

Correlated Error Bursts and QEC

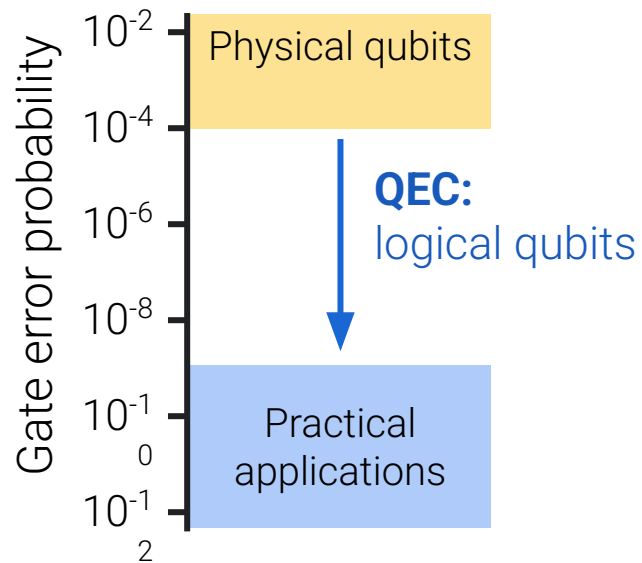
Gabrielle Roberts

Vlad Kurilovich, Alex Opremcak, Matt McEwen, Kevin Miao,
John Mark Kreikebaum, Kevin Satzinger, and many others

Quantum error correction: a bridge to practical applications

Hardware goal

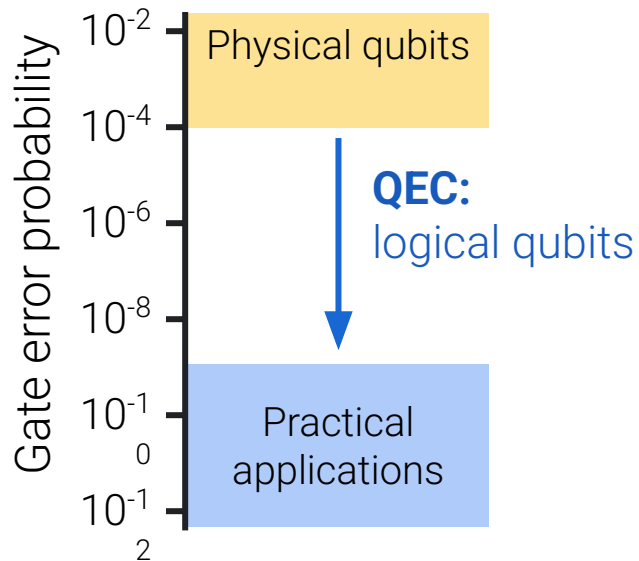
Build qubits with
gate error $\sim 10^{-10}$



Quantum error correction: a bridge to practical applications

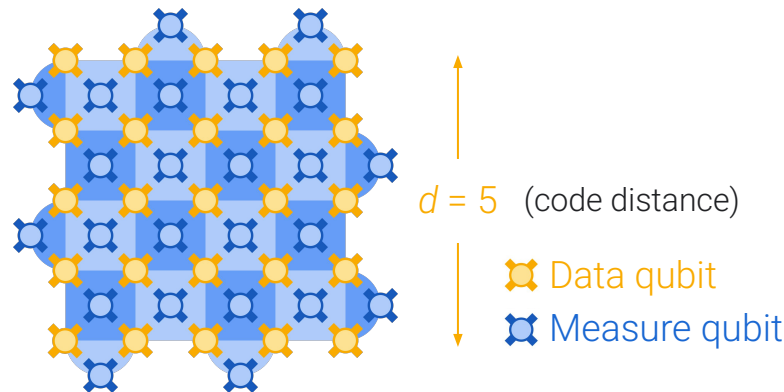
Hardware goal

Build qubits with gate error $\sim 10^{-10}$



Surface code logical qubit

Distribute quantum state over d^2 physical qubits



With sufficient **performance**,
increase d to **exponentially suppress** errors
(in theory)

Exponential Suppression of Errors

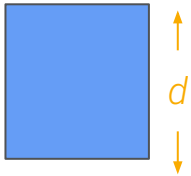
Trade many good physical qubits for one excellent logical qubit

Threshold:

Suppress errors with scale
when hardware is *good enough*

Empirical formula:

$$\text{Logical error per cycle } \epsilon_d = C \cdot \left(\frac{\text{Physical error rate}}{\text{Threshold error rate}} \right)^{(distance+1)/2}$$



Exponential Suppression of Errors

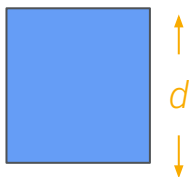
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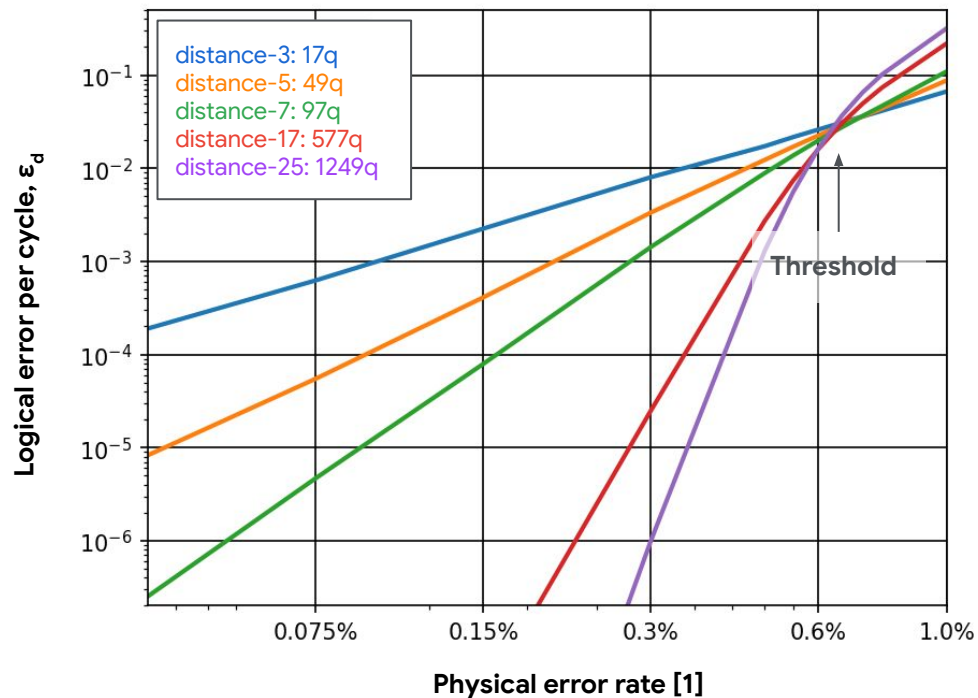
Suppress errors with scale
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Empirical formula:

$$\text{Logical error per cycle } \epsilon_d = C \cdot \left(\frac{p}{p_{th}} \right)^{(d+1)/2}$$



\uparrow
 $1/\Lambda$



Exponential Suppression of Errors

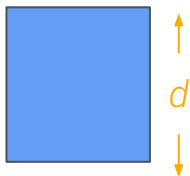
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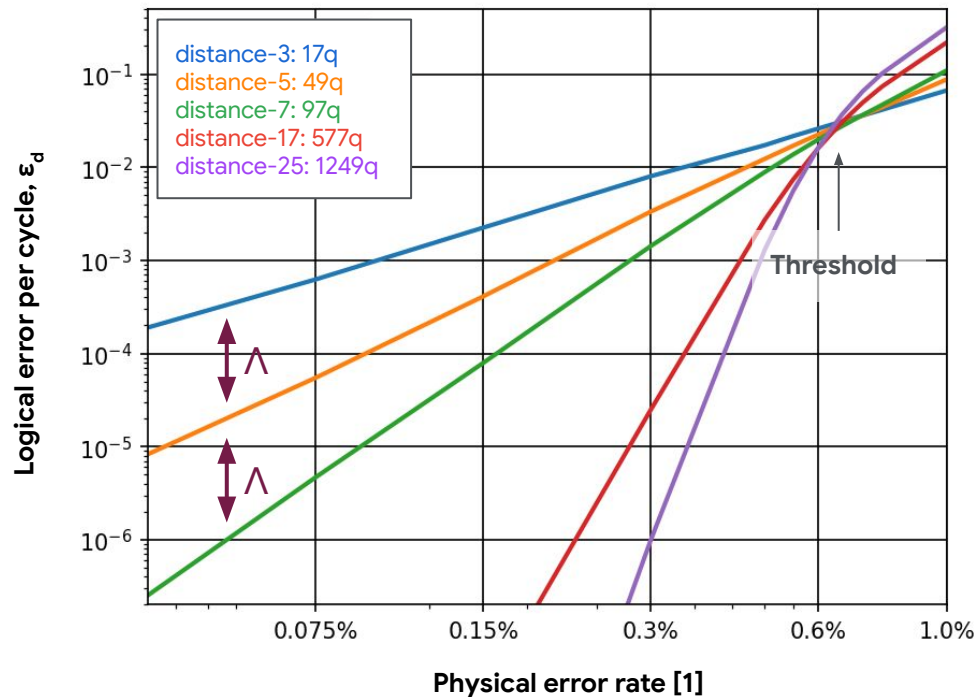
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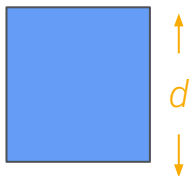
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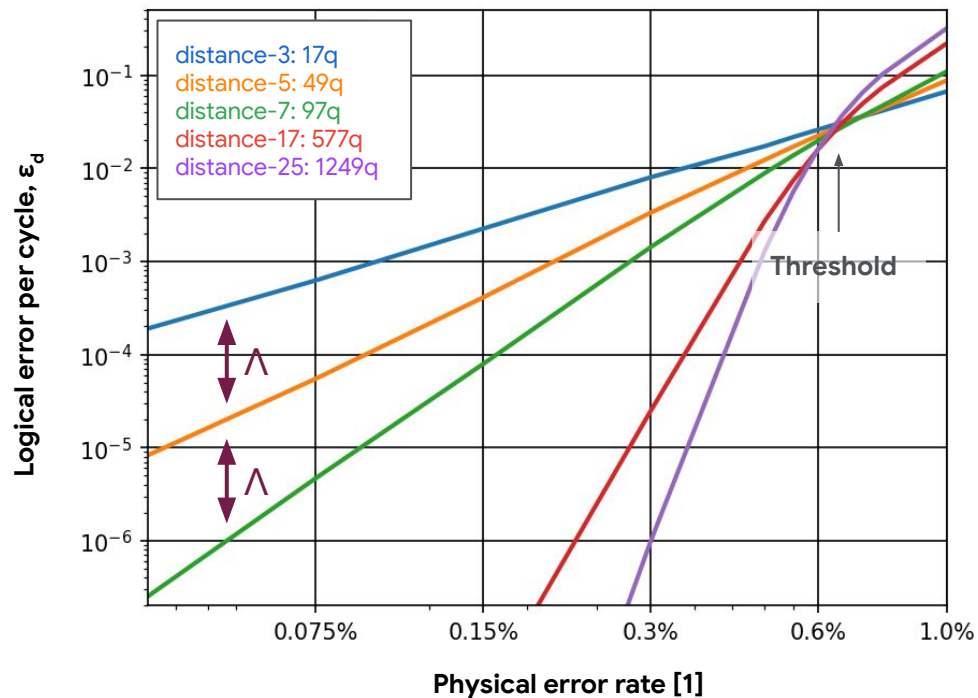
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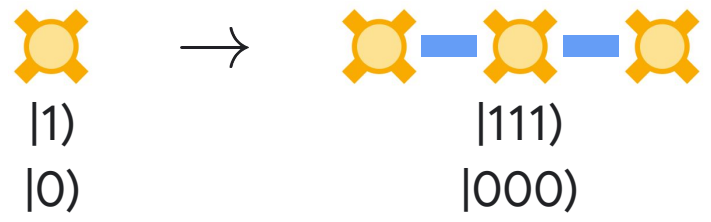


\uparrow
 $1/\Lambda$



**QEC: a path to extremely low error rates,
if hardware is good enough and errors are local**

Repetition Code



Repetition Code

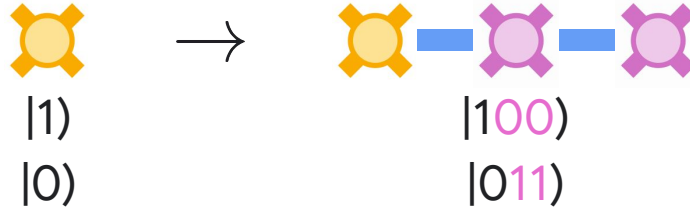


Repetition Code



If only **one** error occurred, majority vote is guaranteed to succeed

Repetition Code



If only **one** error occurred, majority vote is guaranteed to succeed
Does **not** protect from two errors

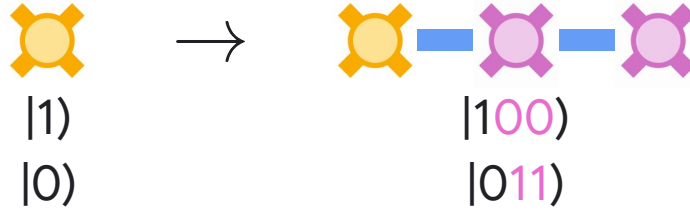
Repetition Code



If only **one** error occurred, majority vote is guaranteed to succeed
Does **not** protect from two errors



Repetition Code



If only **one** error occurred, majority vote is guaranteed to succeed
Does **not** protect from two errors



Repetition Code



If  \rightarrow  with probability p ,

then a logical error occurs with a probability $p_L \propto p^{(d+1)/2}$

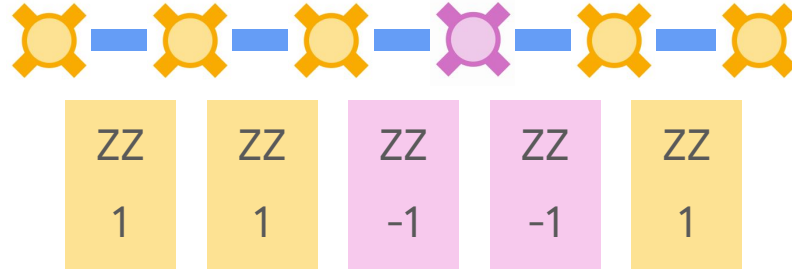
Quantum Repetition Code

$$|\psi\rangle_L = \alpha|000000\rangle + \beta|111111\rangle$$



Quantum Repetition Code

$$|\psi\rangle_L = \alpha|000000\rangle + \beta|111111\rangle$$



Detail: instead of measuring data qubits directly (collapses the state), we instead do pair-wise parity measurements to locally detect an error.

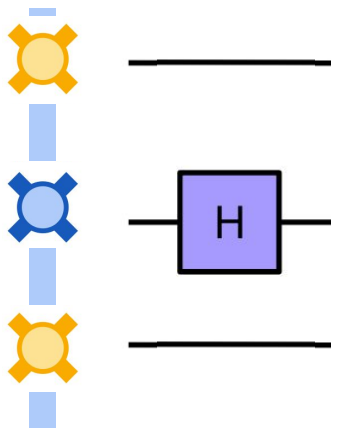
Syndrome Extraction



$|0\rangle$



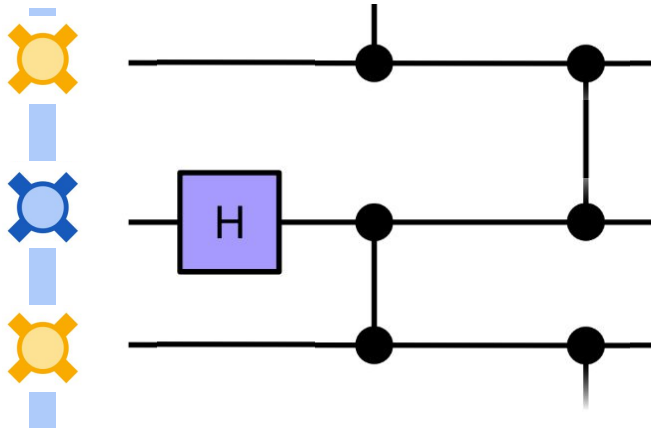
Syndrome Extraction



$|0\rangle$

$|0\rangle+|1\rangle$

Syndrome Extraction



$|0\rangle$

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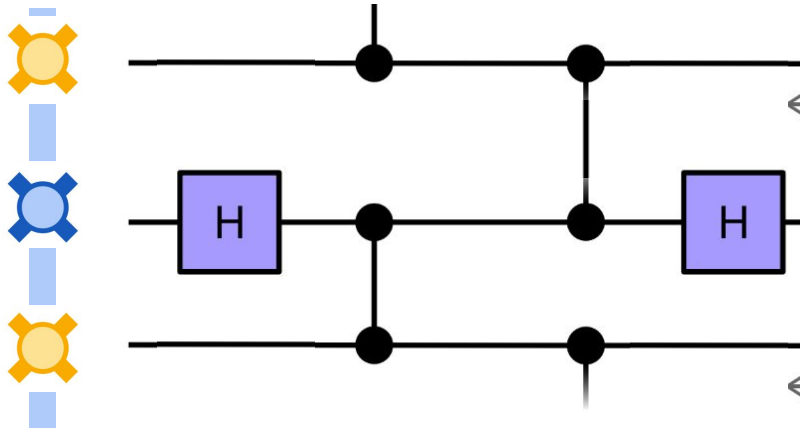
$|0\rangle+|1\rangle*(Z_1)(Z_2)$

Even parity: $|0\rangle+|1\rangle \rightarrow |+\rangle$

Odd parity: $|0\rangle-|1\rangle \rightarrow |-\rangle$



Syndrome Extraction



$|0\rangle$

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Even parity: $|0\rangle+|1\rangle \rightarrow |+\rangle$

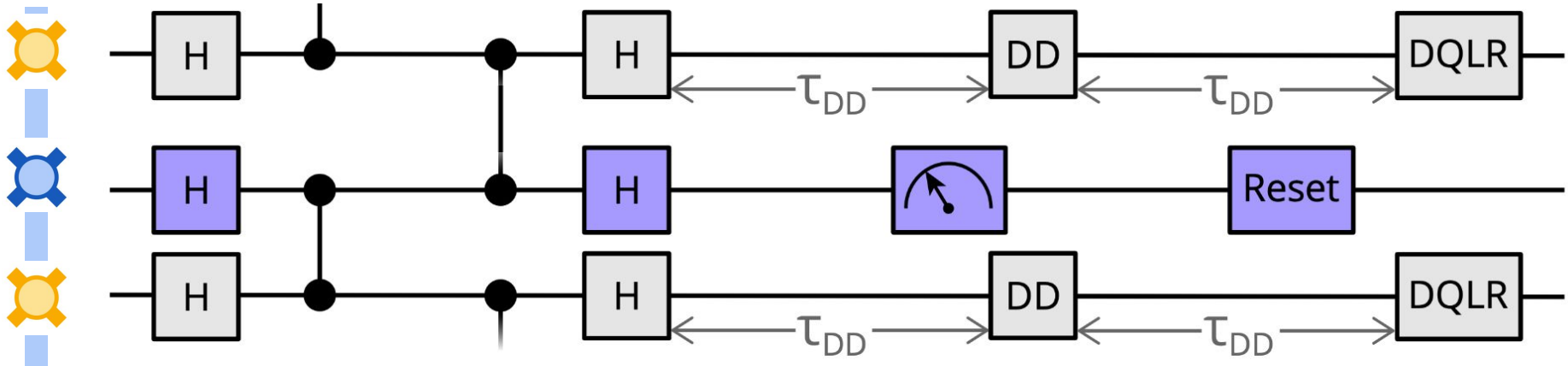
$|0\rangle$

Odd parity: $|0\rangle-|1\rangle \rightarrow |-\rangle$

$|1\rangle$



Syndrome Extraction



$|0\rangle$

$|0\rangle+|1\rangle$

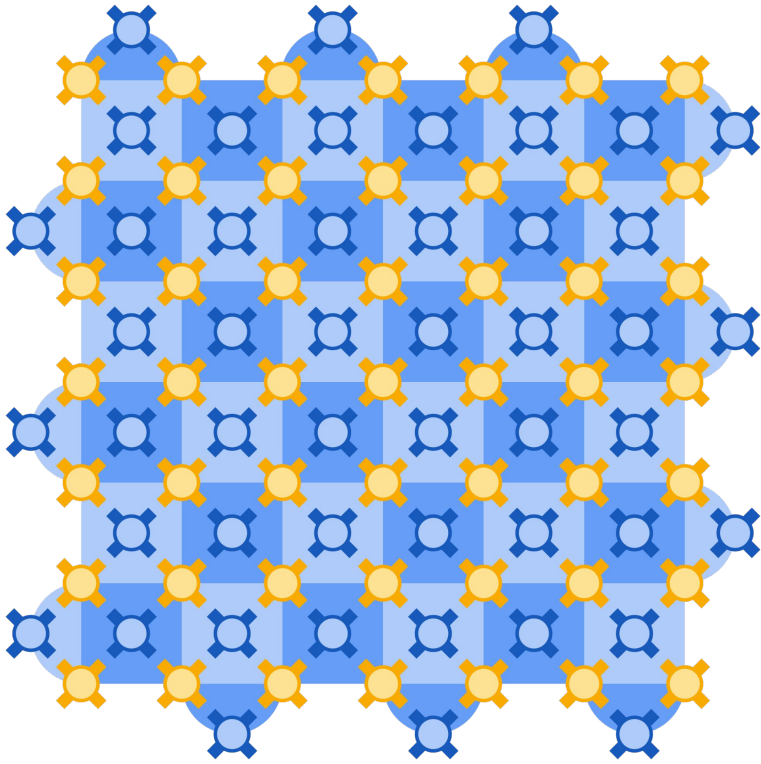
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Even parity: $|0\rangle+|1\rangle \rightarrow |+\rangle$ $|0\rangle$

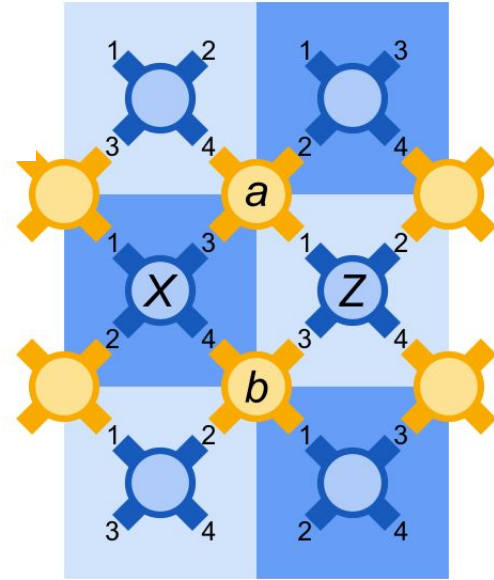
Odd parity: $|0\rangle-|1\rangle \rightarrow |-\rangle$ $|1\rangle$



Surface Code Logical Qubit

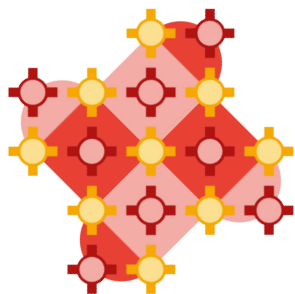


2D logical qubit protects against bit AND
phase: product of repetition codes

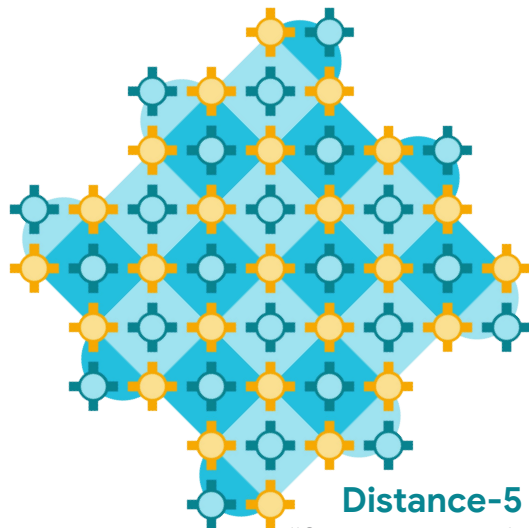


Quantum error correction

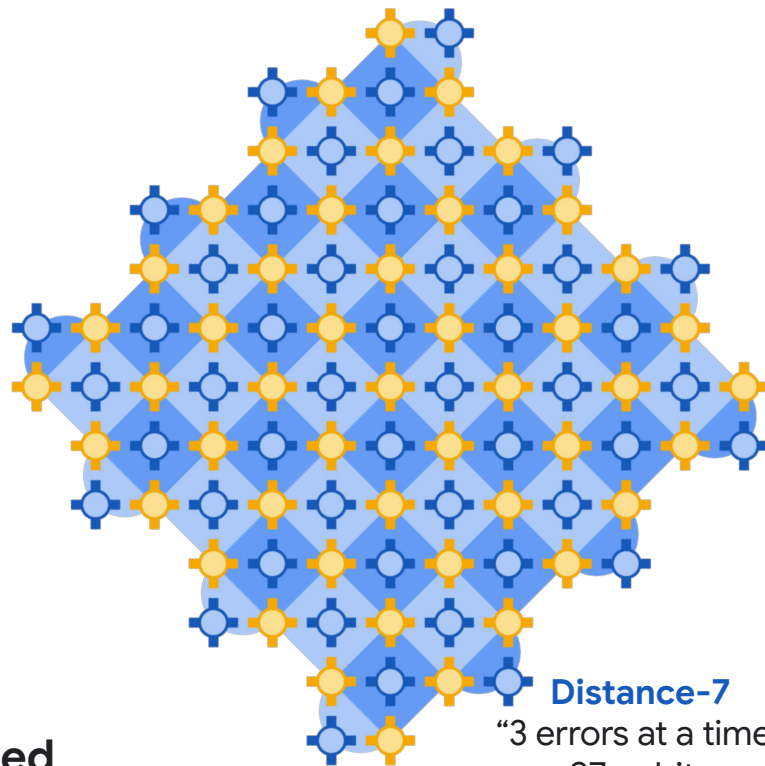
Good **logical** qubit from faulty **physical** qubits



Distance-3
"1 error at a time"
17 qubits



Distance-5
"2 errors at a time"
49 qubits

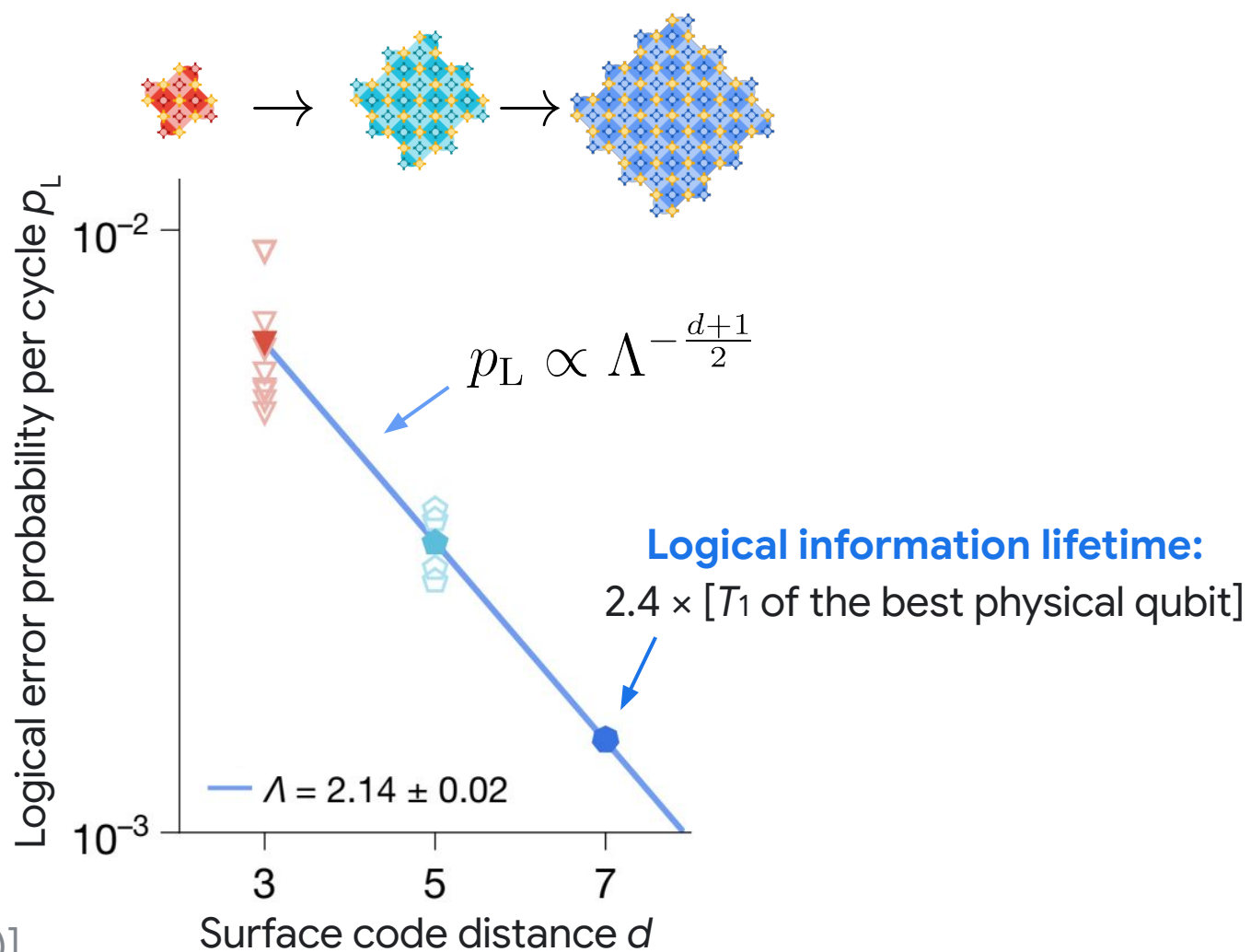


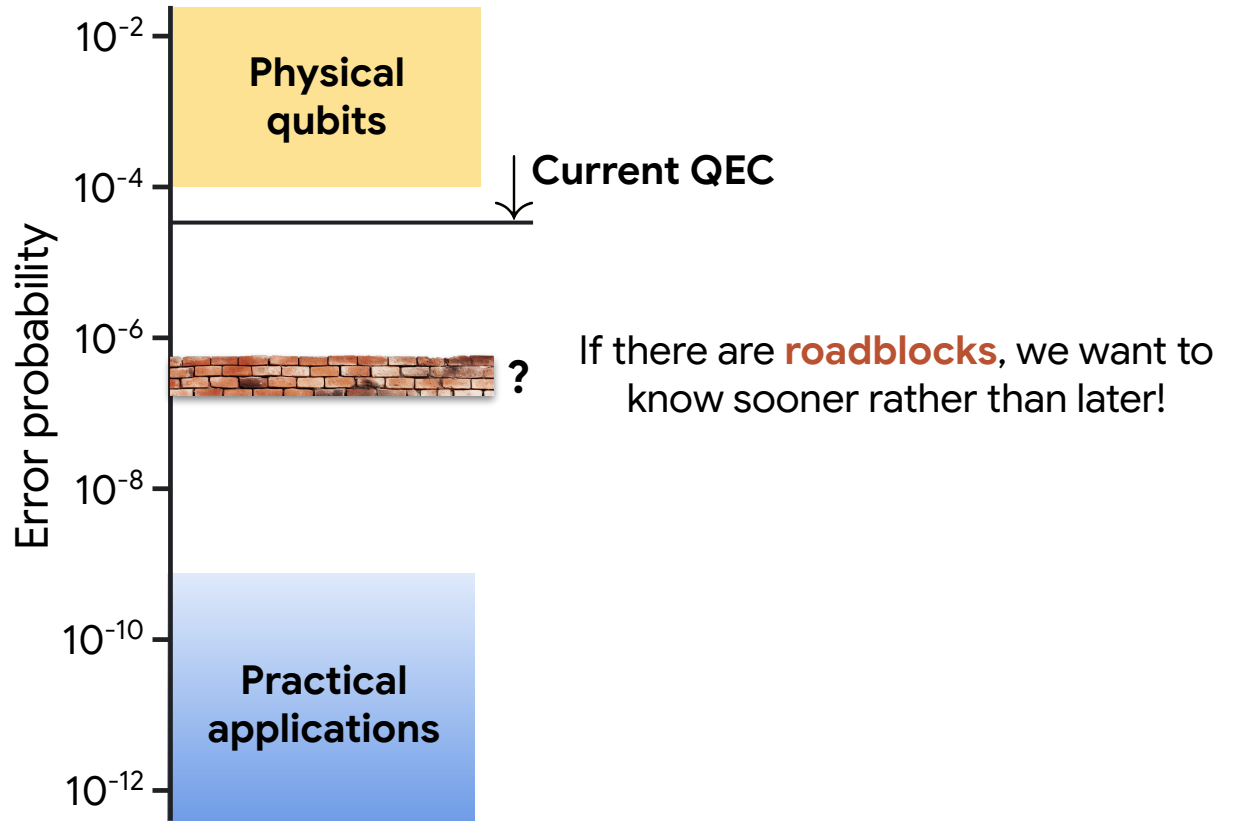
Distance-7
"3 errors at a time"
97 qubits

Logical error rate:

$$p_L \propto \Lambda^{-\frac{d+1}{2}}$$

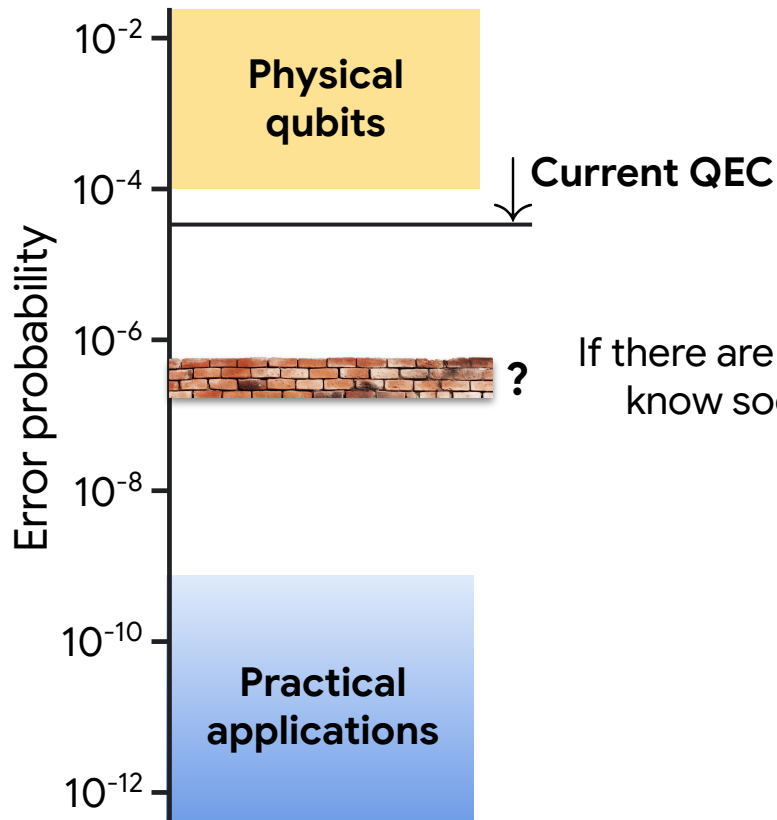
...provided errors are **rare** and **uncorrelated**





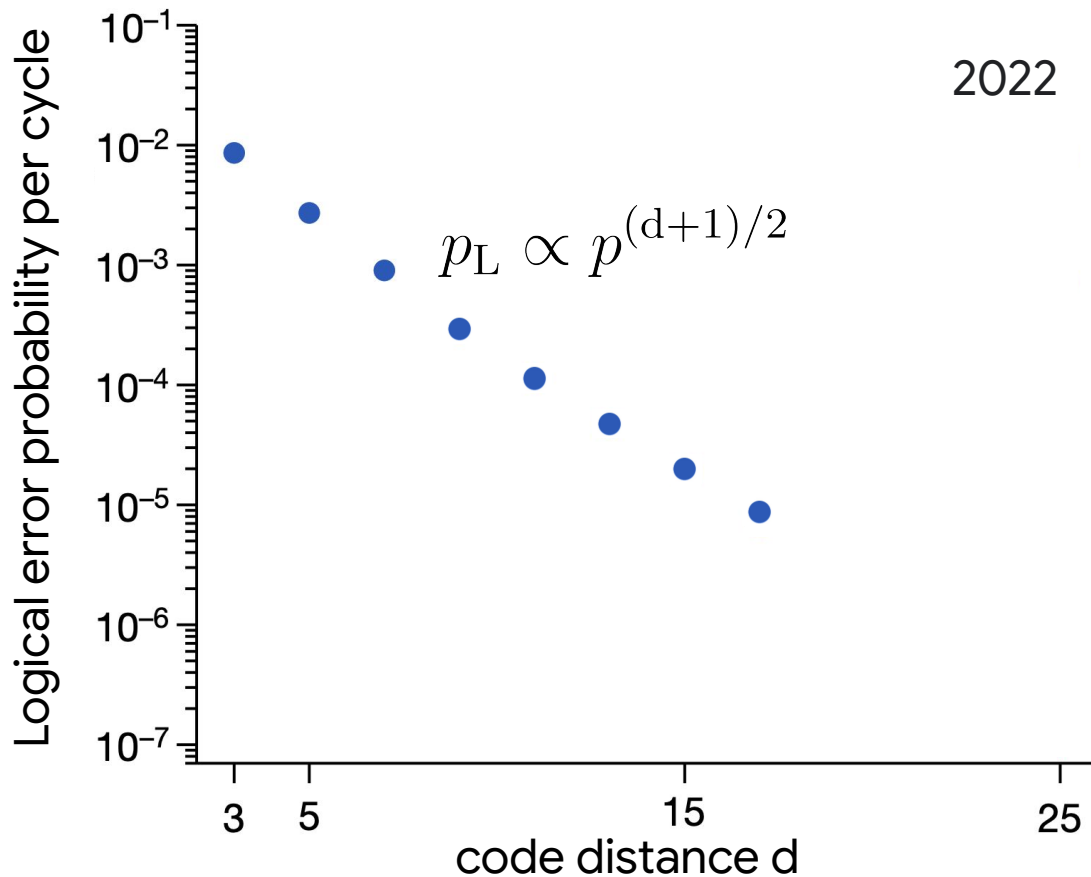
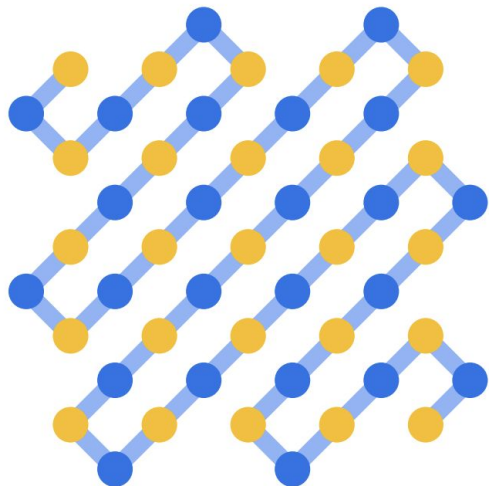
Another nice fact about the quantum repetition code: it's 1D, so you can get to much longer distances with far fewer qubits:

Use it to probe the super-low logical error regime!



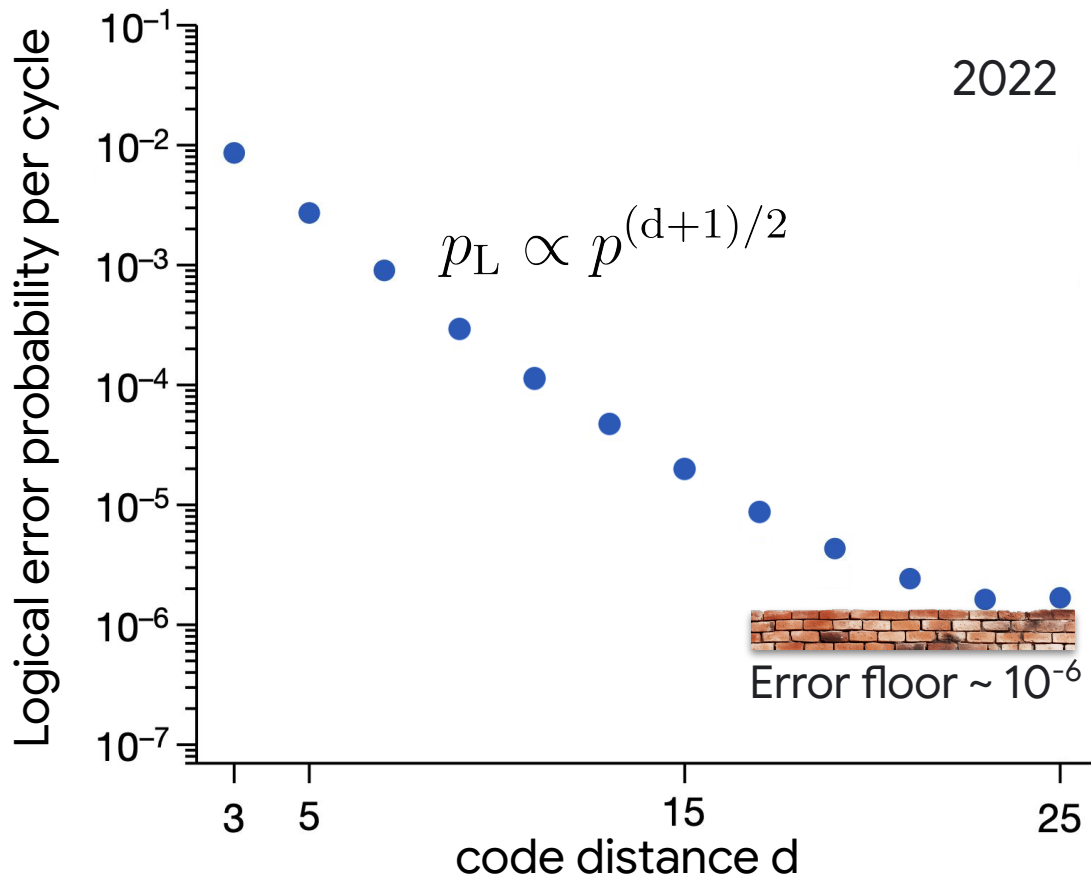
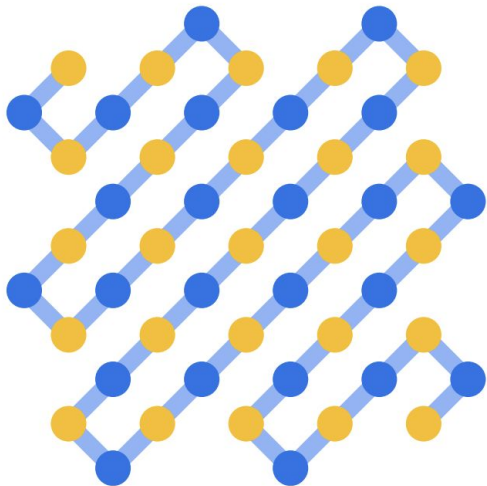
If there are **roadblocks**, we want to know sooner rather than later!

How does this prediction work in practice?

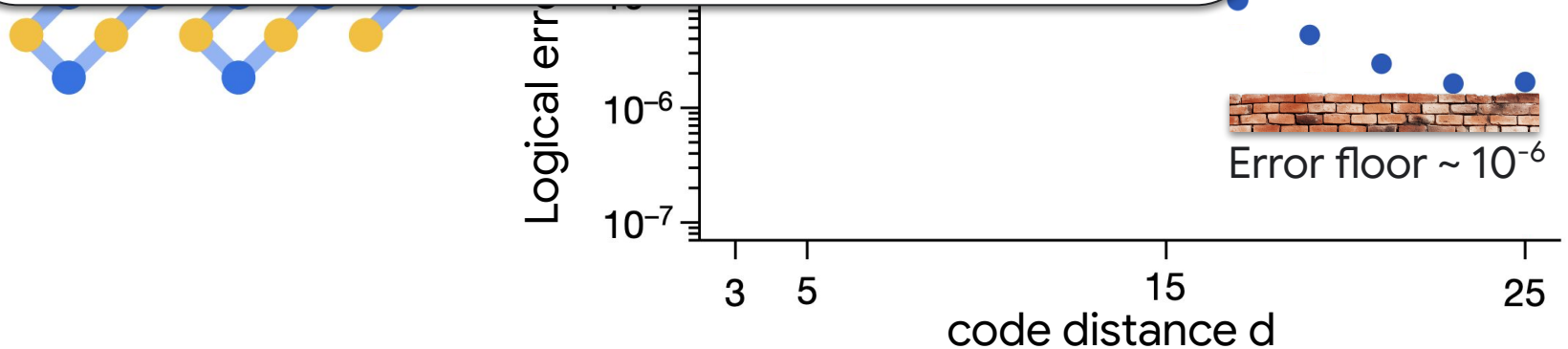
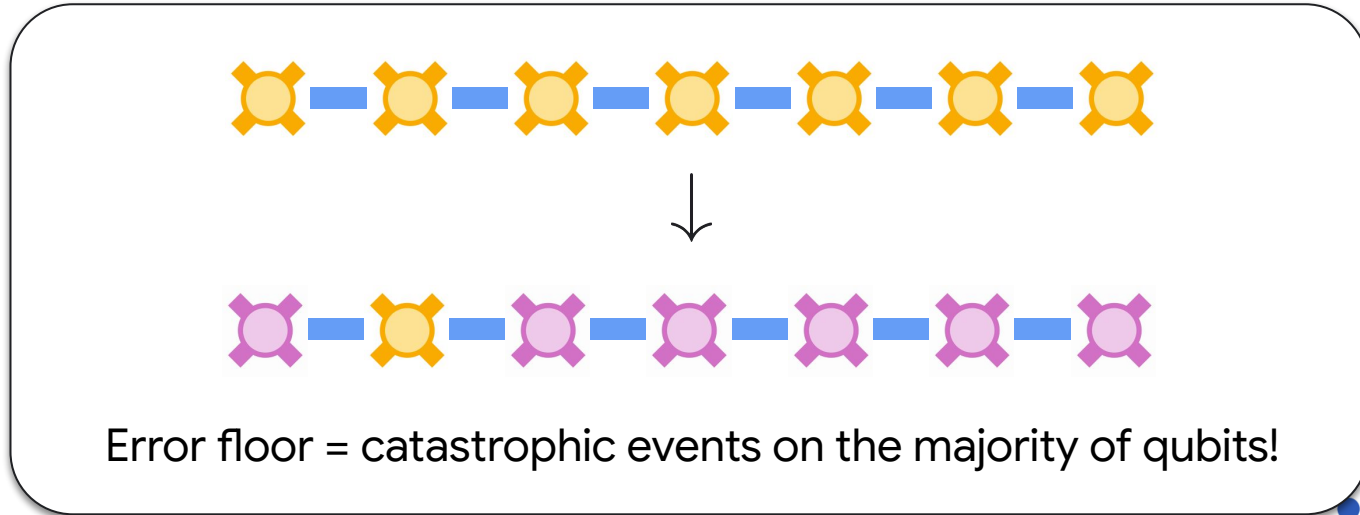


2022

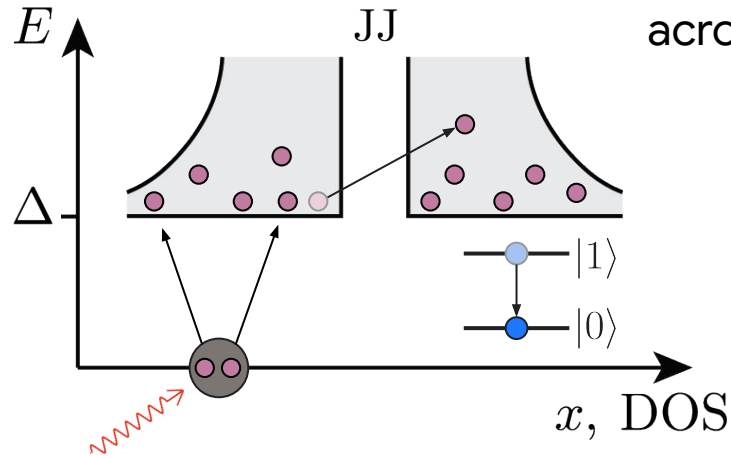
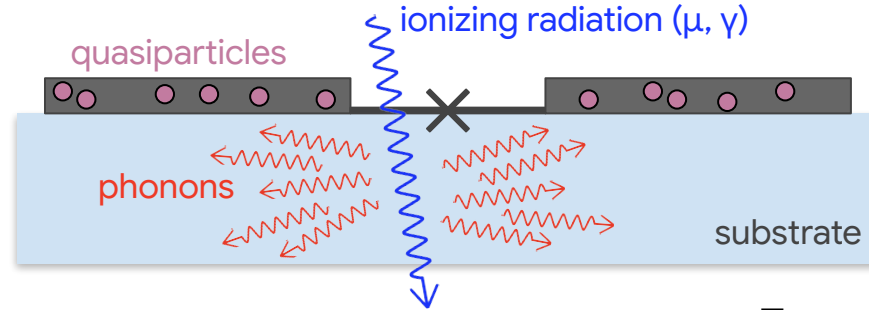
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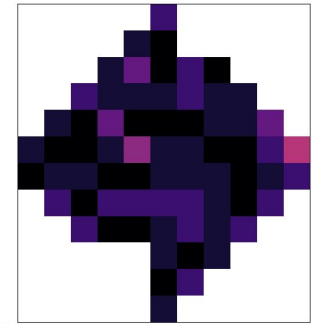


Origin of bursts: impacts of radioactive particles



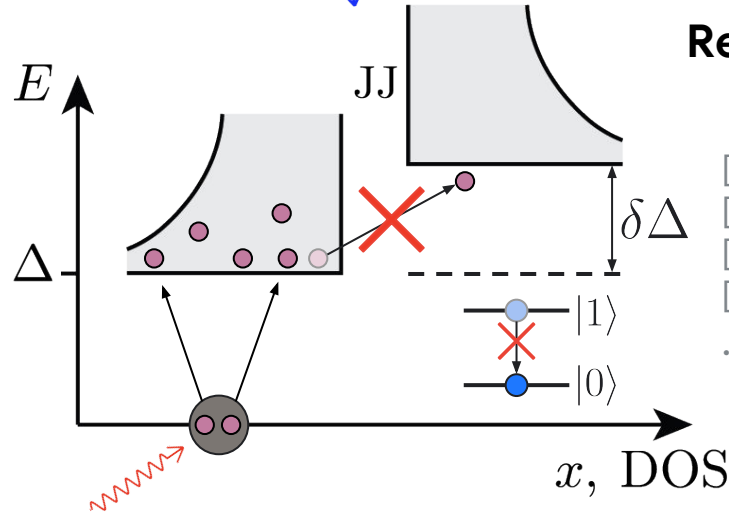
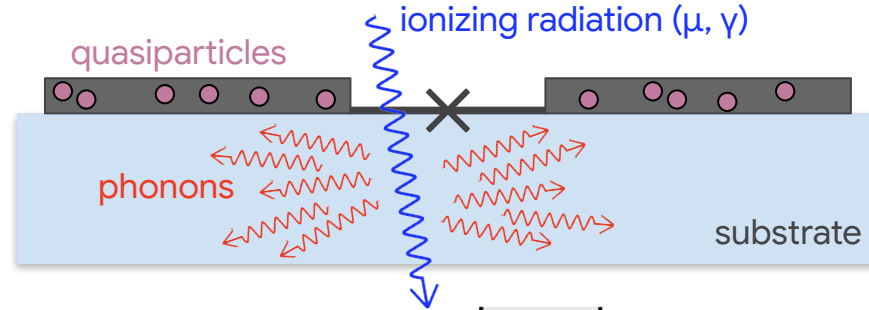
Tunneling of quasiparticles
across the Josephson junction

→ T_1 errors



[C.D. Wilen et al (2021)]
[M. McEwen et al (2022)]
[P.M. Harrington et al (2024)]
...and many others

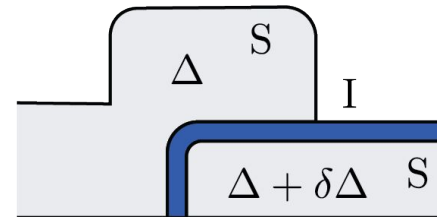
Origin of bursts: impacts of radioactive particles



Remedy: potential barrier
for quasiparticles

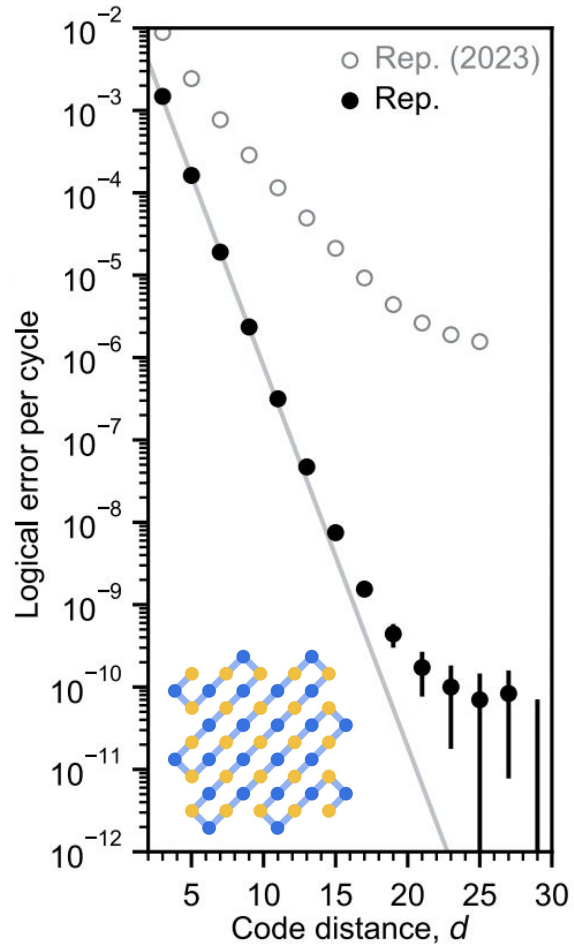
- [T. Connolly, P. Kurilovich et al (2024)]
- [S. Diamond et al (2022)]
- [P. Kamenov et al (2023)]
- [H. Nho, et al (2025)]

...



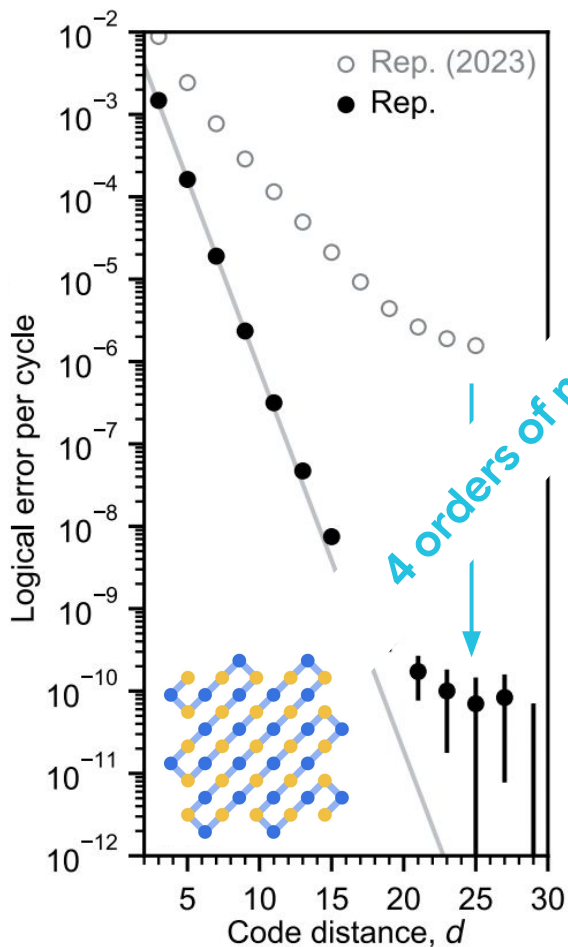
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Correlated error bursts in a gap engineered qubit array



[Nature **638**, 920 (2025)]

Correlated error bursts in a gap engineered qubit array

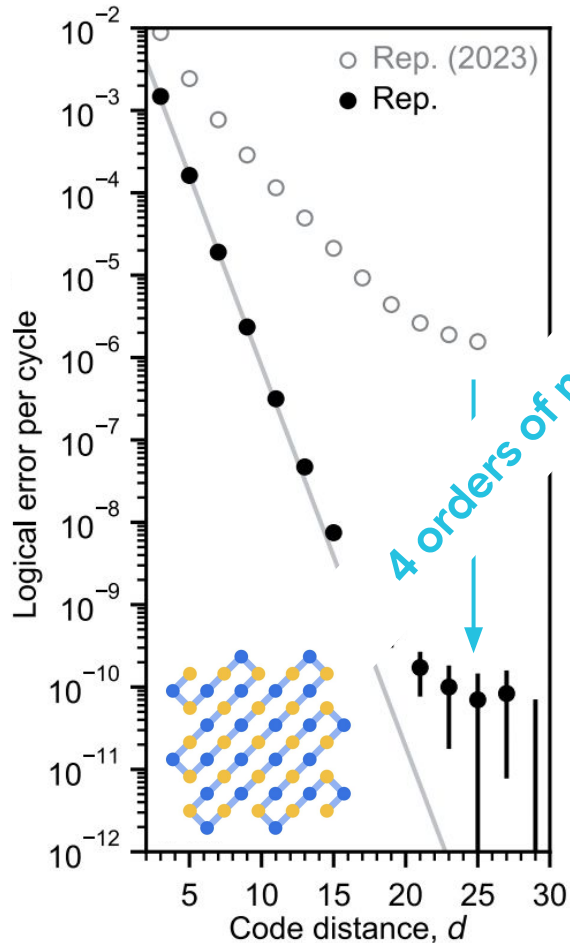


Good news: error floor $\sim 10^{-10}$

~ 1 logical error / hour

[Nature **638**, 920 (2025)]

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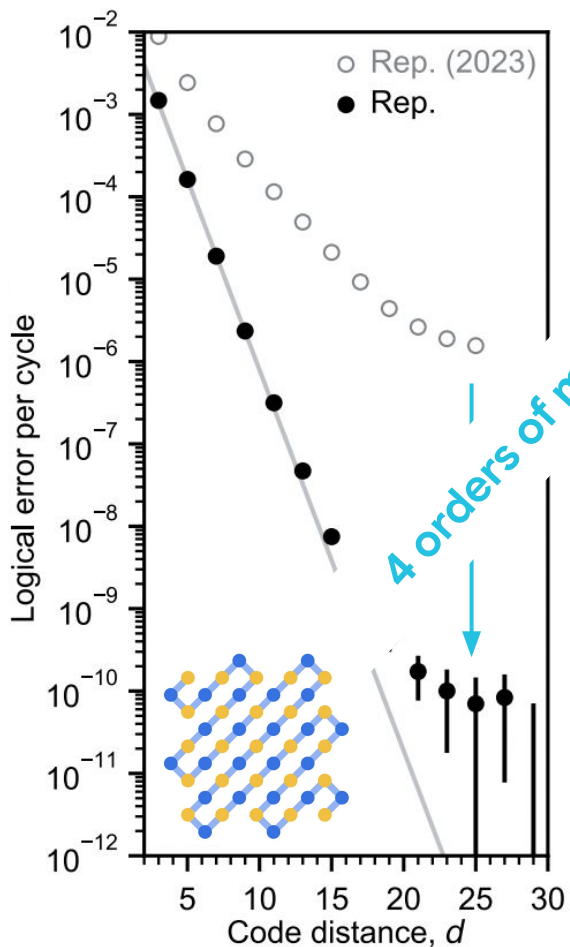
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Bad news: the floor is still there!

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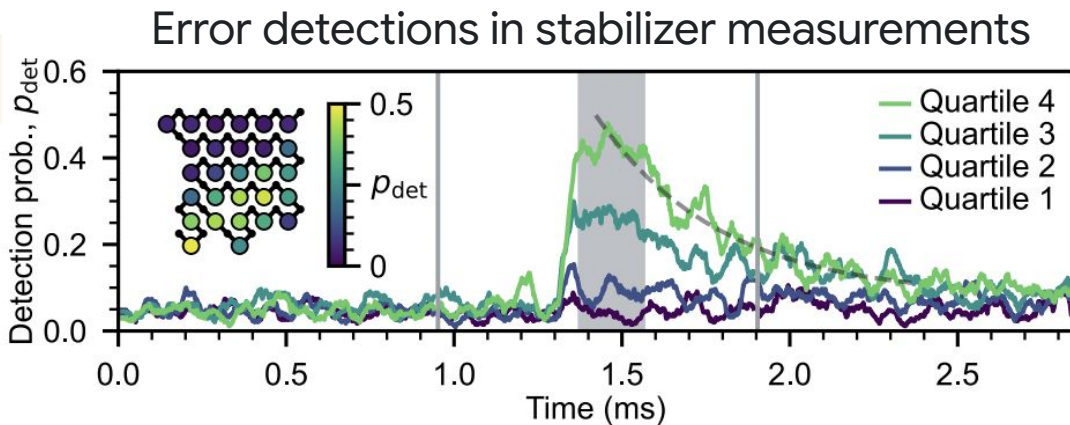
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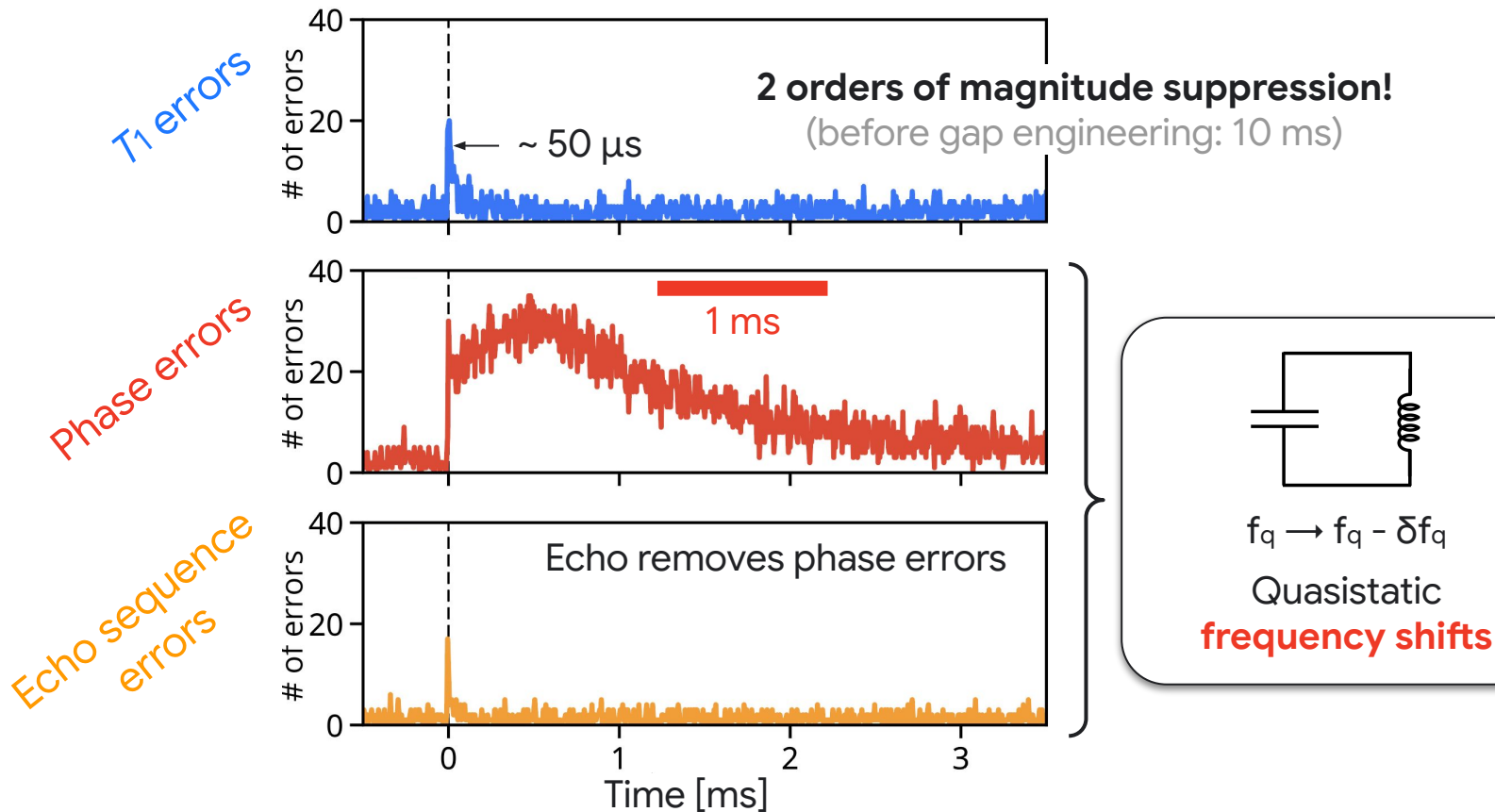
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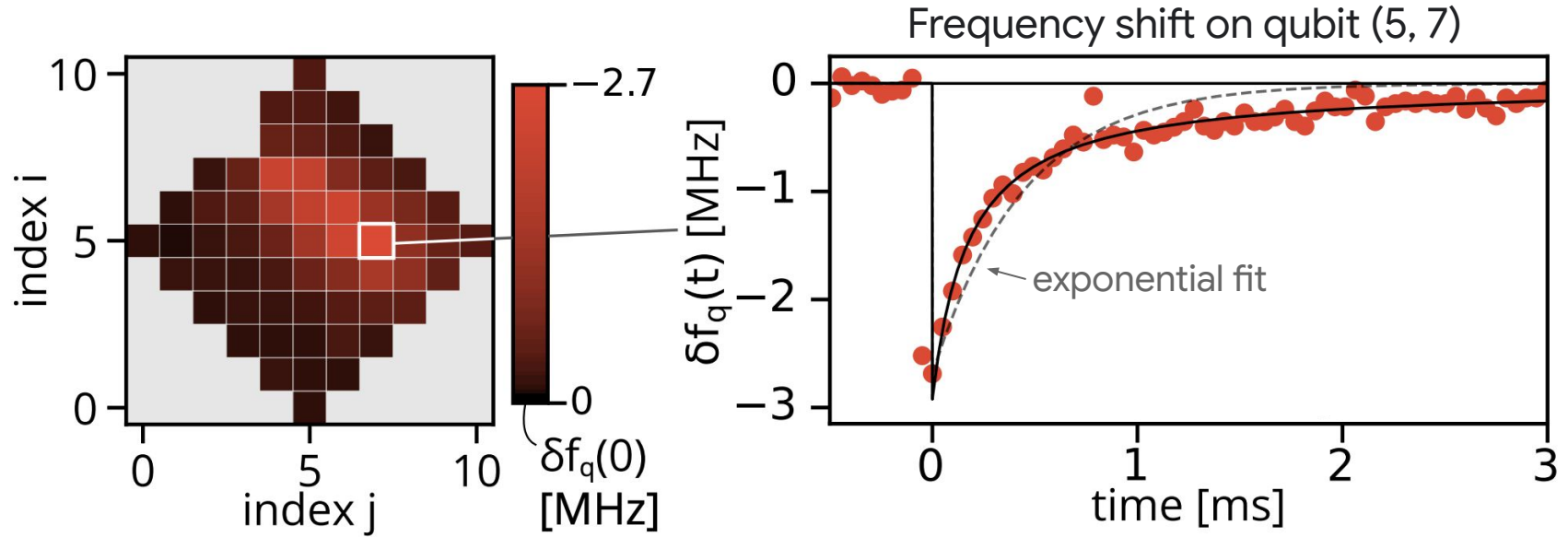
[Nature 638, 920 (2025)]

High repetition rate array-wide error checks

On every qubit on the grid, cycle the error check sequence:



Time-resolved frequency shift measurements (tomography)



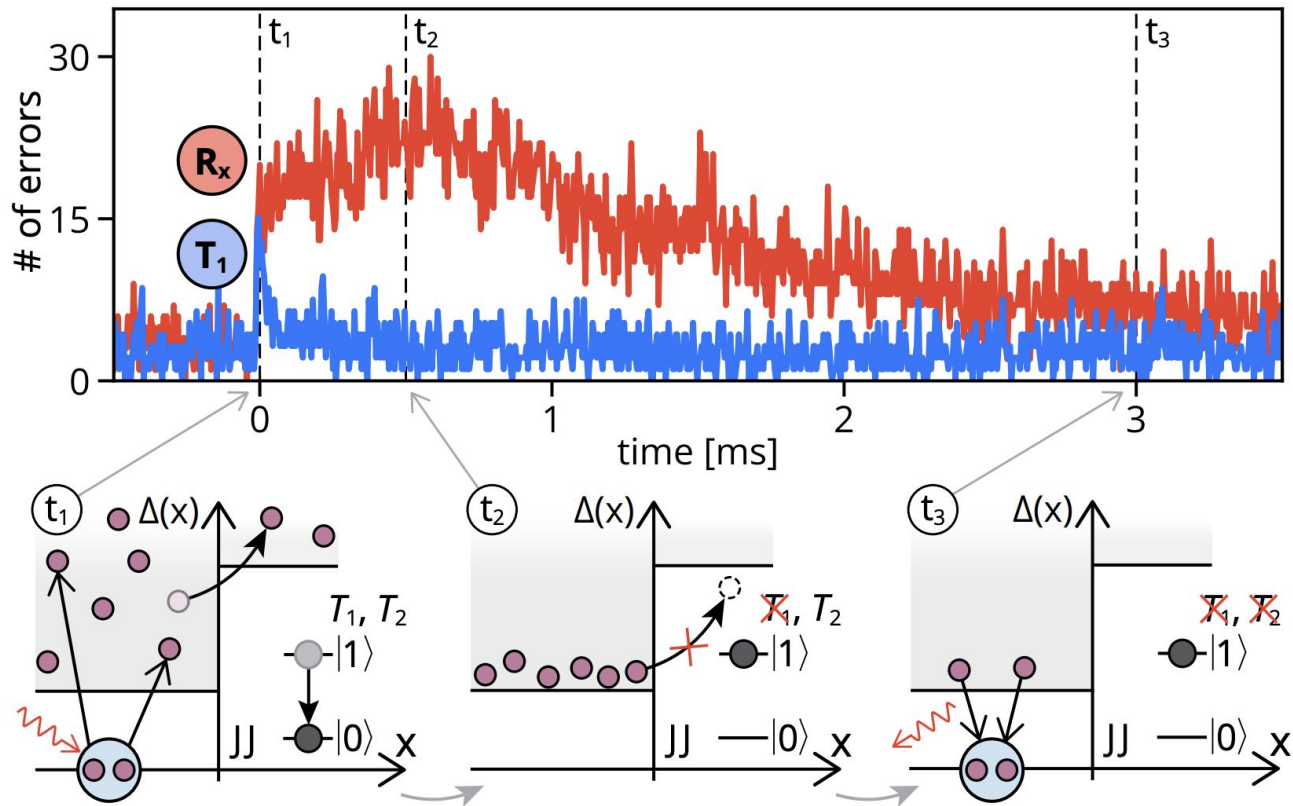
Main features:

- (i) Always negative, ~ 1 MHz
- (ii) Non-exponential recovery, takes ~ 1 ms

Physical picture

$$E_J \rightarrow E_J - \delta E_J$$

$$f_q \rightarrow f_q - \delta f_q$$



Bursts in gap engineered devices:

Transient T_1 errors ($\sim 50 \mu\text{s}$) and negative, long lasting ($\sim 1 \text{ ms}$) frequency shifts

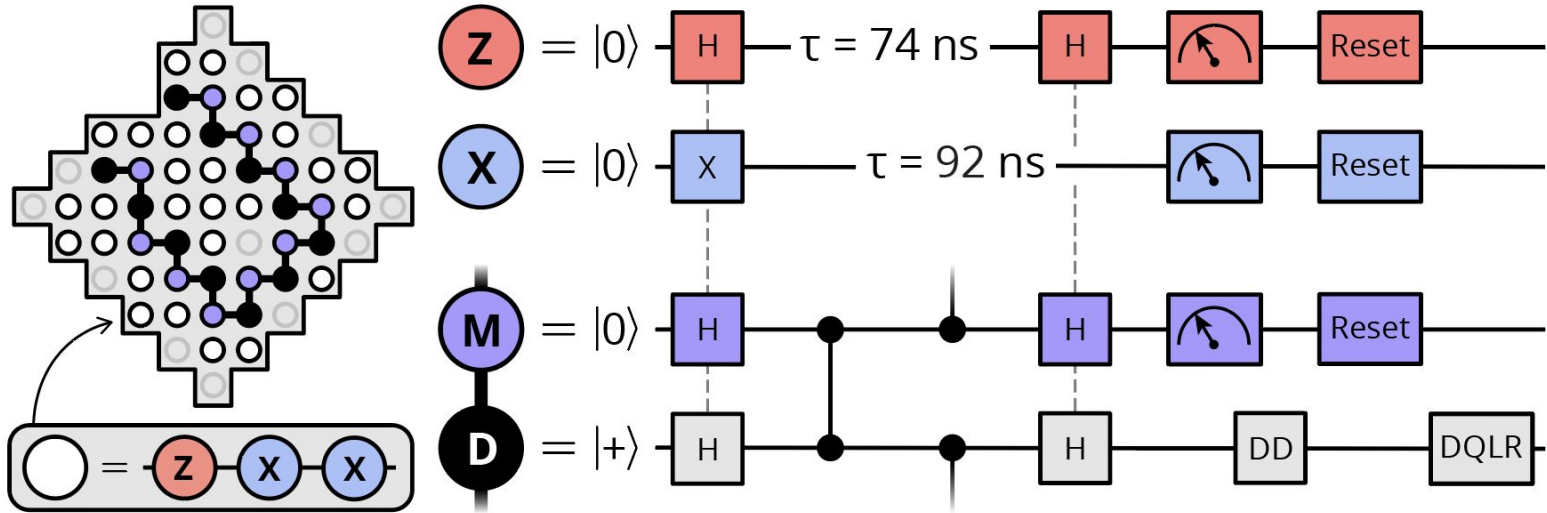
“Hot” QPs

“Cold” QPs

Correlating phase errors with QEC error detections

Repetition code on one part of the array

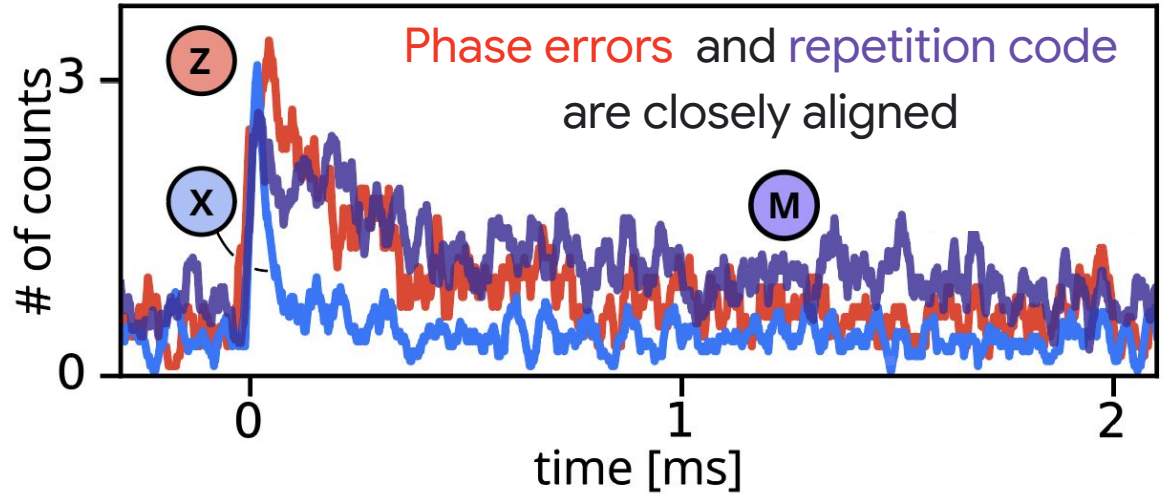
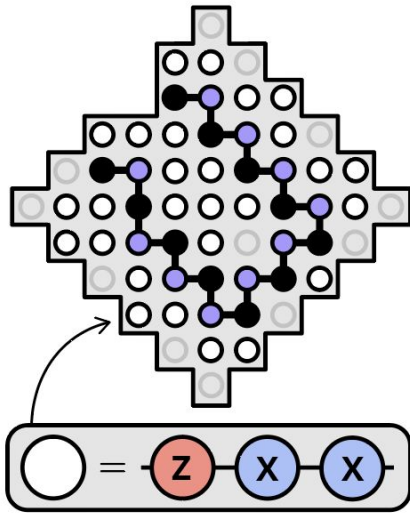
Phase and T_1 error checks on the complementary part



Correlating phase errors with QEC error detections

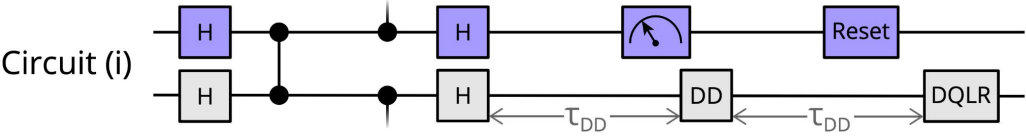
Repetition code on one part of the array

Phase and T_1 error checks on the complementary part



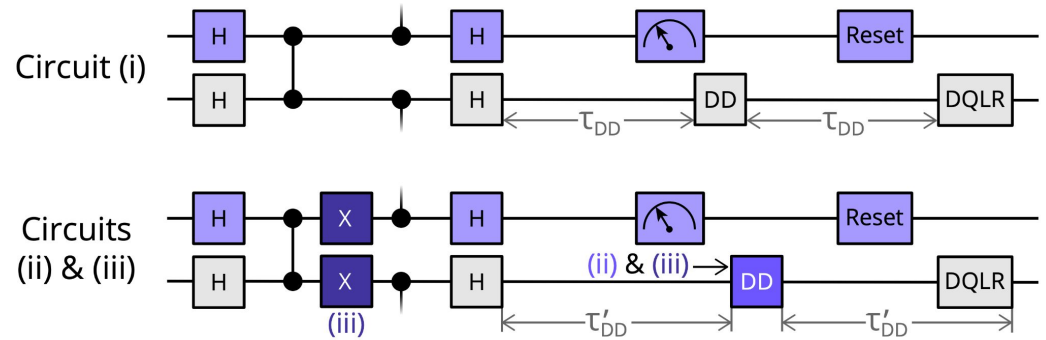
[see arXiv:2506.18228 for details]

Correlating phase errors with QEC error detections



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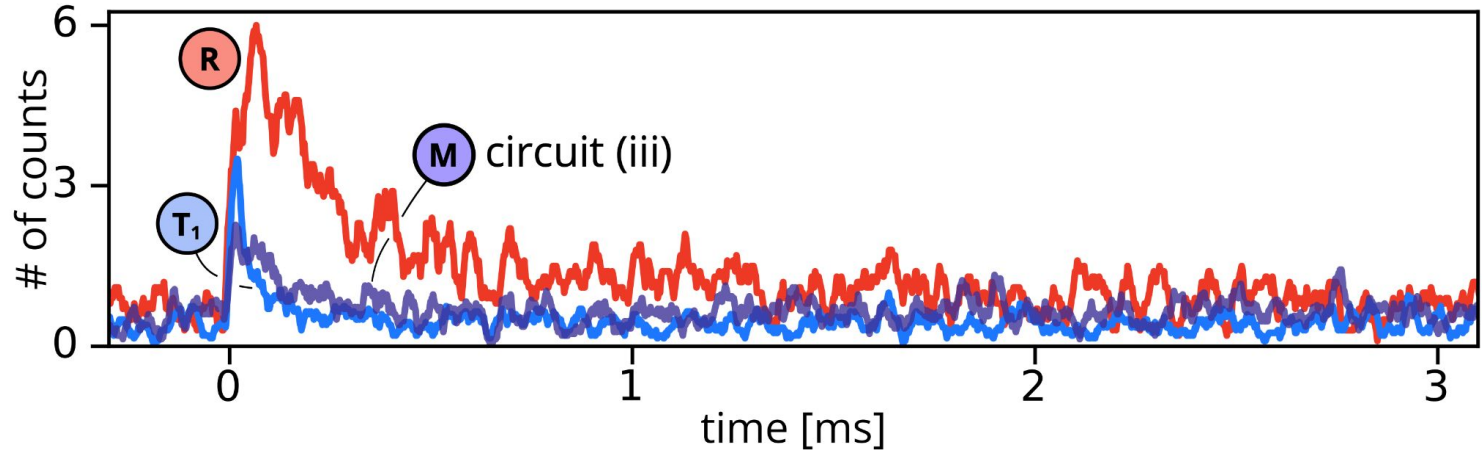
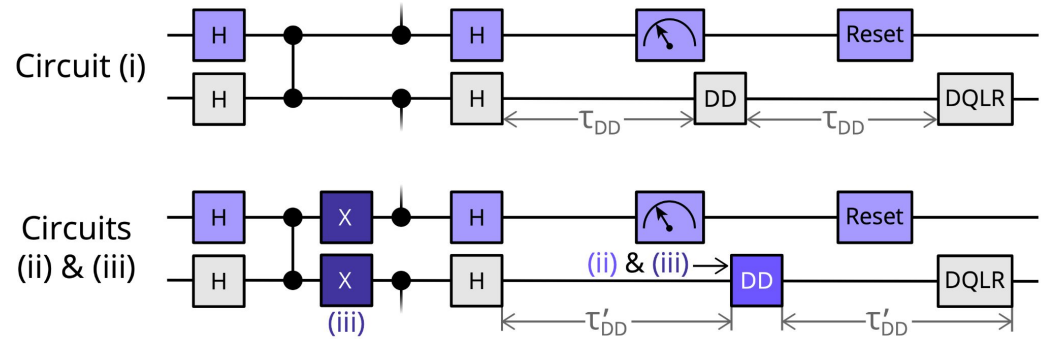
Correlating phase errors with QEC error detections - add echos?



[see arXiv:2506.18228 for details]

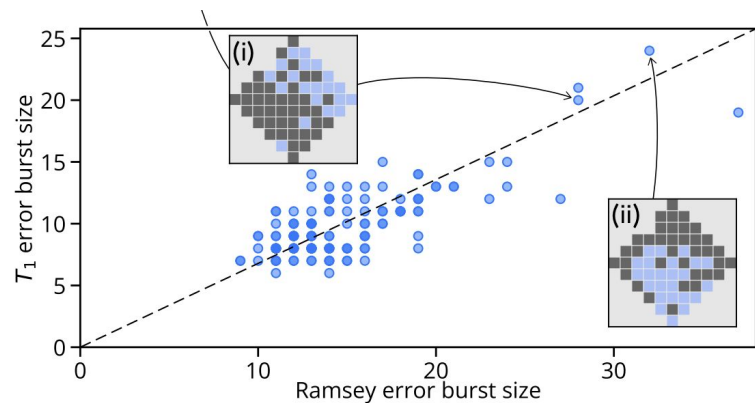
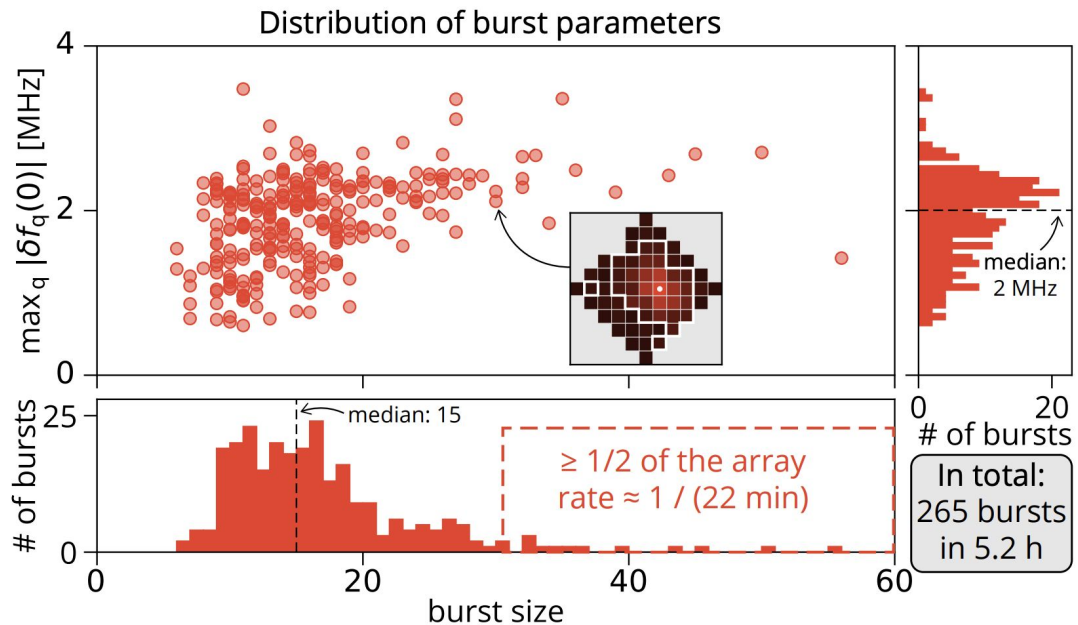
Correlating phase errors with QEC error detections - add echos?

Adding an **echo** (and **centering DD**) collapses the QEC error detection onto the **T_1 error** burst

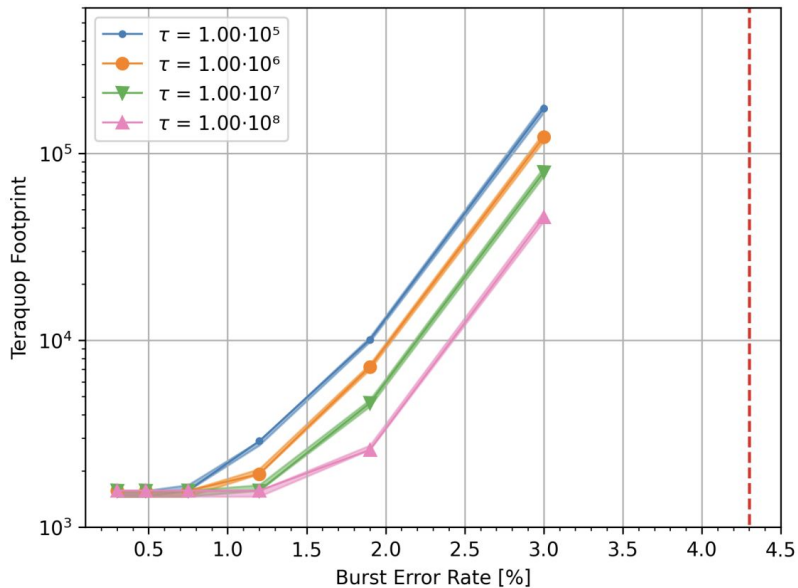
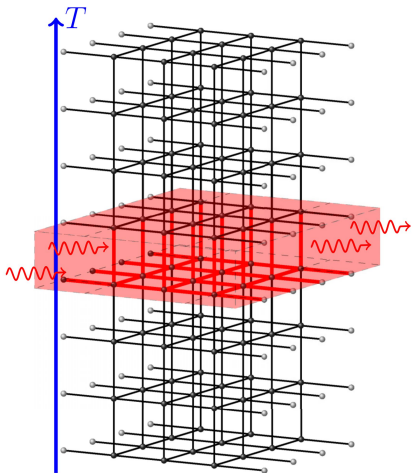


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Costs of remaining T1 burst

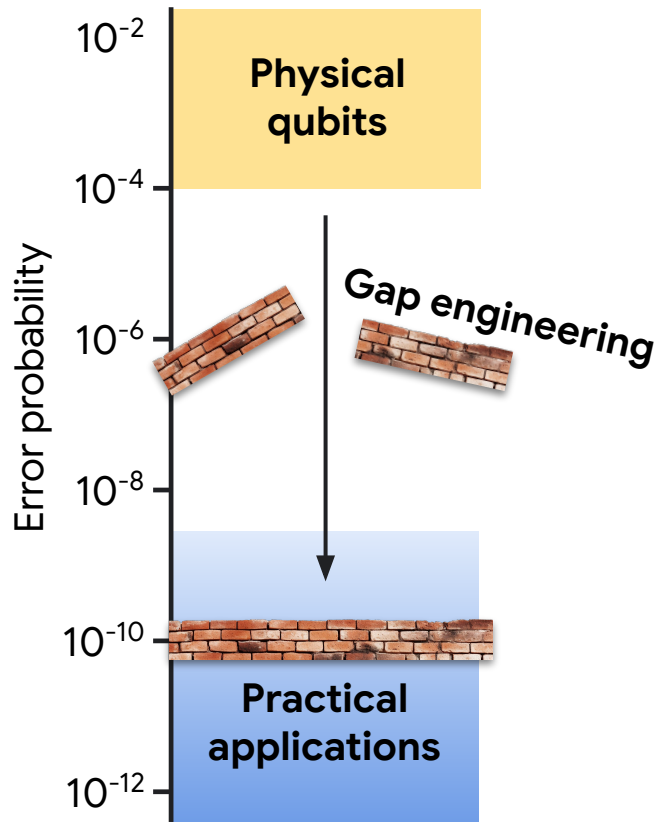


Costs of remaining T1 burst

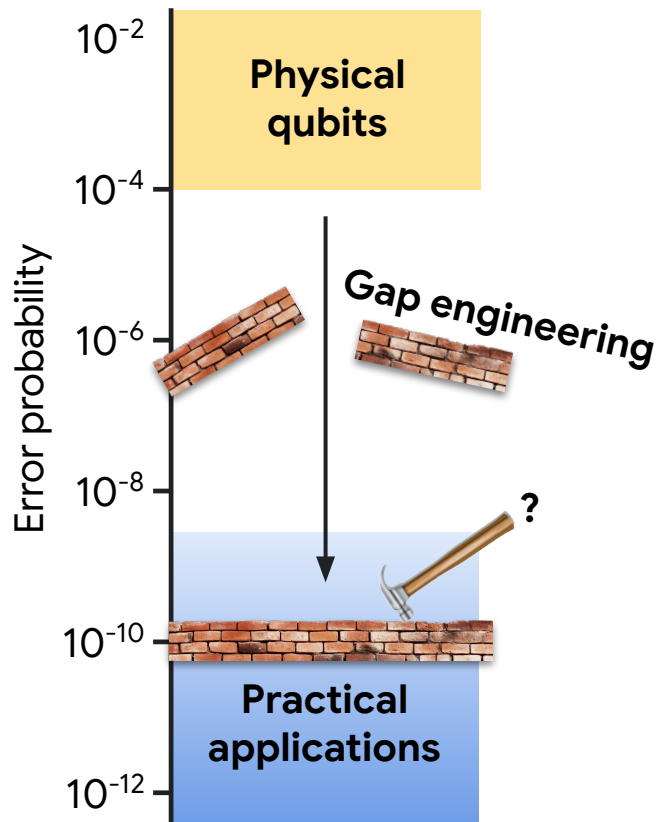


Still want burst to be
as SMALL in time
and space as
possible

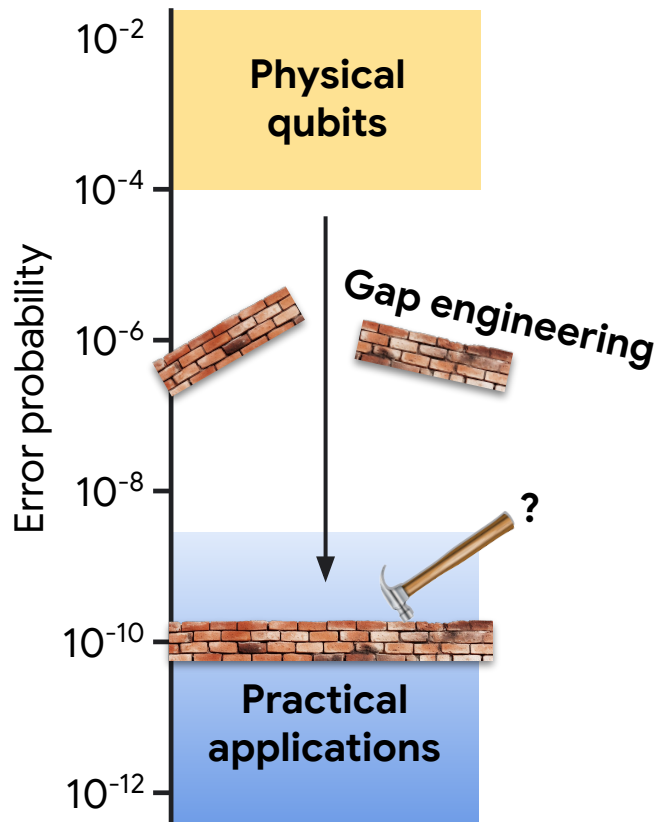
[see S. Tan et al (2026)]



[Image by pngtree.com]



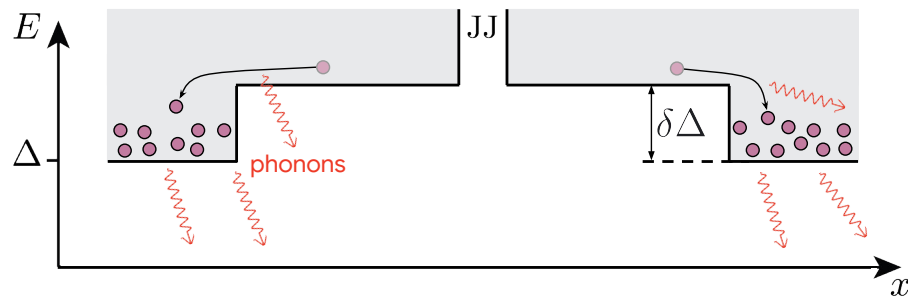
[Image by pngtree.com]

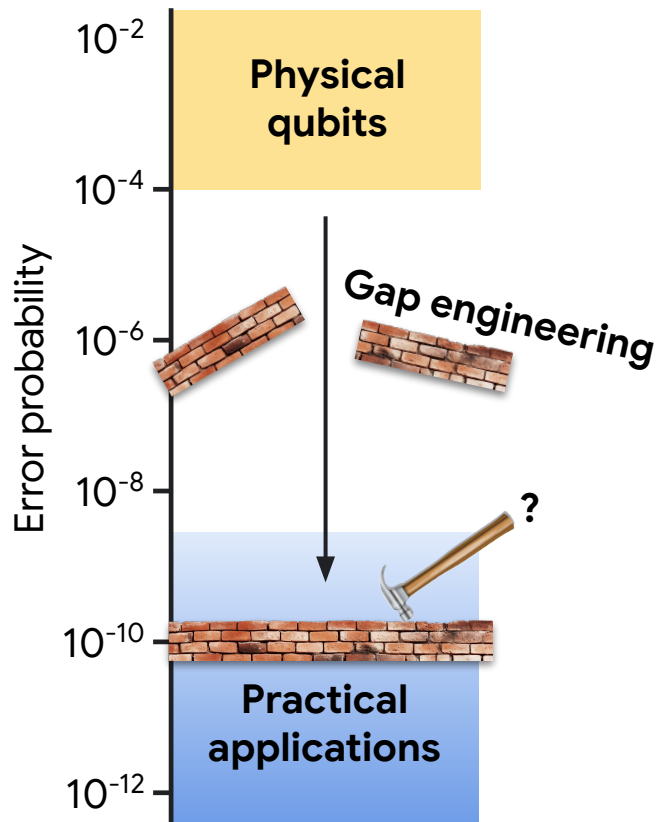


[Image by pngtree.com]

Quasiparticle traps

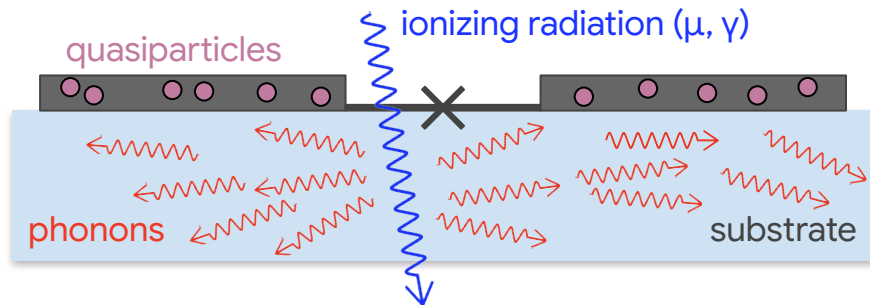
[see, e.g., R.-P. Riwar et al (2016, 2019)]





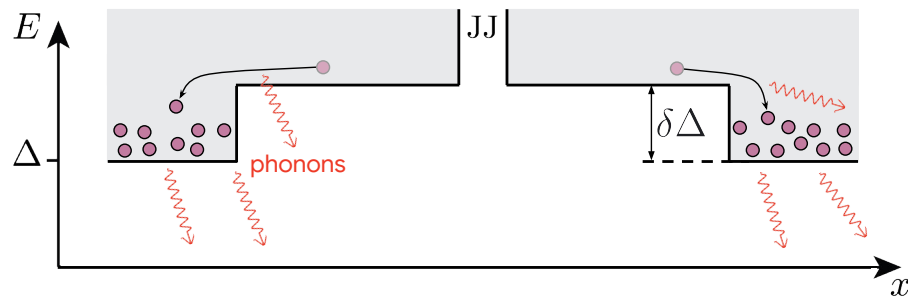
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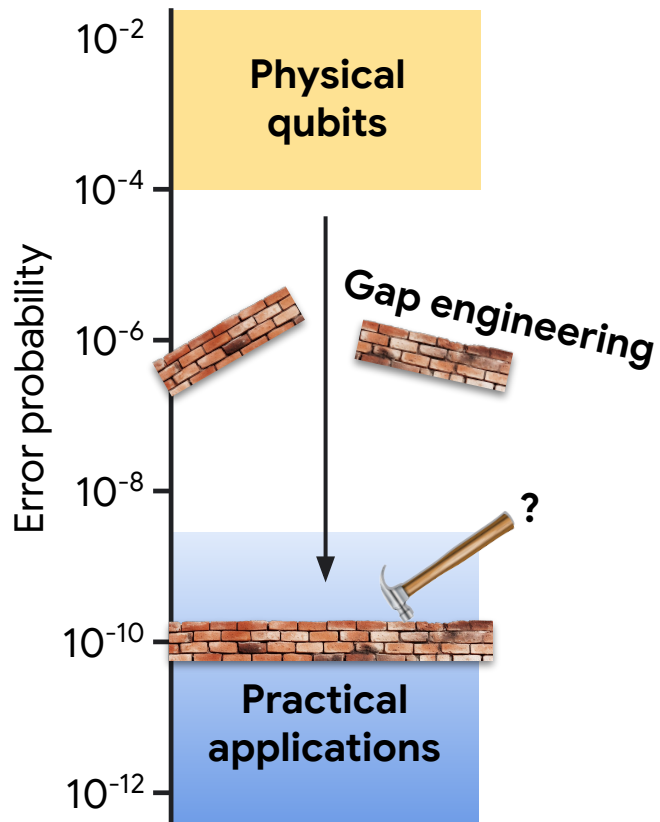
Phonon traps [see V. Iaia et al (2022)]



Quasiparticle traps

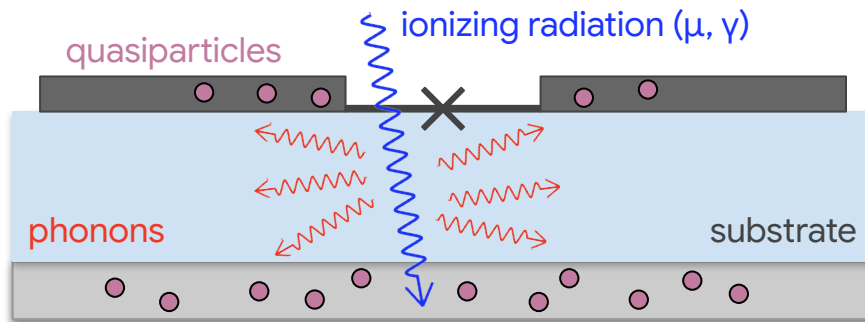
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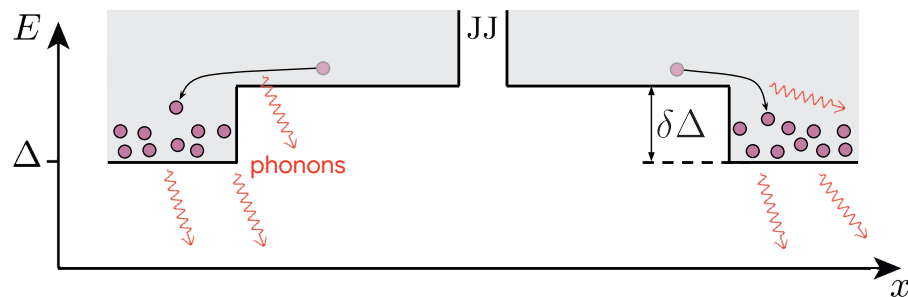
[Image by pngtree.com]

Phonon traps [see V. Iaia et al (2022)]



Quasiparticle traps

[see, e.g., R.-P. Riwar et al (2016, 2019)]



Summary

Radioactivity leads to error bursts in SC quantum processors (very bad for QEC)

We dramatically suppressed the problem in Willow chips using **gap engineering**

Some bursts remain; we know where they come from and have ideas for how to deal with them

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Vlad Kurilovich



Alex Opremcak



Matt McEwen



...and many others!

Summary

Background radiation leads to error bursts in SC quantum processors

Old devices (pre-Willow)

No gap engineering

Main type of error bursts:

Bit flip errors

(qubit energy relaxation)

Burst duration:

~10 ms

Repetition code error floor:

10^{-6}

New devices (Willow)

Gap engineered qubits

Main type of error bursts:

Phase flips errors

(qubit frequency shifts)

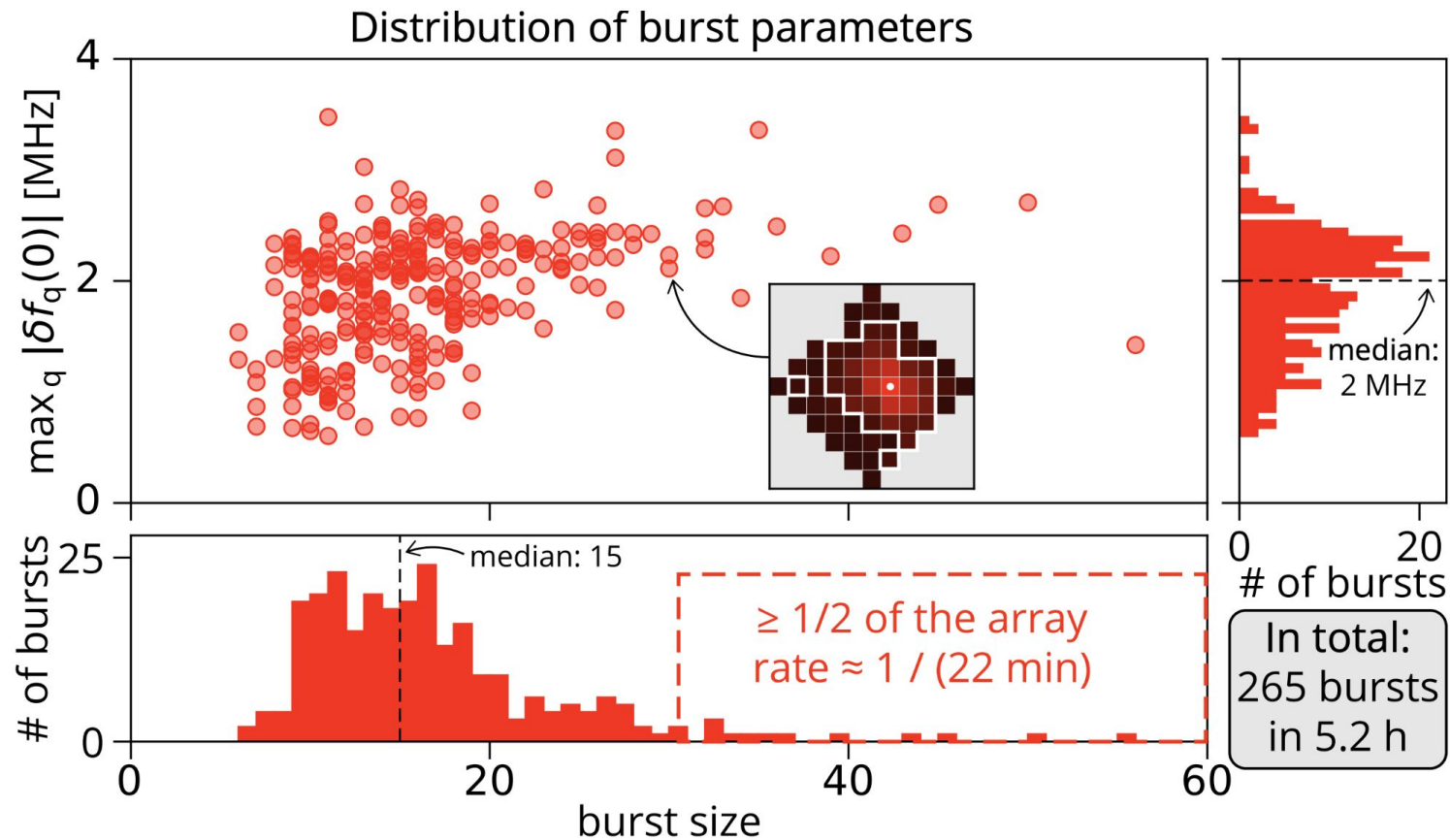
Burst duration:

~1 ms

Repetition code error floor:

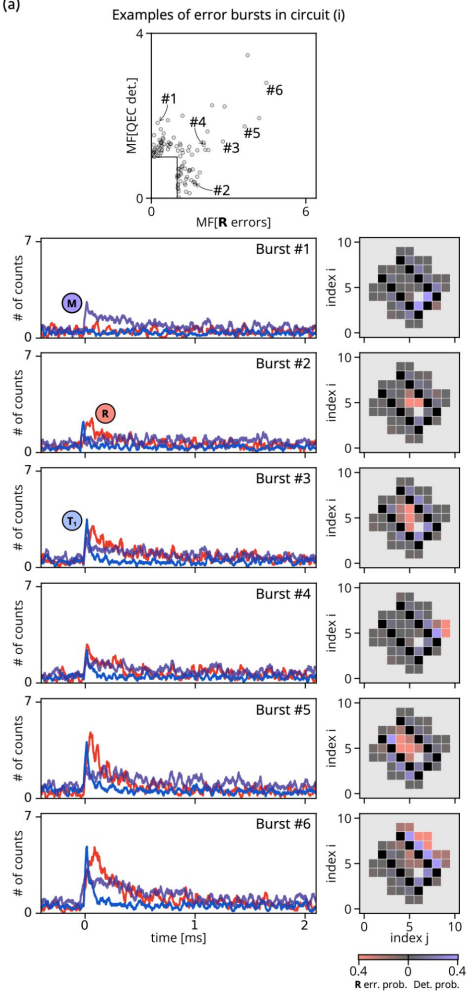
10^{-10}

Library of bursts

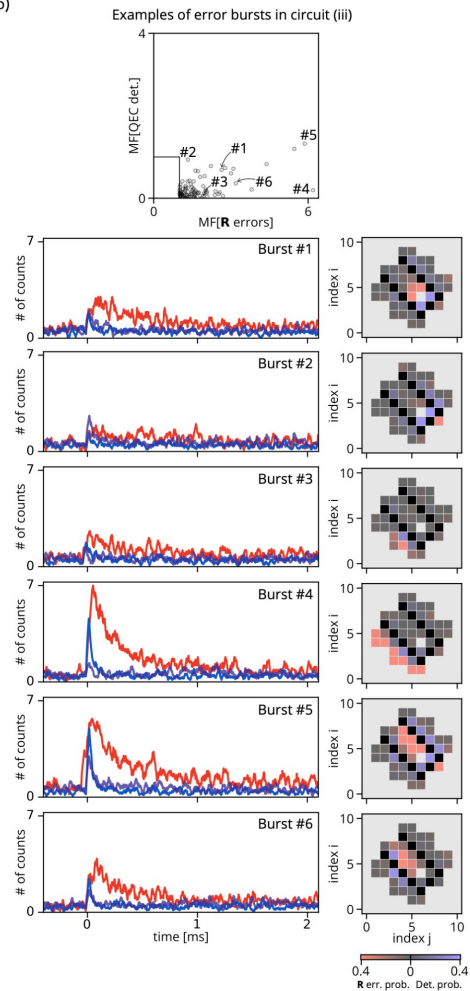


Library of bursts

(a)

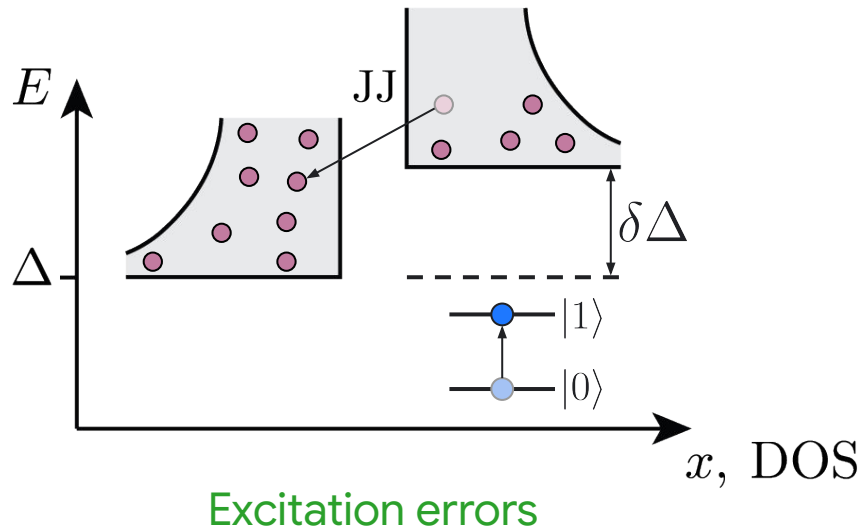
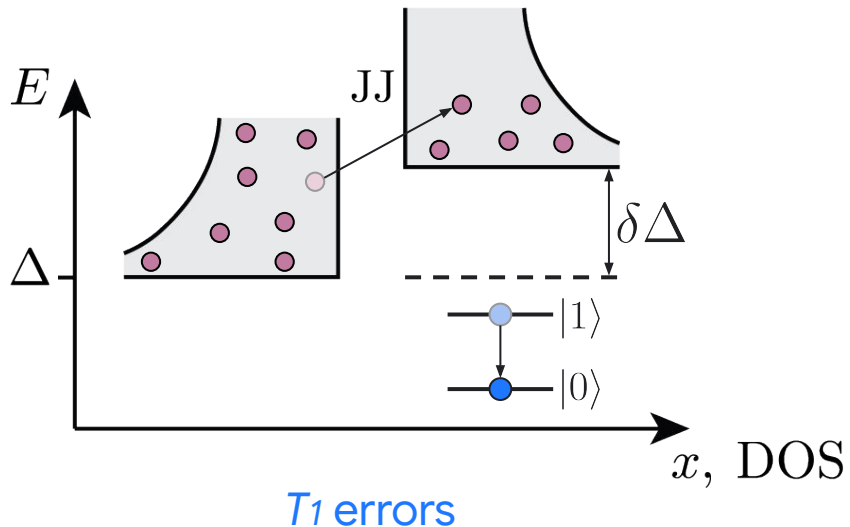


(b)



What about excitation errors?

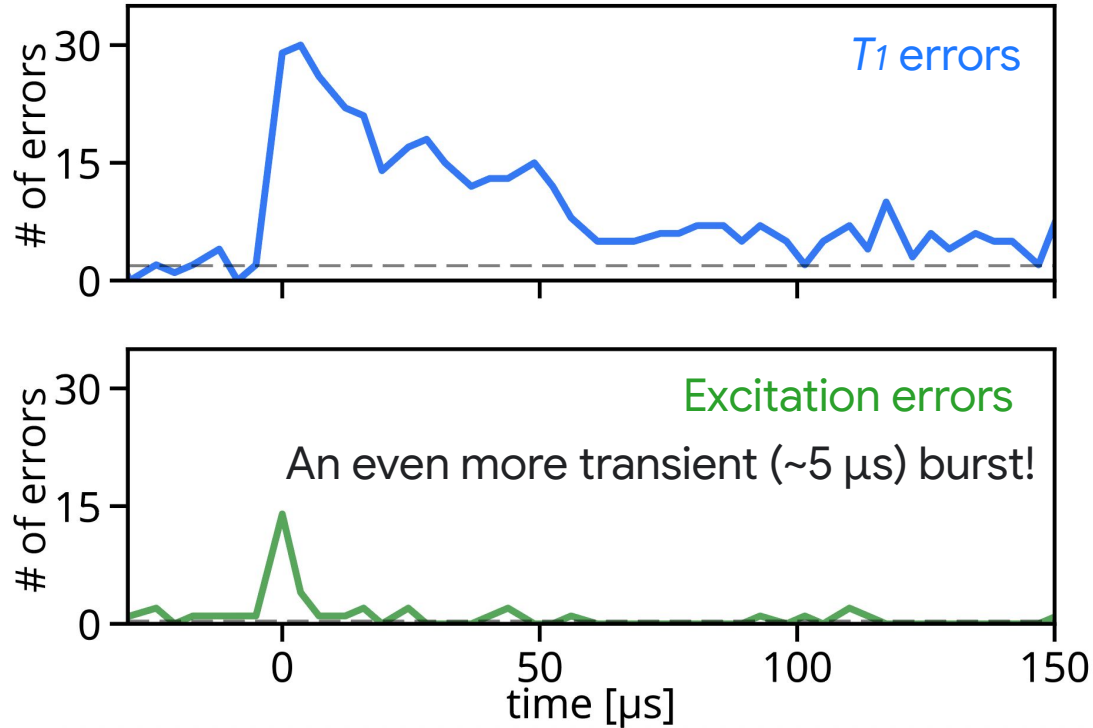
“Hot” QPs should be able to not only relax the qubit (T_1 errors), but also excite it!



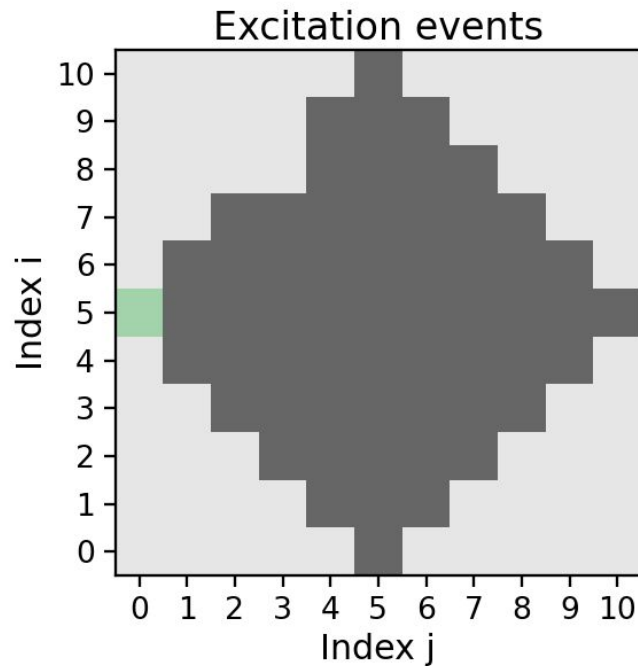
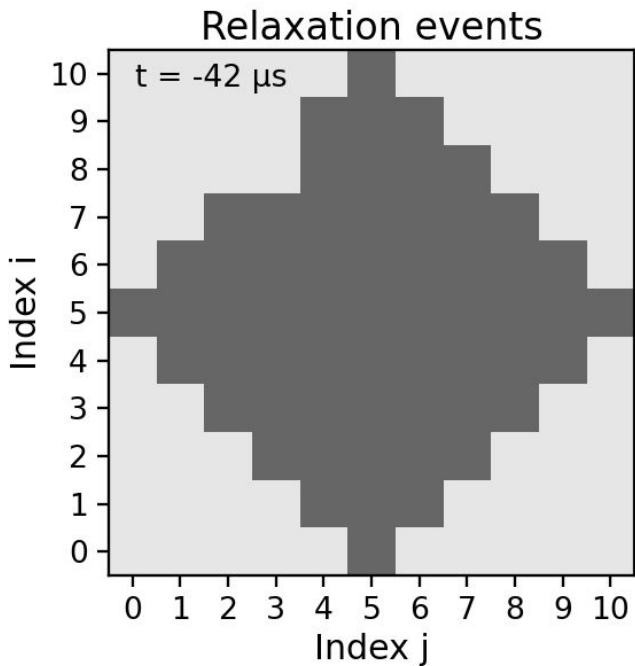
What about excitation errors?



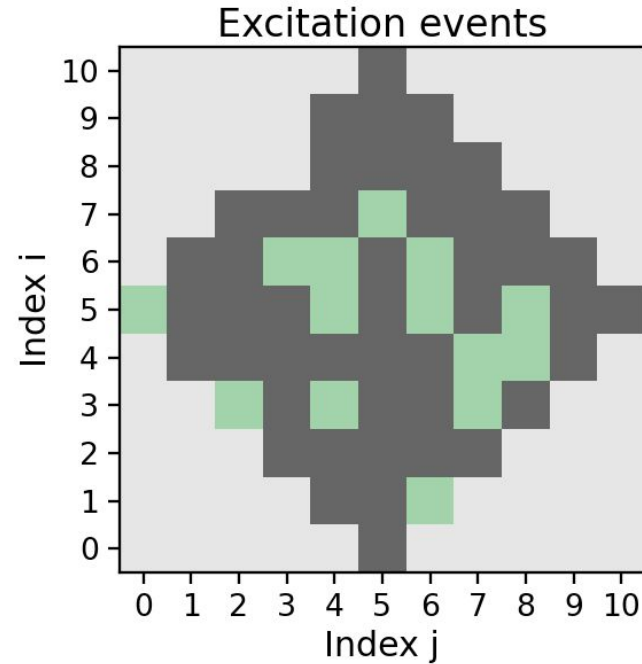
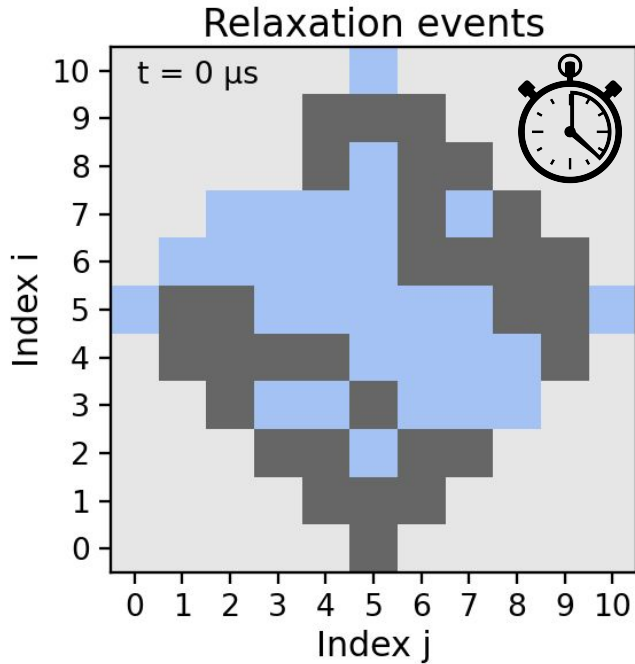
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What about excitation errors?

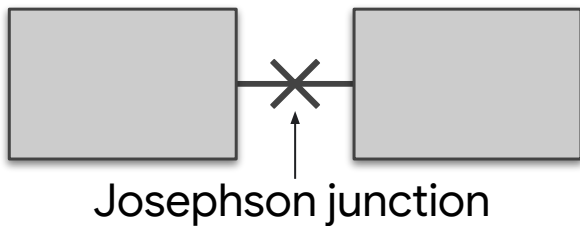


Bursts in gap engineered devices:

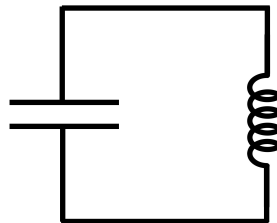
Negative, long lasting (~ 1 ms) frequency shifts + transient T_1 errors (~ 50 μ s)

[*Bonus*: weak, very transient excitation errors (~ 5 μ s)]

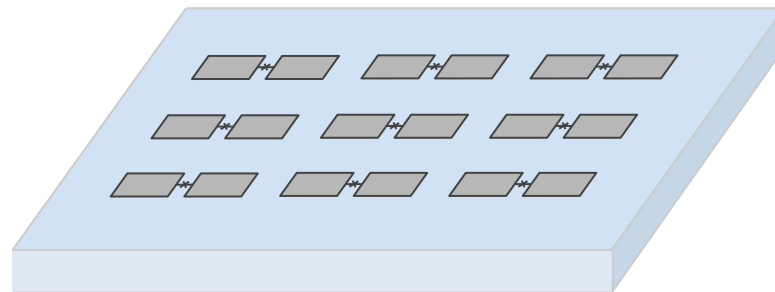
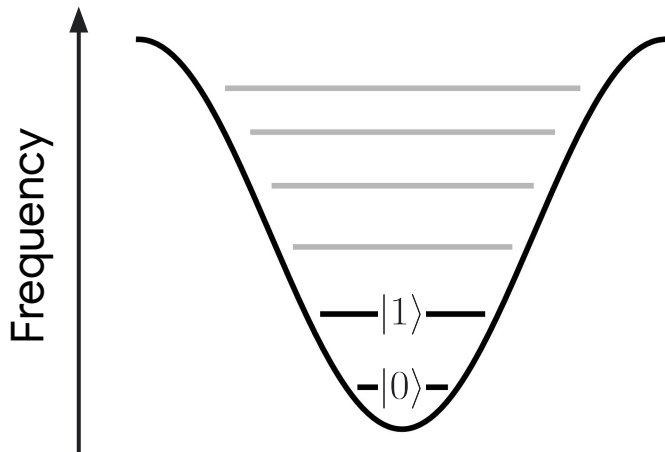
Superconducting qubits reminder



\approx



Weakly nonlinear
resonator
(junction = inductor)



Silicon substrate

[Koch et al., PRA **76** 042319 (2007)]

[Schuster Thesis (Yale, 2007); Kelly Thesis (UCSB, 2015)]