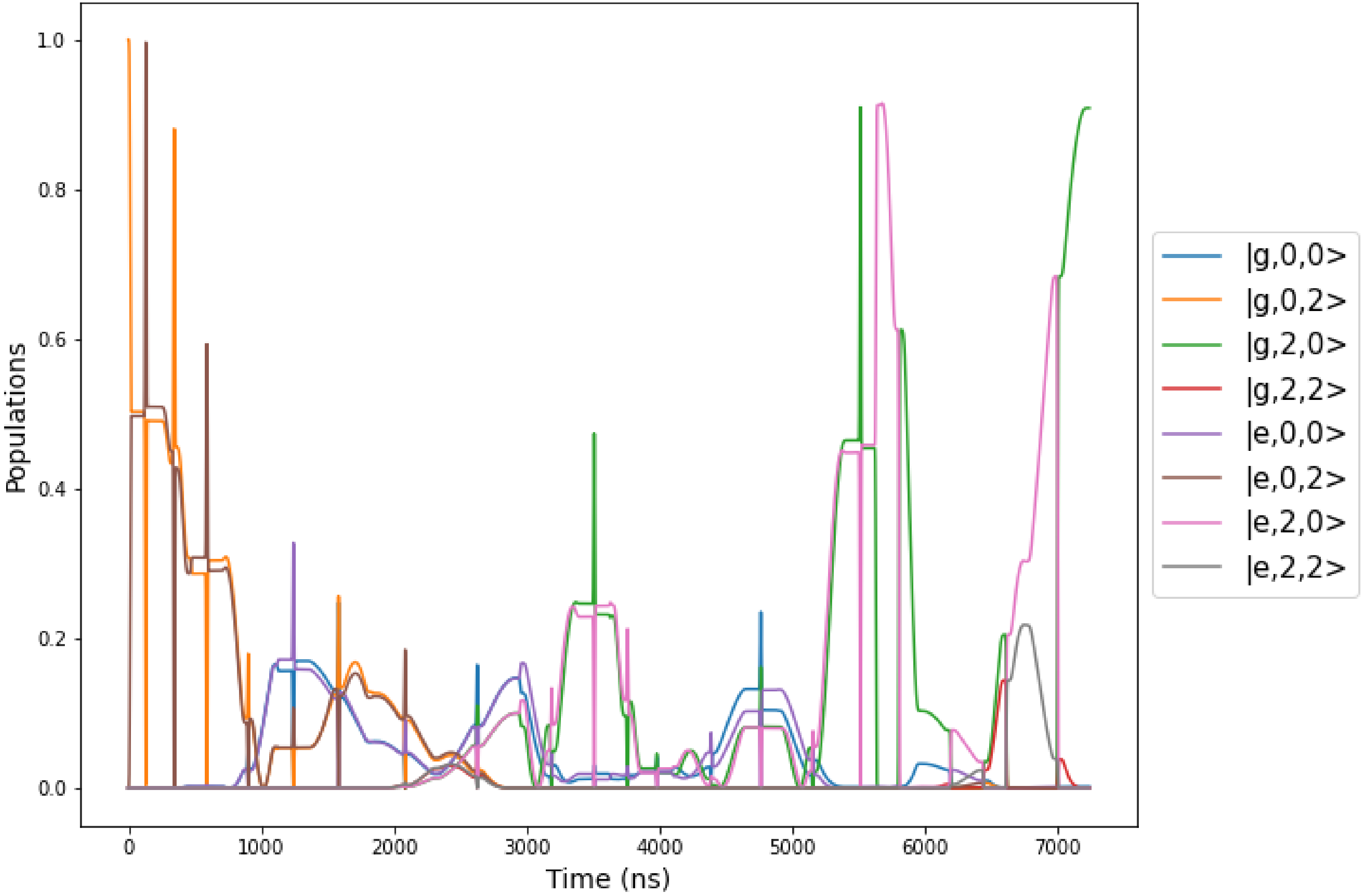
* Alec Eickbusch, Zhenghao Ding, …, Michel Devoret. W34. 00005. APS March Meeting (2022).

Two Mode ECD : $|g01\rangle \rightarrow |g10\rangle$



Batch Optimizer Fidelity: 0.995308

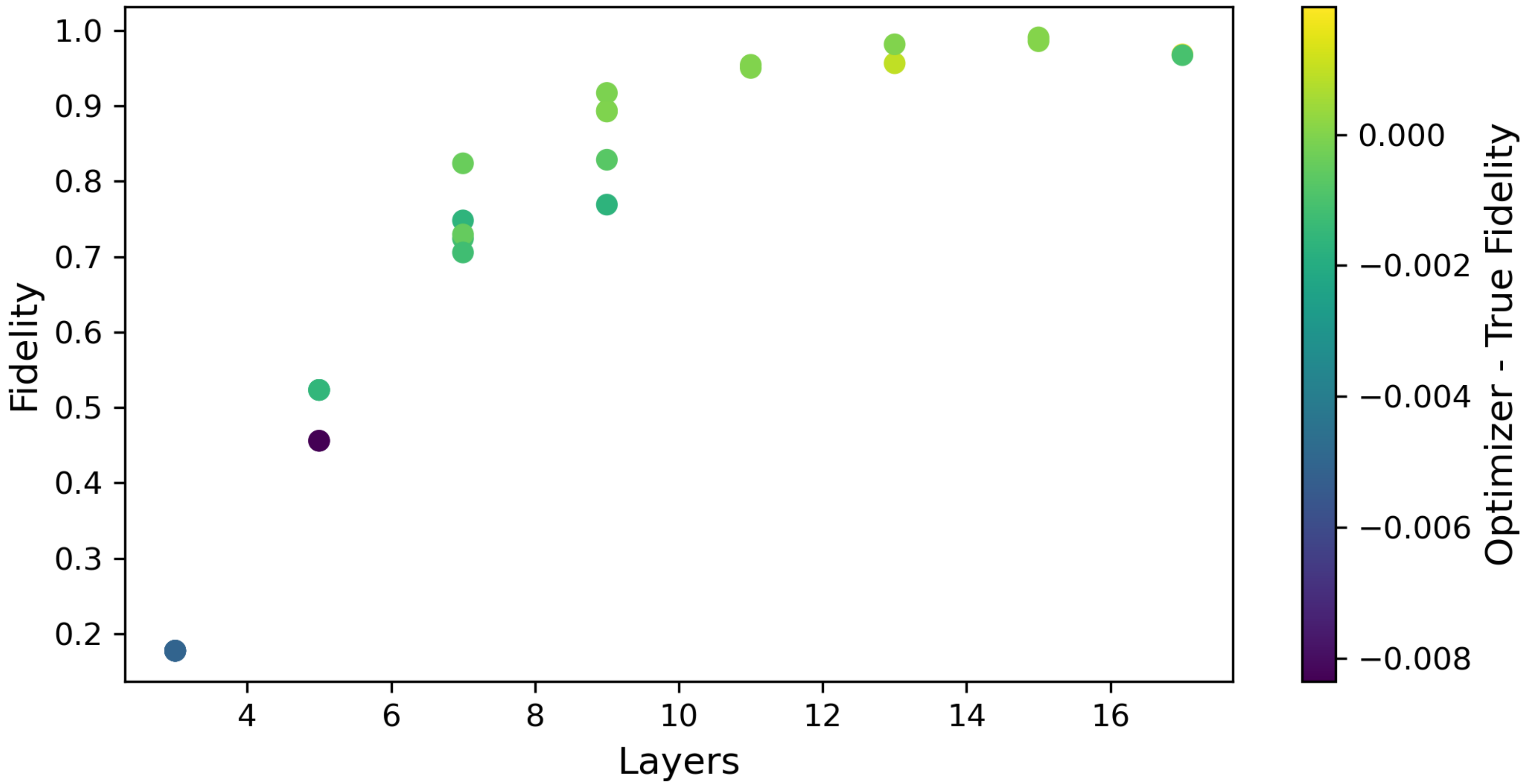
Two Mode ECD: $|g02\rangle \rightarrow |g20\rangle$



Batch Optimizer Fidelity: 0.92192787

Two Mode ECD: Simultaneous State Transfer

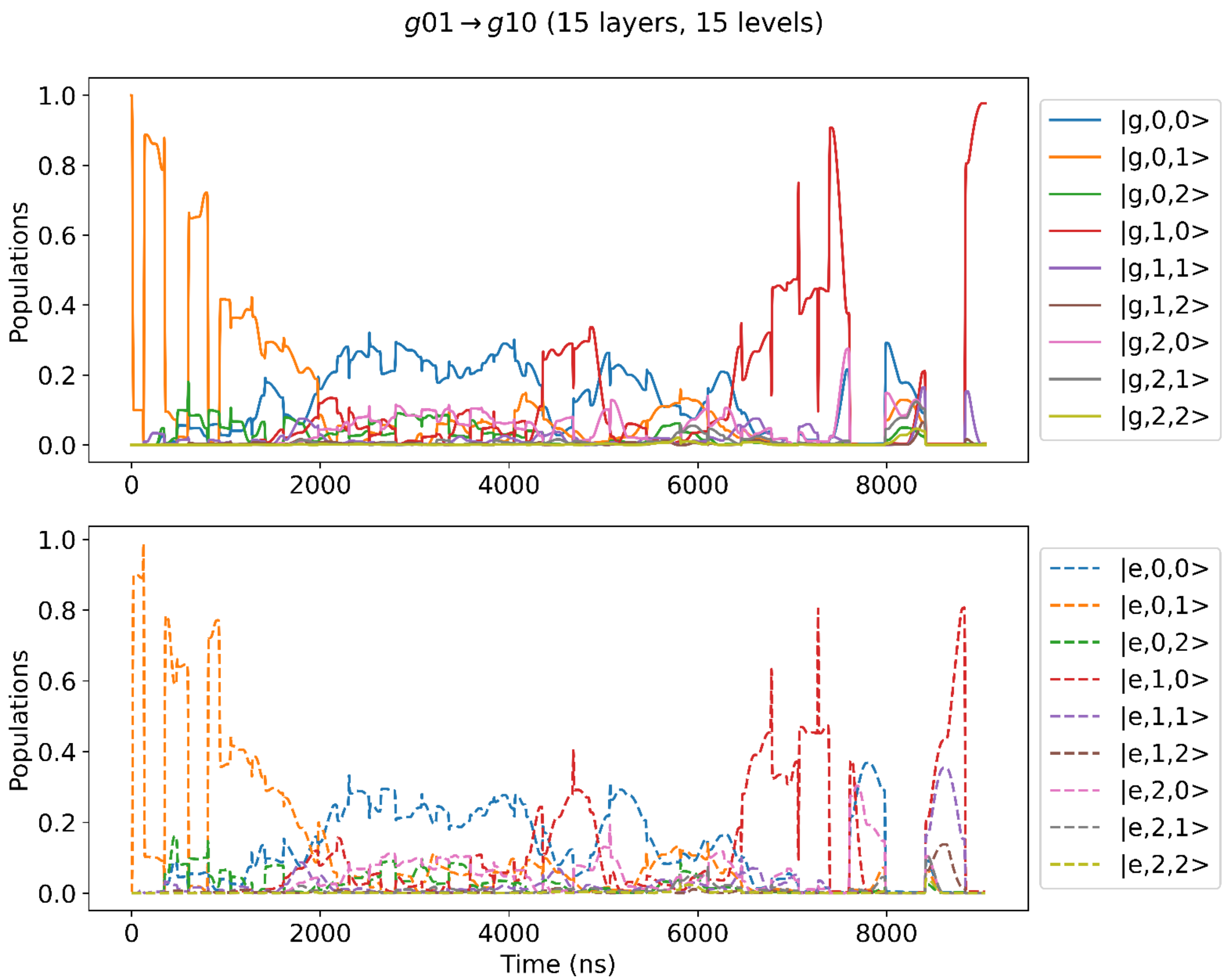
$\boldsymbol{g01} \rightarrow \boldsymbol{g10}$ and $\boldsymbol{g02} \rightarrow \boldsymbol{g20}$ (15 levels in each mode)



Two Mode ECD: Simultaneous State Transfer

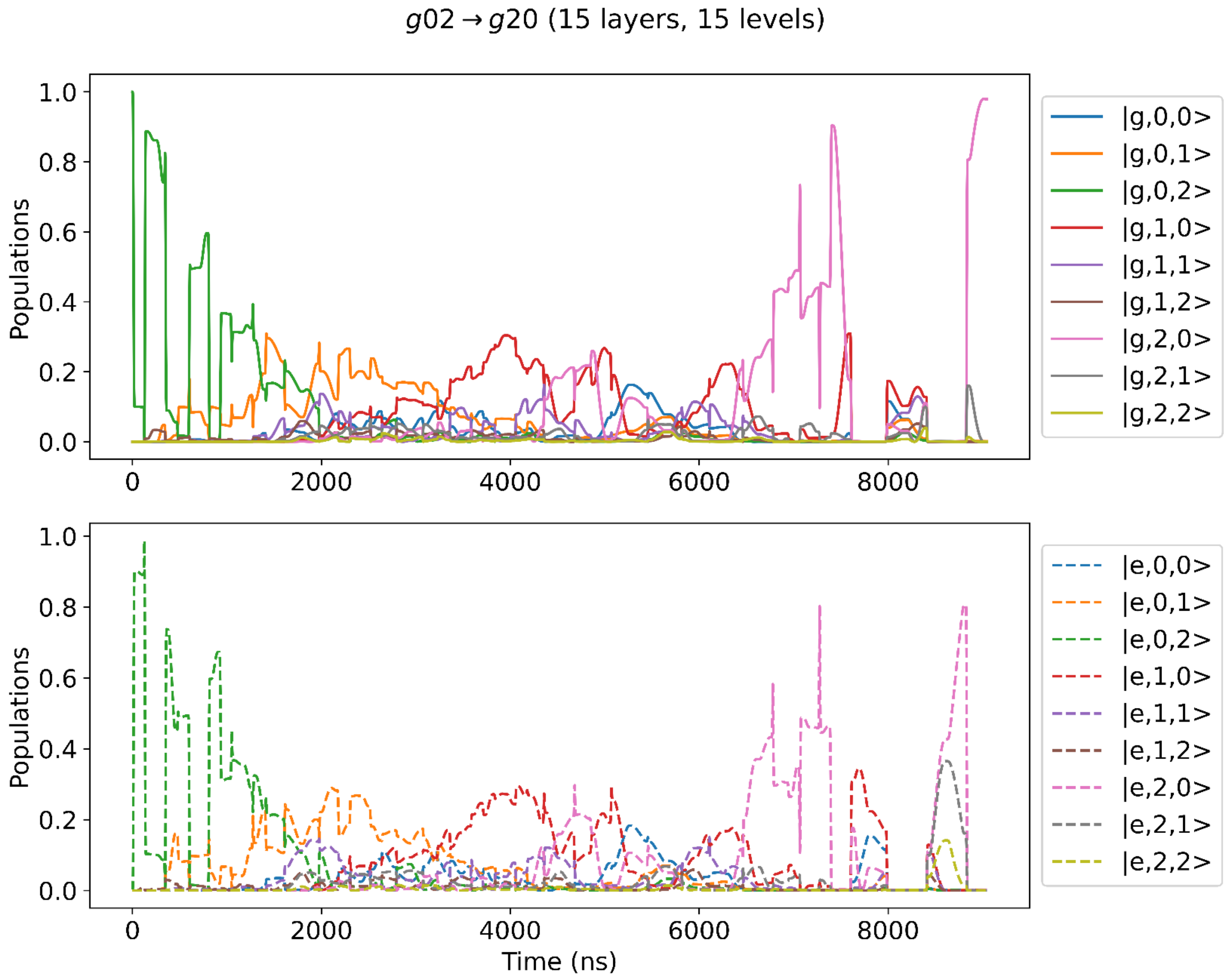
- **Parameters Optimized** for both $g01 \rightarrow g10$ and $g02 \rightarrow g20$

- **Qutip Simulation** of $g01 \rightarrow g10$



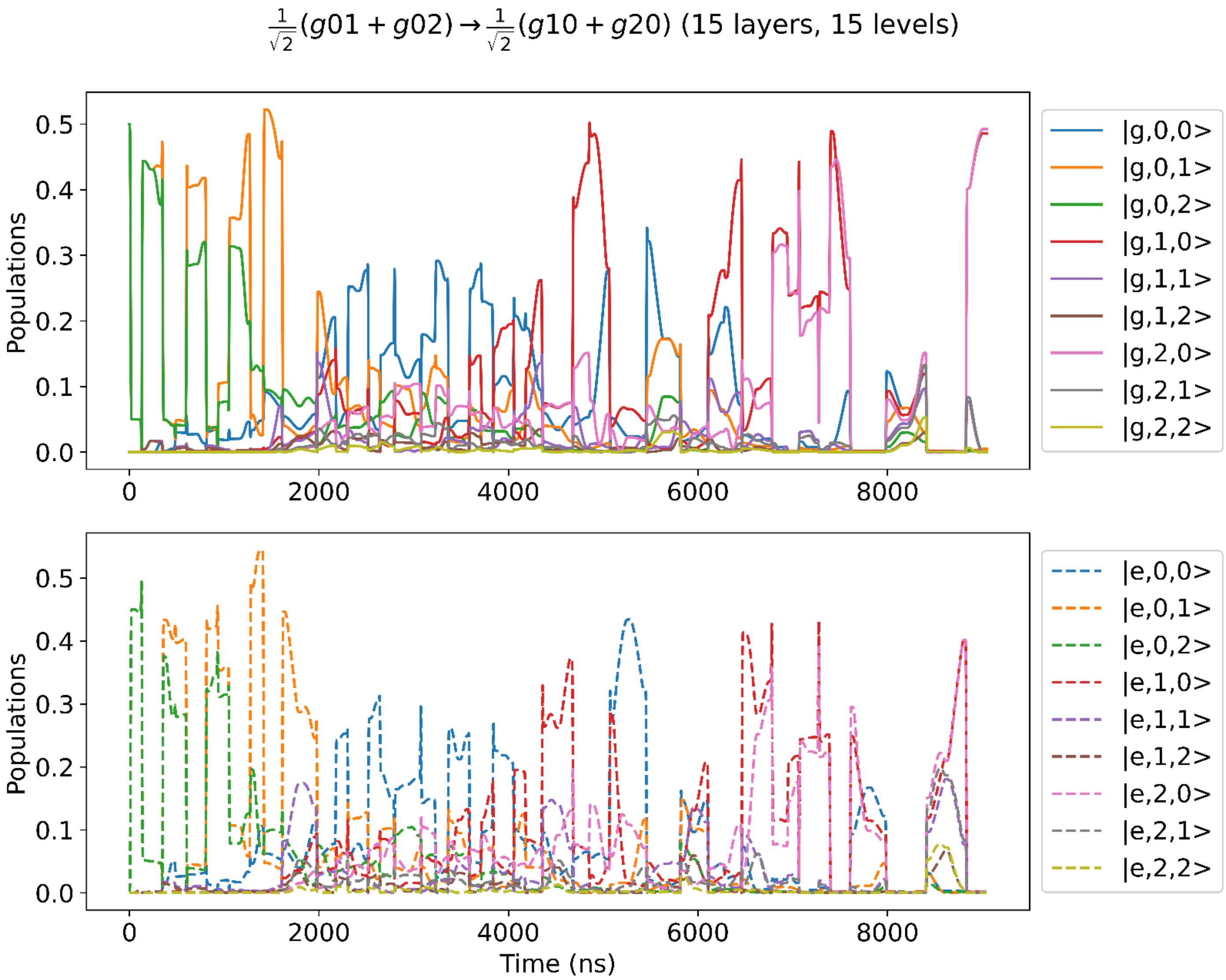
Two Mode ECD: Simultaneous State Transfer

- **Parameters Optimized** for both $g01 \rightarrow g10$ and $g02 \rightarrow g20$
- **Qutip Simulation** of $g02 \rightarrow g20$



Two Mode ECD: Simultaneous State Transfer

- **Parameters Optimized** for both $g01 \rightarrow g10$ and $g02 \rightarrow g20$
- **Qutip Simulation** of $(g01 + g02)$ $\downarrow$ $(g10 + g20)$



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

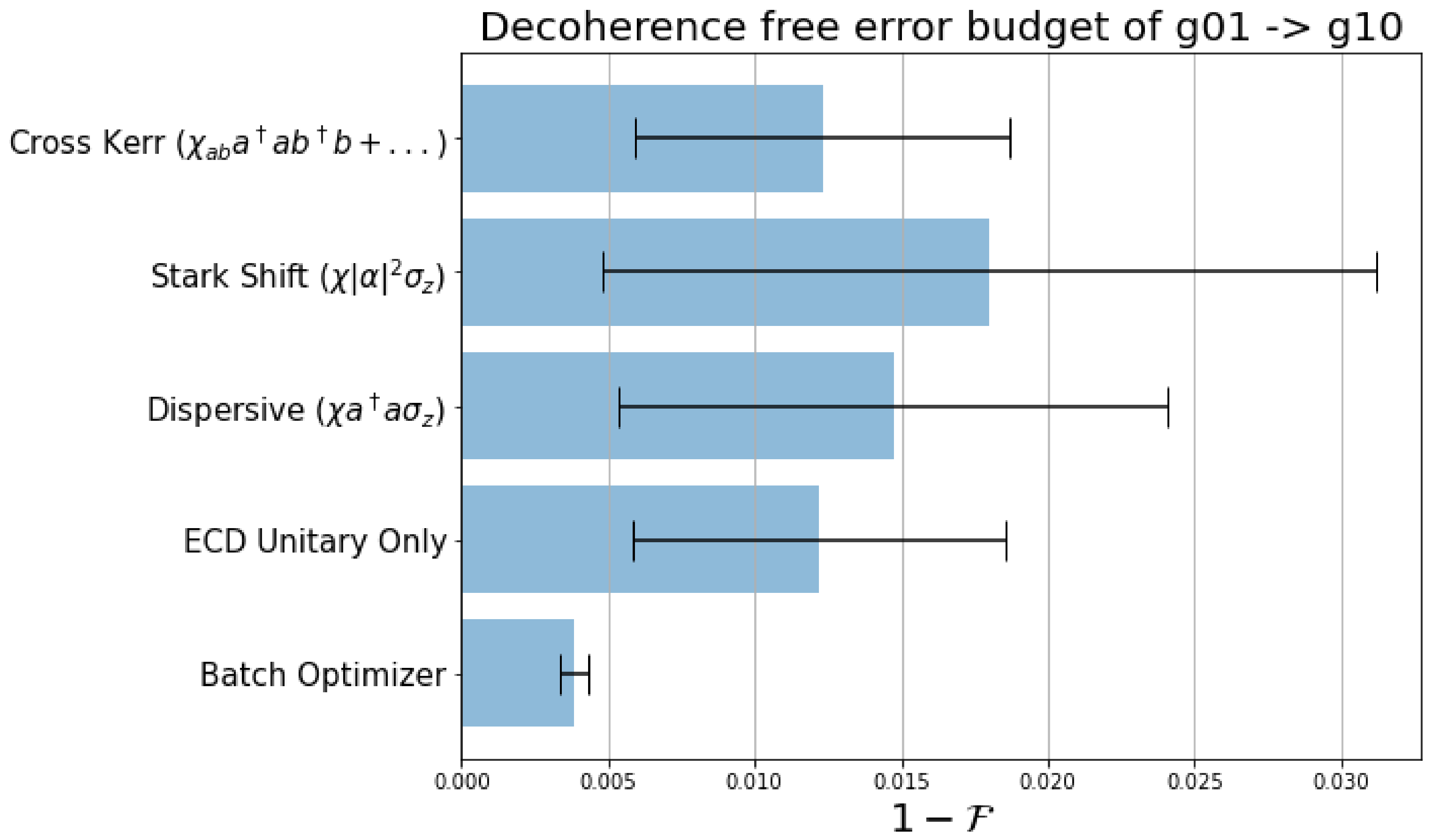
Echoed out when β flips

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

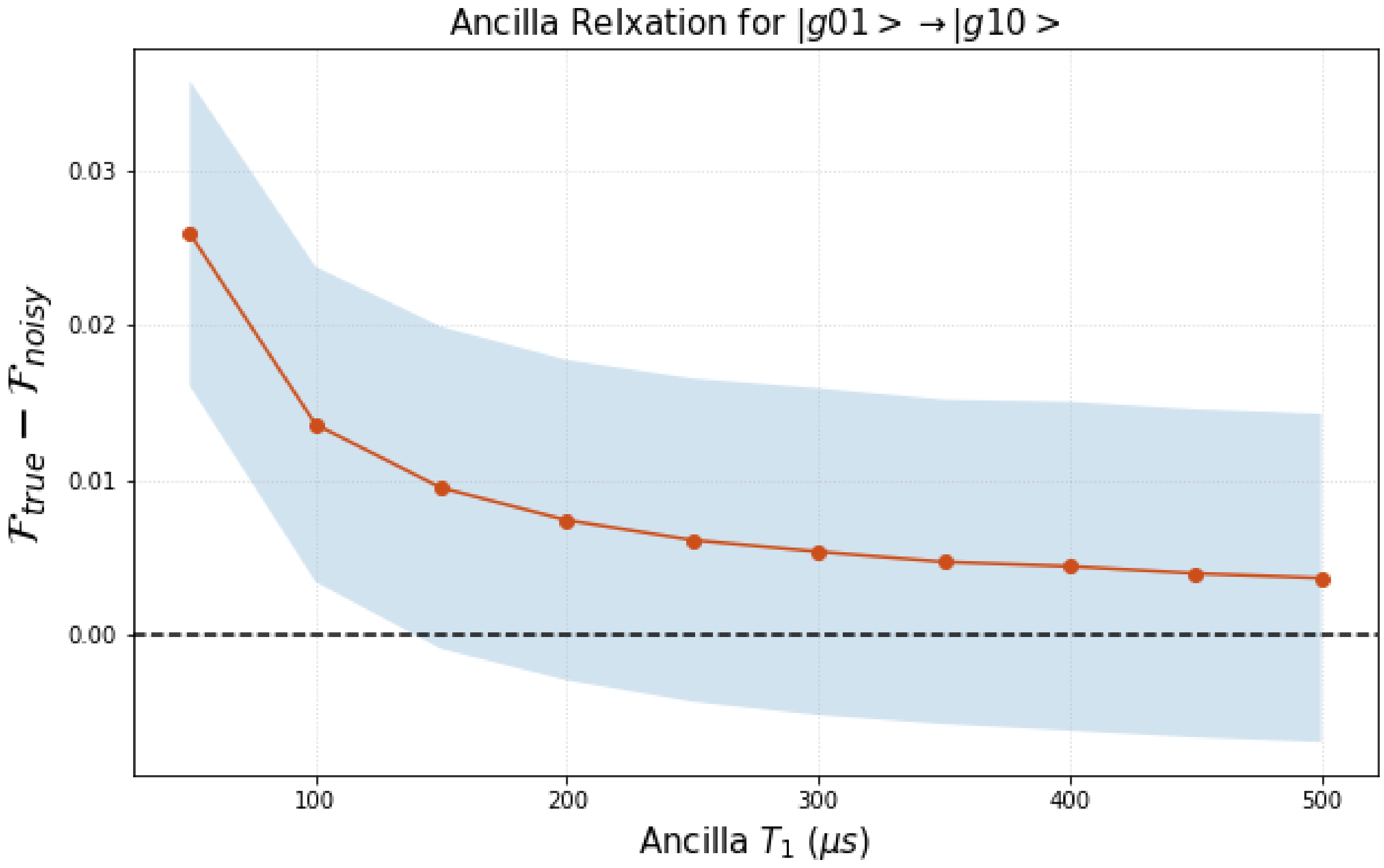
Note $\chi_{ab} = \sqrt{\kappa_a \kappa_b} = \frac{\chi_a \chi_b}{\alpha'} \approx 0.33$ Hz … good!

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

Two Mode ECD : QuTip Noise Simulations



Two Mode ECD : QuTip Noise Simulations

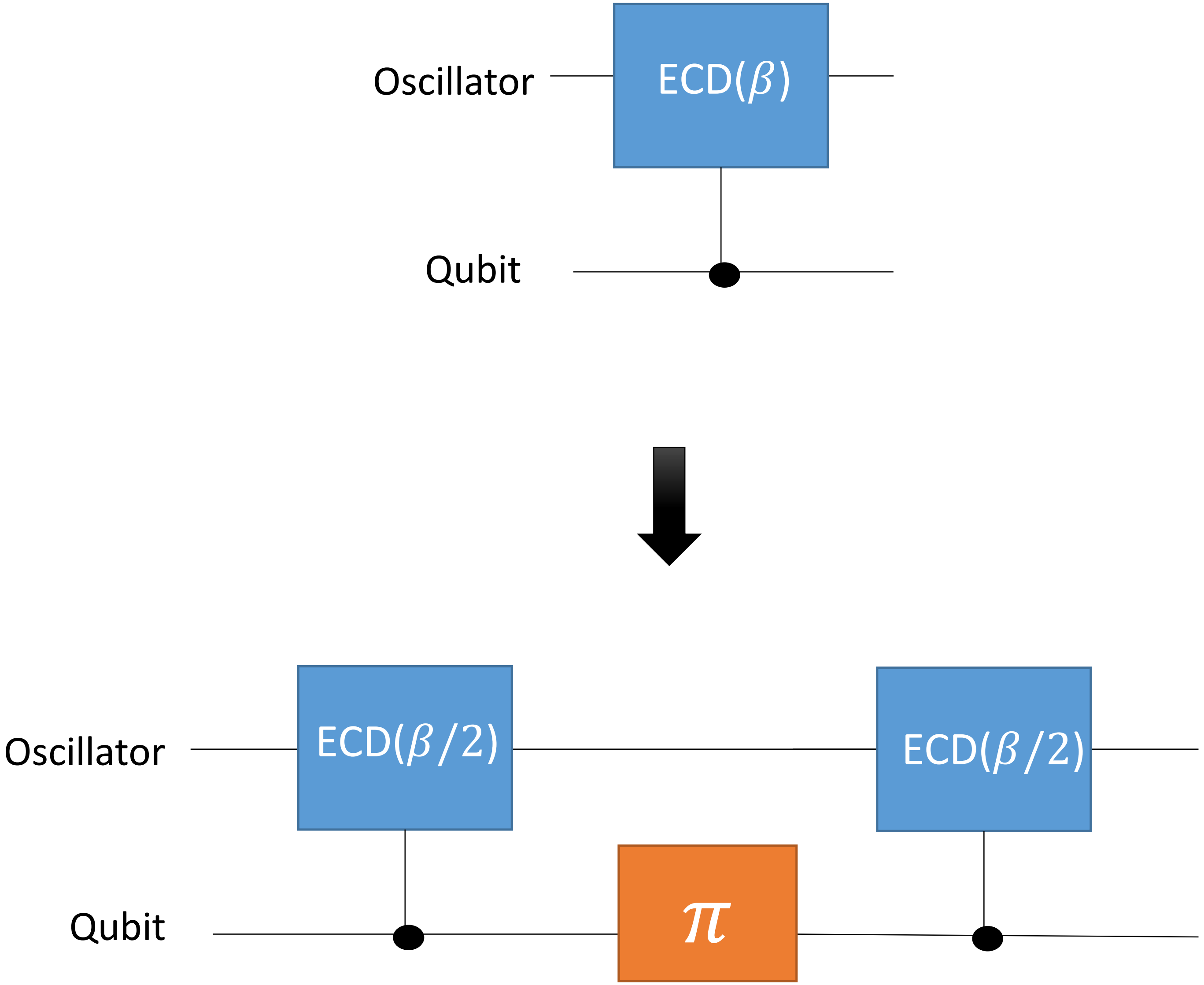


Ancilla with better coherence times such as flux protected qubits may improve gate fidelities.

Meta Echoes

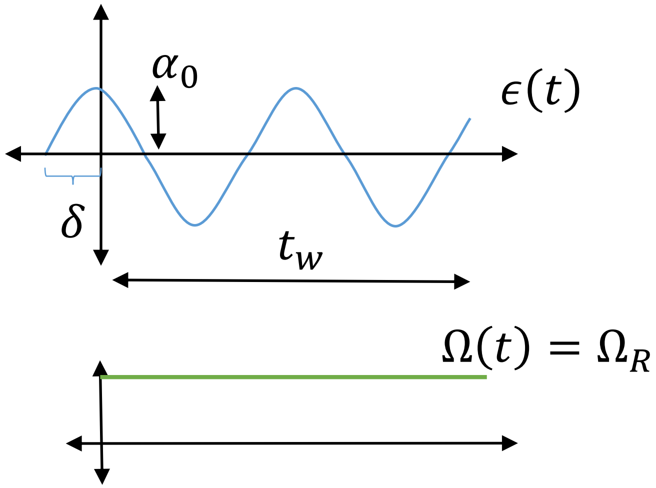
- Terms of form $\chi a^{+} a \sigma_z$ not completely echoed out by a single pi pulse since measurement of $a^{+}a$ does not always yield $|\alpha|^2$

- So insert more pi pulses (qubit echoes) in the ECD pulse sequence



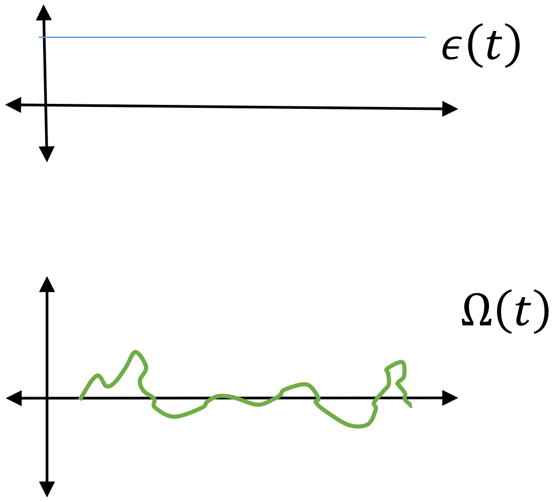
Circle Grape

Sideband Drives



- Changing $\epsilon(t)$
- Constant $\Omega(t)$

Circle Grape



- Constat $\epsilon(t)$
- Changing $\Omega(t)$

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

Sent to Optimizer

Similarly grap-ifying Sideband Drives?
Sending $\delta(t)$ to the optimizer

Circle Grape