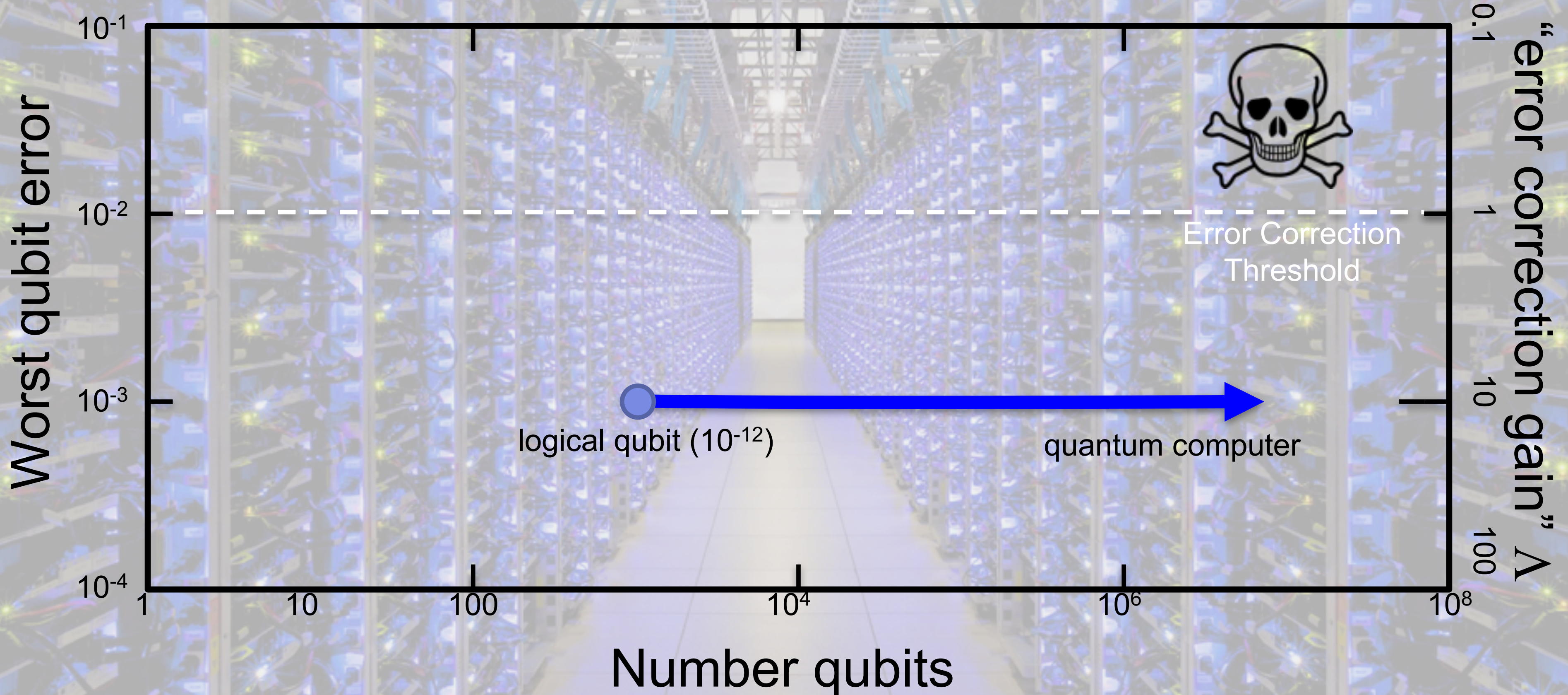
The Quantum Space Race

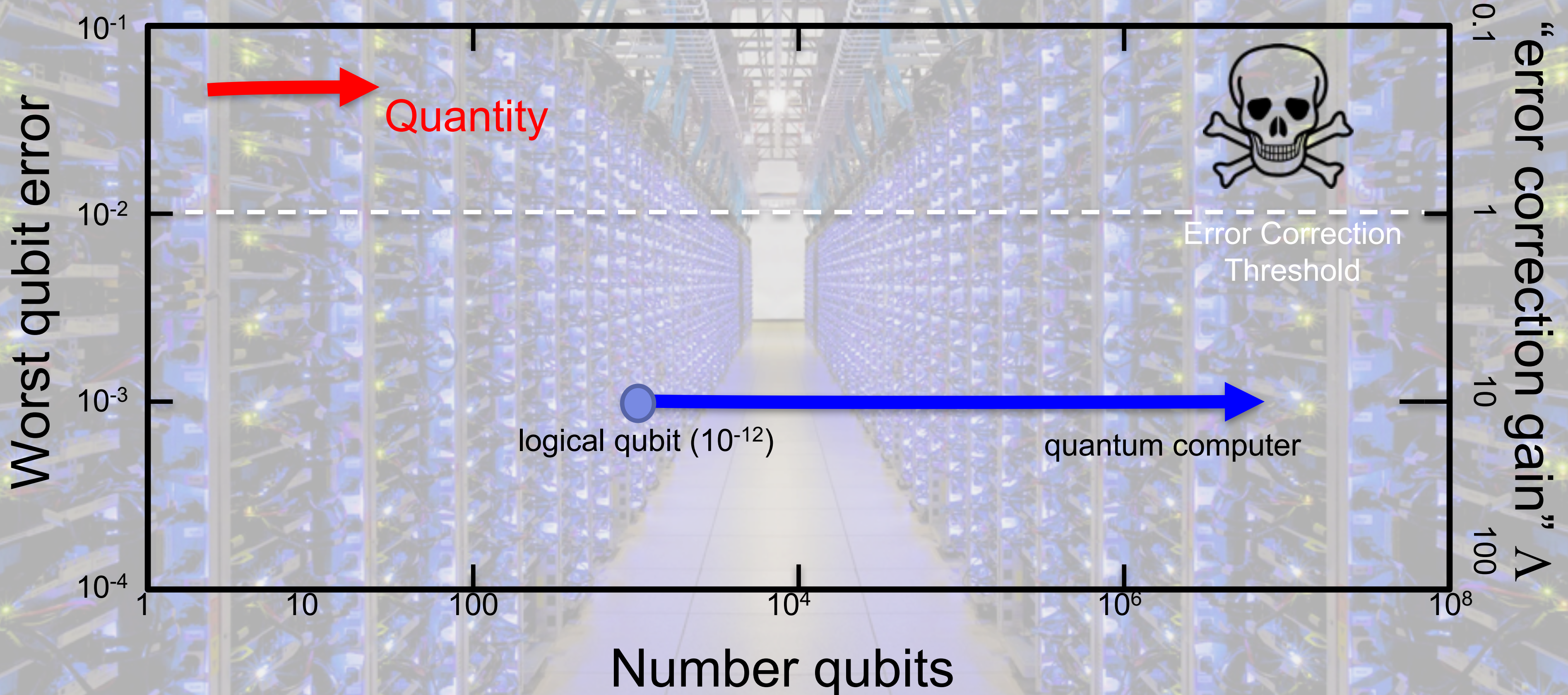
John Martinis, Google

Hardware Challenges:
- Quantity
- Quality

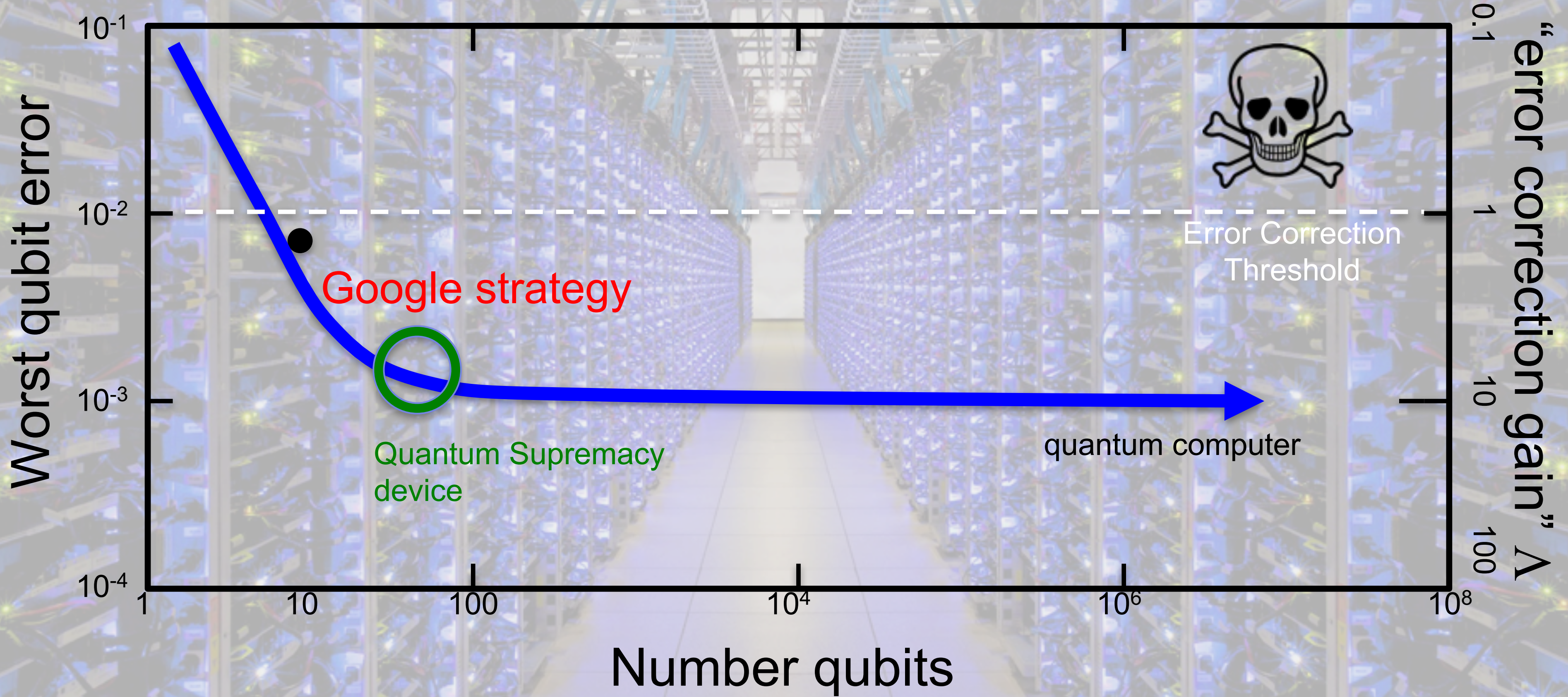
Systems: Quantity and Quality



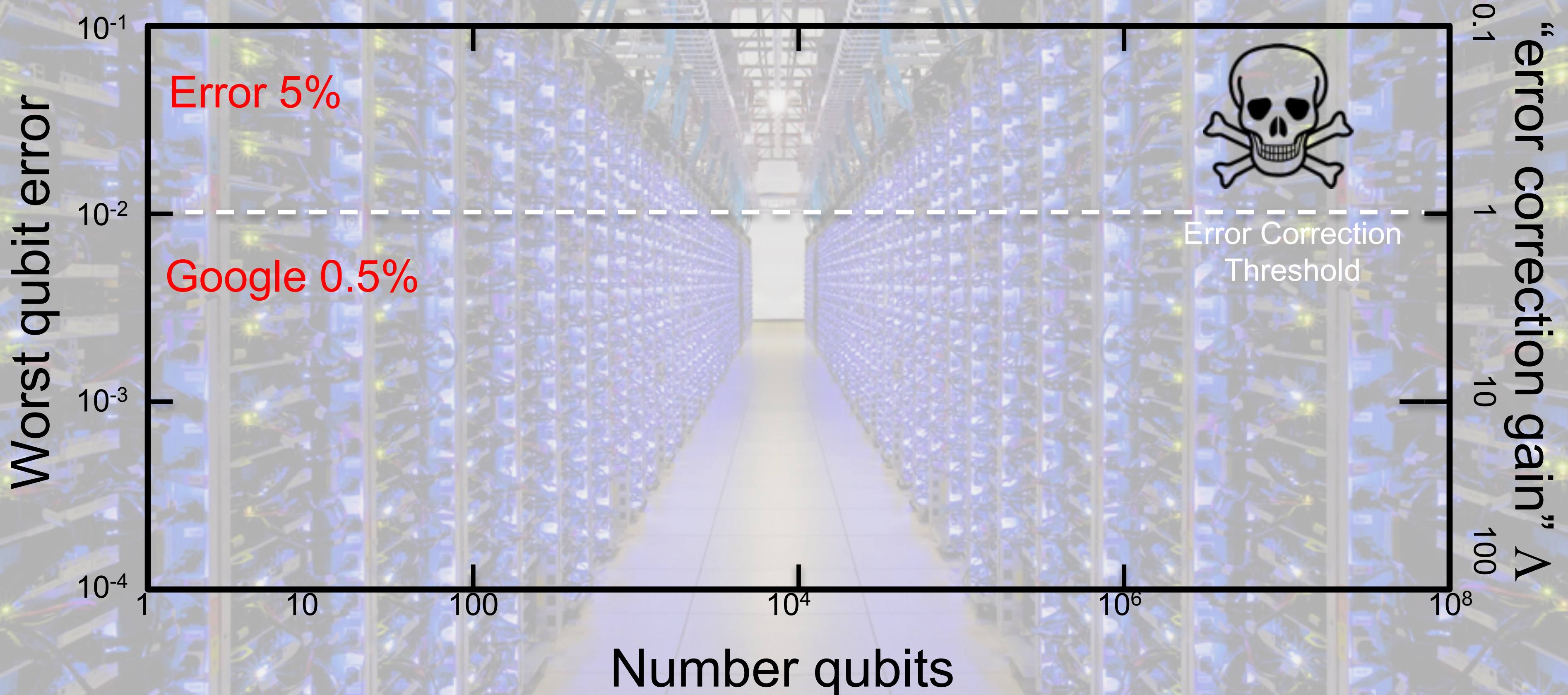
Systems: Quantity and Quality



Systems: Quantity and Quality

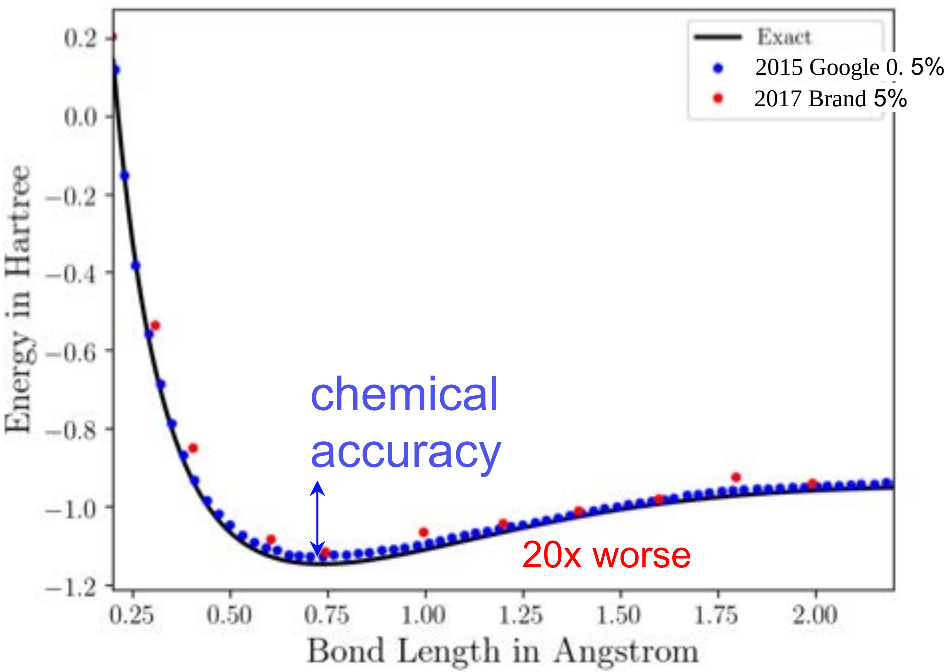


Systems: Quantity and Quality

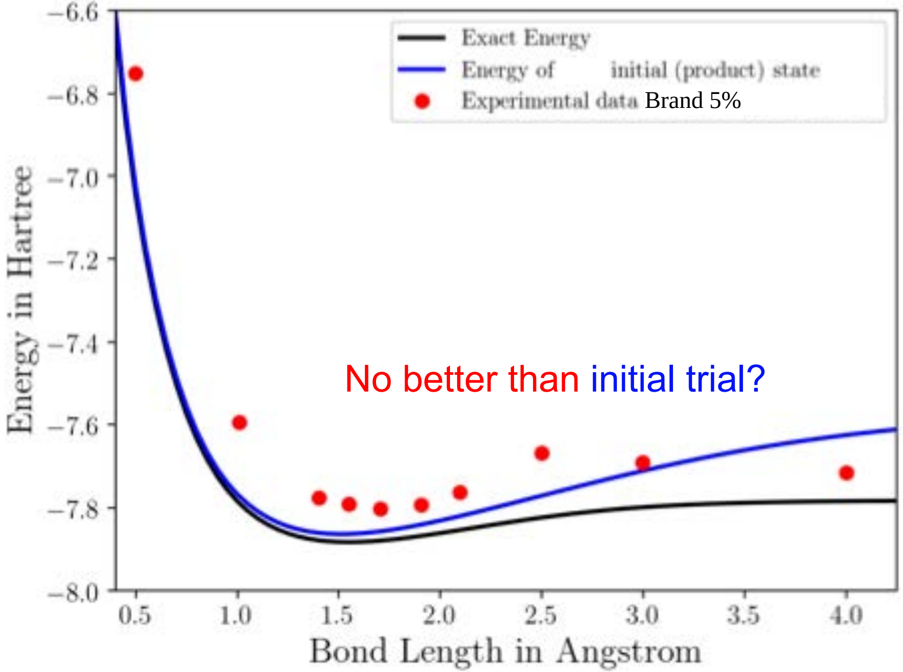


Quality in Quantum Chemistry Experiments

H_2 Molecule



LiH Molecule



Quality:

1) Need quality to claim useful
2) Need low errors for accurate predictions

Comparison of Qubit Systems for Google & IBM

Dec 2017

Different system designs

IBM: fixed frequency qubits — better coherence

Google: tunable qubits — faster gates

Compare qubit devices Google 5 and 9 with IBM 20

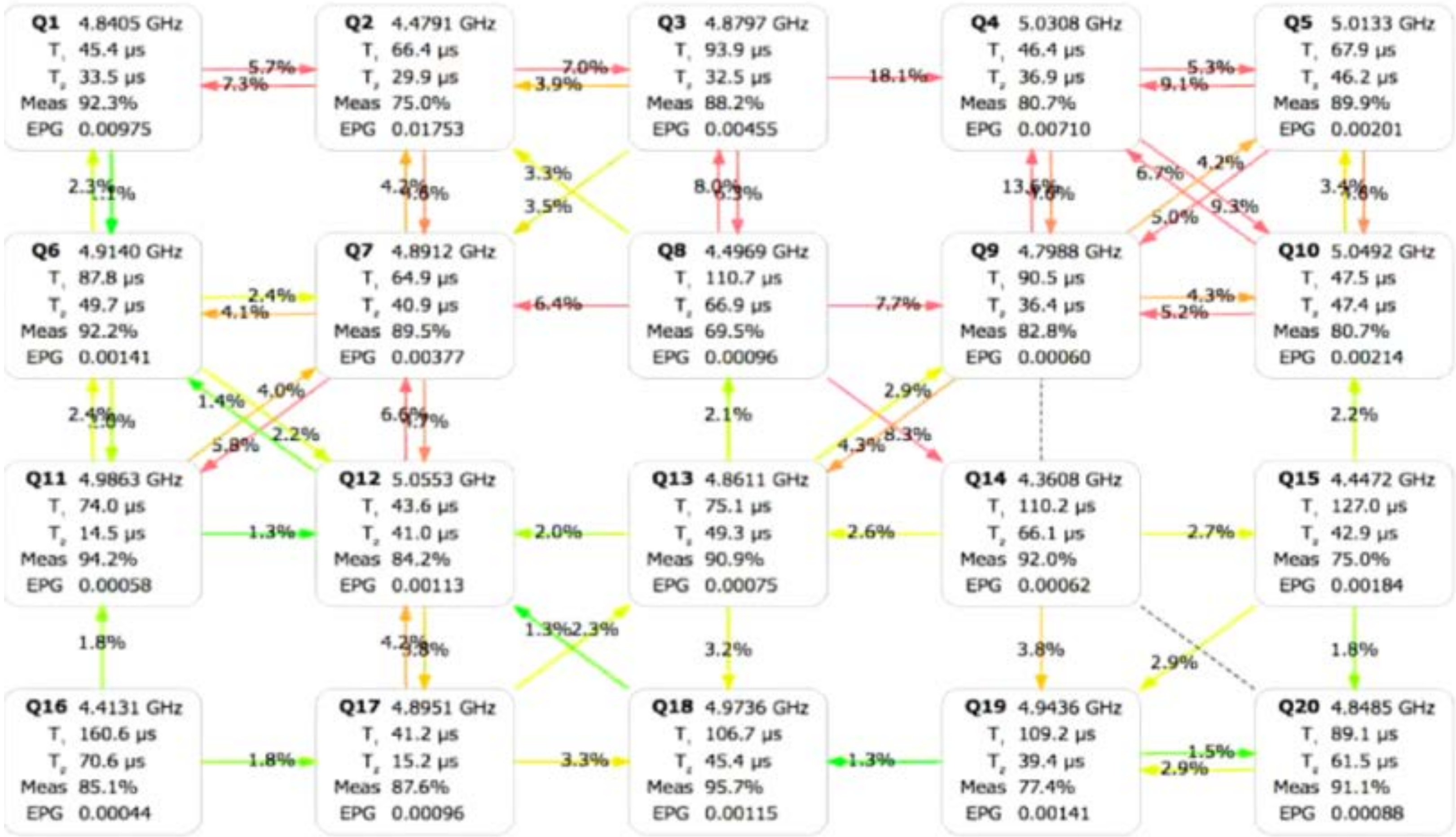
Not completely fair, as good performance harder with 2D architecture,
but at least not comparing with 2 qubit device

Google will soon have 2D data on supremacy device, expect same as 1D

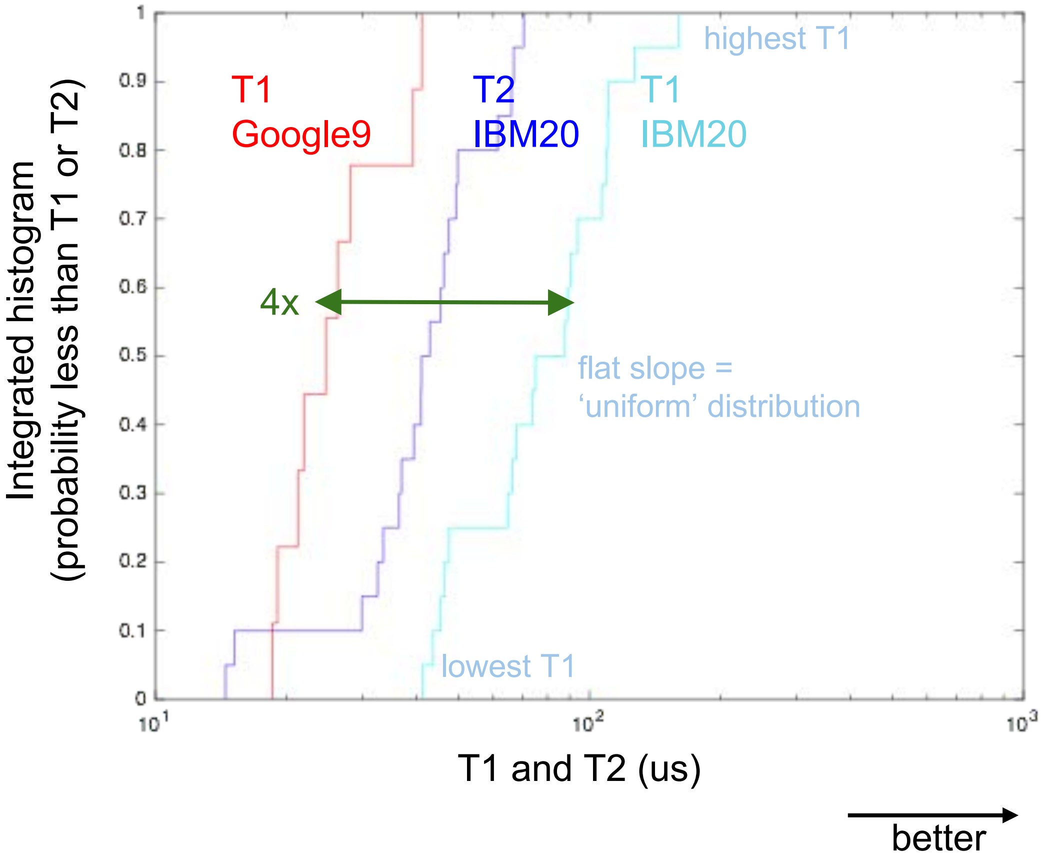
Systems: statistics from **all** qubits (not just best)

Compare with histogram integral, better display for small statistics

IBM Data from ThinkQ Conference (preliminary!)



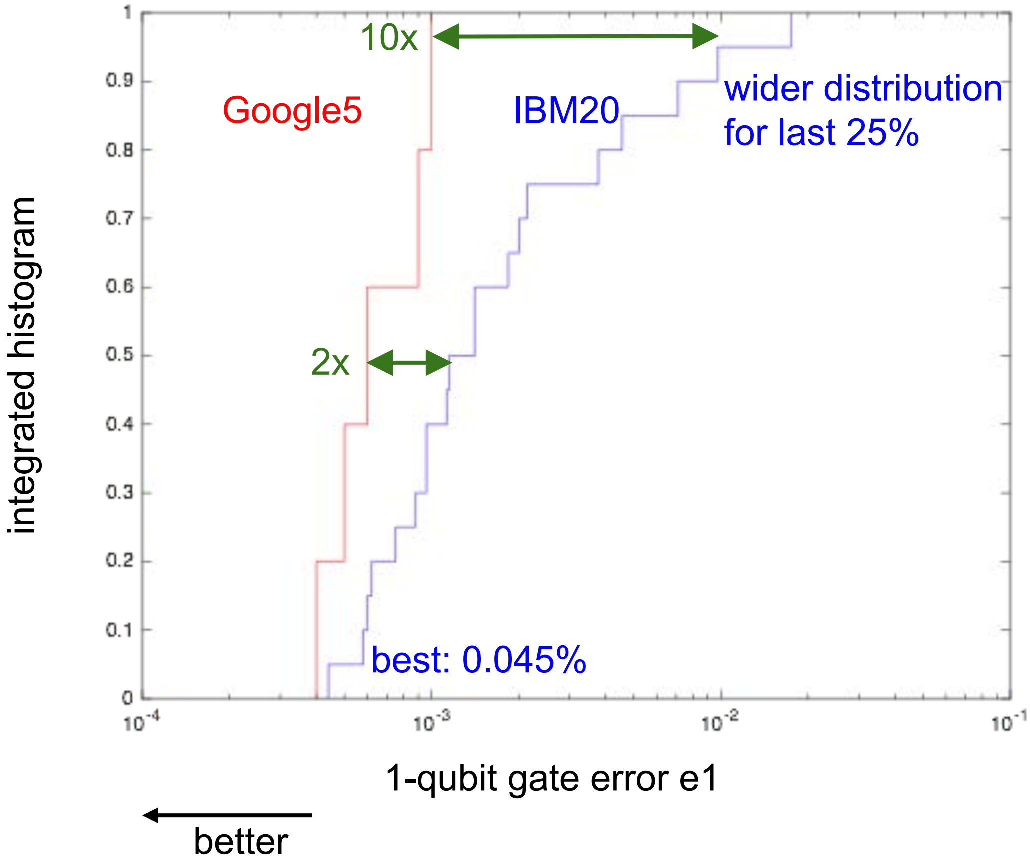
Everyone Quotes T1 and T2



Google now improved ~2x

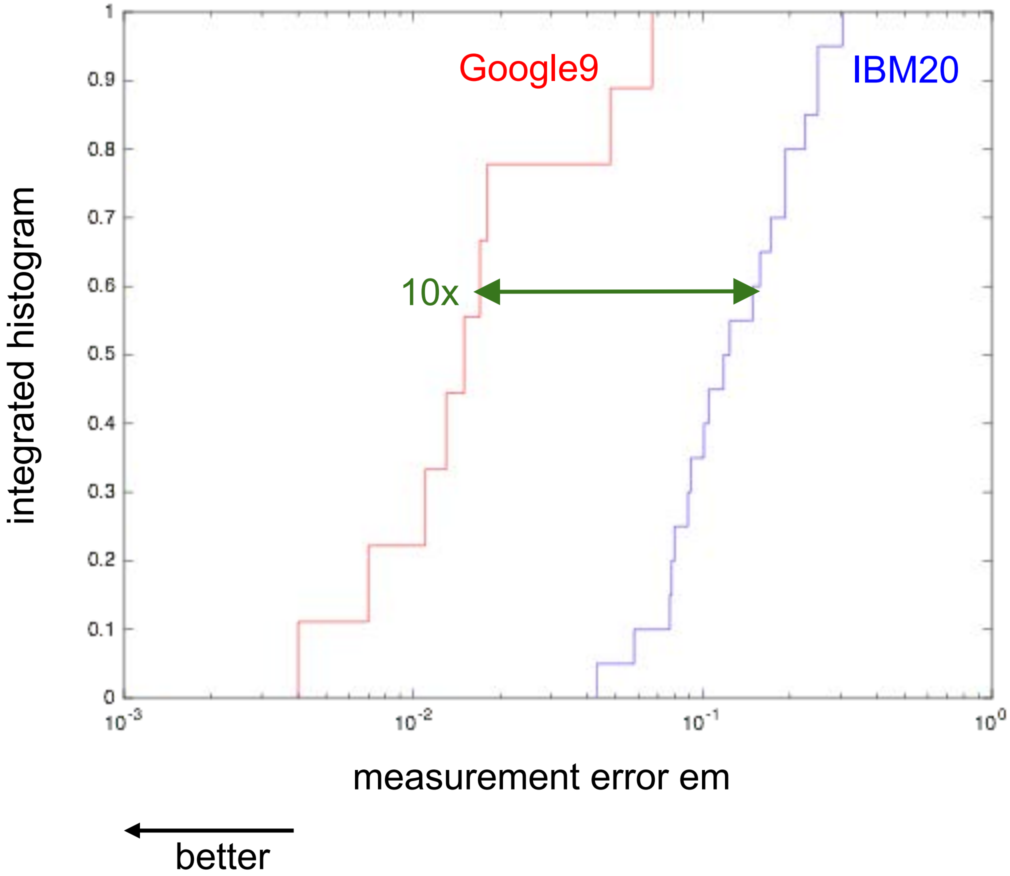
Google 4x worse in T1

Single Qubit Gate Errors



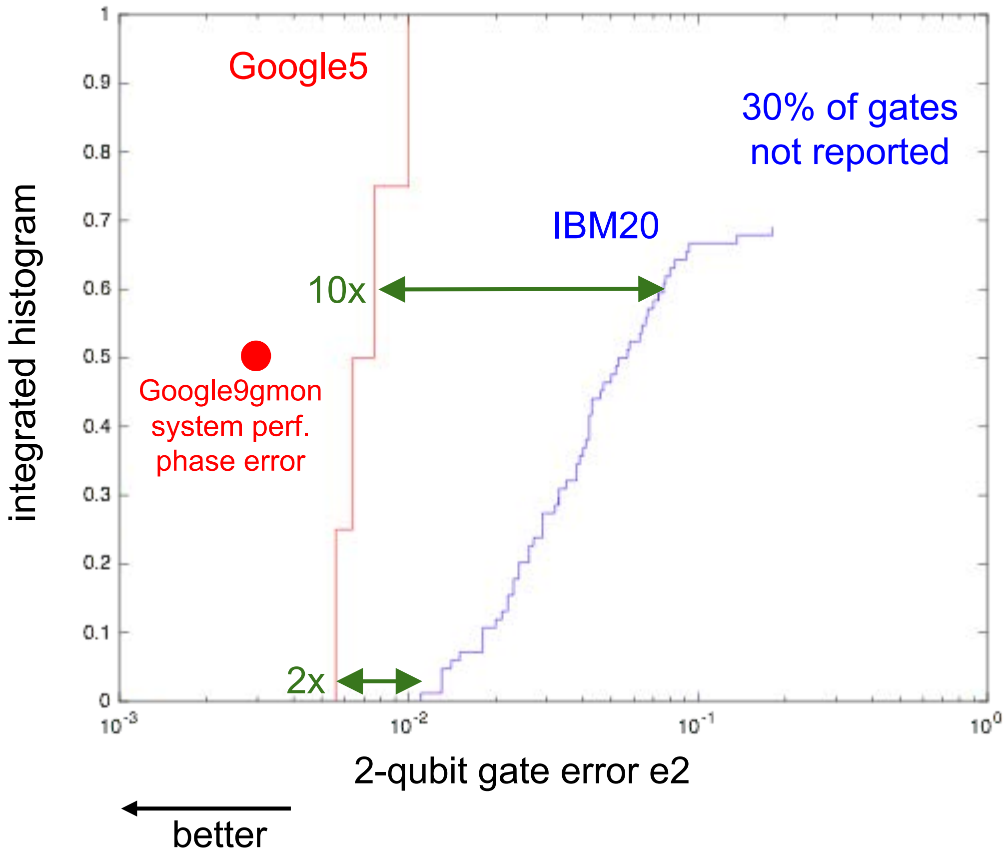
Google better
by ~ 2-10x

Measurement Errors



Google better by ~ 10x

Two Qubit Gate Errors (most critical)



Google better by ~ 2-10x

System Benchmarking

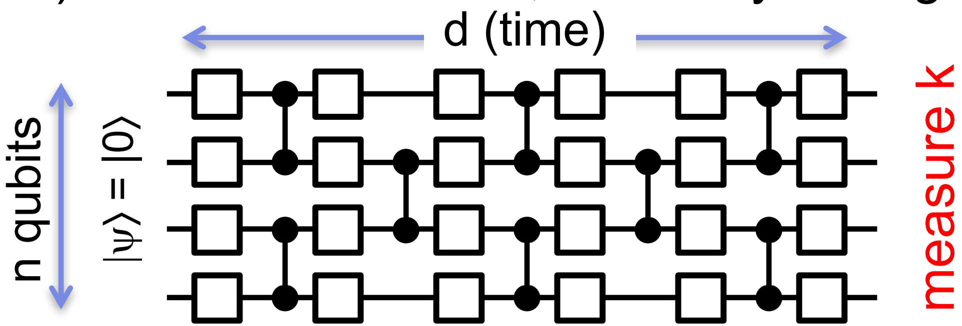
T1 & T2 coherence metric not reliable

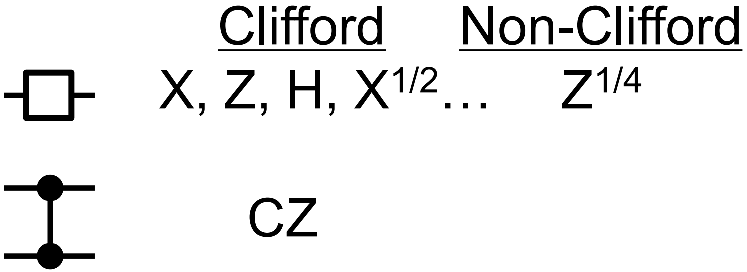
✅ Gate fidelity more realistic

✅ Future: system fidelity with
    10-80: quantum supremacy
    49+: error correction rate

Quantum Supremacy Algorithm: Qubit Speckle

1) Choose 1 instance, randomly from gateset





2) Run quantum computer, measure k (2ⁿ possible outcomes)

repeat sampling 100,000 times

1 s

(Random guess: any outcome k has probability $p_{cl} = 1/2^n$)

days
200 drives

3) Calculate $|\psi\rangle$, $p(k) = |\langle k|\psi\rangle|^2$ store in lookup table

4) Correlation: cross entropy

$$S = \langle \ln p(k)/p_{cl} \rangle$$

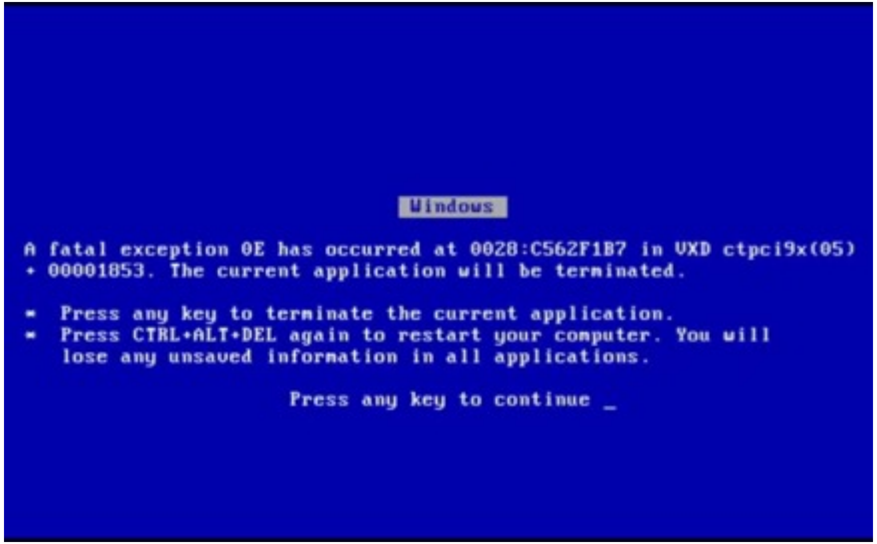
5) Compare to theory

$S_{qu} \cong 0.42$ quantum

6) Try another instance

$S_{cl} \cong -0.58$ classical

speckle = coherence
predict = fidelity



Intrinsic Errors in Quantum Computation

$$S_{tot} \cong P_0\, S_{qu} + (1-P_0)\, S_{cl}$$

Probability of no error:

$P_0 = \exp[\,-N_g\, \varepsilon_g\,]$

Average number of errors:

$N_g\, \varepsilon_g = 49 \times 7 \times 0.005 = 1.7$

Need: Quantity with Quality

Low-Depth Quantum Supremacy

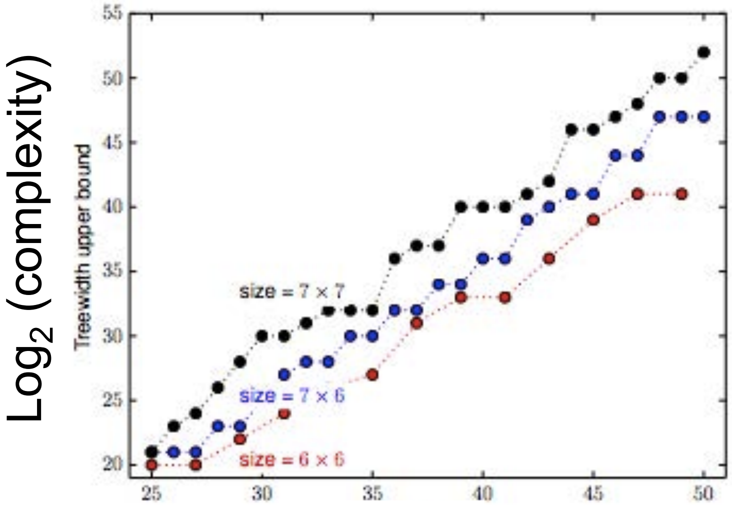
Integrate Schr. eq'n 2^n

Feynman path integral 2^{Depth}

First discussed by Boixo et. al. (Google)

- IBM: supercomputer

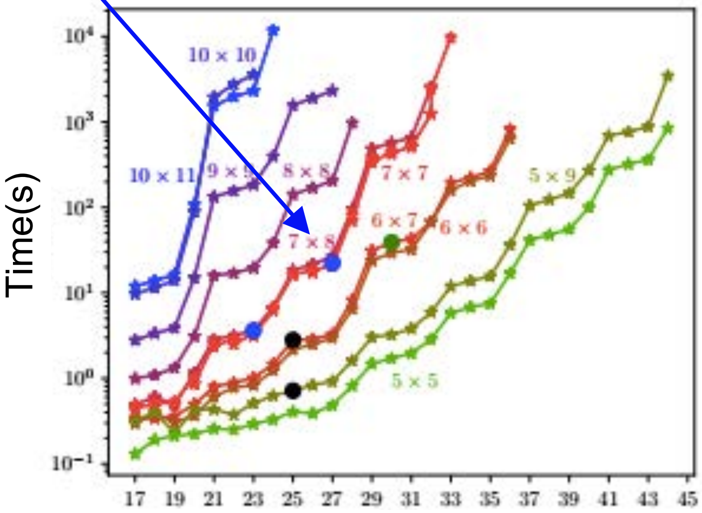
Google: workstation (data center)



Depth

arXiv:1608:00263

FIG. 13. Numerical upper bound for the treewidth of the interaction graph of the Ising model corresponding to circuits with 6 × 6, 7 × 6, and 7 × 7 qubits as a function of the circuit depth (see Sec. V B).

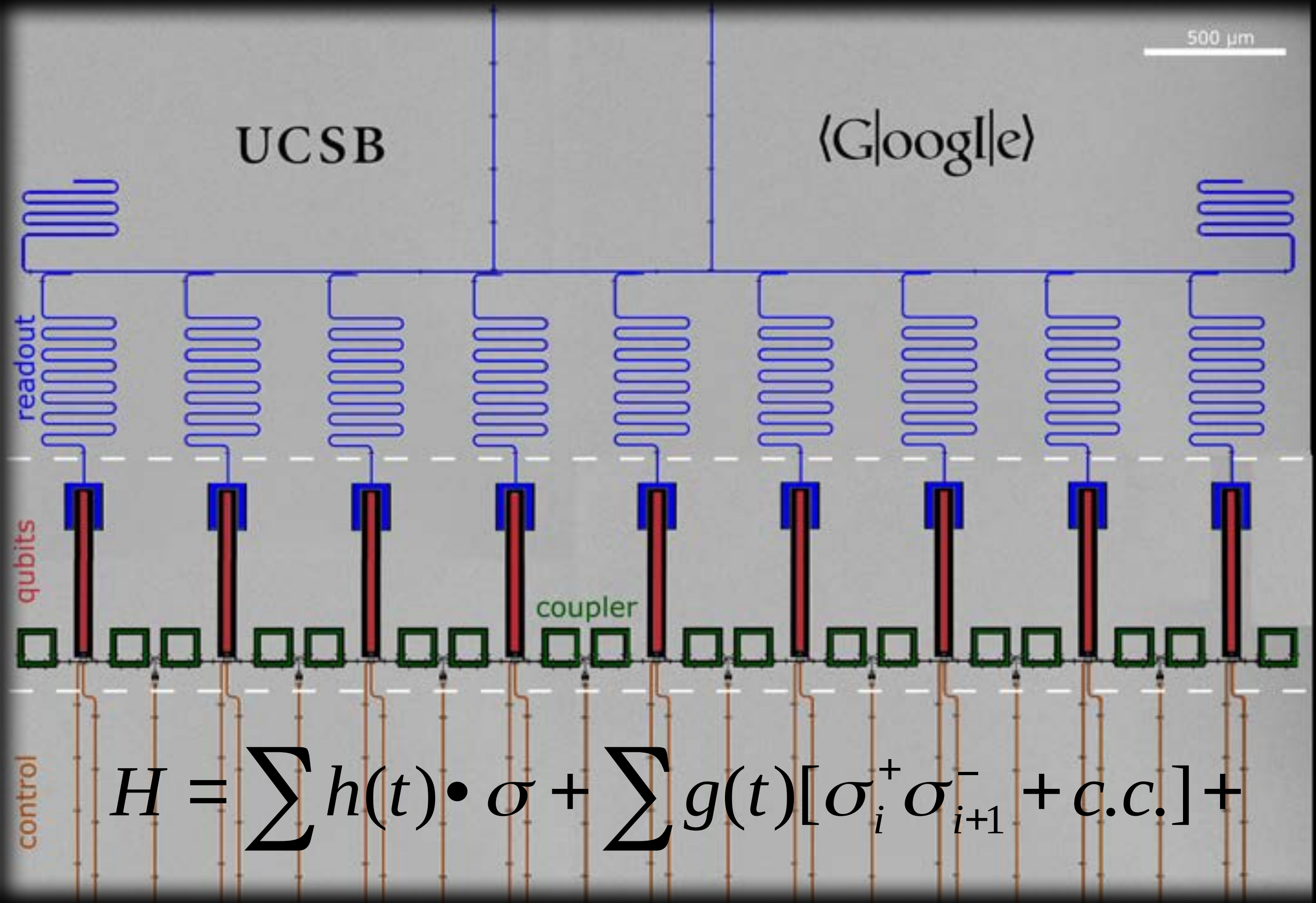


Depth

arXiv:1712.05384

FIG. 1. Time per output probability for a typical instance as a function of depth on a single workstation, using TensorFlow as the engine for the computation and a vertical elimination ordering (see Sec. IV A). Different colors corresponds to dif-

Quantum Supremacy with gmon Qubits

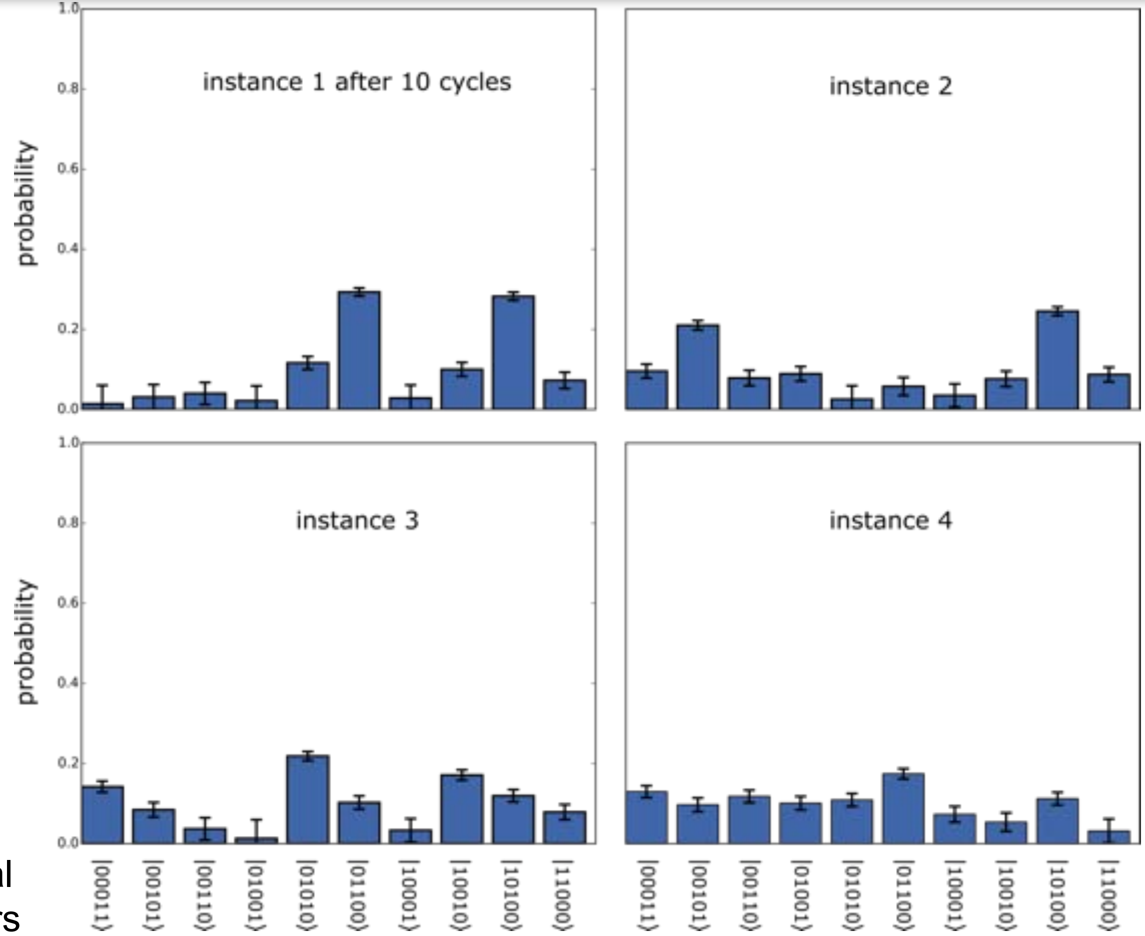


$$H = \sum h(t) \bullet \sigma + \sum g(t)[\sigma_i^+ \sigma_{i+1}^- + c.c.] +$$

9-qubit gate calibrated from 8 2-qubit gates

h ~ 200 MHz
g ~ 30 MHz
t: 1 ns to 20 us
Cal. to ~0.1MHz

Typical dataset with 5 qubits

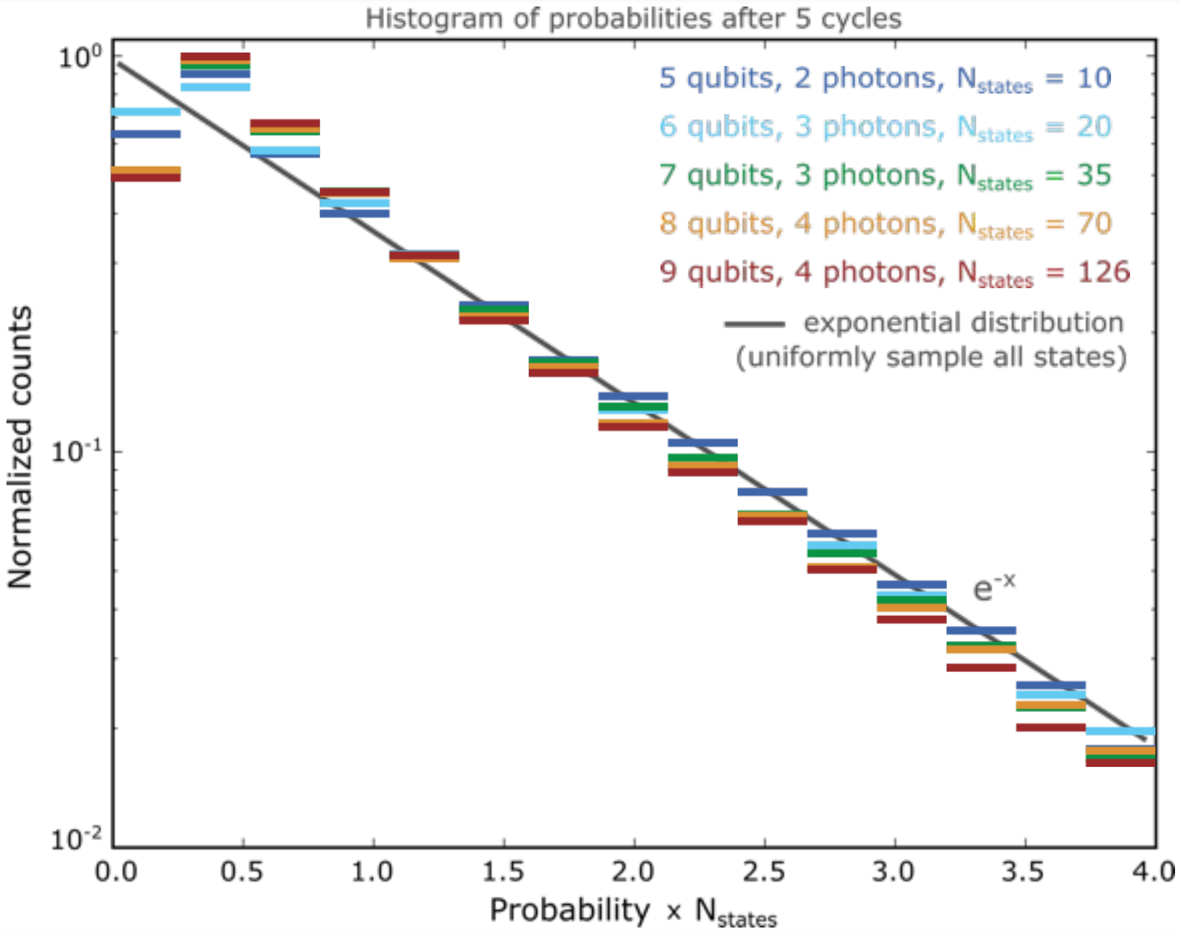


statistical
error bars

quantum info
just from
prob. histograms

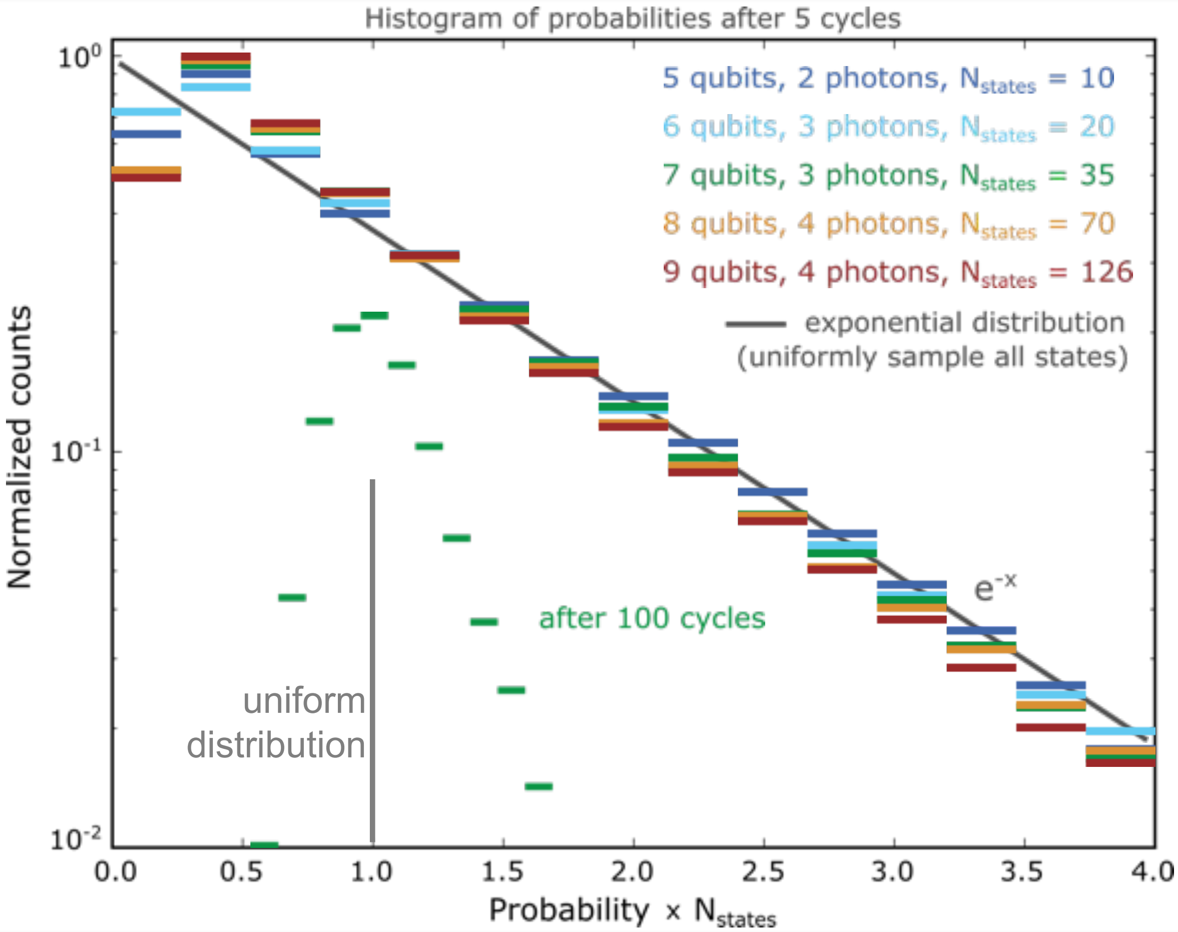
photon conserving
states

Histogram of measured probabilities



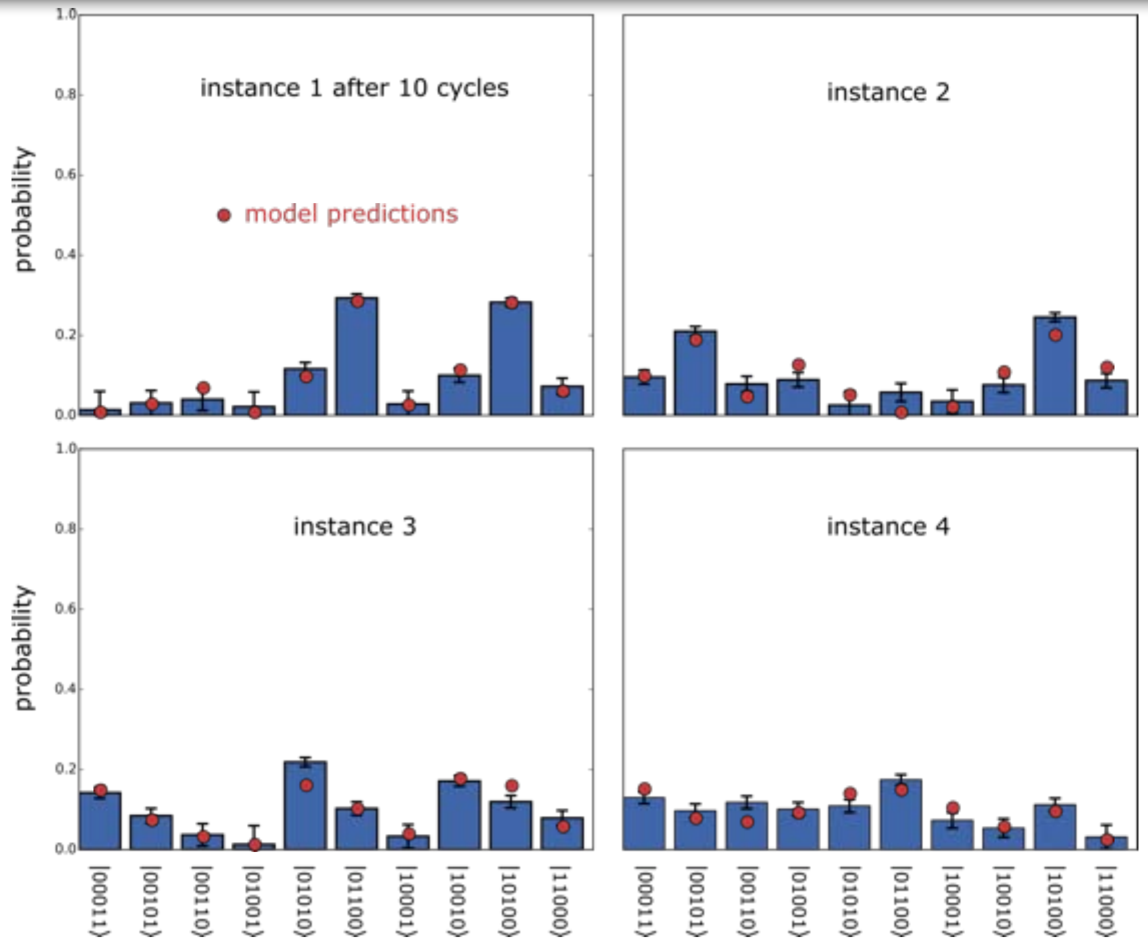
Collapses to exponential distribution

Histogram of measured probabilities



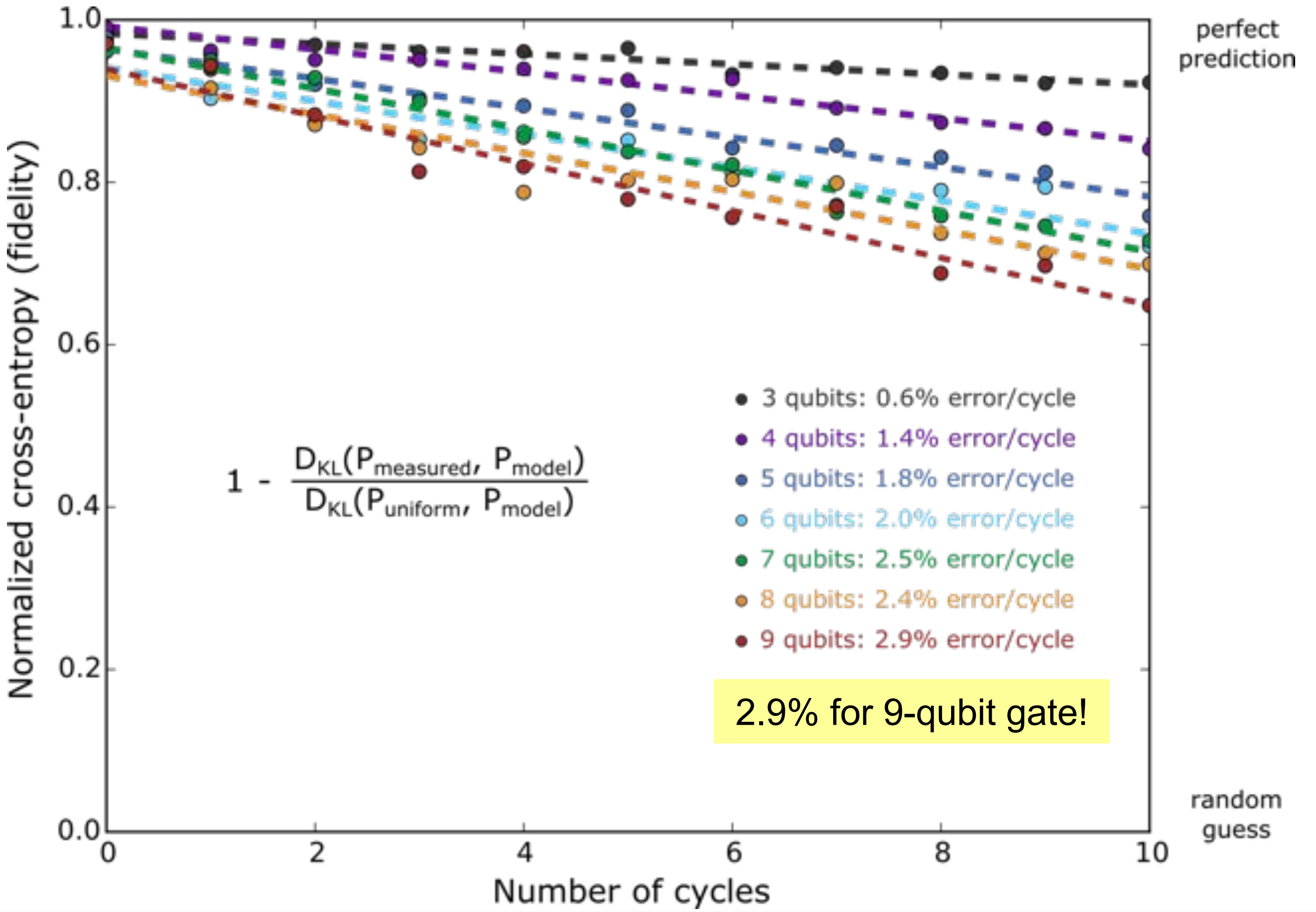
decoherence kills qubit speckle

Compare probabilities of experiment and theory



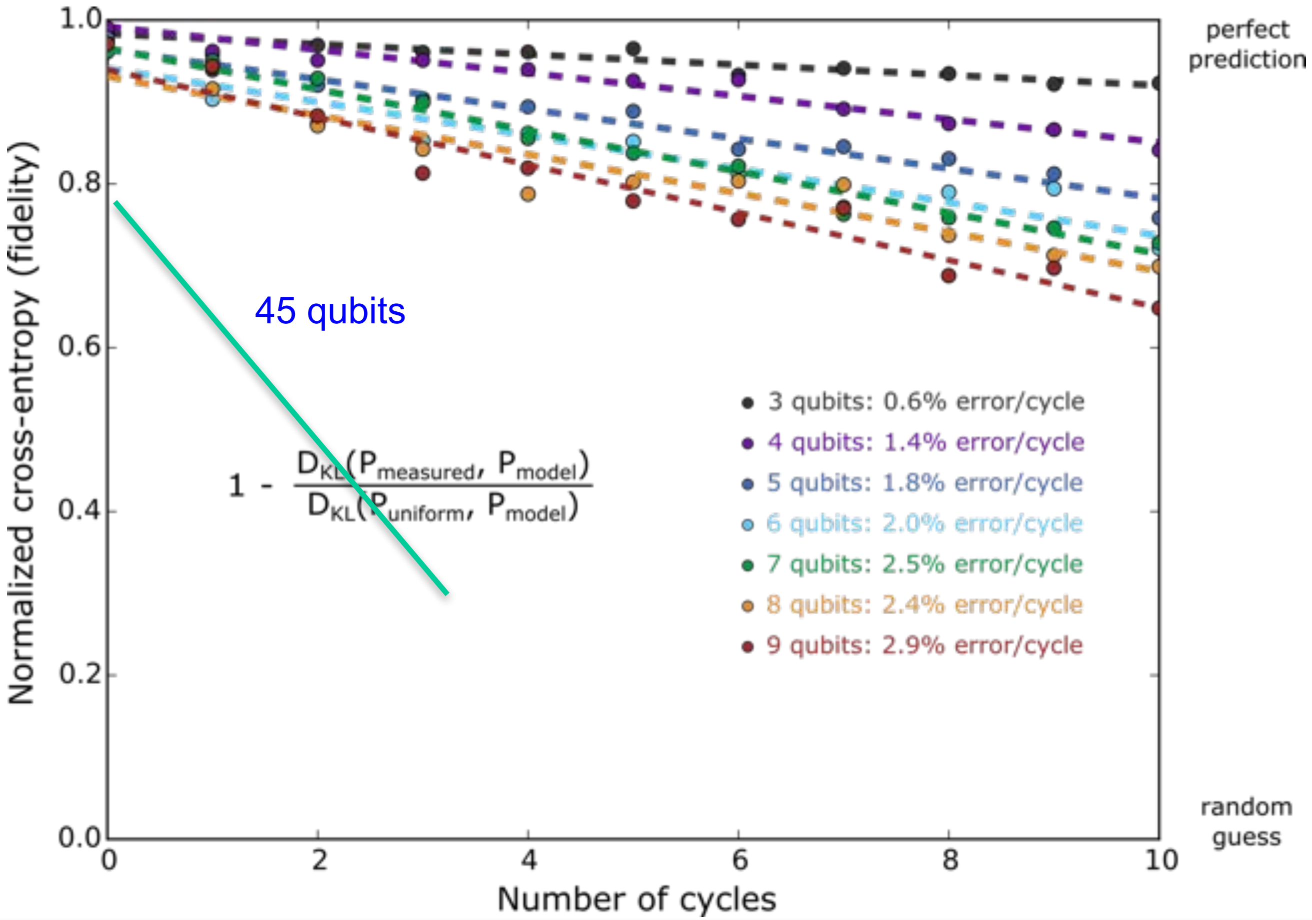
speckle pattern matches theory

Measuring fidelity



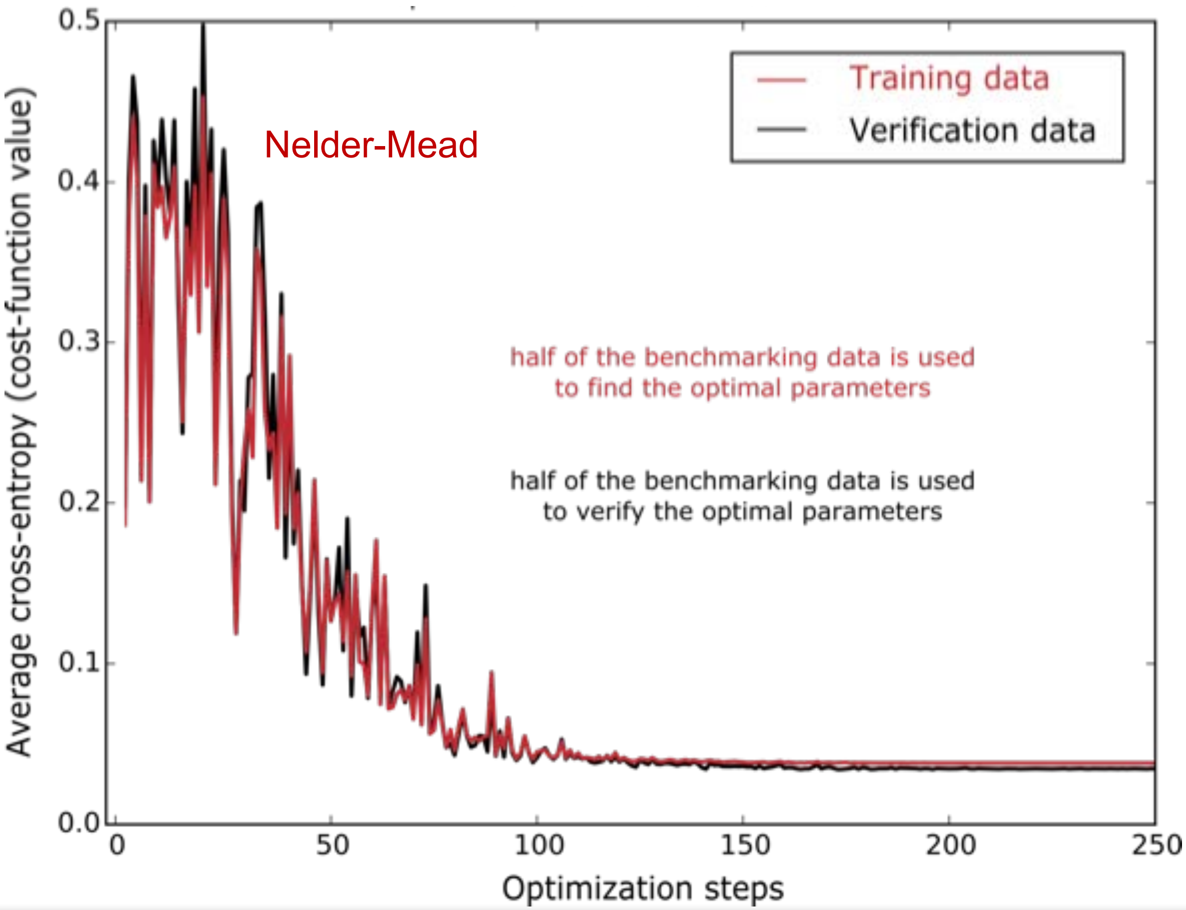
0.3% error per gate & cycle

Scaled fidelity for 45 qubits



supremacy possible with margin

Useful: Learning a better control model

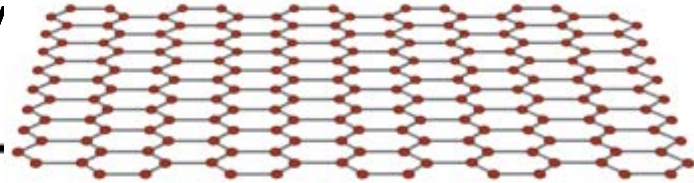


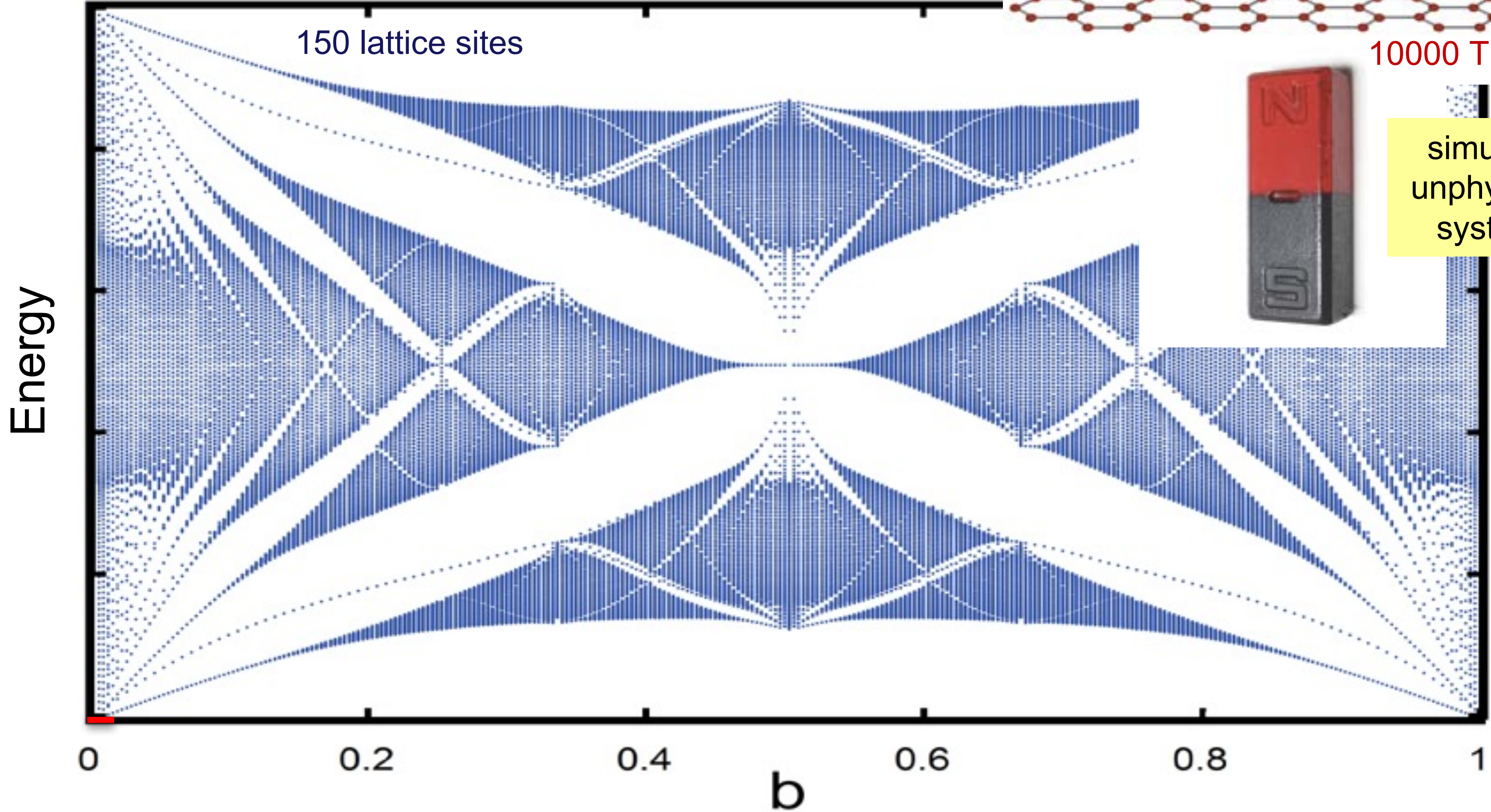
Tuneup flux offsets
(as drifty)

training
verified

Hofstadter Butterfly

$$H(b) = t\sum_{i}^{N_Q} \cos(2\pi i b)\sigma_i^Z + t\sum_{<i,j>}^{N_Q-1} (\sigma_i^X\sigma_j^X + \sigma_i^Y\sigma_j^Y)$$



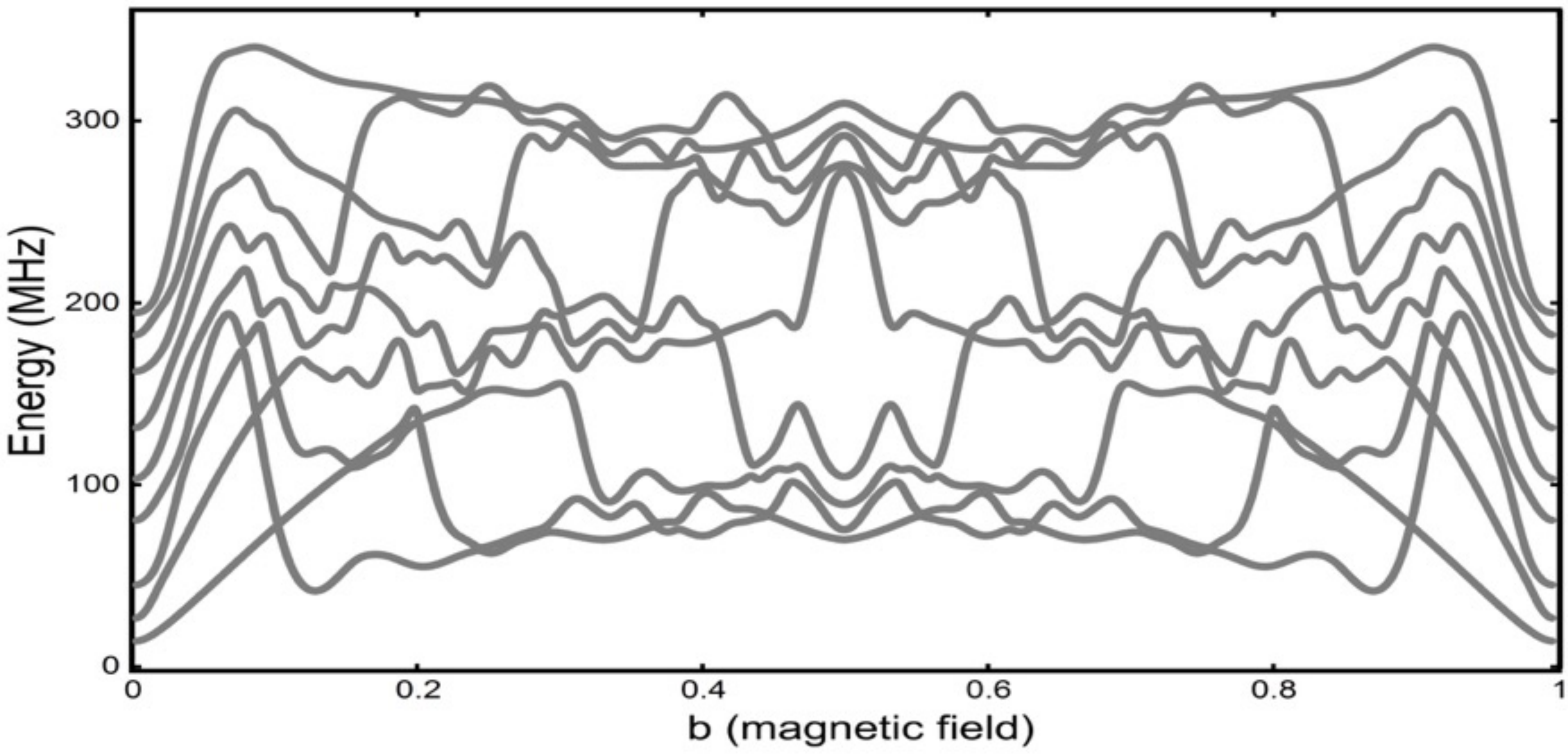


10000 T

simulate unphysical system

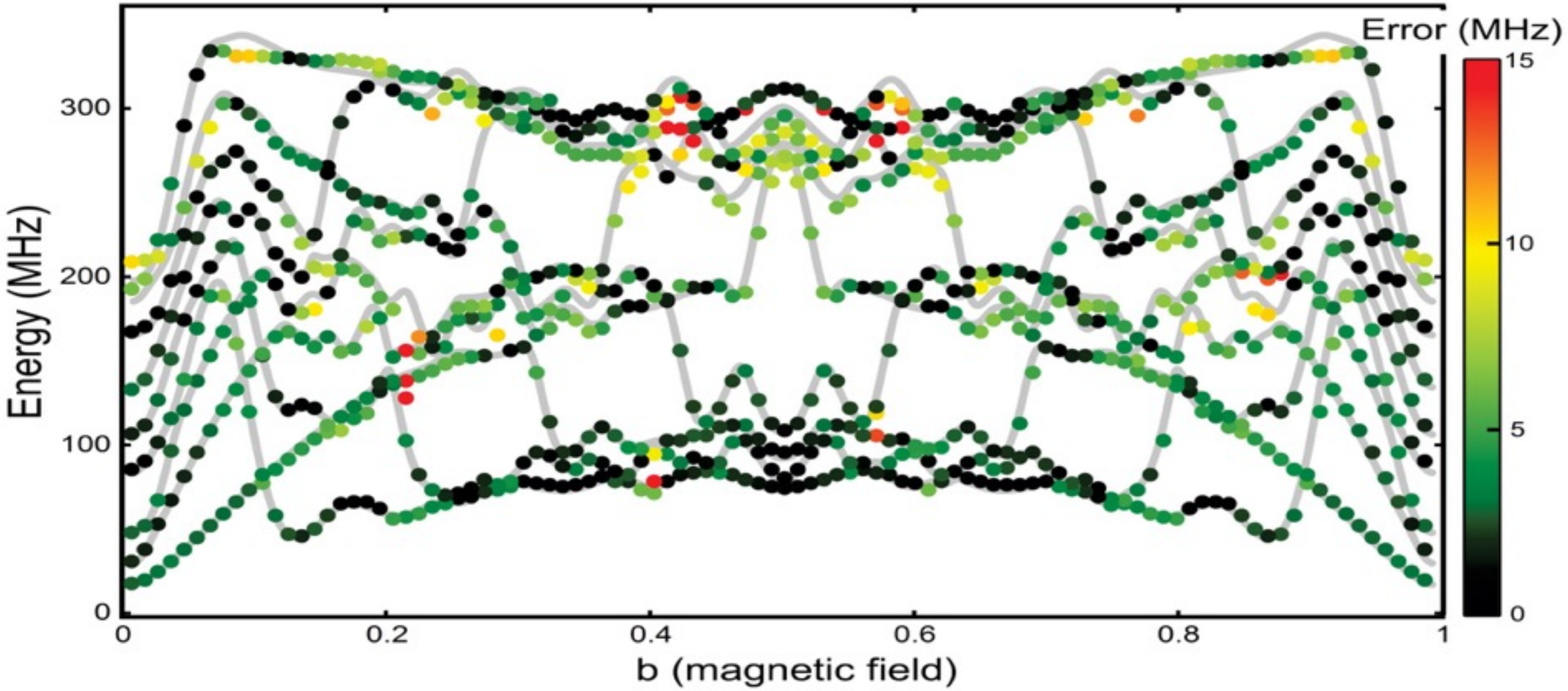
9 Qubits: theory

fractal nature gives complex spectrum

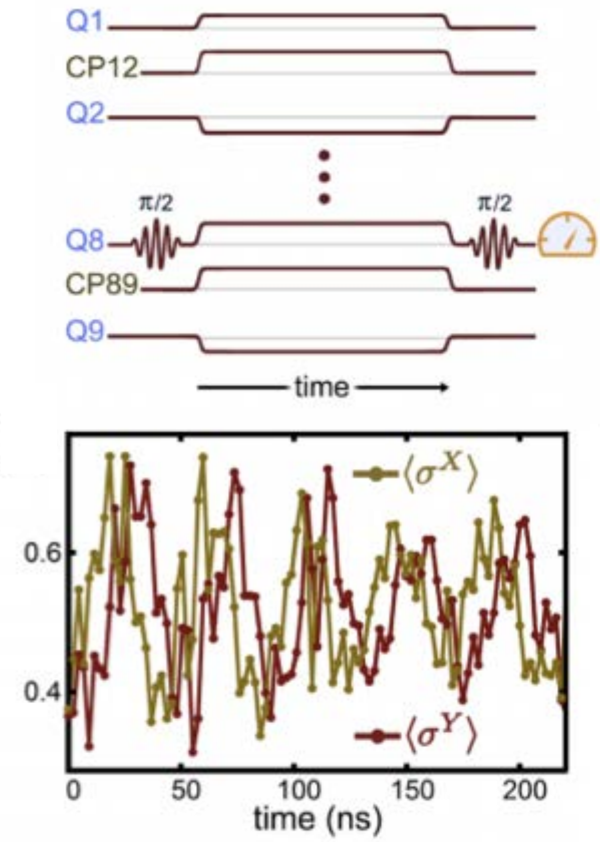


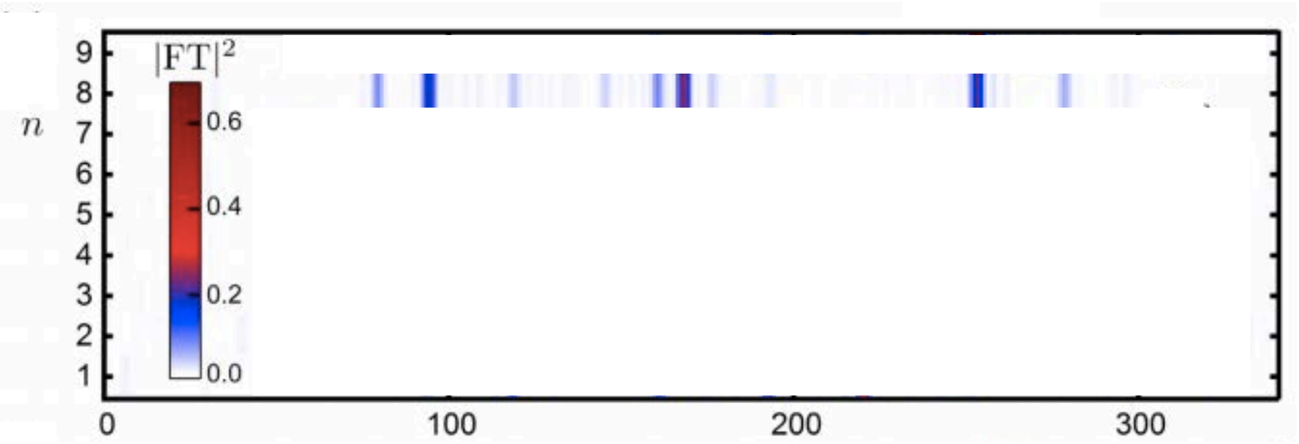
9 Qubits: theory + experiment

extract complex
physically useful information



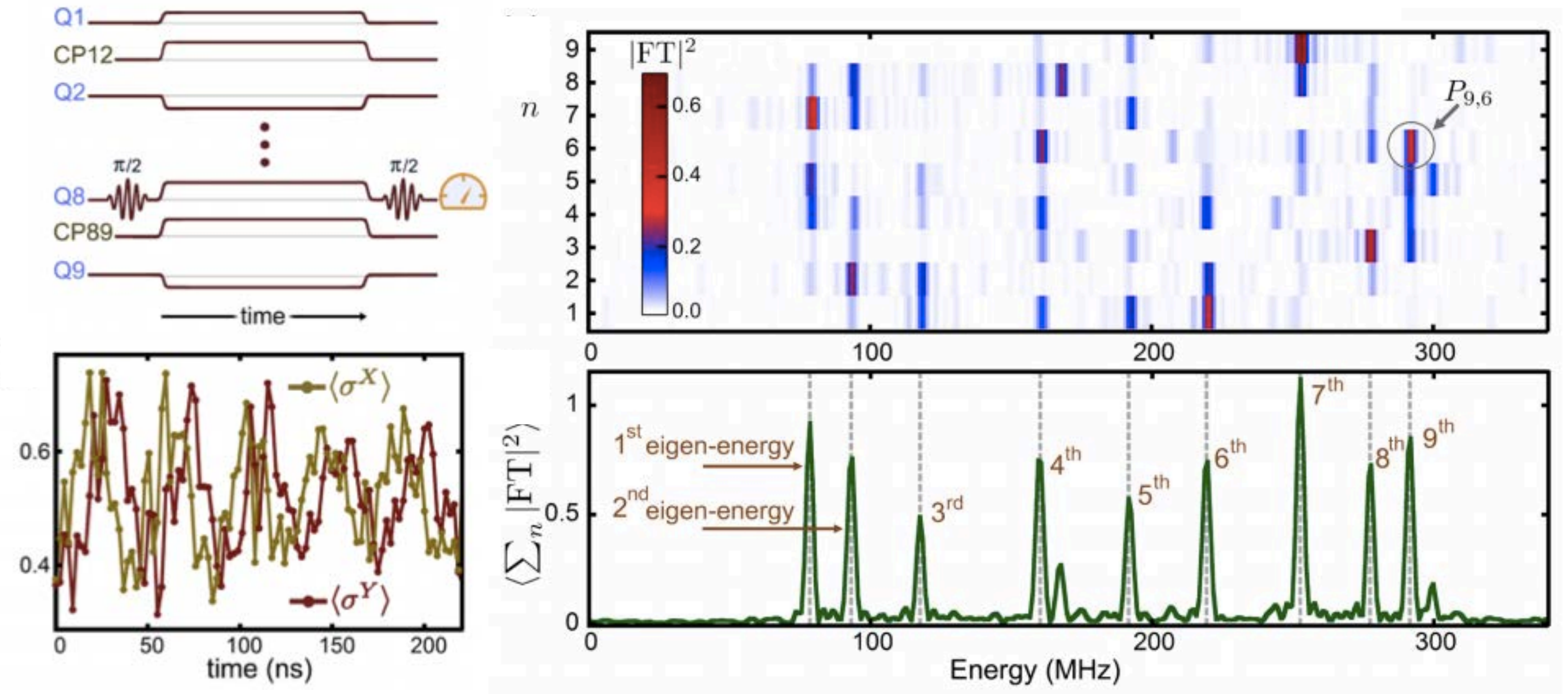
1-Excitation Spectroscopy





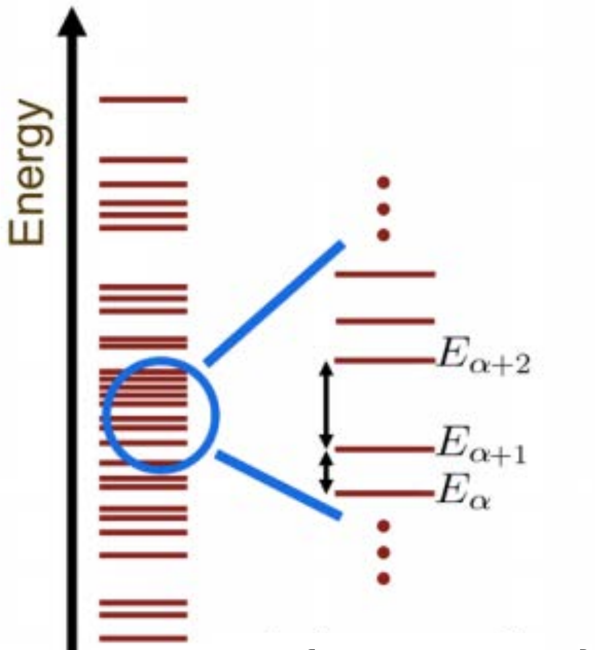
$$\chi_1(n) = \langle \sigma_n^X \rangle + i \langle \sigma_n^Y \rangle$$

1-Excitation Spectroscopy



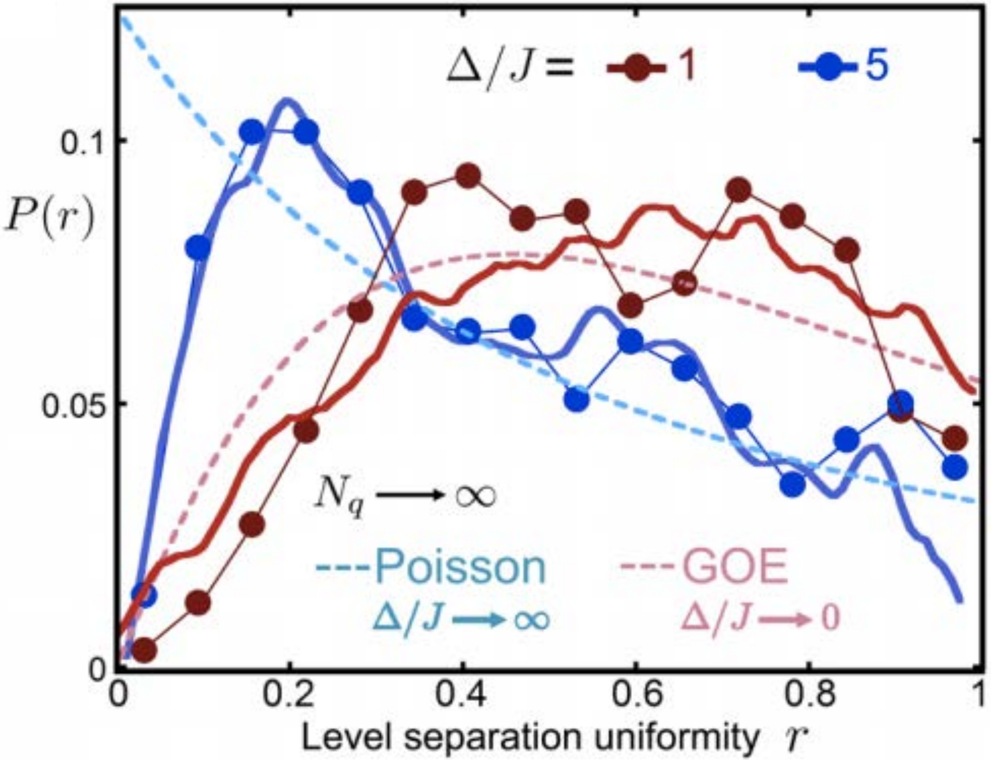
$$\chi_1(n) = \langle \sigma_n^X \rangle + i \langle \sigma_n^Y \rangle$$

Energy-Level Statistics



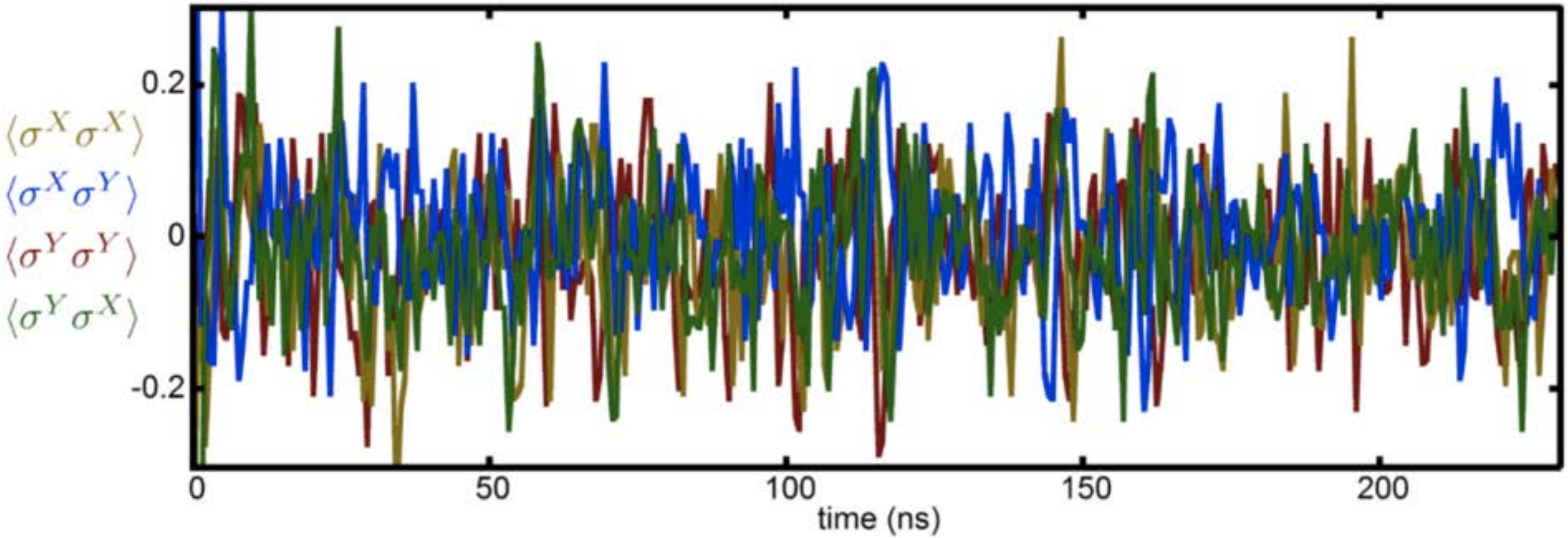
$$r_\alpha \equiv \frac{\min\{\Delta E_\alpha - \Delta E_{\alpha-1}\}}{\max\{\Delta E_\alpha - \Delta E_{\alpha-1}\}}$$

$$P_{\mathrm{GOE}}(r) = \frac{27}{4}\frac{r+r^2}{(1+r+r^2)^{5/2}}, \quad P_{\mathrm{Poisson}}(r) = \frac{2}{(1+r)^2}$$

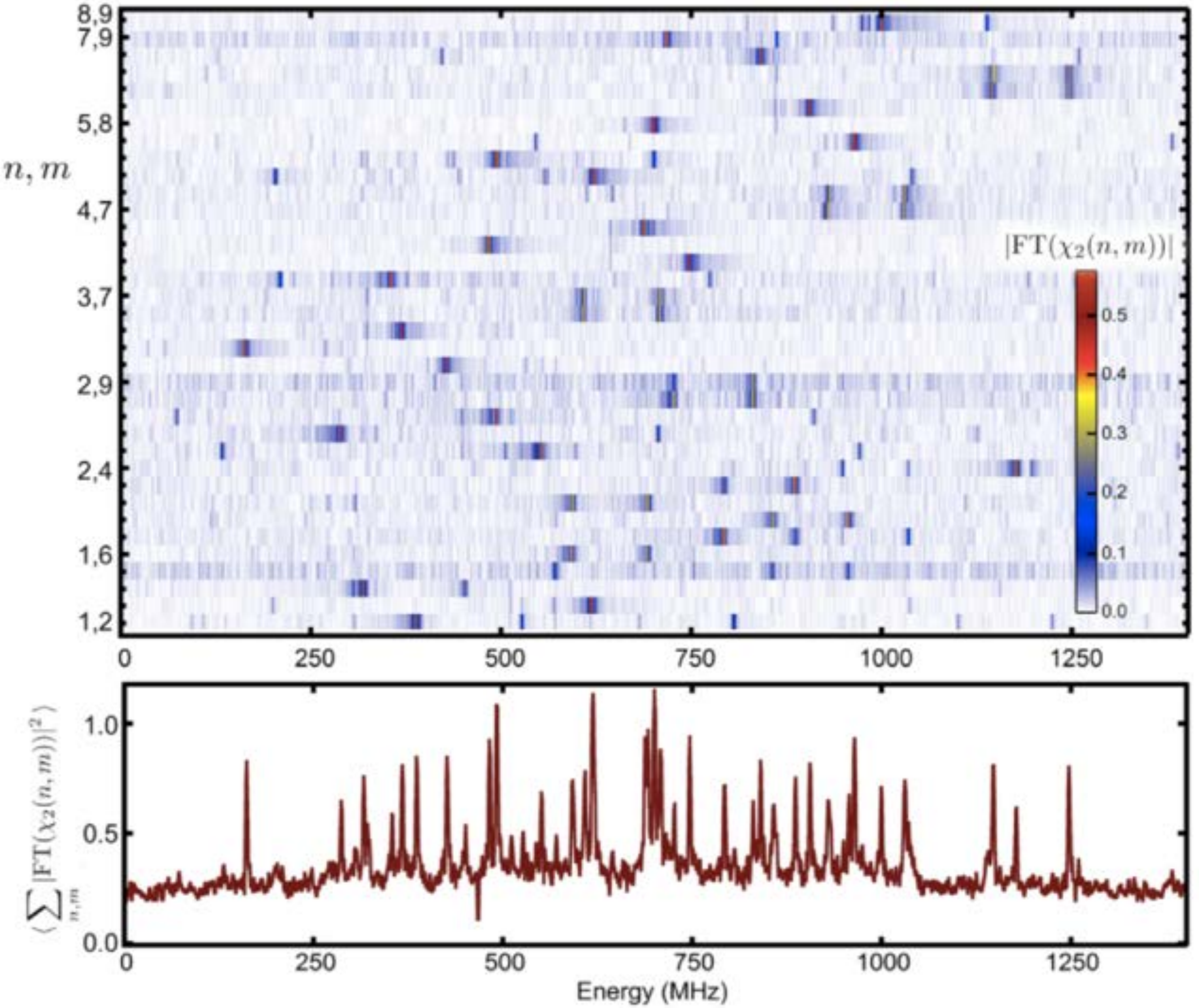


2-Excitation Spectroscopy

$$\chi_2(n,m) \equiv \langle \sigma_n^X \sigma_m^X \rangle - \langle \sigma_n^Y \sigma_m^Y \rangle + i \langle \sigma_n^X \sigma_m^Y \rangle + i \langle \sigma_n^Y \sigma_m^X \rangle$$

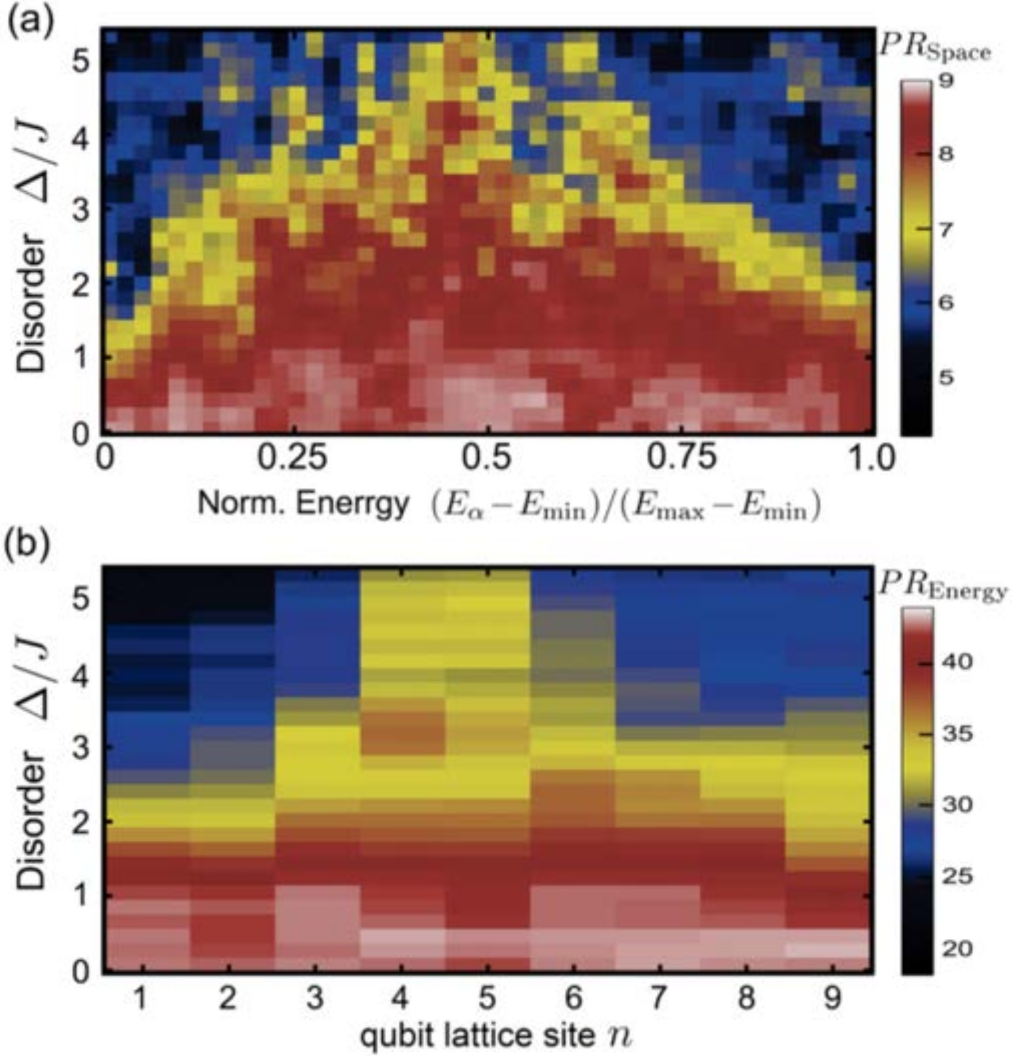


2 Excitation Spectroscopy



Now 45 energy levels

Participation Ratio & Mobility Edges

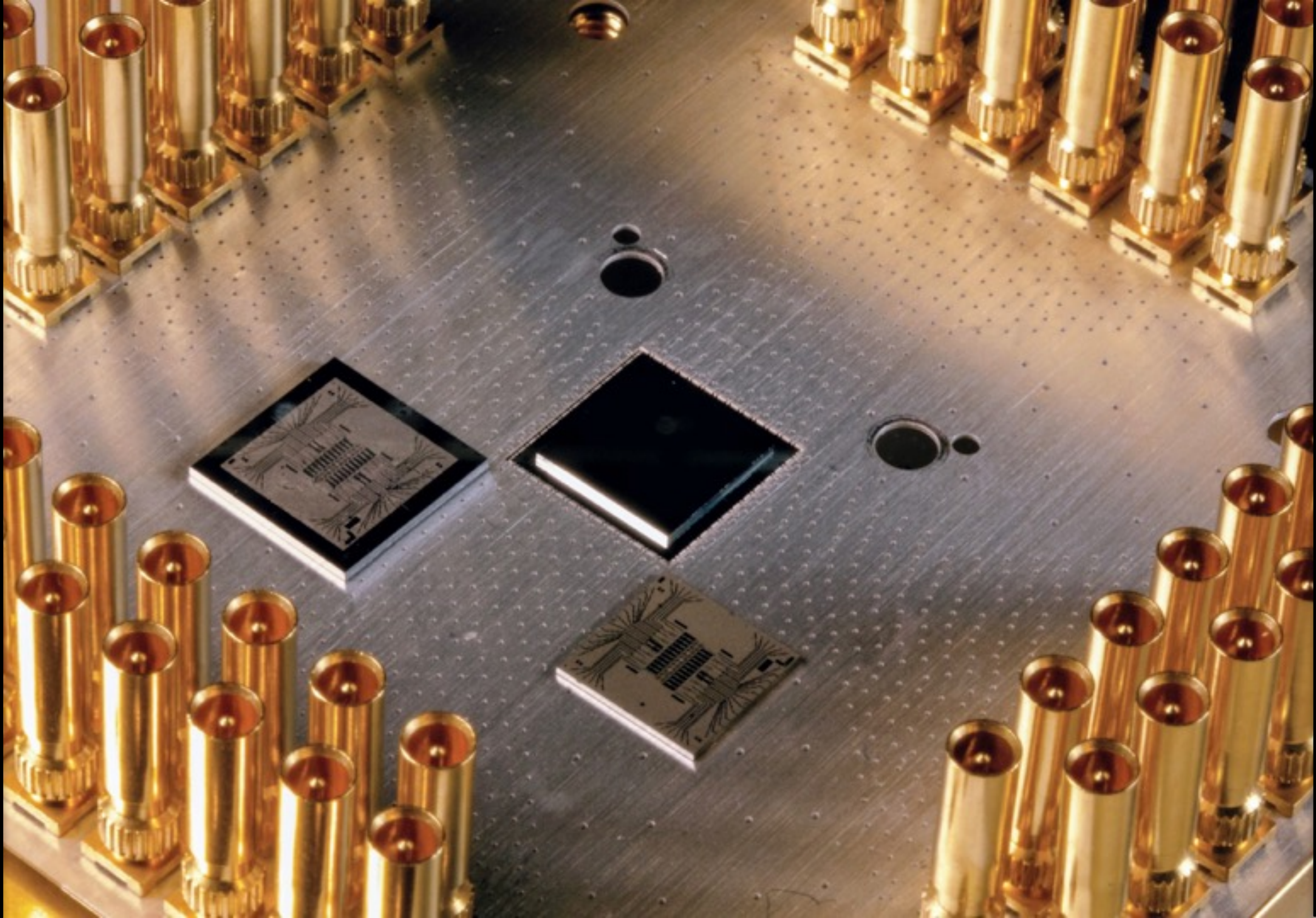


2nd moment of probabilities:

$$PR_{\text{Space}}(\alpha) \equiv 1/\sum_n P_{\alpha,n}^2$$

$$PR_{\text{Energy}}(n) \equiv 1/\sum_\alpha P_{\alpha,n}^2$$

Disorder causes eigenstates to move to center of energy band and lattice



Google Quality

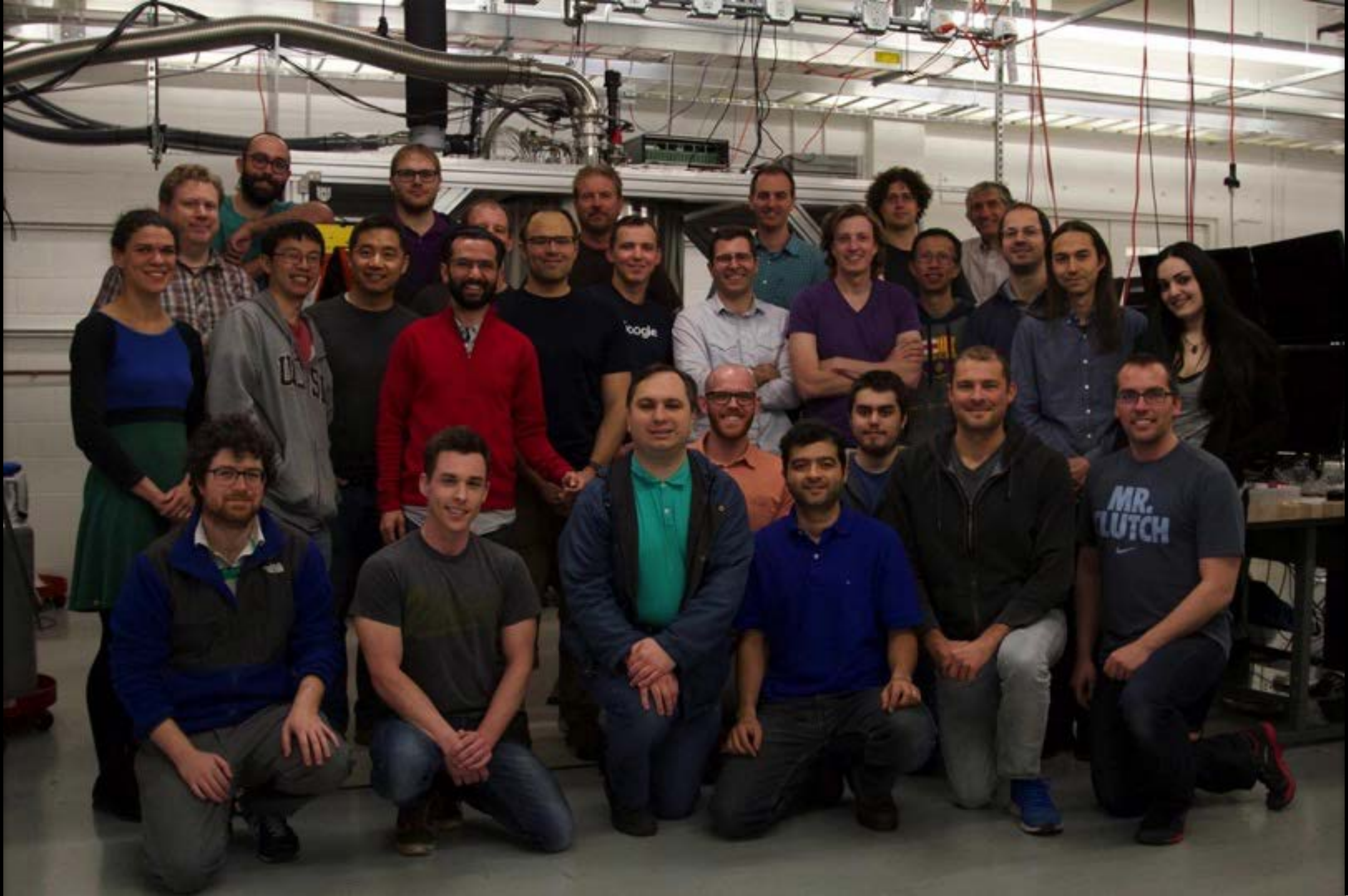
Quantum supremacy device (sq. array) in test

  Quantity + Quality

2-10x quality takes time

2018

Bristlecone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