Cat qubit stabilization with a DC-biased Josephson junction

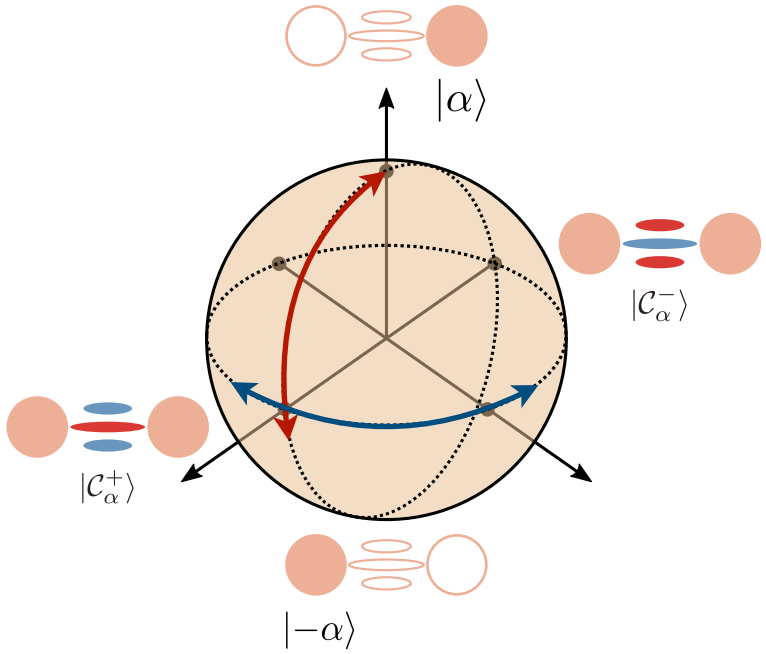
Marco Paradina

Benasque spring school on Superconducting Qubit Technology 2025

Cat qubits

See **Alice & Bob booth** for more on cat qubits

ALICE & BOB



$$\Gamma_{\text{bit-flip}} \propto e^{-\lambda|\alpha|^2}$$

$$\Gamma_{\text{phase-flip}} = 2\kappa_1 |\alpha|^2$$

[Jeong & Kim 2002, Ralph et al. 2003]
[M. Mirrahimi et al., NJP, 2013, (Yale, Paris)]

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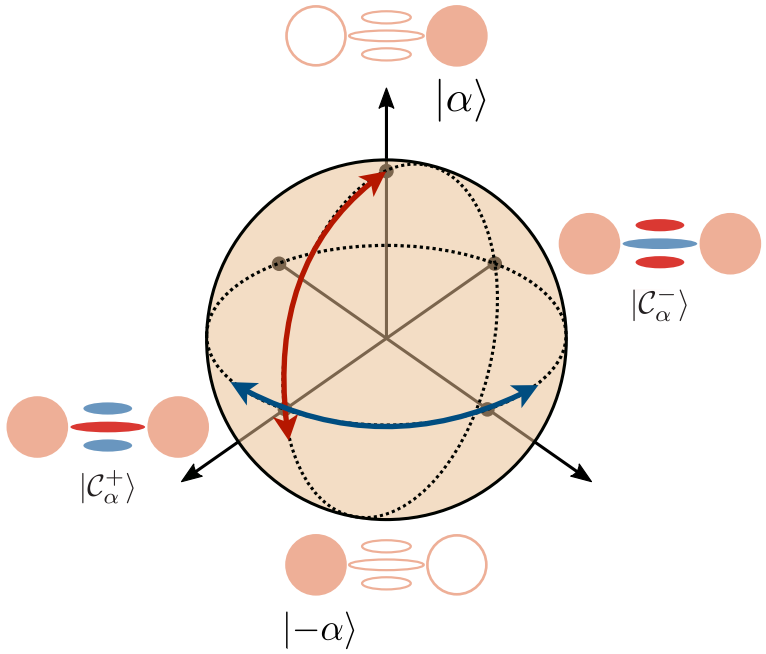

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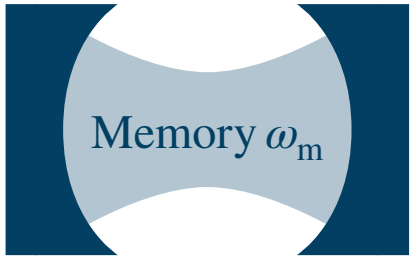
Stabilize $\{|-\alpha\rangle, |+\alpha\rangle\}$ manifold

[Jeong & Kim 2002, Ralph et al. 2003]
[M. Mirrahimi et al., NJP, 2013, (Yale, Paris)]

Using dissipation to stabilize cat qubits



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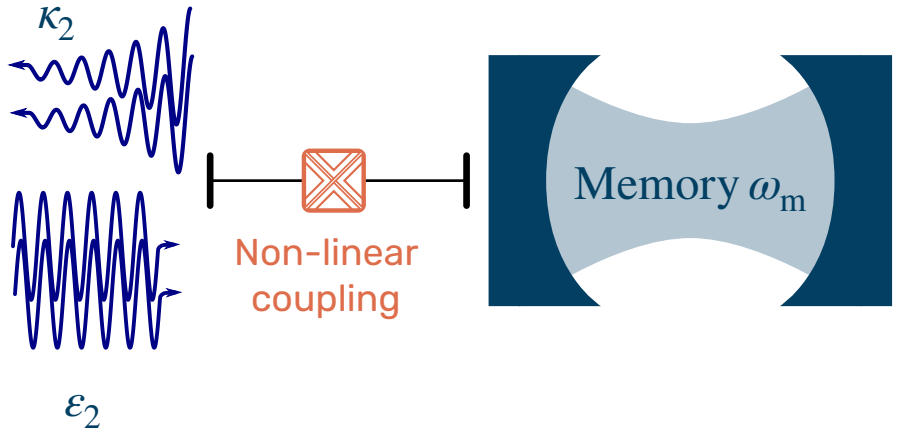


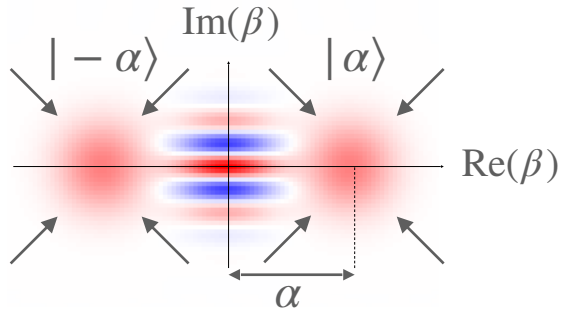
Drive $\rightarrow \hat{H}/\hbar = i\varepsilon_2 \hat{a}^{\dagger 2} + h.c.$

Loss $\rightarrow L = \sqrt{\kappa_2} a^2$

Effective dissipation

$L = \sqrt{\kappa_2}(\hat{a}^2 - \alpha^2)$

$\alpha = 2\varepsilon_2/\kappa_2$



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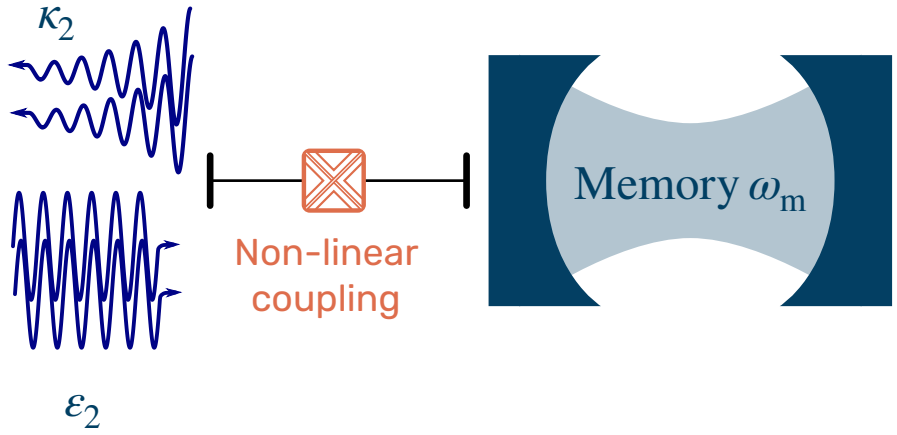

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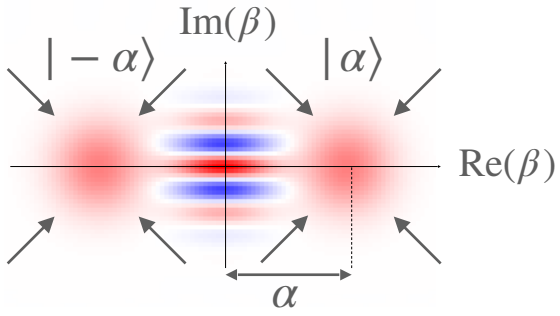

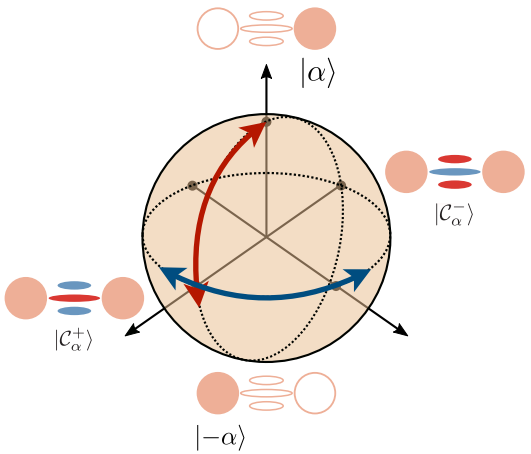

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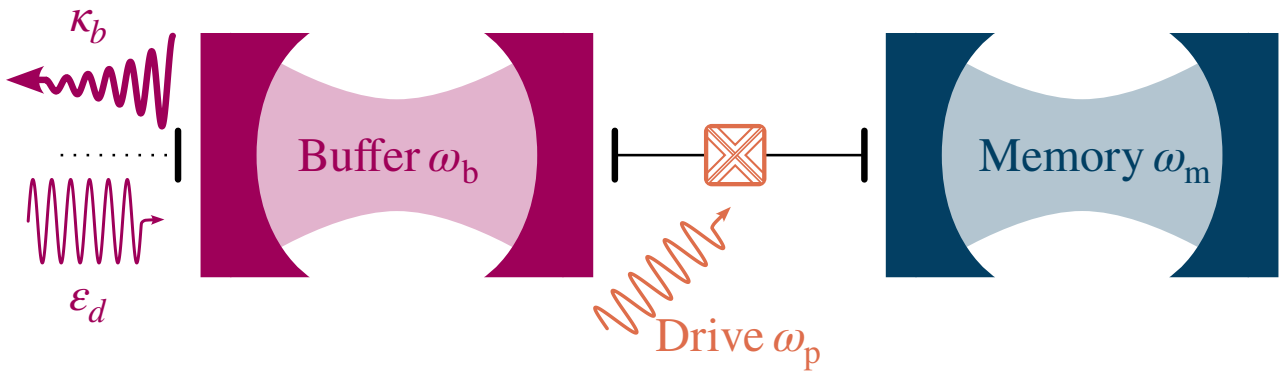

[Z. Leghtas et al. Science, 2015 (Yale)]

[S. Touzard et al. PRX 2018 (Yale)]

[R. Lescanne et al. Nat phys 2020 (ENS Paris)]

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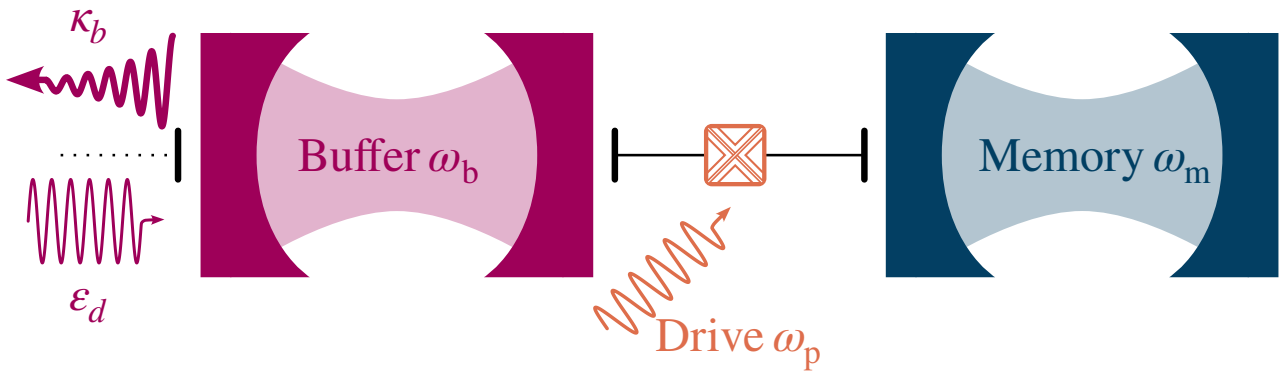

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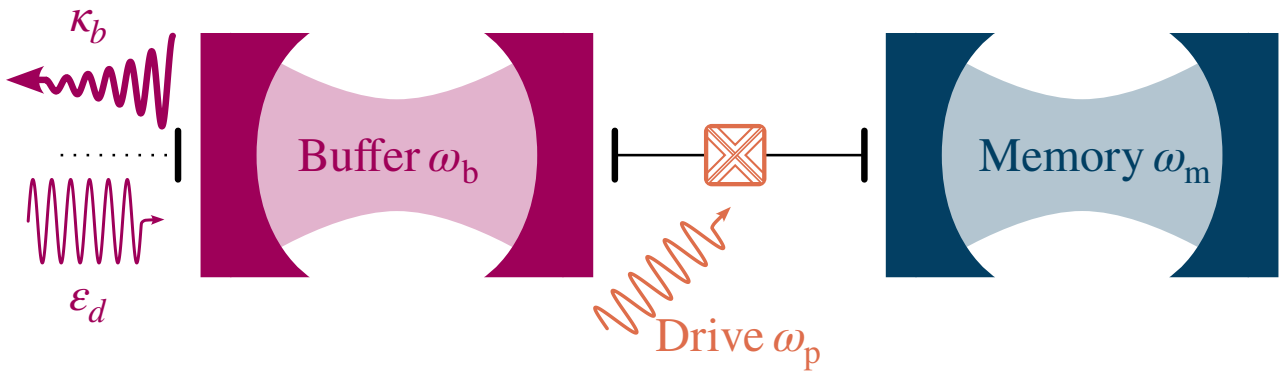

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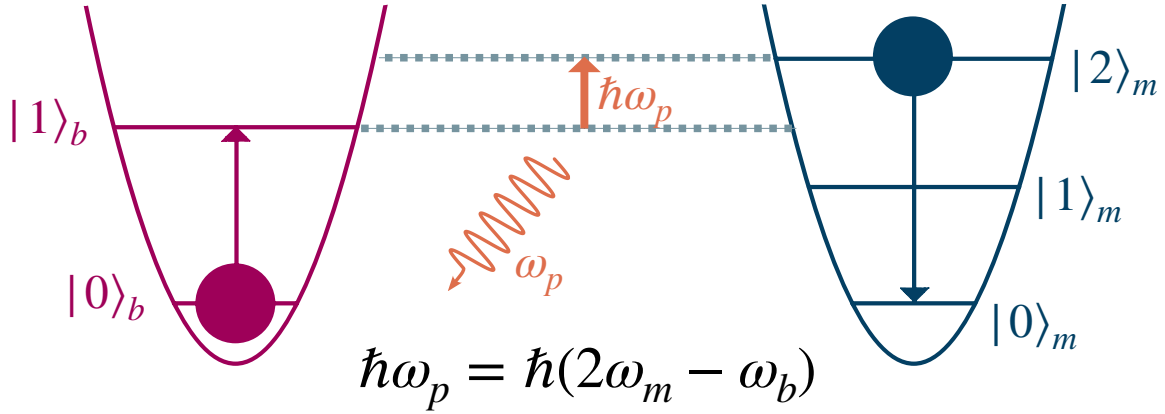

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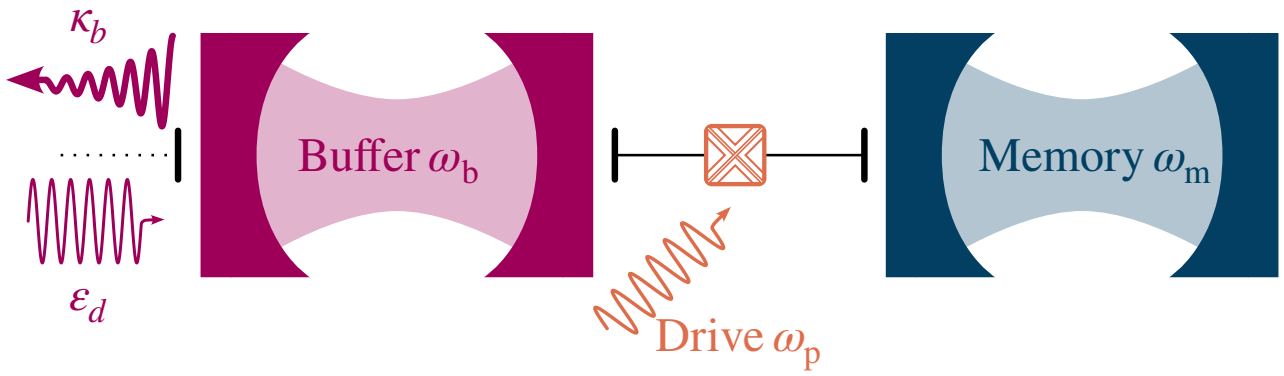

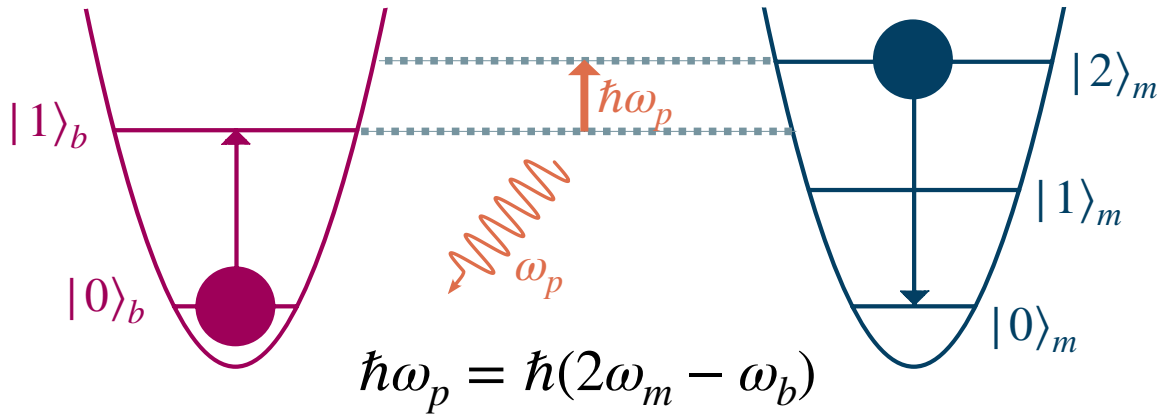

$$\hat{H}/\hbar = g_2\,\hat{a}^{\dagger 2}\hat{b} + g_2^*\,\hat{a}^2\hat{b}^\dagger$$

Buffer drive & buffer dissipation

$$\hat{L}_2 = \sqrt{\kappa_2}\left(\hat{a}^2 - \alpha^2\right)$$
$$\text{with } \kappa_2 = 4\left|g_2\right|^2/\kappa_b$$

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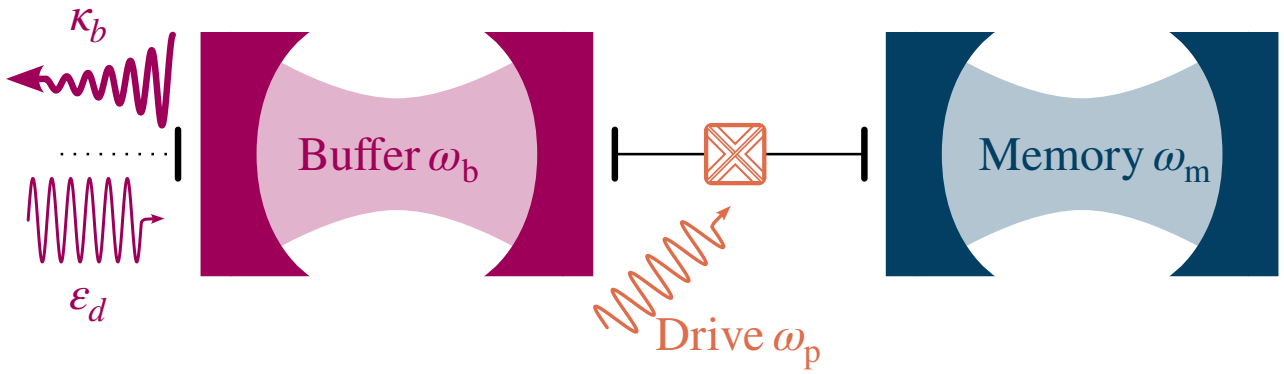

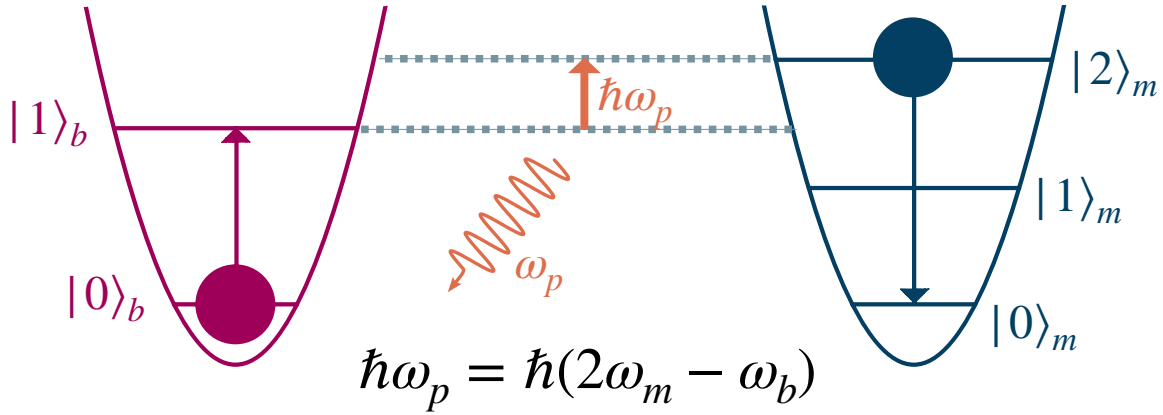

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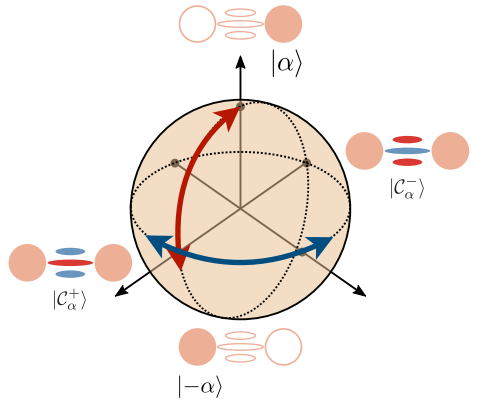

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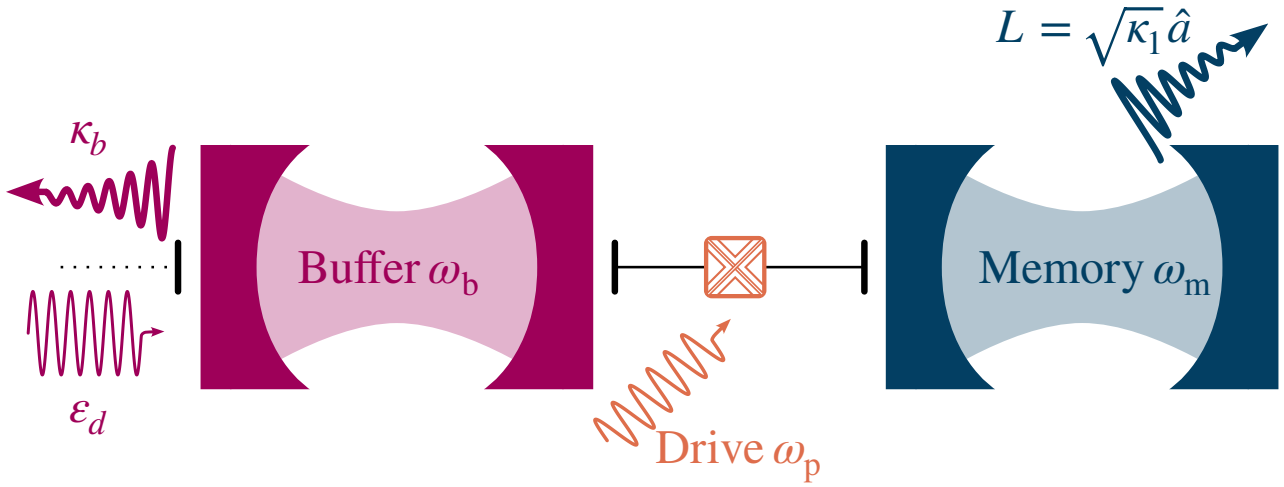

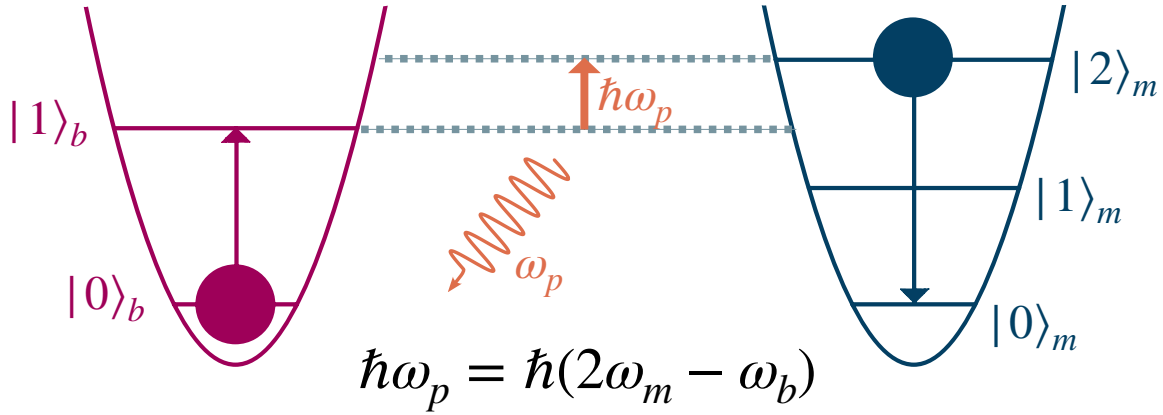

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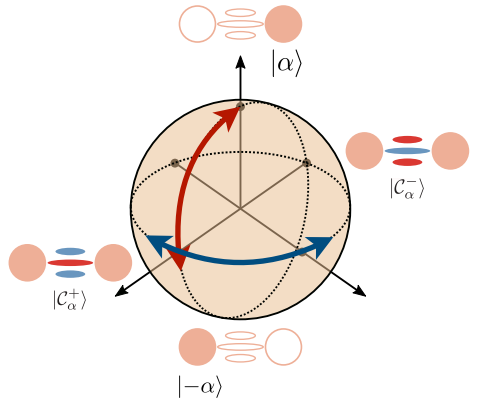

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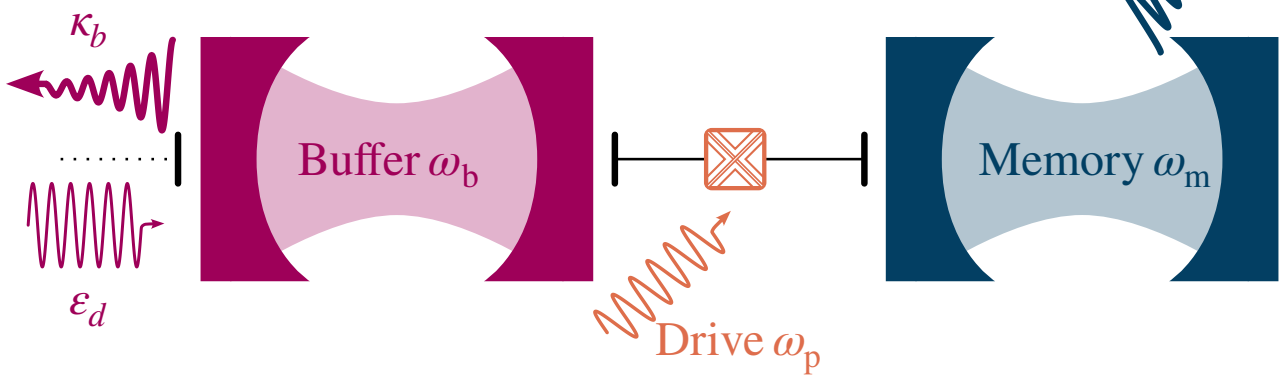
Using dissipation to stabilize cat qubits

$L = \sqrt{\kappa_1}\,\hat{a}$ → Increases $\Gamma_{\text{phase-flip}}$



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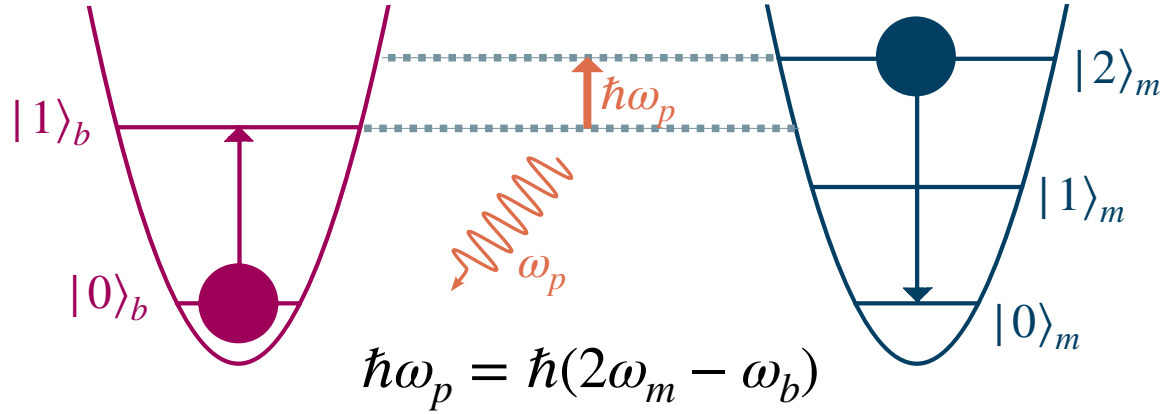

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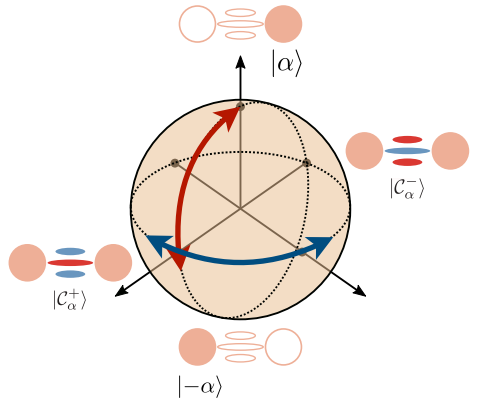

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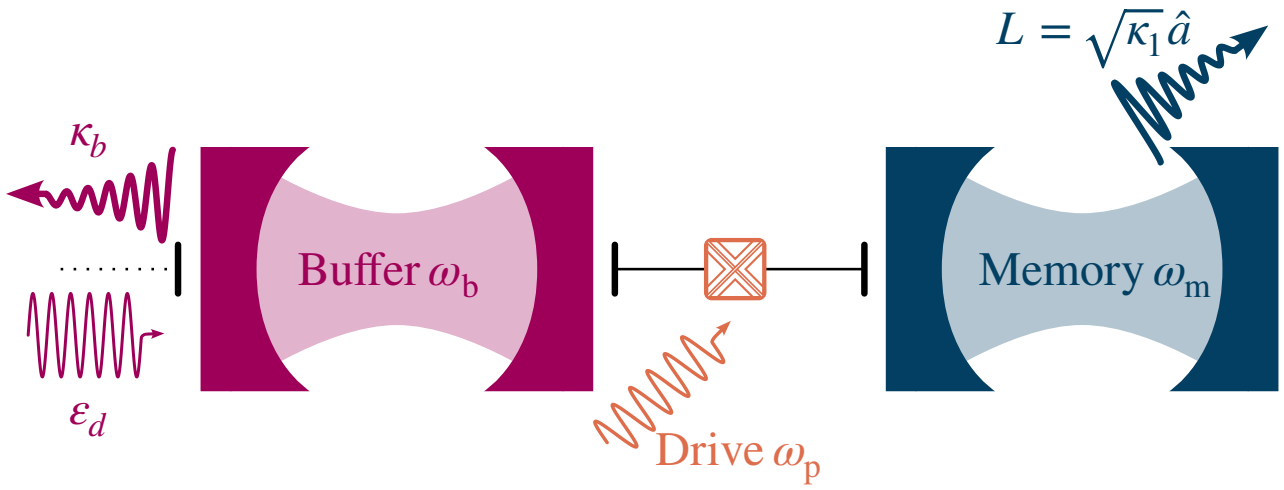

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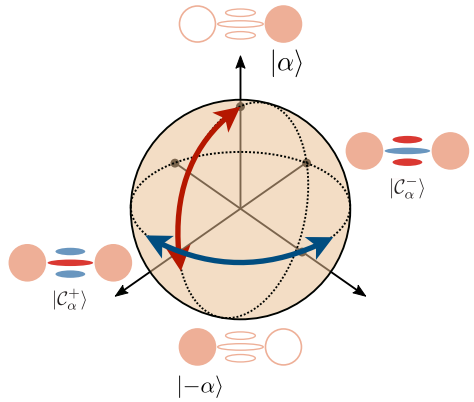
Goal

$$\frac{\text{stabilization}}{\text{errors}} = \frac{\kappa_2}{\kappa_1}\ \text{large}$$



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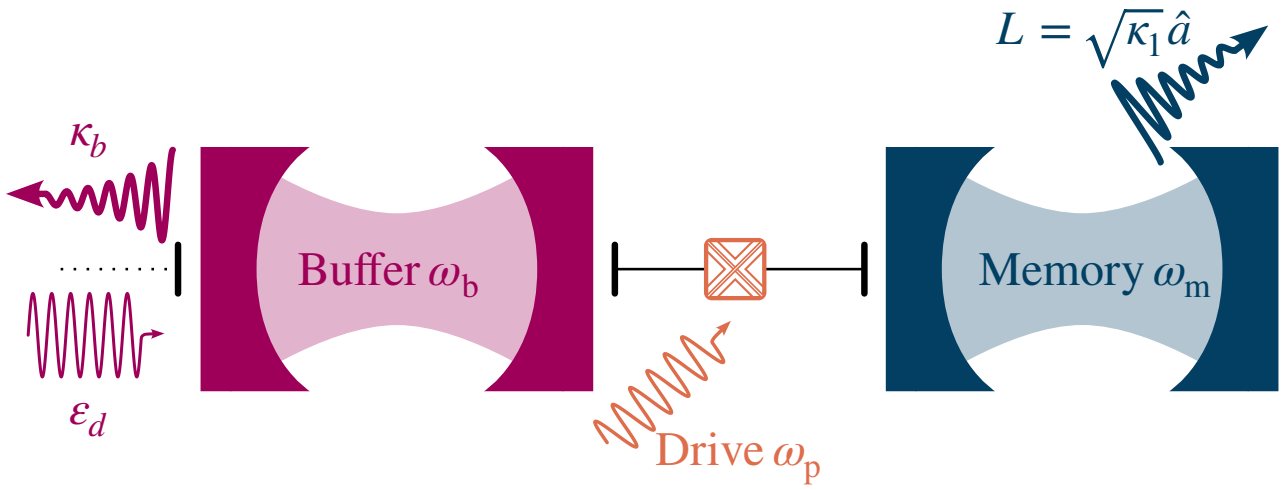

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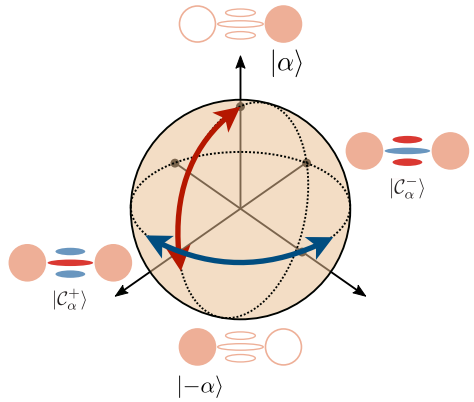
Threshold

$$\frac{\kappa_2}{\kappa_1} > 1000$$



[F-M. Le Regent et al. Quantum, 2015 (A&B, ENS Paris)]
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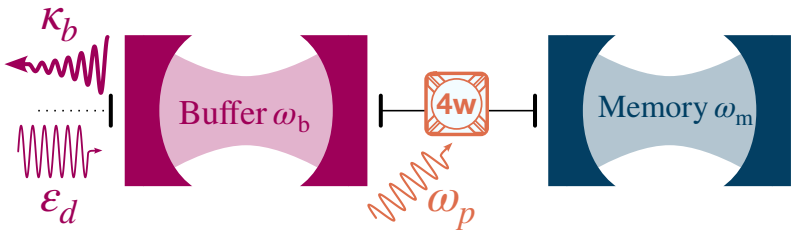
State of the art

ATS: 4-wave mixing



$$\omega_p = 2\omega_m - \omega_b$$

$$\kappa_2^{\max}/2\pi = 0.9\,\mathrm{MHz}$$

$$\frac{\kappa_2}{\kappa_1} \approx 100$$

[U. Réglade at al. , Nature 2024 (A&B, ENS Paris)]
[H. Putterman at al. , Nature 2025 (AWS]
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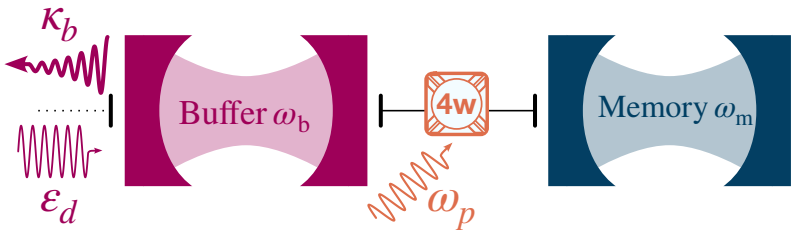

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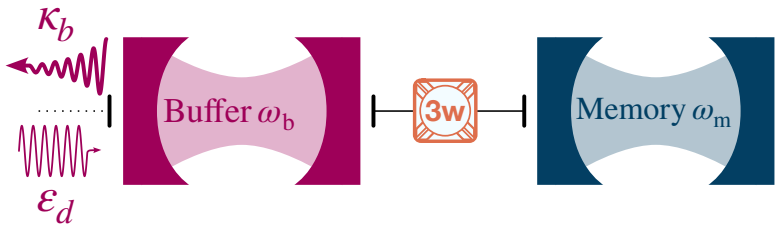
Autoparametric cat: 3-wave mixing



$$2\omega_m = \omega_b$$

$$\kappa_2^{\max}/2\pi = 2\,\mathrm{MHz}$$

$$\frac{\kappa_2}{\kappa_1} \approx 150$$

[A. Marquet at al. , PRX 2024 (A&B, ENS Lyon)]

State of the art

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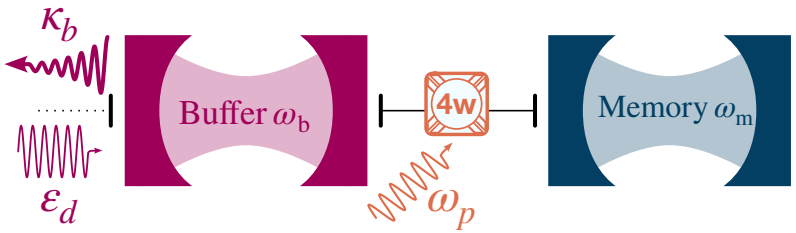

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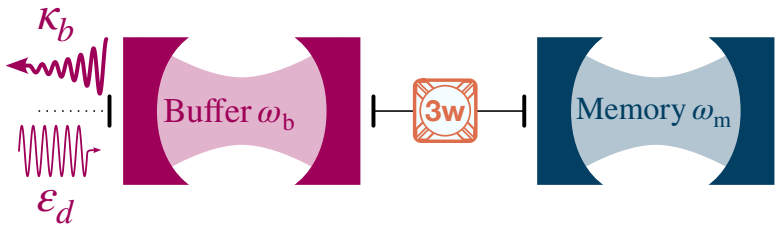

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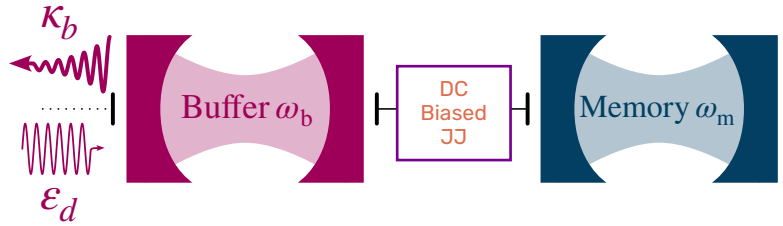
New approach: DC-biased junction



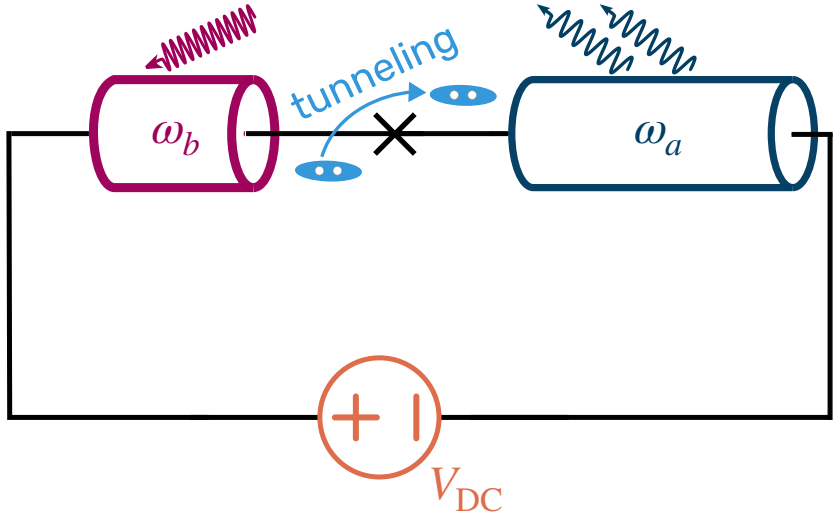
Replace wave-mixing with a quantum conductor

↓

Push $\frac{\kappa_2}{\kappa_1}$ beyond state of the art

The DC-pative cat: a new approach

Dissipation engineering with a DC-biased Josephson junction



Energy matching condition

$$2eV_{\mathrm{DC}} = \hbar(2\omega_a - \omega_m)$$

$$\hat{H}/\hbar = g_2\, \hat{a}^{\dagger 2}\hat{b} + g_2^*\, \hat{a}^2\hat{b}^\dagger$$

[M. Hofheinz at al. , PRL 2011 (A&B, CEA Saclay)]
[A. Peugeot at al. , PRX 2021 (Saclay)]
[T. Assaoui at al. , arxiv 2024 (A&B, ENS Paris)]
[G. Aiello at al. , Nat. Comm. 2022 (Saclay)]

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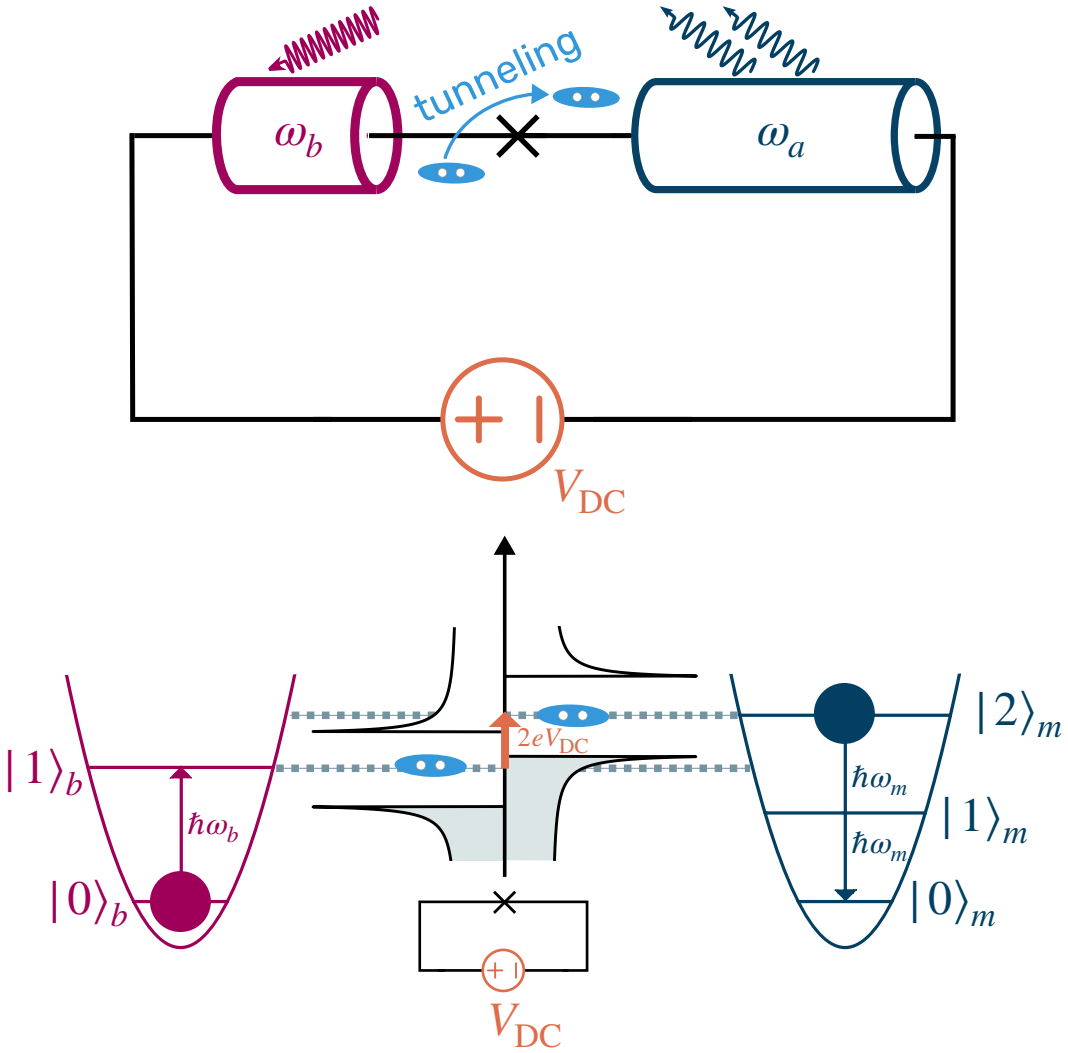

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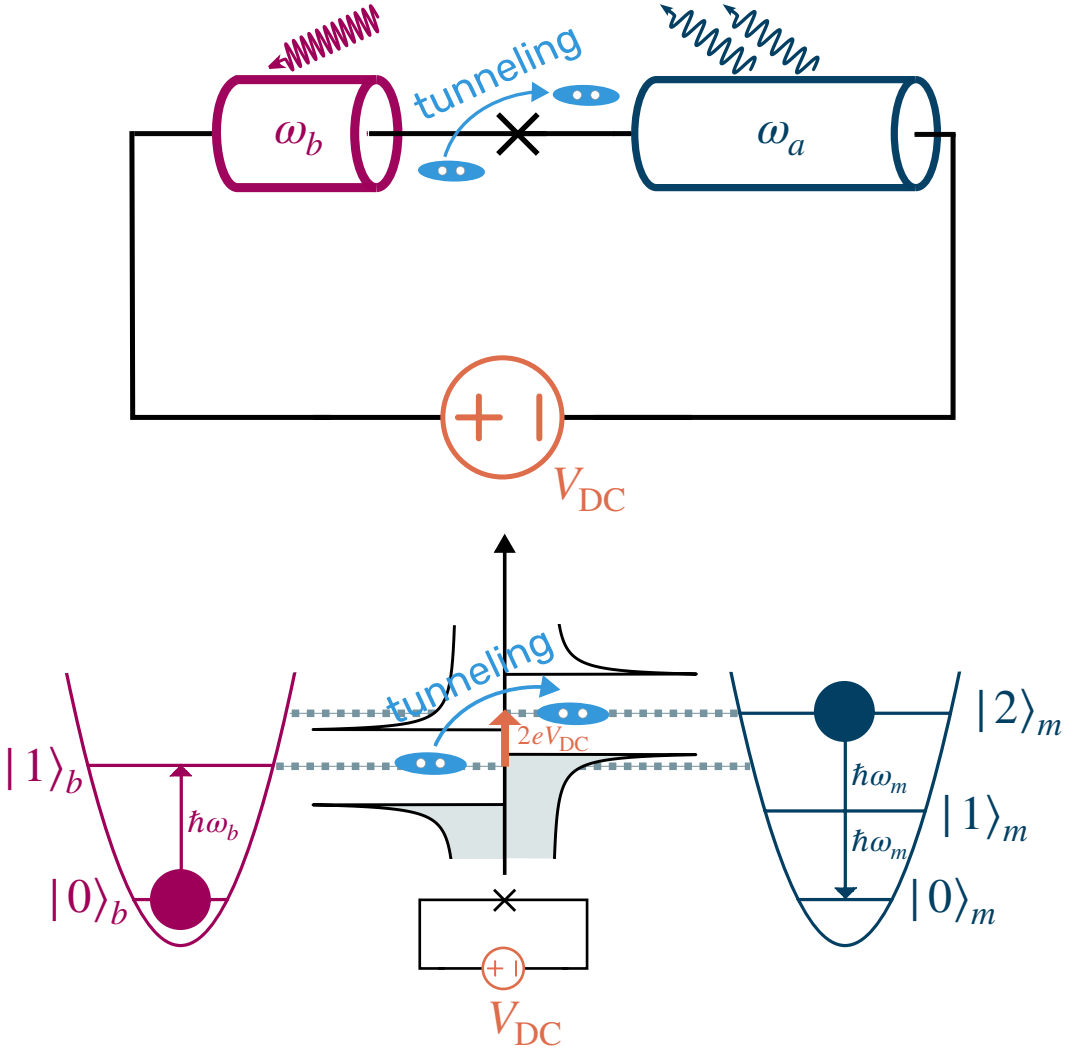

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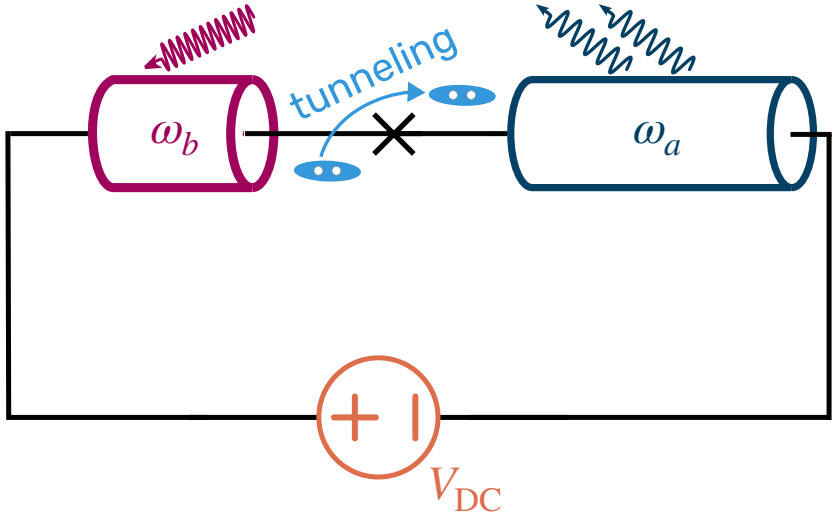
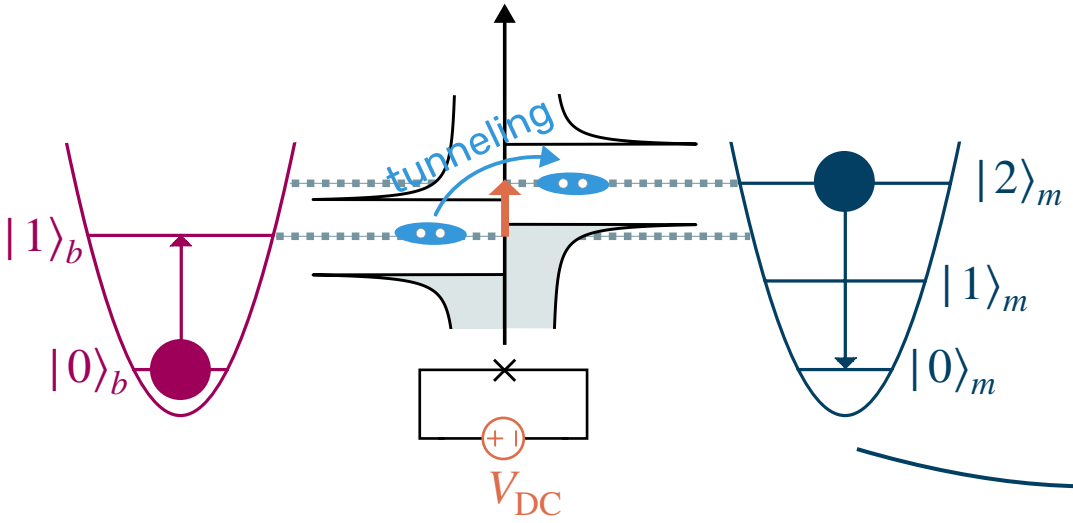
[G. Aiello at al. , Nat. Comm. 2022 (Saclay)]

The DC-pative cat: a new approach

Dissipation engineering with a DC-biased Josephson junction





Energy matching condition

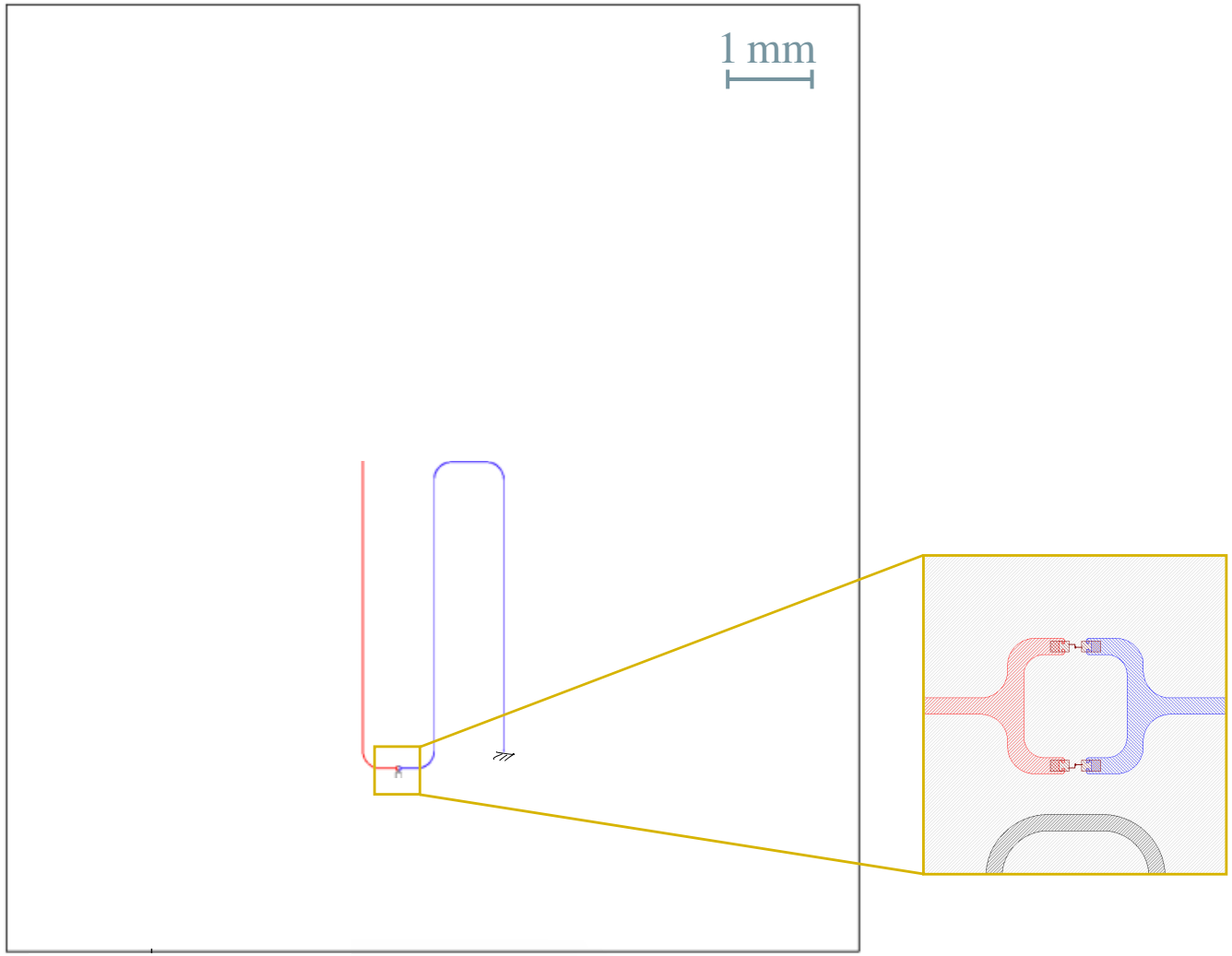
$$2eV_{DC} = \hbar(2\omega_a - \omega_m)$$

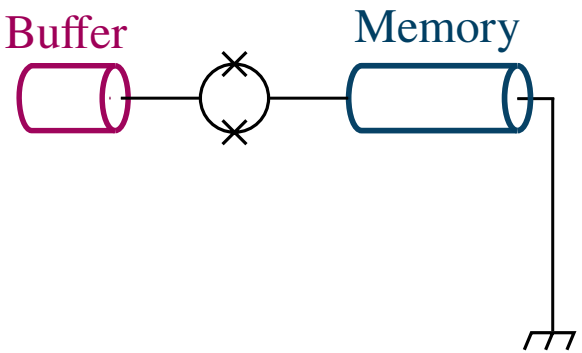
$$\hat{H}/\hbar = g_2\,\hat{a}^{\dagger 2}\hat{b} + g_2^*\,\hat{a}^2\hat{b}^\dagger$$

Must be a high Q resonator

[M. Hofheinz at al. , PRL 2011 (A&B, CEA Saclay)]
[A. Peugeot at al. , PRX 2021 (Saclay)]
[T. Assaoui at al. , arxiv 2024 (A&B, ENS Paris)]
[G. Aiello at al. , Nat. Comm. 2022 (Saclay)]

Our design





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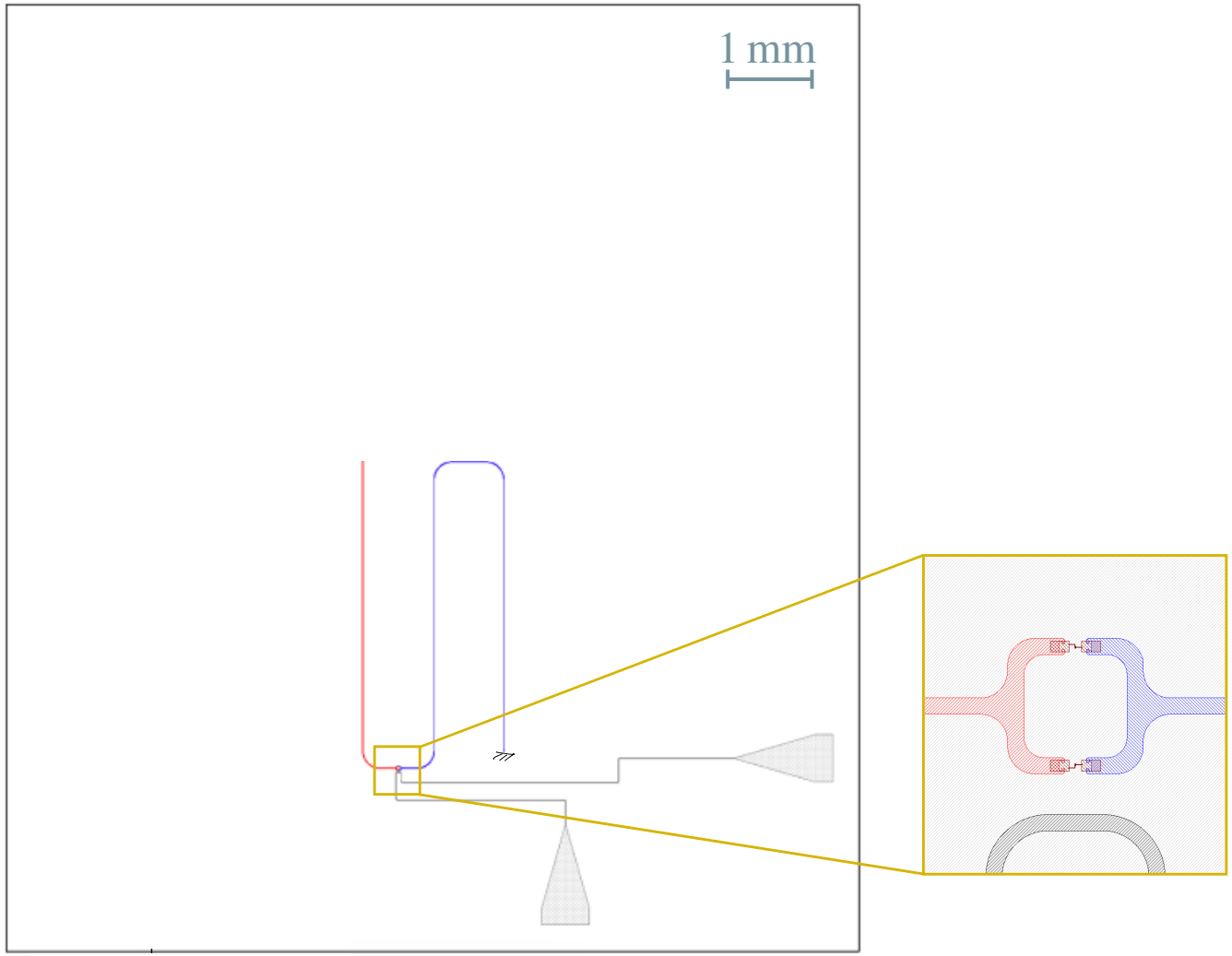
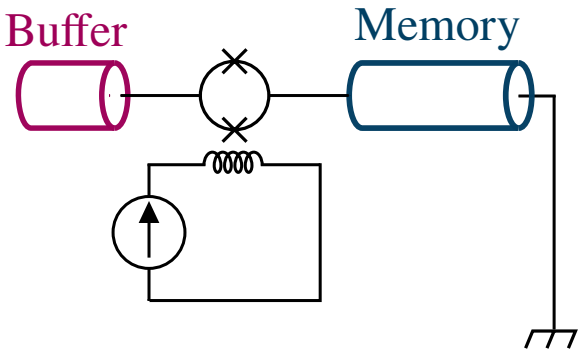




Our design

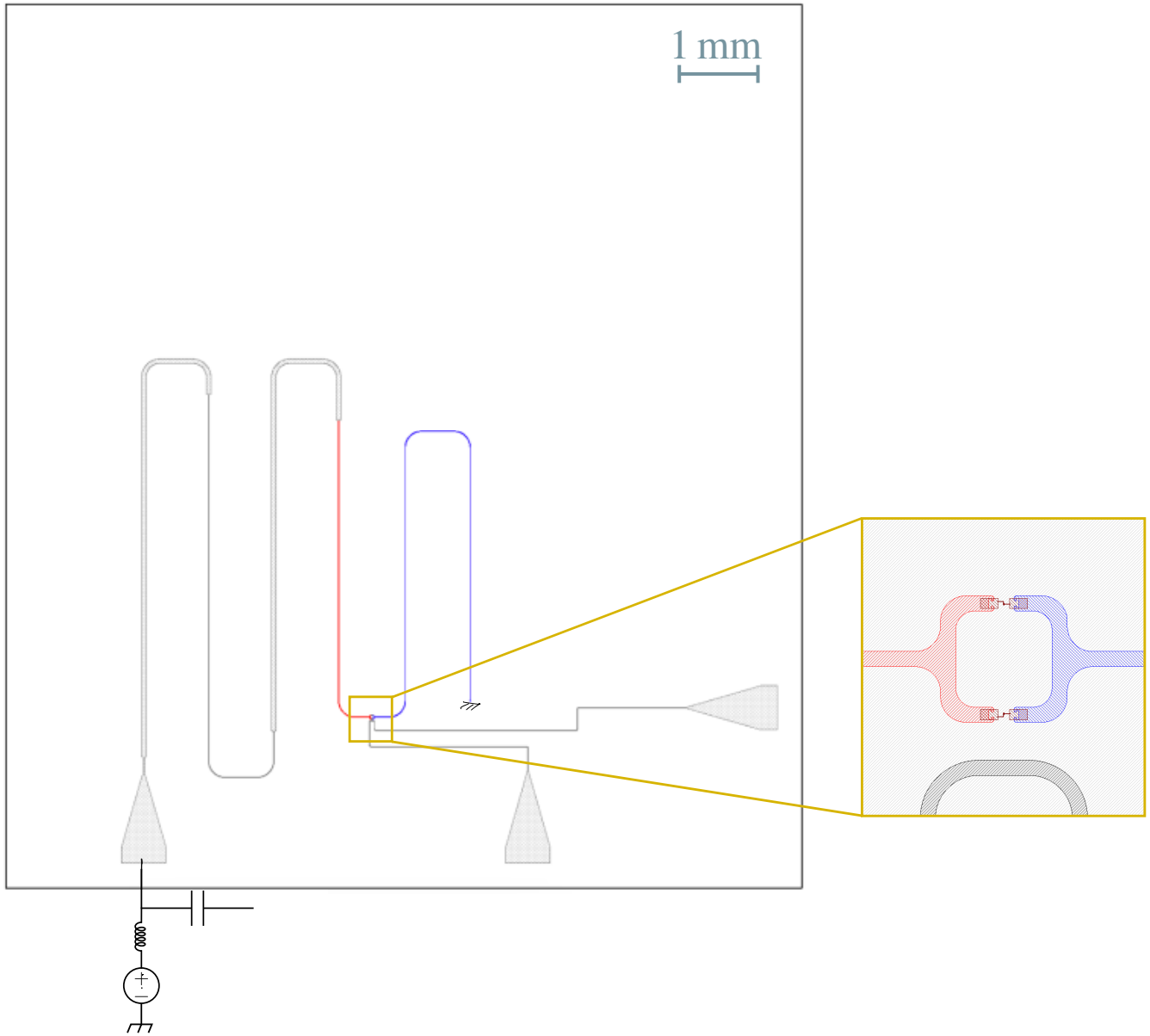
At $V \neq 0$

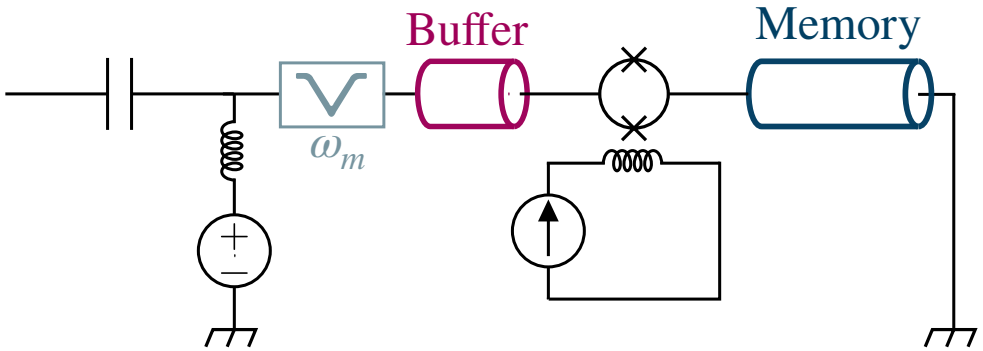
$\omega_b/2\pi = 7.6\,\mathrm{GHz}$

$\omega_m/2\pi = 4\,\mathrm{GHz}$

$\kappa_b^{\mathrm{tot}}/2\pi = 150\,\mathrm{MHz}$

$\kappa_m^{\mathrm{coupling}}/2\pi = 1\,\mathrm{kHz}$





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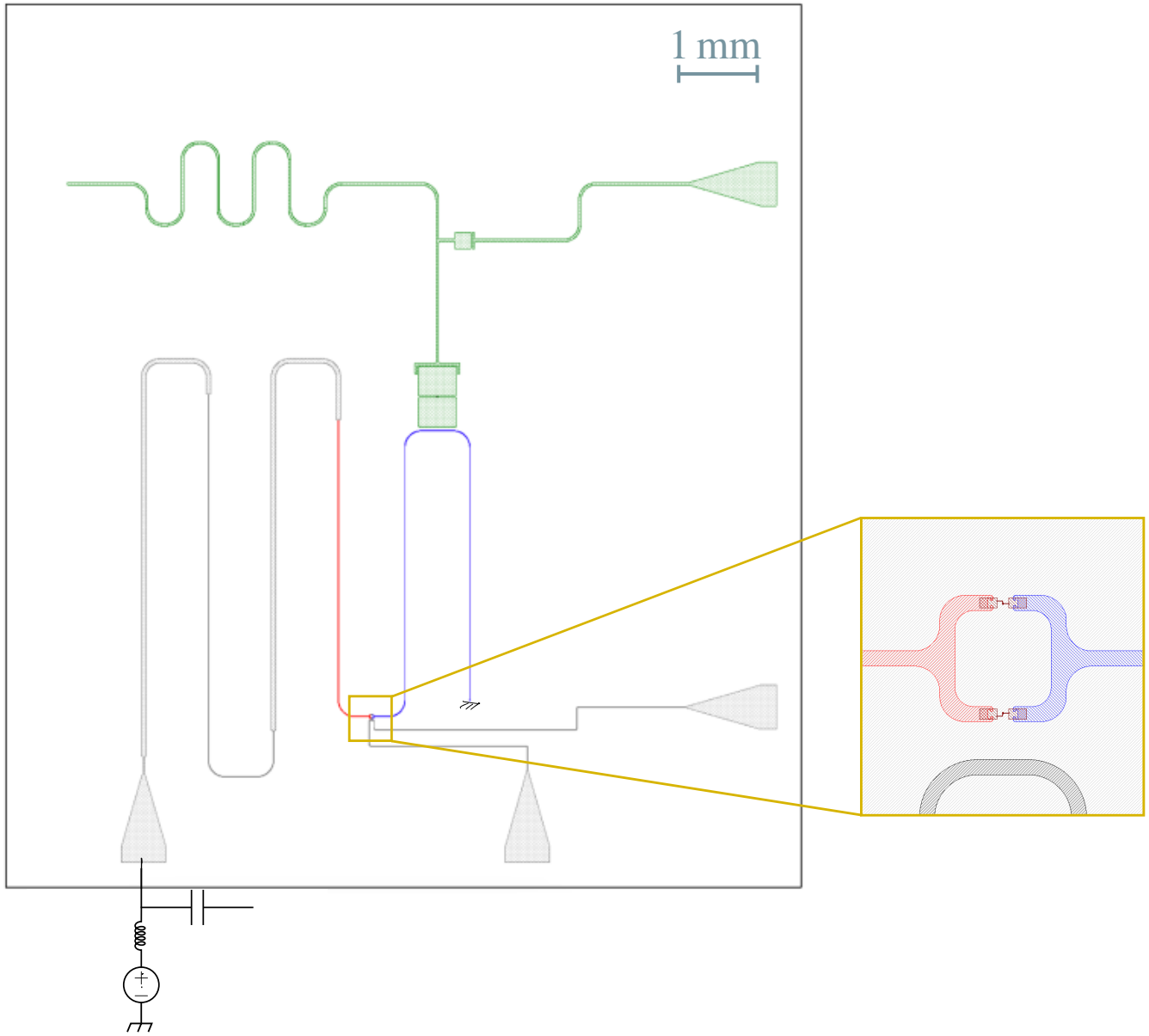

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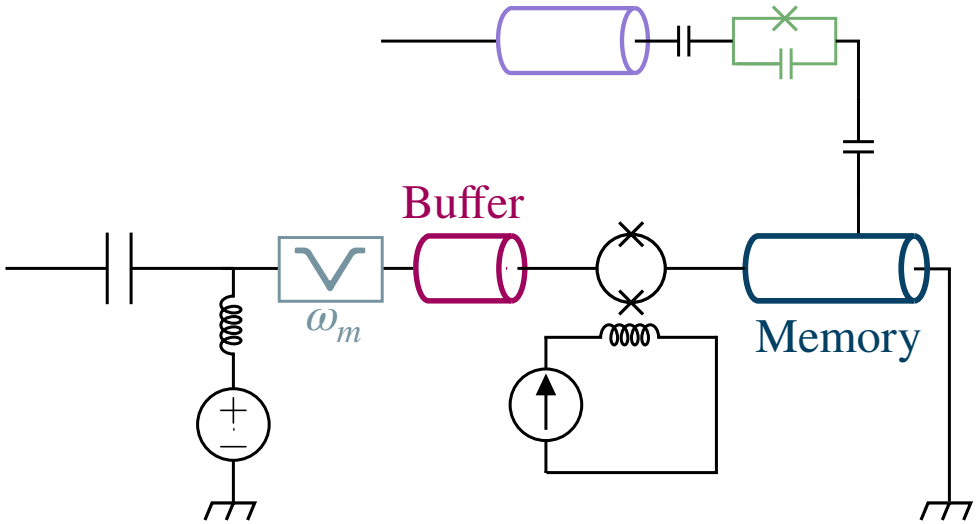

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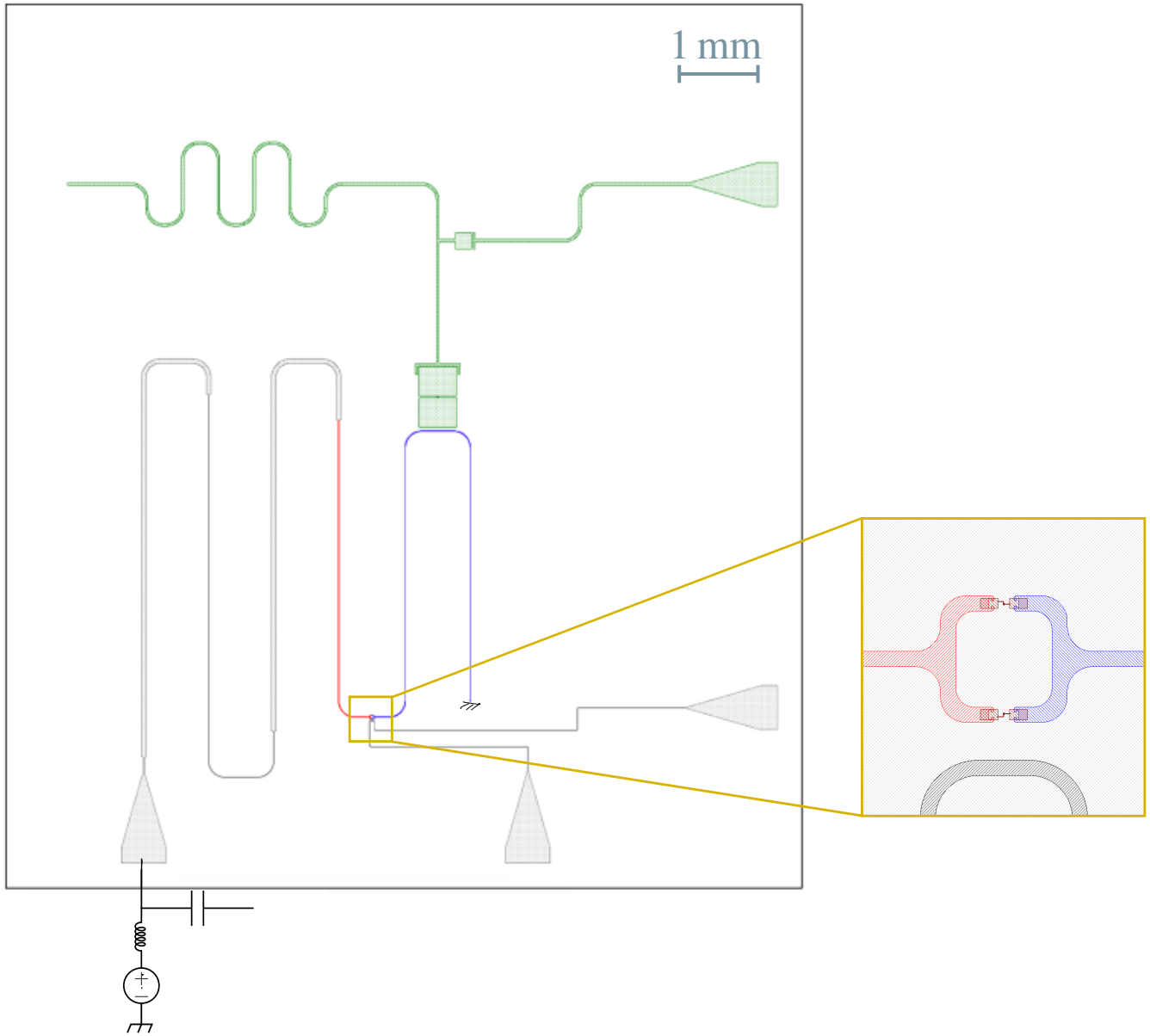

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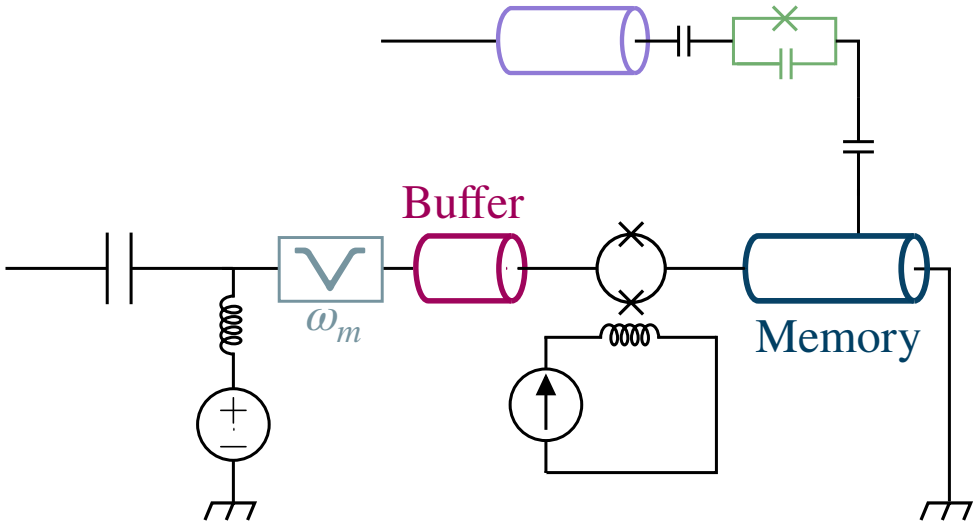
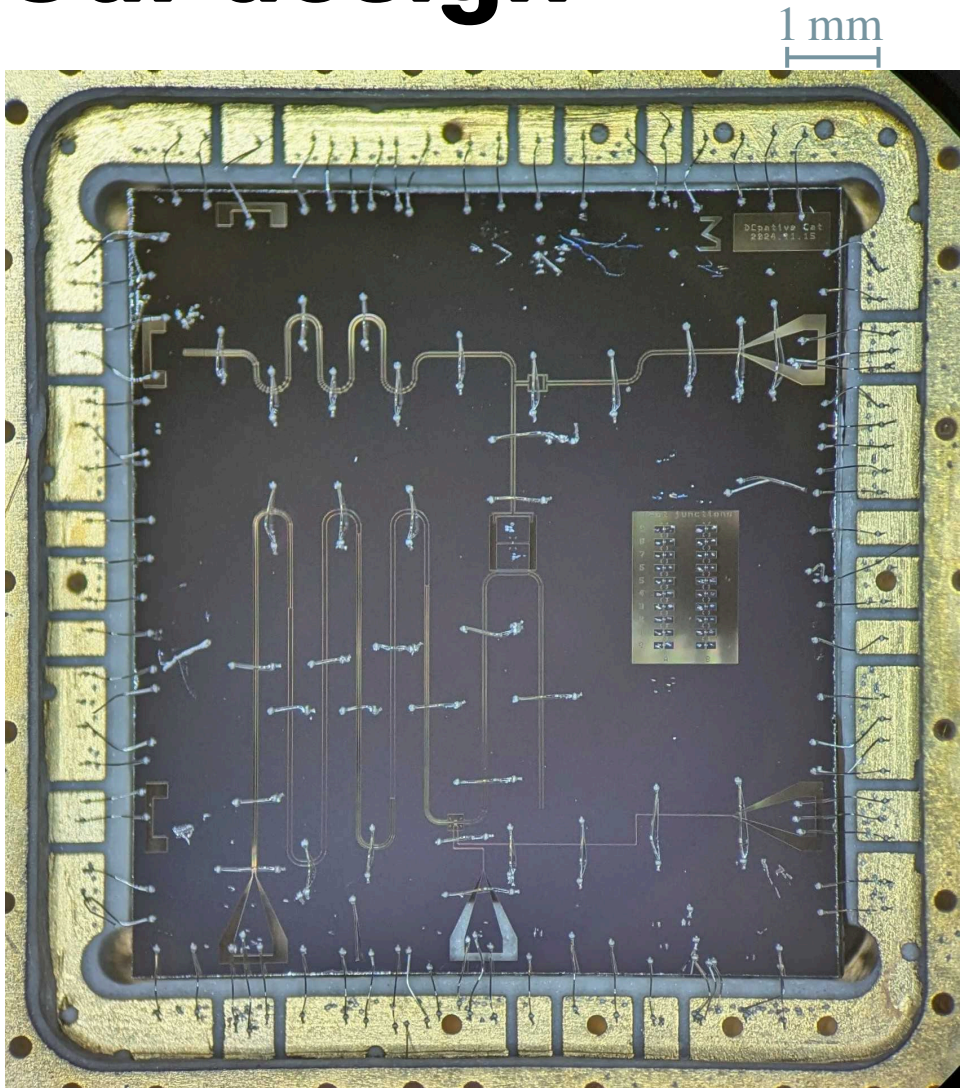


Expected

$\kappa_2/2\pi \approx 10\,\mathrm{MHz}$

$\frac{\kappa_2}{\kappa_1} \approx 250$

Our design



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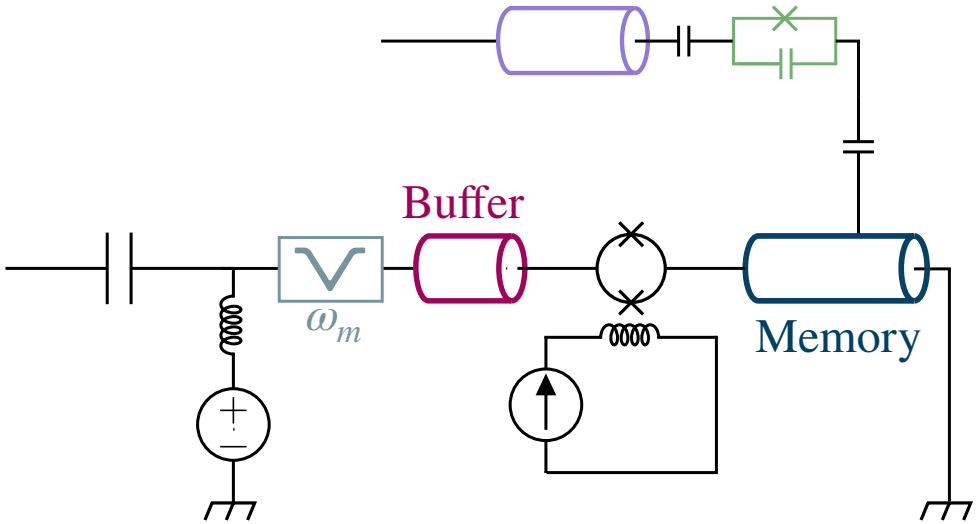

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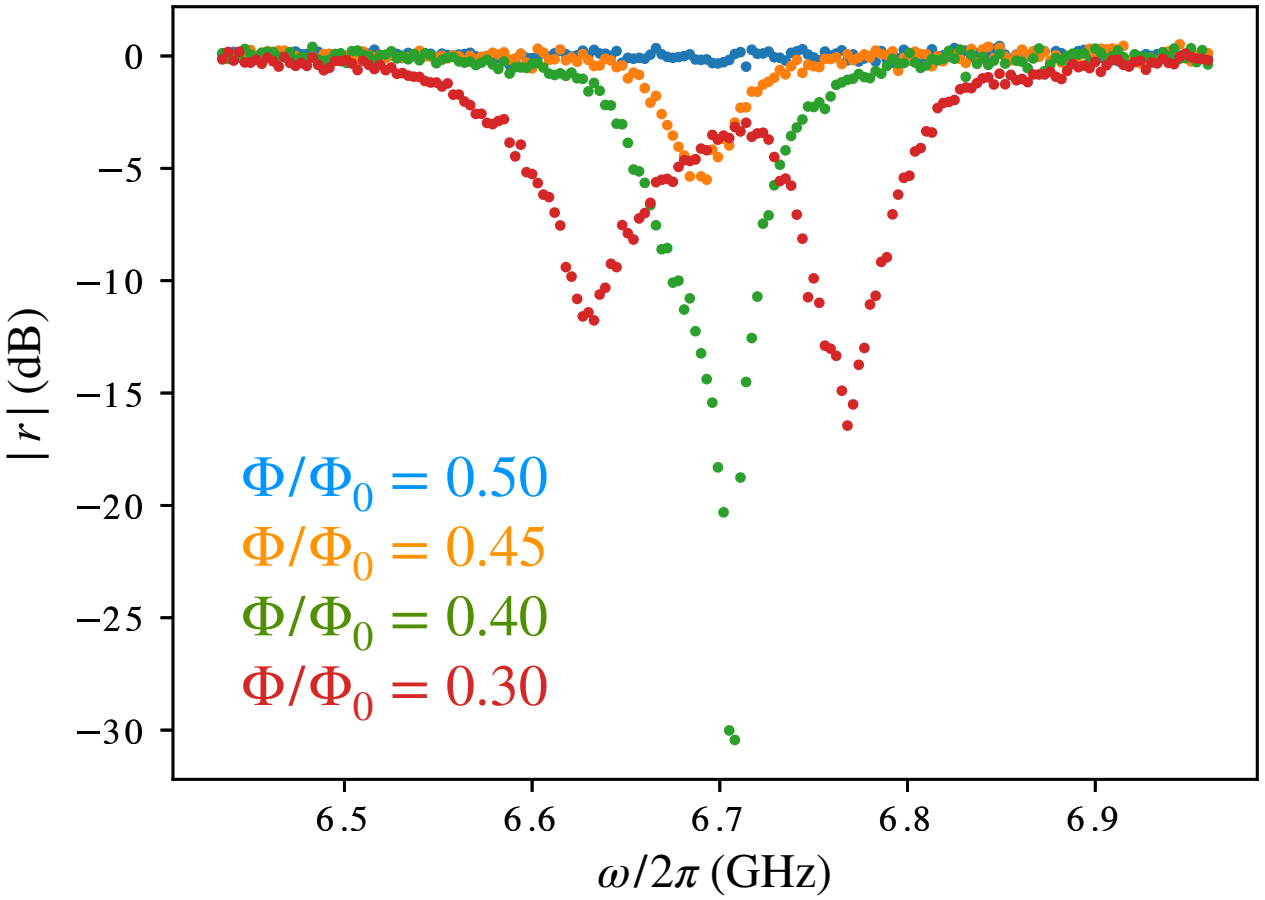
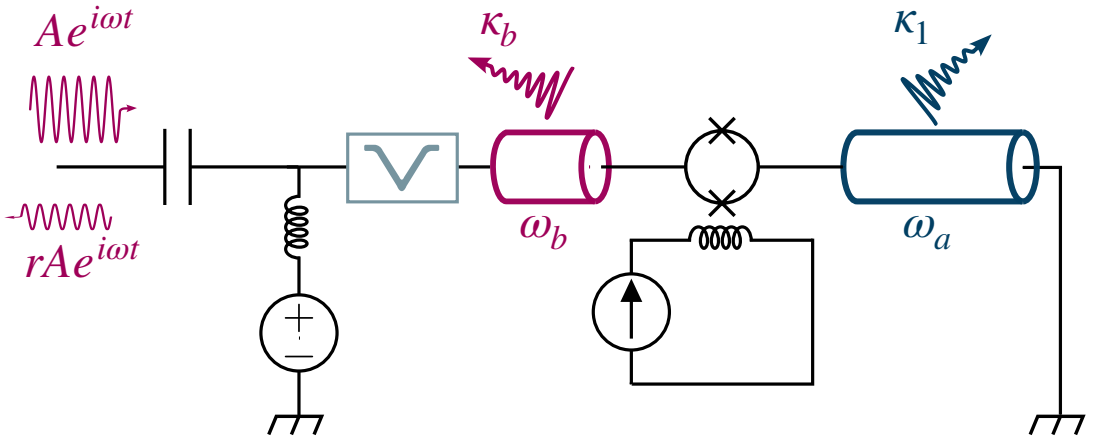
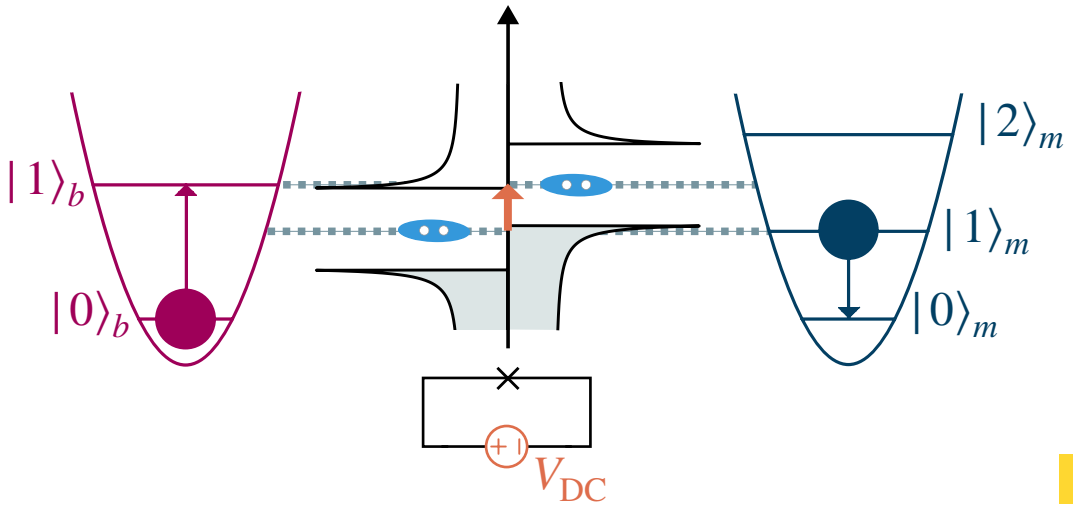
1-to-1 photon exchange



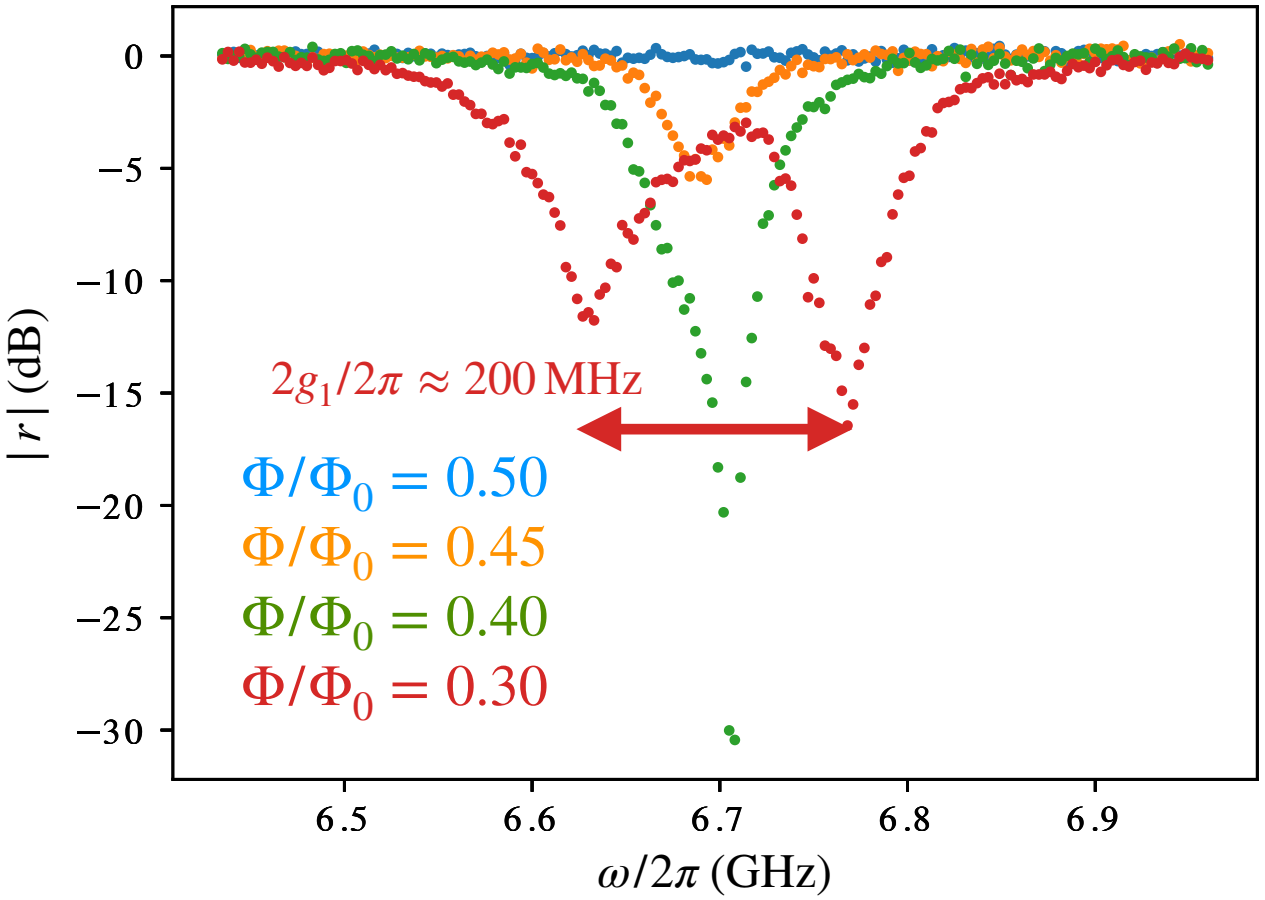


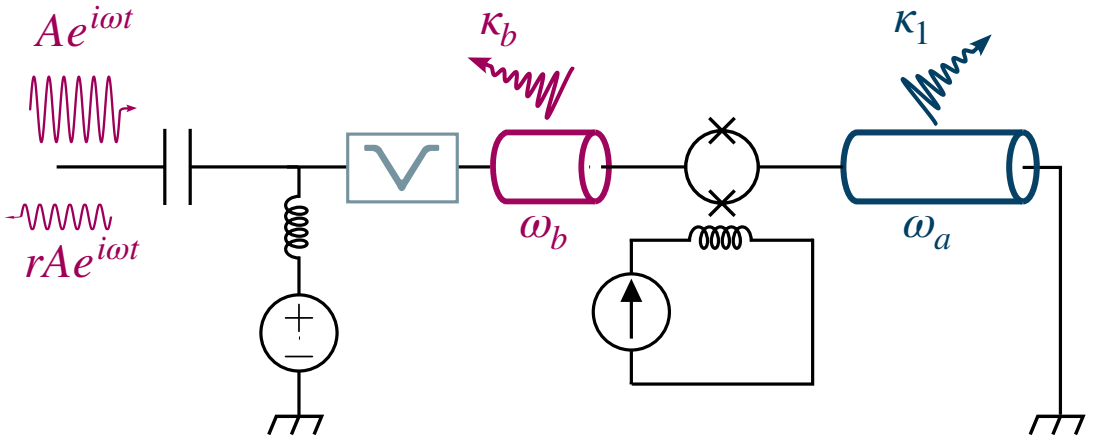
$$\frac{2eV_{\mathrm{DC}}}{\hbar} = \omega_b - \omega_m$$

$$\hat{H}/\hbar = g_1(\Phi_{\mathrm{ext}})\,\hat{a}\,\hat{b}^\dagger + \mathrm{h.c.}$$



1-to-1 photon exchange





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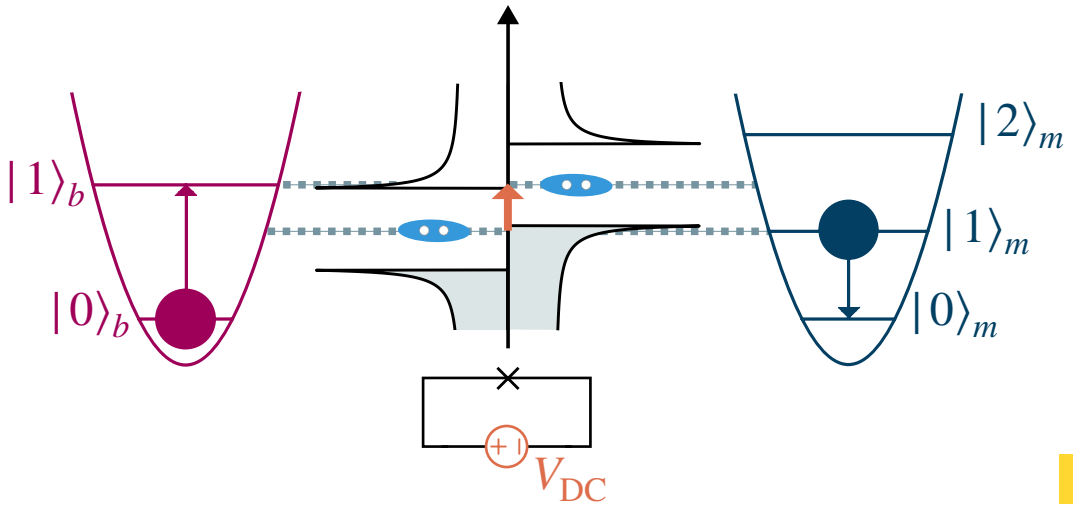

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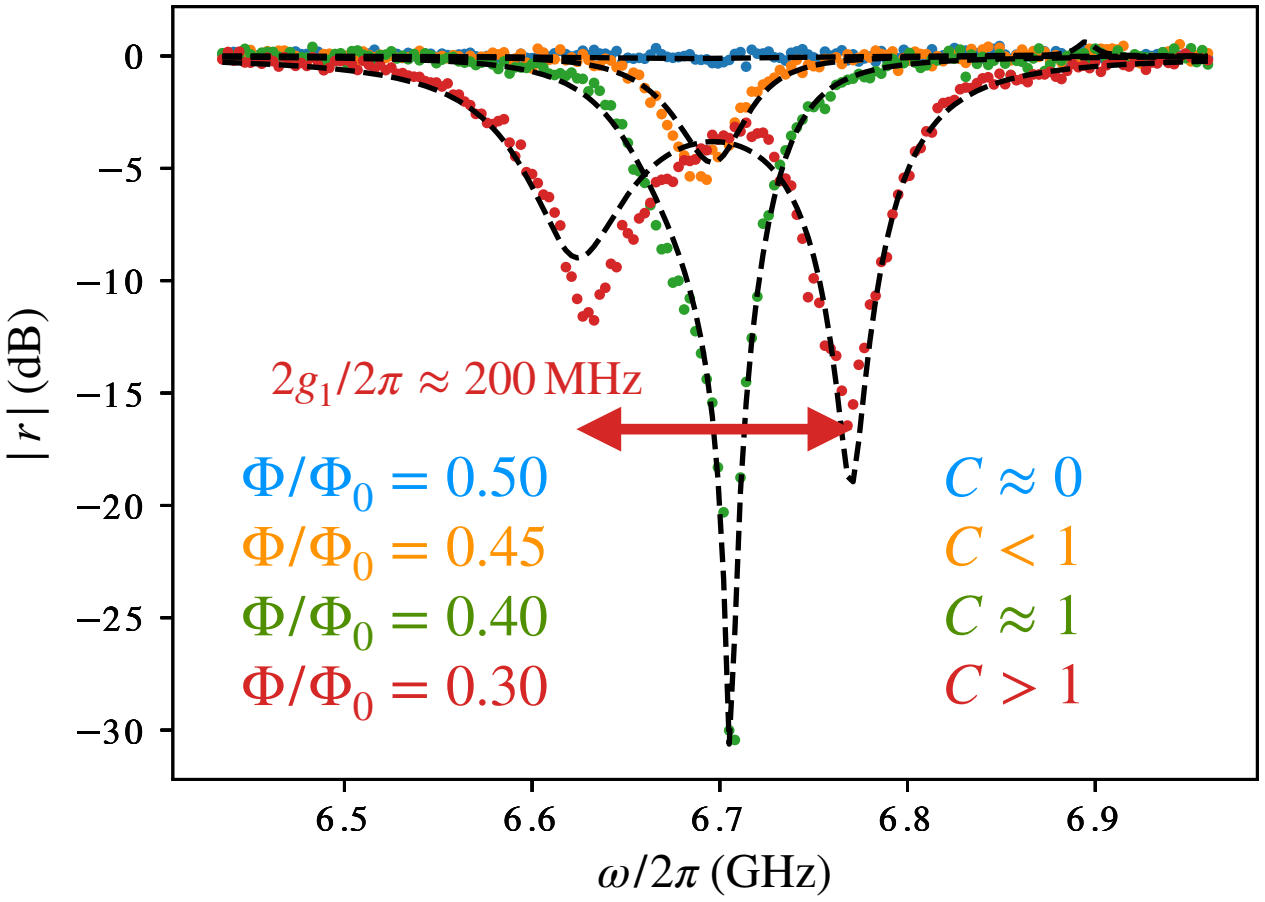
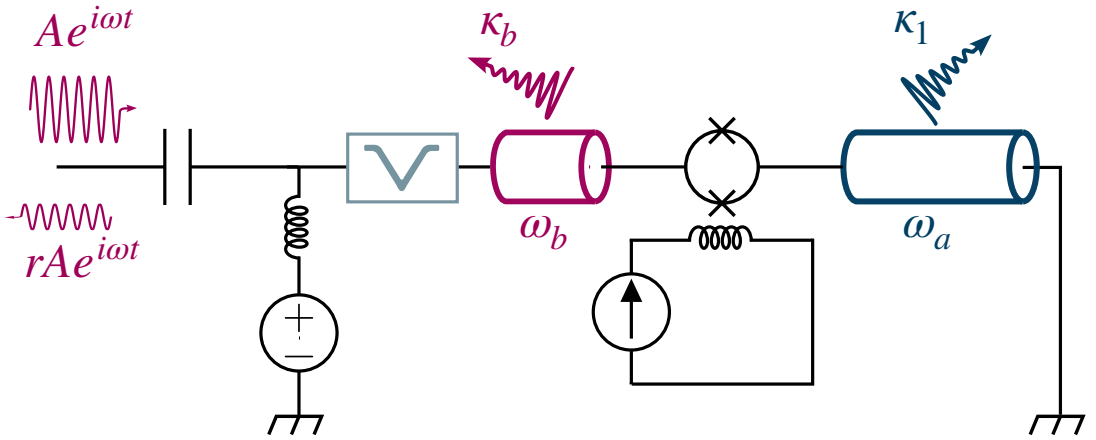


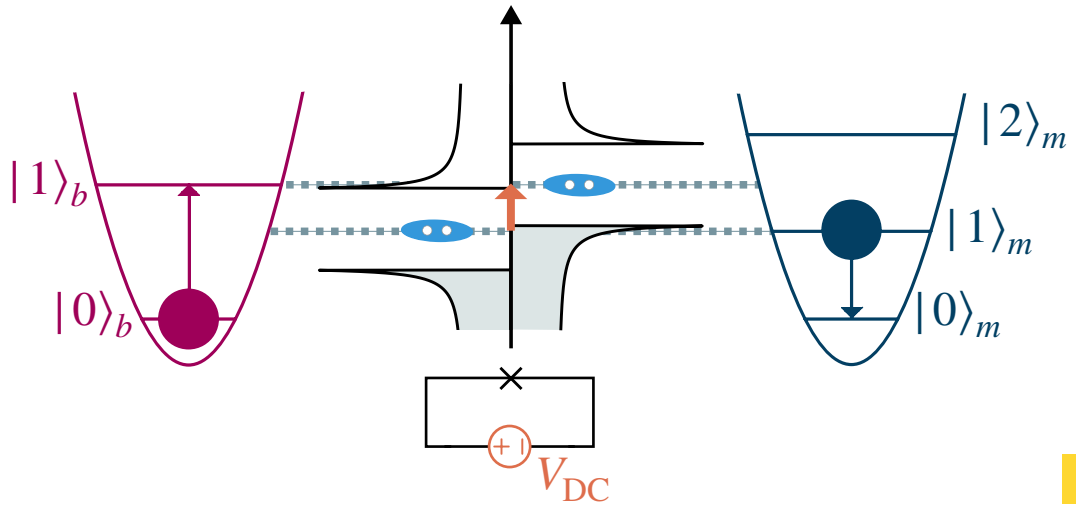


Cooperativity:

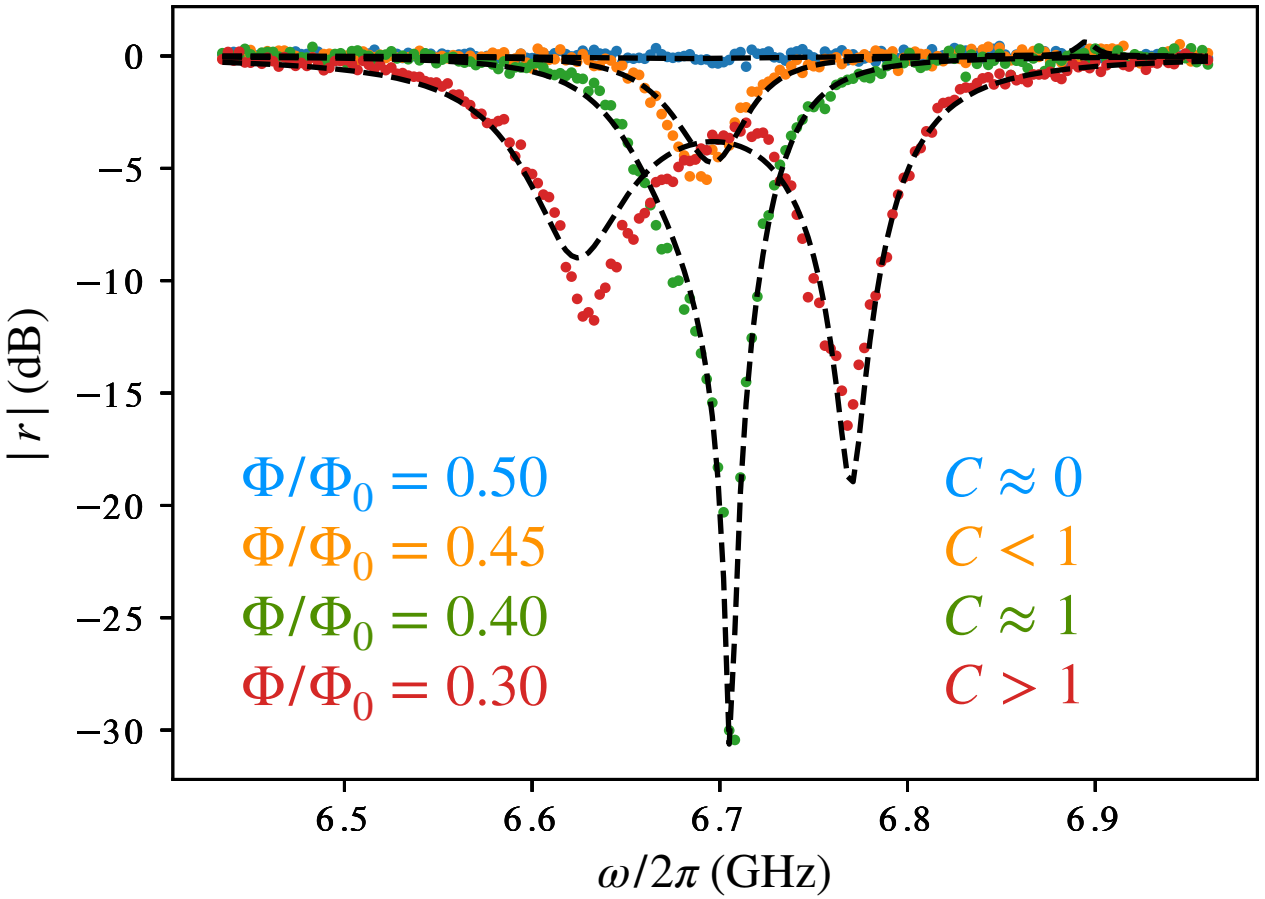
$$C = \frac{4|g_1|^2}{\kappa_b \kappa_m}$$

$$\frac{2eV_{\mathrm{DC}}}{\hbar} = \omega_b - \omega_m$$

$$\hat{H}/\hbar = g_1(\Phi_{\mathrm{ext}})\,\hat{a}\,\hat{b}^\dagger + \mathrm{h.c.}$$

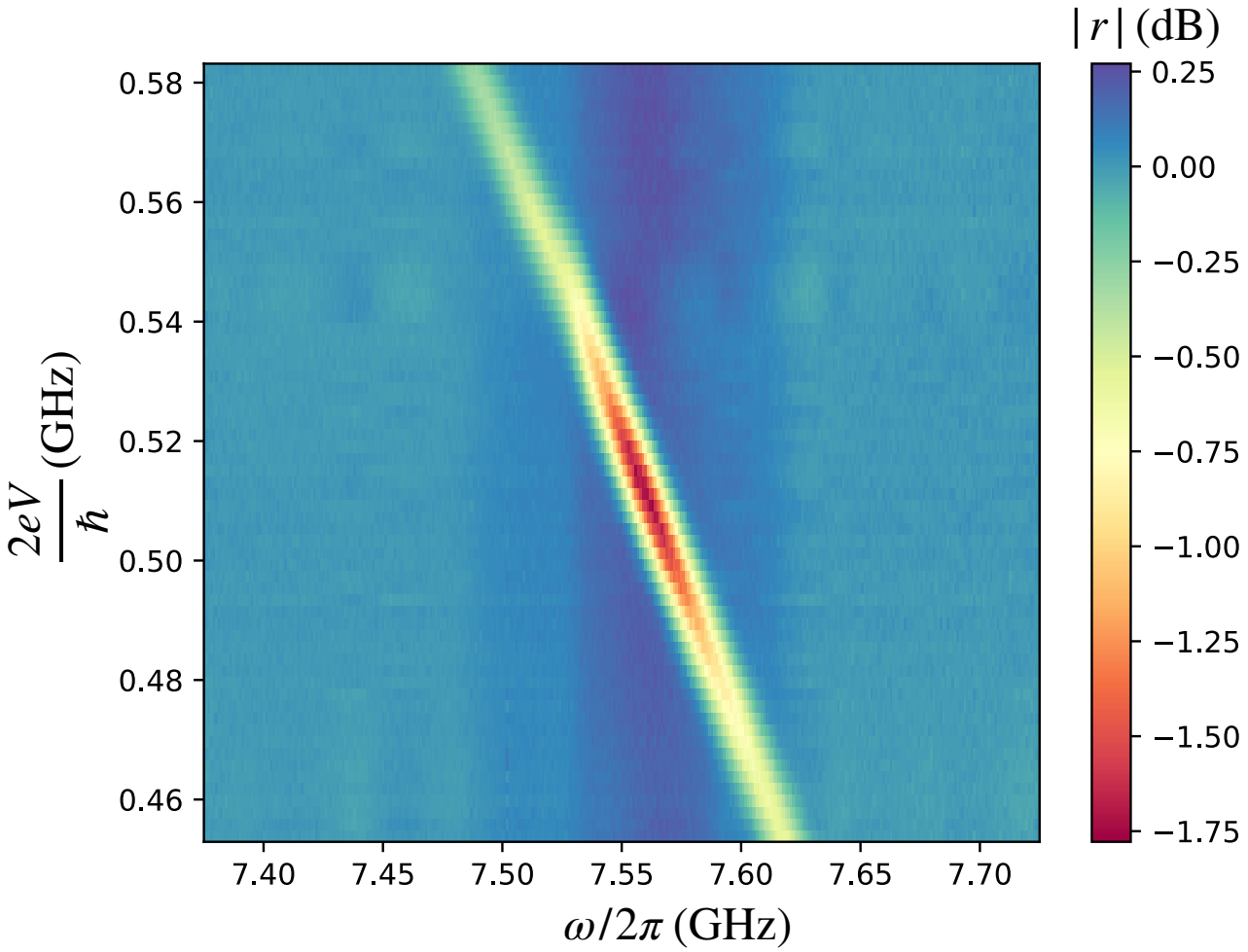


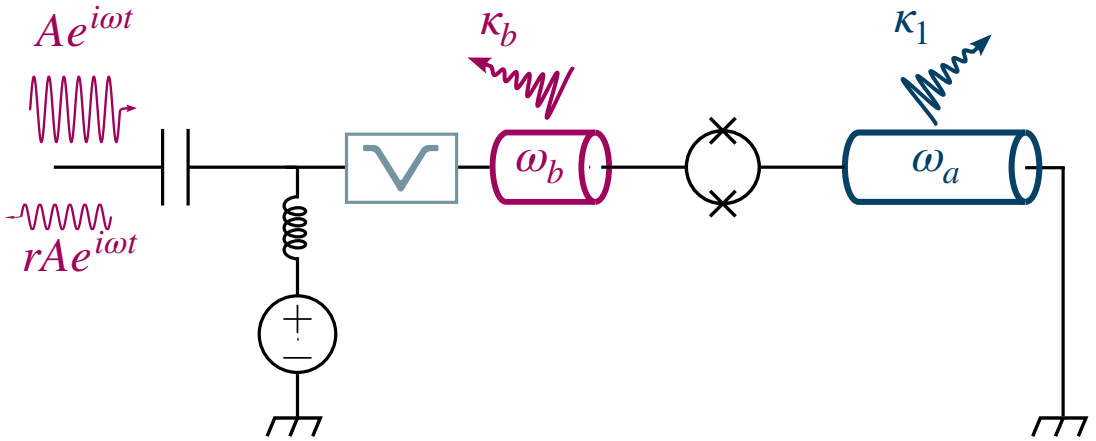
1-to-1 photon exchange



Evidence of 1-to-1 photon exchange

2-to-1 photon exchange





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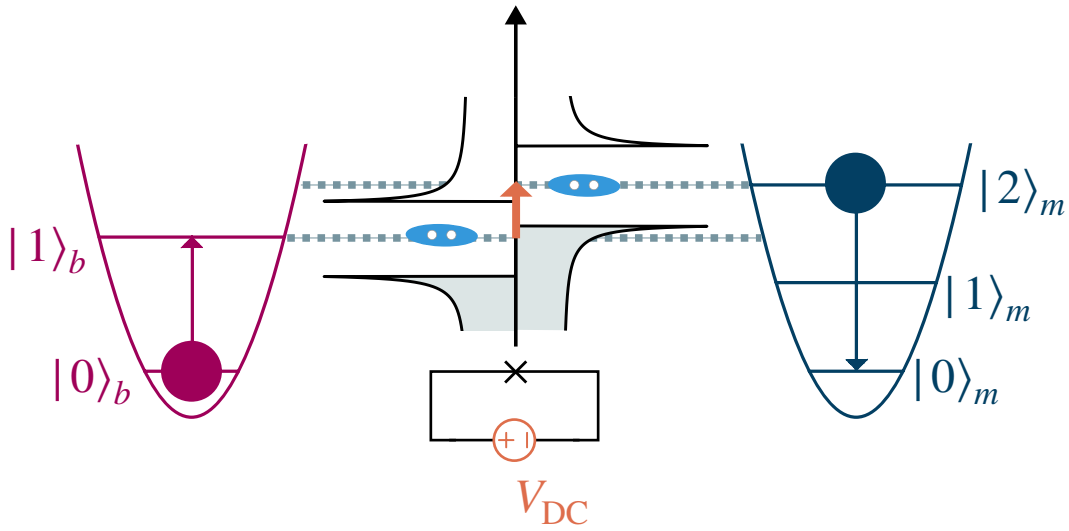
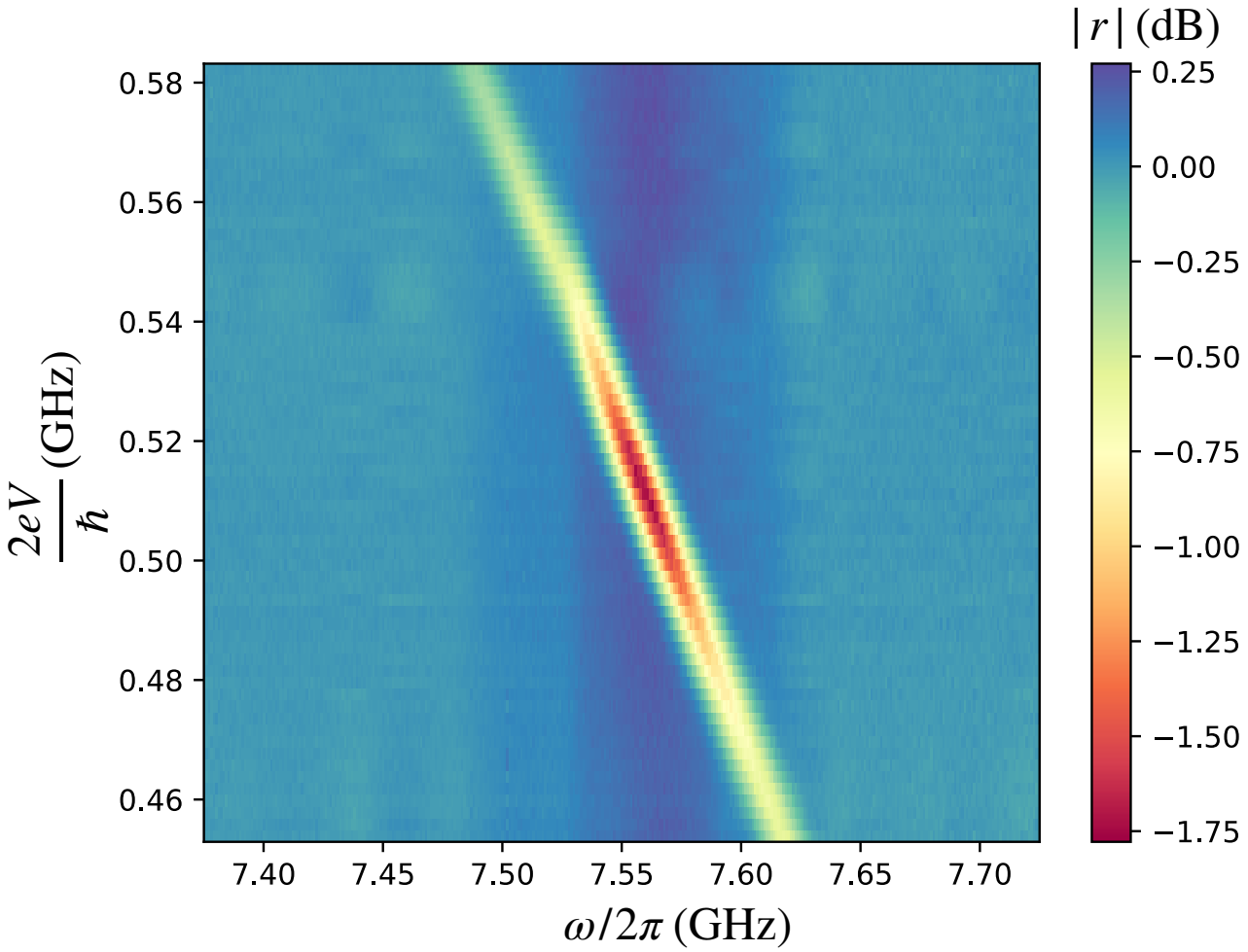
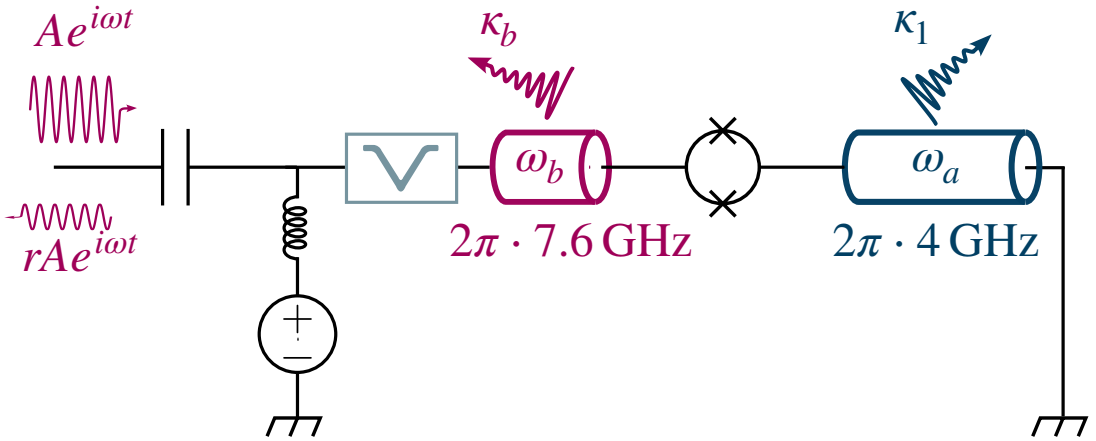


2-to-1 photon exchange





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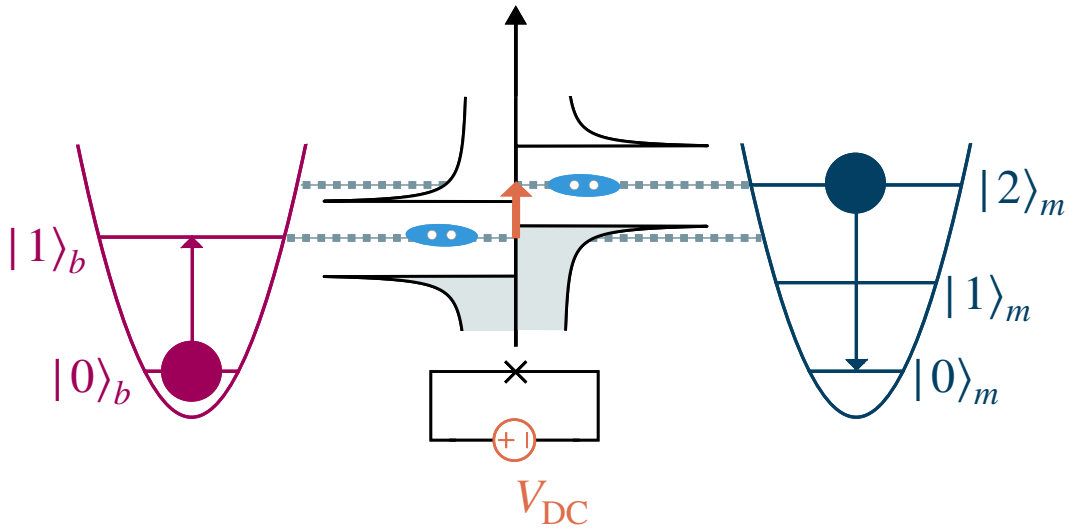
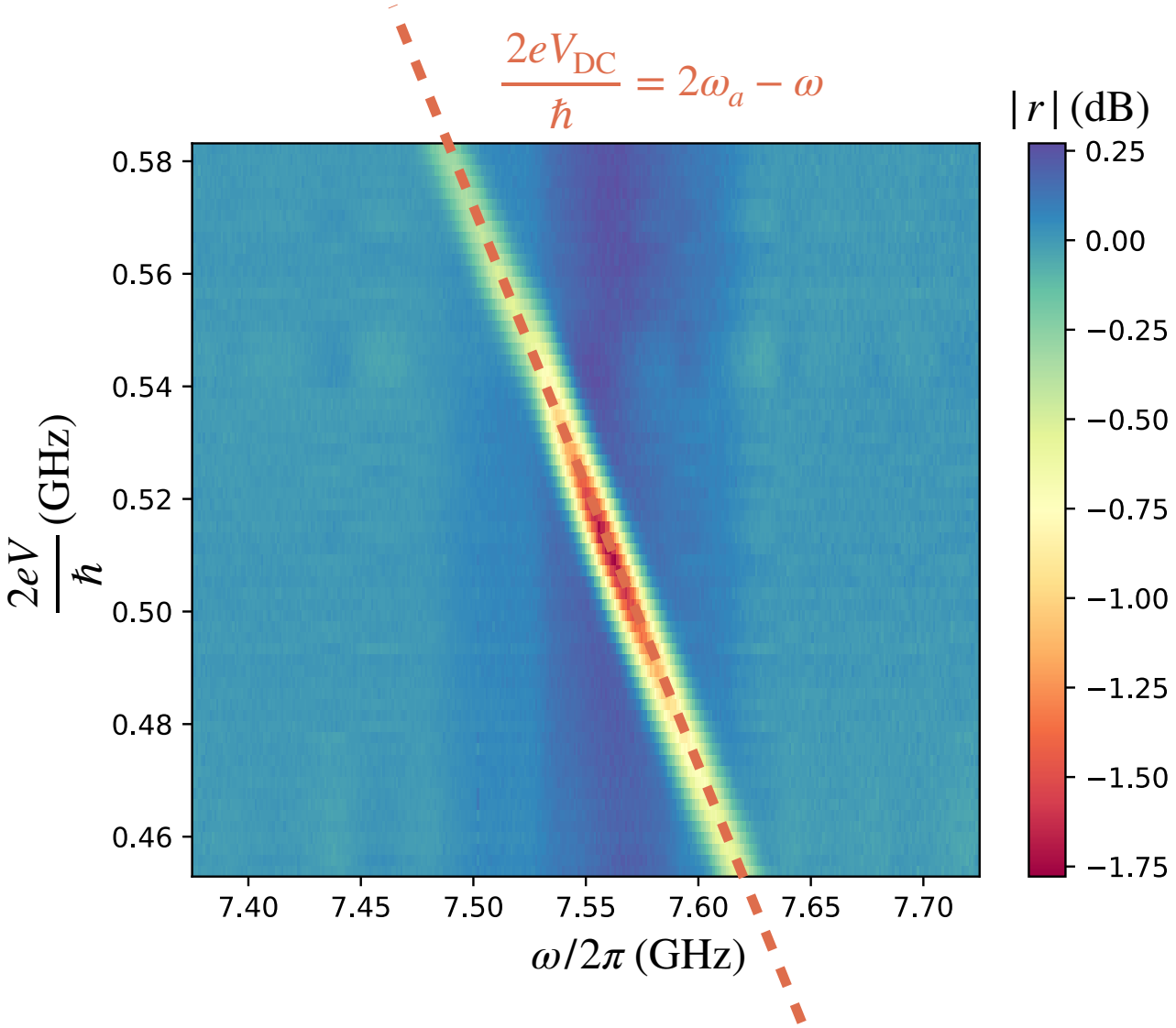
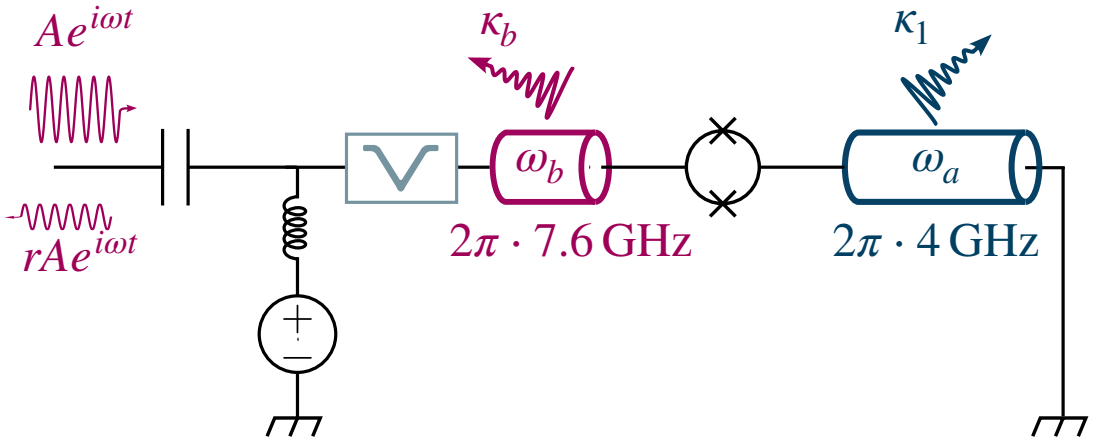


2-to-1 photon exchange





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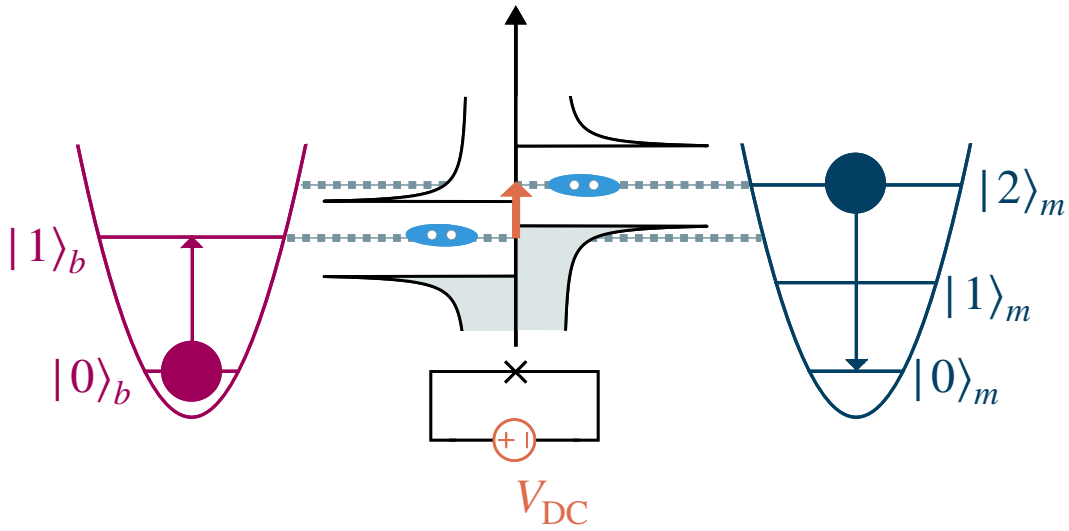

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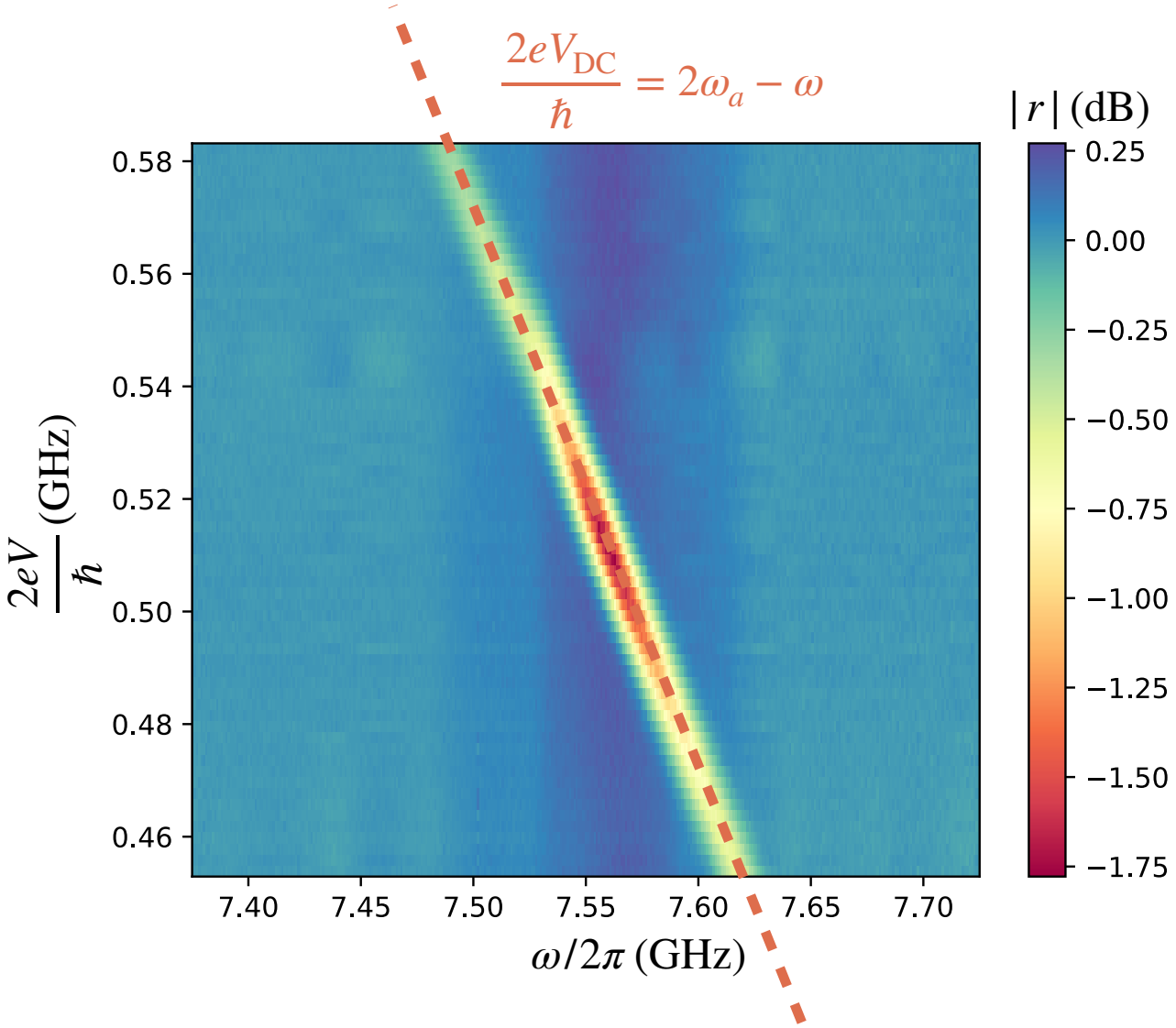
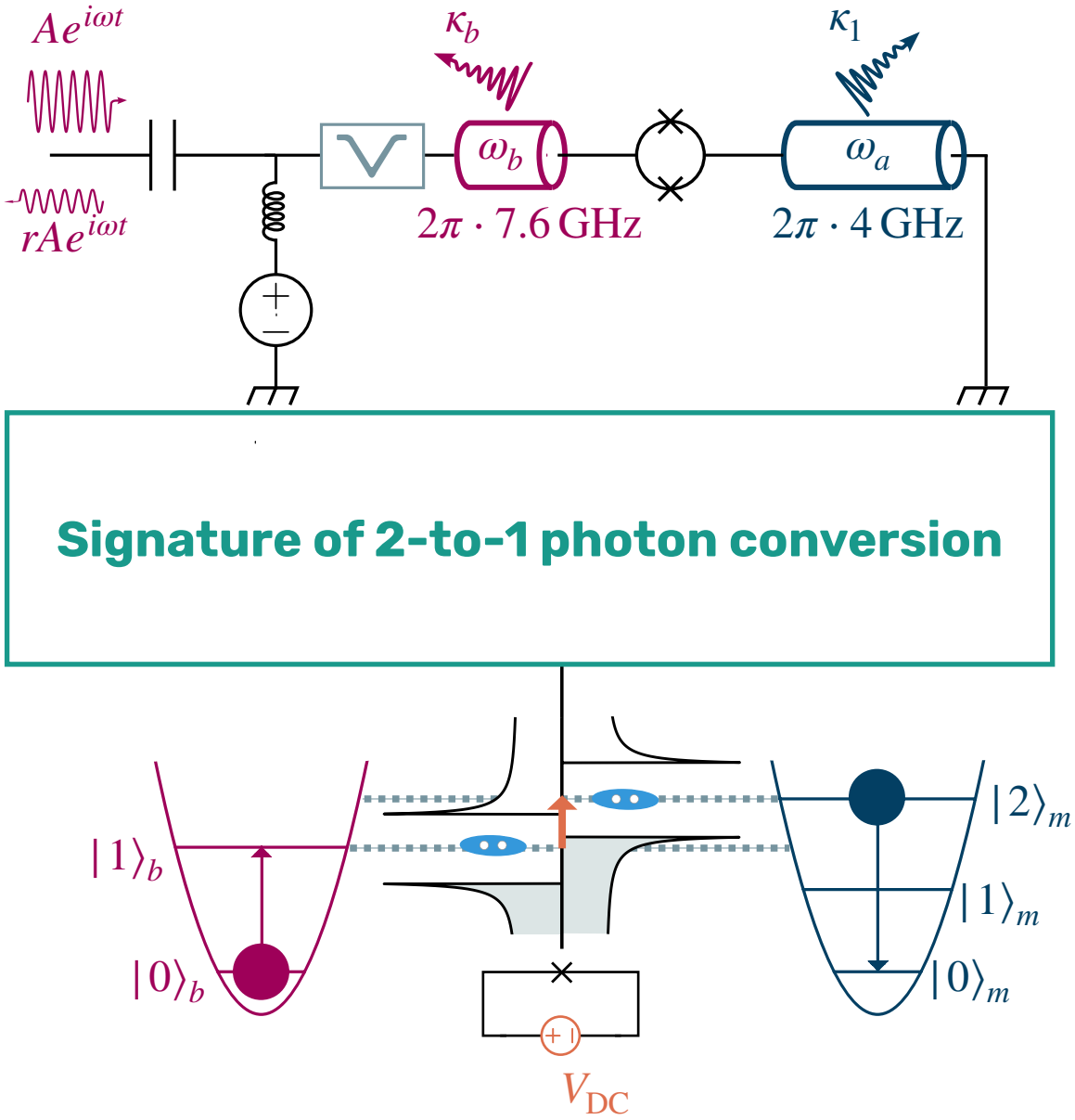
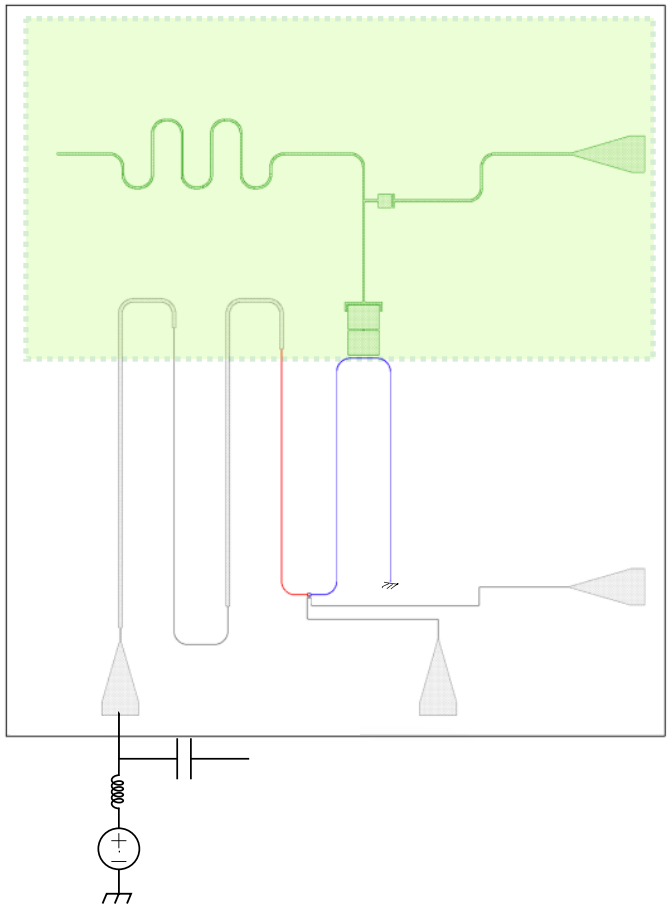
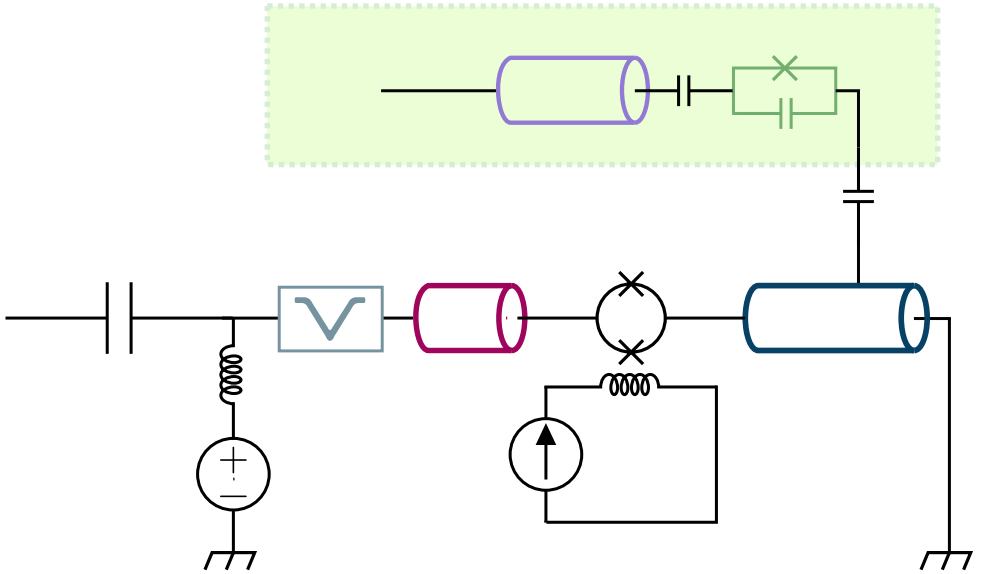




A qubit to read the memory





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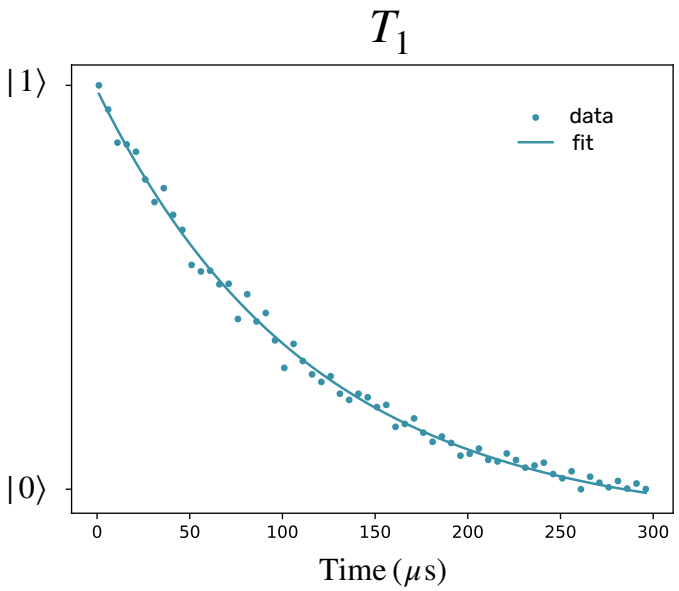

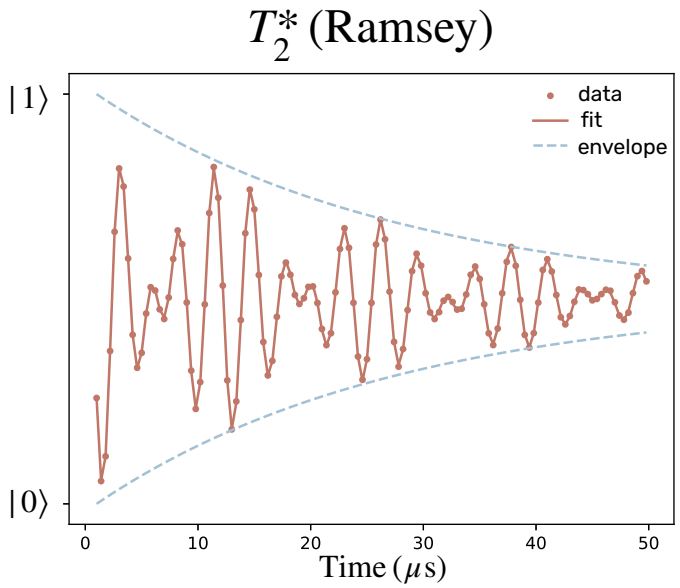

$$T_1 = 115\,\mu\text{s}$$
$$T_2^* = 25\,\mu\text{s}$$
$$\chi/2\pi = 1.5\,\text{MHz}$$

$$T_{1_{\text{mem}}} = 3.2\,\mu\text{s}$$

$$\kappa_m^{\text{tot}} > 10\kappa_m^{\text{coupling}}$$

Memory-qubit dispersive coupling:

$$\hat{H}/\hbar = \hbar\omega_m\,\hat{a}^\dagger\hat{a} + \frac{\hbar\omega_q}{2}\,\hat{\sigma}_z - \hbar\chi\,\hat{a}^\dagger\hat{a}\,\frac{\hat{\sigma}_z}{2}$$

$$\omega_q(\hat{a}^\dagger\hat{a}) = \omega_q(0) - \chi\hat{a}^\dagger\hat{a}$$

[D. I. Schuster at al. Nature 2007 (Yale)]
[B. R. Johnson at al. Nat. Phys. 2010 (Yale)]

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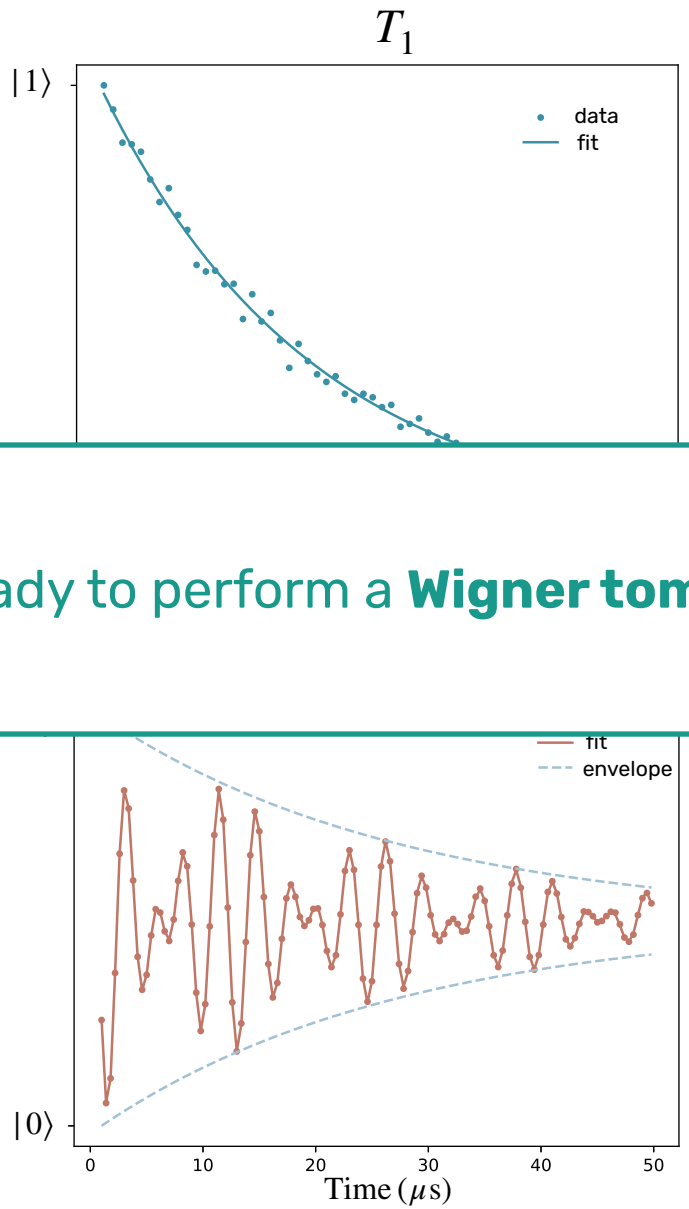

Ready to perform a **Wigner tomography**

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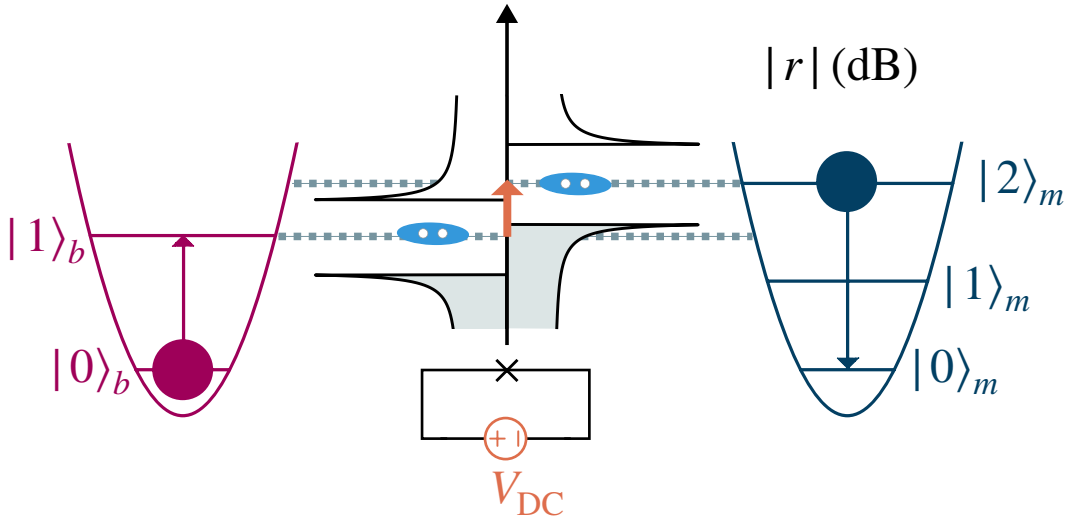
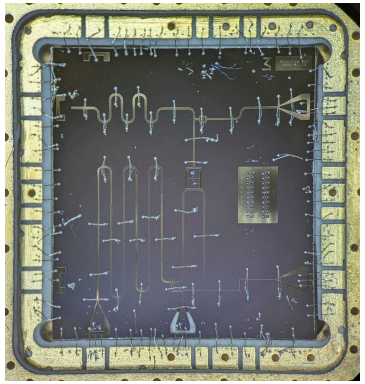
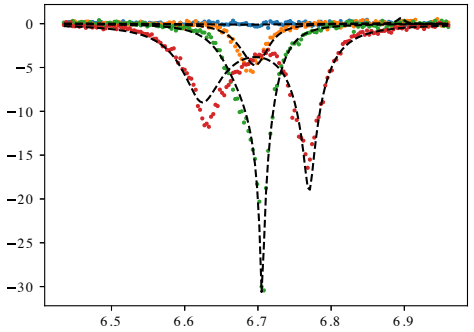
Conclusions

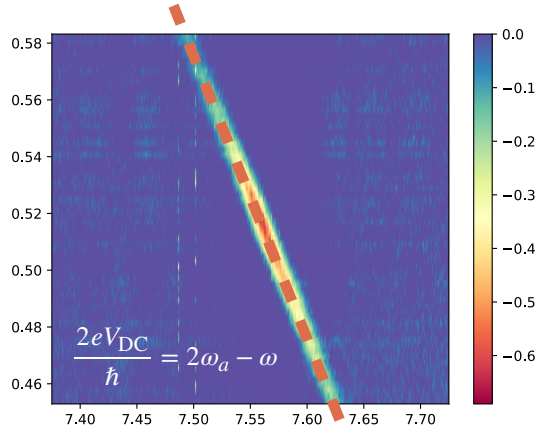
- New paradigm for cat qubit stabilization



- Designed and fabricated sample
- Evidence of 1-to-1 photon conversion
- Signature of 2-photon dissipation



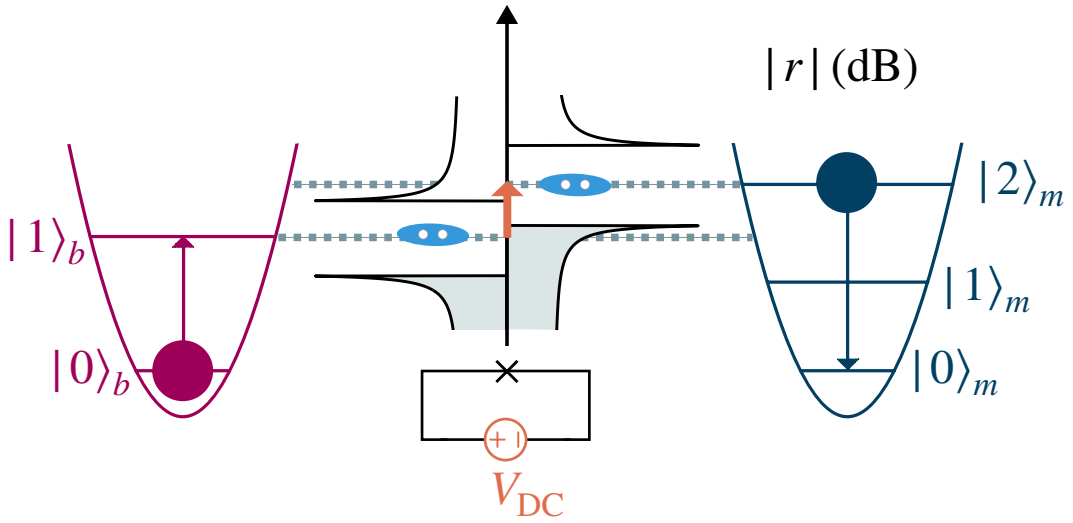




- **Next**: Wigner tomography as conclusive proof of 2-photon dissipation

Conclusions

- New paradigm for cat qubit stabilization



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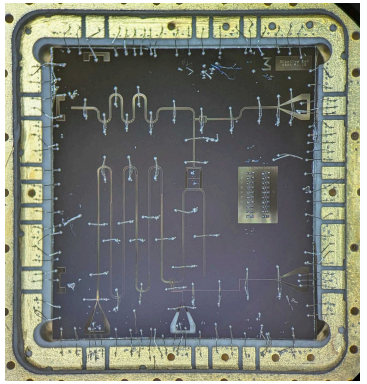
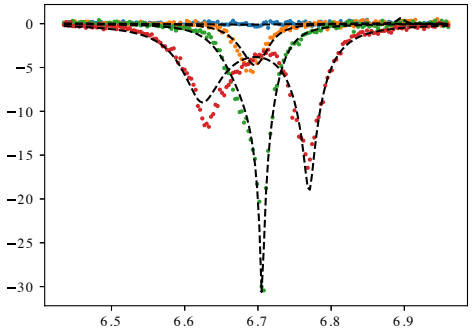
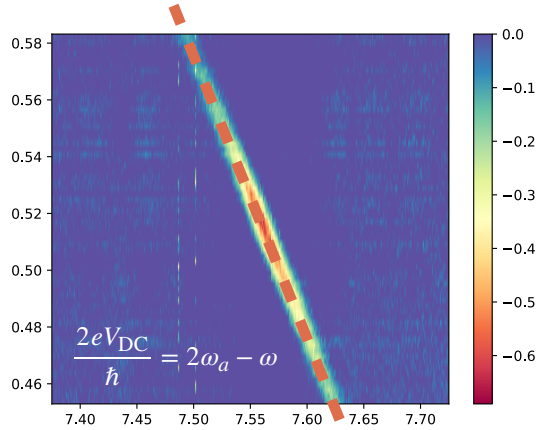
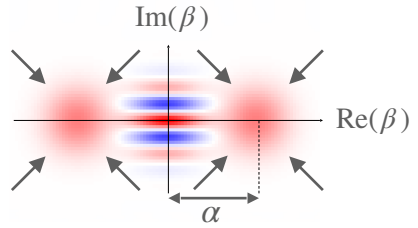




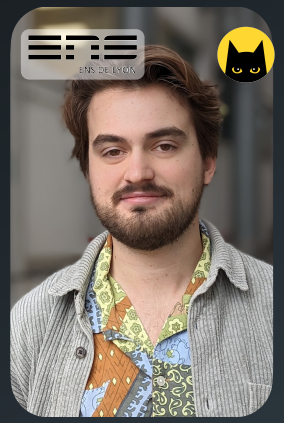


- **Next**: Wigner tomography as conclusive proof of 2-photon dissipation
- **Perspective**: also implement 2-photon drive → Cat qubit stabilization

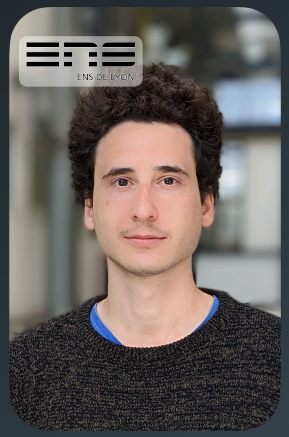


Thanks!

M. Paradina



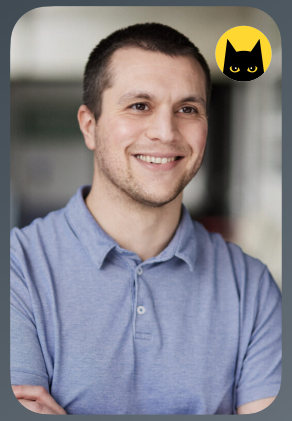
A. Peugeot



J.-L. Ville

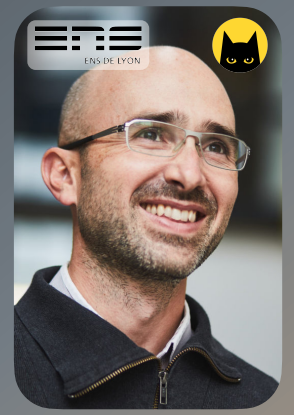
A. Murani

S. Jezouin



A. Bienfait

B. Huard



ENS DE LYON

cnrs

ALICE & BOB

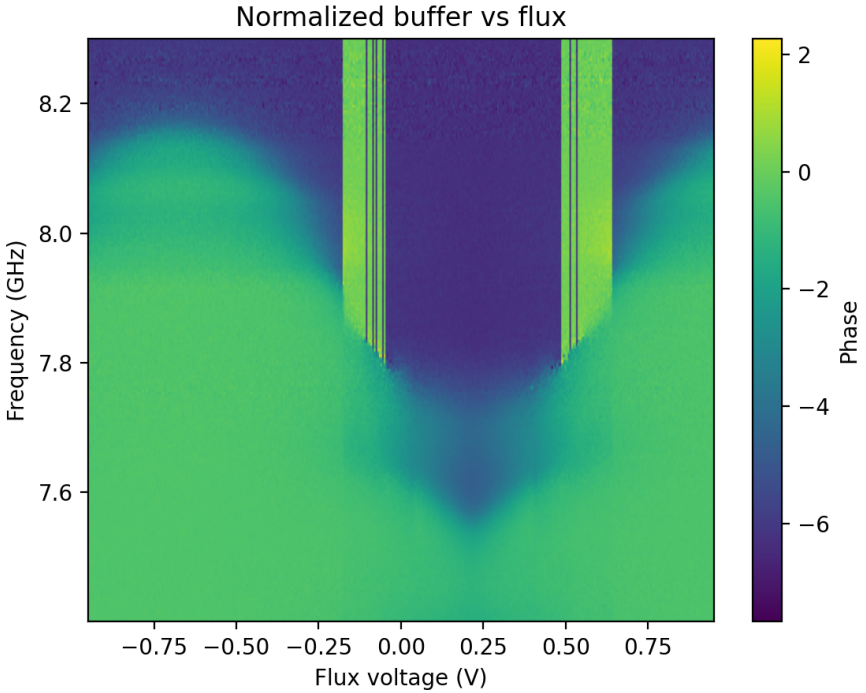
ROBUST SUPERQ

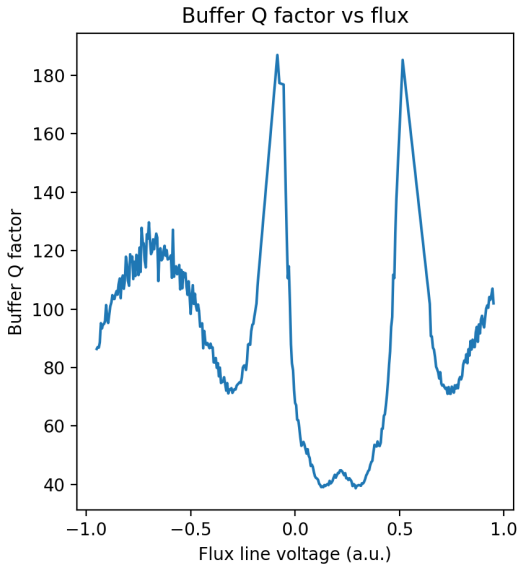
FRANCE 2030

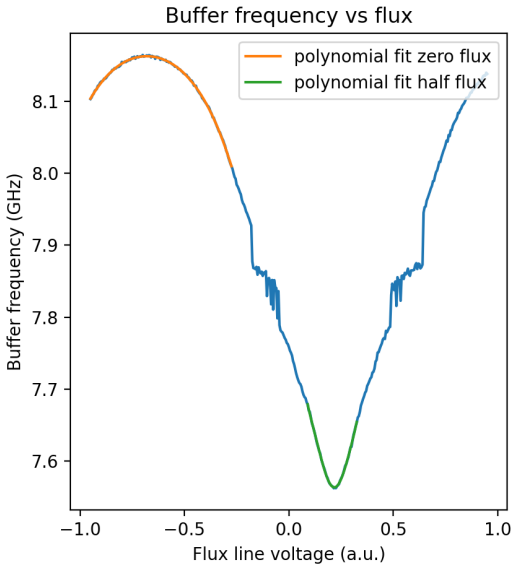
bpifrance

Extras

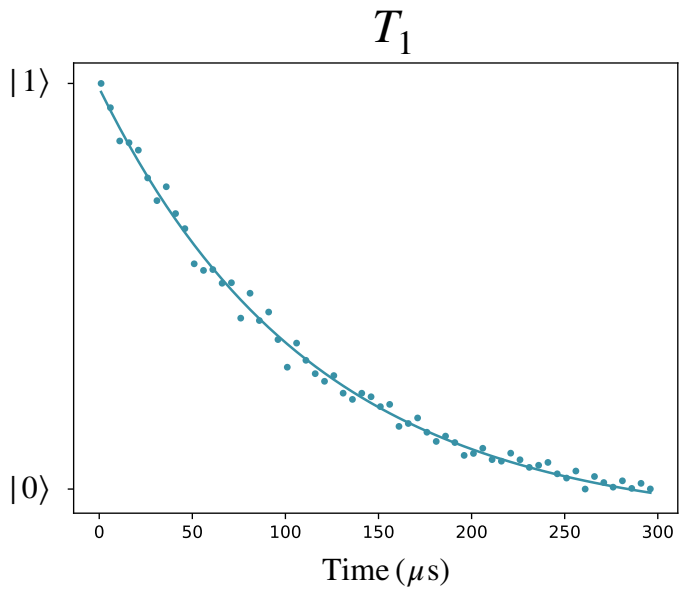
Buffer spectroscopy VS flux







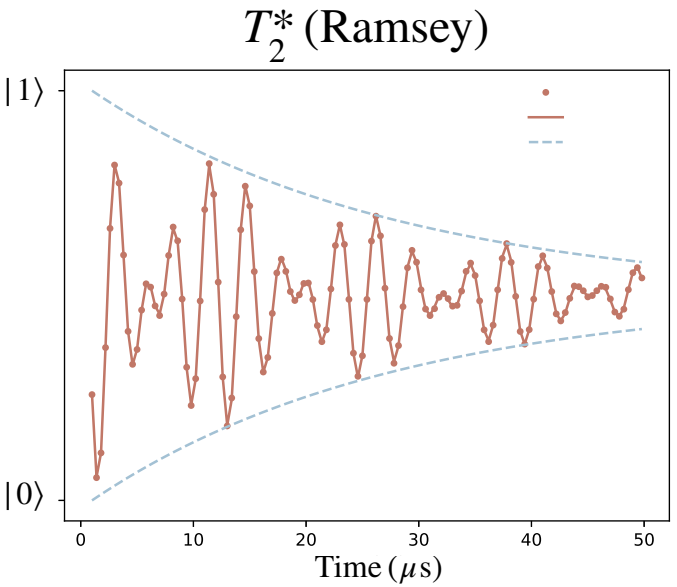
A qubit to read the memory

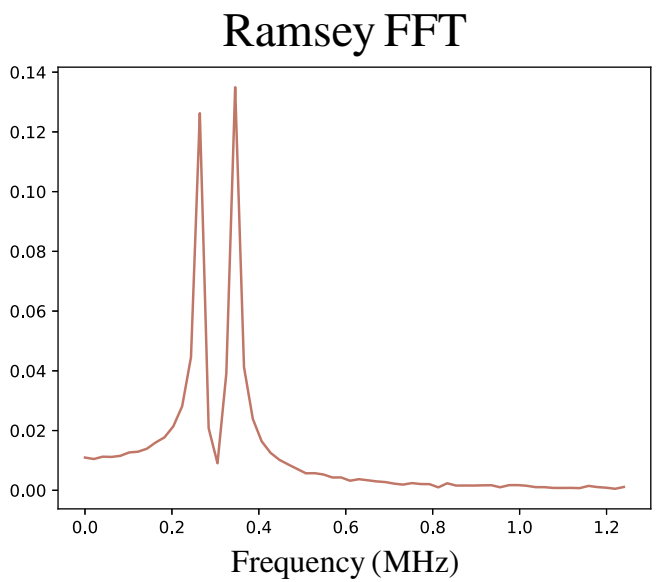


$$T_1 = 115\,\mu\text{s}$$
$$T_2^* = 25\,\mu\text{s}$$
$$\chi/2\pi = 1.5\,\text{MHz}$$

$$T_{1_{\text{mem}}} = 3.2\,\mu\text{s}$$

$$\kappa_m^{\text{tot}} > 10\kappa_m^{\text{coupling}}$$





Memory-qubit dispersive coupling:

$$\hat{H}/\hbar = \hbar\omega_m\,\hat{a}^\dagger\hat{a} + \frac{\hbar\omega_q}{2}\,\hat{\sigma}_z - \hbar\chi\,\hat{a}^\dagger\hat{a}\,\frac{\hat{\sigma}_z}{2}$$

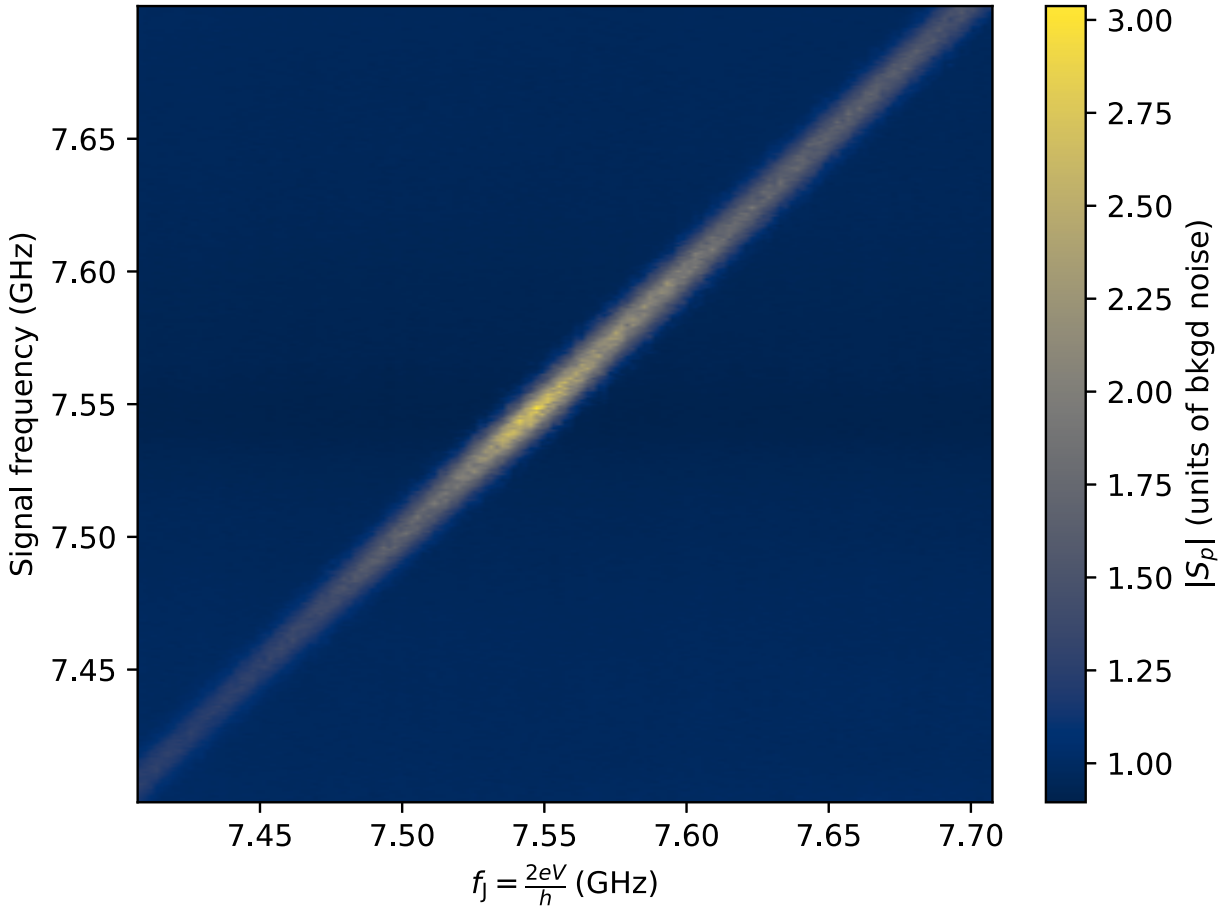
$$\omega_q(\hat{a}^\dagger\hat{a}) = \omega_q(0) - \chi\hat{a}^\dagger\hat{a}$$

[D. I. Schuster at al. Nature 2007 (Yale)]
[B. R. Johnson at al. Nat. Phys. 2010 (Yale)]

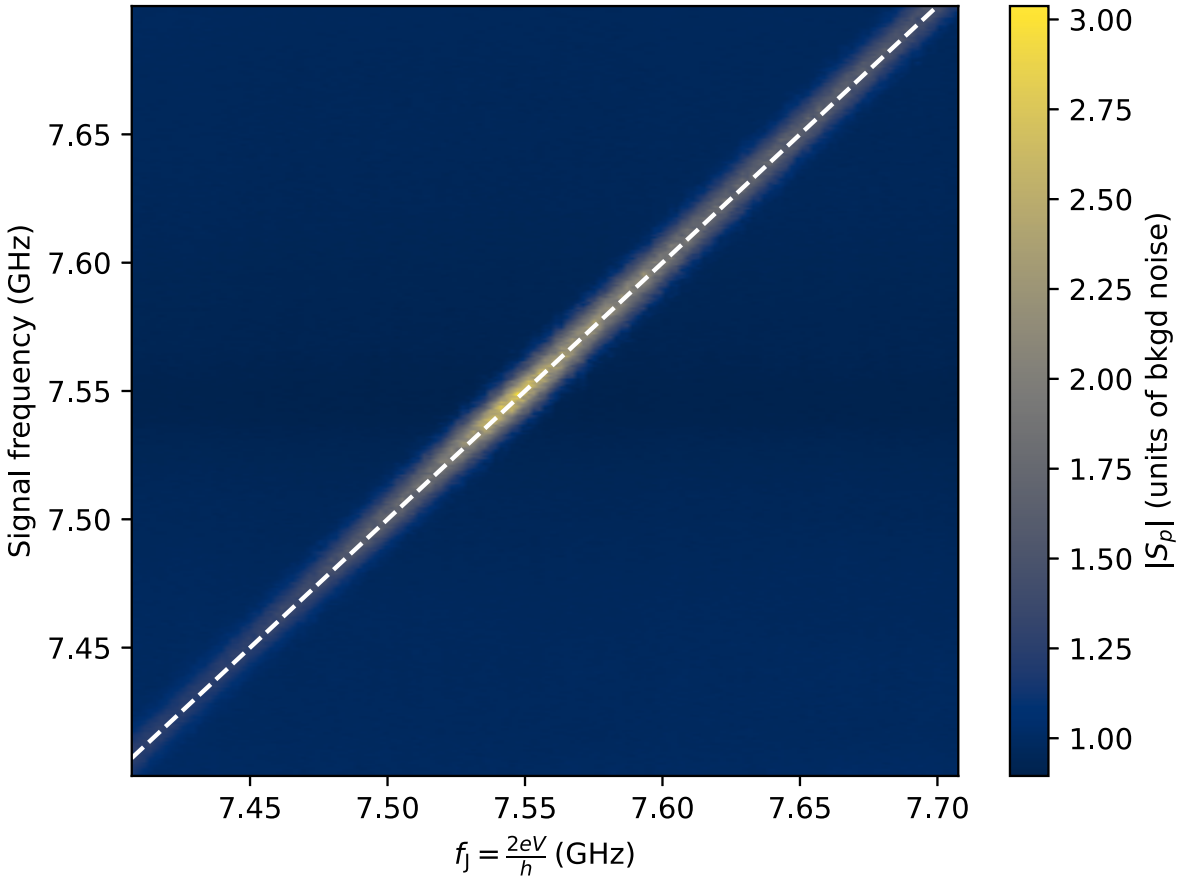
Memory

$$Q_c = 4 * 10^6$$
$$Q_i = 7 * 10^4$$
$$Q_{\text{tot}} = 7 * 10^5$$
$$\kappa_i = 60\,\text{kHz}$$

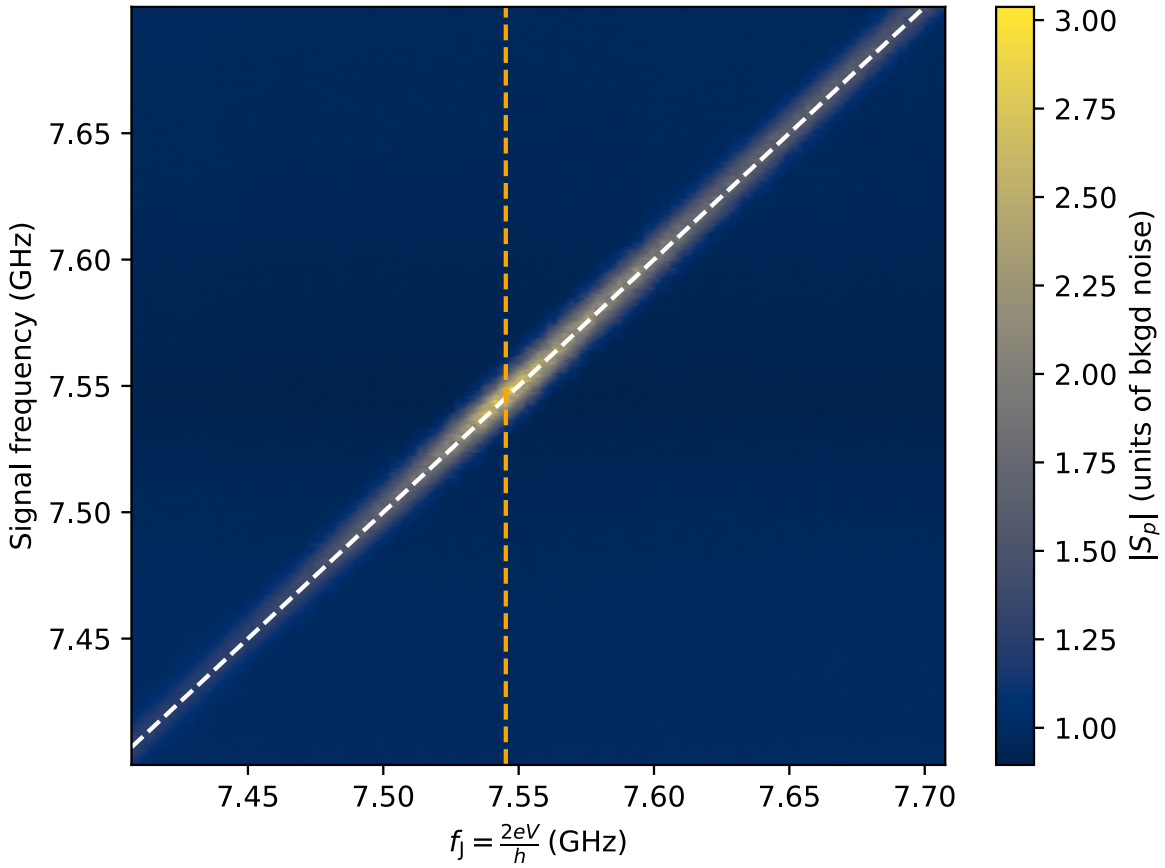
Josephson emission



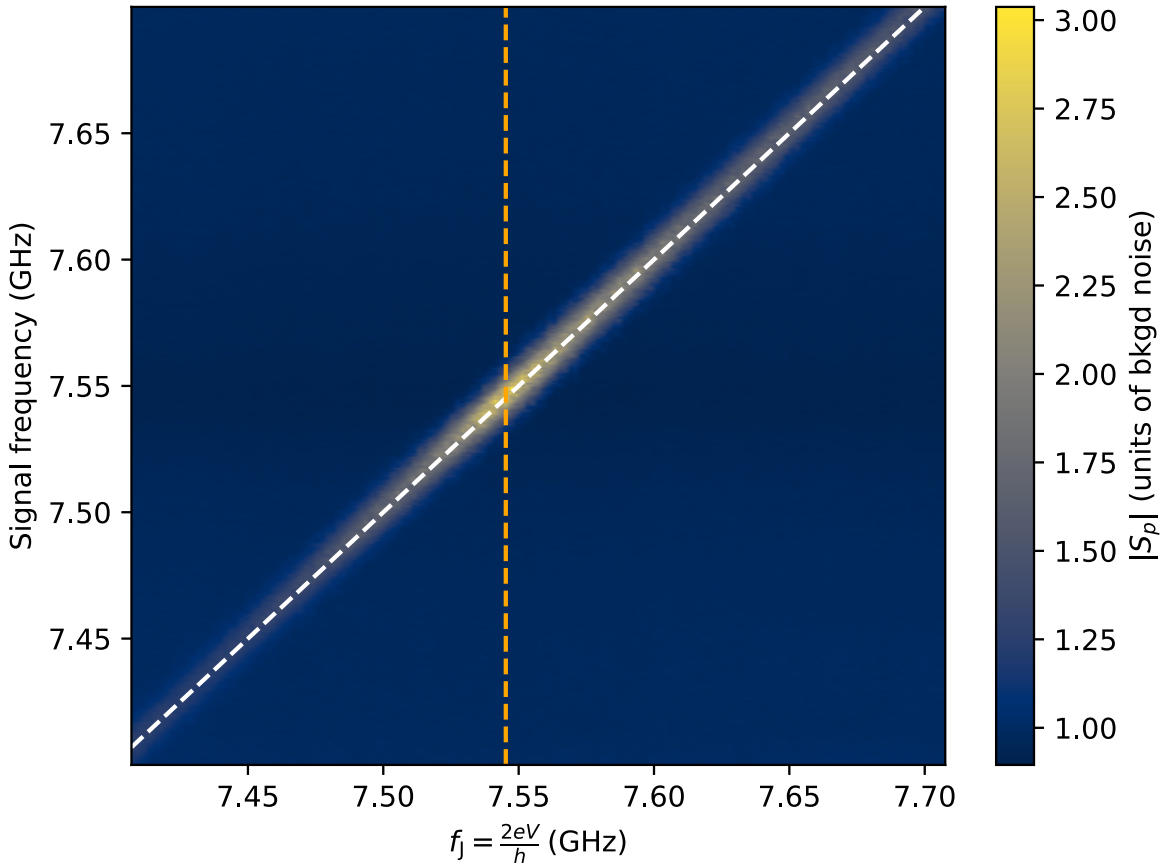
Josephson emission

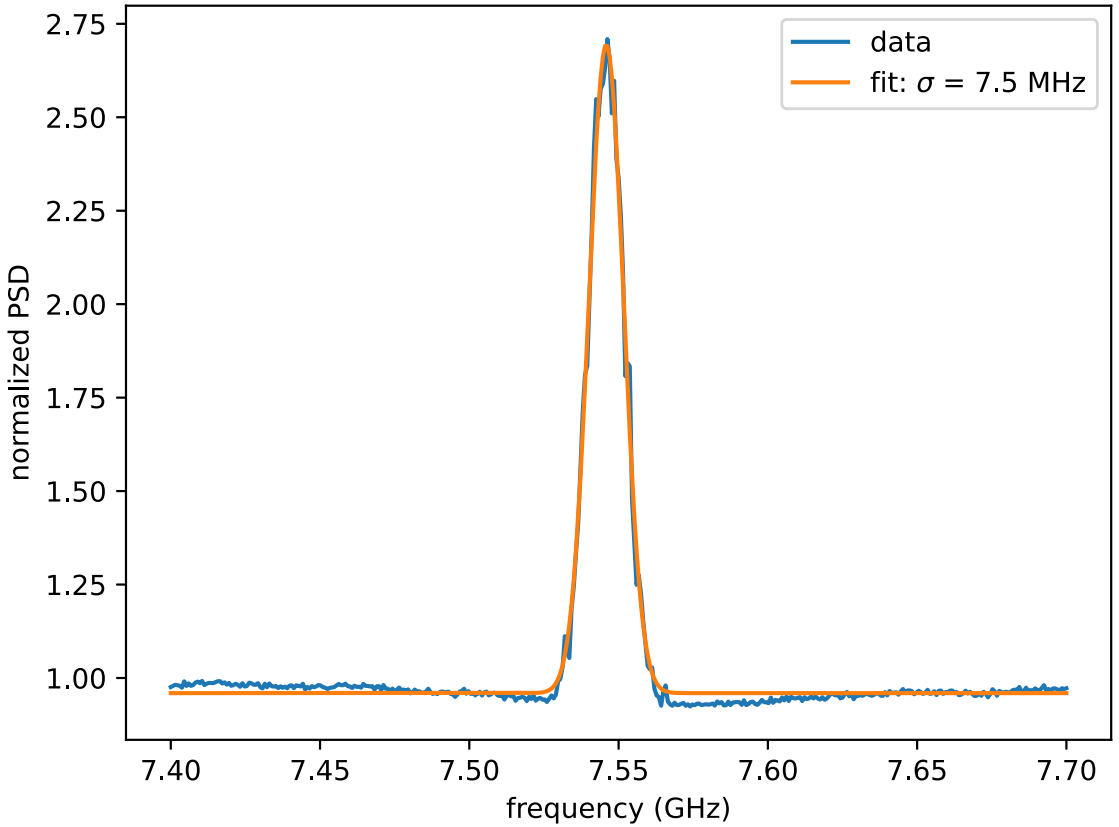


Josephson emission

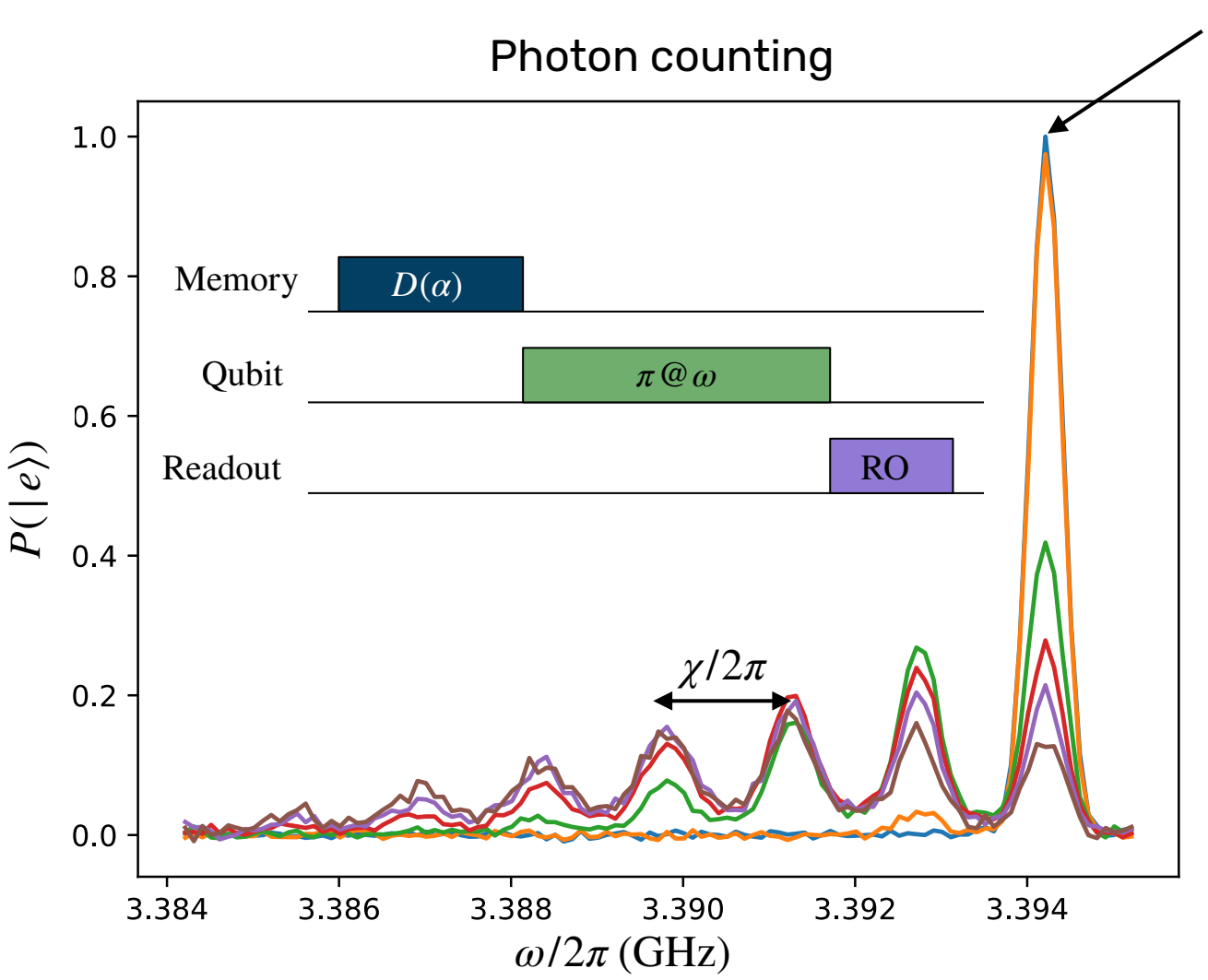


Josephson emission





A qubit to read the memory



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A qubit to read the memory