QC WARE

Q2B

2017

Quantum Supremacy: Checking a Quantum Computer with a Classical Supercomputer

John Martinis, UCSB & Google

The Quantum Space Race

Hardware Challenges:
- Quantity
- Quality

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

Bits and Qubits

<u>Classical bit:</u>

0 or 1

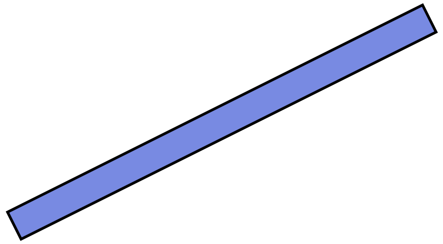
Coin on table

Digital: self-correcting

<u>Quantum bit:</u>

$$\psi = \cos\theta |0\rangle + \sin\theta\, e^{i\phi} |1\rangle$$

Coin in space



Analog: sensitive to small errors

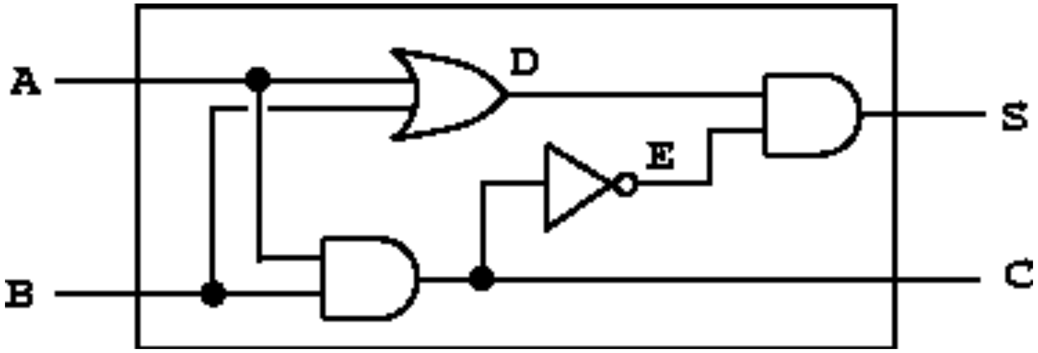
Any Logic Built from Universal Gates

<u>Classical circuit:</u>

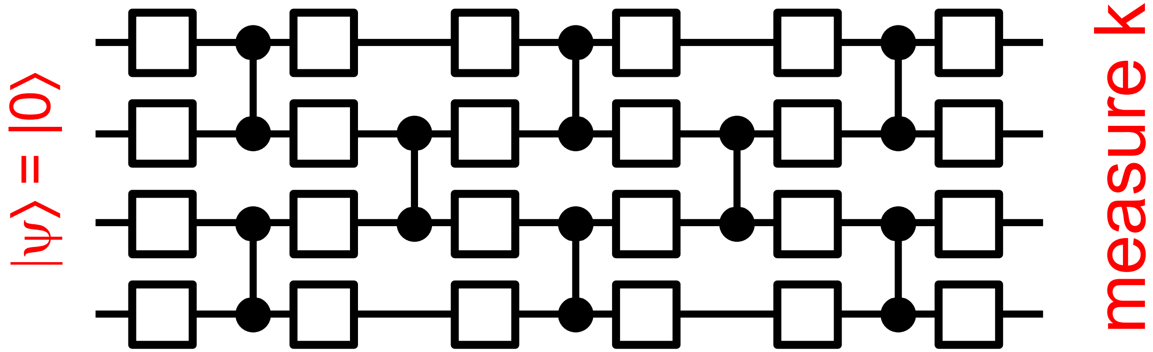
1 bit NOT
2 bit AND
Wiring fan-out

<u>Quantum circuit:</u>

1 qubit rotation
2 qubit CNOT
-No copy-



Space (layout) →

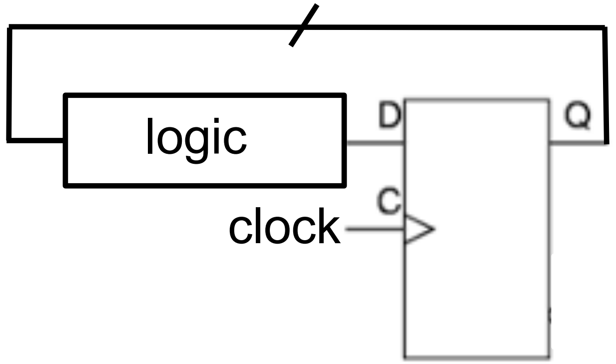


Time (sequence) →

Full Digital (Clocked) Logic

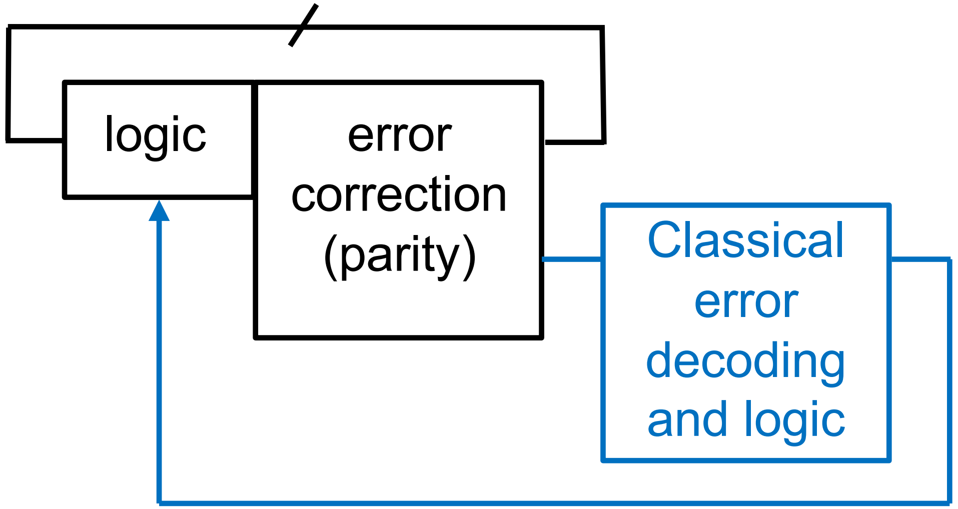
<u>Classical system:</u>

D flip-flop aligns timing to clock



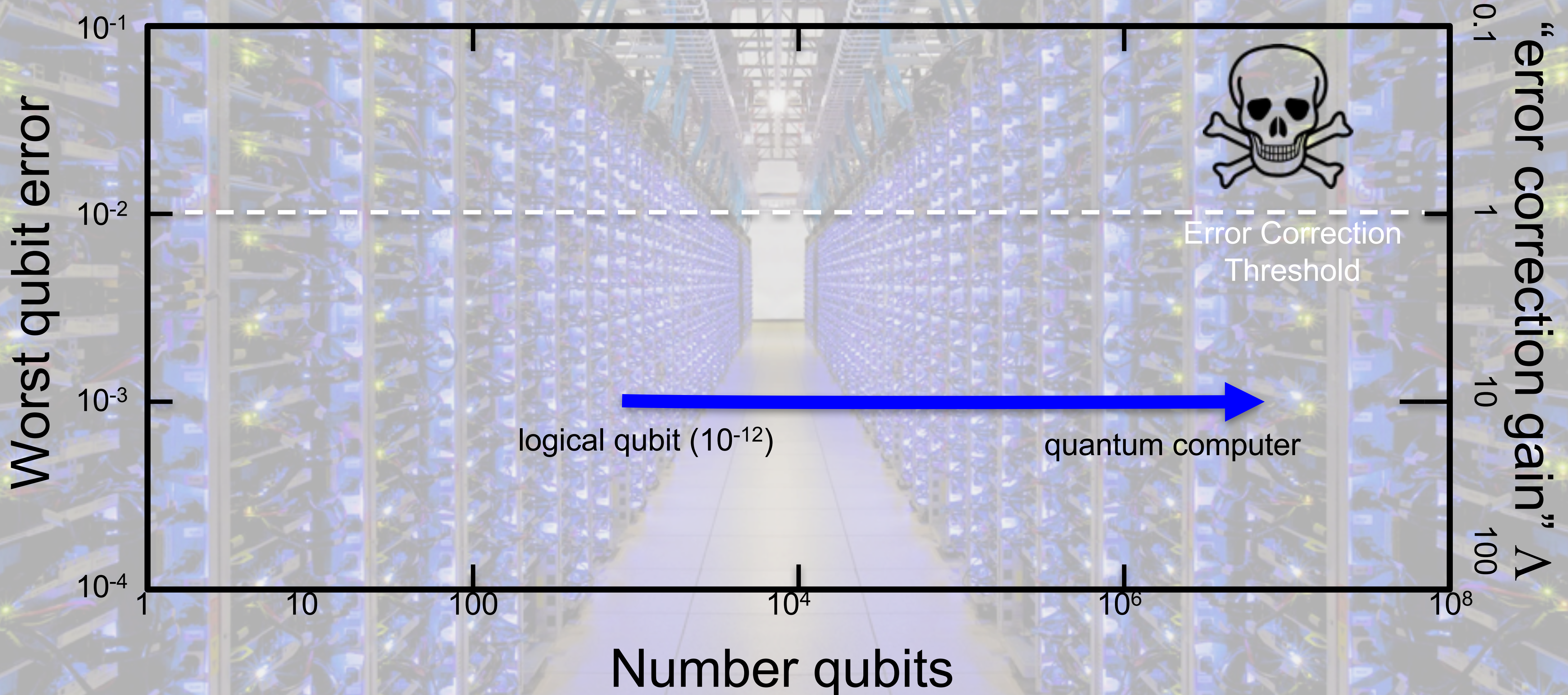
<u>Quantum system:</u>

Error correction aligns amplitude and phase each round, makes “quantum flip-flop”

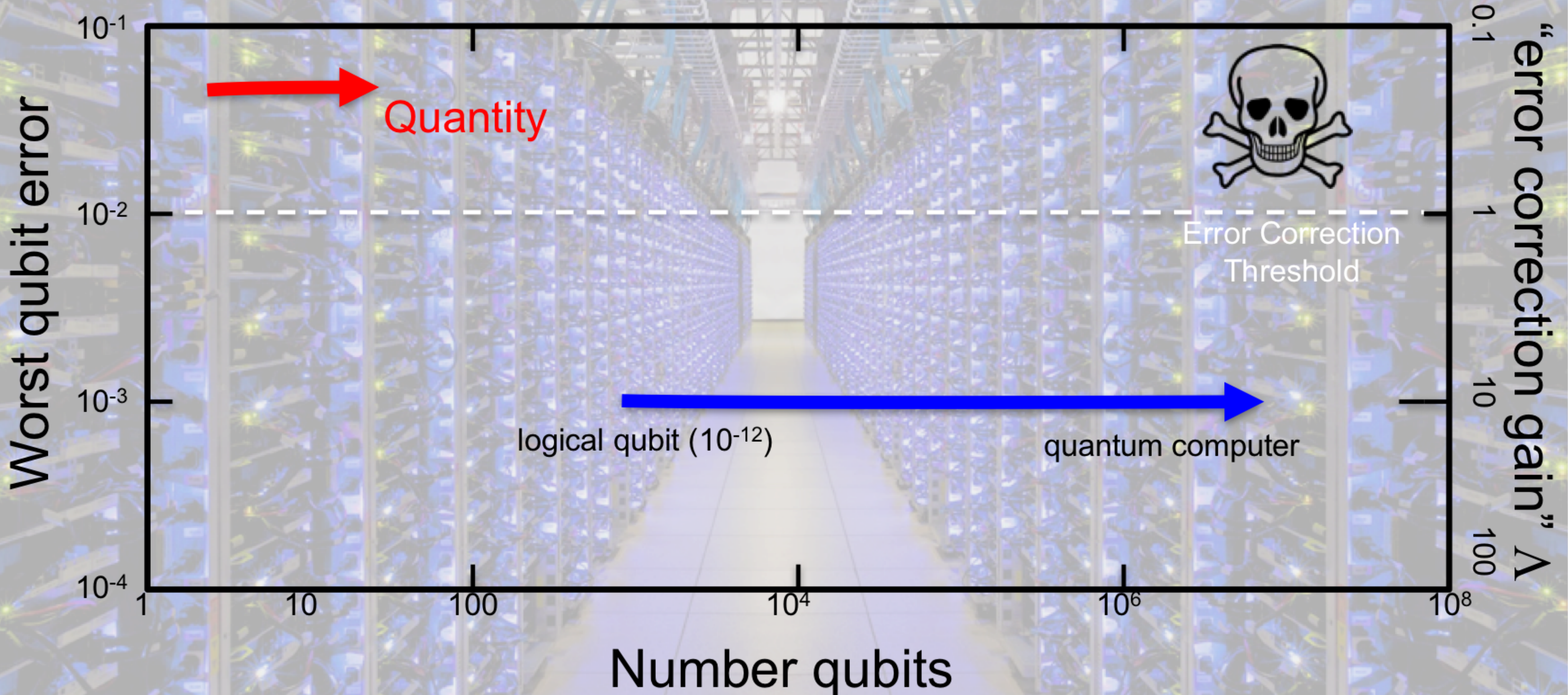


10^{-12} errors: 1000 qubits + 0.1% errors

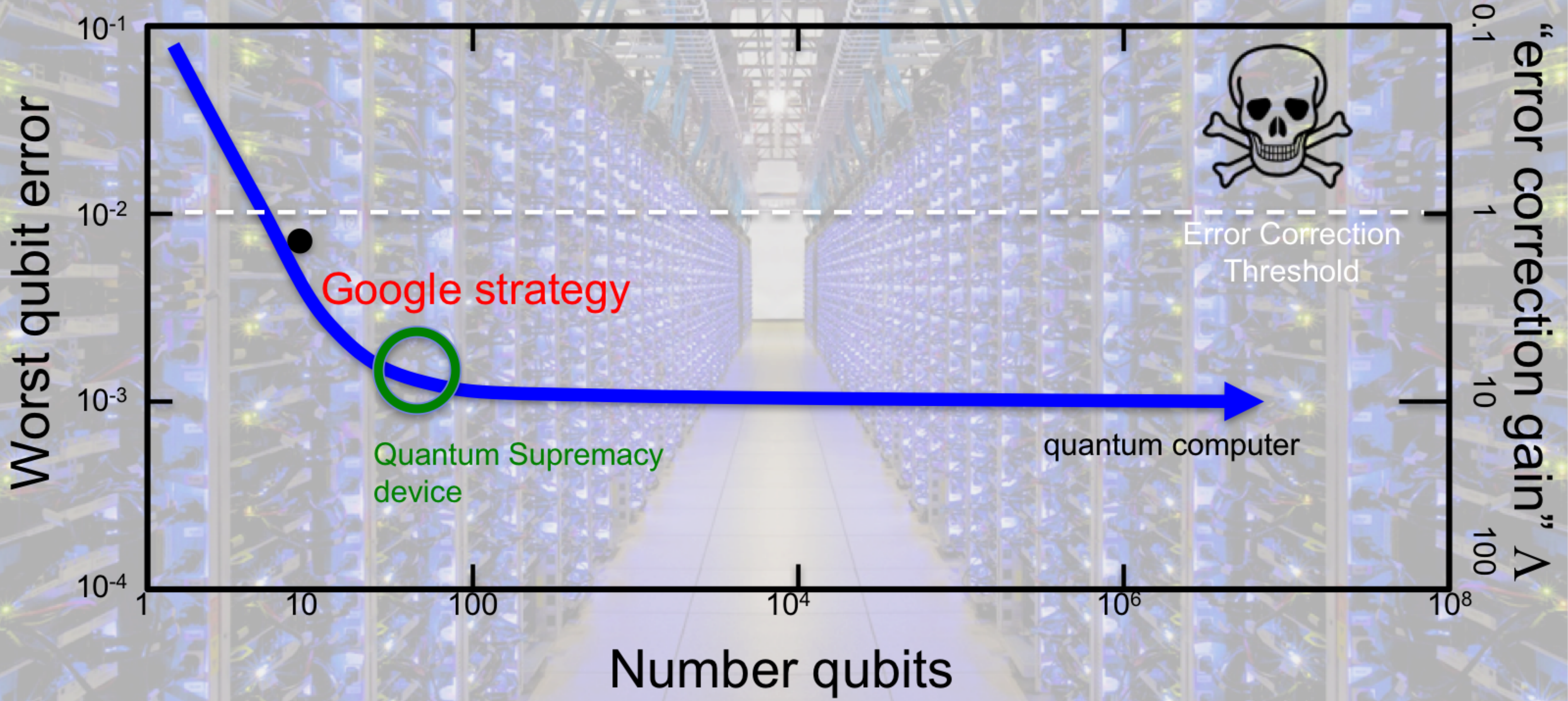
Systems: Quantity and Quality



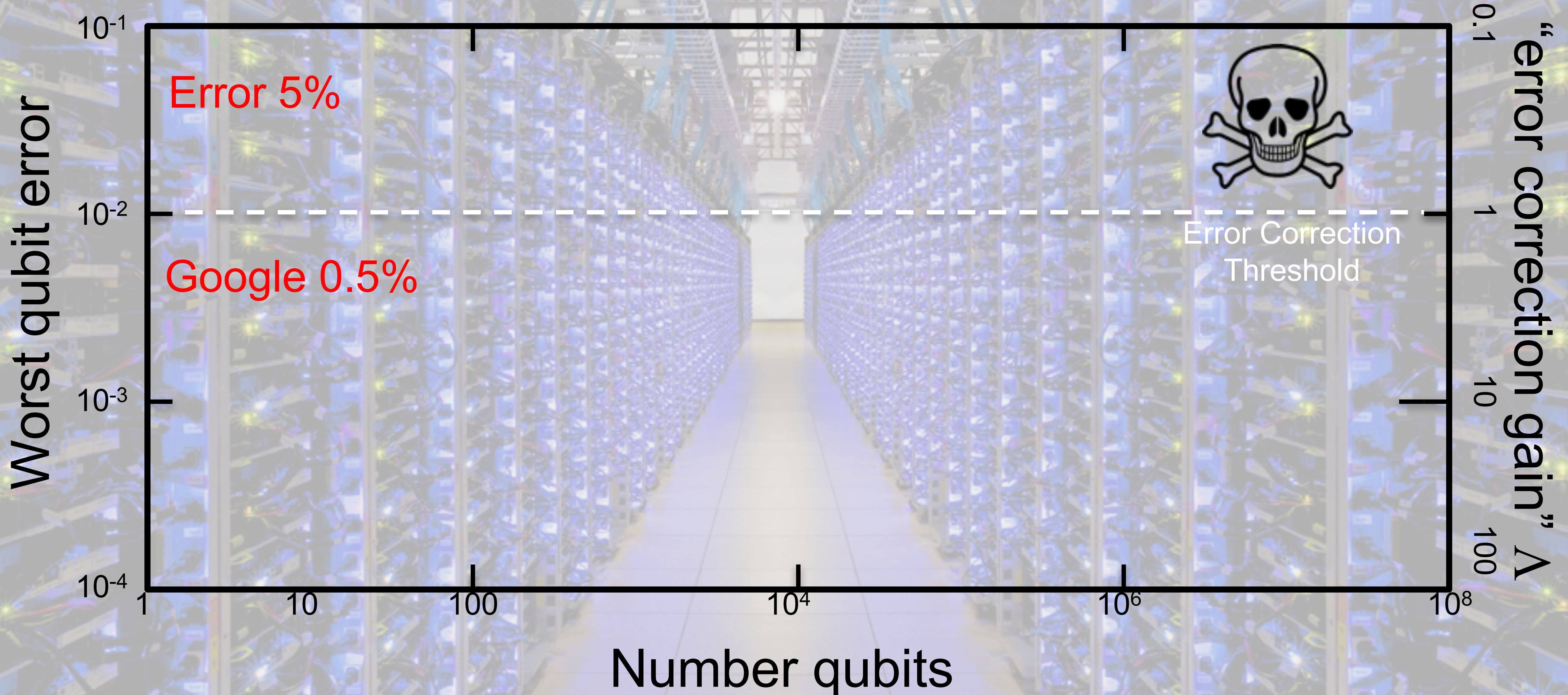
Systems: Quantity and Quality



Systems: Quantity and Quality

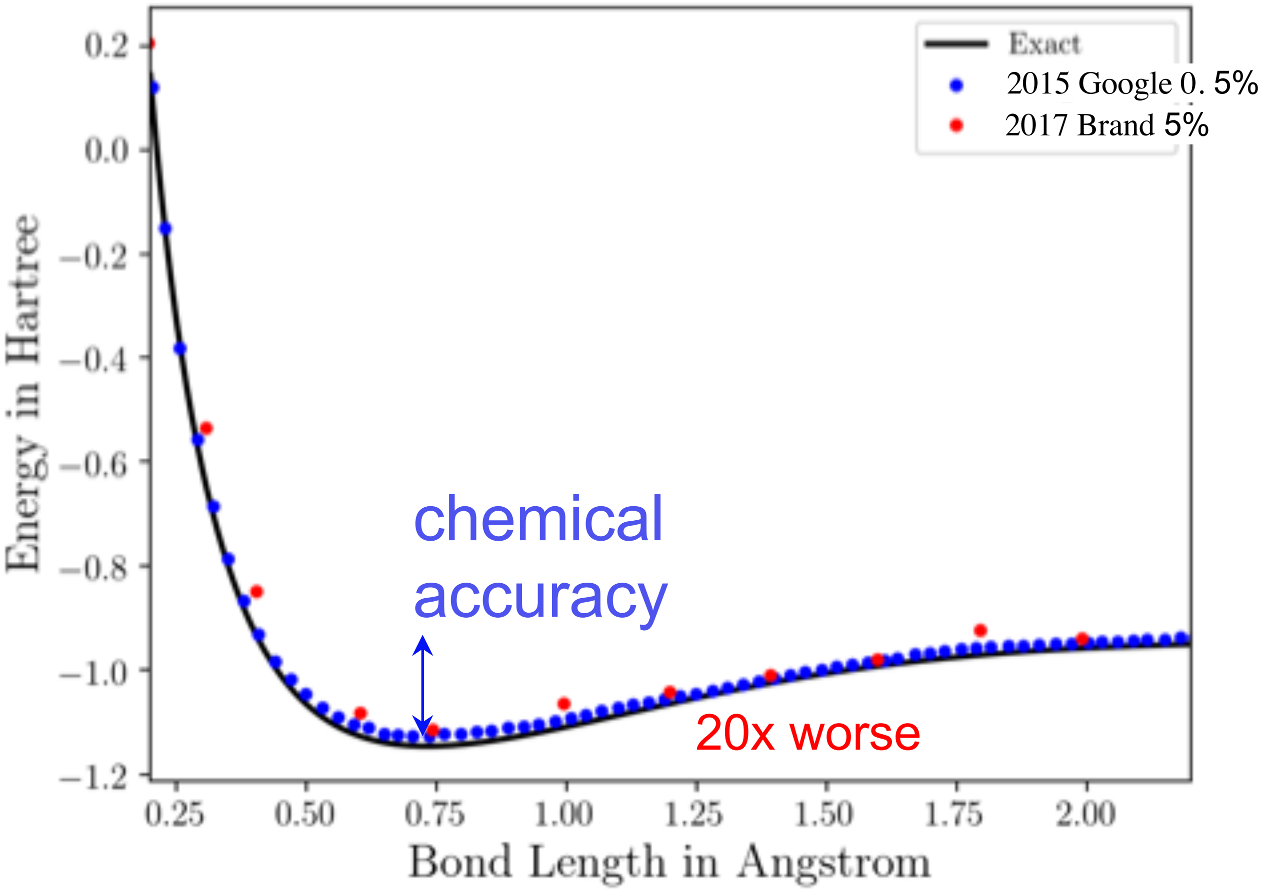


Systems: Quantity and Quality

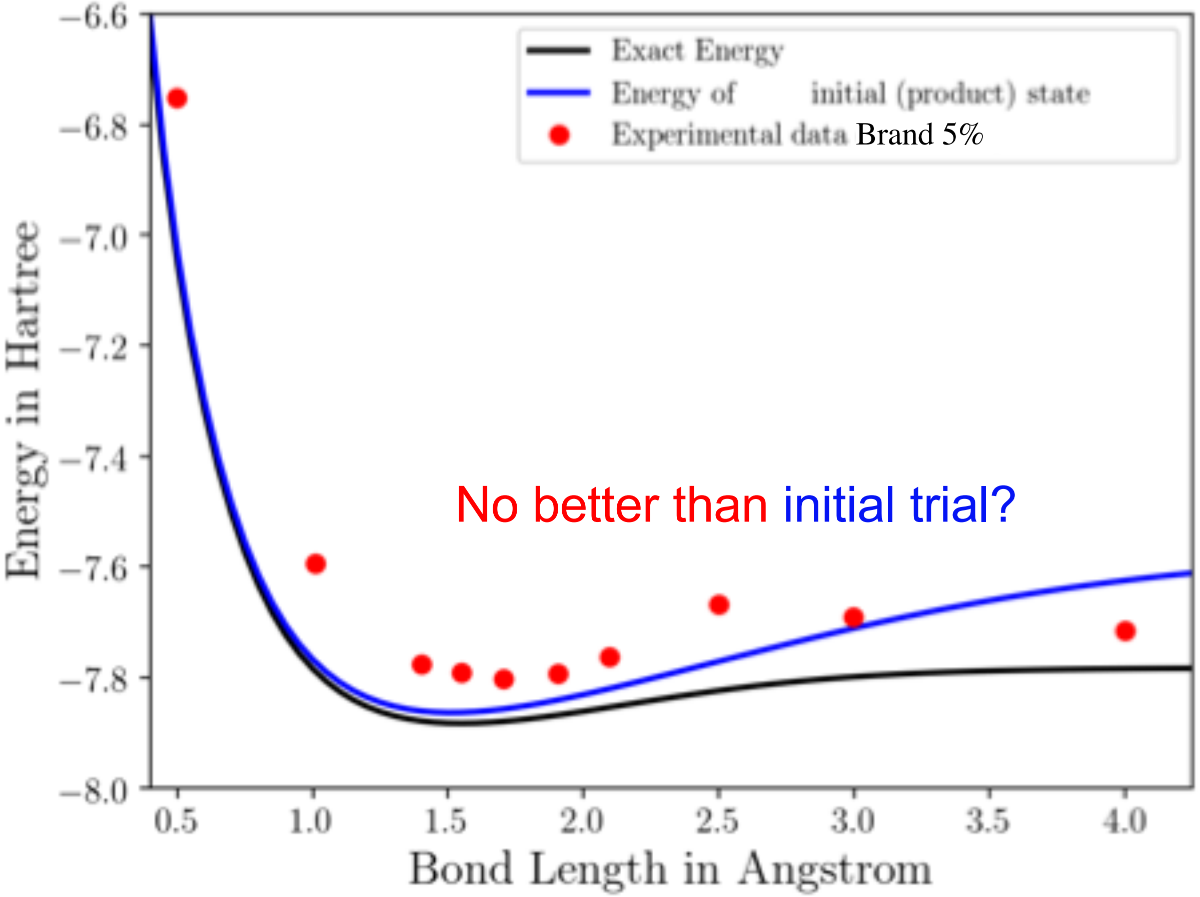


Quality in Quantum Chemistry Experiments

H_2 Molecule



LiH Molecule



Quality:

1) Need low errors for accurate predictions
2) Need figure of merit for useful

Quantum Supremacy

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

Cautions:

1) How know a hard problem?
   50 qubits not necessarily computationally complex

2) From example:
   50 qubits with simple answer and without need for good control likely solvable by short computation

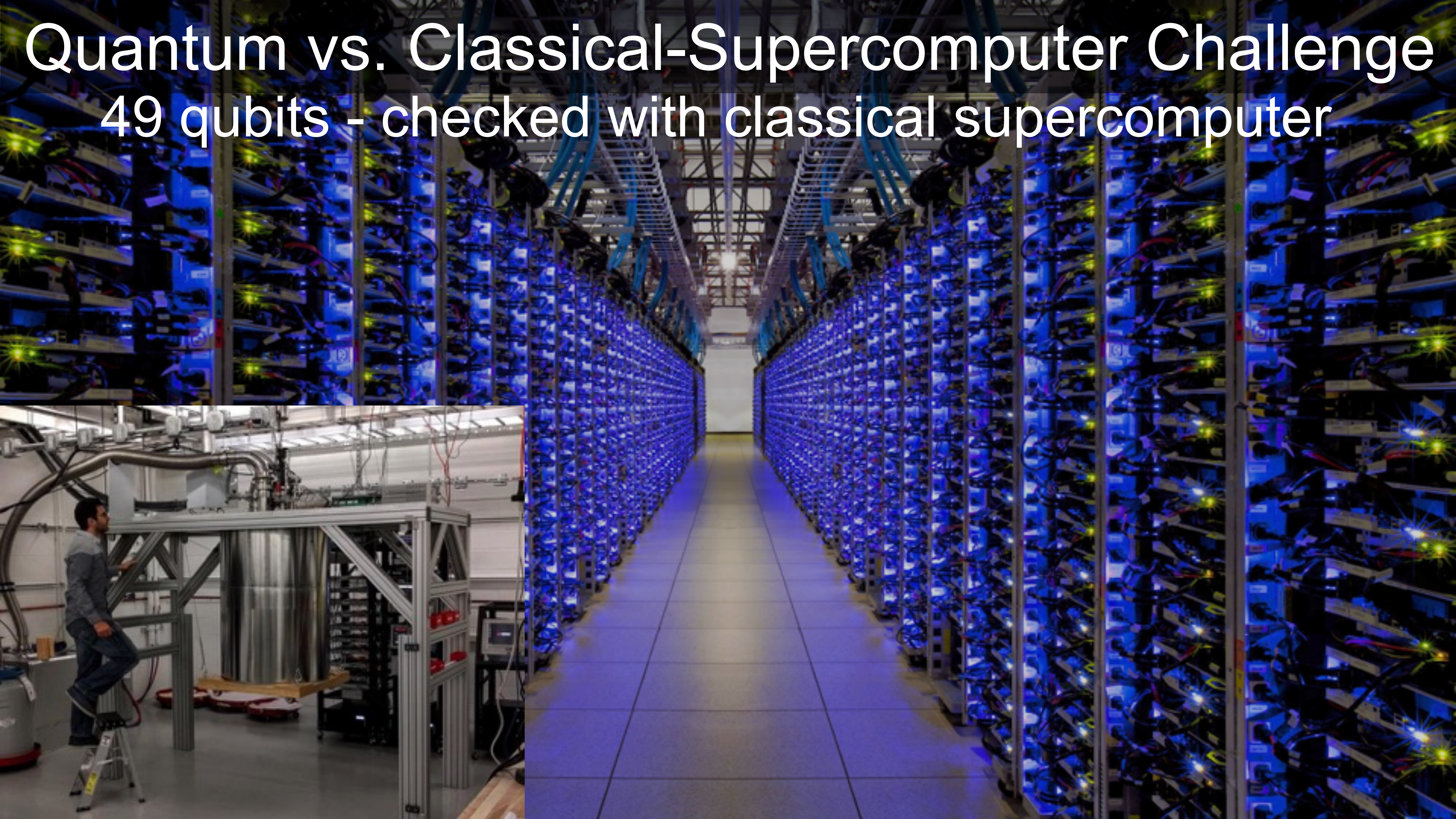
Google: QS++

1) **Exponential:** demonstrate exponentially growing computation space
2) **Hard:** Unstructured problem, so provably hard (but not “useful”)
3) **Quality:** need low 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

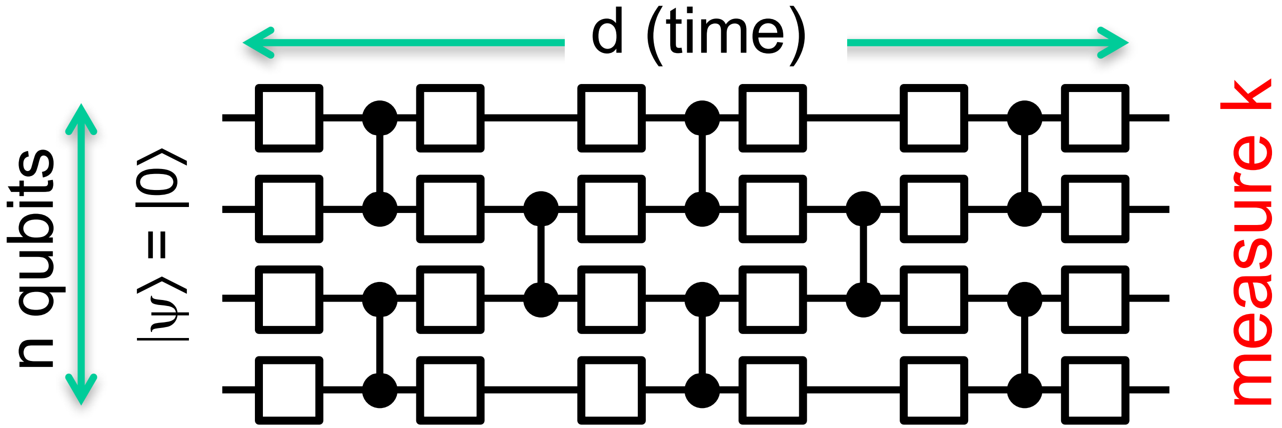
Quantum vs. Classical-Supercomputer Challenge

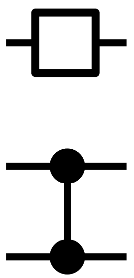
49 qubits - checked with classical supercomputer



Quantum Supremacy Algorithm: Qubit Speckle

1) Choose 1 instance, randomly from gateset





	Clifford	Non-Clifford
(single-qubit gate)	X, Z, H, $X^{1/2}$…	$Z^{1/4}$
(two-qubit gate)	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 $p_{cl} = 1/2^n$)

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

days
200 drives

4) Correlation: cross entropy

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

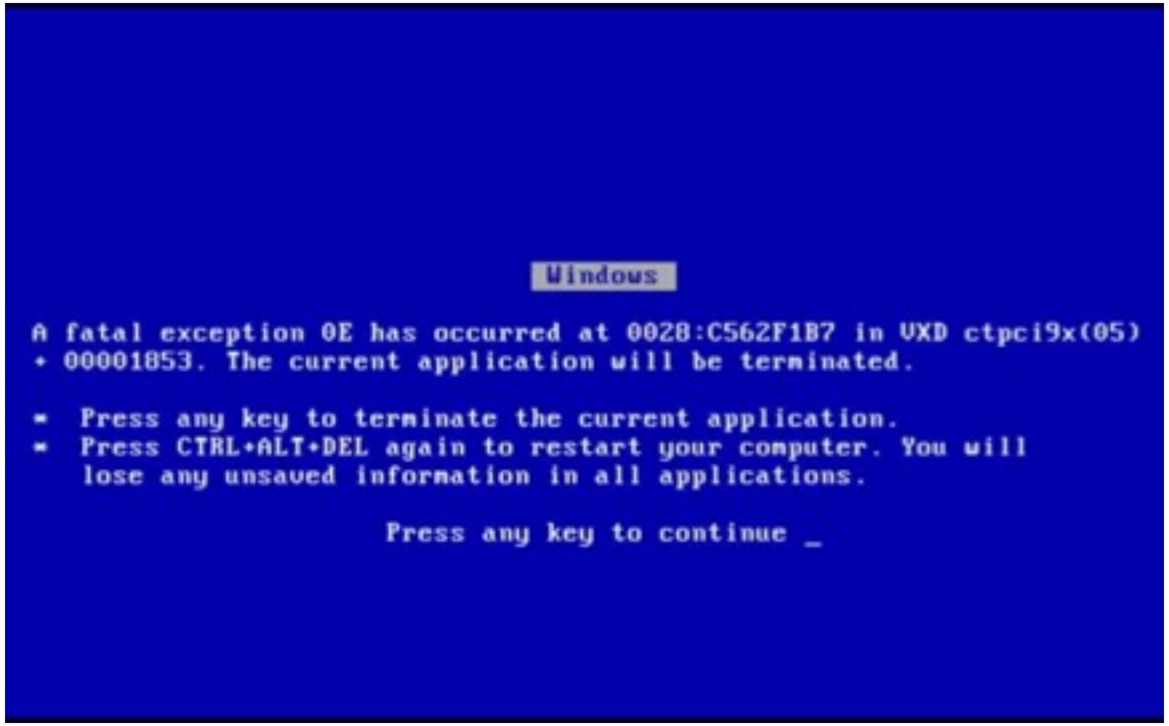
5) Compare to theory

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

6) Try another instance

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

speckle = coherence
predict = fidelity



Intrinsic Errors in Quantum Computation

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

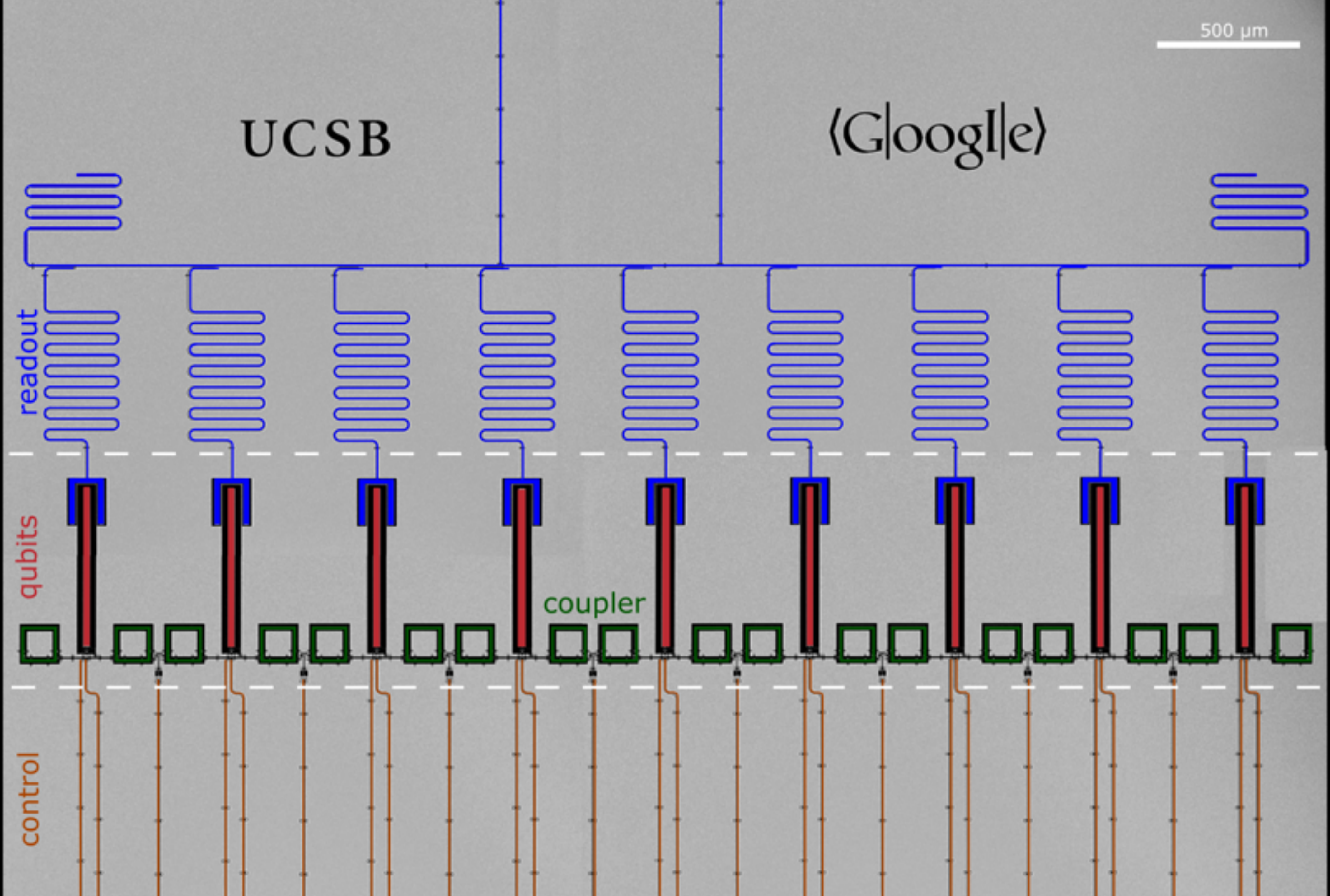
Probability of no error:

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

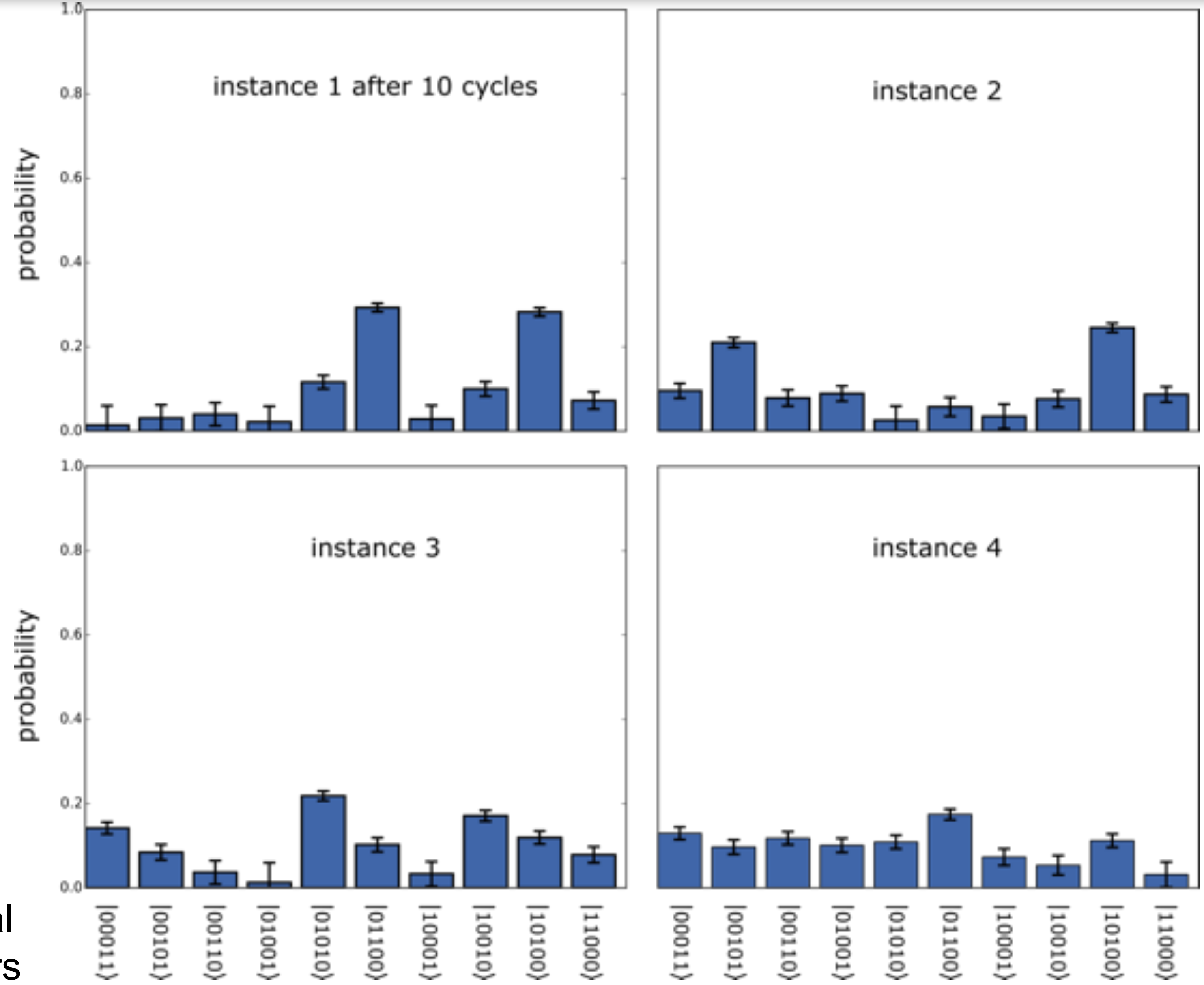
Average number of errors:

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

Need: Quantity with Quality


500 μm
UCSB
⟨G|oogl|e⟩
readout
qubits
coupler
control

Typical dataset with 5 qubits

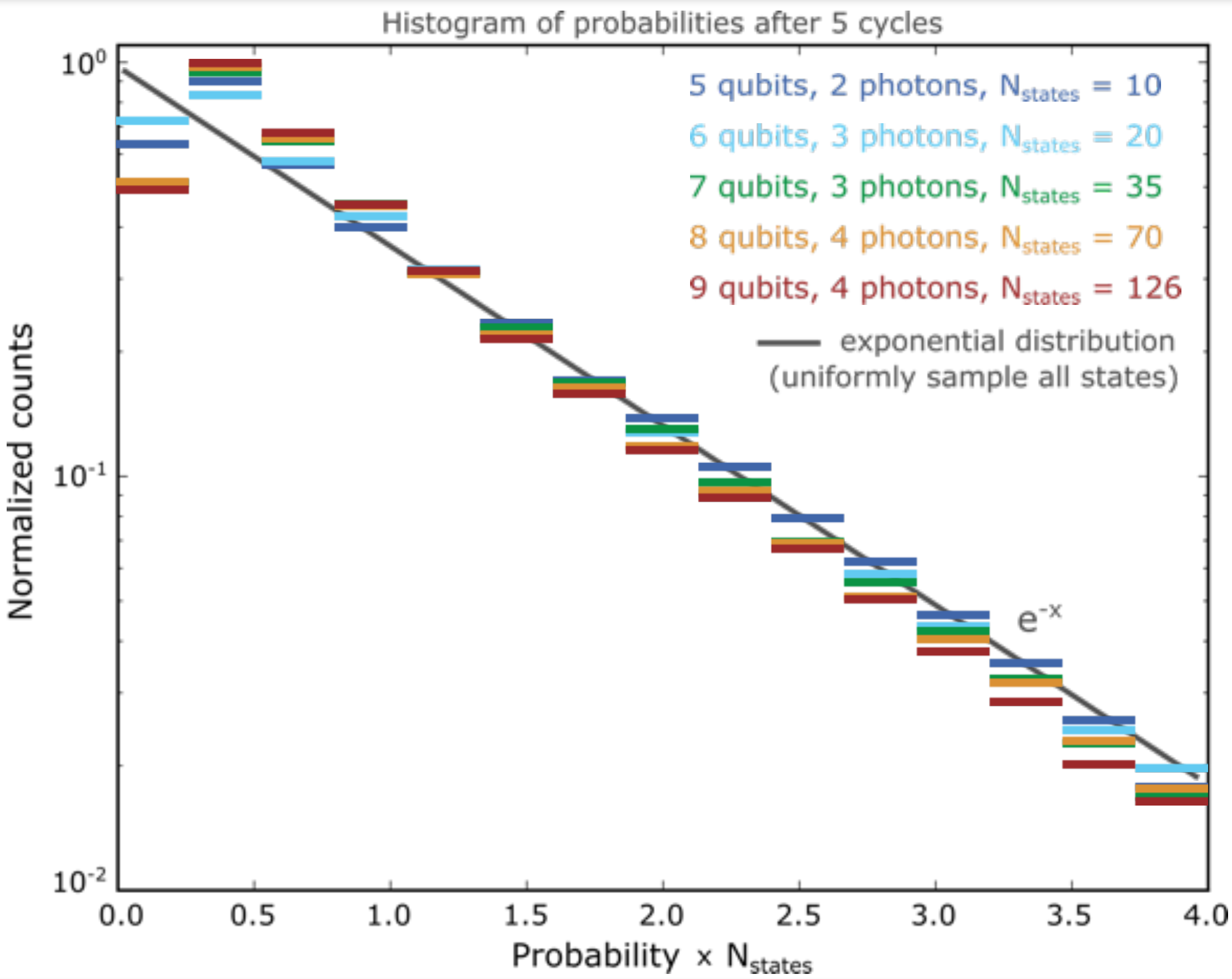


statistical
error bars

quantum info
just from
prob. histograms

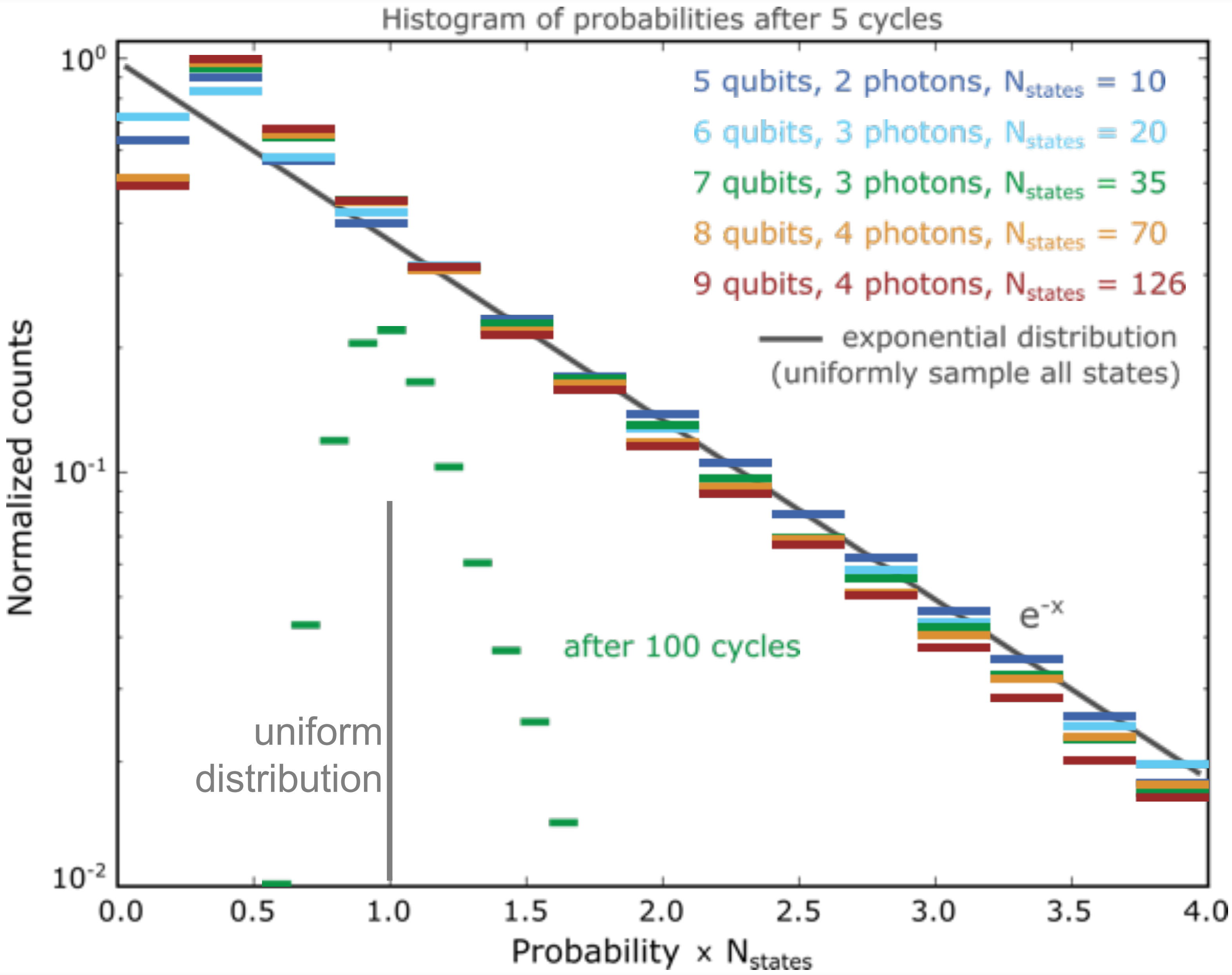
photon conserving
states

Histogram of measured probabilities



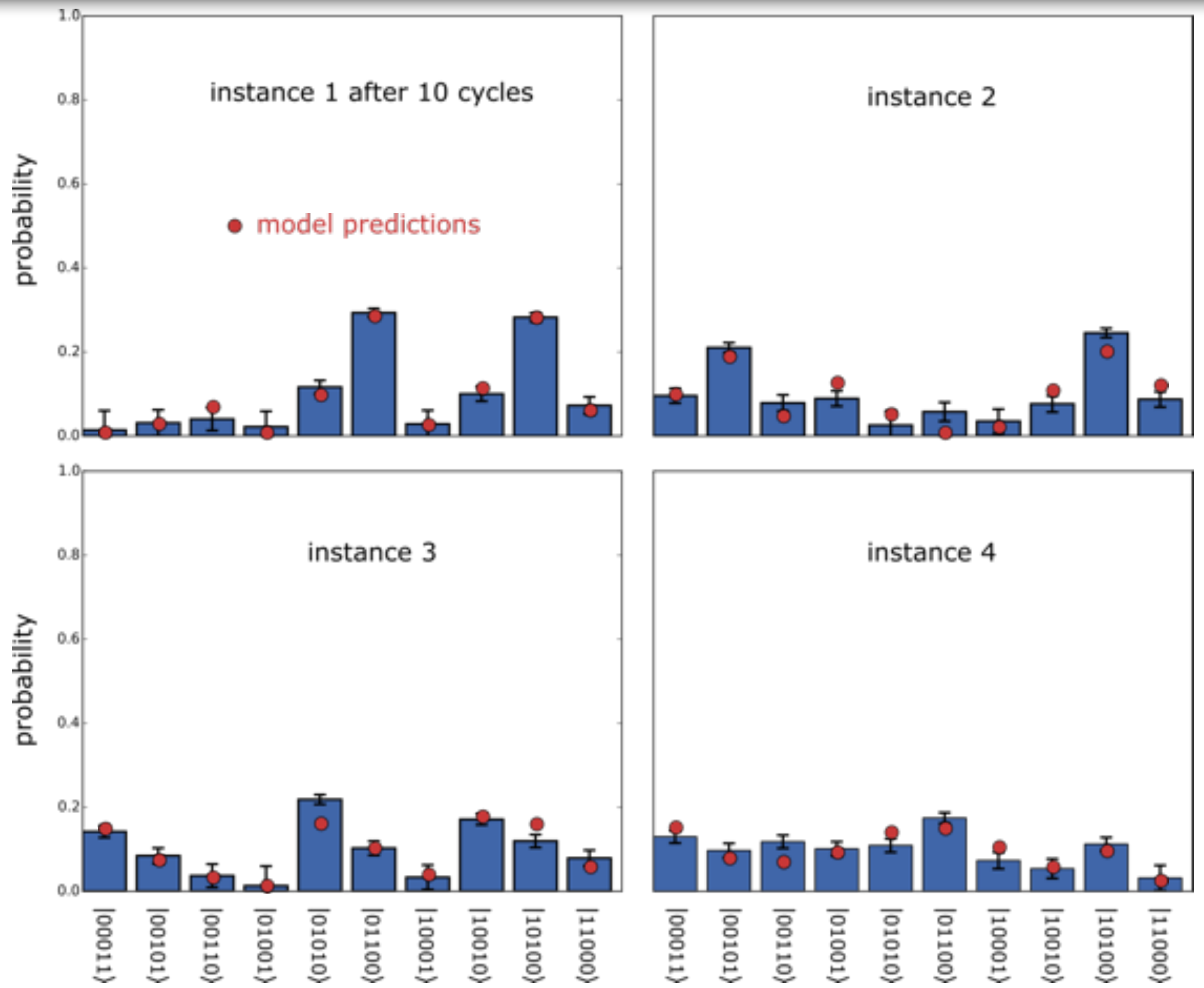
Collapses to exponential distribution

Histogram of measured probabilities



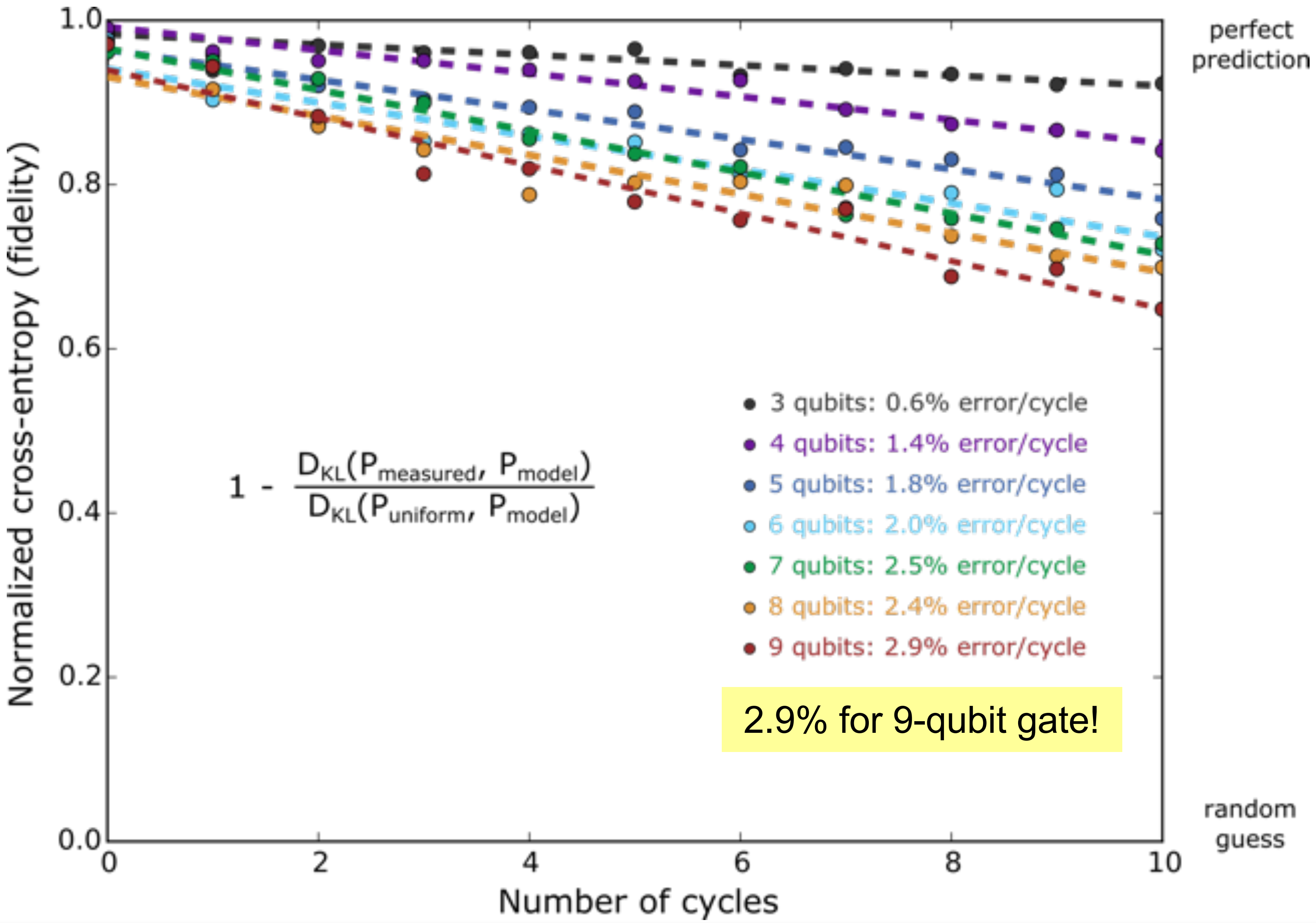
decoherence kills qubit speckle

Compare probabilities of experiment and theory



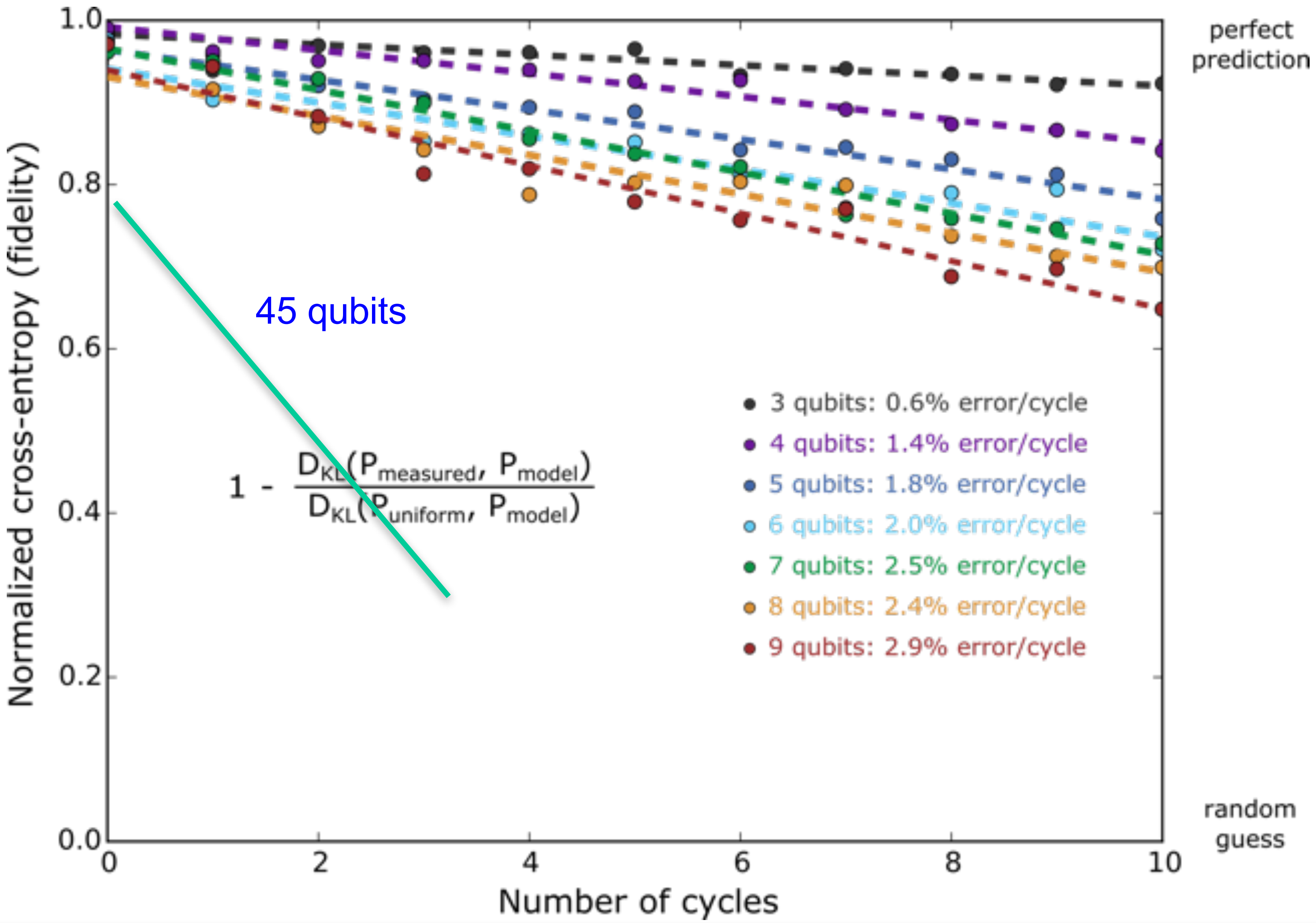
speckle pattern matches theory

Measuring fidelity



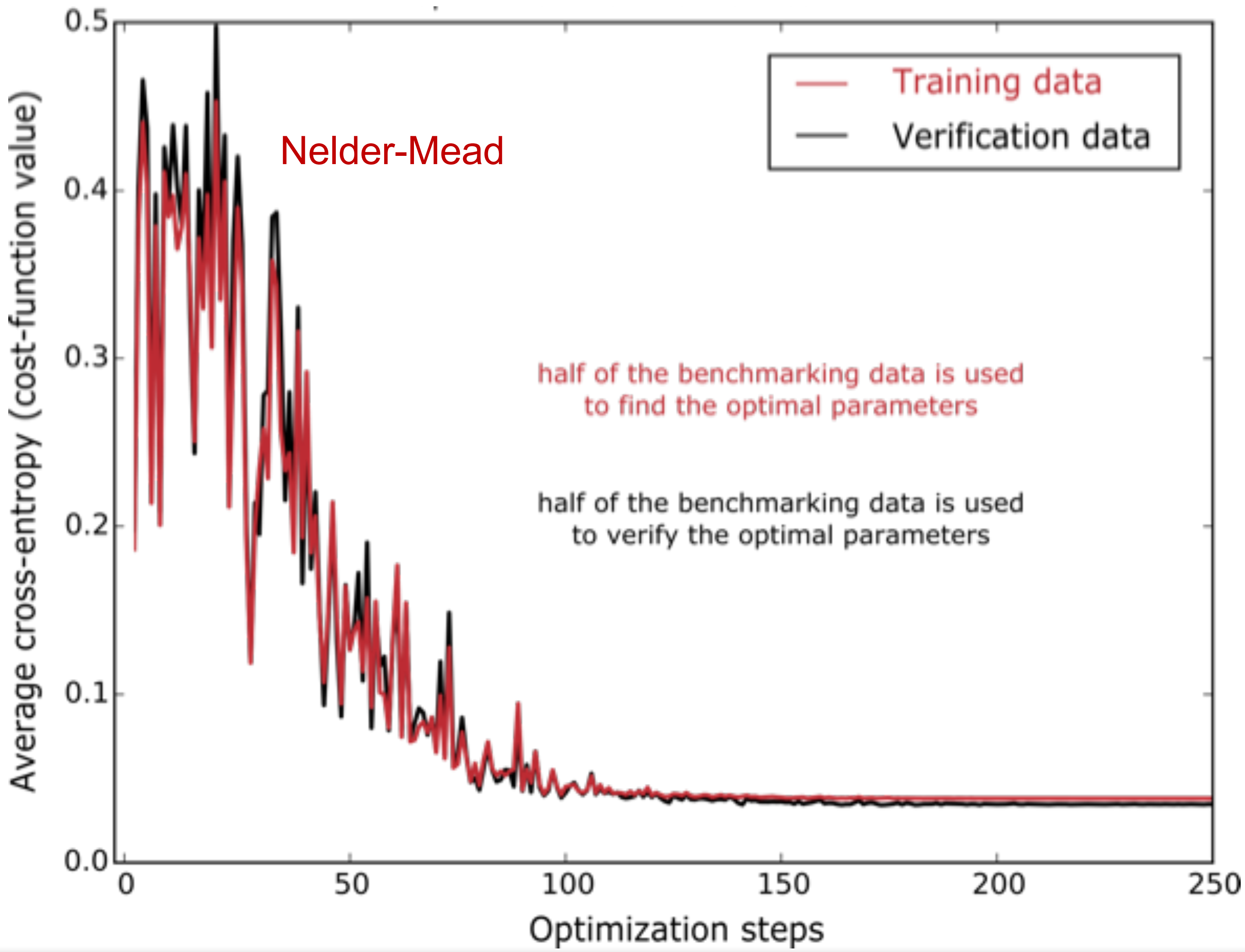
0.3% error per gate & cycle

Scaled fidelity for 45 qubits



supremacy possible with margin

Useful: Learning a better control model

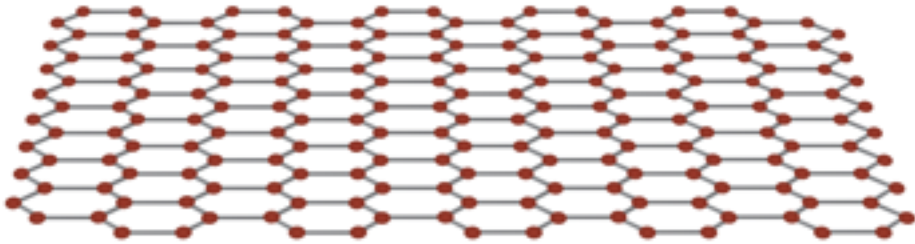


Tuneup flux offsets
(as drifty)

training
verified

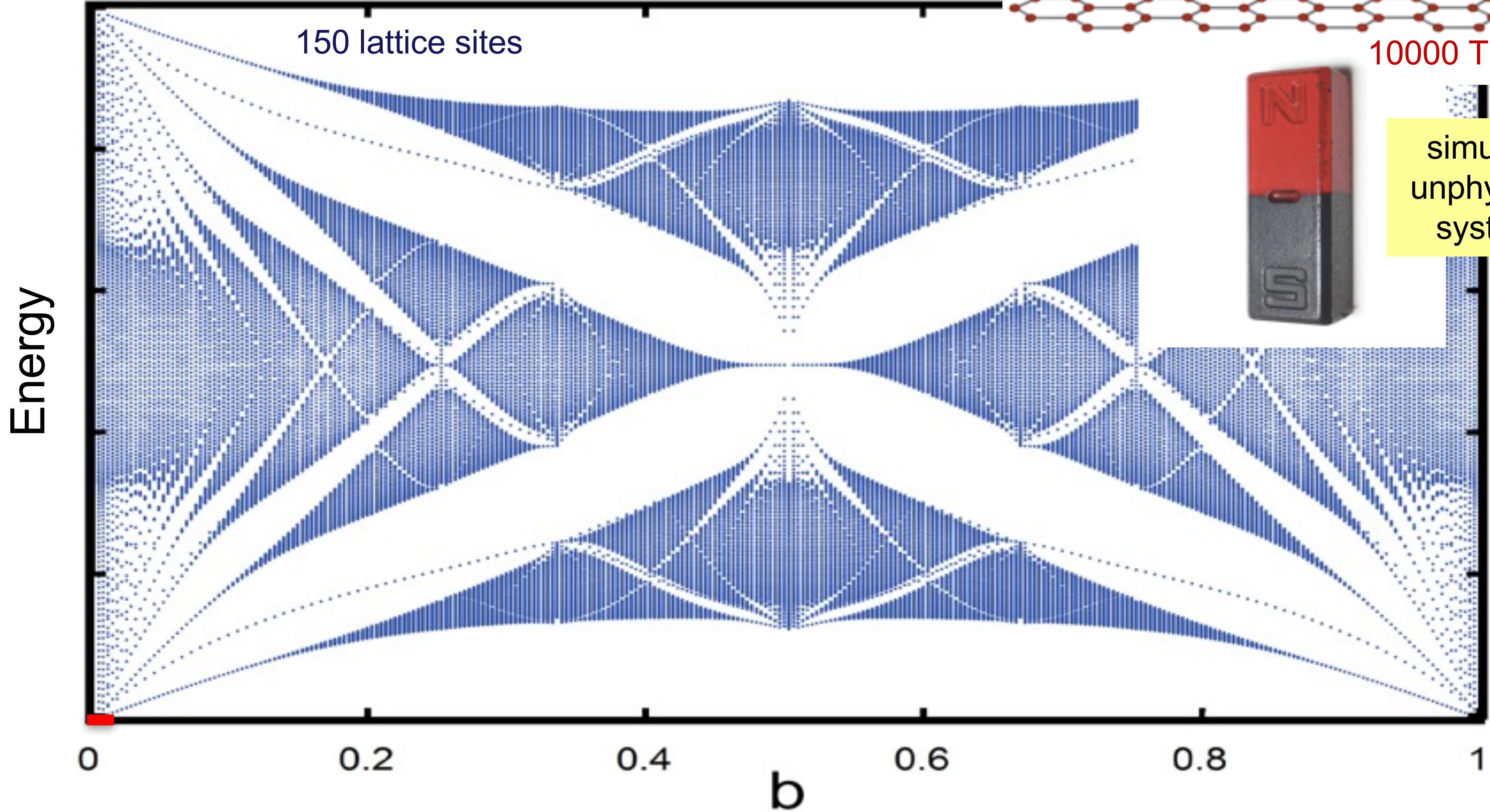
Hofstadter Butterfly

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



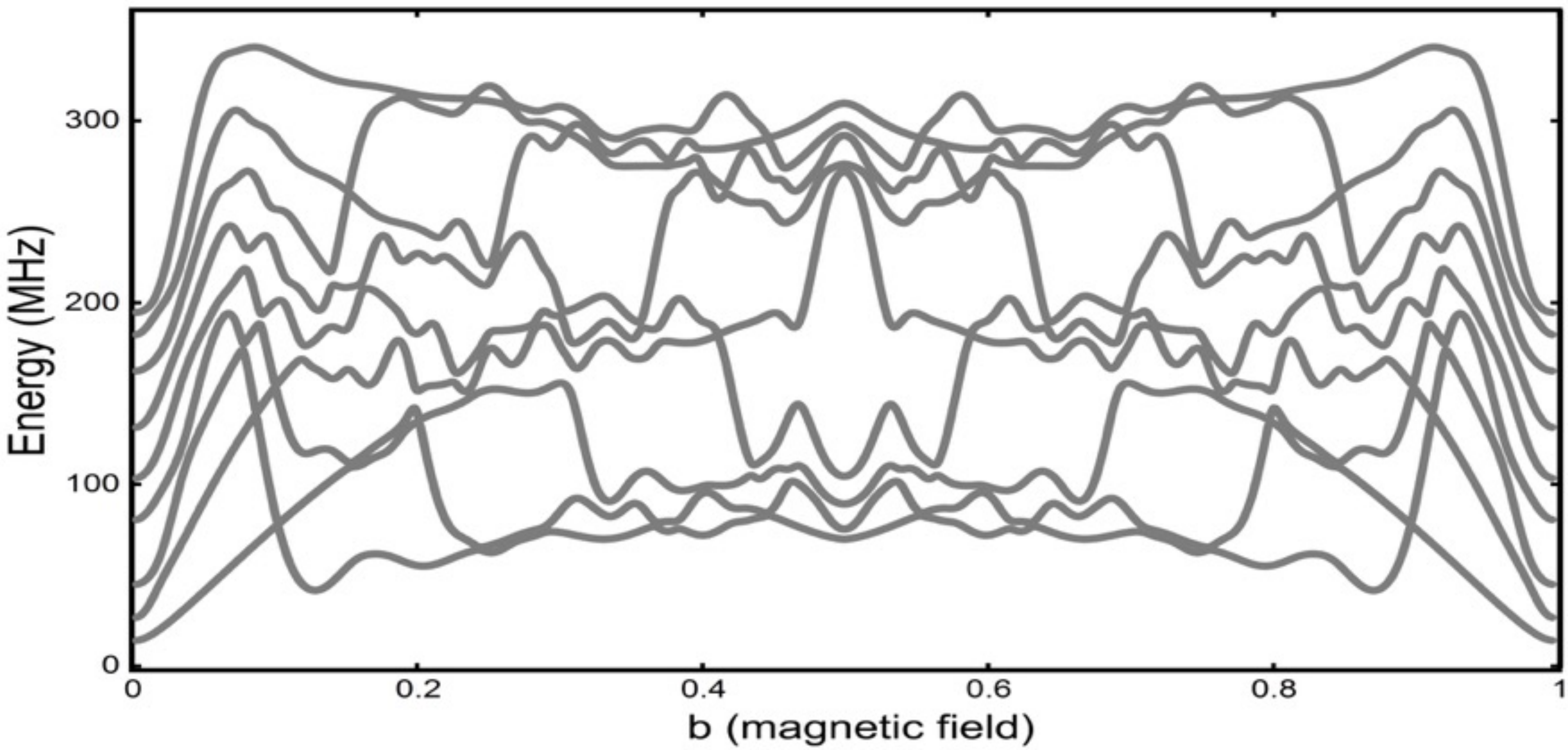
10000 T

simulate unphysical system



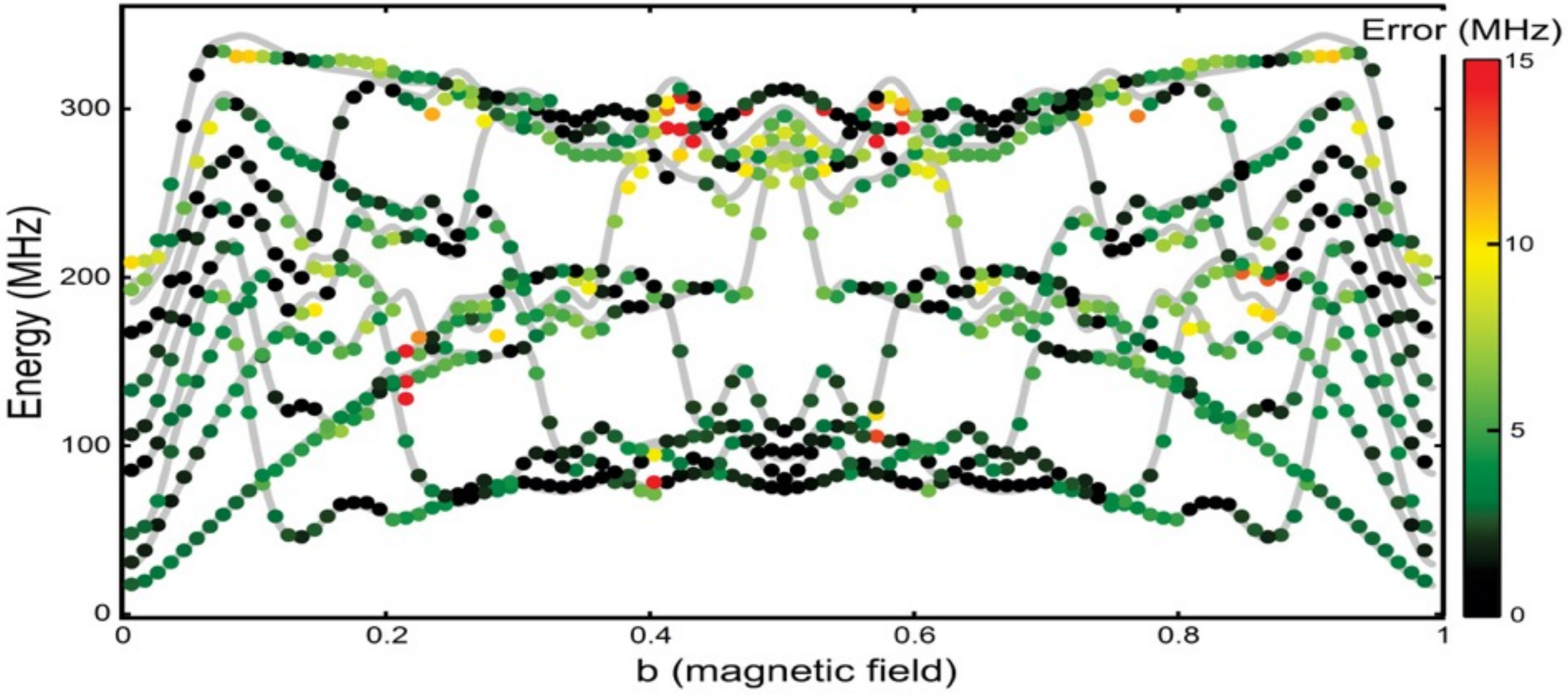
9 Qubits: theory

fractal nature gives complex spectrum



9 Qubits: theory + experiment

extract complex
physically useful information



More System Metrics

1) Quantity

2) Quality
   - 2-qubit errors
   - Measure errors
   - 1-qubit errors

3) Device speed
   - 100,000 difference in technologies
   - Affects calibration
   - Affects $/user

4) Qubit connectivity
   - 2D array works for error correction …
   - Serial (vs parallel) is slower

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%

Quality

2) 22 qubit device in test (2x11 array)
   - Performance similar to 9 qubit device
   - (better crosstalk)

Quantity

3) Quantum supremacy device in fabrication
   - Square array
   - Testing in 2 weeks
   - Working towards Quantum Cloud offering

Bristlecone

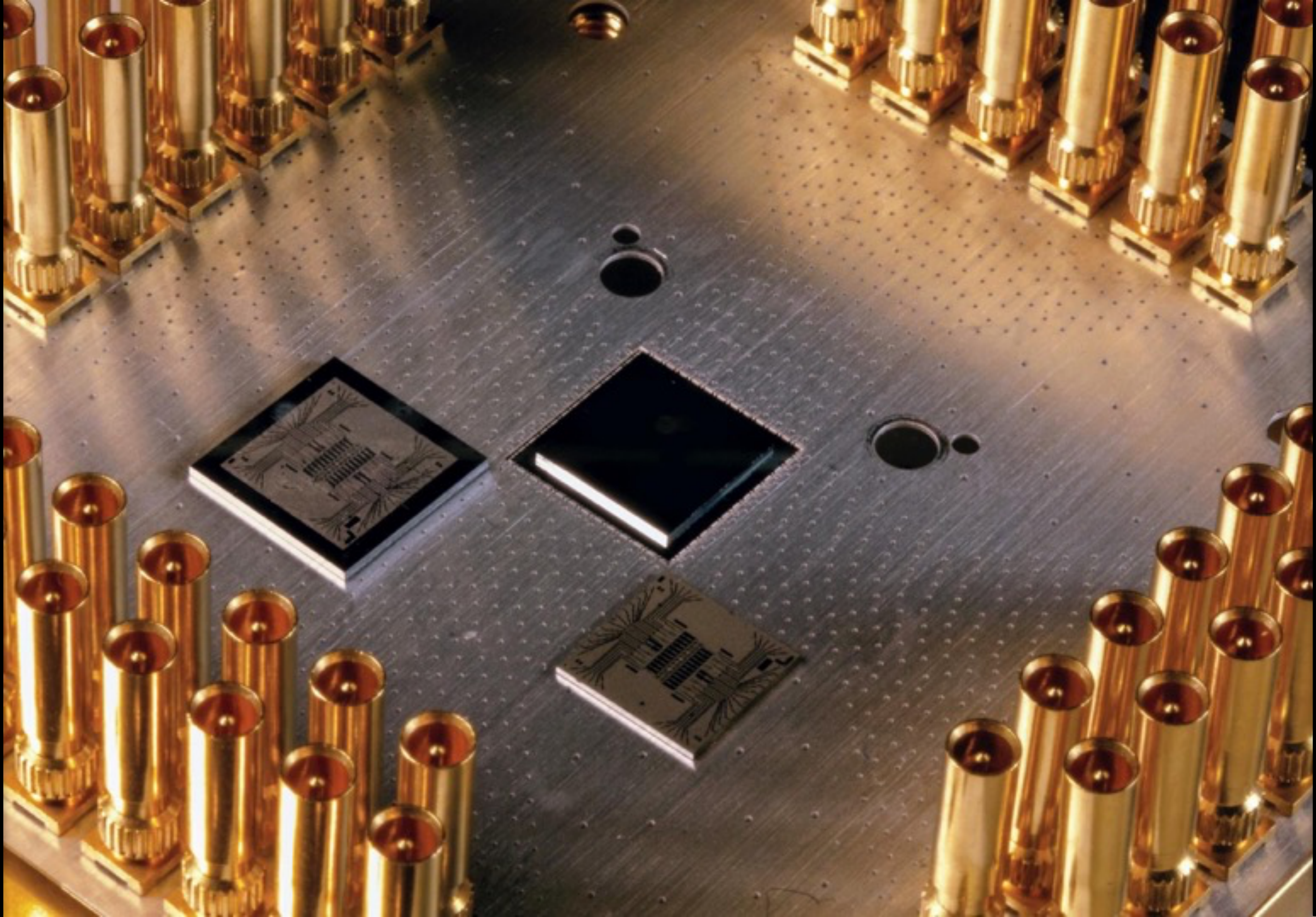
4) Technology path scalable to 1000+ qubits

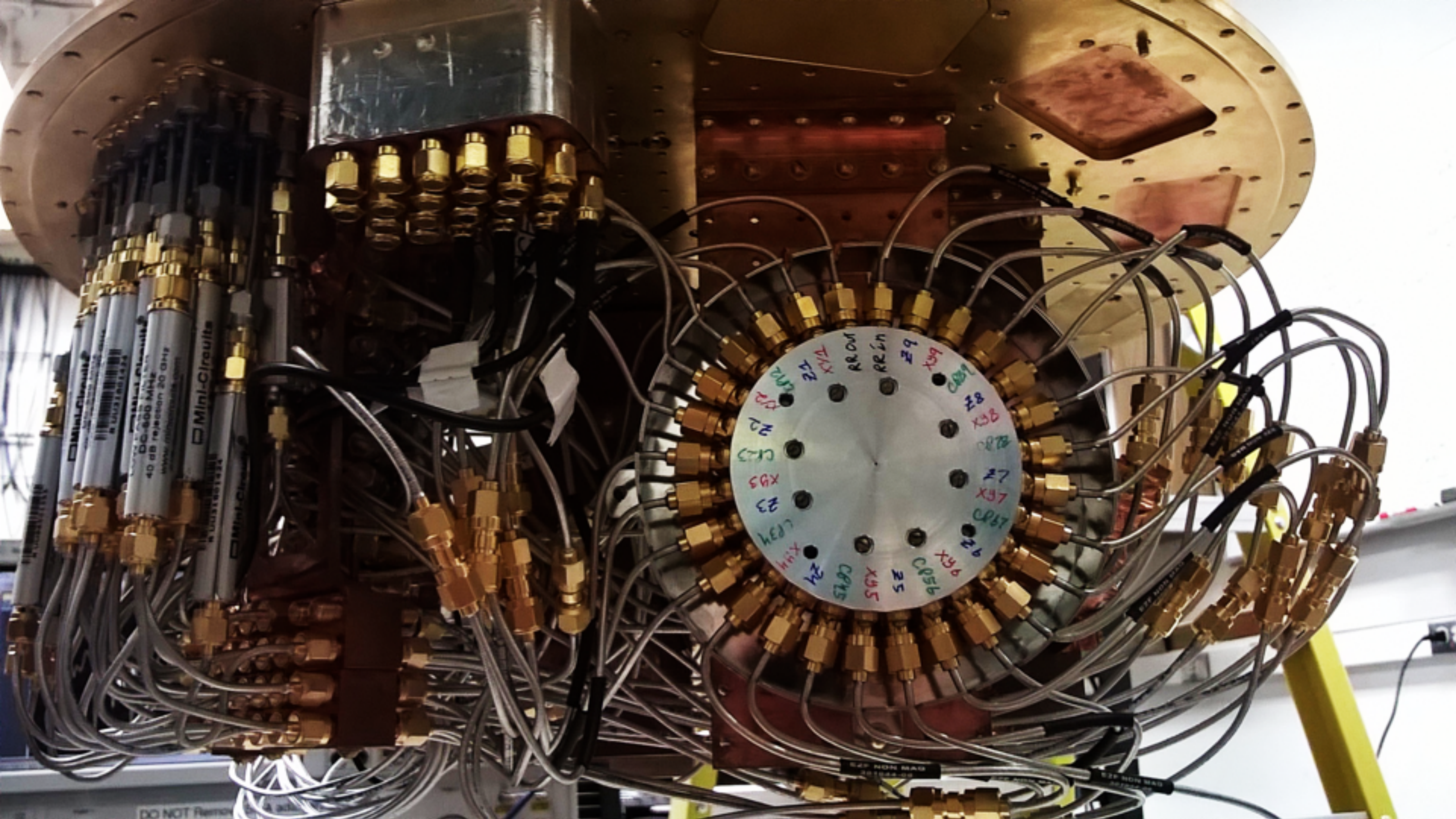
Summary: Ask 3 Questions

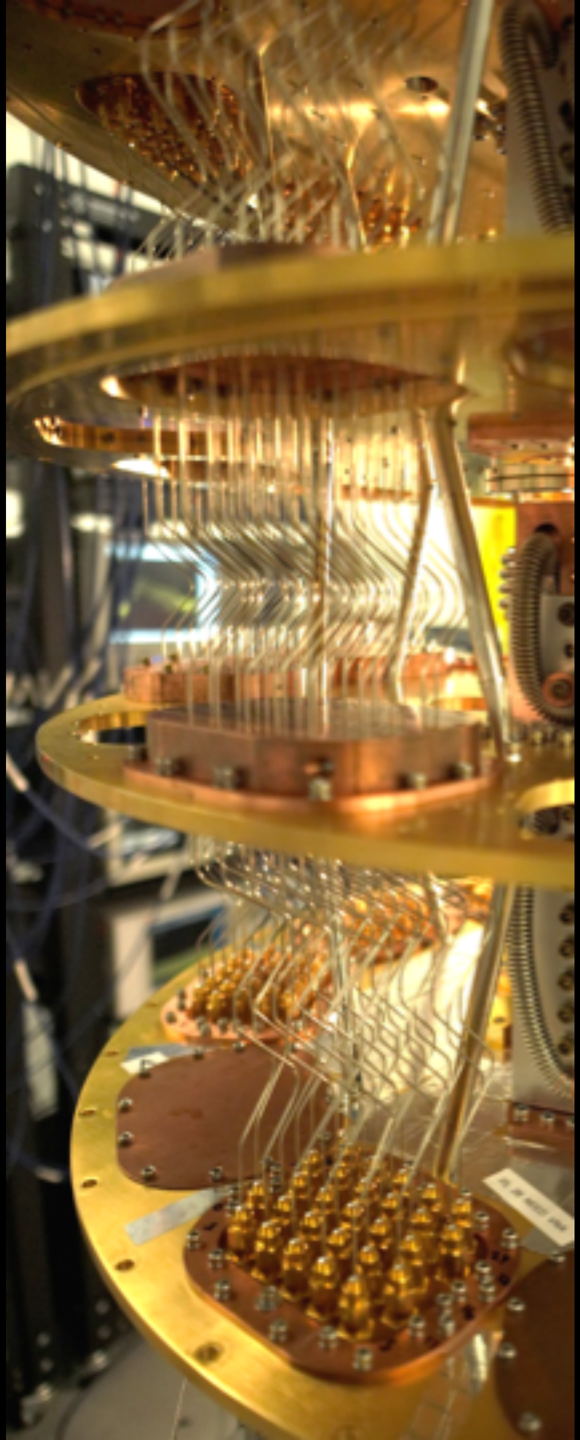
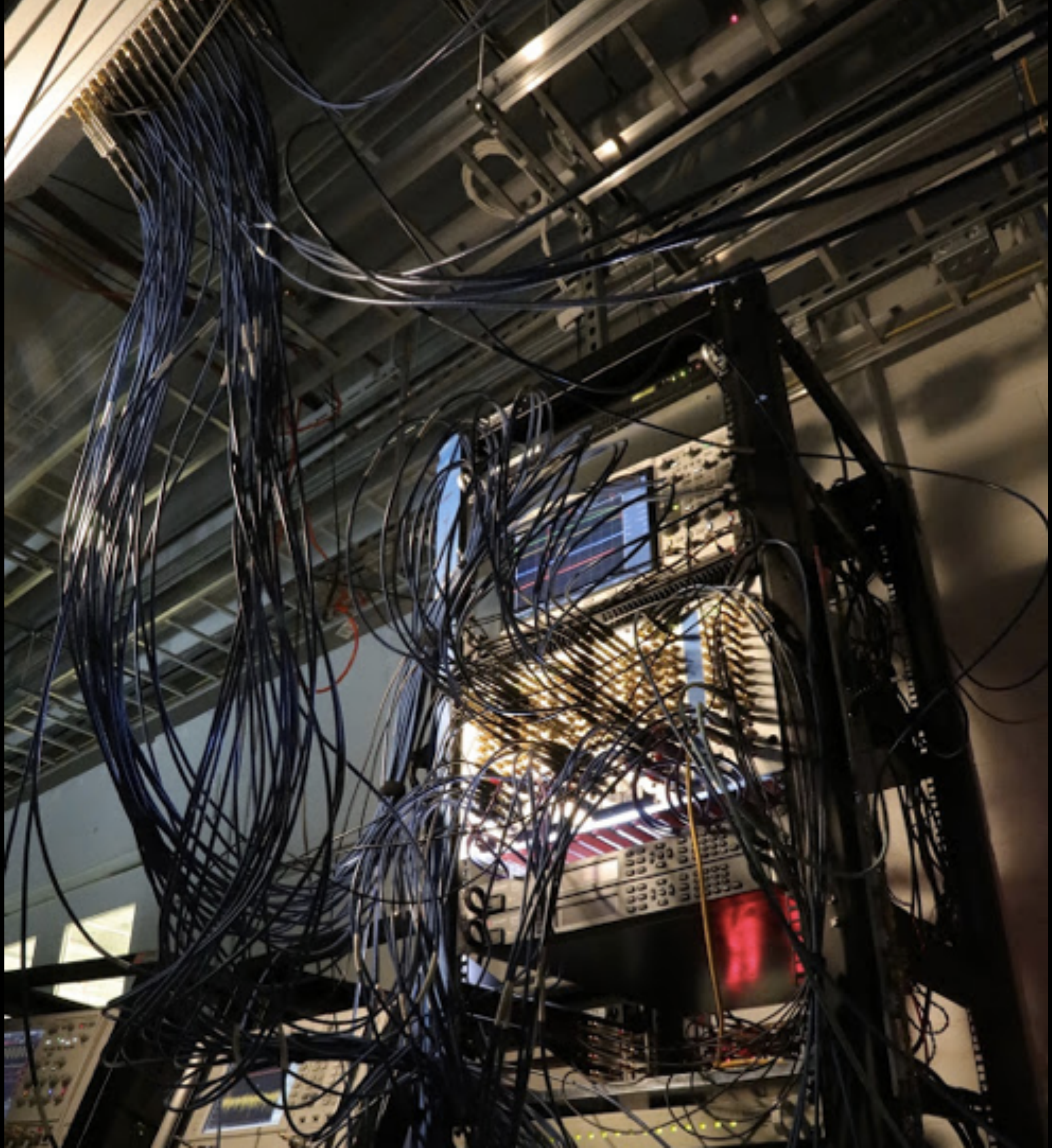
1) Quantity and quality

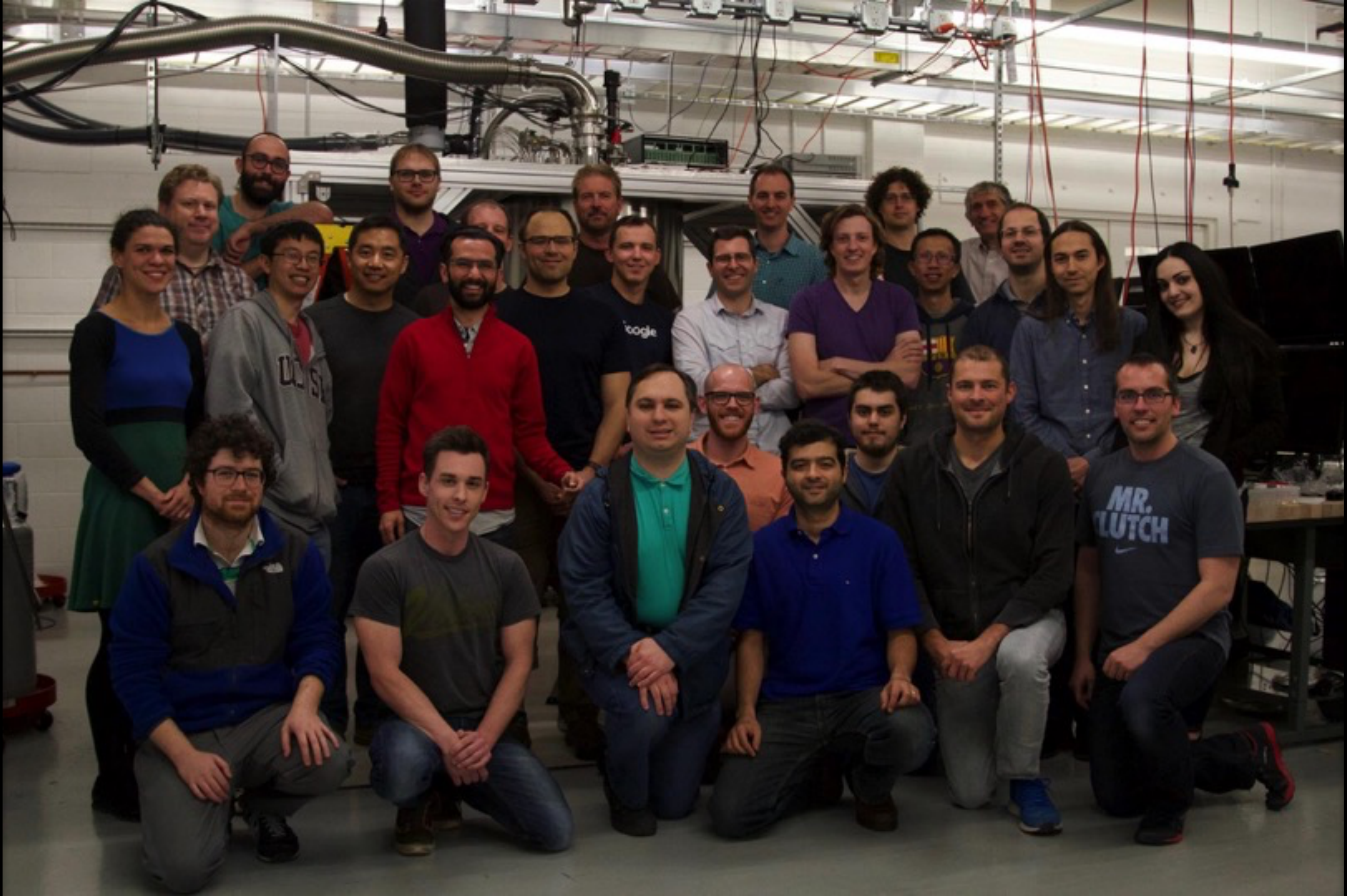
2) Quality(quantity)

3) Worst system error (2-qubit)



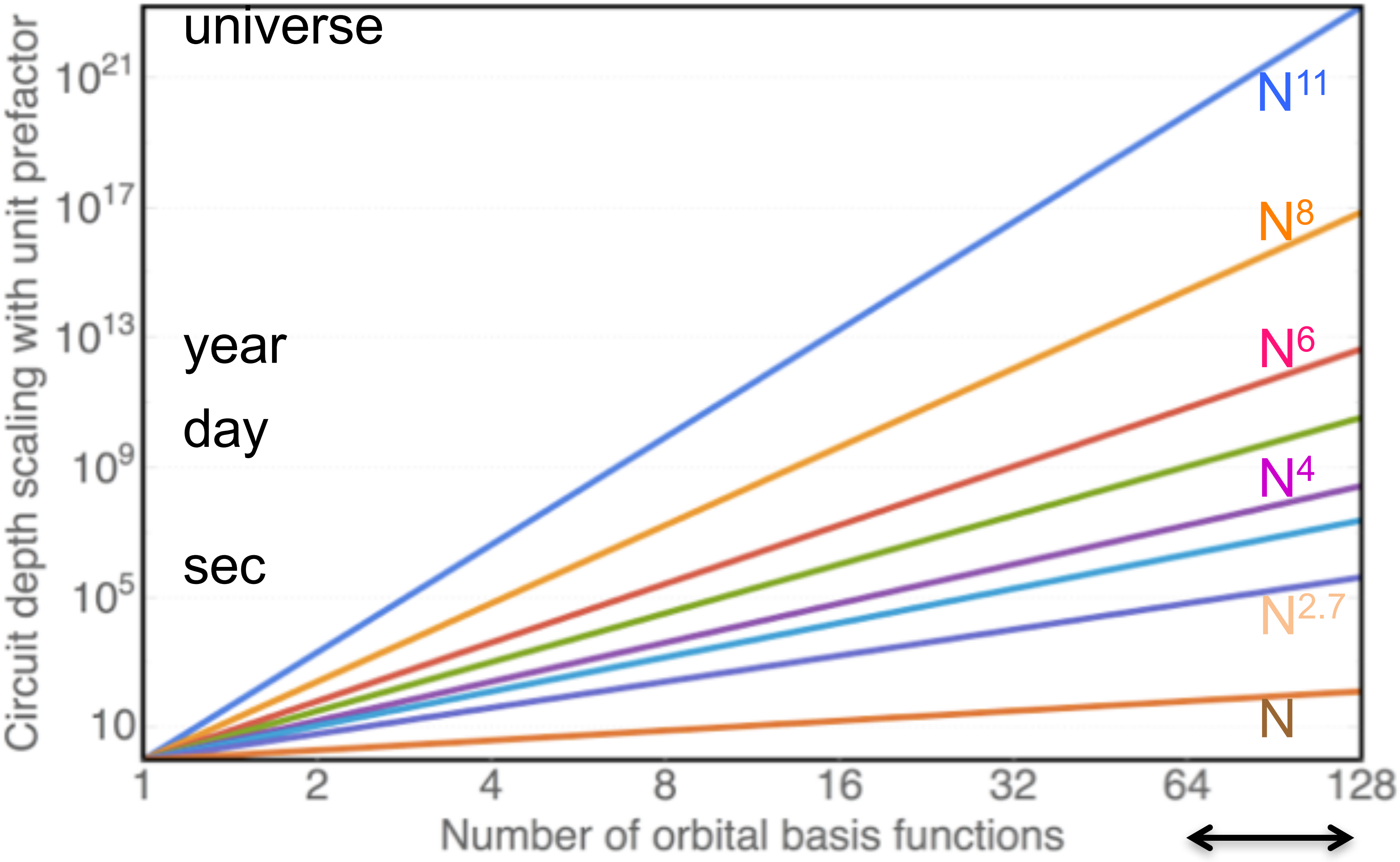

Mini-Circuits
DC-600 MHz
40 dB rejection 20 GHz
XY1
Z1
RR out
RR in
Z9
XY9
CR89
Z8
XY8
CR78
Z7
XY7
CR67
Z6
XY6
CR56
Z5
XY5
CR45
Z4
XY4
CR34
Z3
XY3
CR23
Z2
XY2
CR12
EZF NON MAG


MR.
CLUTCH

Huge Progress in Algorithms (Quantum Chemistry)

Year	Reference	Total Depth
1985	Feynman	(proposal)
2005	Aspuru-Guzik [1]	$\mathcal{O}(\text{poly}(N))$
2010	Whitfield [2]	$\mathcal{O}(\text{poly}(N))$
2012	Seeley [3]	$\mathcal{O}(\text{poly}(N))$
2013	Perruzzo [4]	$\mathcal{O}(\text{poly}(N))$
2013	Toloui [5]	$\mathcal{O}(\text{poly}(N))$
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]	$\tilde{\mathcal{O}}(N^{5})$
2015	Babbush [12]	$\tilde{\mathcal{O}}(\eta^2 N^{3})$
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]	$\tilde{\mathcal{O}}(N^{2.67})$
2017	Babbush [15]	$\mathcal{O}(N)$

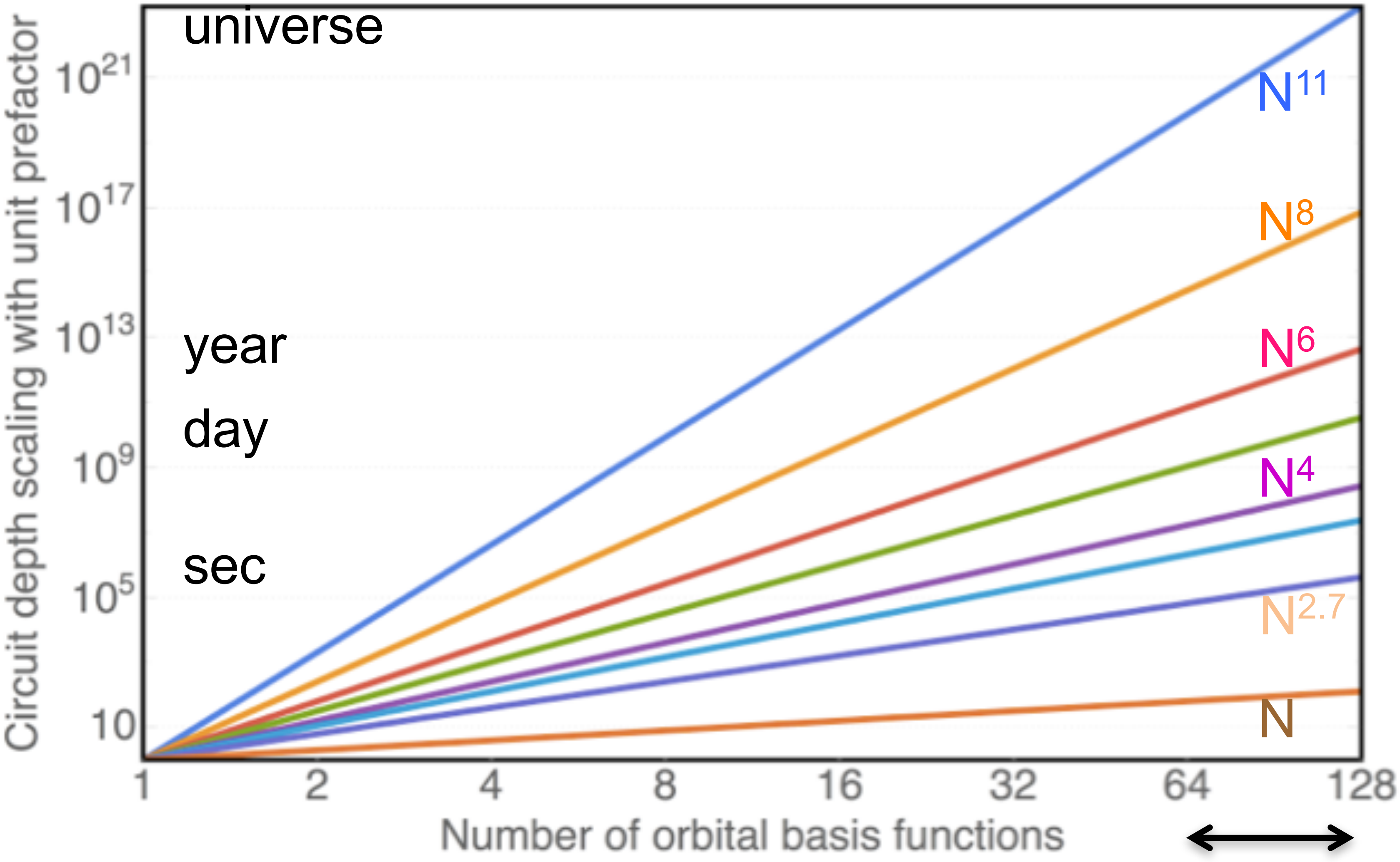


Exact: 100 logical qubits (error corrected)

Approximate: 100 physical qubits (?)

Huge Progress in Algorithms (Quantum Chemistry)

Year	Reference	Total Depth
1985	Feynman	(proposal)
2005	Aspuru-Guzik [1]	$\mathcal{O}(\text{poly}(N))$
2010	Whitfield [2]	$\mathcal{O}(\text{poly}(N))$
2012	Seeley [3]	$\mathcal{O}(\text{poly}(N))$
2013	Perruzzo [4]	$\mathcal{O}(\text{poly}(N))$
2013	Toloui [5]	$\mathcal{O}(\text{poly}(N))$
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]	$\tilde{\mathcal{O}}(N^{5})$
2015	Babbush [12]	$\tilde{\mathcal{O}}(\eta^2 N^{3})$
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]	$\tilde{\mathcal{O}}(N^{2.67})$
2017	Babbush [15]	$\mathcal{O}(N)$



Useful QC now possible?

OpenFermion: The Electronic Structure Package for Quantum Computers

Open source library for quantum simulation of fermions

- Generate fermionic Hamiltonian from molecule geometry, charges, etc.
- Map fermions to qubits (e.g. Jordan-Wigner)
- Compile to a variety of gate sets

Modern software engineering practices

Contribution (Pull Request) → **Automatic Testing**: Extensive tests (>99% coverage); Enforce no decrease in coverage → **Code Review**: Feedback on design choices; Google style & PEP8 enforced

Framework and platform agnostic

- Works above LIQUID, ProjectQ, [insert your platform here]
- Runs on Windows, Mac, and Linux

OpenFermion is a community effort!

- Submit your changes at openfermion.org
- Collaborators include Google, Rigetti, NASA, Harvard, ETH Zurich, University of Michigan, Dartmouth, Oxford, the Department of Energy, ...

QC WARE

Q2B

2017