Title: Within Chaos lies Advantage: Beyond-Classical Quantum Computation with Superconducting Qubits

Speakers: Xiao Mi

Series: Machine Learning Initiative

Date: June 06, 2022 - 3:00 PM

URL: https://pirsa.org/22060040

Abstract: The past decade has witnessed tremendous advancements in the size, coherence and control accuracy of qubits across various material platforms. In the case of superconducting qubits fabricated from Josephson junctions, quantum systems with over 50 qubits and >99% gate fidelities can now be reliably fabricated. In this talk, I will introduce the basics of superconducting qubits, with a particular focus on the implementation and calibration of two-qubit gates. I will then describe an experiment demonstrating quantum computational advantage on a specific task, namely sampling from random quantum circuits comprising 53 qubits [1]. The success of this experiment hinges on the chaotic dynamics underlying the random circuits, which generates sufficiently large entanglement to challenge classical simulation within the coherence times of the qubits. To systematically study the physics of quantum chaos, we perform a second experiment which investigates the "fingerprints" of chaos on local quantum observables [2]. We demonstrate how the two fundamental mechanisms of quantum chaos, operator spreading and operator entanglement, may be diagnosed by reversing the flow of time and measuring the so-called out-of-time-order correlators (OTOCs). Additionally, we find that with proper error-mitigation strategies, even local quantum observables such as OTOCs may be measured up to accuracies requiring non-trivial classical computational resources to simulate. These works pave a critical path toward using quantum computers for scientific discovery in the NISQ era.

[1] Google Quantum AI, Nature 574, 505 (2019).

[2] X. Mi et al., Science 374, 1479 (2021).

Zoom Link: https://pitp.zoom.us/j/93446337538?pwd=UXpsUFZ4M0tDSDd6bnA0VFBsazNPQT09

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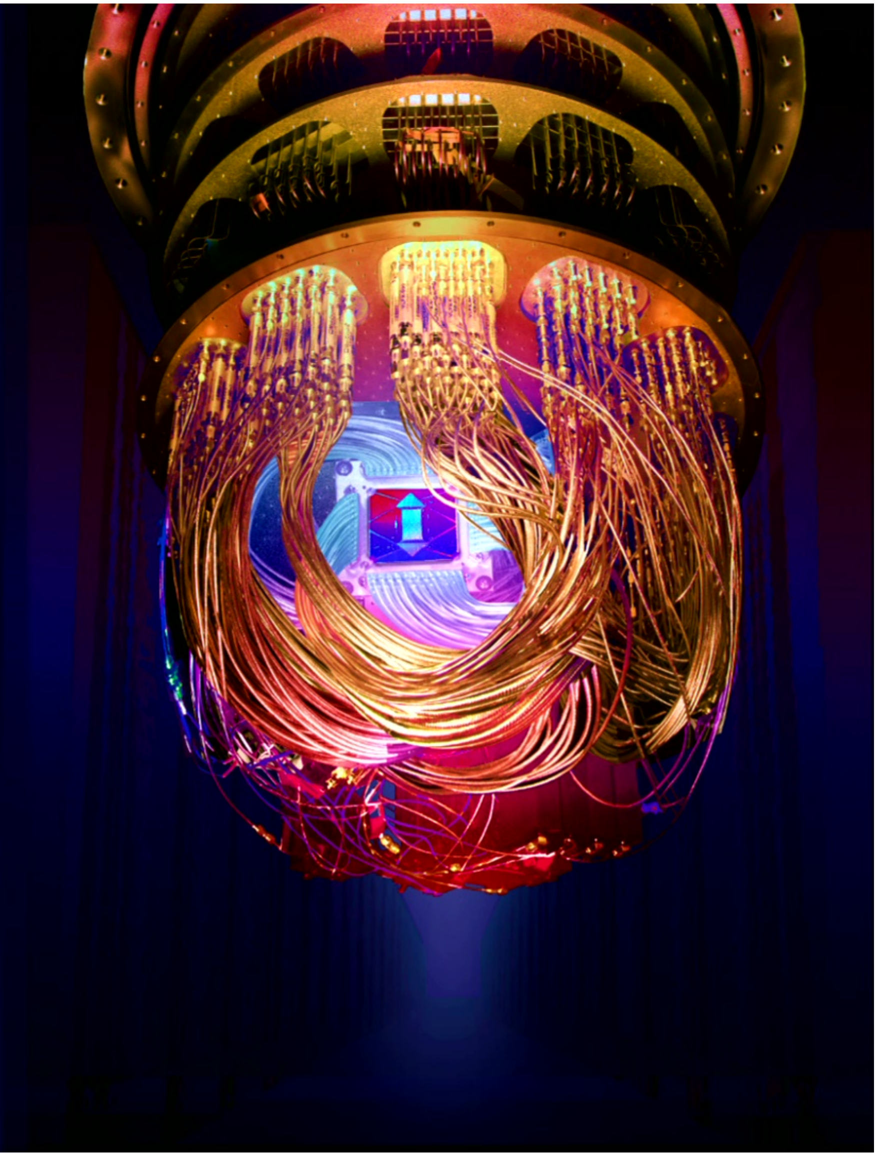
Quantum

Beyond-Classical Quantum Computation with Superconducting Qubits

Xiao Mi (mixiao@google.com)



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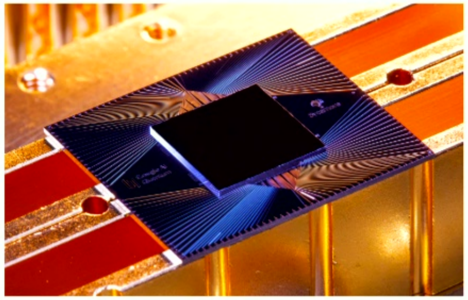
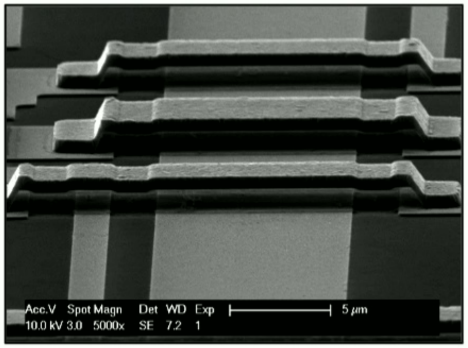
Talk Outline

Quantum Computing with Superconducting Circuits





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QUANTUM SUPREMACY

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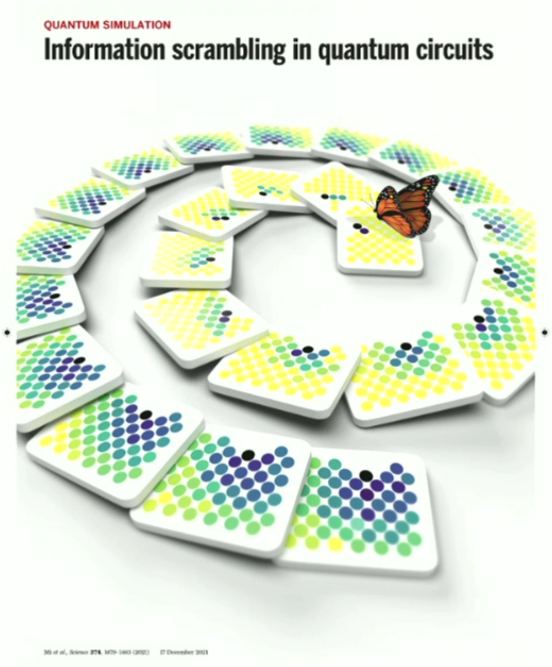
Pathway to NISQ



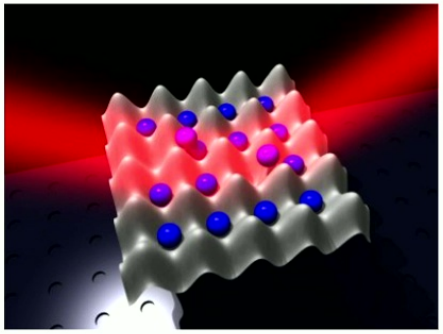
QUANTUM SIMULATION

Information scrambling in quantum circuits

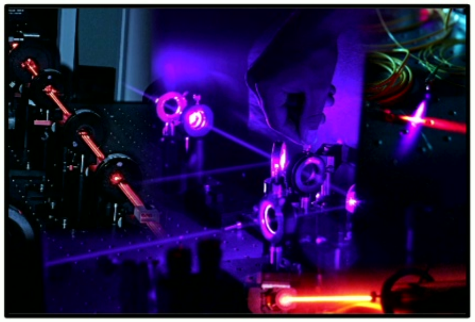
X. Mi, P. Roushan, C. Quintana, K. Kechedzhi
et al., Science **374**, 1479 (2021).

The Qubit Menagerie

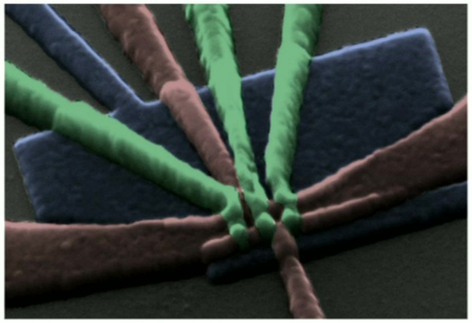
Neutral Atoms



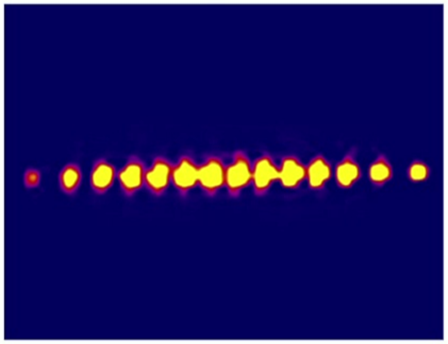
Linear Optics



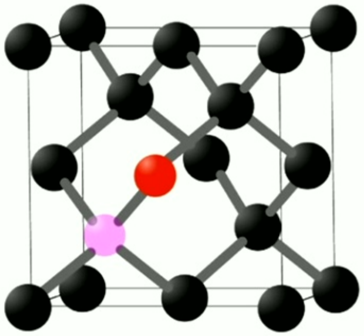
Gate-Defined Quantum Dots



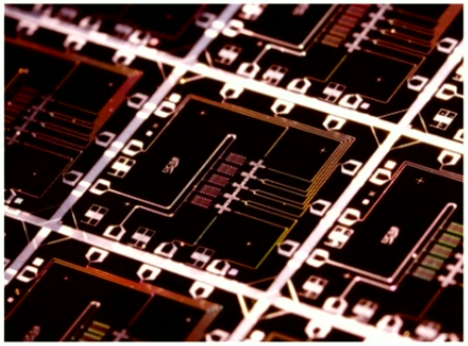
Trapped Ions



NV Centers

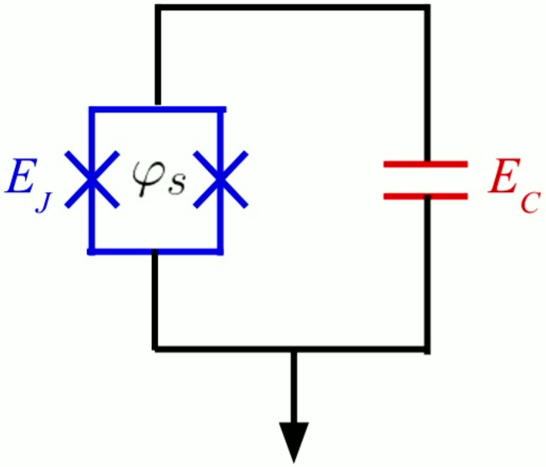


Superconducting Circuits



Superconducting Qubit: Frequency-Tunable Transmon

Transmon: Non-Linear LC Oscillator

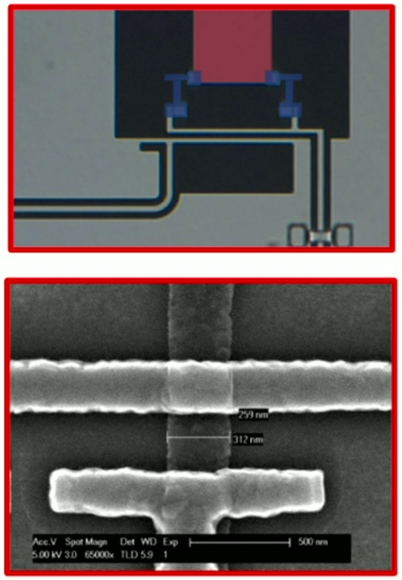


$$\hat{H} = 4E_C\hat{q} - E_J(\varphi_s)\cos\hat{\phi}$$

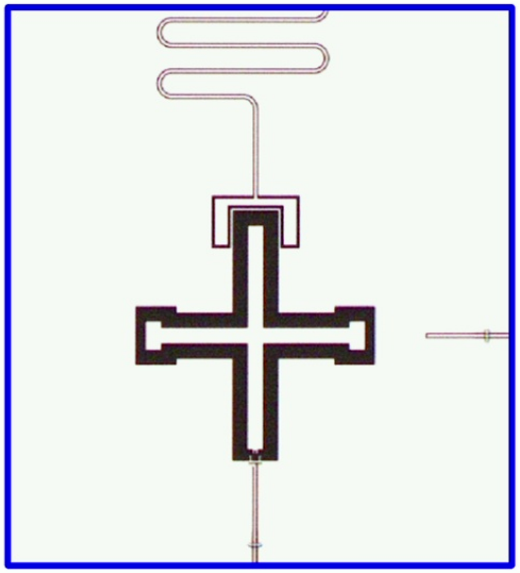
Charge

Flux

Josephson Junctions (“Inductor”)



Capacitor



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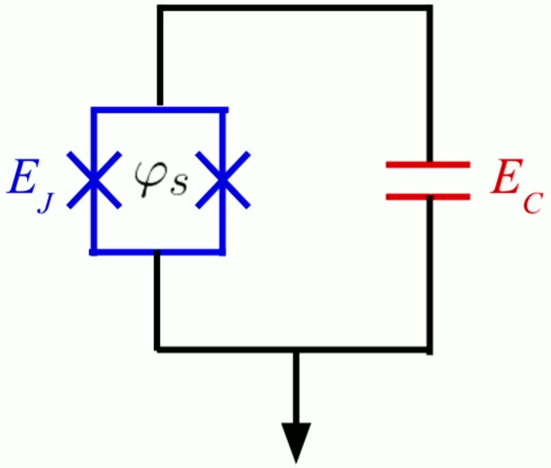
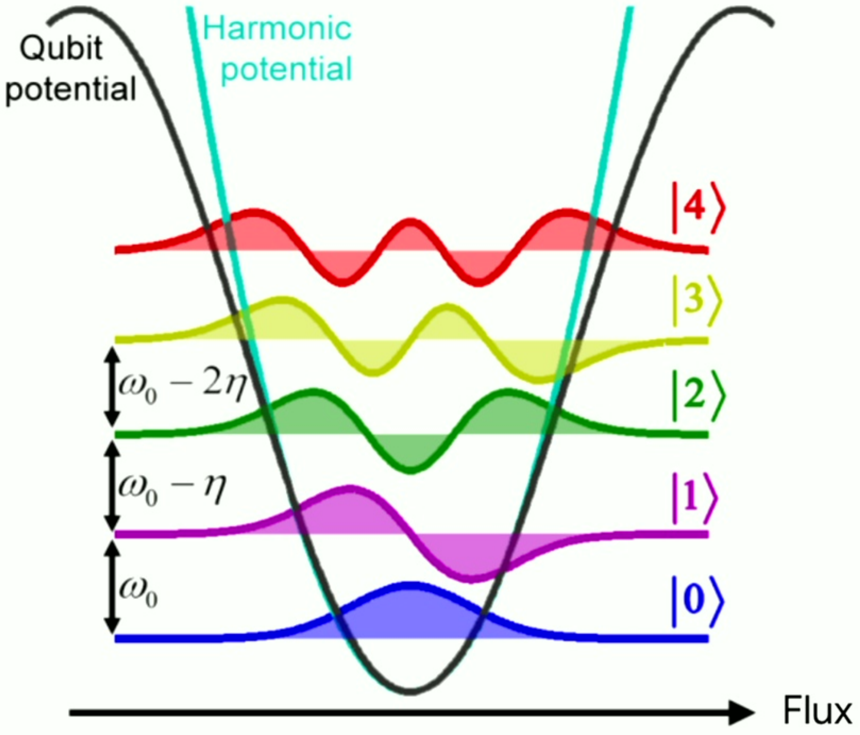
Solving the Transmon Hamiltonian: Anharmonic Oscillator

Transmon: Non-Linear LC Oscillator



$$\hat{H} = 4E_C \underset{\underset{\text{Charge}}{\uparrow}}{\hat{q}} - E_J(\varphi_s)\cos \underset{\underset{\text{Flux}}{\uparrow}}{\hat{\phi}}$$

Unequal Frequency Spacing → Effective Qubit



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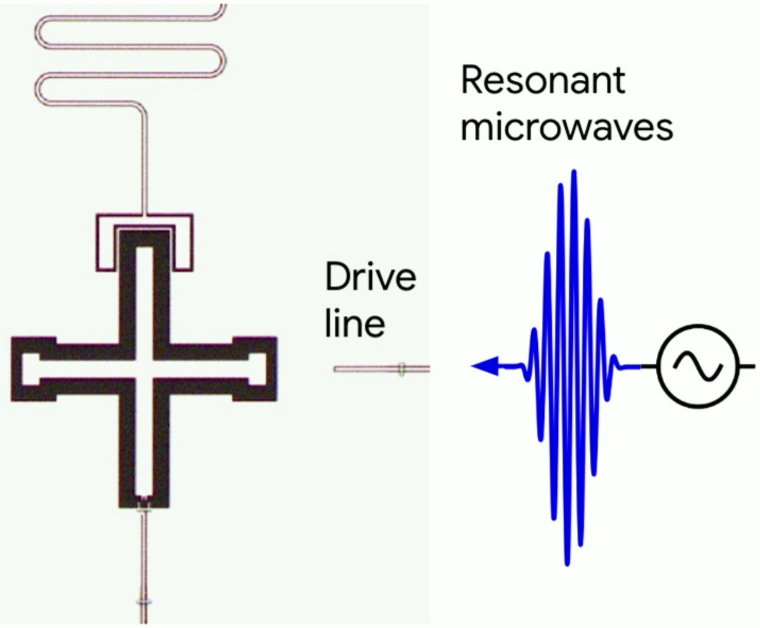
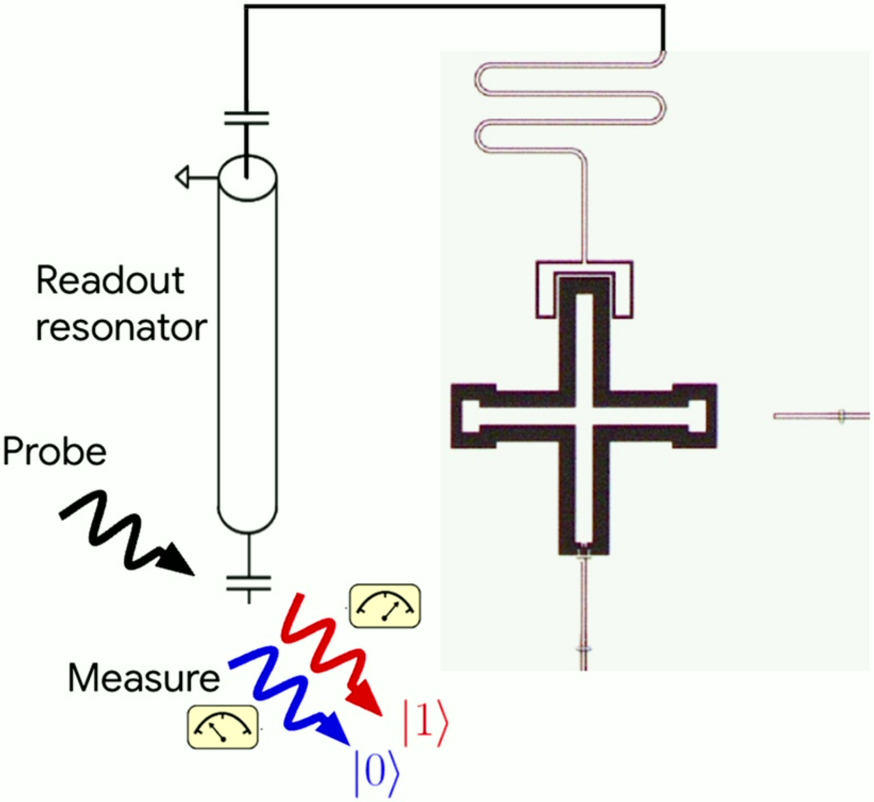
Single-Qubit Gate and Readout

Single-Qubit Gate (Fidelity ~99.9%)



Dispersive Readout (Fidelity ~97%)



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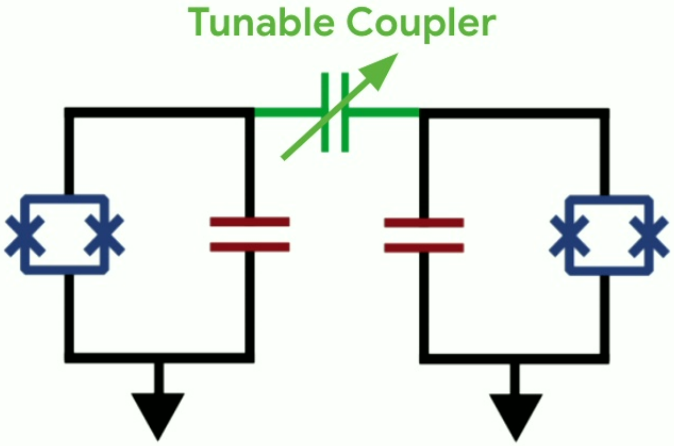
Controlling Two-Qubit Interactions: Tunable Coupler



$$\hat{H}_1 = 4E_C\hat{q}_1 - E_J(\varphi_{s,1})\cos\hat{\phi}_1$$

$$\hat{H}_2 = 4E_C\hat{q}_2 - E_J(\varphi_{s,2})\cos\hat{\phi}_2$$

$$\hat{H} = \hat{H}_1 + \hat{H}_2 + g\hat{q}_1\hat{q}_2$$

Qubit Hamiltonian

$$\hat{H}_{int} = \underbrace{g(\hat{X}_1\hat{X}_2 + \hat{Y}_1\hat{Y}_2)}_{\text{iSWAP}} + \underbrace{\frac{4g^2}{\eta}\hat{Z}_1\hat{Z}_2}_{\text{CPHASE}}$$

“Heisenberg XXZ Model”

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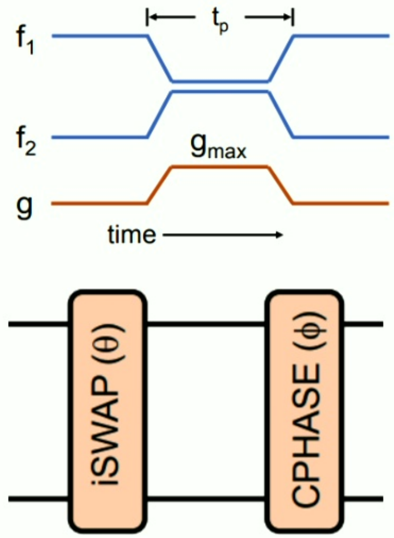
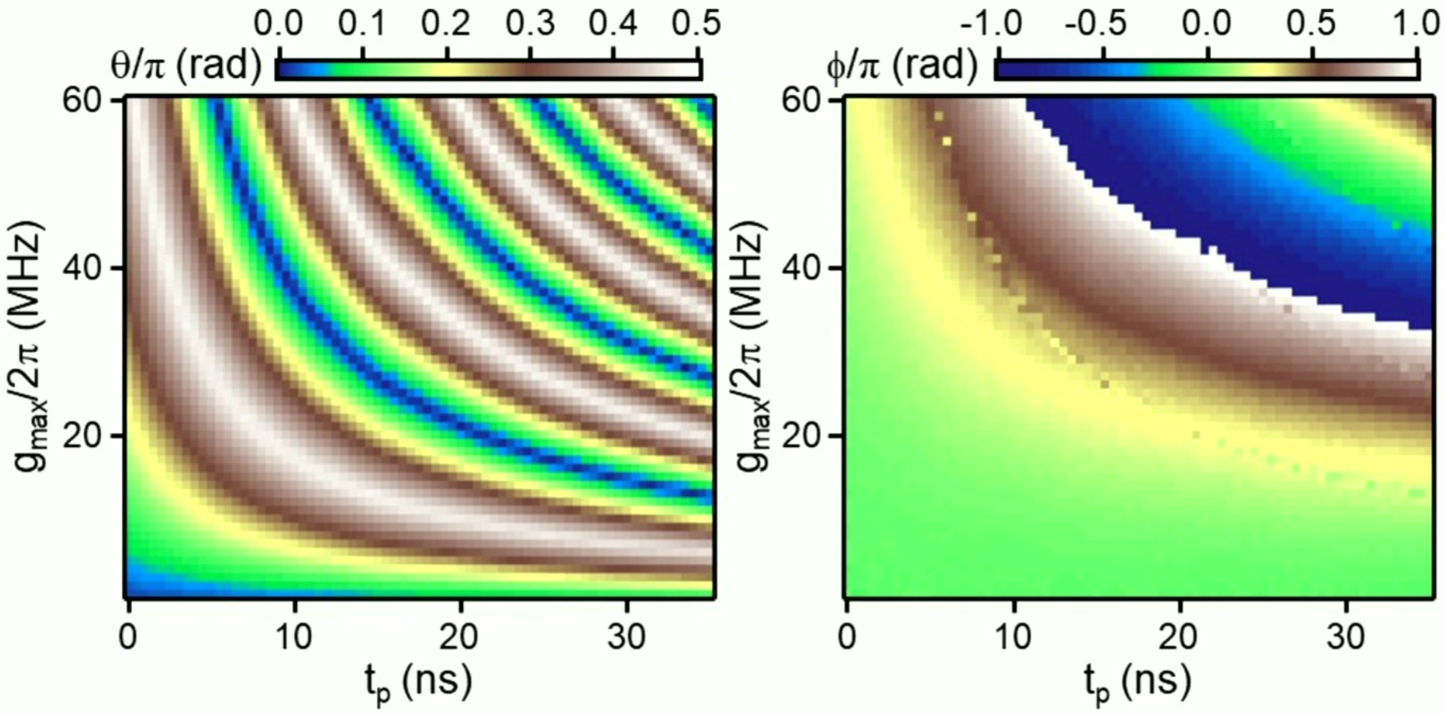
Realizing a Family of Two-Qubit Gates



>99.0% fidelity for arbitrary gates



A. Morvan, T. I. Andersen, X. Mi, C. Neill *et al.*, submitted

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2-Qubit Gate Calibration: Unitary Model

Generic 2-Qubit Unitary Model (FSIM)

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i(\Delta_+ + \Delta_-)}\cos\theta & -ie^{i(\Delta_+ - \Delta_{-,\mathrm{off}})}\sin\theta & 0 \\ 0 & -ie^{i(\Delta_+ + \Delta_{-,\mathrm{off}})}\sin\theta & e^{i(\Delta_+ - \Delta_-)}\cos\theta & 0 \\ 0 & 0 & 0 & e^{i(2\Delta_+ - \phi)} \end{pmatrix}$$

θ: iSWAP angle
ϕ: Conditional phase
Δ_+, Δ_-, $\Delta_{-,\mathrm{off}}$: Single-qubit phases

Goal: **Accurate** measurement of unitary parameters.

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2-Qubit Gate Calibration: Floquet Calibration

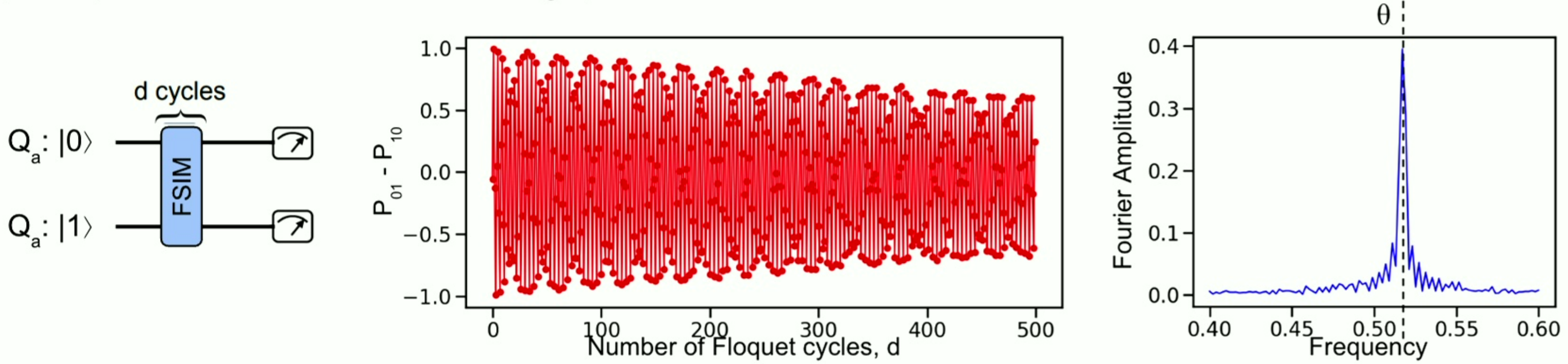
Unitary Model (FSIM)

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i(\Delta_+ + \Delta_-)}\cos\theta & -ie^{i(\Delta_+ - \Delta_{-,\mathrm{off}})}\sin\theta & 0 \\ 0 & -ie^{i(\Delta_+ + \Delta_{-,\mathrm{off}})}\sin\theta & e^{i(\Delta_+ - \Delta_-)}\cos\theta & 0 \\ 0 & 0 & 0 & e^{i(2\Delta_+ - \phi)} \end{pmatrix}$$

→

θ: iSWAP angle
ϕ: Conditional phase
Δ_+, Δ_-, $\Delta_{-,\mathrm{off}}$: Single-qubit phases

Example: Calibration of iSWAP Angle



Key: Coherent **amplification** of **single** parameter

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2-Qubit Gate Calibration: Floquet Calibration

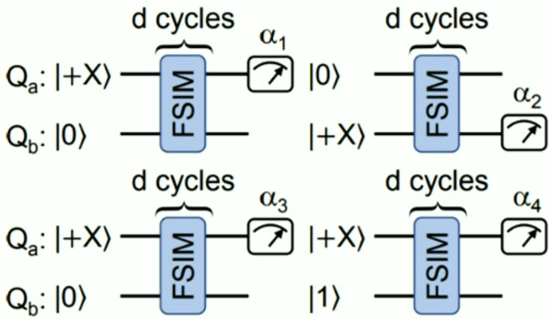
Unitary Model (FSIM)

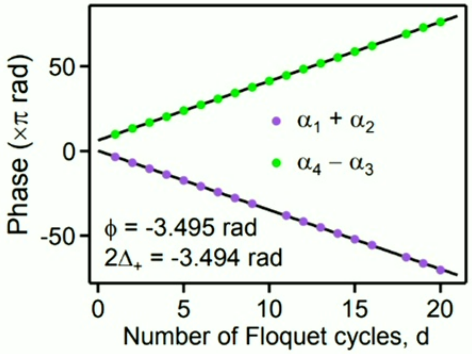
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i(\Delta_+ + \Delta_-)}\cos\theta & -ie^{i(\Delta_+ - \Delta_{-,\mathrm{off}})}\sin\theta & 0 \\ 0 & -ie^{i(\Delta_+ + \Delta_{-,\mathrm{off}})}\sin\theta & e^{i(\Delta_+ - \Delta_-)}\cos\theta & 0 \\ 0 & 0 & 0 & e^{i(2\Delta_+ - \phi)} \end{pmatrix}$$

θ: iSWAP angle
ϕ: Conditional phase
Δ_+, Δ_-, $\Delta_{-,\mathrm{off}}$: Single-qubit phases

Example: Calibration of Single-qubit and Conditional Phases

$\alpha = \tan^{-1}(\langle\hat{Y}\rangle/\langle\hat{X}\rangle)$





Key: Coherent **amplification** of **single** parameter

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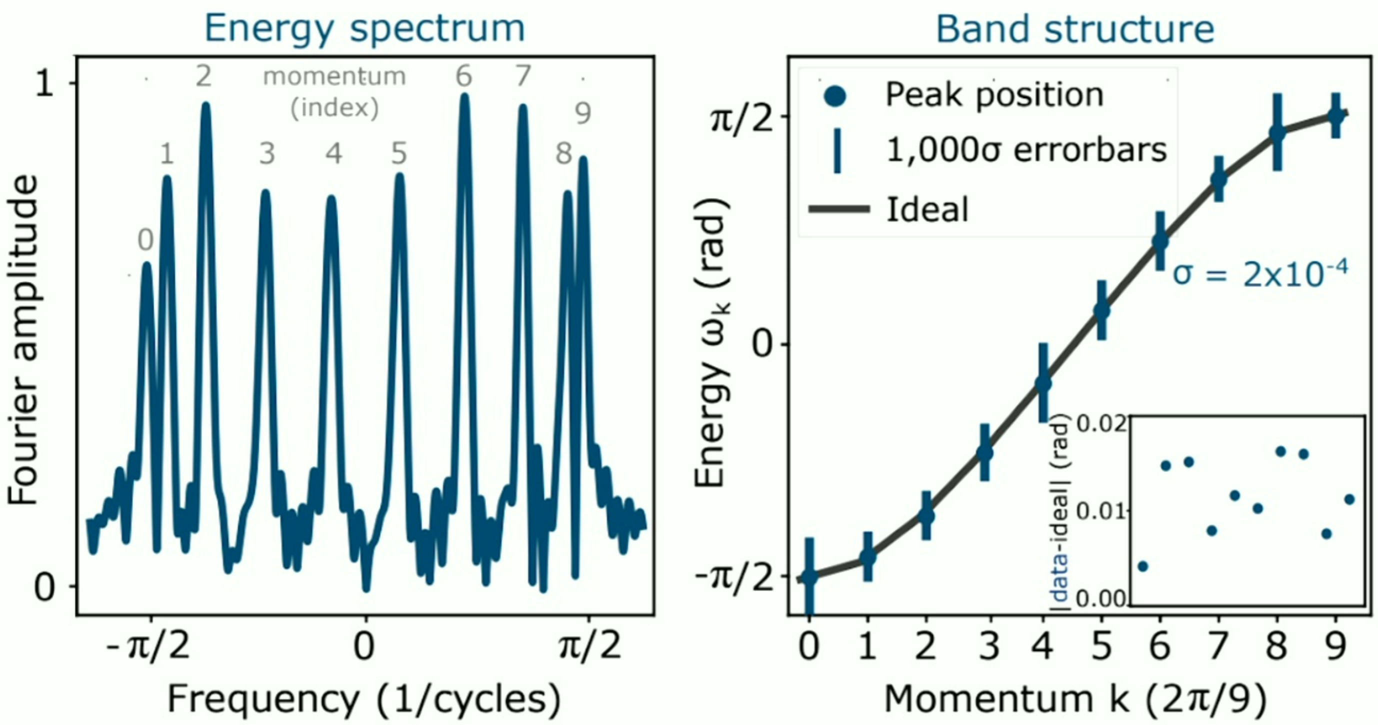
Validating Gate Accuracy: Computing Band Structure of a Quantum Ring



0.01 rad error!

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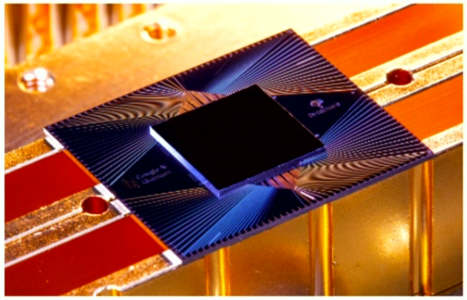
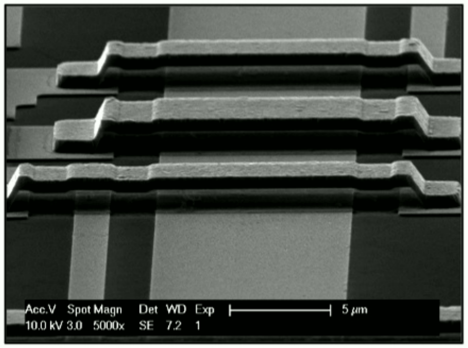
C. Neill, T. McCourt, X. Mi *et al.*, Nature **594**, 508 (2021)

A “Beyond-Classical” Task

Quantum Computing with Superconducting Circuits





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Pathway to NISQ

QUANTUM SIMULATION

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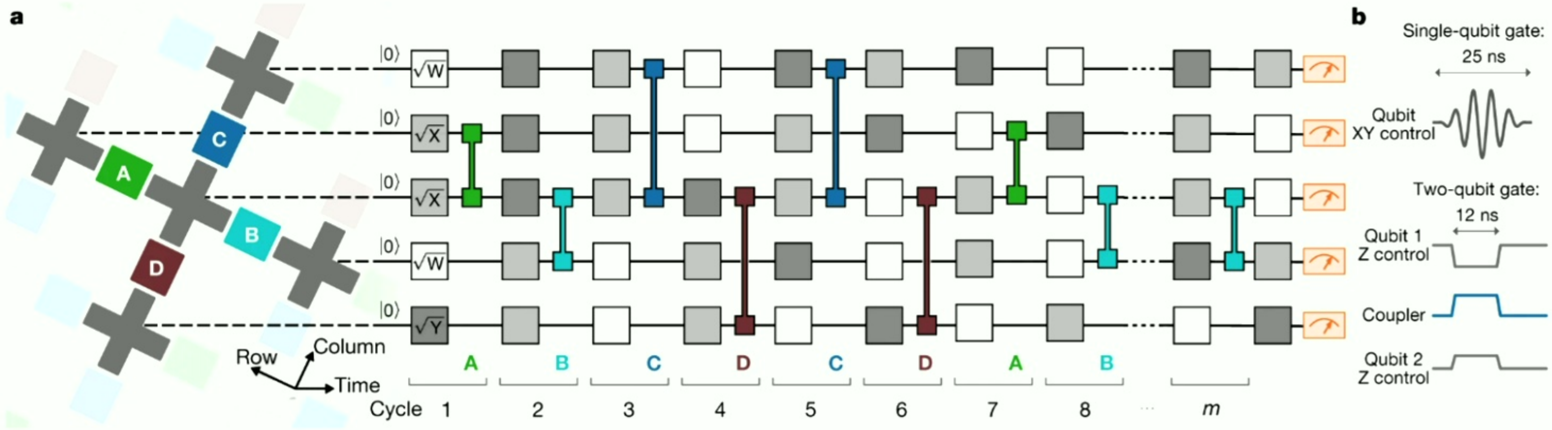
Challenging Classical Computers with Random Circuits



Single Qubit Gates:

$$U_{1q} = \begin{bmatrix} \cos\frac{\theta}{2} & -ie^{-i\chi}\sin\frac{\theta}{2} \\ -ie^{i\chi}\sin\frac{\theta}{2} & \cos\frac{\theta}{2} \end{bmatrix}$$

$$\theta = \frac{\pi}{2}, \phi \in [0, \frac{\pi}{2}, \frac{\pi}{4}]$$

Two-Qubit Gate:

$$U_{2q} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -i & 0 \\ 0 & -i & 0 & 0 \\ 0 & 0 & 0 & e^{i\phi_{CZ}} \end{bmatrix}$$

Circuit designed to be maximally **chaotic**

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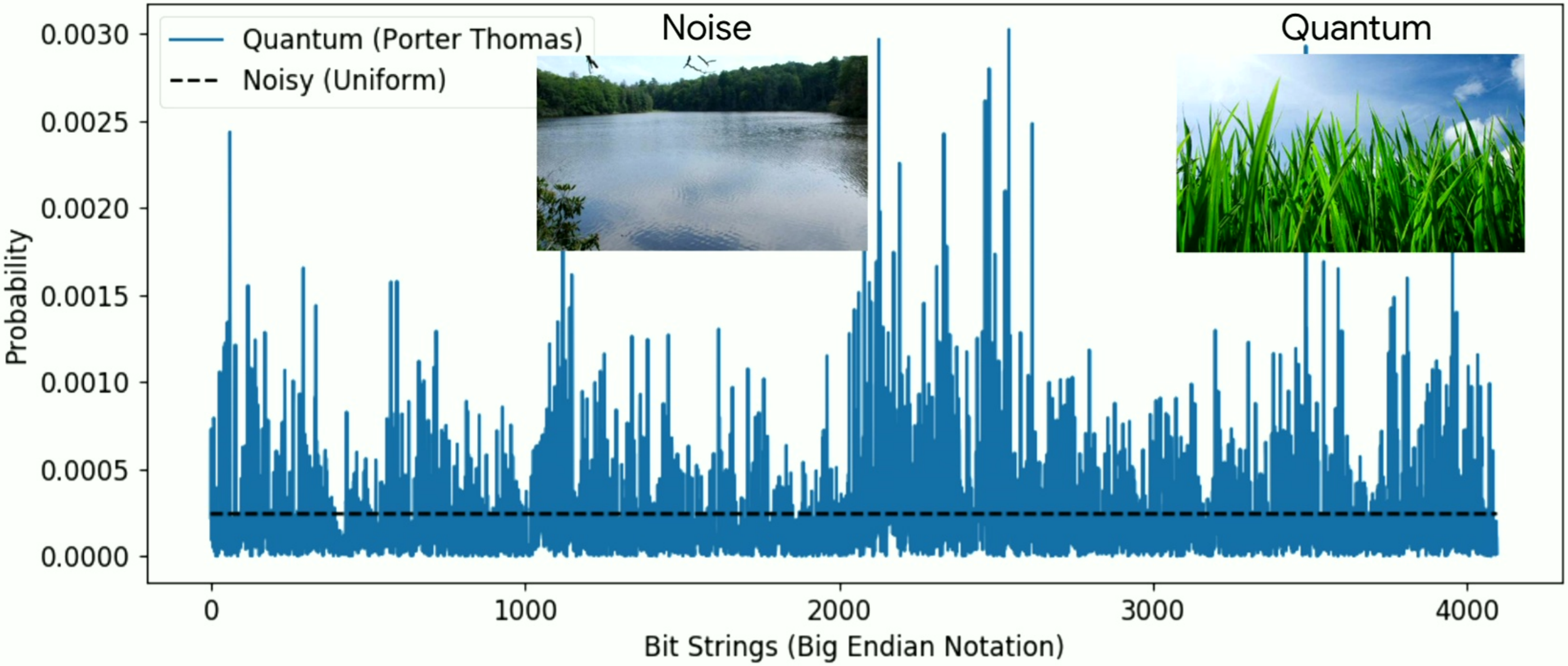
Characterizing Random Circuits: Probability Distribution



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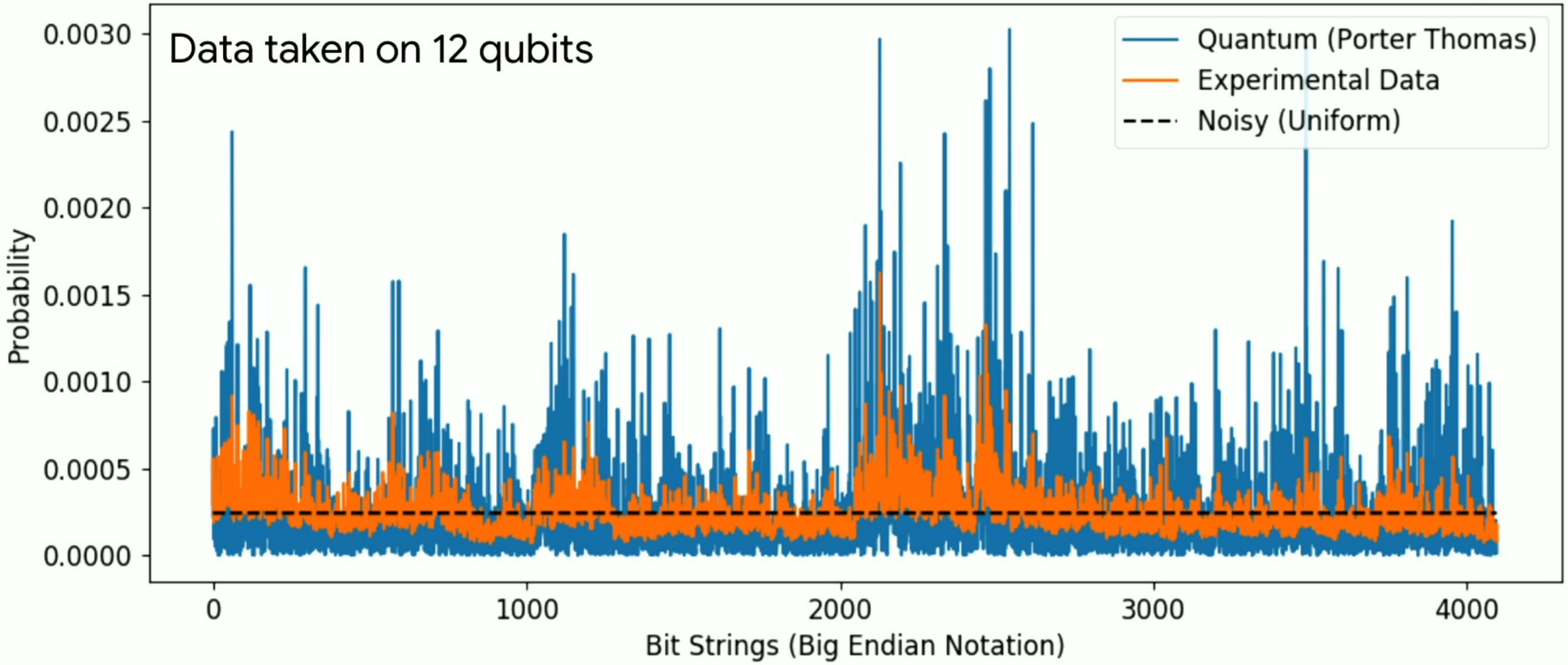
Probability Distributions: Good, Bad and Hardware



To challenge classical computers, we need a measure of **fidelity**

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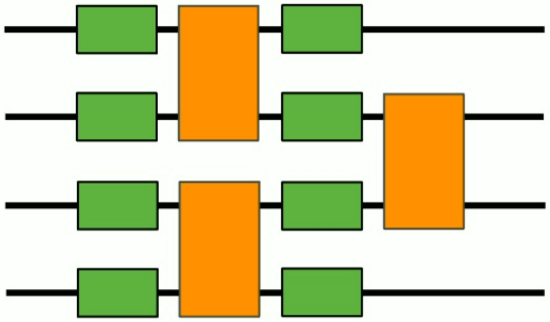
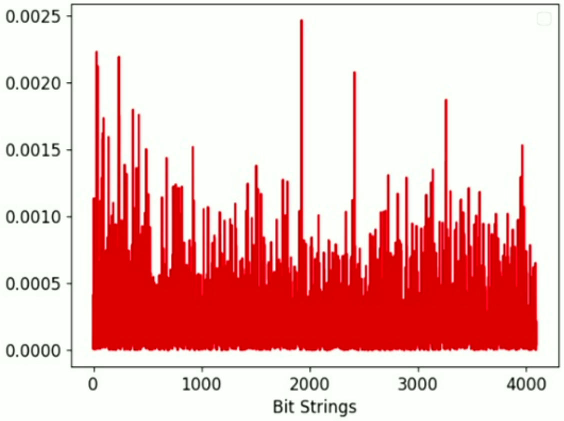
Estimating Fidelity: Cross-Entropy Benchmarking

Compile Random Circuits



Compute Ideal Output



Sample from Hardware &
Compute Cross Entropies

Ideal: $Dp_q^2 - 1$

Measured: $\langle Dp_q - 1 \rangle_q$

Fidelity: Measured / Ideal

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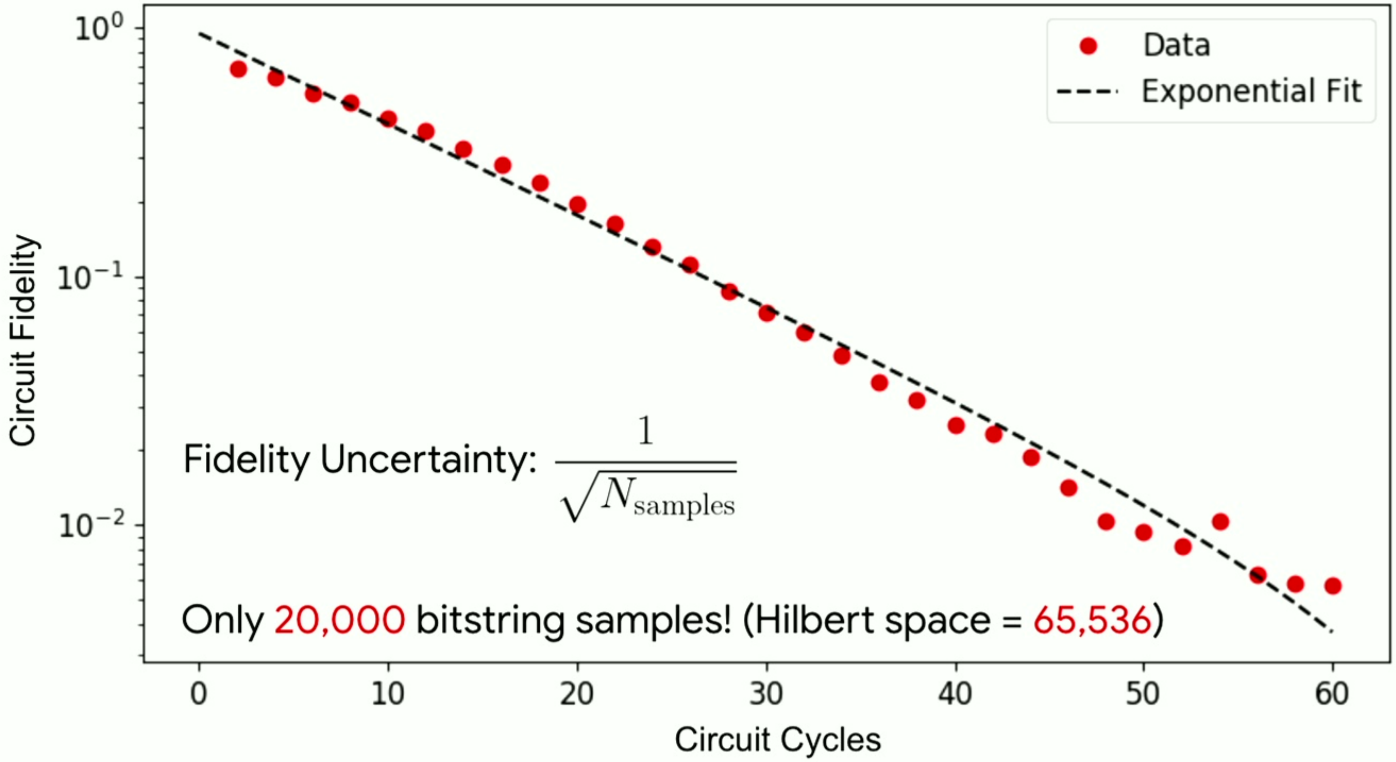
Estimating Fidelity: Cross-Entropy Benchmarking

Example 16-qubit XEB Data



Fidelity Uncertainty: $\frac{1}{\sqrt{N_{\text{samples}}}}$

Only 20,000 bitstring samples! (Hilbert space = 65,536)

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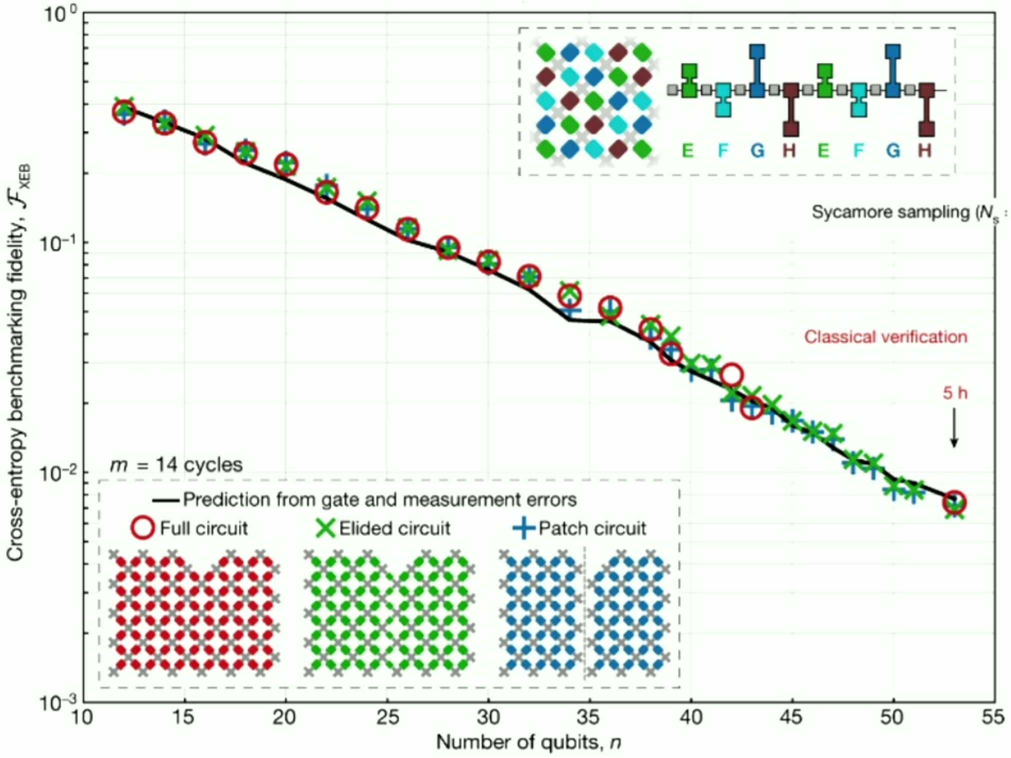
Fidelity Estimation vs System Size

"Easy" Circuits



- Classical computation of "easy" circuits yields fidelity estimates.
- All three circuits yield same circuit fidelity!

Google Quantum AI, Nature **574**, 505 (2019).

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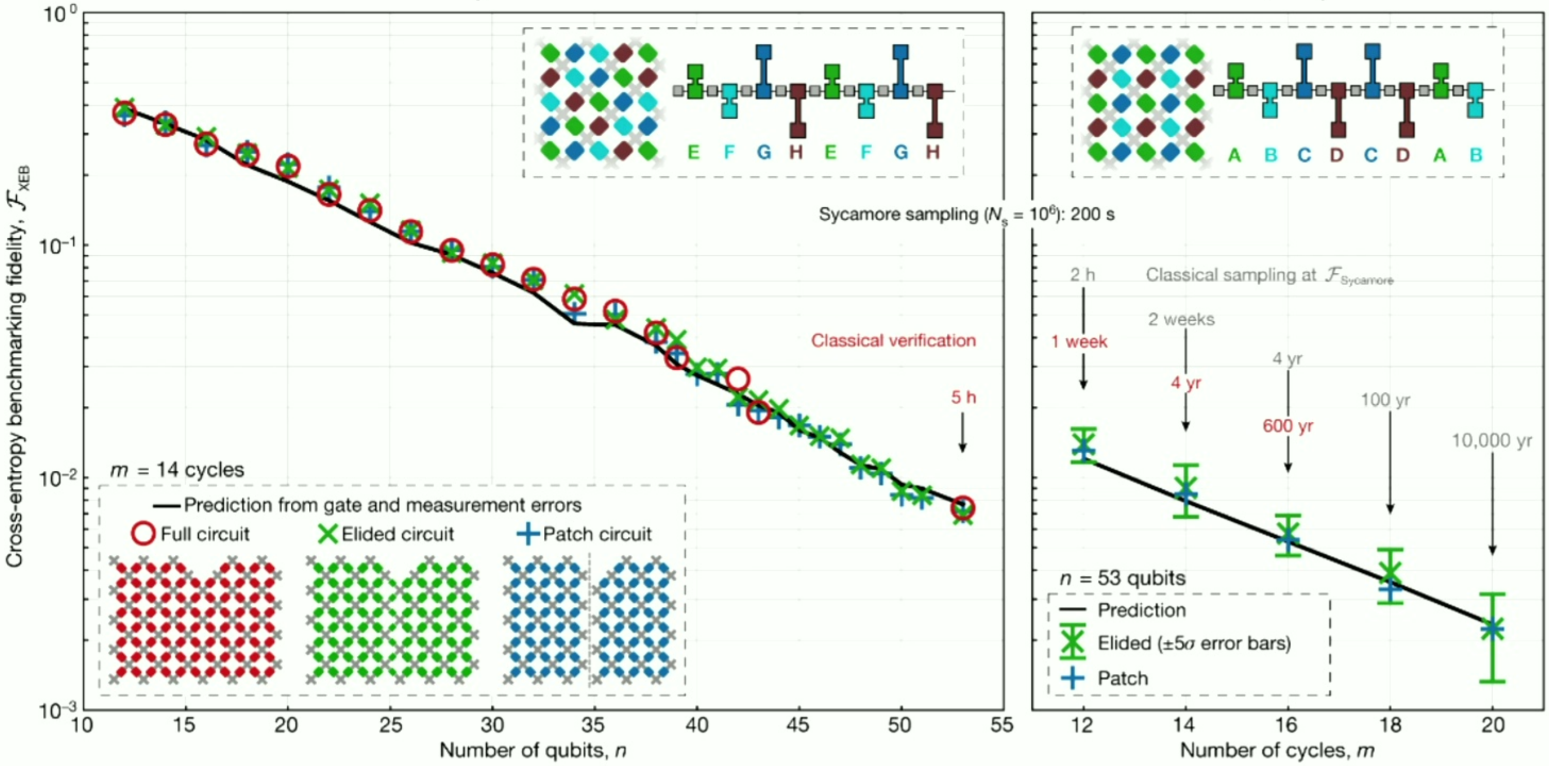
Beyond-Classical Demonstration

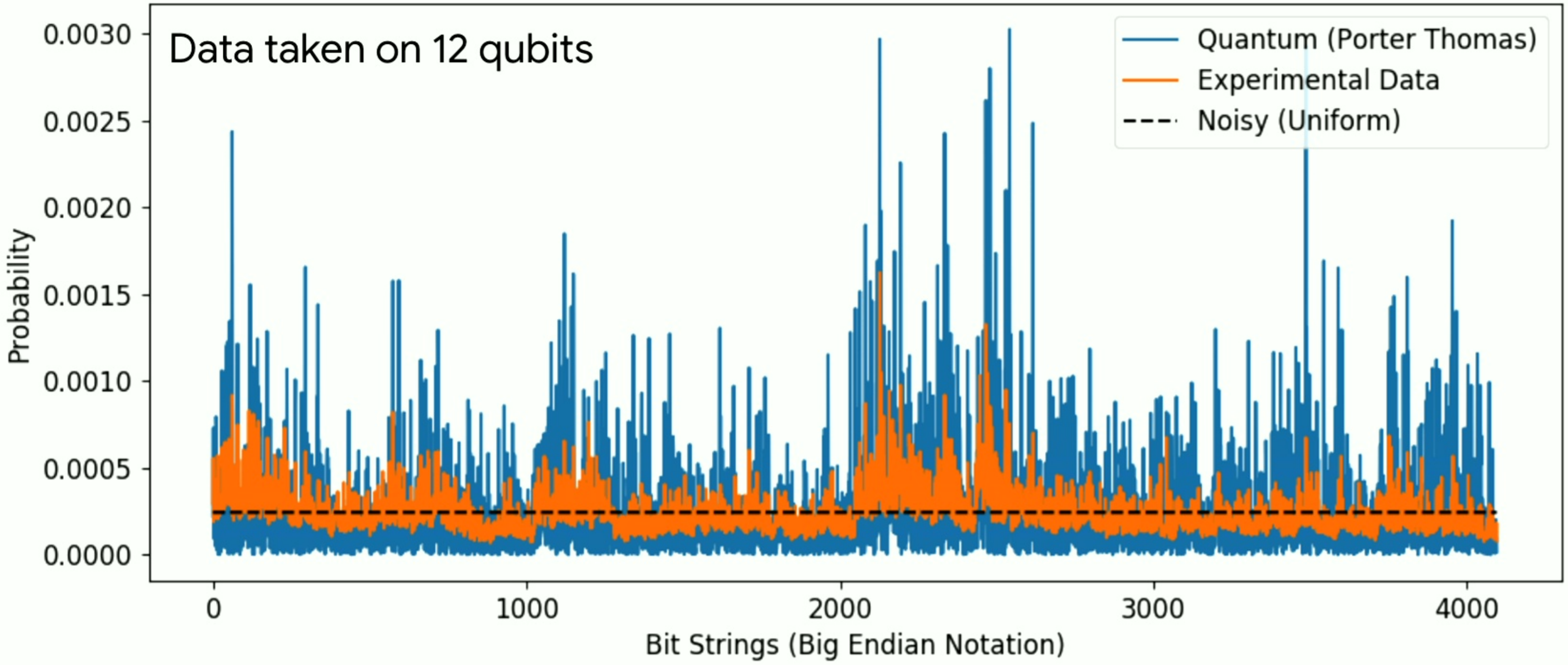


“Easy” Circuits

“Hard” Circuits (Beyond-Classical)

Google Quantum AI, Nature **574**, 505 (2019).

Probability Distributions: Good, Bad and Hardware



To challenge classical computers, we need a measure of **fidelity**

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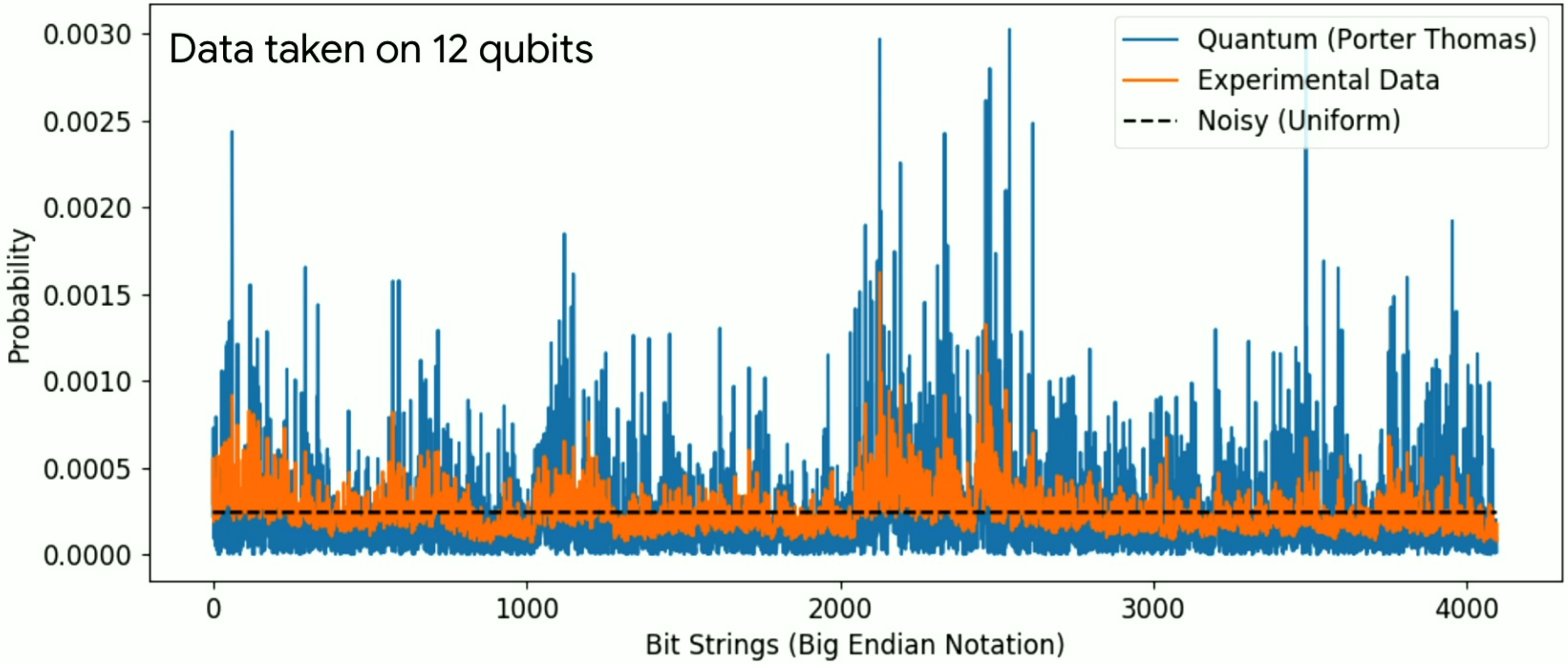
Probability Distributions: Good, Bad and Hardware



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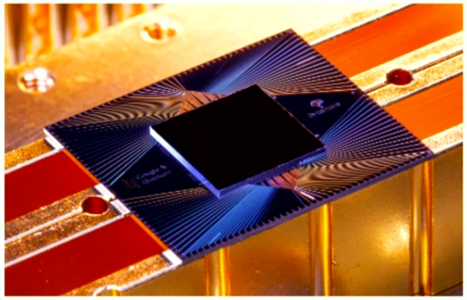
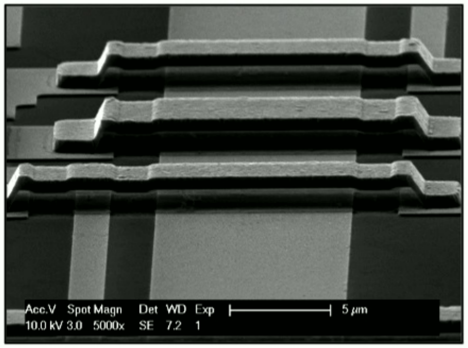
Pathway to NISQ

Quantum Computing with Superconducting Circuits





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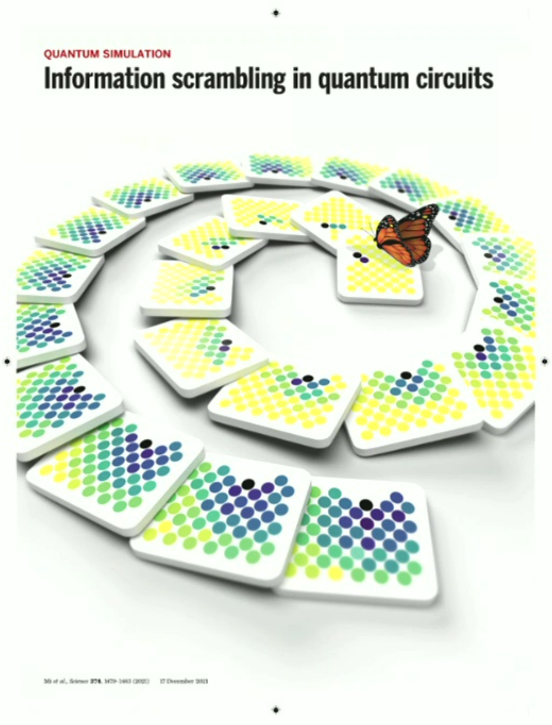

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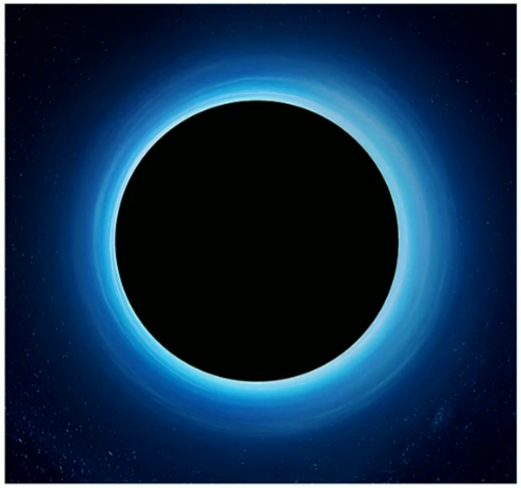
From Beyond-Classical to Physical Phenomena

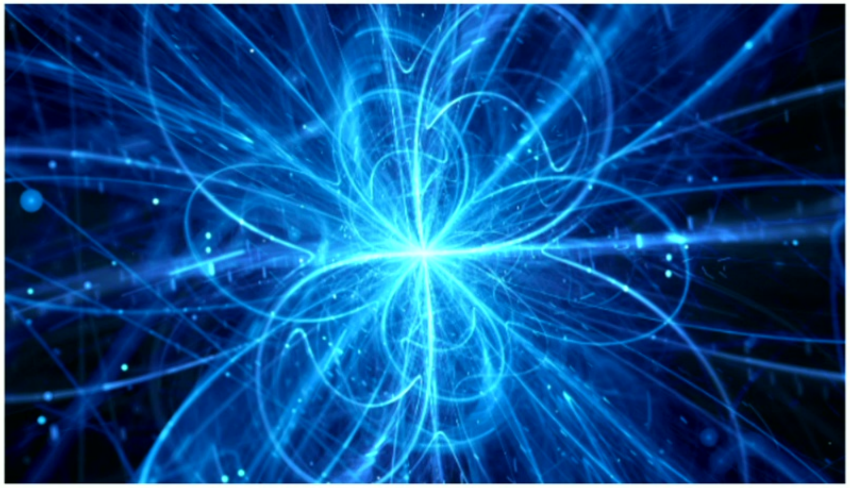
"Not from the stars do I my judgement pluck…
But from thine eyes my knowledge I derive." – Sonnet 14

Simple State



Unitary Evolution

A "Quantum Universe" (10^{16} Dimensions)



- "Beyond-classical" experiment: Sampling from global state of the entire universe.
- Physics, chemistry: Interested in local quantum observables.

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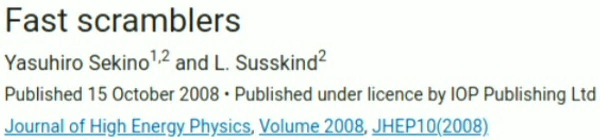
The Physics of Quantum Chaos: Scrambling

- Scrambling is the **spreading** of **local** information into the many degrees of freedom of the **entire system**.
- It is an **ubiquitous** mechanism in nature.

Quantum Gravity



Fast scramblers

Yasuhiro Sekino[1,2] and L. Susskind[2]

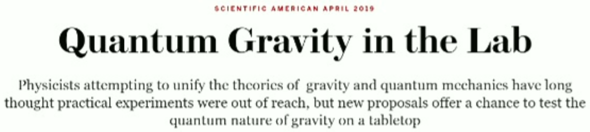
Published 15 October 2008 • Published under licence by IOP Publishing Ltd

Journal of High Energy Physics, Volume 2008, JHEP10(2008)

Towards the fast scrambling conjecture

Nima Lashkari, Douglas Stanford, Matthew Hastings, Tobias Osborne & Patrick Hayden

Journal of High Energy Physics **2013**, Article number: 22 (2013) | Cite this article

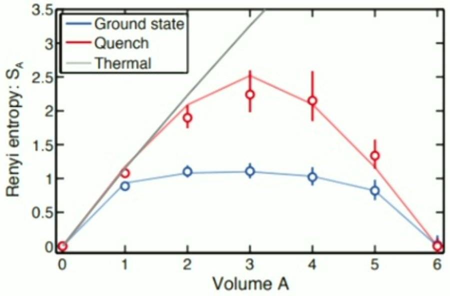


SCIENTIFIC AMERICAN APRIL 2019

Quantum Gravity in the Lab

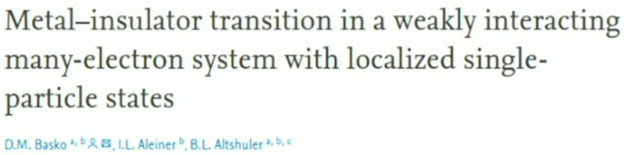
Physicists attempting to unify the theories of gravity and quantum mechanics have long thought practical experiments were out of reach, but new proposals offer a chance to test the quantum nature of gravity on a tabletop

Thermalization



A. M. Kaufman *et al.*, Science 2016
H. Bernien *et al.*, Nature 2017
A. Lukin *et al.*, Science 2019
T. Brydges *et al.*, Science 2019

Unconventional Quantum Phases



Metal–insulator transition in a weakly interacting many-electron system with localized single-particle states

D.M. Basko [a, b], I.L. Aleiner [b], B.L. Altshuler [a, b, c]

Editors' Suggestion

Thermal diffusivity and chaos in metals without quasiparticles

Mike Blake, Richard A. Davison, and Subir Sachdev
Phys. Rev. D **96**, 106008 – Published 13 November 2017

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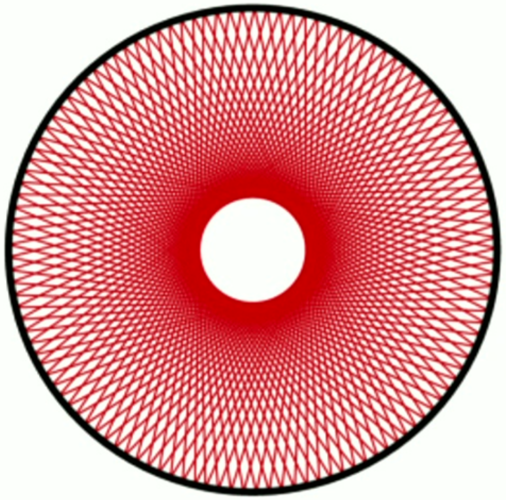
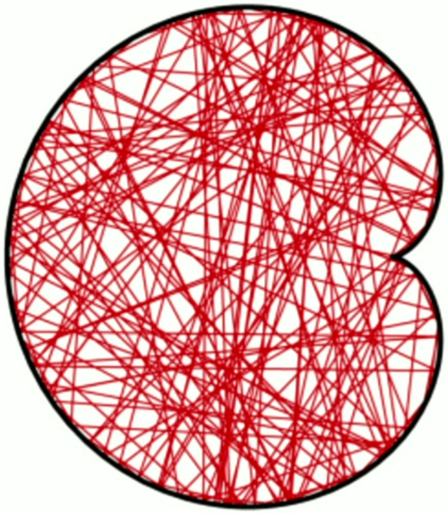
What is Scrambling: A Classical Analogy

Global Evolution

Integrable / Non-Scrambling



Non-integrable / Scrambling

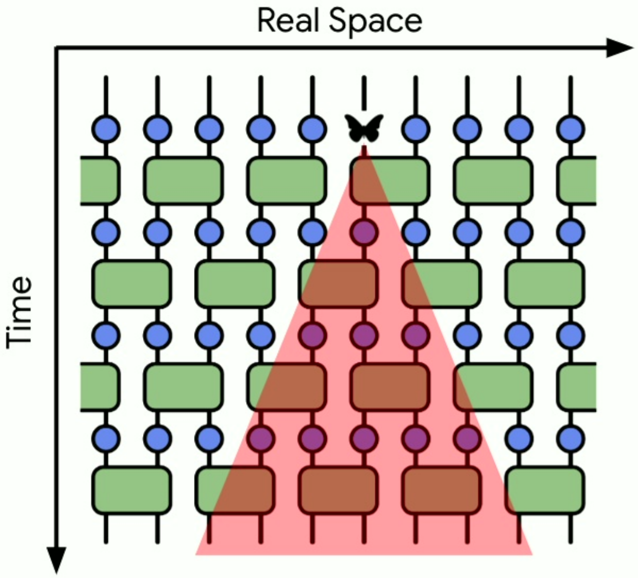


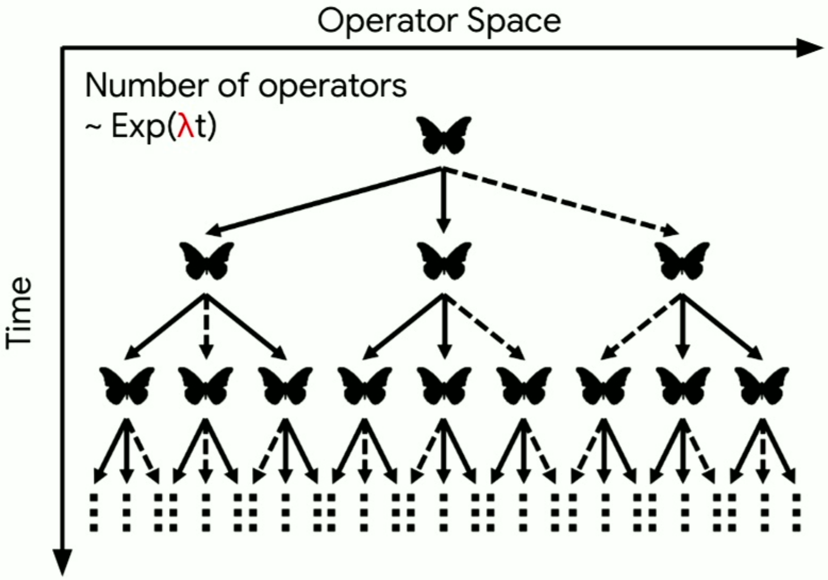
Local Observable

The “Butterfly Effect”

Scrambling is the key to **computational complexity** of classical dynamics.

Quantum Scrambling: A Butterfly in Two Worlds





Operator **Spreading** (Computationally **Easy**)

Operator **Entanglement** (Computationally **Hard**)

I. Aleiner *et al.*, Ann. Phys. **375**, 378 (2016)
C. W. von Keyserlingk *et al.*, PRX **8**, 021013 (2018)
A. Nahum et al., PRX **8**, 021014 (2018)
V. Khemani *et al.*, PRX **8**, 031057 (2018)

Can we distinguish the two mechanisms in experiment?

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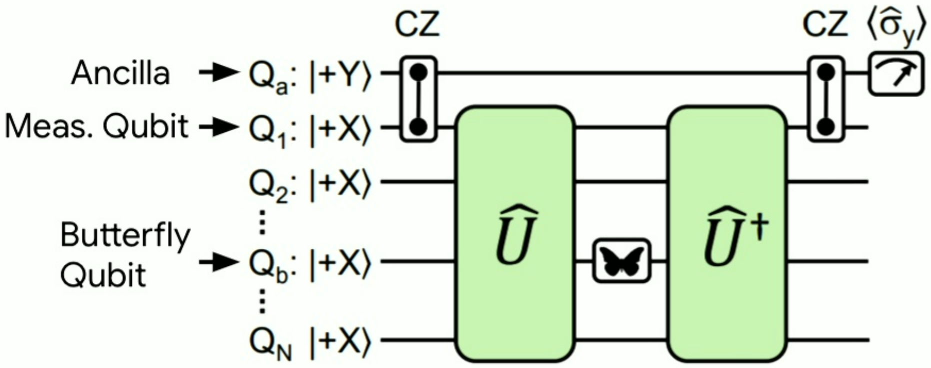
Diagnosing Quantum Scrambling with Local Observables



B. Swingle *et al.*, PRA **94**, 040302 (2016)
B. Swingle *et al.*, PRA **97**, 062113 (2018)

Out-of-time-order Correlator (OTOC)

$$\boxed{C(t) = \langle \hat{O}^\dagger(t)\, \hat{M}^\dagger\, \hat{O}(t)\, \hat{M}\rangle.}$$

Nobody panic! It's just the commutator between two qubits (Q_1 and Q_b).

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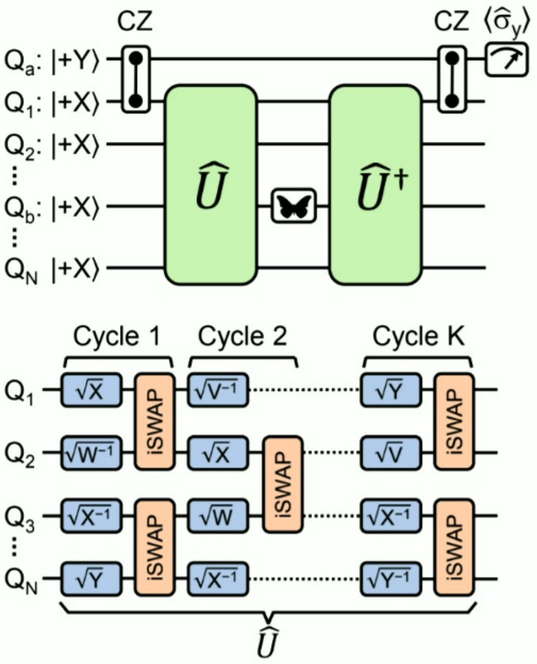
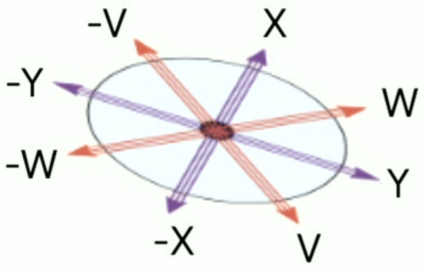
Scrambling Circuit Implementation



Single-Qubit Gates:



Two-Qubit Gate:

$$\mathrm{iSWAP} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

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et al., Science **374**, 1479 (2021).

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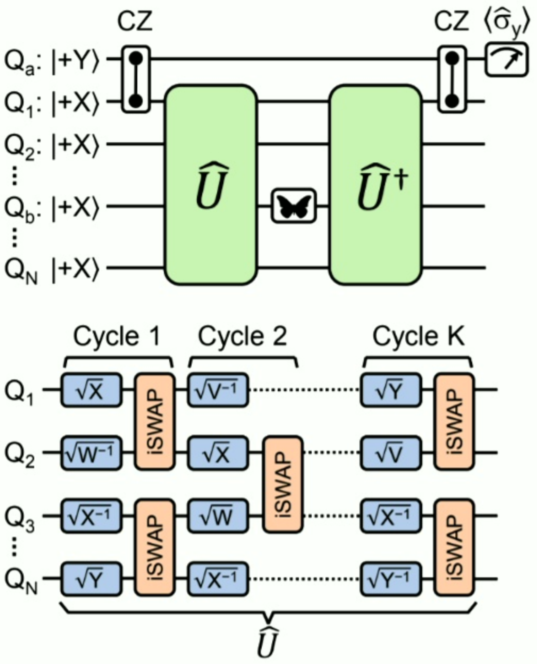
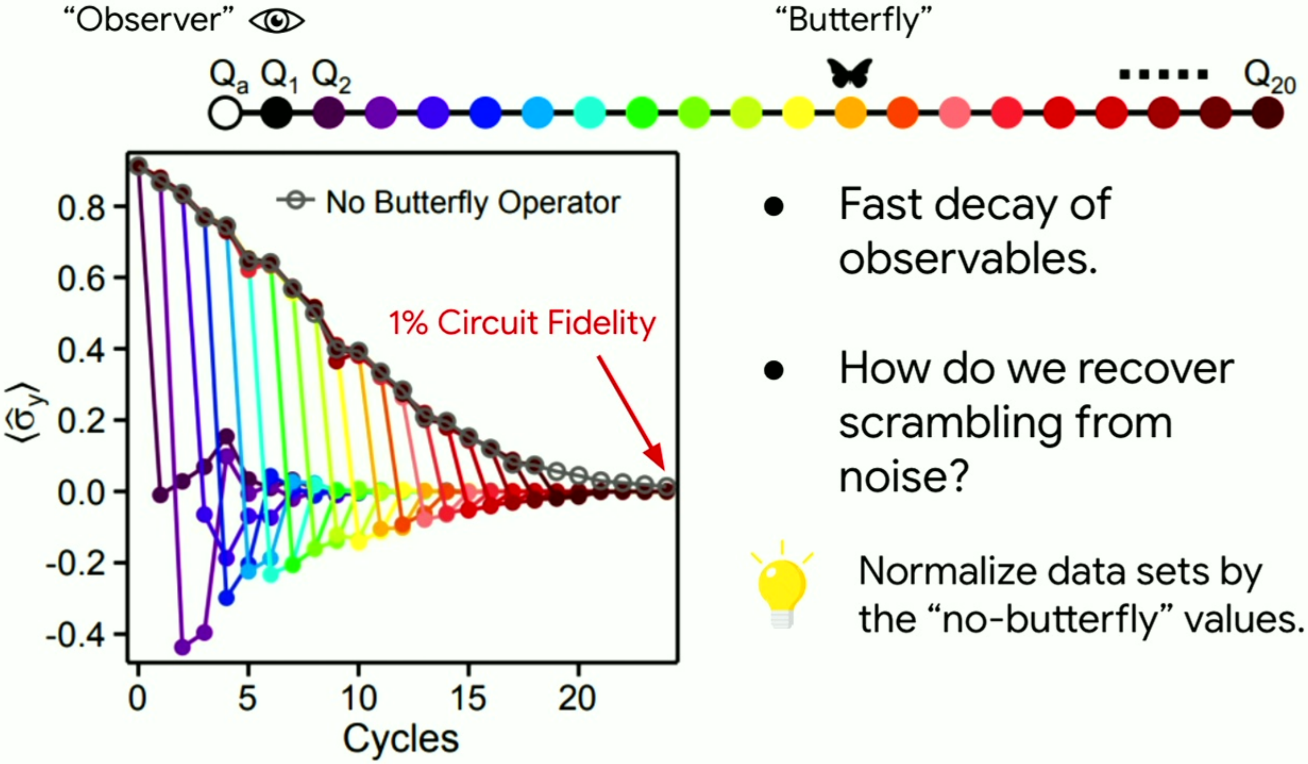
Average-OTOCs and Operator Spreading (1D)





- Fast decay of observables.
- How do we recover scrambling from noise?

Normalize data sets by the "no-butterfly" values.

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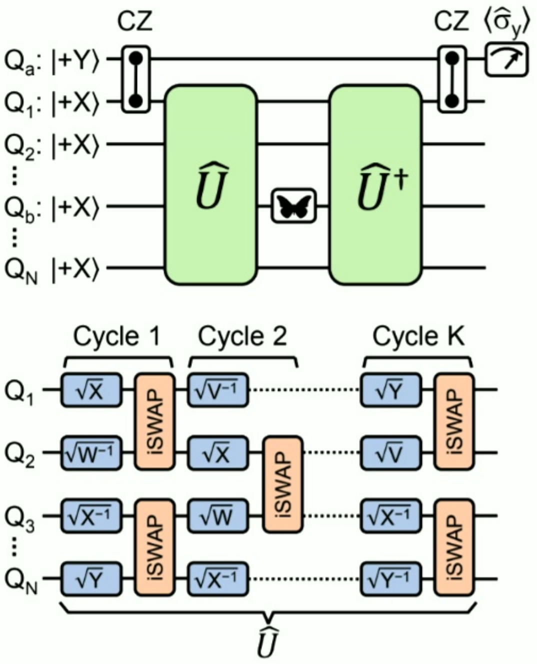
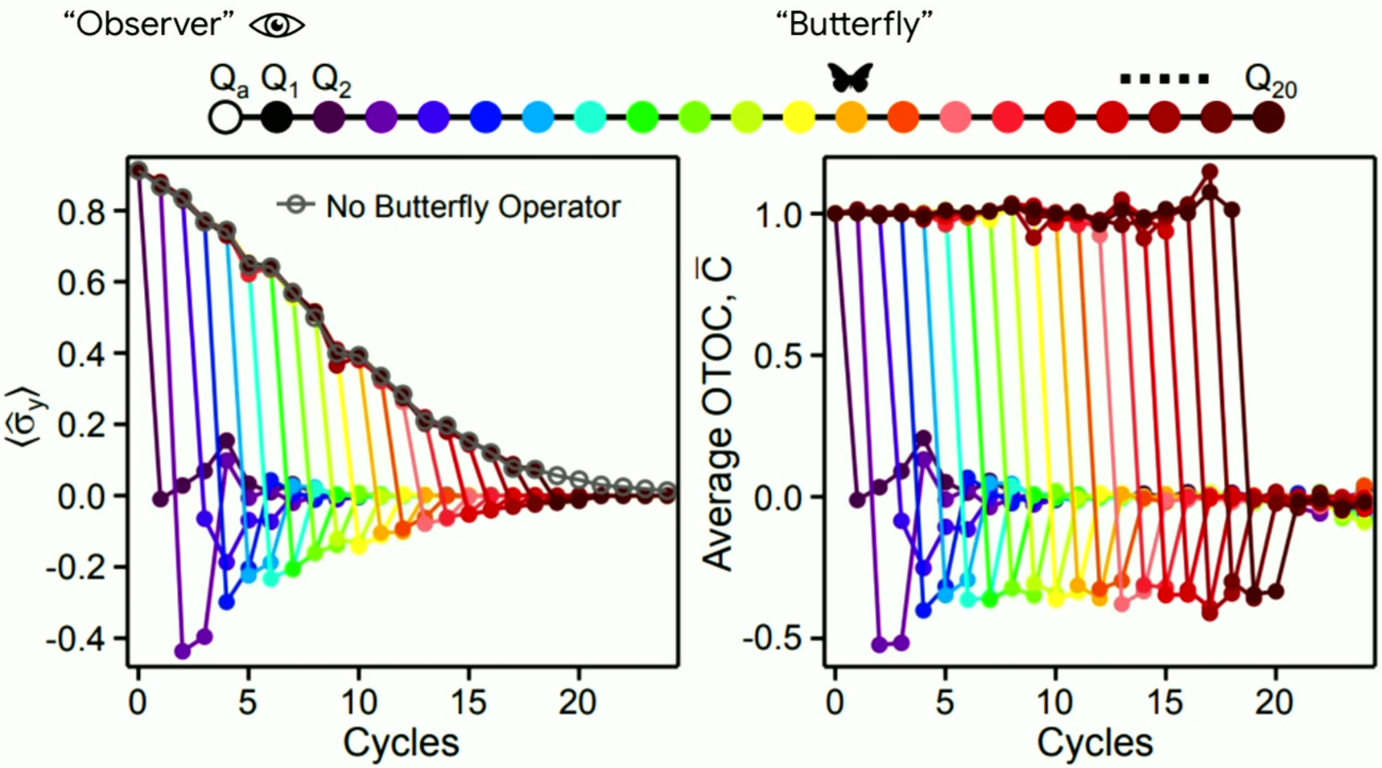
Recovering Coherent Information from Noisy Circuits





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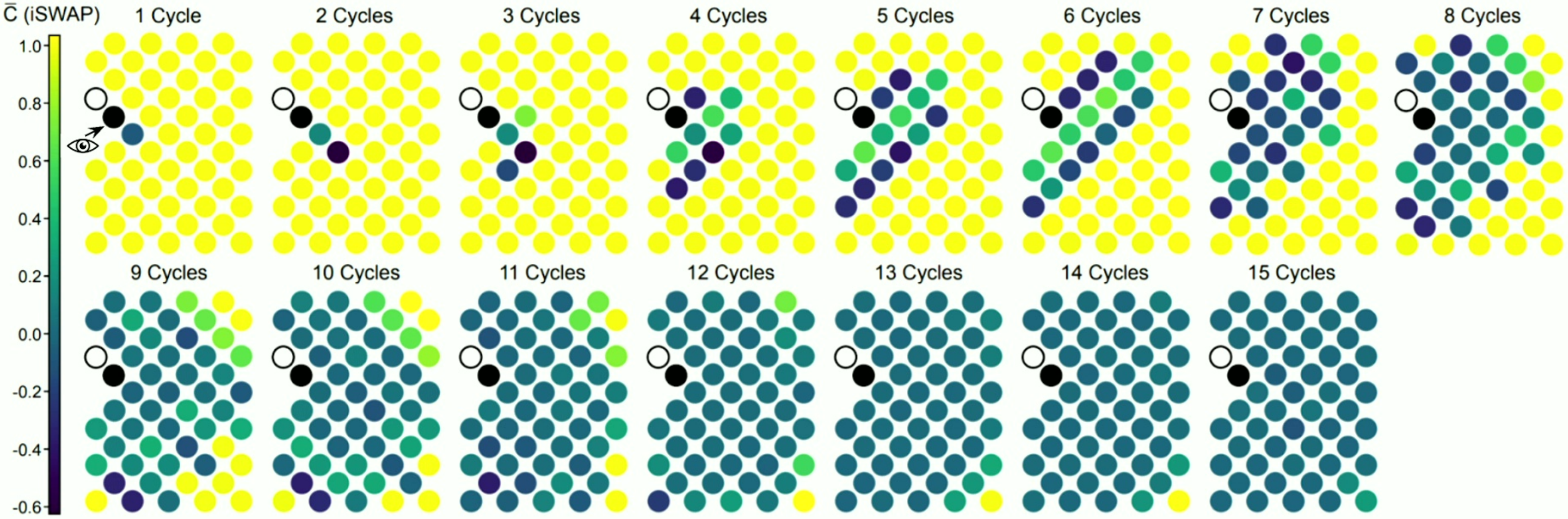
Operator Spreading in 2D (iSWAP)



iSWAP: Maximal Spreading Velocity (“Butterfly Velocity”)

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et al., Science **374**, 1479 (2021).

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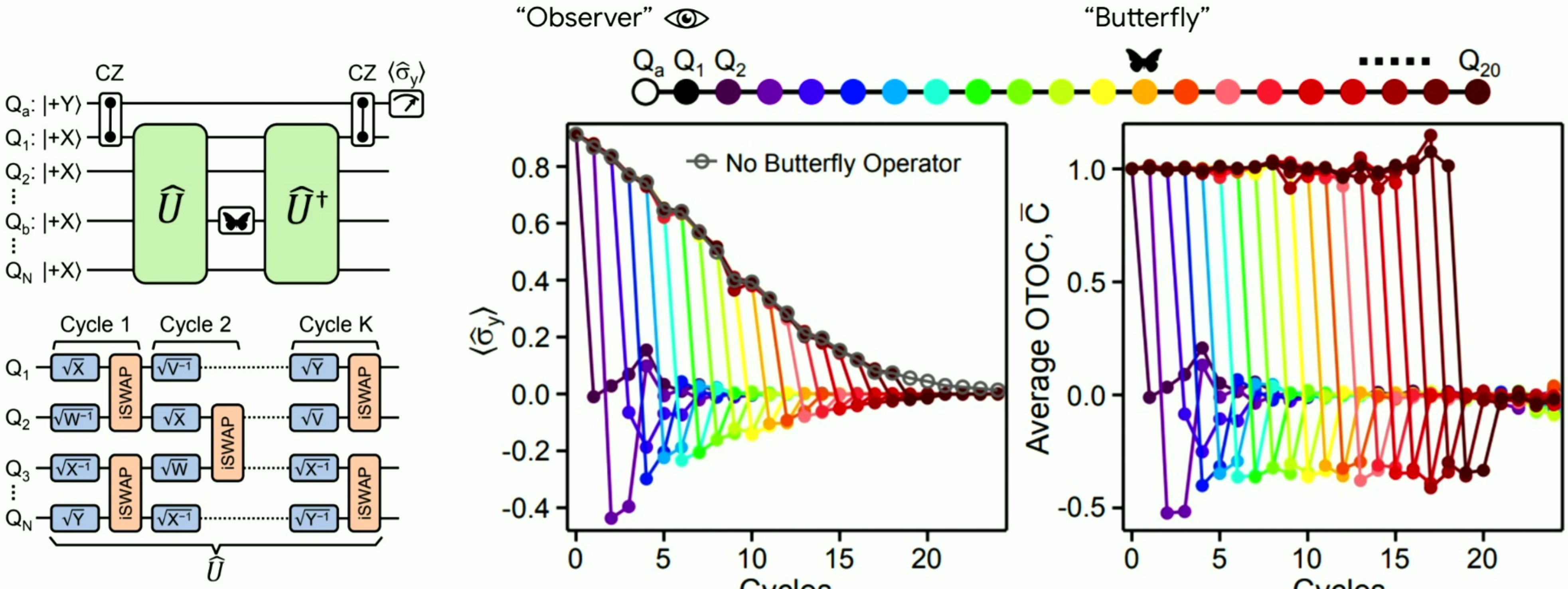

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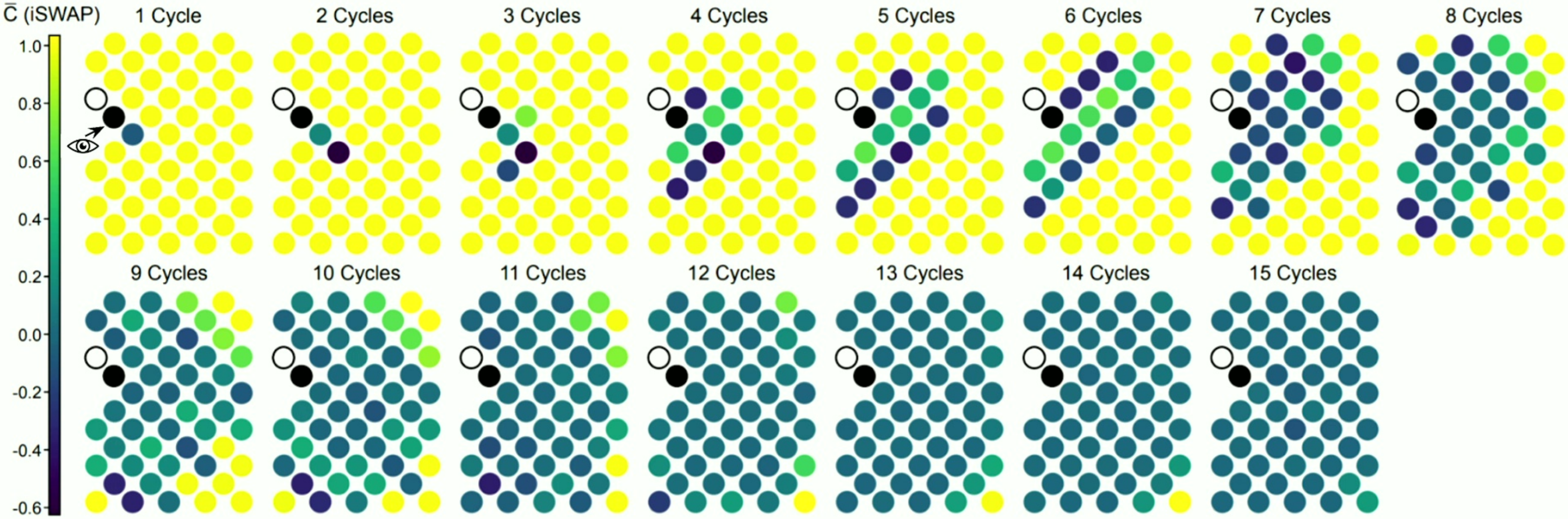

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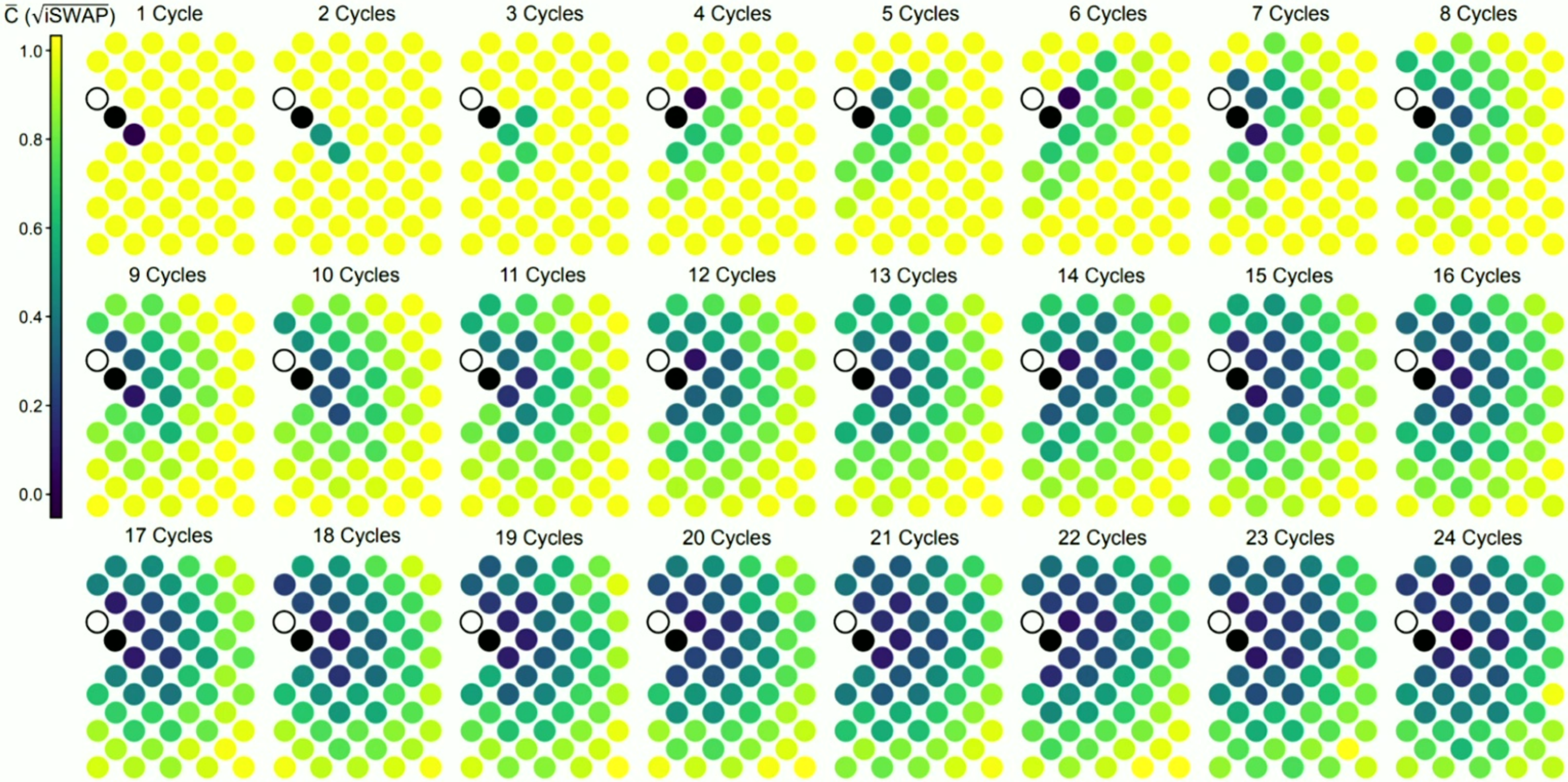

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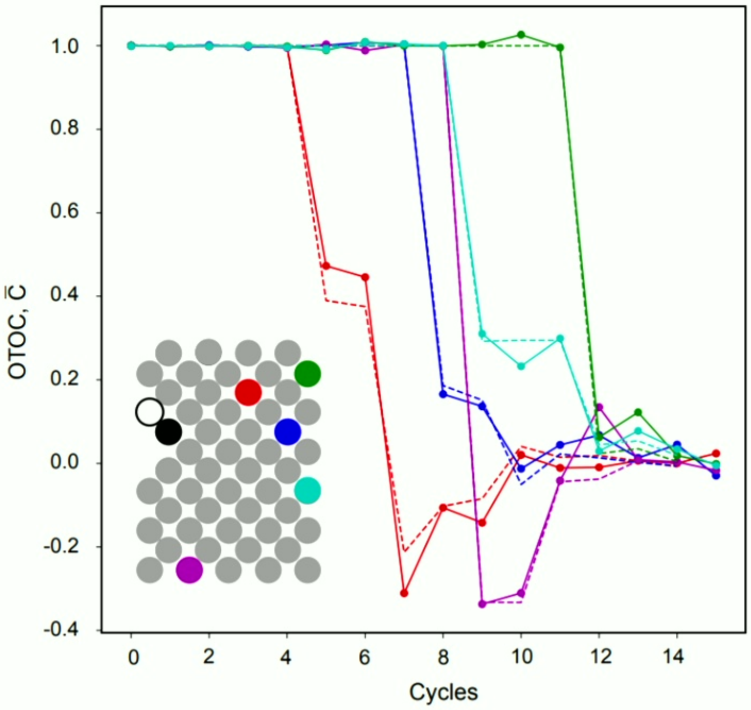
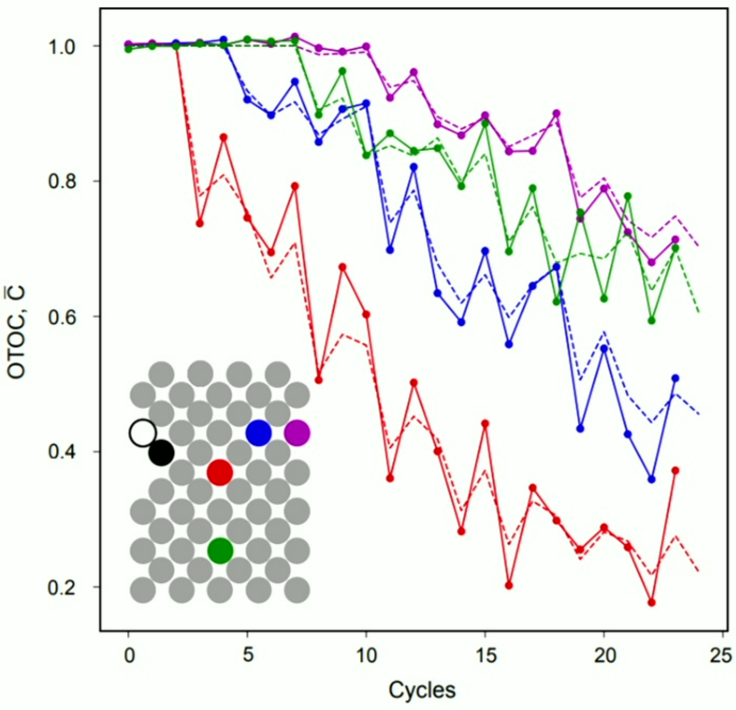
Classical Simulation of Operator Spreading


iSWAP Average-OTOCs


√iSWAP Average-OTOCs

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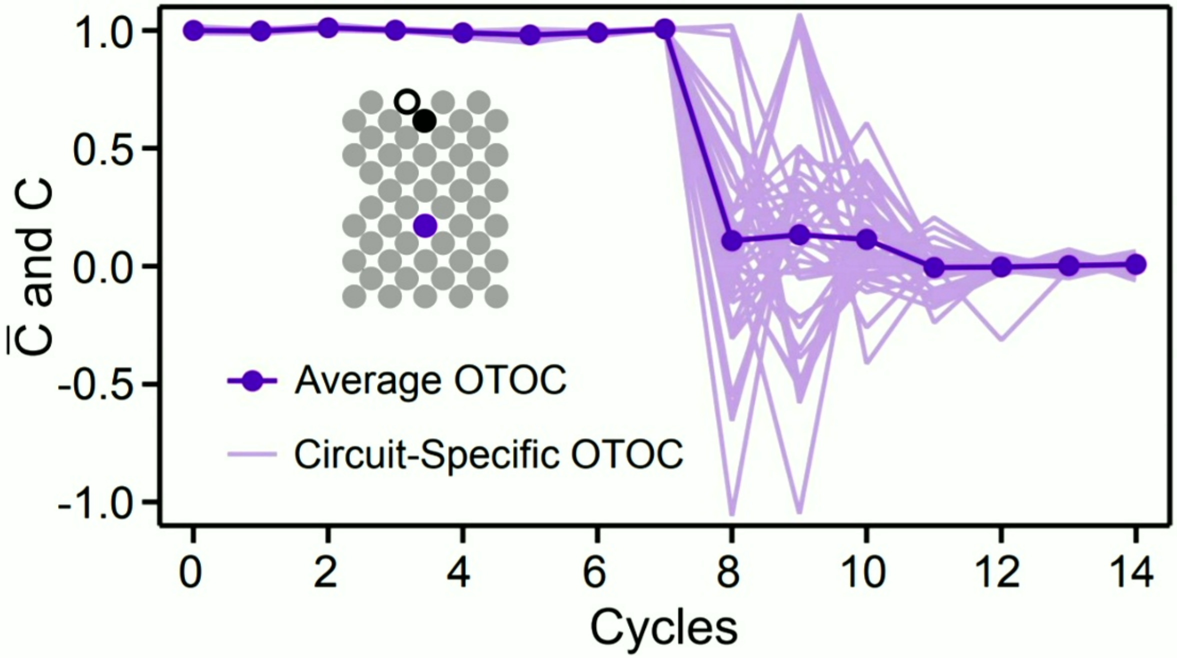
Average OTOC vs OTOC Fluctuation



- Average OTOC has different decay profile than OTOCs of individual circuits.
- **OTOC fluctuation** may reveal operator entanglement.

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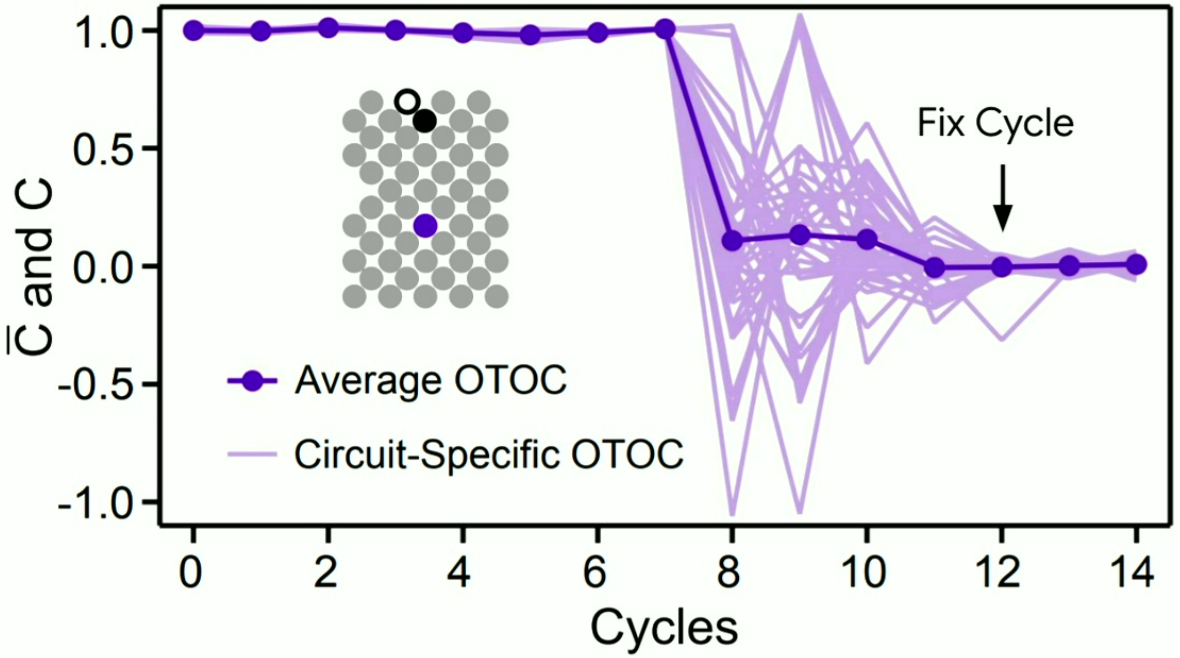
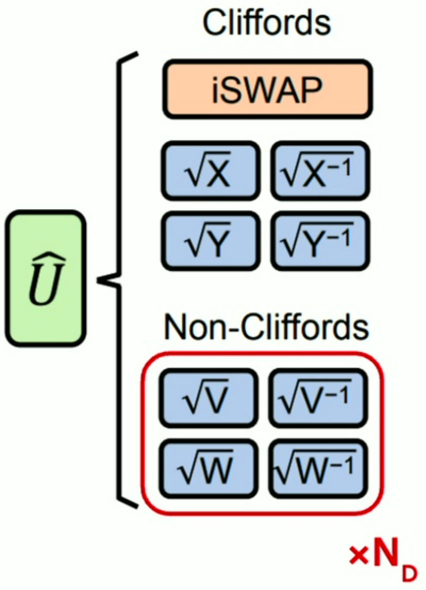
Tuning Operator Entanglement with Non-Cliffords



Adjust number of Non-Cliffords



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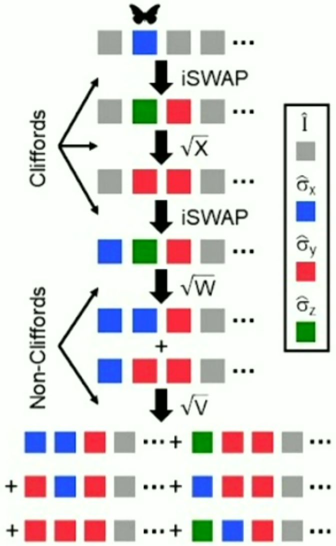
Operator Dynamics for Different Gates



- Cliffords: Operator Spreading
- Non-Cliffords: Operator Entanglement

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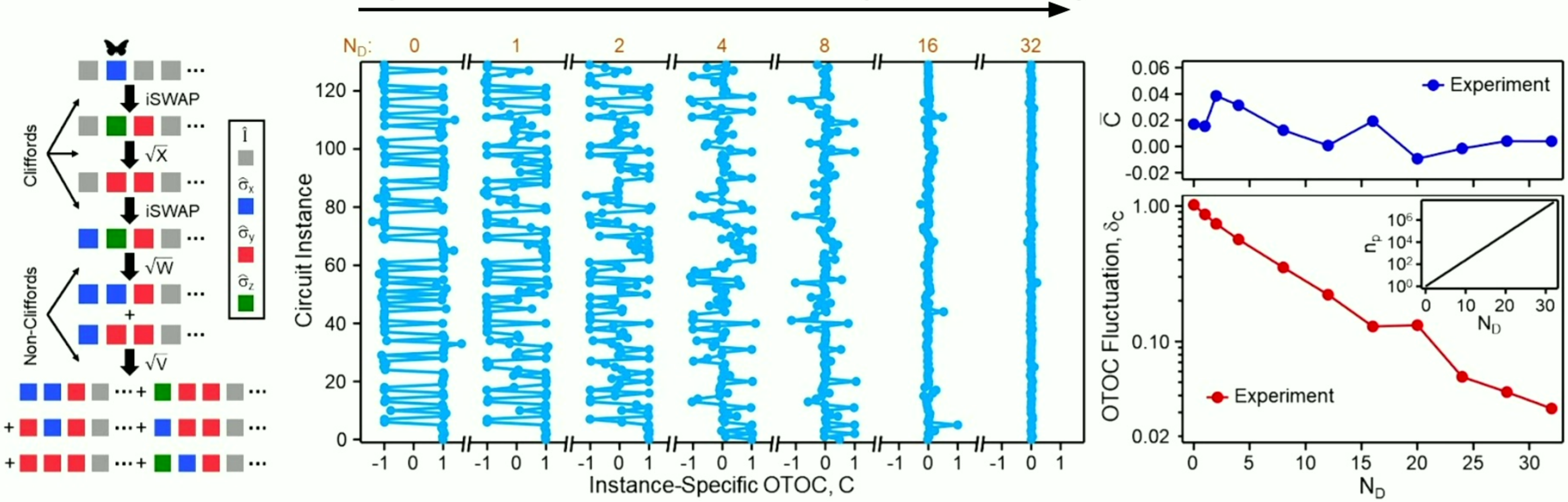
OTOC Fluctuation vs Operator Entanglement

Increasing number of non-Cliffords → Increasing Operator Entanglement



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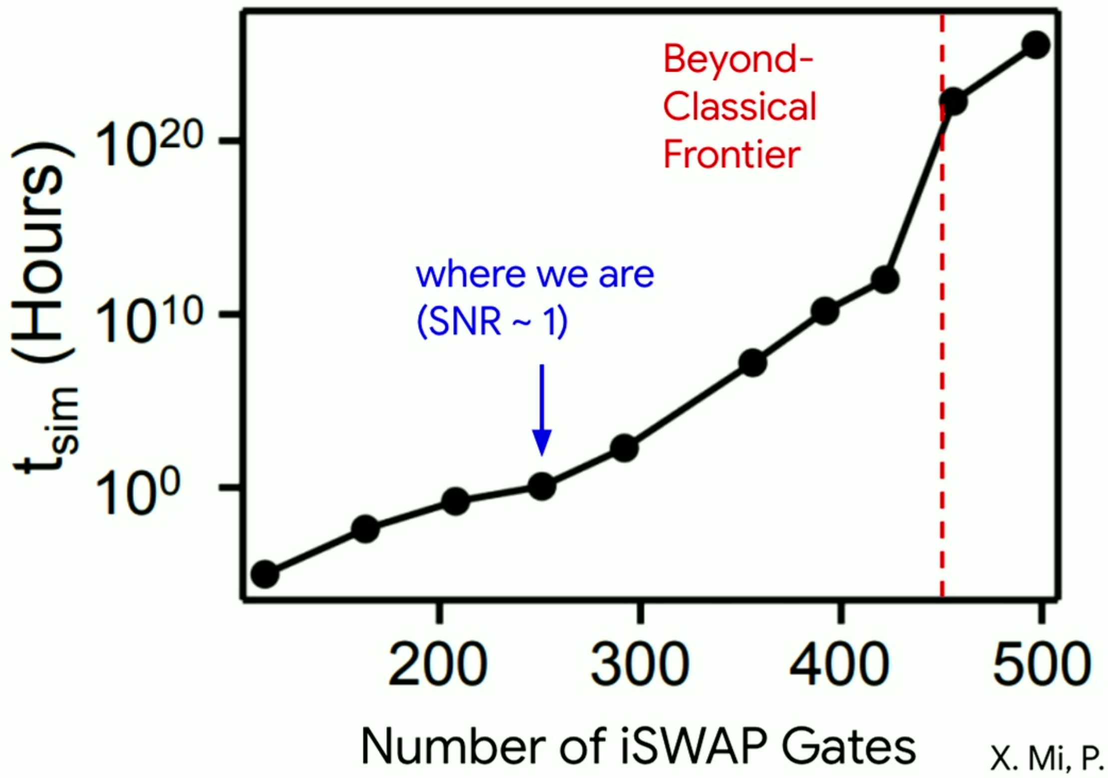
Computational Complexity of Quantum Scrambling

Time to simulate one OTOC on a single CPU



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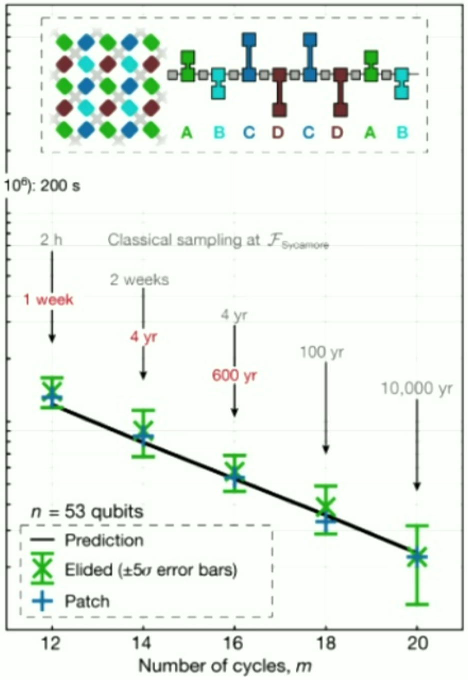
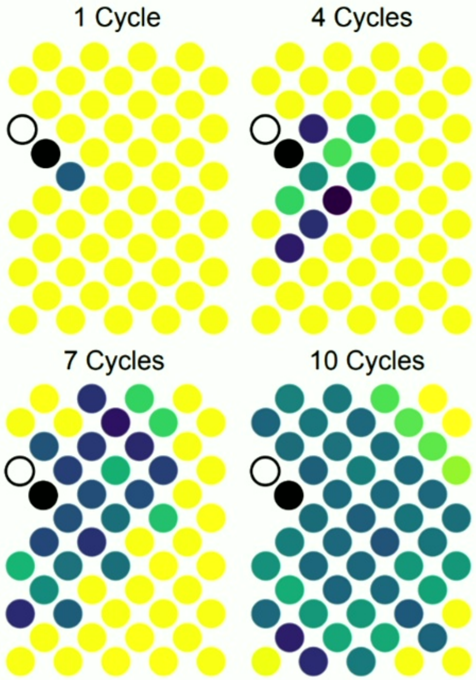
An Exciting Time for Quantum Computing

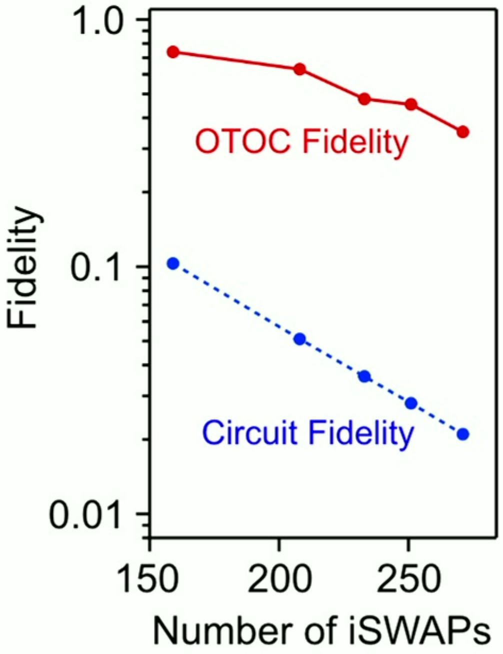
“Beyond-Classical” Capability



Physics Discovery Platform



Error-Mitigation Works!



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“To unpath’d waters, undream’d shores” - Winter’s Tale

Acknowledgement

Experiment (Google AI-Quantum)

Pedram Roushan

Chris Quintana

Charles Neill

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Igor Aleiner

Vadim Smelyanskiy

Simulation (NASA Ames)

Salvatore Mandrà

Jeffrey Marshall

\+ **Support from the entire Google AI-Quantum team!**

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Questions?

Here for the week. Reach out to mixiao@google.com or drop by room 461 for any discussion.

Second talk on Thursday 3pm at IQC:

“Simulating Many-body Phases of Matter with Superconducting Qubit Processors”

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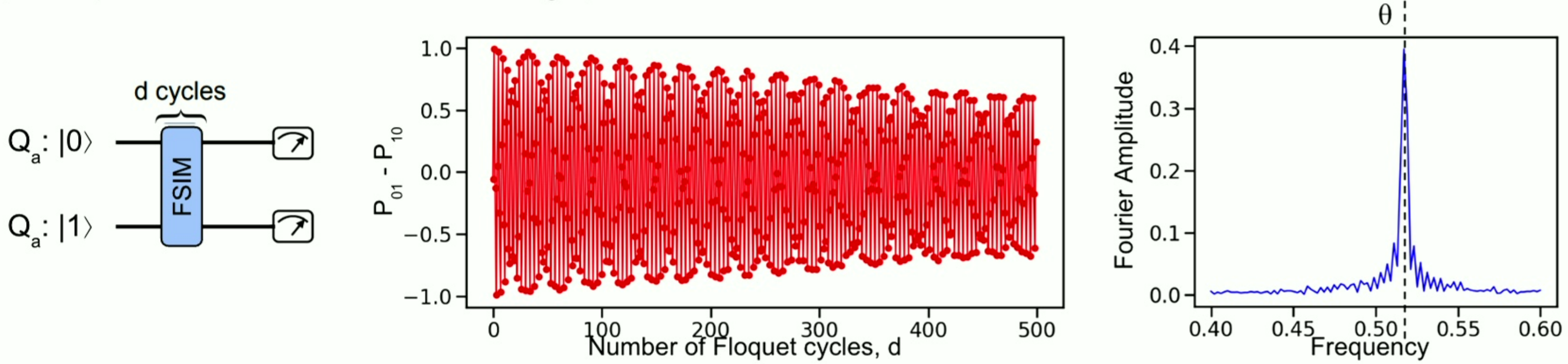
2-Qubit Gate Calibration: Floquet Calibration

Unitary Model (FSIM)

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & e^{i(\Delta_+ + \Delta_-)}\cos\theta & -ie^{i(\Delta_+ - \Delta_{-,\text{off}})}\sin\theta & 0 \\ 0 & -ie^{i(\Delta_+ + \Delta_{-,\text{off}})}\sin\theta & e^{i(\Delta_+ - \Delta_-)}\cos\theta & 0 \\ 0 & 0 & 0 & e^{i(2\Delta_+ - \phi)} \end{pmatrix}$$

θ: iSWAP angle
ϕ: Conditional phase
Δ_+, Δ_-, $\Delta_{-,\text{off}}$: Single-qubit phases

Example: Calibration of iSWAP Angle



Key: Coherent **amplification** of **single** parameter

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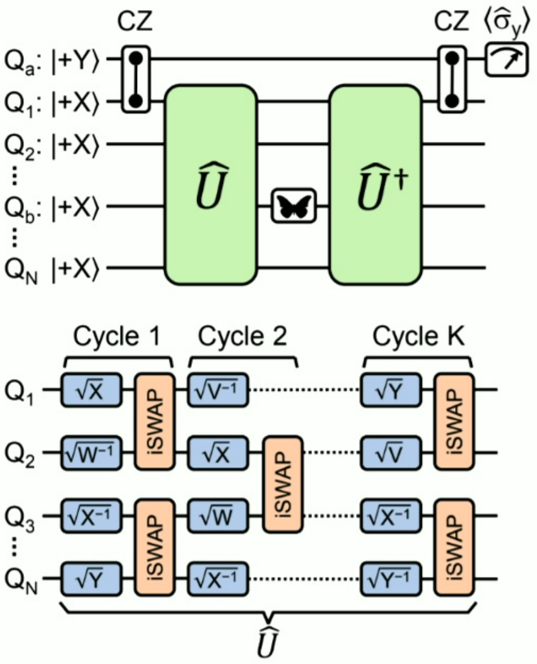
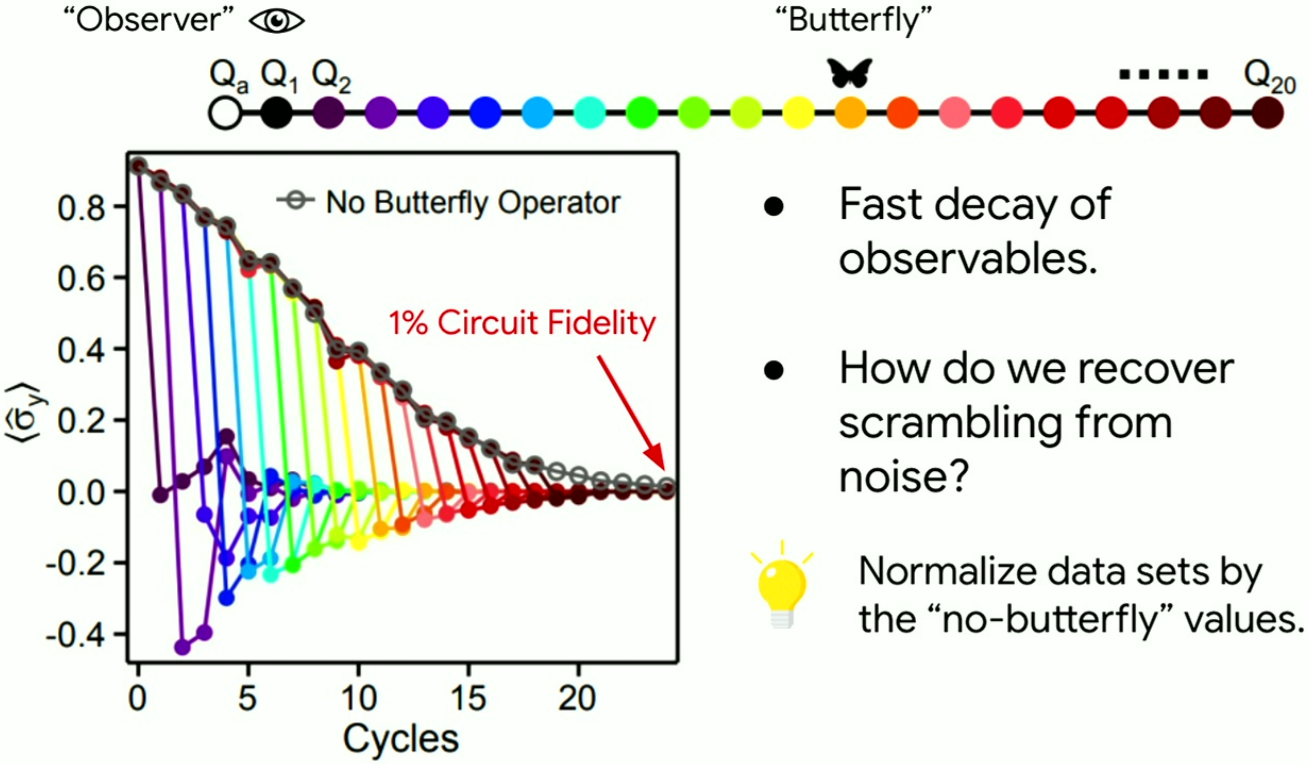
Average-OTOCs and Operator Spreading (1D)





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