# Coherent-state process tomography of continuous-variable quantum gates

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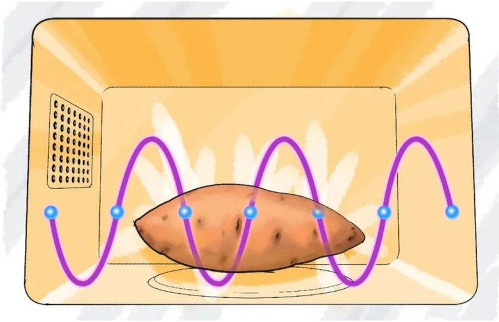
Quantum Nanophotonics 2023
Benasque, March 15

2020·LAB CHALMERS WACQT Intermodulation products Q-CTRL

# Preface: Quantum Optics *vs* Microwave Quantum Optics



Lasers and photodetectors

Optical fibers, integrated waveguides

Real or synthetic atoms

Quantum at room $T$

Wafeform generators and digitizers

Coaxial cables and waveguides

Synthetic atoms

Quantum at cryogenic $T$

**Light-matter interactions described by same equations: Jaynes-Cummings *and beyond***

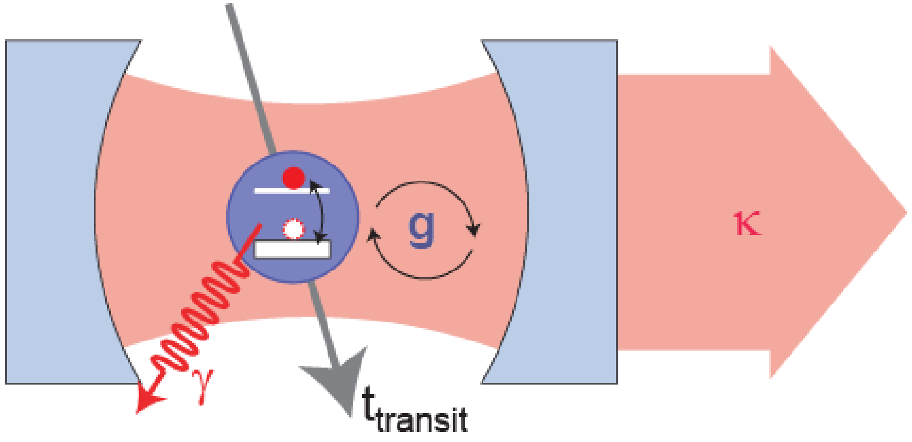
**Some things are EASY**

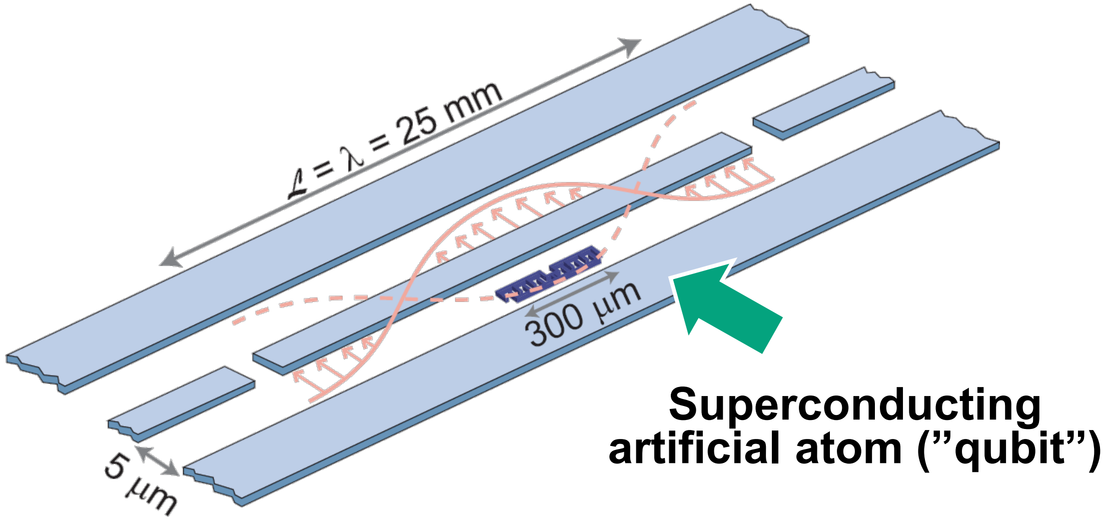
**Some things are HARD**

**Some things are HARD**

**Some things are EASY**

# From Cavity QED to Circuit QED




Raimond et al., Rev Mod Phys 73, 565 (2001)
Haroche & Raimond, OUP Oxford (2006)
Ye et al., Science 320, 1734 (2008)

Blais et al., Phys Rev A 69, 062320 (2004)
Wallraff et al., Nature 431, 162 (2004)
Schoelkopf & Girvin, Nature 451, 664 (2008)

**Quantum information processing** (Google, IBM…)
**Microwave quantum optics**

# This talk

## Part I. Waveguide QED: project overview

- Symmetry-selective couplings
- Structured environments and atom-photon bound states
- Quantum thermodynamics with hot waveguides

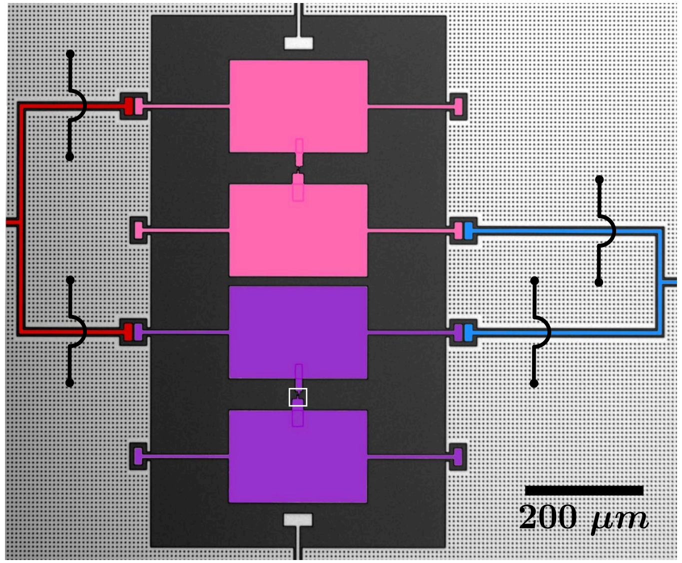
## Part II. Coherent-state process tomography of a quantum gate

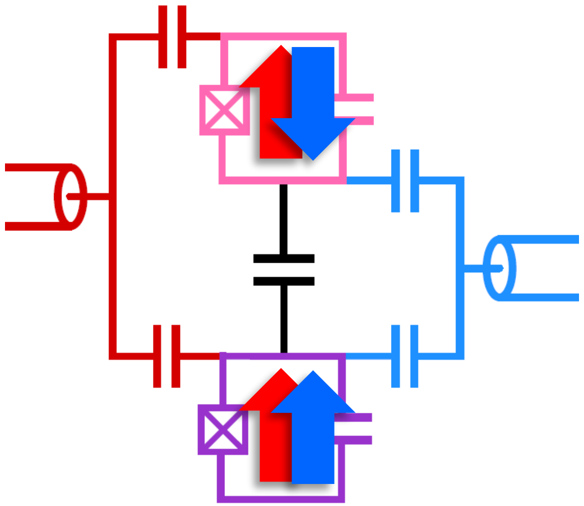
- Quantum computation with bosonic modes
- Deterministic preparation of nonclassical states
- X-gate on qubit encoded in a bosonic mode and its tomography

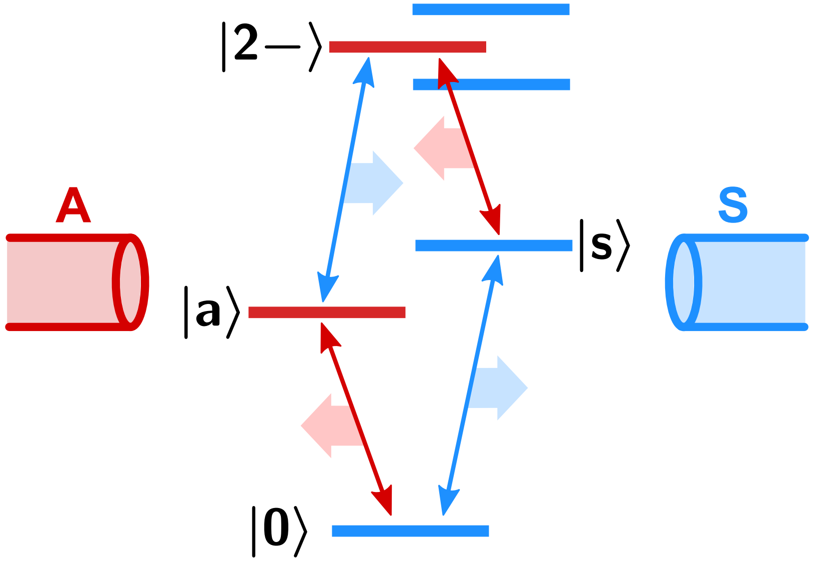
Wigner functions!

# Part I

# Symmetry-selective coupling of an artificial molecule to microwave waveguides

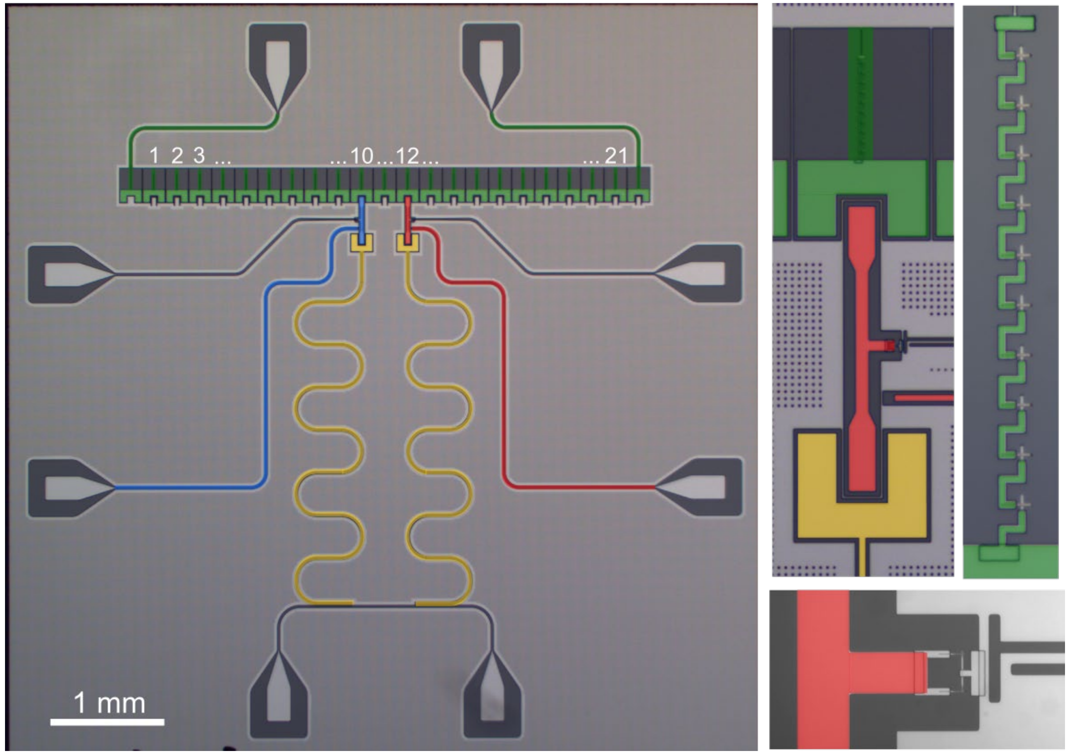


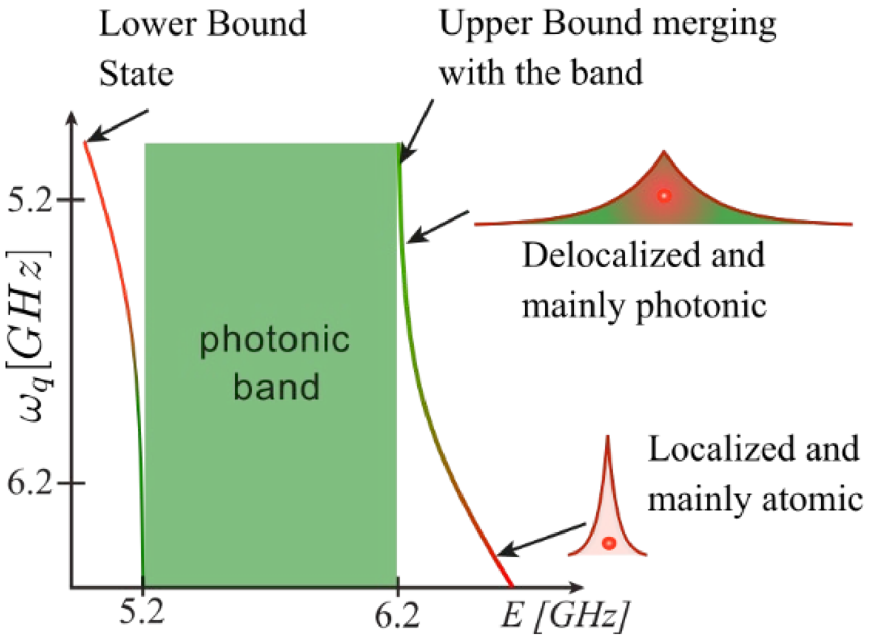






Aamir et int. SG, PRL **129**, 123604 (2022)

# Quantum emitters coupled to a structured environment: Atom-photon bound states and their interaction

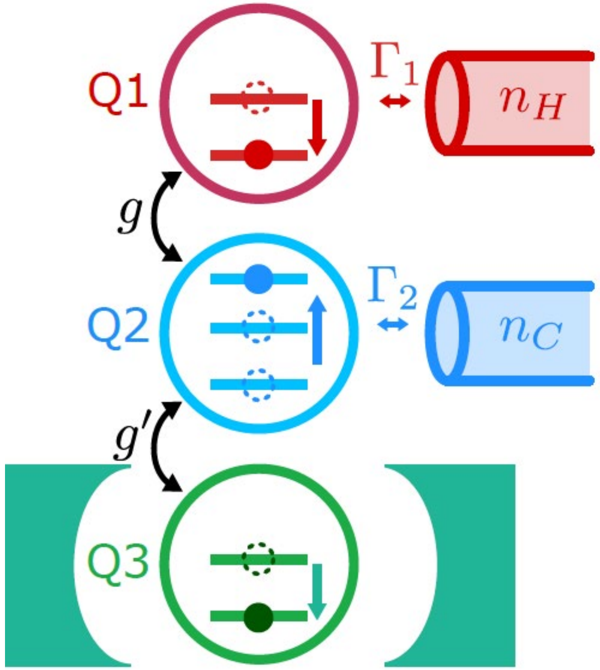


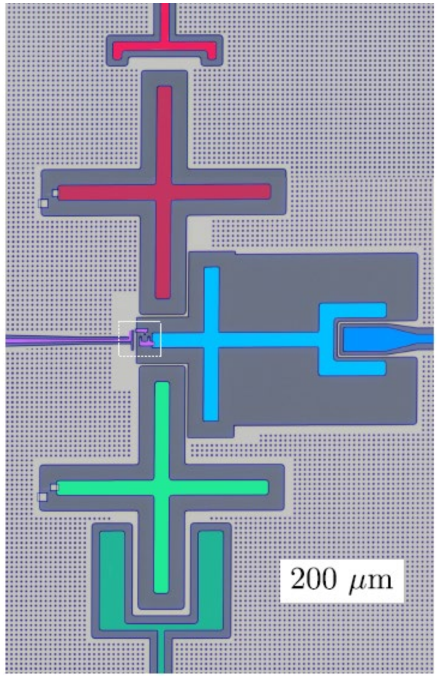



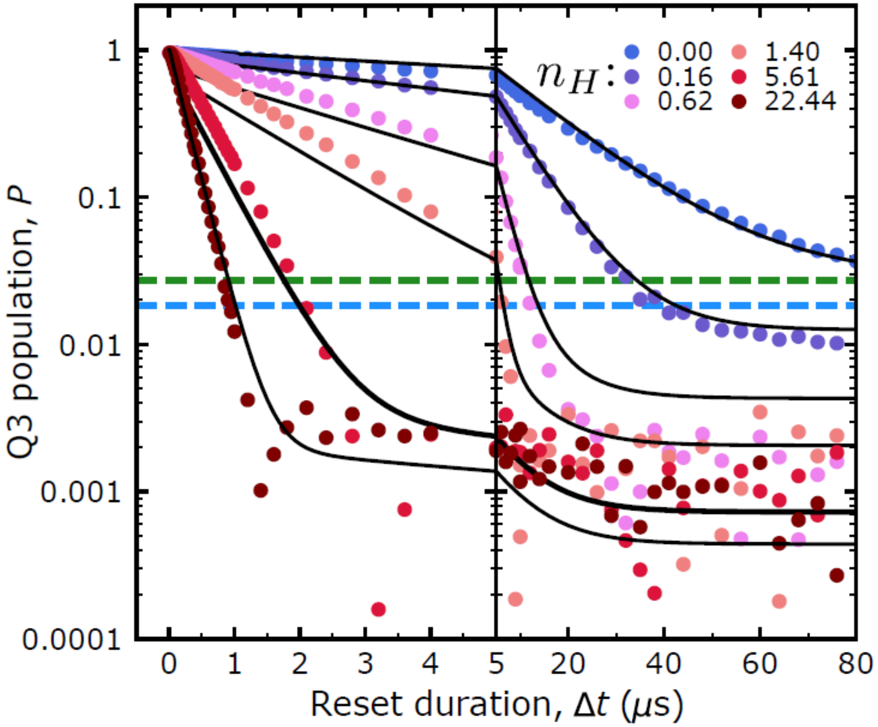

Scigliuzzo et int. SG, Phys. Rev. X **12**, 031036 (2022)

# Quantum thermal machines coupled to waveguides

## … Waveguide QTD?



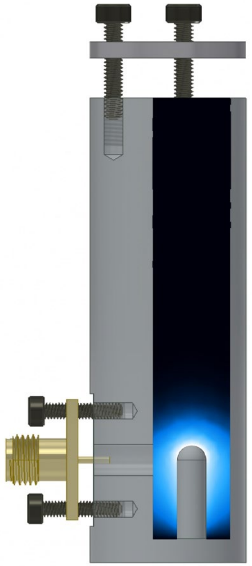



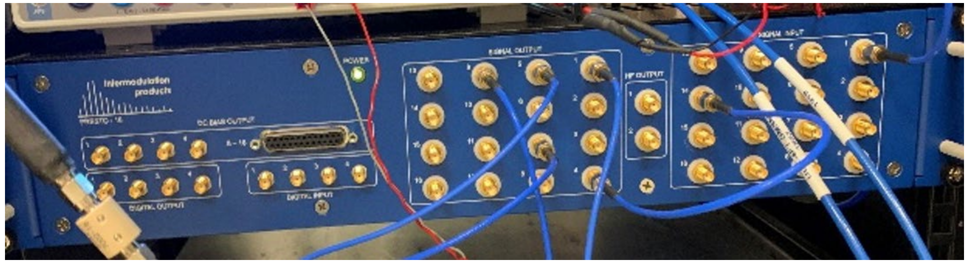

Aamir et int. SG, in preparation

# Part II

# Quantum computation with bosonic modes

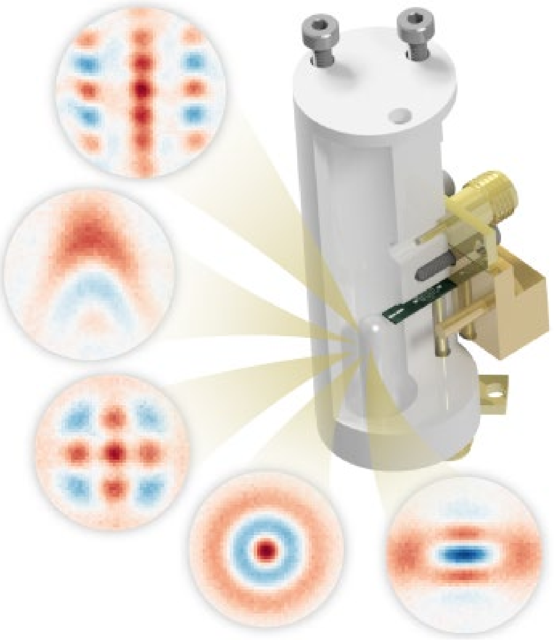


High-quality Al microwave cavities
Kudra *et int* Delsing, APL **117**, 070601 (2020)



Microwave transceiver based on RFSoC
Tholén *et int* Haviland, Rev. Sci. Instr. **93**, 104711 (2022)

State preparation with SNAP-displacement sequences
Kudra *et int* SG, PRX Quantum **3**, 030301 (2022)



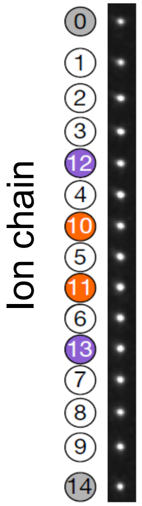
**Coherent-state quantum process tomography (experiment)**
**Mikael Kervinen, Marina Kudra, Shahnawaz Ahmed, Axel Eriksson, Fernando Quijandría, Anton Frisk Kockum, Per Delsing, and SG, arXiv:2303.01451**

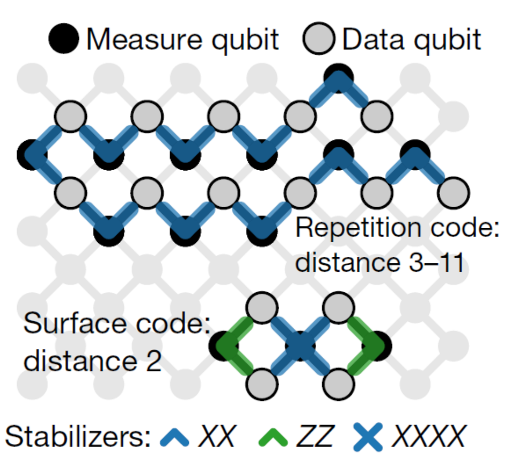
Gradient-Descent Quantum Process Tomography (theory)
Ahmed, Quijandría & Kockum, arXiv:2208.00812

Selective photon addition for quantum error correction
Kudra *et int* SG, arXiv:2212.12079

# Towards quantum error correction: logical qubits

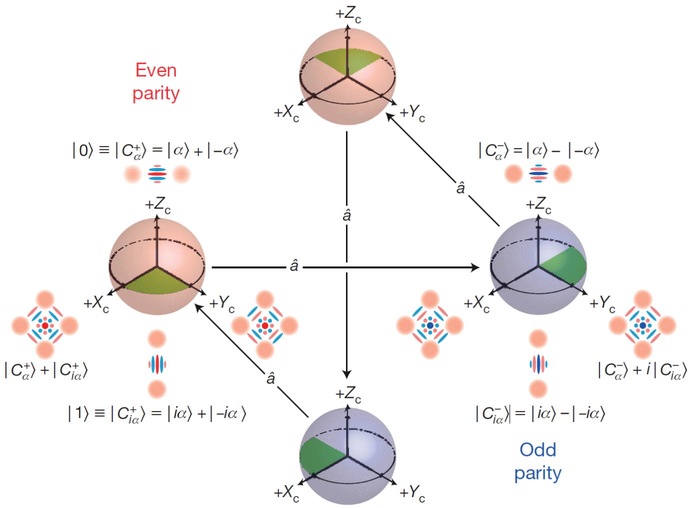
## Multiple two-level systems




Andersen, *et int*, Wallraff, Nat Phys 16, 875 (2020)
Marques, *et int*, DiCarlo, Nat Phys 18, 80 (2022)
Google Quantum AI, Nature 595, 383 (2021)
Krinner, *et int*, Wallraff, Nature 605, 669 (2022)
Egan, et int, Monroe, Nature 598, 281 (2021)

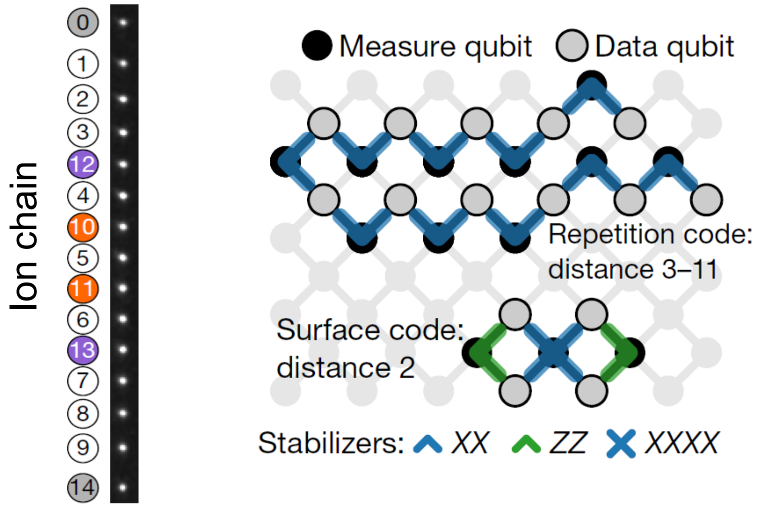
## Single harmonic oscillator




Ofek, et int, Schoelkopf, Nature 536, 441 (2016)
Lescanne, et int, Leghtas, Nature Phys 16, 509 (2020)
Grimm, et int, Devoret, Nature 584, 7820 (2020)
Campagne-Ibarcq, et int, Devoret, Nature 584, 7821 (2020)
Gertler, *et int*, Wang, Nature 590, 7845 (2021)

# Towards quantum error correction: logical qubits

## Multiple two-level systems

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Marques, *et int*, DiCarlo, Nat Phys 18, 80 (2022)
Google Quantum AI, Nature 595, 383 (2021)
Krinner, *et int*, Wallraff, Nature 605, 669 (2022)
Egan, et int, Monroe, Nature 598, 281 (2021)

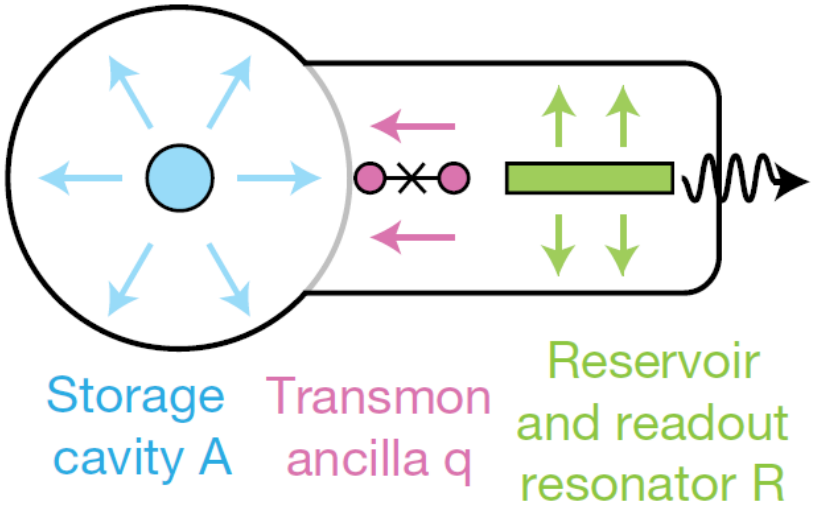
## Single harmonic oscillator

Resource-efficient
Long coherence times
One dominant error mechanism

Control? Needs nonlinearity

Ofek, et int, Schoelkopf, Nature 536, 441 (2016)
Lescanne, et int, Leghtas, Nature Phys 16, 509 (2020)
Grimm, et int, Devoret, Nature 584, 7820 (2020)
Campagne-Ibarcq, et int, Devoret, Nature 584, 7821 (2020)
Gertler, *et int*, Wang, Nature 590, 7845 (2021)

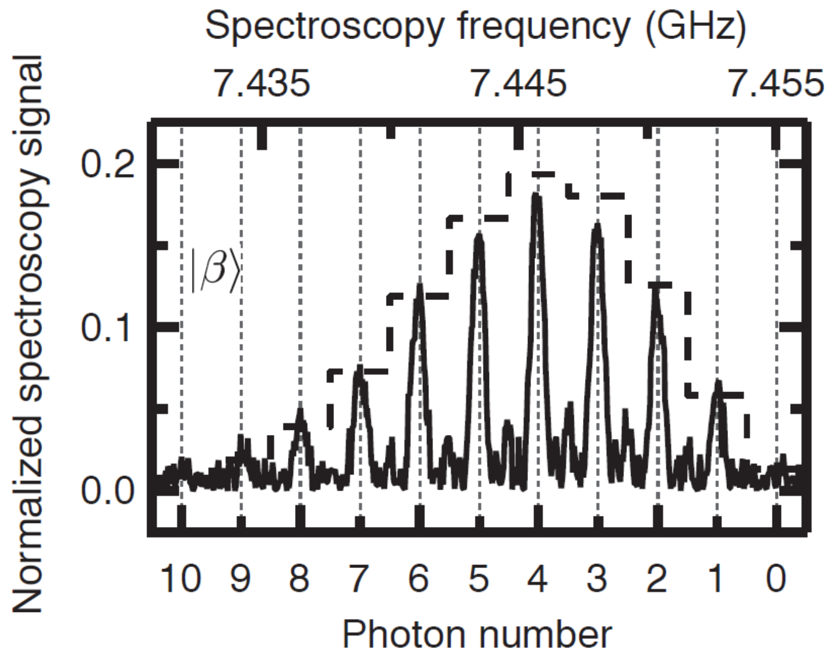
# Harmonic oscillator + ancillary qubit = universal control



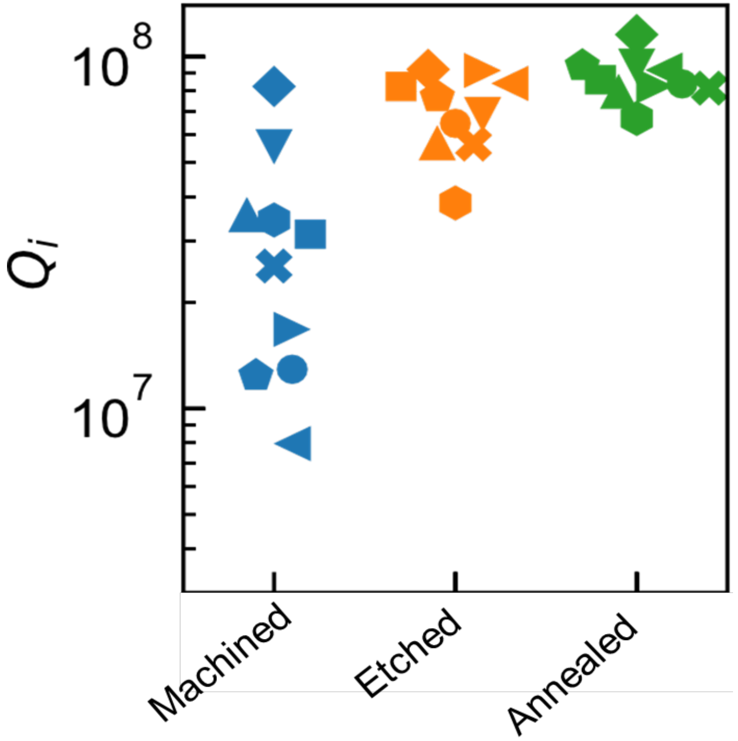

Gertler, *et int*, Wang, Nature 590, 7845 (2021)
Vlastakis *et int* Schoelkopf, Science 342, 6158 (2013)
Krastanov *et int* Jiang, PRA 92, 040303 (2015)
Heeres *et int* Schoelkopf, PRL 115, 137002 (2015)
--- Nat Commun 8, 94 (2017)
Eickbusch *et int* Devoret, Nat Phys 18, 1464 (2022)

**Strong dispersive regime**

$$H = \omega_r a^\dagger a + \omega_q b^\dagger b + \chi a^\dagger a b^\dagger b$$



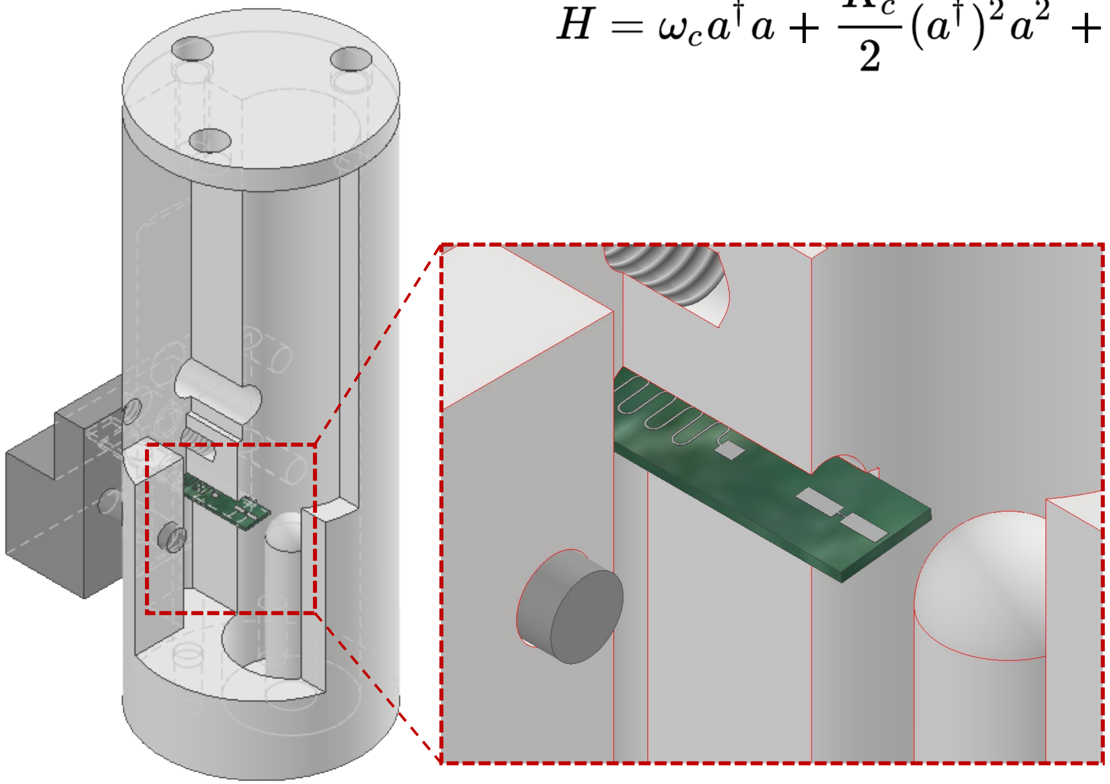
# Quantum memory: 3D aluminum cavity




Kudra, …, SG, Wickman, and Delsing, APL **117**, 070601 (2020)

# Transmon coupled to 3D cavity

$$H = \omega_c a^\dagger a + \frac{K_c}{2}(a^\dagger)^2 a^2 + \omega_q b^\dagger b + \chi_{qc} a^\dagger a b^\dagger b + \chi'_{qc}(a^\dagger)^2 a^2 b^\dagger b$$

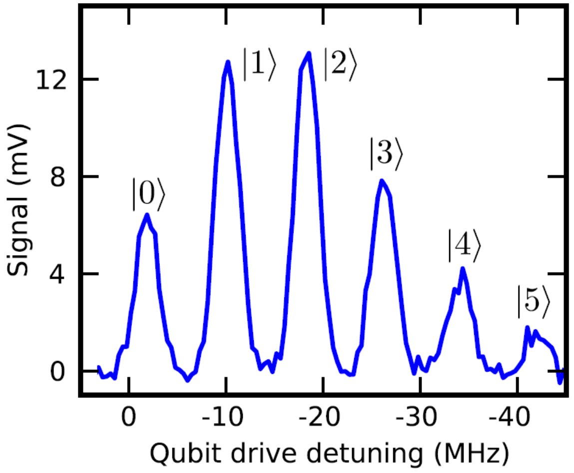


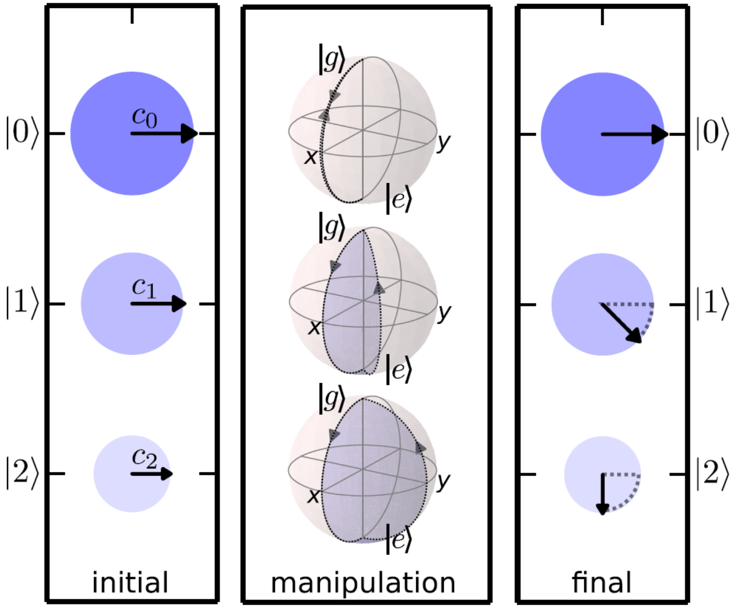
| Parameter | Symbol | Value |
|---|---|---|
| Transmon frequency | $\omega_q/2\pi$ | 6.281 GHz |
| Cavity frequency | $\omega_c/2\pi$ | 4.454 GHz |
| Readout resonator frequency | $\omega_r/2\pi$ | 7.348 GHz |
| Transmon-cavity cross-Kerr | $\chi_{qc}/2\pi$ | −2.22 MHz |
| Transmon-resonator cross-Kerr | $\chi_{qr}/2\pi$ | −1.4 MHz |
| Cavity self-Kerr | $K_c/2\pi$ | −2.7 kHz |
| Transmon anharmonicity | $\alpha_q/2\pi$ | −353 MHz |
| Transmon-cavity higher-order cross-Kerr. | $\chi'_{qc}/2\pi$ | −14 kHz |
| Transmon energy decay time | $T_{1q}$ | ≈ 38 µs |
| Transmon pure dephasing time | $T_{\Phi q}$ | ≈ 127 µs |
| Cavity decay time | $T_{1c}$ | ≈ 315 µs |
| Transmon thermal population | $\bar{n}_q$ | 0.005 |
| Cavity thermal population | $\bar{n}_c$ | 0.003 |

# Selective Number-dependent Arbitrary phase (SNAP) gates

$$S(\vec{\theta}): \sum c_n |n\rangle \otimes |g\rangle \rightarrow \sum c_n e^{i\theta_n} |n\rangle \otimes |g\rangle$$

How do we do it?
I will explain

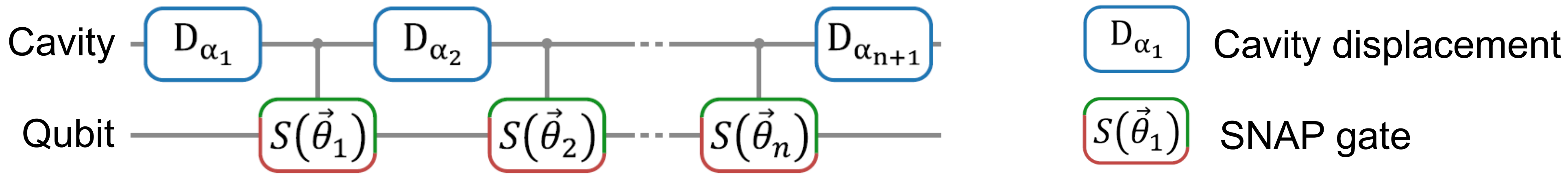


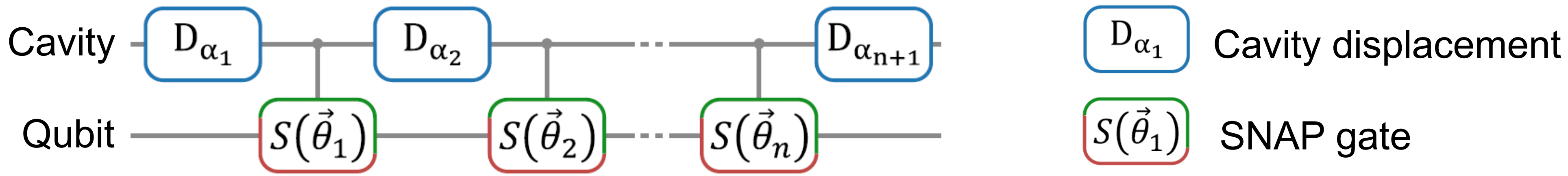

**SNAP + Displacements = Universal control**
**How efficient?**

Heeres *et int* Schoelkopf, PRL 115, 137002 (2015)
Krastanov *et int* Jiang, PRA 92, 040303 (2015)
Fösel *et int* Jiang, ArXiv:2004.14256
Kudra et int SG, PRX Quantum 3, 030301 (2022)

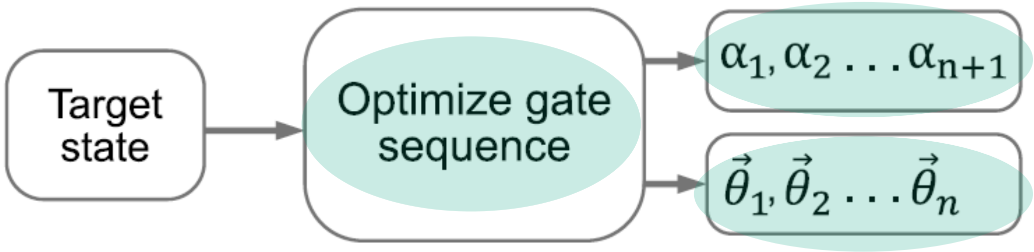
# Two-step optimization of SNAP gate sequences



# Two-step optimization of SNAP gate sequences




**1**




Gradient-based optimization of fidelity to target state

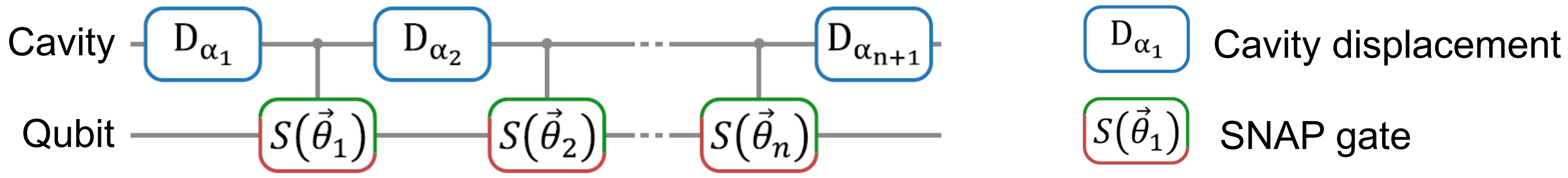
Amplitudes of displacement pulses

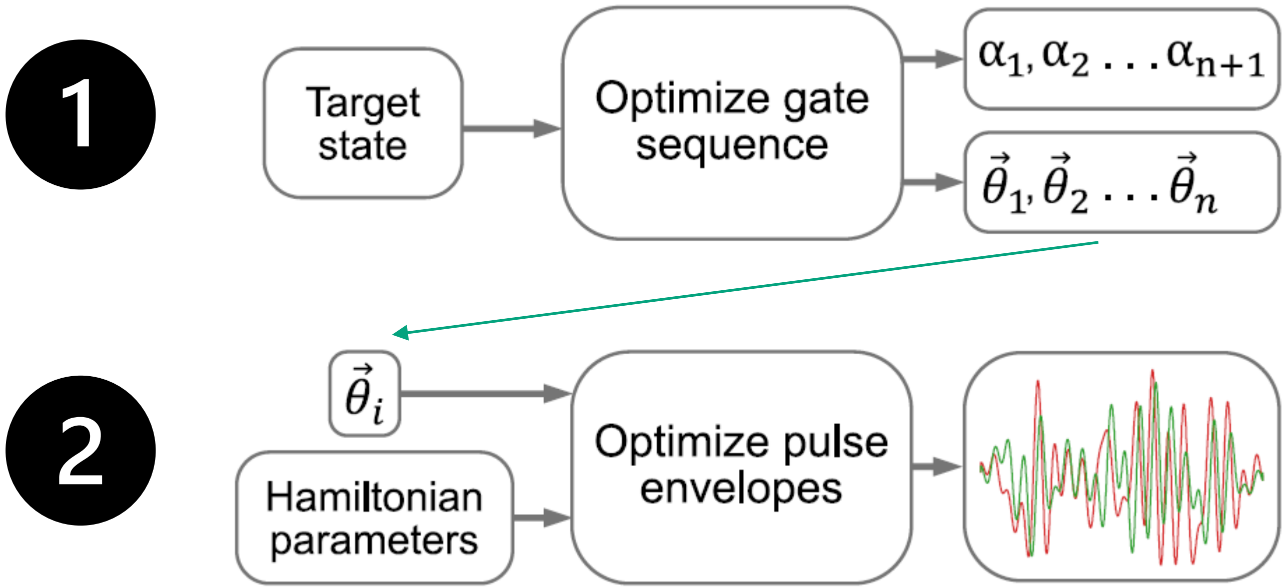
Phases to impart to Fock states

*m*: largest targeted Fock state **Up to *m* = 17!**

$$\vec{\theta}_i = (\theta_{i,0}, \theta_{i,1}, \ldots, \theta_{i,m})$$

# Two-step optimization of SNAP gate sequences



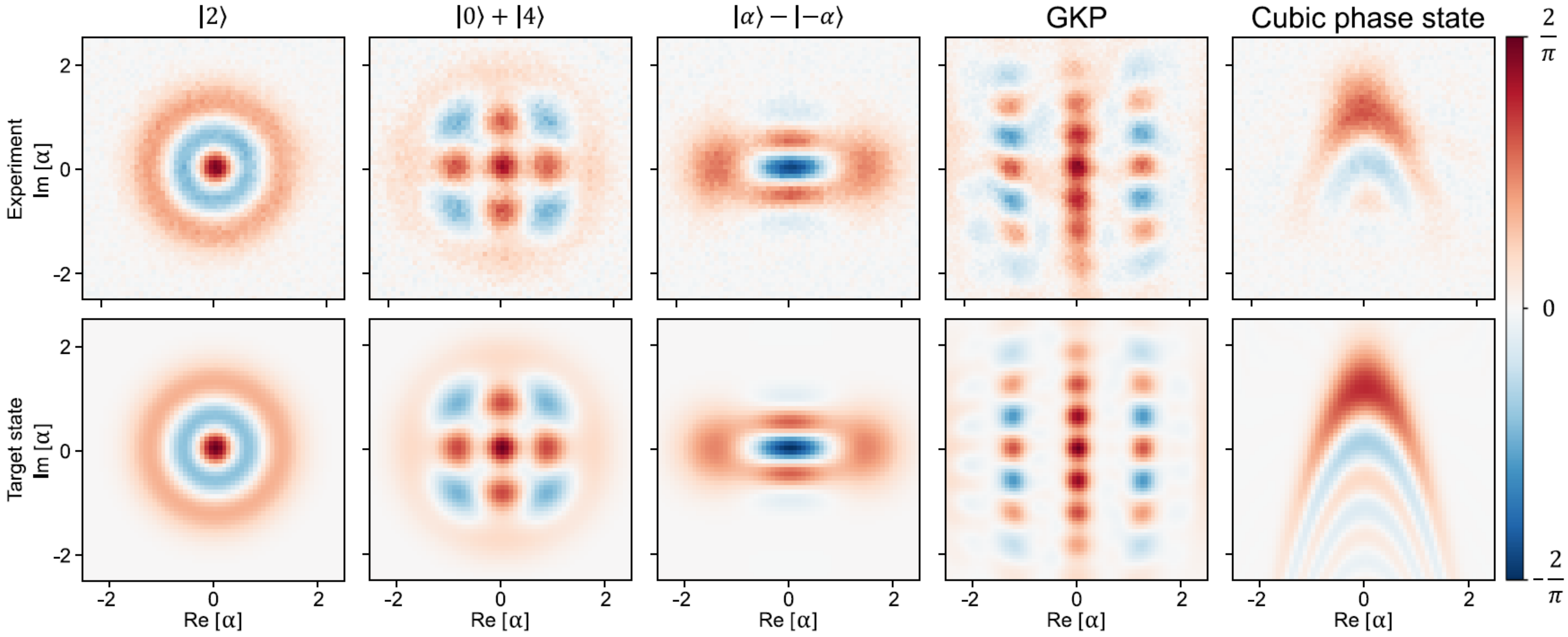




From calibration measurements[1]

Q-CTRL

[1] P. Reinhold, Ph.D. thesis, Yale Univ. (2019)

# Some states we can generate with SNAP+displacements



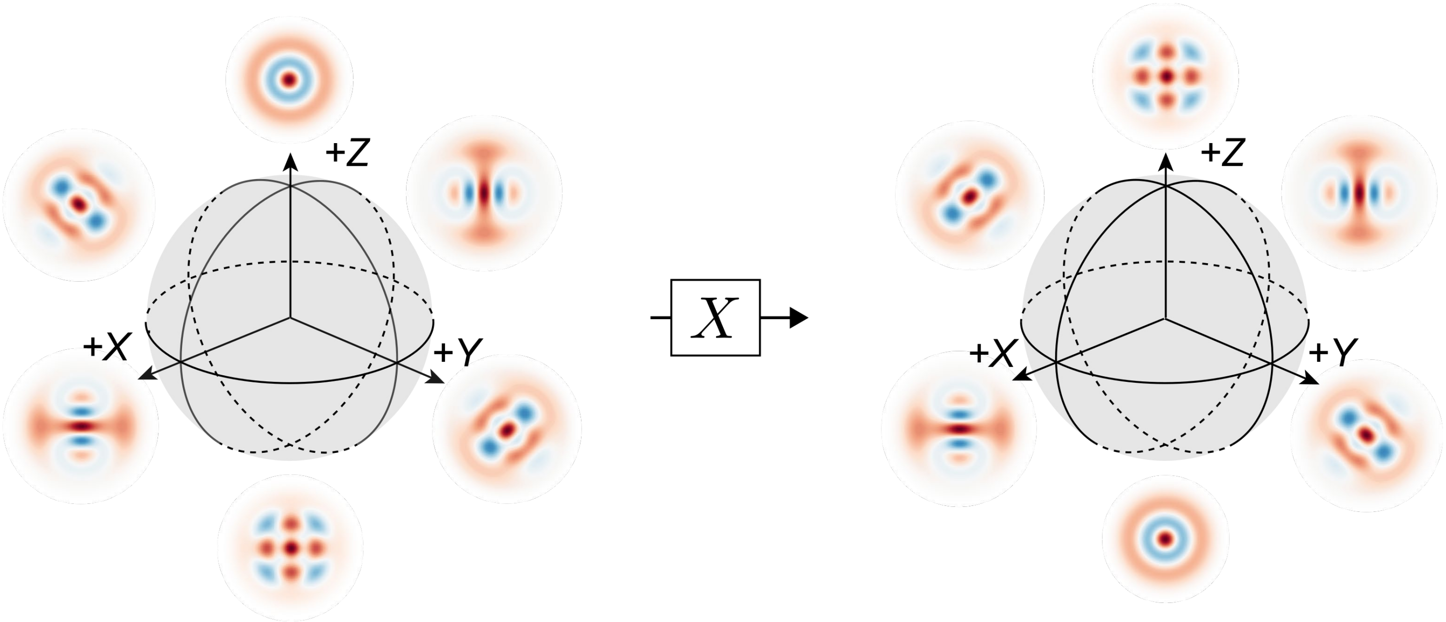

Kudra *et int* SG, PRX Quantum 3, 030301 (2022)

# From states to gates: X-gate in binomial encoding

**Binomial encoding**

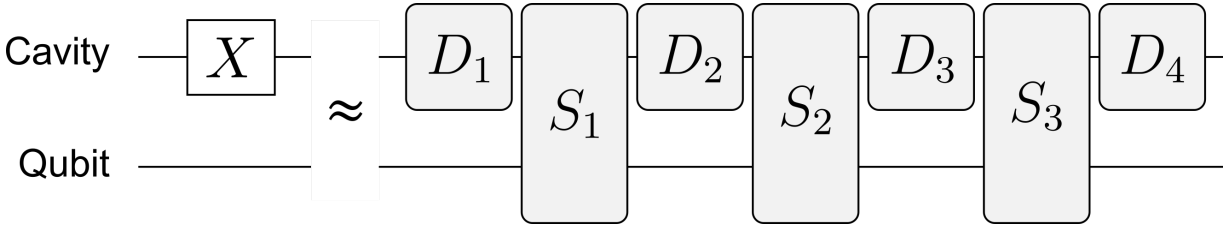
$|0_L\rangle = |2\rangle$

$|1_L\rangle = |0\rangle + |4\rangle$




**Gate decomposition**

**Ideal fidelity: 99.6%**

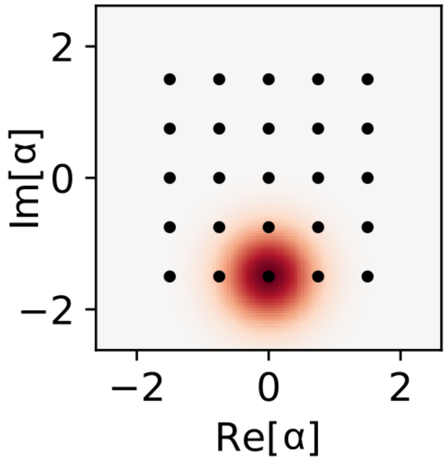



**But how to characterize the gate?**

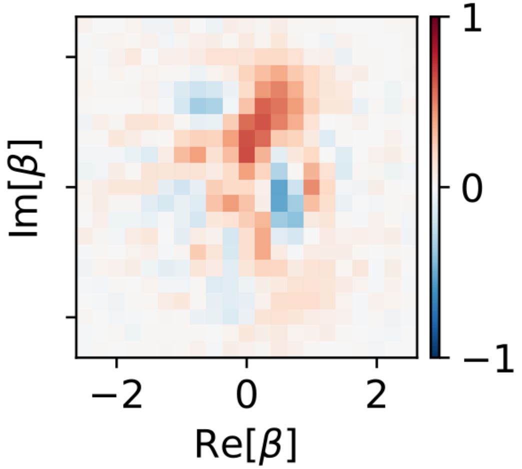
# Coherent-state quantum process tomography (csQPT)

Cycle over coherent probes

Prepare coherent probe → Apply target process → Perform Wigner tomography → Reconstruct process



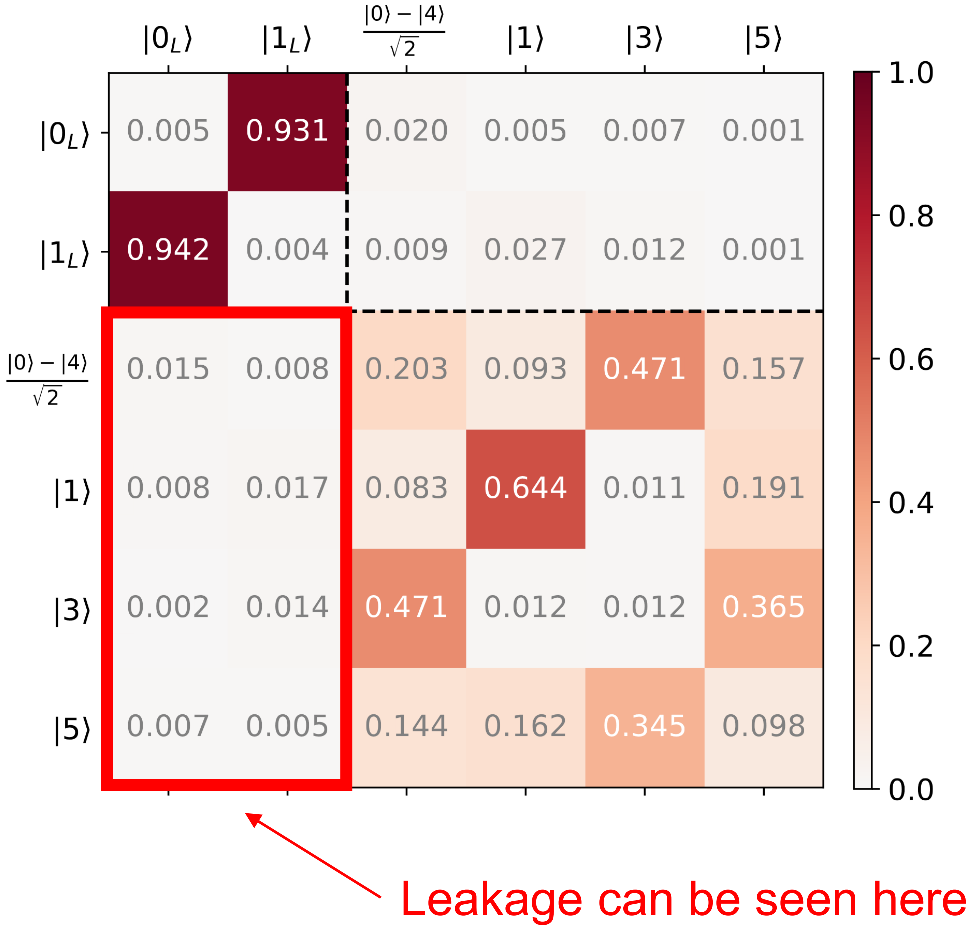

$\mathcal{E}$




$\chi_{\mathcal{E}}$

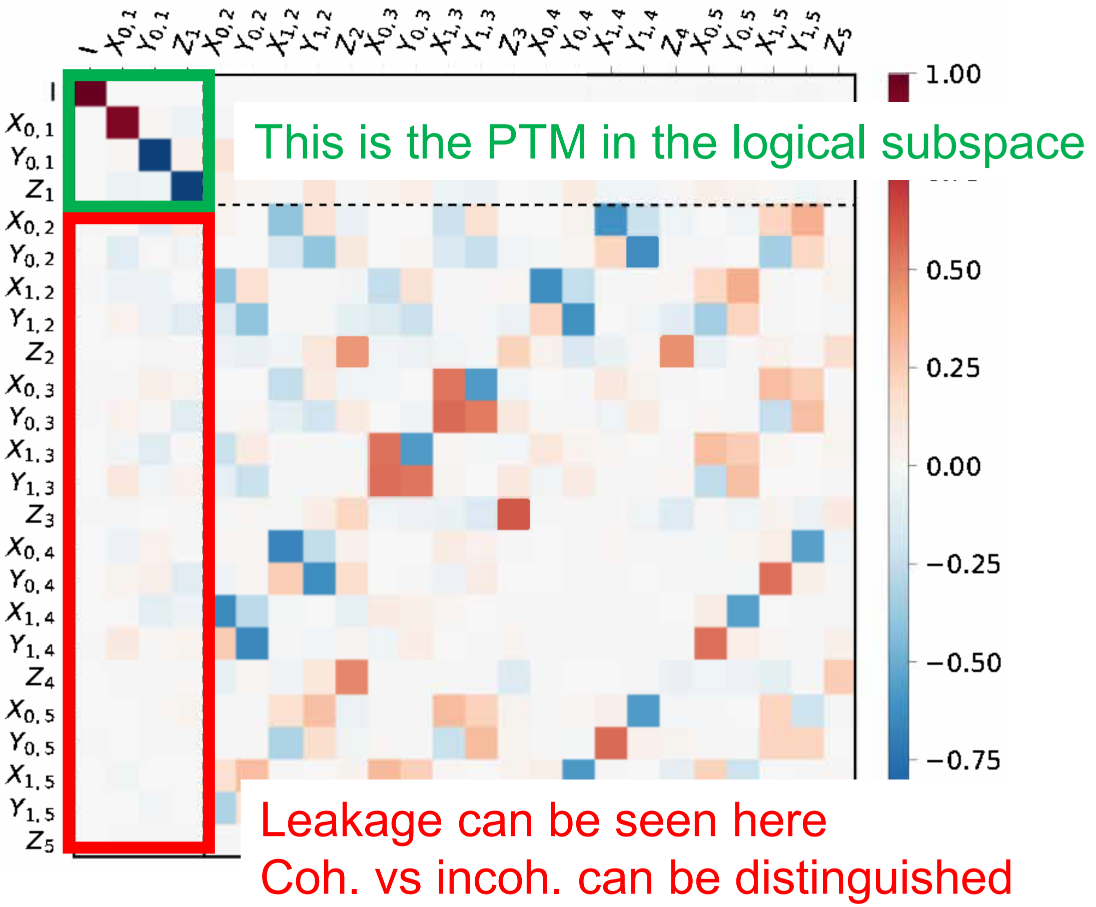
Lobino et al., Science **322**, 563 (2008). Kervinen et int SG, arXiv:2303.01451. Ahmed, Quijandría & Kockum, arXiv:2208.00812.

# Results: population transfer matrix




- Truncated up to the first 6 Fock states
- The logical basis is completed to span the truncated Hilbert space
- Visualizes population transfer within and outside of computational subspace
- Can be used to detect leakage
- Does not provide full information on the process

# Results: Generalized Pauli transfer matrix ("Gell-Mann transfer matrix")



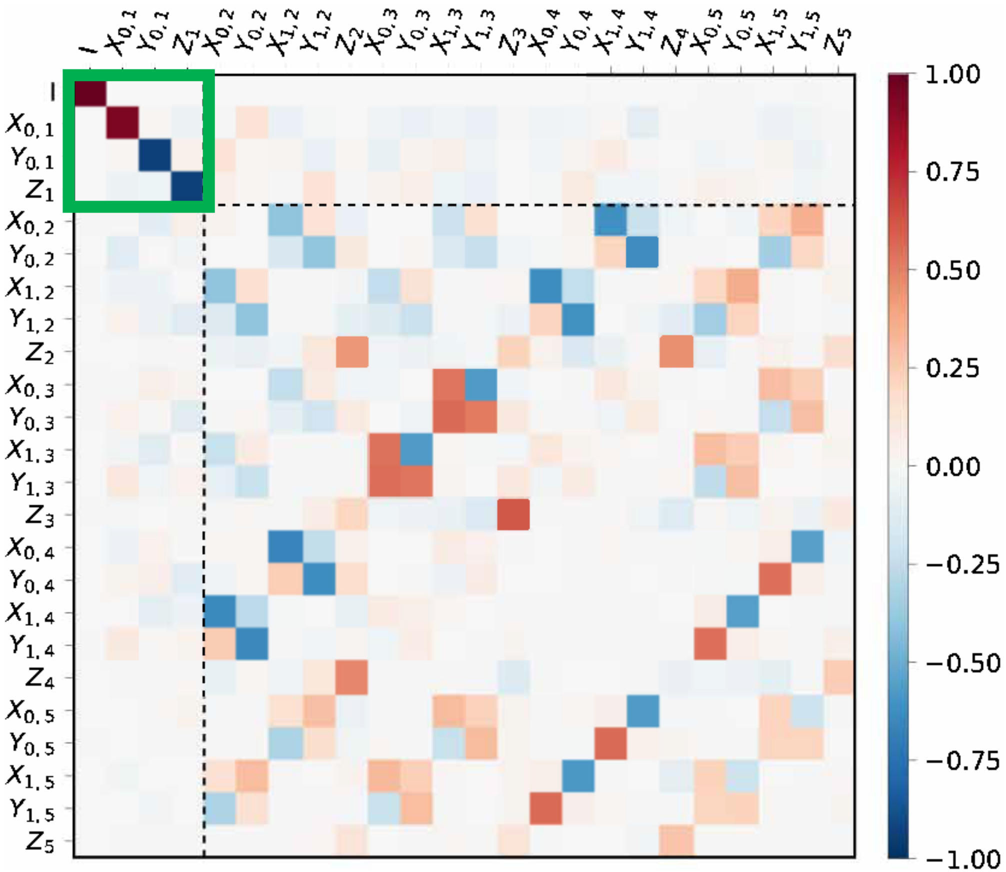

**Gell-Mann matrices.** A collection of Hermitian, traceless, orthonormal matrices $\{G_i\}$ forming an operator basis for SU(N). Generalize Pauli matrices for N>2.

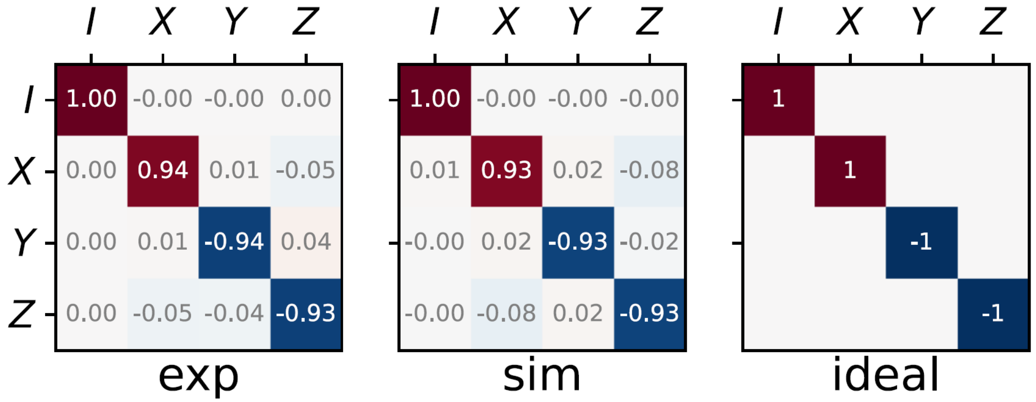
**Gell-Mann transfer matrix (GMTM).** A matrix representation of a process $\mathcal{E}$ on a *d*-dimensional Hilbert space, defined as $\mathrm{GMTM}_{ij} = \mathrm{Tr}[G_i \mathcal{E}(G_j)]$. Generalize Pauli transfer matrix (PTM).

We arranged Gell-Mann matrices so that the top left bock is the Pauli transfer matrix in the logical subspace.

We are only showing Gell-Mann matrices that couple to the logical subspace

# Results: Generalized Pauli transfer matrix (“Gell-Mann transfer matrix”)




Reduced Pauli transfer matrix agrees within 1% with simulation incl. qubit and cavity loss

Gate fidelity:

- Measured: 96.8%
- Simulated: 96.4%
- Ideal: 99.6%

# Advantages of coherent-state process tomography

Our implementation of csQPT:

- Requires **no encoding / decoding operations**, only displacements (most trusted operation)
- Returns **full process matrix** in the extended Hilbert space
- Uses a novel **gradient-descent-based optimization algorithm** to learn the Kraus representation of the process

Reduces SPAM errors

Detect leakage errors

Efficient reconstruction from a reduced number of data points

# Thank you!

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Knut and Alice Wallenberg Foundation

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More questions? simoneg@chalmers.se

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