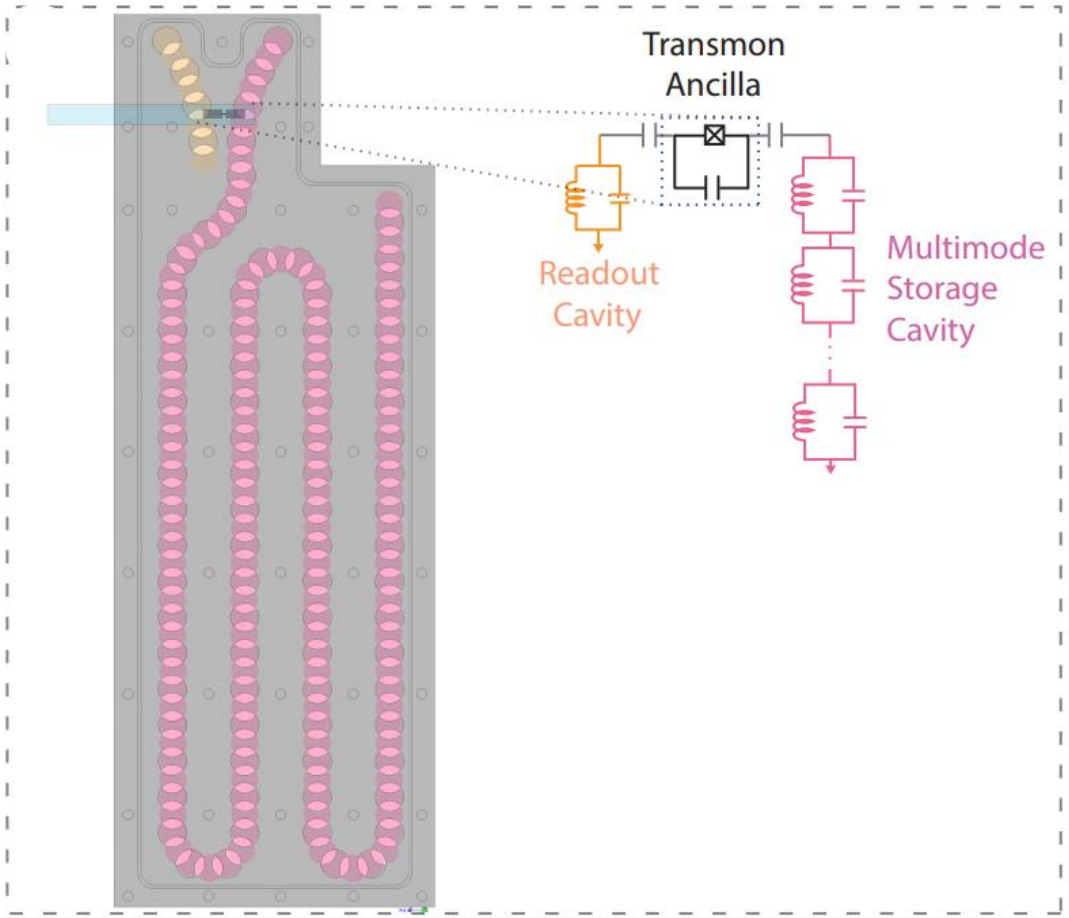
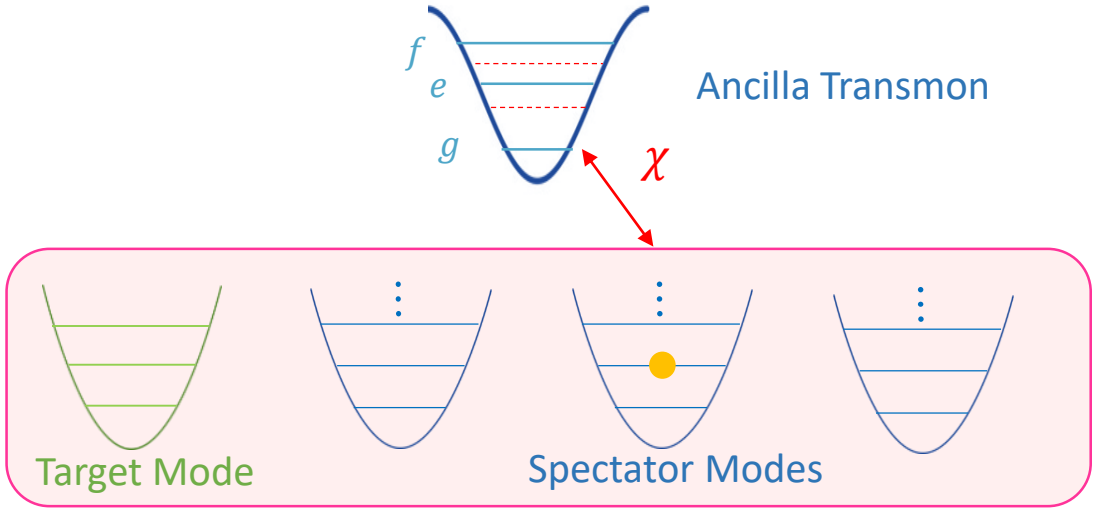
Updates on Multimode ECD (Theory)

August 4, 2023

Aim

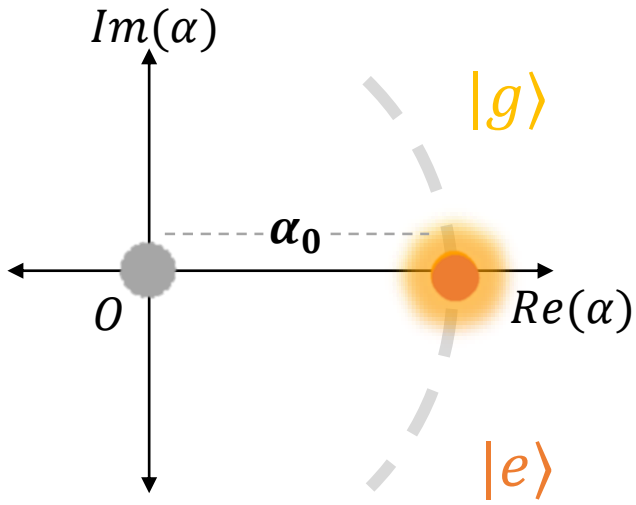




Enact **high-speed** multimode gate operations while **reducing propagation of ancilla errors** into the cavity.

Displacement Enhanced Interactions

Large cavity displacements as a *switch* to enhance cavity-ancilla interaction strength



- Weak $\chi/2\pi \sim 30$ kHz but strong $\chi\alpha_0/2\pi \sim 1$ MHz

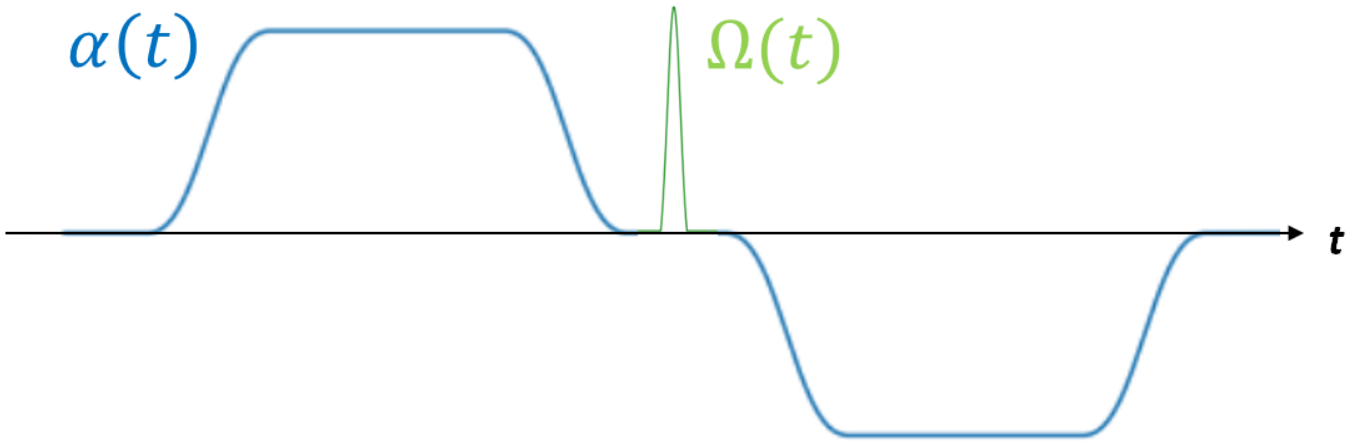
$$\chi a^\dagger a \sigma_z \quad \Rightarrow \quad \chi\left(\alpha_0 a^\dagger + \alpha_0^* a\right)\sigma_z$$

$$D(\alpha_0)$$

$$|\alpha_0| \leq \sqrt{n_{crit}} = \Delta/2g$$

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

Echoed Conditional Displacements



$$\chi a^\dagger a \sigma_z$$

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

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

Echo →

$$-\chi a^\dagger a \sigma_z$$

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

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

At T/2,

$$\alpha \rightarrow -\alpha$$
$$\sigma_z \rightarrow -\sigma_z$$

echoes out unwanted terms from Hamiltonian

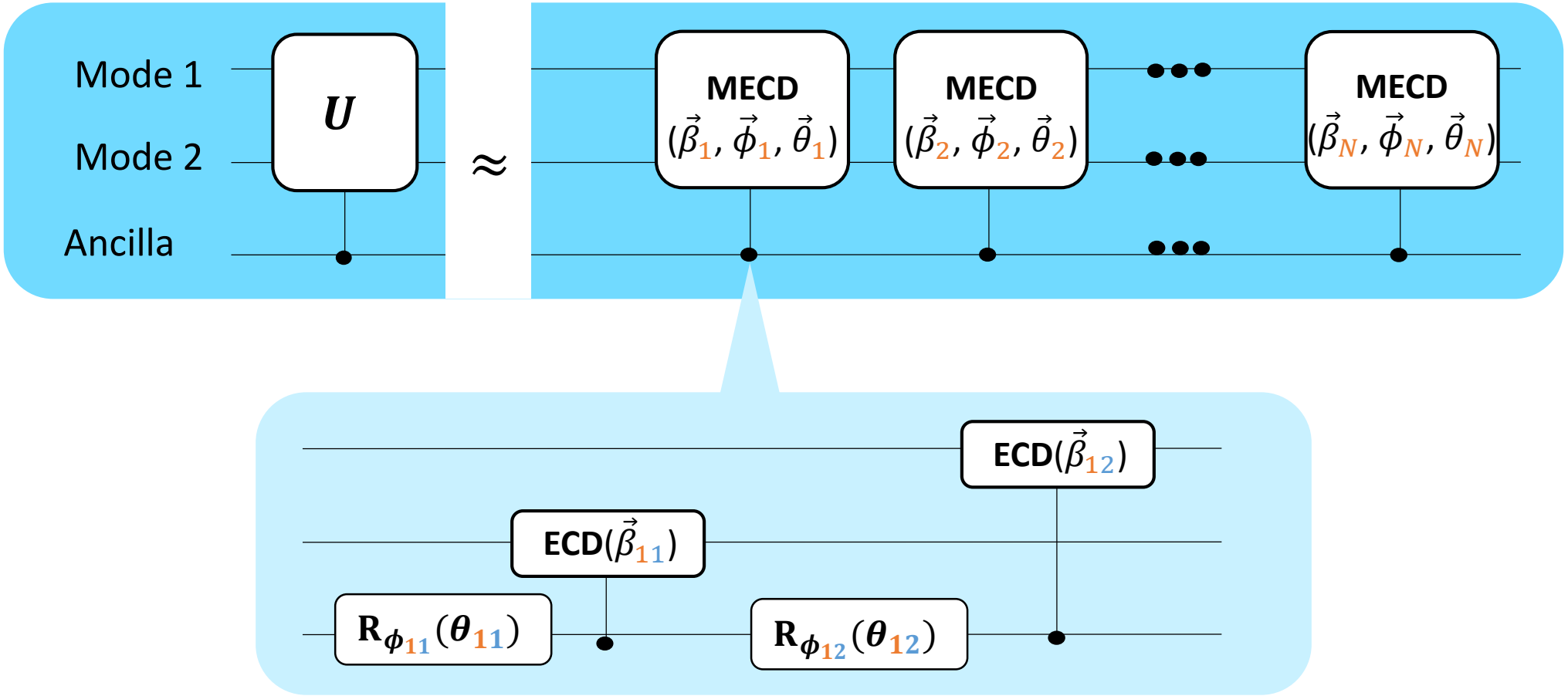
Q: Echo of $\chi a^{\dagger} a \sigma_z$ partial?

1. It seems that $\chi a^{\dagger} a \sigma_z$ is only partially echoed out. But in S4A, use of classical variable, the derivation shows that $\chi a^{\dagger} a \sigma_z$ is completely removed from the unitary. Mismatch?

1. Whether Qutrit ansatz is correct?

Multimode ECD

Find pulse parameters $\vec{\beta}, \vec{\gamma}, \vec{\phi}, \vec{\theta}$ which realize a target unitary U

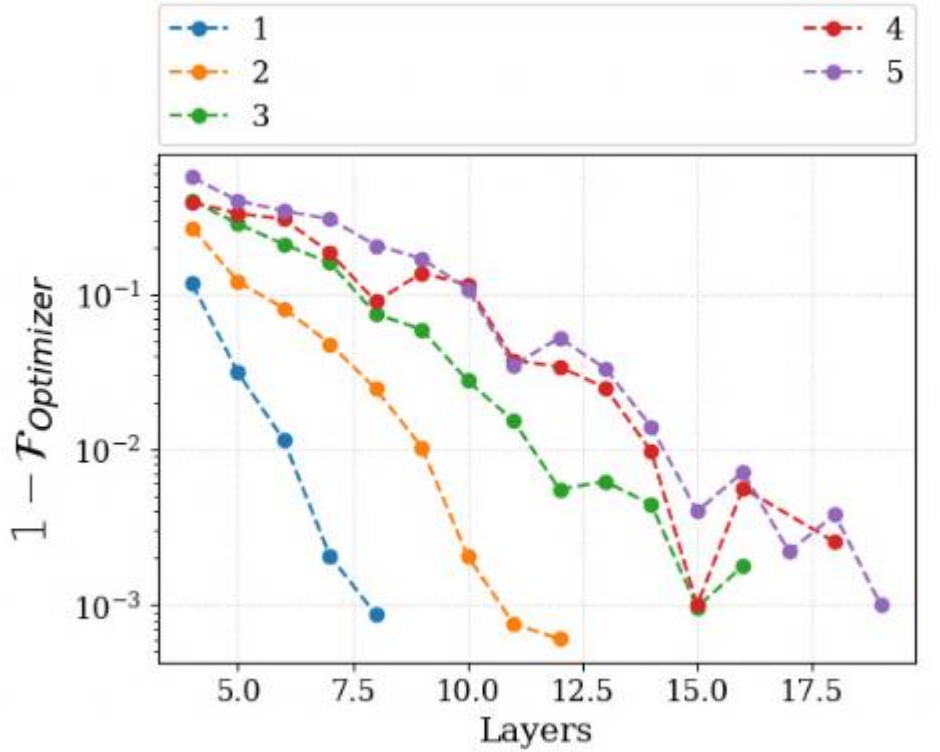


Multimode ECD

Task: Swapping photons between two modes

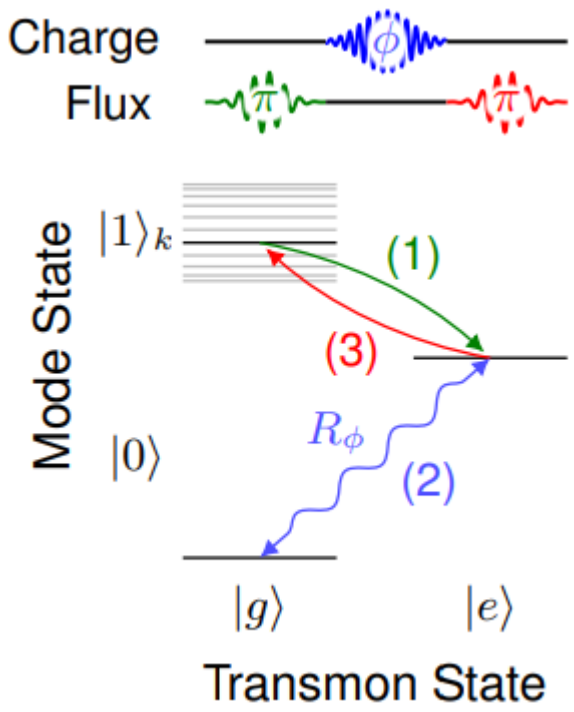
$$|g0n\rangle \rightarrow |gn0\rangle$$

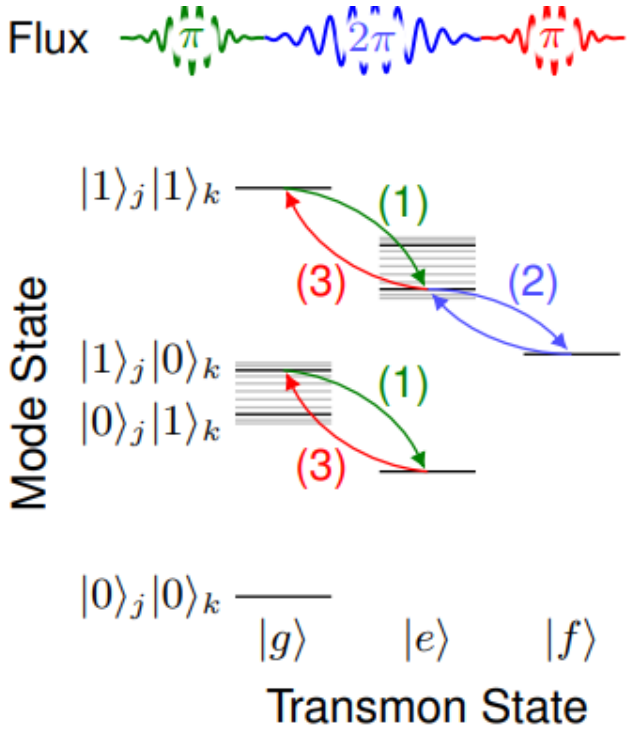
Problem: High Fidelity Pulses are **long** (5-15 μs) compared to typical ancilla transmon lifetime (100 μs)



Idea: f -state

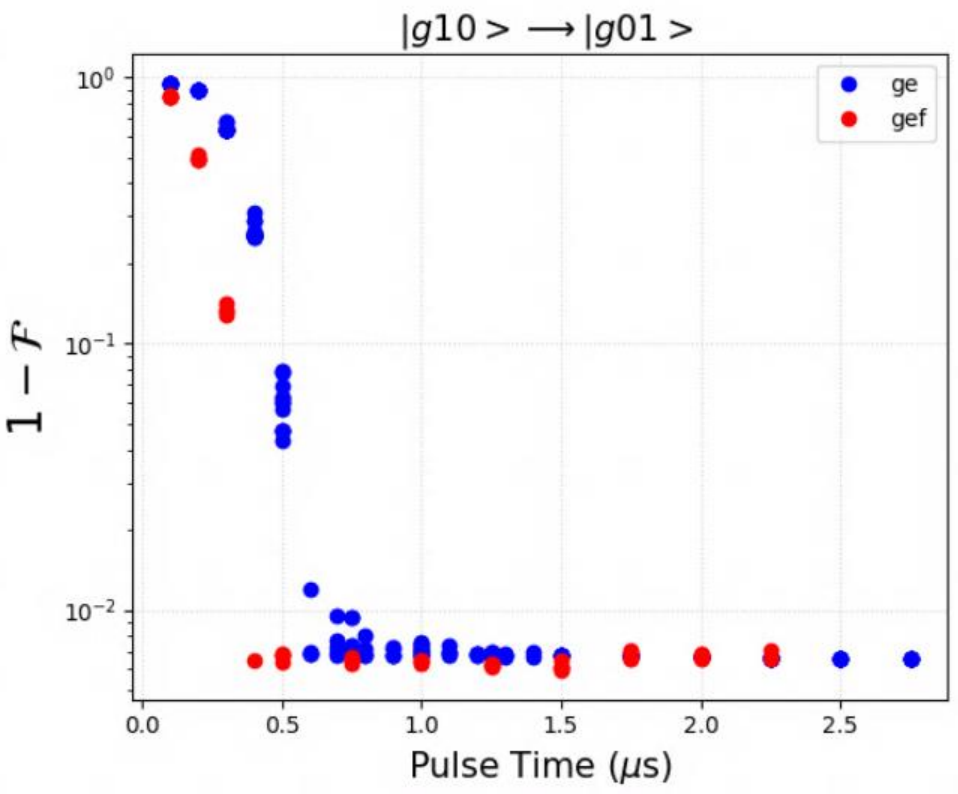
- Naik et. al required f-state of the transmon to perform multimode gates.
- Maybe f-state can help find ECD sequences with lower layer count.

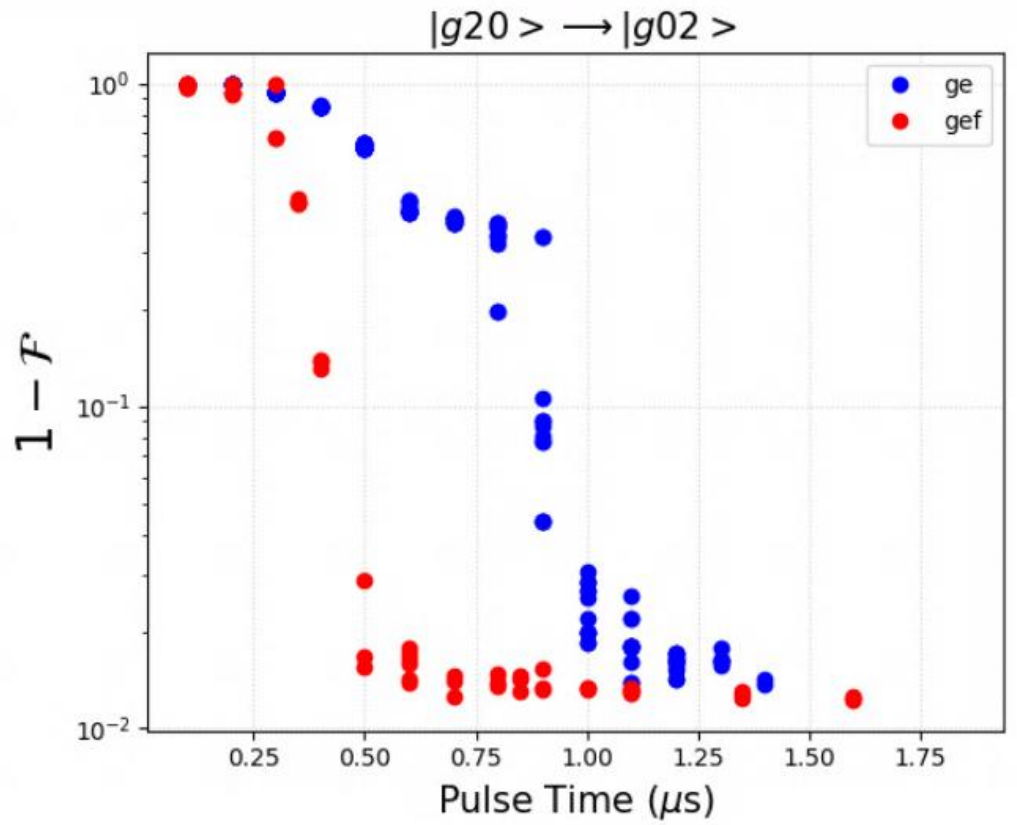




Naik, R.K., Leung, N., Chakram, S. *et al*. *Nat Commun* **8**, 1904 (2017).

Circle GRAPE with f state





- Both modes displaced to $D(\alpha = 30)$
- Optimizing qubit drives :
  - Only ge qubit drive
  - Both ge and ef qubit drive

Upshot: Inclusion of a ef qubit drive improves convergence

ECD with f-state

Objective: Realize ECD gates with **qutrit** ancilla

$$\mathrm{E}CD = \begin{bmatrix} D\left(\frac{\beta}{2}\right) & \\ & D\left(-\frac{\beta}{2}\right) \end{bmatrix}$$

$$\mathrm{E}CD_{ge} = \begin{bmatrix} D\left(\frac{\beta}{2}\right) & & \\ & D\left(-\frac{\beta}{2}\right) & \\ & & 1 \end{bmatrix}$$

$$\mathrm{E}CD_{ef} = \begin{bmatrix} 1 & & \\ & D\left(\frac{\beta}{2}\right) & \\ & & D\left(-\frac{\beta}{2}\right) \end{bmatrix}$$

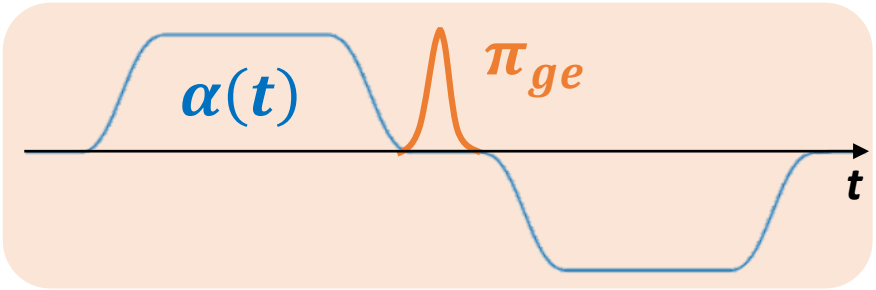
ECD_{ge}

Question: What pulse sequence would realize $\mathrm{E}CD_{ge}$?

Note that $H = \chi a^\dagger a \sigma_{ge}^z + \chi a^\dagger a |f\rangle\langle f| + \epsilon(t) a^\dagger + \epsilon^\star(t) a$

Dispersive Interaction

Cavity Drive



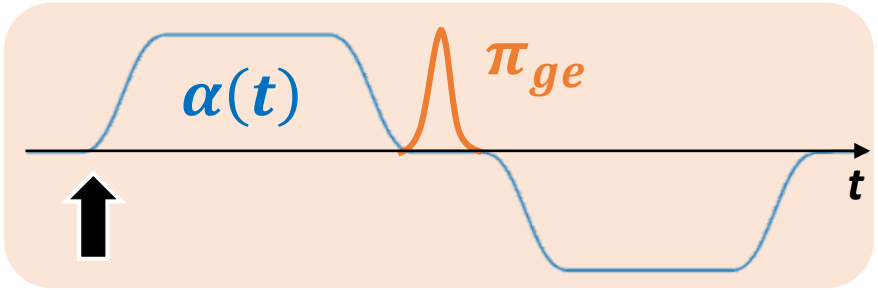
Realizes the Unitary

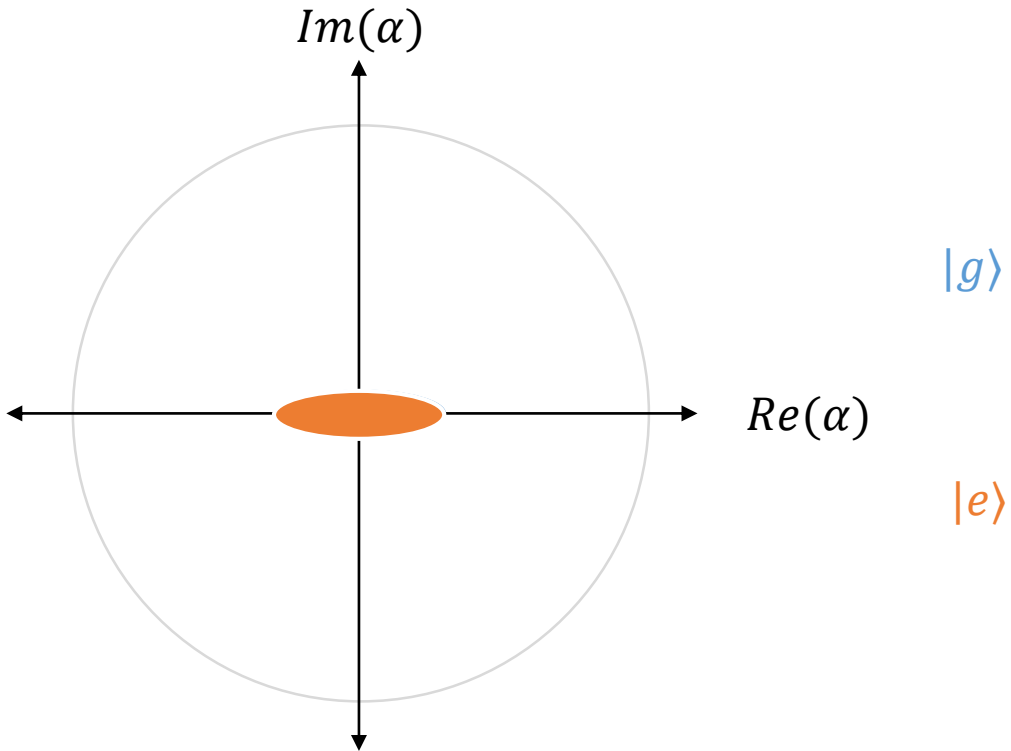
$$U = e^{\frac{i}{2}\begin{bmatrix} -\theta_{ge} & & \\ & \theta_{ge} & \\ & & \theta_f \end{bmatrix}} \times$$

$$e^{\begin{bmatrix} -\delta_{ge} & & \\ & \delta_{ge} & \\ & & \delta_f \end{bmatrix} a^\dagger - h.c.} \times$$

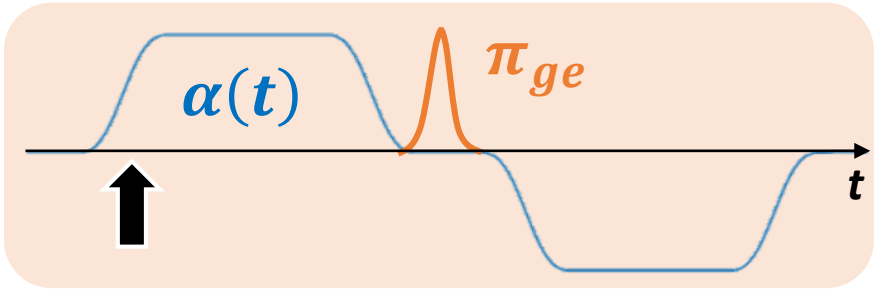
$$e^{i\phi_f a^\dagger a |f\rangle\langle f|}$$

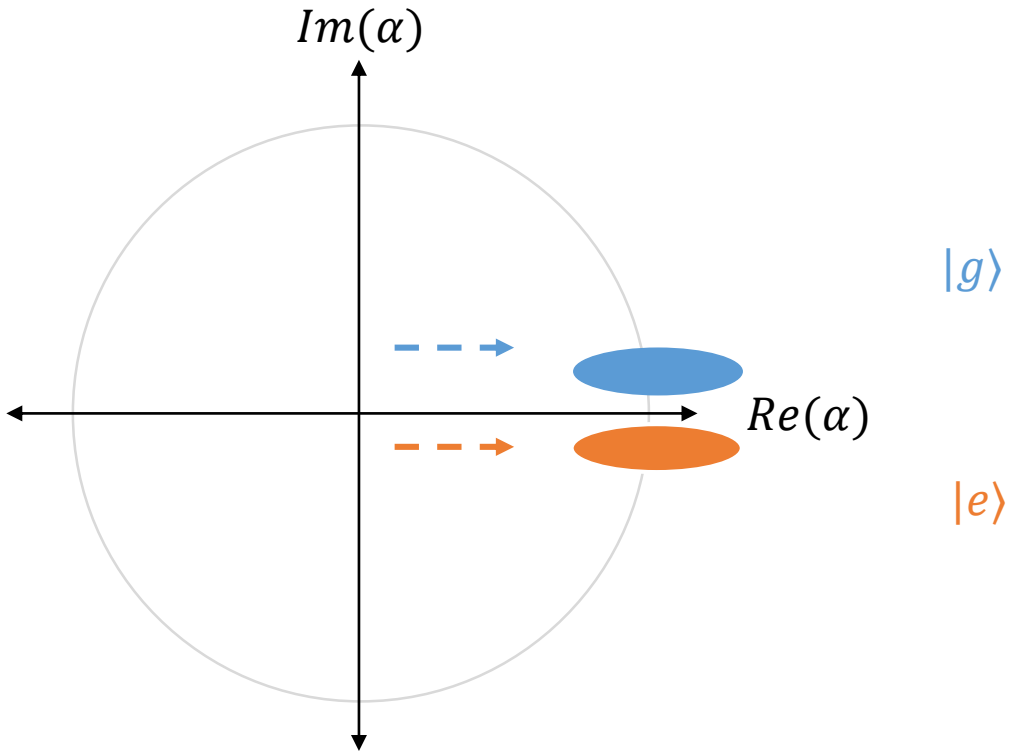
ECD_{ge}





ECD_{ge}





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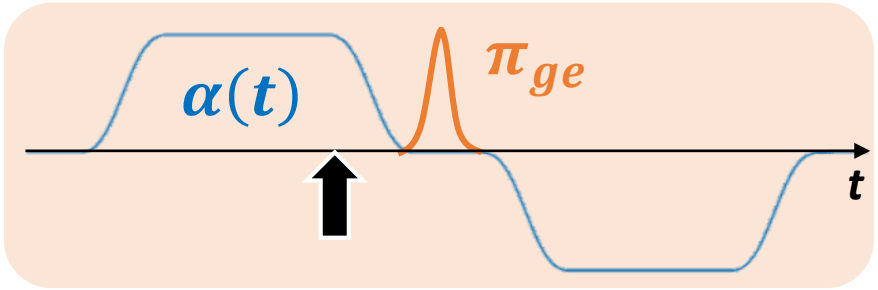

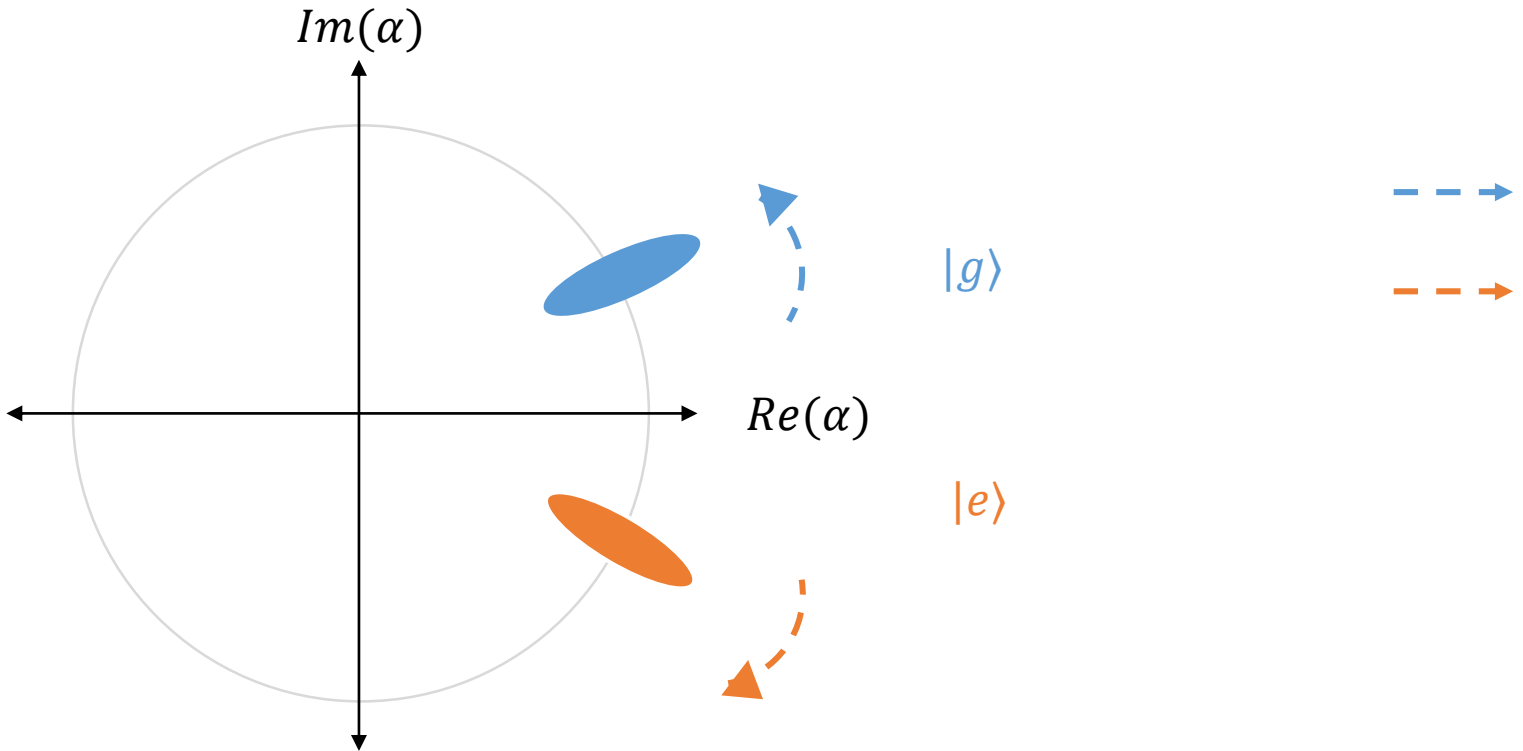

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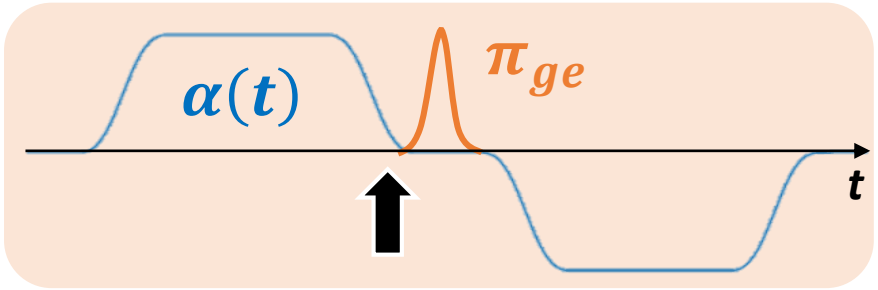

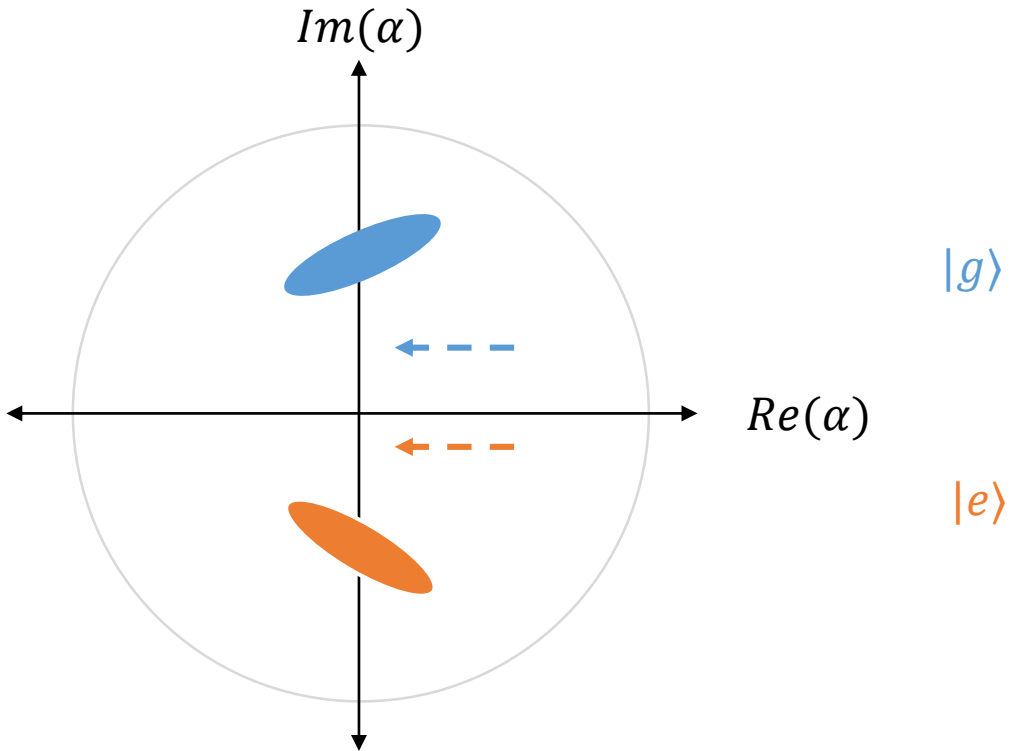

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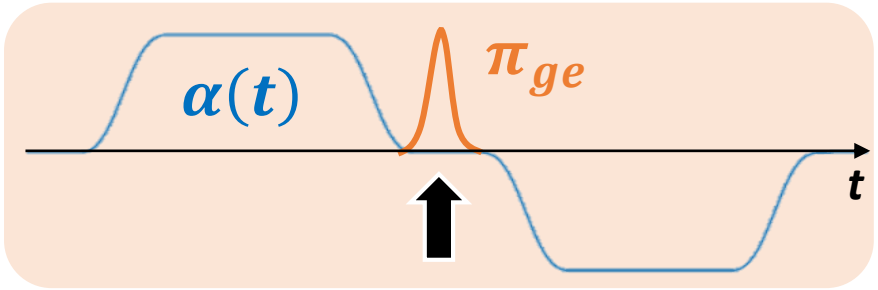

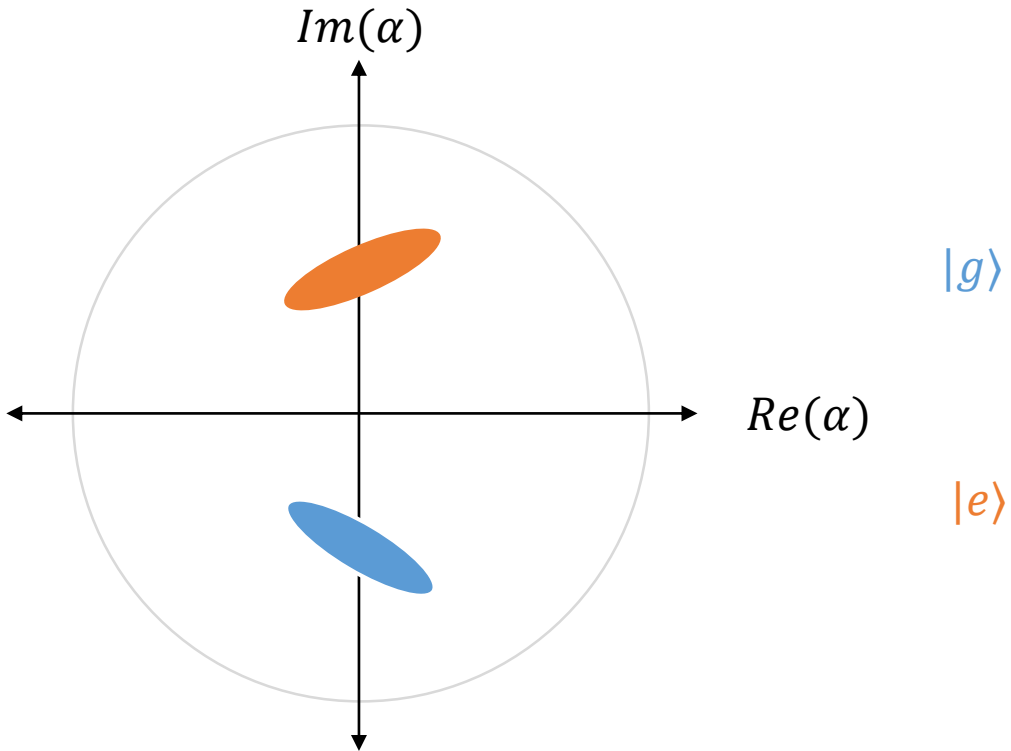

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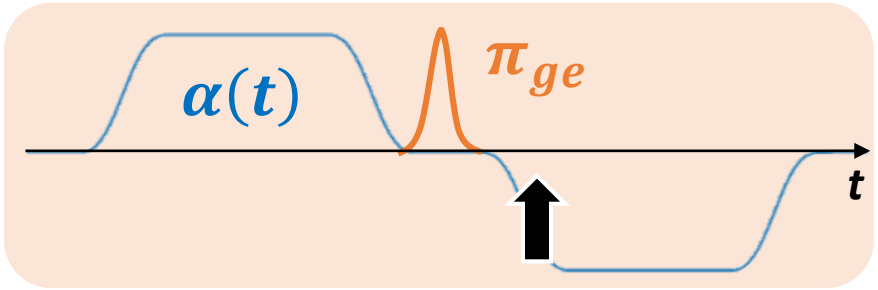

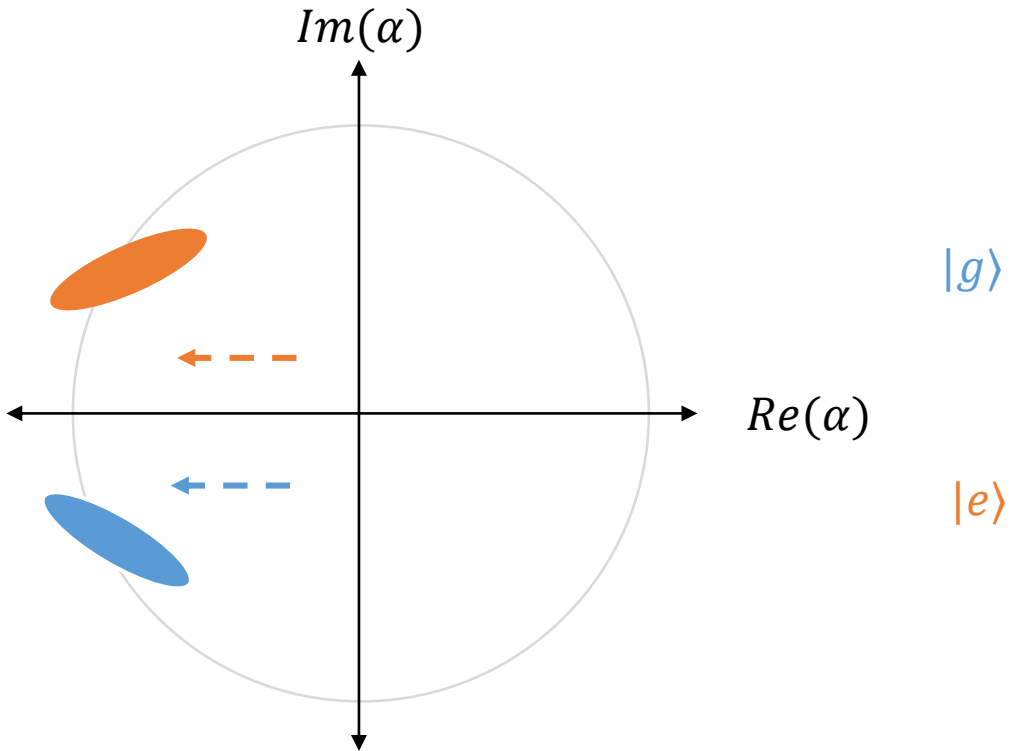

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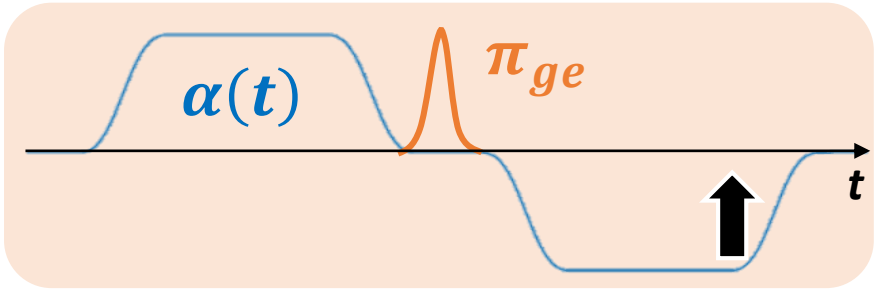

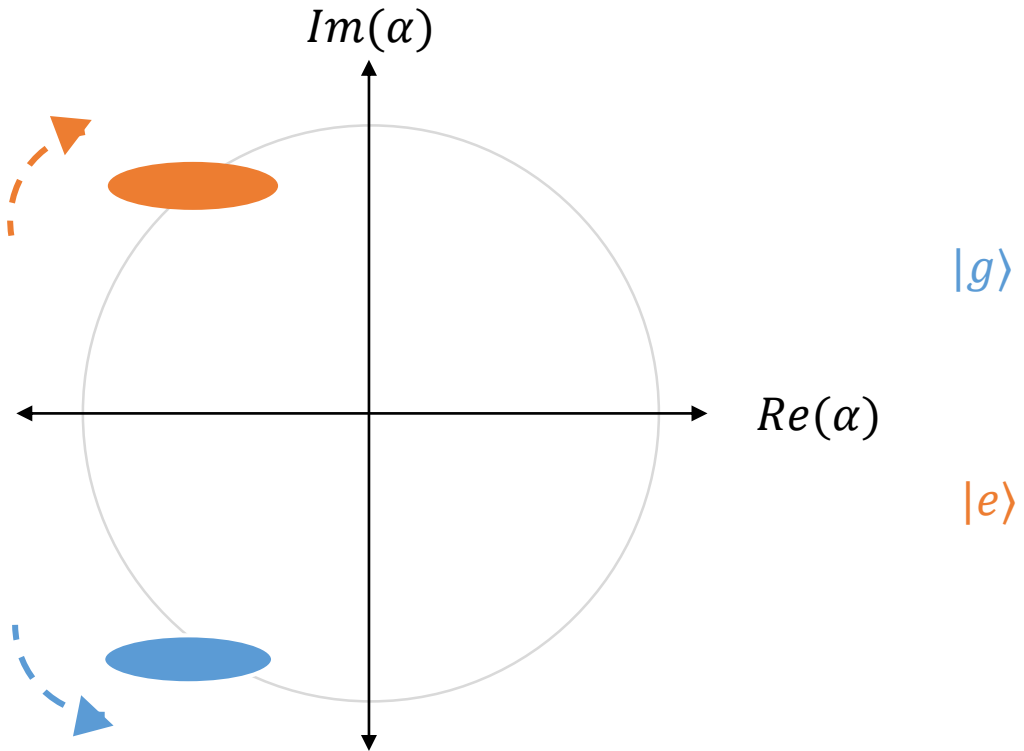

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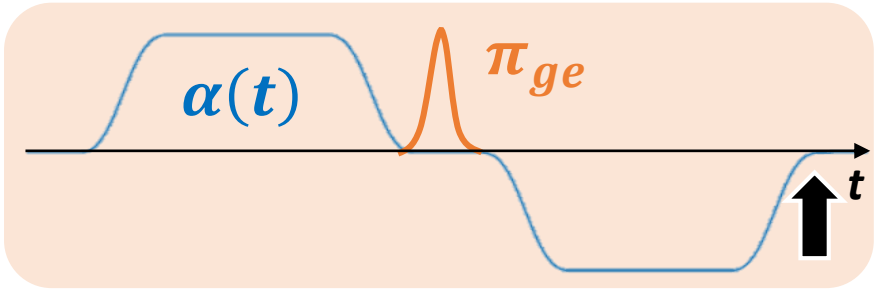
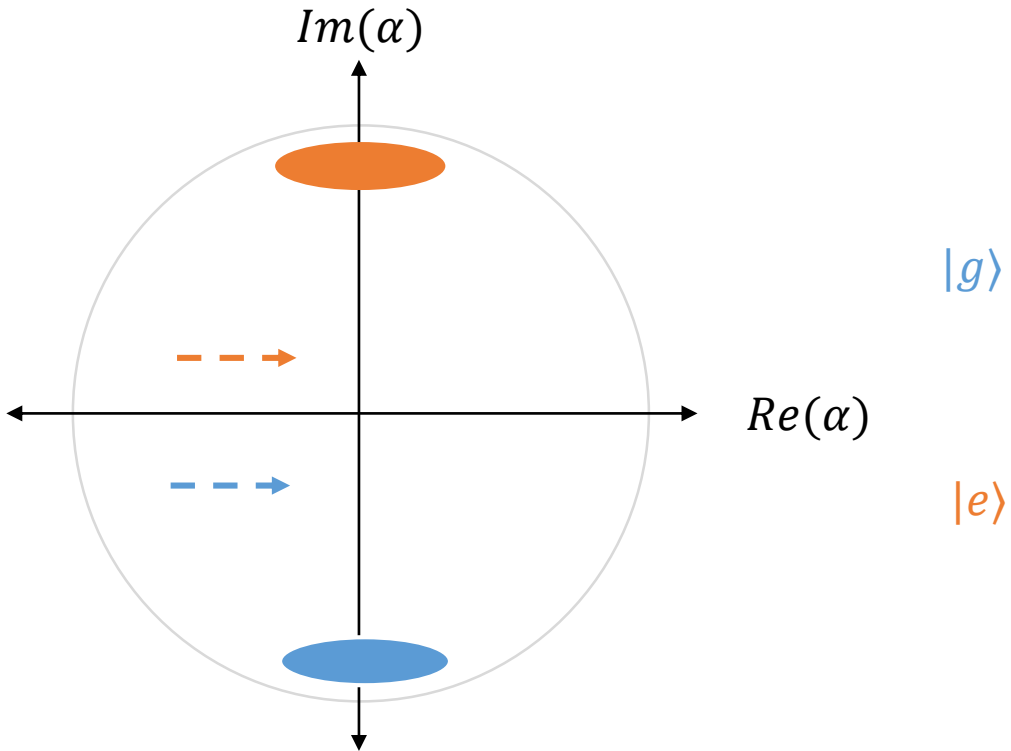
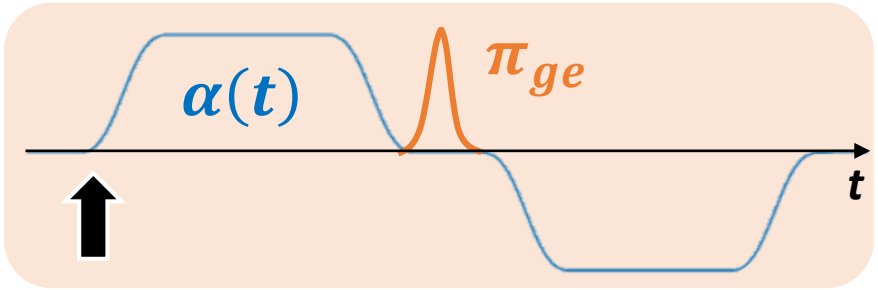
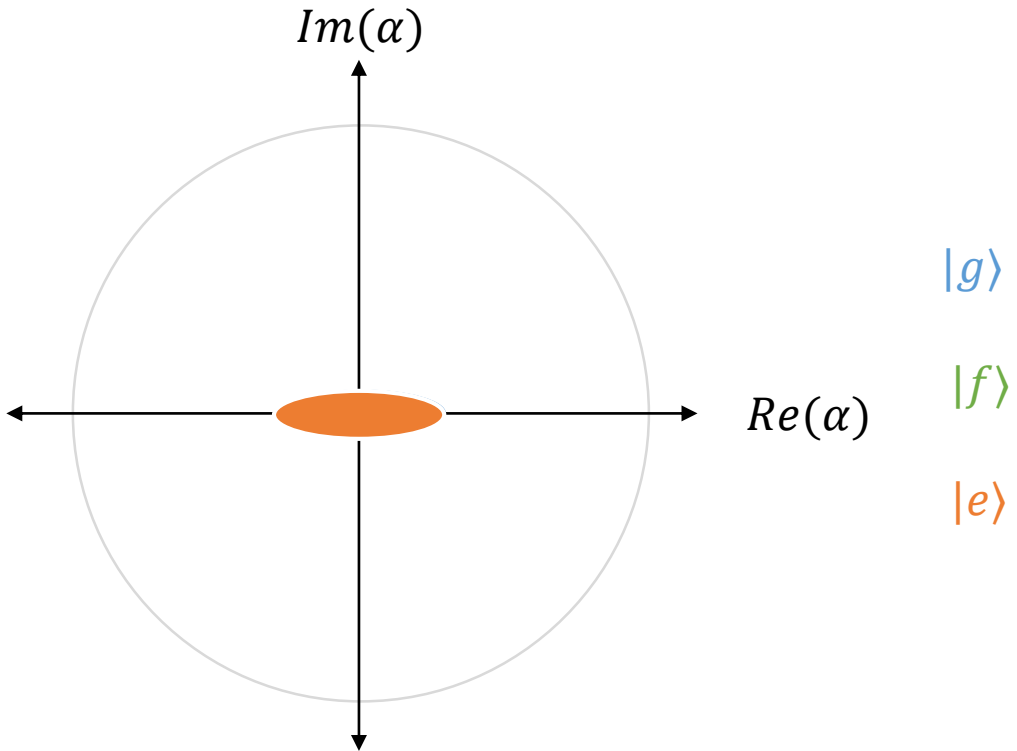




Now adding in f state

ECD_{ge}





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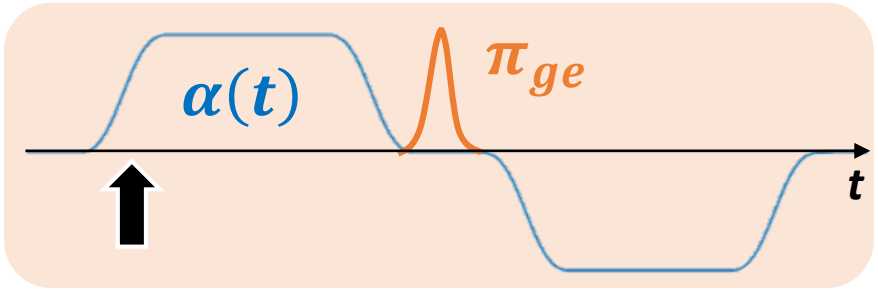

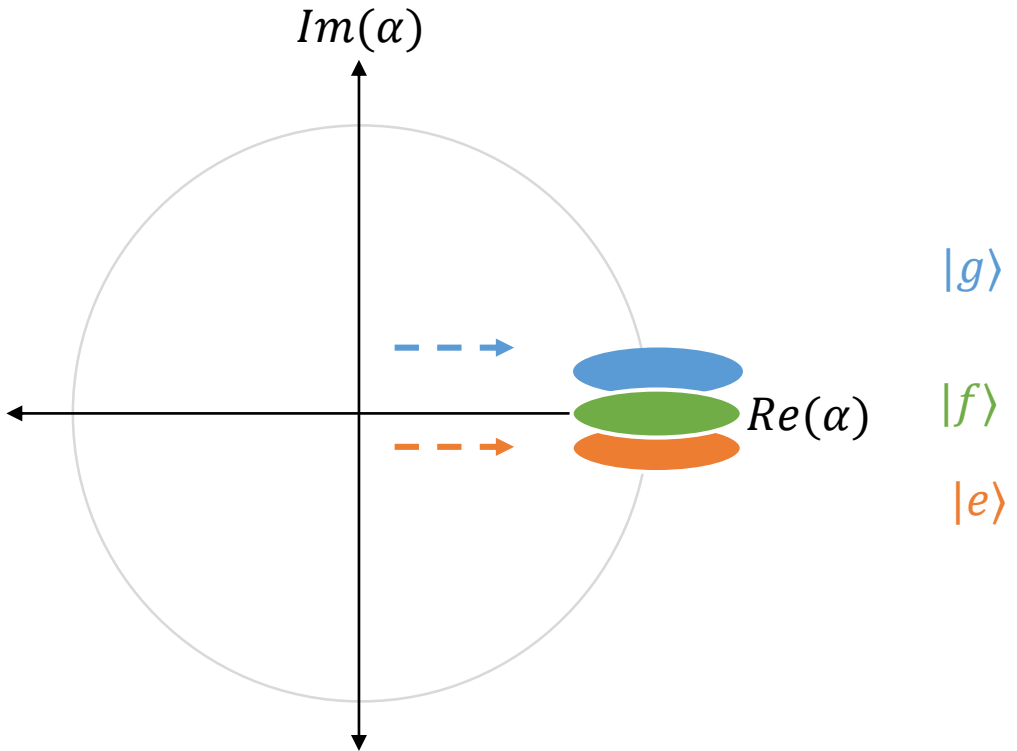

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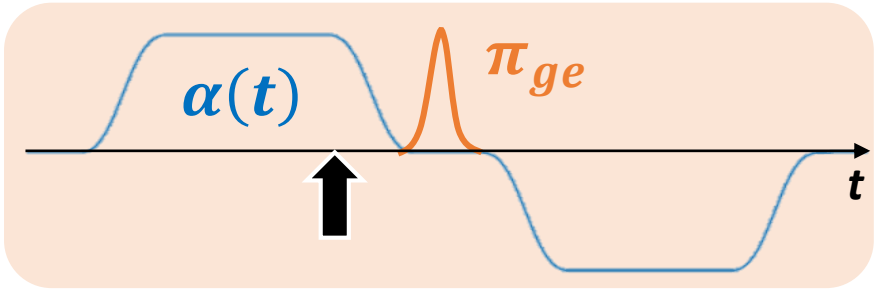

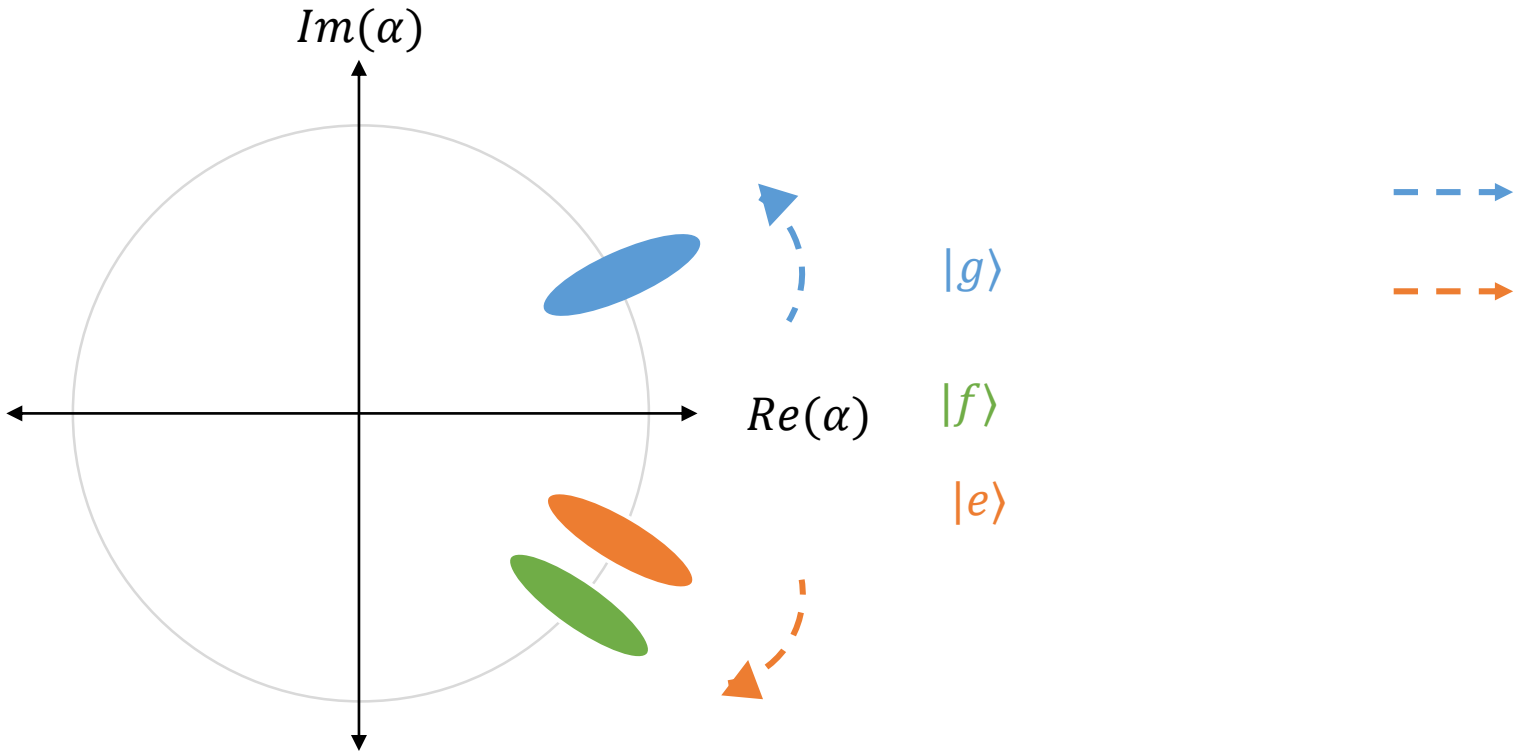

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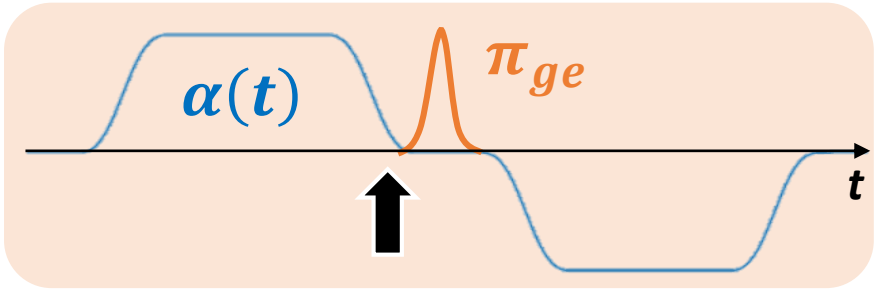

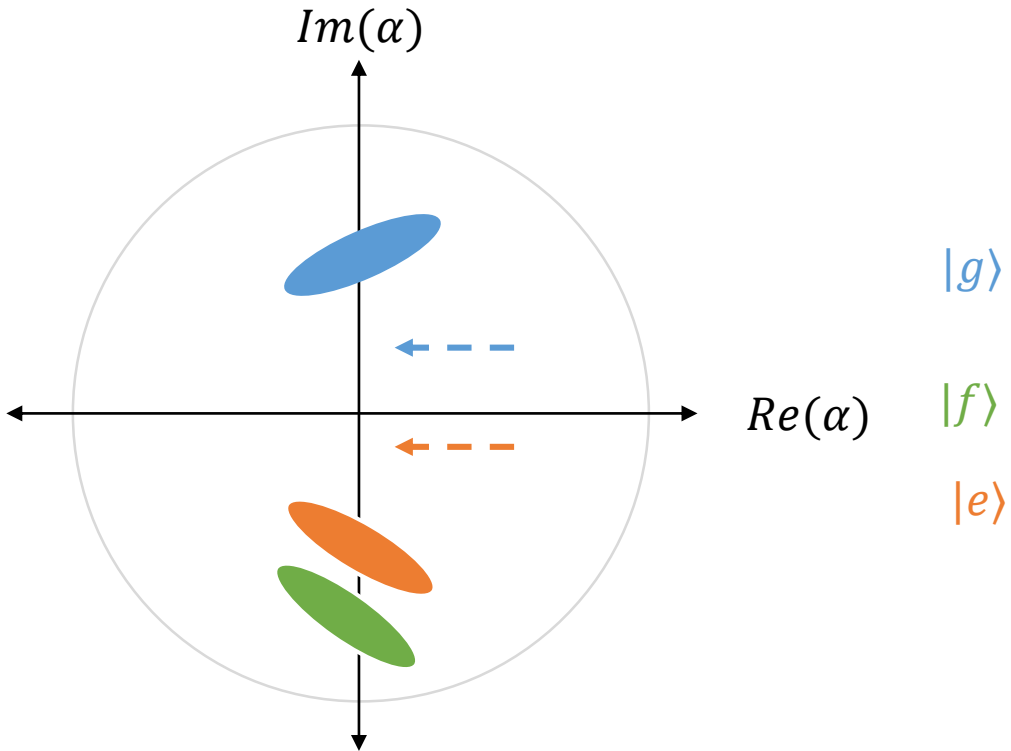

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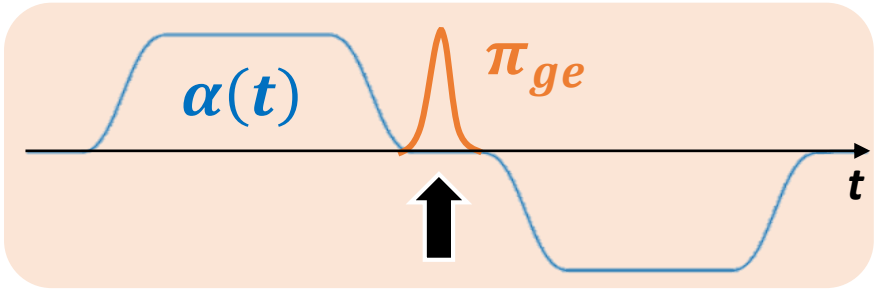

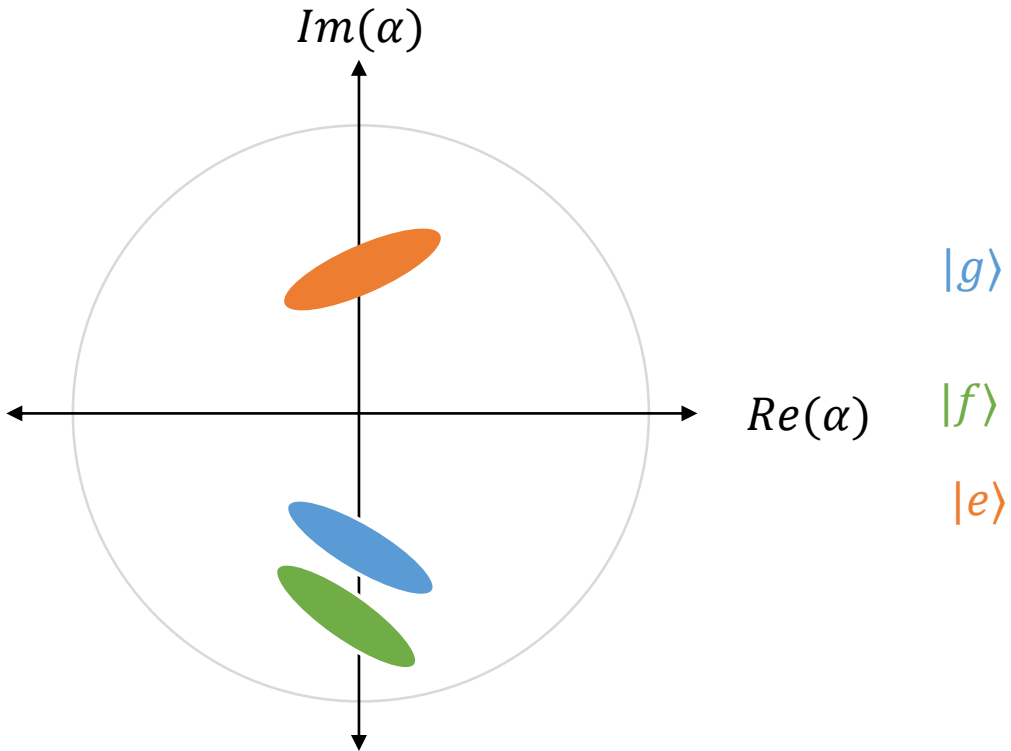

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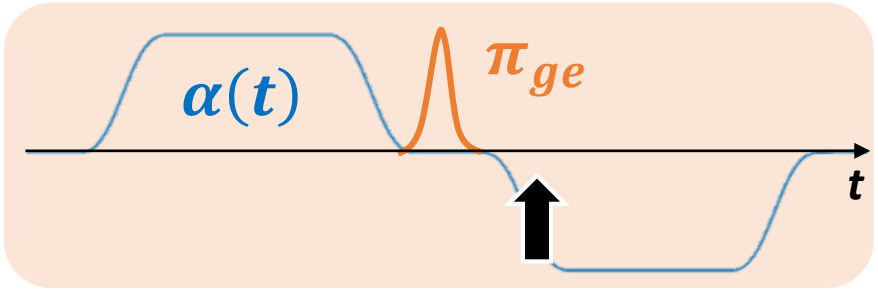

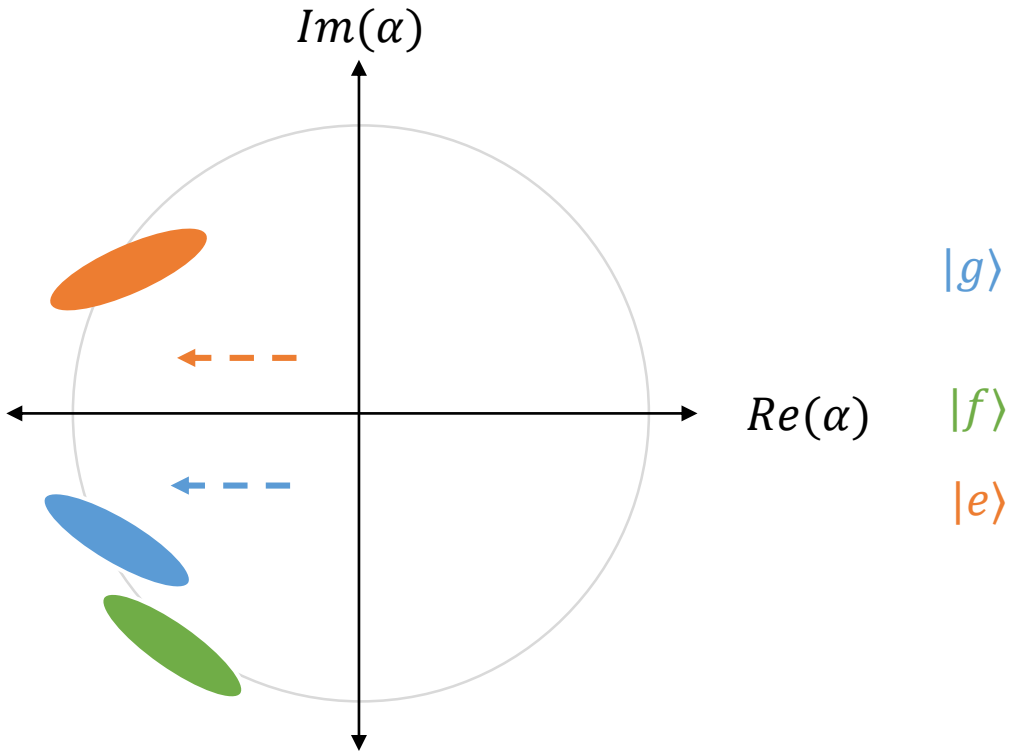

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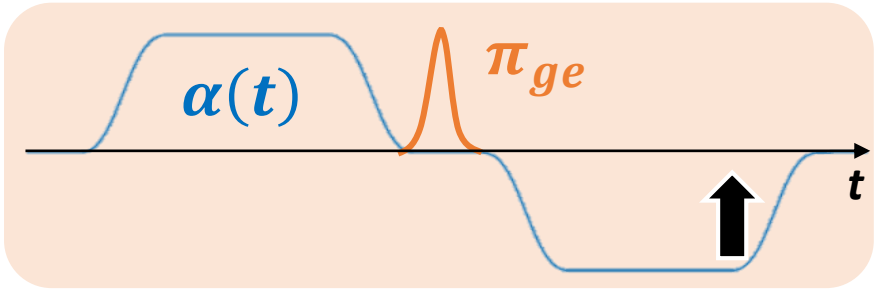

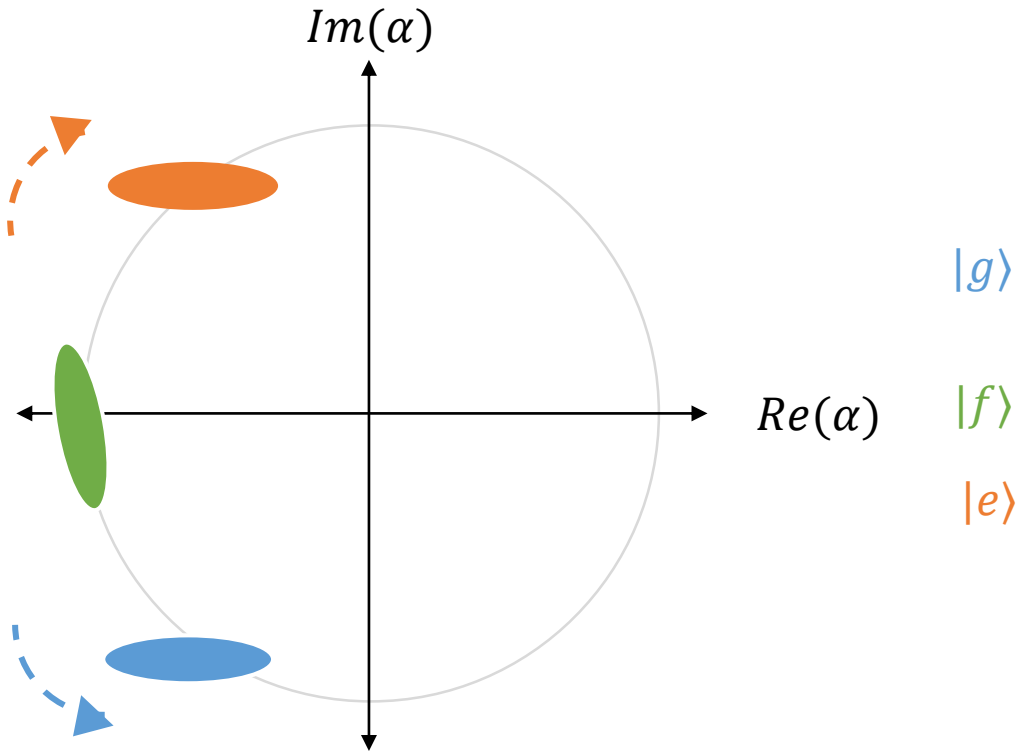

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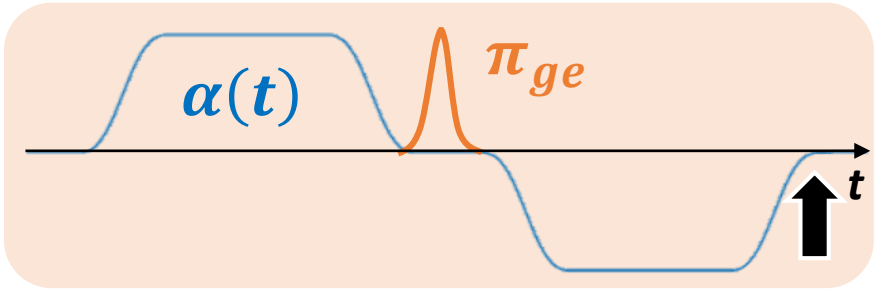
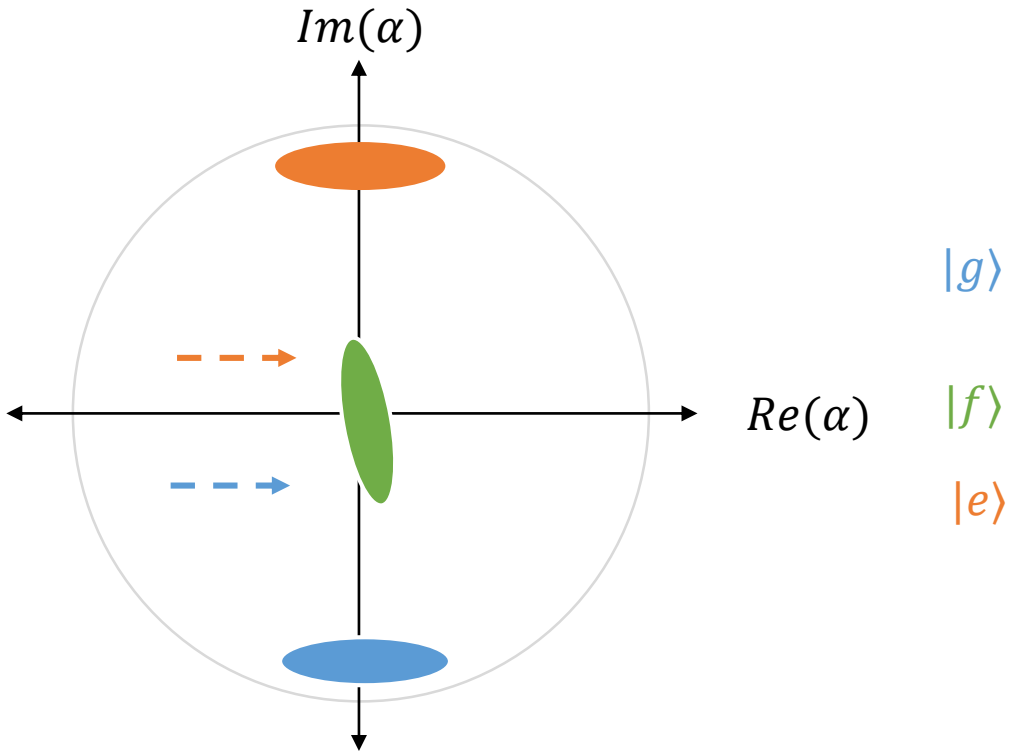




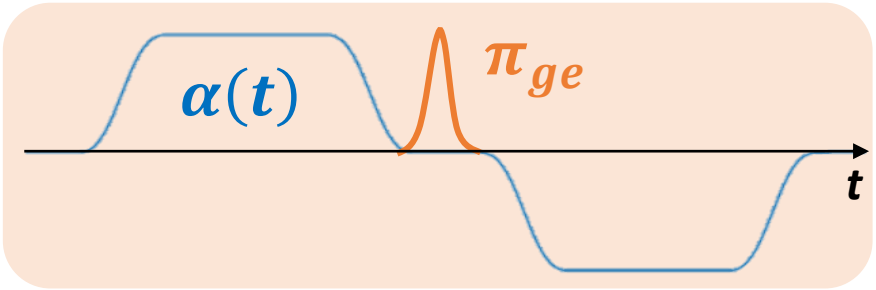
ECD_{ge}

Question: What pulse sequence would realize $\mathrm{E}CD_{ge}$?

Note that $H = \chi a^\dagger a \sigma_{ge}^z + \chi a^\dagger a |f\rangle\langle f| + \epsilon(t) a^\dagger + \epsilon^\star(t) a$

Dispersive Interaction

Cavity Drive



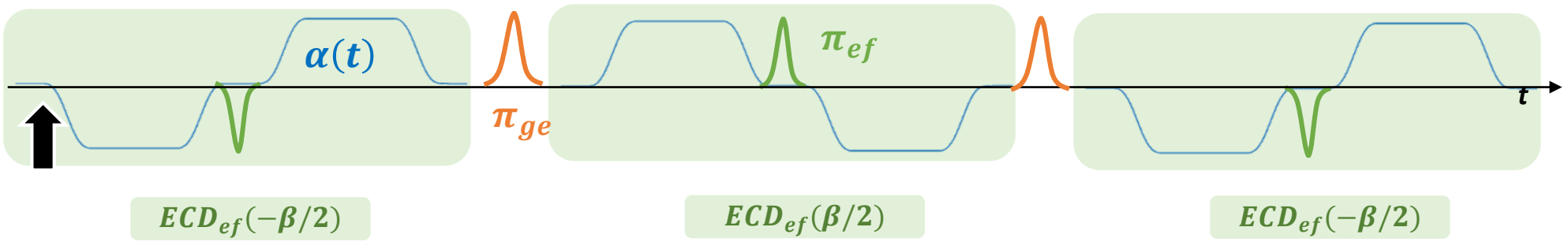
Realizes the Unitary

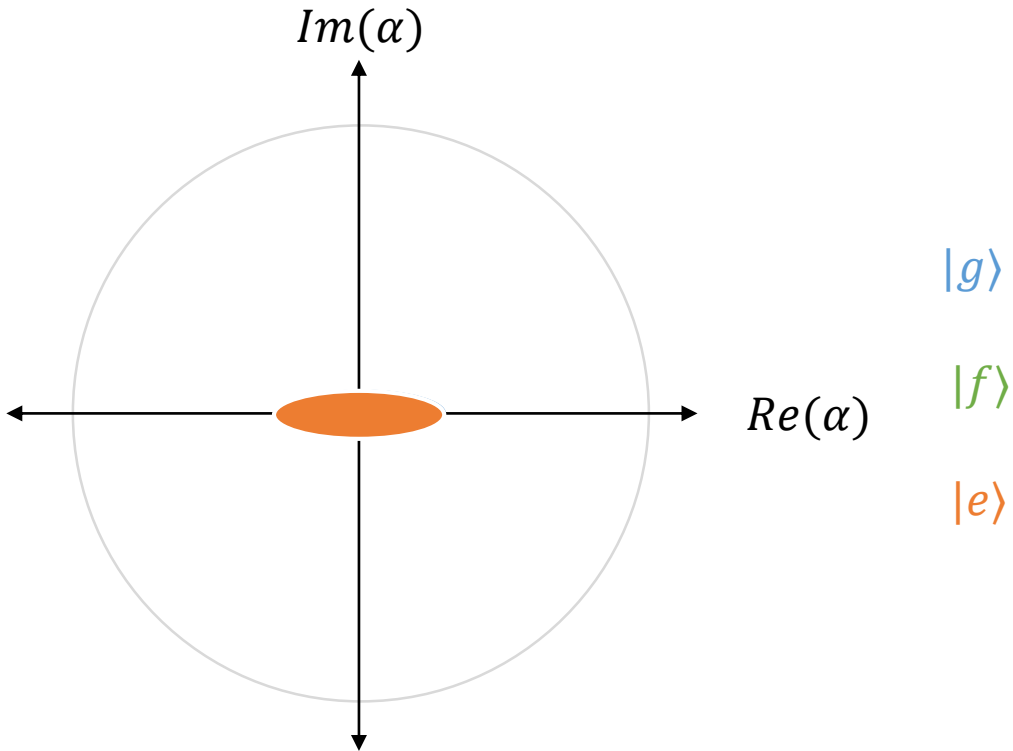
$$U = e^{\frac{i}{2}\begin{bmatrix} -\theta_{ge} & & \\ & \theta_{ge} & \\ & & \theta_f \end{bmatrix}} \times$$

$$e^{\begin{bmatrix} -\delta_{ge} & & \\ & \delta_{ge} & \\ & & \delta_f \end{bmatrix} a^\dagger - h.c.} \times$$

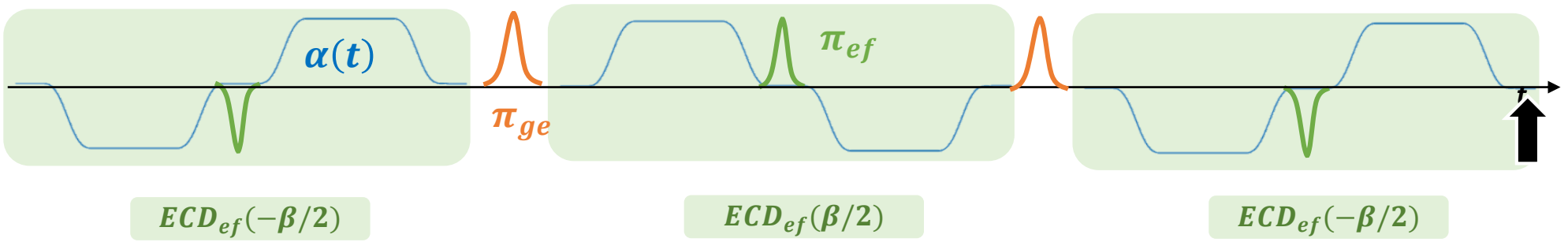
$$e^{i\phi_f a^\dagger a |f\rangle\langle f|}$$

New form of $ECD_{ge}(\beta)$

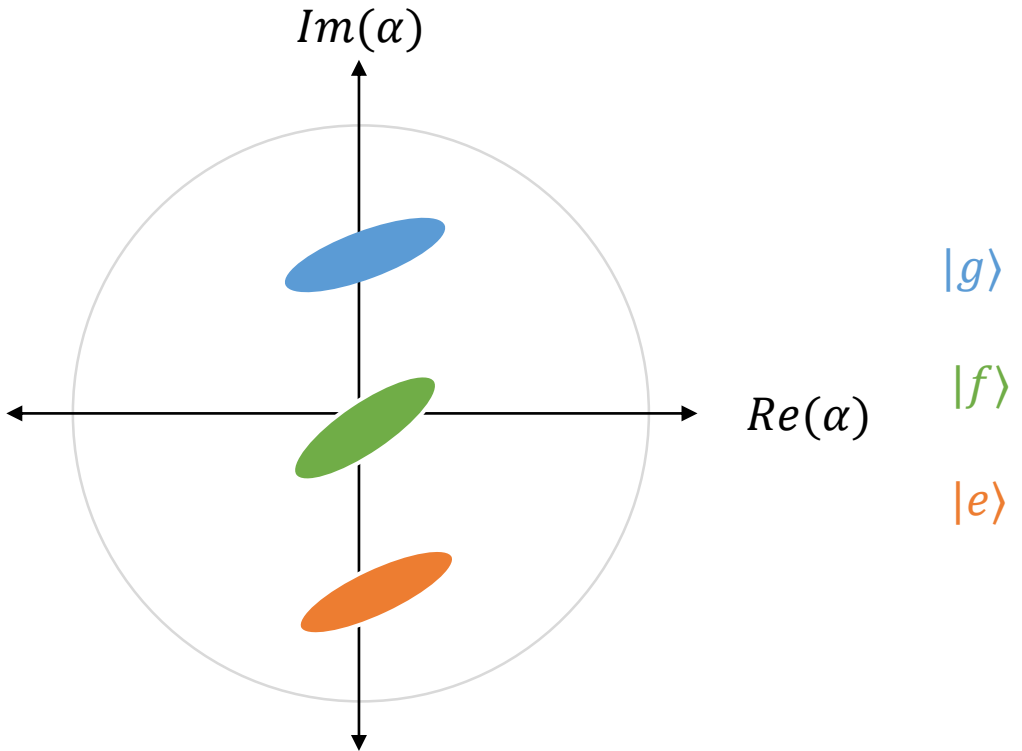




New form of $ECD_{ge}(\beta)$

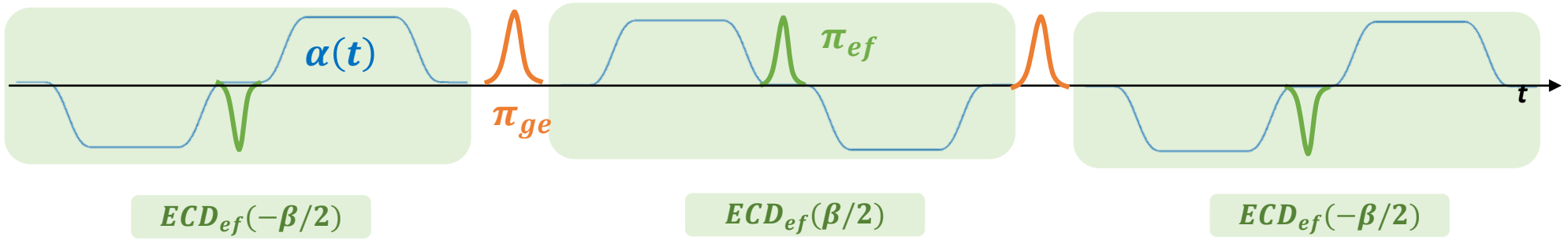


Claim:

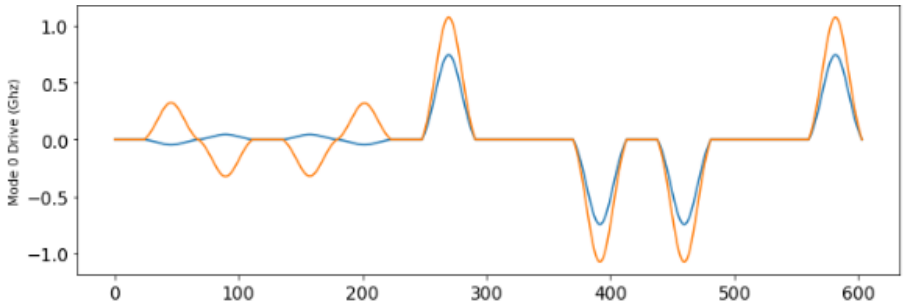


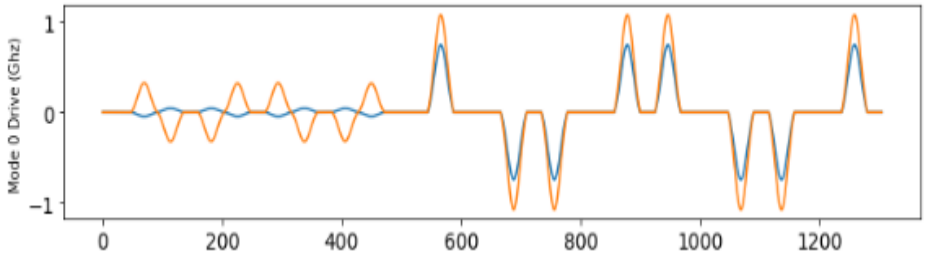
Summary

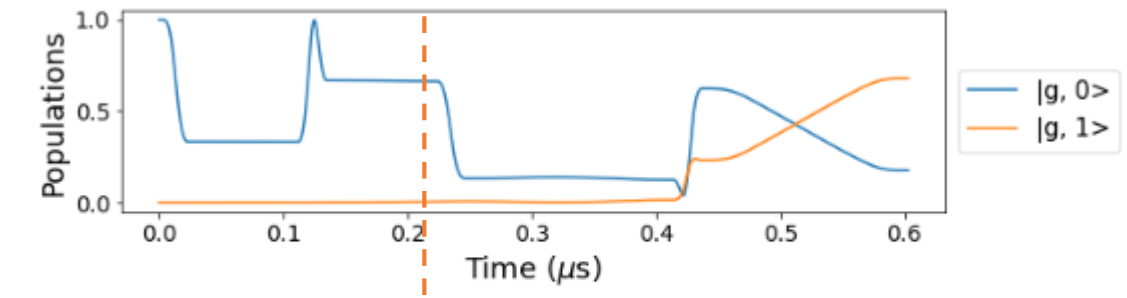
- Generalized ECD to multimode system
- Inclusion of ef qubit drive improved convergence
- ECD with Qutrit ancilla (In progress)
  - Coming up with a pulse sequence to realize ECD_{ge}

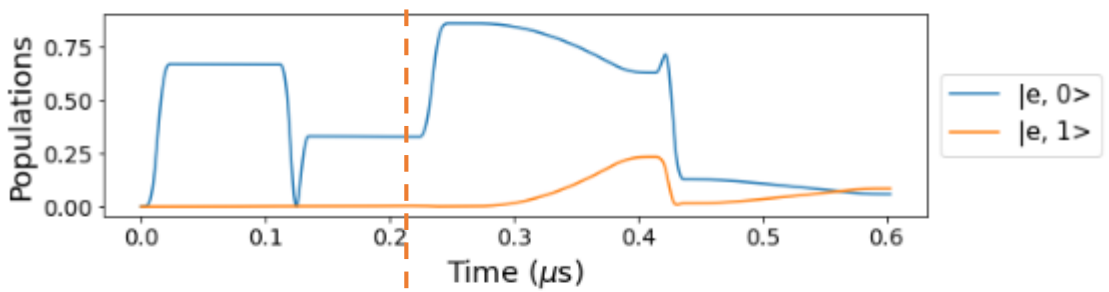


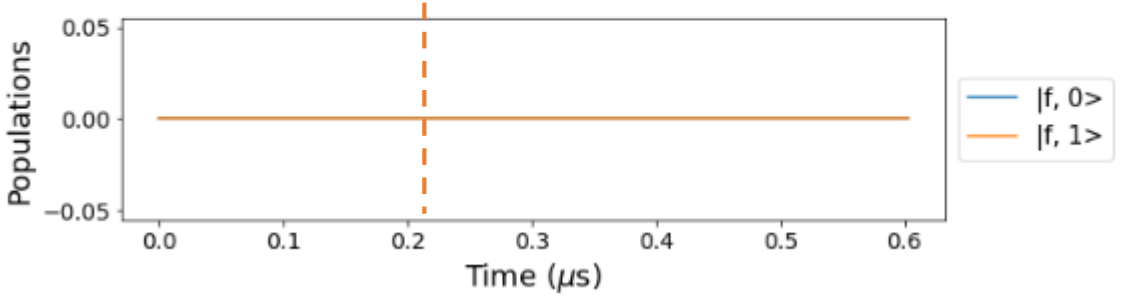
Scratch

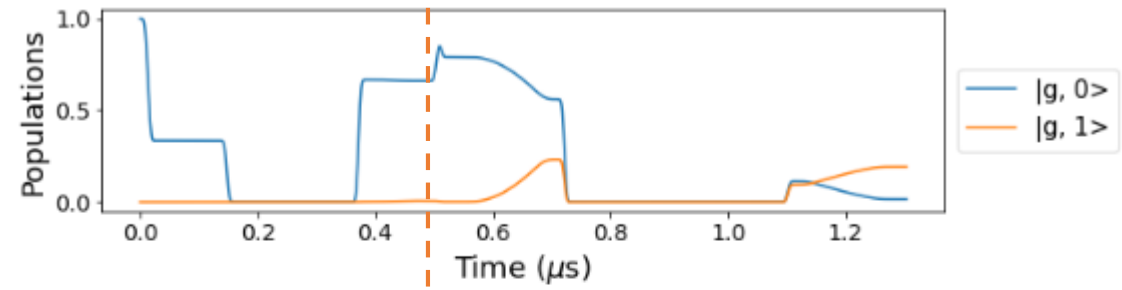

Mode 0 Drive (Ghz)
1.0
0.5
0.0
−0.5
−1.0
0
100
200
300
400
500
600

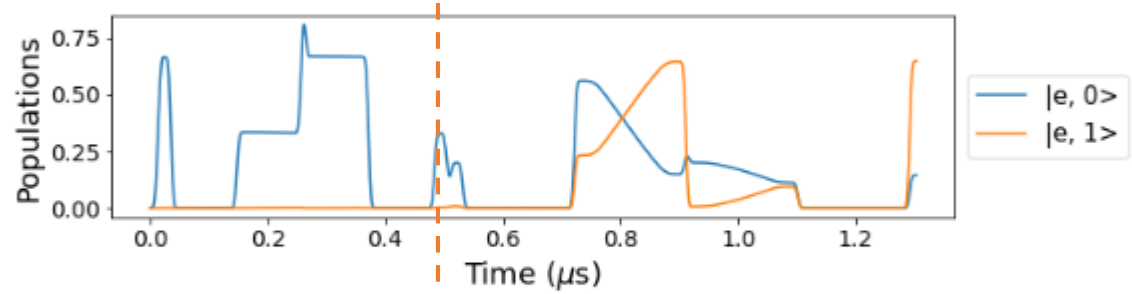

Mode 0 Drive (Ghz)
1
0
−1
0
200
400
600
800
1000
1200

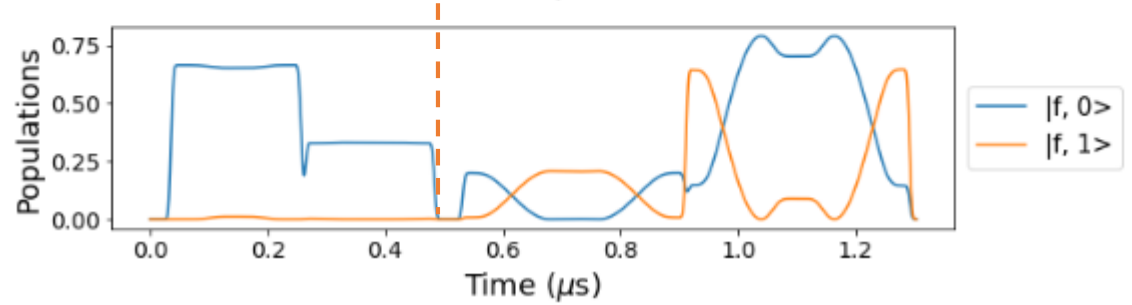

Populations
1.0
0.5
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Time (μs)
|g, 0>
|g, 1>


Populations
0.75
0.50
0.25
0.00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Time (μs)
|e, 0>
|e, 1>


Populations
0.05
0.00
−0.05
0.0
0.1
0.2
0.3
0.4
0.5
0.6
Time (μs)
|f, 0>
|f, 1>


Populations
1.0
0.5
0.0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Time (μs)
|g, 0>
|g, 1>

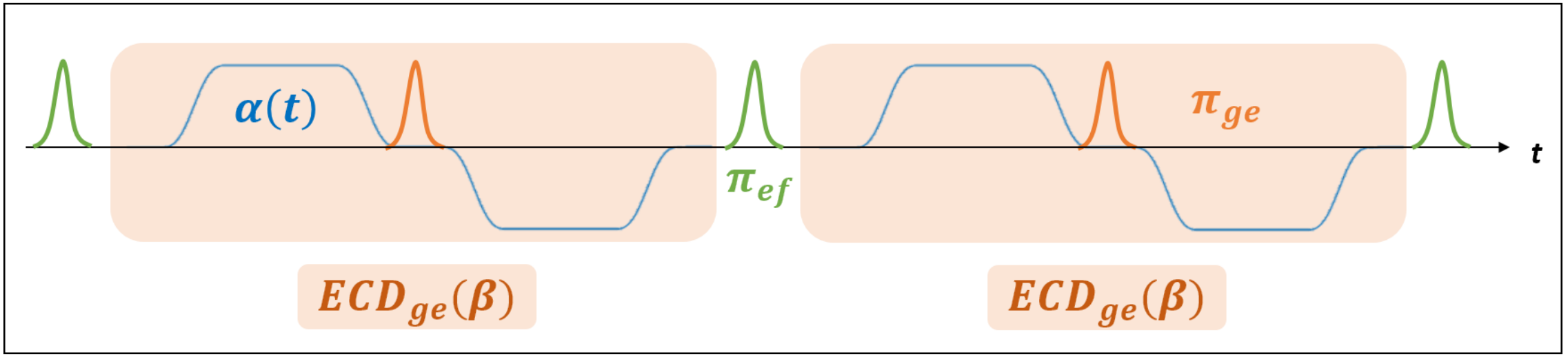

Populations
0.75
0.50
0.25
0.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Time (μs)
|e, 0>
|e, 1>


Populations
0.75
0.50
0.25
0.00
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Time (μs)
|f, 0>
|f, 1>

First Guess for ECD_{ge}

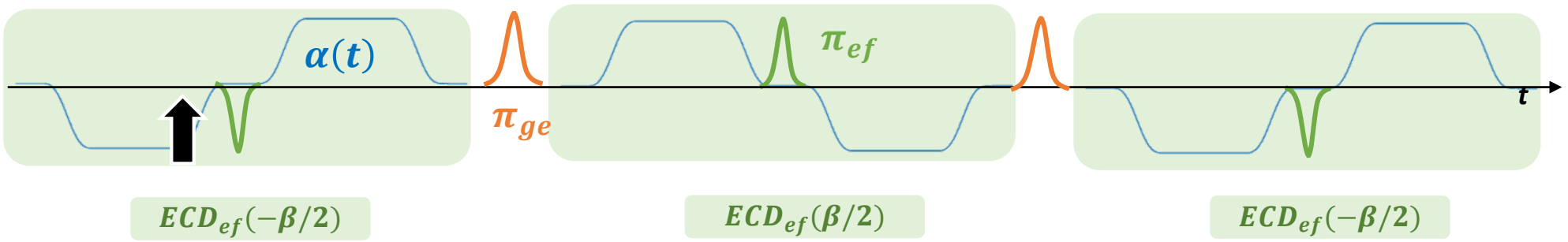
Question: Does the following pulse sequence echo out the unwanted f-state terms?

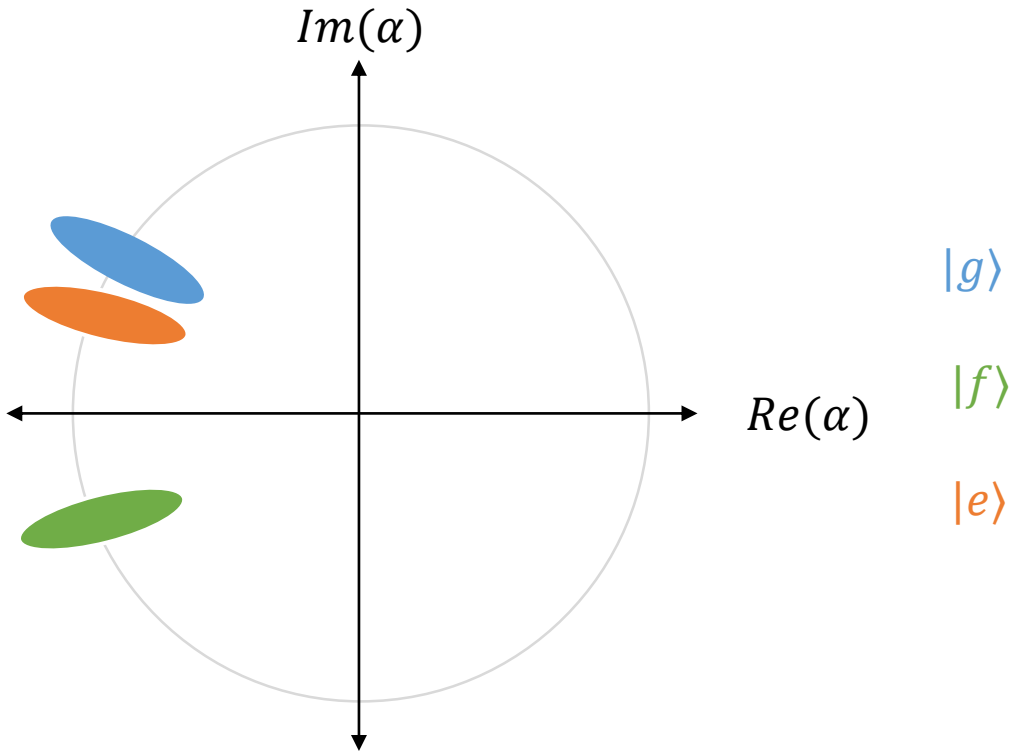
Not completely



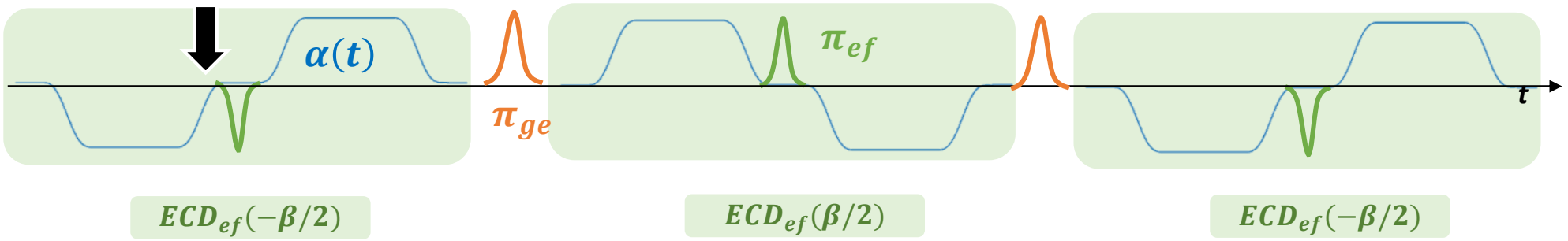
$$U = e^{\frac{i}{2}(\theta_{ge}-\theta_f)\sigma_{ge}^z} \times e^{\begin{bmatrix}\delta_f & & \\ & \delta_{ge} & \\ & & -\delta_{ge}\end{bmatrix}a^\dagger - h.c.} \times e^{i\phi_f a^\dagger a|g\rangle\langle g|} \times e^{\begin{bmatrix}-\delta_{ge} & & \\ & \delta_f & \\ & & \delta_{ge}\end{bmatrix}a^\dagger - h.c.} \times e^{i\phi_f a^\dagger a|e\rangle\langle e|}$$

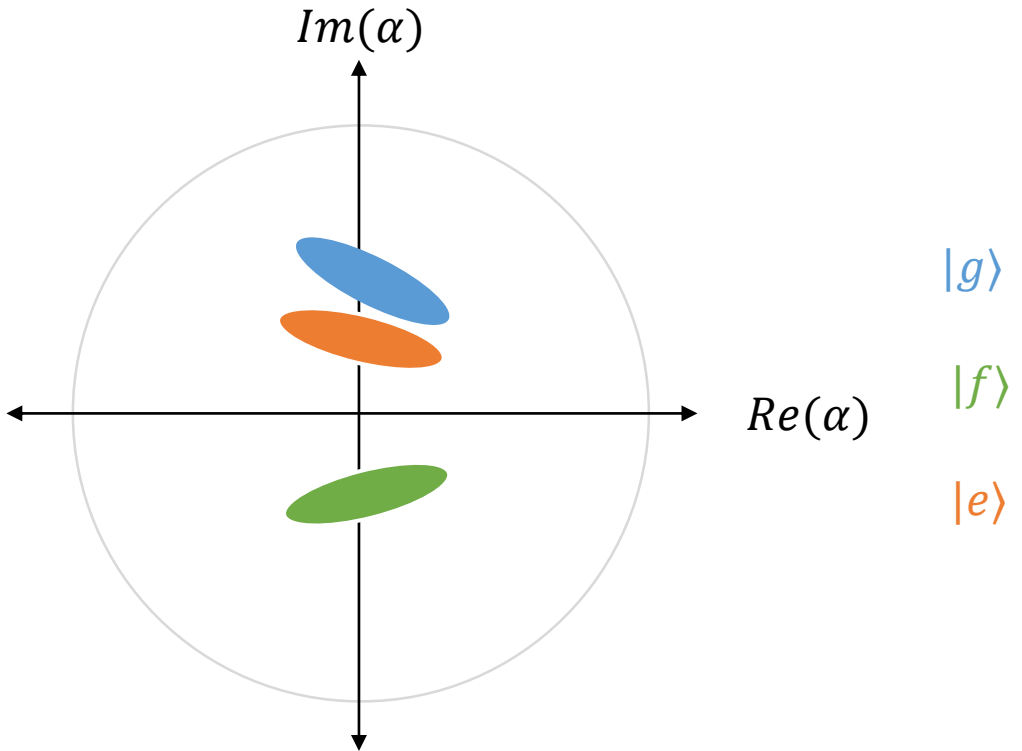
New form of $ECD_{ge}(\beta)$



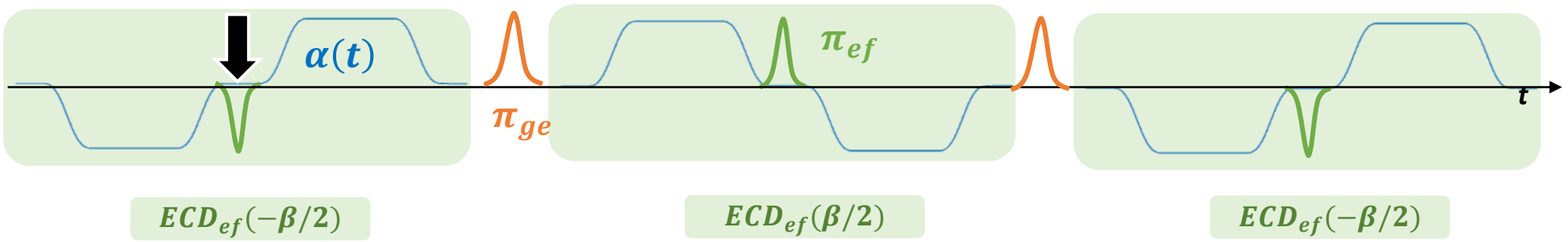


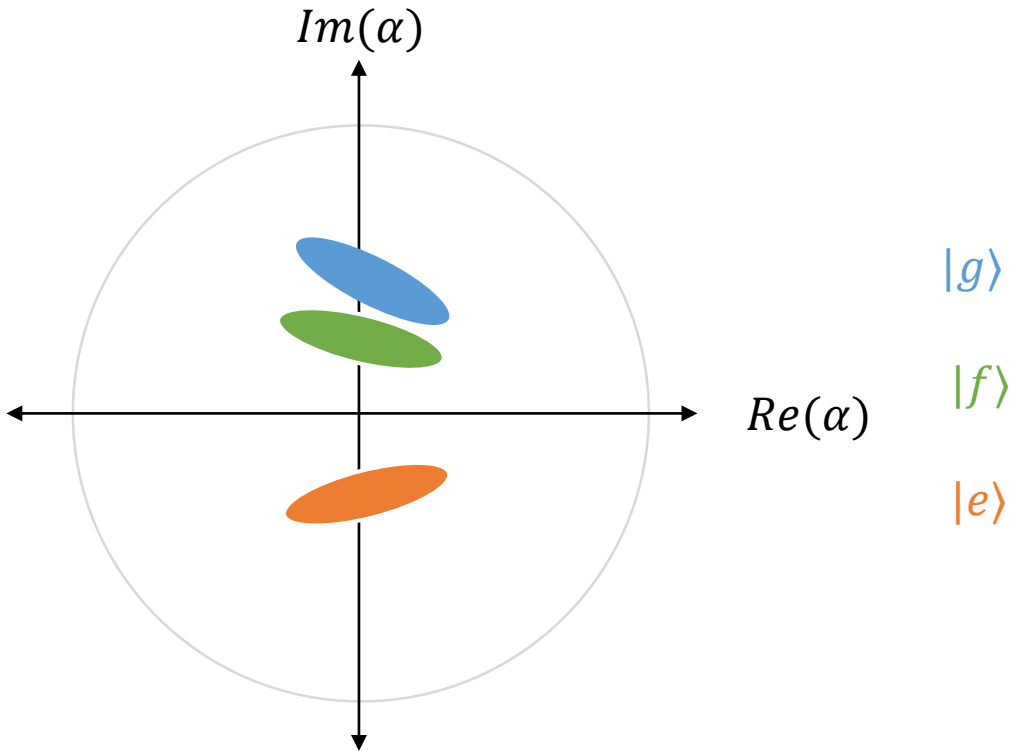
New form of $ECD_{ge}(\beta)$



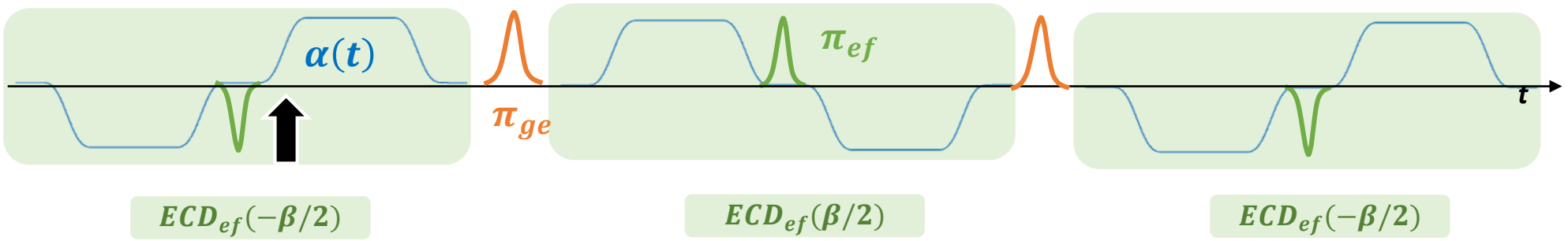


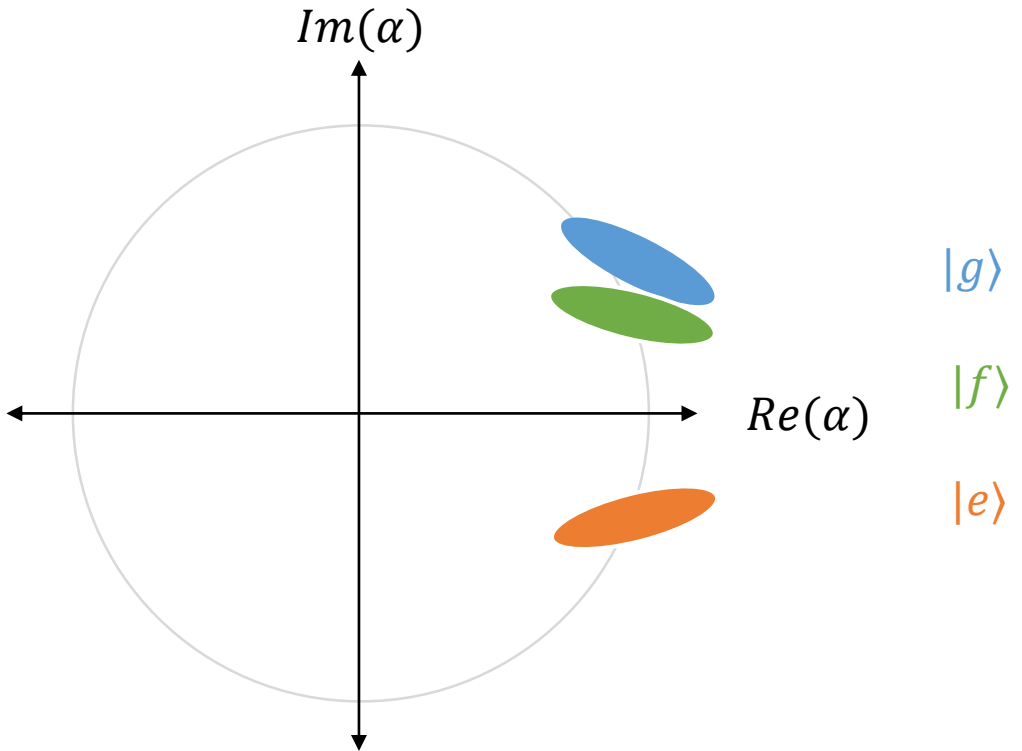
New form of $ECD_{ge}(\beta)$



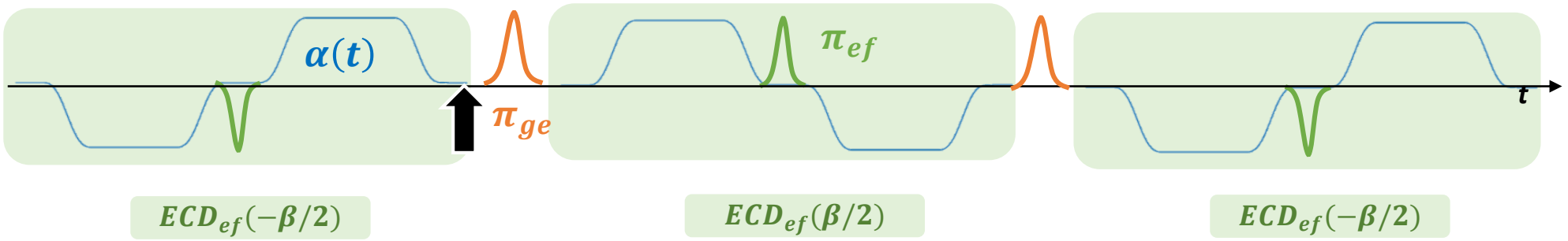


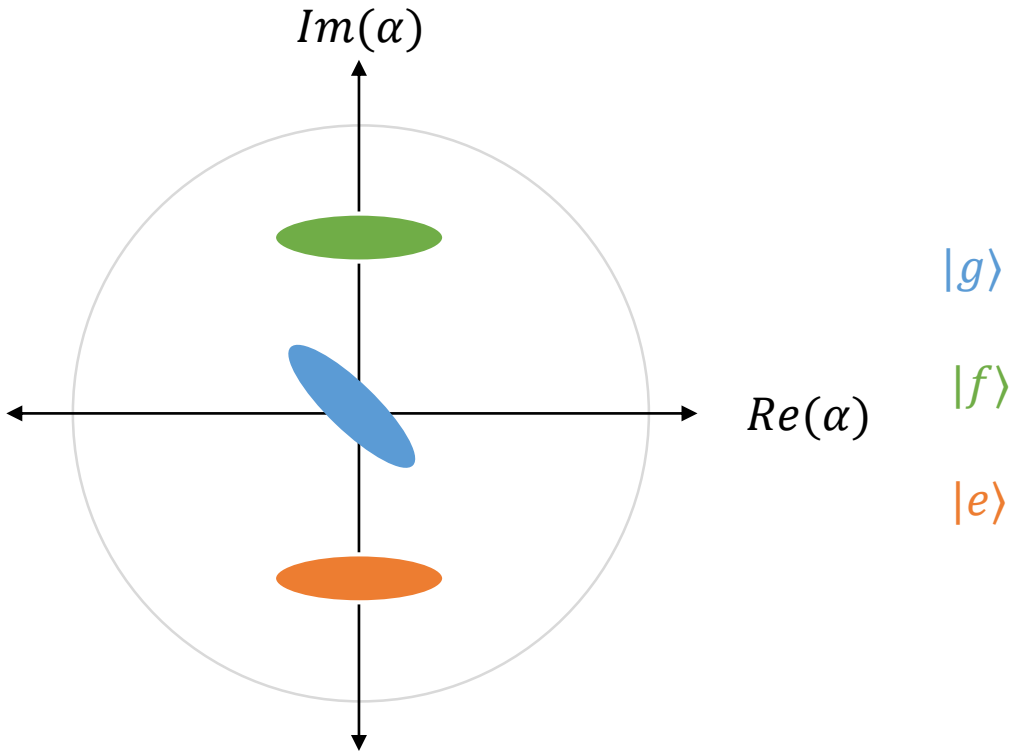
New form of $ECD_{ge}(\beta)$



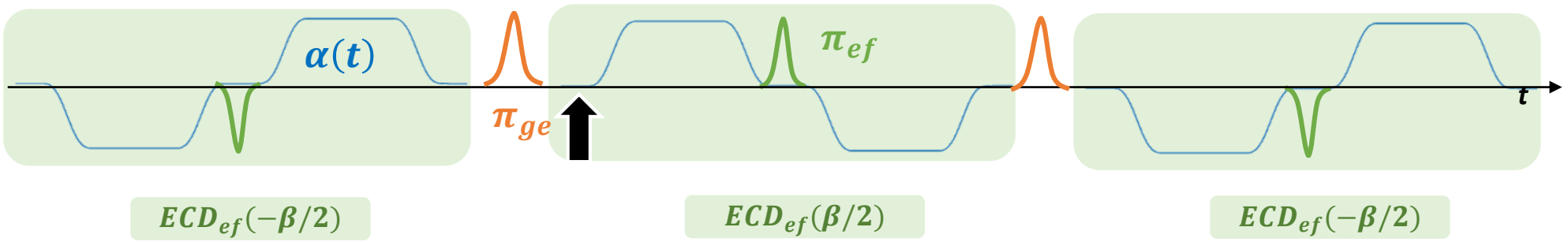


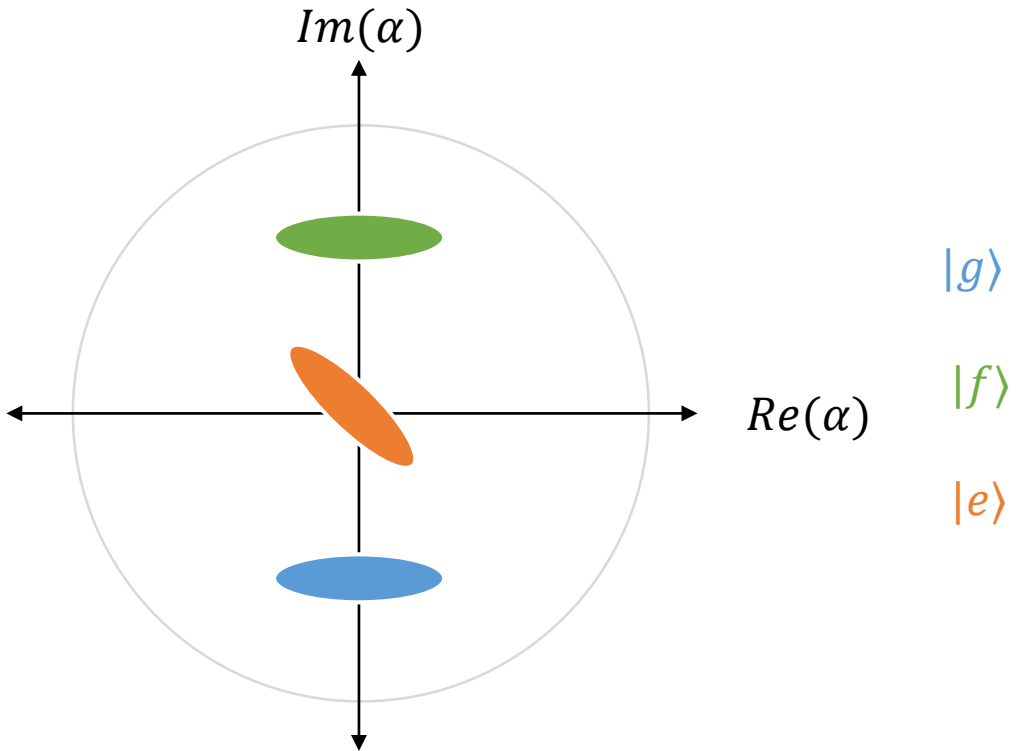
New form of $ECD_{ge}(\beta)$



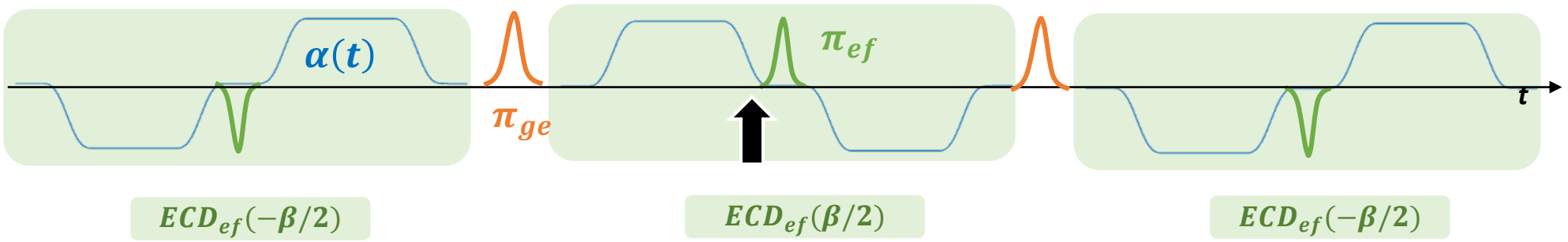


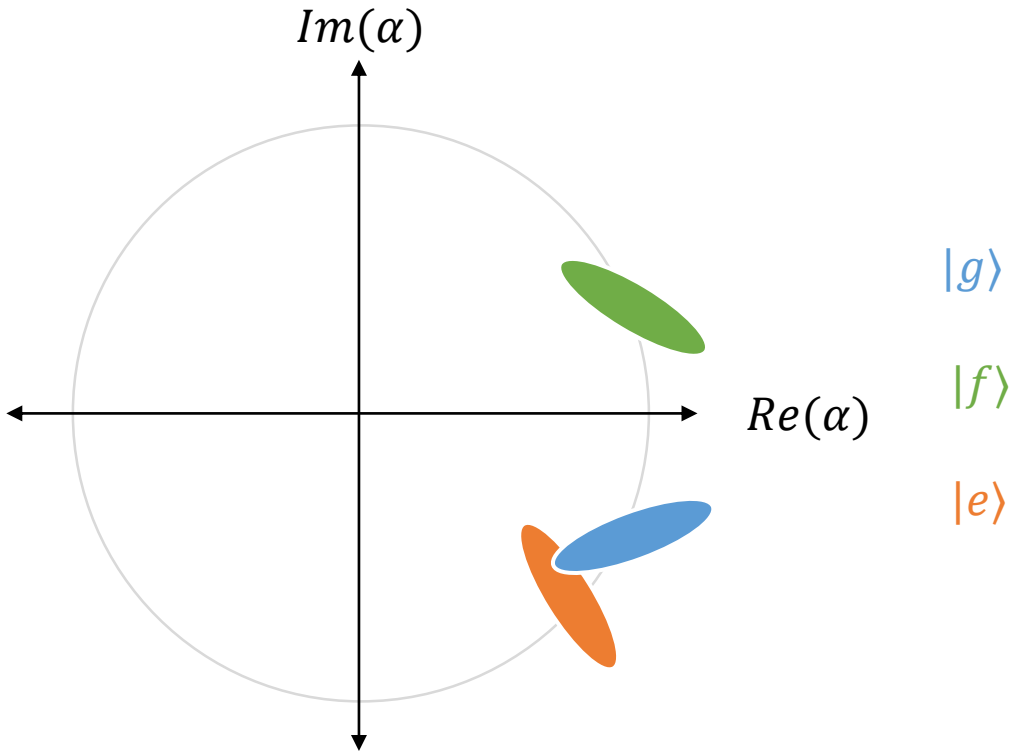
New form of $ECD_{ge}(\beta)$





New form of $ECD_{ge}(\beta)$





New form of $ECD_{ge}(\beta)$