Combined Dissipative and Hamiltonian Confinement of Cat Qubits

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QUANTIC, Inria Paris

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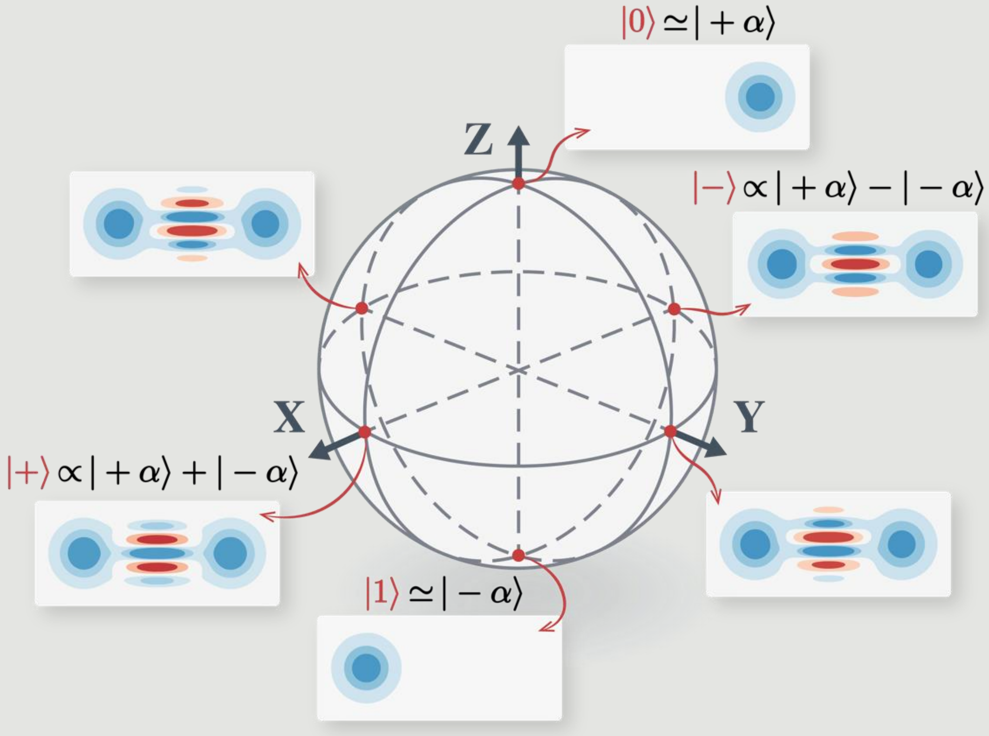
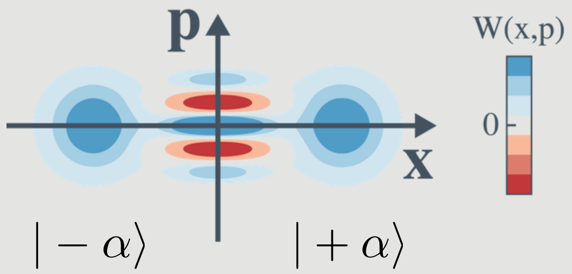
Cat qubits are exponentially noise-biased qubits



Bloch Sphere Representation of a Cat Qubit

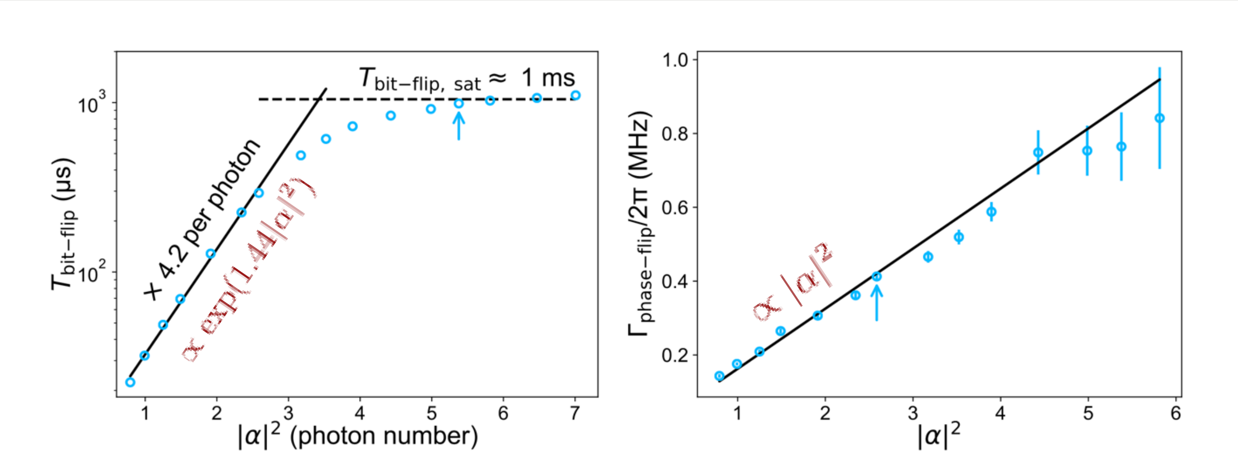
Cat states: coherent superposition of coherent states in a quantum oscillator



where $\hat{a}|\pm\alpha\rangle = \pm\alpha|\pm\alpha\rangle$

$\hat{a} = \hat{x} + i\hat{p}$

Cat qubits are exponentially noise-biased towards phase-flips



(Experimental data from Lescanne, Leghtas *et al.*, *2019*)

Cochrane *et al*., PRA (1999); Leghtas *et al*., PRA (2013); Mirrahimi *et al*., NJP (2014); Lescanne, Legthas et al., Nat.Phy. (2019)

Confining a cat qubit with engineered Hamiltonians or dissipation

To confine an oscillator to the cat qubit codespace, two main approaches exist.

Two-photon dissipation $\hat{\mathcal{L}}_2 = \mathcal{D}[\hat{a}^2 - \alpha^2]$

- C_α is a subspace of fixed points

$$\hat{\mathcal{L}}_2 \hat{\rho} = 0 \quad (\forall \hat{\rho} \in \mathrm{C}_\alpha)$$

- Any initial state converges asymptotically towards C_α

$$\hat{\rho}(t) \xrightarrow[t\to\infty]{} \hat{\rho}_\infty \in \mathrm{C}_\alpha$$

Autonomous stabilization

Kerr Hamiltonian $\hat{H}_{\mathrm{Kerr}} = K(\hat{a}^{\dagger 2} - \alpha^{*2})(\hat{a}^2 - \alpha^2)$

- $|\pm\alpha\rangle$ are degenerate eigenstates

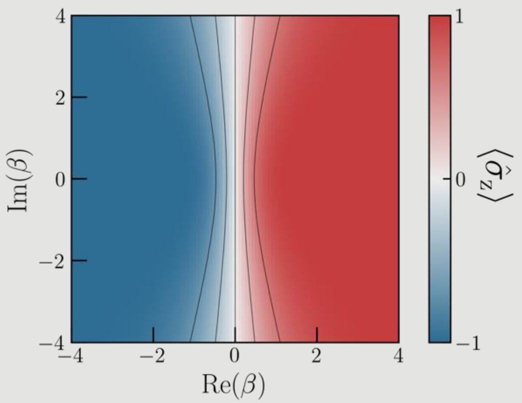
$$\hat{H}_{\mathrm{Kerr}} |\pm\alpha\rangle \propto |\pm\alpha\rangle$$

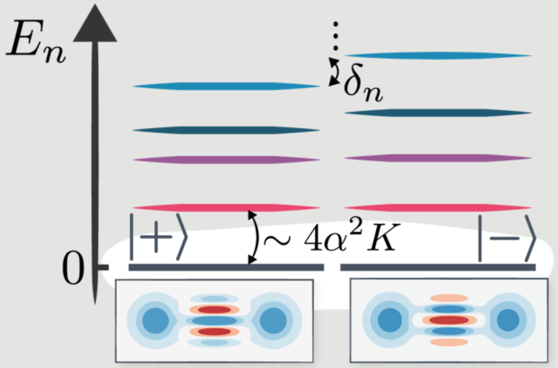
- $|\pm\alpha\rangle$ are gapped from other eigenstates

$$|E_{|\pm\alpha\rangle} - E_{|\psi\rangle}| \gg \kappa_{\mathrm{noise}}$$

Gap protection
(adiabatic theorem, perturbation theory)

$\mathrm{C}_\alpha = \mathrm{span}\{|+\alpha\rangle\langle+\alpha|, |+\alpha\rangle\langle-\alpha|, |-\alpha\rangle\langle+\alpha|, |-\alpha\rangle\langle-\alpha|\}$





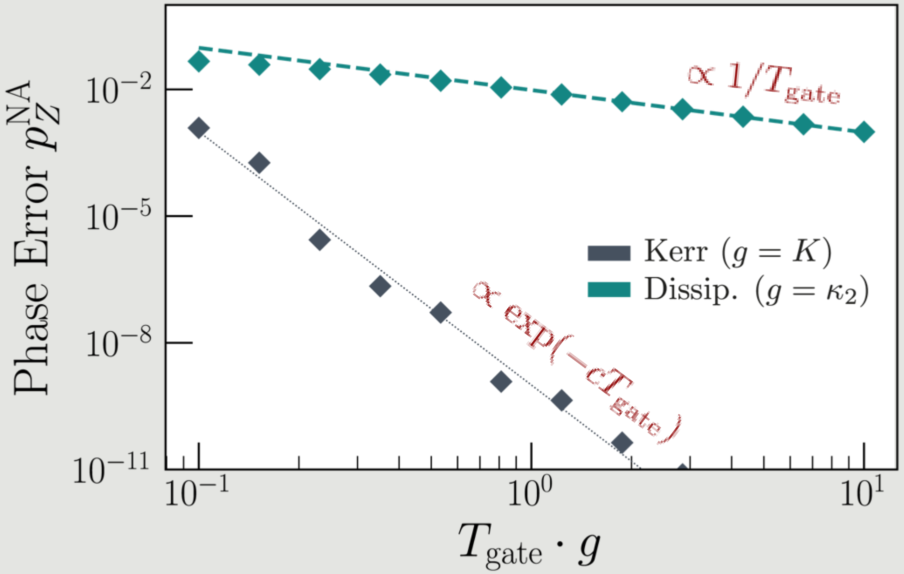
Mirrahimi *et al.*, NJP (2014); Puri *et al.*, npj QI (2017)

Pros and cons of Hamiltonian and dissipative confinement

Kerr confinement provides low-error gate designs, but is subject to thermal and dephasing noise.

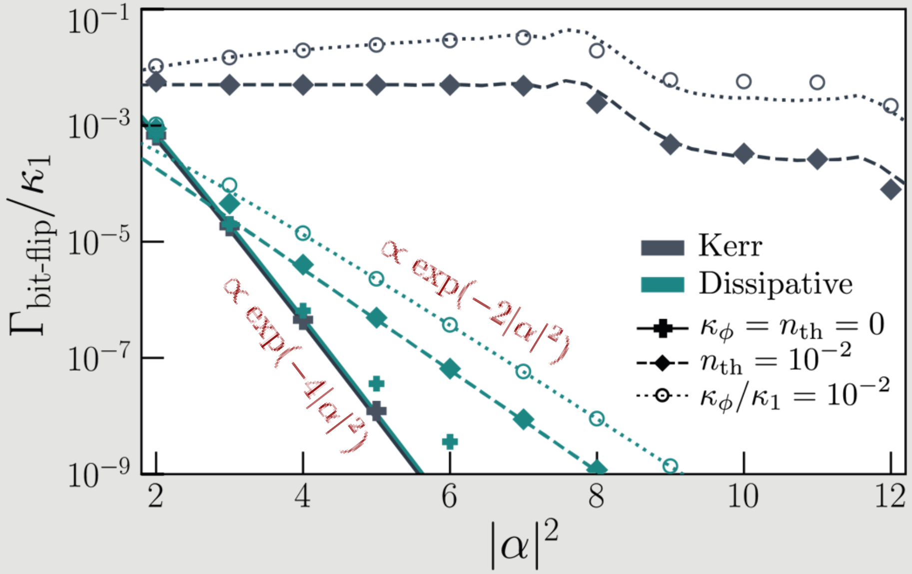
Single-qubit Z gate (noiseless)

$$\dot{\rho} = g\mathcal{L}_{\text{conf}}\rho - i[\varepsilon_Z(t)\hat{a}^\dagger + \varepsilon_Z^*(t)\hat{a}, \rho]$$



Idling qubit (noisy)

$$\dot{\rho} = g\mathcal{L}_{\text{conf}}\rho + \kappa_1\mathcal{D}[\hat{a}]\rho + \kappa_1 n_{\text{th}}\mathcal{D}[\hat{a}^\dagger]\rho + \kappa_\phi\mathcal{D}[\hat{a}^\dagger\hat{a}]\rho$$



- Dissipative: linear scaling of gate-… …nential suppression at any $|\alpha|^2$
- Kerr: exponential scaling of gate-i… …suppression up to $\mathcal{O}(\kappa_l)$ up to $\mathcal{O}(\kappa_l)$

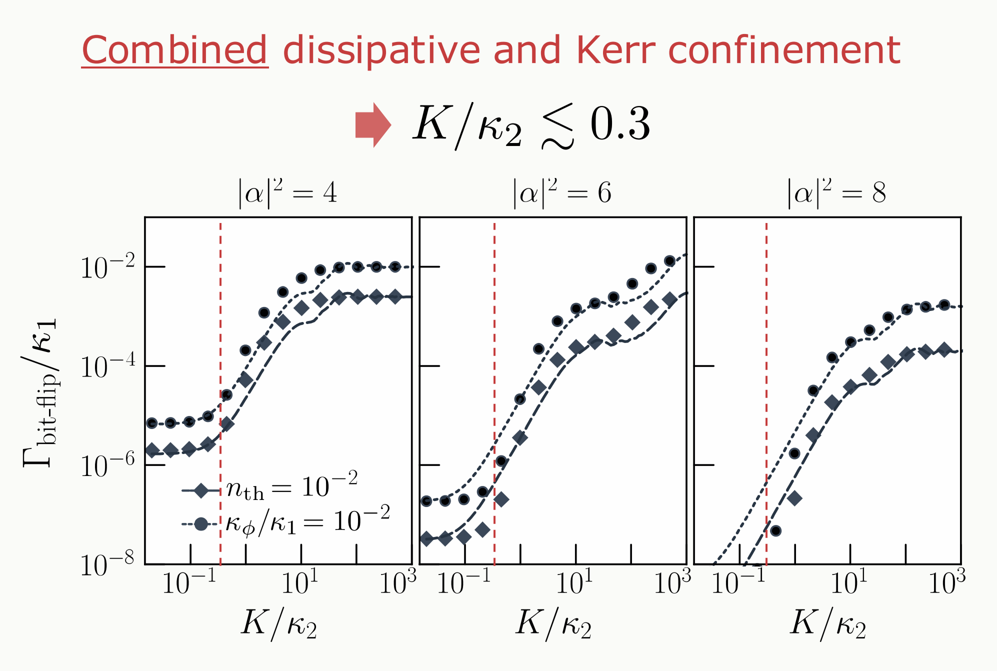
How to benefit from both?

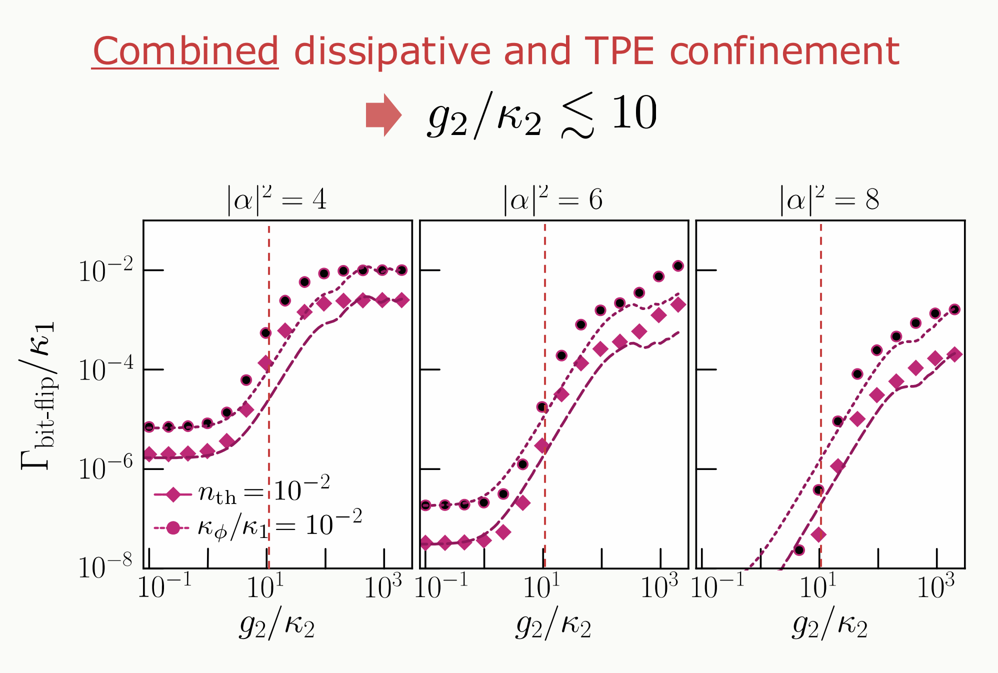
$(\kappa_l = \kappa_1 n_{\text{th}} + |\alpha|^2\kappa_\phi)$

Putterman *et al.*, arXiv (2021); Xu *et al.*, arXiv (2021); Gautier *et al.*, arXiv (2021)

Combining Dissipative and Hamiltonian confinement

To benefit from the best of both worlds, we could use both confinement methods simultaneously

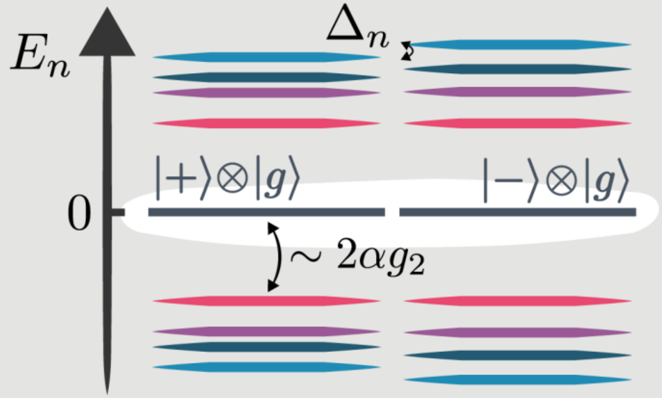




New cat qubit Hamiltonian confinement coined Two-Photon Exchange (TPE)

$$\hat{H}_{\text{TPE}} = g_2(\hat{a}^2 - \alpha^2)\hat{\sigma}_+ + \text{h.c.}$$

- Gapped Hamiltonian
- Degenerate subspace given by the cat qubit



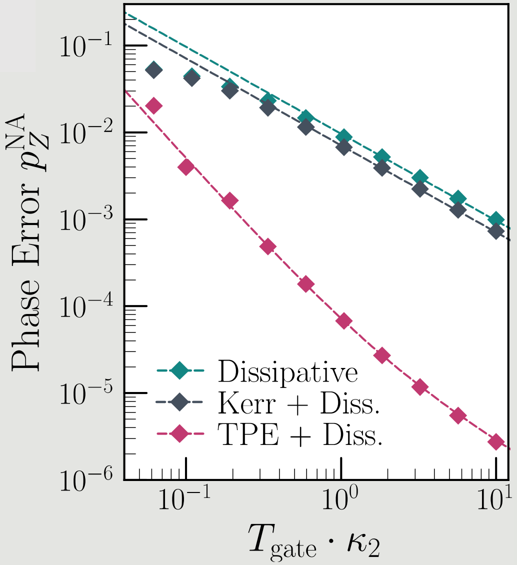
Gautier *et al.*, arXiv (2021)

Combined confinement for gate engineering

The combined confinement schemes are investigated at the bias-preserving working points, i.e. $K/\kappa_2 = 0.3$ and $g_2/\kappa_2 = 10$

Single-qubit Z gate

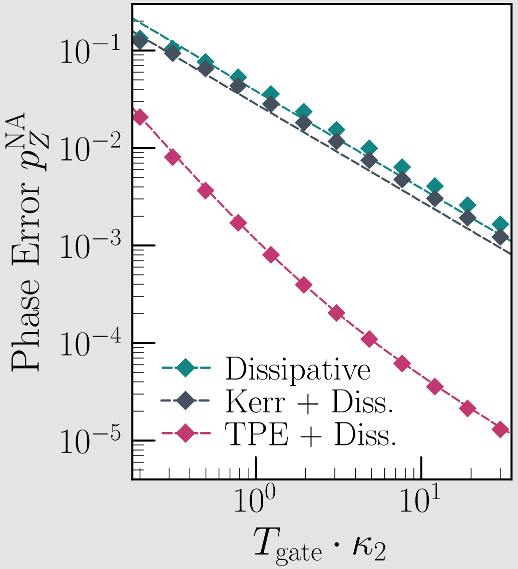
$$\dot{\rho} = g\mathcal{L}_{\text{conf}}\rho - i[\varepsilon_Z(t)\hat{a}^\dagger + \varepsilon_Z^*(t)\hat{a}, \rho]$$



$$p_Z = \frac{1}{1 + \frac{4g_2^2}{\kappa_2^2}} \frac{\pi^2}{16|\alpha|^4\kappa_2 T_{\text{gate}}}$$

Two-qubit CNOT gate

$$\dot{\rho} = g\mathcal{L}_{\text{conf}}^{(co)}\rho - i[\hat{H}_{CX}, \rho]$$



- Up to x100 two-qubit gate fidelity improvement
- Reduced leakage compared to dissipative gate designs
- Repetition code threshold: 0.7% (Diss.) ➡ 2% (TPE + Diss.)

Gautier *et al.*, arXiv (2021). Threshold calculation by Jérémie Guillaud.

Thanks for your attention!

arXiv:2112.05545

Mazyar Mirrahimi's invited talk | Session Z40 | Friday 12:30PM

Engineering a combined TPE and dissipative confinement

Potential energy of the ATS
(Assymetrically Threaded SQUID)

$$U(\varphi) = \frac{1}{2}E_L\varphi^2 - 2E_J\left[\varepsilon(t)\sin(\varphi) - \eta\cos(\varphi)\right]$$

$$\hat{H} = g_2(\hat{a}^2 - \alpha^2)\hat{b}^\dagger + \text{h.c.}$$

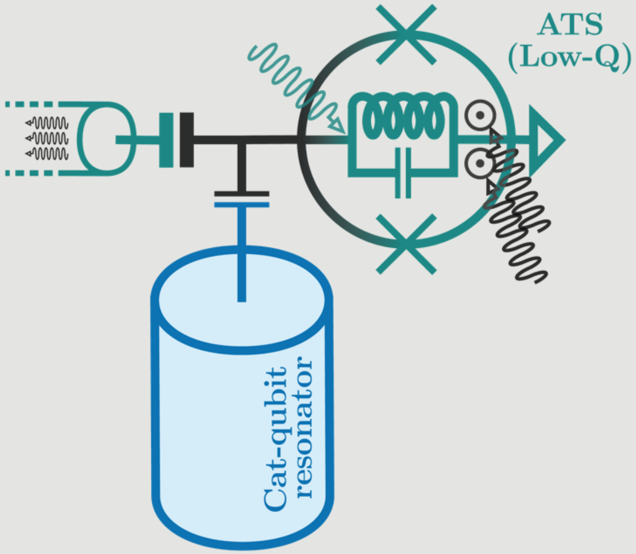
$\kappa_b \gg g_2$

$$\kappa_2\mathcal{D}[\hat{a}^2 - \alpha^2]$$

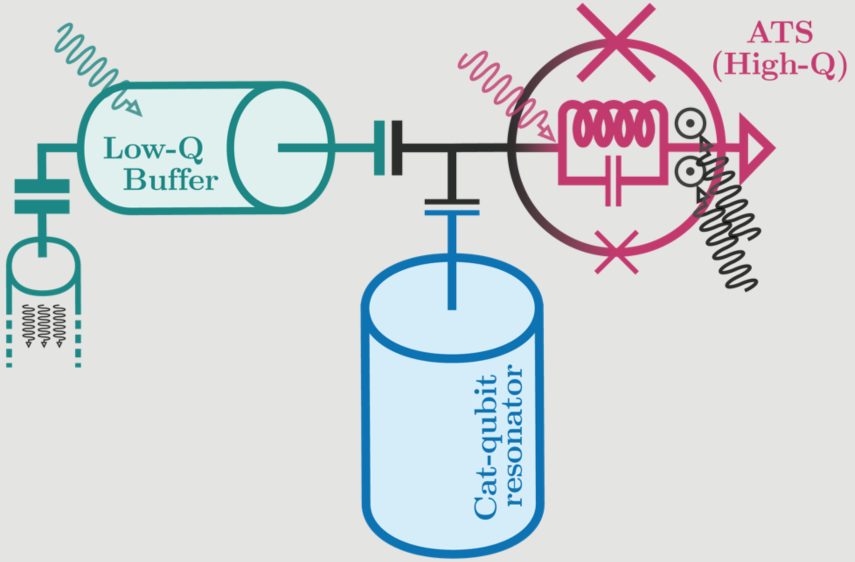
$$\hat{H} = g_{2,l}(\hat{a}^2 - \alpha^2)\hat{b}_\text{l}^\dagger + \text{h.c.} + g_{2,h}(\hat{a}^2 - \alpha^2)\hat{b}_\text{h}^\dagger + \text{h.c.} - \chi_{hh}\hat{b}_\text{h}^{\dagger 2}\hat{b}_\text{h}^2$$

$\kappa_b \gg g_{2,l}$ → $\kappa_2\mathcal{D}[\hat{a}^2 - \alpha^2]$

$\chi_{hh} \gg g_{2,h}$ → $g_{2,h}(\hat{a}^2 - \alpha^2)\hat{\sigma}_+ + \text{h.c.}$



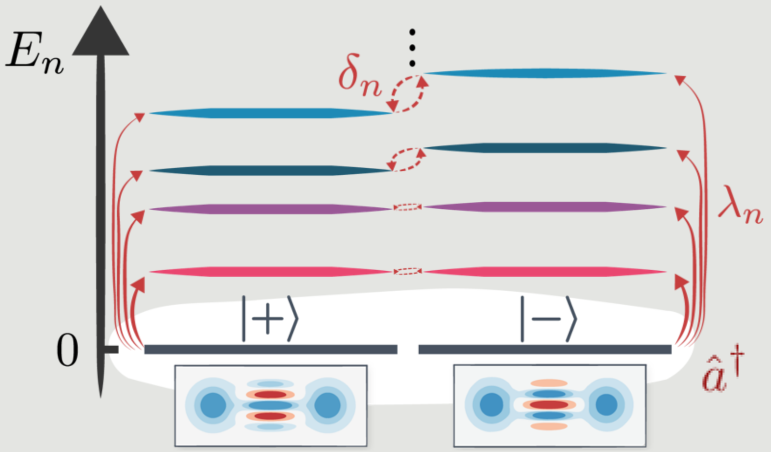
Dissipative cat qubit circuit design



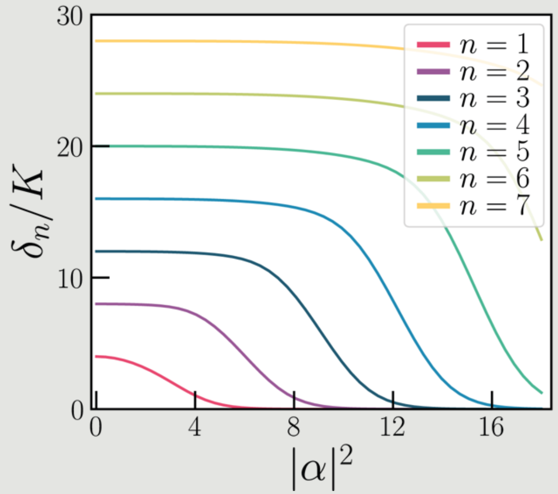
Combined TPE + Diss. circuit proposition

Bit-flip induced by thermal and dephasing noise

Why is Kerr confinement subject to thermal and dephasing noise?

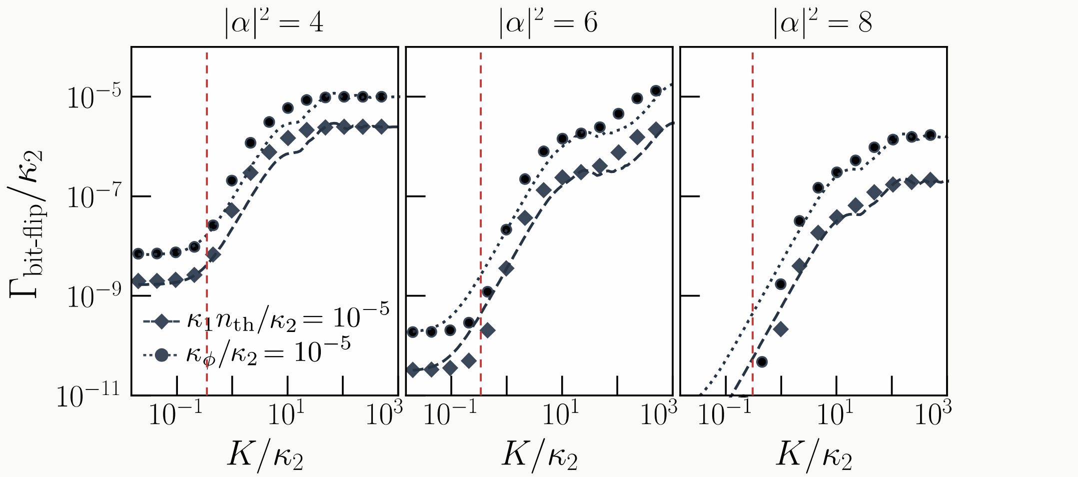


1. System initially in the cat codespace
2. At t=0, thermal excitation event
3. All Kerr eigenstates are populated
4. Dephasing of +/- branches induces bit-flip



- Suppressed exponentially for $|\alpha|^2 \gtrsim 4Kn$
- Diverge with n

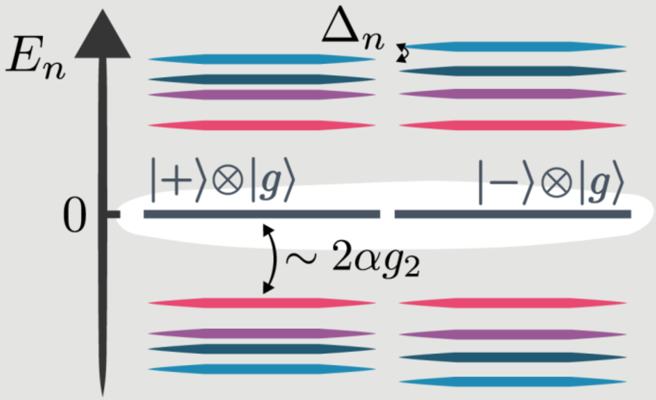
Combined dissipative and Kerr confinement ➡ $K/\kappa_2 \lesssim 0.3$



Gautier *et al.*, arXiv (2021)

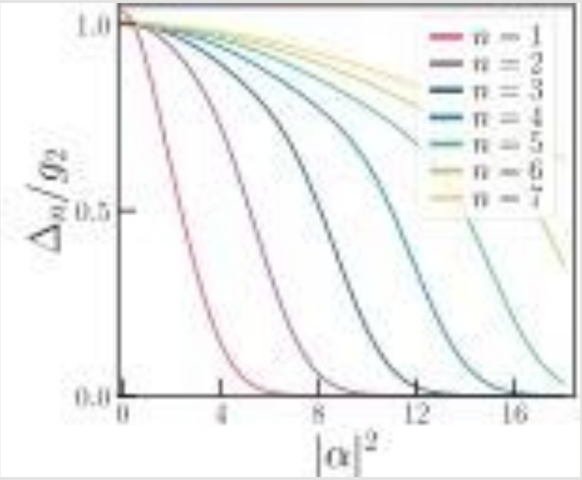
Two-Photon Exchange Hamiltonian confinement

New cat qubit Hamiltonian confinement coined <u>Two-Photon Exchange</u> (TPE)



$$\hat{H}_{\mathrm{TPE}} = g_2(\hat{a}^2 - \alpha^2)\hat{\sigma}_+ + \mathrm{h.c.}$$

- Gapped Hamiltonian (adiabatic theorem)
- Square root scaling of energies



- Suppressed exponentially for $|\alpha|^2 \gtrsim 4Kn$
- Bounded by g_2 !

<u>Combined</u> dissipative and TPE confinement ➡ $g_2/\kappa_2 \lesssim 10$