Adventures in Phase Space: Why Bosons are Better than Qubits for Quantum Error Correction

Experiment
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Theory
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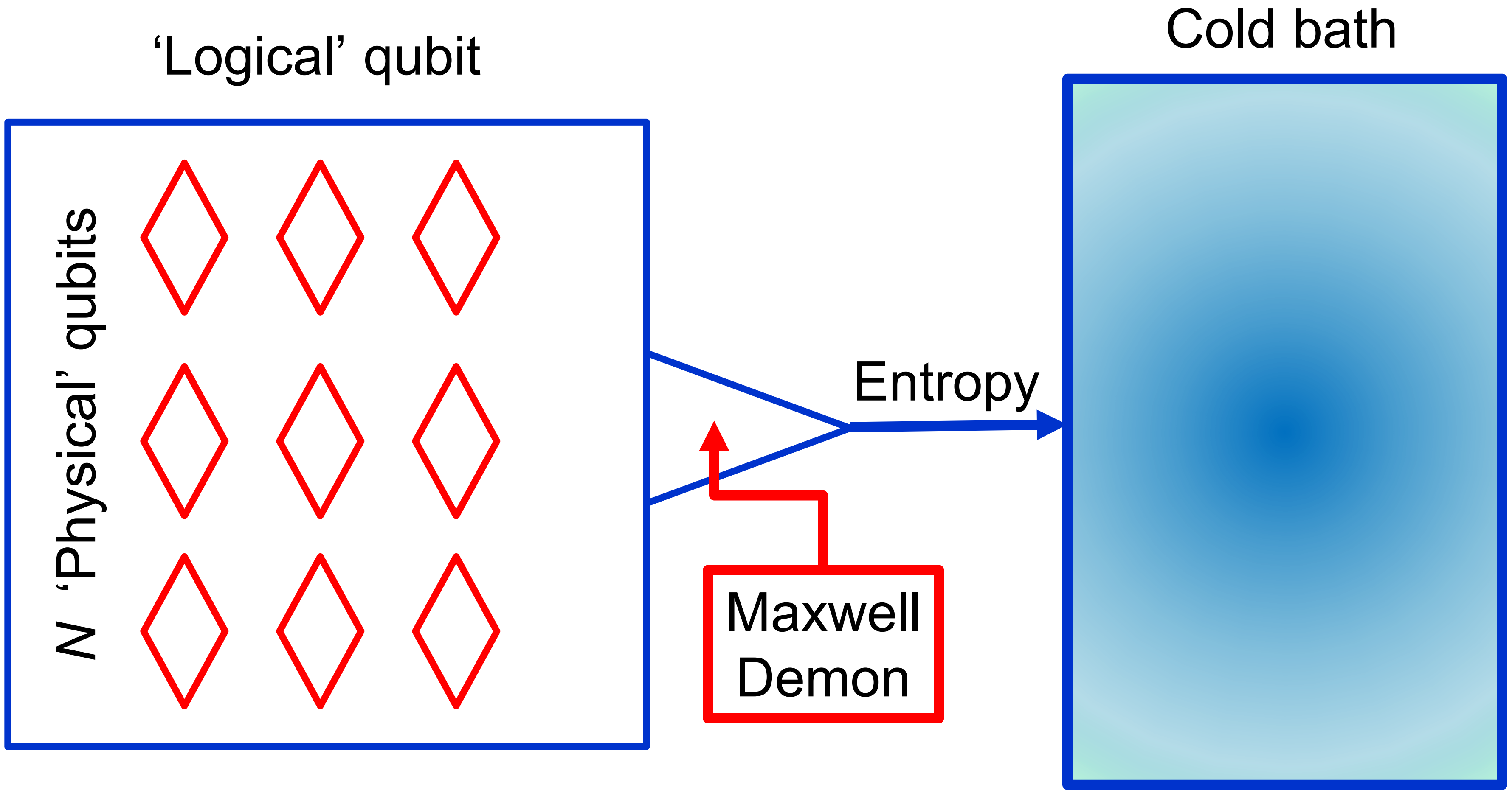
Disclosure: SMG is a consultant and equity holder in Quantum Circuits, Inc. and an equity holder in IBM, Inc.

No matter how much progress there is in increasing coherence times, we still must contend with the fundamental law of quantum devices:

There is no such thing as too much coherence.

We need quantum error correction!

Theme: Modifying Non-Equilibrium Quantum Dynamics with a 'Maxwell Demon' to keep a qubit alive



Take-home message:

Quantum error correction

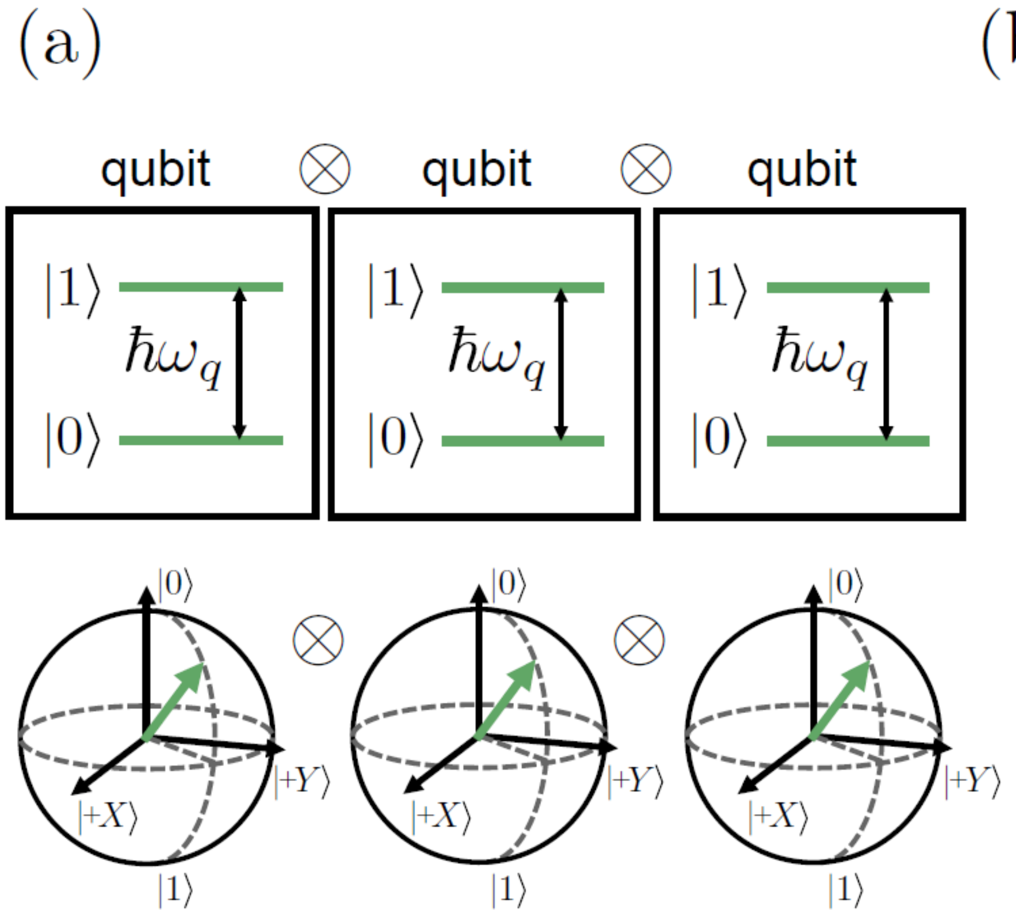
&

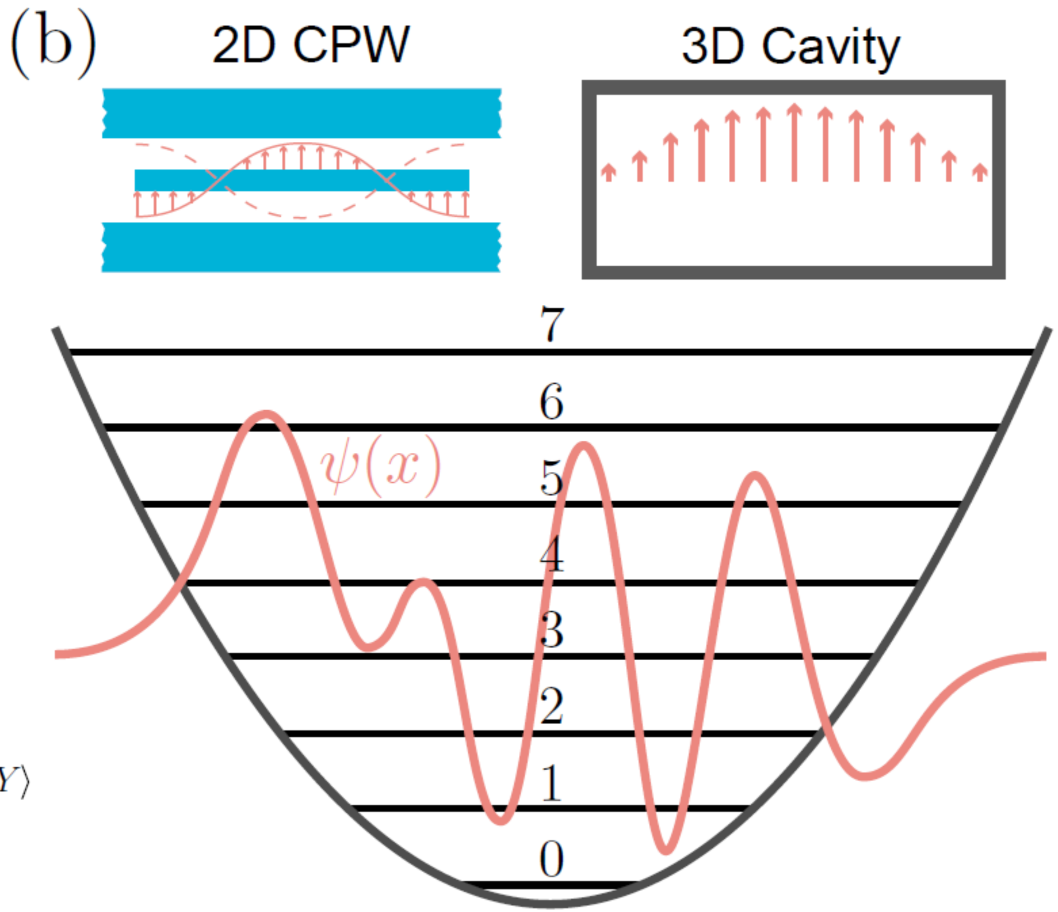
Quantum simulations of physical models containing bosons

are both vastly more efficient on hardware containing ‘native’ bosons

Discrete variable (transmon qubits)

Continuous variable (microwave or mechanical oscillators)





Boson Fock (photon number) states

$$|\psi\rangle = a_0|000\rangle + a_1|001\rangle + a_2|010\rangle + a_3|011\rangle + a_4|100\rangle + a_5|101\rangle + a_6|110\rangle + a_7|111\rangle$$

$$|\psi\rangle = a_0|0\rangle + a_1|1\rangle + a_2|2\rangle + a_3|3\rangle + a_4|4\rangle + a_5|5\rangle + a_6|6\rangle + a_7|7\rangle$$

The Quantum Error Correction Problem

I am going to give you an unknown quantum state.

If you measure it, it will change randomly due to state collapse (‘back action’).

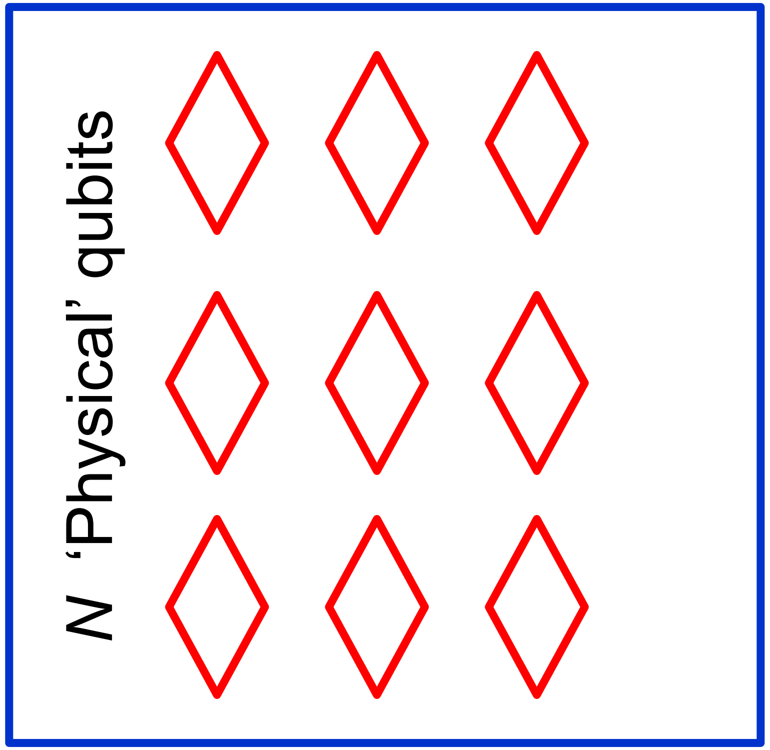
If it develops an error, please fix it.

***Mirable dictu*: It can be done!**

- No-go theorem for error correction in classical analog computation.
- Quantum machines have both analog and digital features.
- Rules of the QEC game:
  - Noise demon has *universal* computational power using arbitrary K-local (bounded Pauli weight) gates (e.g. 1- and 2-qubit (continuous) gates).
  - Noise demon has bounded speed (we hope).
  - You have *less* computational power—only non-universal Clifford gates and measurements.
- You can win!
  (If you are faster than the demon and don’t make too many mistakes yourself)

Quantum Error Correction for an unknown state requires storing the quantum information *non-locally* in (non-classical) *correlations* over multiple physical qubits.

'Logical' qubit

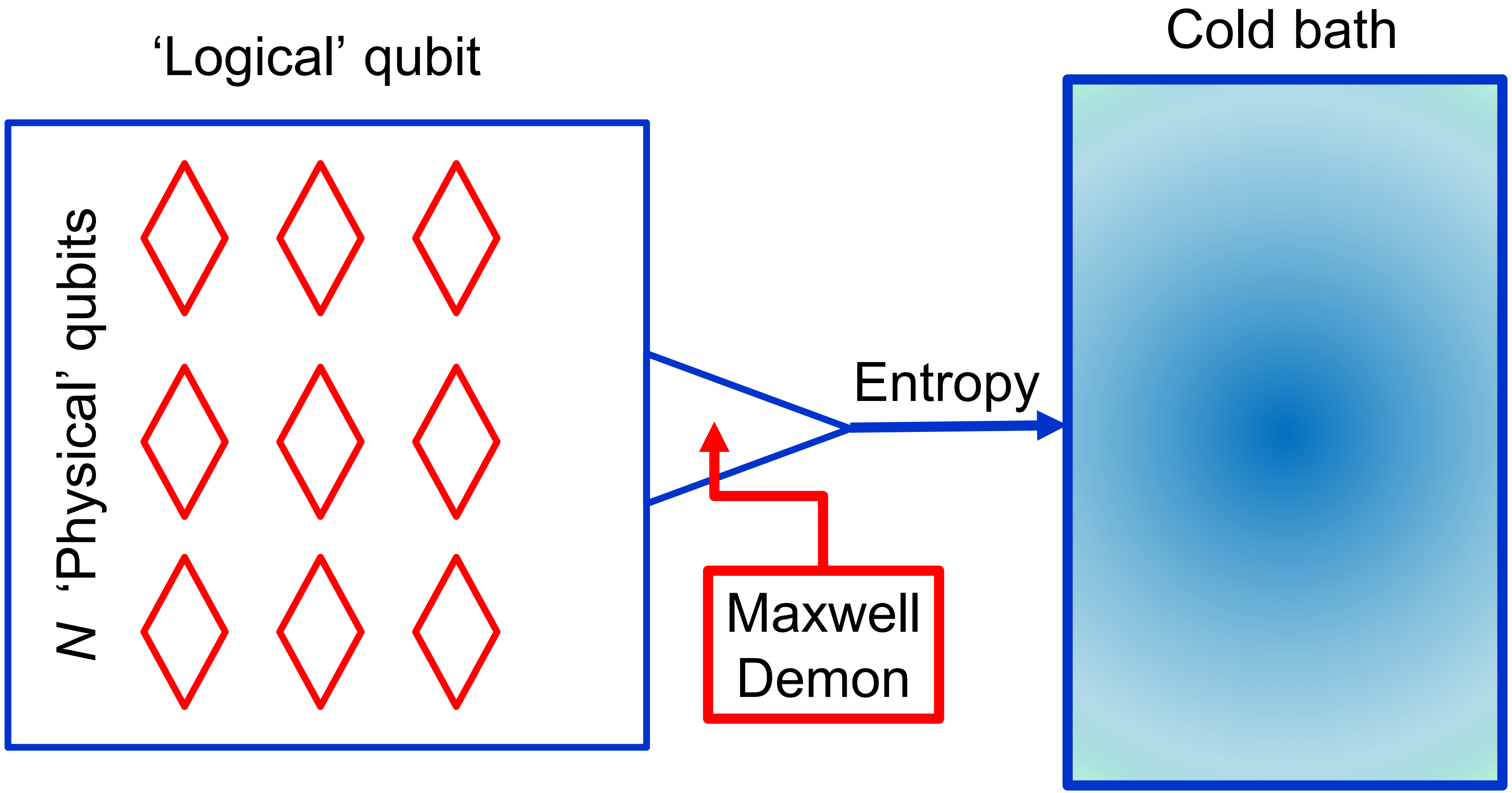


Non-locality: No single physical qubit can "know" the state of the logical qubit.

Special multi-qubit measurements can tell you about errors without telling you the logical state in which the error occurred.

Miracle: Quantum errors are analog (i.e. continuous). Measured errors are discrete (i.e. digital). State collapse is our friend!

Quantum Error Correction



N qubits have errors *N* times faster. Maxwell demon must overcome this factor of *N* – *and not introduce errors of its own! (or at least not uncorrectable errors)*

Definition of "better" (QEC Gain)

Average channel fidelity

M. Nielsen, Phys. Lett. A (2002)
["Channel" = CPTP map]

$$\overline{\mathcal{F}}[\mathcal{E}] = \int d\psi \langle\psi|\mathcal{E}(|\psi\rangle\langle\psi|)|\psi\rangle$$

Short time expansion

$$\overline{\mathcal{F}}(\delta t) = 1 - \frac{1}{2}\gamma_{\mathcal{E}}\,\delta t$$

Amplitude damping + dephasing

$$\gamma_{\mathcal{E}} = \frac{\gamma_1 + 2\gamma_2}{3}$$

Pauli channel

$$\gamma_{\mathcal{E}} = \frac{\gamma_X + \gamma_Y + \gamma_Z}{3}$$

<u>QEC gain</u> $G = \frac{\min_i [\gamma_{\mathcal{E}}^{(i)}]}{\gamma_L}$ [Min over all uncorrectable encodings]

"Break-even" $G = 1$

courtesy V. Sivak

Stabilizer Codes

N qubits have 2^N states. Define a 2D logical code subspace: $\mathcal{C} = \text{span}\ \{|0_L\rangle, |1_L\rangle\}$

and logical operators

$$X_L = |0_L\rangle\langle 1_L| + |1_L\rangle\langle 0_L|, \quad Z_L = |0_L\rangle\langle 0_L| - |1_L\rangle\langle 1_L|, \quad Y_L = +iX_L Z_L$$

using $N-1$ stabilizers $\{S_j; j = 1, \ldots, N-1\}$ and imposing $N-1$ constraints

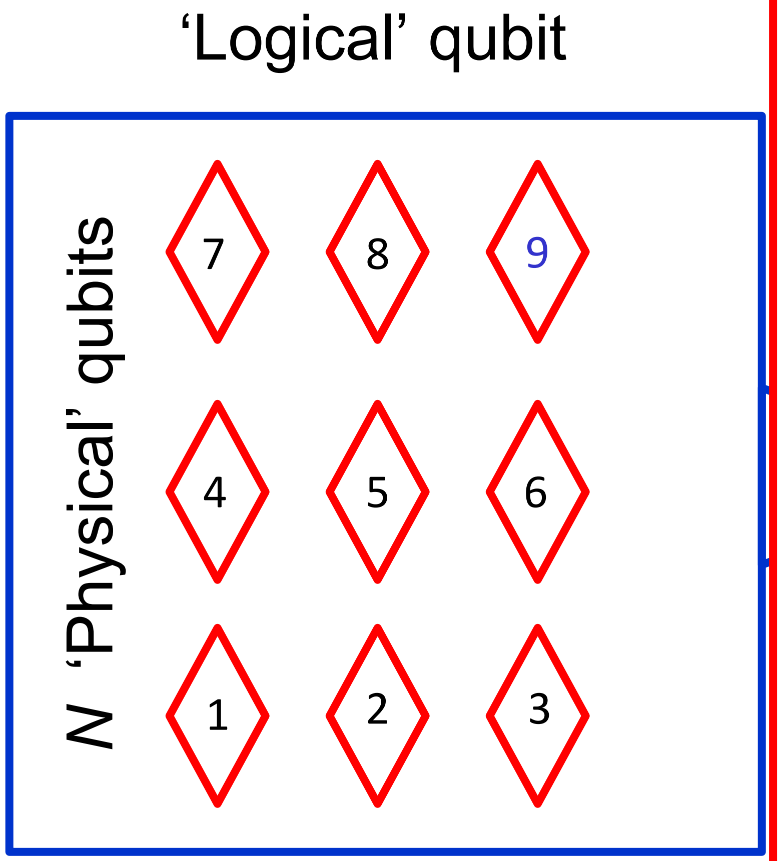
$$\mathrm{S}_j |\psi_{\text{code}}\rangle = (+1)|\psi_{\text{code}}\rangle, \forall j.$$

Stabilizers are mutually commuting and commute with logical operators.

[So can be measured simultaneously and without affecting logical state.]

Stabilizers anti-commute with physical errors so measurement of stabilizers give error syndromes that collapse the error state without collapsing the logical state.

Example stabilizer code



9 qubit Shor code can correct 1 error: X,Y, or Z

3 types of errors x 9 locations = 27 possible error states + (no-error state) = 28

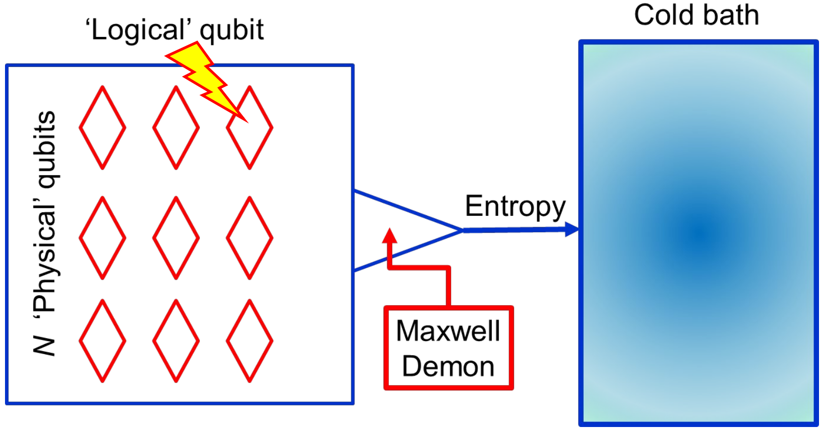
Code requires 8 stabilizer measurements

- $Z_1Z_2, Z_2Z_3, Z_4Z_5, Z_5Z_6, Z_7Z_8, Z_8Z_9$
  → Detect bit flip errors
- $X_1X_2X_3X_4X_5X_6, X_4X_5X_6X_7X_8X_9$
  → Detect phase flip errors

Very difficult multi-qubit measurements!
[N.B. cannot measure Z_1, Z_2 separately and multiply results! Need *joint* measurements.]

Quantum error correction with qubits is very hard!

3N possible
Pauli errors



3x9 + 1 = 28
error states

Idea of Bosonic Codes:
Don't use material objects as qubits.

Use microwave photon states stored in high-Q superconducting resonators.

Cat code (first to exceed break-even):
Ofek, et al., *Nature* **536**, 441–445 (2016)

Binomial Code:
Michael et al., *Phys. Rev. X* **6**, 031006 (2016)
Hu et al., *Nature Physics* **15**, 503 (2019)
Ni et al., *Nature* **616**, 556 (2023)

Autonomous Code (T4C truncated cat):
Gertler et al., *Nature* **590**, 243 (2021)

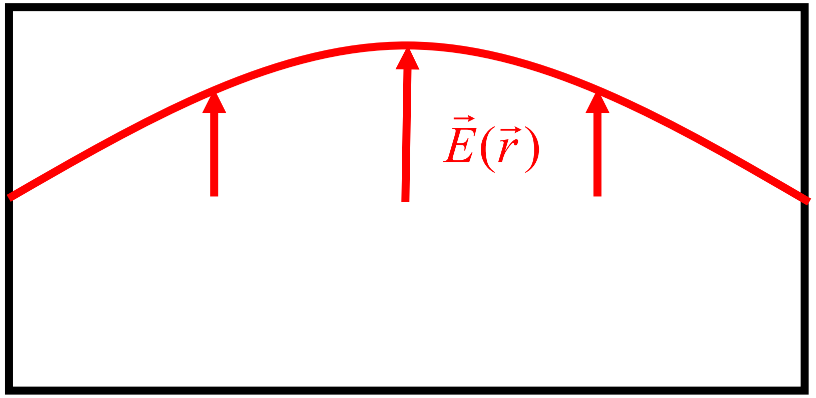
GKP Codes:
cQED Campagne-Ibarcq et al. *Nature* **584**, 368 (2020)

Ions de Neeve et al., *Nature Physics* **18**, 296 (2022)
Flühman et al., *Nature* **566**, 513–517 (2019)

Theory Royer et al., *Phys. Rev. Lett.* **125**, 260509 (2020)
PRX Quantum **3,** 010335 (2022)

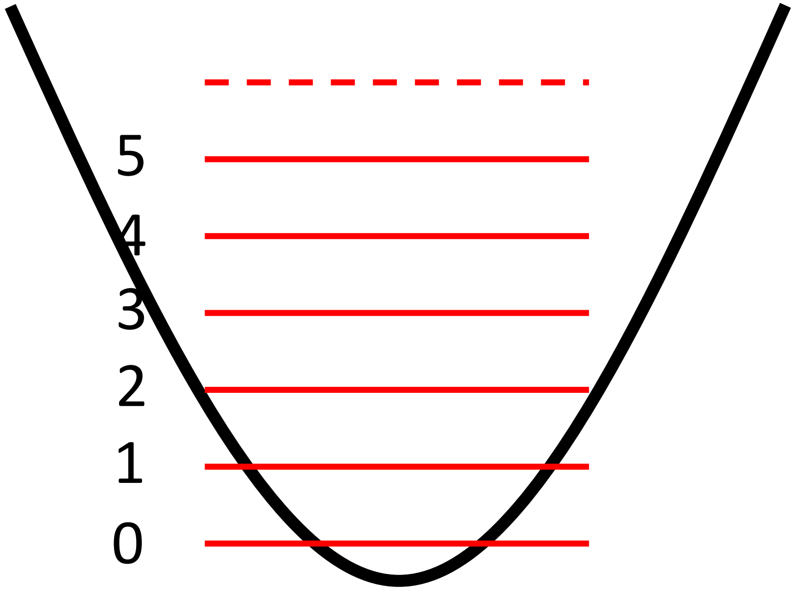
CQED Sivak et al., *Nature* **616**, 50 (2023)

Bosonic code reviews:
W. Cai et al., *Fund. Res.* **1**, 50 (2021)
A. Joshi et al., *Q. Sci. Tech.* **6**, 033001 (2021)



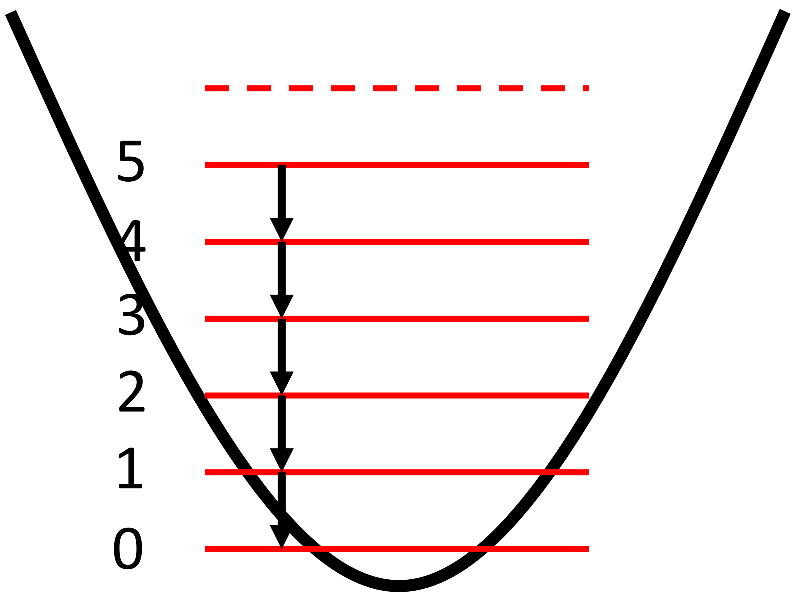
Single-mode microwave resonators (harmonic oscillators) are empty boxes (vacuum surrounded by superconducting walls)

$$H = \hbar\omega a^{\dagger} a = \hbar\omega \hat{n}$$



"Hardware Efficiency"

Oscillators have many quantum levels so can replace multiple physical qubits without adding more 'moving parts.'



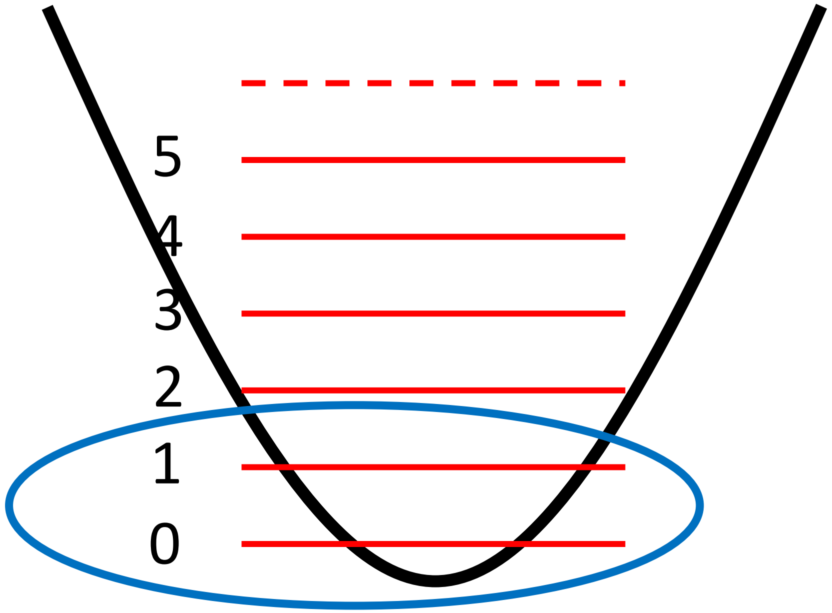
Single-mode weakly damped oscillators have a very simple error model: photon loss

Only a single mode and only one kind of error
—photon loss –
NOT *3N* errors as for qubits.

$$|\psi\rangle = \alpha|0_L\rangle + \beta|1_L\rangle$$

Need only a few (1 or 2)
easy-to-measure stabilizers such as
photon number parity or oscillator translation

Bosonic Quantum Error Correction Codes



Harmonic oscillator has an infinite number of states. A qubit has only two states.

We need to pick out two orthogonal states to act as 'logical code words' to hold one qubit's worth of (protected) information.

$$\frac{dE}{dt} = -\kappa E \Rightarrow \frac{d\langle\hat{n}\rangle}{dt} = -\kappa\langle\hat{n}\rangle$$

Simplest code: $|0_L\rangle = |0\rangle \quad |1_L\rangle = |1\rangle$

Has smallest possible number of photons and therefore longest lifetime.
But <u>not</u> error correctable after photon loss: $\alpha|0\rangle + \beta|1\rangle \rightarrow |0\rangle$

This is what we have to beat to reach break-even.

Meet the sample

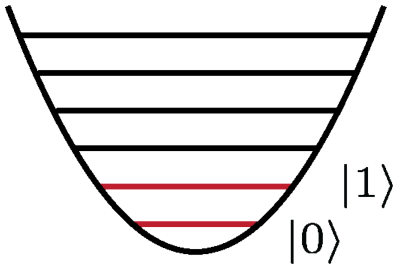
$$H/\hbar = \frac{\chi}{2}\sigma_z(a^\dagger a) + \frac{k}{2}(a^\dagger a)^2 + \frac{\chi'}{4}\sigma_z(a^\dagger a)^2$$

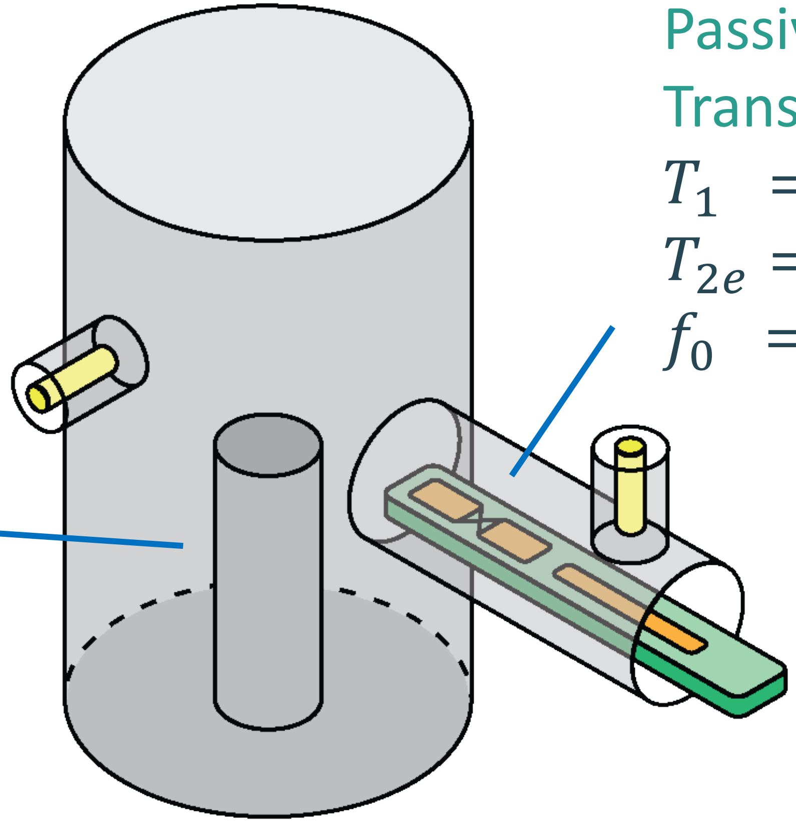
◂ Problematic for the grid code

$$\sigma_z = |g\rangle\langle g| - |e\rangle\langle e|$$

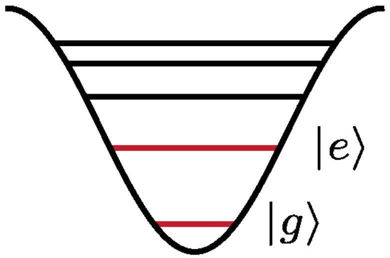
Weakly coupled
$\chi = 46.5$ kHz → $k = -4.8$ Hz
$\chi' = 5.8$ Hz

Passive qubit encoding #1:
Oscillator Fock states $\{|0\rangle, |1\rangle\}$
$T_1 = 610\ \mu s$
$T_2 = 980\ \mu s$
$f_0 = 4.479$ GHz





Passive qubit encoding #2:
Transmon states $\{|g\rangle, |e\rangle\}$
$T_1 = 280\ \mu s$
$T_{2e} = 240\ \mu s$
$f_0 = 5.921$ GHz



Coaxial high-Q cavity [M. Reagor *et al.*, (PRB, 2016)]; **Stripline ancilla chip geometry** [C. Axline *et al.*, (APL, 2016)]; **Tantalum transmon** [S. Ganjam *et al.*, (in preparation, 2022)], [A. Place *et al.*, (Nature Comm., 2021)].

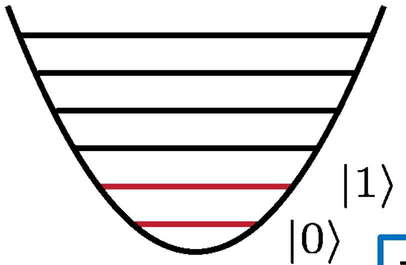
Experimental physics question: defining break-even for bosonic codes

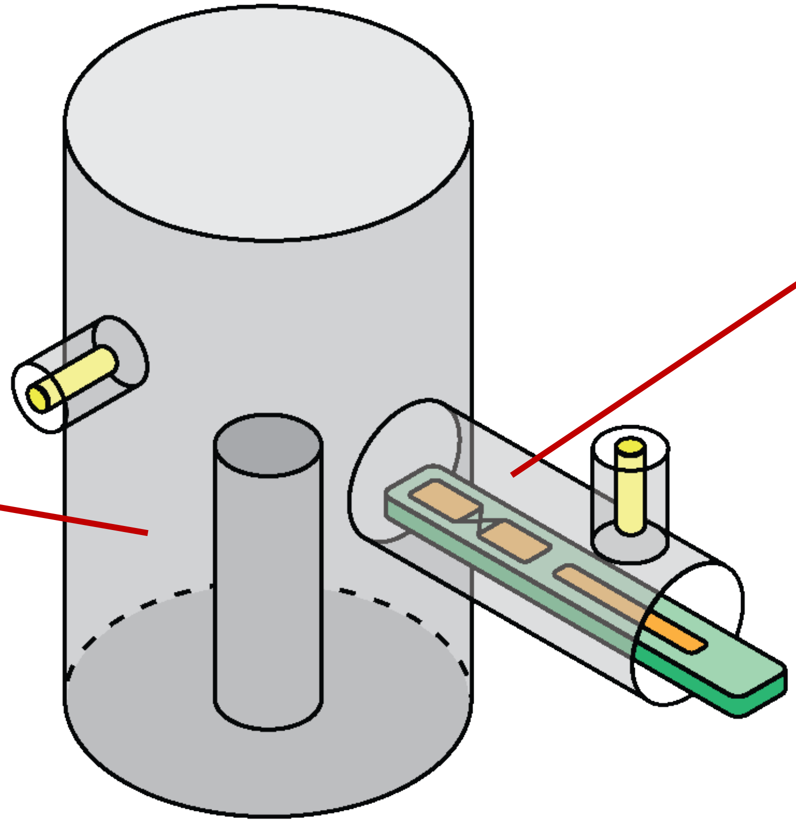
Can we leverage active quantum error correction to create

a "logical qubit" better than all constituent "physical qubits"?

Physical Qubit #2: Cavity
Fock |0>,|1>

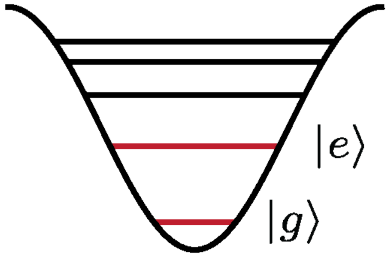
$T_1 = 610$ us
$T_2 = 980$ us





Physical Qubit #1:
Transmon $|g\rangle, |e\rangle$

$T_1 = 280$ us
$T_{2e} = 240$ us



Transferring QI from transmon to cavity strongly increases lifetime but does NOT constitute QEC "Gain." No QEC yet.

courtesy V. Sivak

First code to (slightly) exceed break even: Schrödinger Cat Code

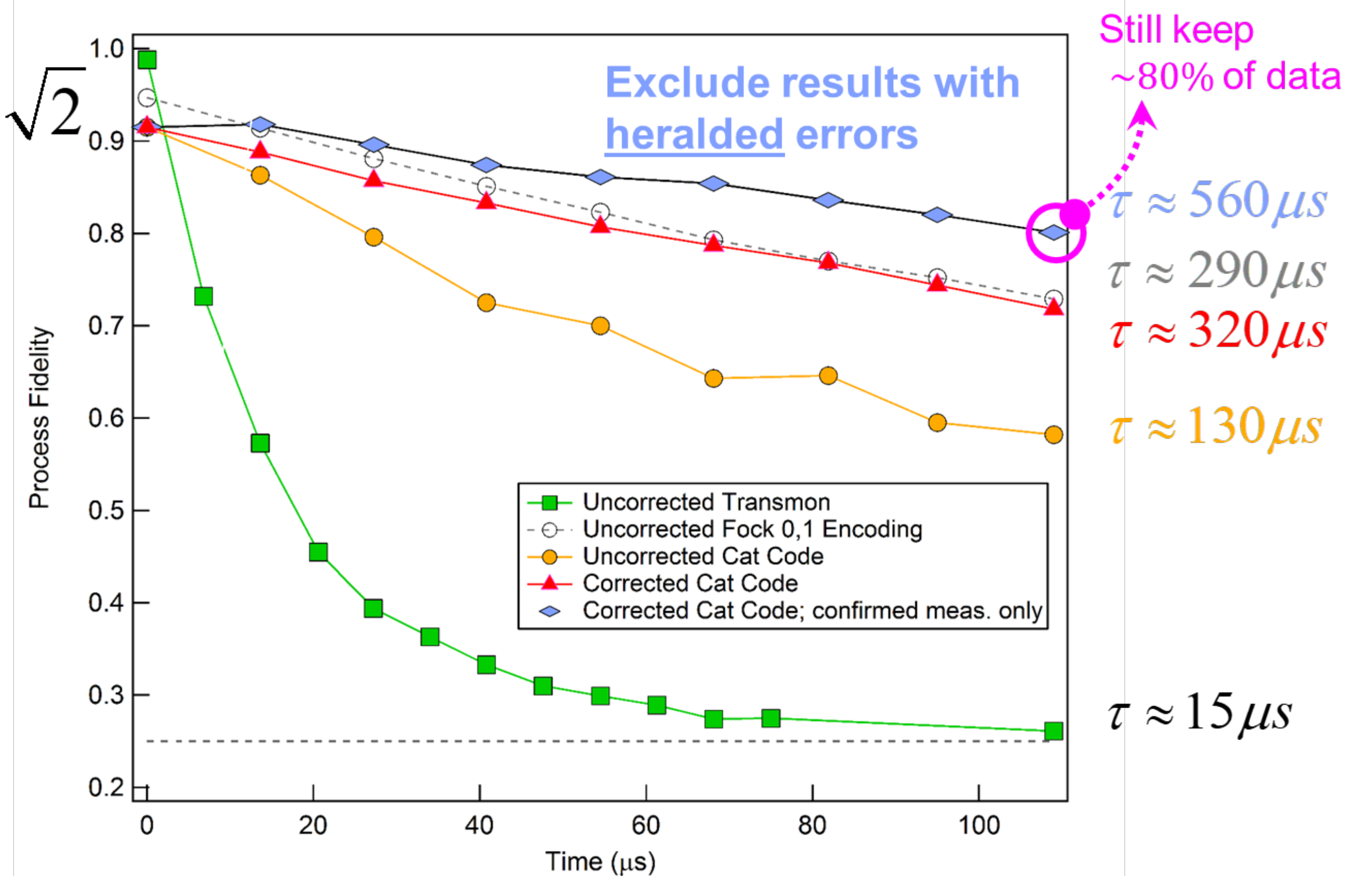
$$\left|\Psi\right\rangle = \psi_0\left|0_L\right\rangle + \psi_1\left|1_L\right\rangle$$

$$\left|0_L\right\rangle = \left|\alpha\right\rangle + \left|-\alpha\right\rangle$$

$$\left|1_L\right\rangle = \left|i\alpha\right\rangle + \left|-i\alpha\right\rangle$$

$$\alpha = \sqrt{2}$$

$\left|0_L\right\rangle$ $\left|1_L\right\rangle$ $\left|X_L\right\rangle$



Store a ***qubit*** as a
superposition
of two cats of same ***parity***

QEC Gain G:
1.1x break even (unheralded)
1.75x break even (heralded)

Theory: Leghtas, Mirrahimi, et al., *PRL* **111**, 120501 (2013)
Experiment: Ofek et al. *Nature* **536**, 441 (2016)

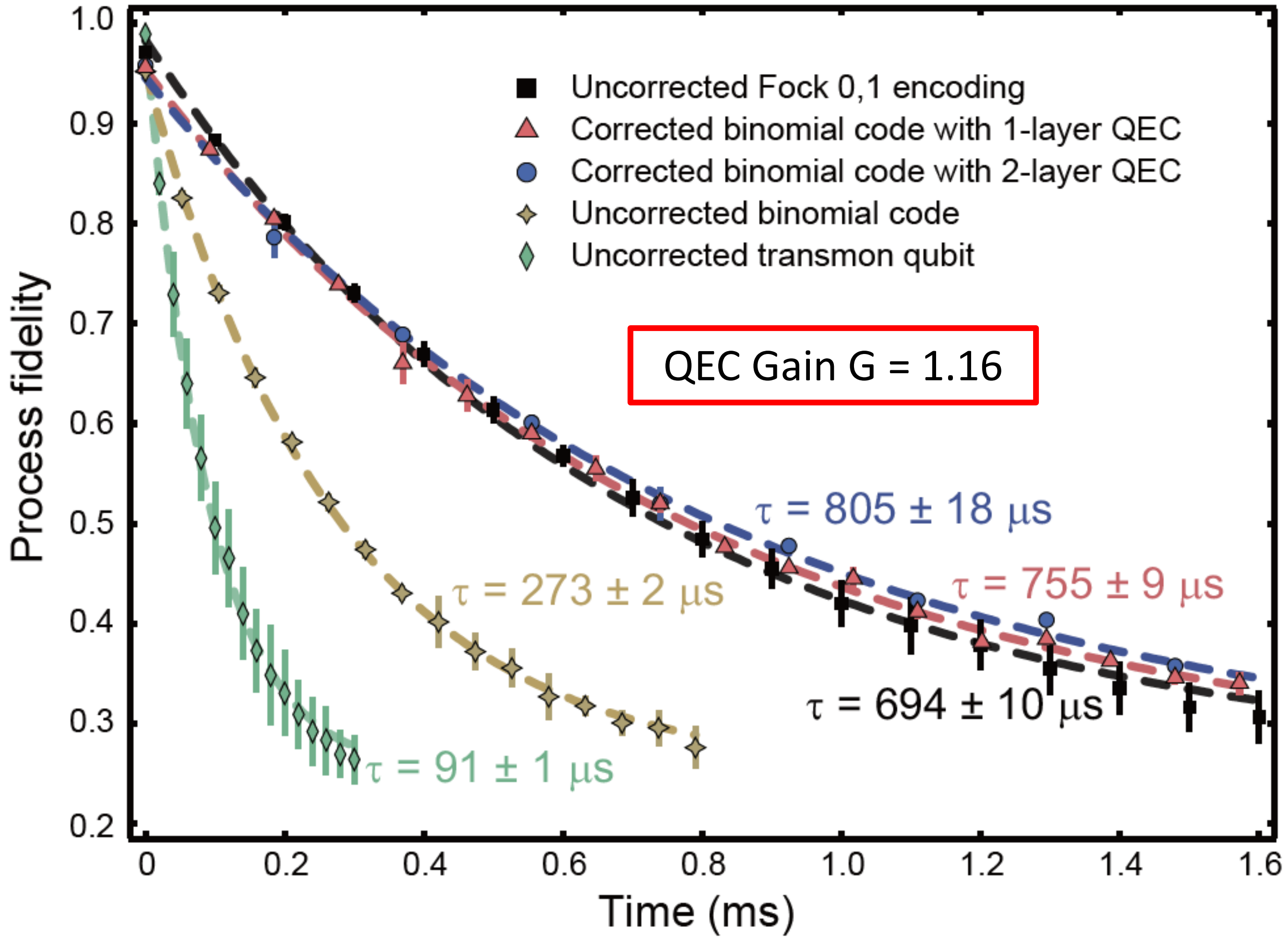
'Beating the break-even point with a discrete-variable-encoded logical qubit,'

Zhongchu Ni, et al. *Nature* **616**, 56 (2023)

Binomial Code
Phys. Rev. X 6, 031006 (2016)
Logical code words
(even parity)

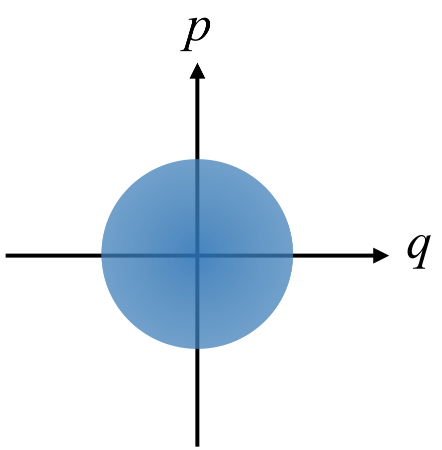
$$|0_L\rangle = \frac{|0\rangle + |4\rangle}{\sqrt{2}}$$

$$|1_L\rangle = |2\rangle$$



Prior work reached 92% of break-even
Luyan Sun group (Tsinghua)
Nature Phys. **15**, 503 (2019)

Gottesman-Kitaev-Preskill Bosonic Code
and the
Geometry of Phase Space



'Encoding a qubit in an oscillator'
D. Gottesman, A. Kitaev, and J. Preskill, *Phys. Rev. A* **64**, 012310 (2001).

Perspective:
'Quantum Error Correction with the Gottesman-Kitaev-Preskill Code'
Arne L. Grimsmo and Shruti Puri, *PRX Quantum* **2**, 020101 (2021)

Bosonic QEC with (idealized) GKP states of an oscillator

Stabilizers define code space:

$$S_p\,|0_L\rangle = S_q\,|0_L\rangle = (+1)|0_L\rangle$$

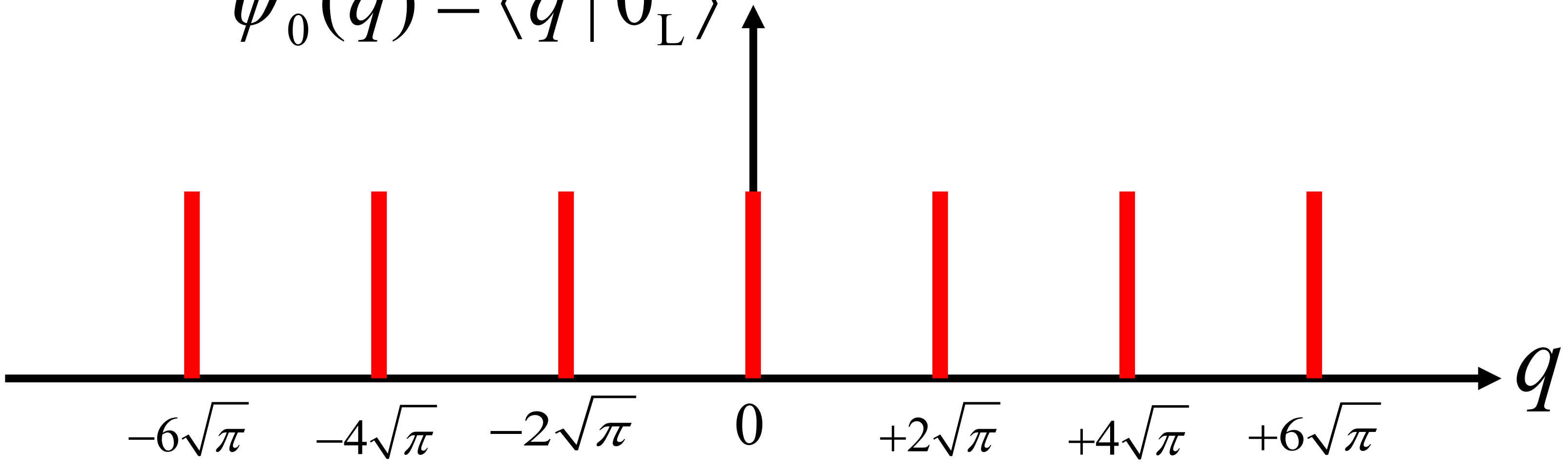
$$S_p\,|1_L\rangle = S_q\,|1_L\rangle = (+1)|1_L\rangle$$

$$S_p = e^{i2\sqrt{\pi}\hat{q}}$$

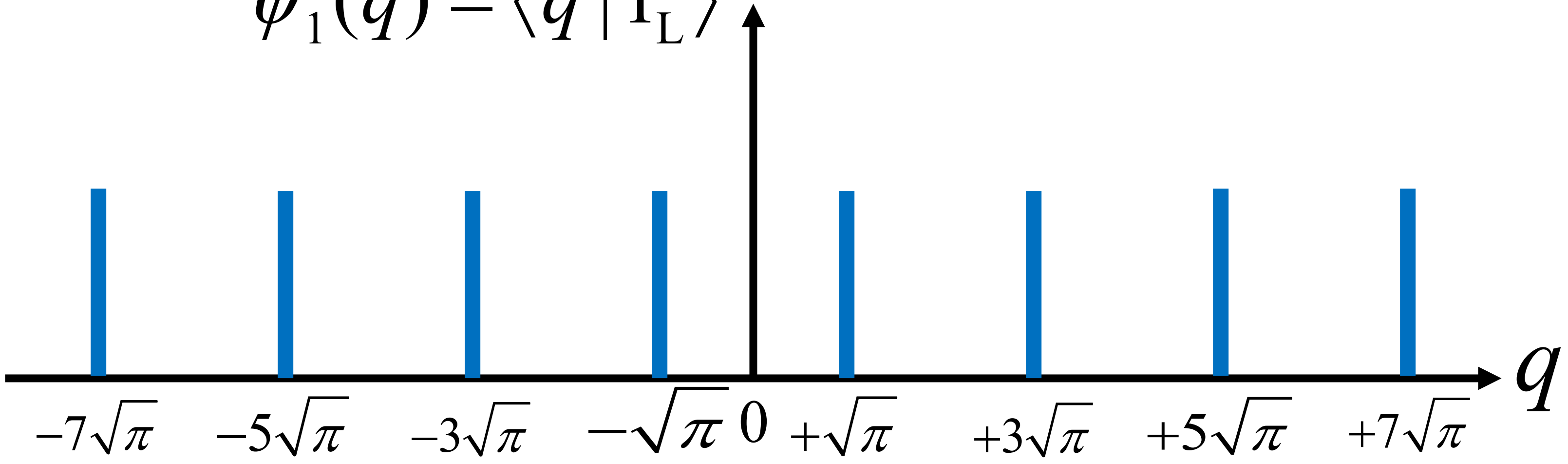
$$S_q = e^{i2\sqrt{\pi}\hat{p}}$$

GKP wave functions

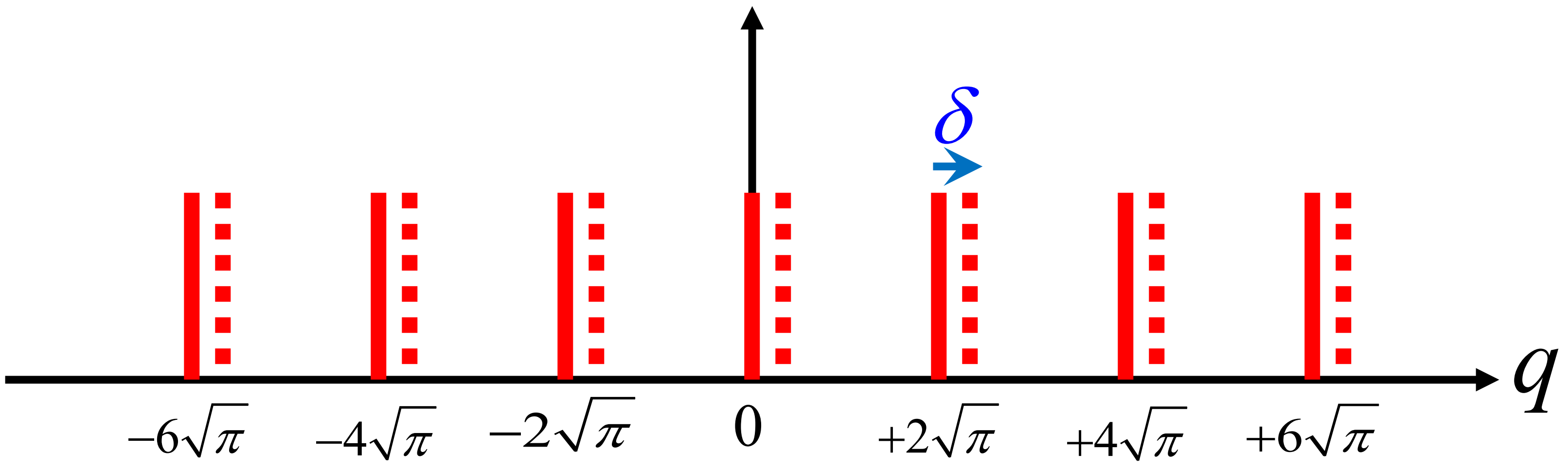
$$\psi_0(q) = \langle q\,|\,0_L\rangle$$



$$\psi_1(q) = \langle q\,|\,1_L\rangle$$



Bosonic QEC with GKP states of an oscillator



Code space is stabilized by:

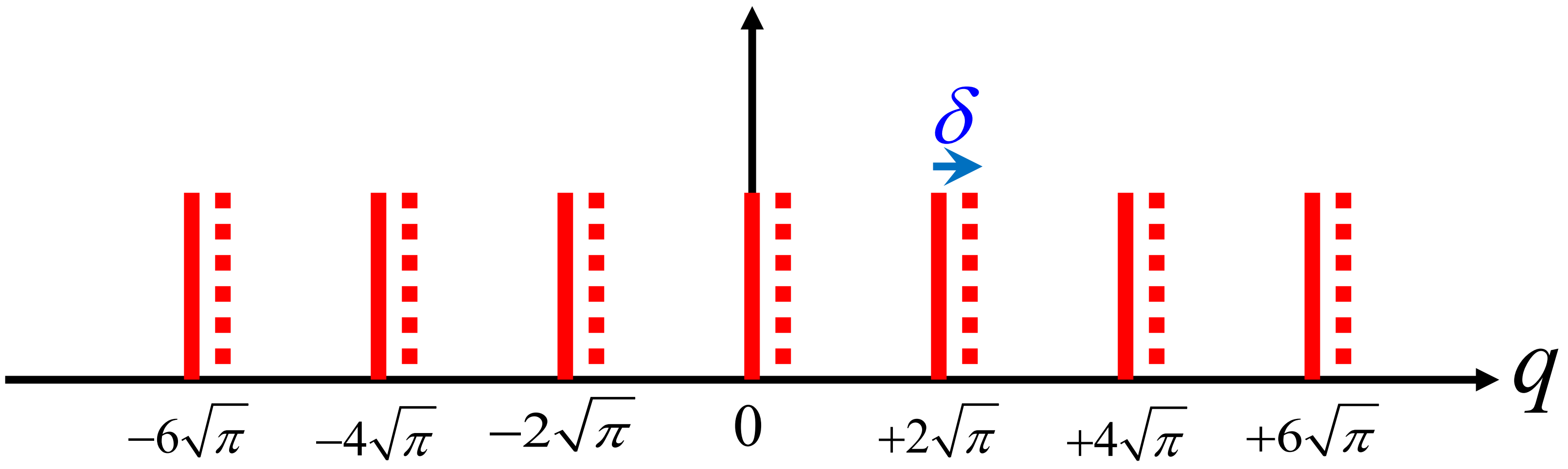
$$S_p = e^{i2\sqrt{\pi}\hat{q}}$$

$$S_q = e^{i2\sqrt{\pi}\hat{p}}$$

N.B. Unlike ordinary qubit stabilizers, these have a continuum of eigenvalues on the unit circle corresponding to continuous drift of position or momentum.

$$S_p \left|\Psi_\delta\right\rangle = e^{i2\sqrt{\pi}\delta} \left|\Psi_\delta\right\rangle$$

Continuous stabilizer eigenvalue on the unit circle in the complex plane.



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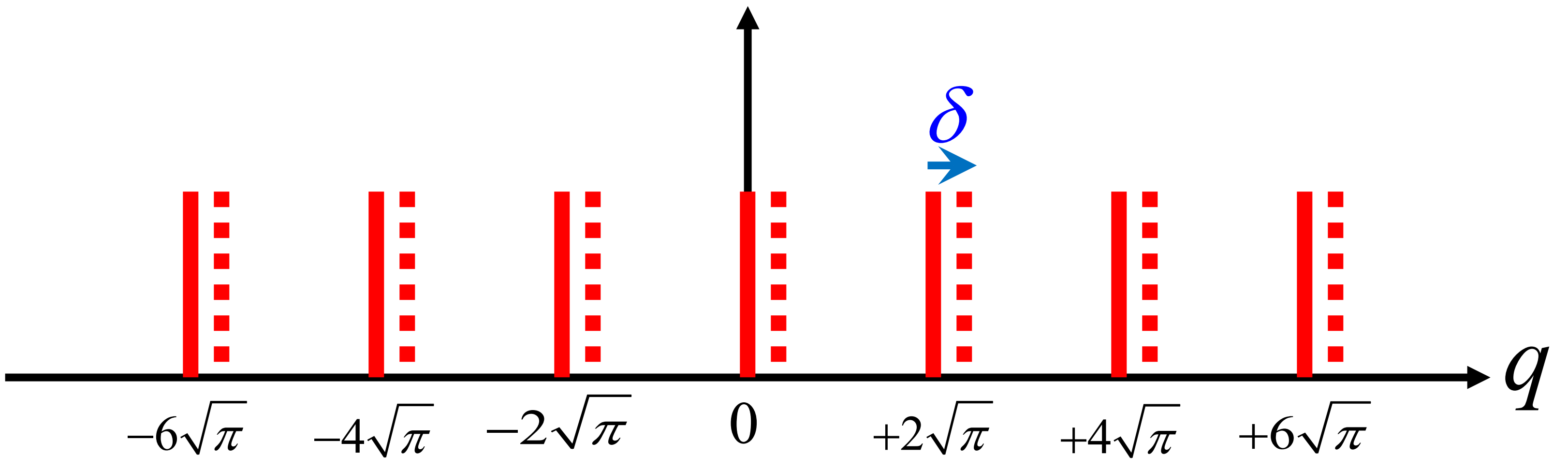
$$S_p |\Psi_\delta\rangle = e^{i2\sqrt{\pi}\delta} |\Psi_\delta\rangle$$

Continuous stabilizer eigenvalue on the unit circle in the complex plane.

ONLY 2 STABILIZERS NEEDED TO REDUCE INFINITE STATE SPACE DOWN TO 2 LOGICAL STATES!

Bosonic QEC with GKP states of an oscillator



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N.B. Unlike ordinary qubit stabilizers, these have a continuum of eigenvalues on the unit circle corresponding to continuous drift of position or momentum.

Stabilization against drift errors in *position q*

Measure stabilizer to detect error:

$$\mathrm{Im}\langle S_p \rangle = \langle \sin[2\sqrt{\pi}\hat{q}] \rangle$$

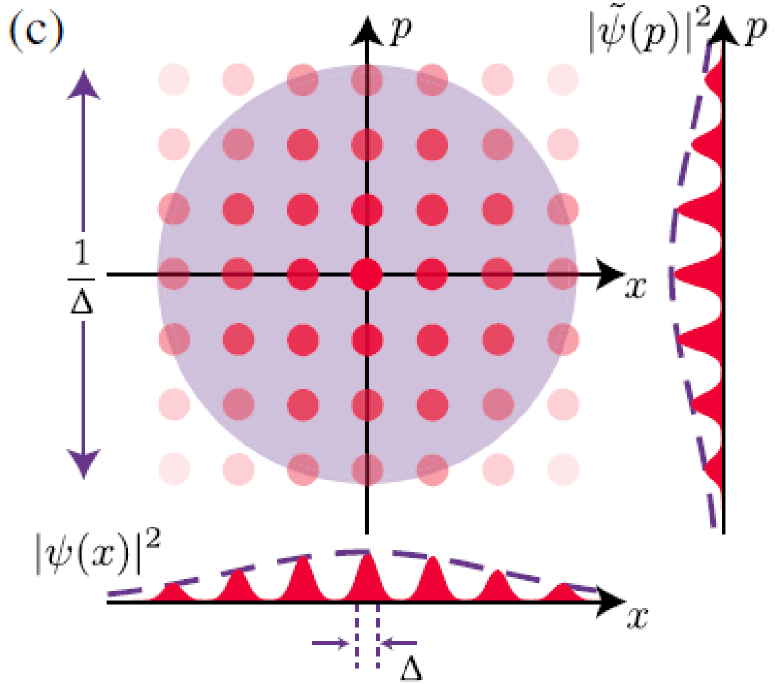
$$= \int dq \sin[2\sqrt{\pi} q] |\psi(q)|^2 = \sin[2\sqrt{\pi}\delta]$$

and feedback to correct.

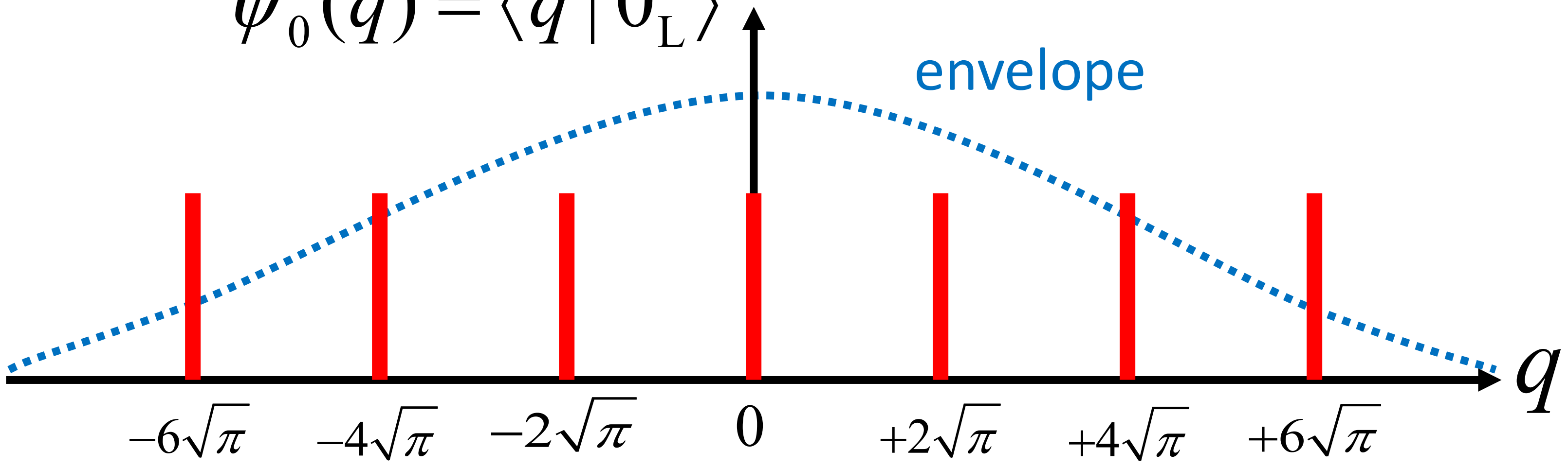
Bosonic QEC with (finite-energy) GKP states of an oscillator

envelope

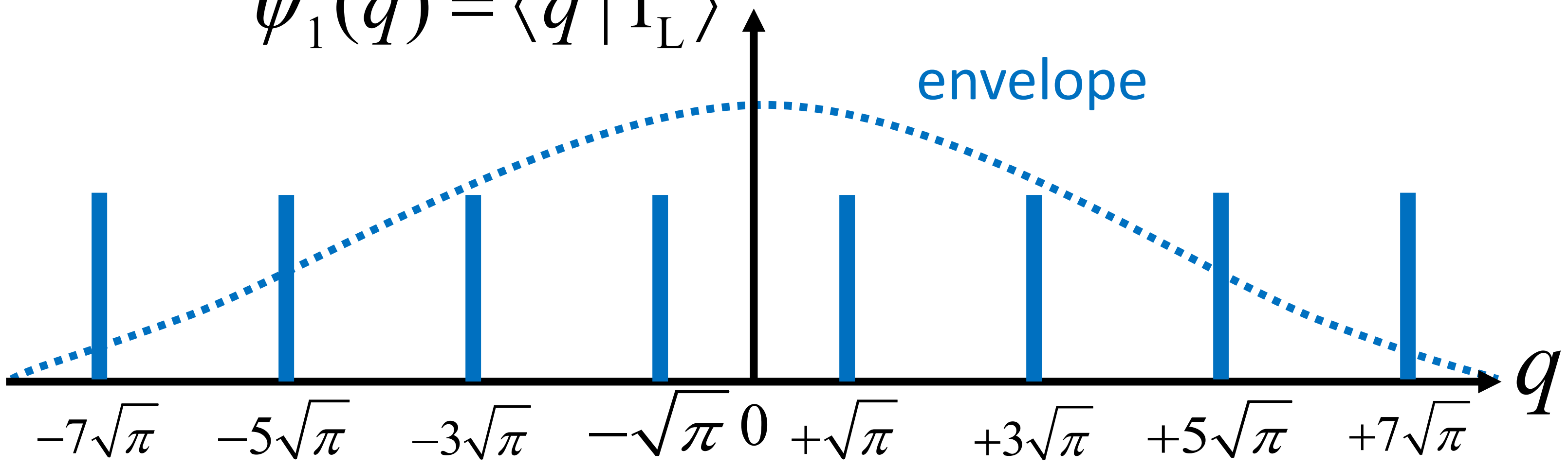
$$|\tilde{0}_\mathrm{L}\rangle \sim e^{-\epsilon\hat{n}}\,|0_\mathrm{L}\rangle$$



$$\psi_0(q) = \langle q\,|\,0_\mathrm{L}\rangle$$



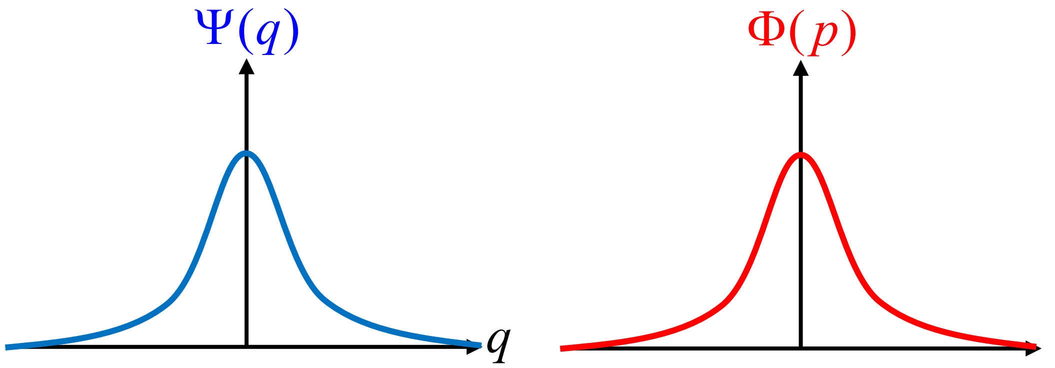
$$\psi_1(q) = \langle q\,|\,1_\mathrm{L}\rangle$$

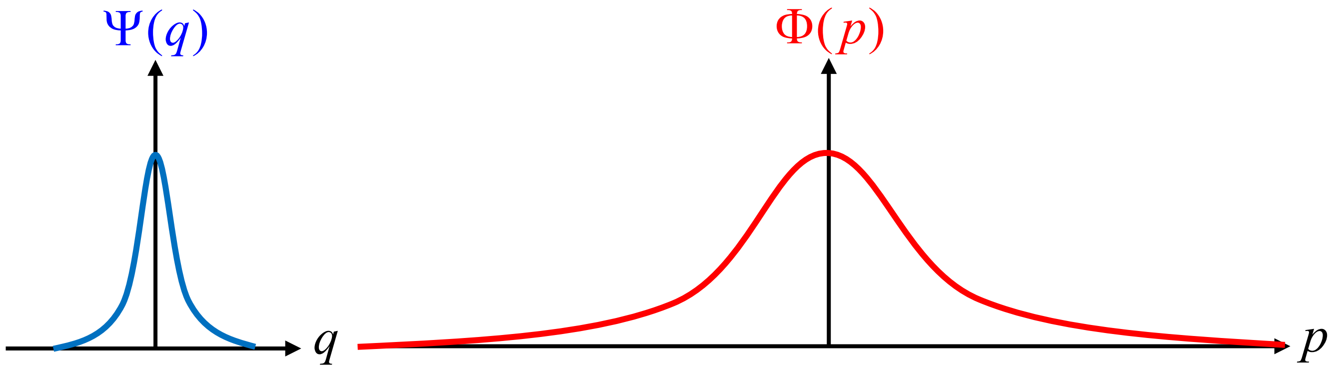


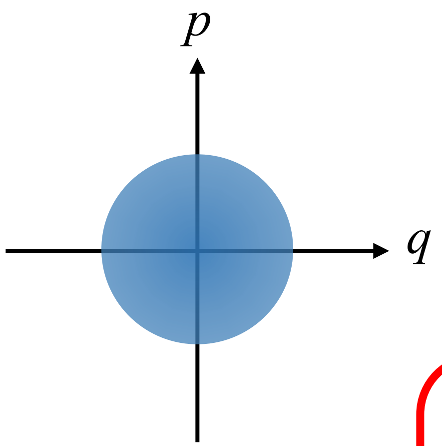
Coherent (vacuum) state of an oscillator

Squeezed state of an oscillator

Geometry of phase space….





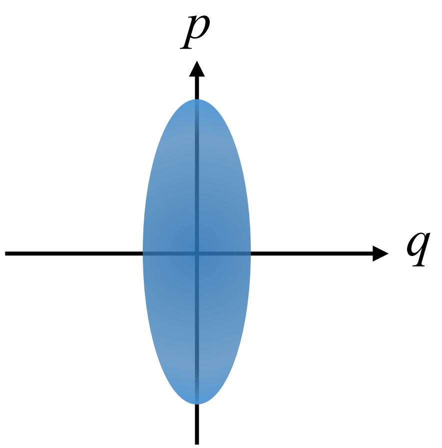


Heisenberg
Uncertainty

$$[\hat{q}, \hat{p}] = i \;\Rightarrow\; \Delta q \Delta p \geq \frac{1}{2}$$

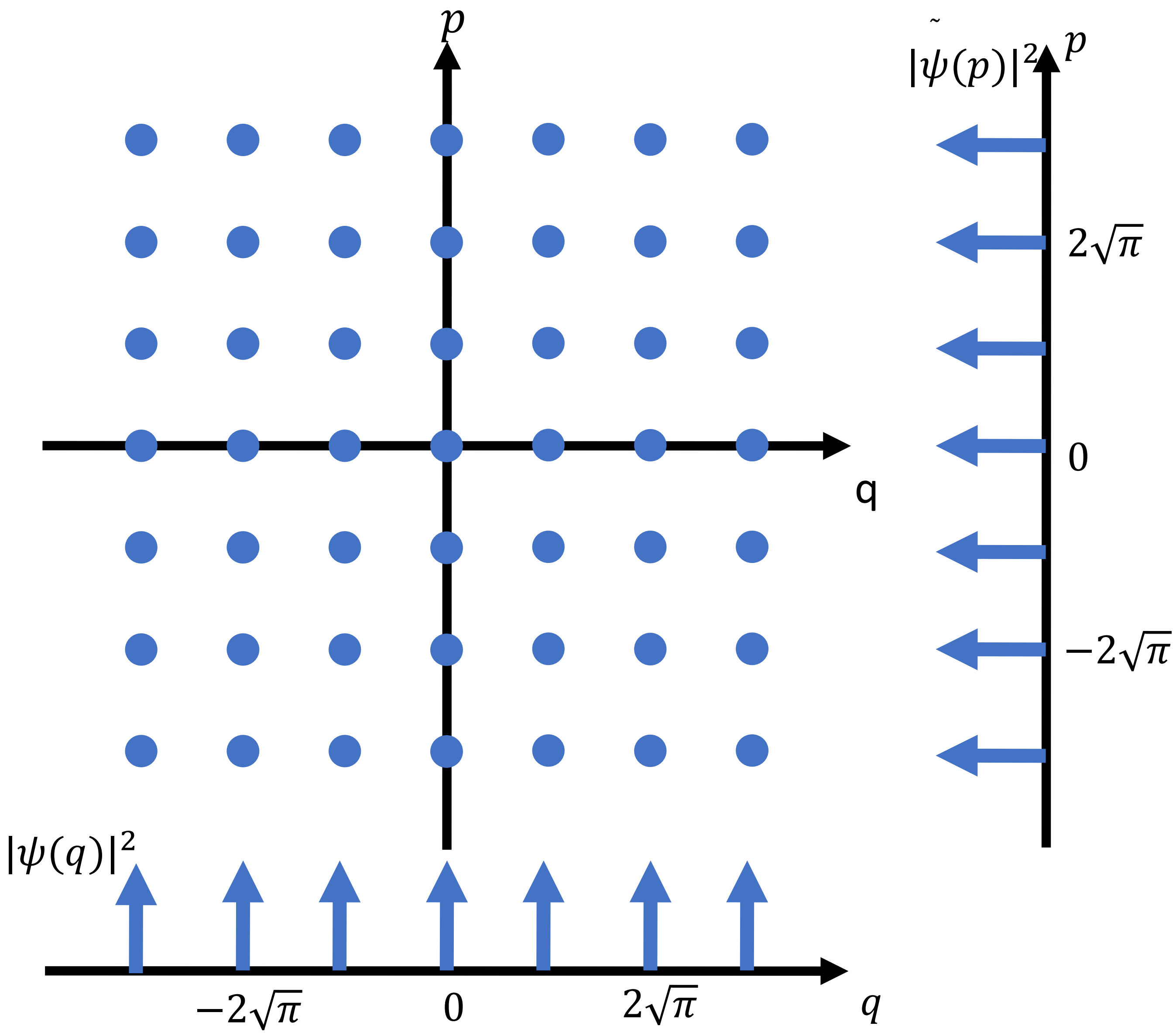
Phase space seems to be 'incompressible'

One state per area $h = 2\pi$



Note: squeezing can be achieved by simply measuring the position of the oscillator with uncertainty less than the zero-point motion.

But recall that a crystal lattice produces sharp Bragg peaks in x-ray diffraction.



Gottesman, Kitaev and Preskill, Phys. Rev. A 64, 012310 (2001)

Proposed encoding a logical qubit in oscillator 'grid' states.

How can the points in this phase space grid be smaller than the minimum uncertainty wave packet?

They seem to be squeezed in both position AND momentum!?

This is possible for special choices of lattice unit cell areas.

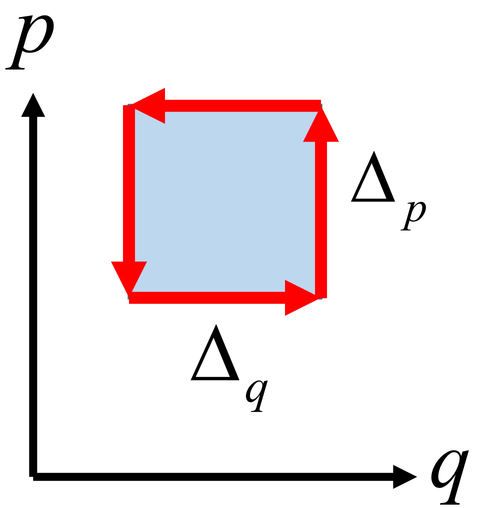
$[\hat{q},\hat{p}] = +i \quad \Rightarrow$ translations in phase space do not commute

$$\mathcal{D}(\Delta_q)\Psi(q) = e^{-i\Delta_q \hat{p}}\Psi(q) = \Psi(q-\Delta_q)$$

$$\mathcal{D}(i\Delta_p)\Psi(q) = e^{i\Delta_p q}\Psi(q)$$

$$\mathcal{D}(\Delta_q)\mathcal{D}(i\Delta_p) = e^{i\Delta_p\Delta_q}\mathcal{D}(i\Delta_p)\mathcal{D}(\Delta_q)$$

area



Harmonic Oscillator Phase Space

Inside the code space: *X,Y,Z* translations obey Pauli group

GKP code space is stabilized by special translations that do commute

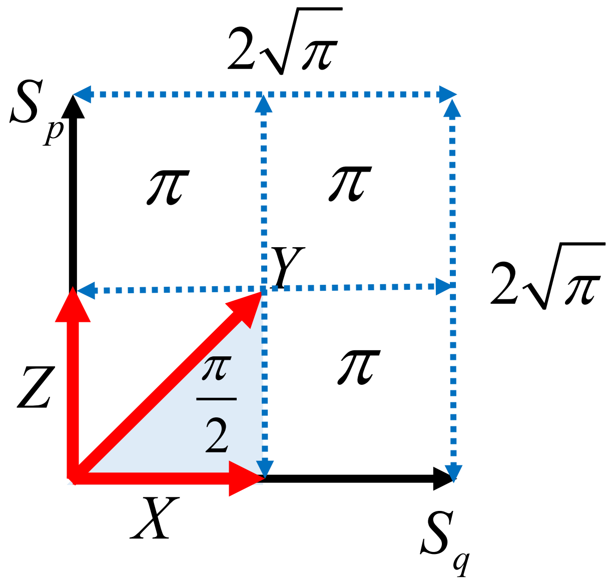
$$S_p = e^{i2\sqrt{\pi}\hat{q}}$$

$$S_q = e^{i2\sqrt{\pi}\hat{p}}$$

$$S_q S_p = e^{i4\pi} S_p S_q$$

$$S|0_L\rangle = (+1)|0_L\rangle$$

$$S|1_L\rangle = (+1)|1_L\rangle$$



Area 4π = 2 states

$$S_p = S_q = 1$$

$$X^2 = S_q = 1$$

$$Z^2 = S_p = 1$$

$$ZX = e^{i\pi} XZ = -XZ$$

$$ZX = e^{i\pi/2} Y = iY$$

Stabilizers and Pauli (and Clifford) operations are translations in phase space.

How do we measure the eigenvalue of a translation?

Qubit state

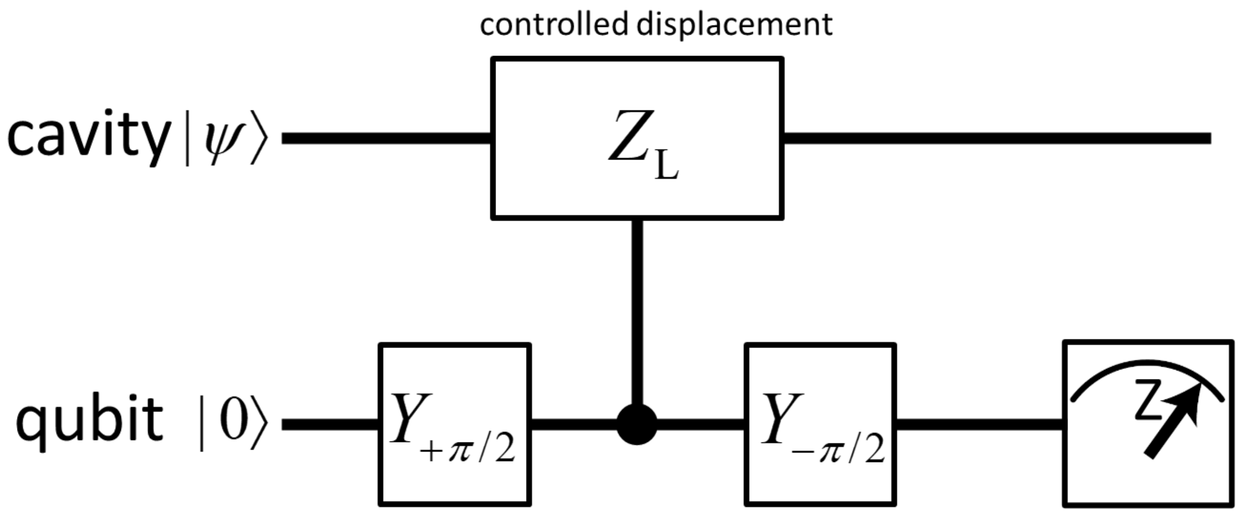
Cavity displacement

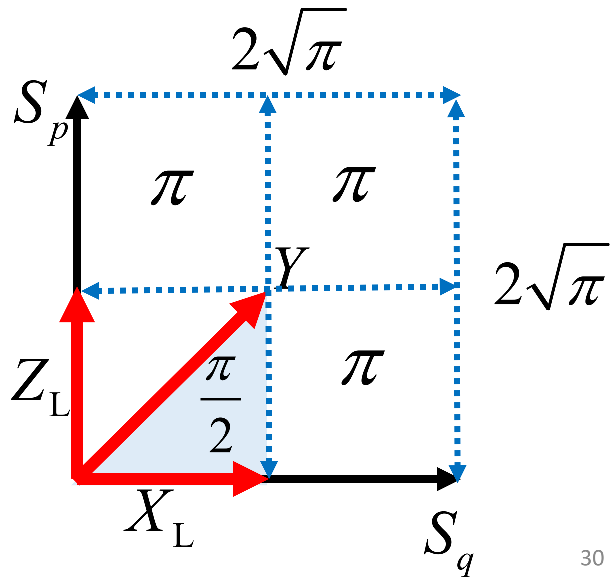
Key ancilla-controlled cavity operation:

Controlled Displacement gate: $\mathcal{D}_c[\alpha] = e^{Z[\alpha a^\dagger - \alpha^* a]} = |0\rangle\langle 0|\mathcal{D}[+\alpha] + |1\rangle\langle 1|\mathcal{D}[-\alpha]$

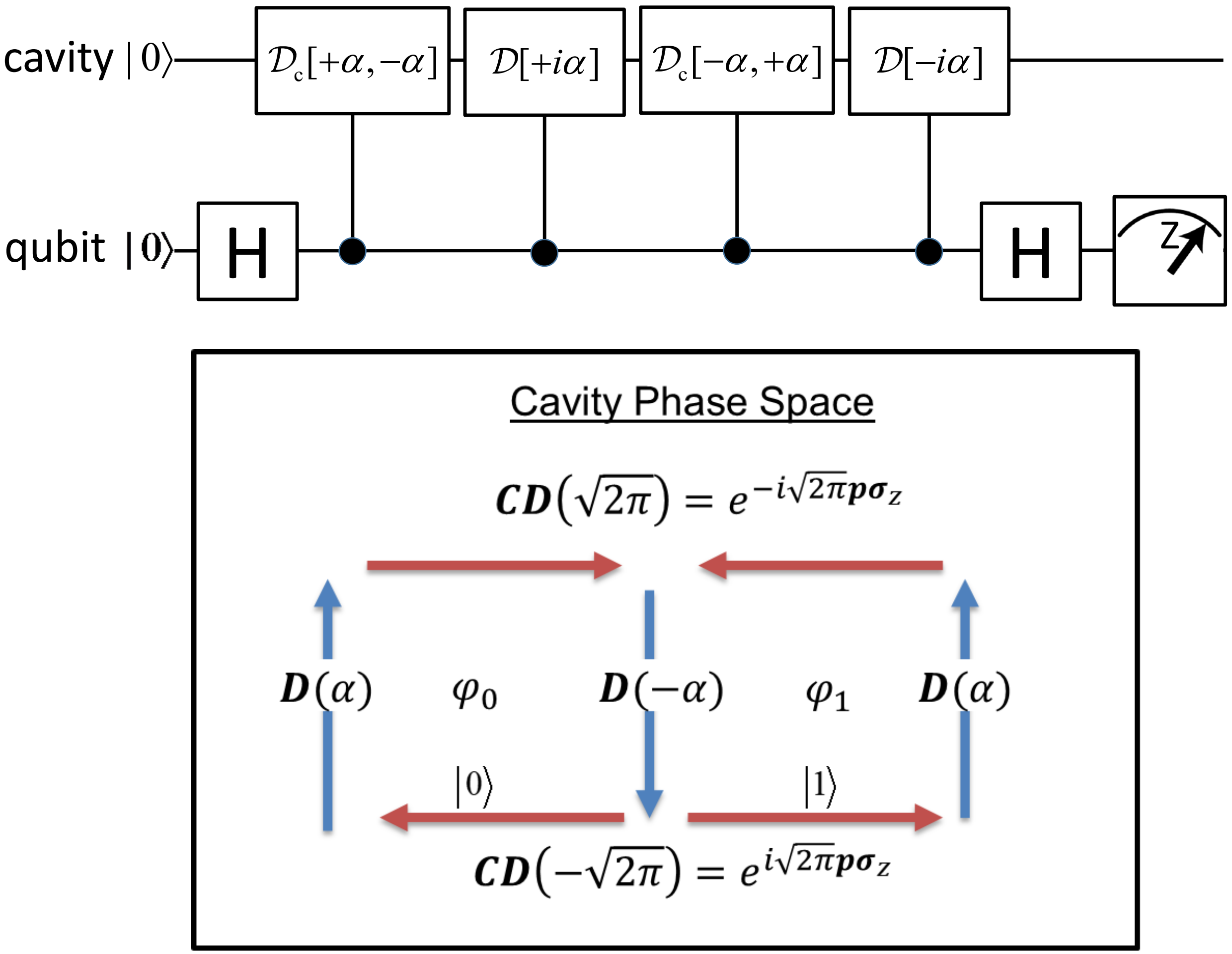
GKP Logical Pauli measurement via phase kick-back on ancilla.

GKP Syndrome measurements are similar but with larger displacements.

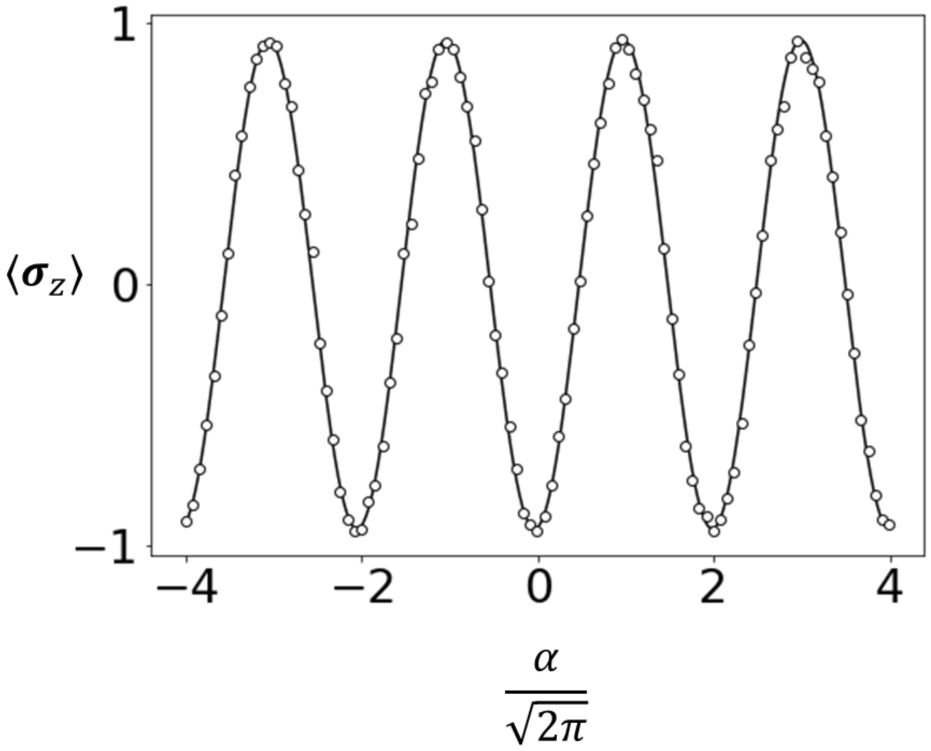




Experimental Calibration of Controlled Displacements Non-Commutativity (Devoret Group)



EXP. DATA: BERRY PHASE OSC.



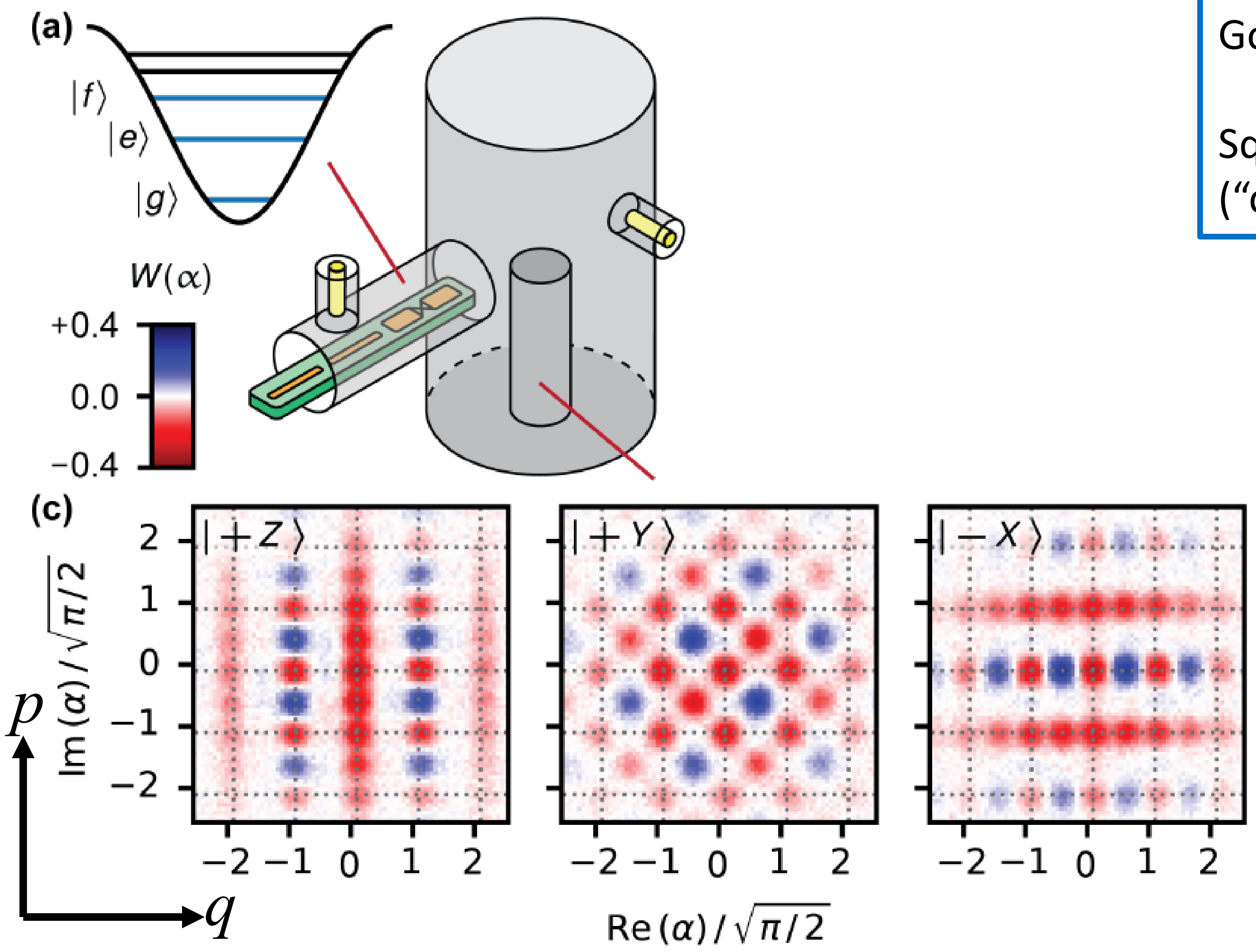
geometric phase acquired over 1 cycle:

$$|0\rangle + |1\rangle \to e^{-i\varphi_0}|0\rangle + e^{i\varphi_1}|1\rangle$$

Campagne-Ibarcq, Eickbusch, Touzard, et al *Nature* **584**, 368 (2020)

Measured 'phase kickback' of controlled unitary

Microwave cavity holds GKP bosonic code



Oscillator phase-space ‘image’
(characteristic function) of GKP code words

‘GKP code’: Continuous variable qubit in an Oscillator
Gottesman, Kitaev, Preskill (2001)

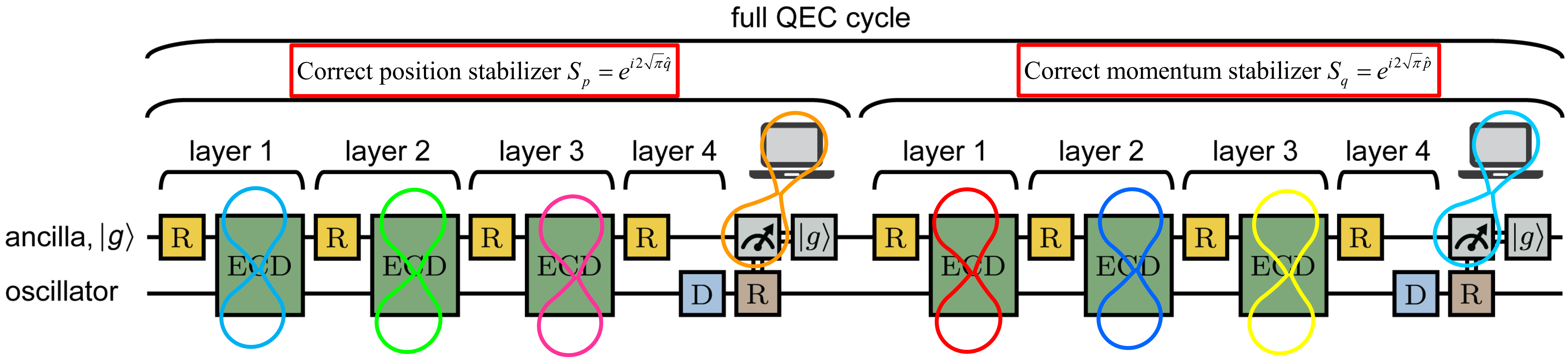
Squeezed state lattice in phase space
(“cat in 35 places at once”)

Logical gates and code stabilizers are simple phase-space translations.

Clifford group operations are all
Gaussian linear optics operations

Sivak et al. [Devoret group],
Nature **616**, 50 (2023)

QEC circuit for the grid code



Improved (autonomous) Syndrome mapping unitary [B. Royer *et al.*, (PRL, 2020)]

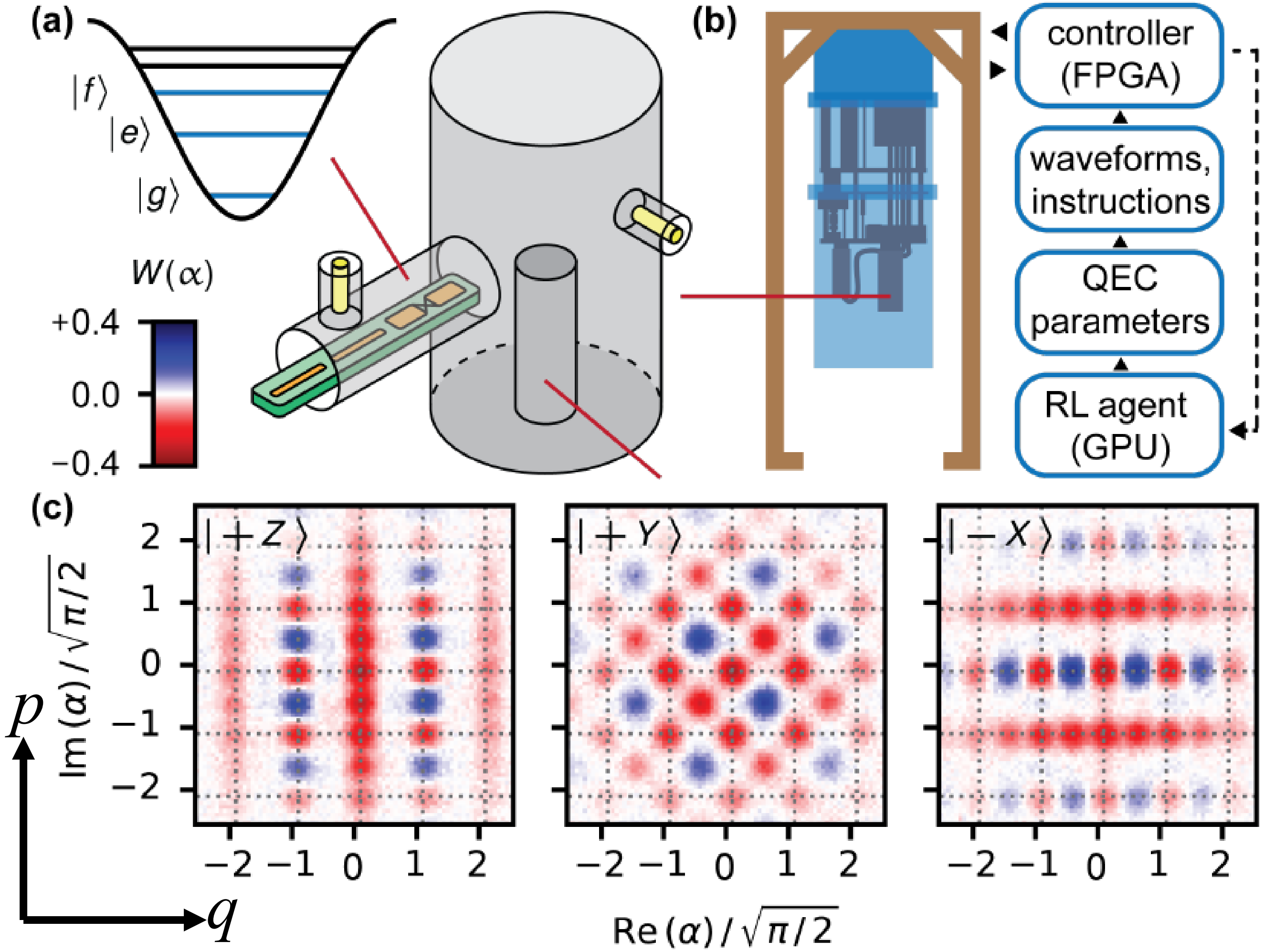
Multi-layered parametrized circuit [A. Eickbusch *et al.*, (Nature Physics, 2022)]

Real-time processing with FPGA [N. Ofek *et al.*, (Nature, 2016)]

Circuit training with reinforcement learning [V. Sivak *et al.*, (PRX, 2022)]

This circuit implements a rank-4 channel: $\{K_{gg}, K_{ge}, K_{eg}, K_{ee}\}$

Microwave cavity holds GKP bosonic code



Oscillator phase-space ‘image’ (characteristic function) of GKP code words

Model-free Reinforcement Learning Agent tunes up ~45 variables in the experimental QEC protocol.

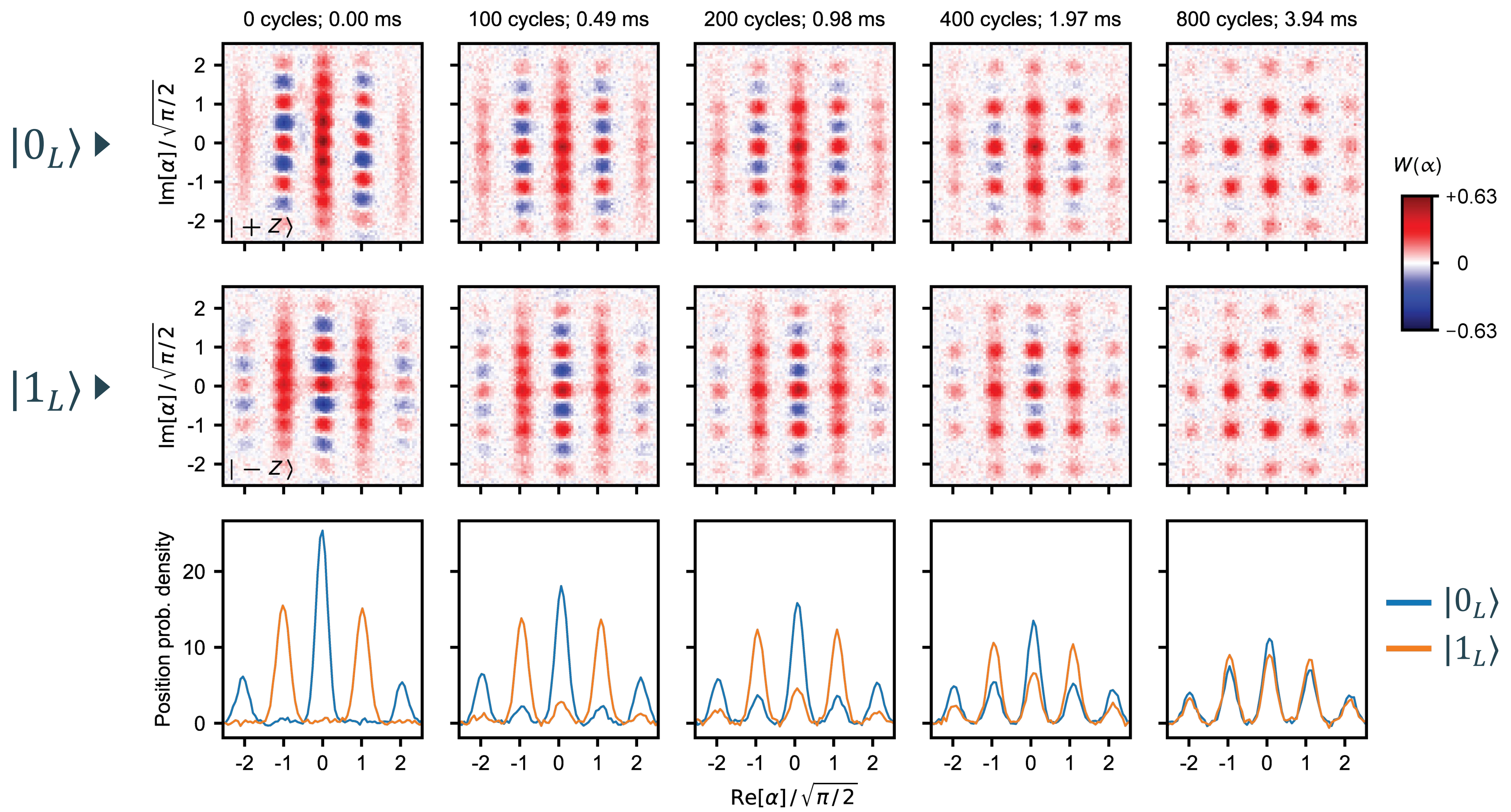
[RL agent chose to slow down the readout to improve QEC fidelity.]

Logical gates and code stabilizers are simple phase-space translations.

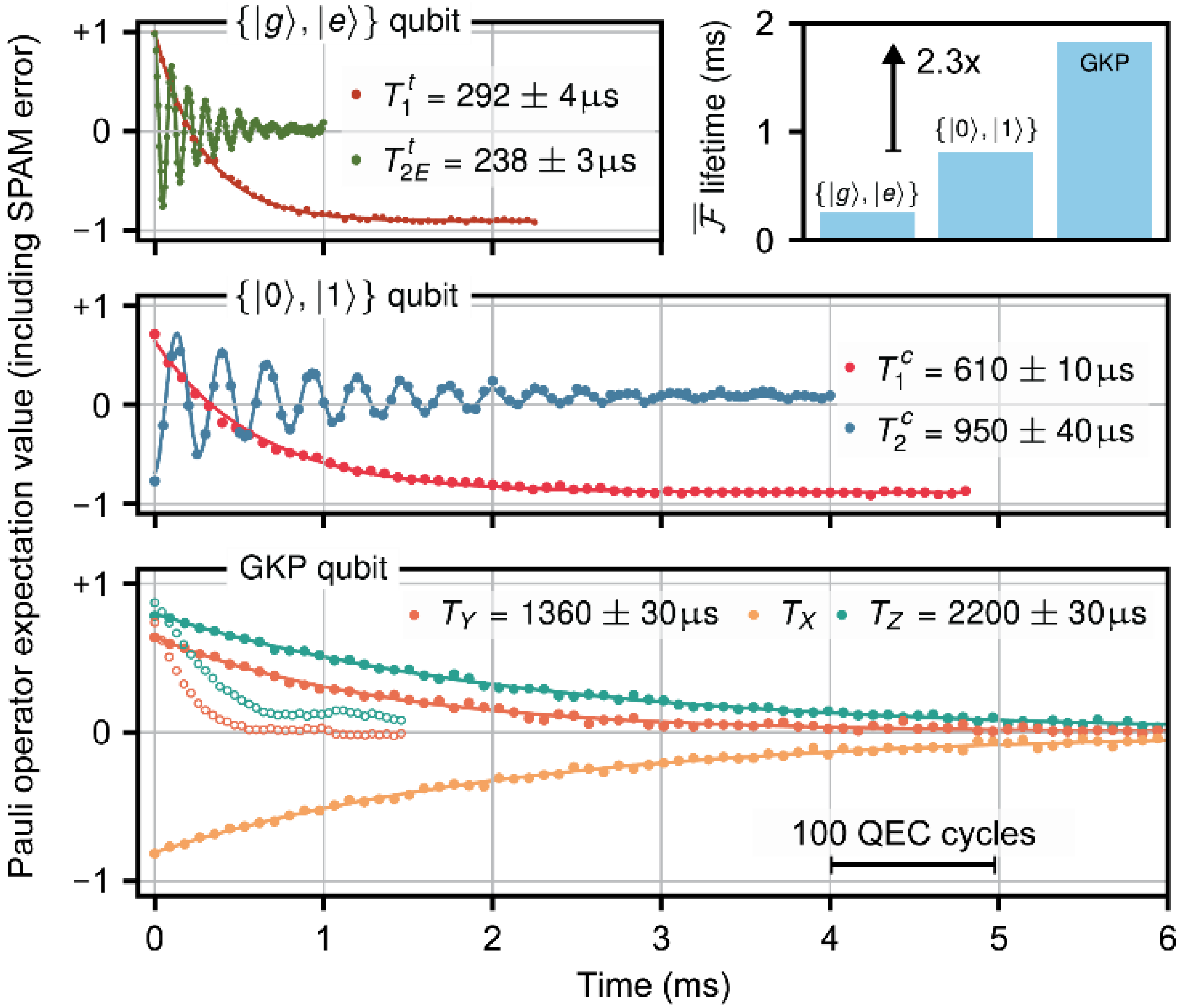
Clifford group operations are all Gaussian linear optics operations

Sivak et al. [Devoret group], *Nature* **616**, 50 (2023)

Wigner tomography (experiment)



Comparison of logical vs. physical qubits



Average channel fidelity

M. Nielsen, Phys. Lett. A (2002)

$$\bar{\mathcal{F}}(\delta t) = 1 - \frac{1}{2}\Gamma\,\delta t$$

{|0⟩, |1⟩} qubit

Amplitude damping + Dephasing

$$\Gamma_{\{01\}} = \frac{2\gamma_2^c + \gamma_1^c}{3}$$

GKP

Pauli channel

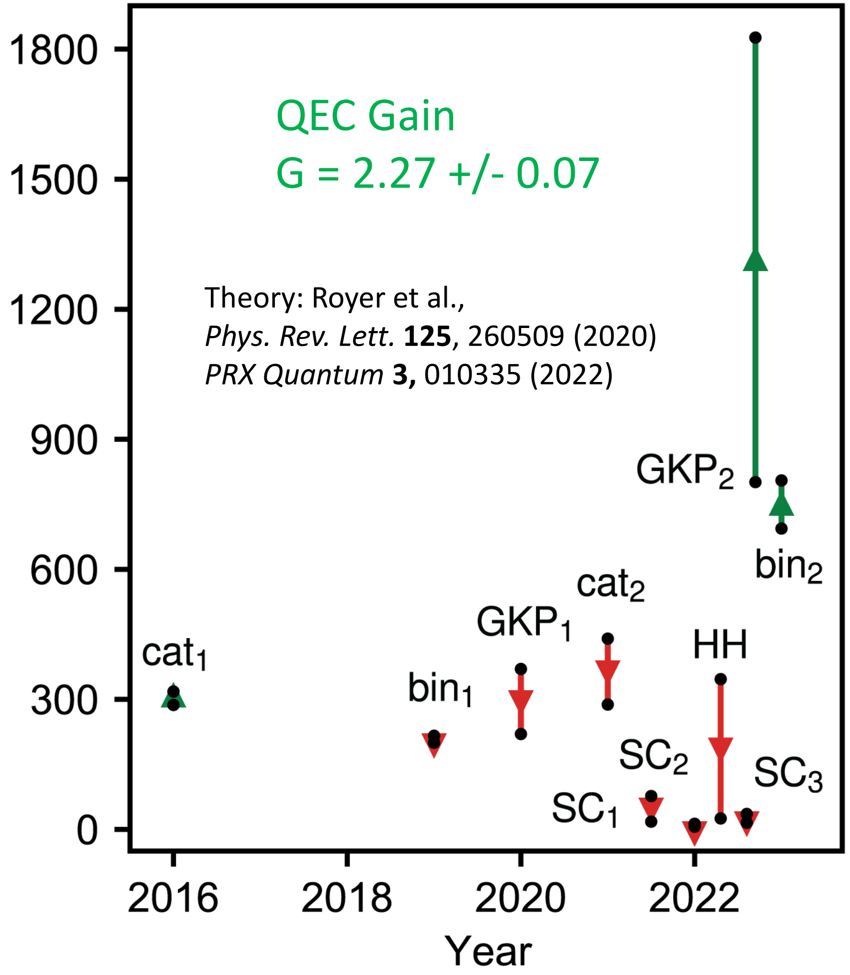
$$\Gamma_{\mathrm{GKP}} = \frac{\gamma_X + \gamma_Y + \gamma_Z}{3}$$

QEC gain:

$$G = \frac{\Gamma_{\{01\}}}{\Gamma_{\mathrm{GKP}}} \approx 2.27 \pm 0.07$$

QEC: state of play

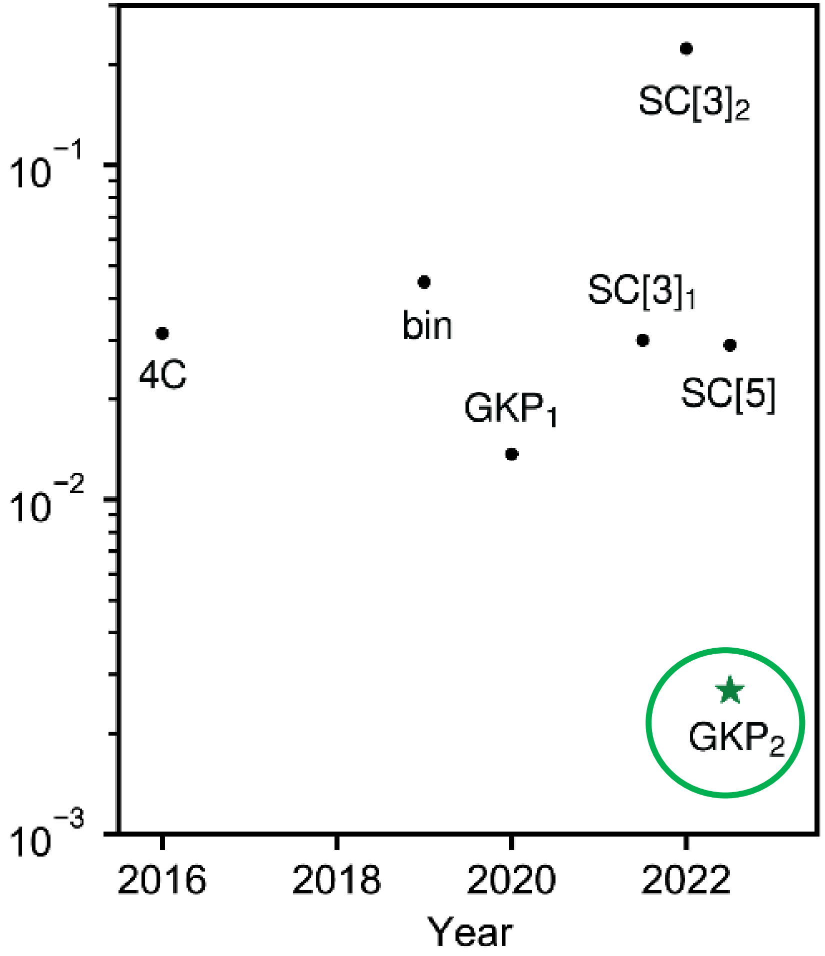
Logical and best physical lifetime (µs)



	QEC experiment
cat_1	N. Ofek *et al.,* (Nature, 2016)
bin_1	L. Hu *et al.,* (Nature Physics, 2019)
GKP_1	P. Campagne-Ibarcq *et al.,* (Nature, 2020)
cat_2	J. Gertler *et al.,* (Nature, 2021)
SC_1	S. Krinner *et al.,* (Nature, 2022)
SC_2	Y. Zhao *et al.,* (PRL, 2022)
SC_3	Google Quantum AI (arXiv:2207.06431, 2022)
HH	N. Sundaresan *et al.,* (arXiv:2203.07205, 2022)
bin_2	Z. Ni *et al.,* (arXiv:2211.09319, 2022)
GKP_2	This work *Nature* **616**, 50 (2023).

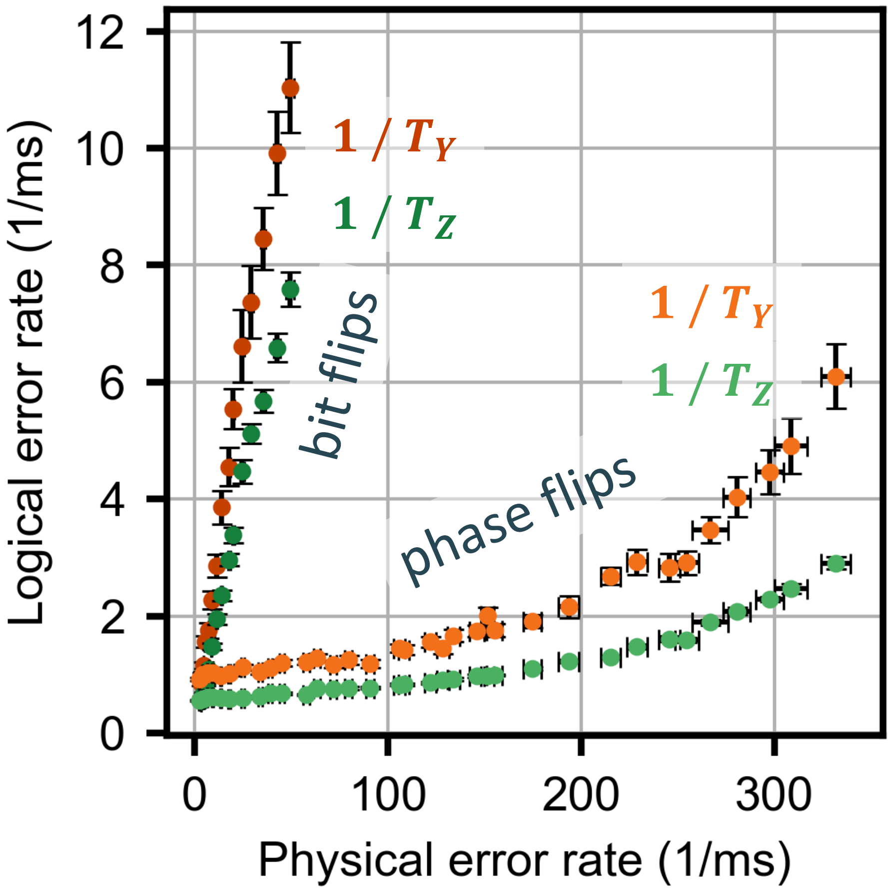
GKP_3 de Neeve et al., (ion trap)
Nature Physics **18**, 296 (2022)
[GKP Gain difficult to estimate]

Logical error probability per QEC cycle

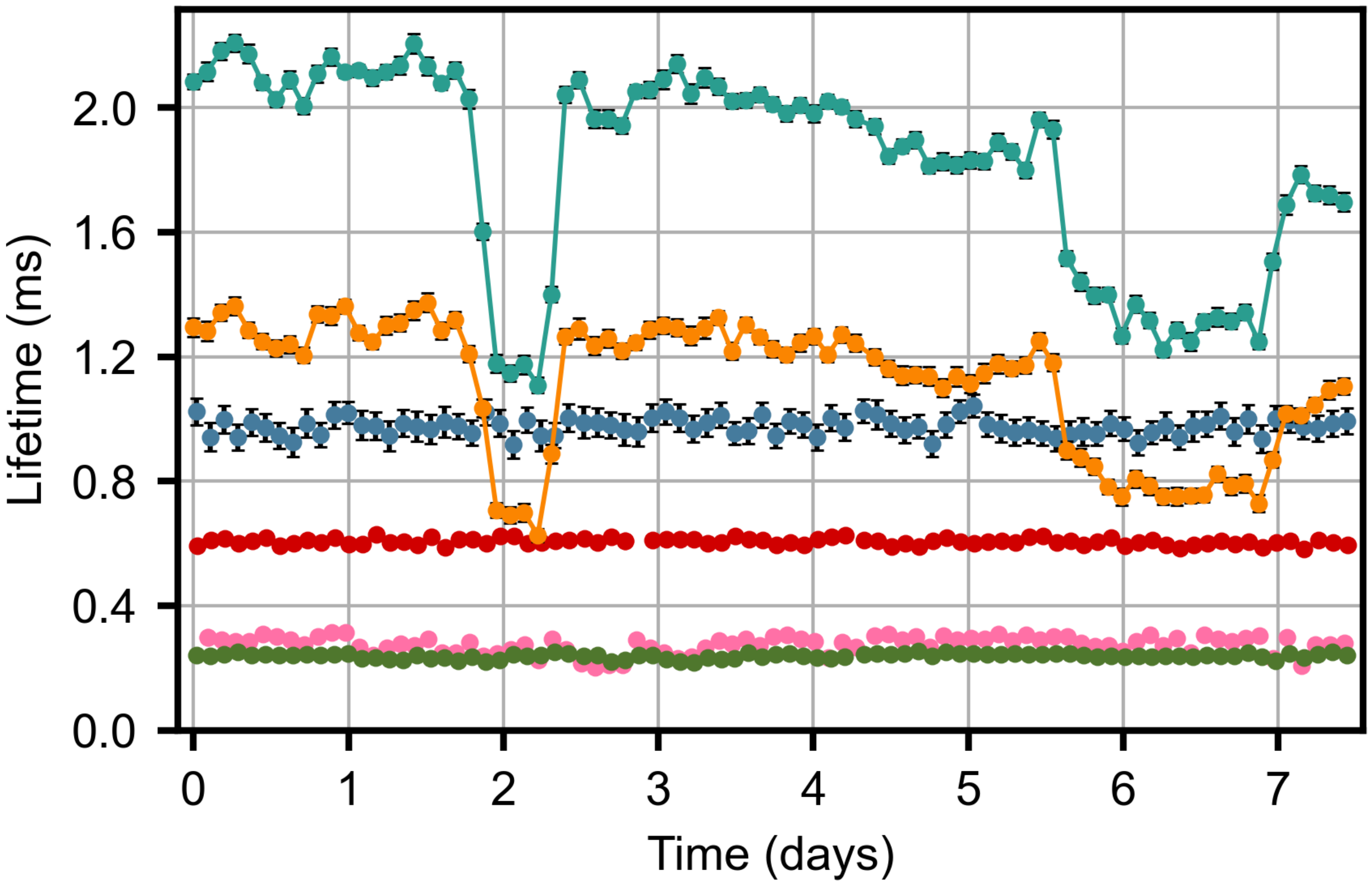


Outlook: short term

Need robustness against ancilla bit-flip errors



Need additional "tuning knob" to avoid performance collapses



| Ancilla T_1, T_{2E} | Oscillator T_1, T_2 | Grid code T_Z, T_Y |

Outlook: long term

Possible roadmap for future hardware-efficient quantum error correction

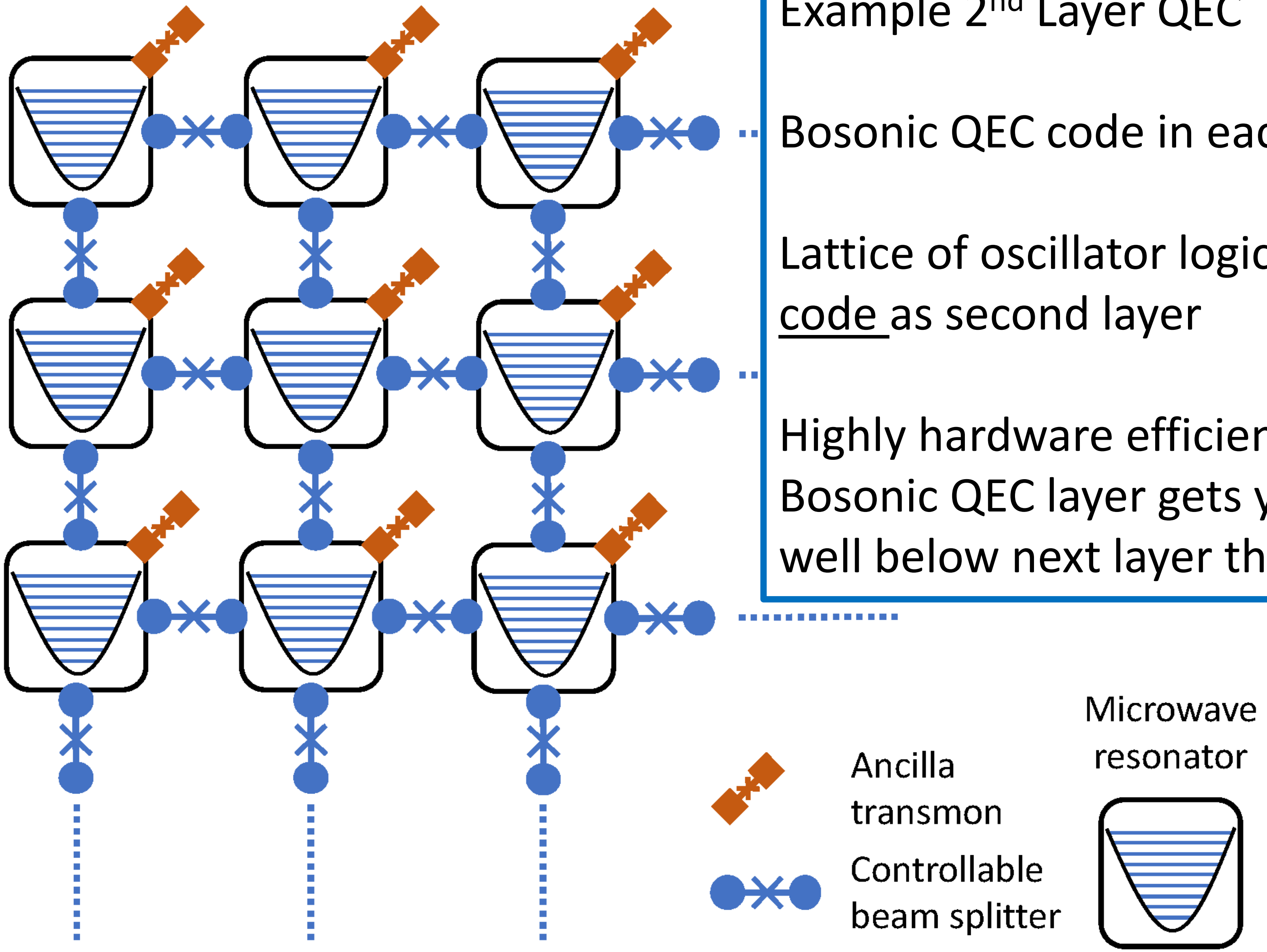
Example 2nd Layer QEC

Bosonic QEC code in each oscillator

Lattice of oscillator logical qubits encoded into surface code as second layer

Highly hardware efficient if Bosonic QEC layer gets you well below next layer threshold

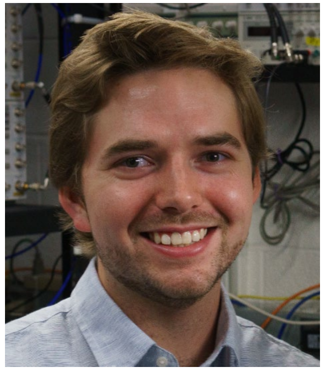
$$p_L \sim \left(\frac{p_{\text{bosonic code}}}{p^{\text{threshold}}_{\text{surface code}}} \right)^{\frac{d+1}{2}}$$



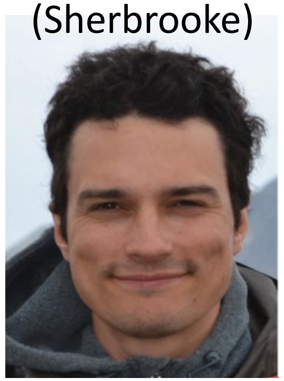
Yale GKP Team

V. Sivak
(Google)

A. Eickbusch



B. Royer
(Sherbrooke)



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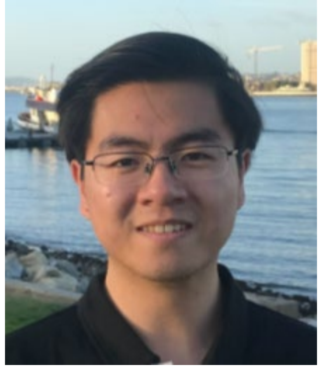
S. Ganjam

A. Miano

S. Singh

B. Brock

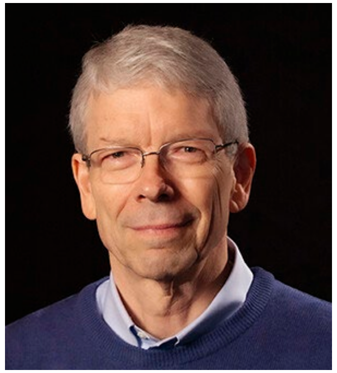
A. Ding



S. Puri

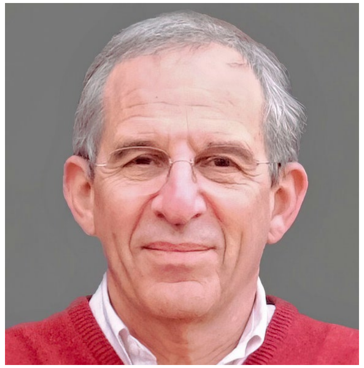
L. Frunzio

S. Girvin



R. Schoelkopf

M. Devoret

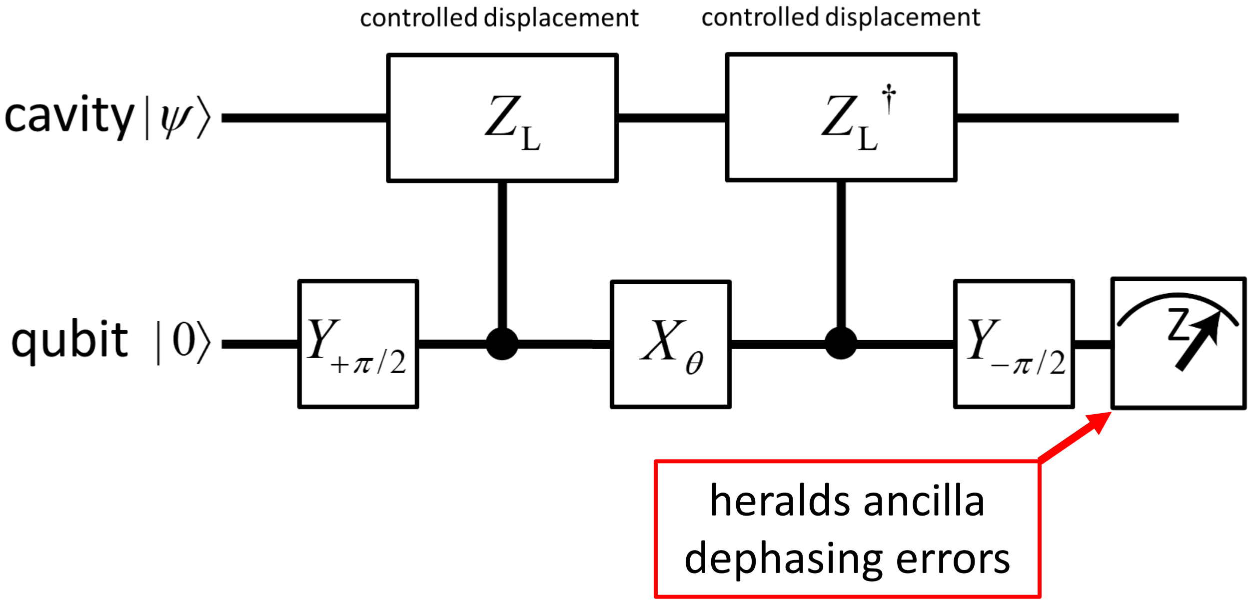


Stabilizers and Pauli (and Clifford) operations are translations in phase space.

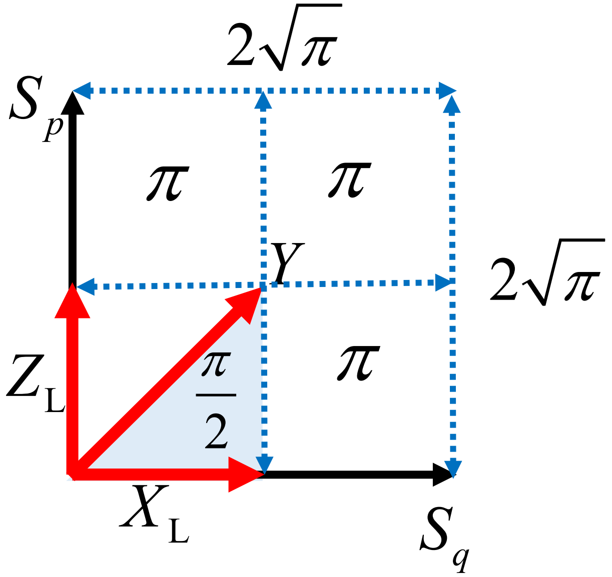
How do we do a continuous Pauli rotation?
Requires superposition of translation and no translation:

$$e^{-i\frac{\theta}{2}Z_{\mathrm{L}}} = \cos\frac{\theta}{2}\hat{I} - i\sin\frac{\theta}{2}Z_{\mathrm{L}}$$

GKP Logical Pauli rotation measurement via exponentiation circuit

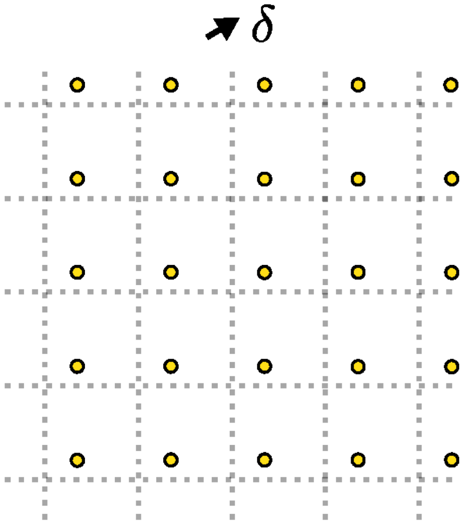


$$(Z_{\mathrm{L}})^2 = S_p = 1$$
$$Z_{\mathrm{L}}^\dagger (Z_{\mathrm{L}})^2 = Z_{\mathrm{L}}$$
$$Z_{\mathrm{L}}^\dagger = Z_{\mathrm{L}}$$



Small-Big-Small (SBS) protocol (autonomous and tuned for finite-energy approximate GKP states)

Small displacement error: $|\psi_\delta\rangle = D(\delta)\,|\psi\rangle$ Still a grid state!

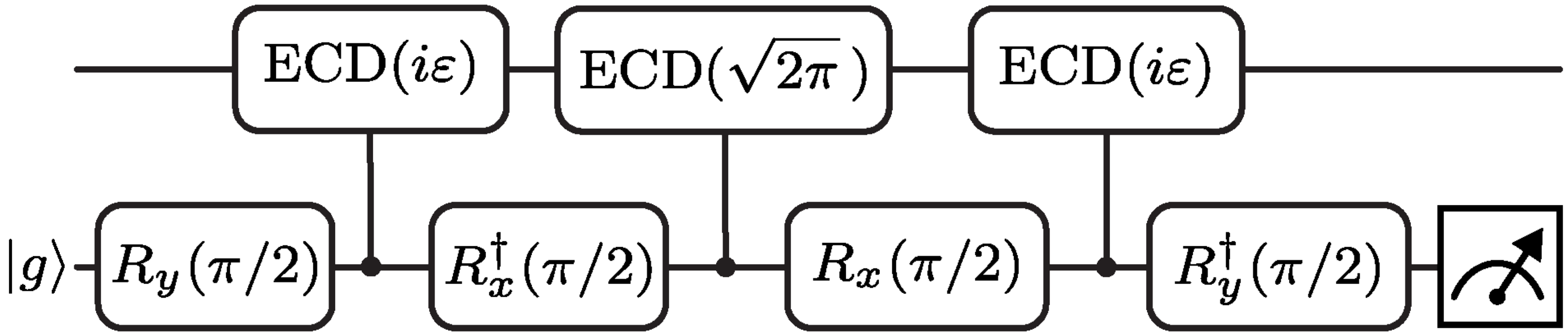


$$S_Z\,|\psi_\delta\rangle = e^{+2i\sqrt{2\pi}\mathrm{Re}[\delta]}|\psi_\delta\rangle$$
$$S_X\,|\psi_\delta\rangle = e^{-2i\sqrt{2\pi}\mathrm{Im}[\delta]}|\psi_\delta\rangle$$

Stabilizer phase estimation

Envelope pre-distortion

Displacement error correction



Ancilla reset

B. Royer *et al.,* (PRL, 2020); B. de Neeve *et al.,* (Nature Physics (2022);
B. Terhal *et al.,* (PRA, 2016); P. Campagne-Ibarcq *et al.,* (Nature, 2020).

courtesy V. Sivak

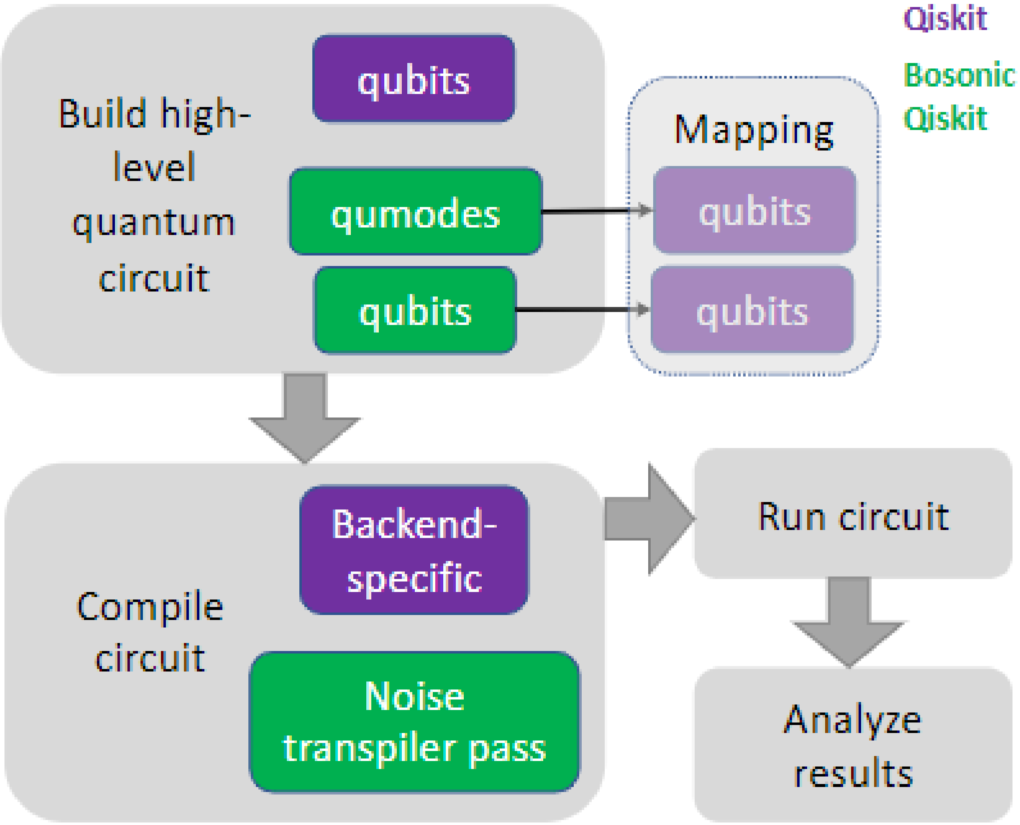
Bosonic Qiskit

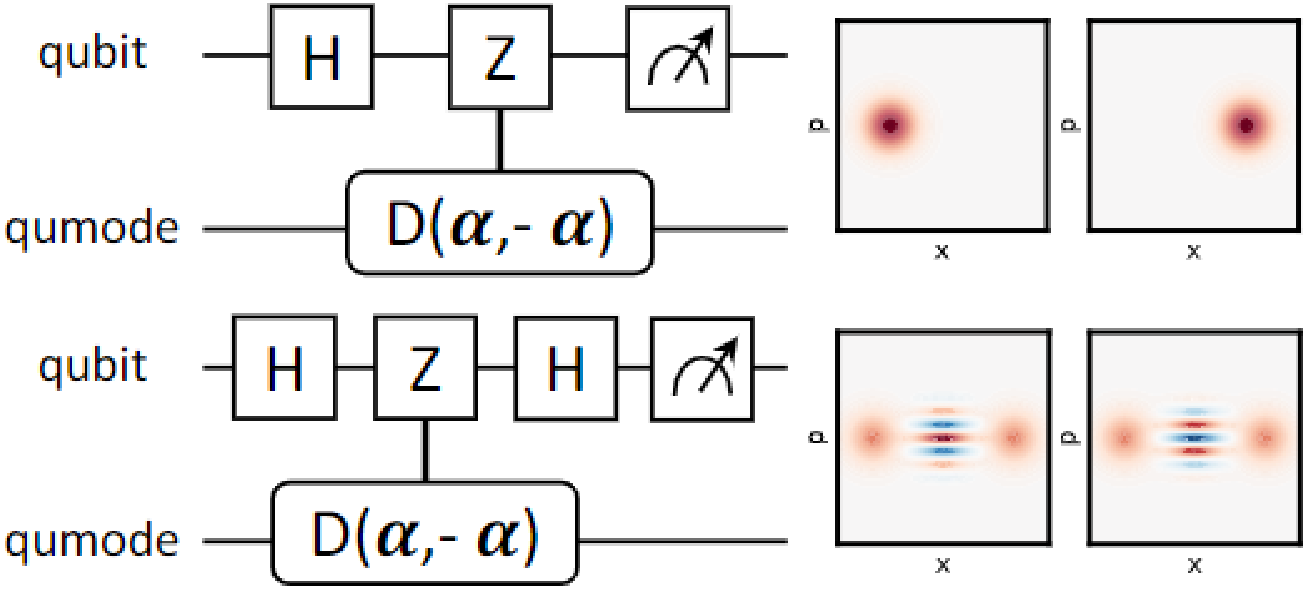
Qiskit SDK extension co-design tool to simulate hybrid hardware containing both qubits and bosonic modes

Details

- **Open-Source code available at: https://github.com/C2QA/bosonic-qiskit**
- **Includes tutorials, example use cases and visualization tools**
- **Experimentally realized gate sets and measurement protocols have been implemented**

Reference https://arxiv.org/abs/2209.11153





C²QA Co-design Center for Quantum Advantage