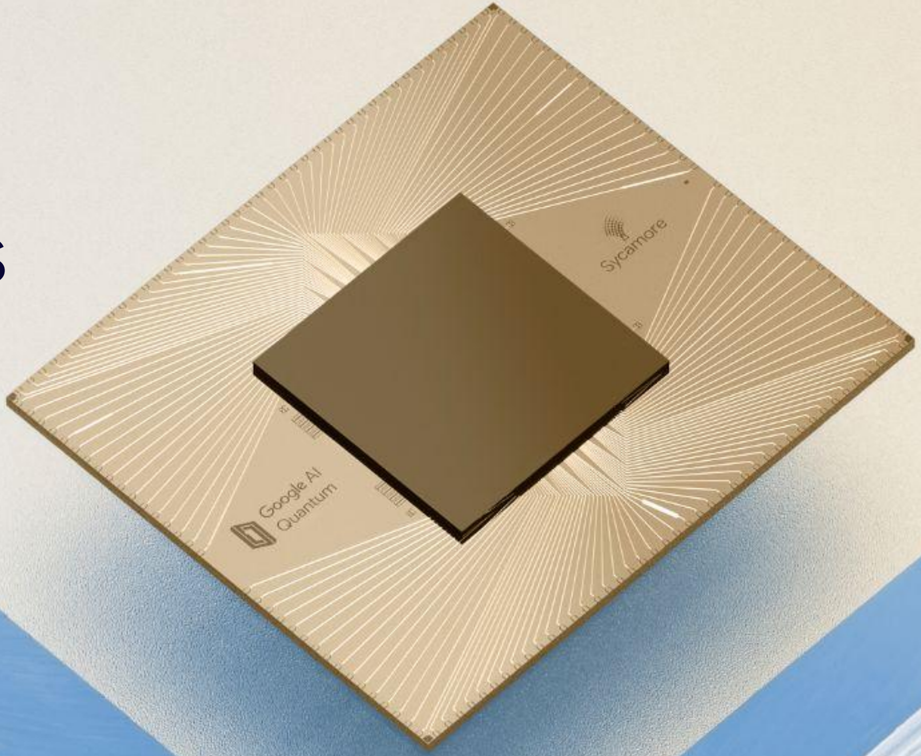
Quantum AI

Status and prospects for quantum computation

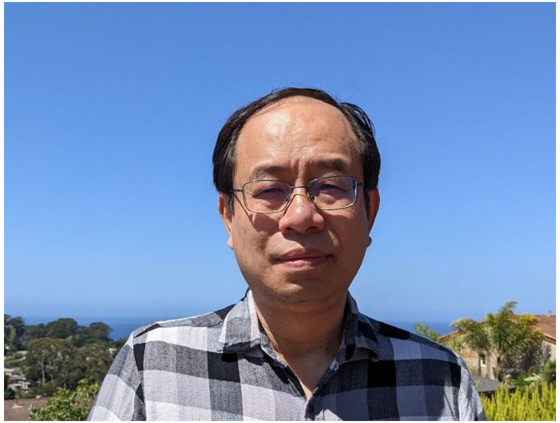


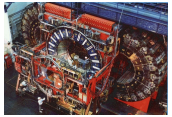
Ping Yeh <pingyeh@google.com>
opinions are my own, not my employer's

LHCP 2022-05-20

Google

Ping Yeh

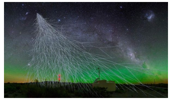




CDF / Fermilab: top quark mass from dilepton channel, Run II data production

AMS / CERN / NASA: data acquisition, particle back-tracing in geomag field

Belle / KEK: b -> eta' branching fraction



Neutrino telescope: Corsika simulation

Google: search quality, personalized home page, mobile app backend, ads attribution, Quantum OS

Influence from HEP

I. The fidelity result and the null hypothesis on quantum supremacy

We use the mean fidelity of ten 53-qubit 20-cycle circuits as the final benchmark of the system. In section VIII G we estimated the fidelity and statistical uncertainty to be $(2.24 \pm 0.18) \times 10^{-3}$ using the linear cross entropy. In section VIII H we estimated the relative systematic uncertainty due to drift to be 4.4%. Combining these 2 estimations we arrive at the final fidelity as $(2.24 \pm 0.10(\text{syst.}) \pm 0.18(\text{stat.})) \times 10^{-3}$.

...

complete the same noisy sampling. Therefore we form the null hypothesis that the fidelity of the quantum computer is $F \leq 10^{-3}$, and the alternative hypothesis that

...

The total uncertainty on fidelity is estimated with addition in quadrature of systematic uncertainty and statistical uncertainty. The mean fidelity of 10 random circuits with 53 qubits and 20 cycles is $(2.24 \pm 0.21) \times 10^{-3}$. The null hypothesis is therefore rejected with a significance of $6\ \sigma$.

Article

Quantum supremacy using a programmable superconducting processor

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The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor[1]. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here we report the use of a processor with programmable superconducting qubits[2–7] to create quantum states on 53 qubits, corresponding to a computational state-space of dimension 2^{53} (about 10^{16}). Measurements from repeated experiments sample the resulting probability distribution, which we verify using classical simulations. Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years. This dramatic increase in speed compared to all known classical algorithms is an experimental realization of quantum supremacy[8–14] for this specific computational task, heralding a much-anticipated computing paradigm.

In the early 1980s, Richard Feynman proposed that a quantum computer would be an effective tool with which to solve problems in physics and chemistry, given that it is exponentially costly to simulate large quantum systems with classical computers[1]. Realizing Feynman's vision poses substantial experimental and theoretical challenges. First, can a quantum system be engineered to perform a computation in a large enough computational (Hilbert) space and with a low enough error rate to provide a quantum speedup? Second, can we formulate a problem that is hard for a classical computer but easy for a quantum computer? By computing such a benchmark task on our superconducting qubit processor, we tackle both questions. Our experiment achieves quantum supremacy, a milestone on the path to full-scale quantum computing[8–14].

In reaching this milestone, we show that quantum speedup is achievable in a real-world system and is not precluded by any hidden physical laws. Quantum supremacy also heralds the era of noisy intermediate-scale quantum (NISQ) technologies[15]. The benchmark task we demonstrate has an immediate application in generating certifiable random numbers (S. Aaronson, manuscript in preparation); other initial uses for this new computational capability may include optimization[16,17], machine learning[18–21], materials science and chemistry[22–24]. However, realizing the full promise of quantum computing (using Shor's algorithm for factoring, for example) still requires technical leaps to engineer fault-tolerant logical qubits[25–29].

To achieve quantum supremacy, we made a number of technical advances which also pave the way towards error correction. We

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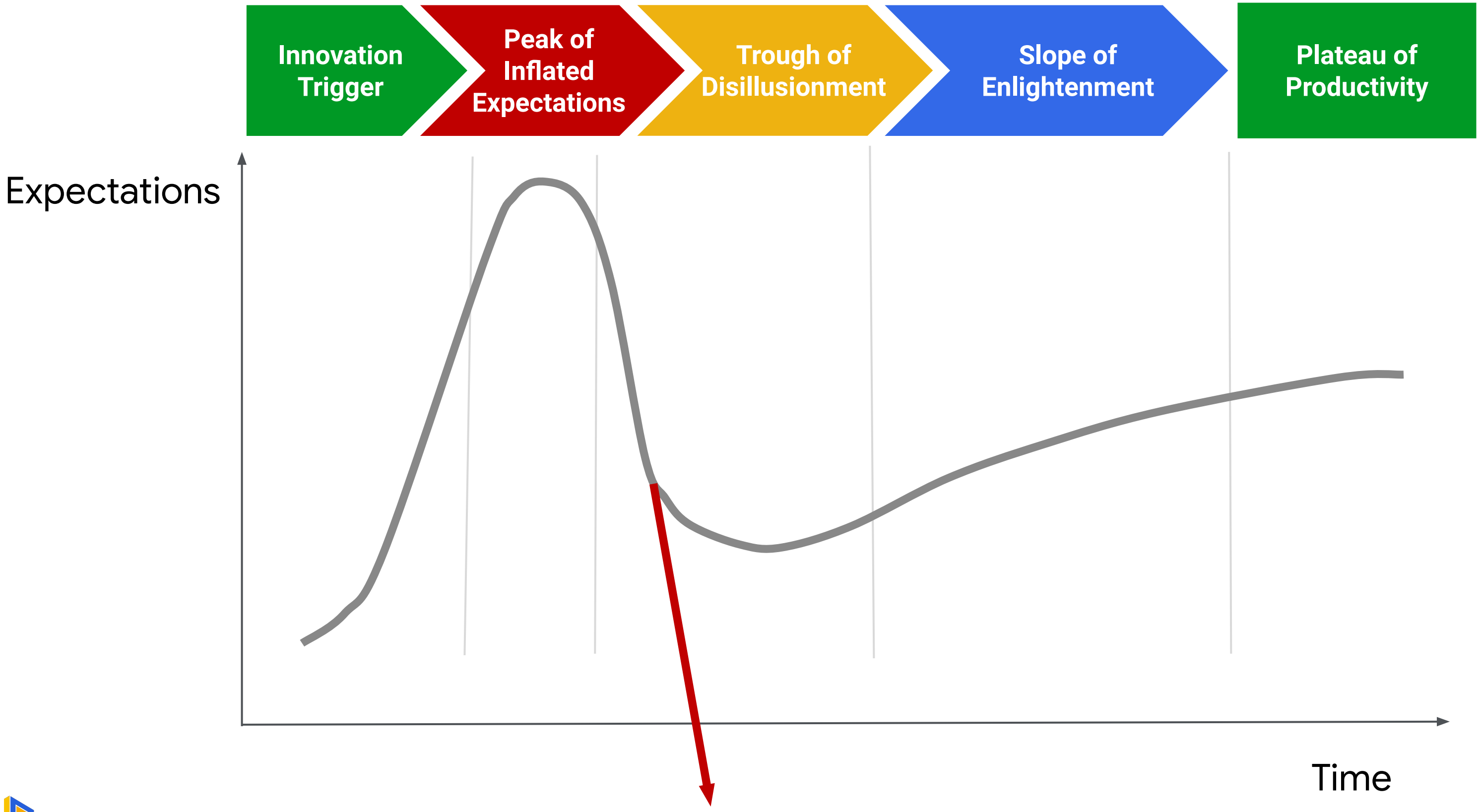
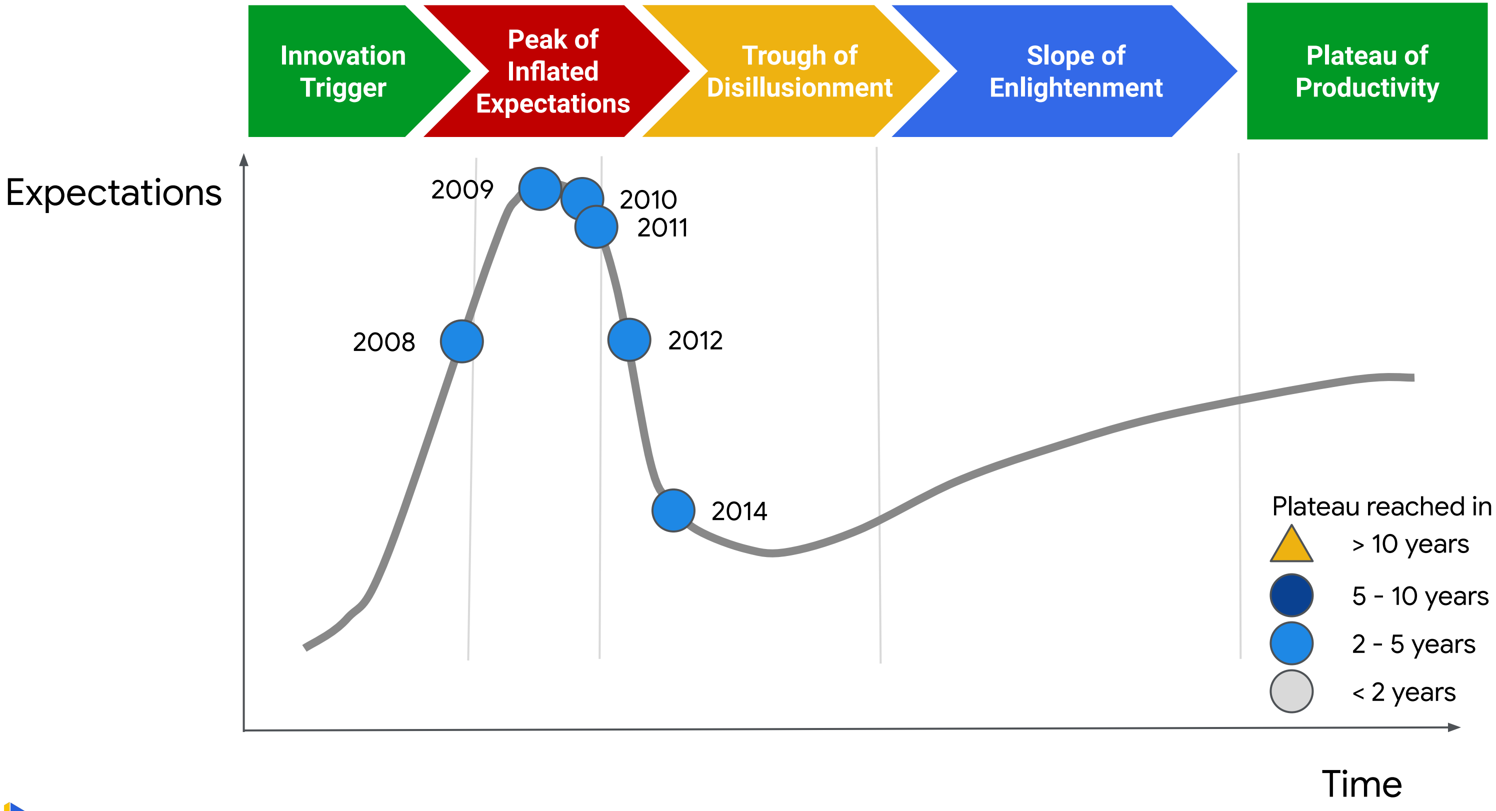
Nature 574, 505-510 (2019)
https://www.nature.com/articles/s41586-019-1666-5

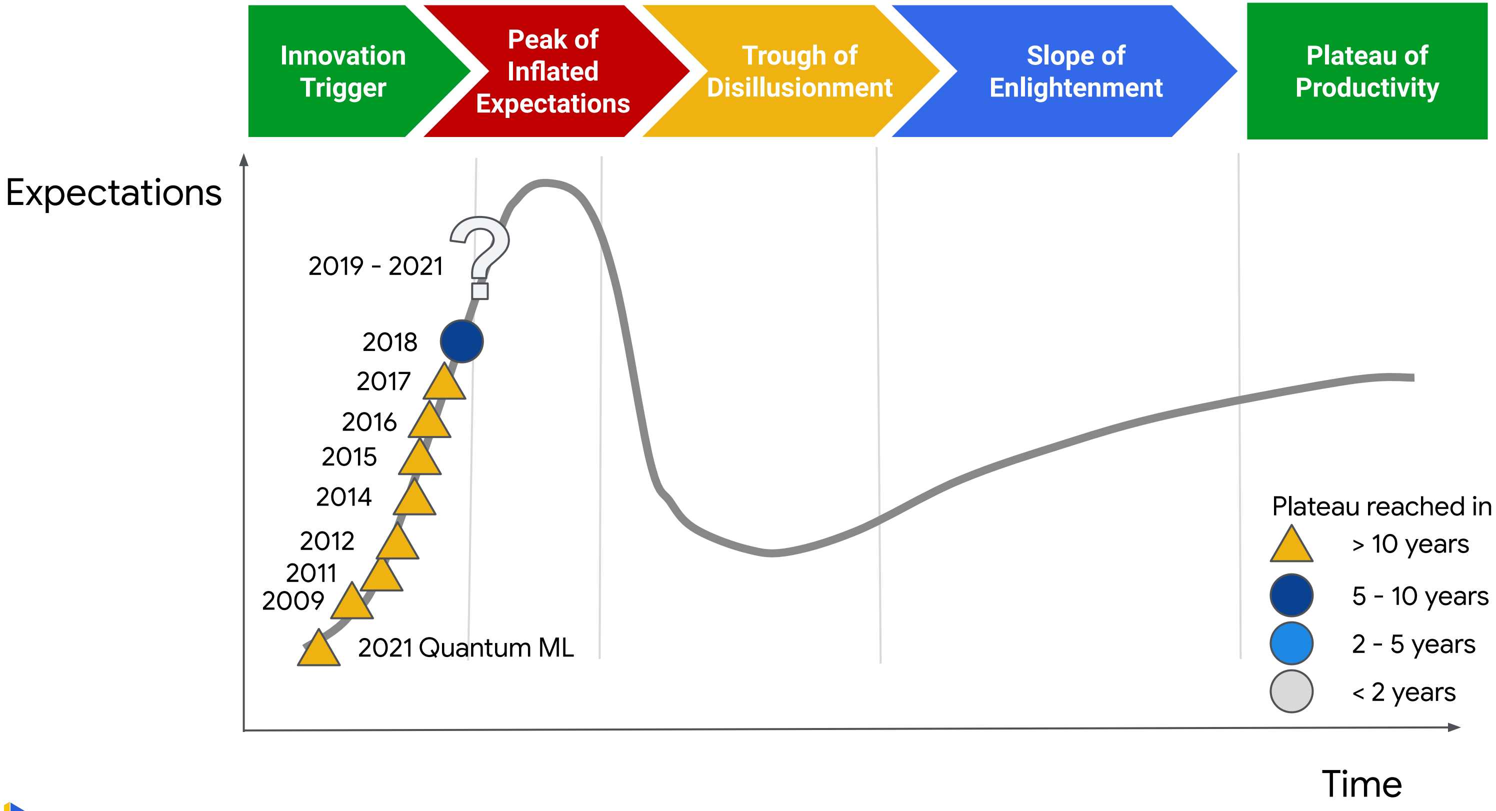
Gartner hype cycle of technologies



Past example: Cloud Computing



Quantum Computing on the hype curve



Quantum Computers

Quantum Computing

Physical qubit systems

Neutral atoms

Trapped ions

Quantum dots

Photons

Nitrogen-vacancy centers

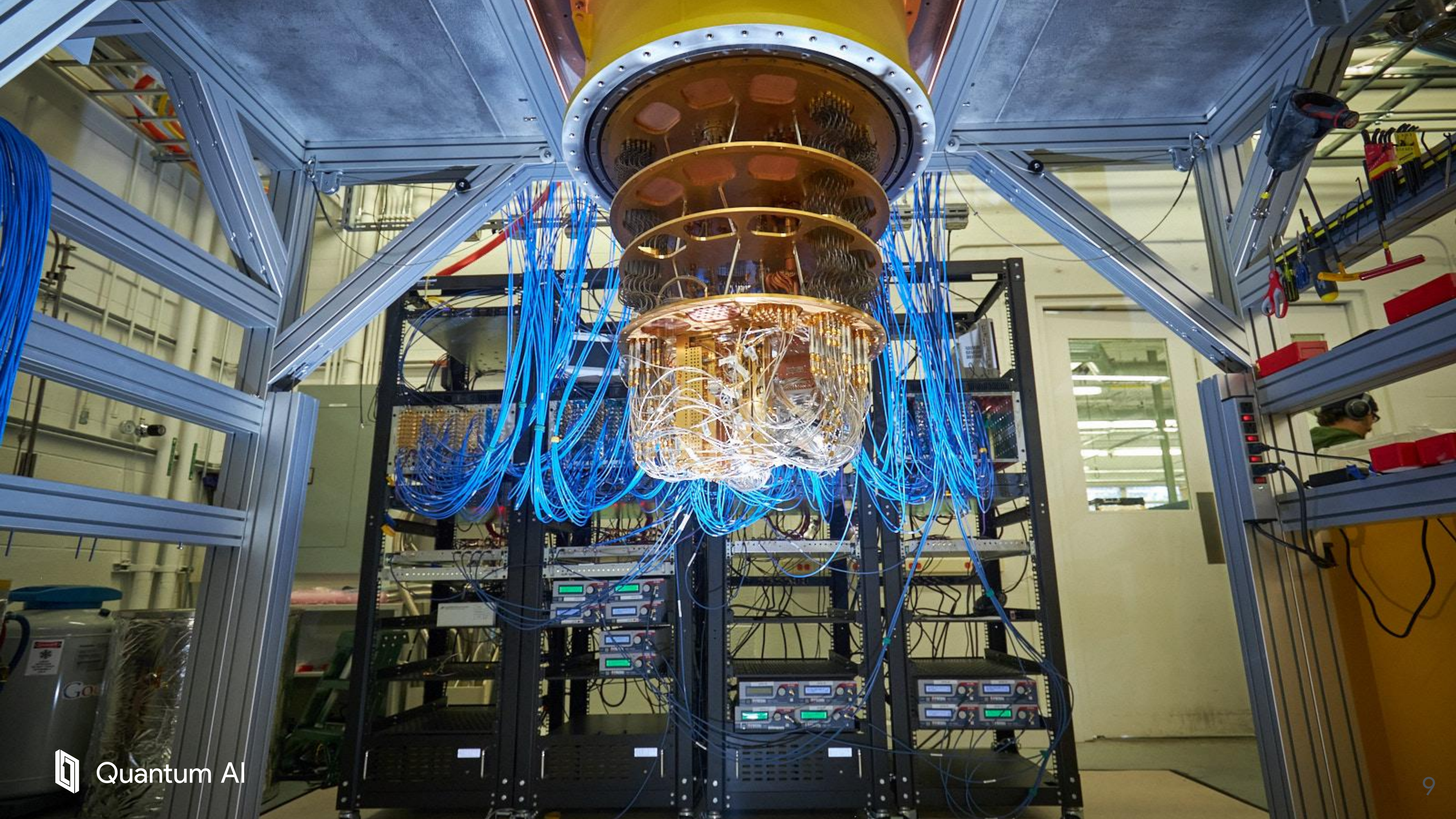
Topological

Superconductors

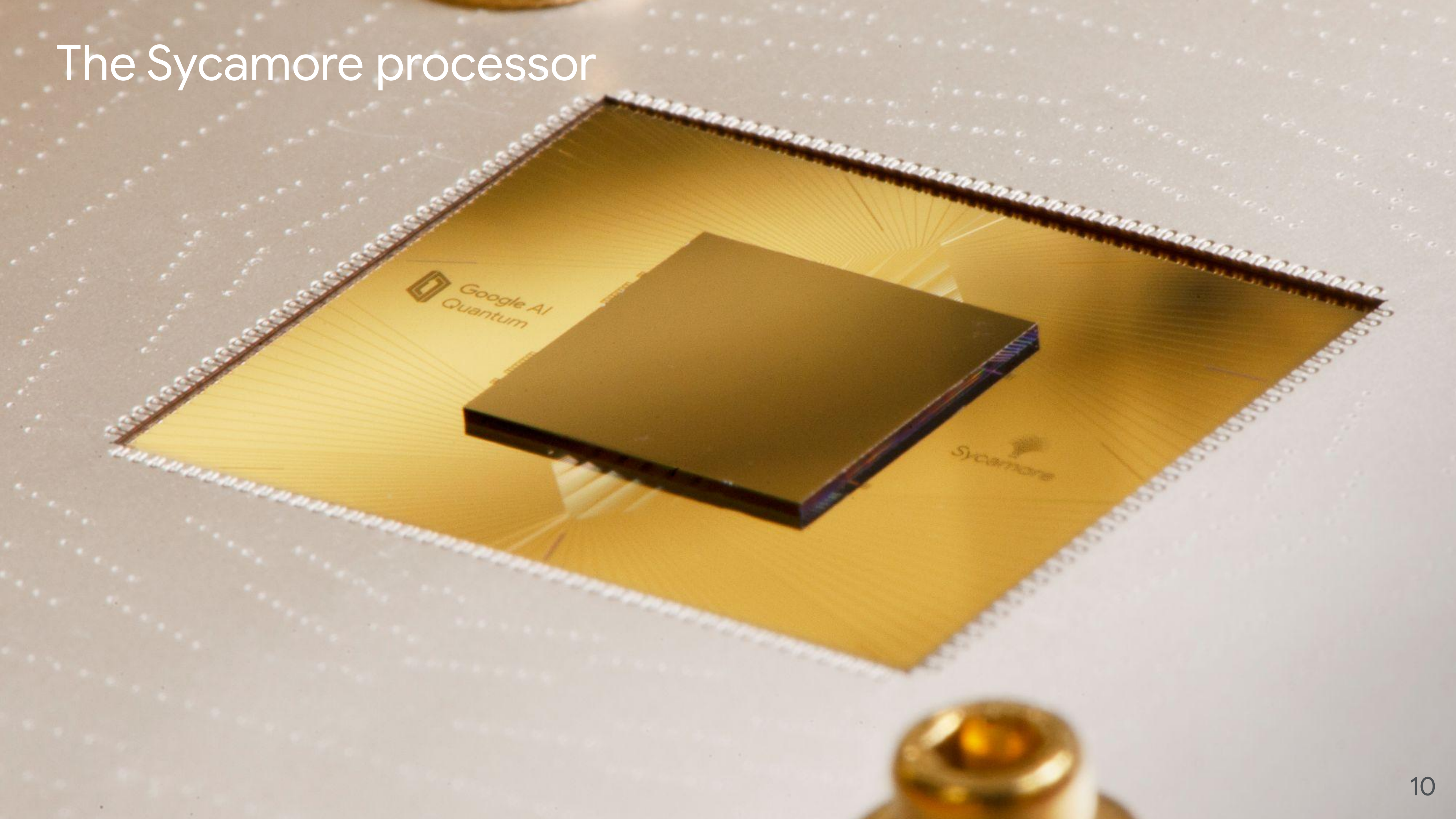
...

Organization	Adiabatic/Annealing	Superconducting	Trapped Ion	Cold/Neutral/Helium Atom	Spin/Quantum Dot/CMOS	Photonic	NV Diamond/NMR	Topological
Organizations:113 Projects:146	6	36	28	11	23	28	8	7
Alibaba/CAS		X						
Alice&Bob		X				X		
Alpine Quantum Technologies			X					
Amazon		X						
Anyon		X						
...								
ETH Zurich / Paul Sherrer Institute		X	X					
Google	X	X						
Griffith Univ./Univ. Of Queensland						X		
Hitachi Cambridge Laboratory					X			
Hon Hai (Foxconn)			X					
Honeywell (Quantinuum)			X					
HRL Laboratories					X			
IBM		X						
ID Quantique						X		
Infineon		X	X		X			
infinityQ					X			
Institut d'Optique				X				
Intel		X			X			
IonQ			X					

source: quantumcomputingreport.com


Quantum AI

The Sycamore processor



Quantum error correction

Quantum system + environment -> error

No-clone theorem: can not copy a qubit of unknown state

~~Classical majority vote algorithm~~

Arbitrary error -> probabilities

- bit flip error (X)
- phase flip error (Z)

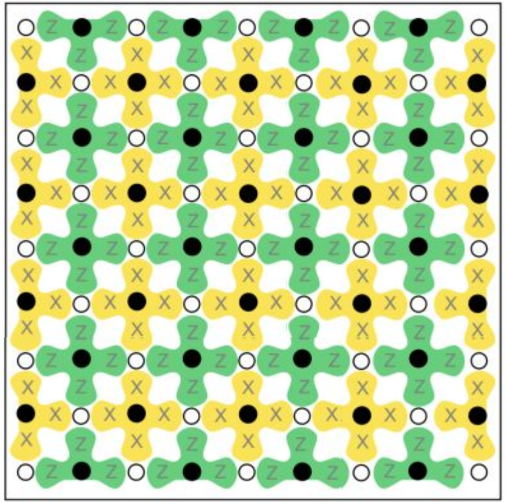
$$\text{Error per logical gate} \propto \left(\frac{\text{Error per physical gate}}{\text{Error correction threshold}} \right)^{(d+1)/2}$$

1 / Λ

○ Data qubit

● Measure qubit

d = 5



(conceptual depiction)

Fowler et. al., Phys. Rev. A 86

Error correction: proof of principle

Article

Exponential suppression of bit or phase errors with cyclic error correction

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Published online: 14 July 2021
Open access
Check for updates

Google Quantum AI*

Realizing the potential of quantum computing requires sufficiently low logical error rates[1]. Many applications call for error rates as low as 10^{-15} (refs. [2–9]), but state-of-the-art quantum platforms typically have physical error rates near 10^{-3} (refs. [10–14]). Quantum error correction[15–17] promises to bridge this divide by distributing quantum logical information across many physical qubits in such a way that errors can be detected and corrected. Errors on the encoded logical qubit state can be exponentially suppressed as the number of physical qubits grows, provided that the physical error rates are below a certain threshold and stable over the course of a computation. Here we implement one-dimensional repetition codes embedded in a two-dimensional grid of superconducting qubits that demonstrate exponential suppression of bit-flip or phase-flip errors, reducing logical error per round more than 100-fold when increasing the number of qubits from 5 to 21. Crucially, this error suppression is stable over 50 rounds of error correction. We also introduce a method for analysing error correlations with high precision, allowing us to characterize error locality while performing quantum error correction. Finally, we perform error detection with a small logical qubit using the 2D surface code on the same device[18,19] and show that the results from both one- and two-dimensional codes agree with numerical simulations that use a simple depolarizing error model. These experimental demonstrations provide a foundation for building a scalable fault-tolerant quantum computer with superconducting qubits.

Many quantum error-correction (QEC) architectures are built on stabilizer codes[20], where logical qubits are encoded in the joint state of multiple physical qubits, which we refer to as data qubits. Additional physical qubits known as measure qubits are interlaced with the data qubits and are used to periodically measure the parity of chosen data qubit combinations. These projective stabilizer measurements turn undesired perturbations of the data qubit states into discrete errors, which we track by looking for changes in parity. The stream of parity values can then be decoded to determine the most likely physical errors that occurred. For the purpose of maintaining a logical quantum memory in the codes presented in this work, these errors can be compensated in classical software[3]. In the simplest model, if the physical error per operation p is below a certain threshold p_{th} determined by quantum computer architecture, chosen QEC code and decoder, then the probability of logical error per round of error correction (ε_L) should scale as:

$$\varepsilon_L = C/\Lambda^{(d+1)/2}. \quad (1)$$

Here, $\Lambda \propto p_{th}/p$ is the exponential error suppression factor, C is a fitting constant and d is the code distance, defined as the minimum number of physical errors required to generate a logical error, and increases with the number of physical qubits[3,21]. More realistic error models cannot be characterized by a single error rate p or a single threshold value p_{th}. Instead, quantum processors must be benchmarked by measuring Λ.

Many previous experiments have demonstrated the principles of stabilizer codes in various platforms such as nuclear magnetic resonance[22,23], ion traps[24–26] and superconducting qubits[19,21,27,28]. However, these results cannot be extrapolated to exponential error suppression in large systems unless non-idealities such as crosstalk are well understood. Moreover, exponential error suppression has not previously been demonstrated with cyclic stabilizer measurements, which are a key requirement for fault-tolerant computing but introduce error mechanisms such as state leakage, heating and data qubit decoherence during measurement[21,29].

In this work, we run two stabilizer codes. In the repetition code, qubits alternate between measure and data qubits in a 1D chain, and the number of qubits for a given code distance is $n_{qubits} = 2d - 1$. Each measure qubit checks the parity of its two neighbours, and all measure qubits check the same basis so that the logical qubit is protected from either X or Z errors, but not both. In the surface code[3,30–32], qubits follow a 2D chequerboard pattern of measure and data qubits, with $n_{qubits} = 2d^2 - 1$. The measure qubits further alternate between X and Z types, providing protection against both types of errors. We use repetition codes up to $d = 11$ to test for exponential error suppression and a $d = 2$ surface code to test the forward compatibility of our device with larger 2D codes.

QEC with the Sycamore processor

We implement QEC using a Sycamore processor[33], which consists of a 2D array of transmon qubits[34] where each qubit is tunably coupled to four nearest neighbours—the connectivity required for the surface

*A list of authors and their affiliations appears at the end of the paper.

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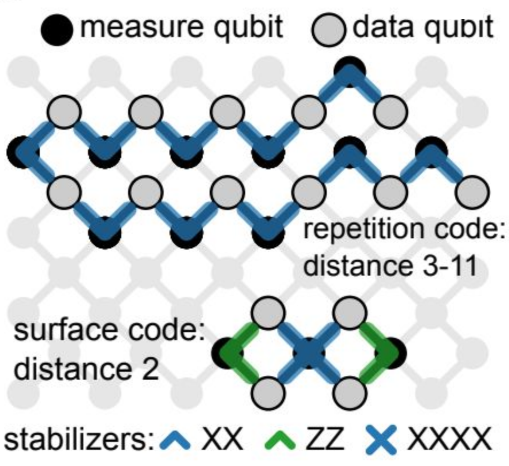
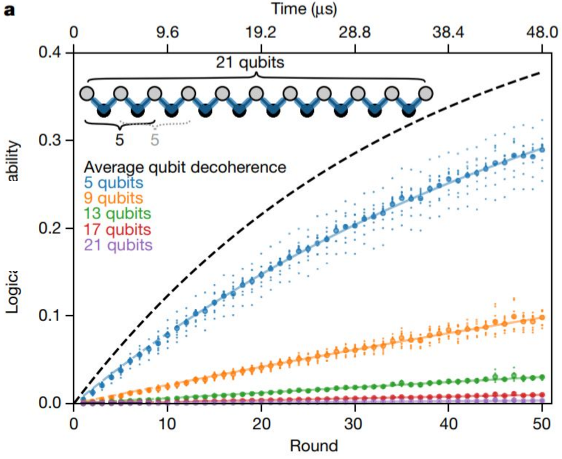
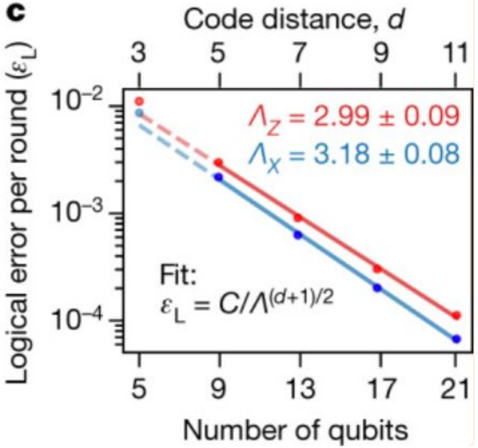
Exponential suppression of bit or phase errors with cyclic error correction



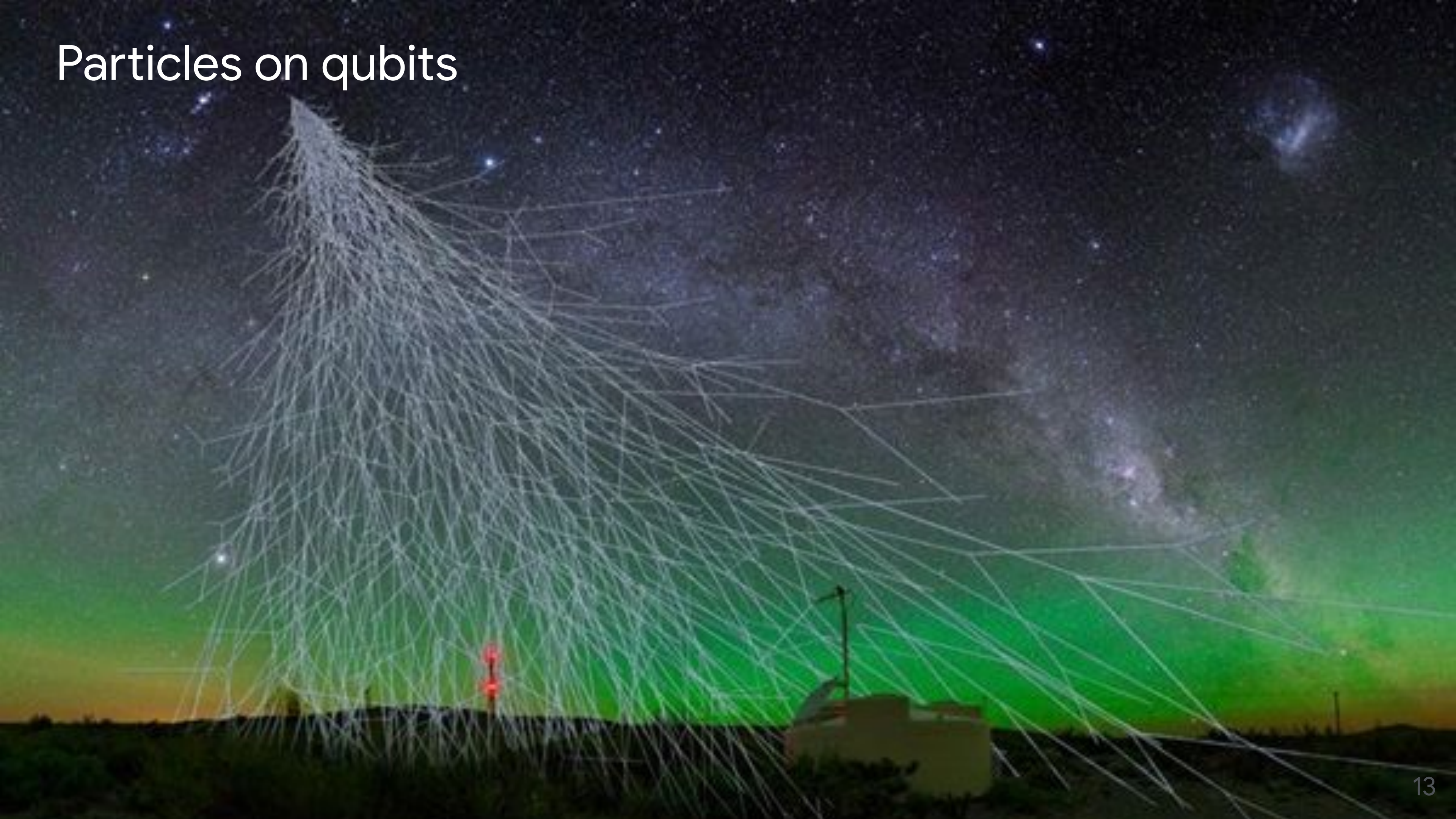
Layout of distance-11 repetition code and distance-2 surface code in the Sycamore processor.



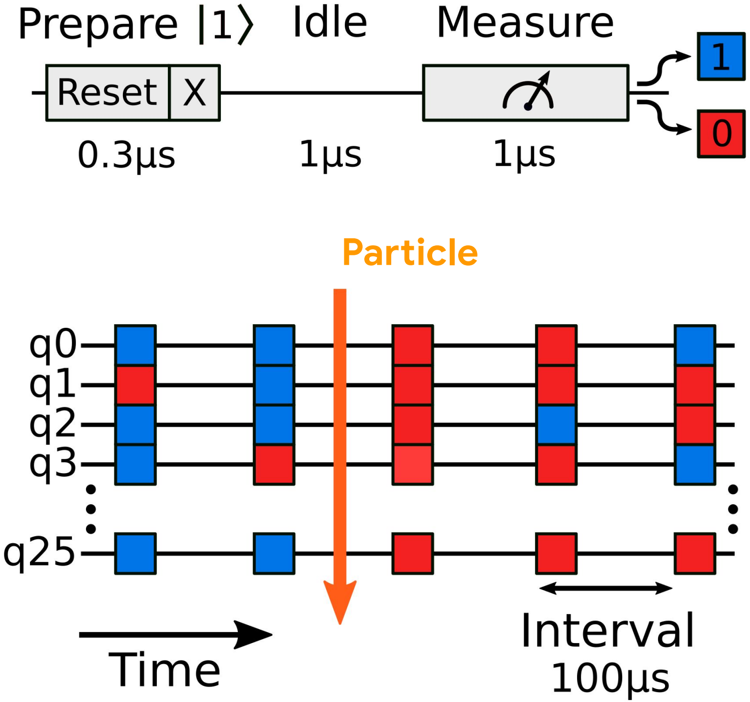


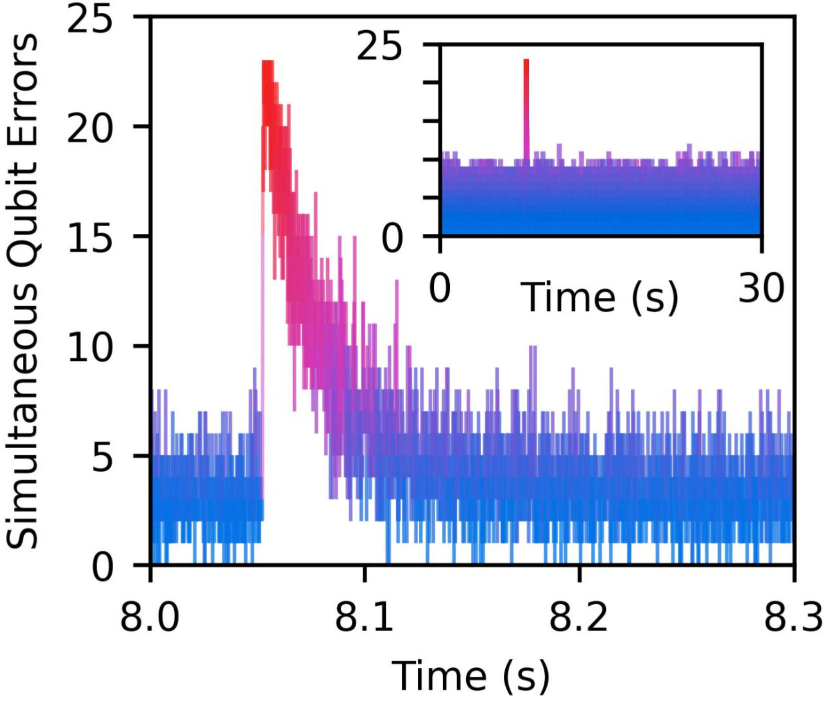
Nature 595, 383–387 (2021)

Particles on qubits

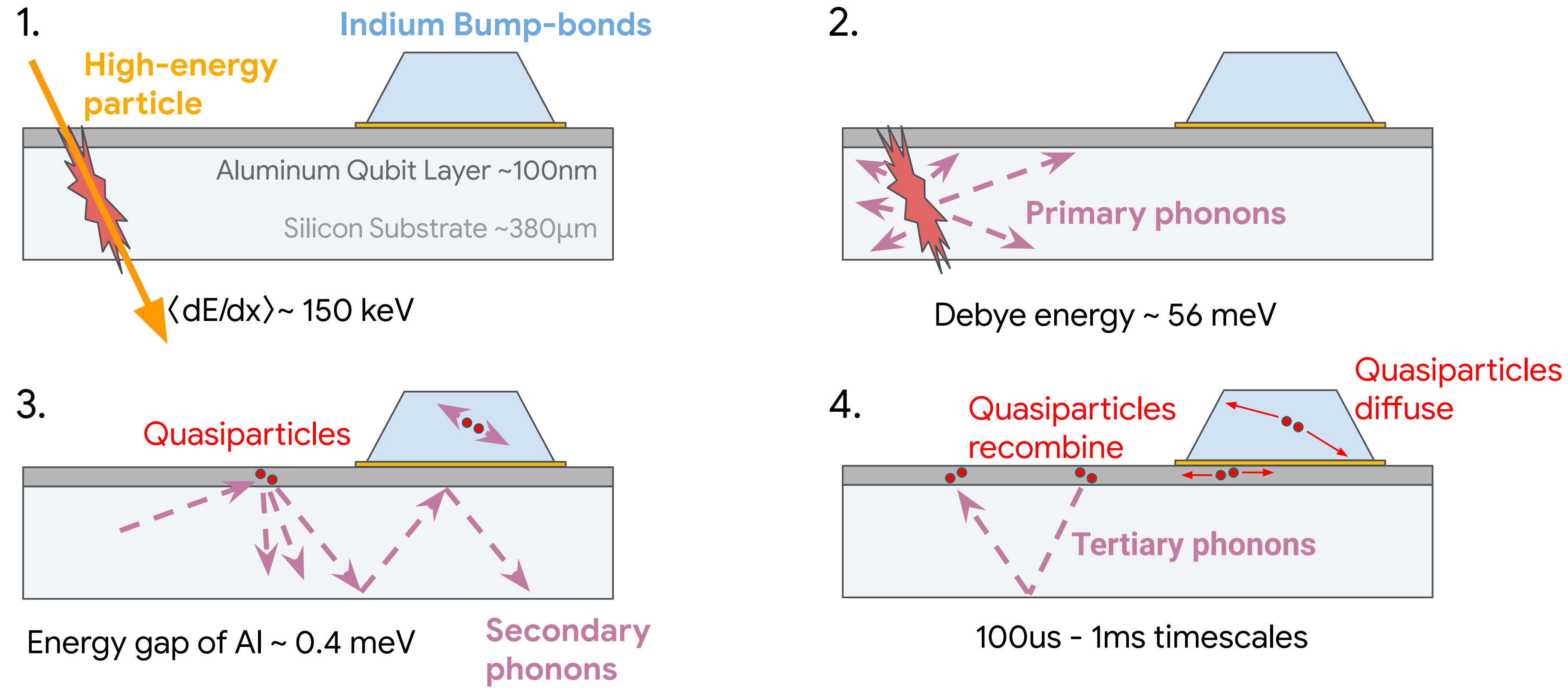


Rapid Repetitive Correlated Sampling





Story of an impact event



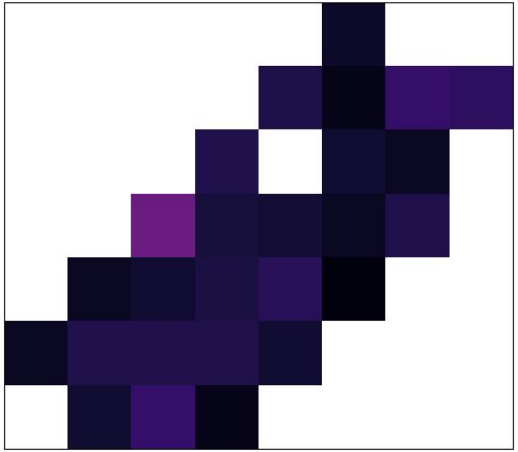
Space-time observations

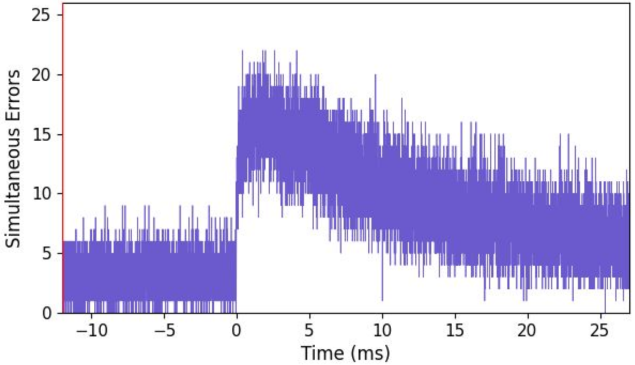
Time scales

- Ballistic spread ~ 10us
- Recombination ~ 1ms
- Thermalization ~ 25ms

Mitigations

- Near term: post-selection
- Long term: mitigation on the chip
  - low-gap phonon absorbers
  - phonon-reducing membranes





Nature Physics 18, 107-111 (2022)

Quantum Computers

Quantum Computing

Quantum Machine Learning

Proof of principle:

Photon + quantum sensor + quantum ML
vs.
Photon + classical sensor + classical ML

Exponentially fewer training samples

Quantum advantage in learning from experiments

Hsin-Yuan Huang,[1,2,*] Michael Broughton,[3] Jordan Cotler,[4,5] Sitan Chen,[6,7] Jerry Li,[8] Masoud Mohseni,[3] Hartmut Neven,[3] Ryan Babbush,[3] Richard Kueng,[9] John Preskill,[1,2,10] and Jarrod R. McClean[3,†]

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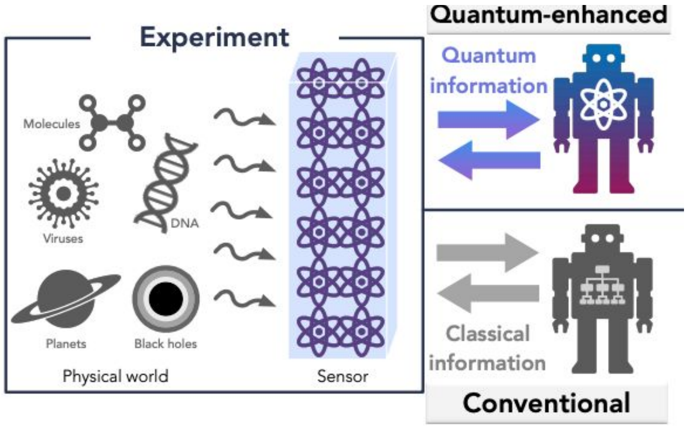
[10]*AWS Center for Quantum Computing, Pasadena, CA 91125, USA*
(Dated: December 3, 2021)

Quantum technology has the potential to revolutionize how we acquire and process experimental



arXiv:2112.00778 (Caltech + Google)

Quantum Simulation

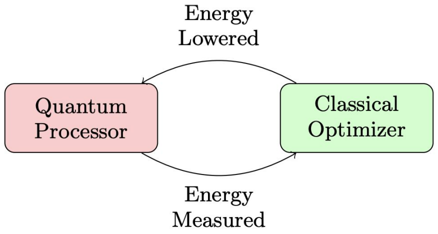
Many processes are quantum in nature

- Biology
- Chemistry
- Condensed matter physics
- Nuclear physics
- Particle physics
- ...

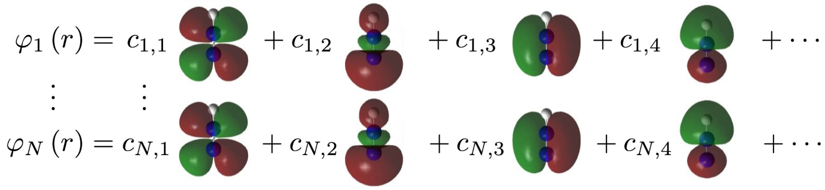
Feynman's killer app:
Using a quantum processor to compute/simulate quantum processes

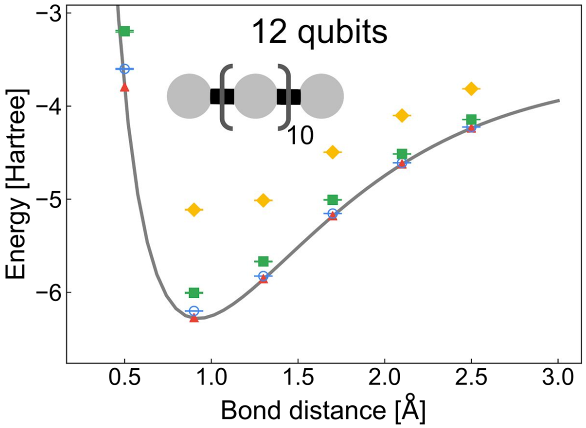
Chemistry example: ground state energy of H_{12}

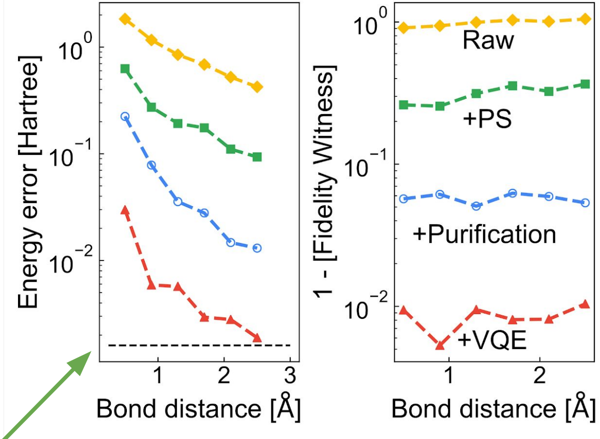
Variational Quantum Eigensolver (VQE)



Ansatz corresponds to a rotated orbital basis







Chemical accuracy

Science 2020; 369(6507): 1084-1089

Physics example: Time crystals

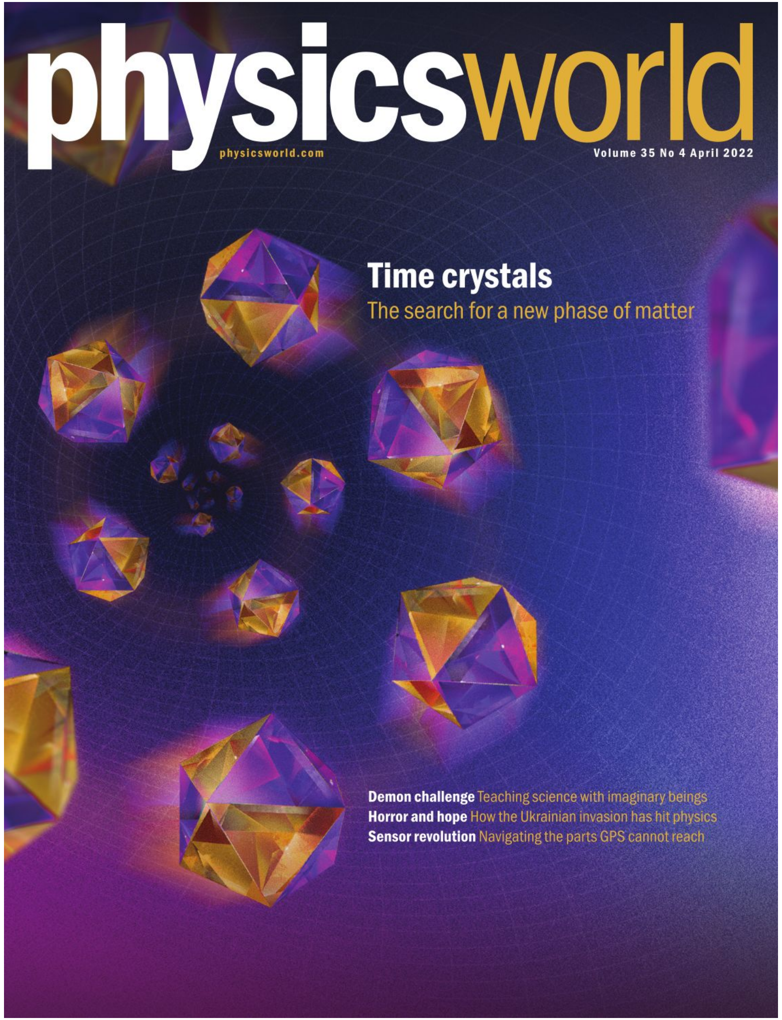
Multi-mode many-body system that repeats configurations in time without taking net energy from the environment

Proposed by Frank Wilczek in 2012

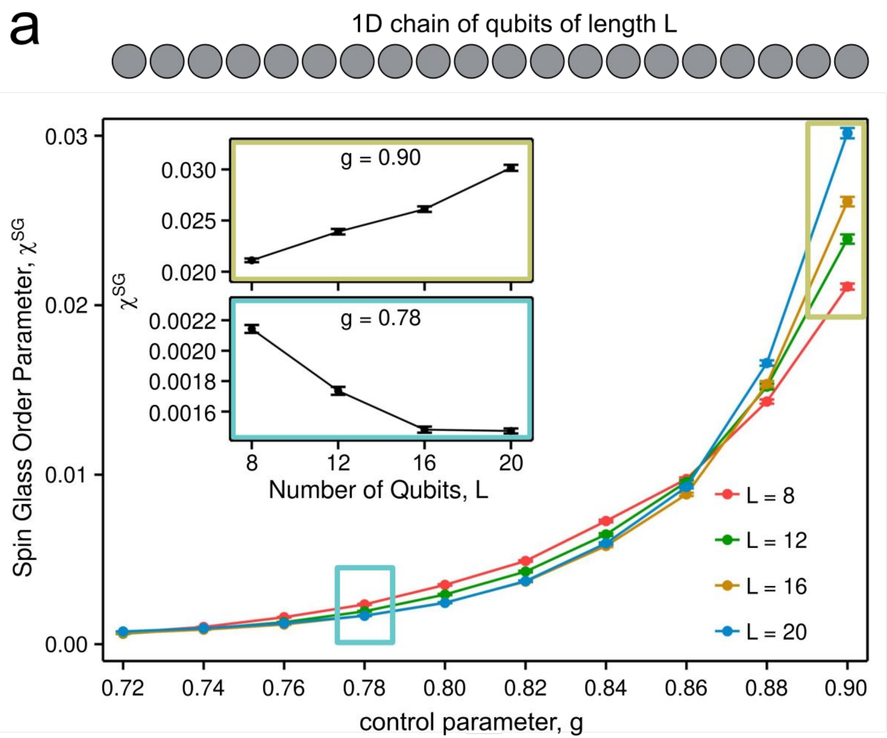
Proved not possible in thermal equilibrium (Watanabe / Oshikawa 2014)

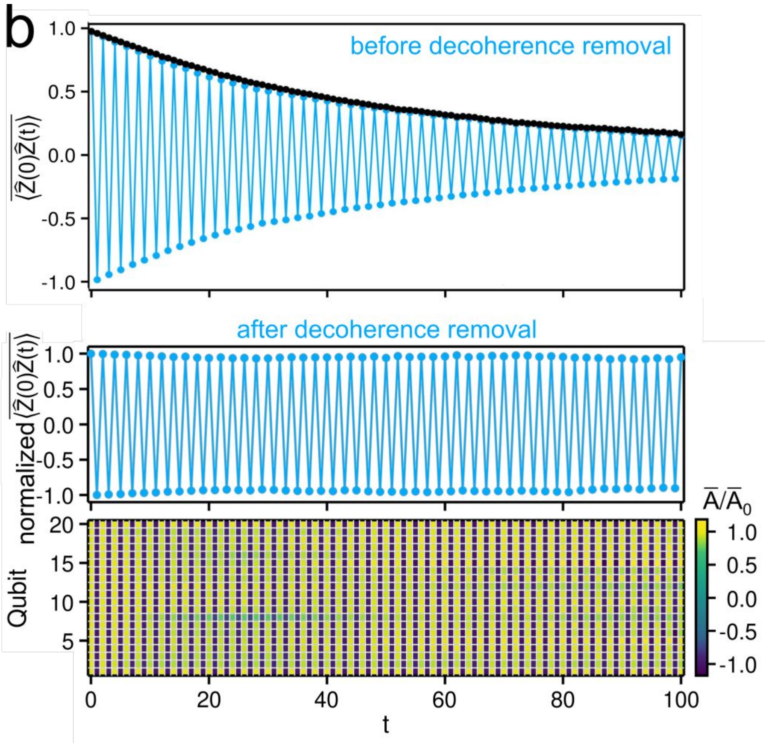
Periodic drive to stay out of equilibrium

- frequency = drive frequency / N



Phase transition and periodicity





Nature 601, 531-536 (2022)

Prospects

By their nature, forward-looking statements involves risks and uncertainties, and I undertake no obligation to update or revise publicly any of the forward-looking statements.

Photosynthesis

Nuclear fusion

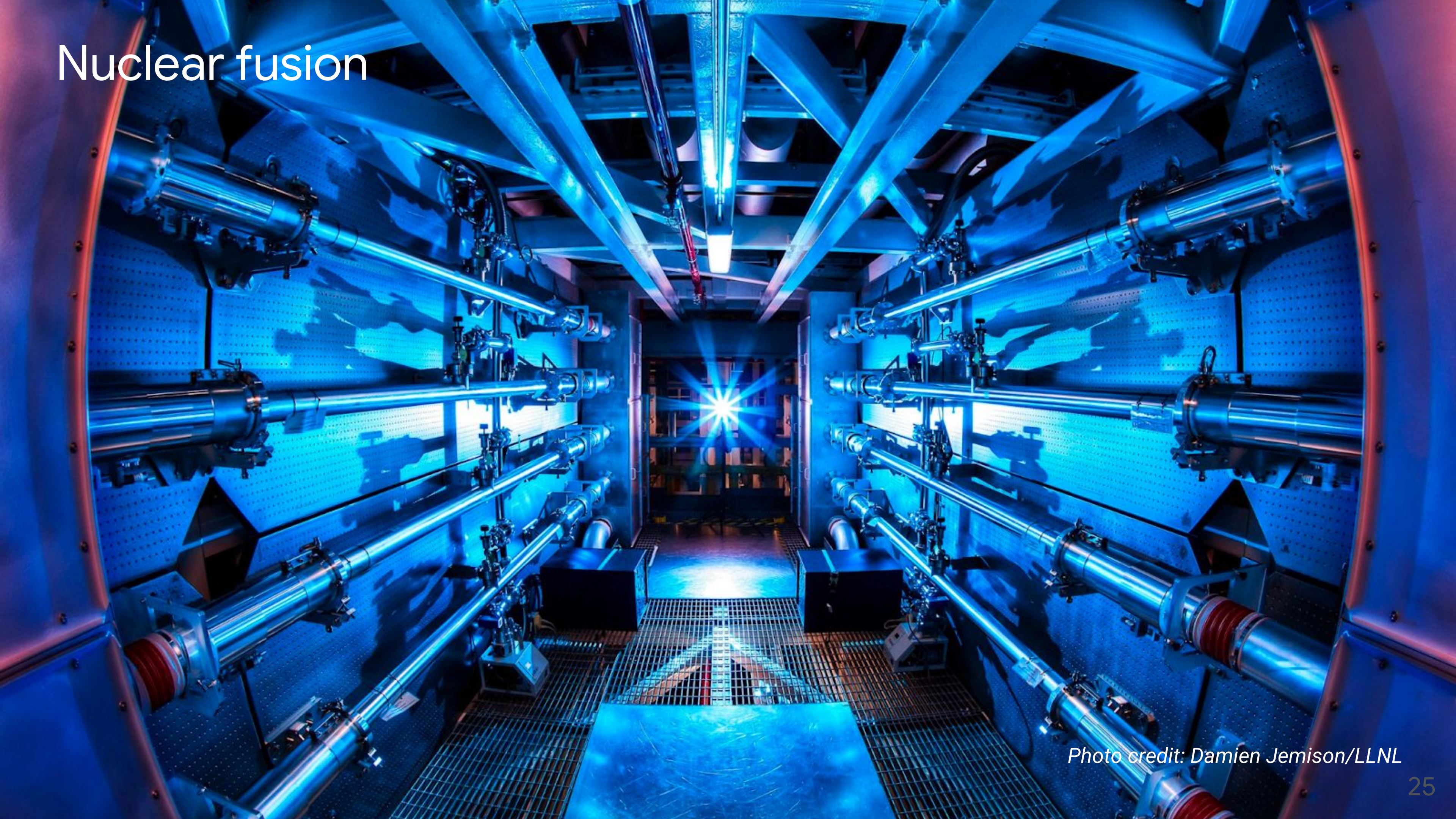
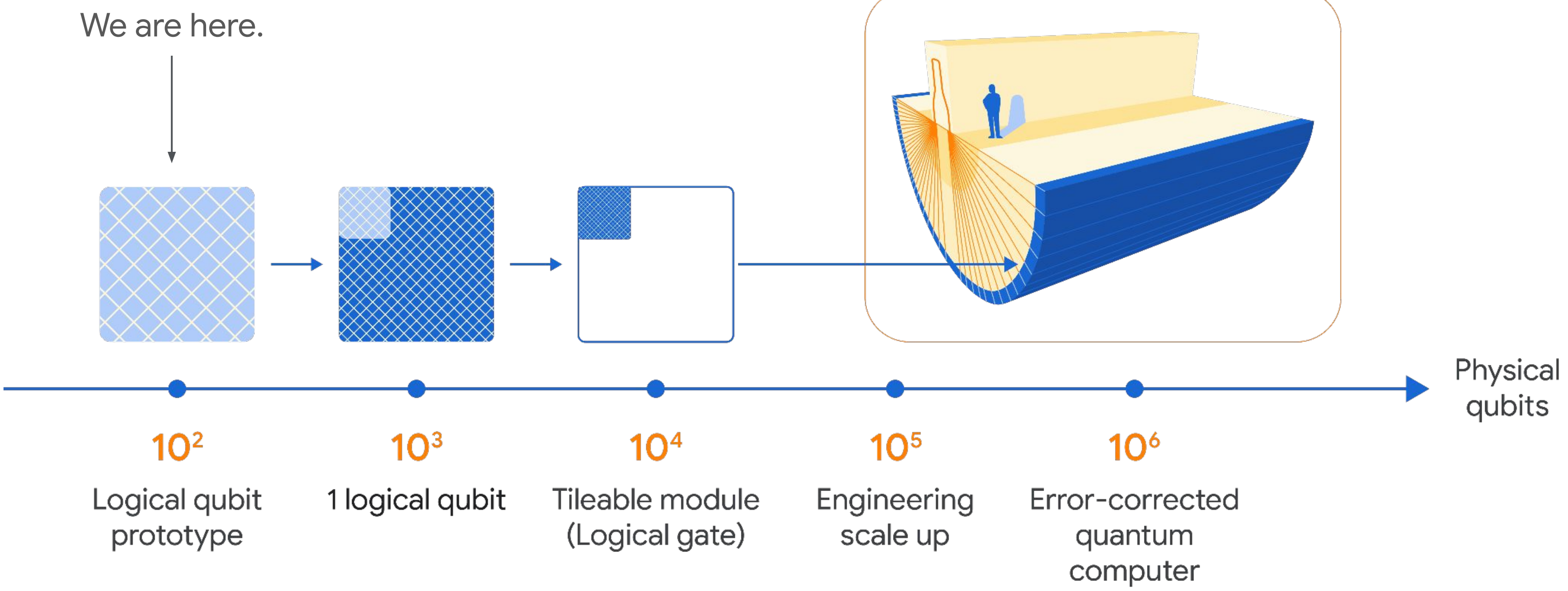


Photo credit: Damien Jemison/LLNL

Roadmap to an error corrected quantum computer



Summary

Building an error-corrected quantum computer is very challenging, likely many years away

Many advances on research now

- Some simulations can already produce good results on NISQ processors
- A quantum processor is a quantum many-body system you can manipulate and control — new research opportunities

Looking forward to HEP applications!

p.s. we're hiring!

Search "Quantum" on careers.google.com

- Calibration research scientist
- Software engineer
- Systems engineer
- Electrical engineer
- Readout hardware engineer
- Packaging simulation engineer
- Fabrication equipment engineer
- Analog mixed signal ASIC engineer
- Cryogenic operations engineer
- ...