Chiral cat code

Enhanced error correction induced by higher-order nonlinearities

IFISC Universitat de les Illes Balears CSIC

Adrià Labay Mora
Roberta Zambrini
Gian Luca Giorgi

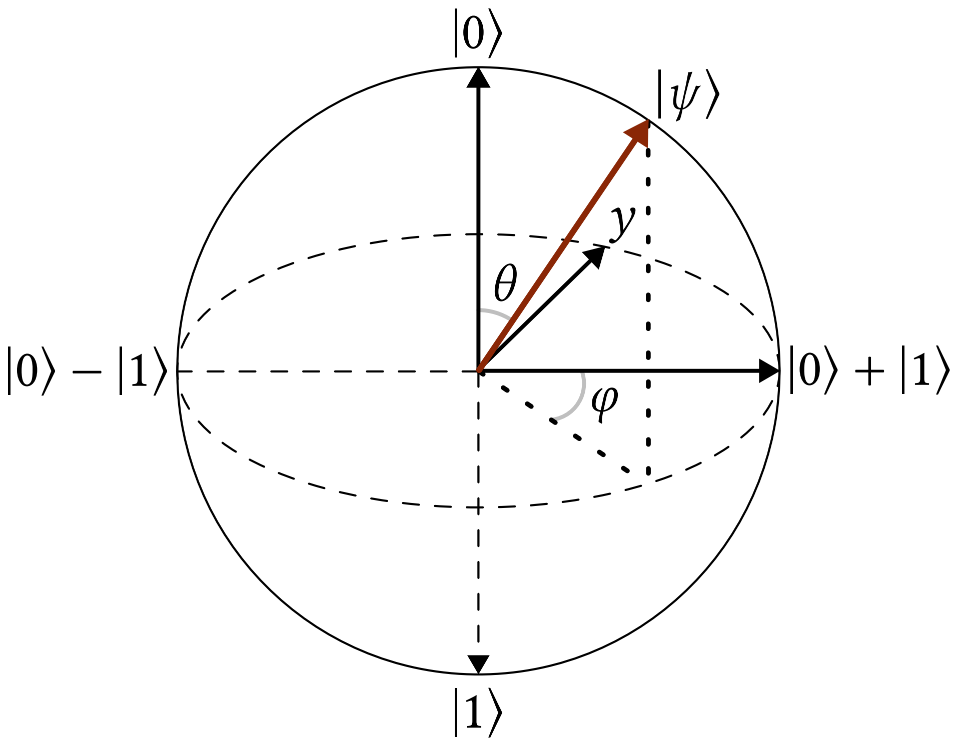
EPFL

Alberto Mercurio
Vincenzo Savona

ALICE & BOB

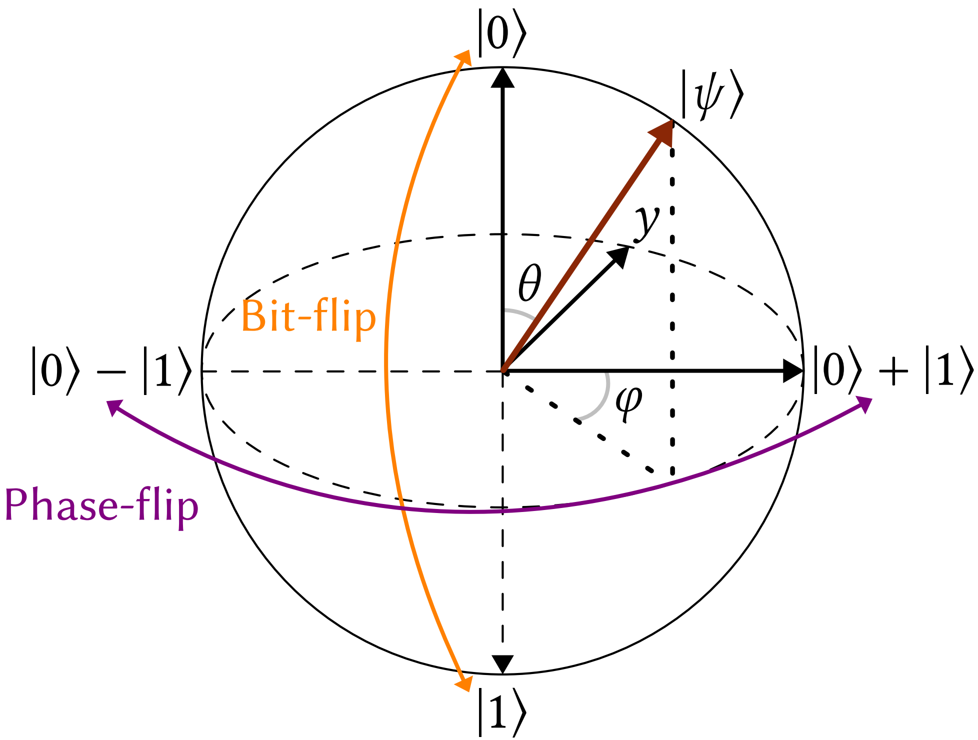
Fabrizio Minganti

Storage of quantum information



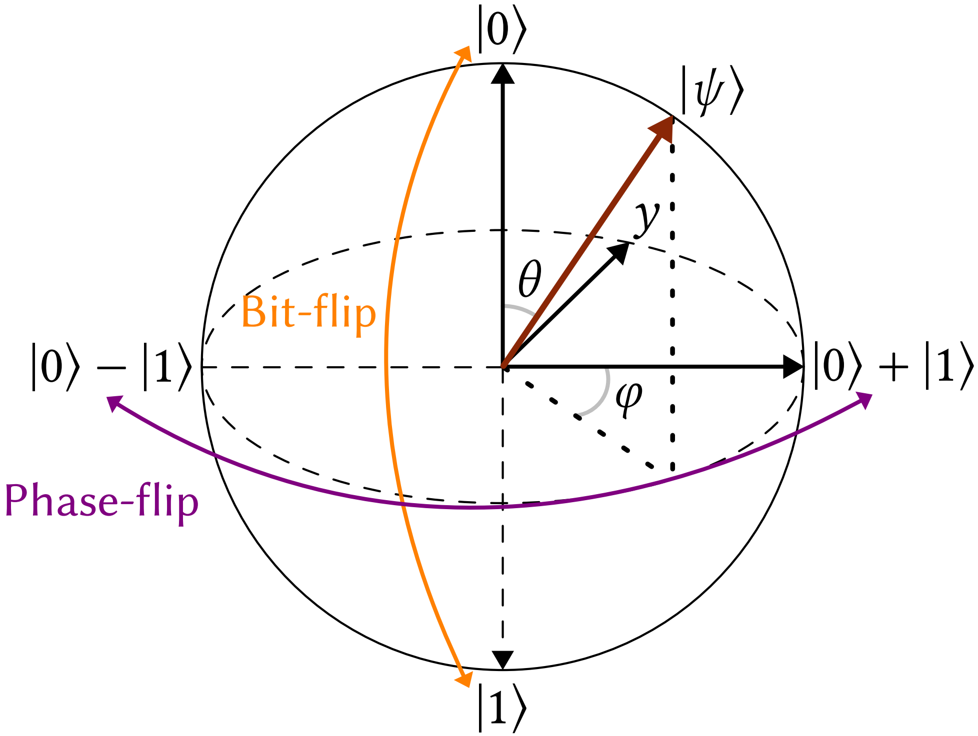
Storage of quantum information

Noise degrades the quantum information



Quantum Error Correction

Redundantly encode information in a larger Hilbert space



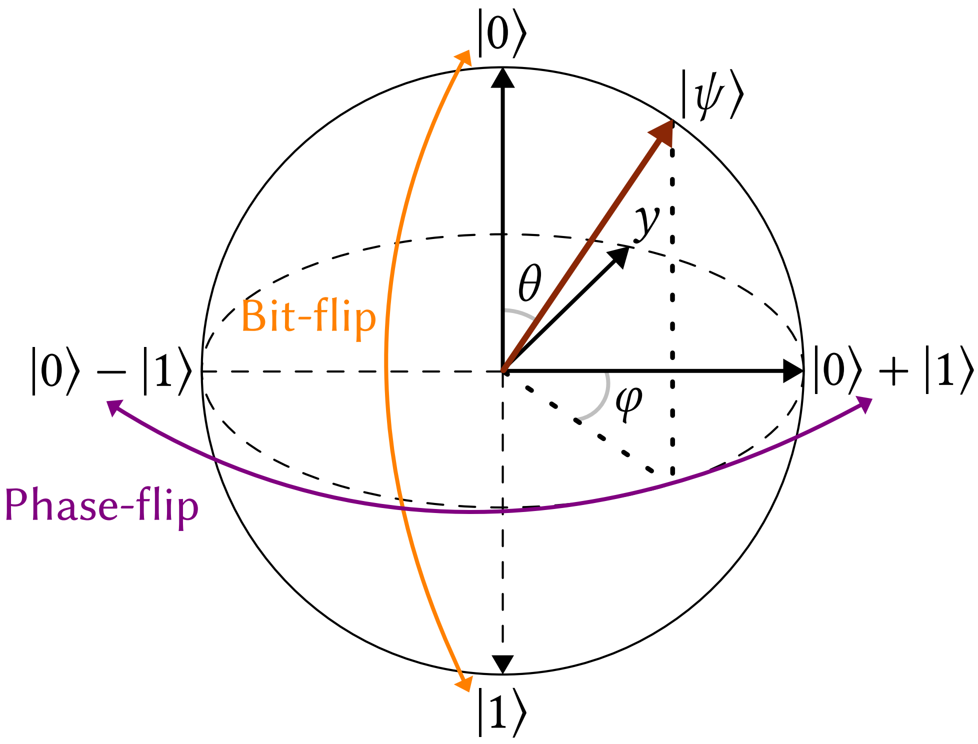
Ex: Three qubit code

$$|0\rangle_L = |000\rangle \qquad |010\rangle \qquad |000\rangle$$
$$\longrightarrow \qquad \longrightarrow$$
$$|1\rangle_L = |111\rangle \qquad |101\rangle \qquad |111\rangle$$

Protects against single bit-flip errors

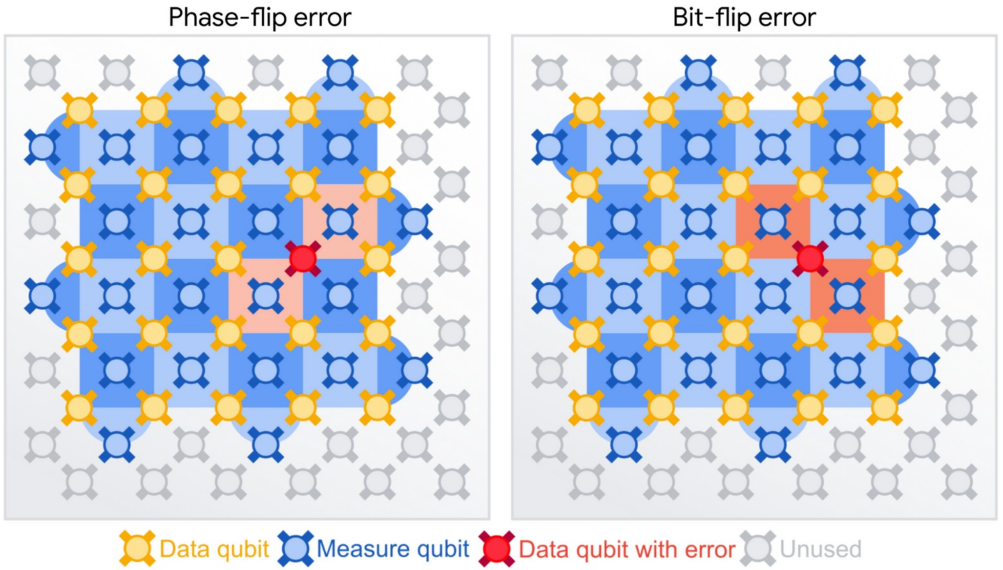
Quantum Error Correction

Redundantly encode information in a larger Hilbert space



Surface code

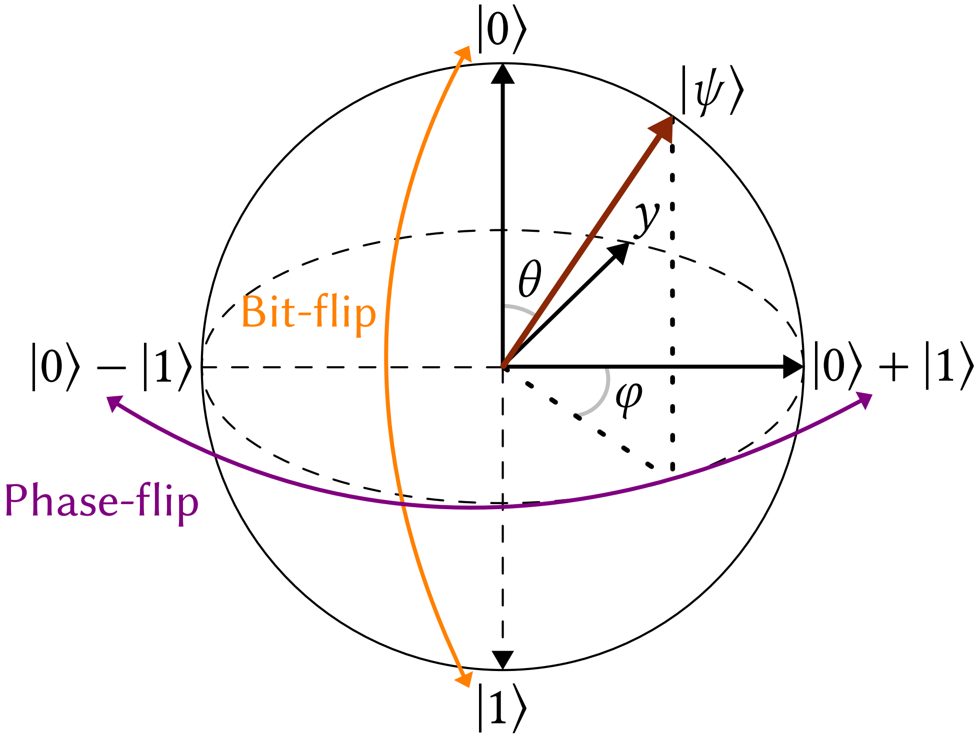
Correct for both bit-flip and phase-flips



Suppressing quantum errors by scaling a surface code logical qubit.
Nature, 2023, 614.7949: 676-681.

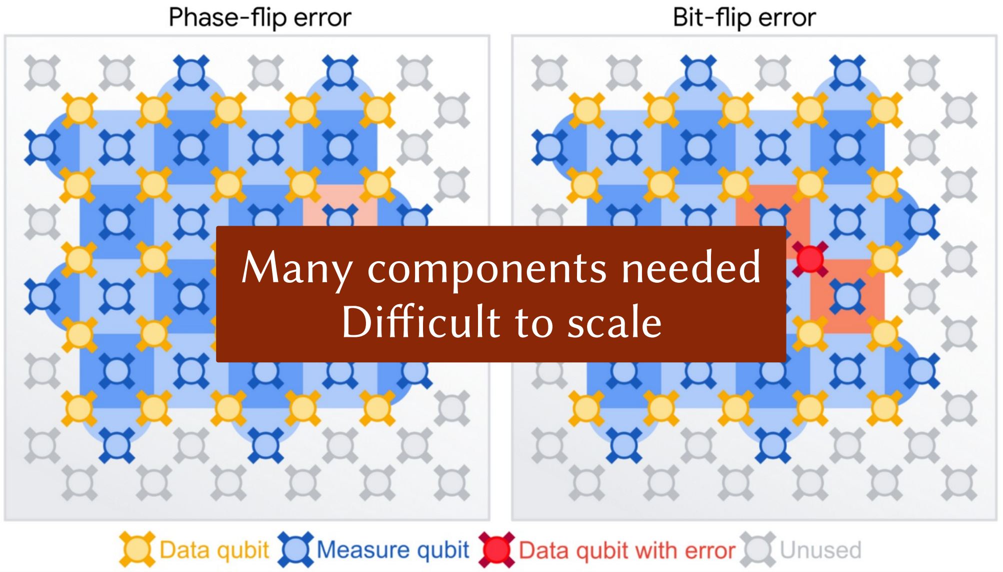
Quantum Error Correction

Redundantly encode information in a larger Hilbert space



Surface code

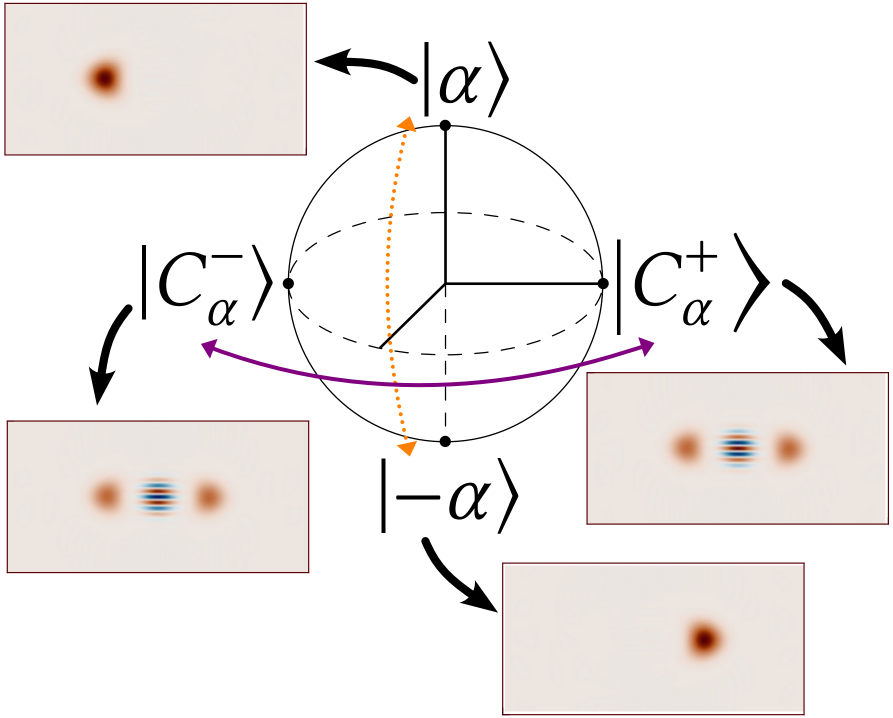
Correct for both bit-flip and phase-flips



Suppressing quantum errors by scaling a surface code logical qubit.
Nature, 2023, 614.7949: 676-681.

Bosonic Quantum Code: **Cat Qubits**

Intrinsically protect against bit-flip errors



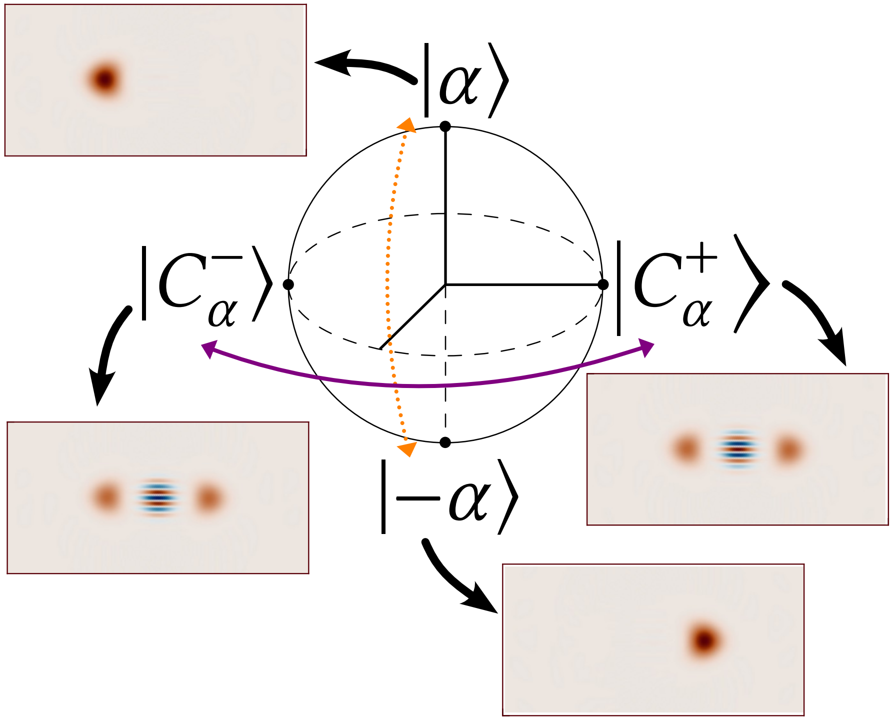
Coherent states used as logical states

$$\text{Z: } |\alpha\rangle = e^{-|\alpha|^2/2} \sum_{k\geq 0} \frac{\alpha^k}{\sqrt{k!}}$$

$$\text{X: } |C_\alpha^\pm\rangle \propto |\alpha\rangle \pm |-\alpha\rangle$$

Bosonic Quantum Code: **Cat Qubits**

Intrinsically protect against bit-flip errors



Coherent states used as logical states

$$\text{Z: } |\alpha\rangle = e^{-|\alpha|^2/2} \sum_{k\geq 0} \frac{\alpha^k}{\sqrt{k!}}$$

$$\text{X: } |C_\alpha^\pm\rangle \propto |\alpha\rangle \pm |-\alpha\rangle$$

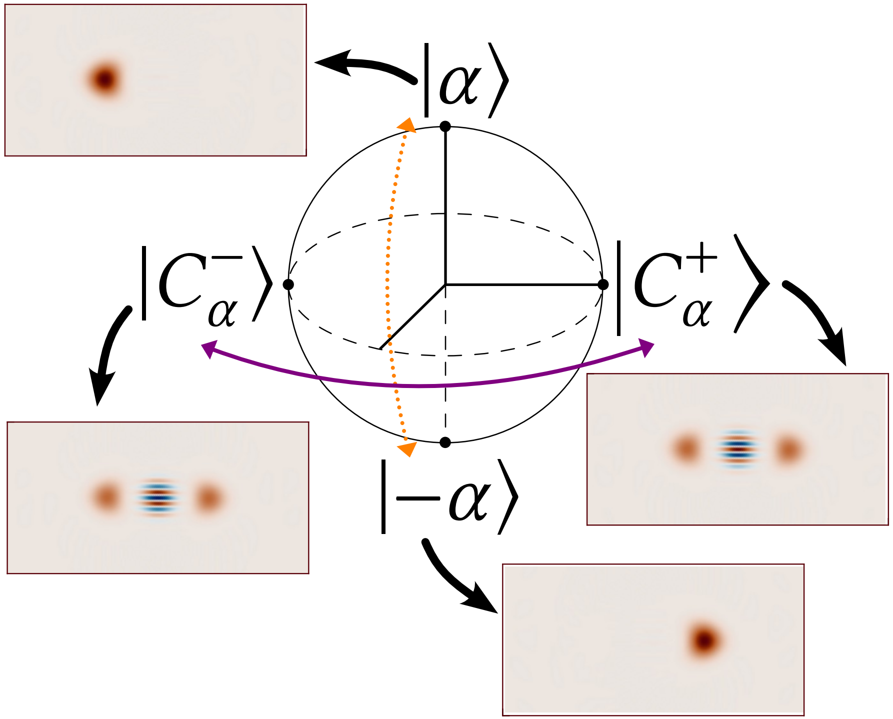
Action of photon-loss events

$$\hat{a}\,|\alpha\rangle = \alpha\,|\alpha\rangle \longrightarrow \text{NO ERROR}$$

$$\hat{a}\,|C_\alpha^\pm\rangle \propto |C_\alpha^\mp\rangle \longrightarrow \text{PHASE-FLIP}$$

Bosonic Quantum Code: **Cat Qubits**

Intrinsically protect against bit-flip errors



Noise-biased qubits

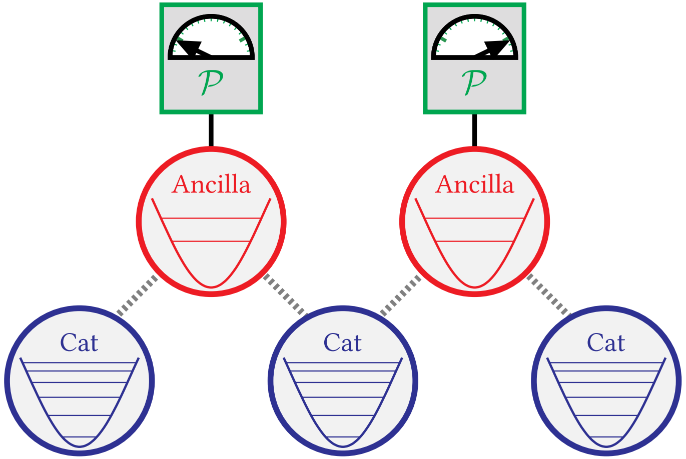
- Bit-flips exponentially suppressed

$$\Gamma_{\mathrm{bf}} \propto e^{-\kappa_{\mathrm{bf}}|\alpha|^2}$$

- Phase-flips only increase linearly

$$\Gamma_{\mathrm{pf}} \propto \kappa_{\mathrm{pf}}|\alpha|^2$$

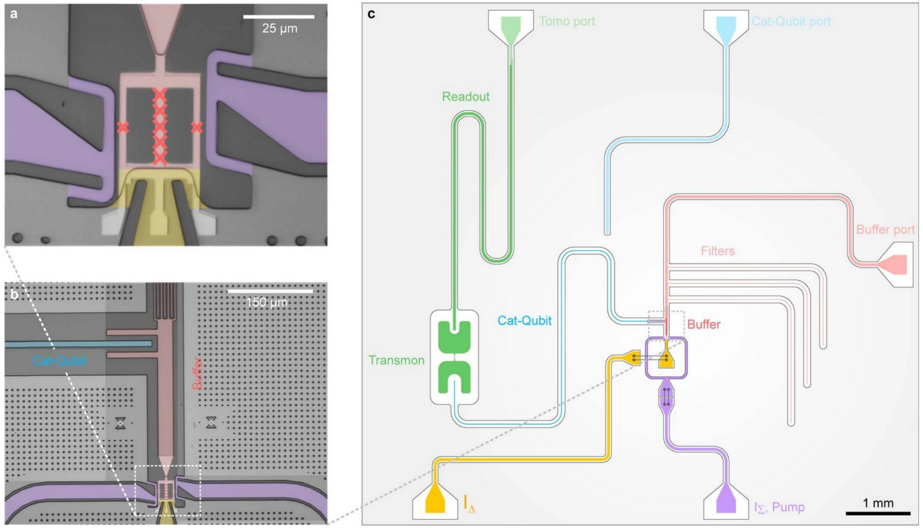
Repetition code



Gilles, L., B. M. Garraway, and P. L. Knight. Physical Review A 49.4 (1994): 2785.
Cochrane, Paul T., Gerard J. Milburn, and William J. Munro. Physical Review A 59.4 (1999): 2631.

Superconducting circuits

The two-photon driven transmon



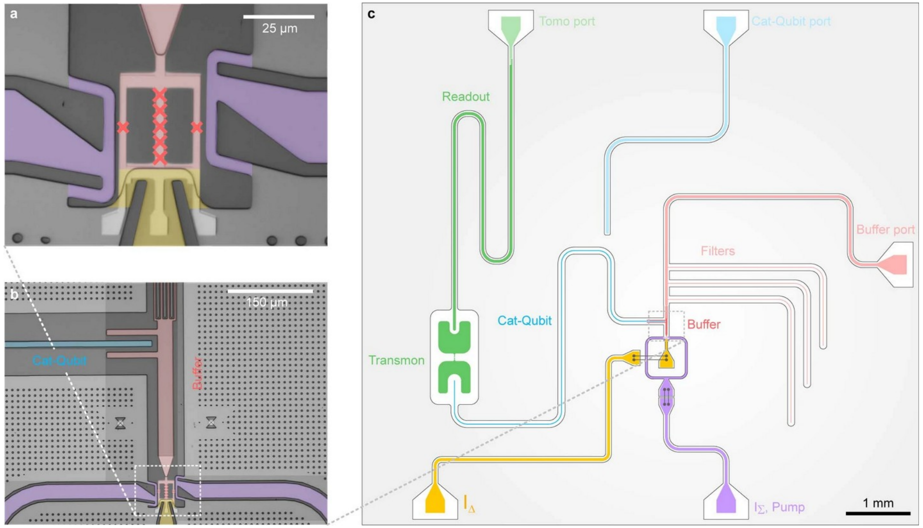
LESCANNE, Raphaël, et al. Nature Physics, 2020, 16.5: 509-513.
KOCH, Jens, et al. Physical Review A—Atomic, Molecular, and Optical Physics, 2007, 76.4: 042319.

$$\hat{H}_{\mathrm{t}} \propto \cos(\hat{\varphi}) \sim K_1 \hat{a}^\dagger \hat{a} - K_2 (\hat{a}^\dagger)^2 \hat{a}^2 + K_3 (\hat{a}^\dagger)^3 \hat{a}^3 + \cdots$$

$$K_3 \ll K_2$$

Superconducting circuits

The two-photon driven transmon



Lescanne, Raphaël, et al. Nature Physics, 2020, 16.5: 509-513.
Koch, Jens, et al. Physical Review A—Atomic, Molecular, and Optical Physics, 2007, 76.4: 042319.

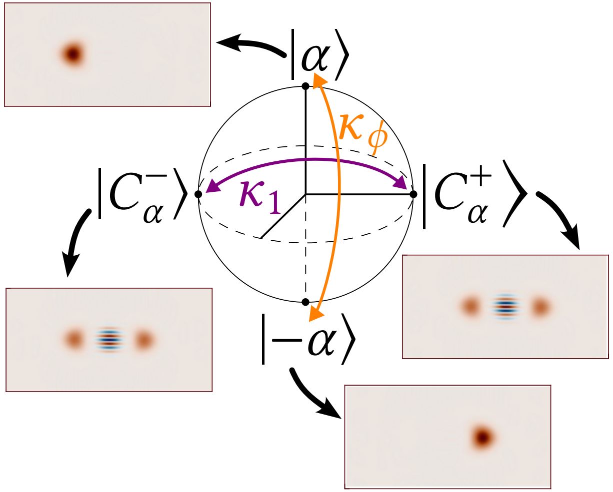
$$\hat{H}_\mathrm{t} \propto \cos(\hat{\varphi}) \sim K_1 \hat{a}^\dagger \hat{a} - K_2 (\hat{a}^\dagger)^2 \hat{a}^2 + K_3 (\hat{a}^\dagger)^3 \hat{a}^3 + \cdots$$

$$\mathcal{L} = -i[\hat{H}_\mathrm{t} + \hat{H}_\mathrm{d}, \hat{\rho}] + \kappa_1 \mathcal{D}[\hat{a}] + \kappa_\phi \mathcal{D}[\hat{a}^\dagger \hat{a}]$$

$$\hat{H}_\mathrm{d} = G(\hat{a}^2 e^{i\omega_d t} + \hat{a}^{\dagger 2} e^{-i\omega_d t})$$

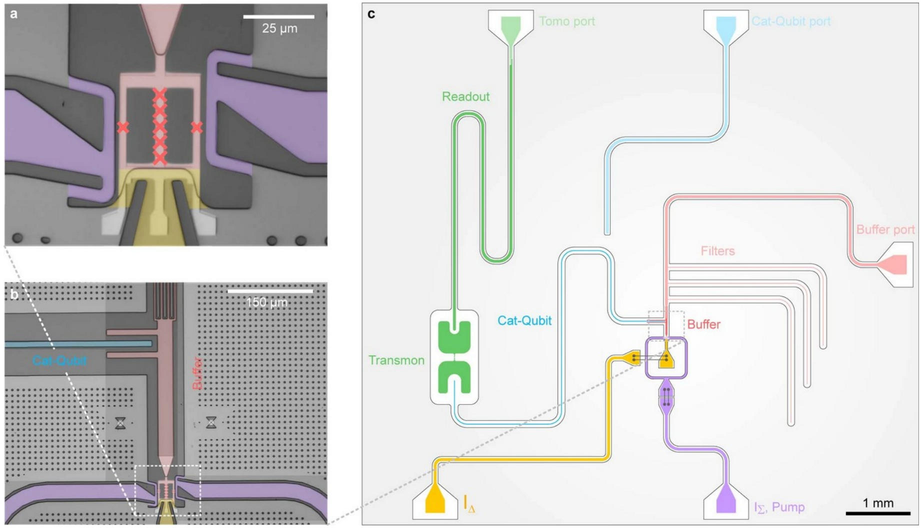
Two main sources of errors:

- Photon-loss κ_1
  (energy loss to the environment)
- Dephasing noise κ_ϕ
  (coupling to other SC components)



Superconducting circuits

The two-photon driven transmon



Lescanne, Raphaël, et al. Nature Physics, 2020, 16.5: 509-513.
Koch, Jens, et al. Physical Review A—Atomic, Molecular, and Optical Physics, 2007, 76.4: 042319.

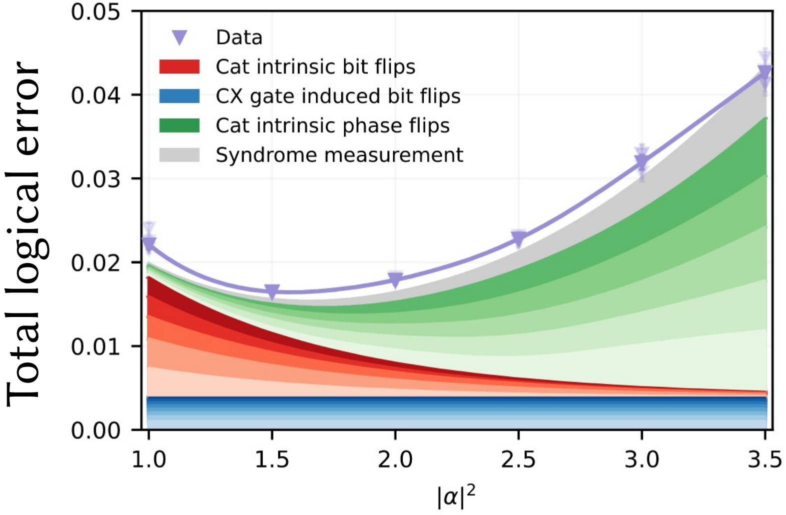
$$\hat{H}_{\mathrm{t}} \propto \cos(\hat{\varphi}) \sim K_1 \hat{a}^\dagger \hat{a} - K_2 (\hat{a}^\dagger)^2 \hat{a}^2 + K_3 (\hat{a}^\dagger)^3 \hat{a}^3 + \cdots$$

$$\mathcal{L} = -i[\hat{H}_{\mathrm{t}} + \hat{H}_{\mathrm{d}}, \hat{\rho}] + \kappa_1 \mathcal{D}[\hat{a}] + \kappa_\phi \mathcal{D}[\hat{a}^\dagger \hat{a}]$$

$$\hat{H}_{\mathrm{d}} = G(\hat{a}^2 + \hat{a}^{\dagger\,2})$$

Two main sources of errors:

- Photon-loss κ_1
  (energy loss to the environment)
- Dephasing noise κ_ϕ
  (coupling to other SC components)

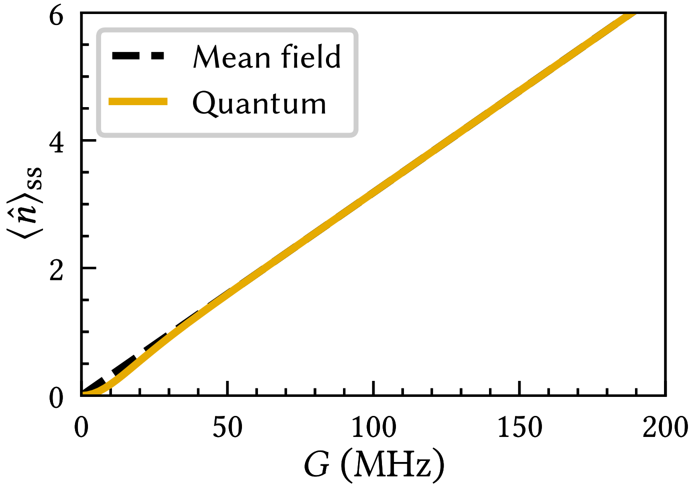


Putterman, Harald, et al. Nature 638.8052 (2025): 927-934.

Noise-biased qubits

Dissipative cats

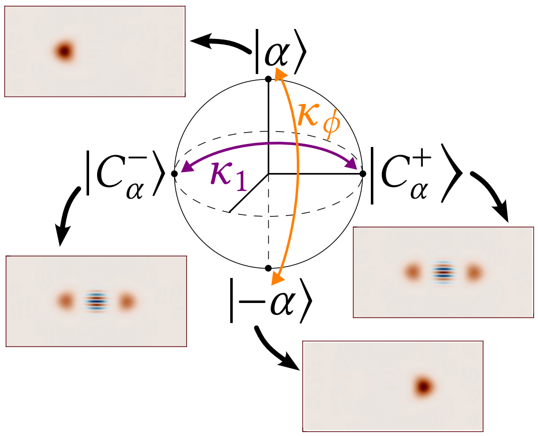
$$\mathcal{L}(\hat{\rho}) = -iG[\hat{a}^{\dagger 2} + \hat{a}^2, \hat{\rho}] + \boxed{\kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}}$$



Mirrahimi, Mazyar, et al. New Journal of Physics 16.4 (2014): 045014.
Leghtas, Zaki, et al. Science 347.6224 (2015): 853-857.
Berdou, Camille, et al. PRX Quantum 4.2 (2023): 020350.

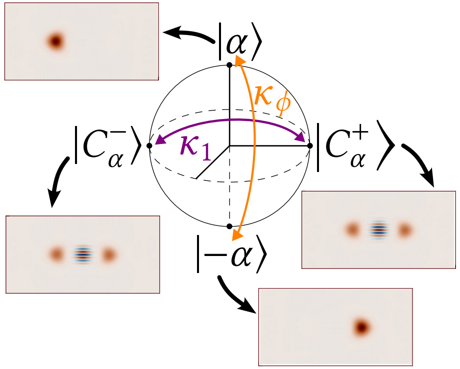
Kerr cats

$$\hat{H} = \boxed{K_2 (\hat{a}^\dagger)^2 \hat{a}^2} + G(\hat{a}^{\dagger 2} + \hat{a}^2)$$



Grimm, Alexander. et. al. (2020). Nature, 584(7820), 205-209.
Puri, Shruti, Samuel Boutin, and Alexandre Blais. npj Quantum Information 3.1 (2017): 18.
Ofek, Nissim, et al. Nature 536.7617 (2016): 441-445.

Noise-biased qubits

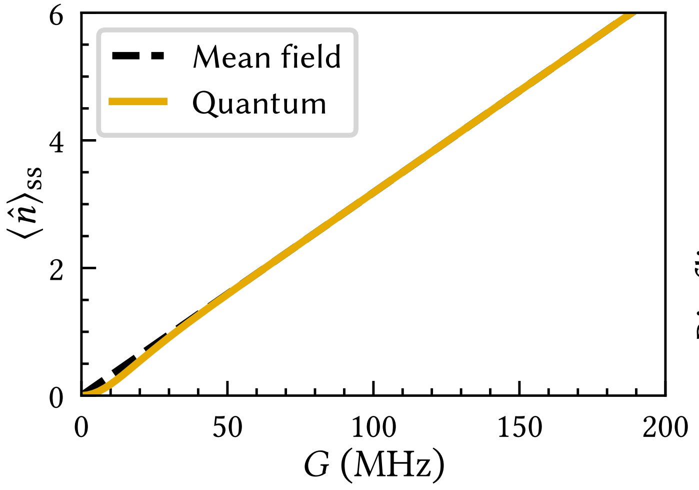


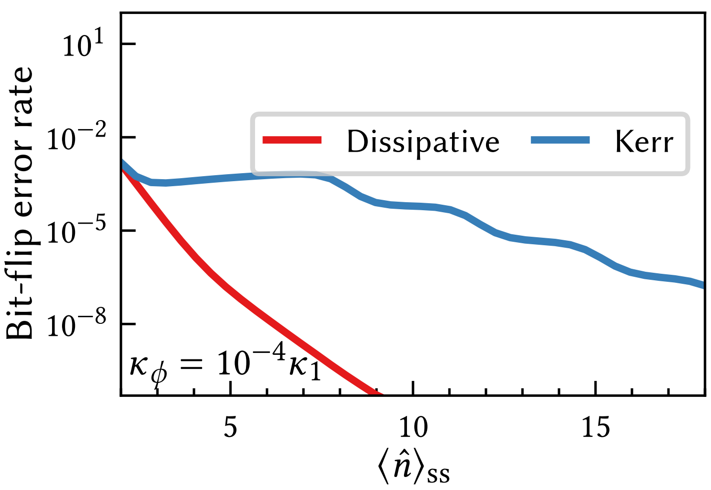
Dissipative cats

$$\mathcal{L}(\hat\rho) = -iG[\hat a^{\dagger 2} + \hat a^2, \hat\rho] + \kappa_2 \mathcal{D}[\hat a^2]\hat\rho$$

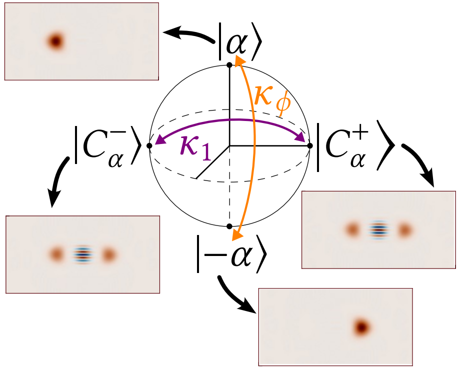
Kerr cats

$$\hat H = K_2(\hat a^\dagger)^2 \hat a^2 + G(\hat a^{\dagger 2} + \hat a^2)$$





Noise-biased qubits

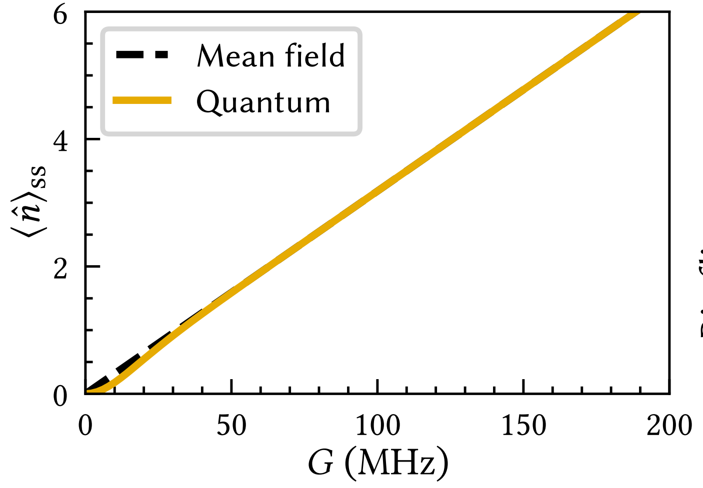


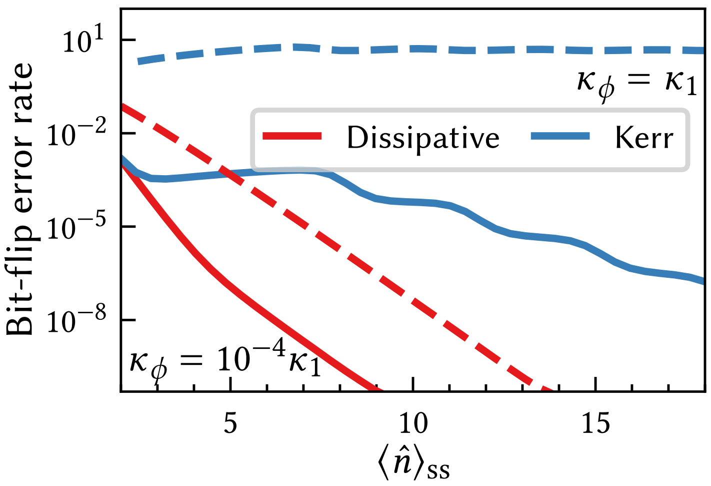
Dissipative cats

$$\mathcal{L}(\hat{\rho}) = -iG[\hat{a}^{\dagger\,2} + \hat{a}^2, \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$$

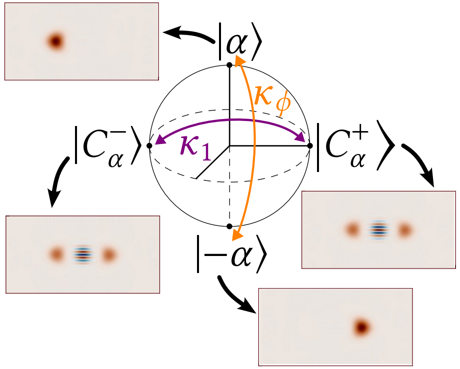
Kerr cats

$$\hat{H} = K_2(\hat{a}^\dagger)^2\hat{a}^2 + G(\hat{a}^{\dagger\,2} + \hat{a}^2)$$





Noise-biased qubits

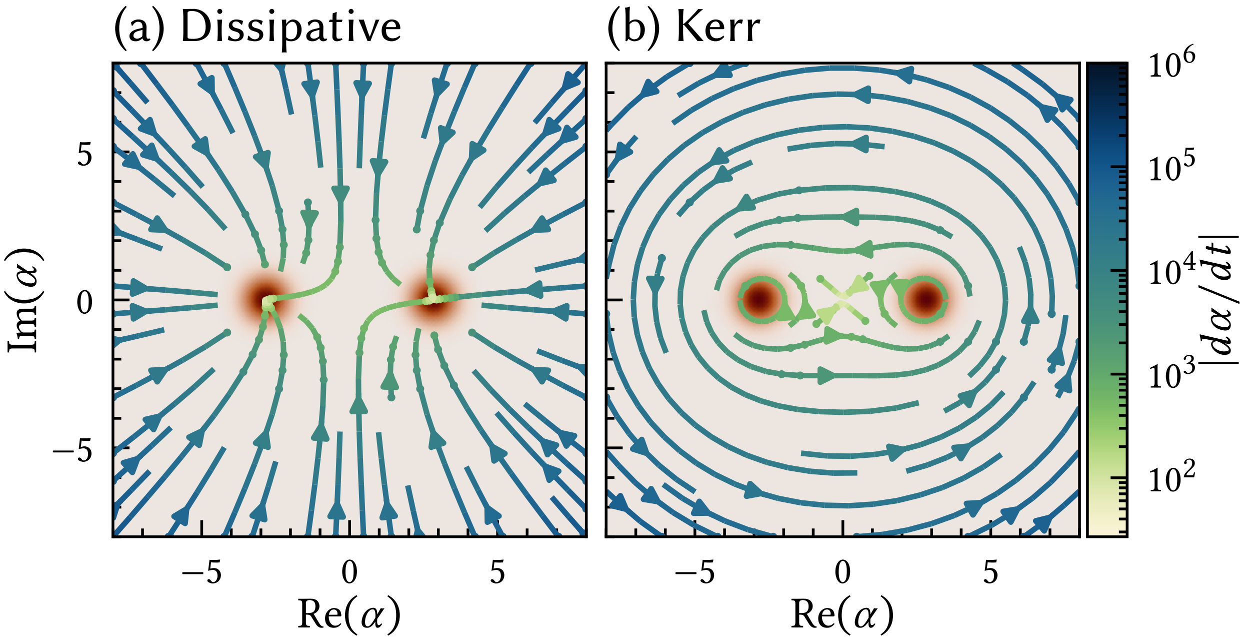


Dissipative cats

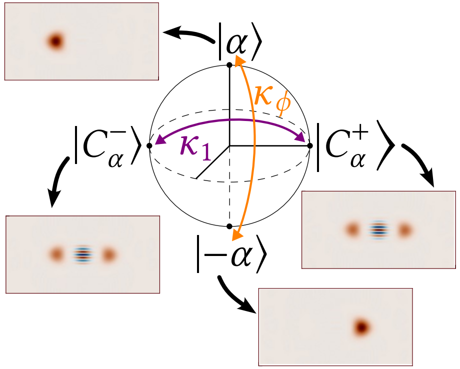
$$\mathcal{L}(\hat{\rho}) = -iG[\hat{a}^{\dagger 2} + \hat{a}^2, \hat{\rho}] + \boxed{\kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}}$$

Kerr cats

$$\hat{H} = \boxed{K_2(\hat{a}^\dagger)^2\hat{a}^2} + G(\hat{a}^{\dagger 2} + \hat{a}^2)$$



Noise-biased qubits

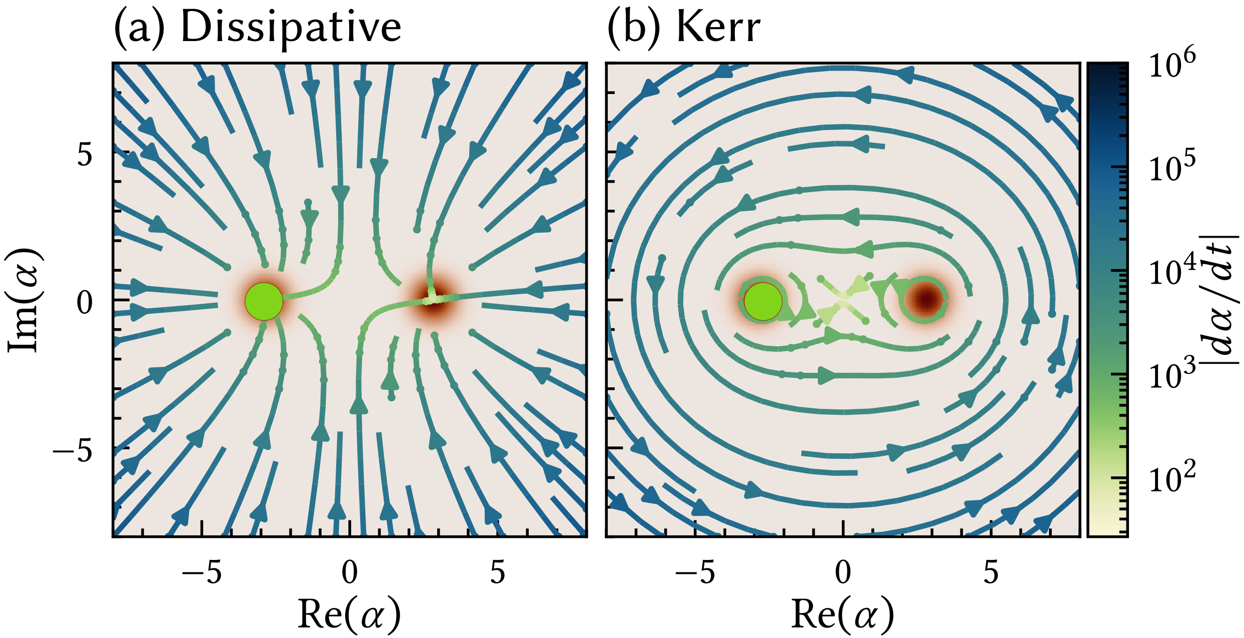


Dissipative cats

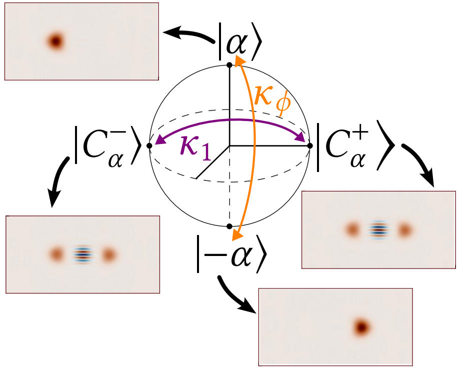
$$\mathcal{L}(\hat{\rho}) = -iG[\hat{a}^{\dagger\,2} + \hat{a}^2, \hat{\rho}] + \boxed{\kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}}$$

Kerr cats

$$\hat{H} = \boxed{K_2(\hat{a}^\dagger)^2\hat{a}^2} + G(\hat{a}^{\dagger\,2} + \hat{a}^2)$$



Noise-biased qubits

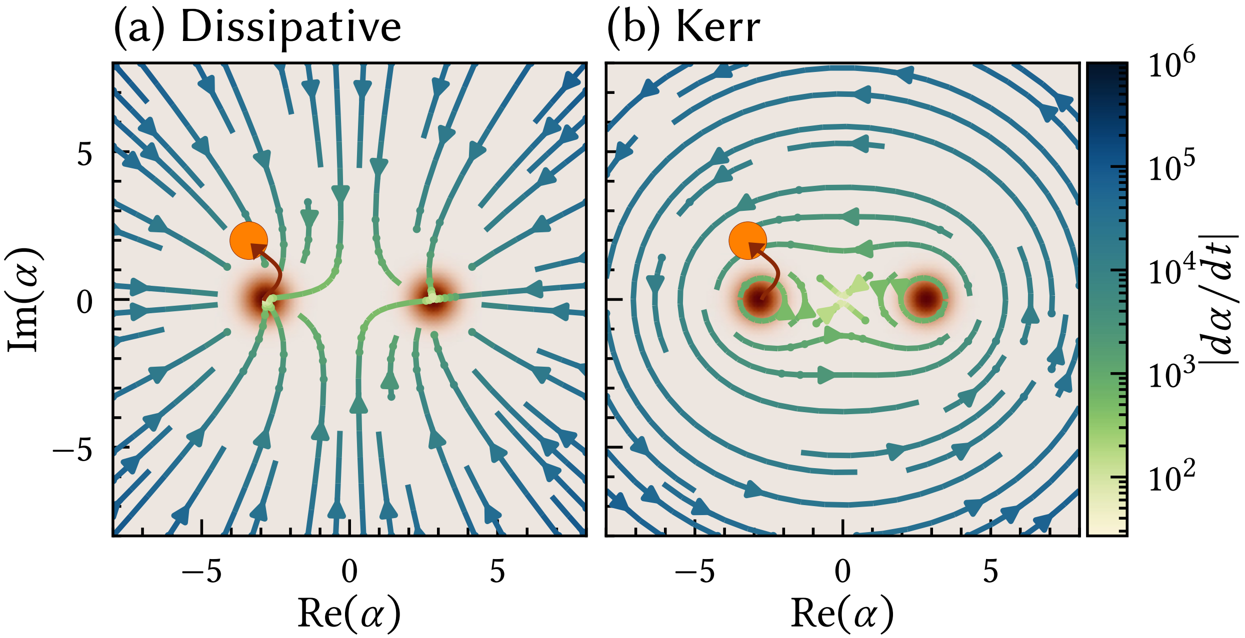


Dissipative cats

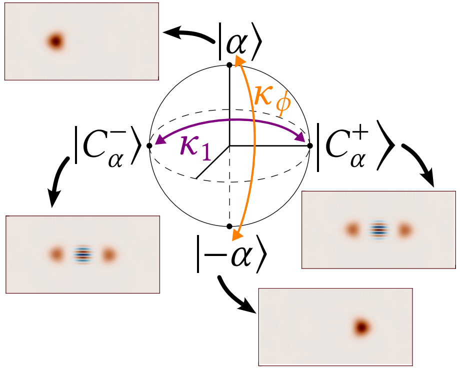
$$\mathcal{L}(\hat{\rho}) = -iG[\hat{a}^{\dagger 2} + \hat{a}^2, \hat{\rho}] + \boxed{\kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}}$$

Kerr cats

$$\hat{H} = \boxed{K_2(\hat{a}^\dagger)^2\hat{a}^2} + G(\hat{a}^{\dagger 2} + \hat{a}^2)$$



Noise-biased qubits

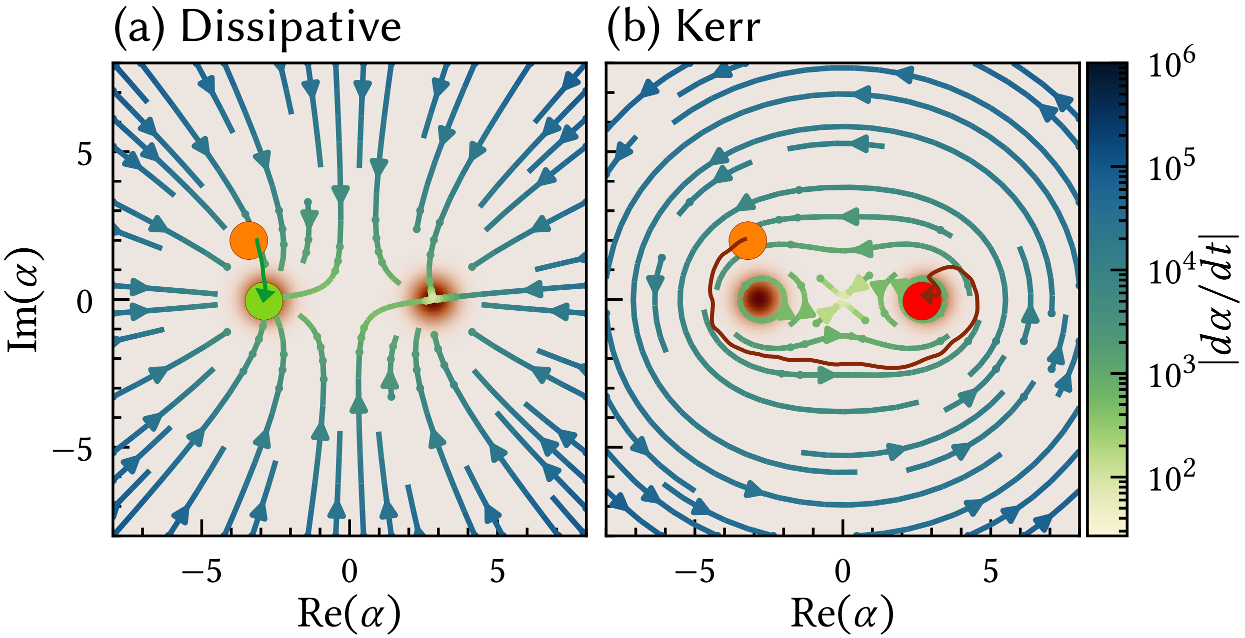


Dissipative cats

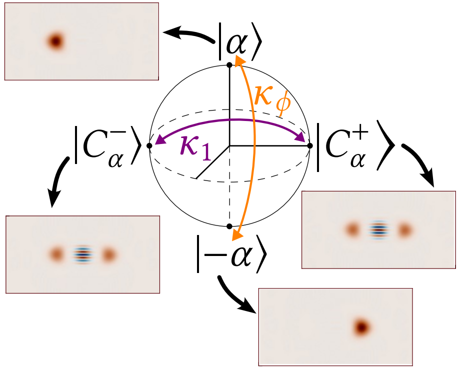
$$\mathcal{L}(\hat\rho) = -iG[\hat a^{\dagger\,2} + \hat a^2, \hat\rho] + \boxed{\kappa_2 \mathcal{D}[\hat a^2]\hat\rho}$$

Kerr cats

$$\hat H = \boxed{K_2(\hat a^\dagger)^2 \hat a^2} + G(\hat a^{\dagger\,2} + \hat a^2)$$



Noise-biased qubits



Dissipative cats

$$\mathcal{L}(\hat{\rho}) = -iG[\hat{a}^{\dagger\,2} + \hat{a}^2, \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$$

Preserve bit-flip protection even with large dephasing

Confinement leads to slow gates

Kerr cats

$$\hat{H} = K_2(\hat{a}^\dagger)^2\hat{a}^2 + G(\hat{a}^{\dagger\,2} + \hat{a}^2)$$

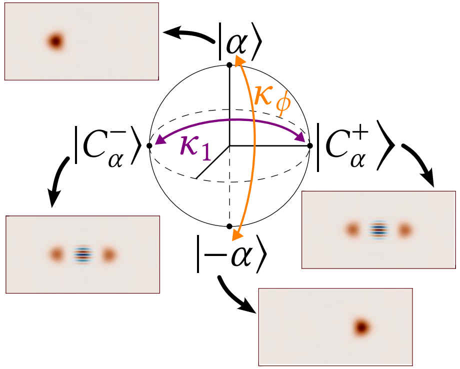
Poor performance with sizable dephasing noise

Fast operations

Mirrahimi, Mazyar, et al. New Journal of Physics 16.4 (2014): 045014.
Leghtas, Zaki, et al. Science 347.6224 (2015): 853-857.
Berdou, Camille, et al. PRX Quantum 4.2 (2023): 020350.

Grimm, Alexander. et. al. (2020). Nature, 584(7820), 205-209.
Puri, Shruti, Samuel Boutin, and Alexandre Blais. npj Quantum Information 3.1 (2017): 18.
Ofek, Nissim, et al. Nature 536.7617 (2016): 441-445.

Noise-biased qubits



Dissipative cats

$$\mathcal{L}(\hat\rho) = -iG[\hat a^{\dagger 2} + \hat a^2, \hat\rho] + \boxed{\kappa_2 \mathcal{D}[\hat a^2]\hat\rho}$$

Preserve bit-flip protection even with large dephasing

Confinement leads to slow gates

Kerr cats

$$\hat H = \boxed{K_2(\hat a^\dagger)^2 \hat a^2} + G(\hat a^{\dagger 2} + \hat a^2)$$

Poor performance with sizable dephasing noise

Fast operations

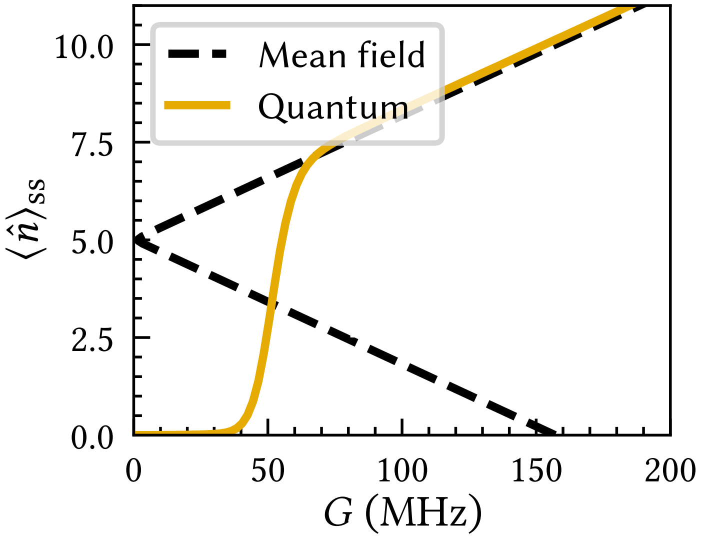
Hybrid cats

Add small 2-photon dissipation to Kerr cats

Gautier, Ronan, Alain Sarlette, and Mazyar Mirrahimi. PRX Quantum 3.2 (2022): 020339.

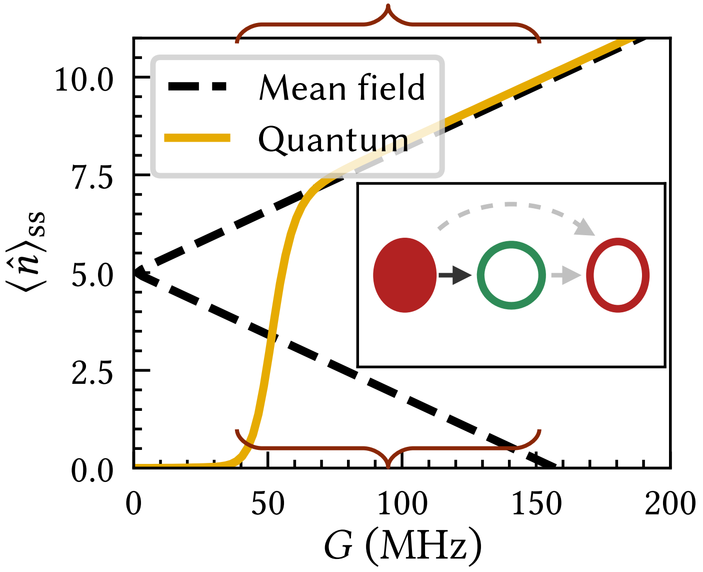
The critical cat

A detuned hybrid cat $\quad \mathcal{L}(\hat{\rho}) = -i[\boxed{\Delta \hat{a}^\dagger \hat{a}} + K_2 \hat{a}^{\dagger\,2}\hat{a}^2 + G(\hat{a}^{\dagger\,2} + \hat{a}^2), \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$



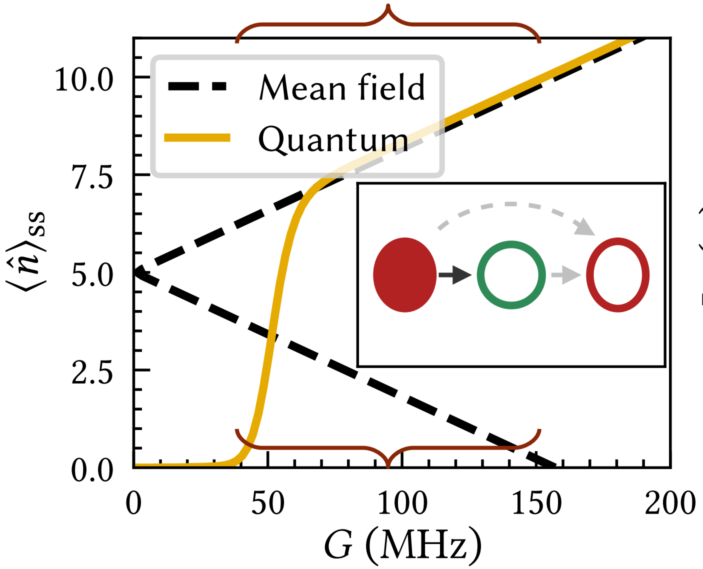
The critical cat

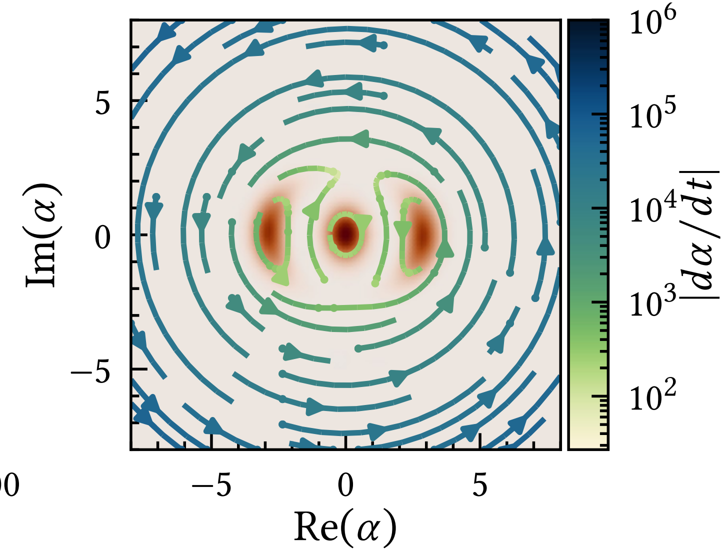
A detuned hybrid cat $\mathcal{L}(\hat{\rho}) = -i[\boxed{\Delta \hat{a}^\dagger \hat{a}} + K_2 \hat{a}^{\dagger\,2} \hat{a}^2 + G(\hat{a}^{\dagger\,2} + \hat{a}^2), \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$



The critical cat

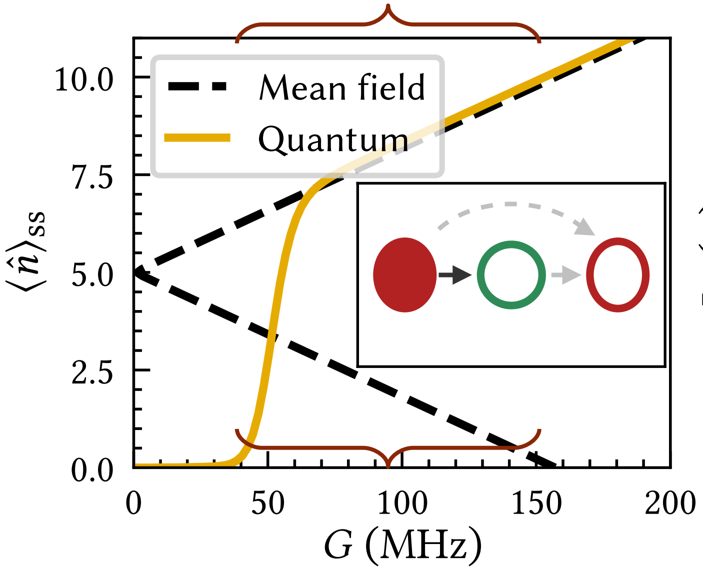
A detuned hybrid cat $\mathcal{L}(\hat{\rho}) = -i[\boxed{\Delta \hat{a}^\dagger \hat{a}} + K_2 \hat{a}^{\dagger\,2}\hat{a}^2 + G(\hat{a}^{\dagger\,2} + \hat{a}^2), \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$

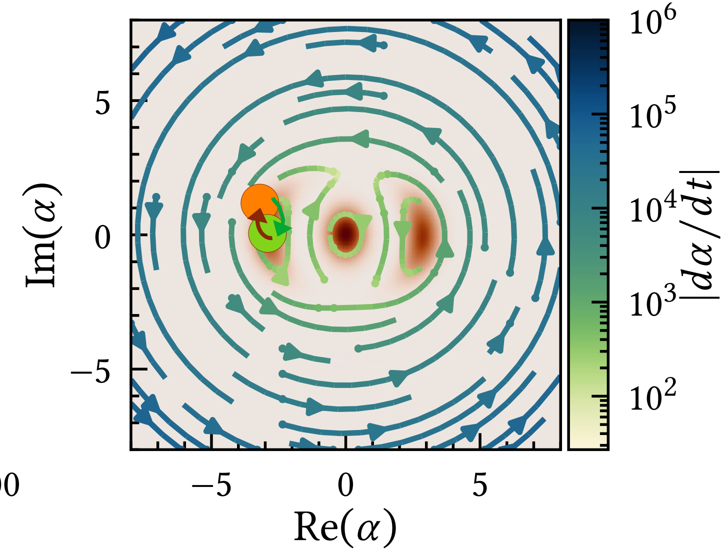




The critical cat

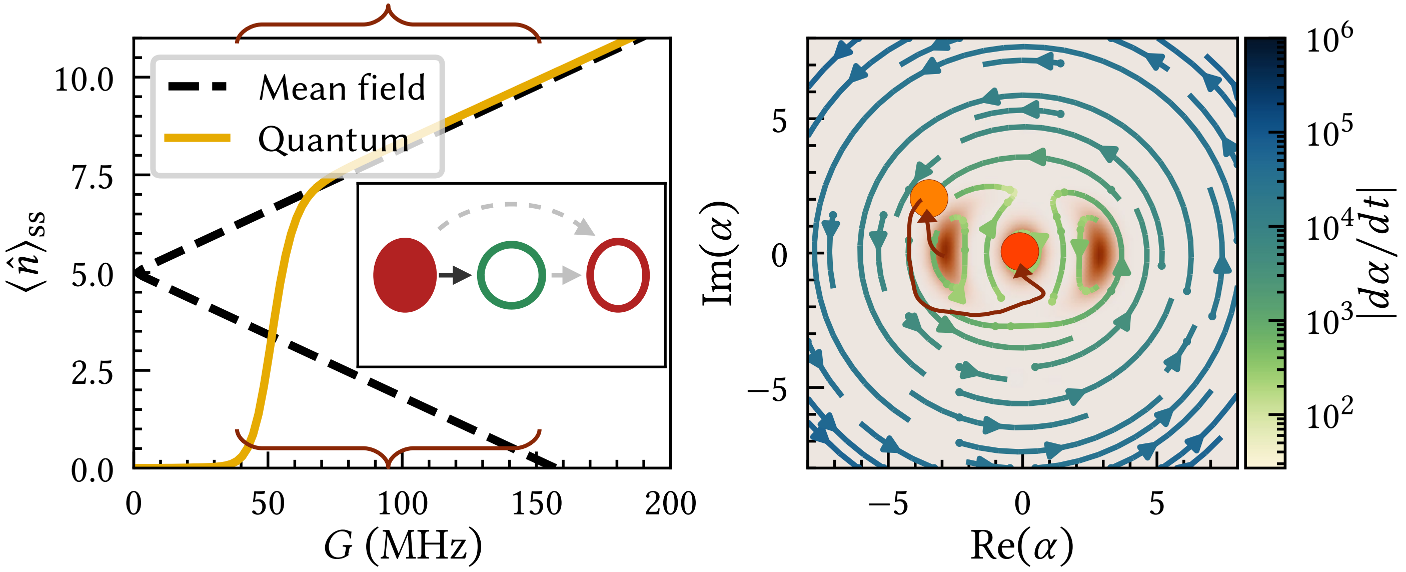
A detuned hybrid cat $\mathcal{L}(\hat{\rho}) = -i[\boxed{\Delta\hat{a}^\dagger\hat{a}} + K_2\hat{a}^{\dagger 2}\hat{a}^2 + G(\hat{a}^{\dagger 2} + \hat{a}^2), \hat{\rho}] + \kappa_2\mathcal{D}[\hat{a}^2]\hat{\rho}$





The critical cat

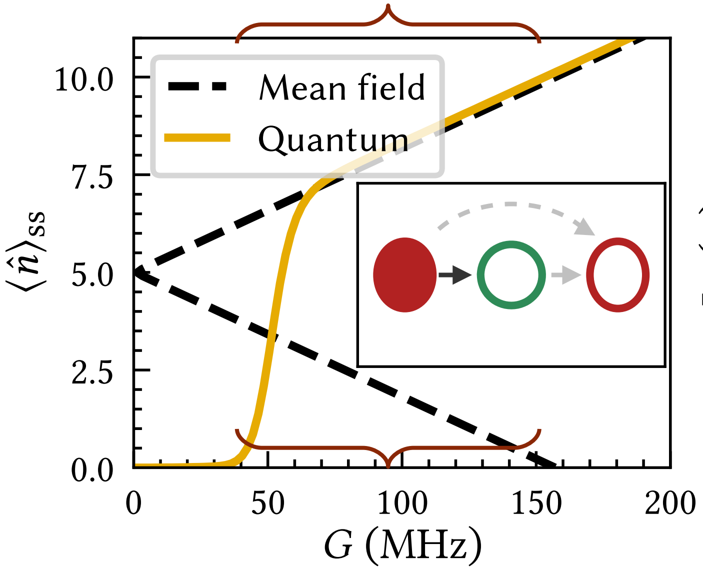
A detuned hybrid cat $\qquad \mathcal{L}(\hat{\rho}) = -i[\boxed{\Delta \hat{a}^\dagger \hat{a}} + K_2 \hat{a}^{\dagger 2} \hat{a}^2 + G(\hat{a}^{\dagger 2} + \hat{a}^2), \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$

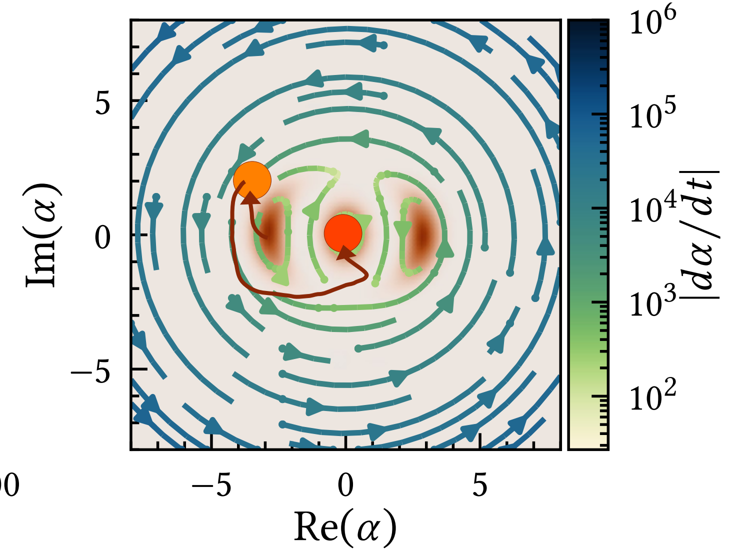


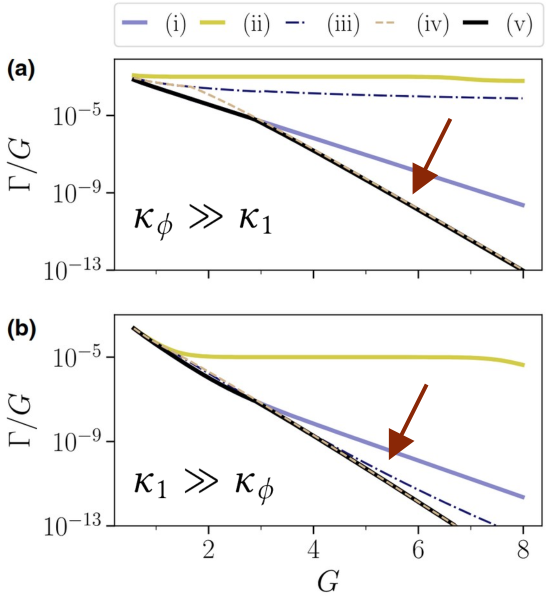
Possibility to detect an error but not correct it

The critical cat

A detuned hybrid cat $\mathcal{L}(\hat{\rho}) = -i[\boxed{\Delta \hat{a}^\dagger \hat{a}} + K_2 \hat{a}^{\dagger 2} \hat{a}^2 + G(\hat{a}^{\dagger 2} + \hat{a}^2), \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$







Possibility to detect an error but not correct it

Recovers protection against dephasing

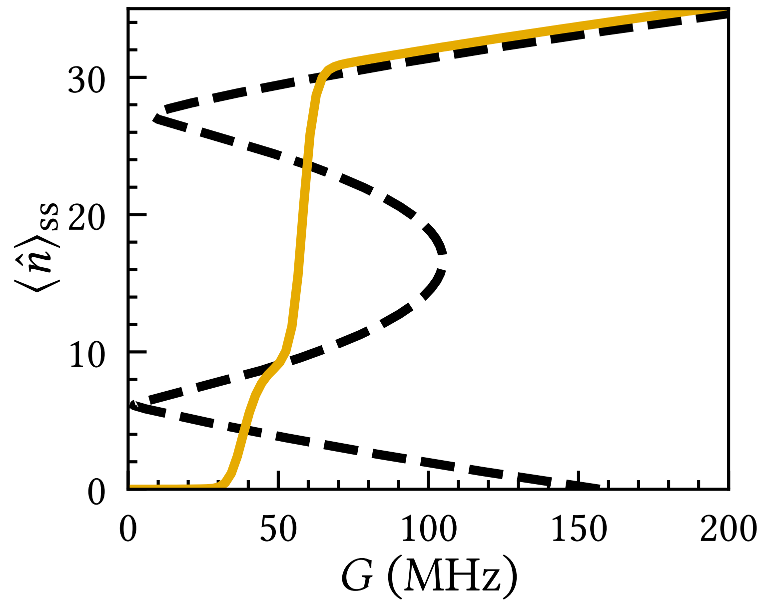
Gravina, L., Minganti, F., & Savona, V. (2023). PRX Quantum, 4(2), 020337.

The chiral cat

A critical cat with higher-order nonlinearities

Recall the transmon Hamiltonian $\longrightarrow$ $\hat{H}_{\mathrm{t}} \propto \cos(\hat{\varphi}) \sim K_1 \hat{a}^\dagger \hat{a} - K_2 (\hat{a}^\dagger)^2 \hat{a}^2 + K_3 (\hat{a}^\dagger)^3 \hat{a}^3 + \cdots$

$$\mathcal{L}(\hat{\rho}) = -i[\Delta \hat{a}^\dagger \hat{a} - K_2 \hat{a}^{\dagger\,2} \hat{a}^2 + \boxed{K_3 \hat{a}^{\dagger\,3} \hat{a}^3} + G(\hat{a}^{\dagger\,2} + \hat{a}^2), \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$$

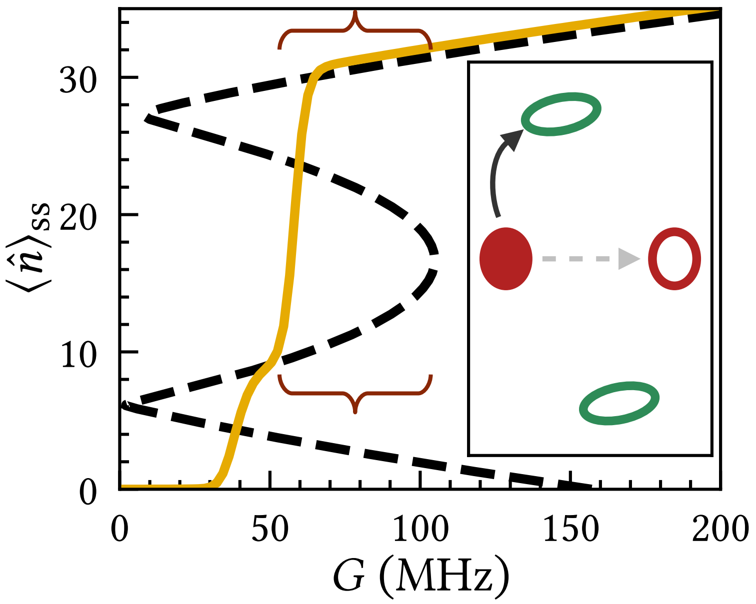


The chiral cat

A critical cat with higher-order nonlinearities

Recall the transmon Hamiltonian $\longrightarrow$ $\hat{H} \propto \cos(\hat{\varphi}) \sim K_1 \hat{a}^\dagger \hat{a} + K_2 (\hat{a}^\dagger)^2 \hat{a}^2 + K_3 (\hat{a}^\dagger)^3 \hat{a}^3 + \cdots$

$$\mathcal{L}(\hat{\rho}) = -i[\Delta \hat{a}^\dagger \hat{a} - K_2 \hat{a}^{\dagger\,2} \hat{a}^2 + \boxed{K_3 \hat{a}^{\dagger\,3} \hat{a}^3} + G(\hat{a}^{\dagger\,2} + \hat{a}^2), \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$$

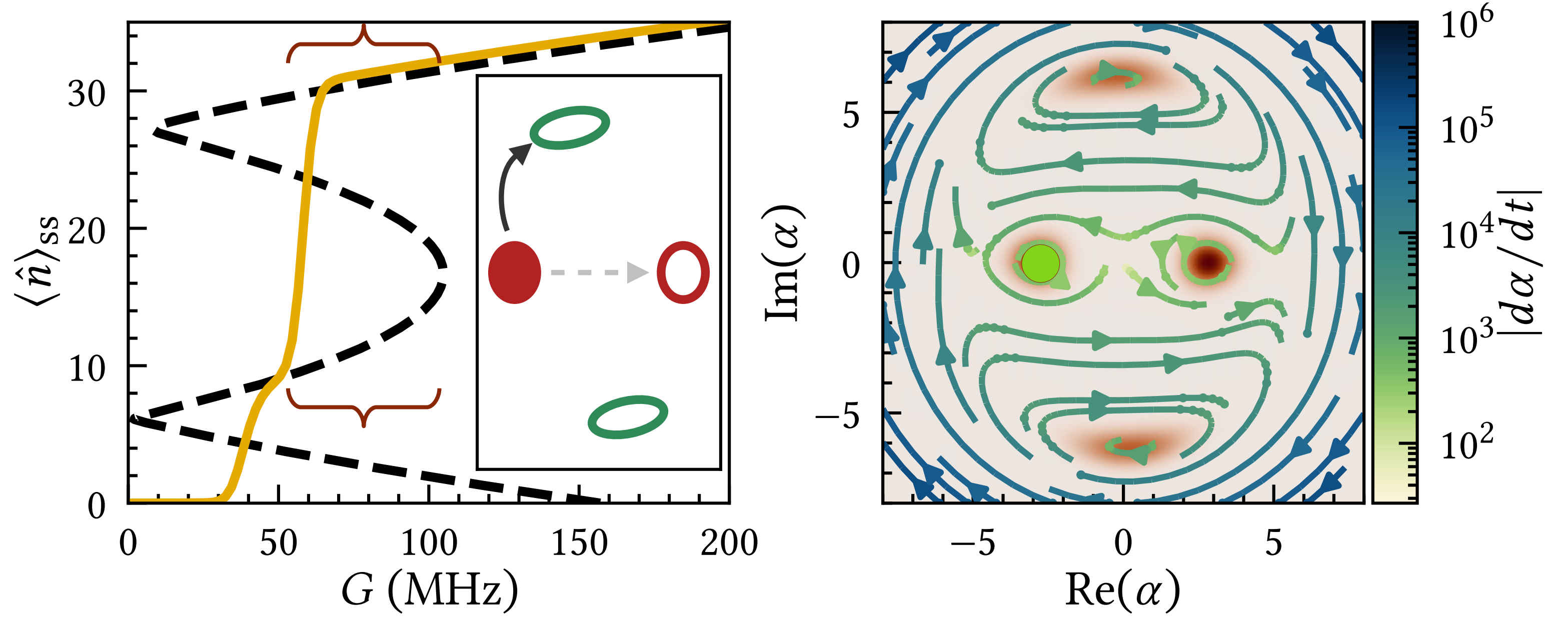


The chiral cat

A critical cat with higher-order nonlinearities

Recall the transmon Hamiltonian $\longrightarrow$ $\hat{H} \propto \cos(\hat{\varphi}) \sim K_1 \hat{a}^\dagger \hat{a} + K_2 (\hat{a}^\dagger)^2 \hat{a}^2 + K_3 (\hat{a}^\dagger)^3 \hat{a}^3 + \cdots$

$$\mathcal{L}(\hat{\rho}) = -i[\Delta \hat{a}^\dagger \hat{a} - K_2 \hat{a}^{\dagger\,2} \hat{a}^2 + \boxed{K_3 \hat{a}^{\dagger\,3} \hat{a}^3} + G(\hat{a}^{\dagger\,2} + \hat{a}^2), \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$$

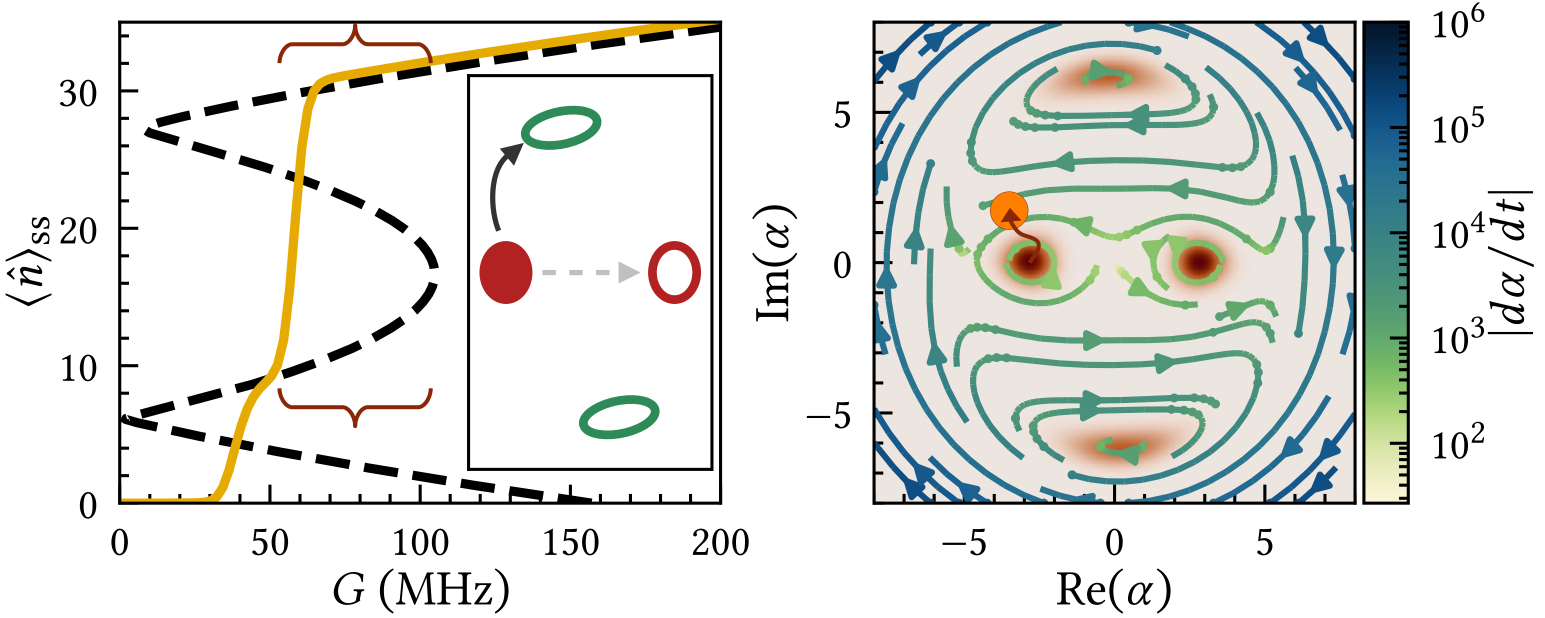


The chiral cat

A critical cat with higher-order nonlinearities

Recall the transmon Hamiltonian $\longrightarrow$ $\hat{H} \propto \cos(\hat{\varphi}) \sim K_1 \hat{a}^\dagger \hat{a} + K_2 (\hat{a}^\dagger)^2 \hat{a}^2 + K_3 (\hat{a}^\dagger)^3 \hat{a}^3 + \cdots$

$$\mathcal{L}(\hat{\rho}) = -i[\Delta \hat{a}^\dagger \hat{a} - K_2 \hat{a}^{\dagger\,2} \hat{a}^2 + \boxed{K_3 \hat{a}^{\dagger\,3} \hat{a}^3} + G(\hat{a}^{\dagger\,2} + \hat{a}^2), \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$$

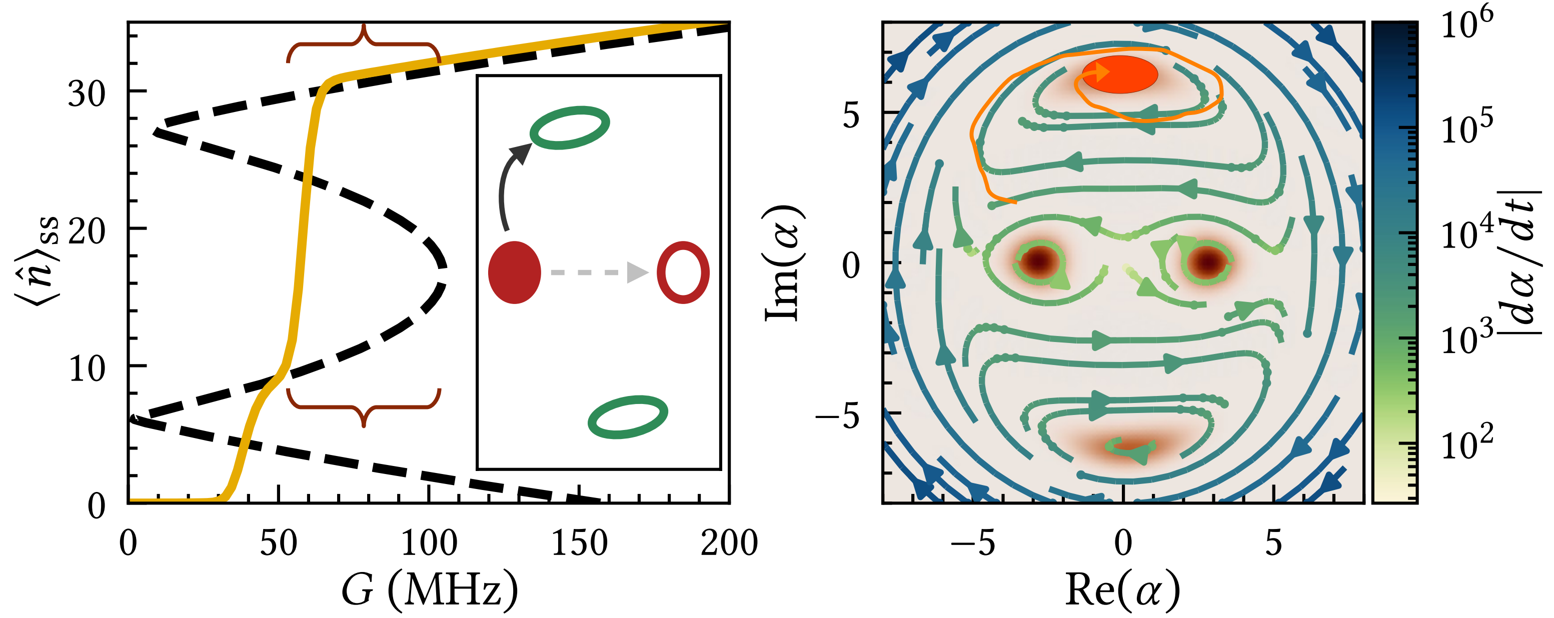


The chiral cat

A critical cat with higher-order nonlinearities

Recall the transmon Hamiltonian $\longrightarrow$ $\hat{H} \propto \cos(\hat{\varphi}) \sim K_1 \hat{a}^\dagger \hat{a} + K_2 (\hat{a}^\dagger)^2 \hat{a}^2 + K_3 (\hat{a}^\dagger)^3 \hat{a}^3 + \cdots$

$$\mathcal{L}(\hat{\rho}) = -i[\Delta \hat{a}^\dagger \hat{a} - K_2 \hat{a}^{\dagger 2} \hat{a}^2 + \boxed{K_3 \hat{a}^{\dagger 3} \hat{a}^3} + G(\hat{a}^{\dagger 2} + \hat{a}^2), \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$$



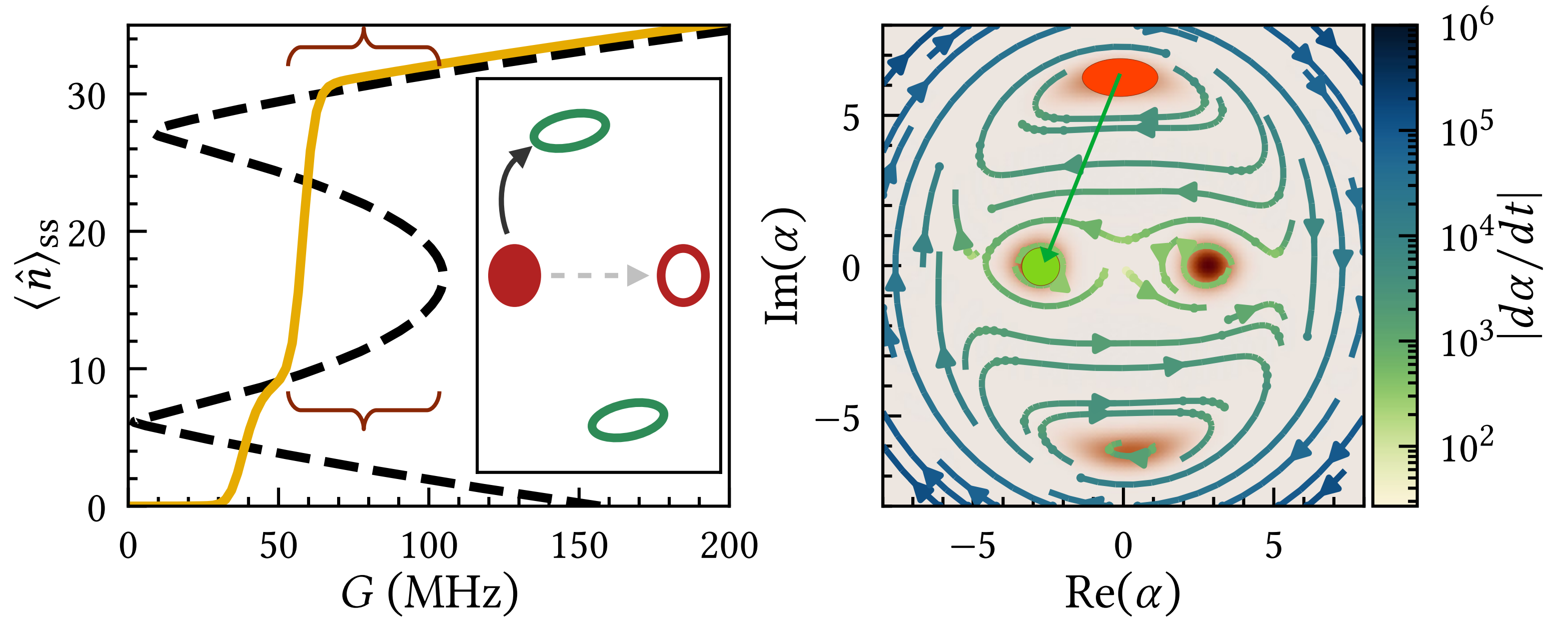
Possibility to detect an error

The chiral cat

A critical cat with higher-order nonlinearities

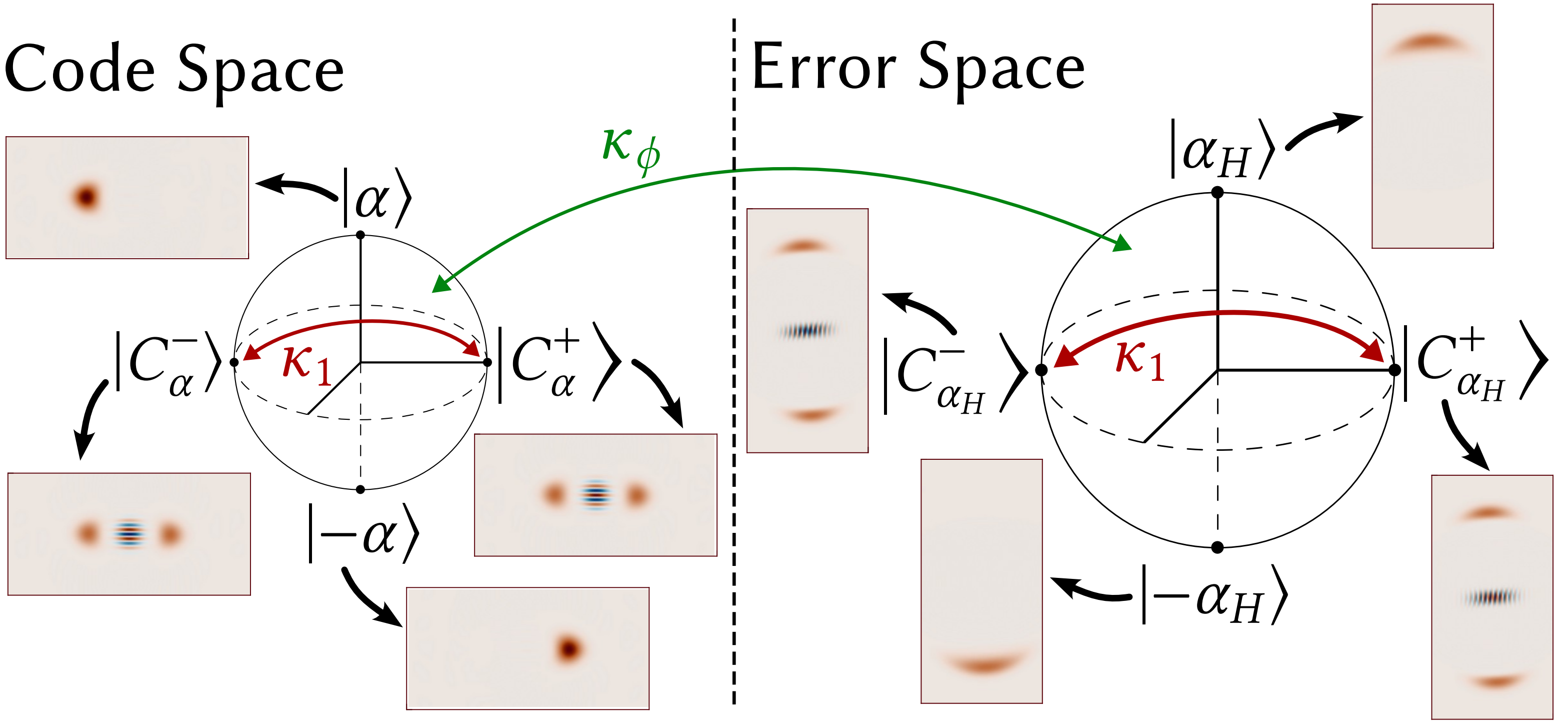
Recall the transmon Hamiltonian $\longrightarrow$ $\hat{H} \propto \cos(\hat{\varphi}) \sim K_1 \hat{a}^\dagger \hat{a} + K_2 (\hat{a}^\dagger)^2 \hat{a}^2 + K_3 (\hat{a}^\dagger)^3 \hat{a}^3 + \cdots$

$$\mathcal{L}(\hat{\rho}) = -i[\Delta \hat{a}^\dagger \hat{a} - K_2 \hat{a}^{\dagger\, 2} \hat{a}^2 + \boxed{K_3 \hat{a}^{\dagger\, 3} \hat{a}^3} + G(\hat{a}^{\dagger\, 2} + \hat{a}^2), \hat{\rho}] + \kappa_2 \mathcal{D}[\hat{a}^2]\hat{\rho}$$



Possibility to detect an error and correct it

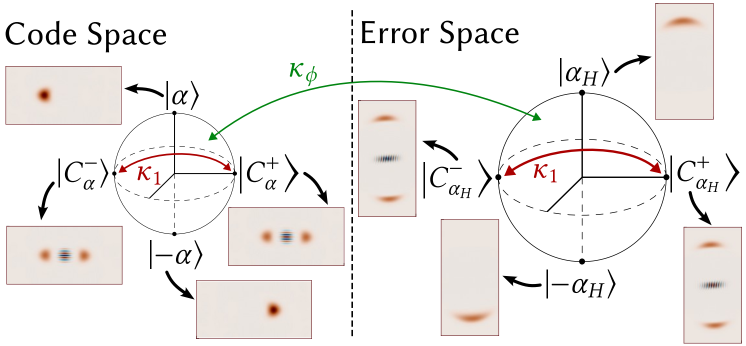
The chiral cat



Two quasi-orthogonal Bloch spheres with different mean photon number

The chiral cat

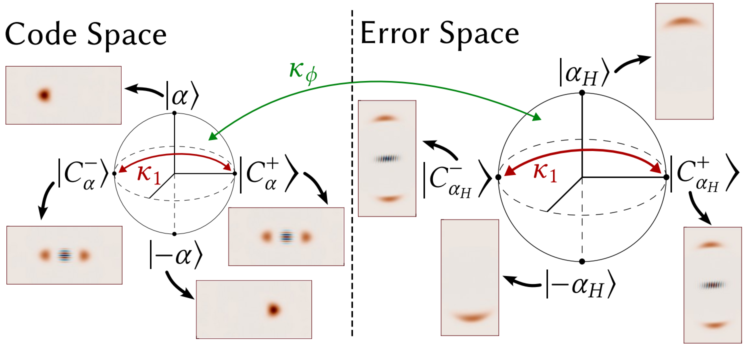
How to perform the recovery?



$$\begin{cases} \hat{\Pi}_H = |\alpha_H\rangle\langle\alpha_H| + |-\alpha_H\rangle\langle-\alpha_H| & \text{Projector onto the high manifold} \\ \hat{R} = |\alpha\rangle\langle\alpha_H| + |-\alpha\rangle\langle-\alpha_H| & \text{Unitary operator from high to low manifold} \end{cases}$$

The chiral cat

How to perform the recovery?

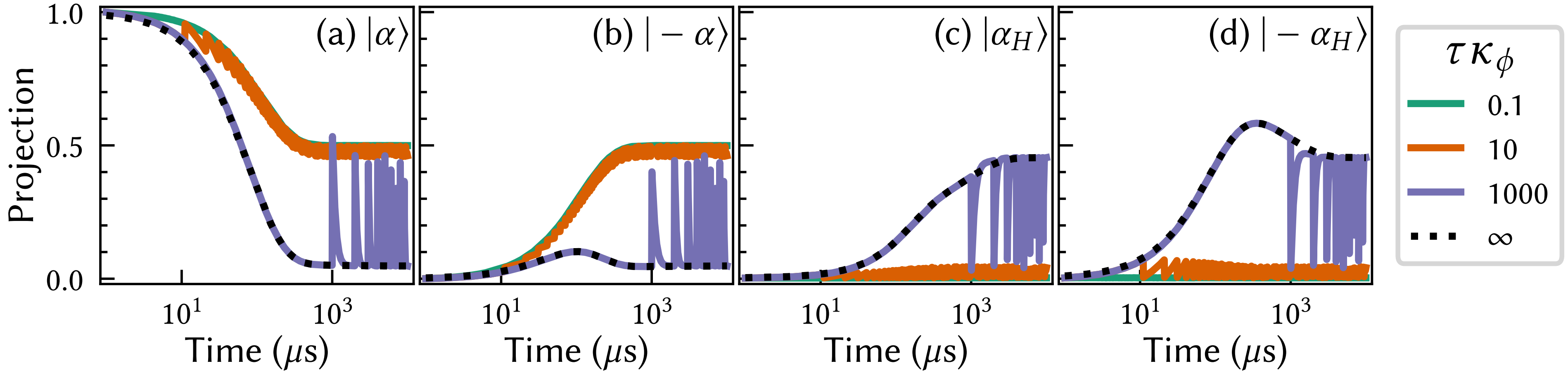


$$\begin{cases} \hat{\Pi}_H = |\alpha_H\rangle\langle\alpha_H| + |-\alpha_H\rangle\langle-\alpha_H| \\ \hat{R} = |\alpha\rangle\langle\alpha_H| + |-\alpha\rangle\langle-\alpha_H| \end{cases}$$

Projector onto the high manifold

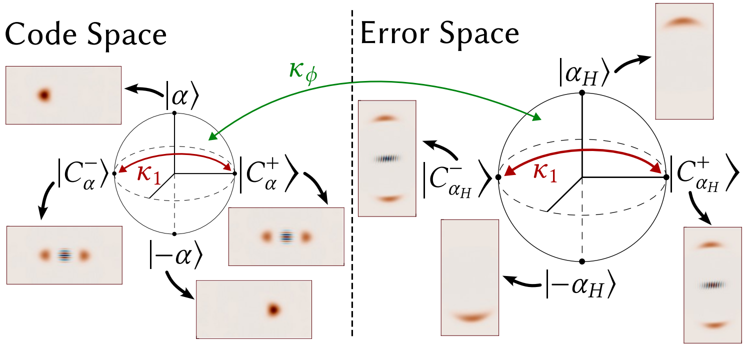
Unitary operator from high to low manifold

$$\hat{\rho}_R = \mathcal{R}(\hat{\rho}) = \hat{R}\hat{\Pi}_H\hat{\rho}\hat{\Pi}_H\hat{R}^\dagger + (\hat{\mathbb{I}} - \hat{\Pi}_H)\hat{\rho}(\hat{\mathbb{I}} - \hat{\Pi}_H) \longrightarrow \hat{\rho}(t+\tau) = \mathcal{R}[e^{\mathcal{L}\tau}\hat{\rho}(t)]$$

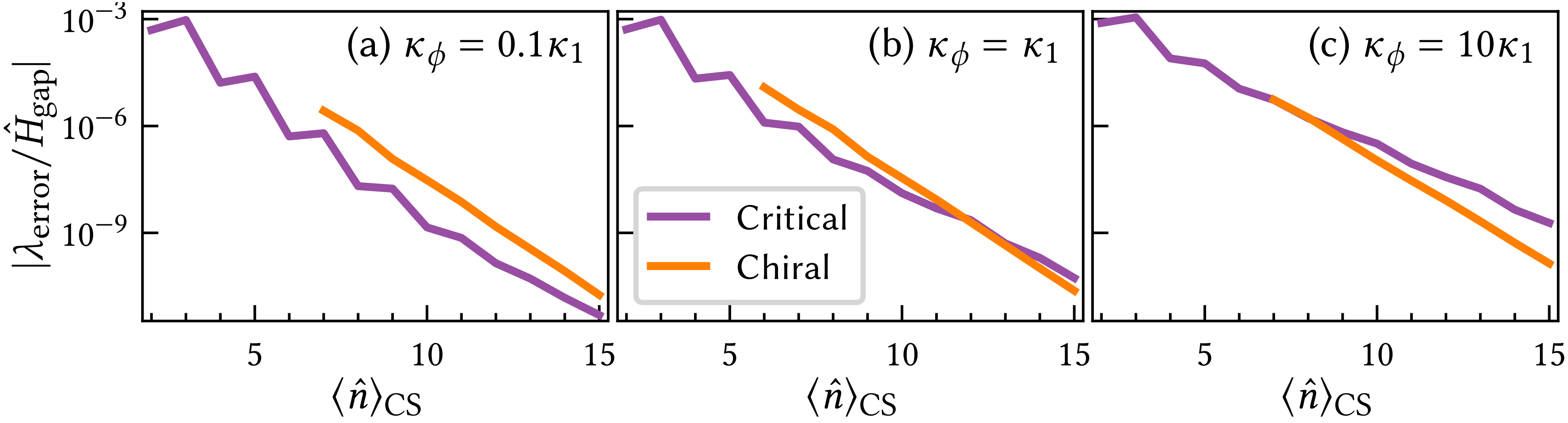


The chiral cat

Protection against dephasing noise

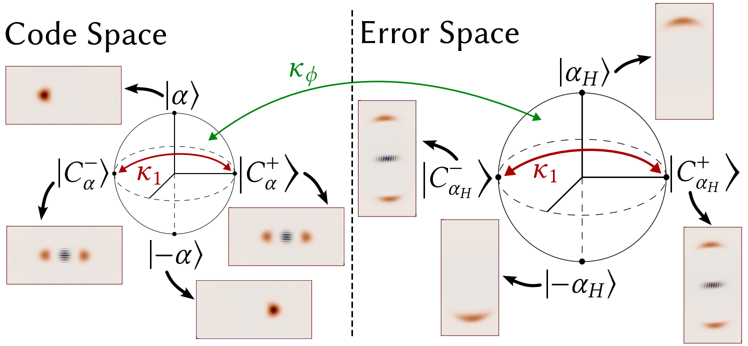


Error rate per number of operations

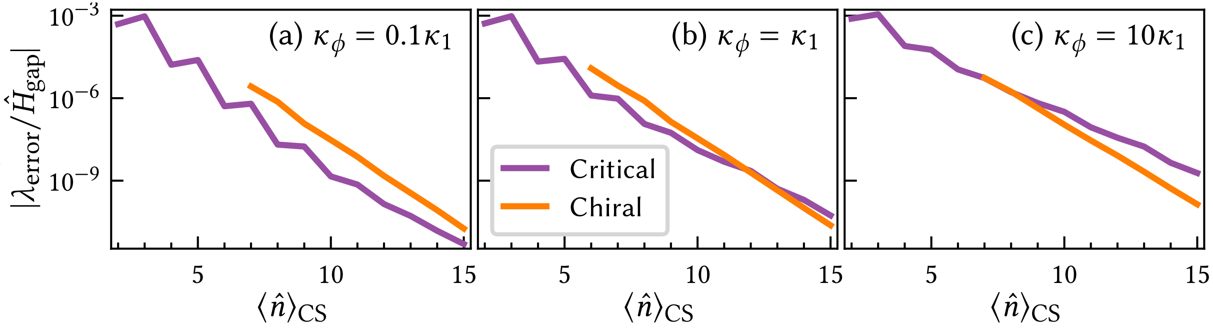


The chiral cat

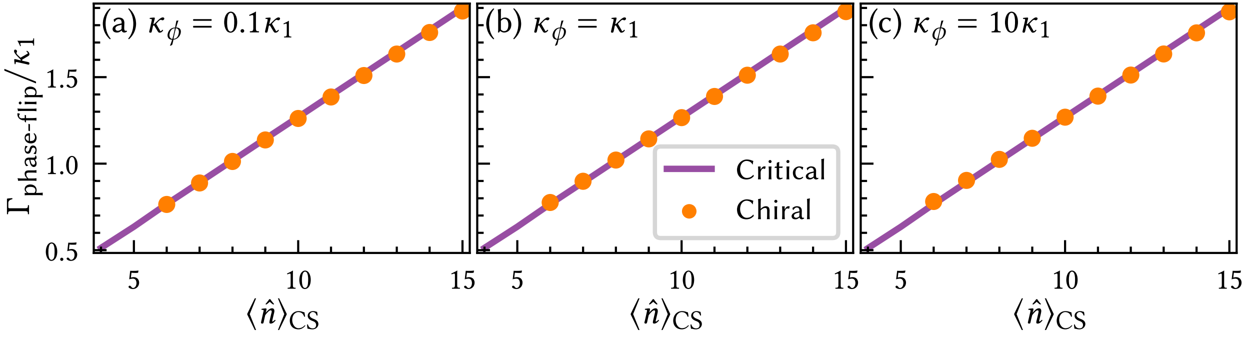
Protection against dephasing noise



Error rate per number of operations

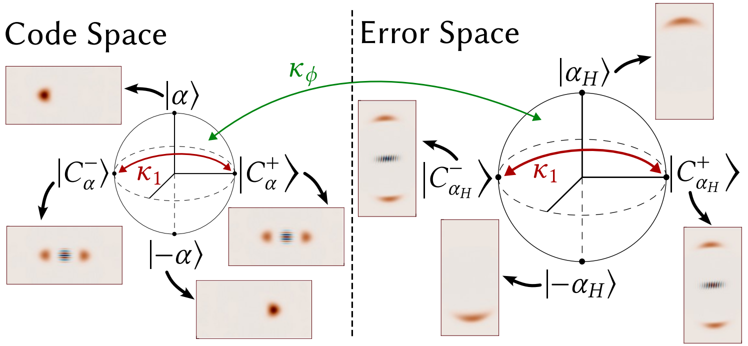


Phase-flip error rate

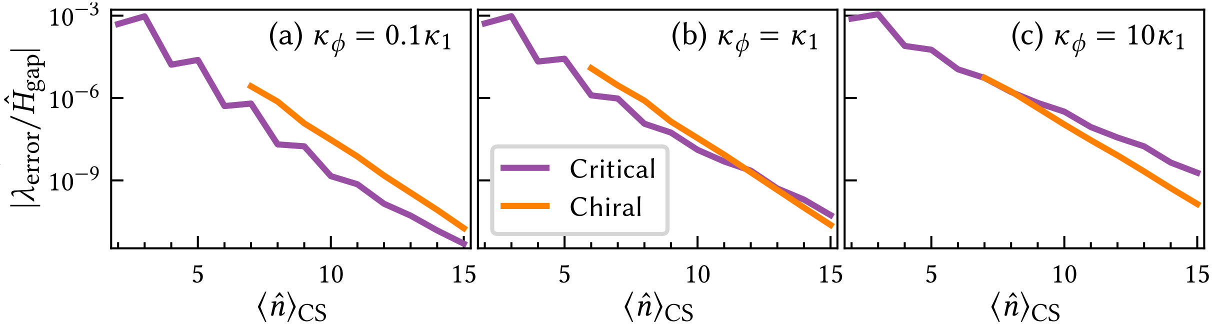


The chiral cat

Protection against dephasing noise

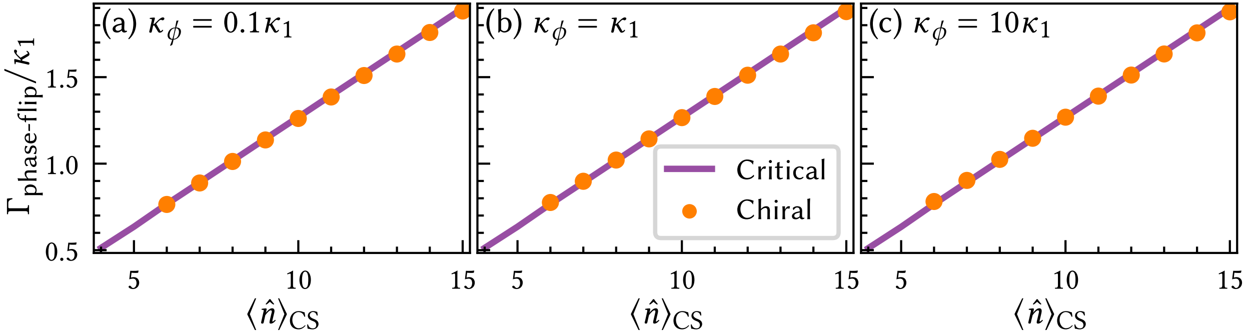


Error rate per number of operations



Bit-flip rate of the high manifold

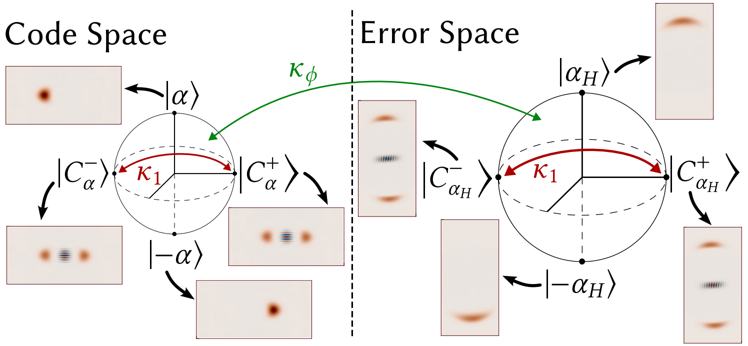
Phase-flip error rate

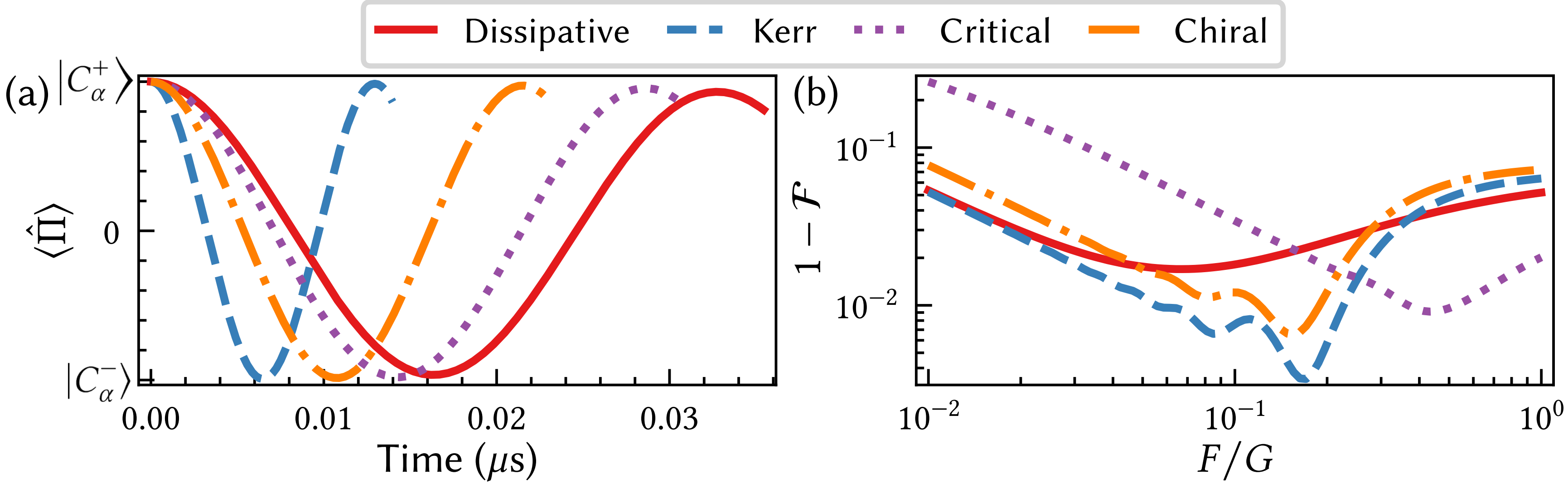


Phase-flip rate of the low manifold

The chiral cat

Z-gate $\longrightarrow$ rotation along the z axis $\hat{H}_z = F(\hat{a} + \hat{a}^\dagger)$





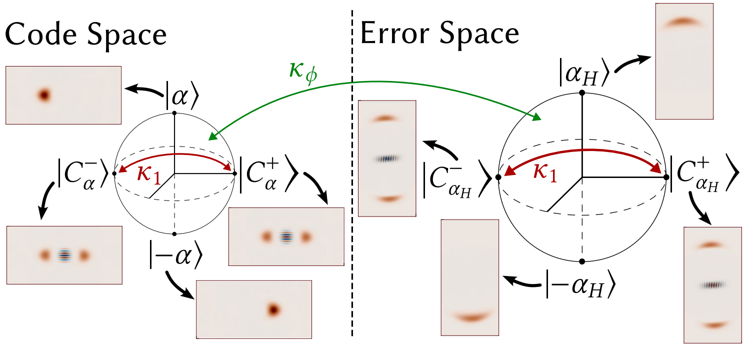
Speed comparable to Kerr cats with minimum error

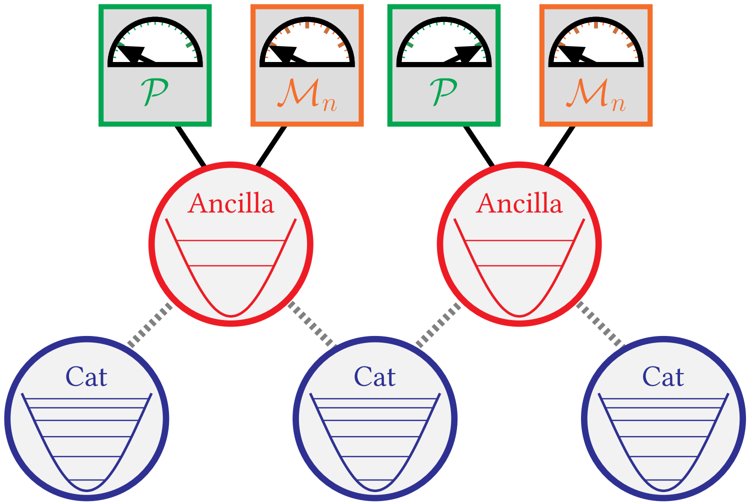
The chiral cat

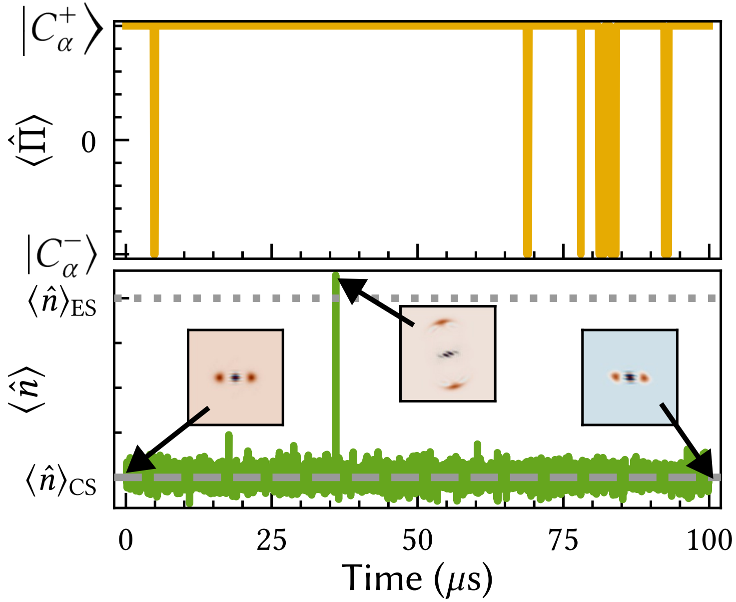
Repetition code

Phase-flip errors detected using parity measurements

Bit-flip errors detected using photon-number measurements



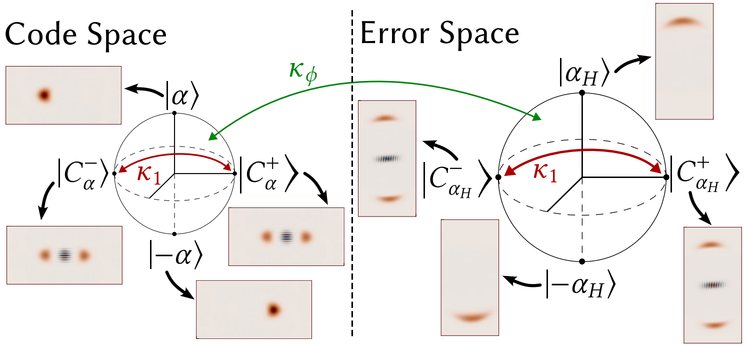


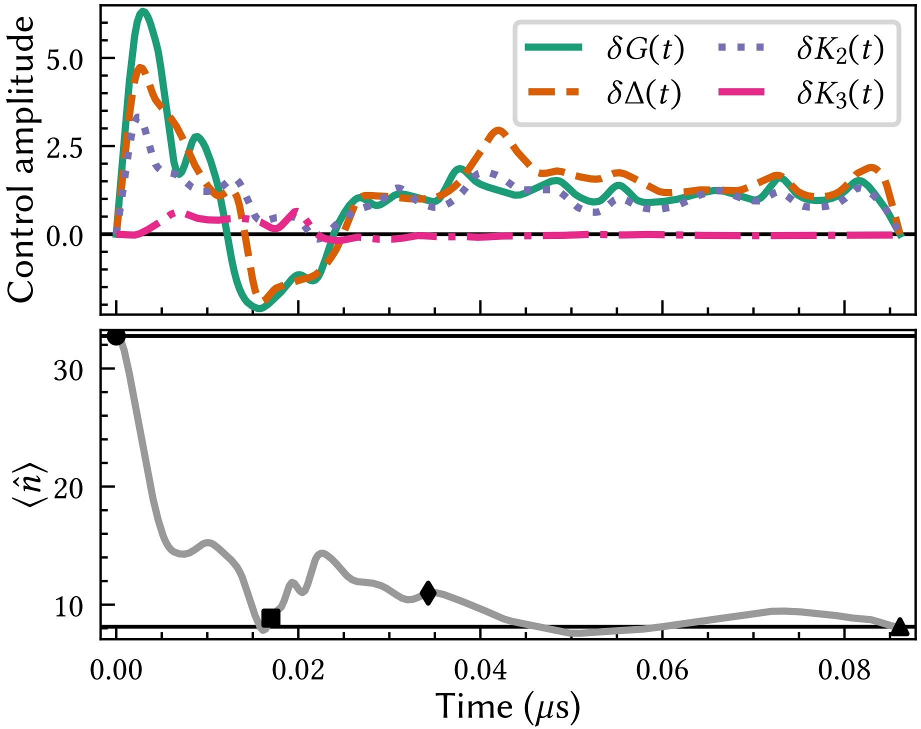


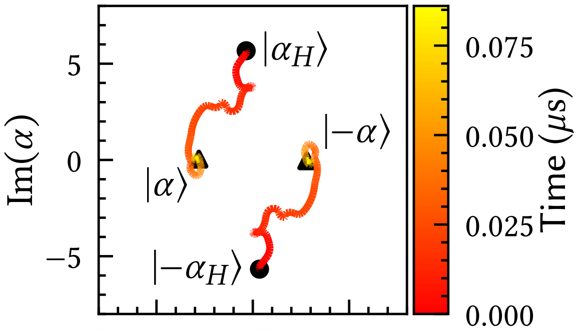
No extra overhead in terms of components
(same ancilla can be used for both bit- and phase-flip measurements)

The chiral cat

Realistic recovery using optimal control

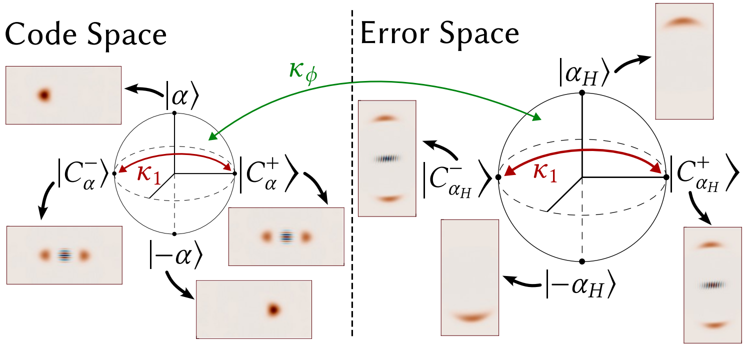


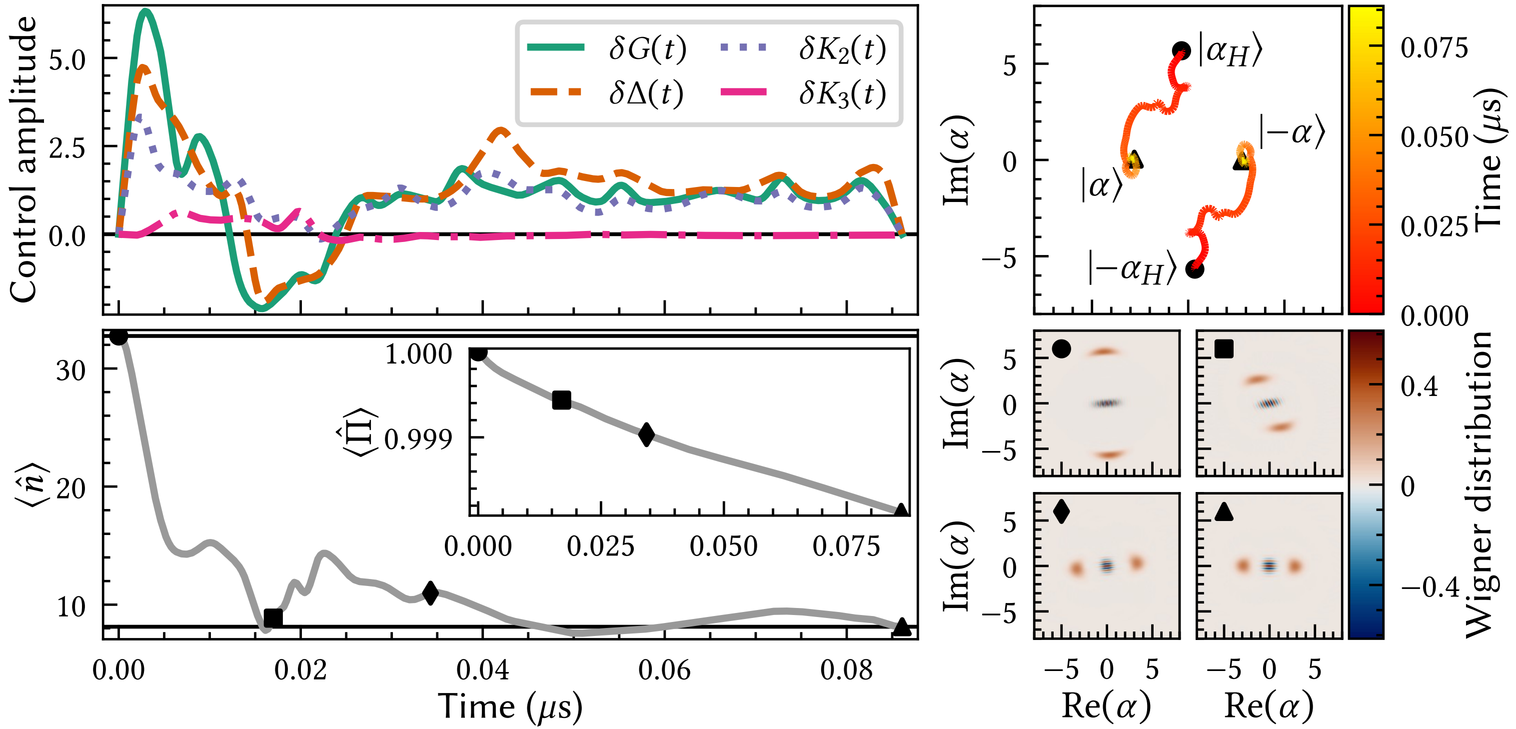




The chiral cat

Realistic recovery using optimal control





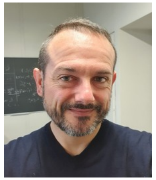
Summary

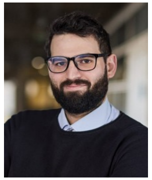
- Higher-order nonlinearity introduces a high-amplitude manifold where quantum information can be stored
- High-manifold acts as a "bit-flip trap"
- Exponential suppression of bit-flip errors even with large dephasing
  - Phase-flip rate remains the same
- Repetition code can be implemented with no extra overhead
- Fast gates with minimal error comparable to Kerr cats
- Optimal control protocol for recovery operation

Gràcies

Read the full paper





IFISC
Universitat de les Illes Balears
CSIC
EPFL
ALICE & BOB
Quantum SPAIN
AGENCIA ESTATAL DE INVESTIGACIÓN
EXCELENCIA MARÍA DE MAEZTU 2023 - 2027
Swiss National Science Foundation