EXPERIMENTAL PROGRESS TOWARDS A BIAS-PRESERVING CNOT GATE BETWEEN TWO KERR-CAT QUBITS

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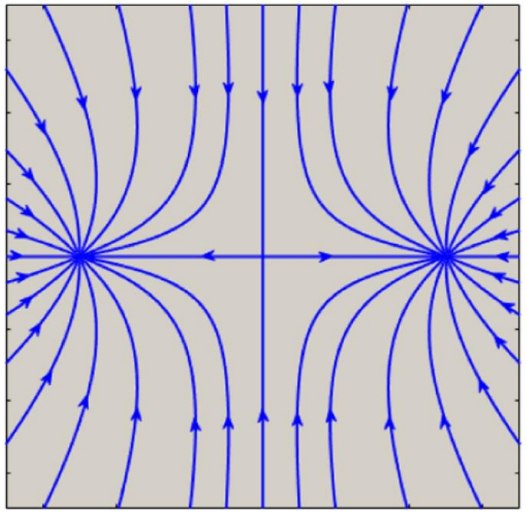
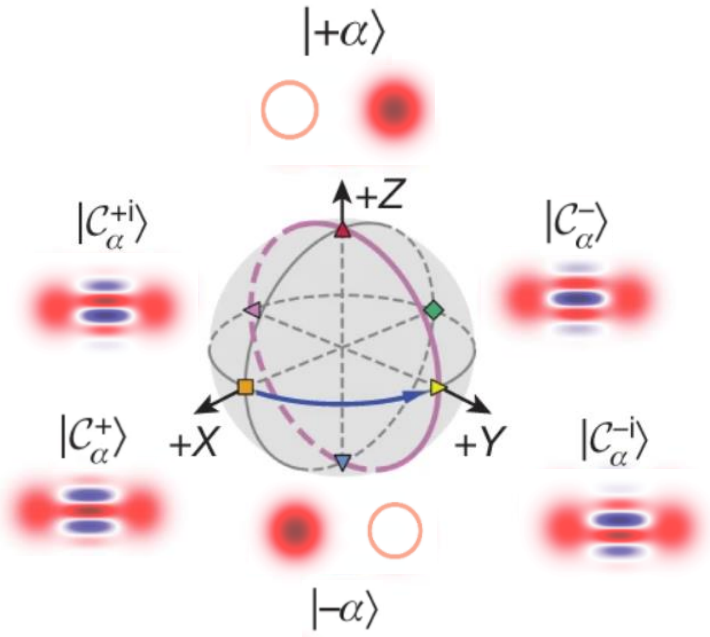
CAT QUBITS

Dissipative cat qubits

Lindbladian confinement:

$$\frac{d\boldsymbol{\rho}}{dt} = \kappa_2 \mathcal{D}[\boldsymbol{a}^2 - \alpha^2]\boldsymbol{\rho}$$





Bit-flip rate suppressed: $\sim e^{-2\bar{n}}$

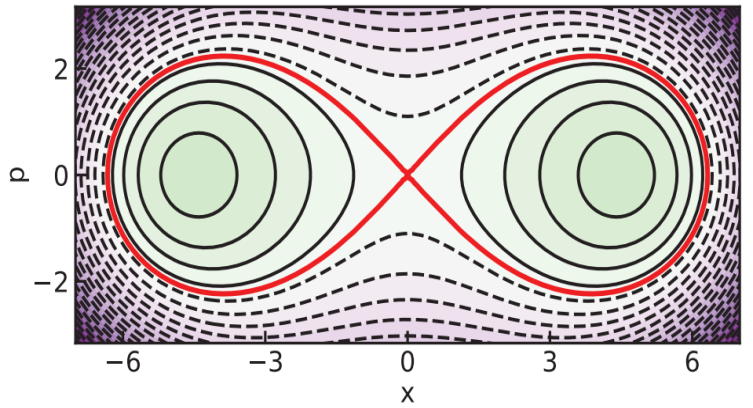
Phase-flip rate: $2\bar{n}\kappa_1$

Mirrahimi, *et al.*, *New J. Phys.* (2014)
Leghtas , *et al.*, *Science* (2015)
Guillaud, *et al.*, *PRX* (2019)
Marquet, *et al.*, *arXiv* (2023)

Kerr-cat qubits

Hamiltonian confinement:

$$\boldsymbol{H}/\hbar = -K(\boldsymbol{a}^{\dagger 2} - \alpha^2)(\boldsymbol{a}^2 - \alpha^2)$$

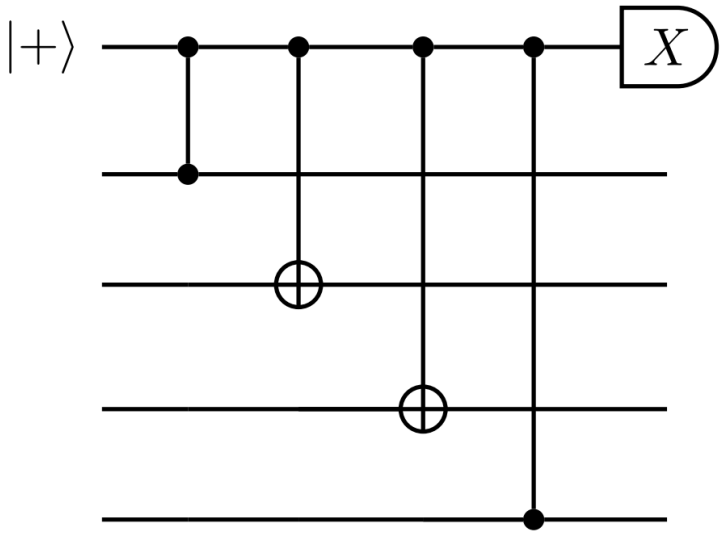


Puri, *et al.*, *npj Quantum Inf.* (2017)
Grimm, Frattini, *et al.*, *Nature* (2020)
Frattini, Cortiñas, *et al.*, *arXiv* (2022)
Iyama, Kamiya, Fujii, *et al.*, *Nat. Comm.* (2024)

MOTIVATION

Intrinsic suppression of bit-flips → Increased surface code thresholds

XZZX for Kerr-cat qubit ($\bar{n} = 6.25$)



Non-bias-preserving CNOT
(CZ + single qubit rot.)
$p_{\text{th}} \sim 3.9\%$

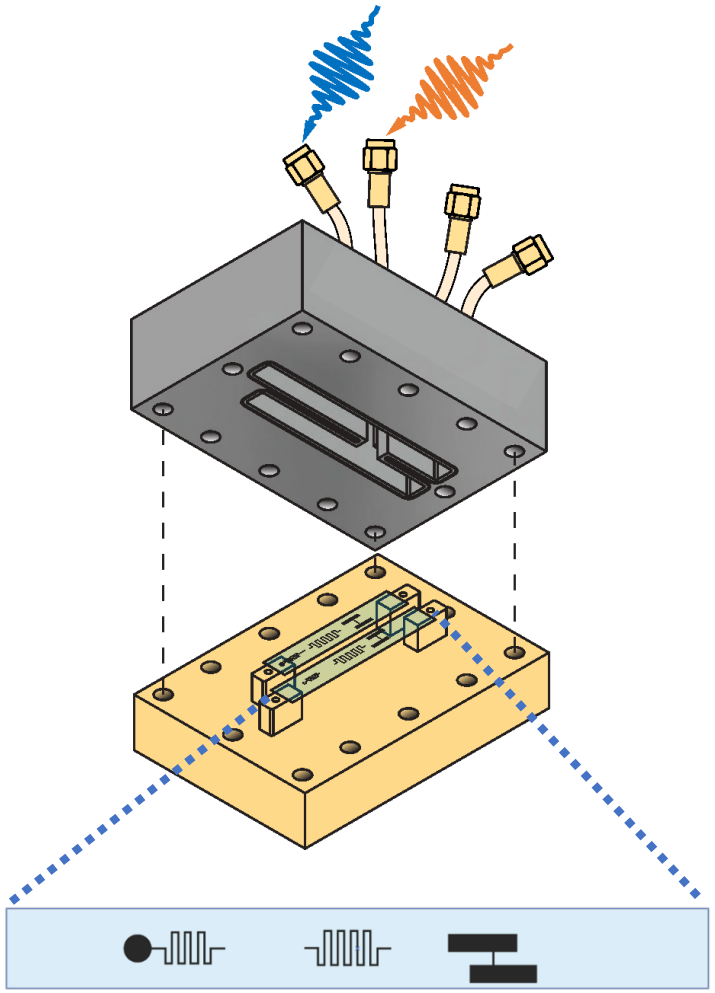
Bias-preserving CNOT
$p_{\text{th}} \sim 6.5\%$

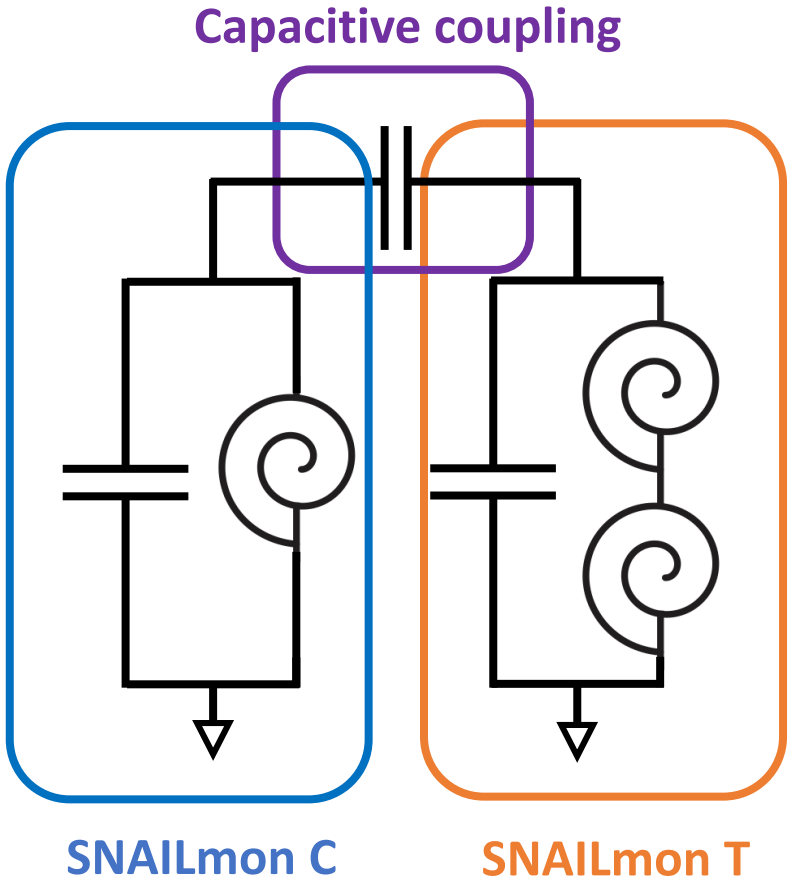
→ **67% increase!**

Darmawan, *et al.*, *PRX Quantum* (2021)

Tuckett, *et al.*, *PRL* (2022)
Bonilla Ataides, *et al.*, *Nat. Comm.* (2020)
Guillaud, *et al.*, *PRX* (2019)

SETUP





Operating point

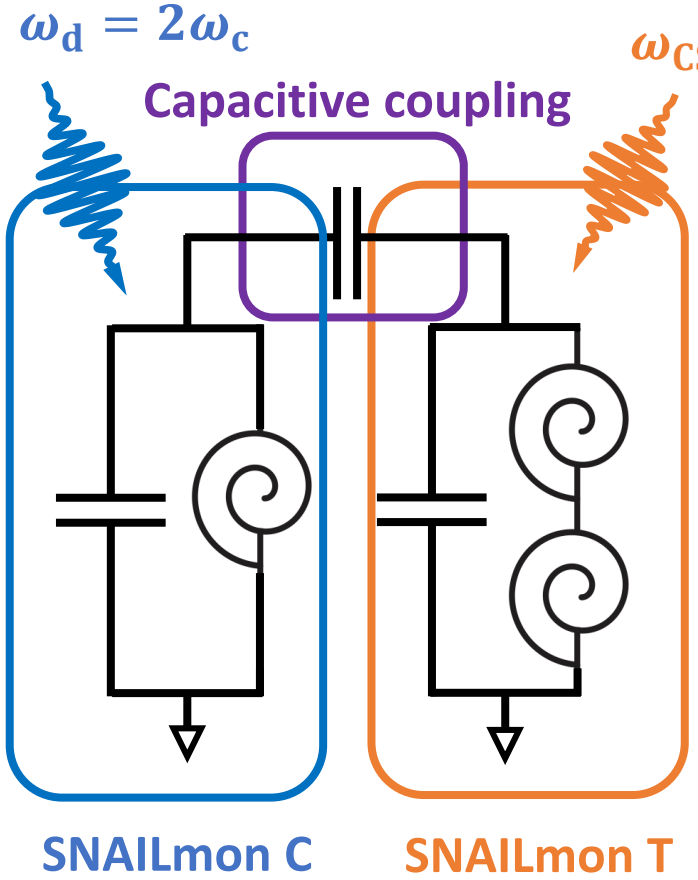
$K_c/2\pi \approx 1.1$ MHz
$T_X^c \approx 25$ µs
$T_1^{SNAIL} \approx 20\ \mu s$

$K_t/2\pi \approx 300$ kHz
$T_X^t \approx 30$ µs
$T_1^{SNAIL} \approx 20\ \mu s$

Frattini, Cortiñas, *et al.*, *arXiv* (2022)
Venkatraman, Cortiñas, *et al.*, *arXiv* (2023)

Frattini, *et al.*, *APL* (2017)
Sivak, *et al.*, *PRA* (2019)

MAIN INGREDIENT: CONTROLLED-SQUEEZING



Displaced frame + rotating frame + RWA

$$H_{CS} = -K_c a_c^{\dagger 2} a_c^2 + \epsilon_2^a \left(a_c^{\dagger 2} + a_c^2\right) - K_t a_t^{\dagger 2} a_t^2 + g_{int}\left(a_t^{\dagger 2} a_c + a_t^2 a_c^\dagger\right)$$

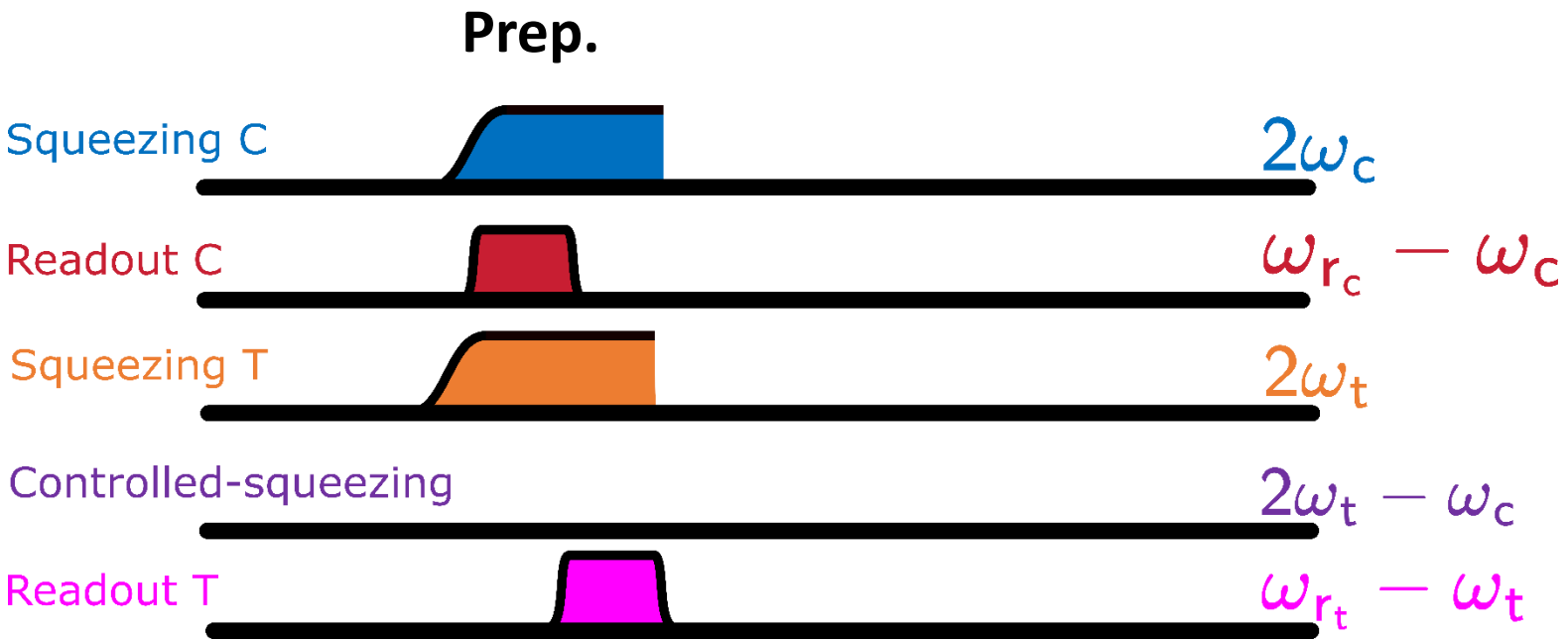
Controlled-squeezing

Frattini, Cortiñas, *et al.*, *arXiv* (2022)
Venkatraman, Cortiñas, *et al.*, *arXiv* (2023)

Puri, *et al.*, *Science Advances* (2020)
Frattini, *Dissertation* (2021)

CNOT GATE SEQUENCE

Squeezing $\epsilon_2^t(a_t^{\dagger 2} + a_t^2)$

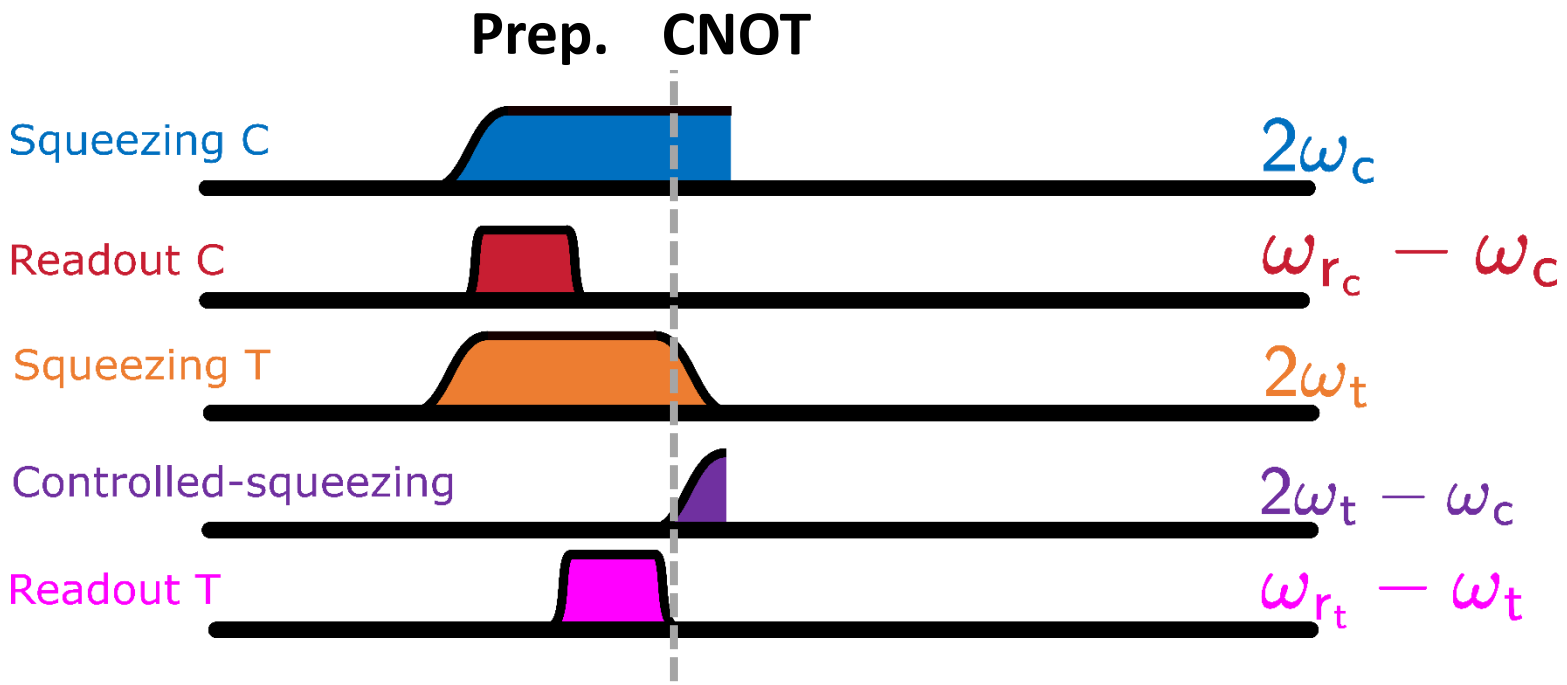


CNOT GATE SEQUENCE

Adiabatic (500 ns)

Squeezing $\epsilon_2^{\mathrm{t}}(a_{\mathrm{t}}^{\dagger 2} + a_{\mathrm{t}}^2)$

CSqueezing $g_{\mathrm{int}}(a_{\mathrm{t}}^{\dagger 2} a_{\mathrm{c}} + a_{\mathrm{t}}^2 a_{\mathrm{c}}^{\dagger})$



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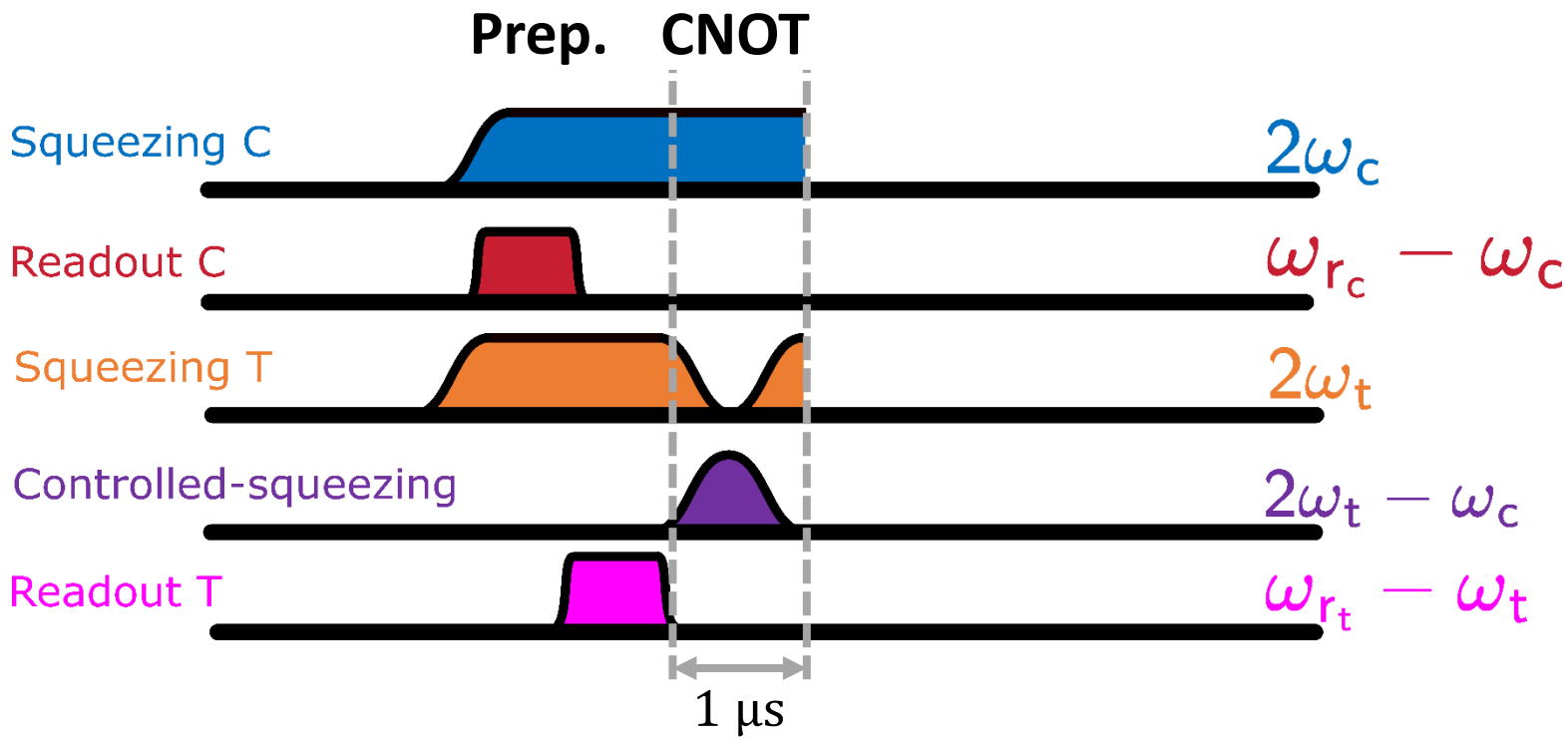

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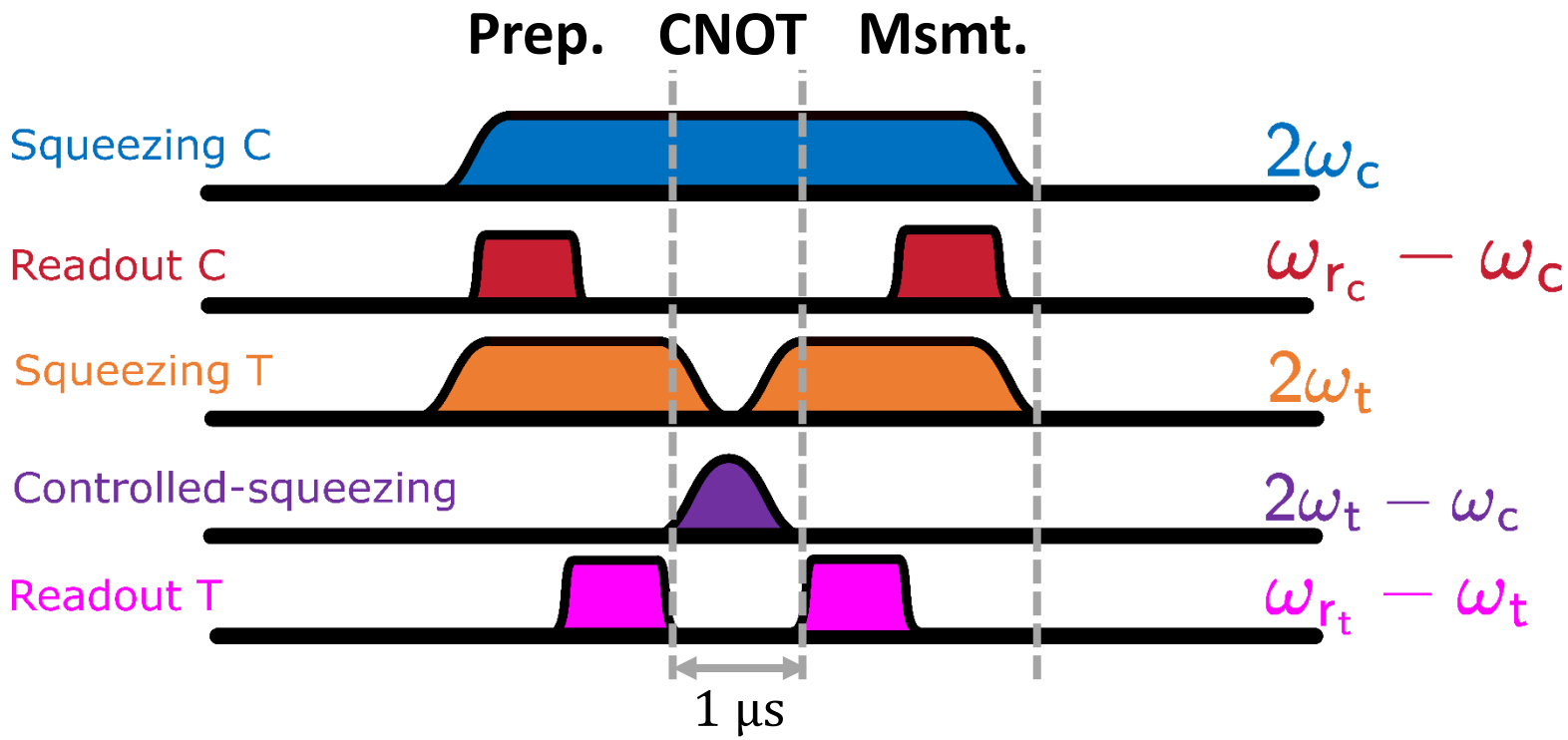

VERIFYING CNOT TABLE

Input |Control, Target⟩	Output |Control, Target⟩
$\|0_c 0_t\rangle = \|+\alpha_c, +\alpha_t\rangle$	$\|0_c 0_t\rangle = \|+\alpha_c, +\alpha_t\rangle$
$\|0_c 1_t\rangle = \|+\alpha_c, -\alpha_t\rangle$	$\|0_c 1_t\rangle = \|+\alpha_c, -\alpha_t\rangle$
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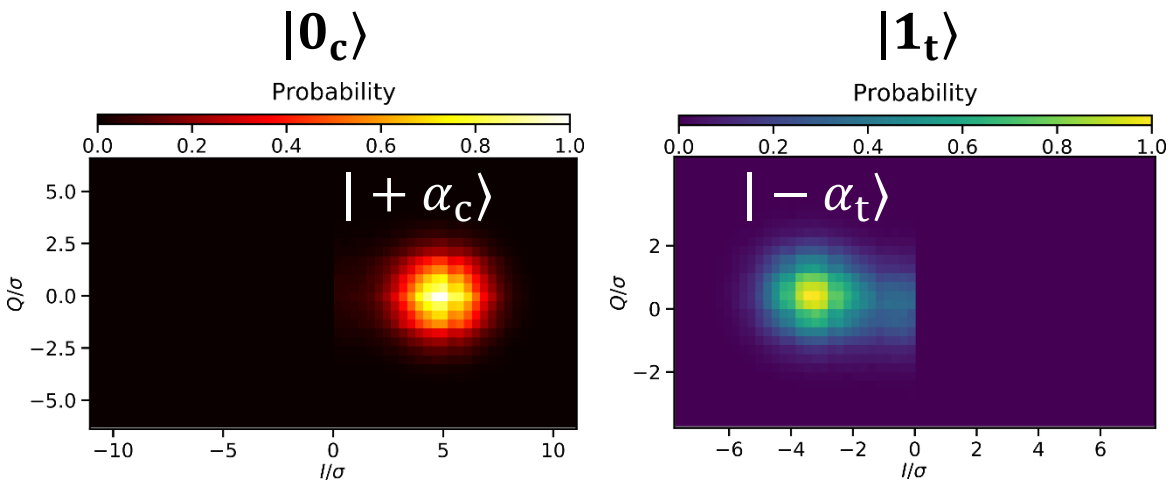
VERIFYING CNOT TABLE

Initial state



Final state

Input $\|\text{Control, Target}\rangle$	Output $\|\text{Control, Target}\rangle$
$\|0_c 0_t\rangle = \|+\alpha_c, +\alpha_t\rangle$	$\|0_c 0_t\rangle = \|+\alpha_c, +\alpha_t\rangle$
$\|0_c 1_t\rangle = \|+\alpha_c, -\alpha_t\rangle$	$\|0_c 1_t\rangle = \|+\alpha_c, -\alpha_t\rangle$
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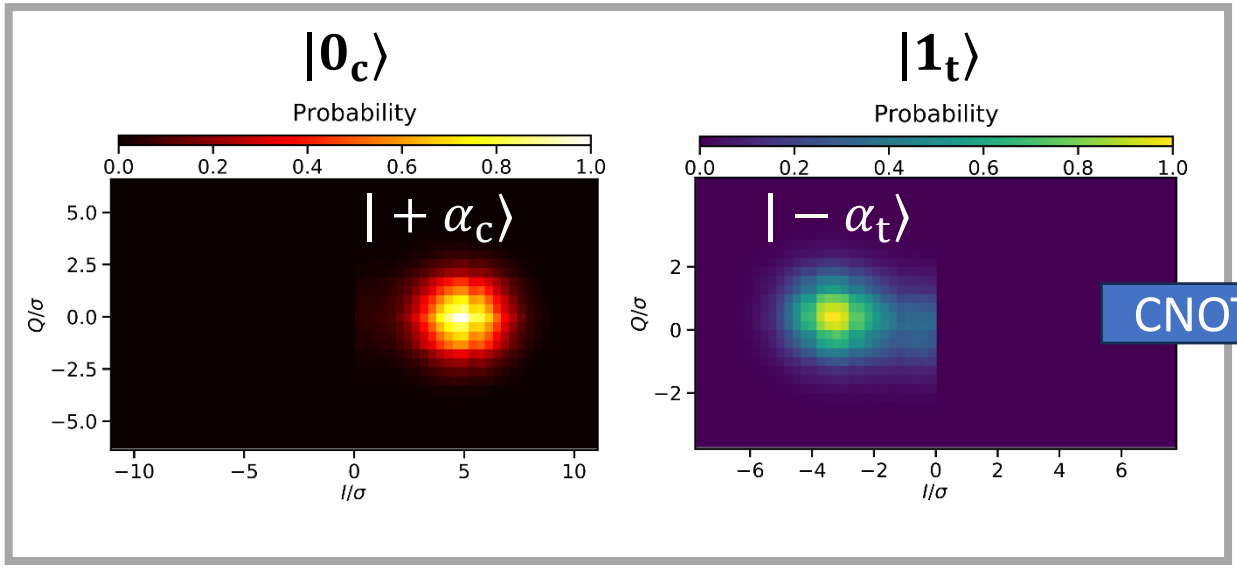
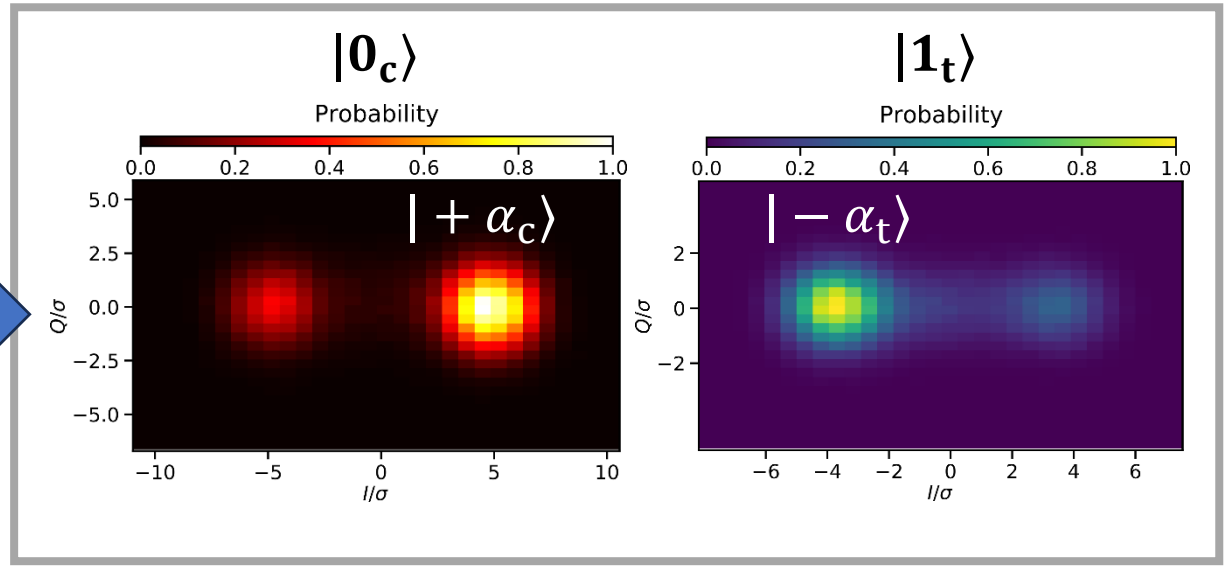
VERIFYING CNOT TABLE

Initial state



Final state



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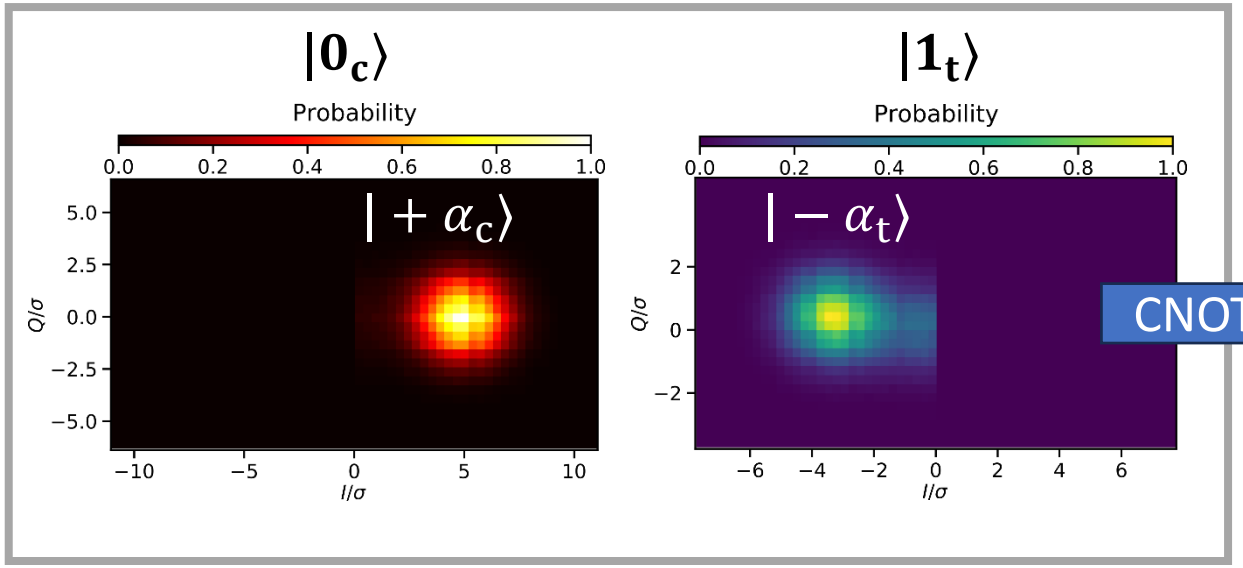
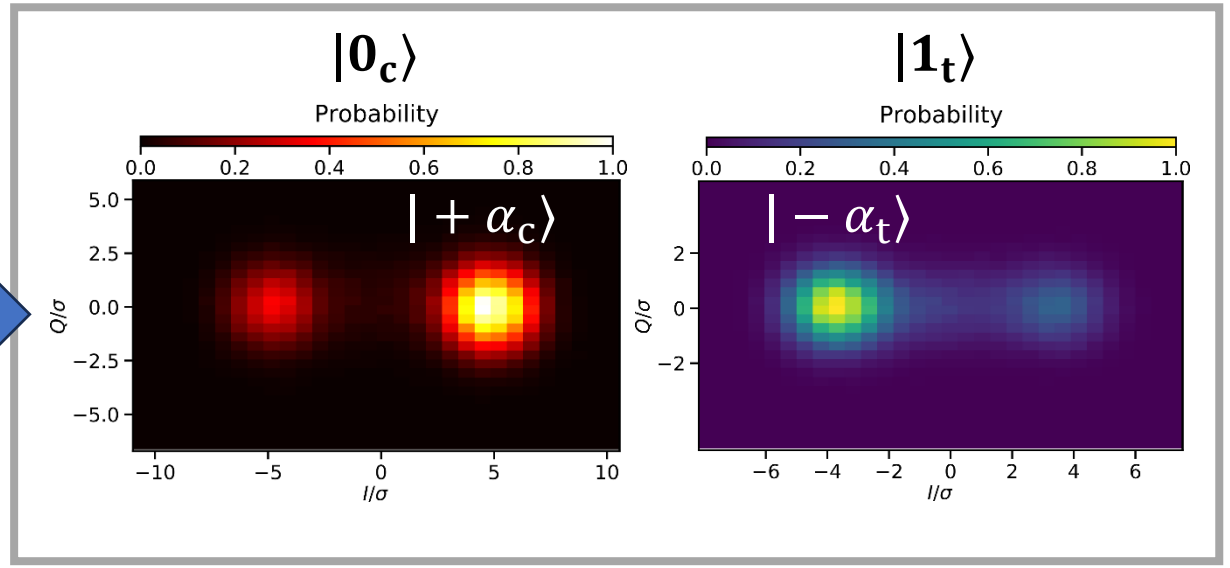
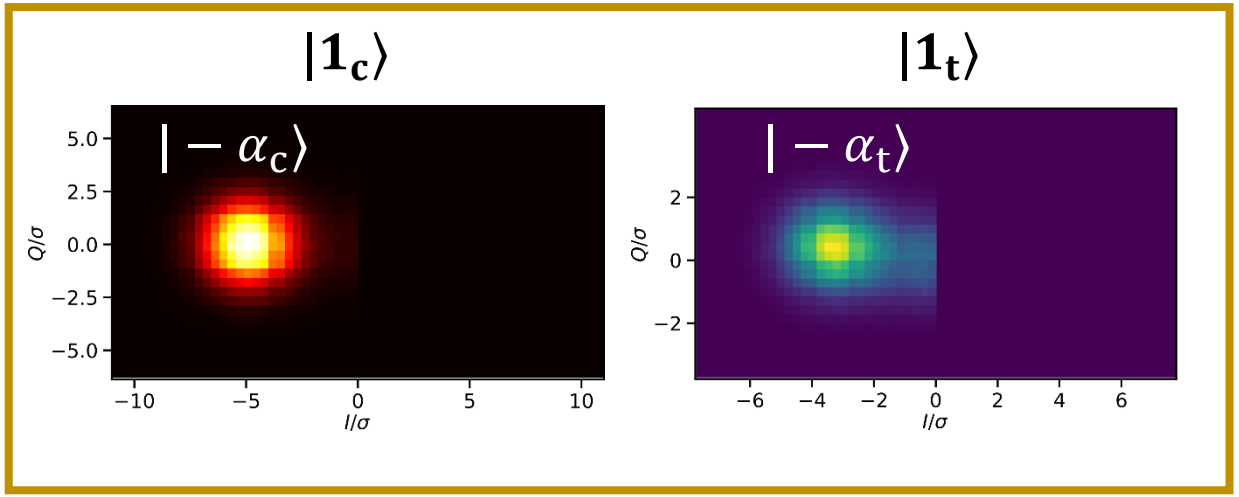


Final state





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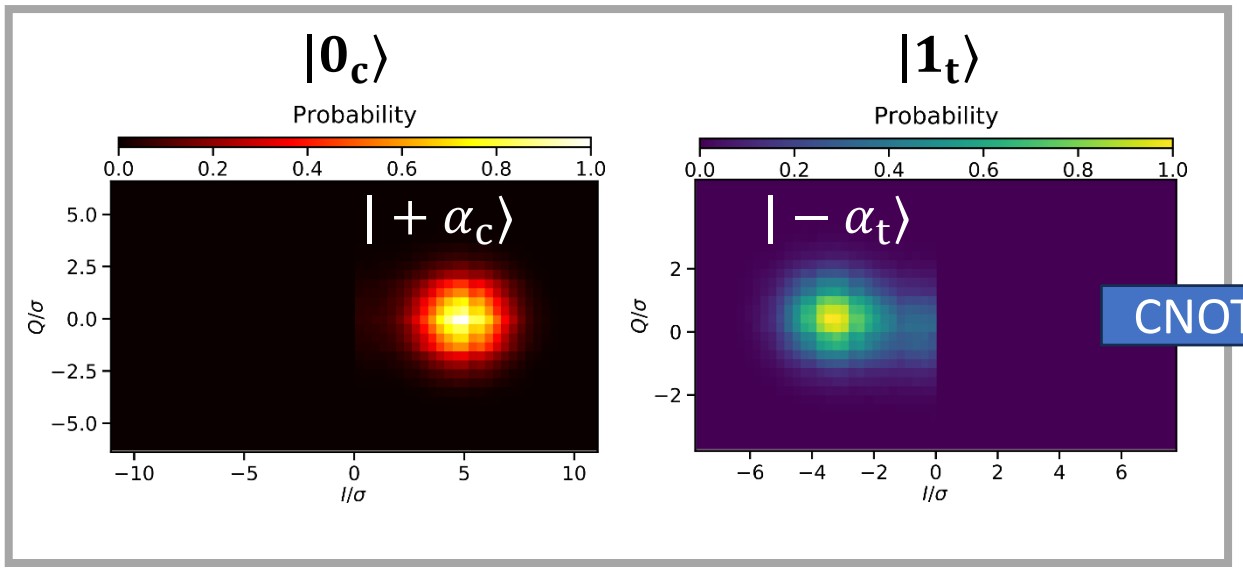

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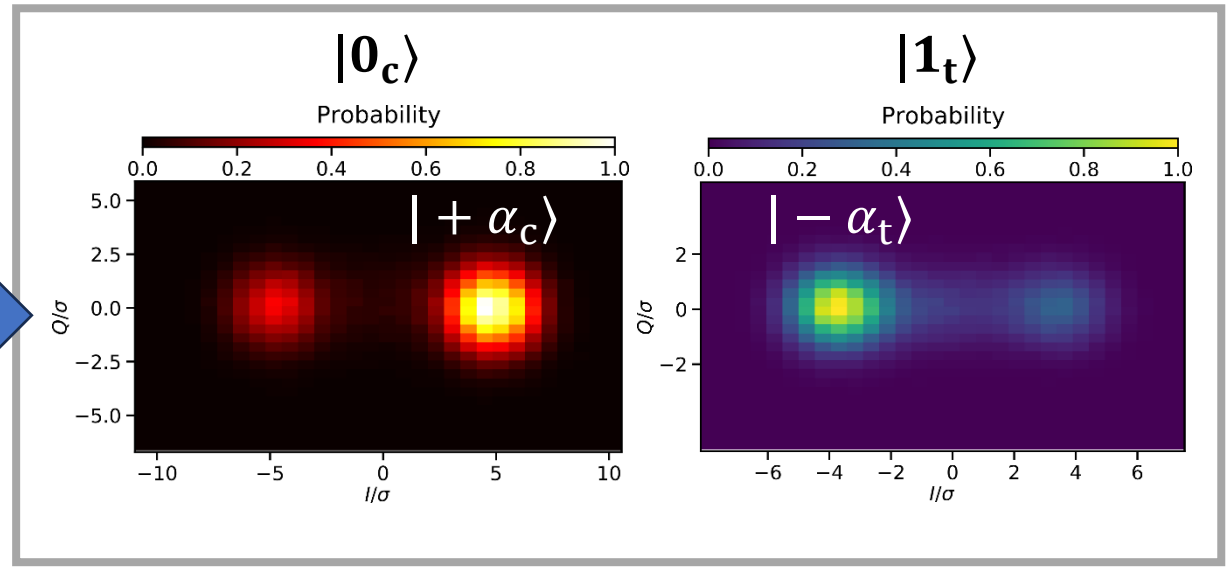

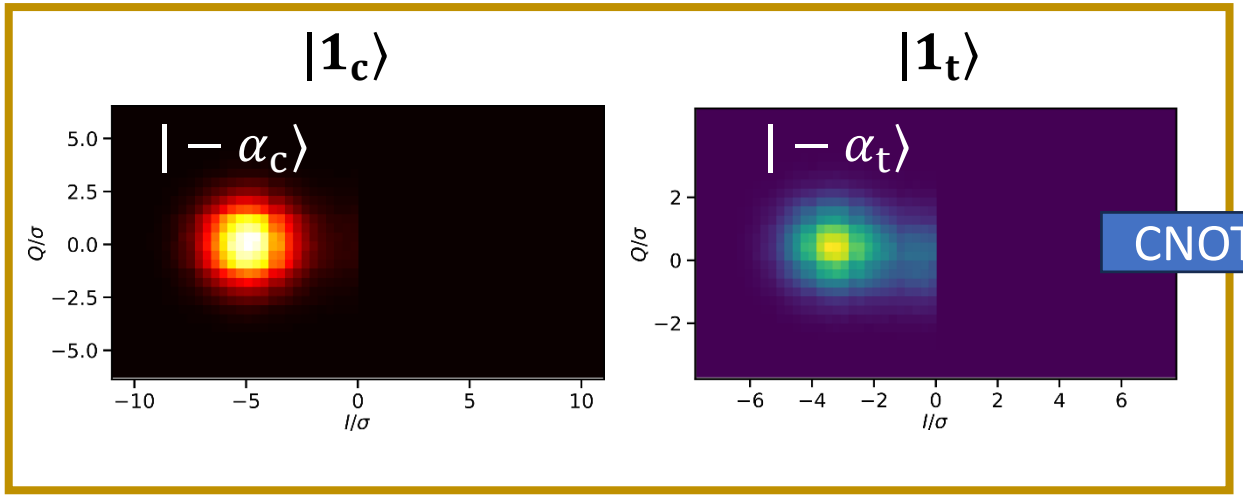

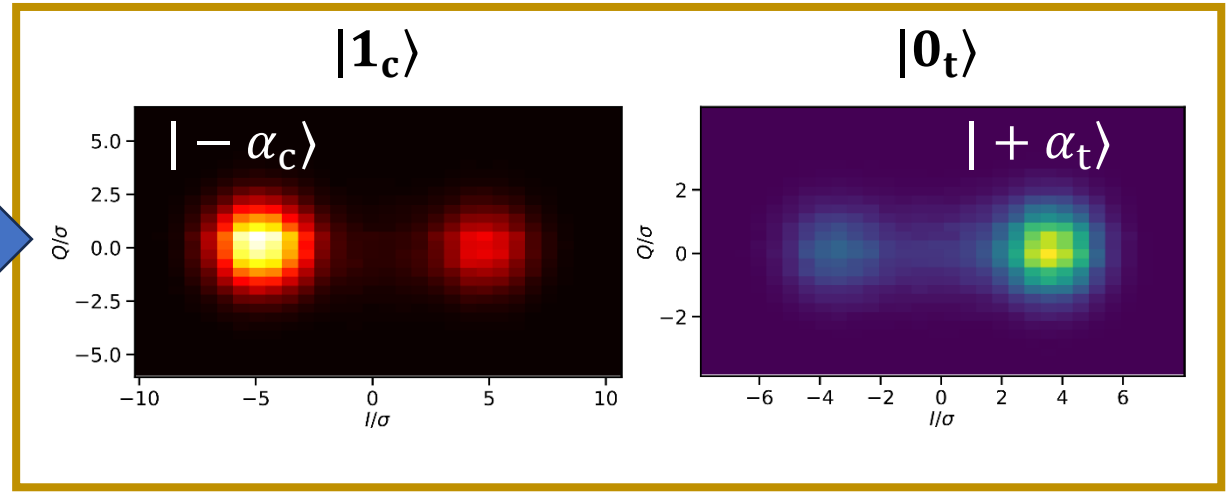

VERIFYING CNOT TABLE

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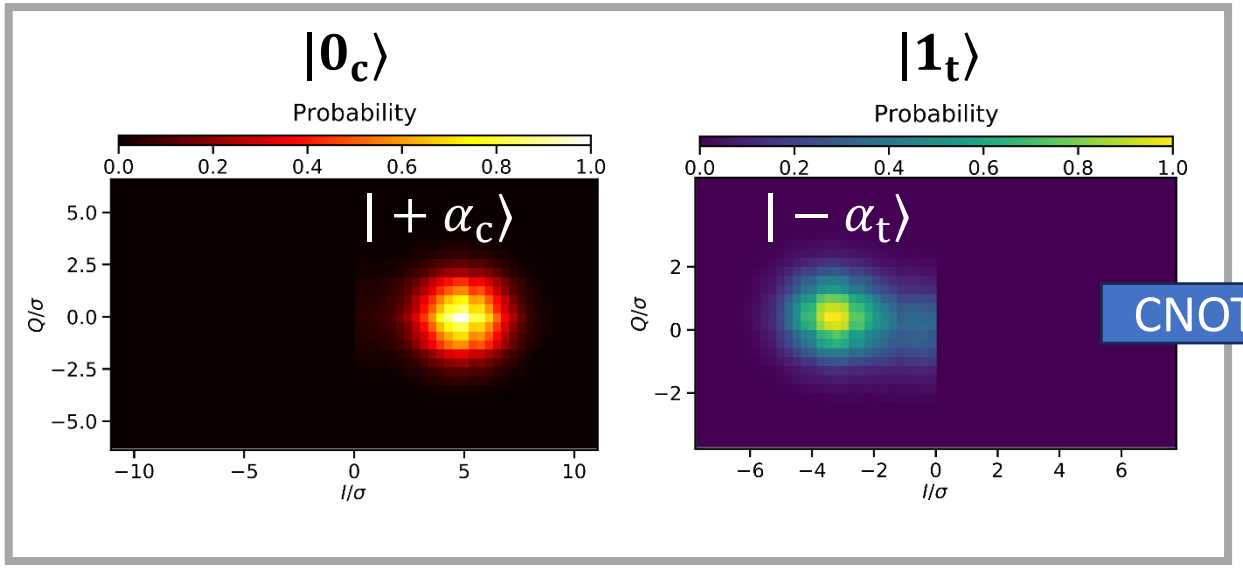
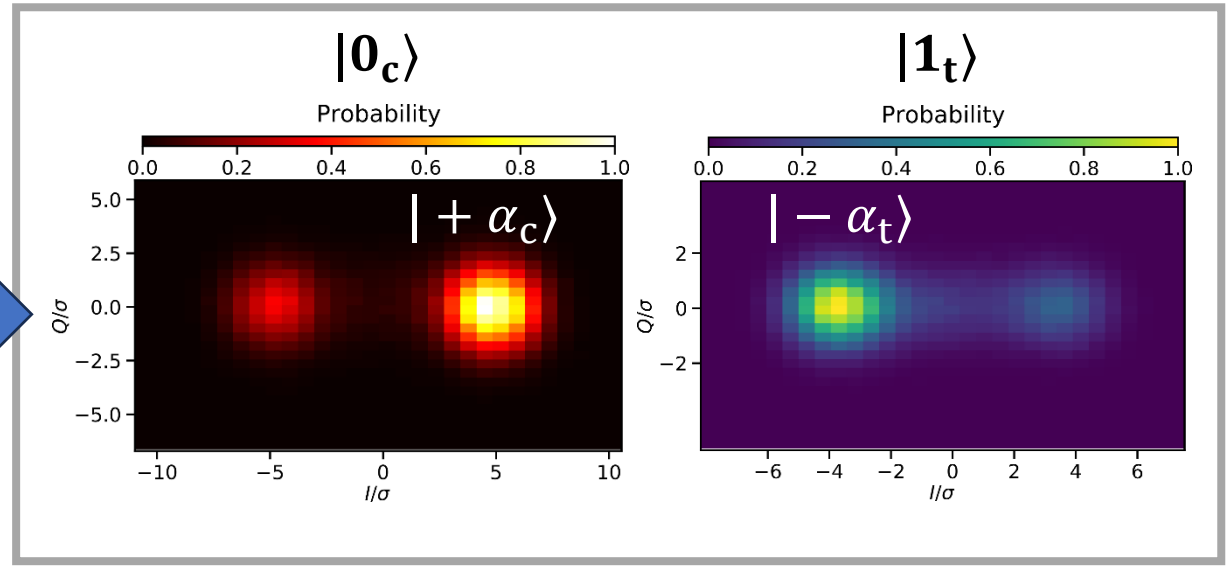
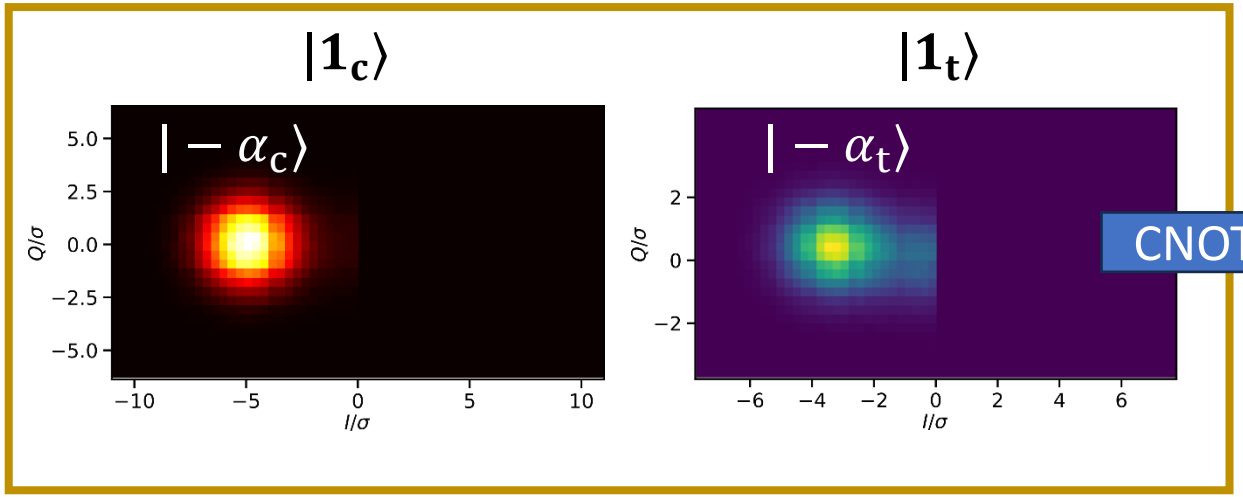


Final state





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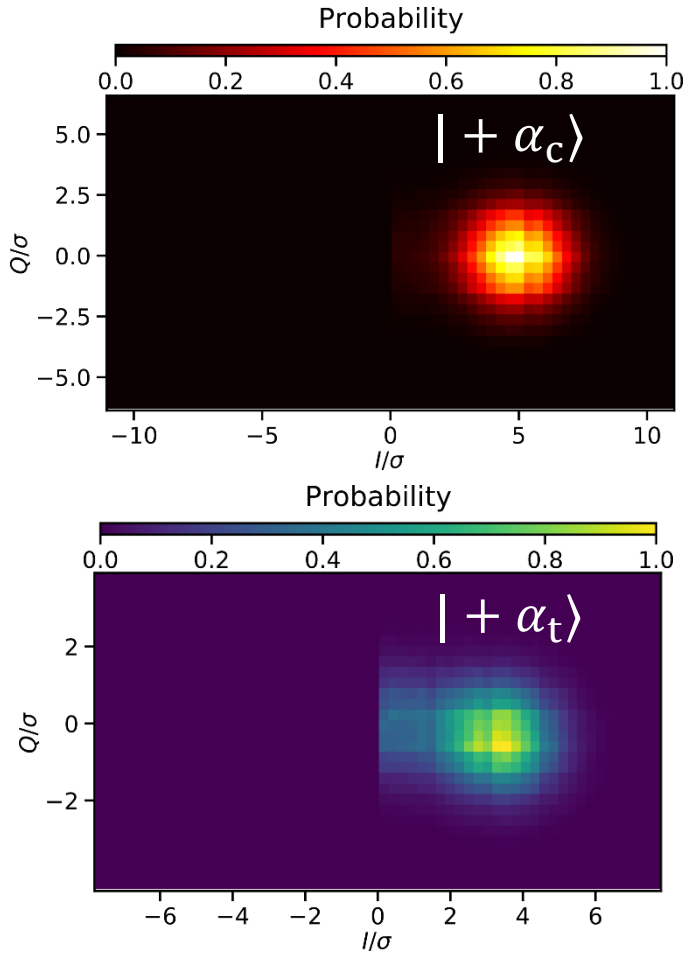
VERIFYING CNOT TABLE

Squeezing $\epsilon_2^t(a_t^{\dagger 2} + a_t^2)$



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VERIFYING CNOT TABLE

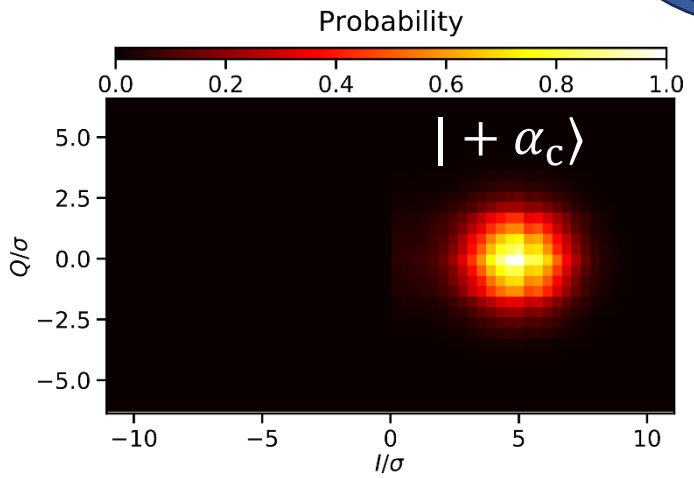
Squeezing $\epsilon_2^{\mathrm{t}}(a_{\mathrm{t}}^{\dagger 2} + a_{\mathrm{t}}^2)$

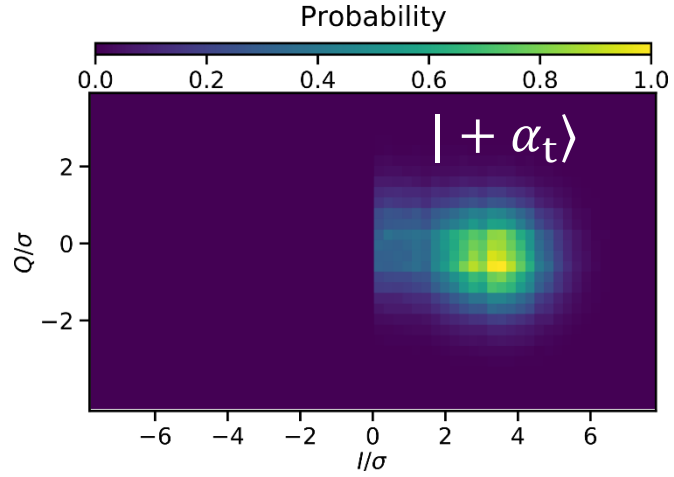
CSqueezing $g_{\mathrm{int}}(a_{\mathrm{t}}^{\dagger 2} a_{\mathrm{c}} + a_{\mathrm{t}}^2 a_{\mathrm{c}}^{\dagger})$

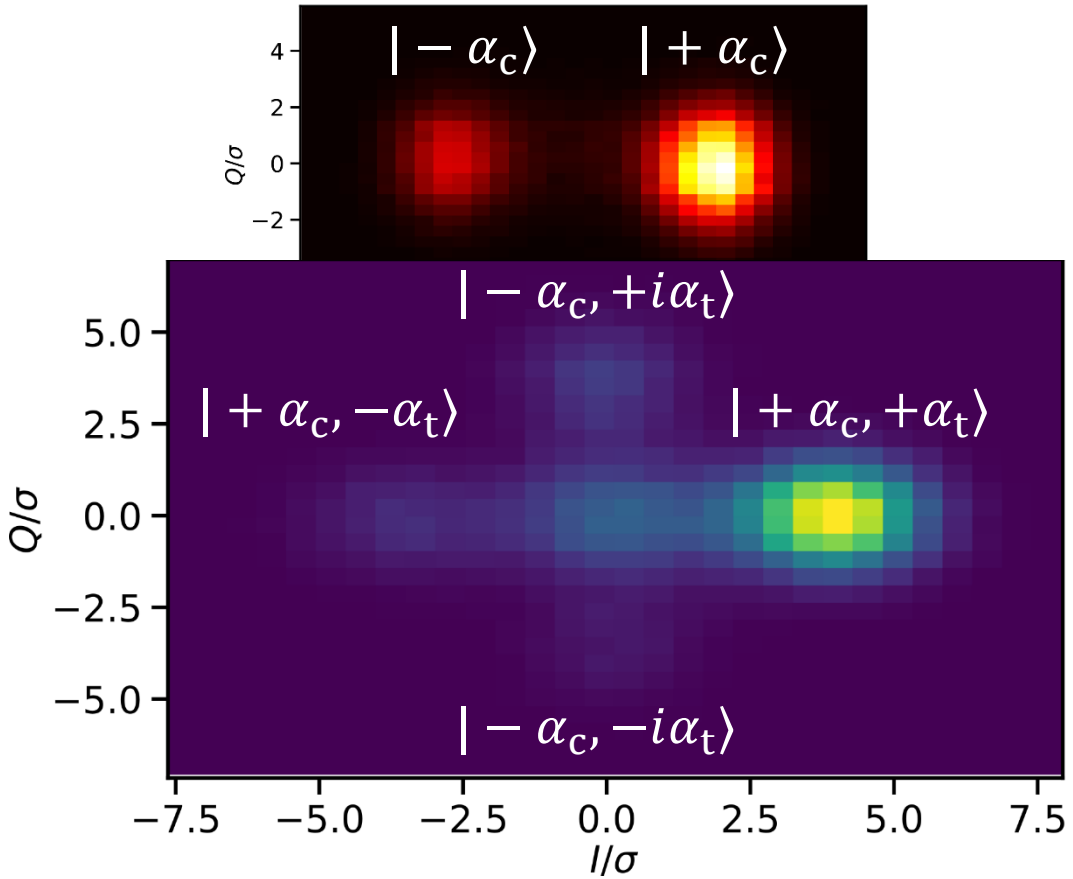
Squeezing $\epsilon_2^{\mathrm{t}}(a_{\mathrm{t}}^{\dagger 2} + a_{\mathrm{t}}^2)$

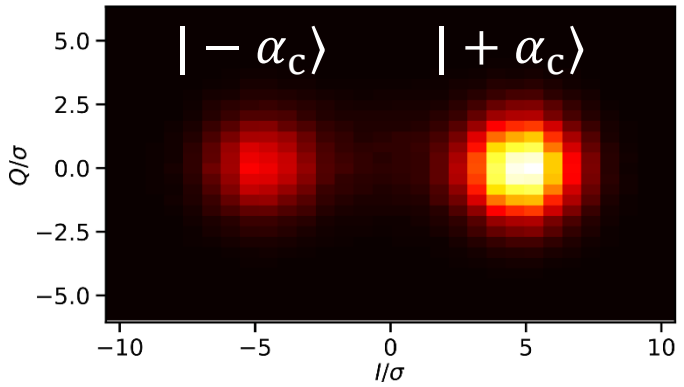
Adiabatic

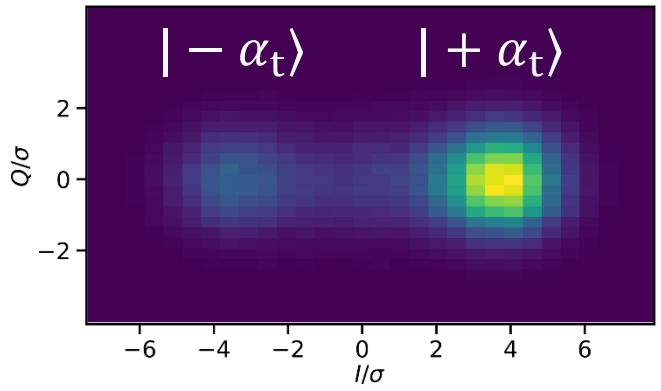
Adiabatic











VERIFYING CNOT TABLE

Squeezing $\epsilon_2^{\mathrm{t}}(a_{\mathrm{t}}^{\dagger 2} + a_{\mathrm{t}}^2)$

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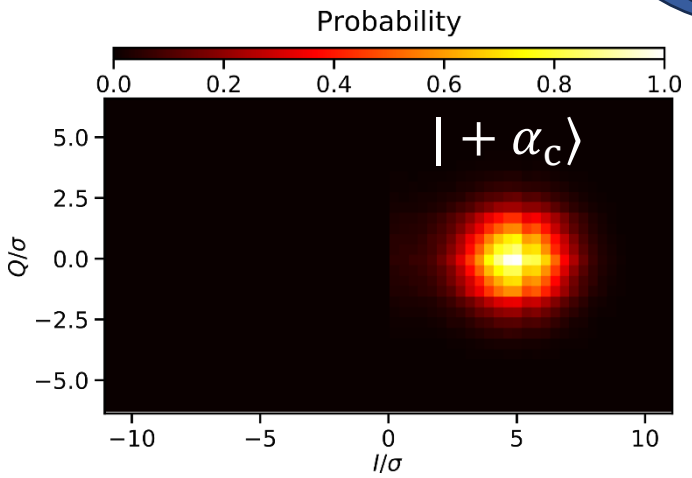
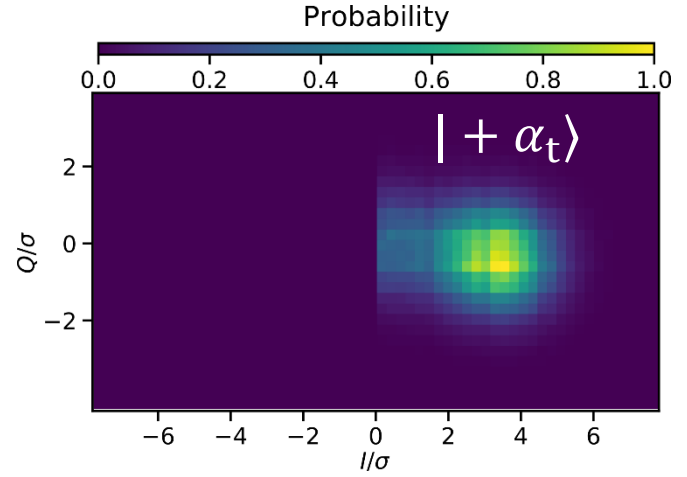
Adiabatic

Squeezing $\epsilon_2^{\mathrm{t}}(a_{\mathrm{t}}^{\dagger 2} + a_{\mathrm{t}}^2)$





Q/σ

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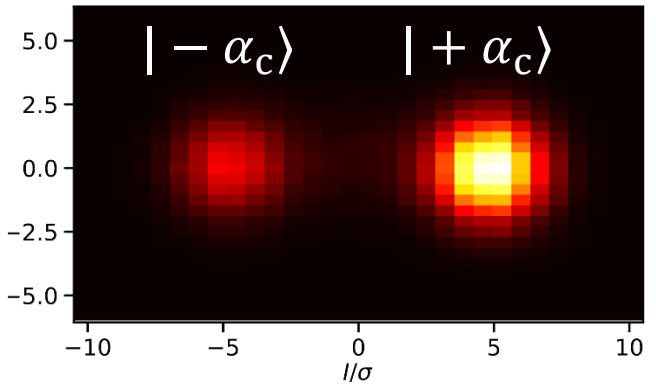
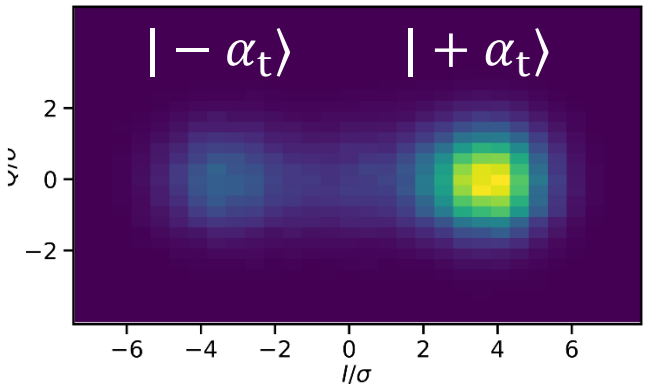
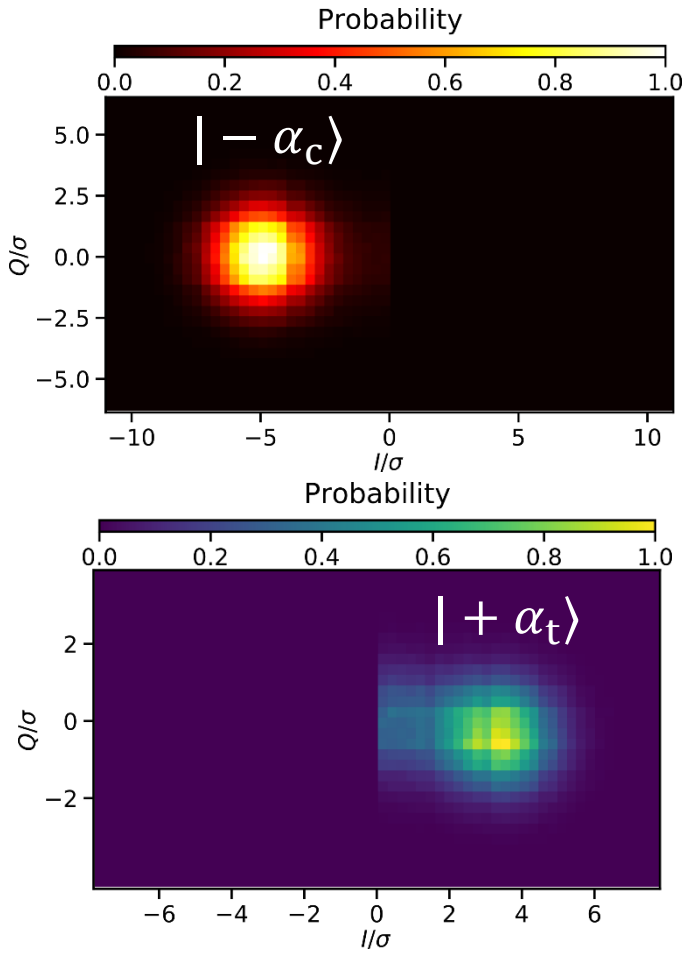




VERIFYING CNOT TABLE

Squeezing $\epsilon_2^{\mathrm{t}}(\boldsymbol{a}_{\mathbf{t}}^{\dagger 2} + \boldsymbol{a}_{\mathbf{t}}^{2})$



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VERIFYING CNOT TABLE

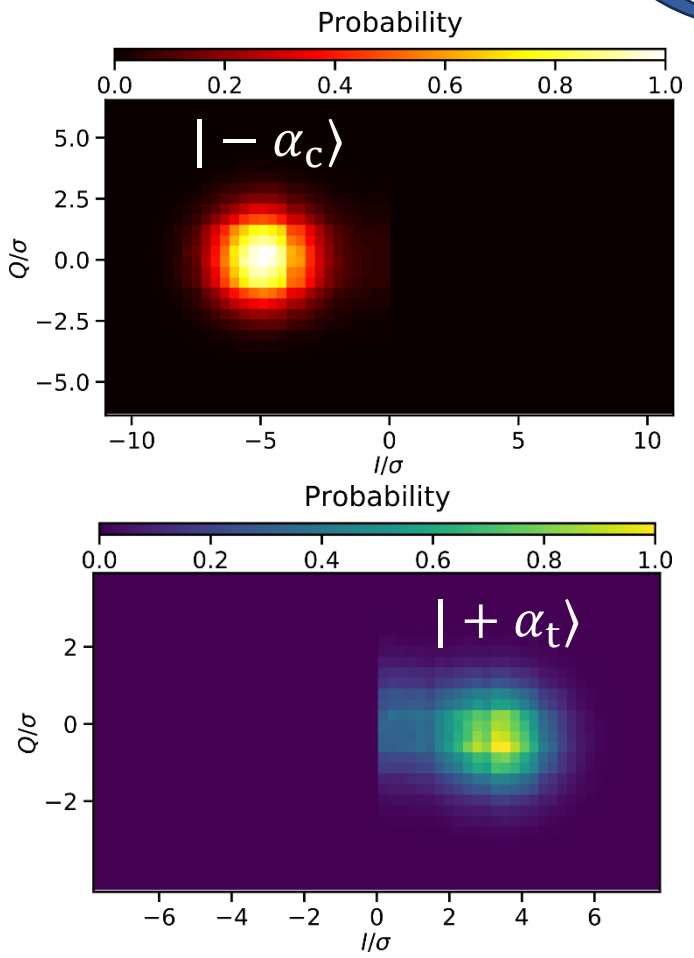
Squeezing $\epsilon_2^{\mathrm{t}}(a_{\mathrm{t}}^{\dagger 2} + a_{\mathrm{t}}^2)$

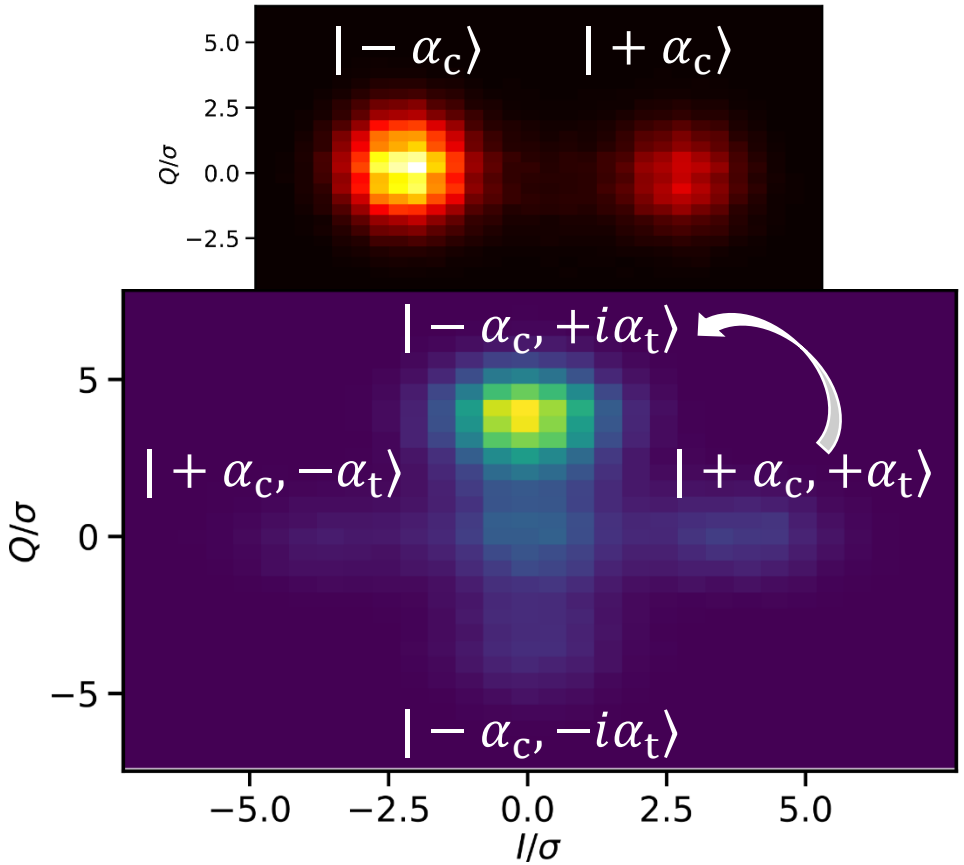
CSqueezing $g_{\mathrm{int}}(a_{\mathrm{t}}^{\dagger 2} a_{\mathrm{c}} + a_{\mathrm{t}}^2 a_{\mathrm{c}}^{\dagger})$

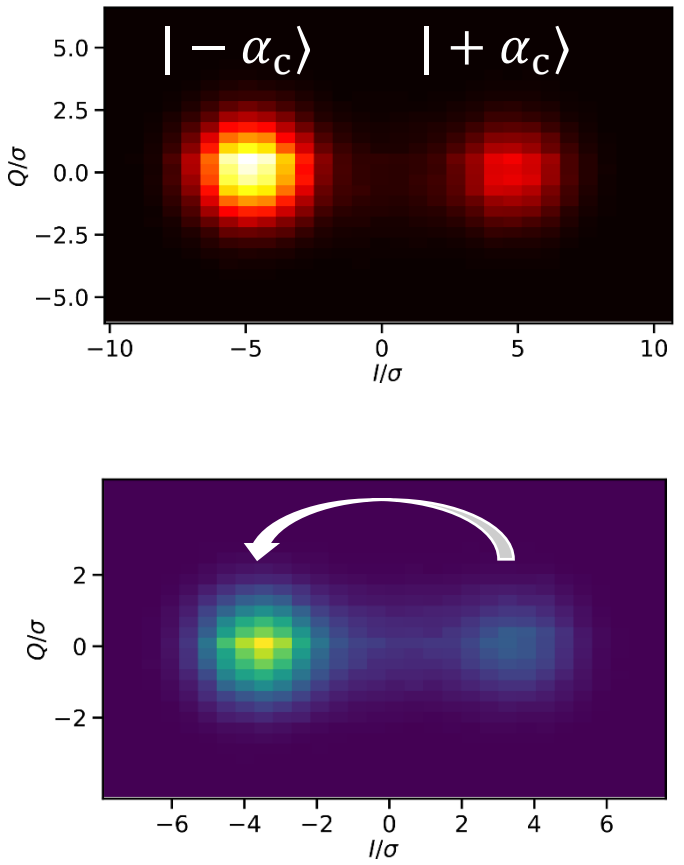
Squeezing $\epsilon_2^{\mathrm{t}}(a_{\mathrm{t}}^{\dagger 2} + a_{\mathrm{t}}^2)$

Adiabatic

Adiabatic







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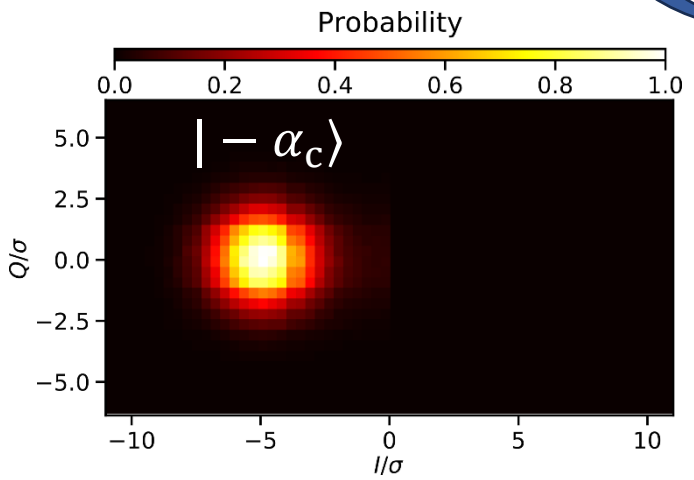

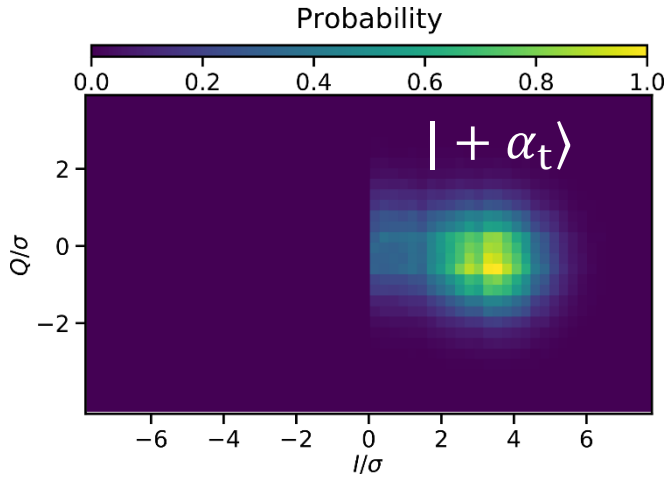

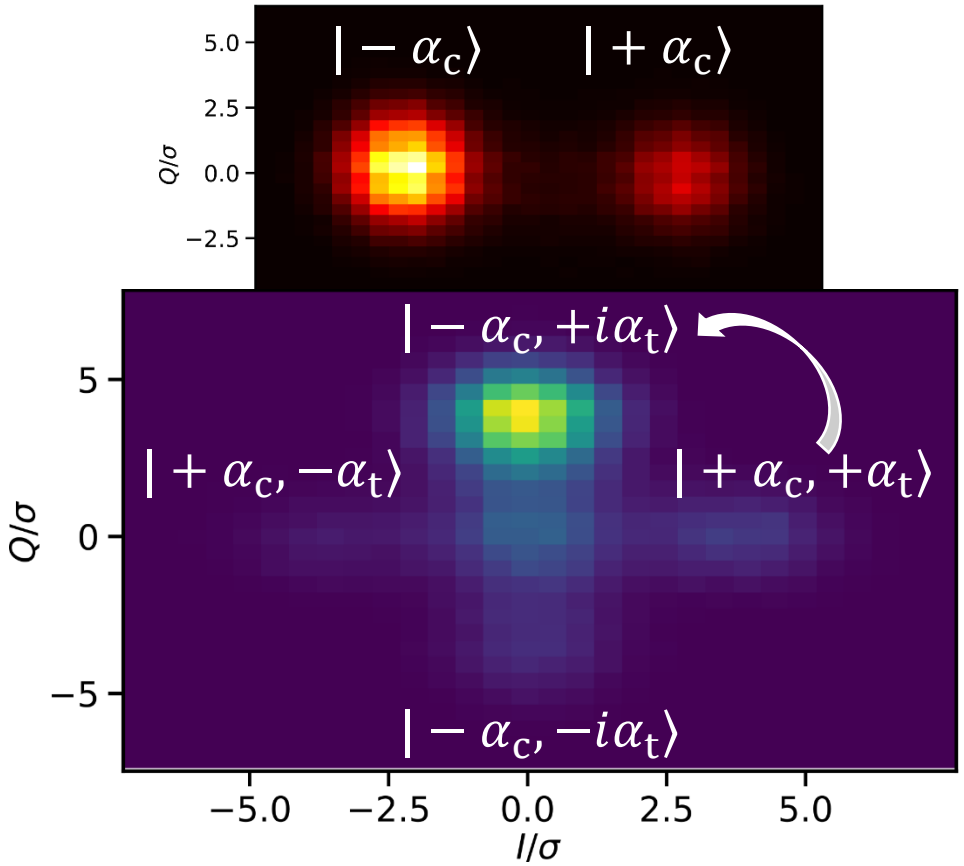

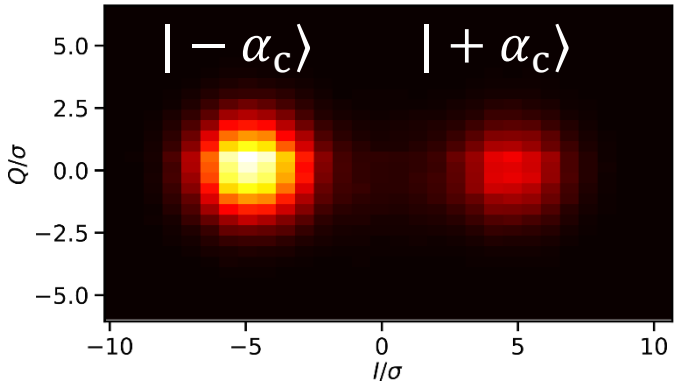

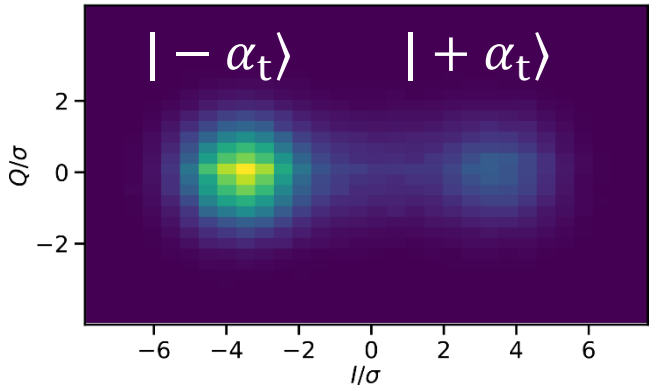

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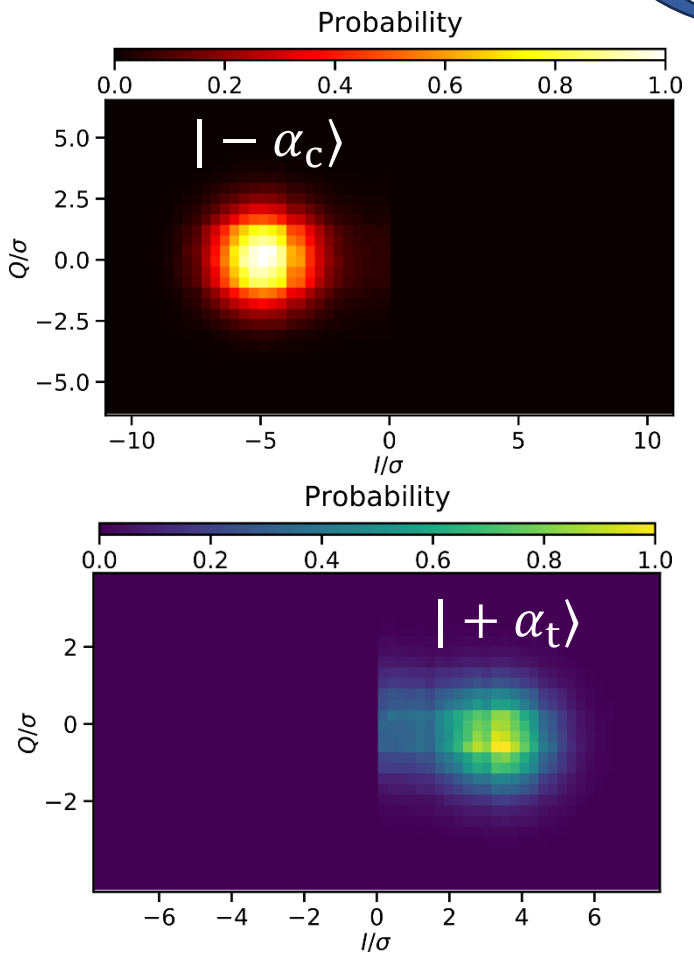
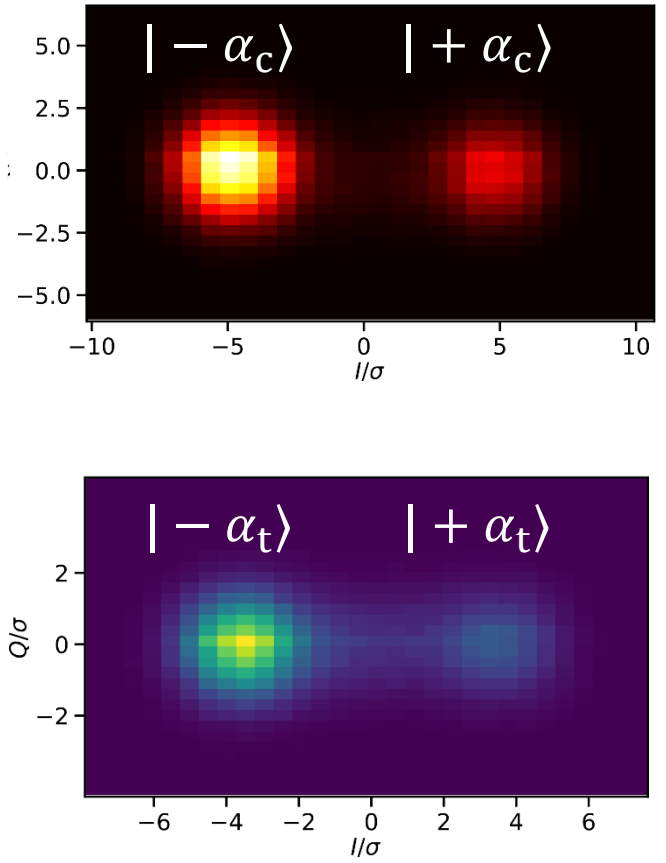


Input $\lvert$Control, Target$\rangle$	Output $\lvert$Control, Target$\rangle$
$\lvert 0_c 0_t\rangle = \lvert +\alpha_c, +\alpha_t\rangle$	$\lvert 0_c 0_t\rangle = \lvert +\alpha_c, +\alpha_t\rangle$
$\lvert 0_c 1_t\rangle = \lvert +\alpha_c, -\alpha_t\rangle$	$\lvert 0_c 1_t\rangle = \lvert +\alpha_c, -\alpha_t\rangle$
$\lvert 1_c 0_t\rangle = \lvert -\alpha_c, +\alpha_t\rangle$	$\lvert 1_c 1_t\rangle = \lvert -\alpha_c, -\alpha_t\rangle$
$\lvert 1_c 1_t\rangle = \lvert -\alpha_c, -\alpha_t\rangle$	$\lvert 1_c 0_t\rangle = \lvert -\alpha_c, +\alpha_t\rangle$



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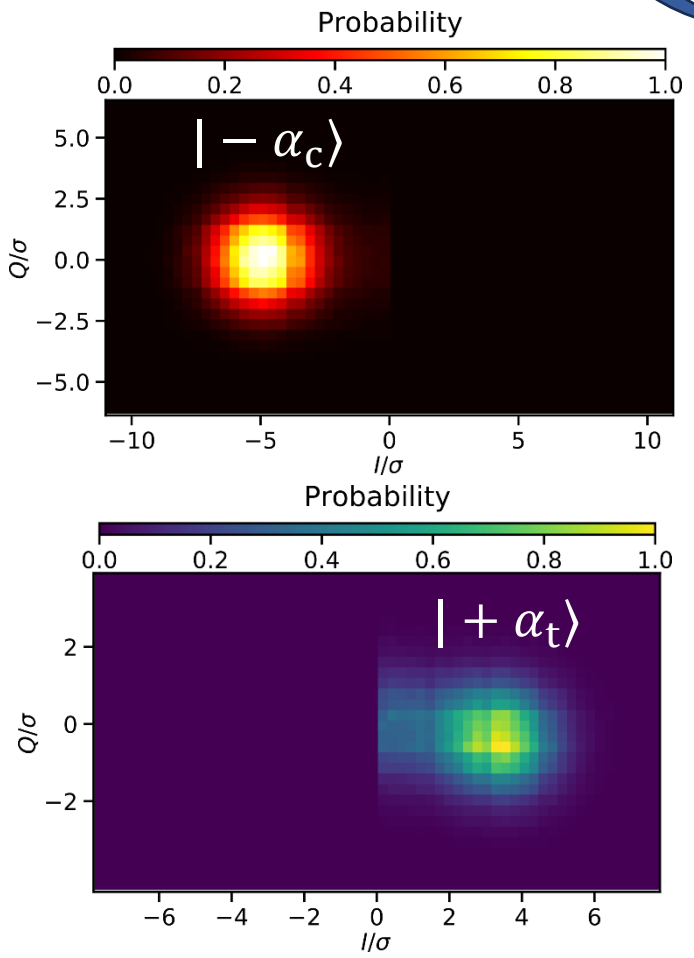

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$\lvert 0_c 1_t\rangle = \lvert +\alpha_c, -\alpha_t\rangle$	$\lvert 0_c 1_t\rangle = \lvert +\alpha_c, -\alpha_t\rangle$
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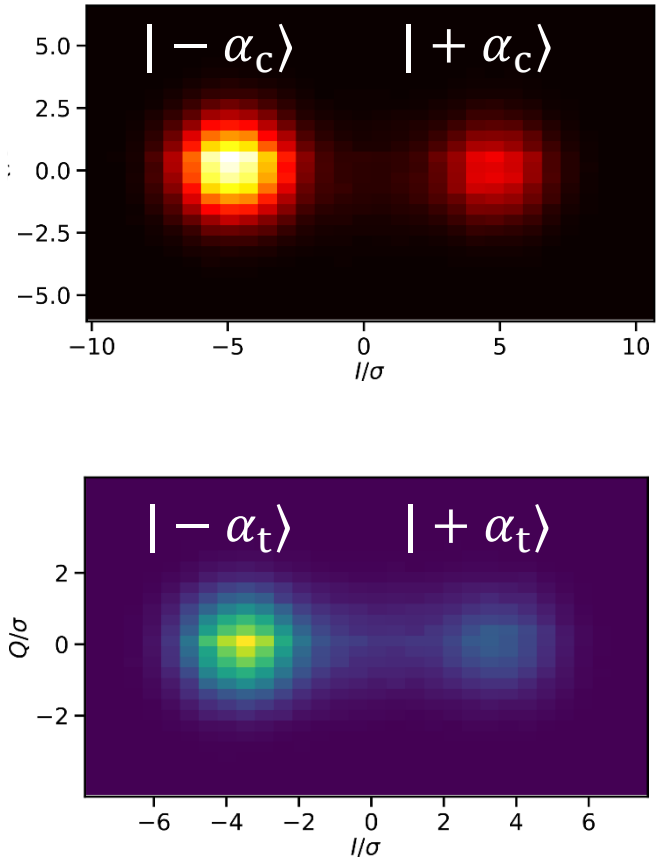
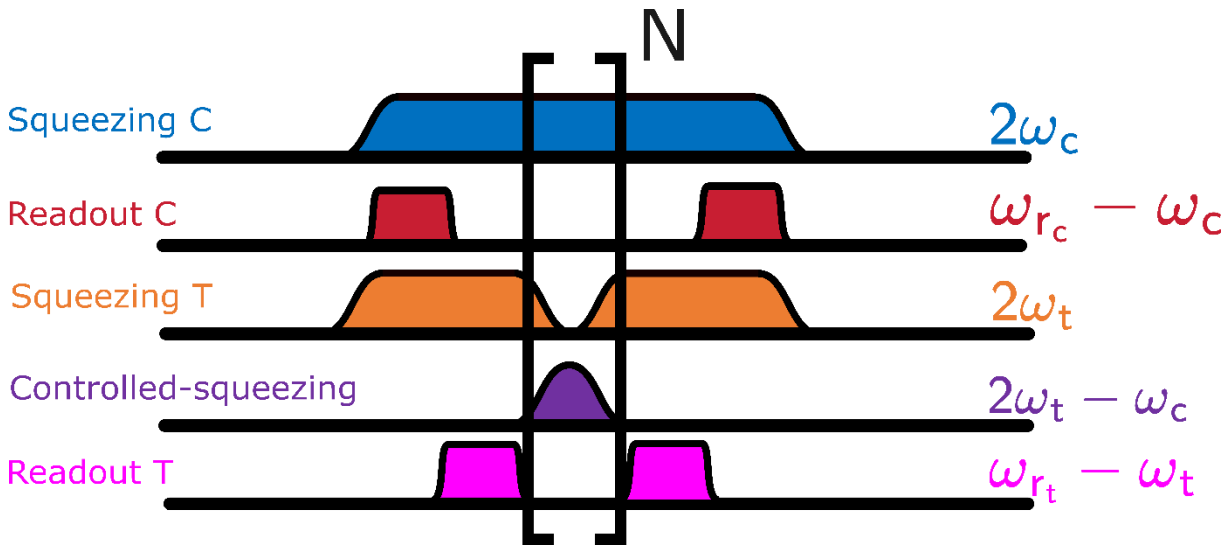
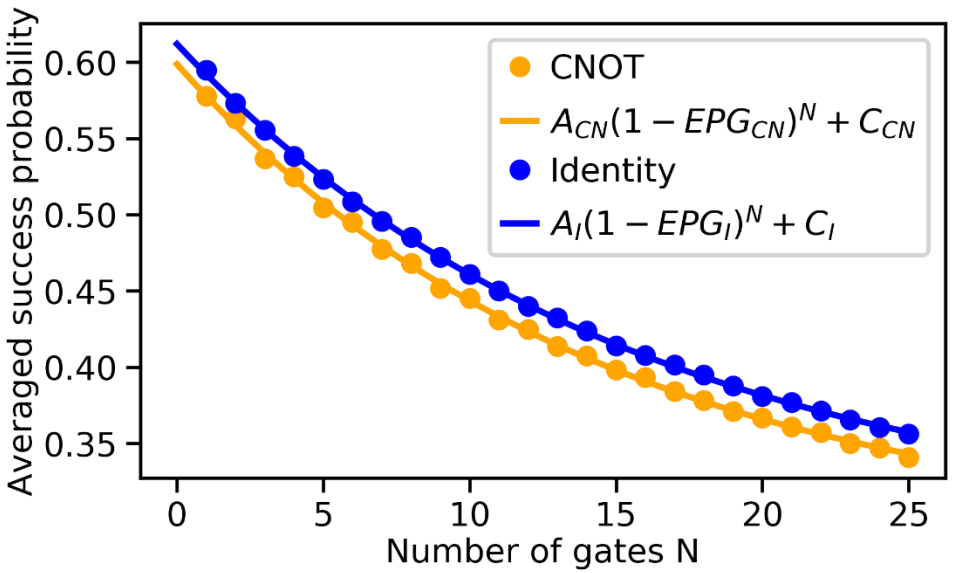
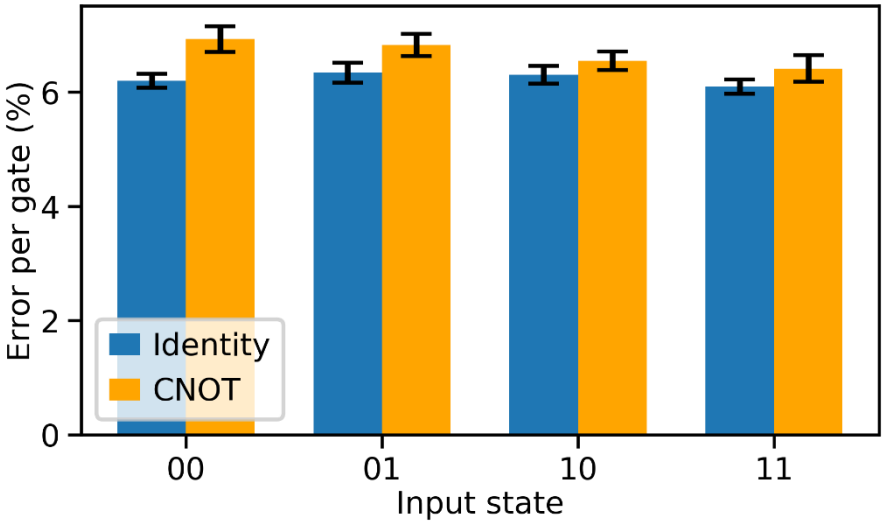


GATE CHARACTERIZATION







Average error per CNOT
$(6.7 \pm 0.2)\%$

Average error per Identity
$(6.2 \pm 0.1)\%$

Only $(8 \pm 4)\%$ of errors caused by CNOT!

SUMMARY & OUTLOOK

- Demonstration of controlled-squeezing for bias-preserving CNOT
- Implemented bias-preserving CNOT for coherent states with $> 93\%$ success probability
- Gate only responsible for $\sim 10\%$ of errors
- Implement bias-preserving CNOT for superpositions