

Quantum Supremacy: Checking a Quantum Computer with a Classical Computer

John Martinis, Google & UCSB



Our Goals for Quantum Supremacy*

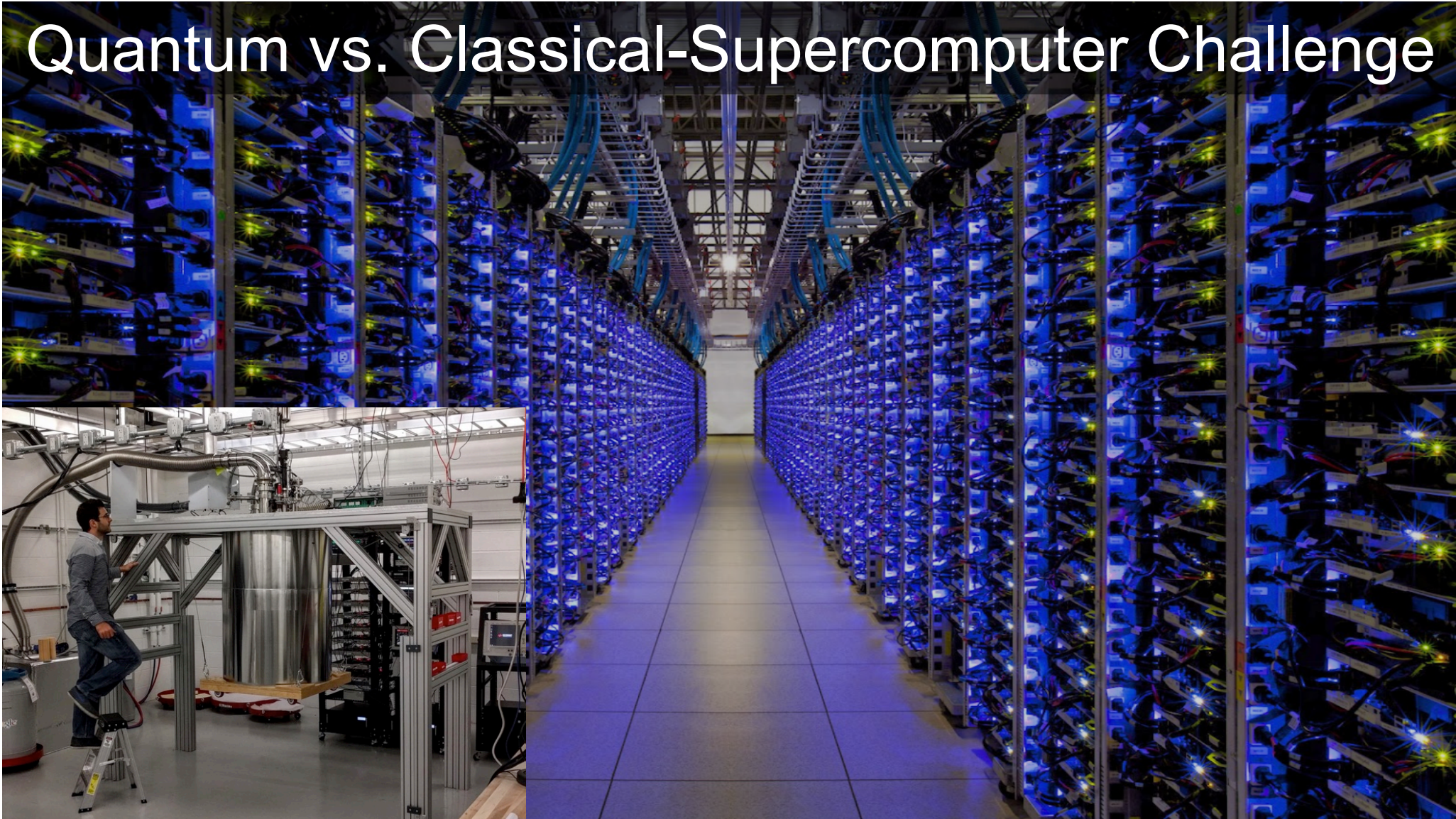
Quantum Supremacy (Preskill): for well defined problem, show more computation power for quantum computer



- 1) Exponential: demonstrate exponentially growing computation space (computational complexity: not guaranteed for more qubits)
- 2) Fidelity: need lower errors in qubit control, used to validate control
- 3) Universal: forward compatible to general purpose computer

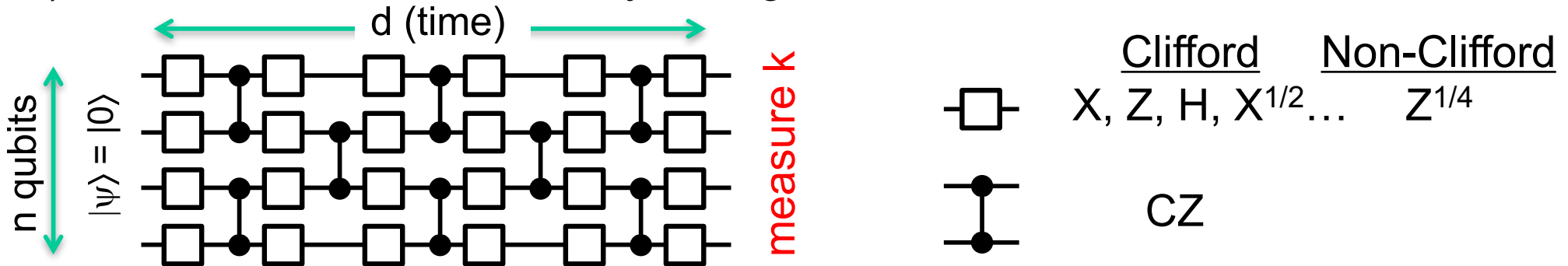
*S. Boixo et. al., arXiv:1608:00263, similar to Boson sampling

Quantum vs. Classical-Supercomputer Challenge



Algorithm for Supremacy Test: Qubit Speckle

1) Choose 1 instance, randomly from gateset



2) Run quantum computer, measure k (2^n possible outcomes)
repeat sampling 100,000 times

1 s

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

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

days
200 drives

4) Correlation: cross entropy

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

5) Compare to theory

$$S_{qu} \cong 0.42 \quad \text{quantum}$$

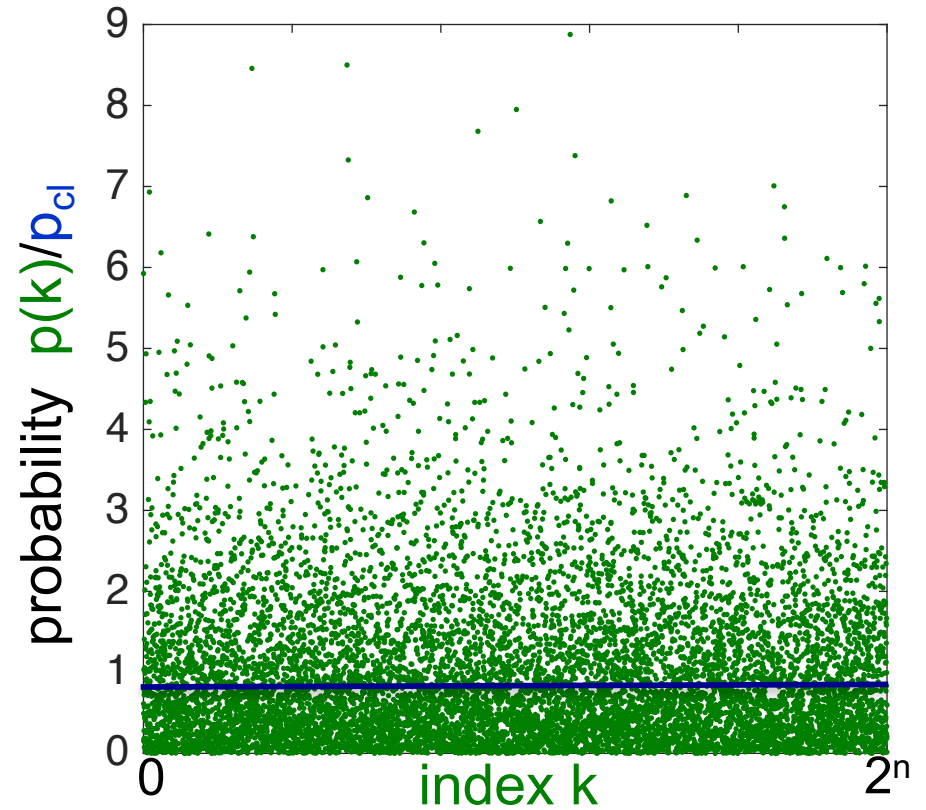
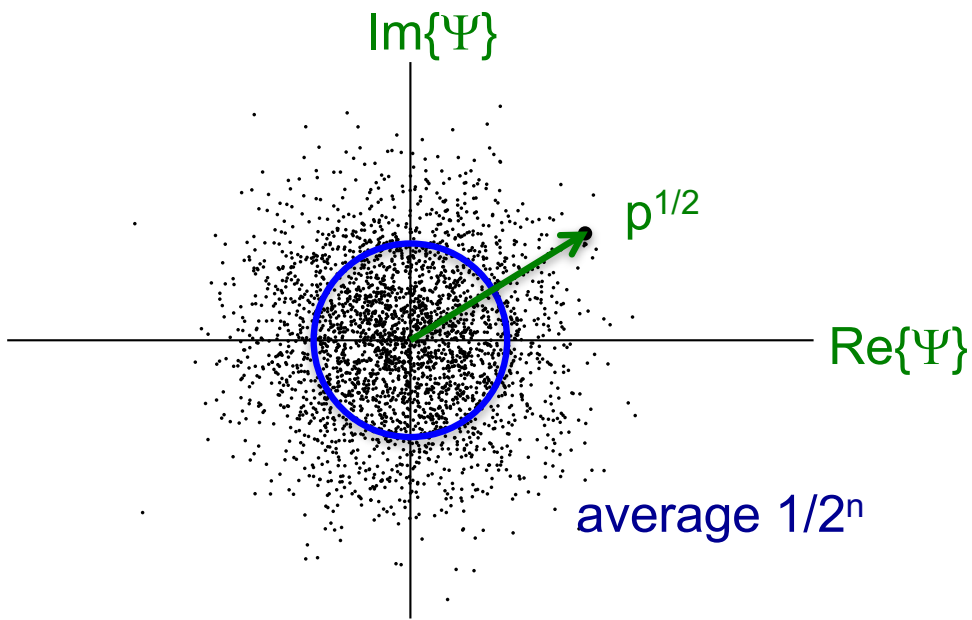
6) Try another instance

$$S_{cl} \cong -0.58 \quad \text{classical}$$

speckle = coherence
predict = fidelity

How Does it Work?

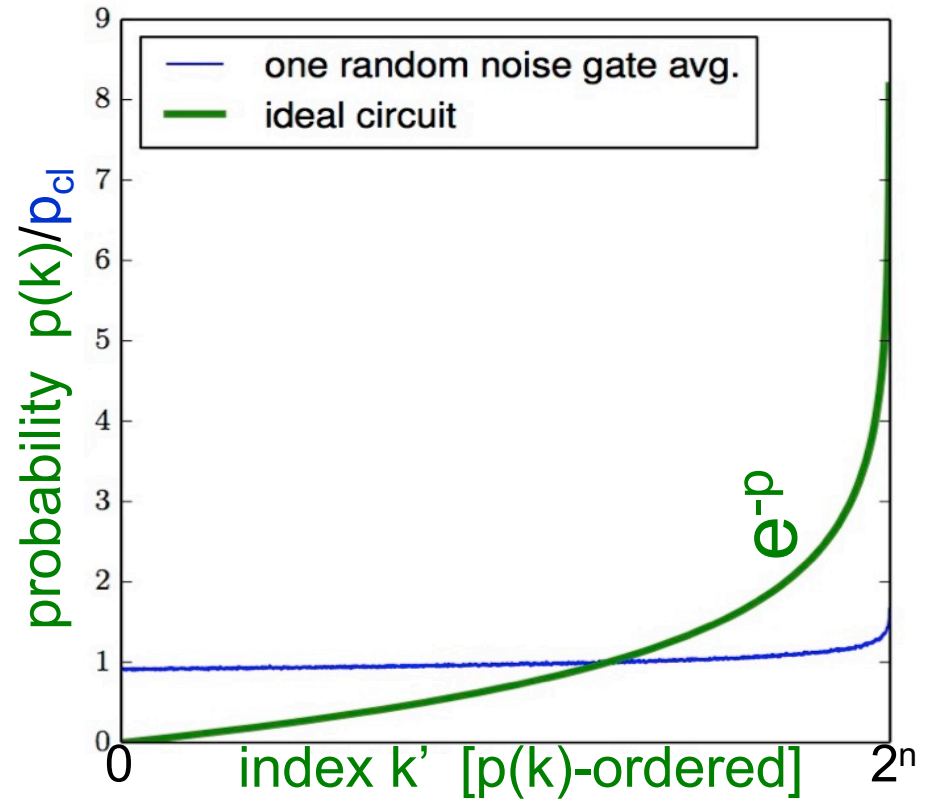
- Gaussian distribution $\text{Re}\{\Psi\}$ & $\text{Im}\{\Psi\}$ gives Porter-Thomas (exponential) distribution



0 errors: exponential

How Does it Work?

- Gaussian distribution $\text{Re}\{\Psi\}$ & $\text{Im}\{\Psi\}$ gives Porter-Thomas (exponential) distribution
- With one error anywhere distribution is flat (classical like)



0 errors: exponential
1+ errors: uniform

How Does it Work?

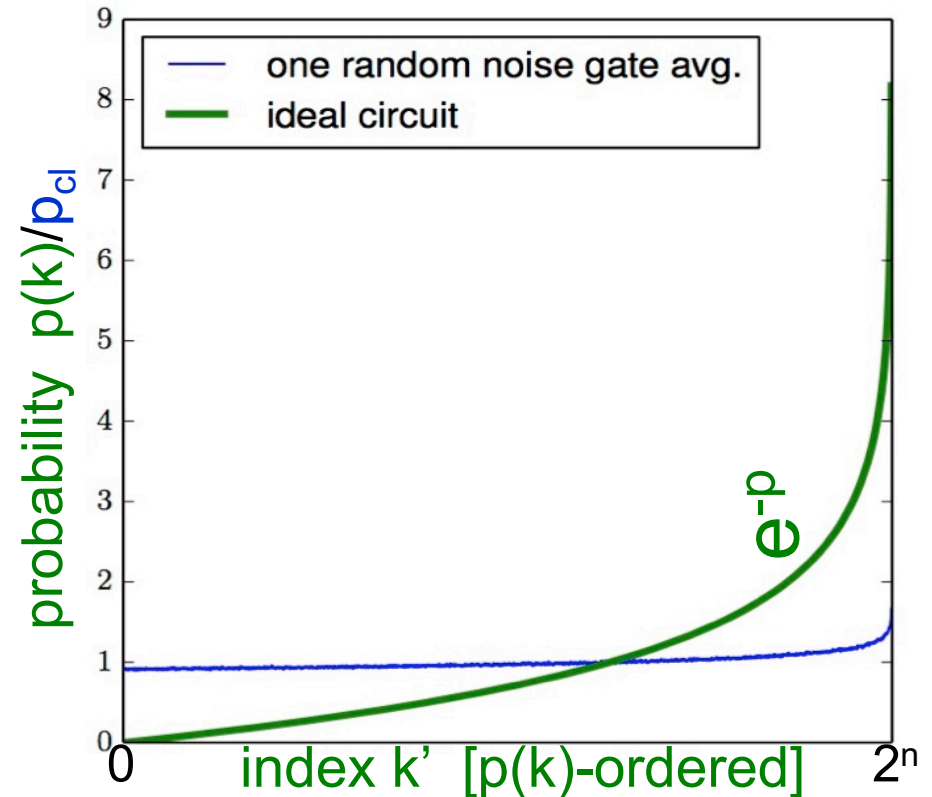
- Gaussian distribution $\text{Re}\{\Psi\}$ & $\text{Im}\{\Psi\}$ gives Porter-Thomas (exponential) distribution
- With one error anywhere distribution is flat (classical like)

$$S_{\text{tot}} \cong \overset{\text{probability of no error}}{P_0} S_{\text{qu}} + (1-P_0) S_{\text{cl}}$$

$$P_0 = (1 - \varepsilon_1)^{nd} (1 - \varepsilon_2)^{nd} (1 - \varepsilon_m)^n$$

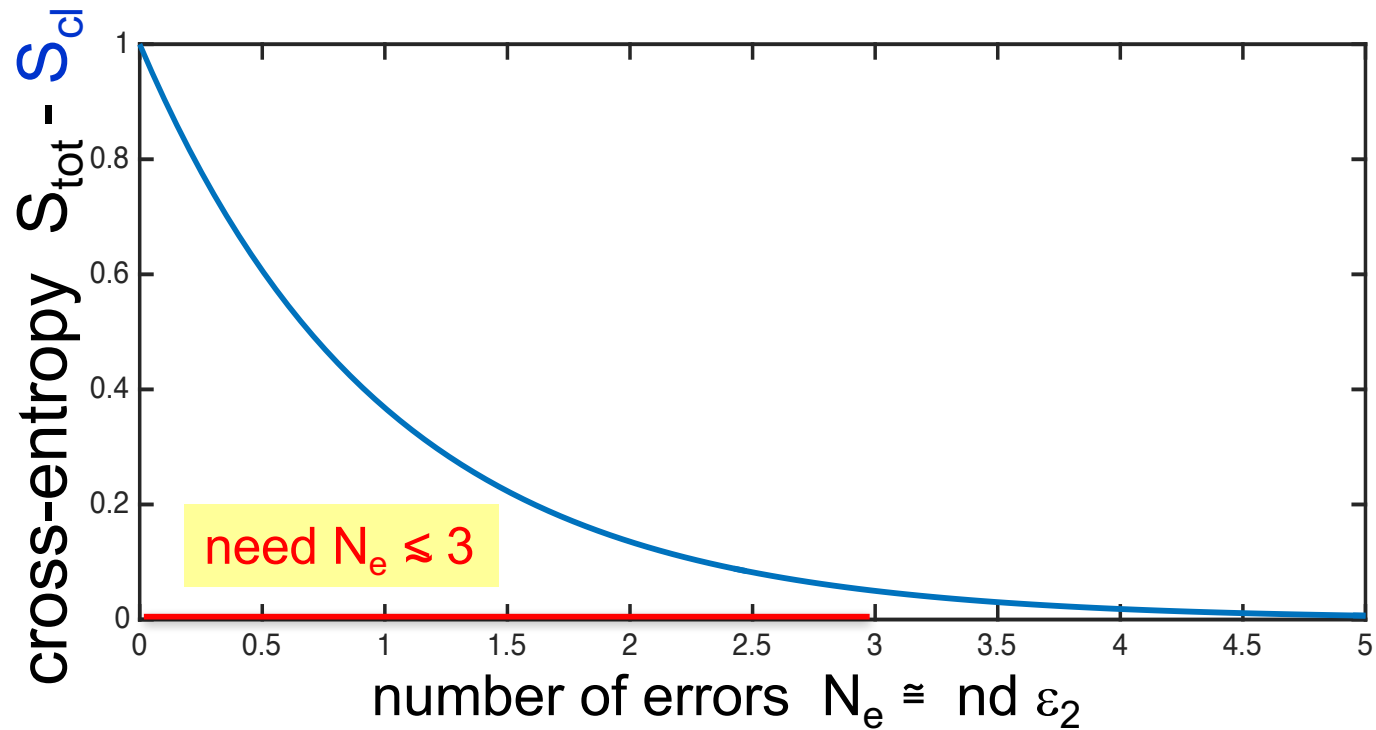
$$\cong \exp[-nd(\varepsilon_1 + \varepsilon_2) + n\varepsilon_m]$$

$$\cong \exp[-N_e] \quad \text{Include all 1, 2, measure errors } \varepsilon$$



0 errors: exponential
1+ errors: uniform

Exponential Decay of Quantum Information



Intrinsic Errors in Quantum Computation

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

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: scaling with low errors

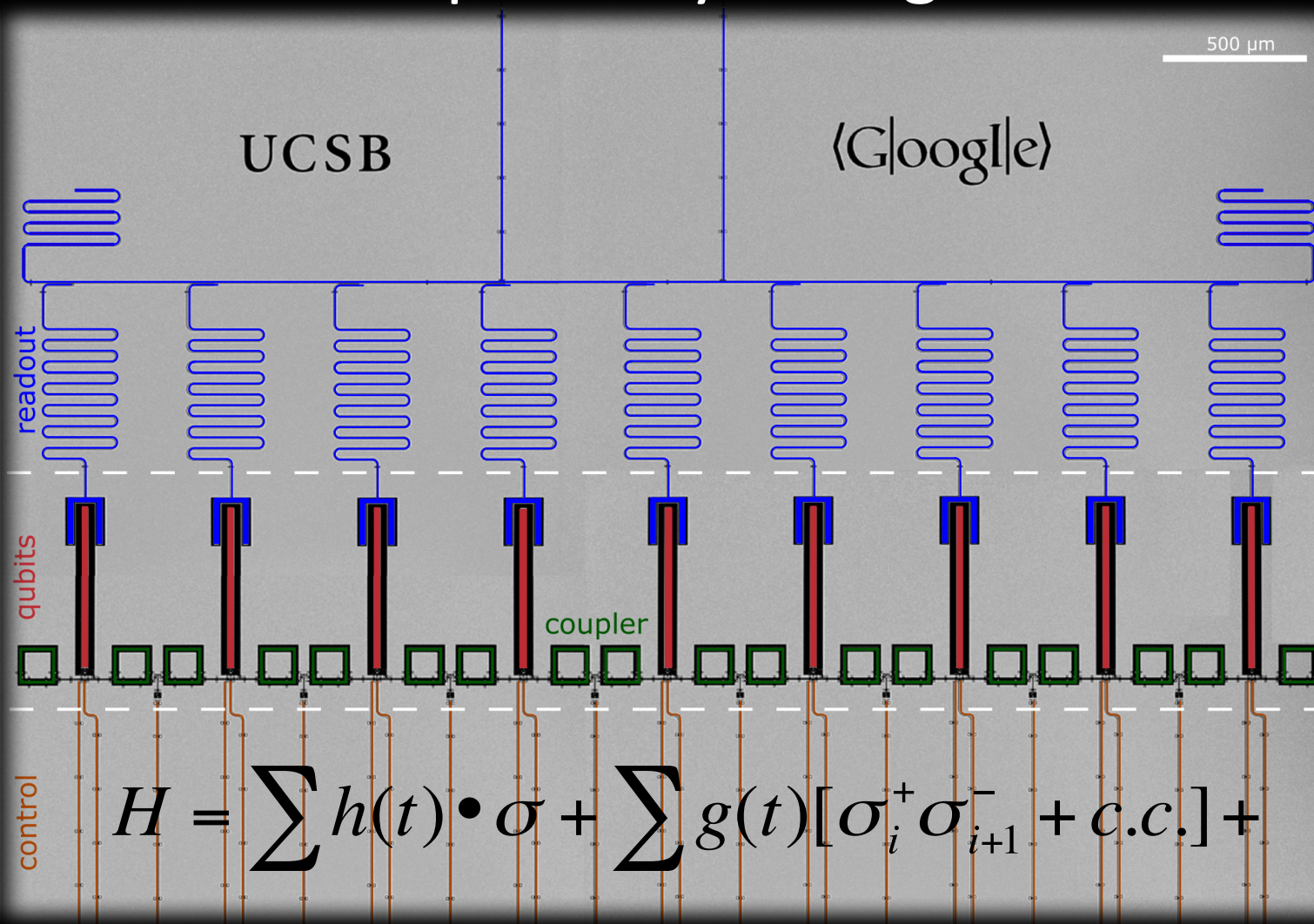
Windows

A fatal exception 0E has occurred at 0028:C562F1B7 in VXD ctpci9x(05) + 00001853. The current application will be terminated.

- * Press any key to terminate the current application.
- * Press CTRL+ALT+DEL again to restart your computer. You will lose any unsaved information in all applications.

Press any key to continue _

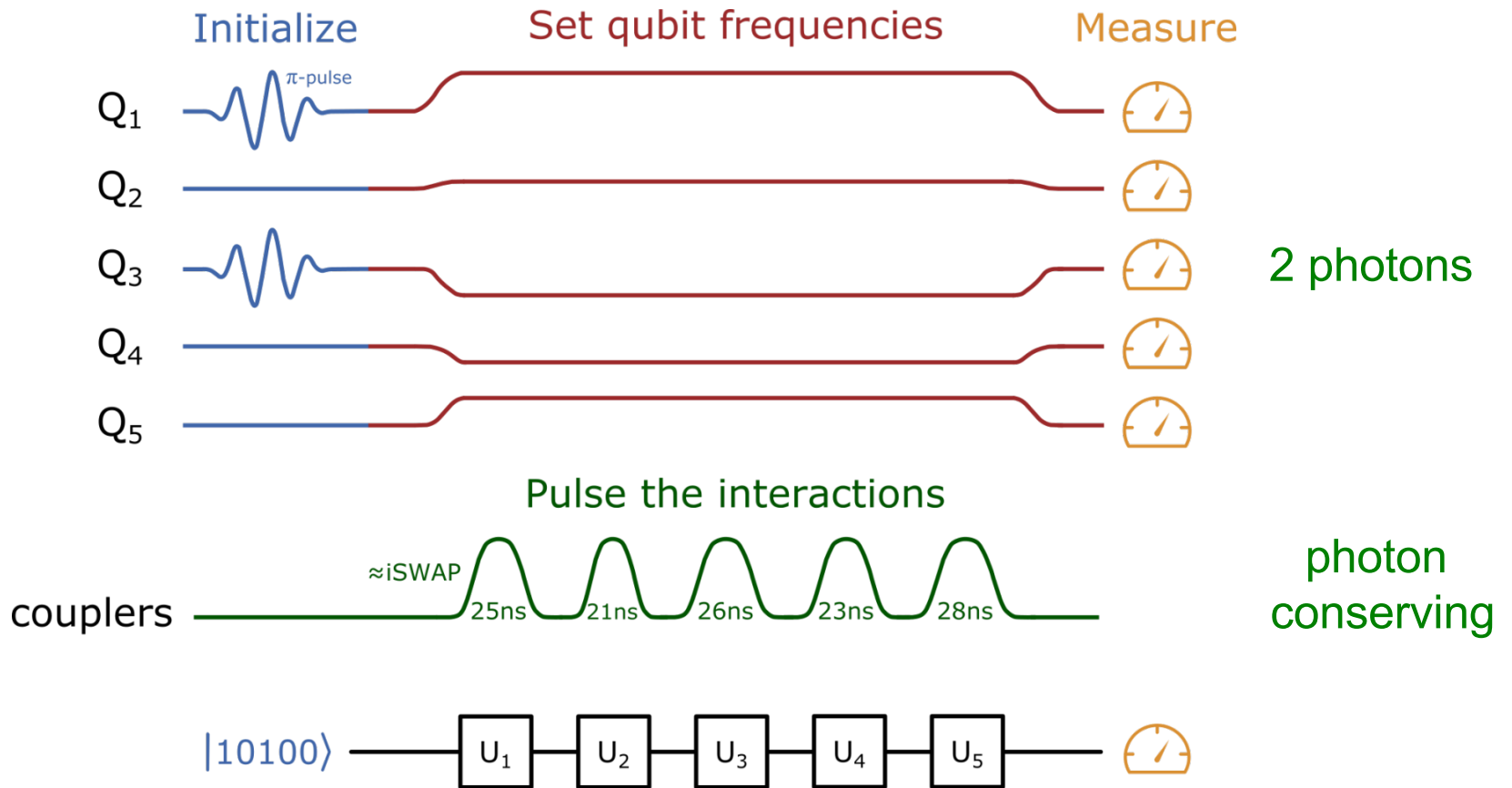
Quantum Supremacy with gmon Qubits



9-qubit gate
calibrated from 8
2-qubit gates

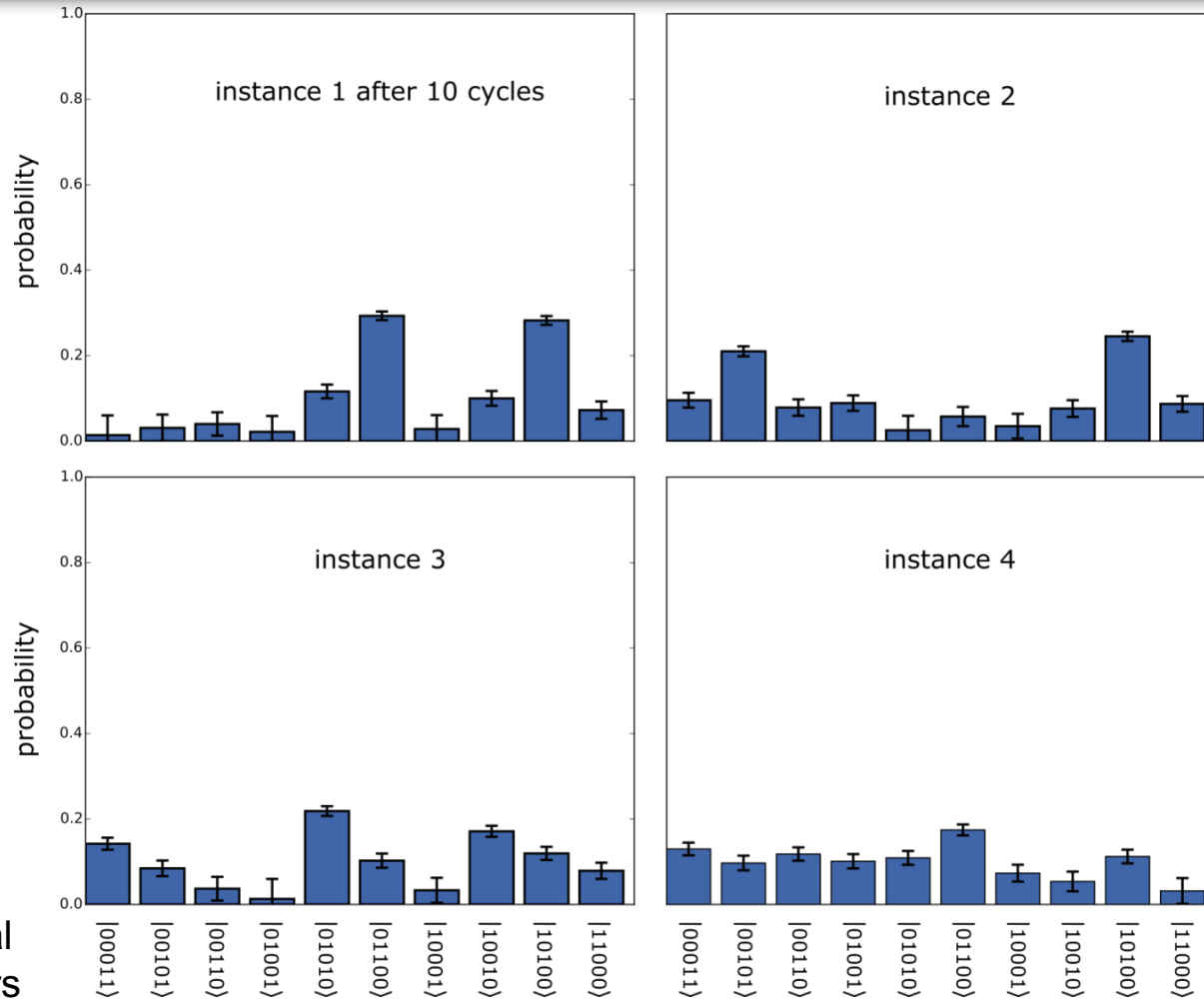
$h \sim 200 \text{ MHz}$
 $g \sim 30 \text{ MHz}$
 $t: 1 \text{ ns to } 20 \text{ us}$
 Cal. to $\sim 0.1 \text{ MHz}$

Pulse sequence (5 qubit example)



Repeat many times, randomly selecting **qubit frequencies** & **pulse lengths/heights**

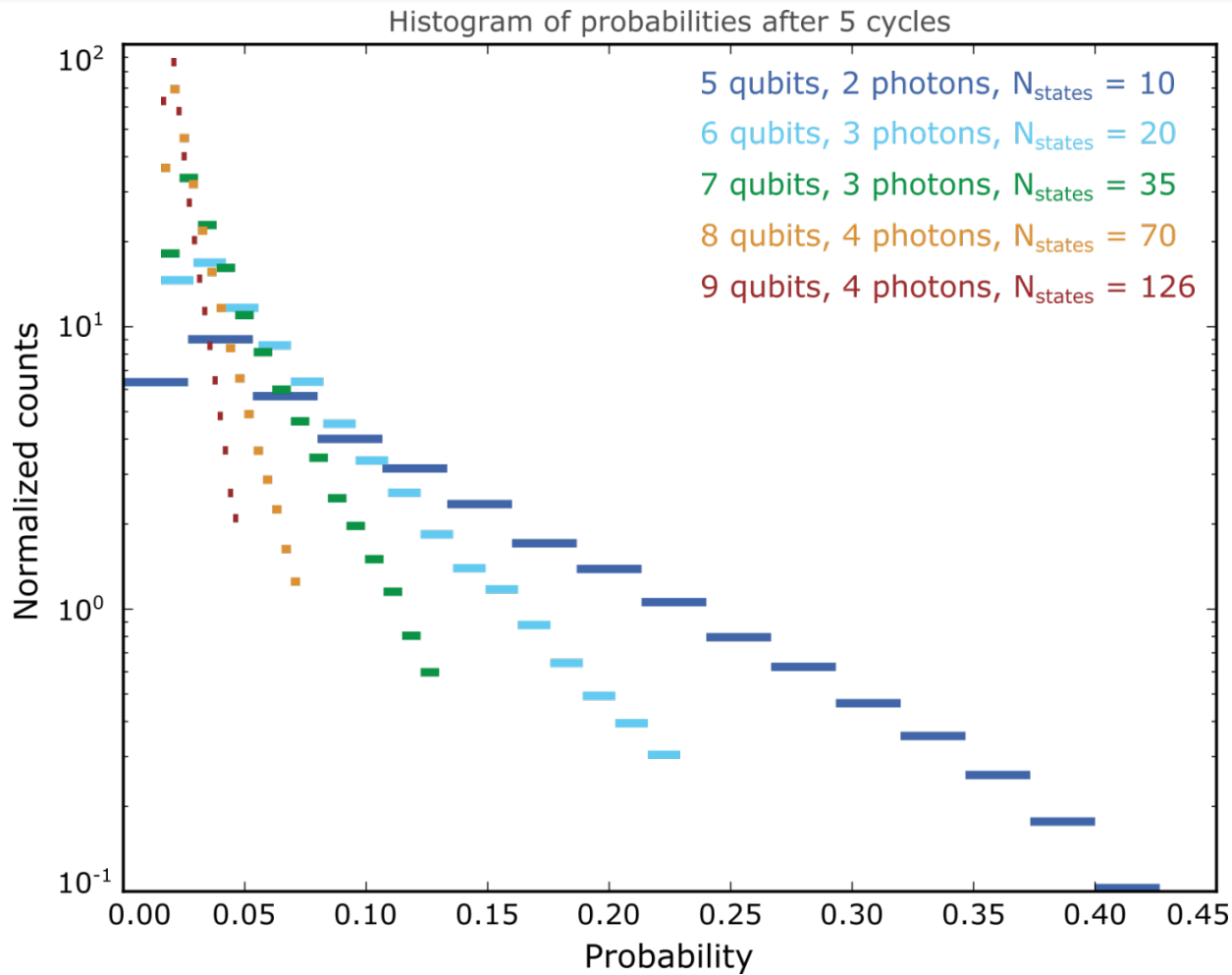
Typical dataset with 5 qubits



quantum info
just from
prob. histograms

photon conserving
states

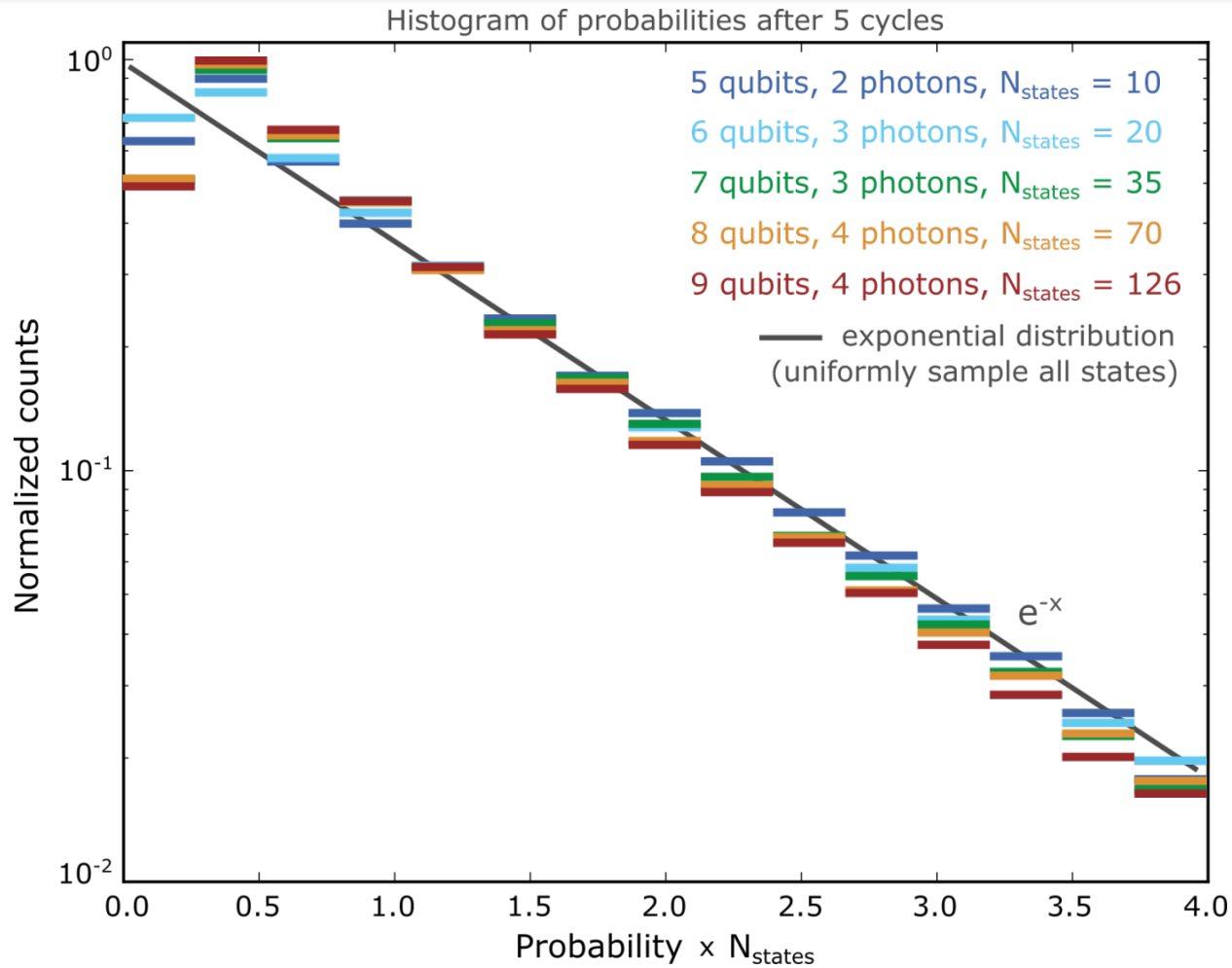
Histogram of measured probabilities



exponential
growth of

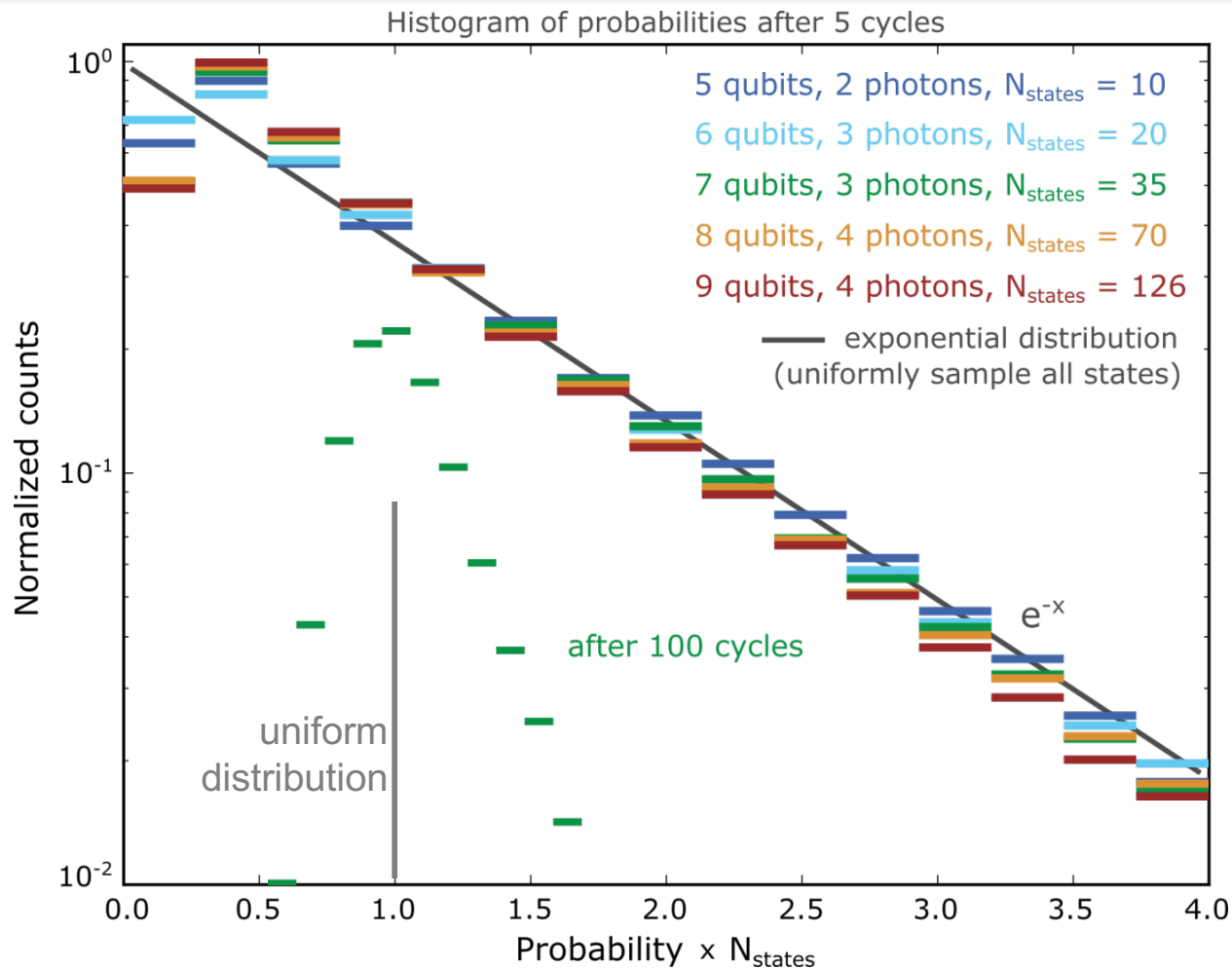
$$N_{\text{states}} \approx 2^n / \sqrt{n}$$

Histogram of measured probabilities



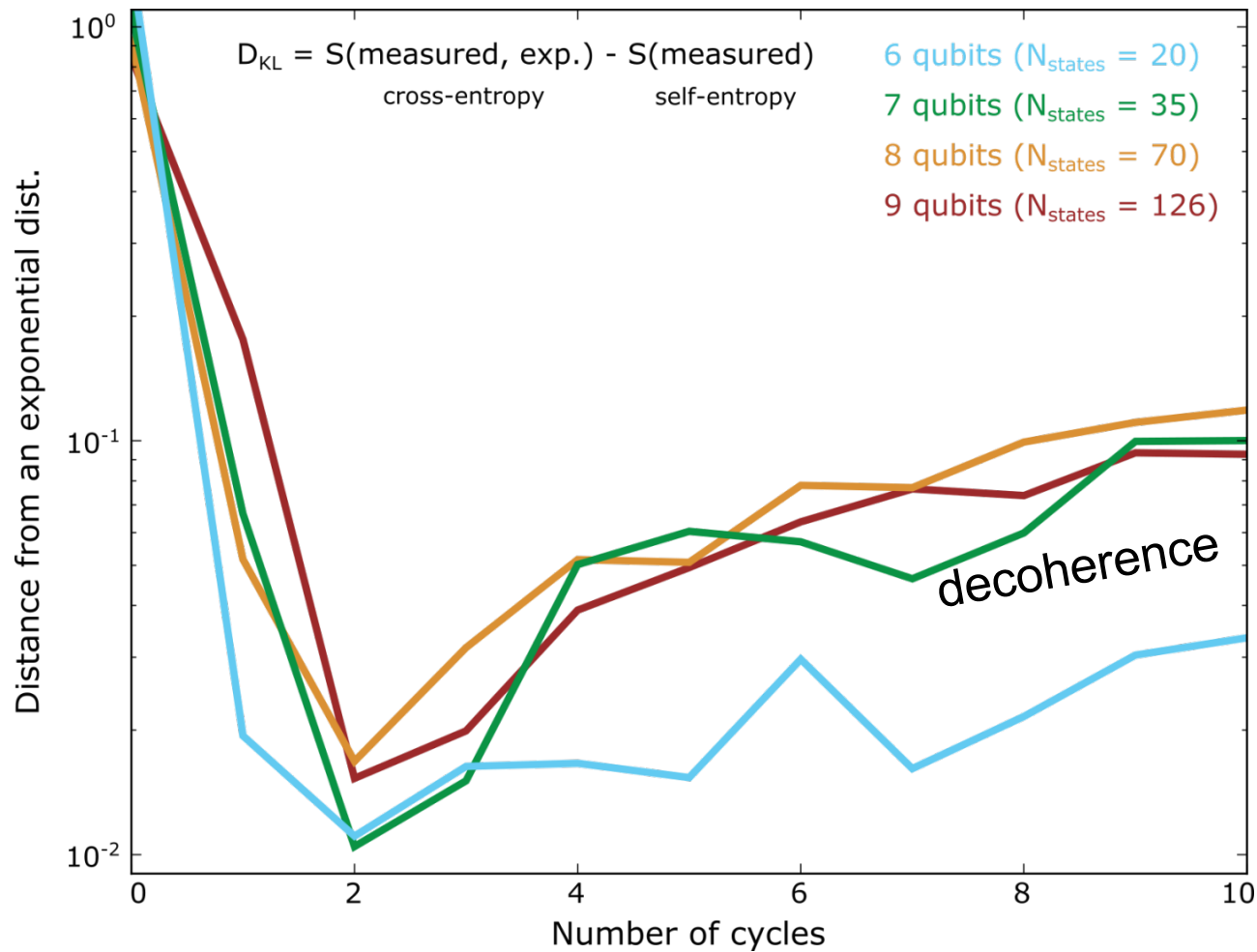
Collapses to exponential distribution

Histogram of measured probabilities



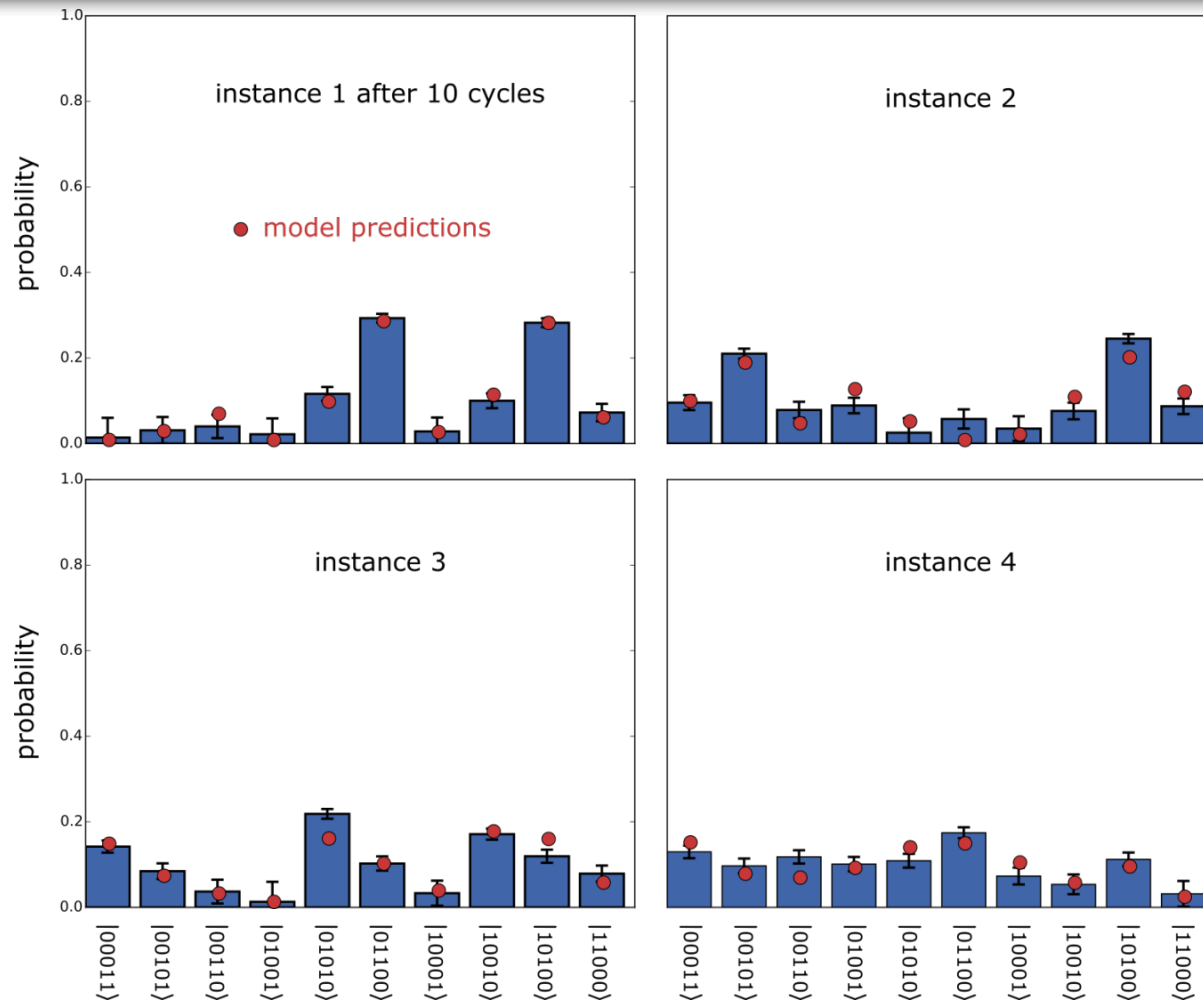
decoherence kills
qubit speckle

Fast growth of entanglement



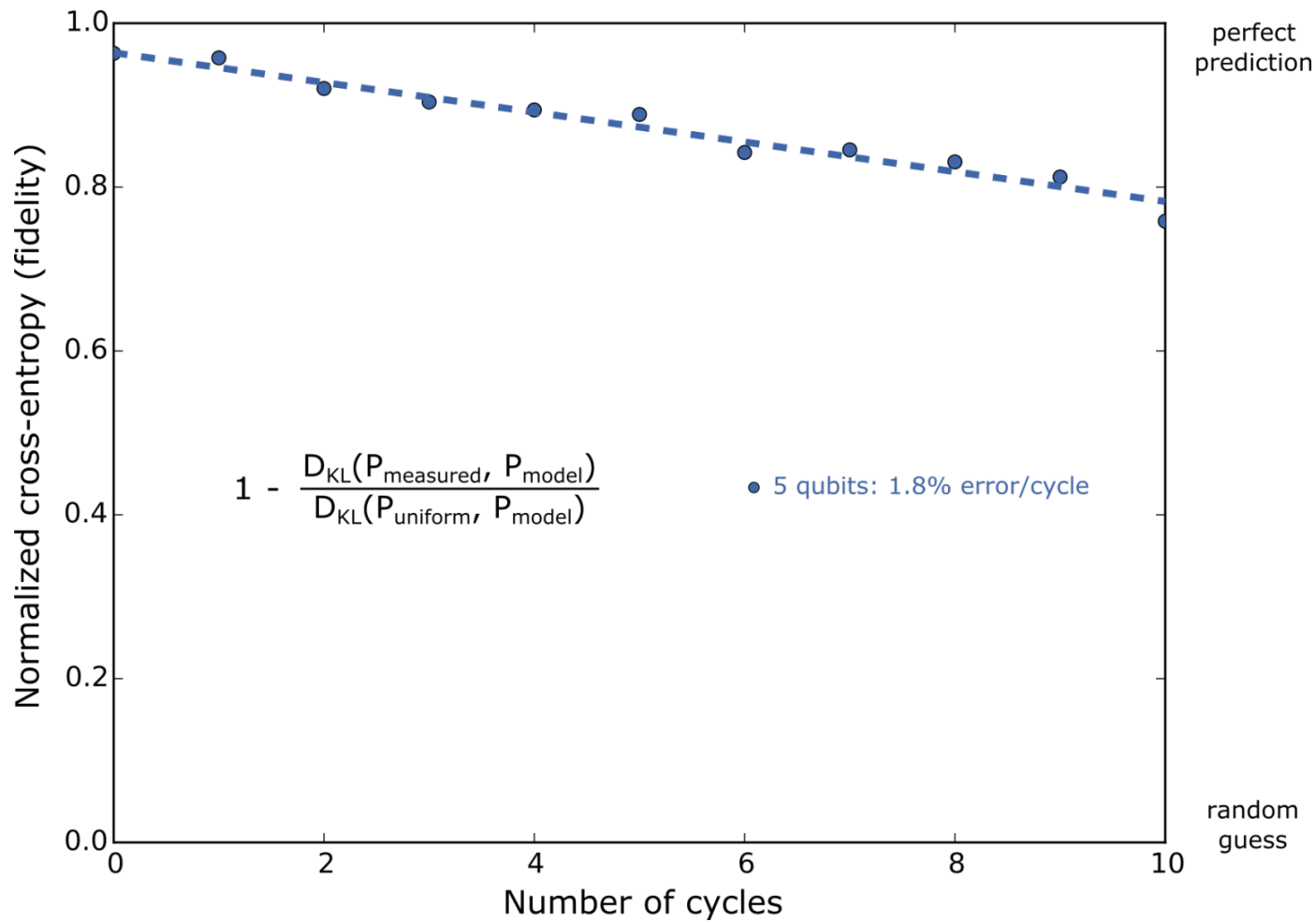
9-qubit interaction:
full entanglement
in 2 cycles (90 ns)

Compare probabilities of experiment and theory



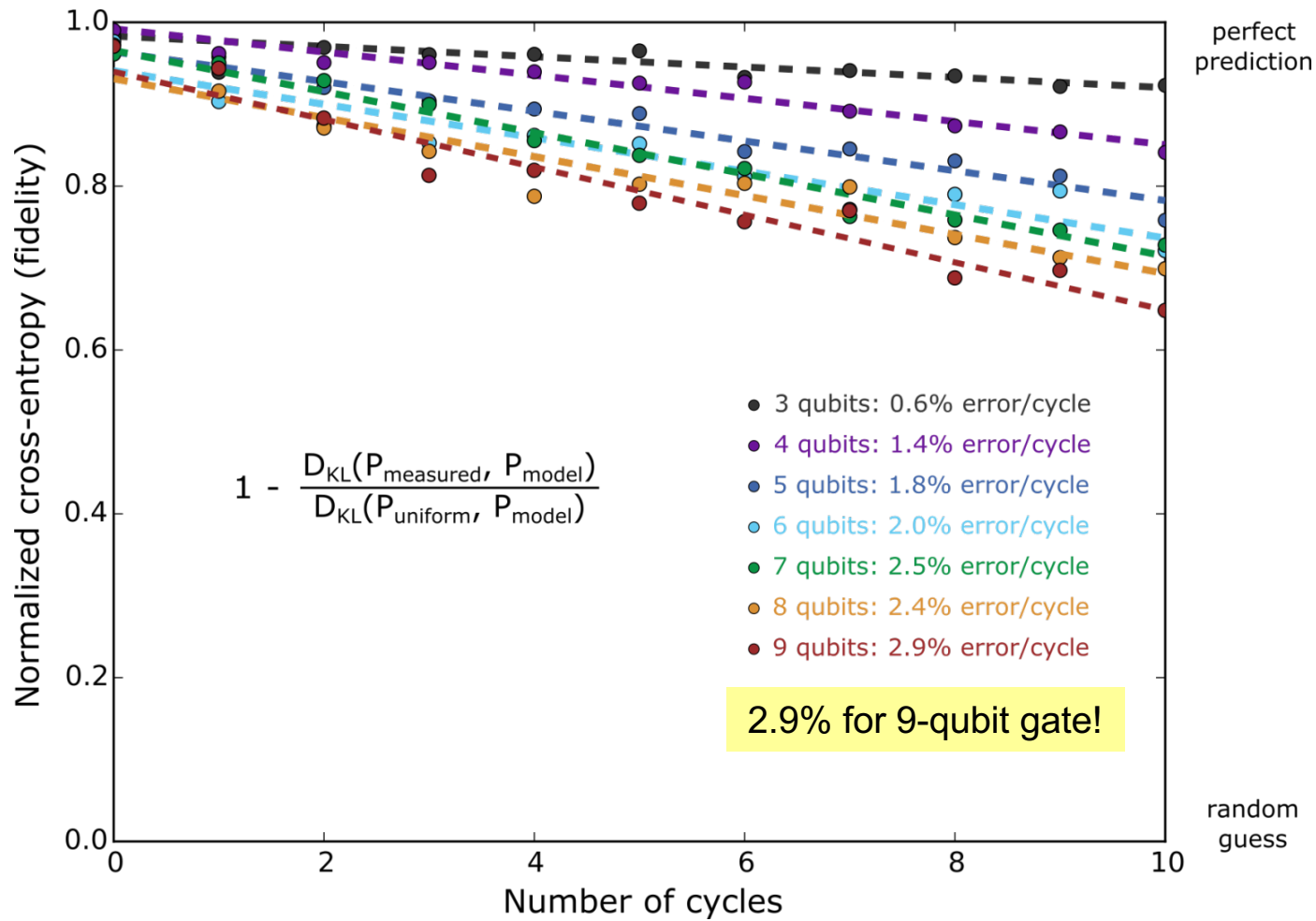
speckle pattern
matches theory

Measuring fidelity

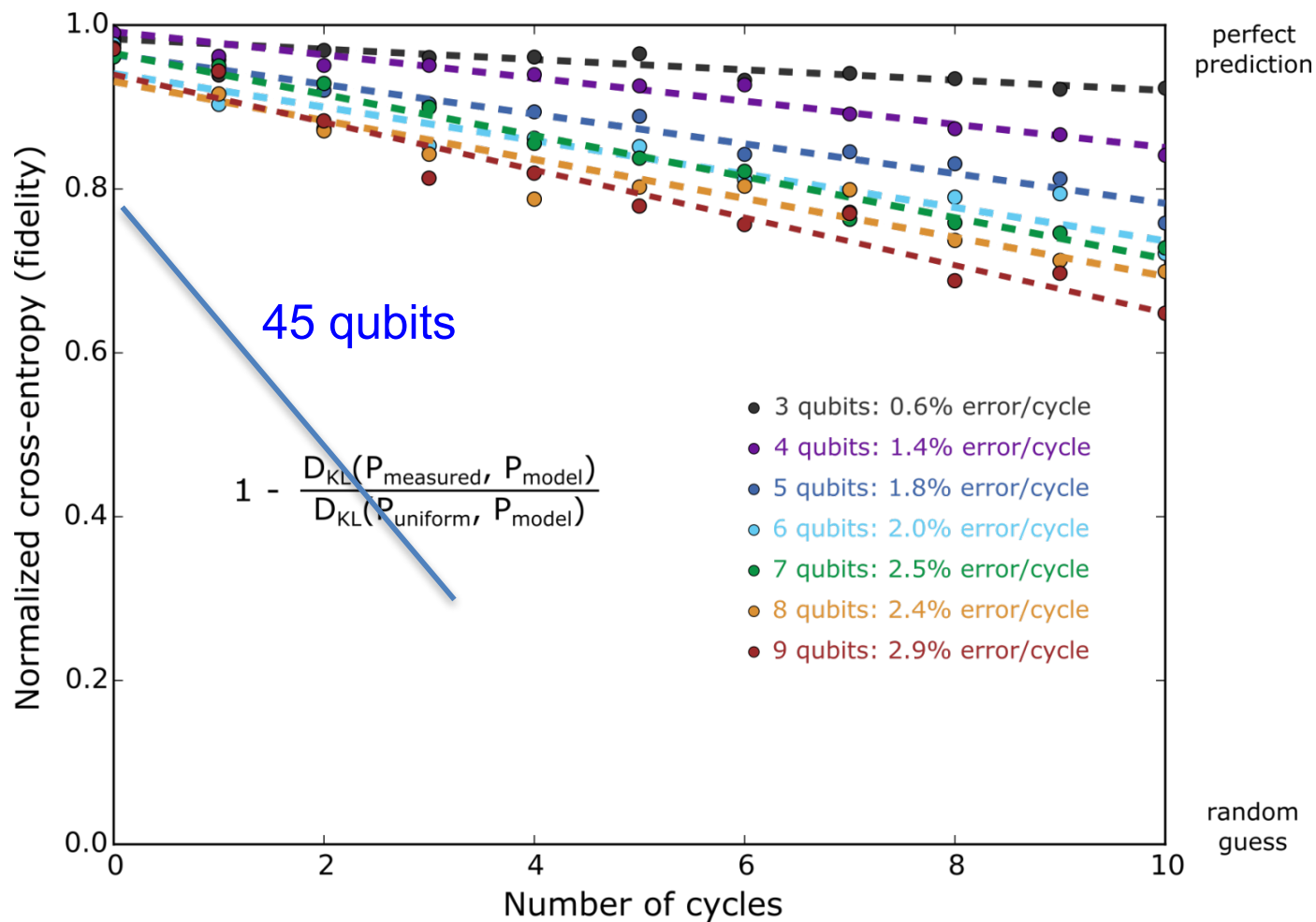


cross entropy
= fidelity

Measuring fidelity

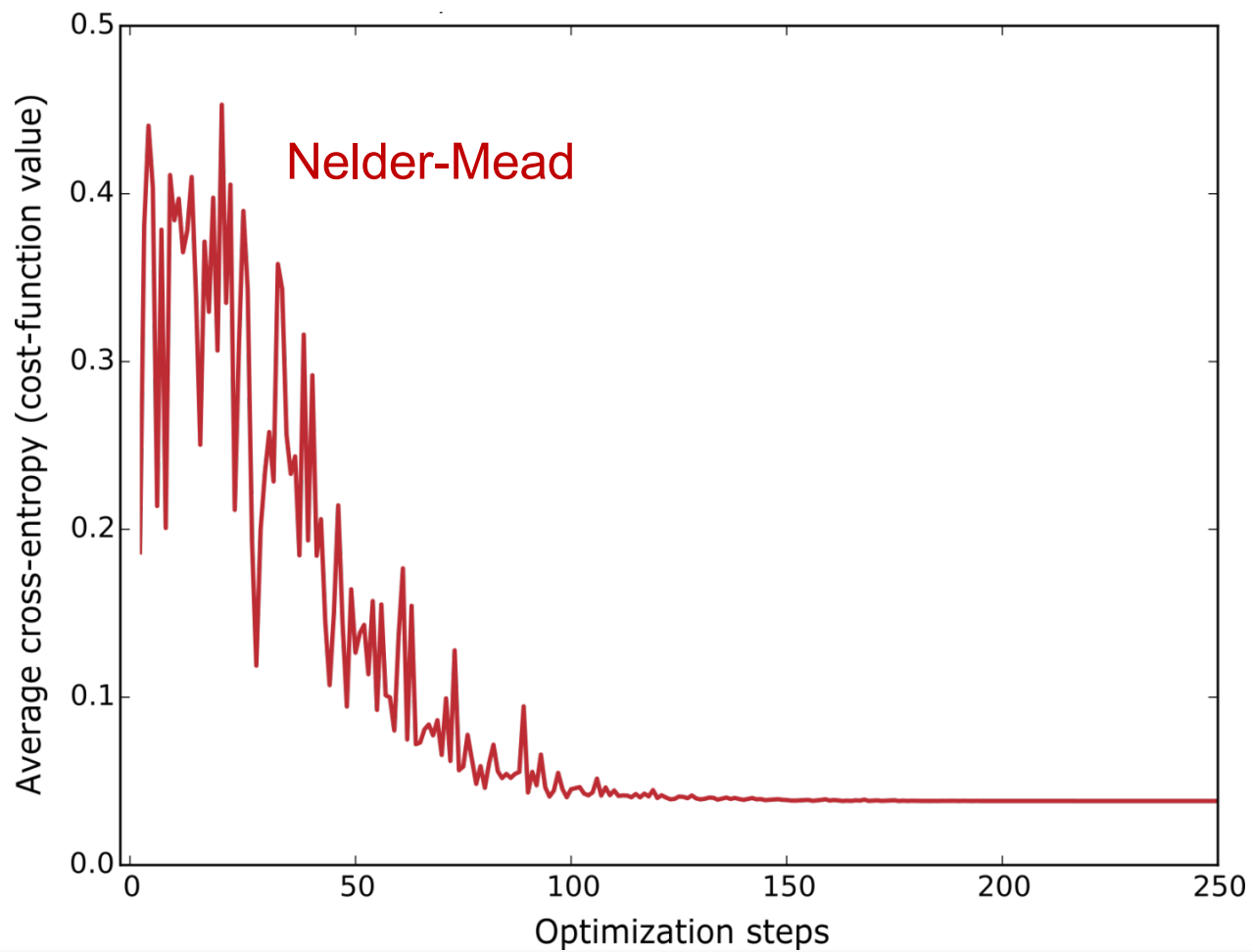


Scaled fidelity for 45 qubits



supremacy possible with margin

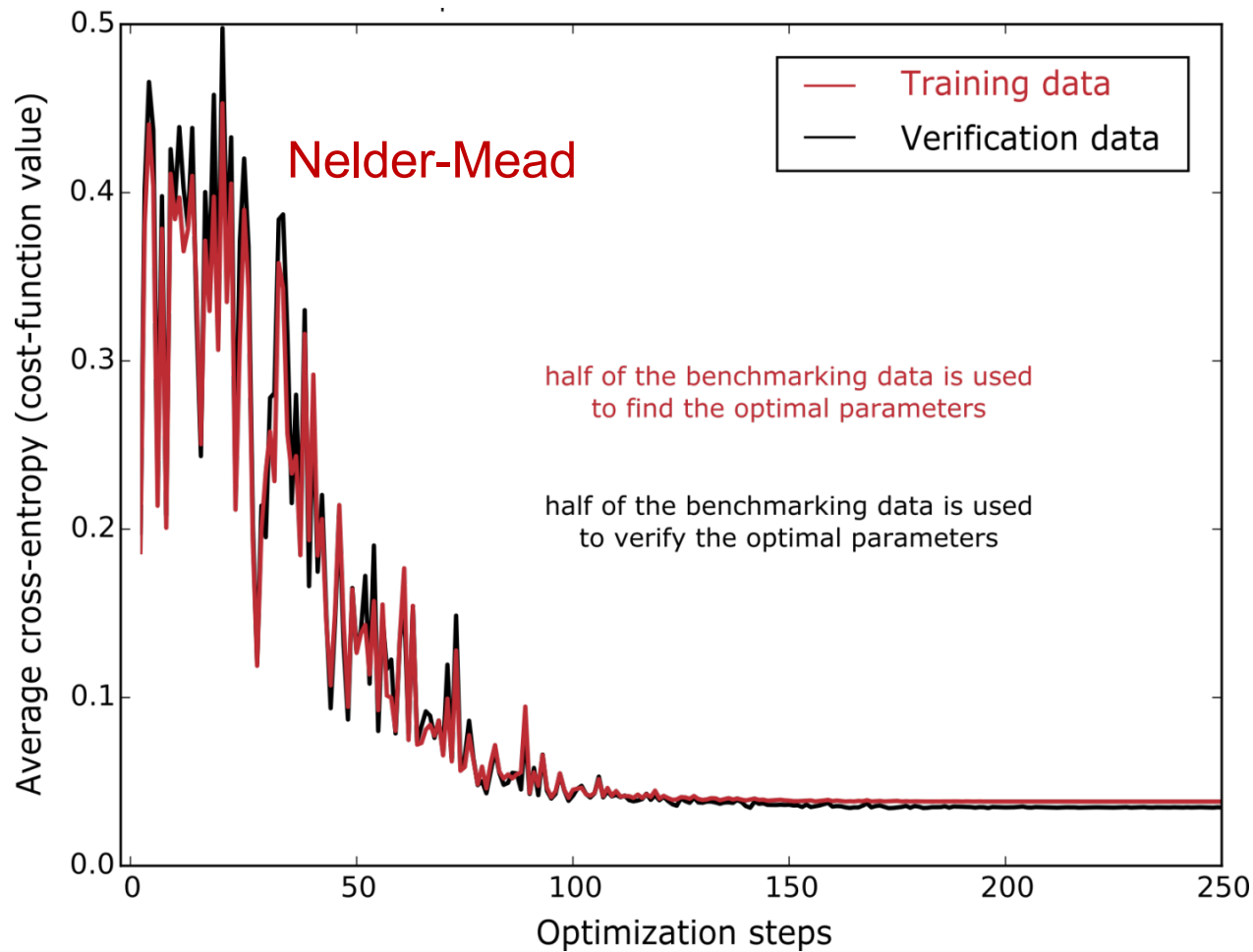
Learning a better control model



Tuneup flux offsets
(as drifty)

significant
improvement

Learning a better control model

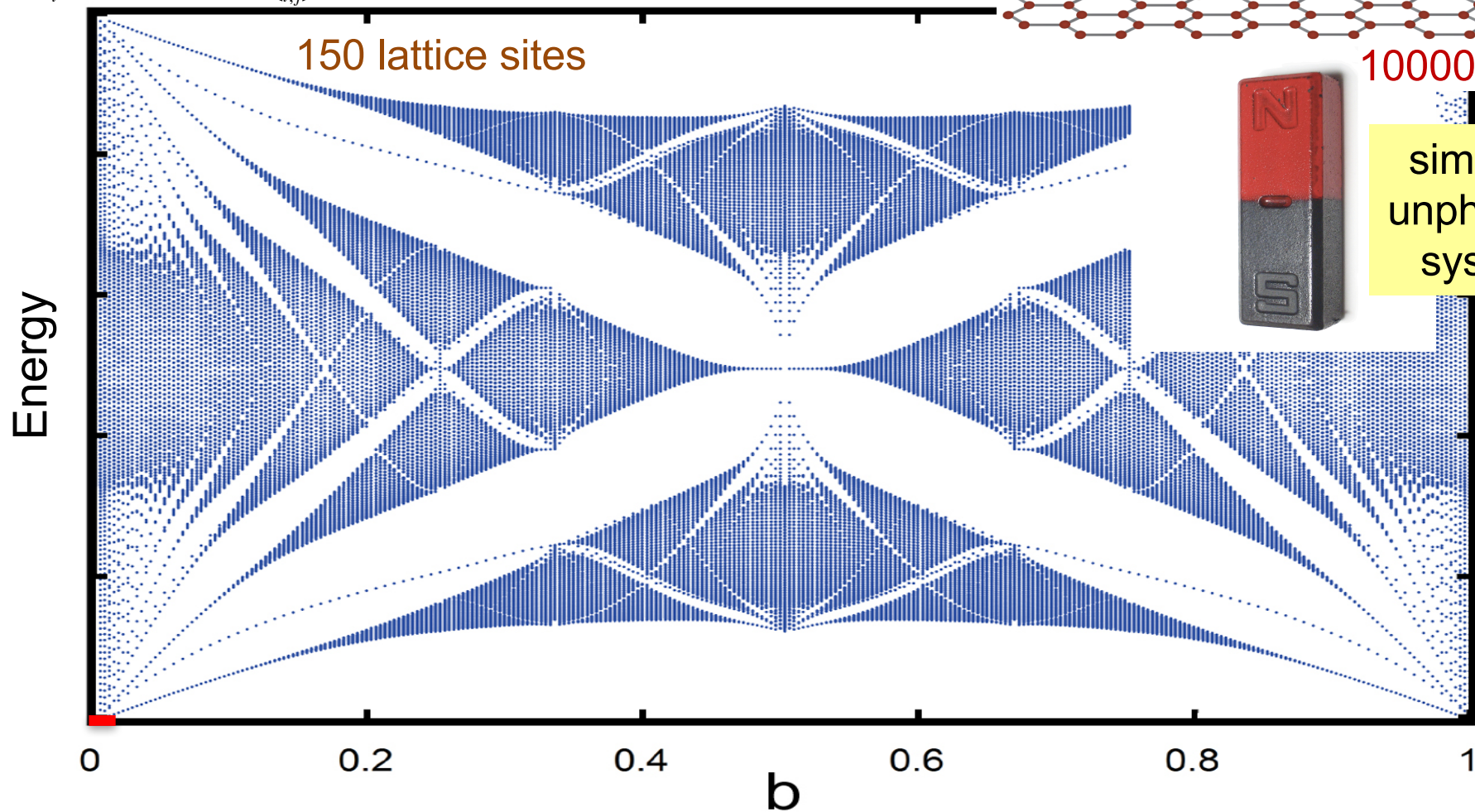
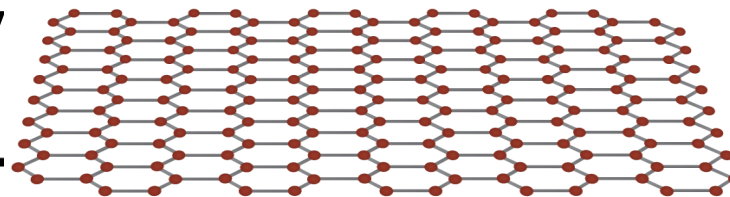


Tuneup flux offsets
(as drifty)

training
verified

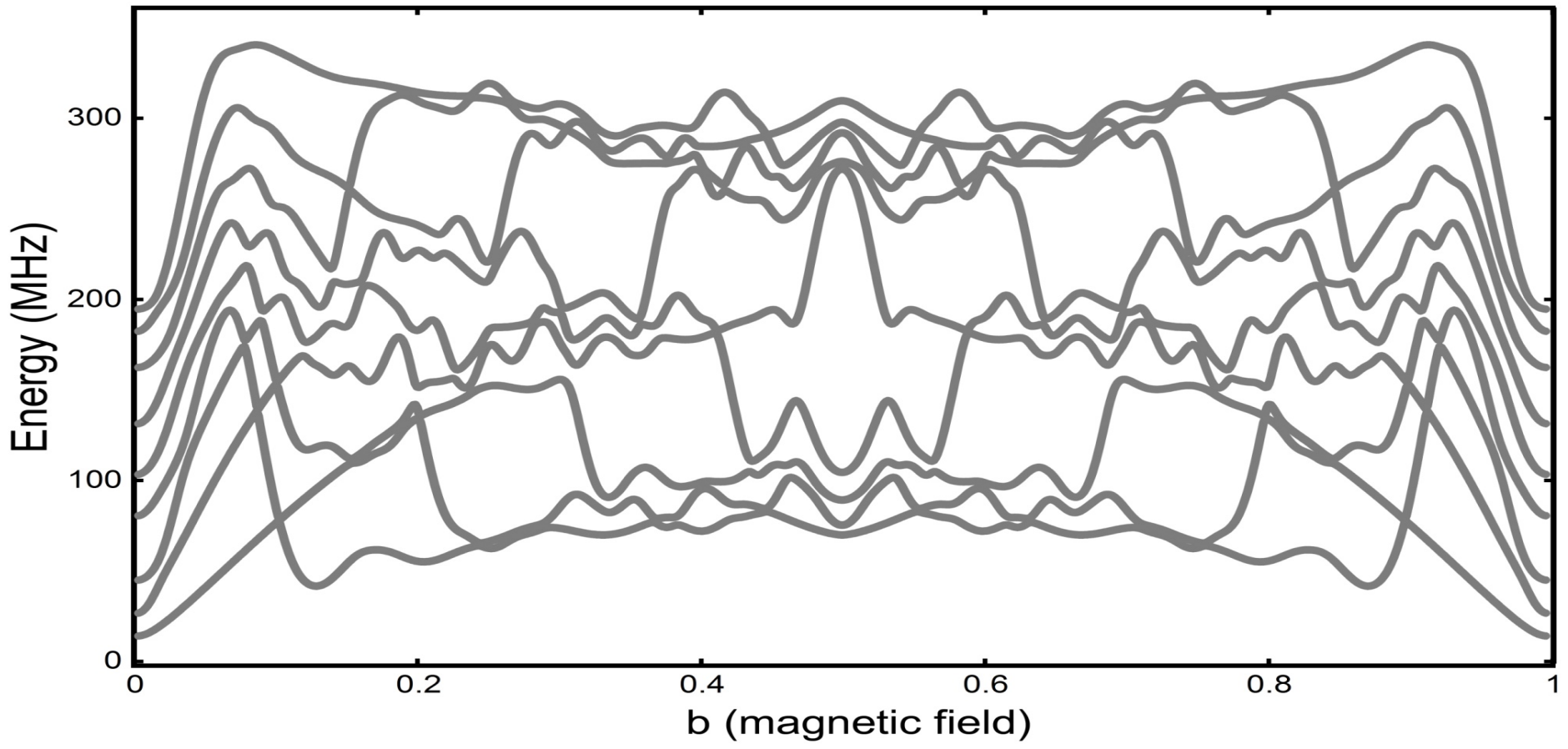
Hofstadter Butterfly

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



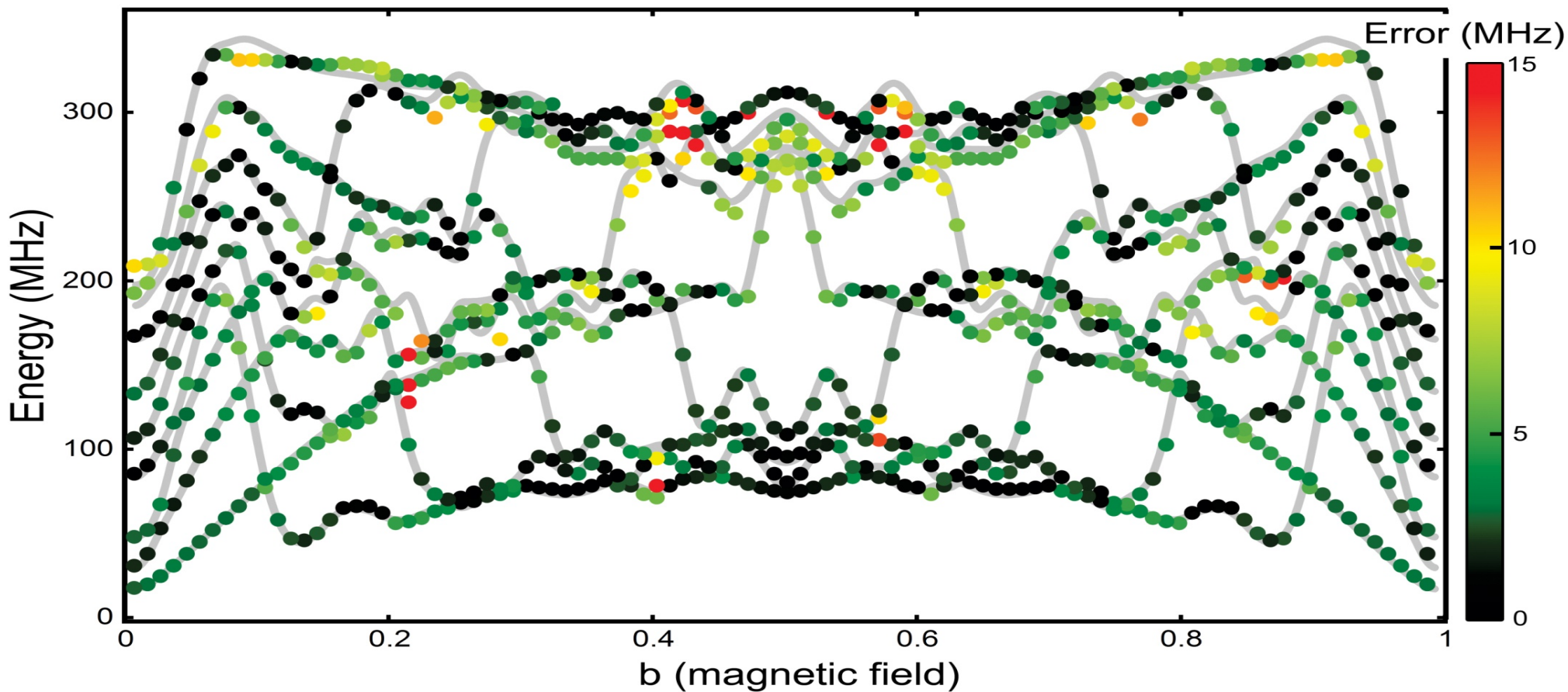
9 Qubits: theory

fractal nature gives complex spectrum

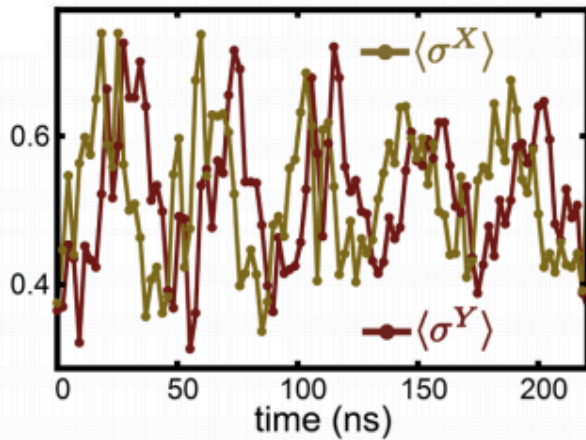
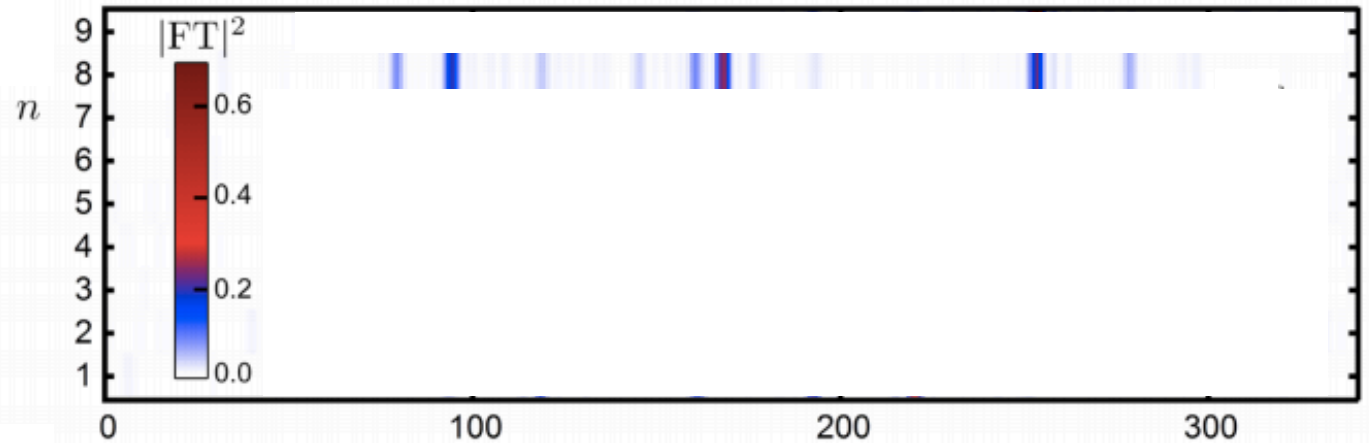
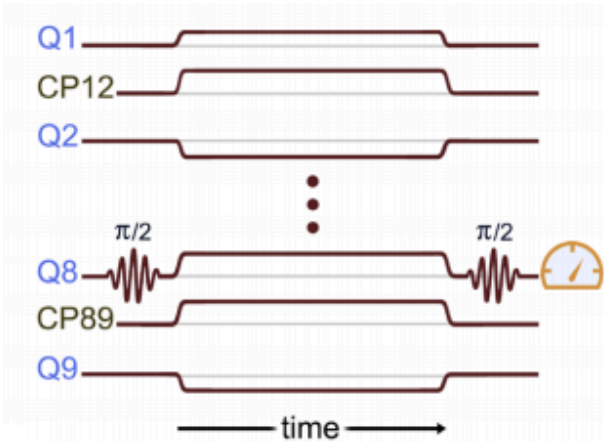


9 Qubits: theory + experiment

extract complex
physically useful information

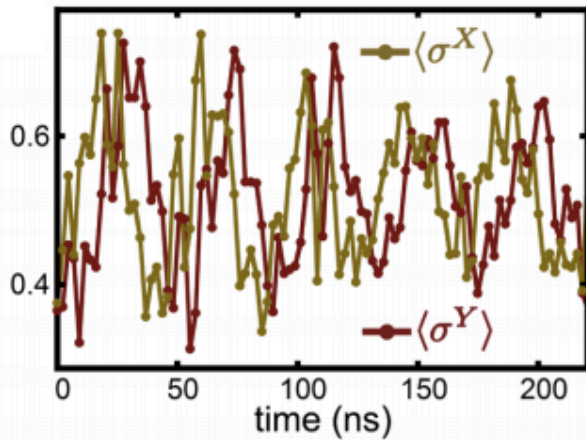
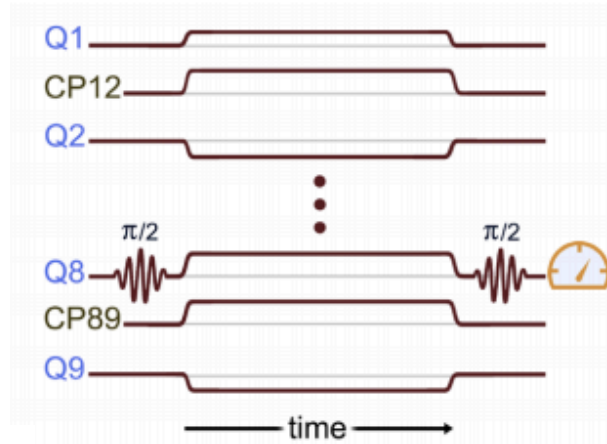


1-Excitation Spectroscopy

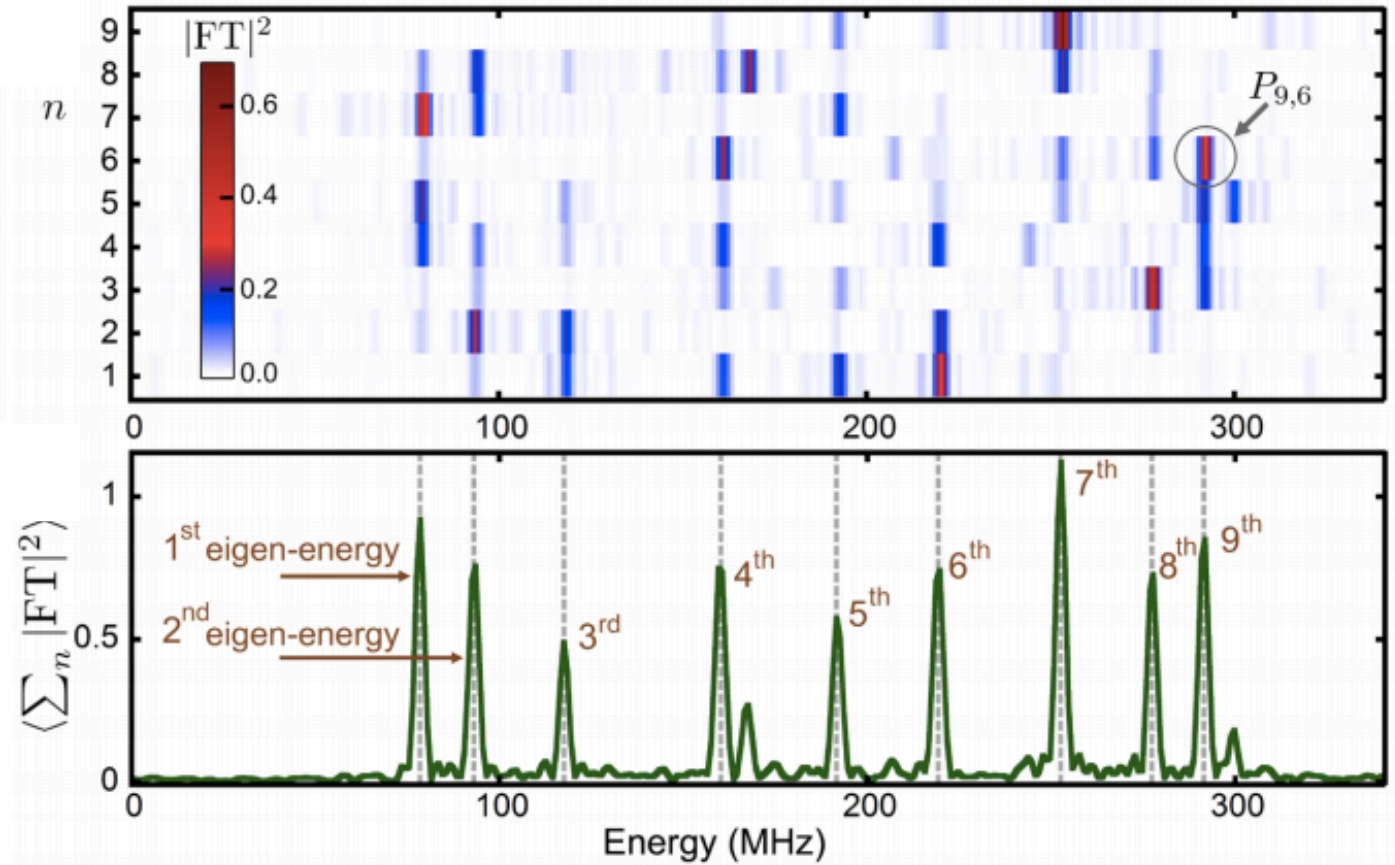


$$\chi_1(n) = \langle \sigma_n^X \rangle + i \langle \sigma_n^Y \rangle$$

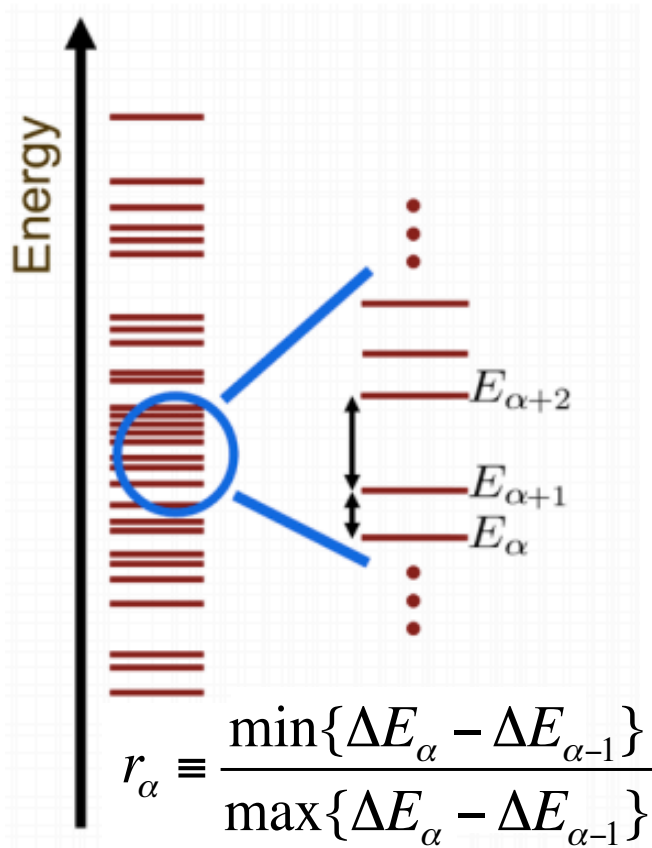
1-Excitation Spectroscopy



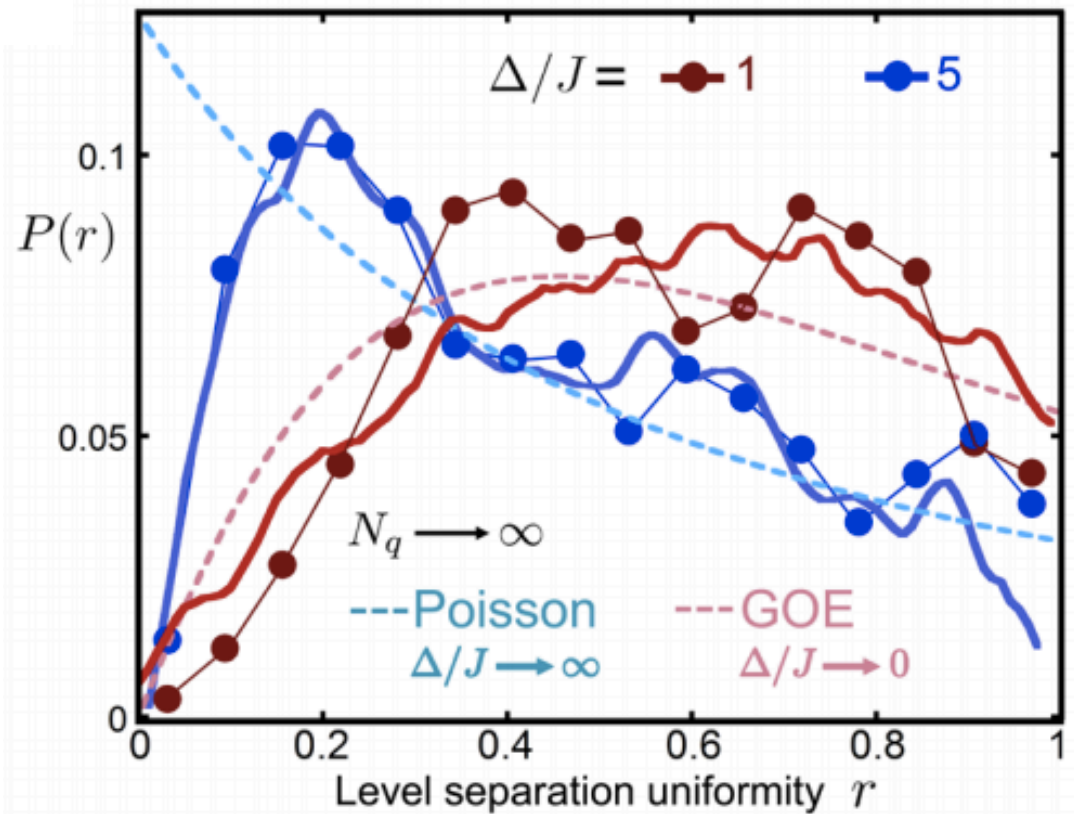
$$\chi_1(n) = \langle \sigma_n^X \rangle + i \langle \sigma_n^Y \rangle$$



Energy-Level Statistics

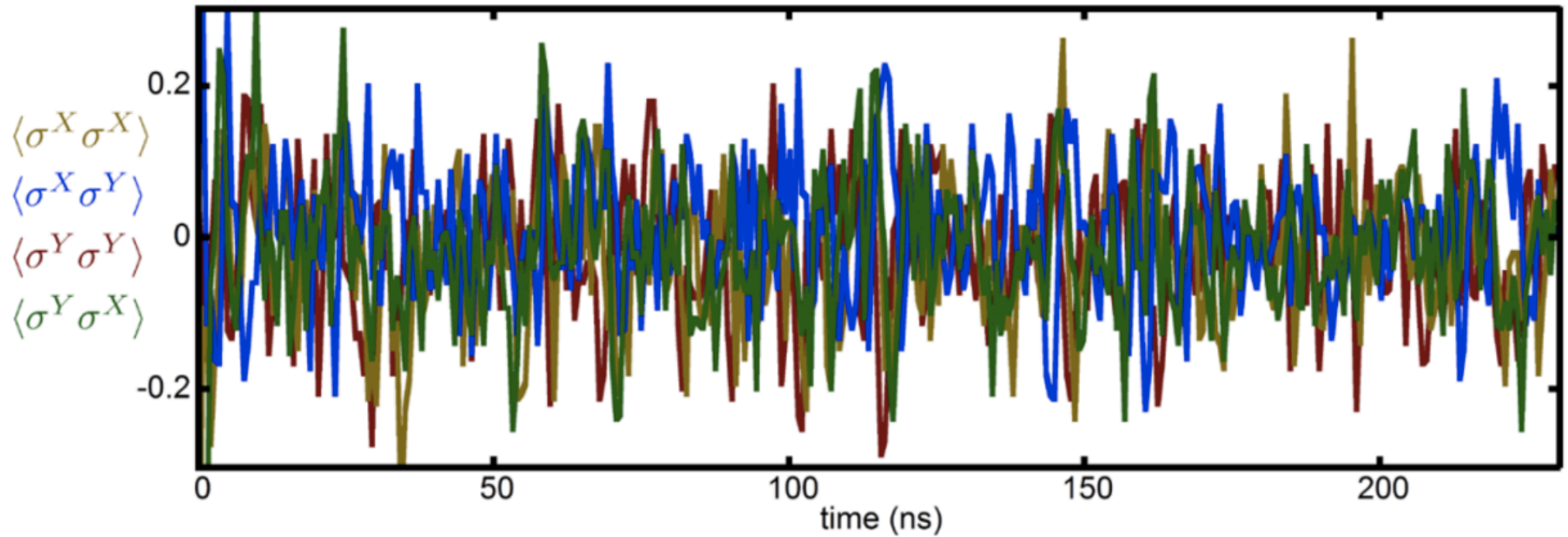


$$P_{\text{GOE}}(r) = \frac{27}{4} \frac{r + r^2}{(1 + r + r^2)^{5/2}}, \quad P_{\text{Poisson}}(r) = \frac{2}{(1 + r)^2}$$



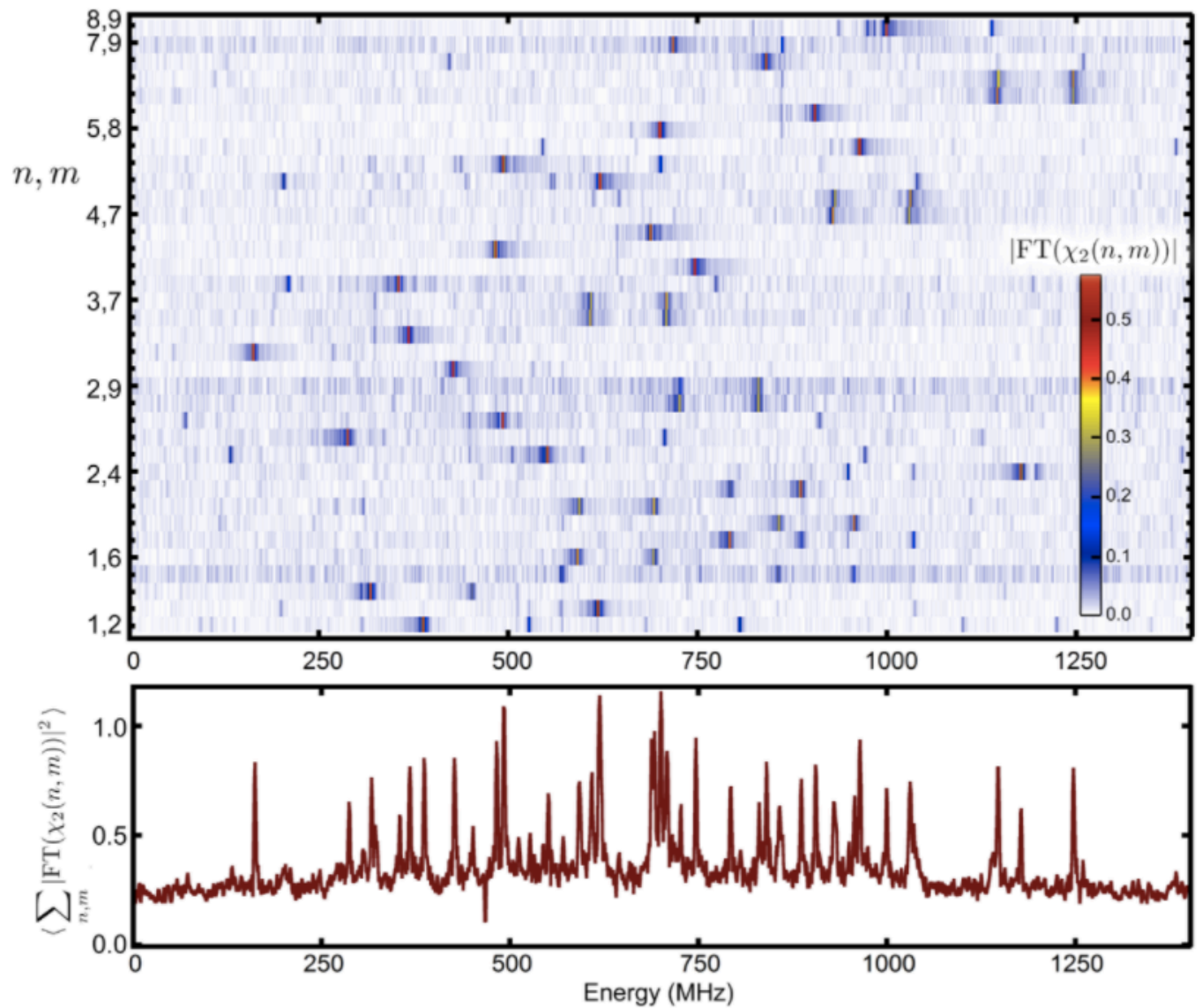
2-Excitation Spectroscopy

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



2 Excitation Spectroscopy

Now 45 energy levels



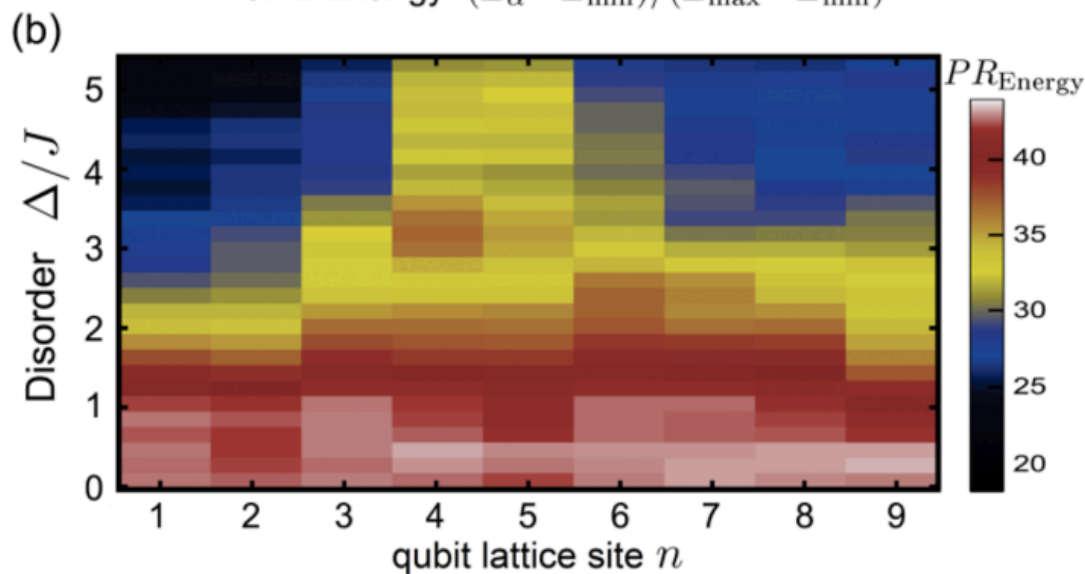
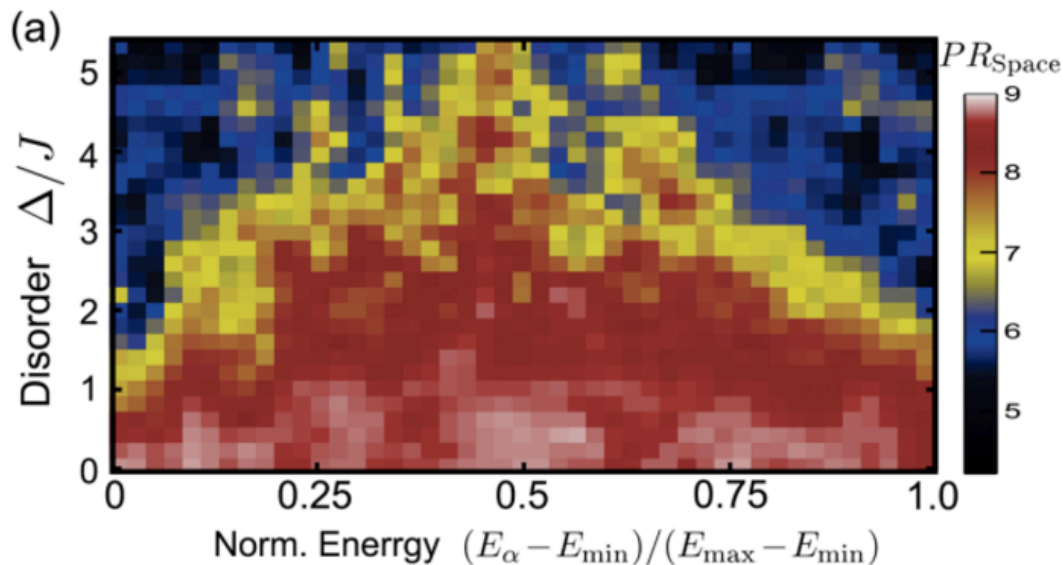
Participation Ratio & Mobility Edges

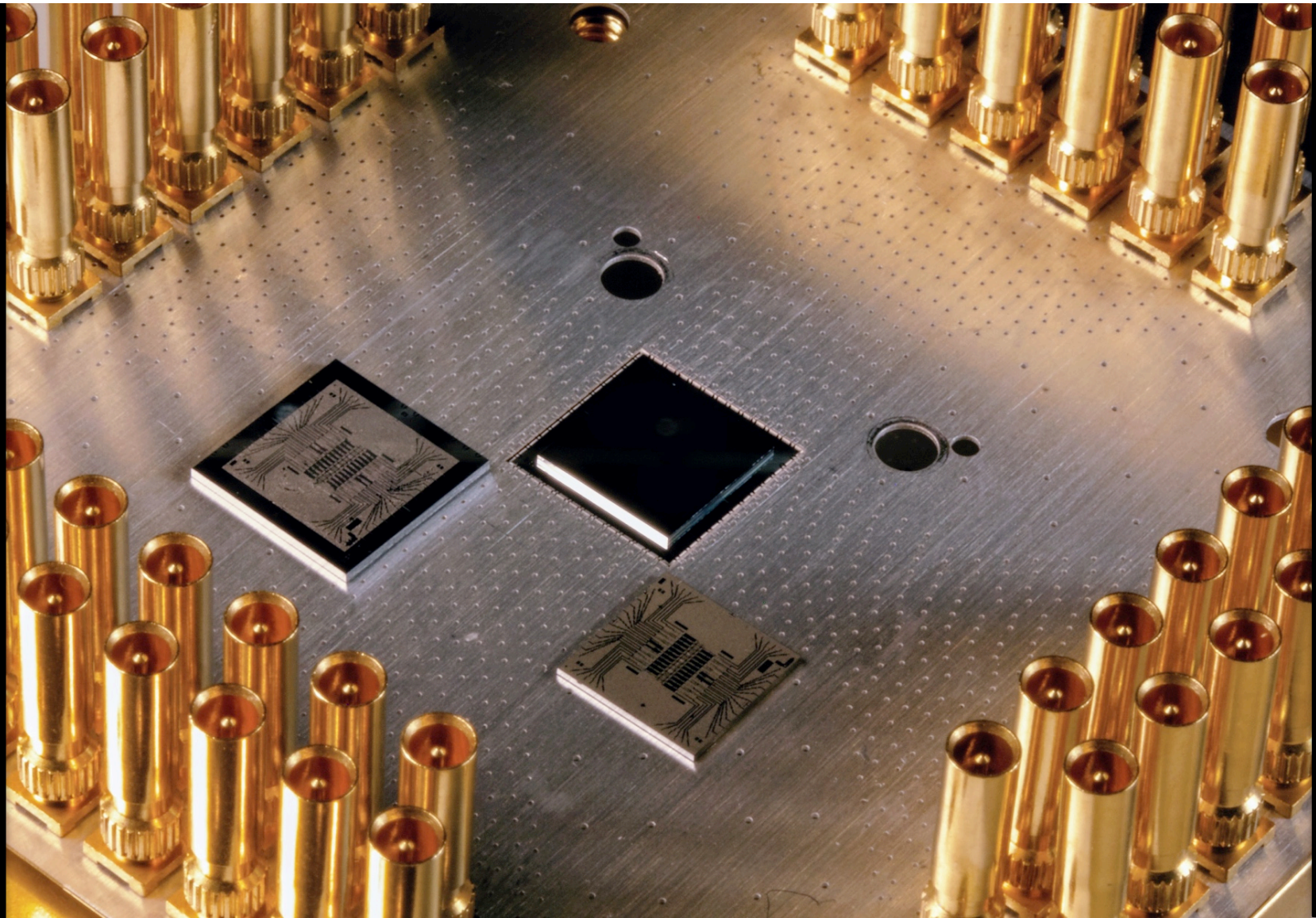
2nd moment of probabilities:

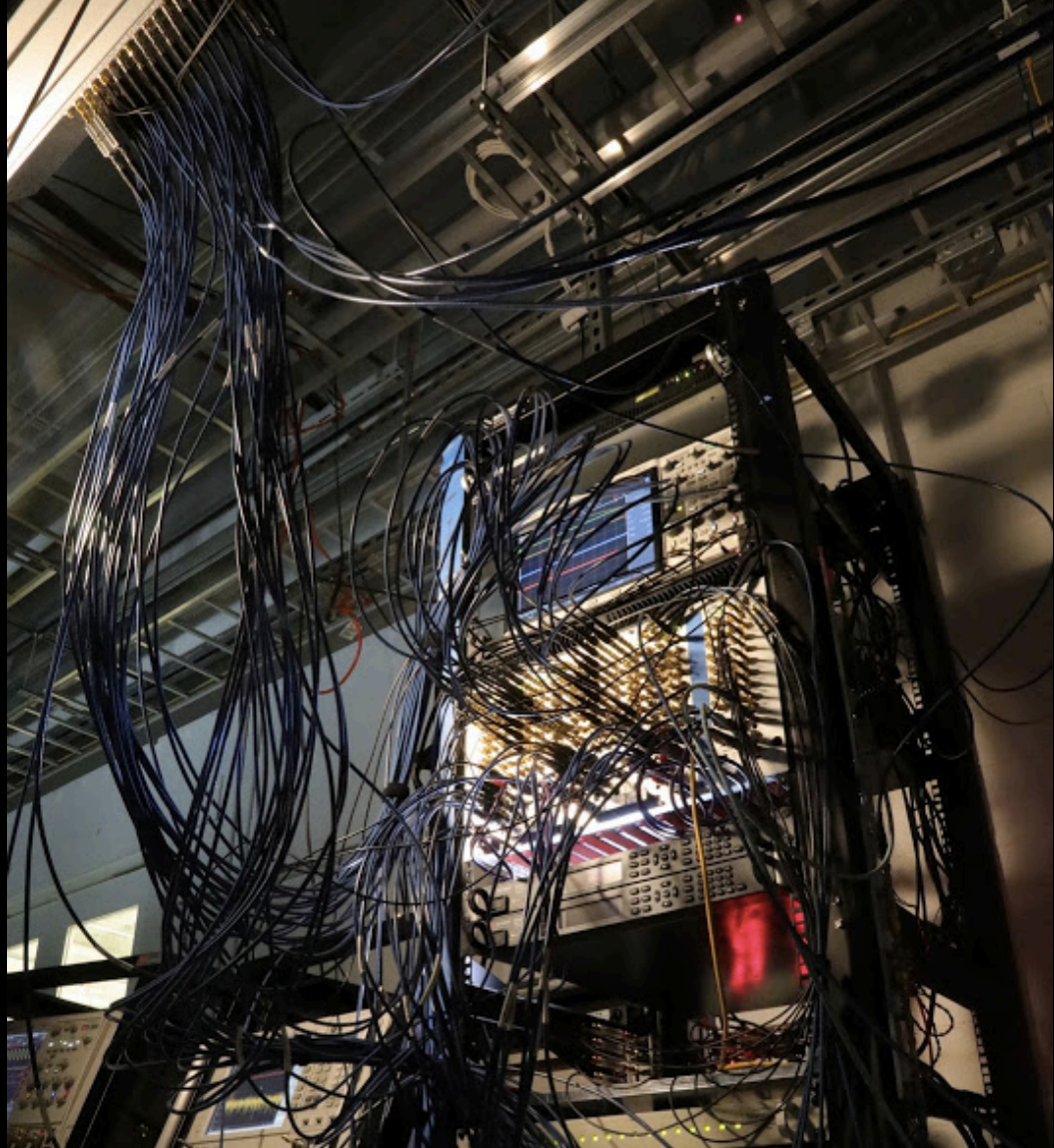
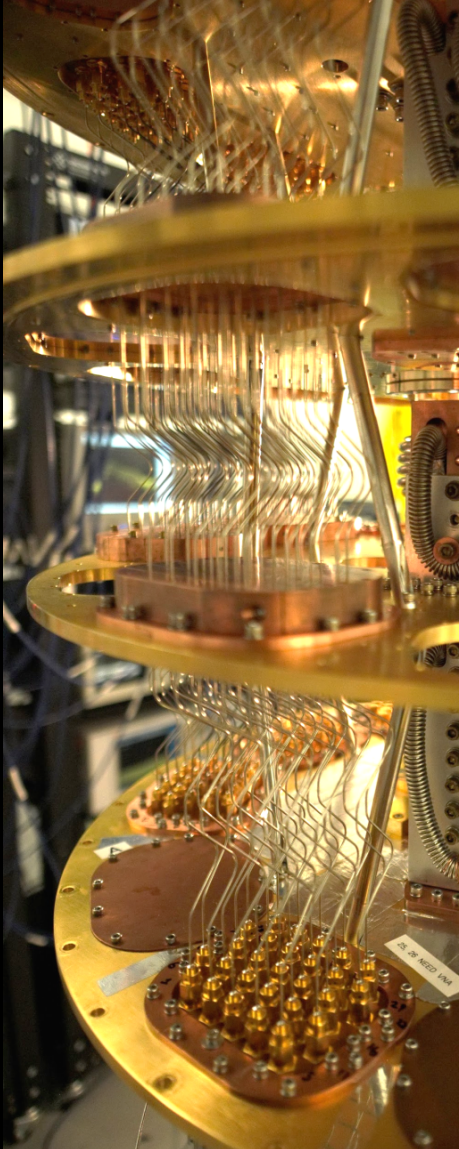
$$PR_{\text{Space}}(\alpha) \equiv 1 / \sum_n P_{\alpha,n}^2$$

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

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

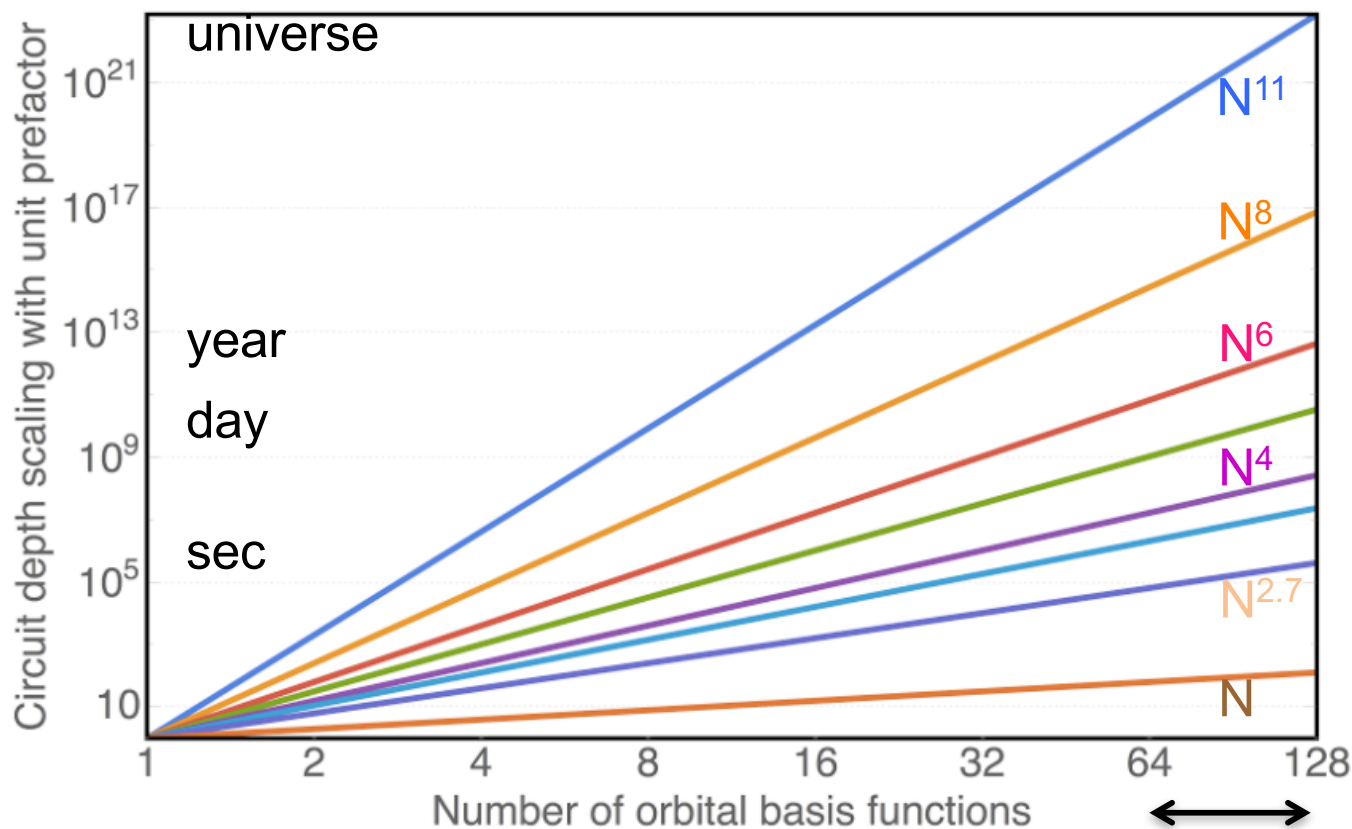






Huge Progress in Algorithms (Quantum Chemistry)

Year	Reference	Total Depth
1985	Feynman	(proposal)
2005	Aspuru-Guzik [1]	$O(\text{poly}(N))$
2010	Whitfield [2]	$O(\text{poly}(N))$
2012	Seeley [3]	$O(\text{poly}(N))$
2013	Perruzzo [4]	$O(\text{poly}(N))$
2013	Toloui [5]	$O(\text{poly}(N))$
2013	Wecker [6]	$O(N^{11})$
2014	Hastings [7]	$O(N^8)$
2014	Poulin [8]	$\sim N^6$
2014	McClean [9]	$\sim N^6$
2014	Babbush [10]	$\sim N^5$
2015	Babbush [11]	$\tilde{O}(N^5)$
2015	Babbush [12]	$\tilde{O}(\eta^2 N^3)$
2015	Wecker [13]	$O(N^4)$
2016	McClean [14]	$O(\eta^2 N^2)$
2017	Babbush [15]	$O(\eta^{1.83} N^{1.67})$
2017	Babbush [15]	$\tilde{O}(N^{2.67})$
2017	Babbush [15]	$O(N)$

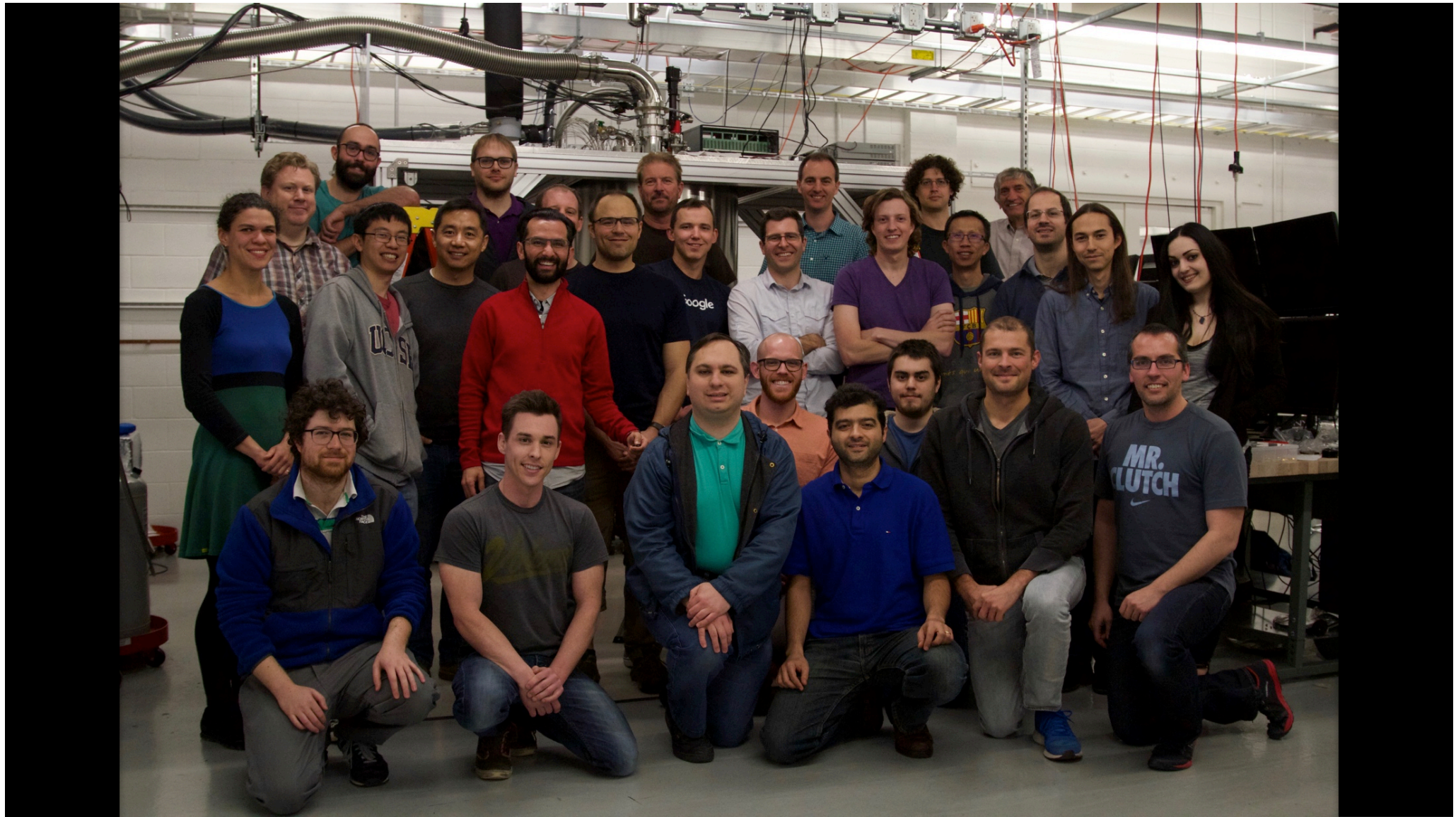


Exact: 100 logical qubits (error corrected)

Approximate: 100 physical qubits (?)

Google Hardware Plans

- 1) 9 qubit devices, both gate based and continuous (gmon)
1 qubit: 0.05-0.1% error
2 qubit 0.5-1%
- 2) 22 qubit device in test (2x11 array)
Single and 2 qubit performance similar to 9 qubit device
- 3) Supremacy device ready to fabricate (square array)
By end of year
- 4) Working on improved annealer (flux qubit)
Better coherence, connectivity and control
2 qubit device shows better annealing performance
9 qubit device in design



Building a Real Quantum Simulator

- For one device, qubits have
Coherence
Coupling
Measurement
Low errors

competing requirements

- Good control each qubit
- Room for control circuitry
- Reprogrammable
- Flexible architecture
- Scalable

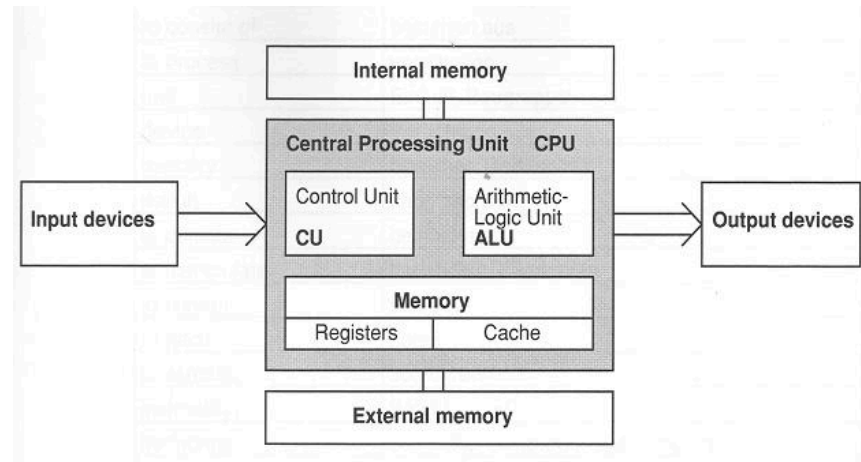
general purpose

What's so hard?

Systems vs. Control:

Can't copy quantum information
Hard to separate into sub-functions

Quantum Systems Engineering



skip design and cal