Quantum Supremacy: Checking a Quantum Computer with a Classical Computer

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Quantum Data

$$|0\rangle + |1\rangle$$

Quantum Data

$$(\,|0\rangle+|1\rangle\,)^2=|00\rangle+|01\rangle+|10\rangle+|11\rangle$$

Really Big Data

$$(|0\rangle+|1\rangle)^n$$

n=50: supercomputer

n=300: more states than atoms in universe

Our Goals for Quantum Supremacy*

1) Exponential: demonstrate exponentially growing computation space (computational complexity: not guaranteed for more qubits)

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

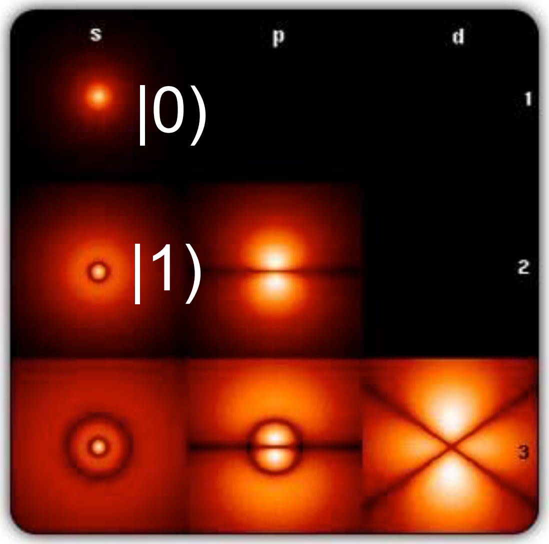
3) Fidelity: need lower errors in qubit control, used to validate control

4) Universal: forward compatible to general purpose computer

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

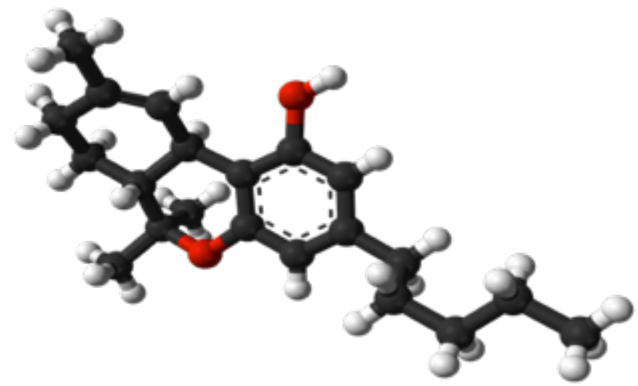
Encoding of quantum bits

H atom:



orbitals

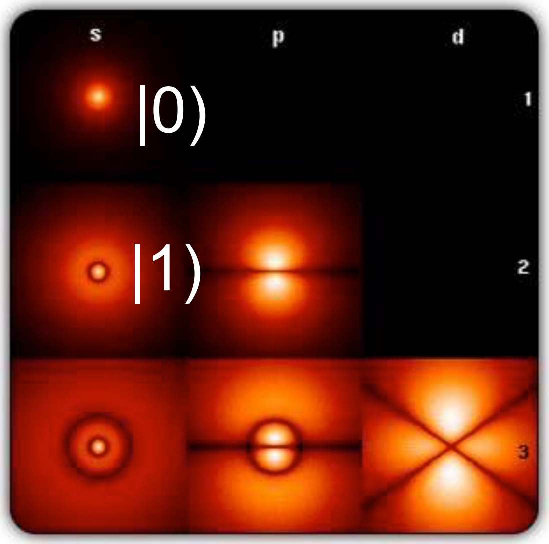
atom circuit:



problem:
light is 1000x bigger

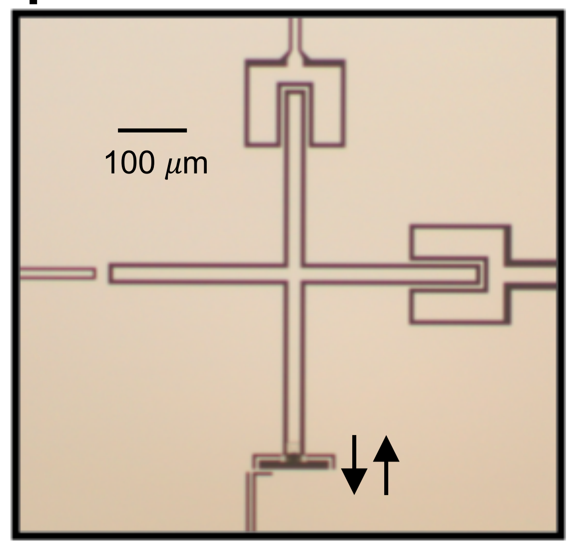
Encoding of quantum bits

H atom:



orbitals

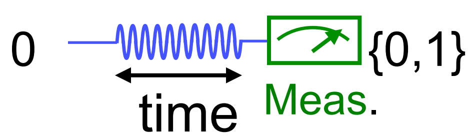
quantum circuit:

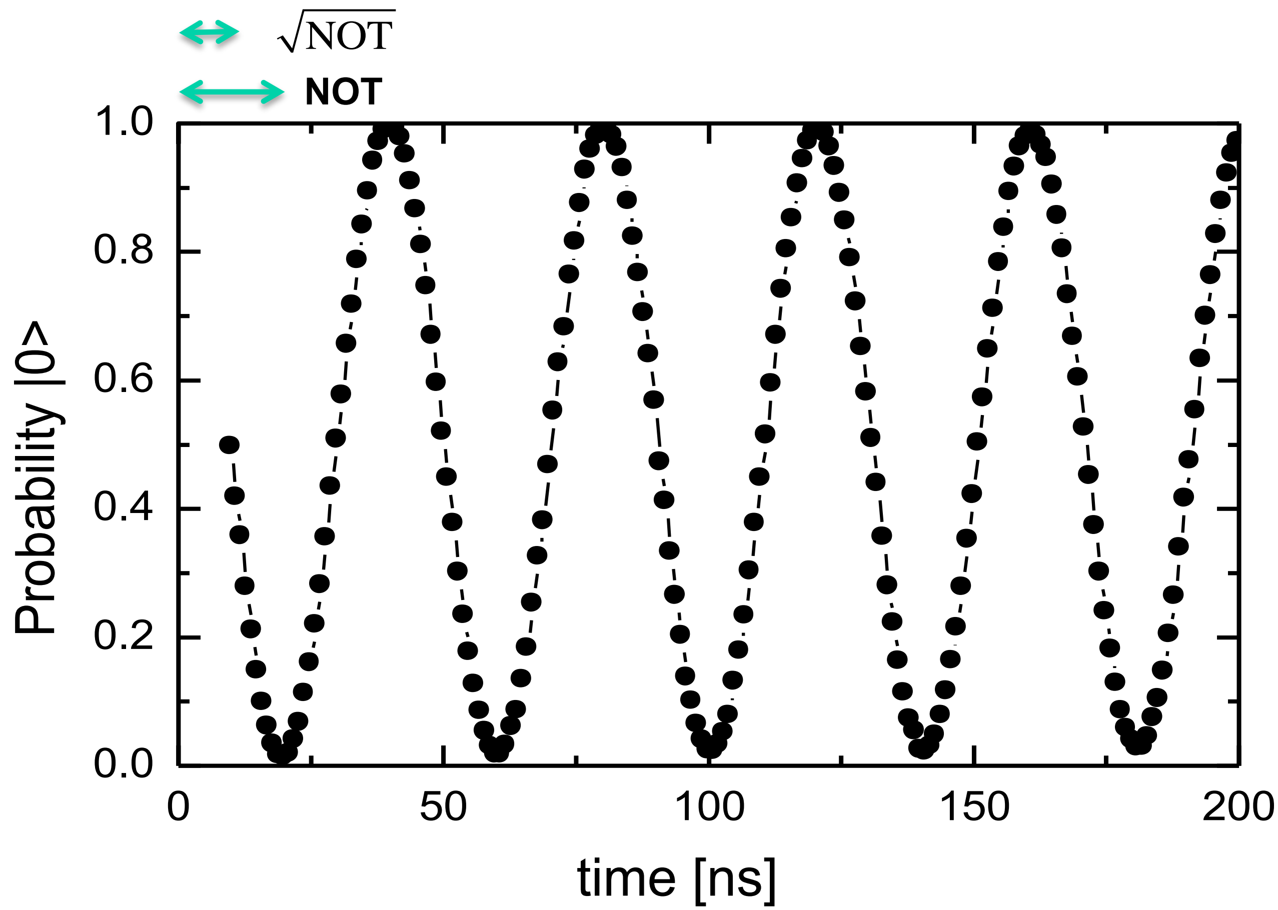


6 GHz microwave oscillator

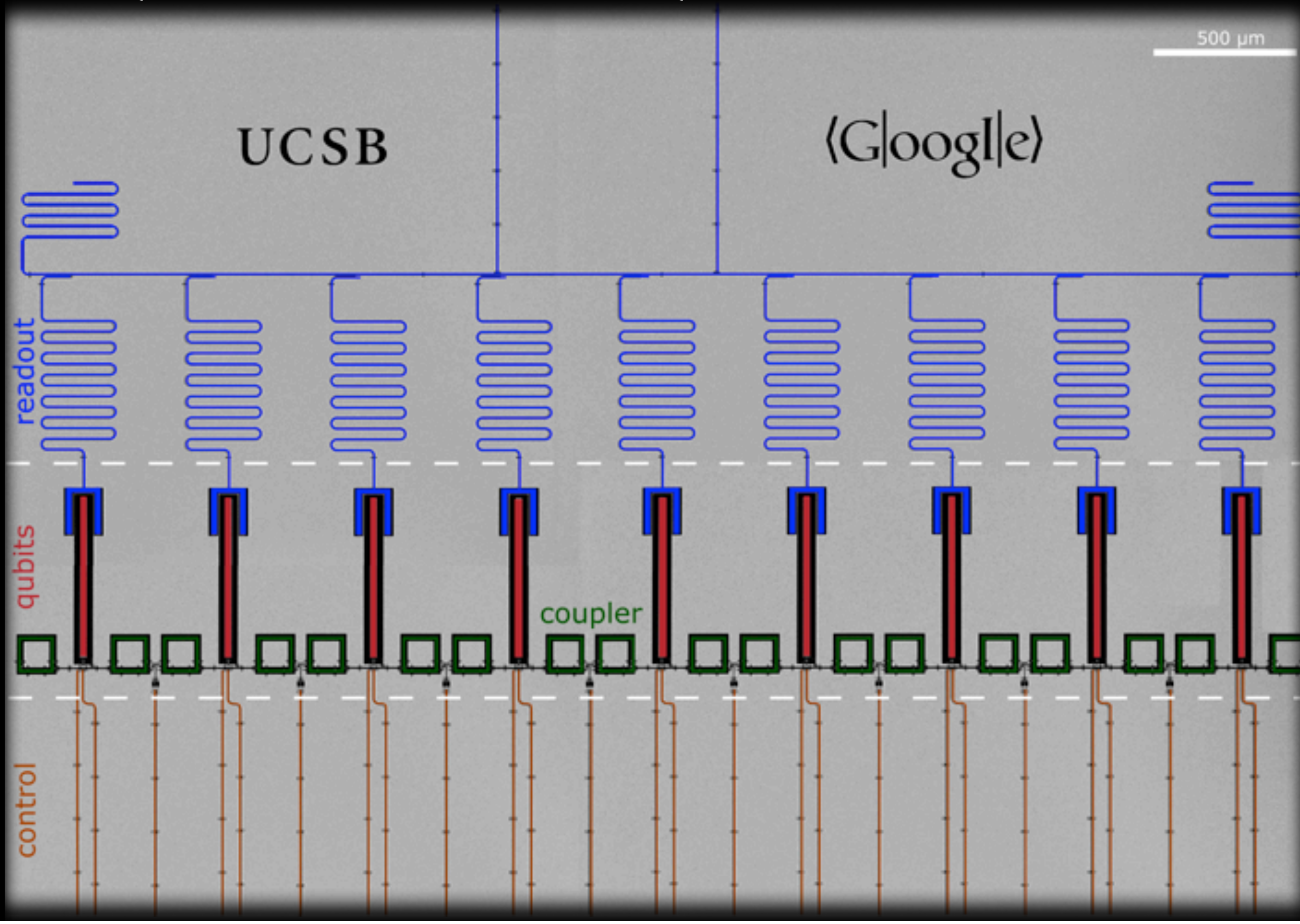
Easier control for large size

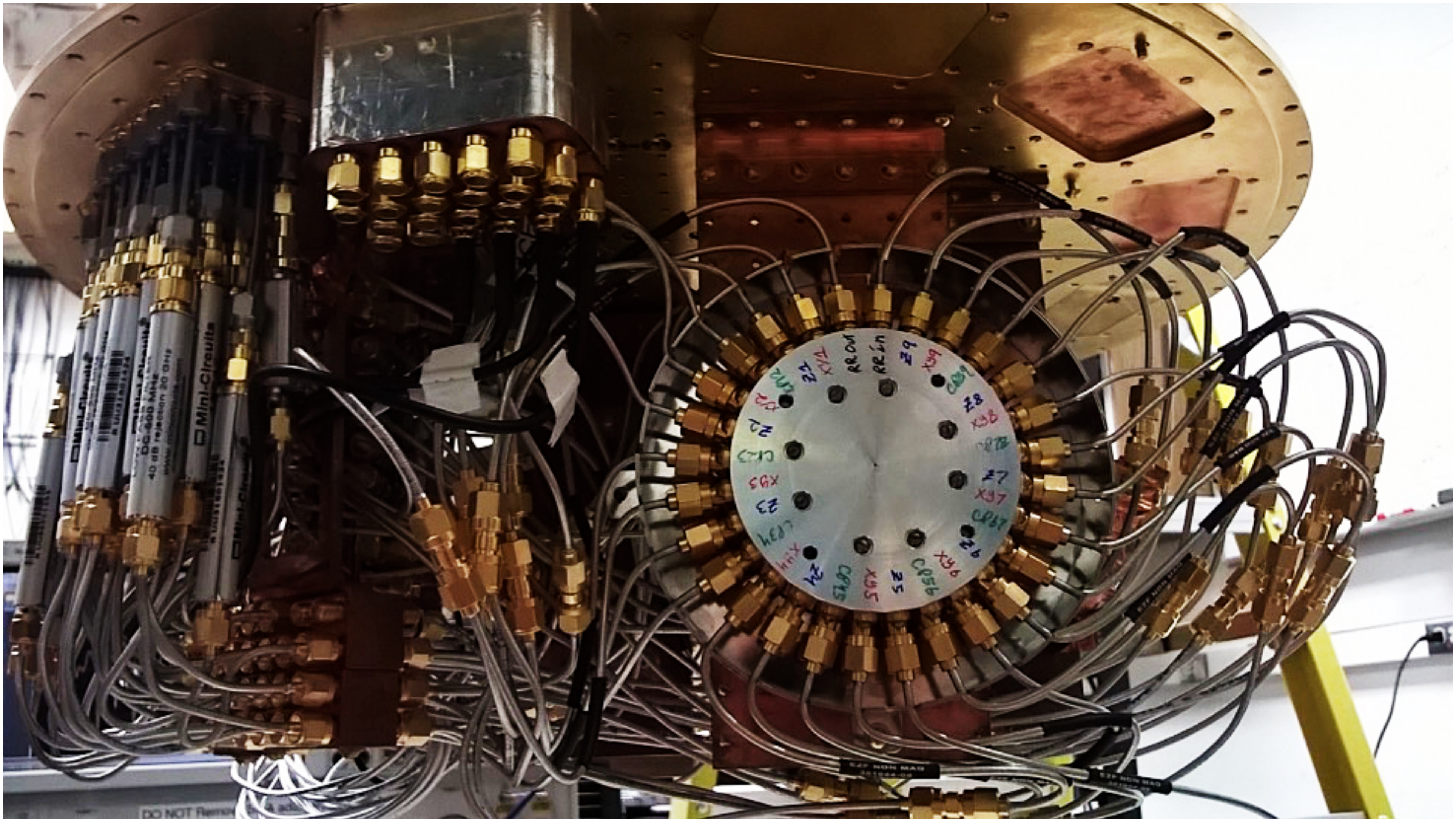
Qubit Operation



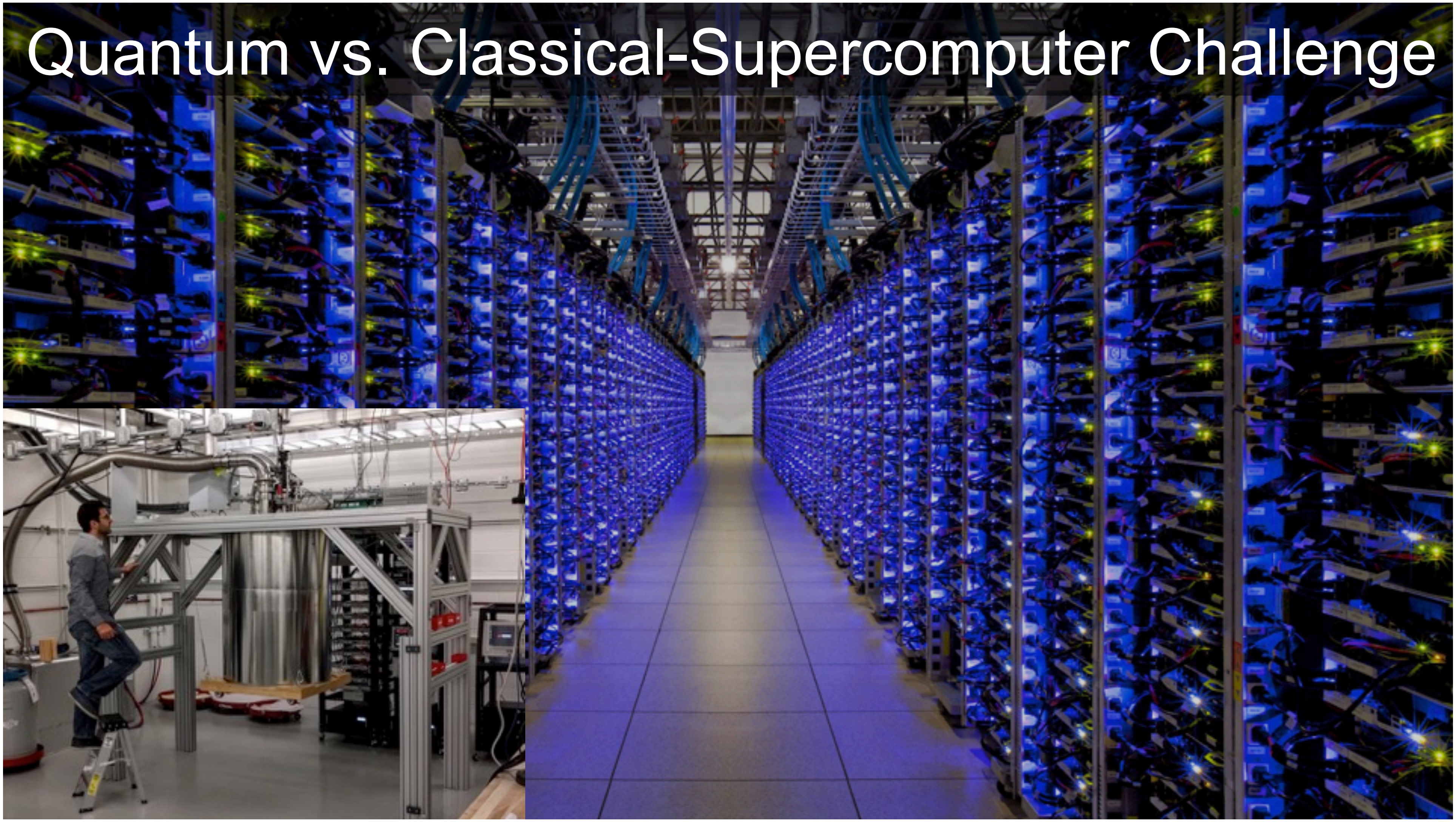


9 Qubit Device for Quantum Simulation



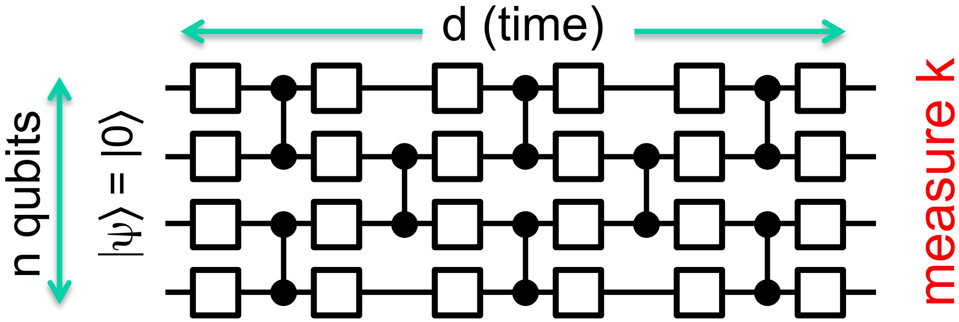

Mini-Circuits
RR Out
RR in

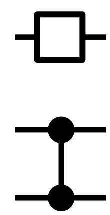
Quantum vs. Classical-Supercomputer Challenge



Algorithm for Supremacy Test: Qubit Speckle

1) Choose 1 instance, randomly from gateset





	Clifford	Non-Clifford
	X, Z, H, $X^{1/2}$…	$Z^{1/4}$
	CZ	

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

repeat sampling 100,000 times

1 s

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

days
200 drives

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

4) Correlation: cross entropy

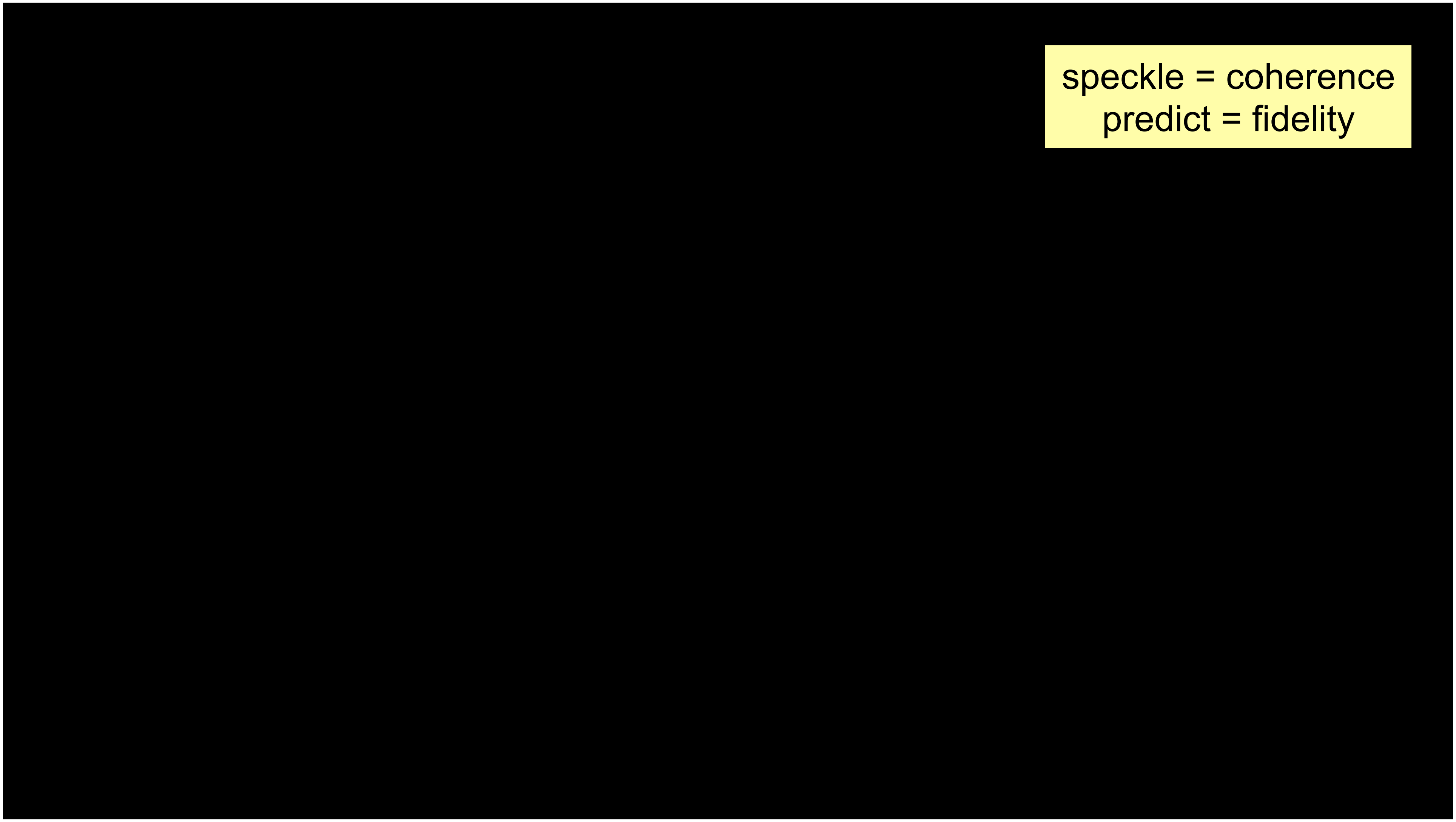
$$S = \langle \ln p(k)/p_{cl} \rangle$$

5) Compare to theory

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

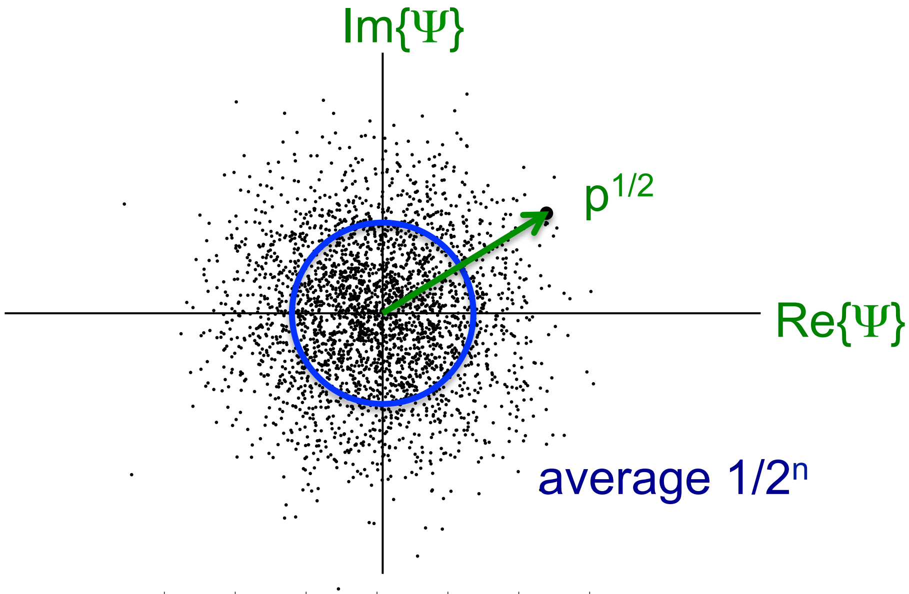
6) Try another instance

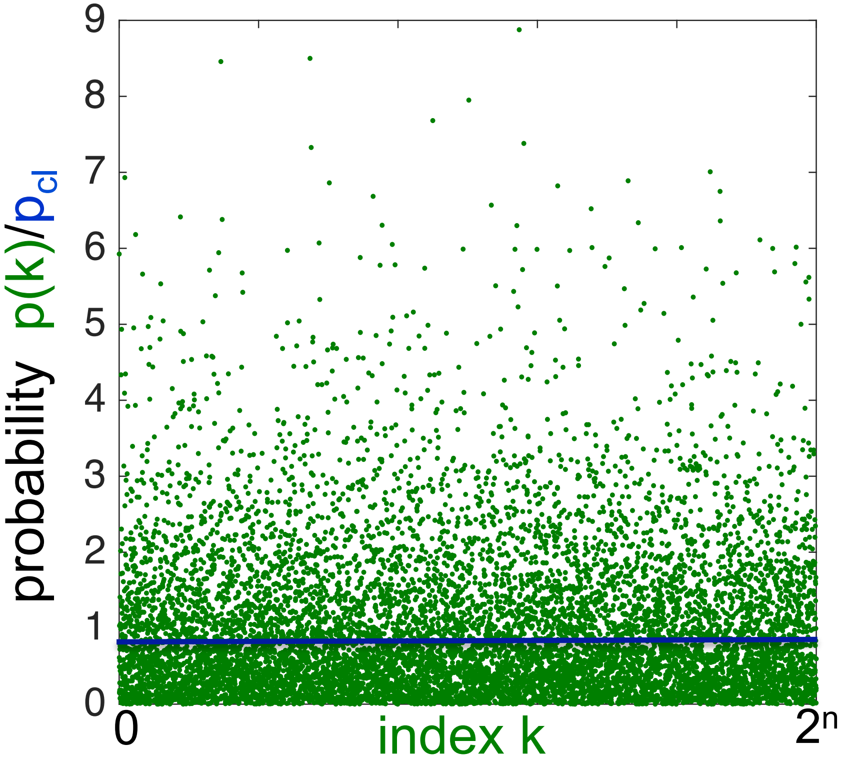
$$S_{cl} \cong -0.58 \quad \text{classical}$$


speckle = coherence
predict = fidelity

How Does it Work?

- Gaussian distribution Re{Ψ} & Im{Ψ} gives Porter-Thomas (exponential) distribution



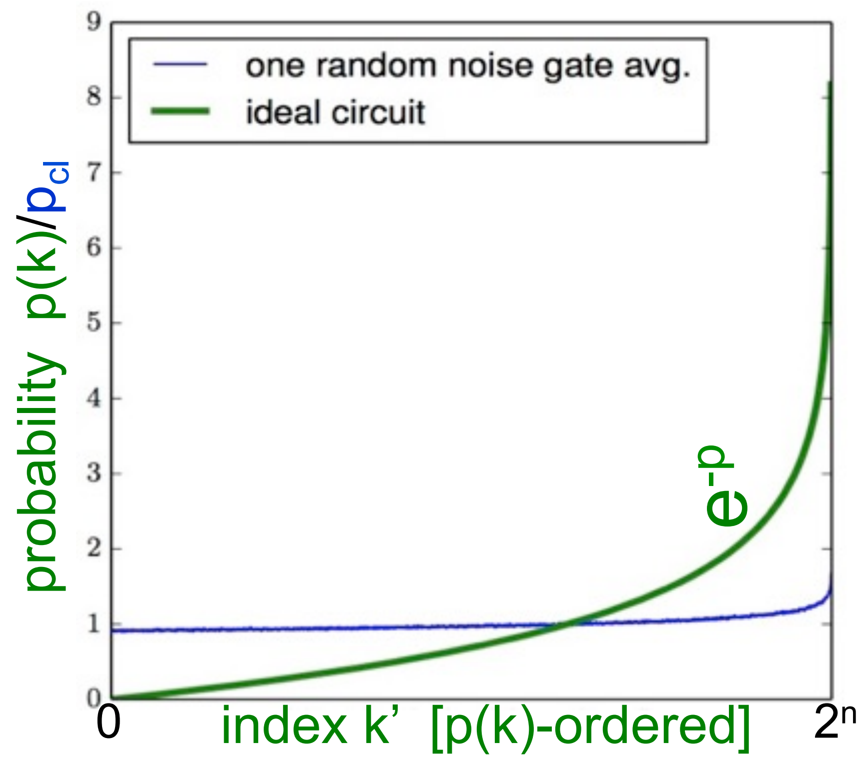


0 errors: exponential

How Does it Work?

- Gaussian distribution Re{Ψ} & Im{Ψ} gives Porter-Thomas (exponential) distribution

- With one error anywhere distribution is flat (classical like)



0 errors: exponential

1+ errors: uniform

How Does it Work?

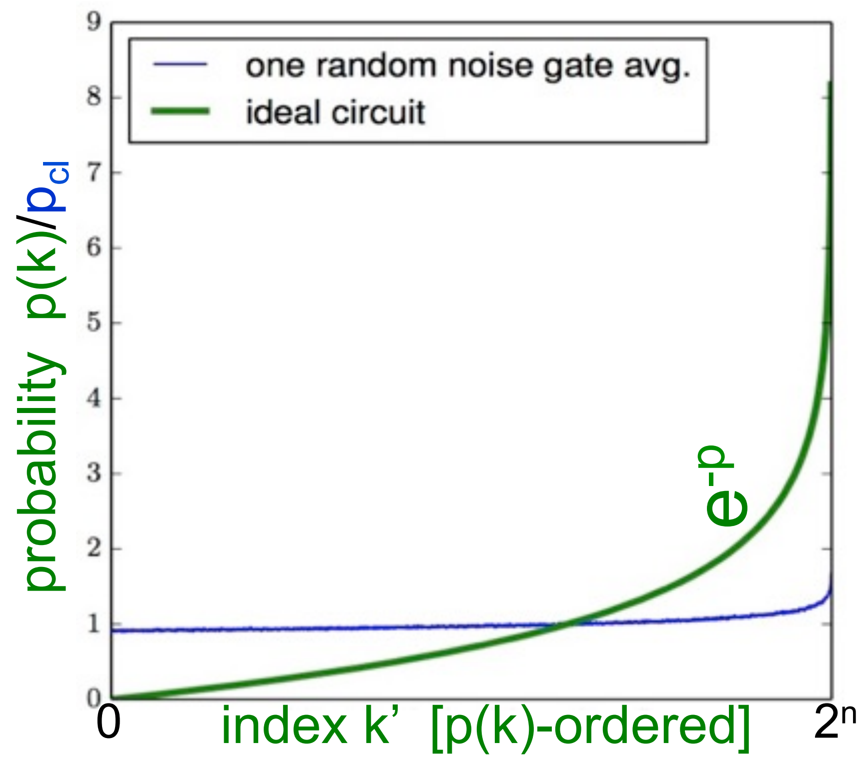
- Gaussian distribution Re{Ψ} & Im{Ψ} gives Porter-Thomas (exponential) distribution
- With one error anywhere distribution is flat (classical like)

probability of no error

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

$$
\begin{aligned}
P_0 &= (1-\varepsilon_1)^{nd}(1-\varepsilon_2)^{nd}(1-\varepsilon_m)^{n} \\
&\cong \exp[-nd(\varepsilon_1+\varepsilon_2)+n\varepsilon_m] \\
&\equiv \exp[-N_e]
\end{aligned}
$$

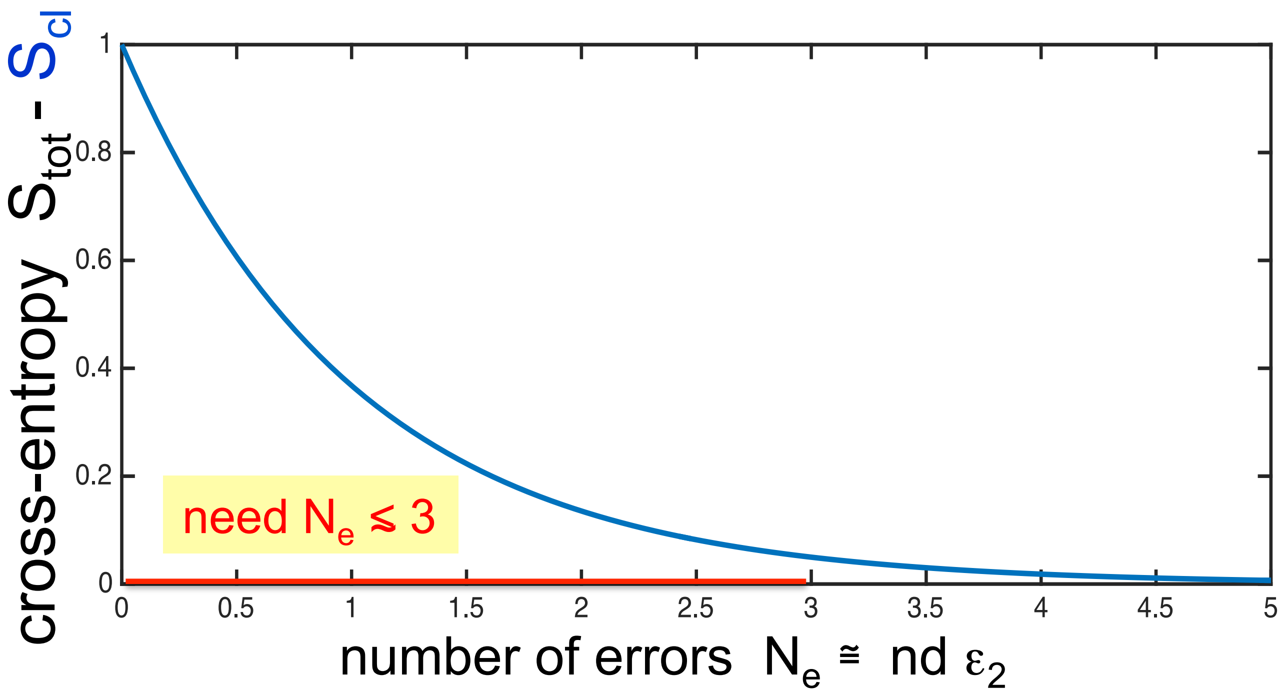
Include all 1, 2, measure errors ε



0 errors: exponential

1+ errors: uniform

Exponential Decay of Quantum Information



Errors Destroy Quantum Computation

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

Probability of no error:

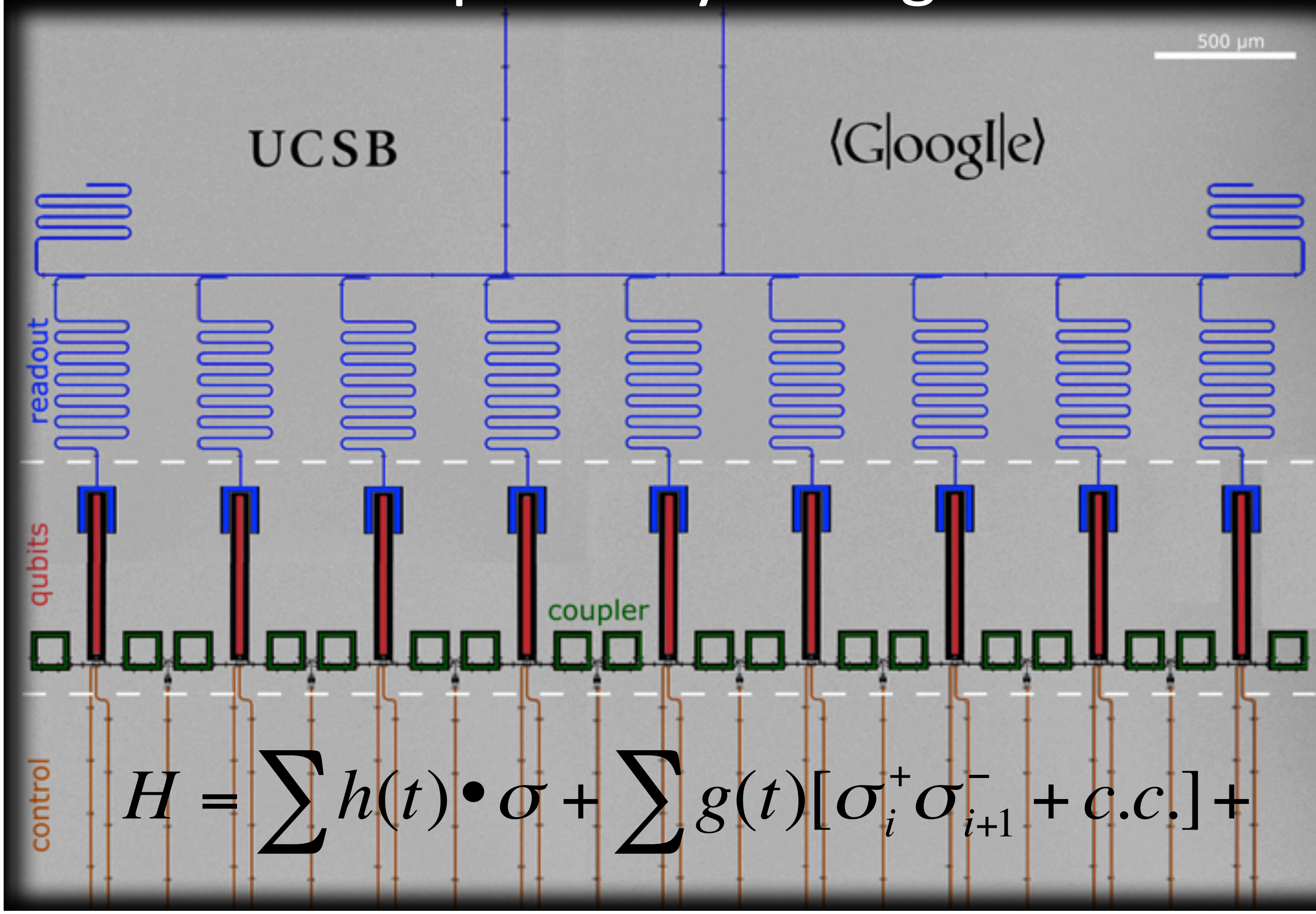
$P_0 = \exp[\,-N_g\, \varepsilon_g\,]$

Average number of errors:

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

Need: scaling with low errors

Quantum Supremacy with gmon Qubits

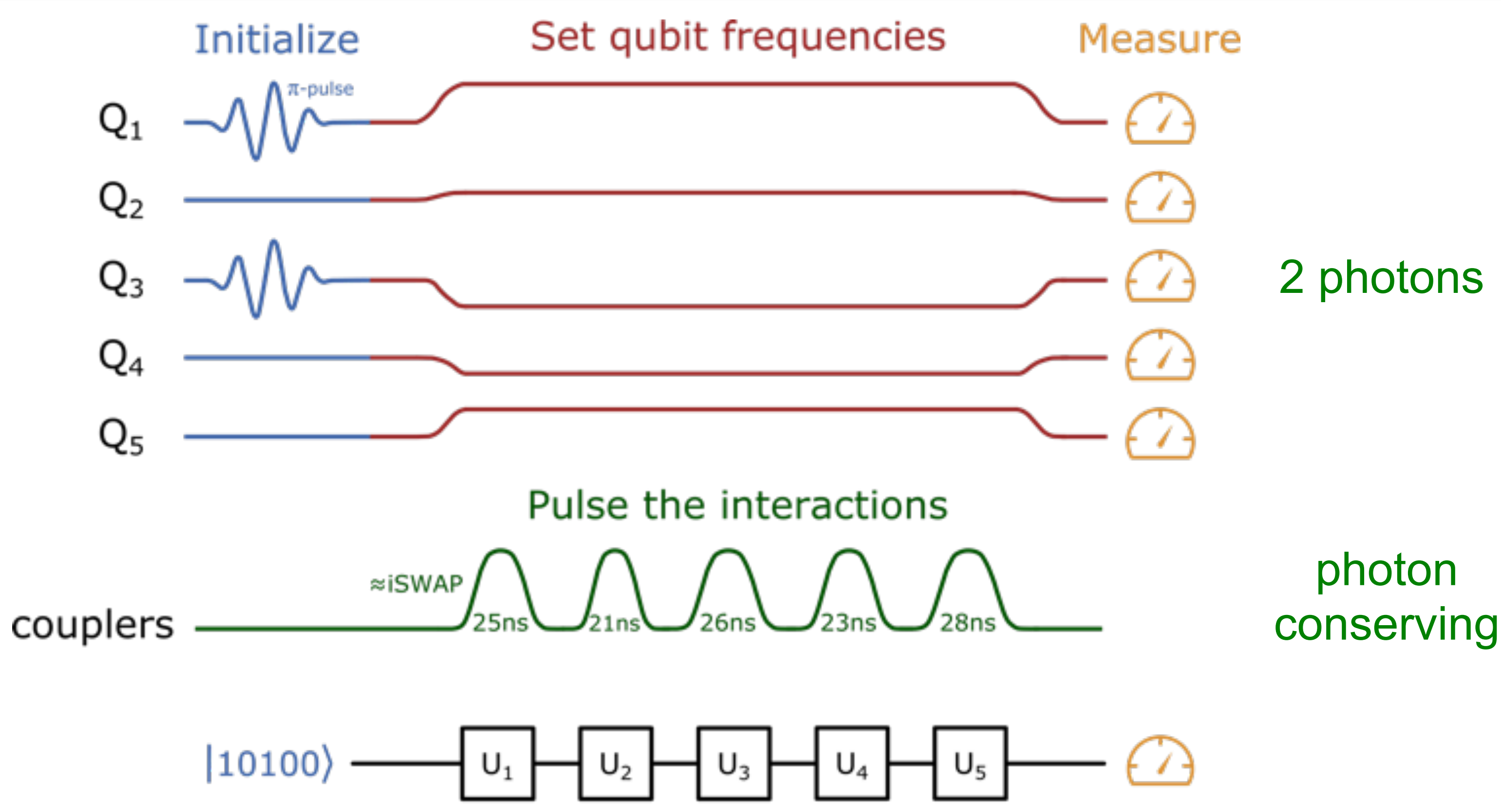


$$H = \sum h(t) \bullet \sigma + \sum g(t)[\sigma_i^+ \sigma_{i+1}^- + c.c.] +$$

9-qubit gate calibrated from 8 2-qubit gates

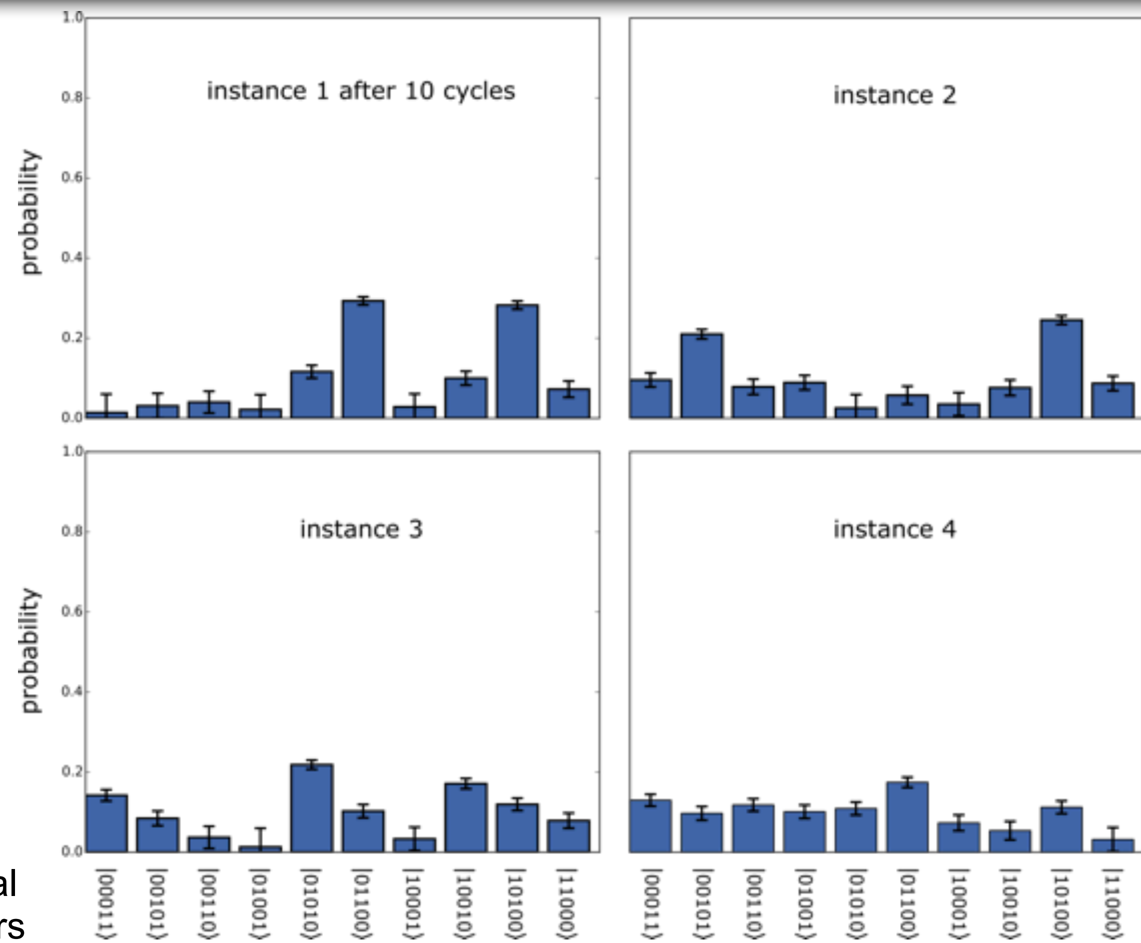
h ~ 200 MHz
g ~ 30 MHz
t: 1 ns to 20 us
Cal. to ~0.1MHz

Pulse sequence (5 qubit example)



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

Typical dataset with 5 qubits

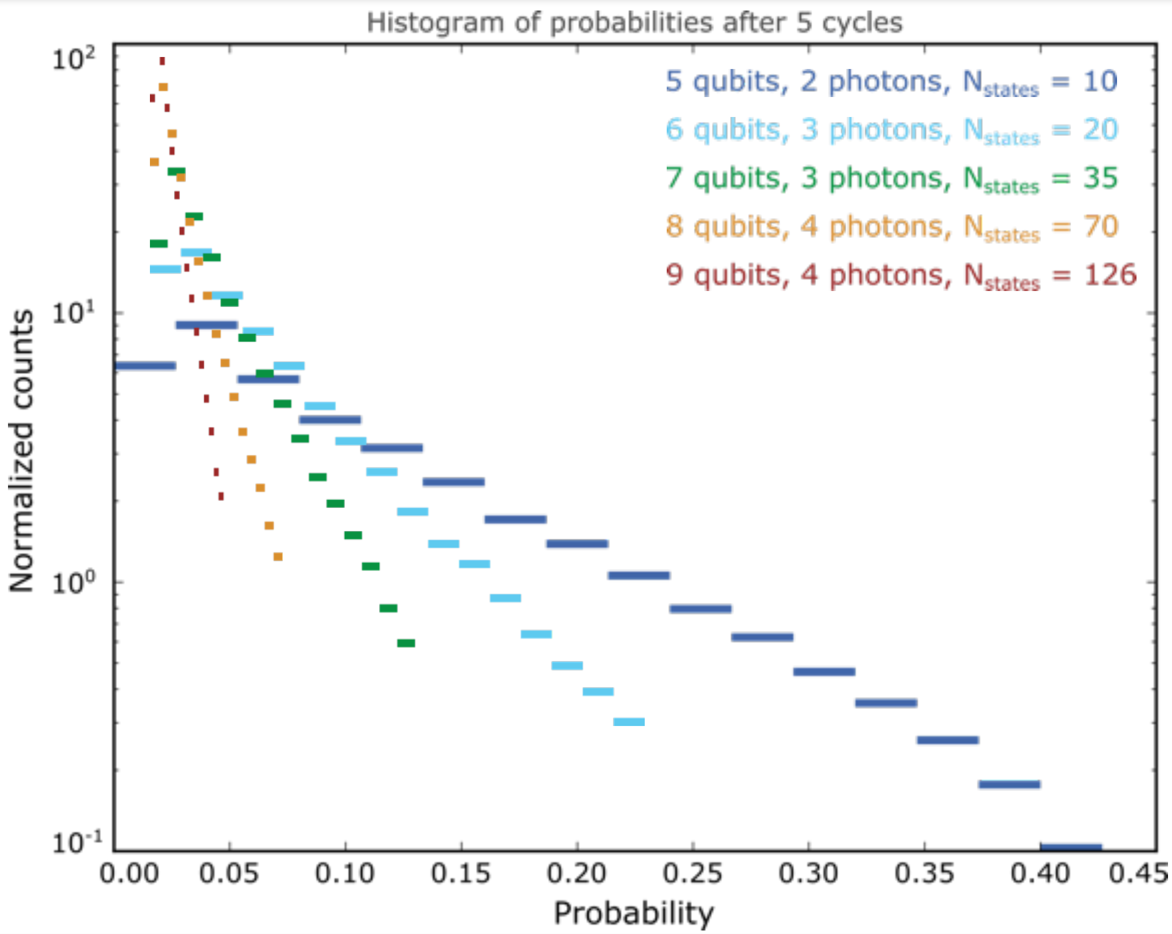


quantum info just from prob. histograms

statistical error bars

photon conserving states

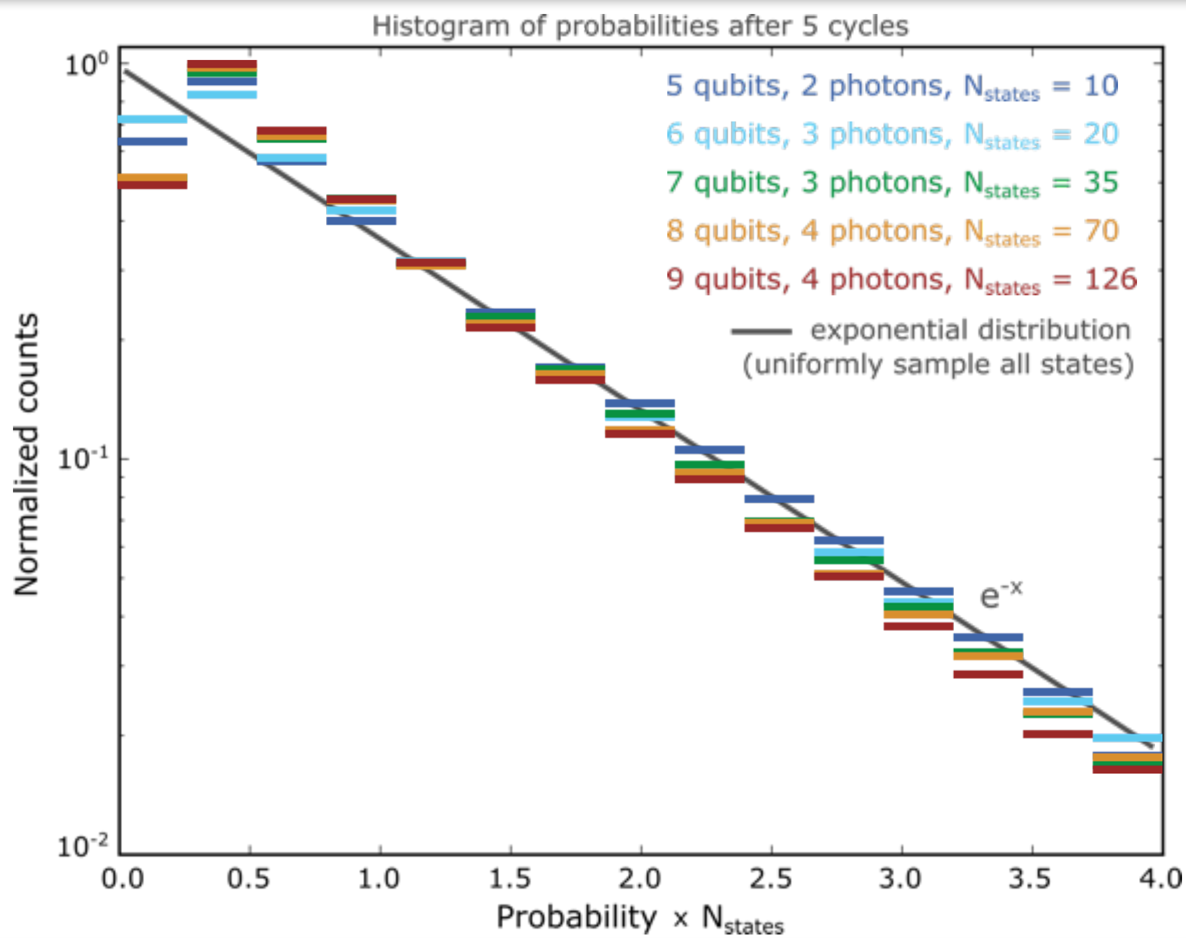
Histogram of measured probabilities



exponential growth of

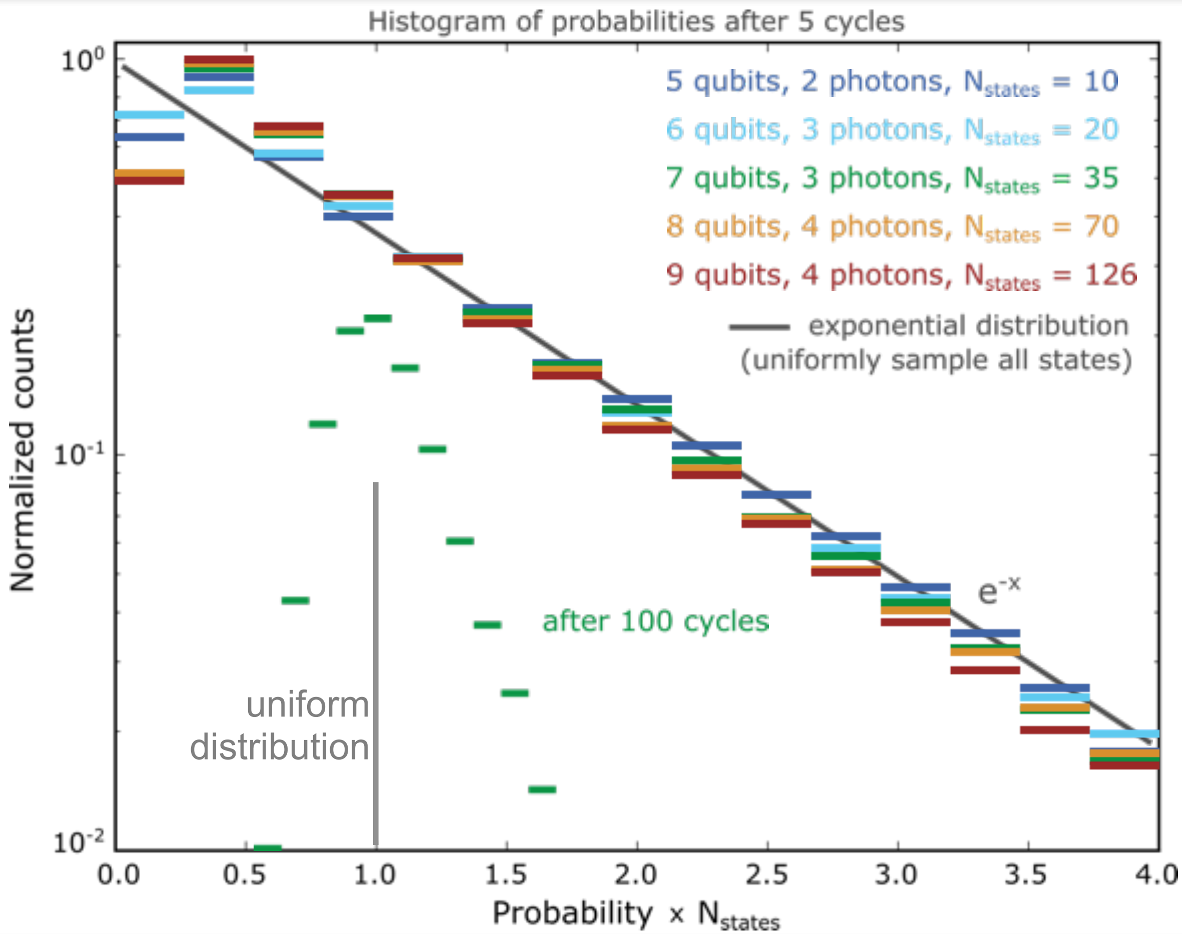
$N_{\text{states}} \approx 2^n / \sqrt{n}$

Histogram of measured probabilities



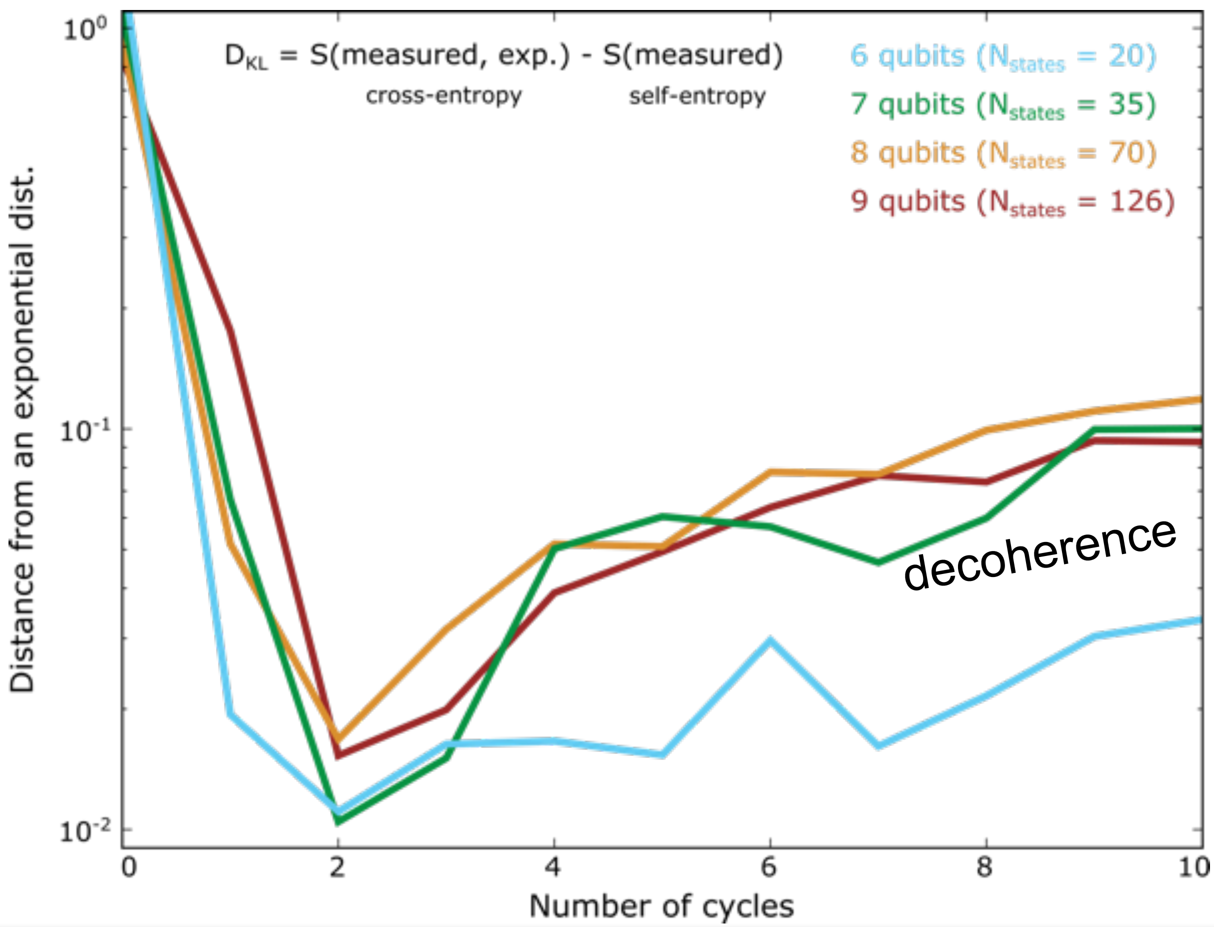
Collapses to exponential distribution

Histogram of measured probabilities



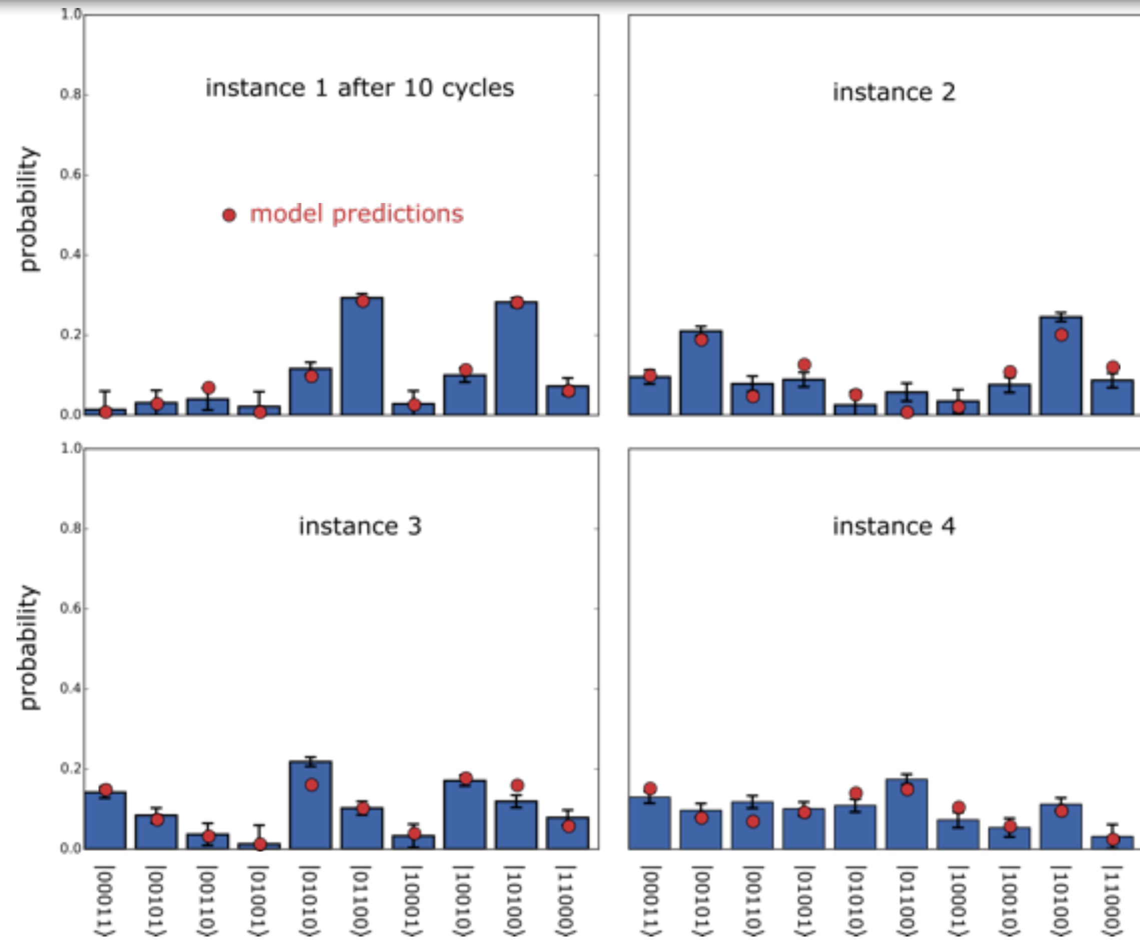
decoherence kills
qubit speckle

Fast growth of entanglement



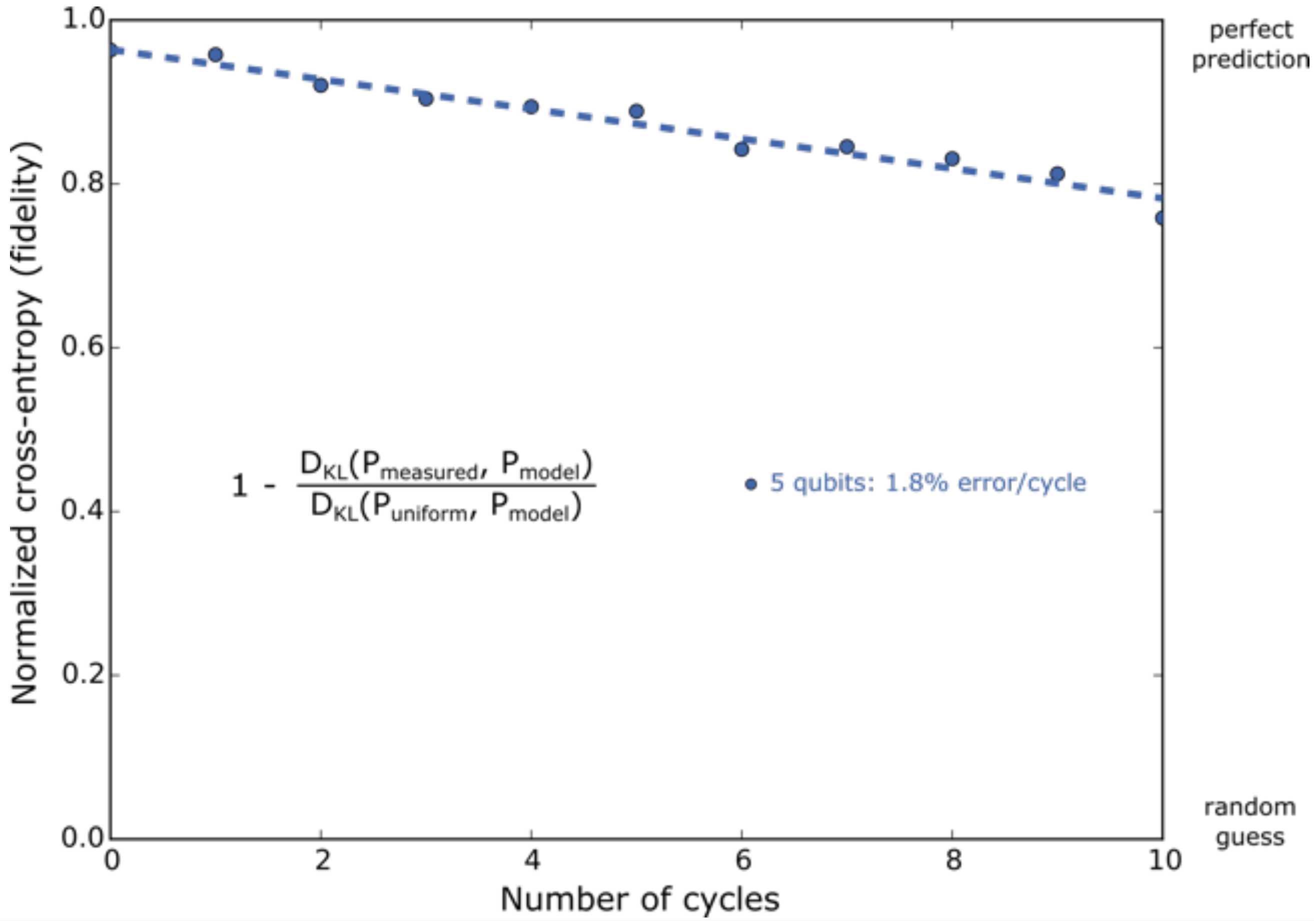
9-qubit interaction:
full entanglement
in 2 cycles (90 ns)

Compare probabilities of experiment and theory



speckle pattern
matches theory

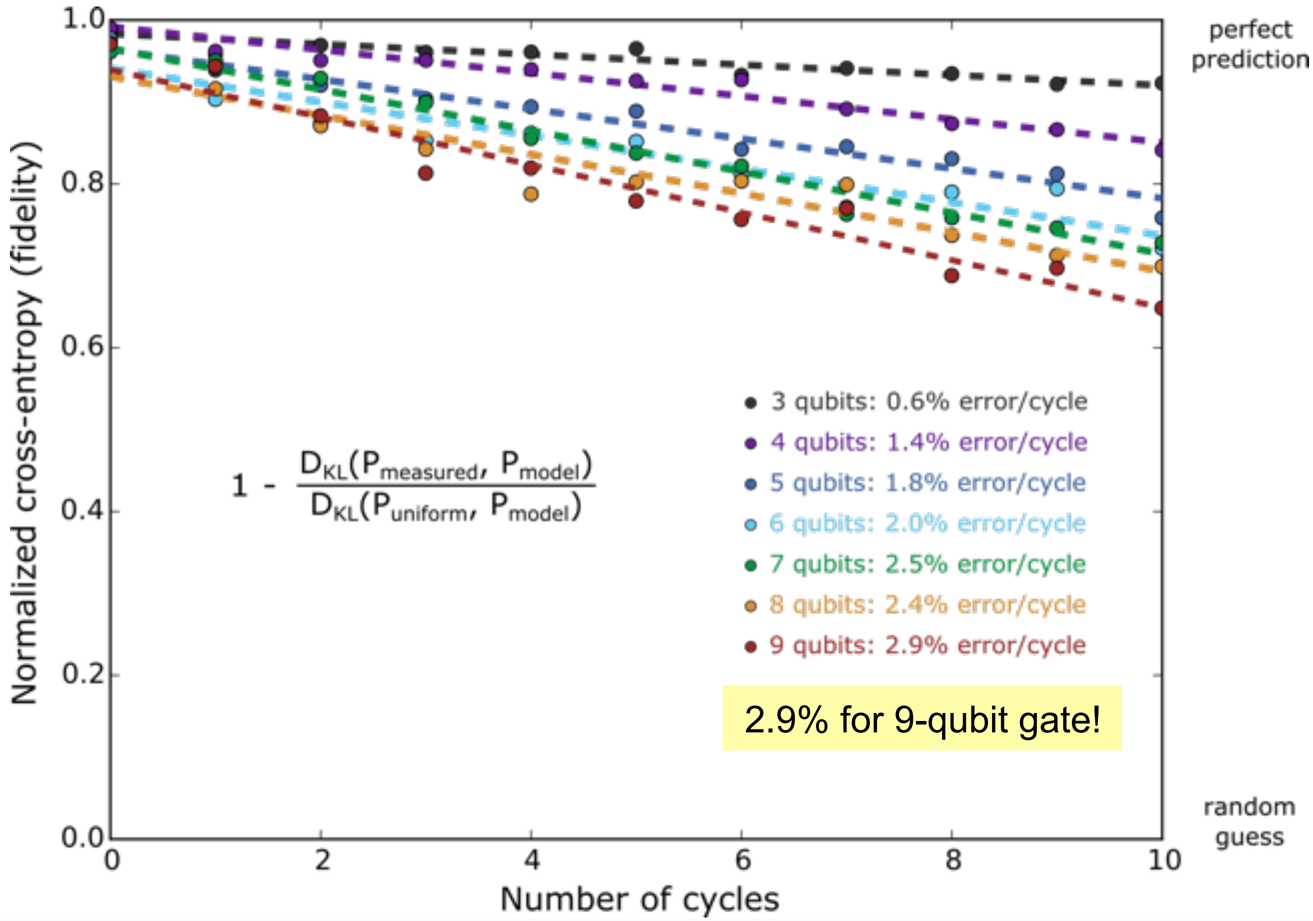
Measuring fidelity



(T1 decay excluded)

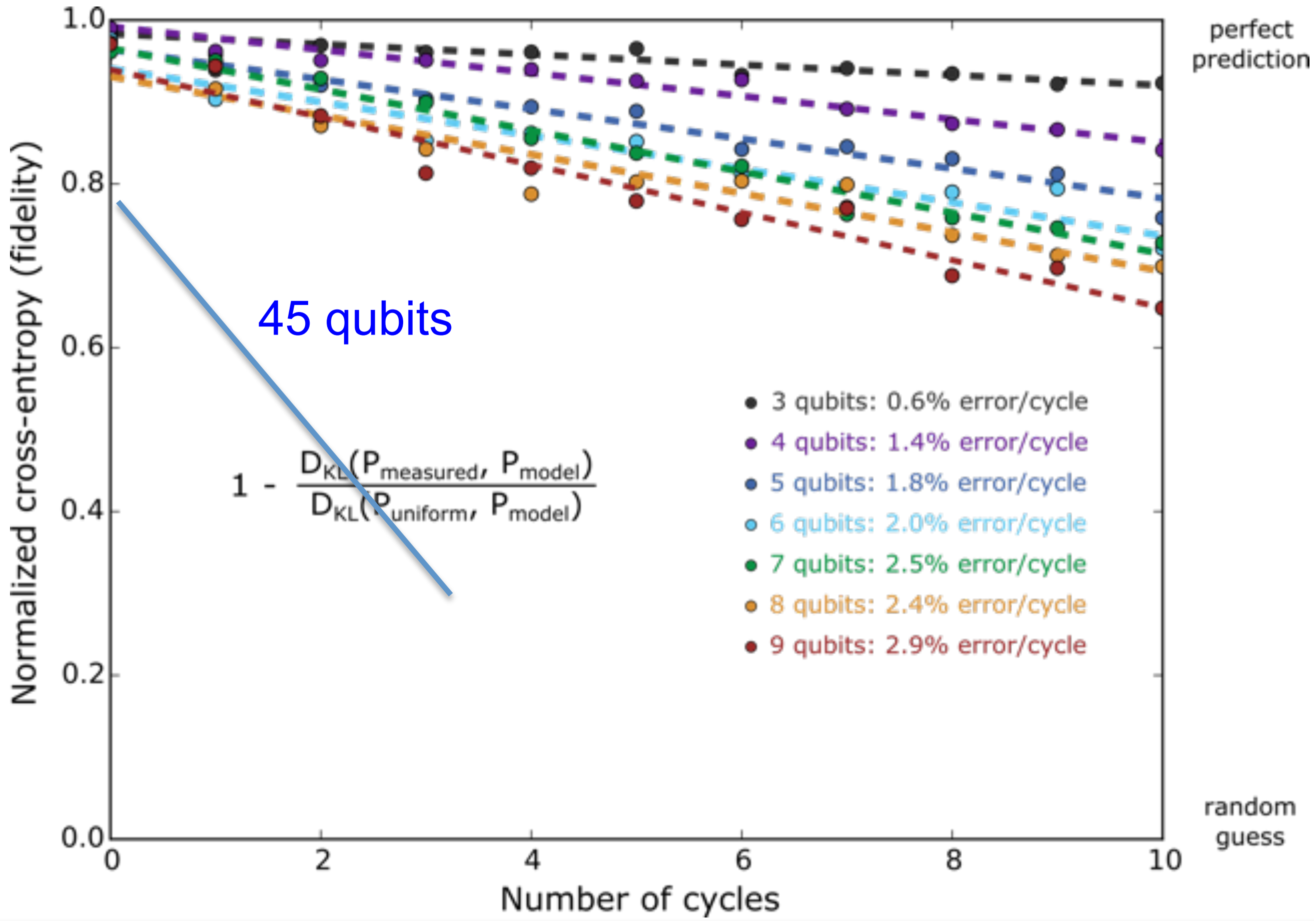
cross entropy
= fidelity

Measuring fidelity



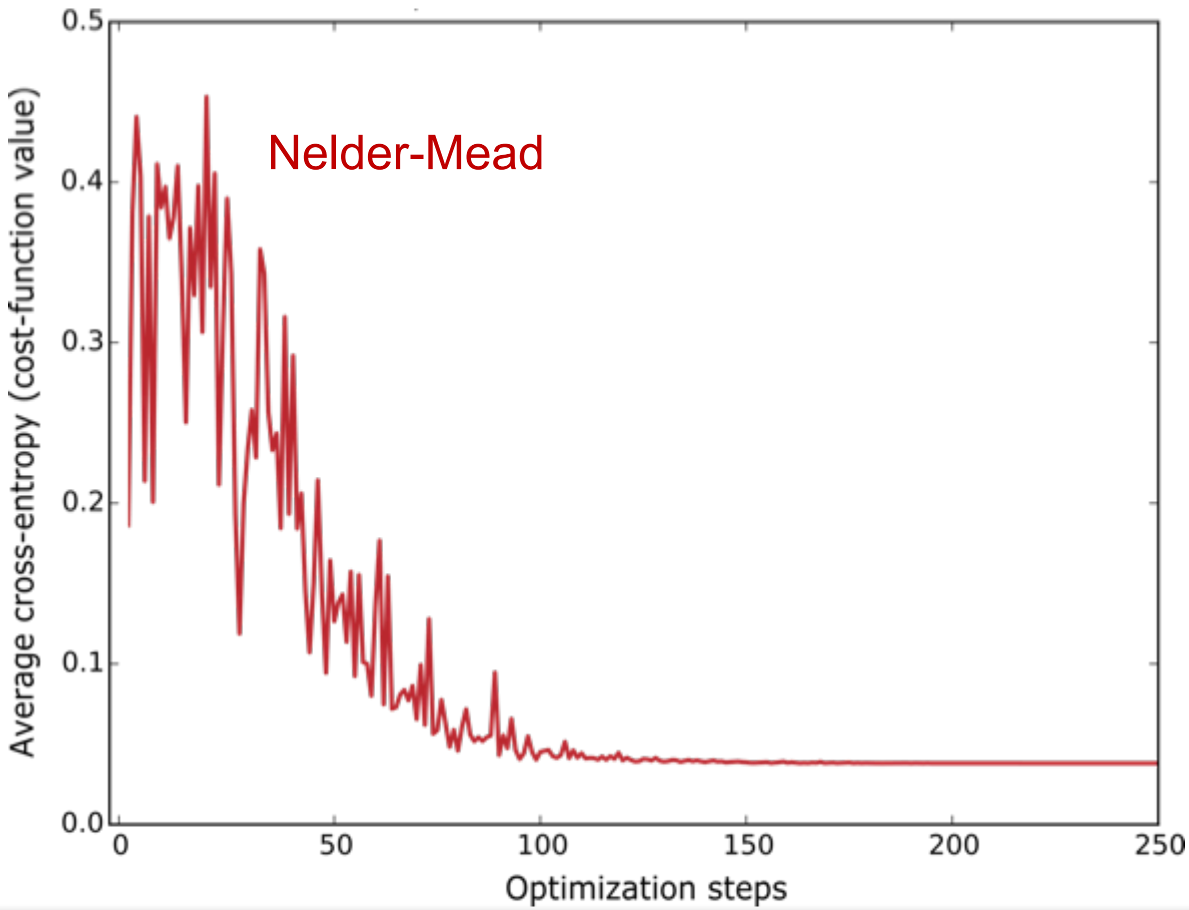
0.3% error
per gate & cycle

Scaled fidelity for 45 qubits



supremacy possible with margin

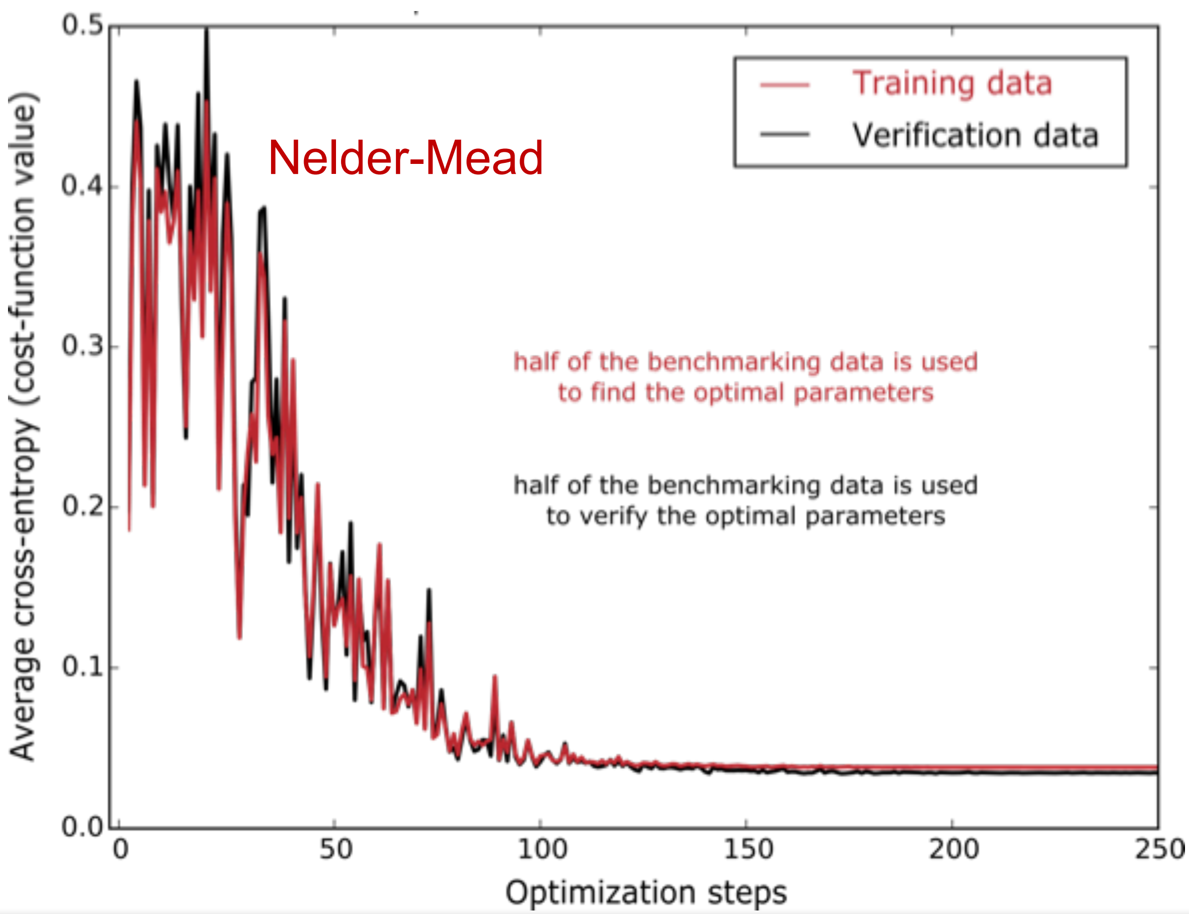
Learning a better control model



Tuneup flux offsets
(as drifty)

significant
improvement

Learning a better control model

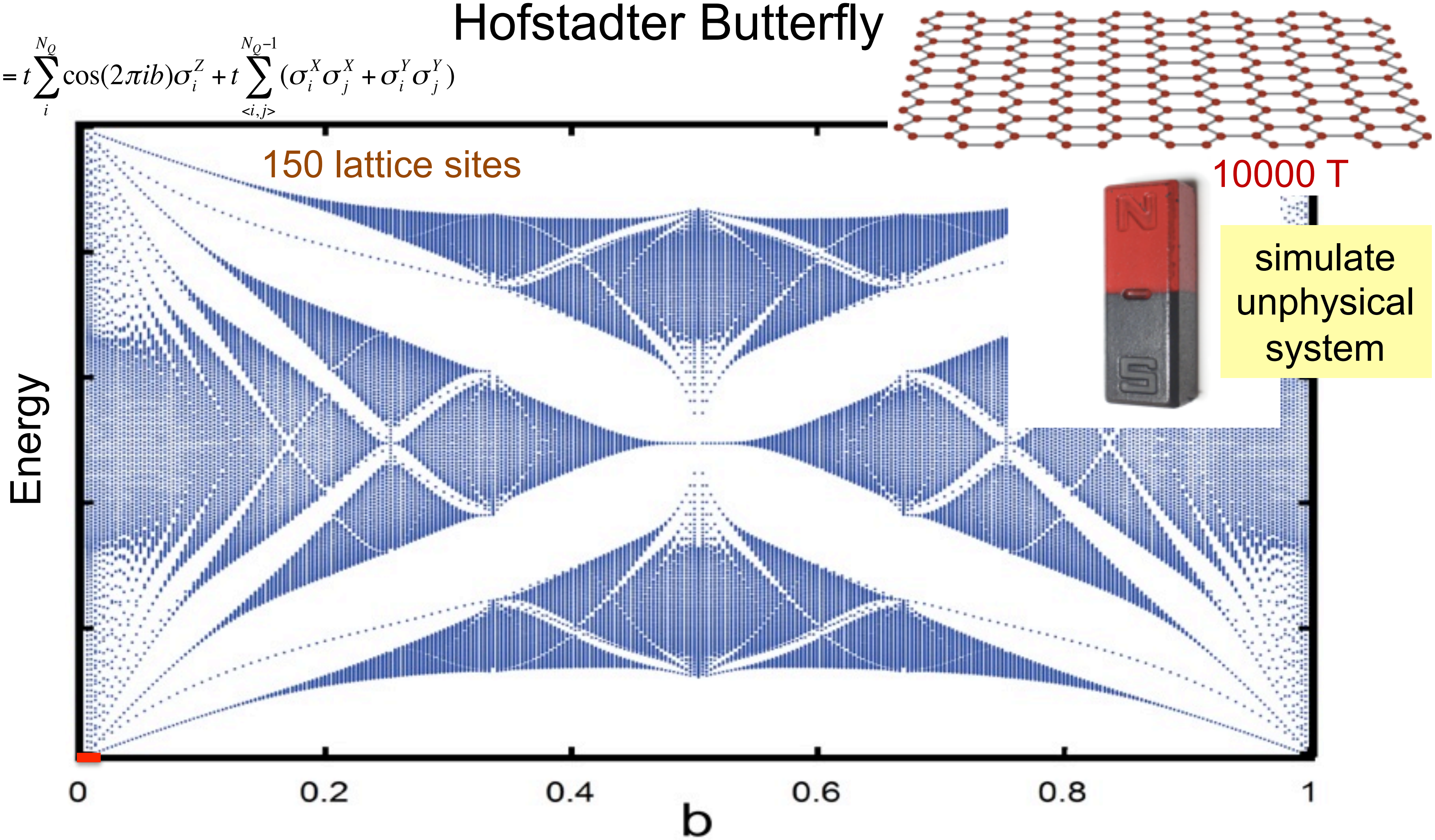


Tuneup flux offsets
(as drifty)

training
verified

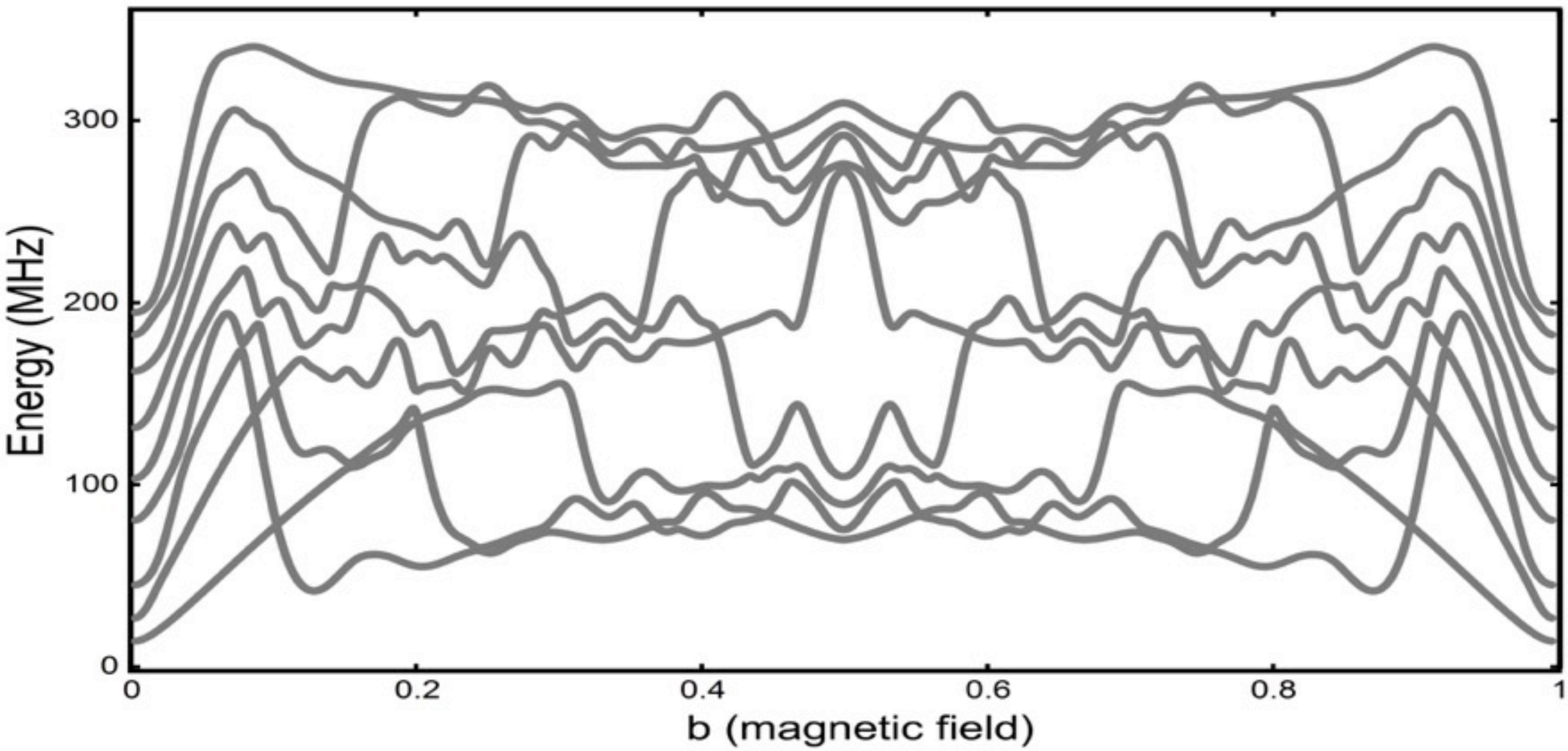
Hofstadter Butterfly

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



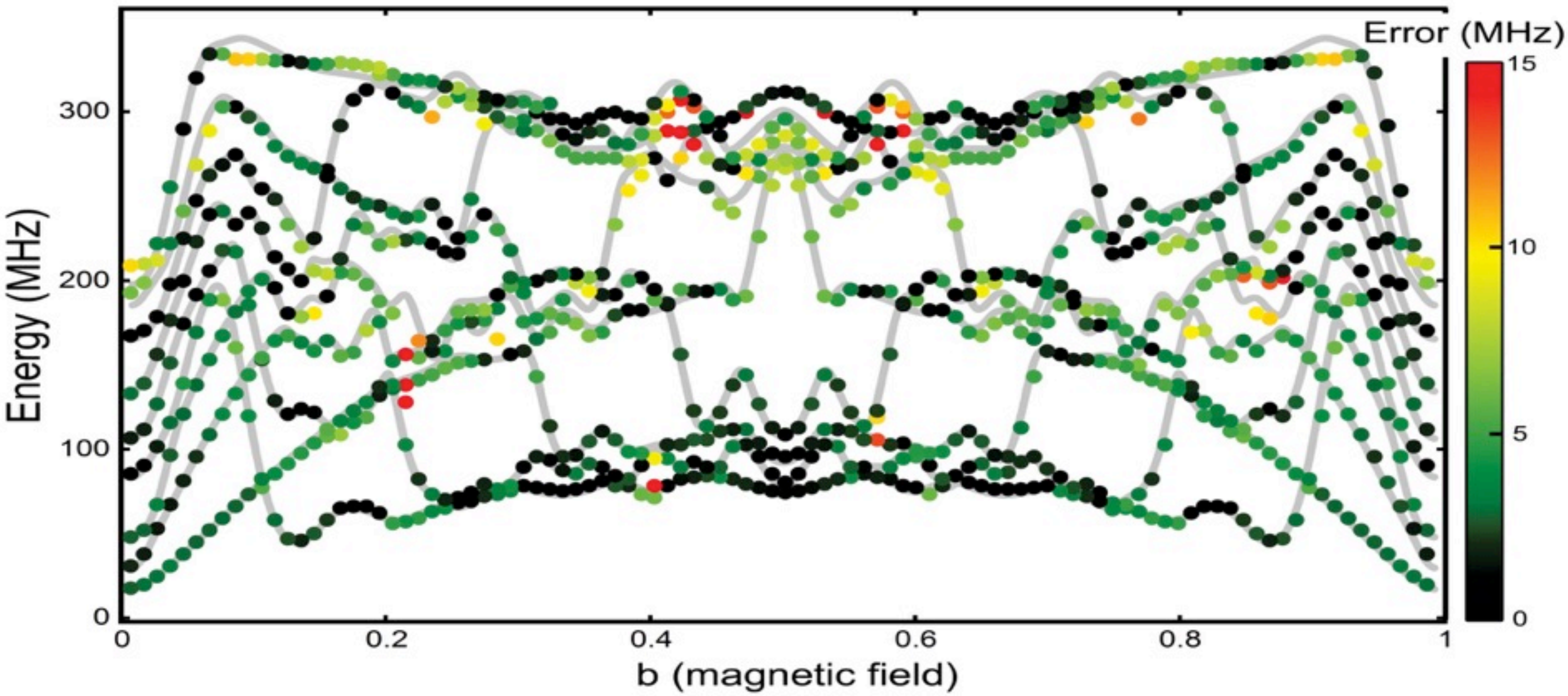
9 Qubits: theory

fractal nature gives complex spectrum

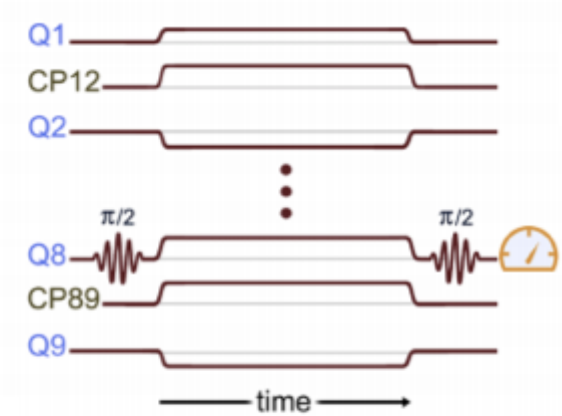


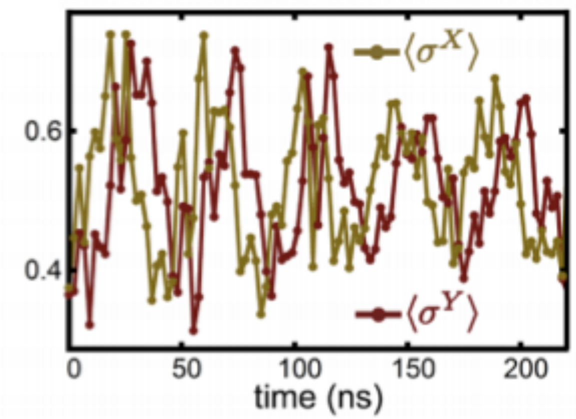
9 Qubits: theory + experiment

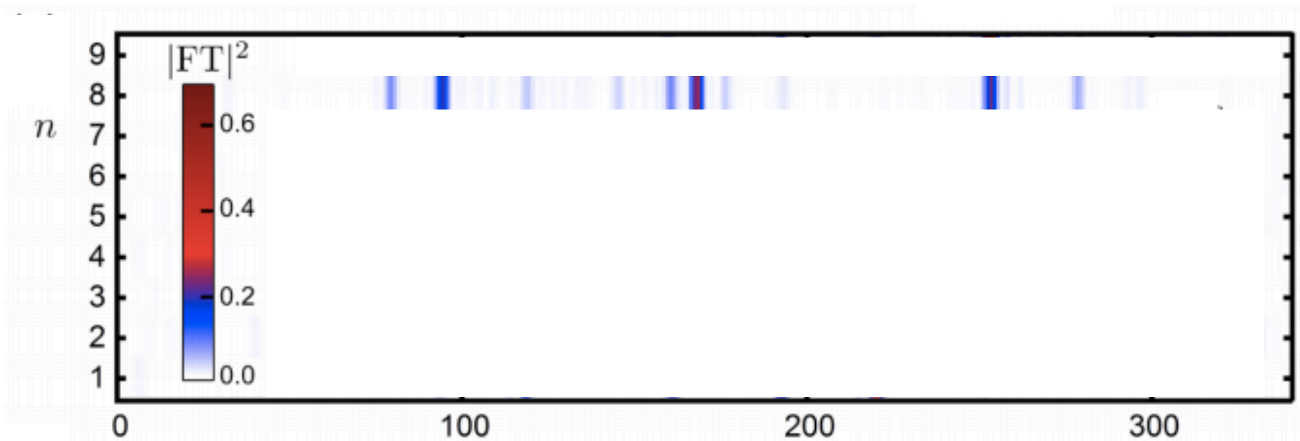
extract complex
physically useful information



1-Excitation Spectroscopy

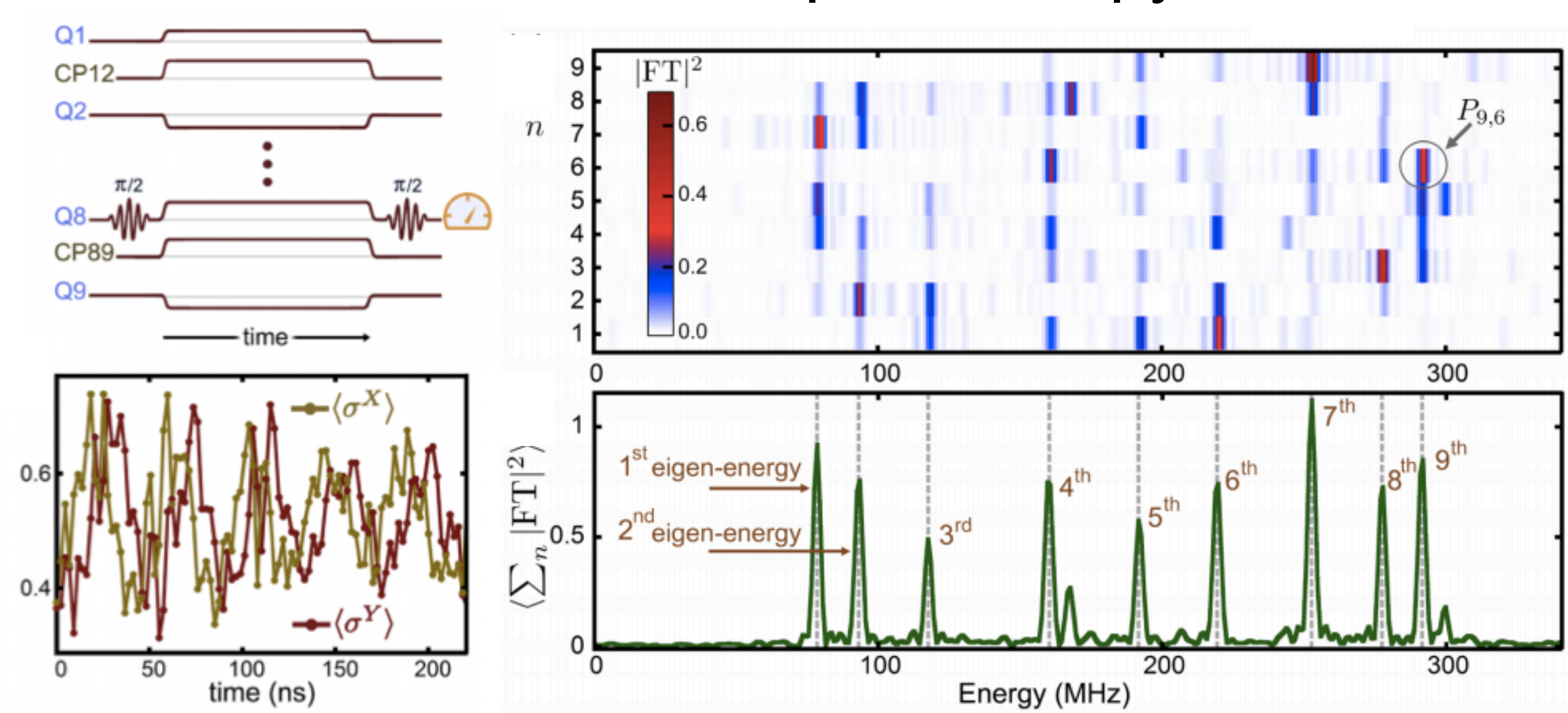






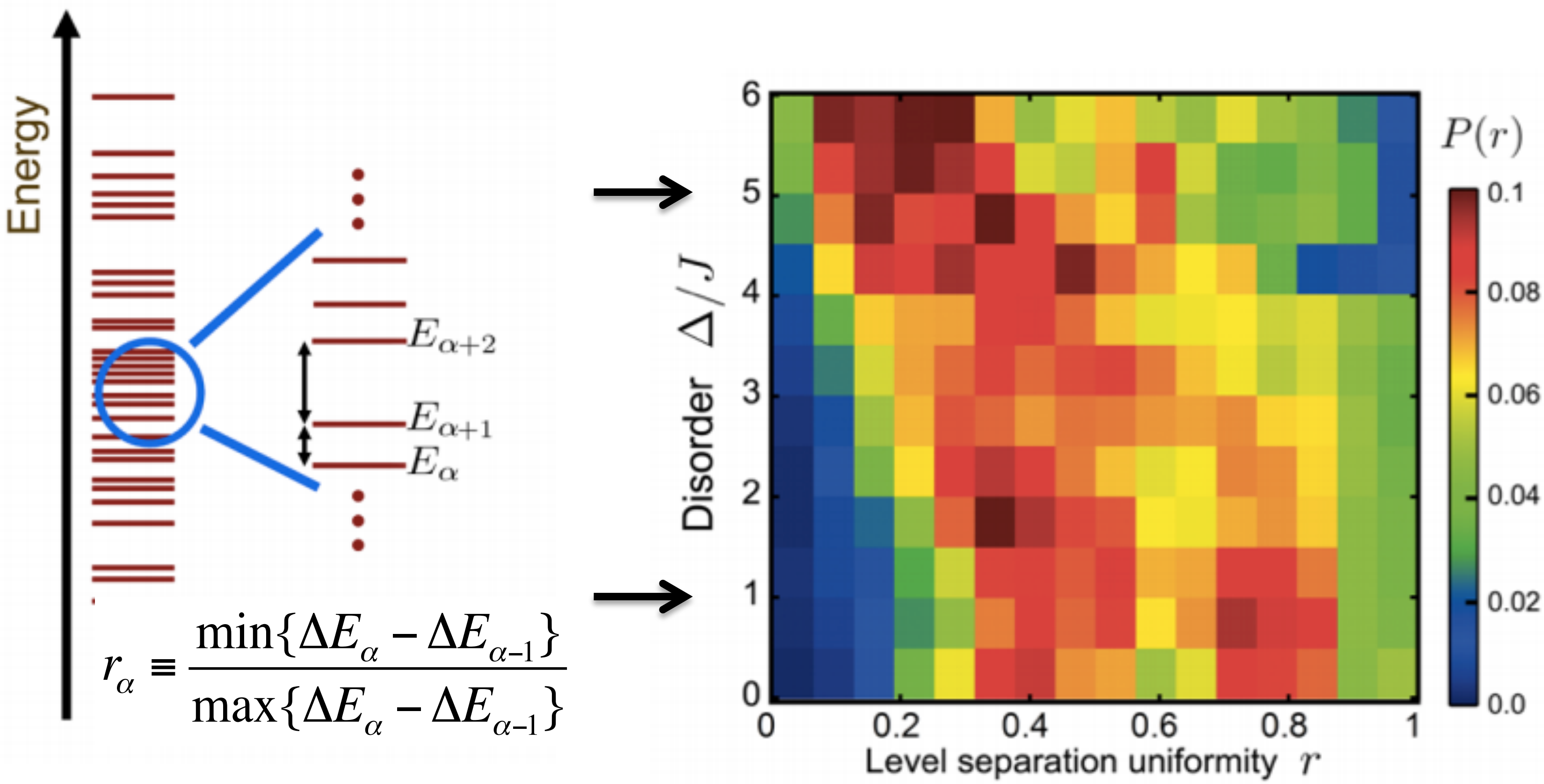
$$\chi_1(n) = \langle \sigma_n^X \rangle + i \langle \sigma_n^Y \rangle$$

1-Excitation Spectroscopy



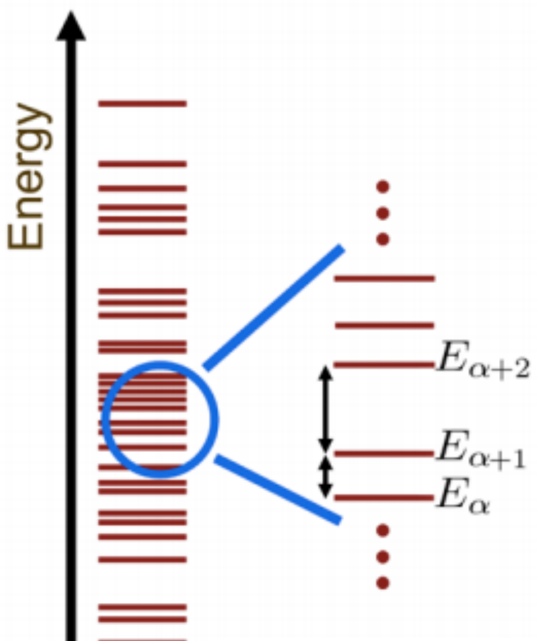
$$\chi_1(n) = \langle \sigma_n^X \rangle + i \langle \sigma_n^Y \rangle$$

Energy-Level Statistics



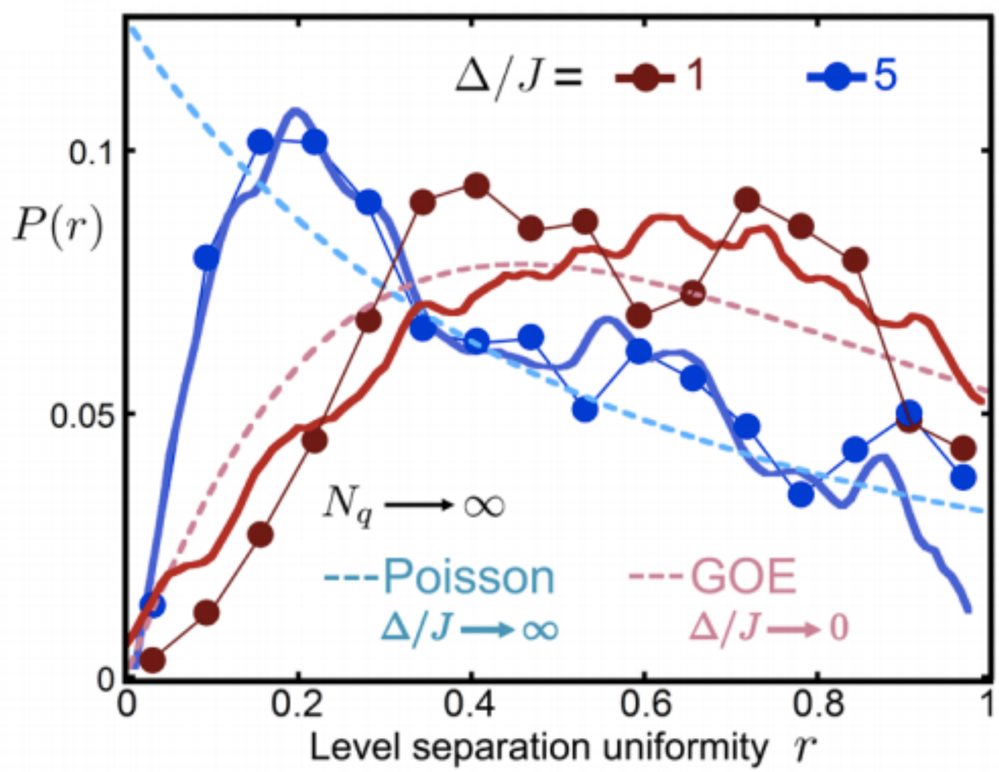
$$r_\alpha \equiv \frac{\min\{\Delta E_\alpha - \Delta E_{\alpha-1}\}}{\max\{\Delta E_\alpha - \Delta E_{\alpha-1}\}}$$

Energy-Level Statistics



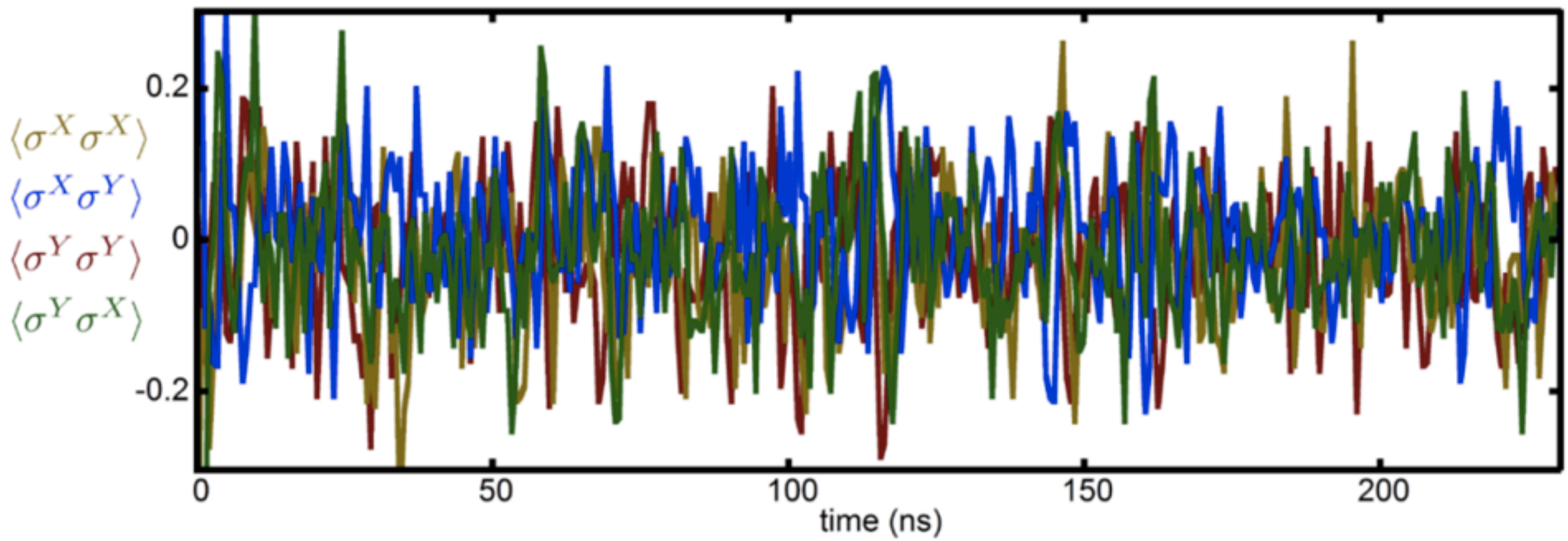
$$r_\alpha \equiv \frac{\min\{\Delta E_\alpha - \Delta E_{\alpha-1}\}}{\max\{\Delta E_\alpha - \Delta E_{\alpha-1}\}}$$

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

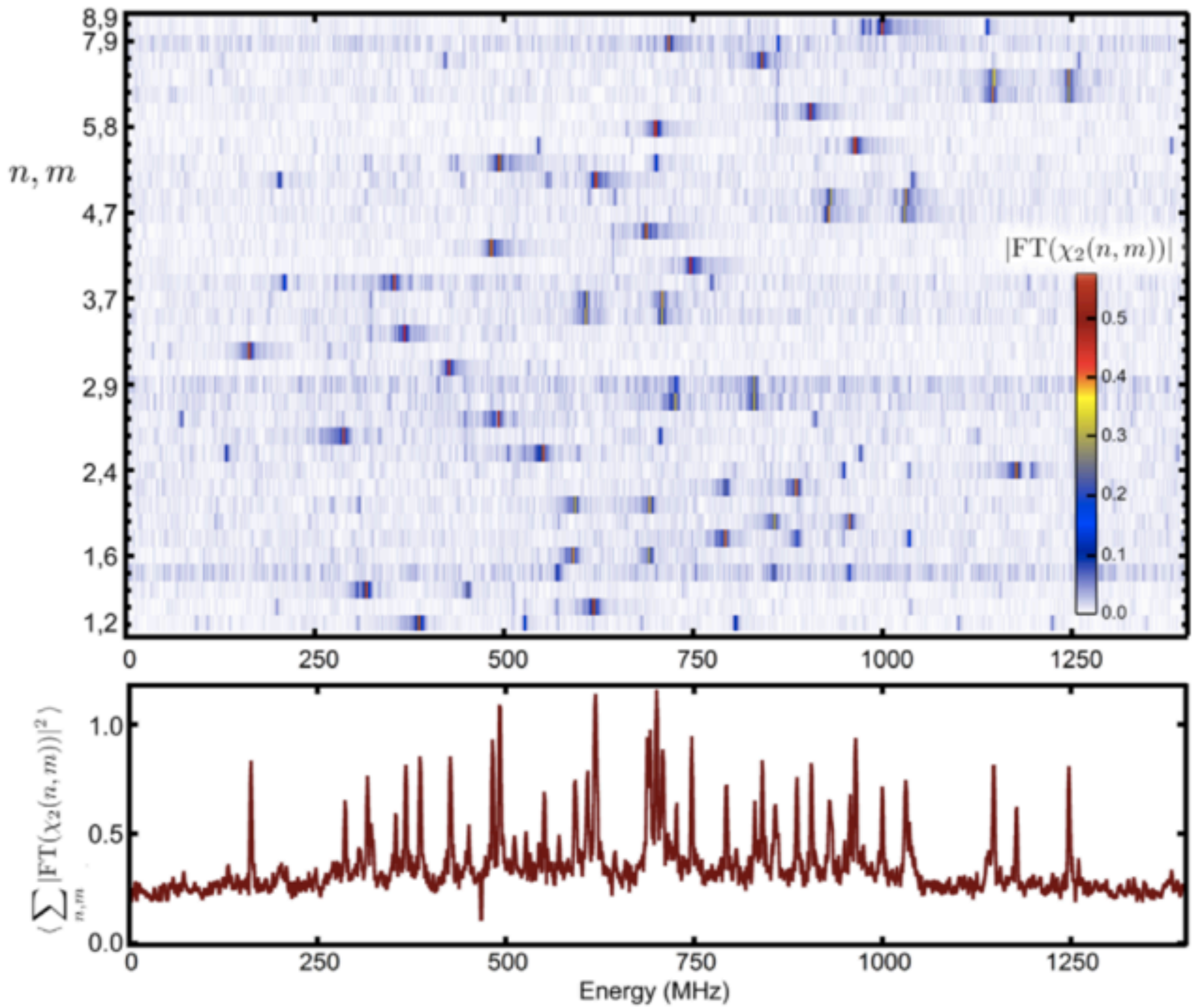


2-Excitation Spectroscopy

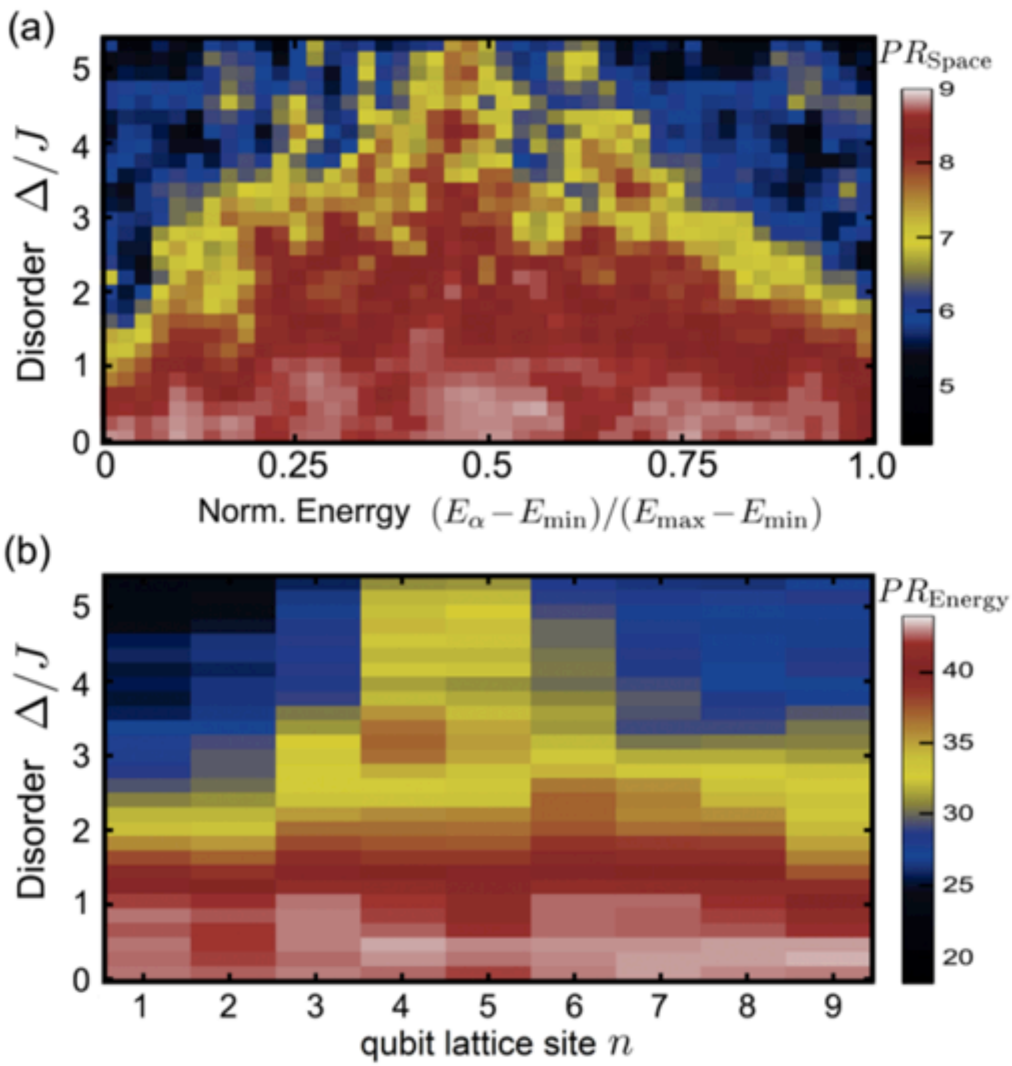
$$\chi_2(n,m) \equiv \langle \sigma_n^X \sigma_m^X \rangle - \langle \sigma_n^Y \sigma_m^Y \rangle + i\langle \sigma_n^X \sigma_m^Y \rangle + i\langle \sigma_n^Y \sigma_m^X \rangle$$



2 Excitation Spectroscopy



Now 45 energy levels



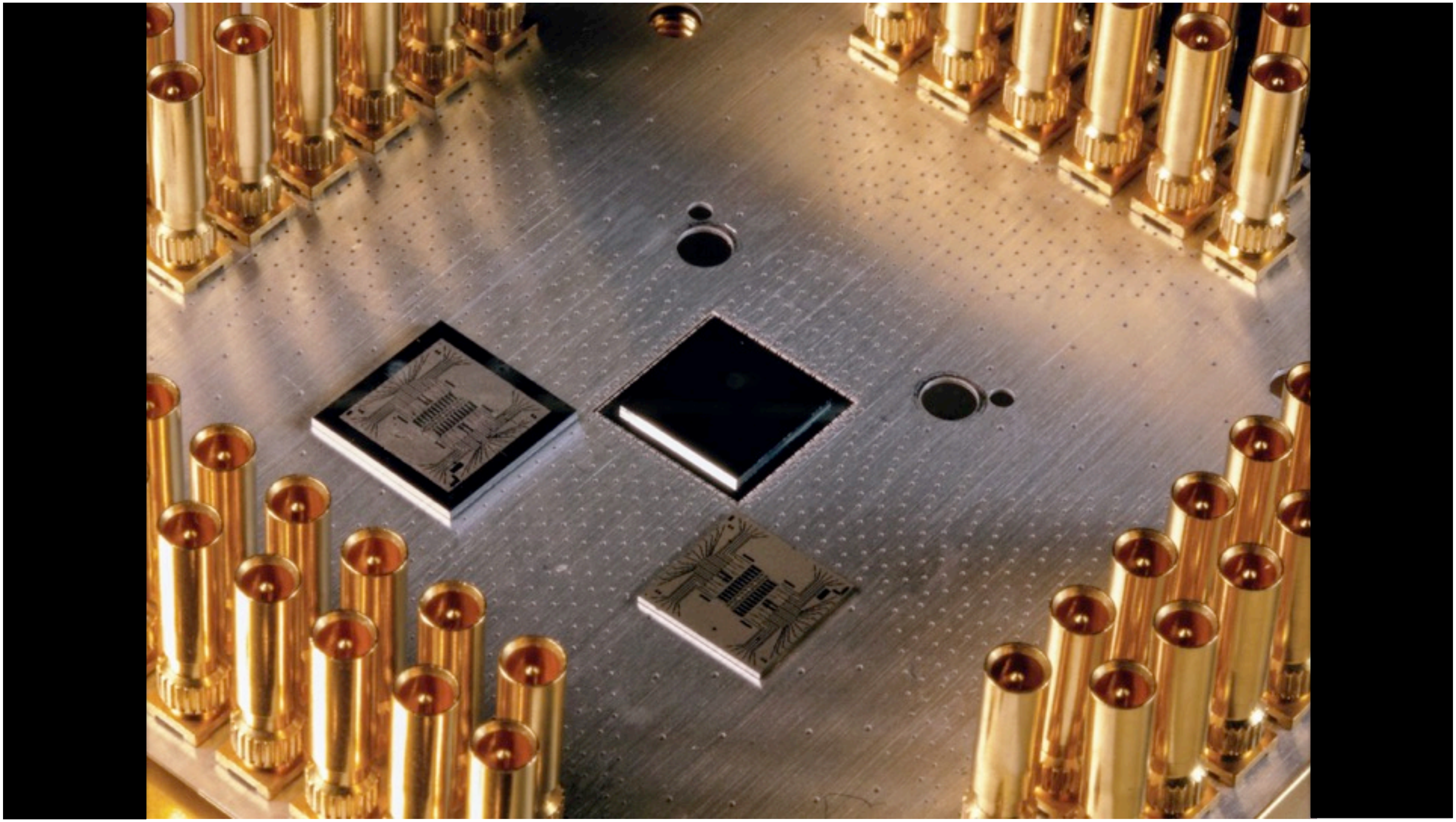
Participation Ratio & Mobility Edges

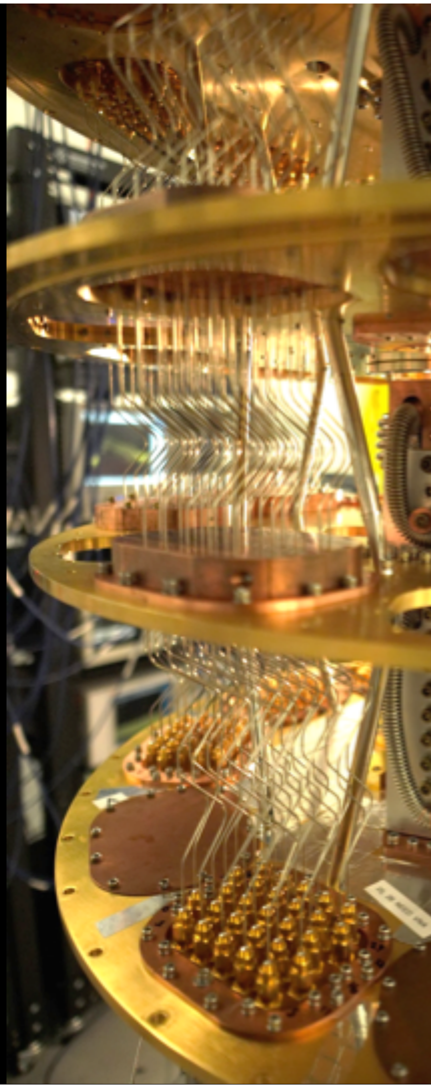
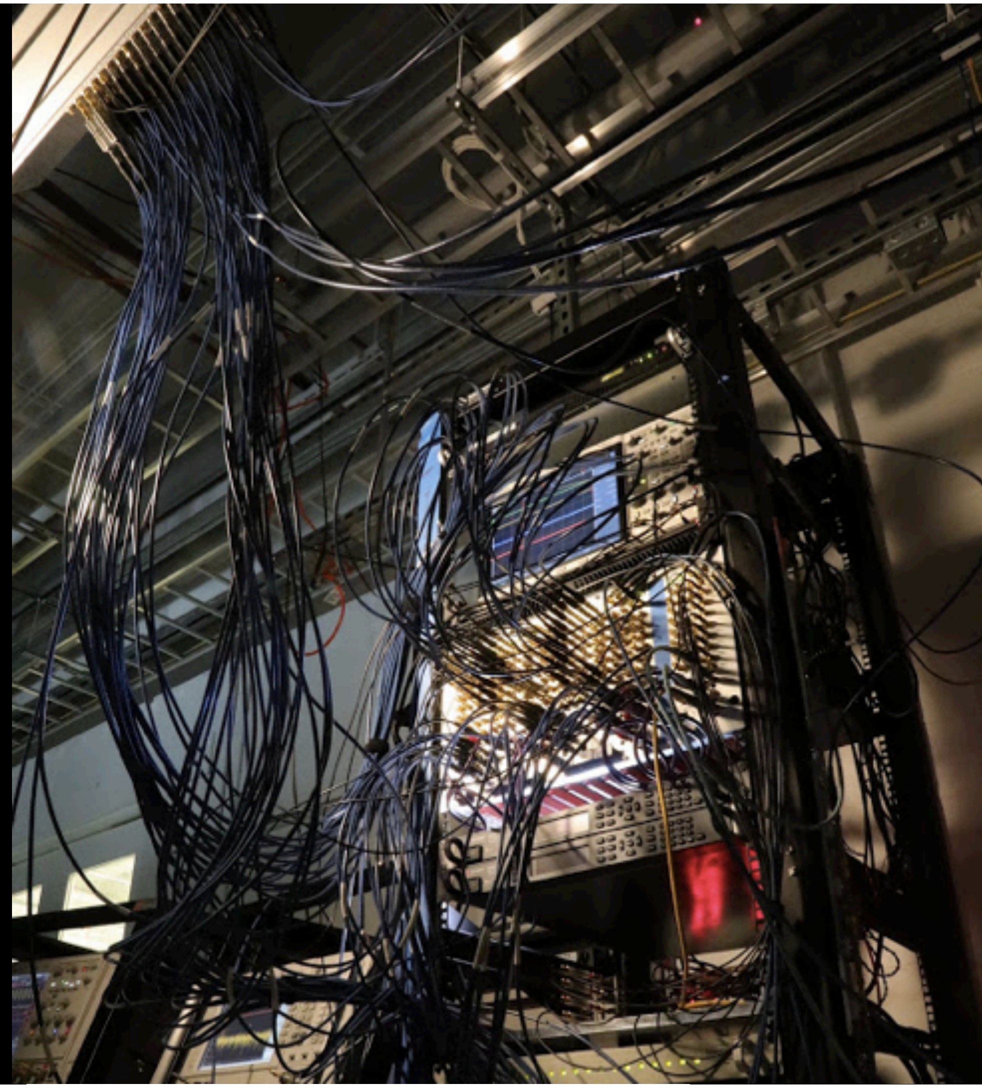
2nd moment of probabilities:

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

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

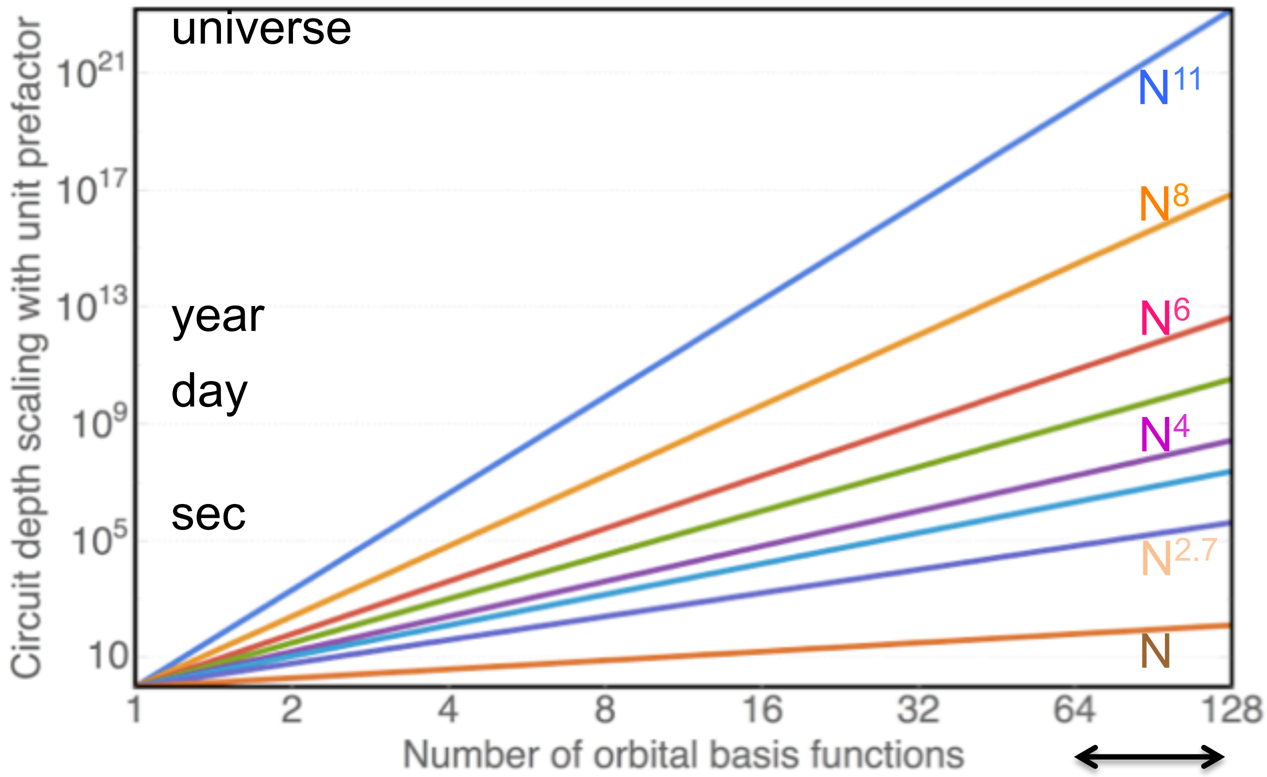
Disorder causes eigenstates to move to center of energy band and lattice



Huge Progress in Algorithms (Quantum Chemistry)

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



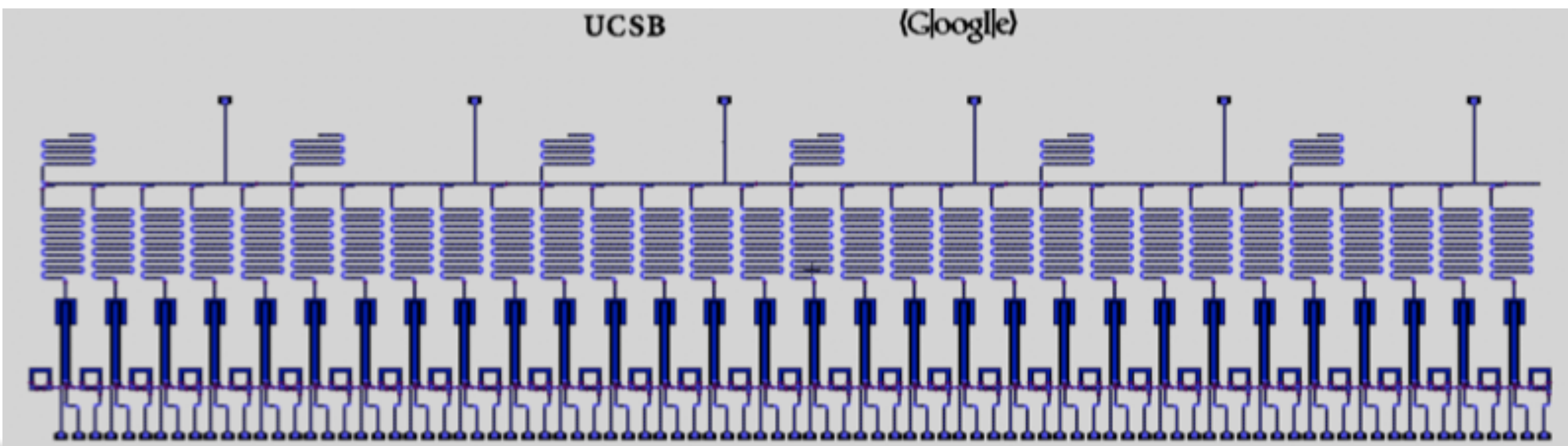
Exact: 100 logical qubits (error corrected)

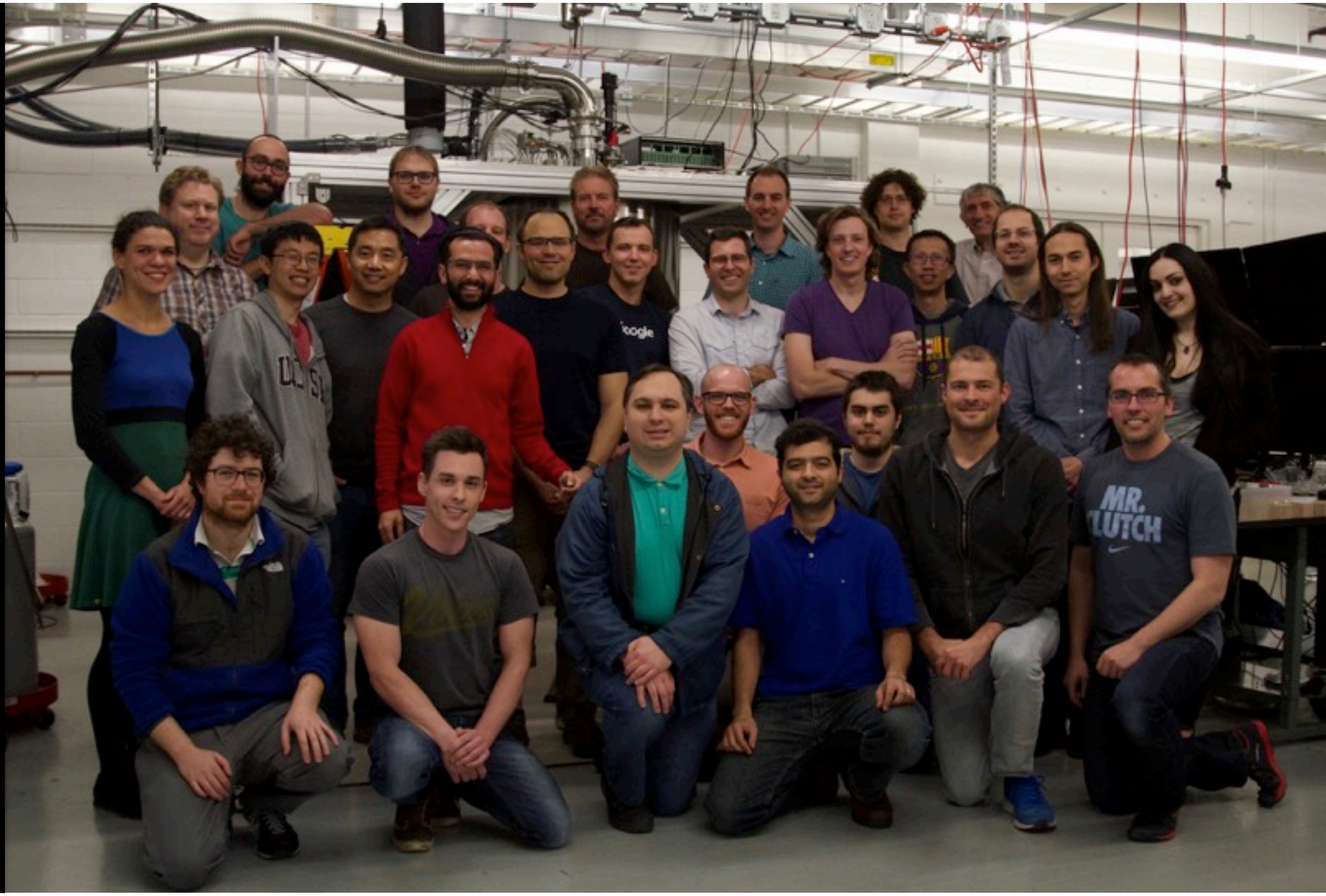
Approximate: 100 physical qubits (?)

Summary & Outlook of Quantum Supremacy

Validation:
- Exponential computation space (now ~500)
- Entanglement with qubit speckle
- Fidelity with cross entropy
- Tune-up

Programmable quantum simulator
- Complex algorithm
- New spectroscopy tool, localization physics




MR.
LUTCH

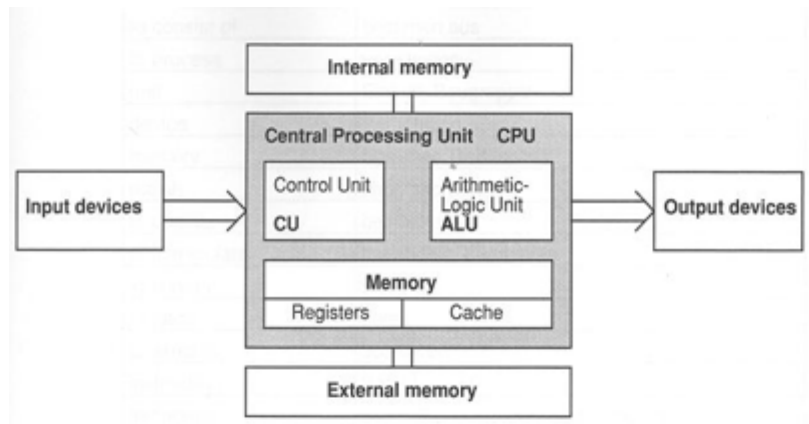
Building a Real Quantum Simulator

- 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