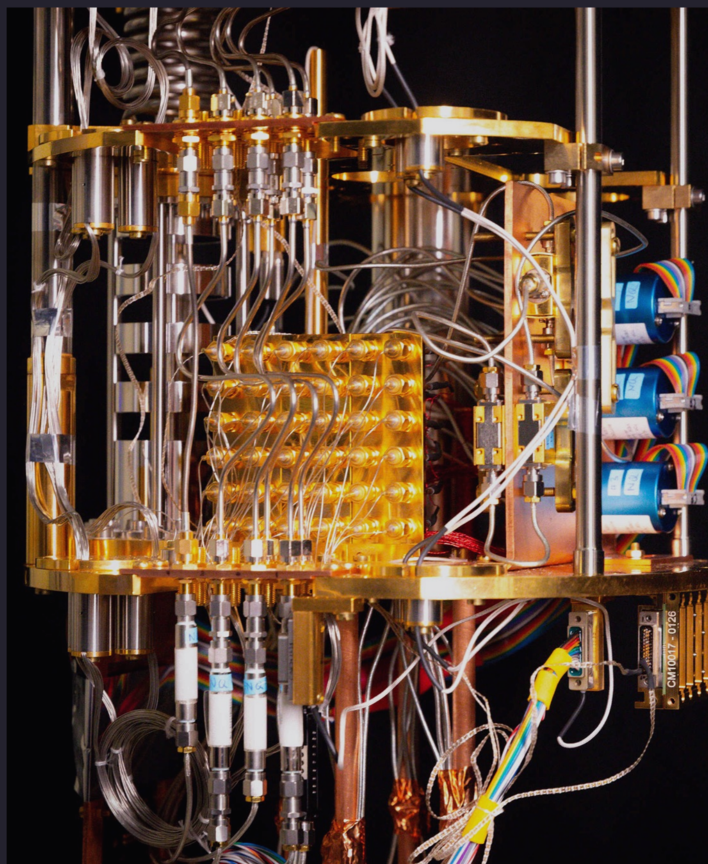


Quantum Error Correction with GKP States in Superconducting Circuits

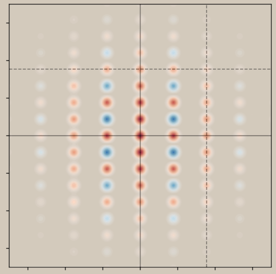
By Nicholas E. Frattini

Date 2024.05.09

Nord Quantique

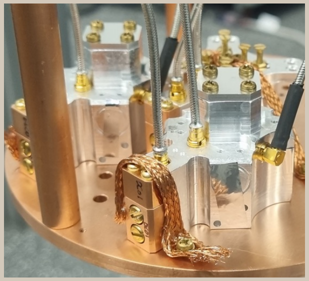
Outline

01 Why bosonic quantum error correction (QEC)?



02 Experimental demonstration of QEC with GKP states

Lachance-Quirion *et al.*, Phys. Rev. Lett. 129, 030501 (2024)



03 Toward better hardware

Error correction is the only game in town

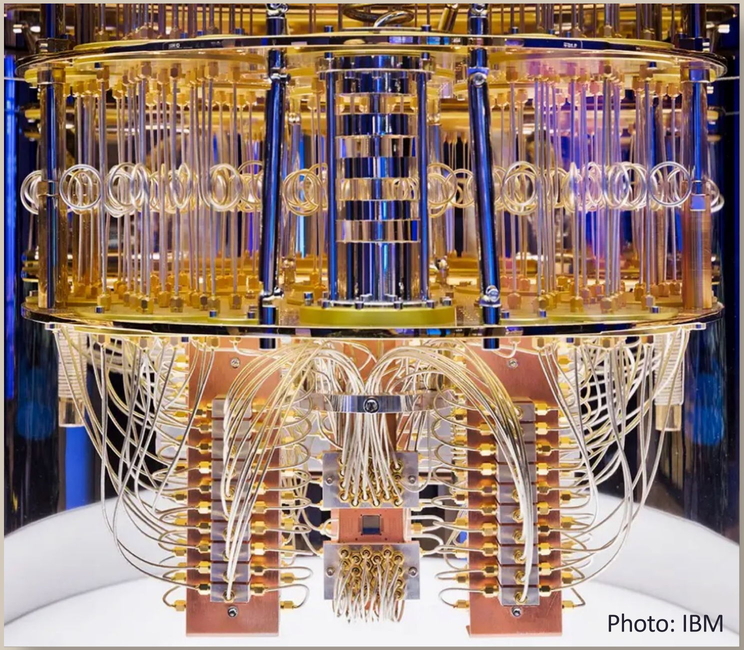


Photo: IBM

Current quantum computers

~10^{-3} errors per qubit per operation

Reduce errors by adding redundancy

Daunting overhead

~10,000 physical qubits / logical

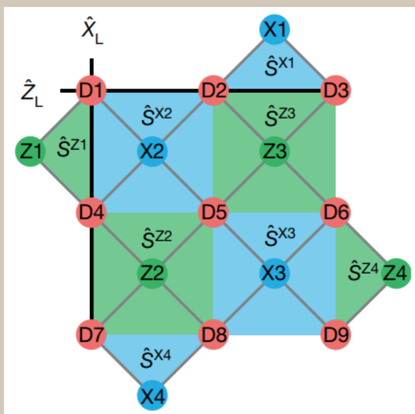
We need better hardware!

Recent surface code implementations in superconducting circuits

Quantum Error Correction (QEC) breakeven - when QEC starts to help

Distance 3 (17 qubits)

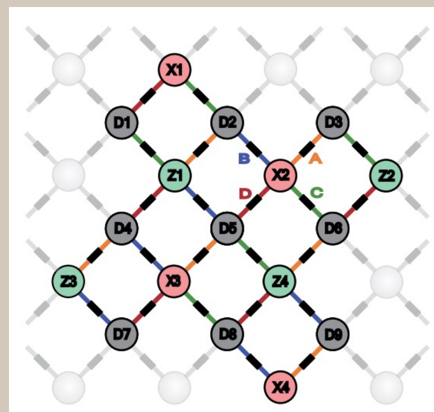
Below QEC break-even



S. Krinner *et al.*, Nature 605, 669 (2022)

Distance 3 (17 qubits)

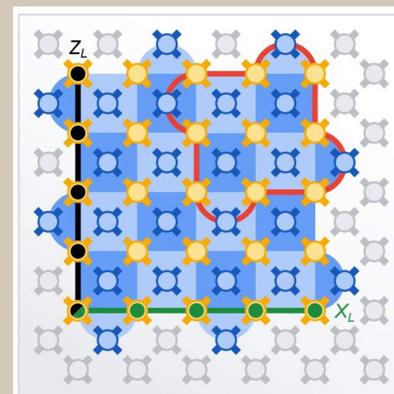
Below QEC break-even



Y. Zhao *et al.*, Phys. Rev. Lett. 129, 030501 (2022)

Distance 5 (49 qubits)

At QEC break-even



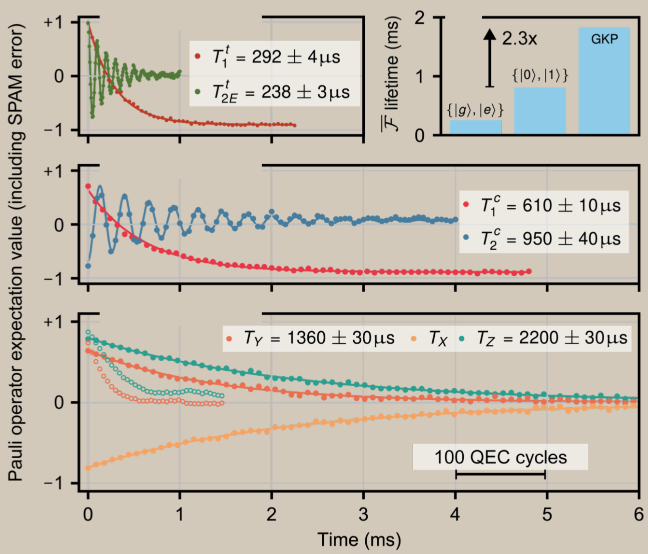
Google Quantum AI, Nature 614, 676-681 (2023)

Recent bosonic codes with GKP states

Only 1 logical qubit + 1 auxiliary qubit

♣

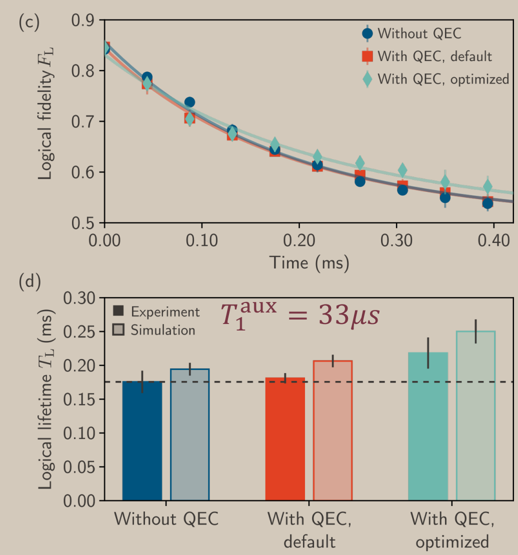
Measurement-based GKP



Yale University

V.V. Sivak *et al.*, Nature 616, 50 (2022)

Autonomous GKP



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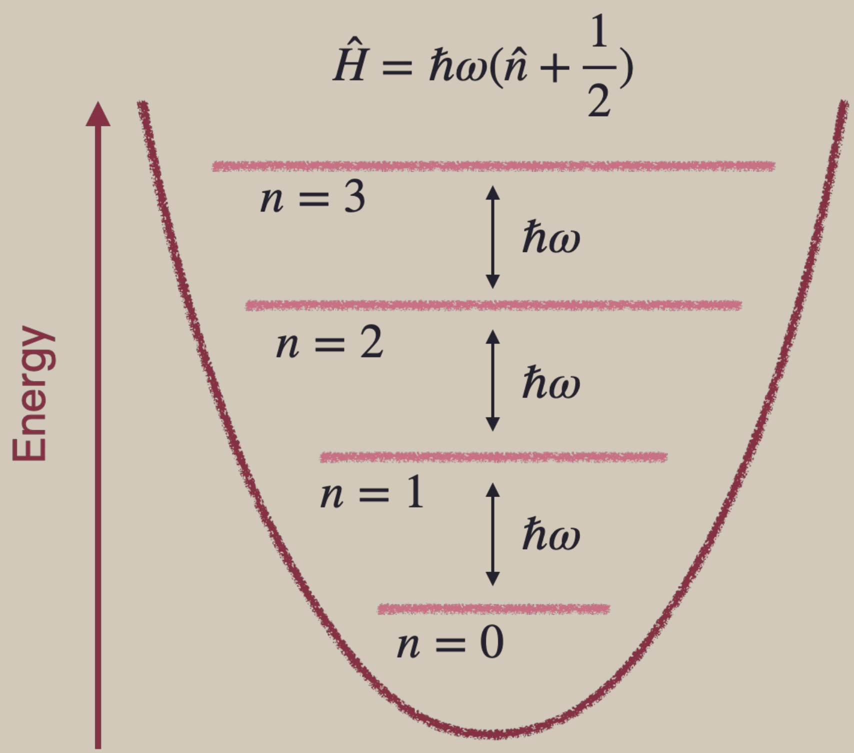
Lachance-Quirion *et al.*, Phys. Rev. Lett. 129, 030501 (2024)

Encoding logical information in bosonic modes

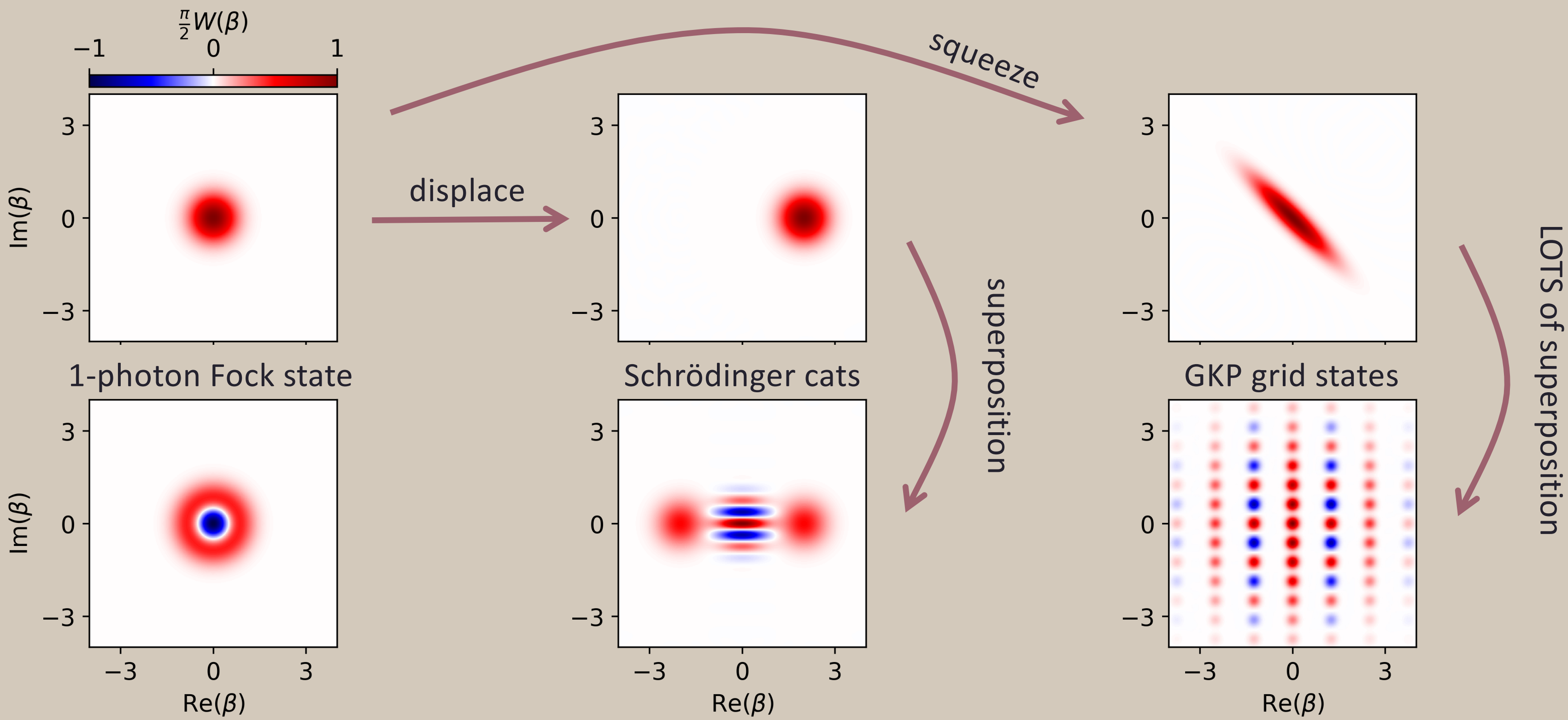


Intrinsic redundancy from a richer encoding space

- Higher photon states provide more quantum levels for error correction
- Using 1 oscillator/qubit allows for logical redundancy

Requires universal control, i.e. to be able to address "all levels individually"

Encodings available in oscillators

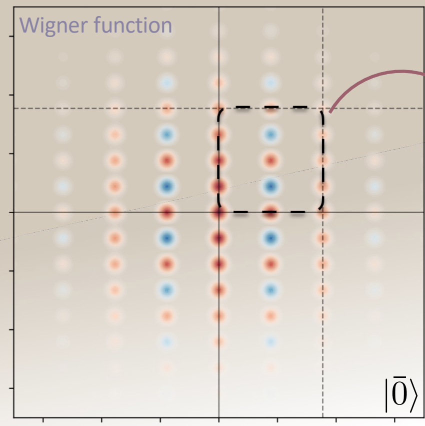


Mirrahimi *et al.*, New J. Phys. (2013).

Gottesman, Kitaev & Preskill, Phys. Rev. A (2001).

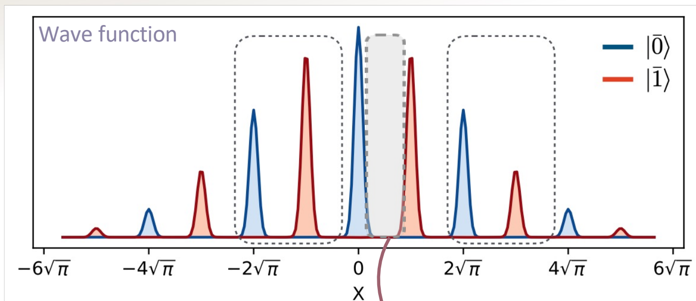
GKP code for autonomous error correction

Engineered robustness to displacement noise



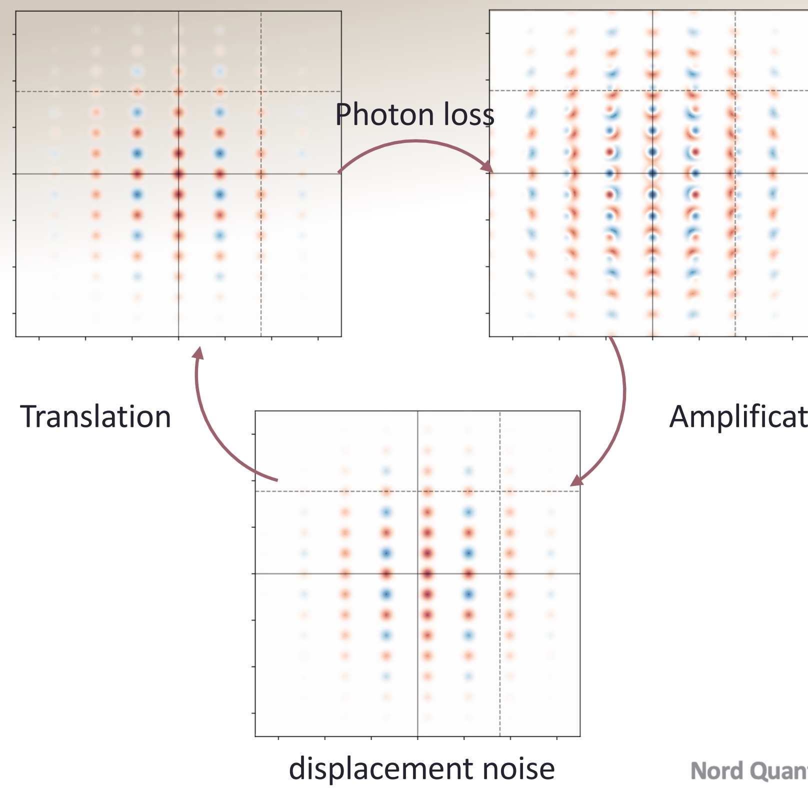
Every square carries full logical information (**redundancy**)

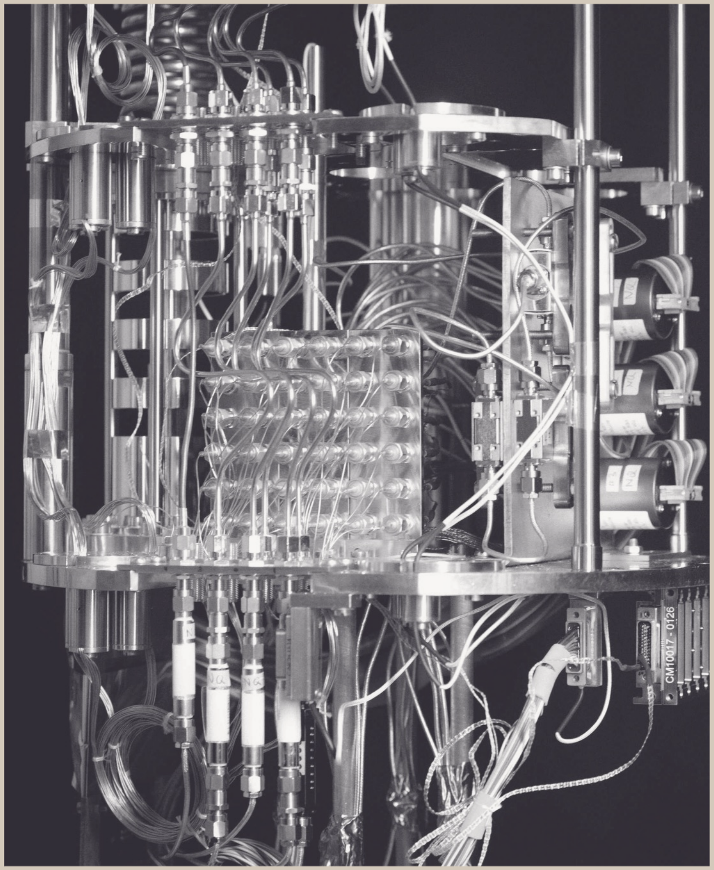
Measure grid structure without measuring logical information (**stabilizers**)



Small displacements can be corrected

Enables robustness against photon loss



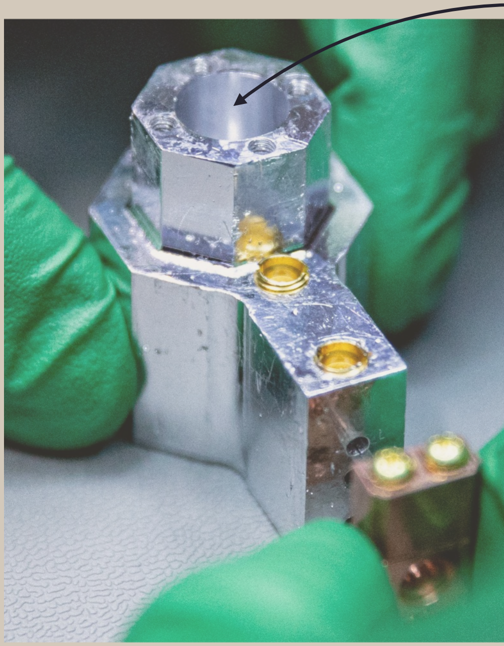


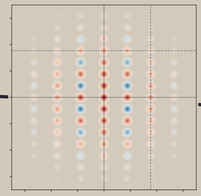
Autonomous QEC

Lachance-Quirion *et al.*, PRL (2024).

Hardware architecture at Nord Quantique

Seamless coaxial cavities



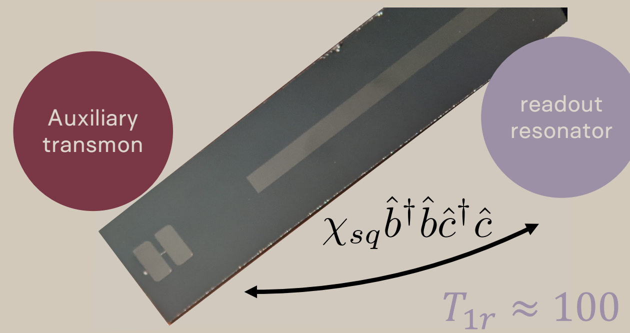


High purity (4N6+) aluminum

$T_{1s} = 0.3 - 1.2$ ms

Auxiliary devices in the coaxline architecture

$T_{1q} = 20 - 90\mu$s



$T_{1r} \approx 100$ ns

Small dispersive coupling regime:

$\chi_{sq}/2\pi \approx -10$ kHz

$K_s/2\pi \approx -1$ Hz

strong coupling to readout mode:

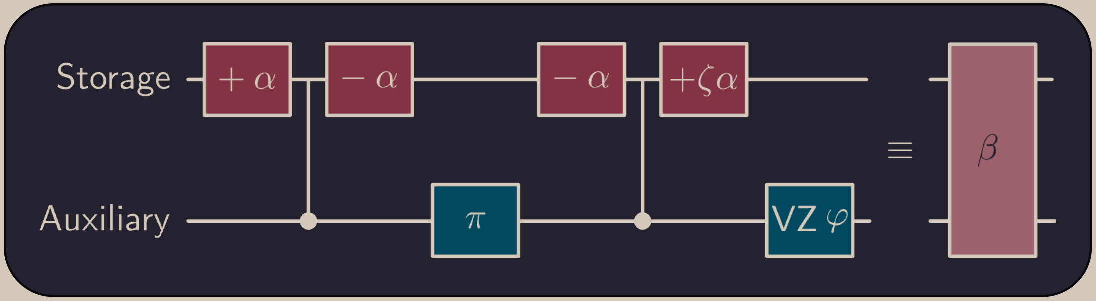
$\chi_{qr}/2\pi \approx -0.4$ MHz

→ Modular architecture, with room for improvements

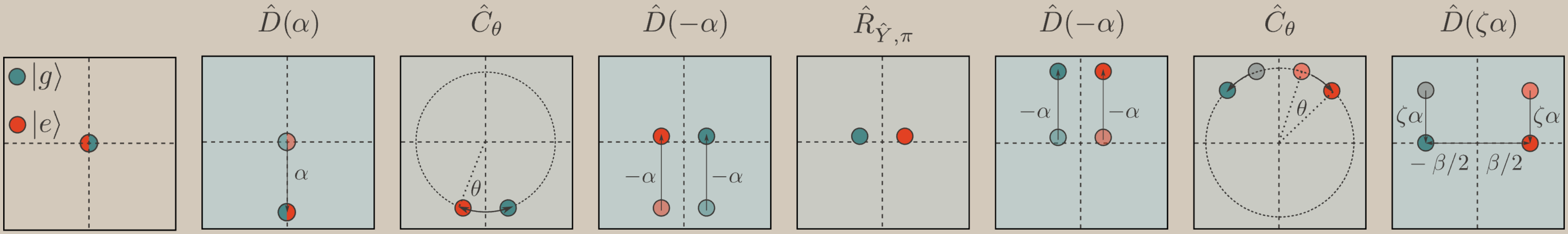
Reagor *et al.*, Phys. Rev. B, (2013).
Axline *et al.*, Appl. Phys. Lett. (2016).

Storage-auxiliary entangling gate:
Echoed conditional displacement (ECD)

P. Campagne-Ibarcq *et al.*, Nature **584**, 368–372 (2020).
A. Eickbusch *et al.*, Nat. Phys. **18**, 1464–1469 (2022).



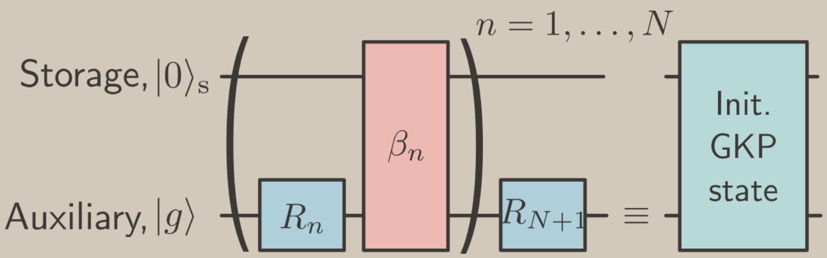
- Constructed from displacements and auxiliary rotations
- High-fidelity gate
- ECD duration: ~1 µs



State initialization and tomography

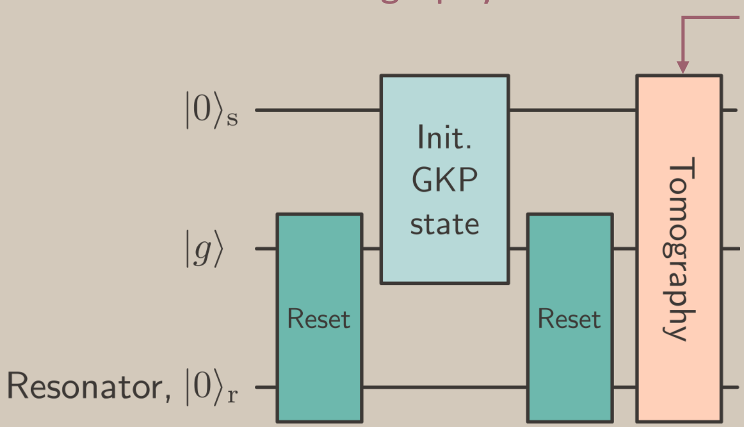
Universal quantum control with ECD

A. Eickbusch *et al.*, Nat. Phys. 18, 1464–1469 (2022).



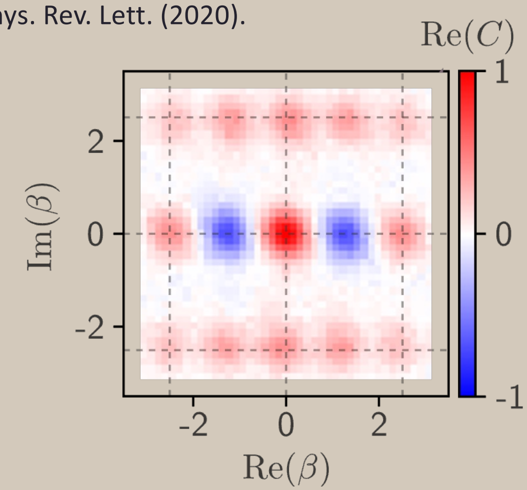
- Find set of rotations and ECDs with gate-level simulations
- For GKP, used *N*=9 for total duration of 11.7 µs

Initialization and tomography



Measurement of characteristic function with ECD

C. Flühmann *et al.*, Phys. Rev. Lett. (2020).



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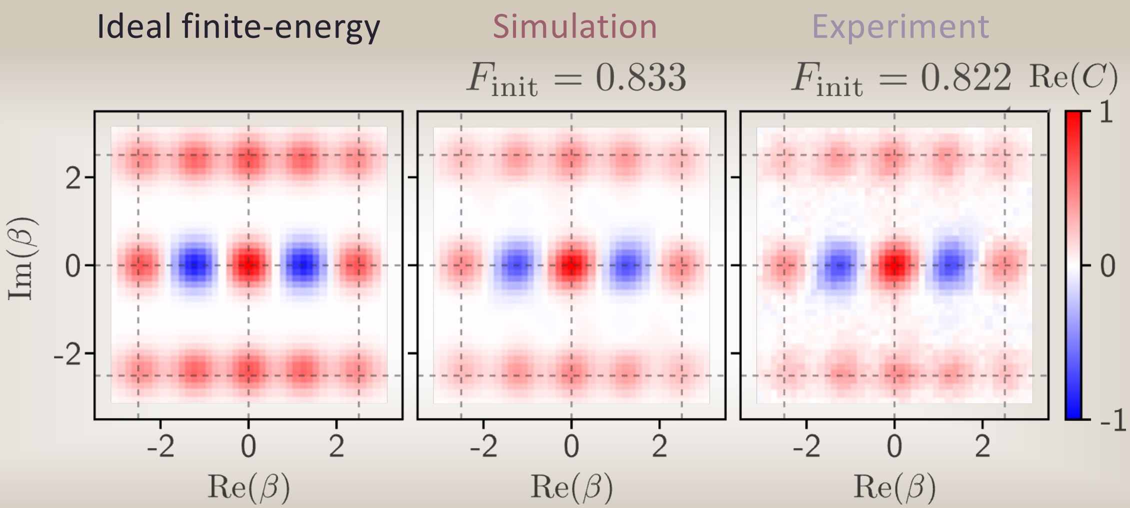
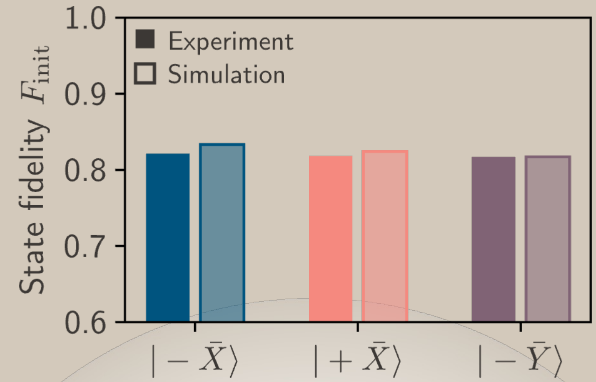
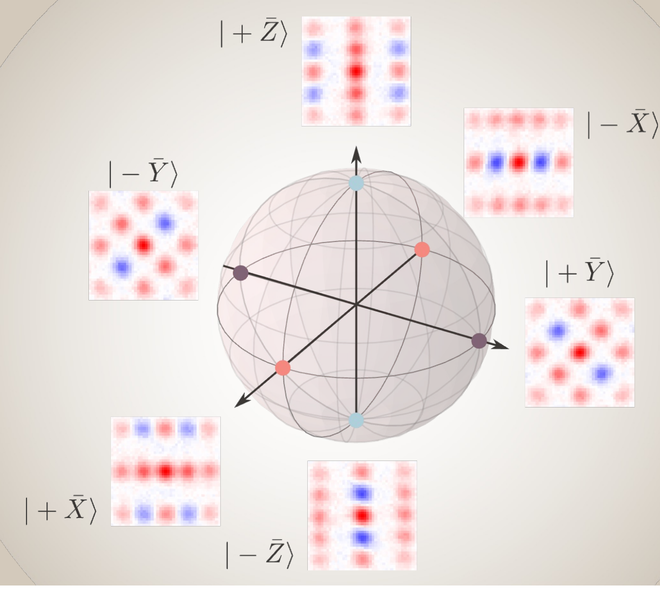
Initialization of GKP logical states







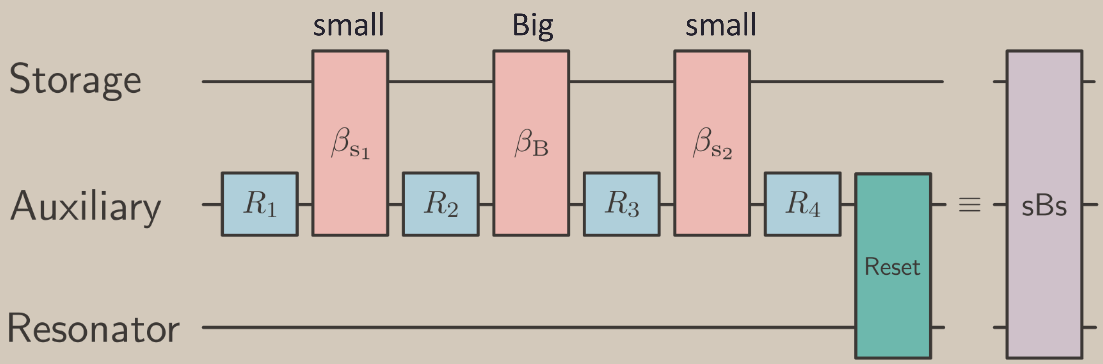
- Quantitative agreement with our simulation platform (within 3.5%)
- Fidelity limited by auxiliary qubit decay (77% of error budget)

Quantum error correction through reservoir engineering

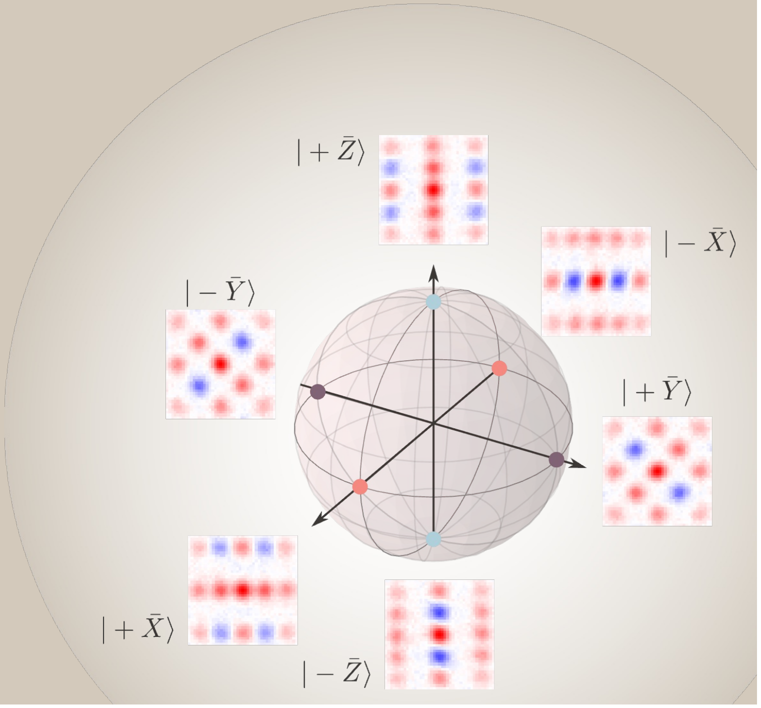
→ Engineer a dissipator whose ground state manifold is the GKP manifold

Single round of the small-Big-small (sBs) protocol

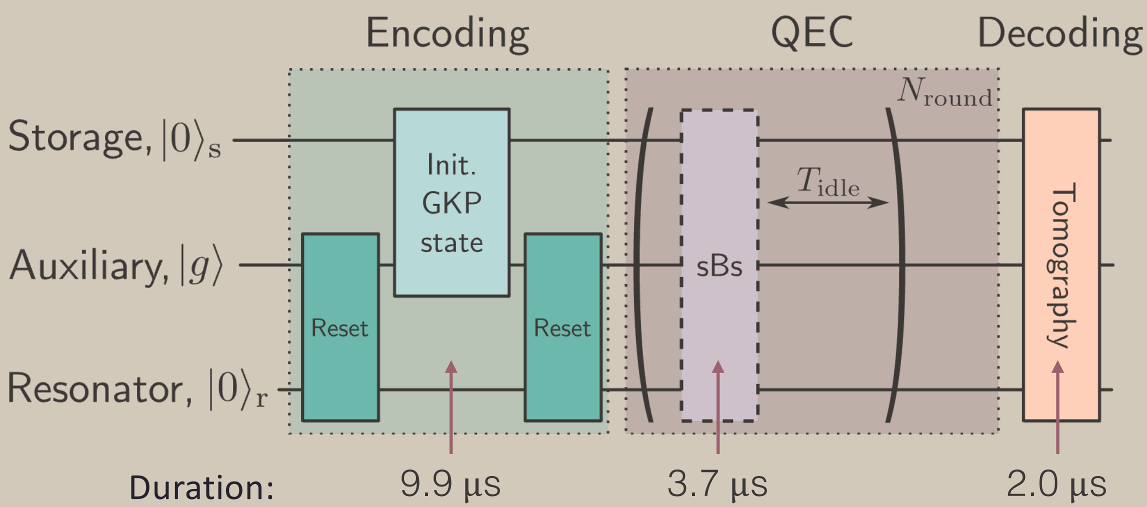
B. Royer *et al.,* Phys. Rev. Lett. **125**, 260509 (2020)



- Choice of small β's set finite-energy envelope Δ
- Alternate between quadratures every round



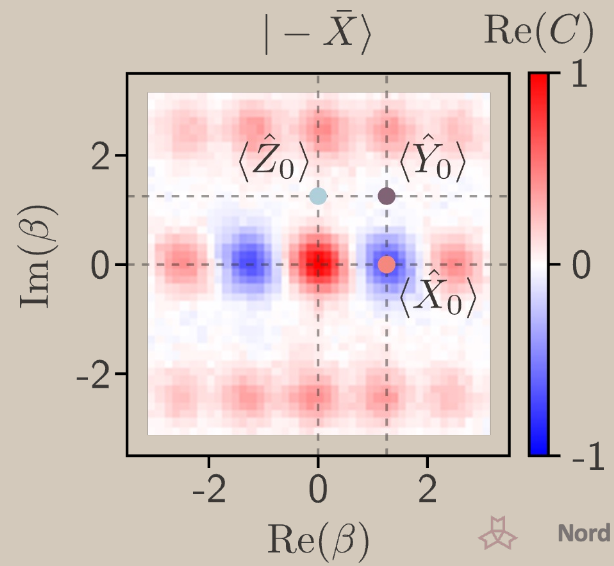
Quantum error correction of GKP logical states



Idle time optimized to trade off impact of single-photon loss and QEC errors

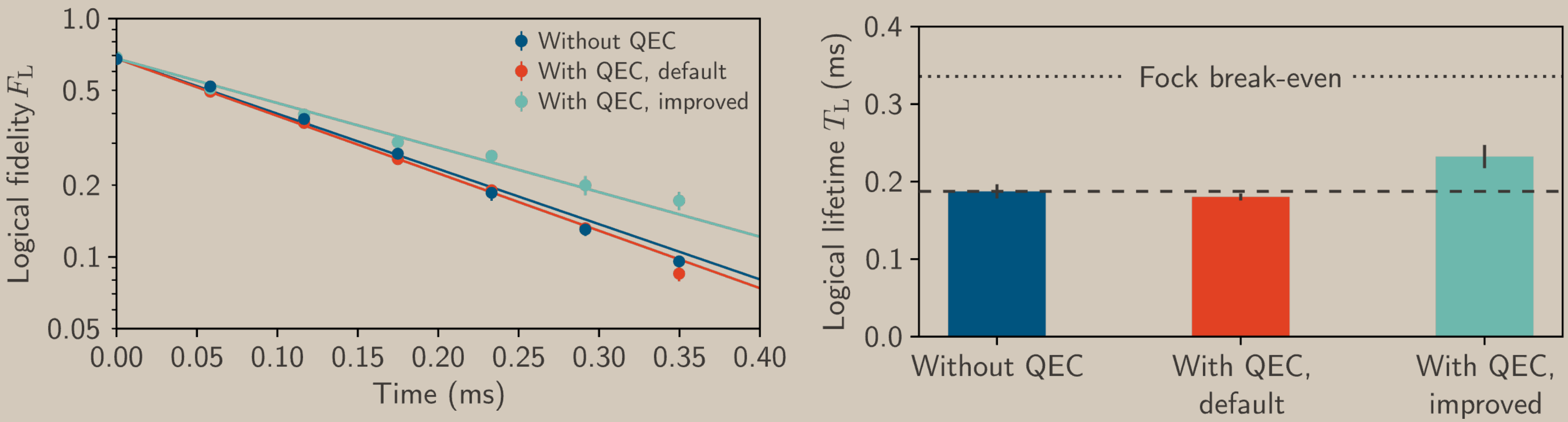
Extract logical fidelity from Pauli expectation values

$$F_L = \frac{1}{6} \sum_{\hat{\mu}_0 = \{\hat{X}_0, \hat{Y}_0, \hat{Z}_0\}} (\langle \hat{\mu}_0 \rangle_+ - \langle \hat{\mu}_0 \rangle_-)$$



Quantum error correction of GKP logical states - Results

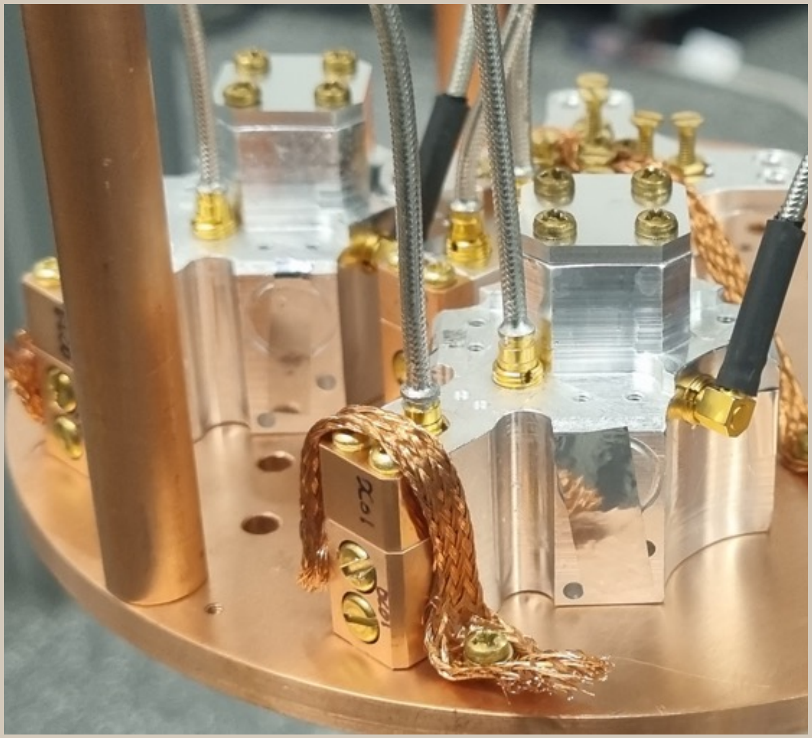
$\Delta = 0.36 \to \Delta' = 0.472$ $|\beta_{s_2}| / |\beta_{s_1}| = 1 \to 1.72$ $T_{idle} = 54.55\ \mu s$



Optimized protocol

- Logical lifetime +29% compared to with QEC, default protocol
- Logical lifetime +24% compared to without QEC

More errors corrected than generated



Improving hardware

Auxiliary qubit lifetime is major limiting factor

Improving microwave loss through fabrication innovation

Choosing new materials & understanding oxides

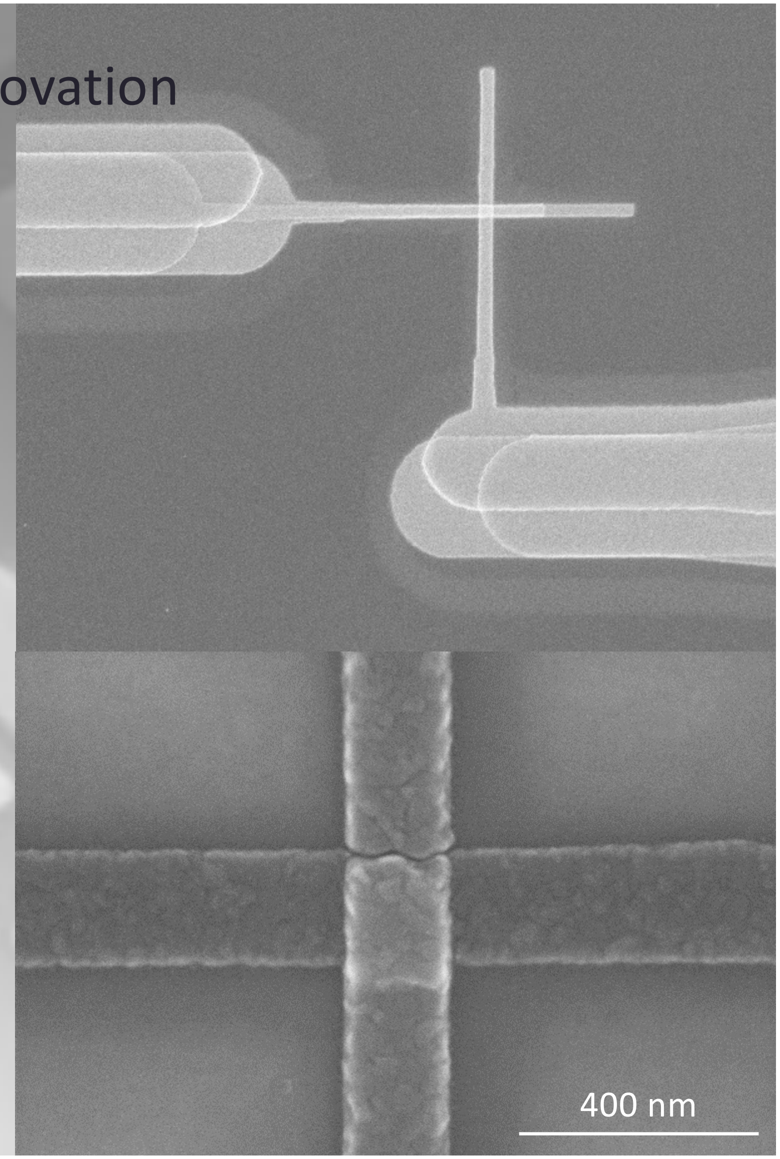
Place *et al.*, Nat Commun (2021)

Low-temperature & low-power loss source identification

Ganjam *et al.*, Nat Commun (2024)

Substrate dielectric loss measurements

Read *et al.*, Phys Rev Appl (2023).



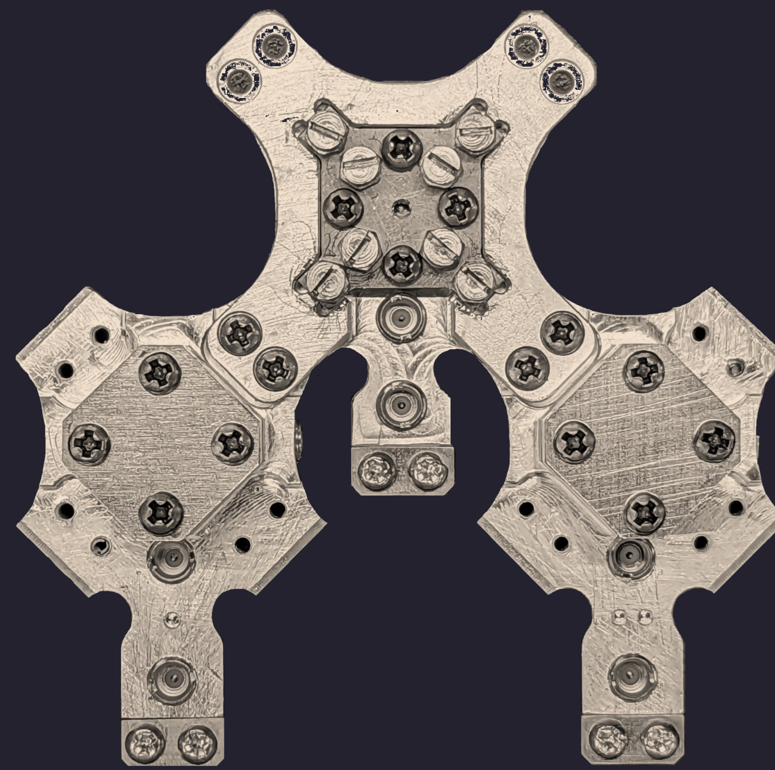
Conclusions and future directions

Bosonic codes enable hardware efficiency

Demonstrated autonomous QEC of GKP states

Fabrication improvements will directly improve QEC

Improve QEC performance alongside
scaling to GKP qubits



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