Quantum AI

Willow and quantum computing below the surface code threshold

Ping Yeh <pingyeh@google.com>
Google Quantum AI

International Symposium on Grids & Clouds March 18, 2025

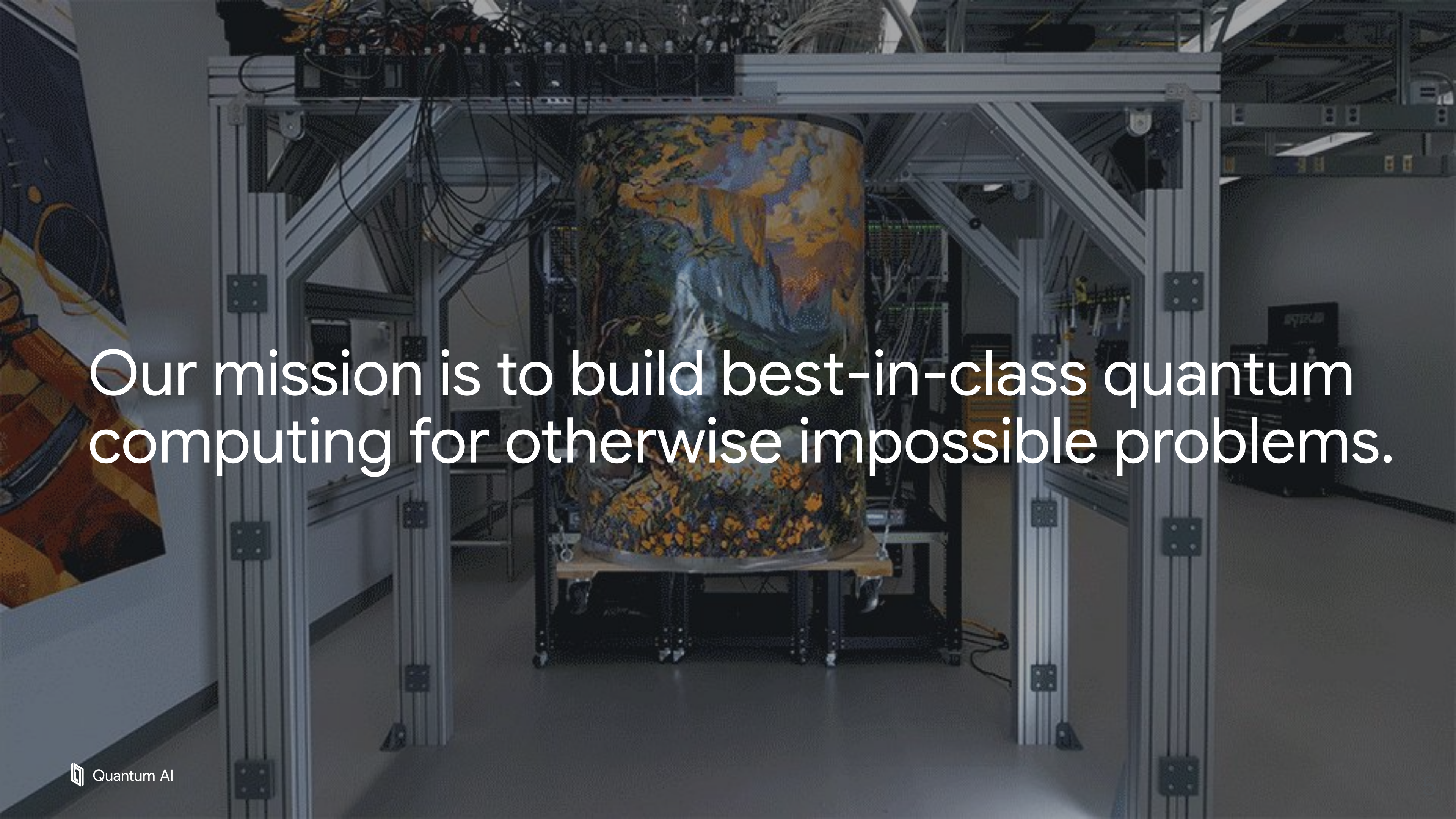
Google

Something I saw near my residence in Taipei

Outline

- Google Quantum AI
- The Willow Processor
- Random Circuit Sampling on Willow
- Quantum Error Correction below threshold
- Outlook

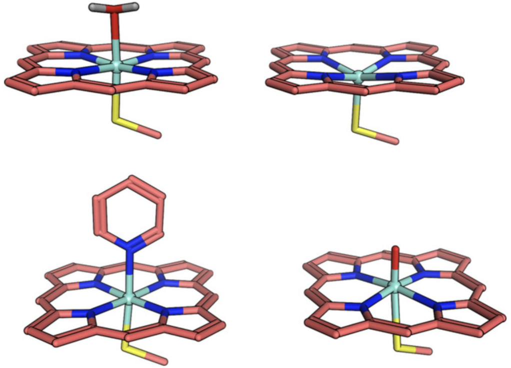
Google Quantum AI



Our mission is to build best-in-class quantum computing for otherwise impossible problems.

Example useful quantum algorithm

Quantum Simulation of Cytochrome P450 Enzyme
(A relatively large problem size)



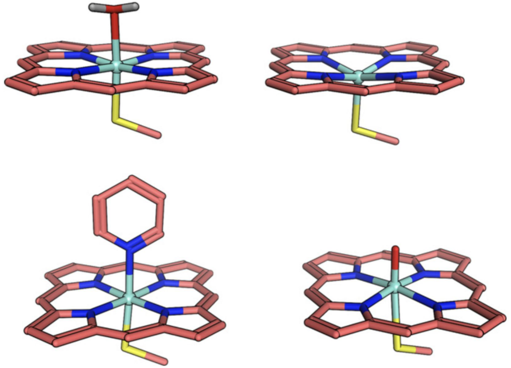
Accelerate drug testing by selecting out drug candidates that are instantly metabolized (~70%)

Requires: 10^9-10^{11} Toffoli operations without error

Goings, Joshua J., et al. PNAS (2022)

Example useful quantum algorithm

Quantum Simulation of Cytochrome P450 Enzyme
(A relatively large problem size)

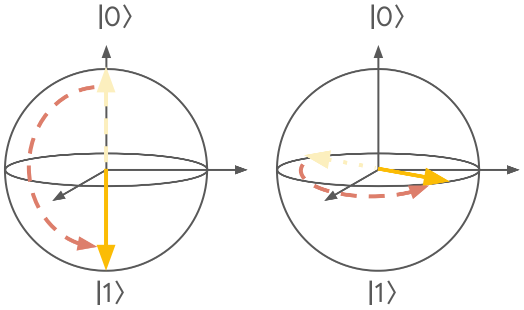


Accelerate drug testing by selecting out drug candidates that are instantly metabolized (~70%)

Requires: 10^9-10^{11} Toffoli operations without error

Challenge:
Many applications take much larger computational capacity than can fit on modern quantum hardware.

Key reason: **Errors**
Qubits are fundamentally error-prone (10^{-2}-10^{-4})



bit-flip error phase-flip error

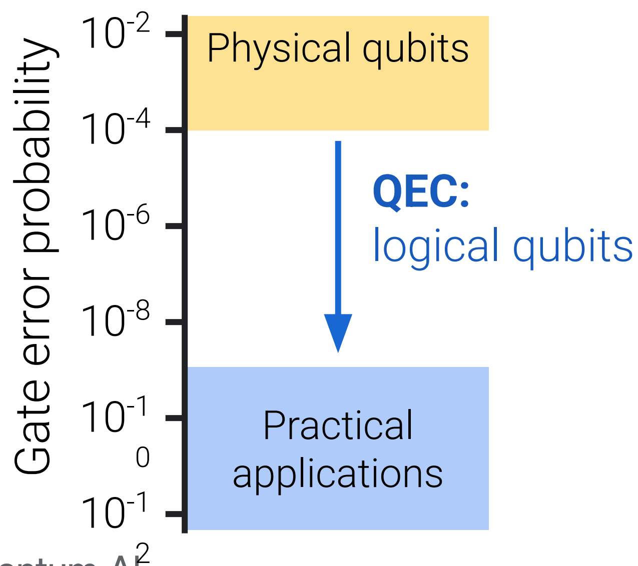
Goings, Joshua J., et al. PNAS (2022)

Quantum error correction

A bridge to practical applications

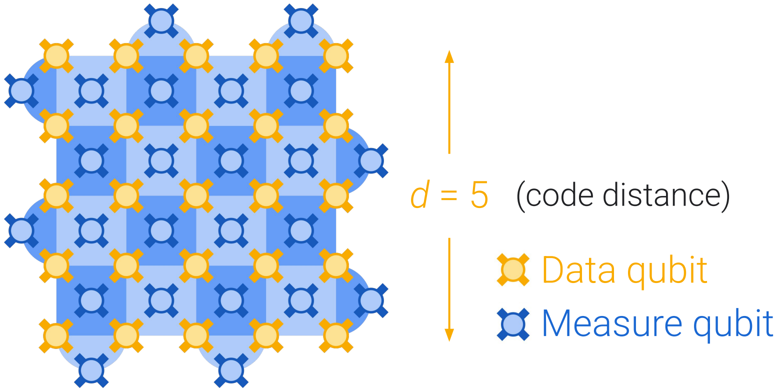
Hardware goal

Build qubits with gate error ~ 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 error suppression

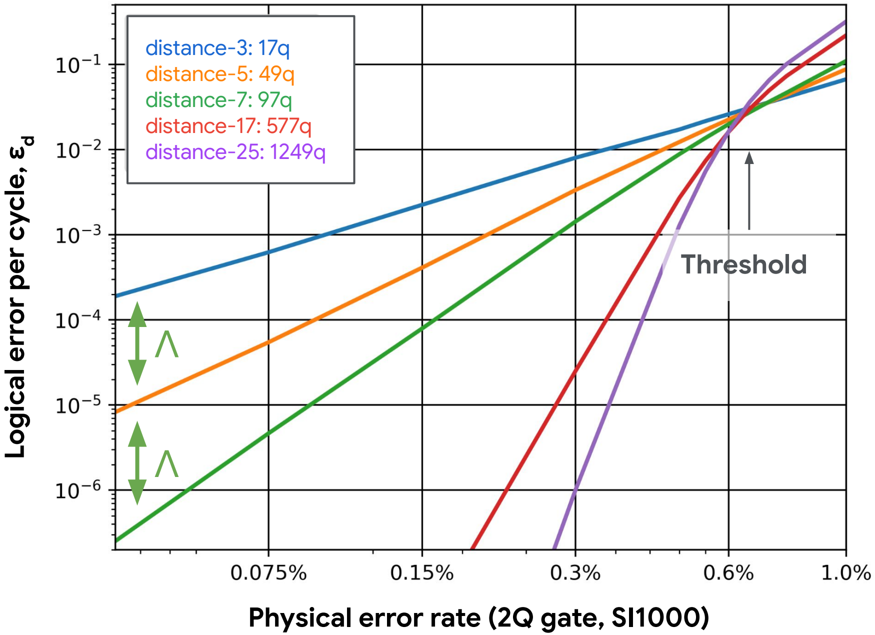
Trade many good physical qubits for an excellent logical qubit

Threshold:

Suppress errors with scale
when hardware is *good enough*

Empirical formula:

$$\text{Logical error per cycle } \varepsilon_d = C\cdot\left(\underset{\substack{\uparrow \\ 1\,/\,\Lambda}}{\frac{\text{Physical error rate}}{\text{Threshold error rate}}}\right)^{(\text{distance}+1)/2}$$

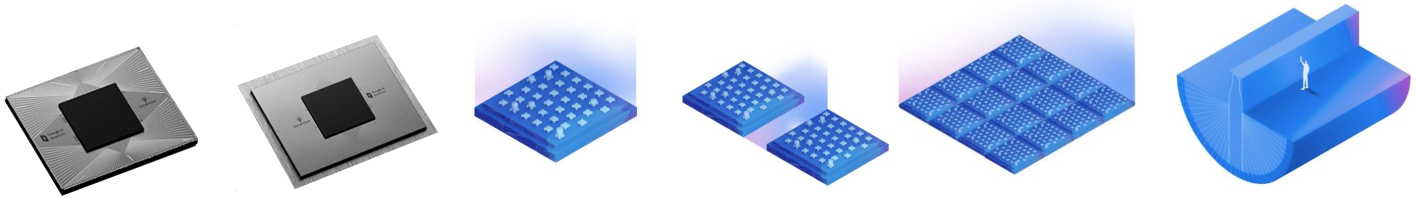


**QEC: a path to extremely low error rates,
if hardware is good enough**

Quantum AI

Fowler et al., *PRA* (2012)

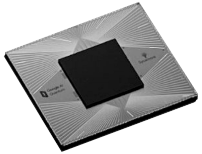
Quantum AI roadmap



	$[10^{-2}]$	$[10^{-6}]$	$[10^{-6}]$	$[10^{-8}]$	$[10^{-13}]$	**Logical error rate**
53	10^2	10^3	10^4	10^5	10^6	**Number of physical qubits**
M1 (2019) Beyond classical benchmark ✓	**M2** (2023) Logical qubit prototype ✓	**M3** (2025+) 1 long-lived logical qubit	**M4** Tileable module (logical gate)	**M5** Engineering scale up	**M6** Error-corrected (EC) quantum computer	

- Early access partners ✓
- Beyond classical NISQ application
- More beyond classical NISQ applications
- Early fault tolerance
- Error corrected applications
- Revenue

Quantum AI roadmap

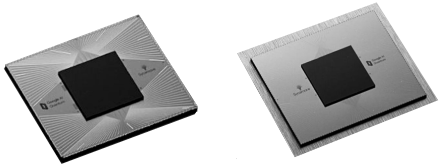


$[10^{-2}]$ $[10^{-6}]$ $[10^{-6}]$ $[10^{-8}]$ $[10^{-13}]$ **Logical error rate**

53 10^2 10^3 10^4 10^5 10^6 **Number of physical qubits**

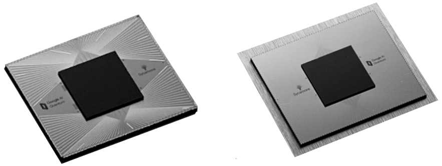
M1 (2019)
Beyond classical benchmark
✔

Quantum AI roadmap



Logical error rate		$[10^{-2}]$	$[10^{-6}]$	$[10^{-6}]$	$[10^{-8}]$	$[10^{-13}]$
Number of physical qubits	**53**	10^{2}	10^{3}	10^{4}	10^{5}	10^{6}
	M1 (2019) Beyond classical benchmark ✓	**M2** (2023) Logical qubit prototype ✓				

Quantum AI roadmap



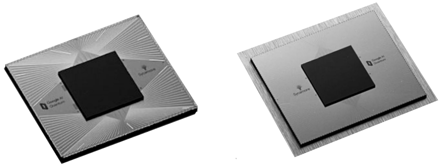
	$[10^{-2}]$	$[10^{-6}]$	$[10^{-6}]$	$[10^{-8}]$	$[10^{-13}]$	**Logical error rate**
53	10^{2}	10^{3}	10^{4}	10^{5}	10^{6}	**Number of physical qubits**

M1 (2019)
Beyond classical benchmark
✔

M2 (2023)
Logical qubit prototype
✔

Sycamore

Quantum AI roadmap



[10^{-2}]

[10

53

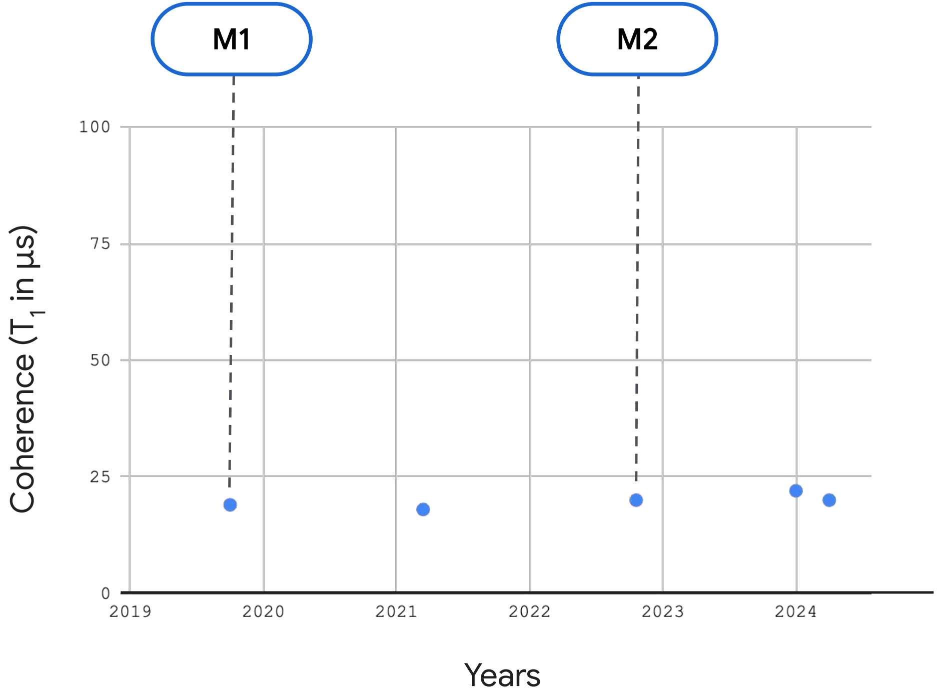
10^2

10

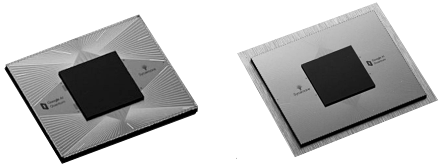
M1 (2019)
Beyond classical benchmark
✔

M2 (2023)
Logical qubit prototype
✔

Sycamore



Quantum AI roadmap



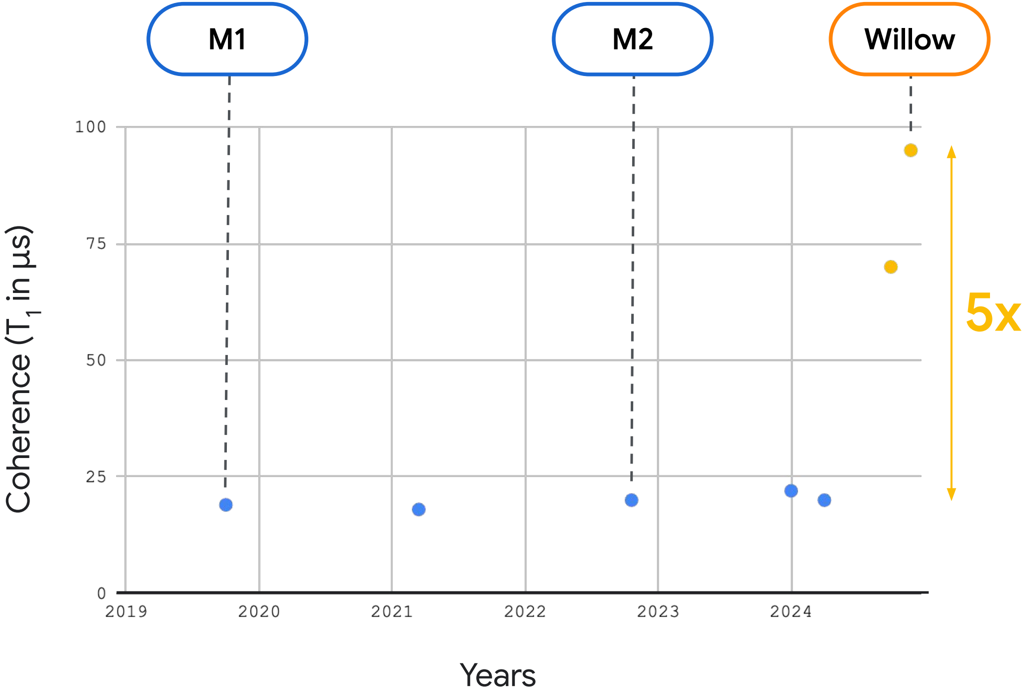
$[10^{-2}]$ [10

53 10^2 10

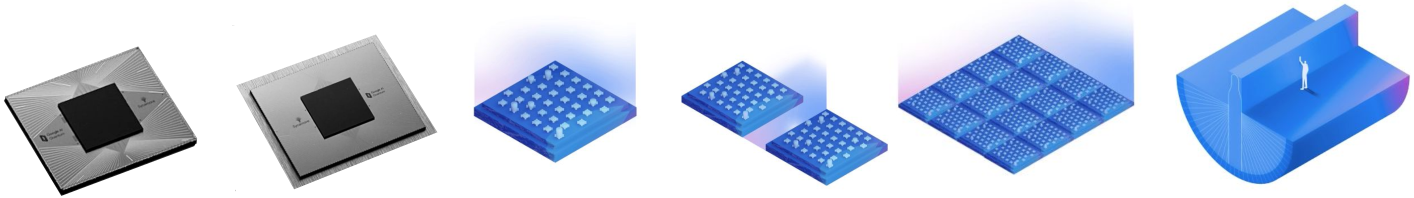
M1 (2019)
Beyond classical benchmark
✔

M2 (2023)
Logical qubit prototype
✔

Sycamore



Our Roadmap



Logical error rate

# of physical qubits

System

53

M1 (2019)
Beyond-classical benchmark
✓

[10^{-2}]
10^2

M2 (2023)
Logical qubit prototype
✓

[10^{-6}]
10^3

M3 (2025+)
1 long-lived logical qubit

[10^{-6}]
10^4

M4
Tileable module (logical gate)

[10^{-8}]
10^5

M5
Engineering scale up

[10^{-13}]
10^6

M6
Error-corrected (EC) quantum computer

Applications

B1 (2021)
10+ Early access partners
✓

B2
Beyond-classical NISQ discovery

B3
3+ Beyond-classical NISQ discoveries

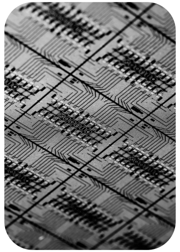
B4
EC benchmark

B5
3+ EC applications

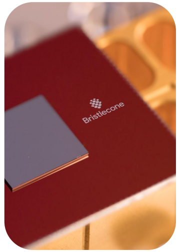
B6
10+ EC applications

Quantum AI

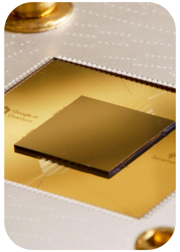
Our Processor Journey



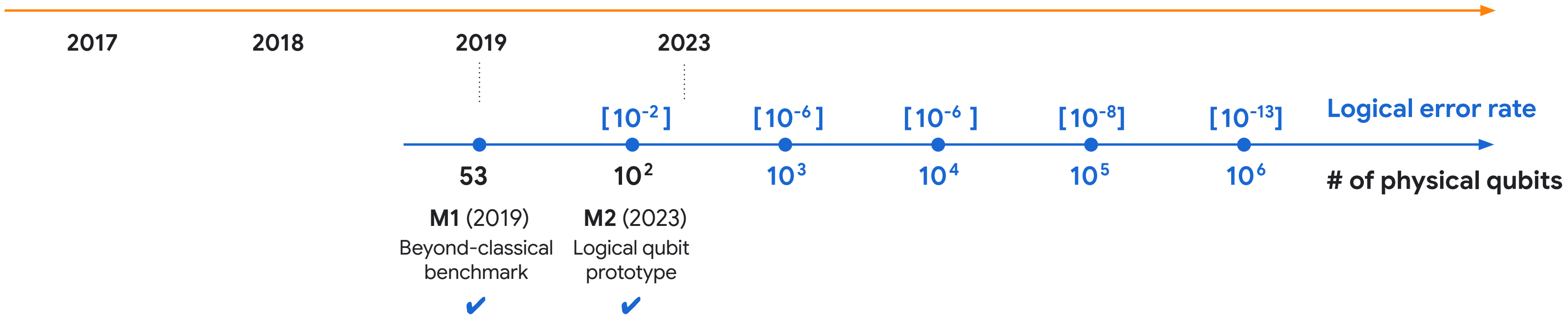
Foxtail



Bristlecone

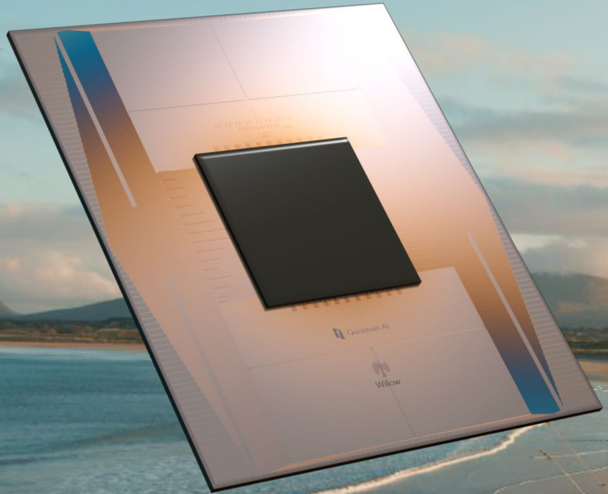


Sycamore



2017	2018	2019	2023					
			$[10^{-2}]$	$[10^{-6}]$	$[10^{-6}]$	$[10^{-8}]$	$[10^{-13}]$	**Logical error rate**
		53	10^{2}	10^{3}	10^{4}	10^{5}	10^{6}	**# of physical qubits**
		M1 (2019) Beyond-classical benchmark ✓	**M2** (2023) Logical qubit prototype ✓					

Introducing Willow



Willow

Introducing Willow

Willow, our newest generation of superconducting processors, enabling progress towards realizing our mission to: **build best-in-class quantum computing for otherwise unsolvable problems.**

Willow Architecture and Performance Overview

First-of-its-kind architecture, featuring 105 qubits and the largest computational volume of any quantum processor.

Architecture

- Square grid of superconducting transmon qubits
- Highly tunable qubits and couplers
- Number of Qubits: 105
- Average Connectivity: 3.47

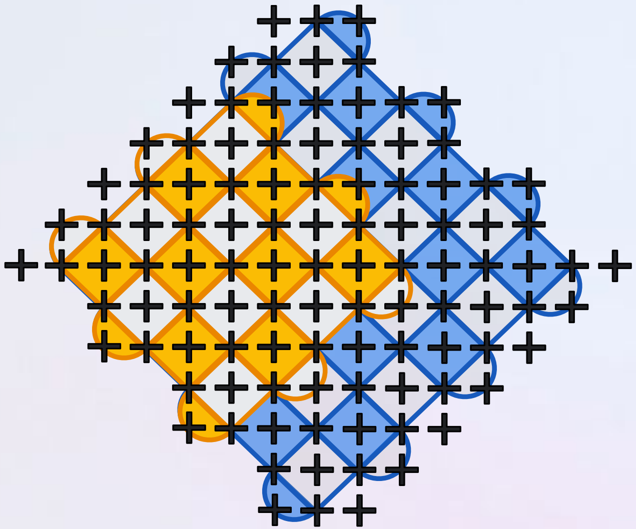
Performance

- 5x increase in T_1, from 20 to 100 µs
- Improved operational fidelities
- Improved calibration flexibility
- Uniquely suited to error correction (and therefore scaling and useful applications)

105 qubit willow

d=7 grid

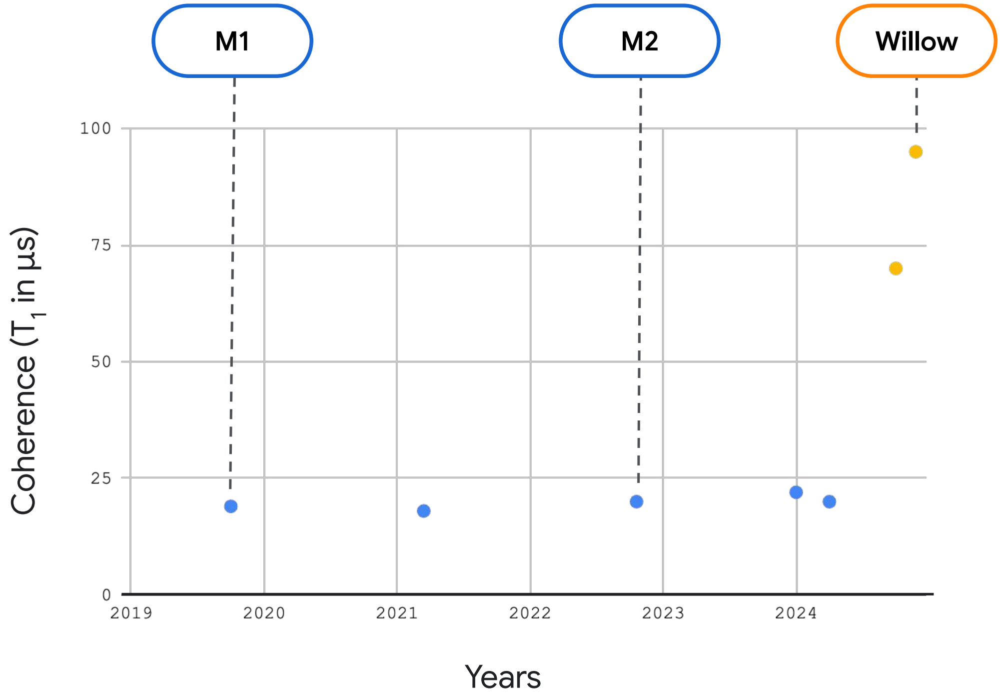
20 distinct d=5 grids



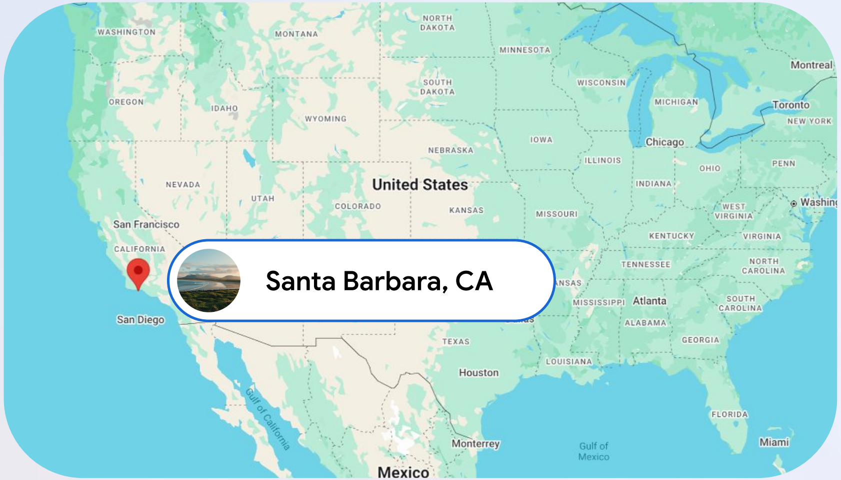
Willow Architecture and Performance: Coherence improvements

5x

Increase in T_1, from 20 to 100 µs



In House Fabrication in Santa Barbara:
One of just a few dedicated superconducting fabs in the world



Willow Architecture and Performance: Key Specifications

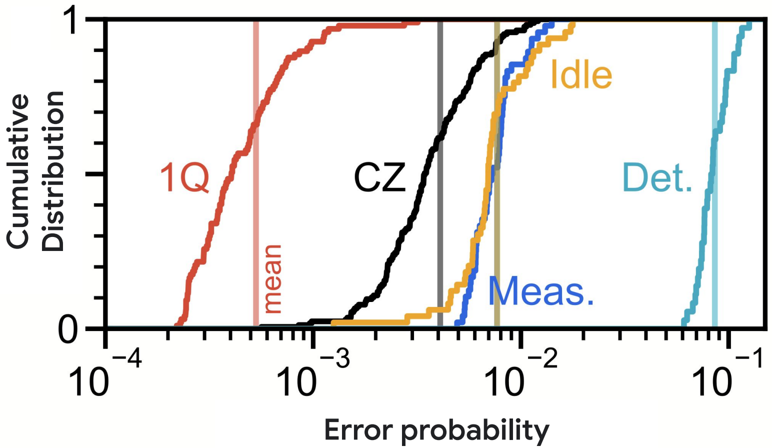
Number of qubits: 105 **Average Connectivity:** 3.47

Specifications	Quantum Error Correction (QEC, chip 1)	Random Circuit Sampling (RCS, chip 2)
T_1 time (mean)	68 µs	98 µs
Single-qubit gate error (mean, simultaneous)	0.035%	0.036%
Two-qubit gate error (mean, simultaneous)	0.33% (CZ)	0.14% (iswap-like)
Measurement error (mean, simultaneous)	0.77% (repetitive, measure qubits)	0.67% (terminal, all qubits)
Measurement Rate (per second)	909,000 (surface code cycle = 1.1 µs)	63,000
Application Performance	$\Lambda_{3,5,7} = 2.14 \pm 0.02$	XEB fidelity depth 40 = 0.1%

Willow Architecture and Performance: Error distributions for QEC

Takeaways:

- Means and medians don't tell the whole story
- Overall, these are about 2x better than our previous generation chip, Sycamore



Cumulative distributions of error probabilities

- ● **Red:** Pauli errors for single-qubit gates
- ● **Black:** Pauli errors for CZ gates
- ● **Blue:** Average identification error for measurement
- ● **Gold:** Pauli errors for data qubit idle during measurement and reset
- ● **Teal:** Weight-4 detection probabilities (distance-7, averaged over 250 cycles)

Error correction will be key to building a fault tolerant quantum computer. And Willow is uniquely capable of effective error correction

One useful way to measure error correction effectiveness is Λ ("lambda"), the error suppression factor.

- Λ is the ratio of the logical error rate for a smaller surface code (e.g. distance 3 code) to that of a larger surface code (e.g. distance 5 code).
- It represents the reduction in logical error rate when increasing the code distance by two, e.g. from 3 to 5 to 7.

Λ>1 indicates that increasing the code distance (i.e. using more qubits for a calculation) *actually improves* the logical error rate, which is essential for building fault-tolerant quantum computers.

With Willow, we show a

$$\Lambda_{3,5,7} = 2.14$$

(where 3,5,7 are the code distances)

Since M2 in 2023,
the physical error rate improved by **2x,**
and logical error rates are **20x better.**

Exponential error suppression

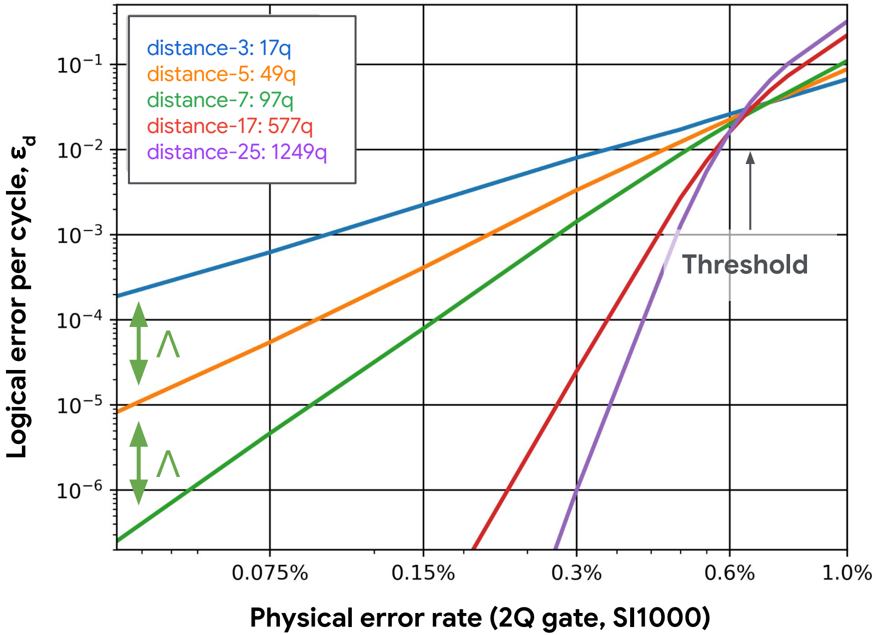
Trade many good physical qubits for an excellent logical qubit

Threshold:

Suppress errors with scale
when hardware is *good enough*

Empirical formula:

$$\text{Logical error per cycle } \varepsilon_d = C \cdot \left(\underbrace{\frac{\text{Physical error rate}}{\text{Threshold error rate}}}_{\uparrow \; 1\,/\,\Lambda} \right)^{(\text{distance}+1)/2}$$



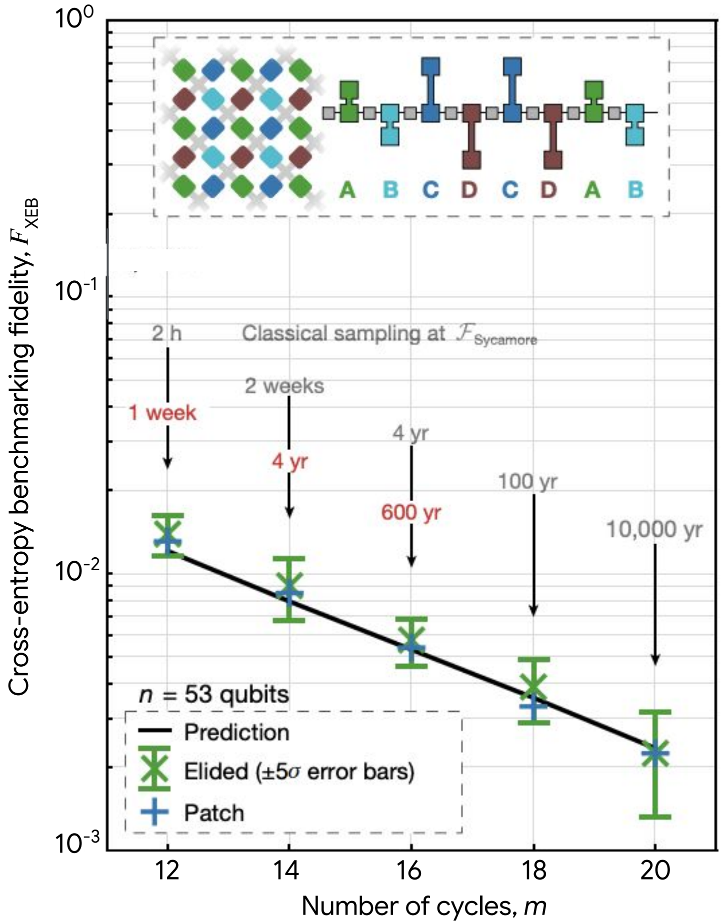
**QEC: a path to extremely low error rates,
if hardware is good enough**

Quantum AI

Fowler et al., *PRA* (2012)

Random Circuit Sampling on Willow

Milestone 1 (M1): Random Circuit Sampling - Beyond classical benchmark



Quantum AI

Arute et al., Nature 2019; Morvan et al., Nature 2024

Random Circuit Sampling on Willow: a step change

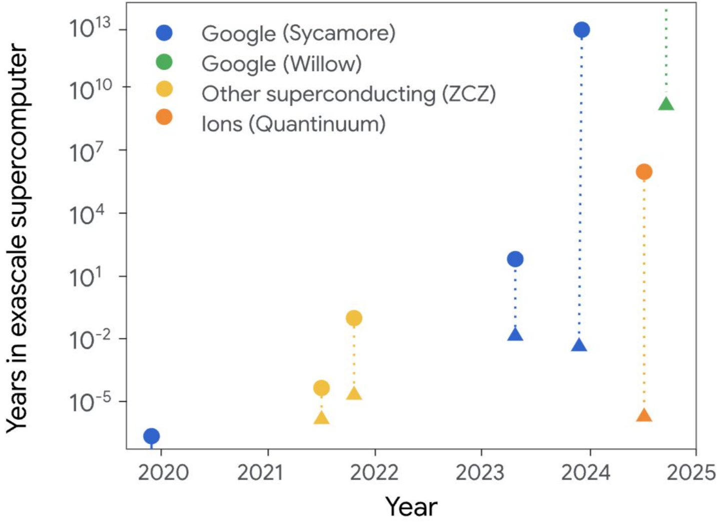
Willow performed a Random Circuit Sampling (RCS) benchmark computation in under 5 minutes that would take the supercomputer Frontier 10^{25} years to complete—specifically ten septillion years or:

10,000,000,000,000,000,000,000,000

Years

Willow Enabled Random Circuit Sampling

Range from an idealized situation with unlimited memory (▲) to a more practical, embarrassingly parallelizable implementation on GPUs (●).

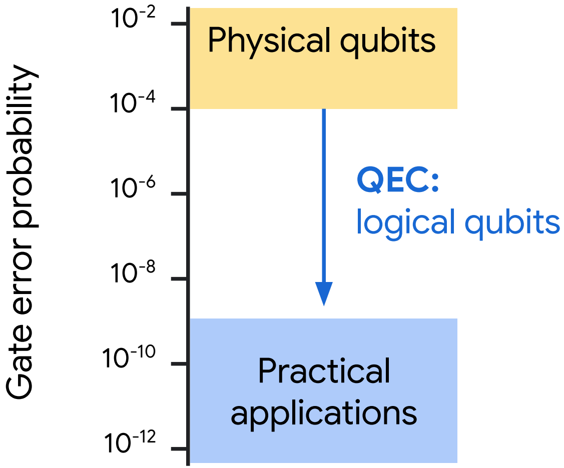


QEC below the surface code threshold

Quantum error correction (QEC) is key to building a fault tolerant quantum computer

Hardware goal

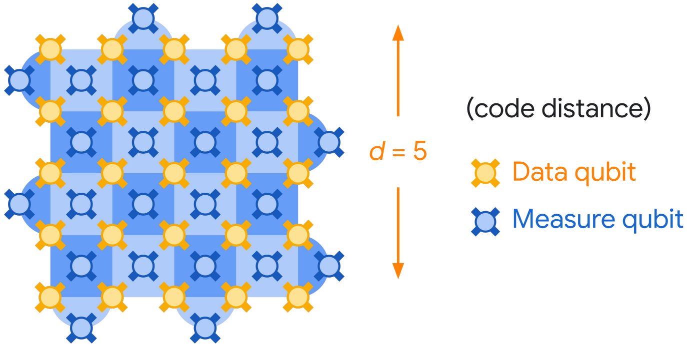
Build qubits with gate error ~ 10^{-10}



Surface code logical qubit

Distribute quantum state over

d^2 physical qubits



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

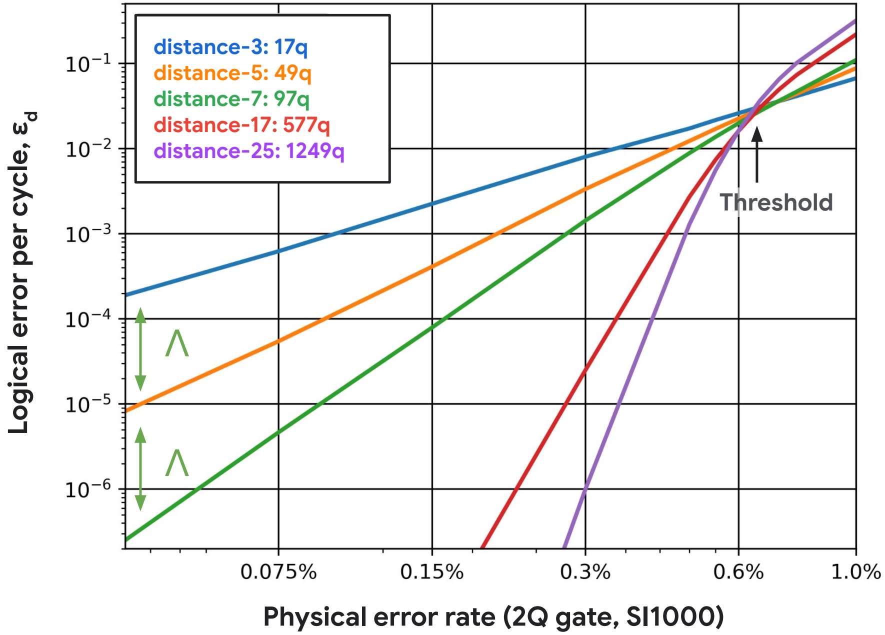
QEC for exponential suppression of errors

Trade many good physical qubits for an excellent logical qubit

Threshold:
Suppress errors with scale
when hardware is *good enough*

Empirical formula:

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

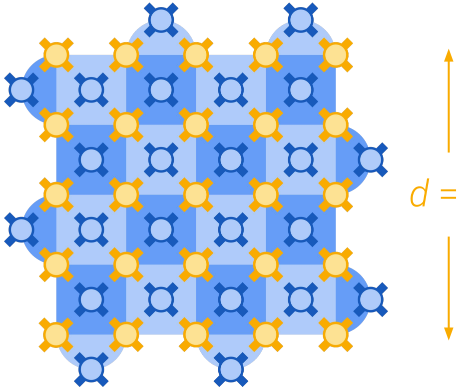


Fowler et al., *PRA* (2012)

QEC: A path to extremely low error rates, if hardware is good enough

Logical qubit: retain 1 qubit degree of freedom

Surface code logical qubit

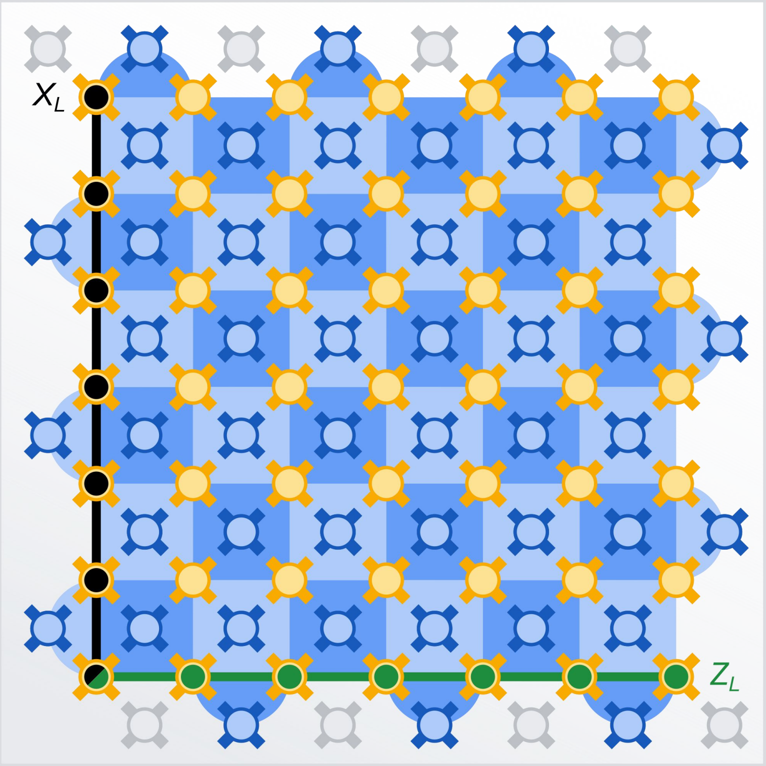


$d = 5$ (code distance)

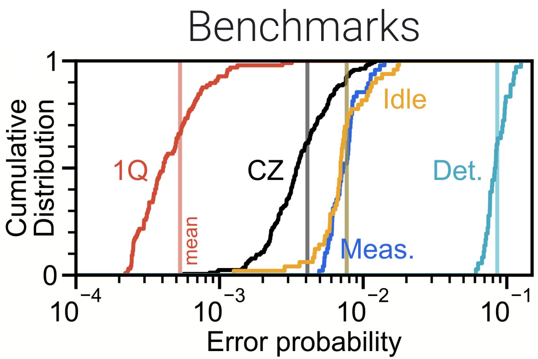
🟡 Data qubits: **d^2**

🔵 Measure qubits: **d^2-1**

Implementing the surface code



105-qubit Willow processor



About 2x better than previous generation (*Nature* **614** (2023))

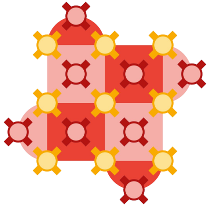
Distance-7 logical qubit

Logical operators X_L, Z_L

In the paper, we also have a 72-qubit processor with similar design (only fits up to d=5)

Scaling from “distance 3” to “distance 7” code

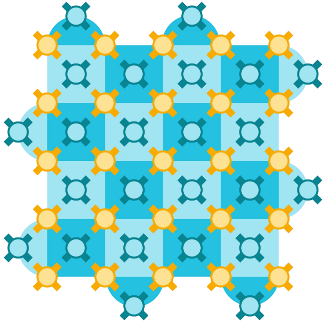
Key challenge: Overcoming additional errors from adding qubits



Distance-3

“1 error at a time”

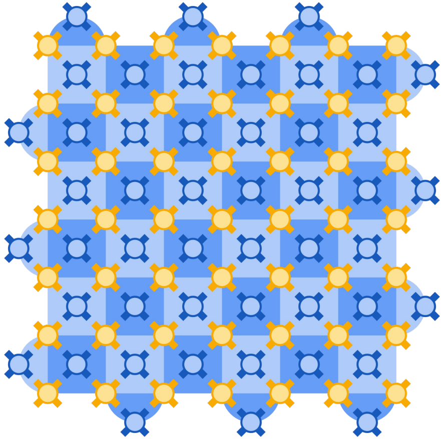
17 qubits



Distance-5

“2 errors at a time”

49 qubits



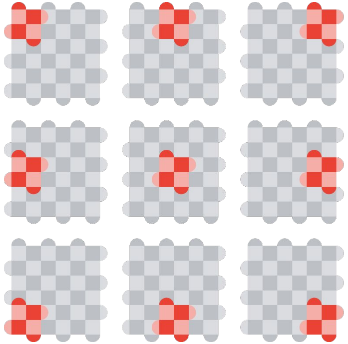
Distance-7

“3 errors at a time”

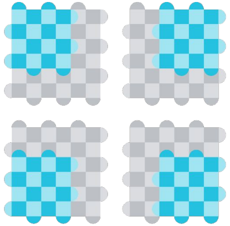
97 qubits

Measuring Λ (error vs. size)

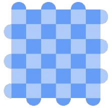
Compare smaller codes to d=7 (covering set with minimal overlap)



d=3: 3x3 array



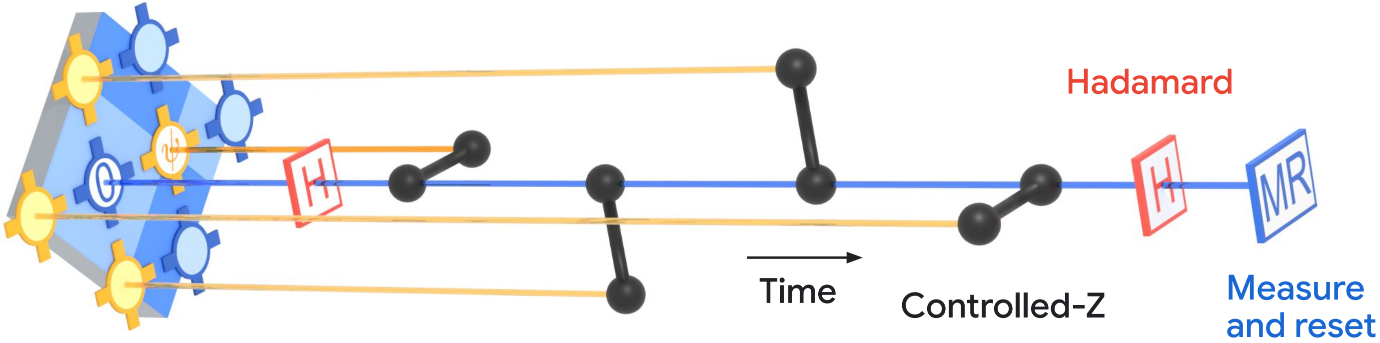
d=5: 2x2 array



d=7

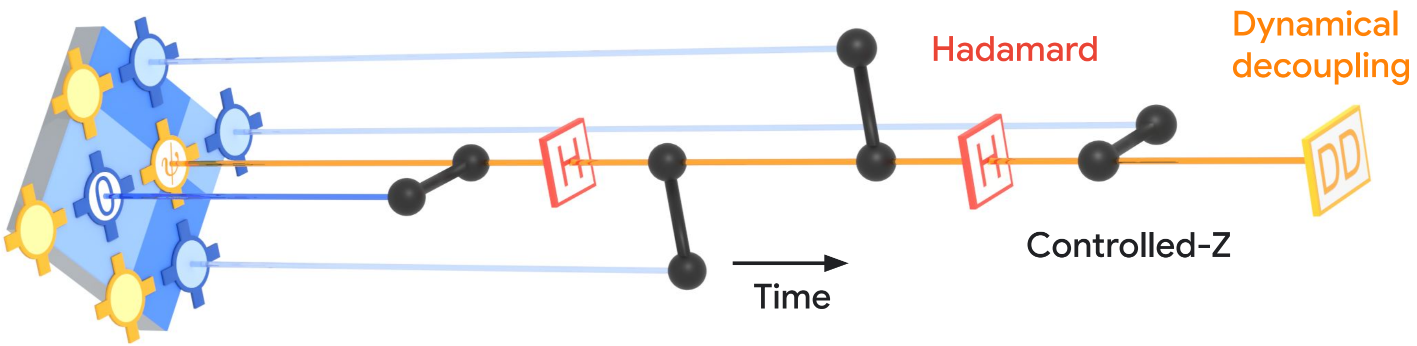
Also, measure a large number of cycles (~ 1/ε) to allow (bad) effects like leakage accumulation to appear

One surface code cycle



Measure qubit checks parity of neighboring qubits

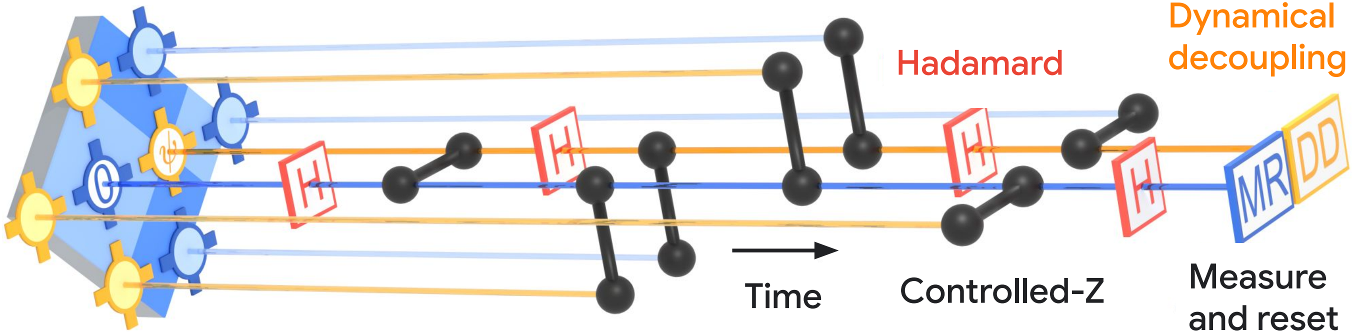
One surface code cycle



Data qubit has parity checked by four neighbors

Wen et al., PRL 90, 016803 (2003)
Bonilla Ataides et al., Nat. Commun. 12, 2172 (2021)

One surface code cycle



Hadamard

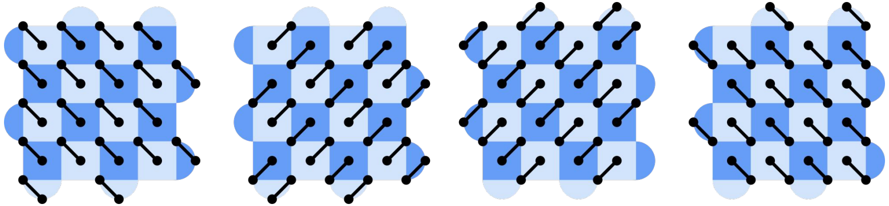
Dynamical decoupling

Time

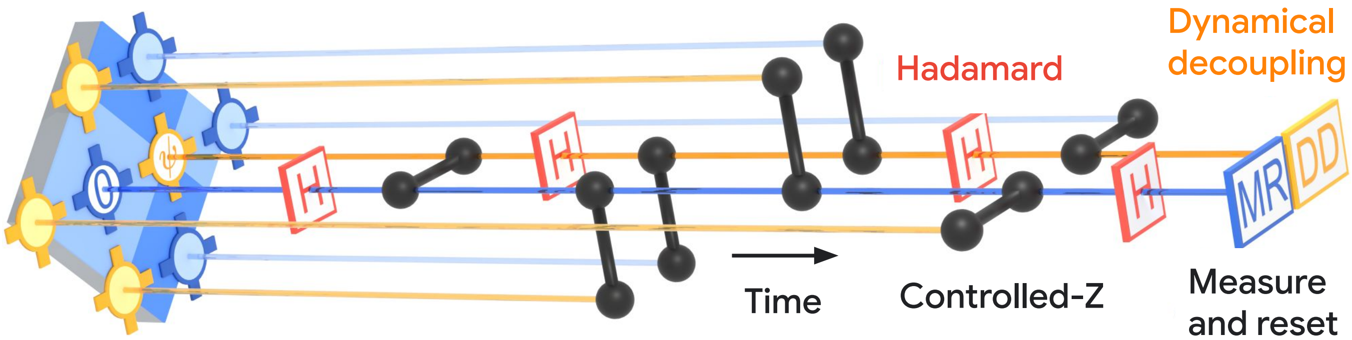
Controlled-Z

Measure and reset

Four layers of CZ gates



One surface code cycle



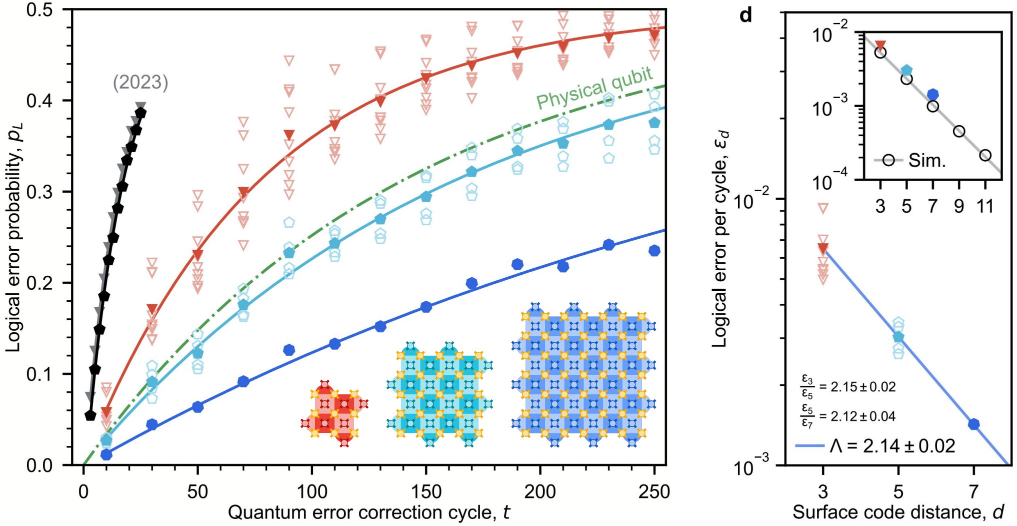
Data idle during measure/reset
≈70% of cycle duration!

Scaling from **d=3** to **d=7** on Willow enables dramatically improved quantum error correction

With Willow, we show a **$\Lambda_{3,5,7}$ = 2.14** (where 3,5,7 are the code distances).

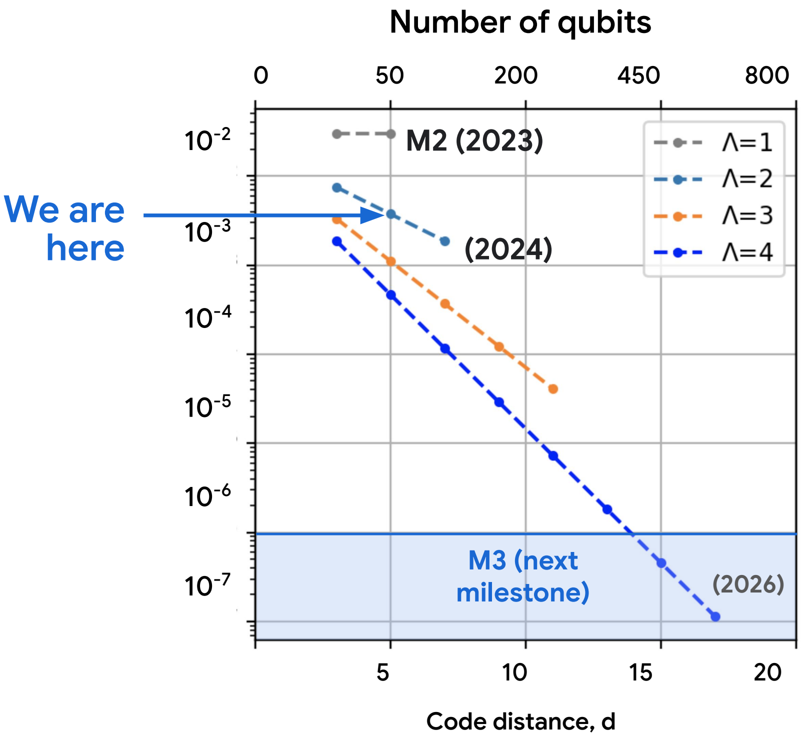
This is **2x better than M2 results** in 2023, with **error 20x better.**

This demonstrates a key strength of the Willow chip: **it is designed with error correction (and therefore scaling) in mind.**



Where do we go from here: M3

(a long-lived logical qubit)



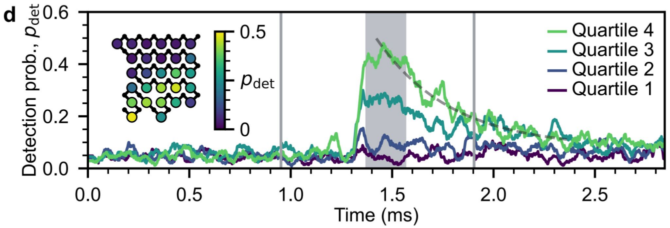
Repetition codes: ultra-low error regime

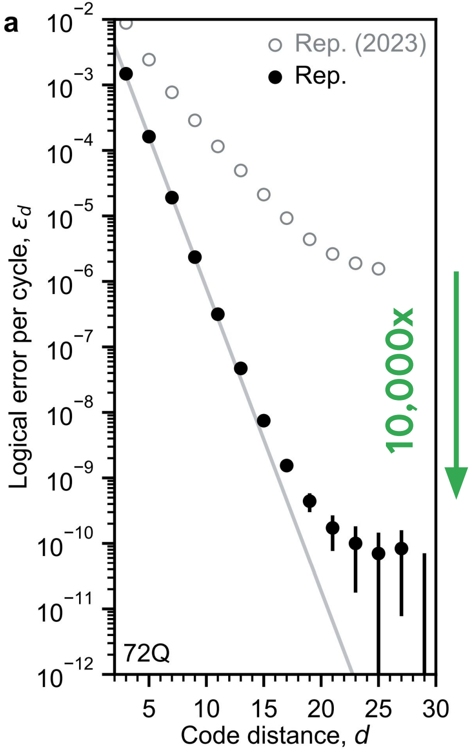
“Easy mode” 1D version of surface code

Exponential suppression over many orders of magnitude ($\Lambda = 8.4$)

Discovered new, rare error mechanism (Ongoing work to diagnose and fix)

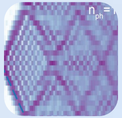
Rare error bursts (roughly one per hour) set floor, 10^{-10}





The road to practical quantum computing

Previous-gen processors are already useful for science discoveries



Formation of robust bound states of interacting microwave photons

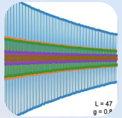
(Morvan et al., Nature 2022)

Purification-based quantum error mitigation of pair-correlated electron simulations

(O'Brien et al., Nature Physics 2023)

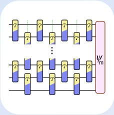
Dynamics of magnetization at infinite temperature in a Heisenberg spin chain

(Rosenberg et al., Science 2024)



Noise-resilient edge modes on a chain of superconducting qubits

(Mi et al., Science 2022)



Measurement-induced entanglement and teleportation on a noisy quantum processor

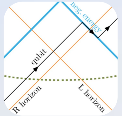
(Hoke et al., Nature 2023)

Stable quantum-correlated many body states via engineered dissipation

(Mi et al., Science 2024)

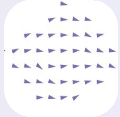
Quantum advantage in learning from experiments

(Huang et al., Science 2022)



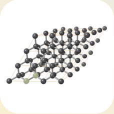
Traversable wormhole dynamics on a quantum processor

(Jafferis et al., Nature 2023)



Thermalization and criticality on an analog-digital quantum simulator

(Anderson et al., in review at Nature)



Unbiasing fermionic quantum Monte Carlo with a quantum computer

(Huggins et al., Nature 2022)

Non-Abelian braiding of graph vertices in a superconducting processor

(Andersen et al., Nature 2023)

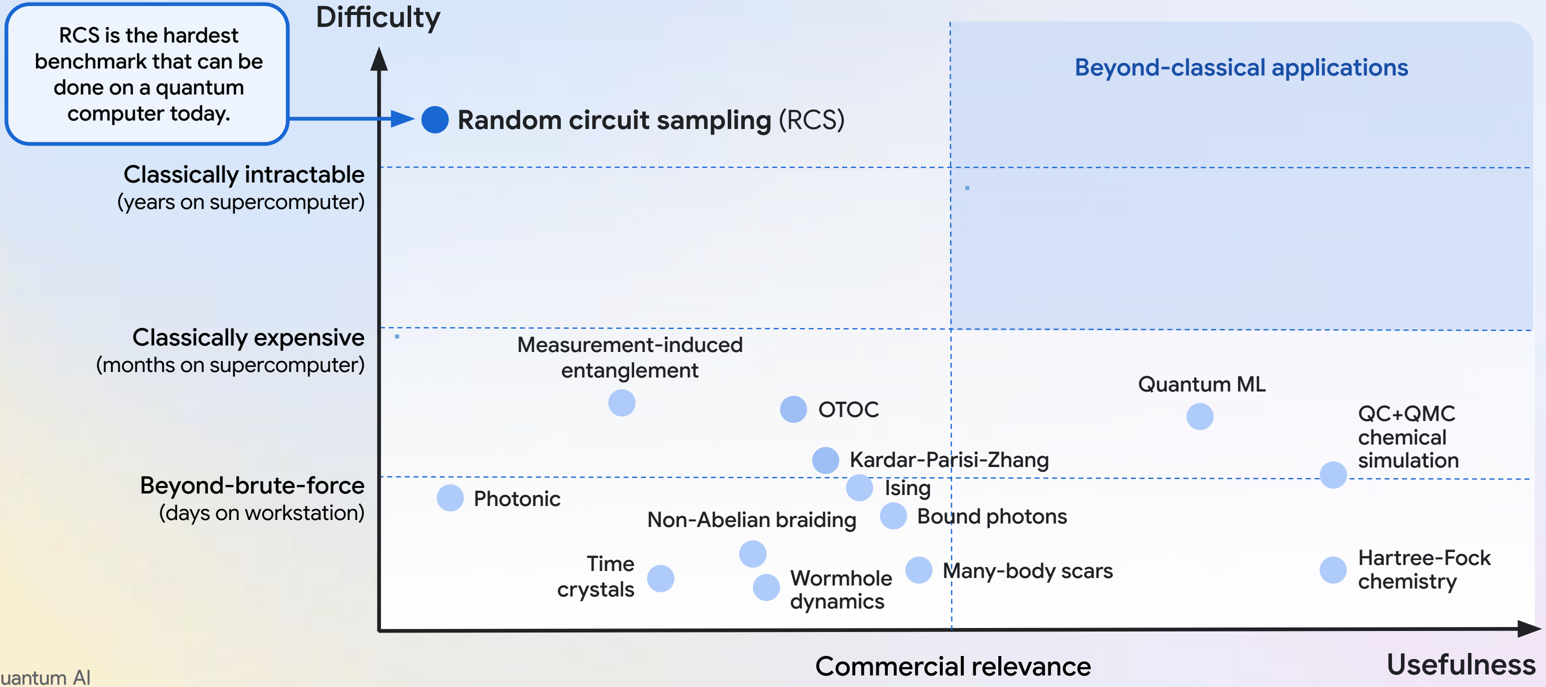
Observation of disorder-free localization and efficient disorder averaging on a quantum processor

(Gayawali et al., in review at Science)

What Willow Means for the Future

Willow is a big step towards developing a large-scale, error-corrected quantum computer.

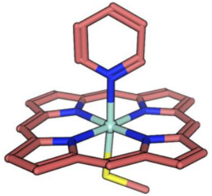
Its' capabilities gets us closer to a system that can deliver commercially useful applications that are not possible on a quantum computer.



RCS is the hardest benchmark that can be done on a quantum computer today.

We have been developing a number of applications, with partners

Boehringer Ingelheim

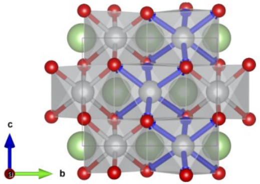


Drug discovery

Cytochrome P450 (anti-target)

PNAS 119, 2203533119 (2022)

BASF We create chemistry

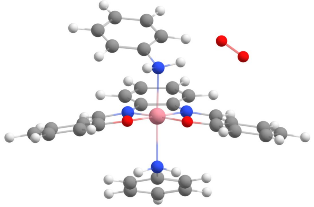


Battery design

$LiNiO_2$ (cathode material)

PRX Quant. 4, 040303 (2023)

covestro



Heterogeneous catalysis

Polyurethane synthesis

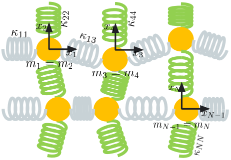
arXiv:2312.07654 (2023)

Sandia National Laboratories

Fusion reactor design

PNAS 121, e2317772121 (2022)

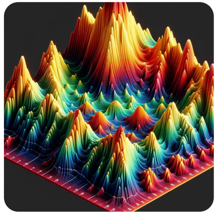
MACQUARIE University



Simulating classical oscillators

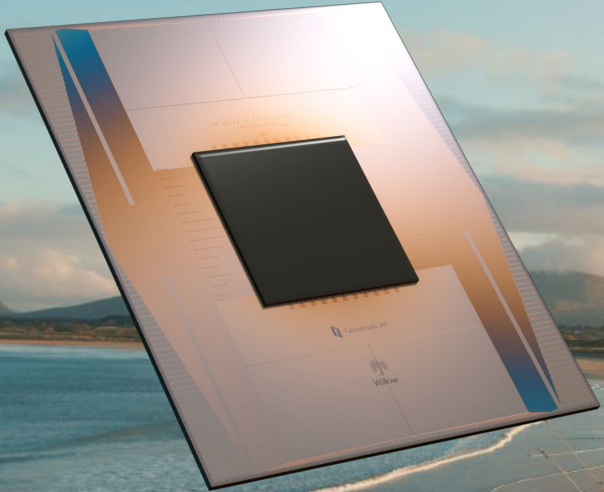
PRX 13, 041041(2023)

STANFORD UNIVERSITY



Classical optimization

arXiv:2408.08292



Willow

Build best-in-class quantum computing for otherwise unsolvable problems