

## Lesson 12. Utility Scale Experiment I

# 1. Opening

This lecture first explains the Utility paper, and provides the assignment of a utility-scale experiment based on the Utility paper.

We start with an overview of the experiments in the paper, that is, what circuits they build for what hamiltonian.

# 12. Utility Scale Experiment I

2024/07/05

Tamiya Onodera

IBM Research – Tokyo  
tonodera@jp.ibm.com

# Course Schedule 2024 (subject to change)

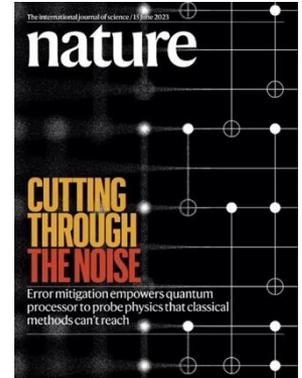
Date	Lecture Title	Lecturer	Date	Lecture Title	Lecturer
4/5	Invitation to the Utility era	Tamiya Onodera	6/7	Classical simulation (Clifford circuit, tensor network)	Yoshiaki Kawase
4/19	Quantum Gates, Circuits, and Measurements	Kifumi Numata	6/14	Quantum Hardware	Masao Tokunari
4/26	LOCC (Quantum teleportation/superdense coding/Remote CNOT)	Kifumi Numata/ Atsushi Matsuo	6/21	Quantum circuit optimization (transpilation)	Toshinari Itoko
5/10	Quantum Algorithms: Grover's algorithm	Atsushi Matsuo	6/28	Quantum noise and quantum error mitigation	Toshinari Itoko
5/15 (Wed)	Quantum Algorithms: Phase estimation	Kento Ueda	7/5	Utility Scale Experiment I	Tamiya Onodera
5/24	Quantum Algorithms: Variational Quantum Algorithms (VQA)	Takashi Imamichi	7/12	Utility Scale Experiment II	Yukio Kawashima
5/30 (Thu)	Quantum simulation (Ising model, Heisenberg, XY model), Time evolution (Suzuki Trotter, QDrift)	Yukio Kawashima	7/19	Utility Scale Experiment III	Kifumi Numata

# Outline

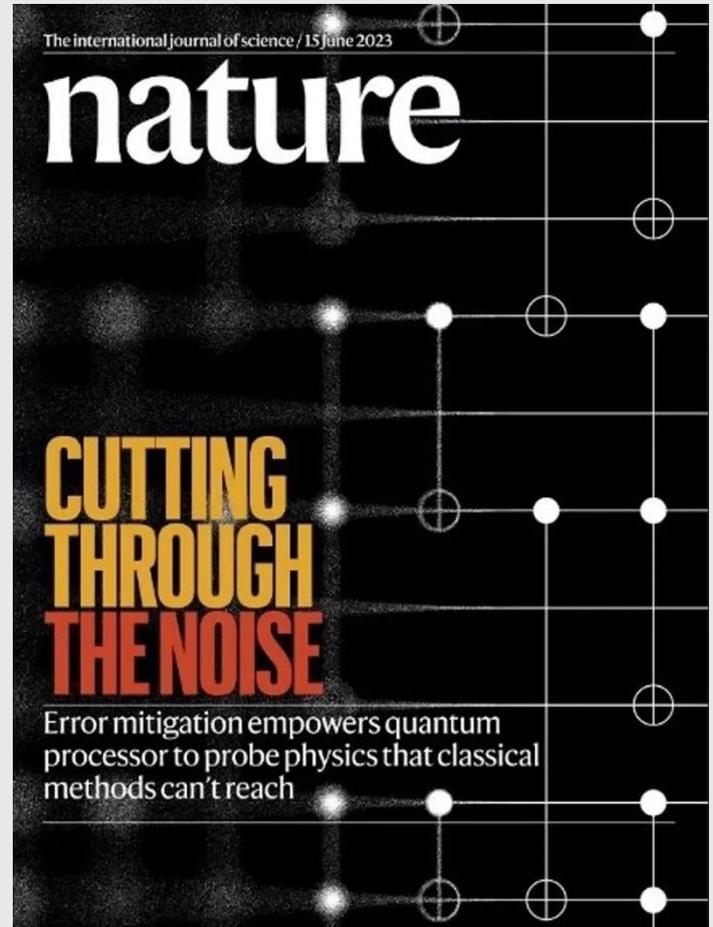
- Introduction of the Utility Paper
  - published in Nature Vol 618, 15 June 2023
  - ushered in an era of Quantum Utility

<Break>

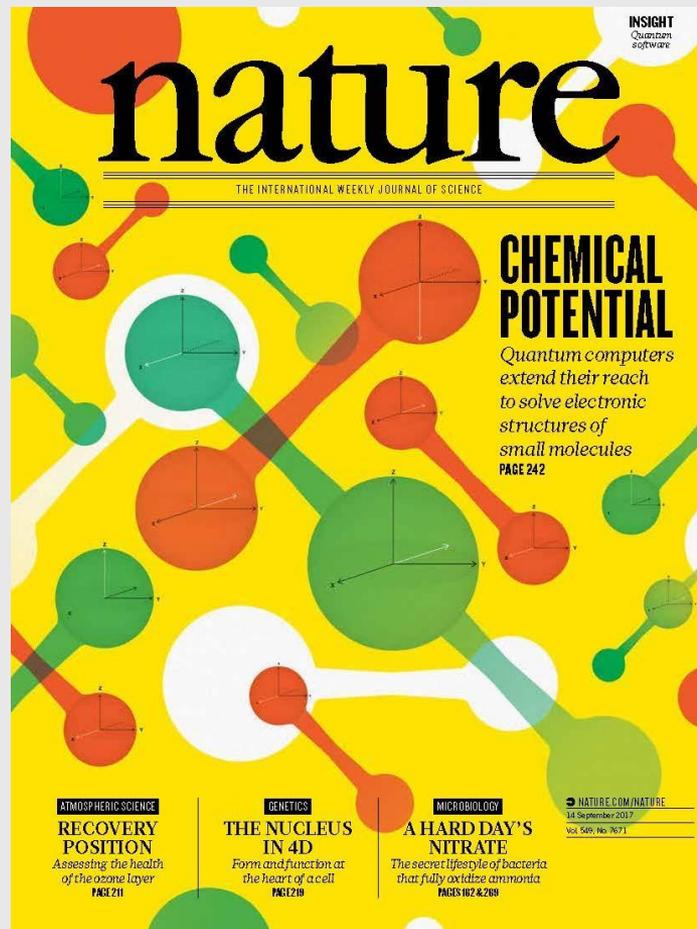
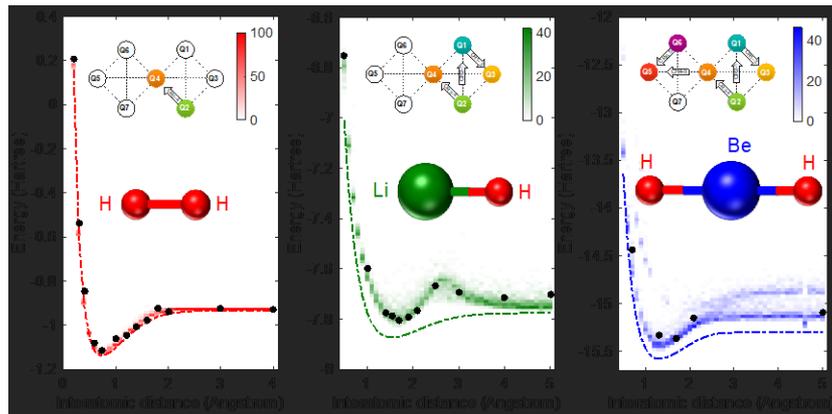
- Jupyter notebook with
  - a simpler experiment based on the Utility paper
  - your assignment



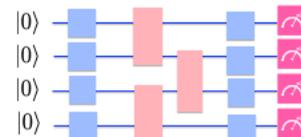
A new era  
has begun:  
Quantum  
Utility



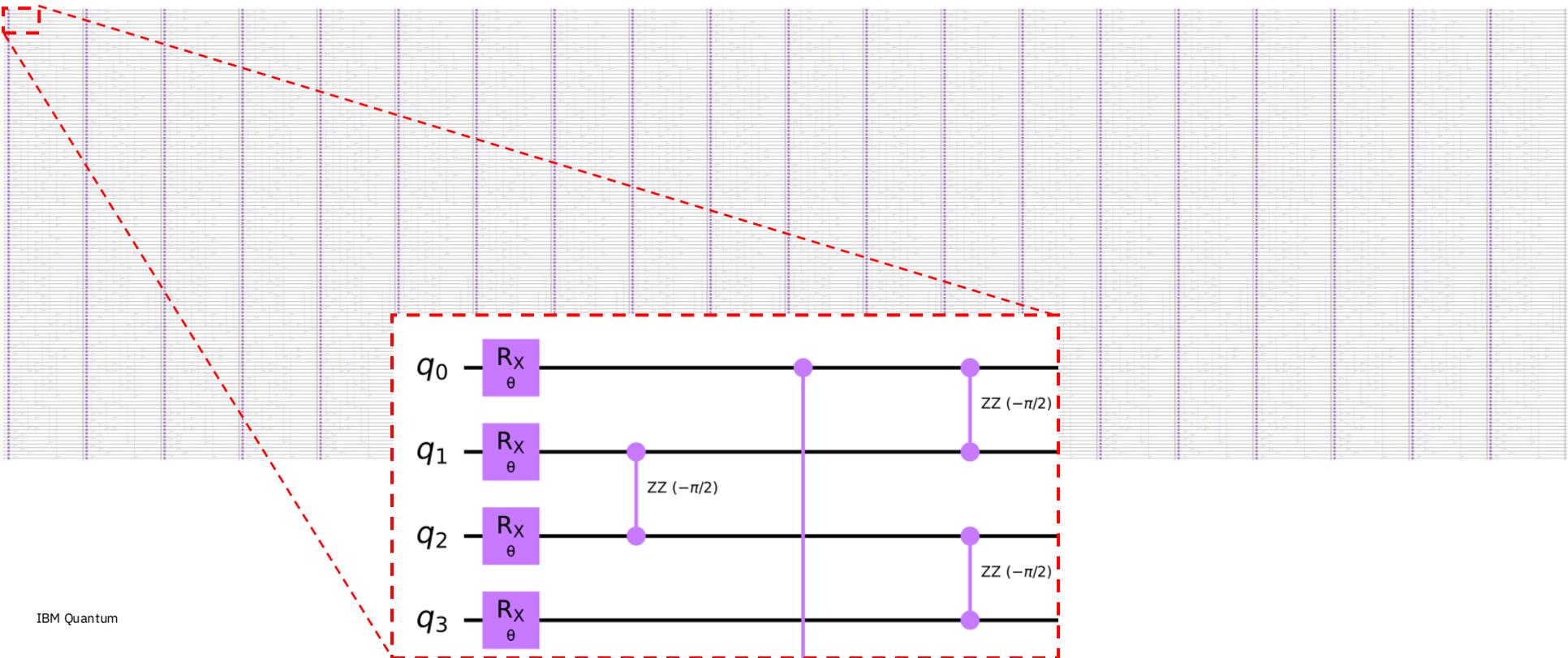
# 6 Years ago..



127 qubit x 60 entangling layers



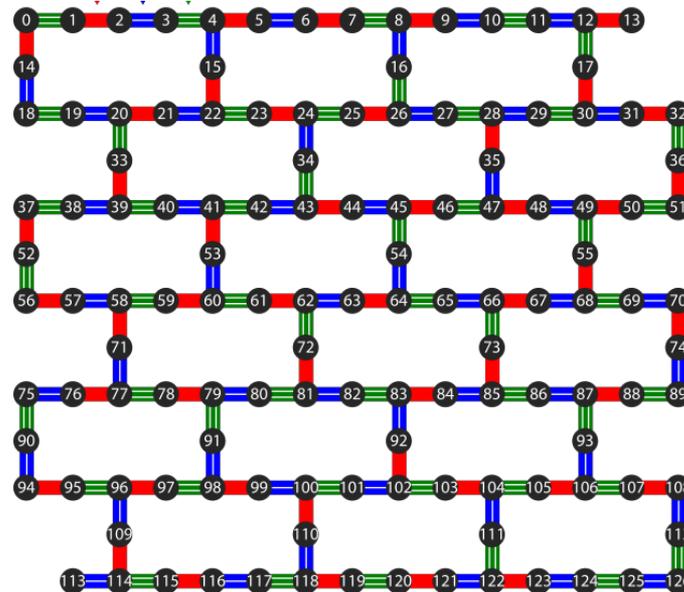
2017: 4 qubit, depth 2



# The experiment

- Spin lattice shares hardware topology (127Q device)

$$H = -J \sum_{(i,j) \in E} Z_i Z_j + h \sum_{i \in V} X_i$$



# The experiment

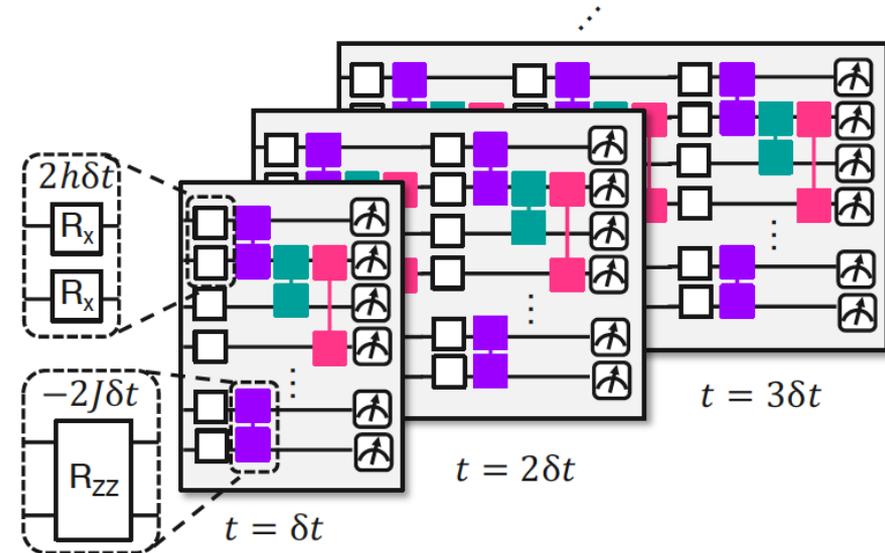
- Spin lattice shares hardware topology (127Q device)

$$H = -J \sum_{(i,j) \in E} Z_i Z_j + h \sum_{i \in V} X_i$$

- (poorly) Trotterized time evolution dynamics

$$e^{-iHt} |\psi_0\rangle \simeq \prod_{n=1}^N e^{-iH_{ZZ}(\delta t)} e^{-iH_X(\delta t)} |\psi_0\rangle$$

RZZ gate      RX gate

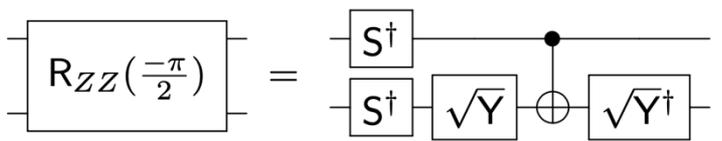
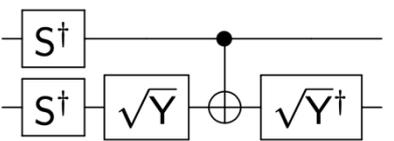


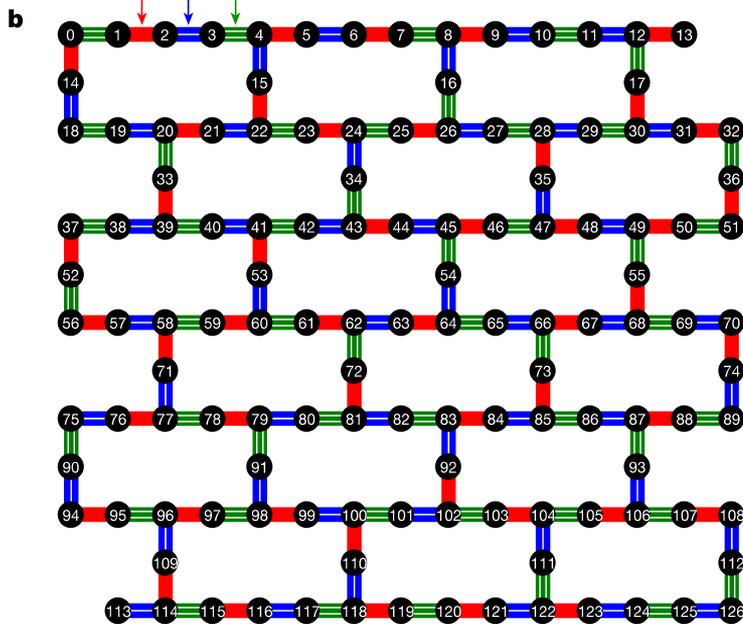
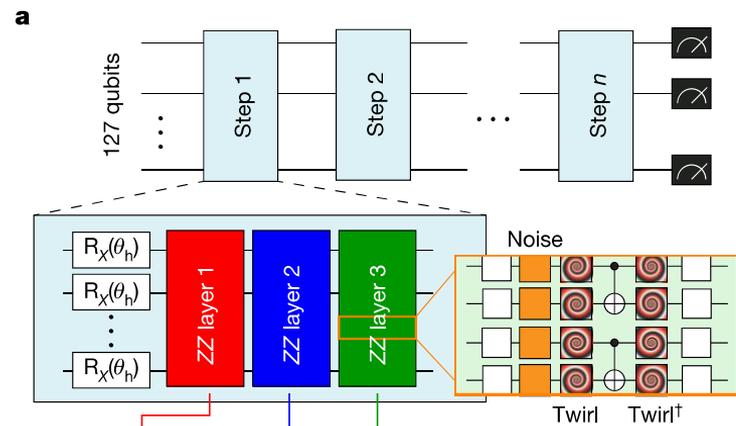
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$$H = -J \sum_{(i,j) \in E} Z_i Z_j + h \sum_{i \in V} X_i$$

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$$e^{-iHt} |\psi_0\rangle \simeq \prod_{n=1}^N e^{-iH_{ZZ}(\delta t)} e^{-iH_X(\delta t)} |\psi_0\rangle$$

- We can express  $\mathbf{R}_{ZZ}(-\frac{\pi}{2})$  with one CNOT   $\mathbf{R}_{ZZ}(-\frac{\pi}{2}) =$  
- Change single qubit gate rotation ( $\theta_h$ ) to explore different parameter range of the circuit



## Lesson 12. Utility Scale Experiment I

# 2. What made the experiment possible

We discuss what made such a large-scale experiment possible. You will see it is tremendous progress of all the fronts: hardware, software, and theory!

# What made this experiment possible?

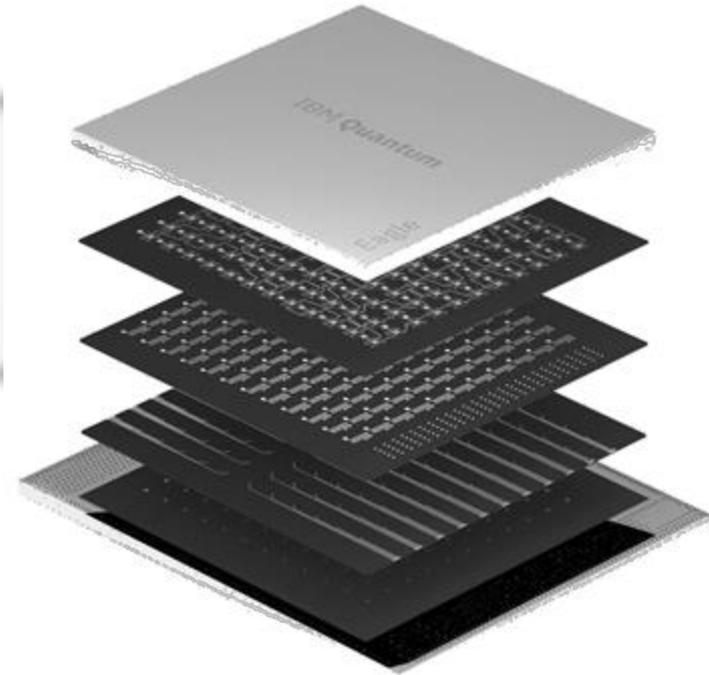
- Building a 127 qubit system



2019  
**Falcon**  
27 Qubits

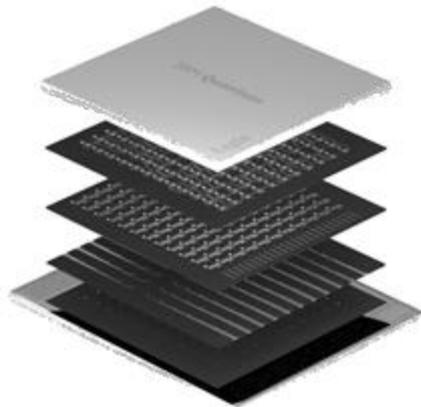
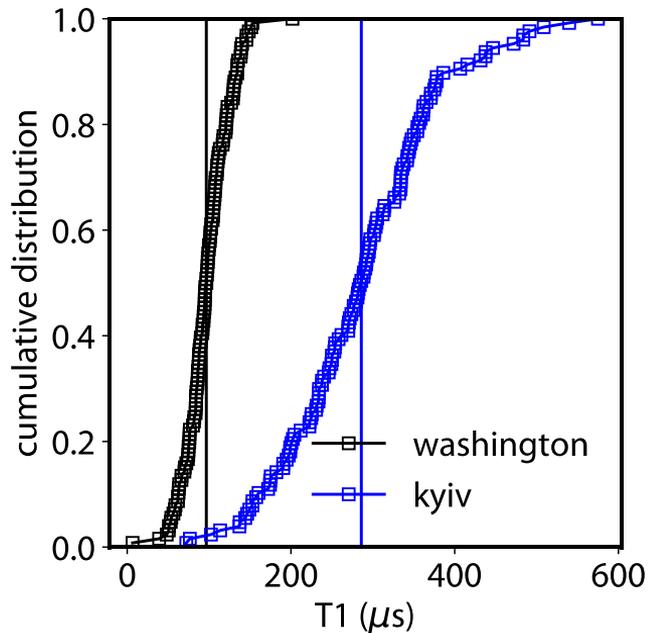
2020  
**Hummingbird**  
65 Qubits

2021  
**Eagle**  
127 Qubits



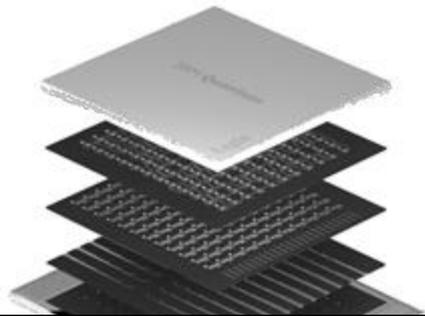
# What made this experiment possible?

- Building a 127 qubit system
- **Coherence improvements**

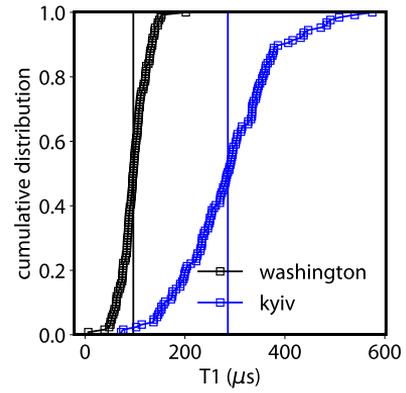
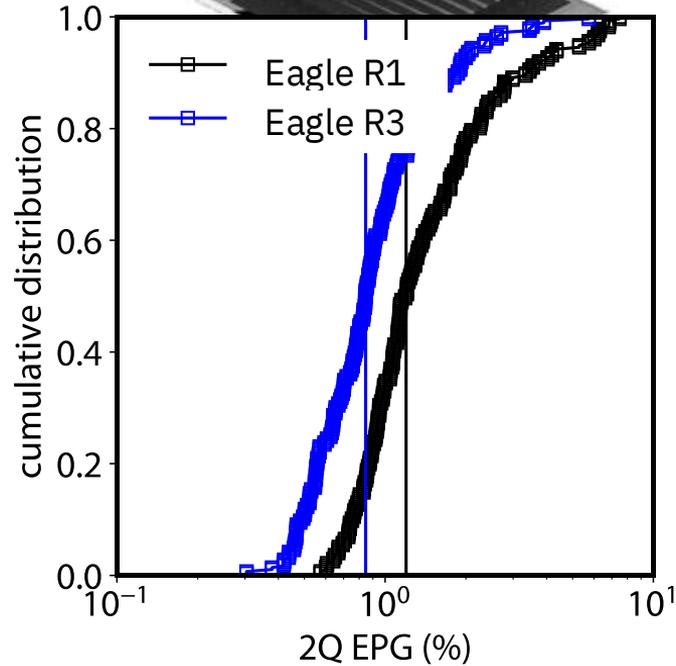
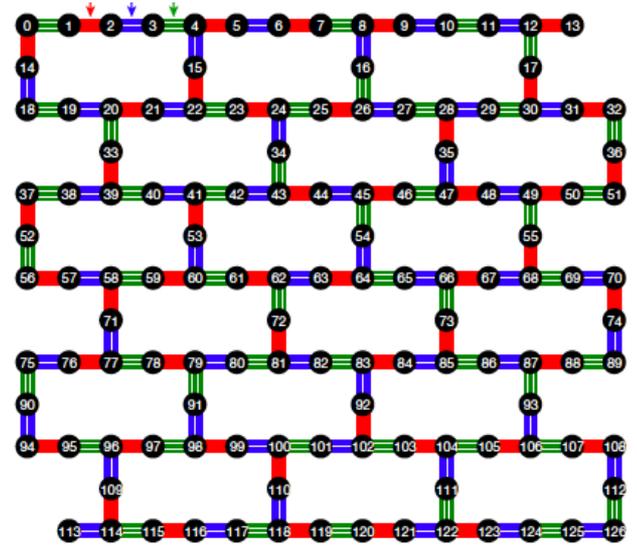


# What made this experiment possible?

- Building a 127 qubit system
- Coherence improvements
- **Advances in device calibration**



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# What made this experiment possible?

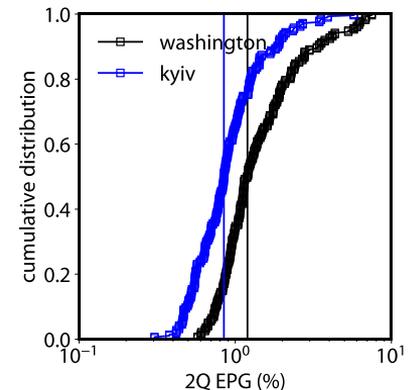
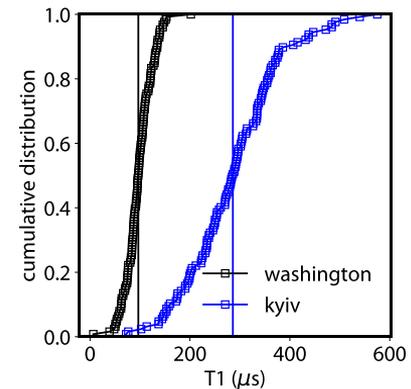
- Building a 127 qubit system
- Coherence improvements
- Advances in device calibration
- **Noise modeling & error mitigation**

(1) Scalable noise characterization

(2) More accurate noise amplification



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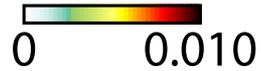
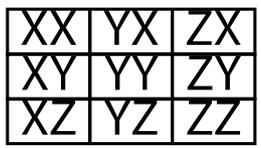
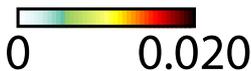
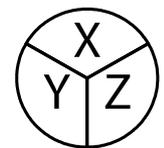


# An efficiently learnable noise model



Reduced model complexity:

$\sim 4^{127} \rightarrow \sim 1700$   
parameters

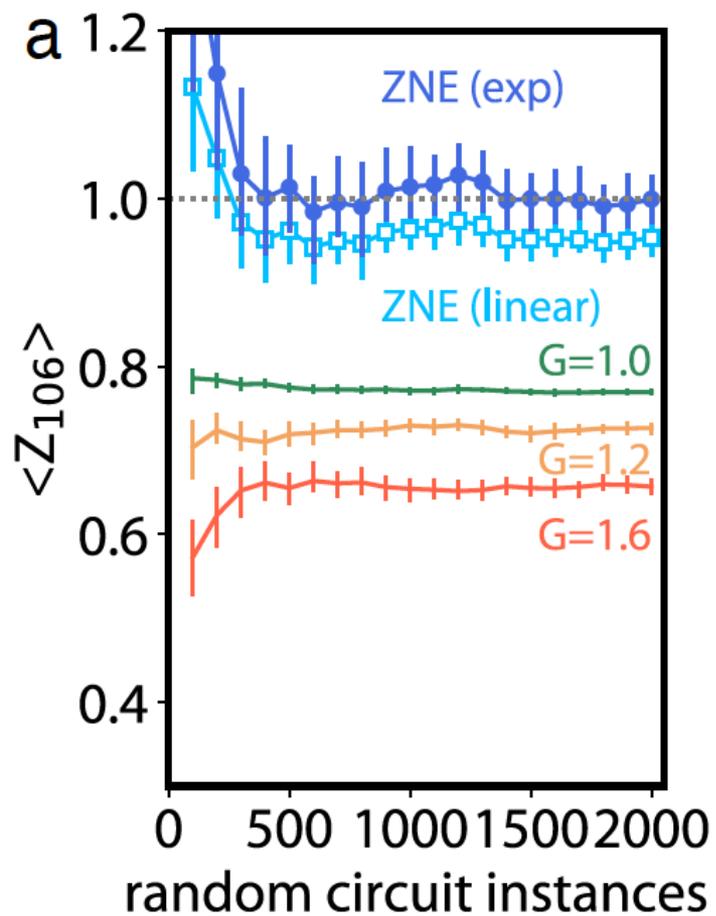


## Lesson 12. Utility Scale Experiment I

# 3. Error Mitigation and Experimental Results

We explain ZNE (Zero Noise Extrapolation with PEA (Probabilistic Error Amplification)), and show the results of running the circuit with 127 qubits x 15 entangling layers on a real device.

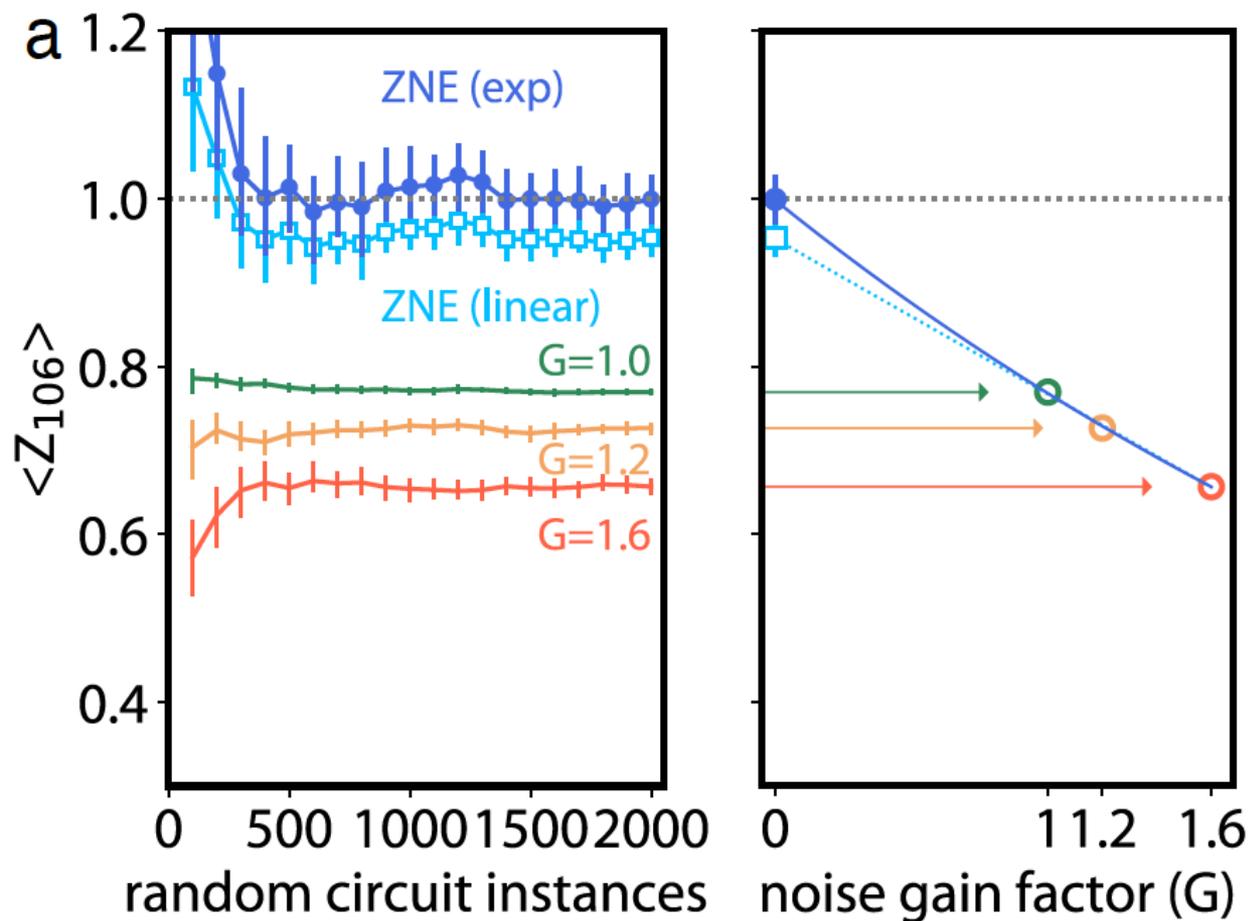
# ZNE using probabilistic error amplification



Exponential extrapolation:

1. Endo et al PRX 8, 031027 (2018).
2. Z. Cai, npj Quantum Information 7, 80 (2021)

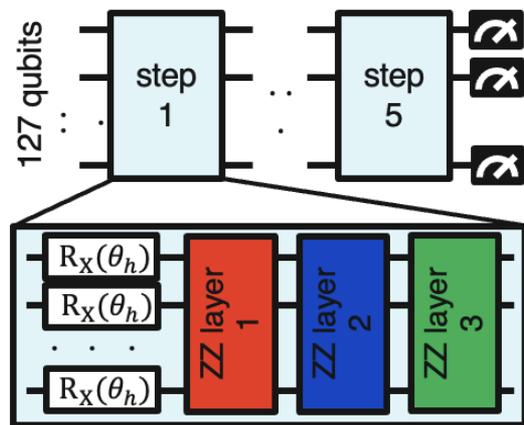
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Exponential extrapolation:

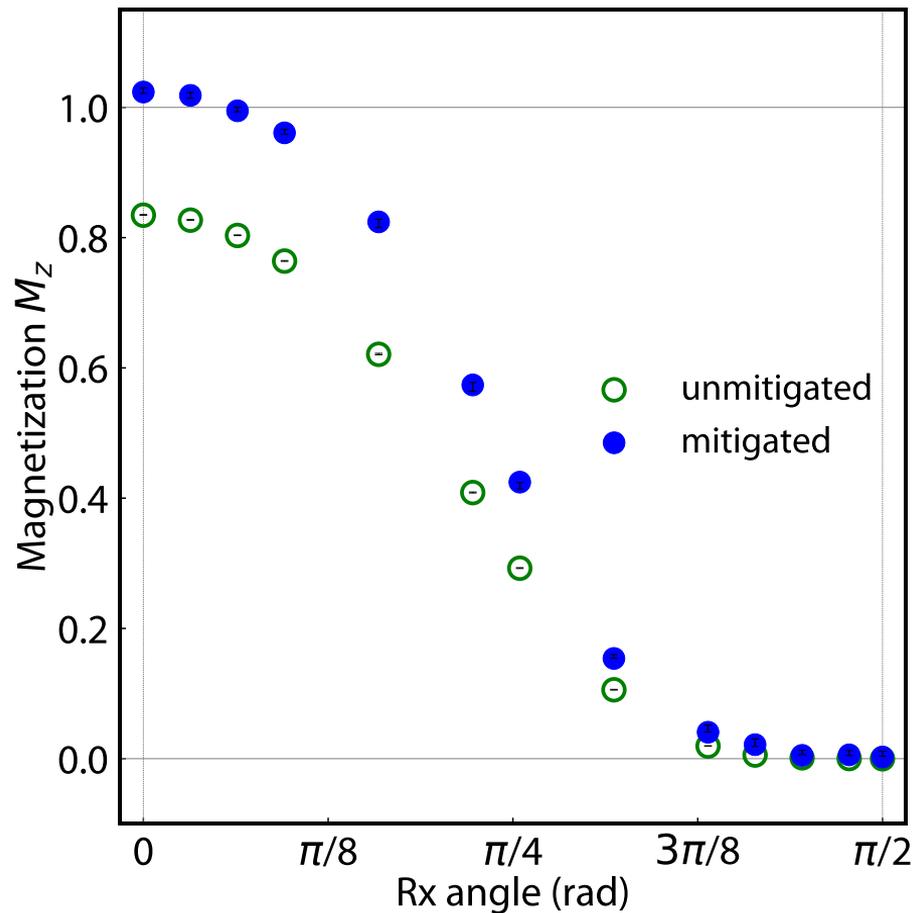
1. Endo et al PRX 8, 031027 (2018).
2. Z. Cai, npj Quantum Information 7, 80 (2021)

# 127 qubit x 15 entangling layers



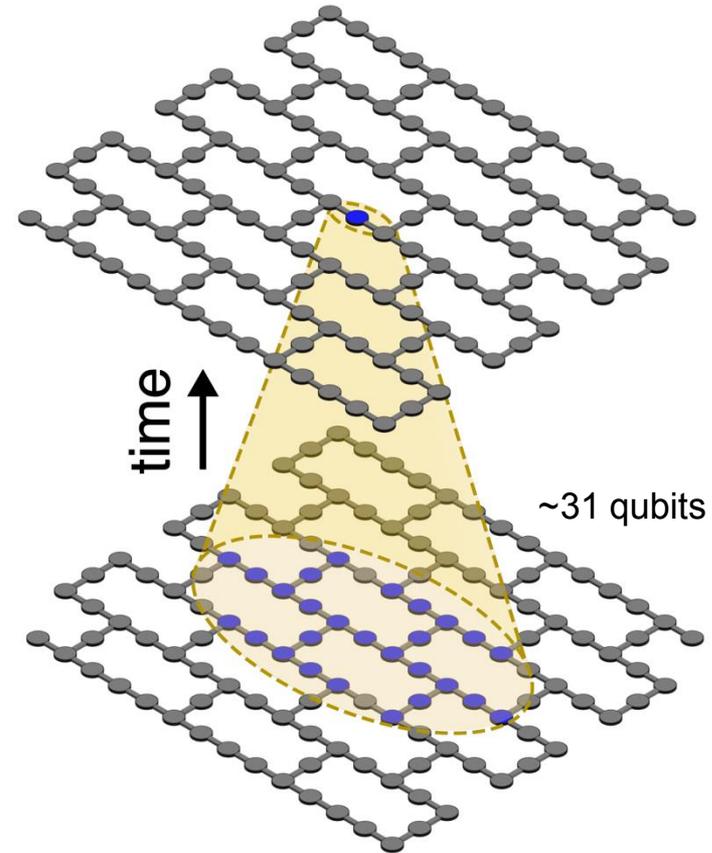
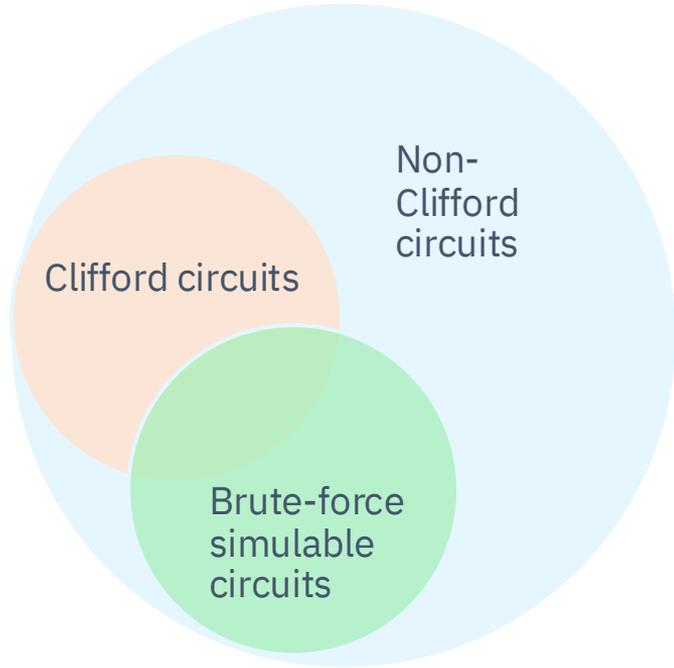
Varying  $\theta_h$

$$\langle M_z \rangle = \frac{1}{127} \sum_i \langle M_{z,i} \rangle$$



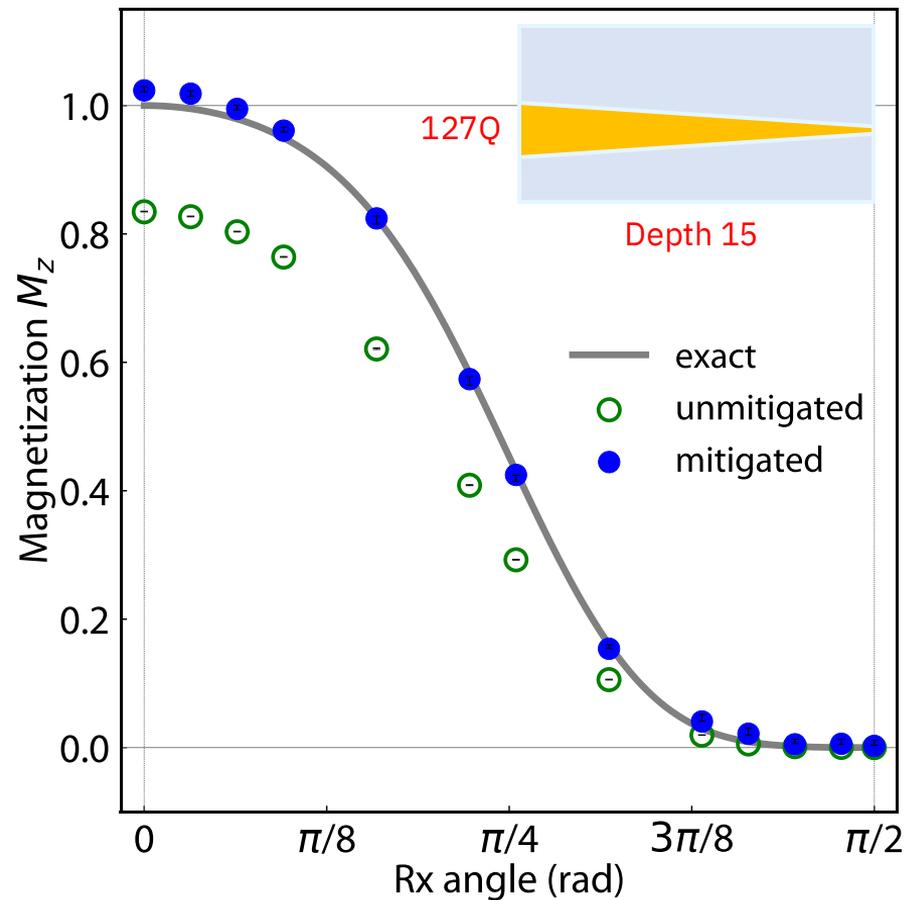
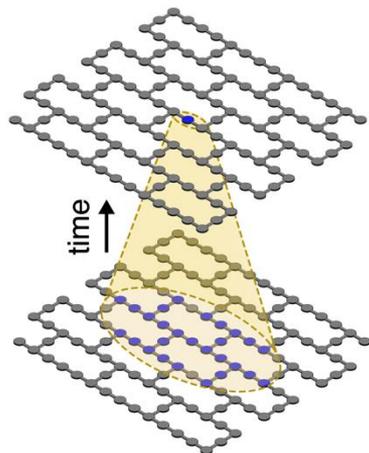
# 127 qubit x 15 entangling layers

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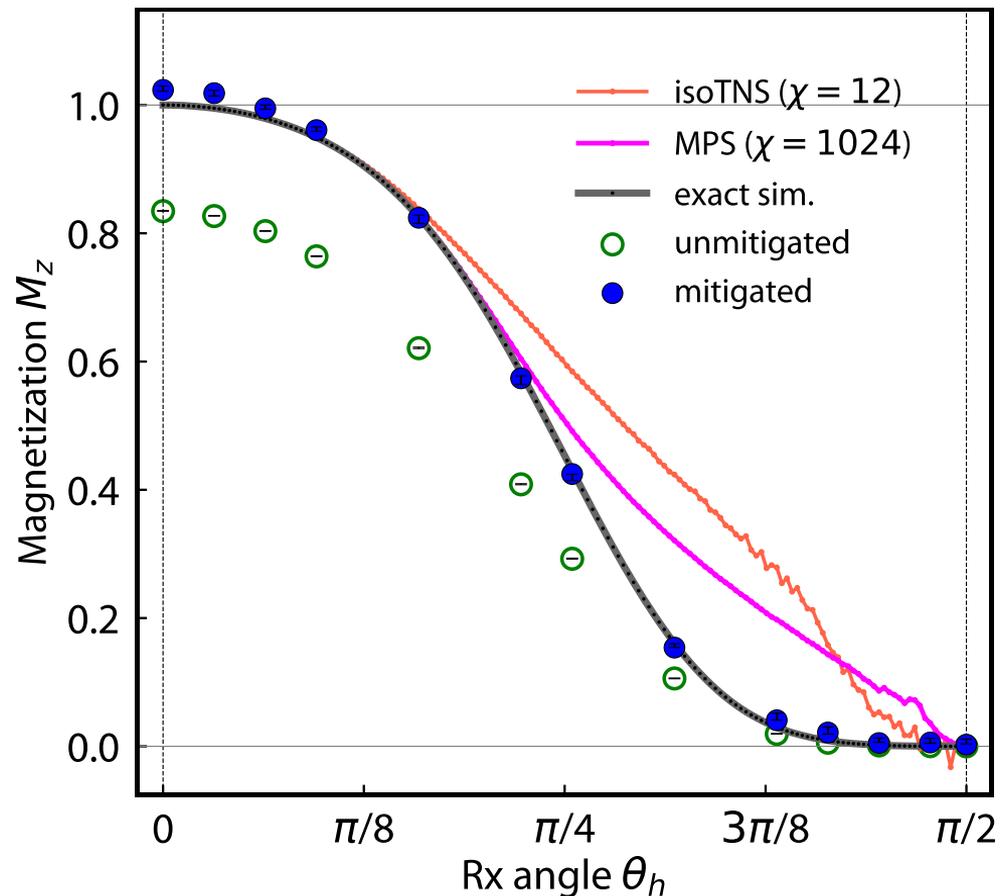
# 127 qubit x 15 entangling layers

- Light cone reductions enable exact verification at Non-Clifford points



# 127 qubit x 15 entangling layers

- Light cone reductions enable exact verification at Non-Clifford points
- MPS and isoTNS methods begin to fail in the limit of increasing entanglement

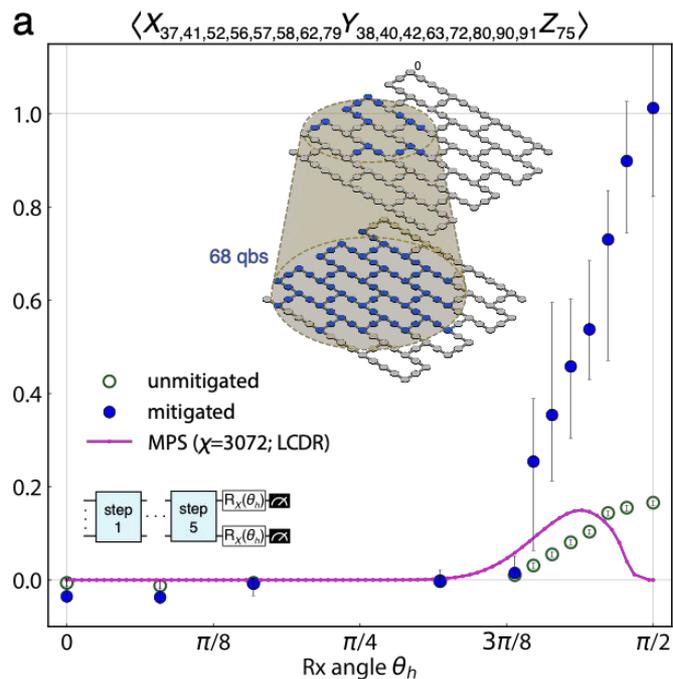


## Lesson 12. Utility Scale Experiment I

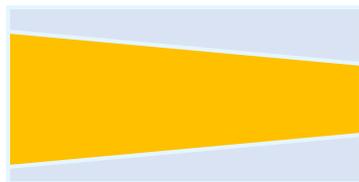
# 4. More Experimental Results

We present the results of running larger circuits which are beyond exact verification, pointing out different classical methods end up with different results. We also summarize the characteristics of the circuit of the utility-scale experiment.

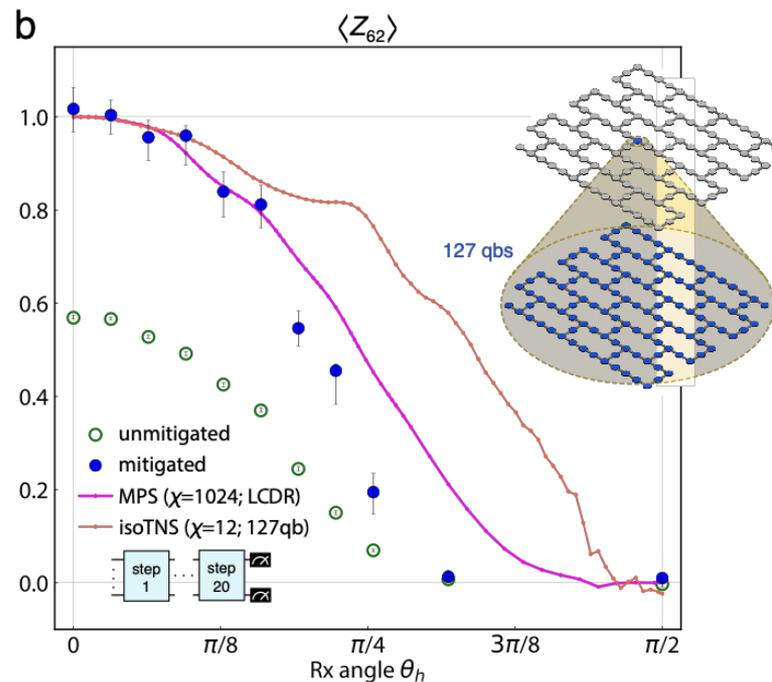
# Beyond exactly verifiable circuit



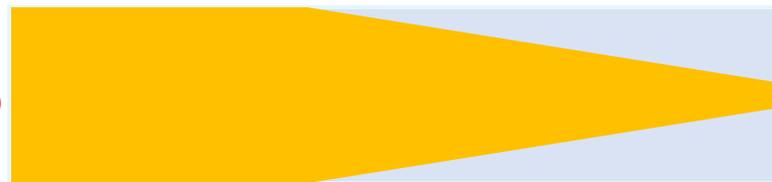
127Q



Depth 15



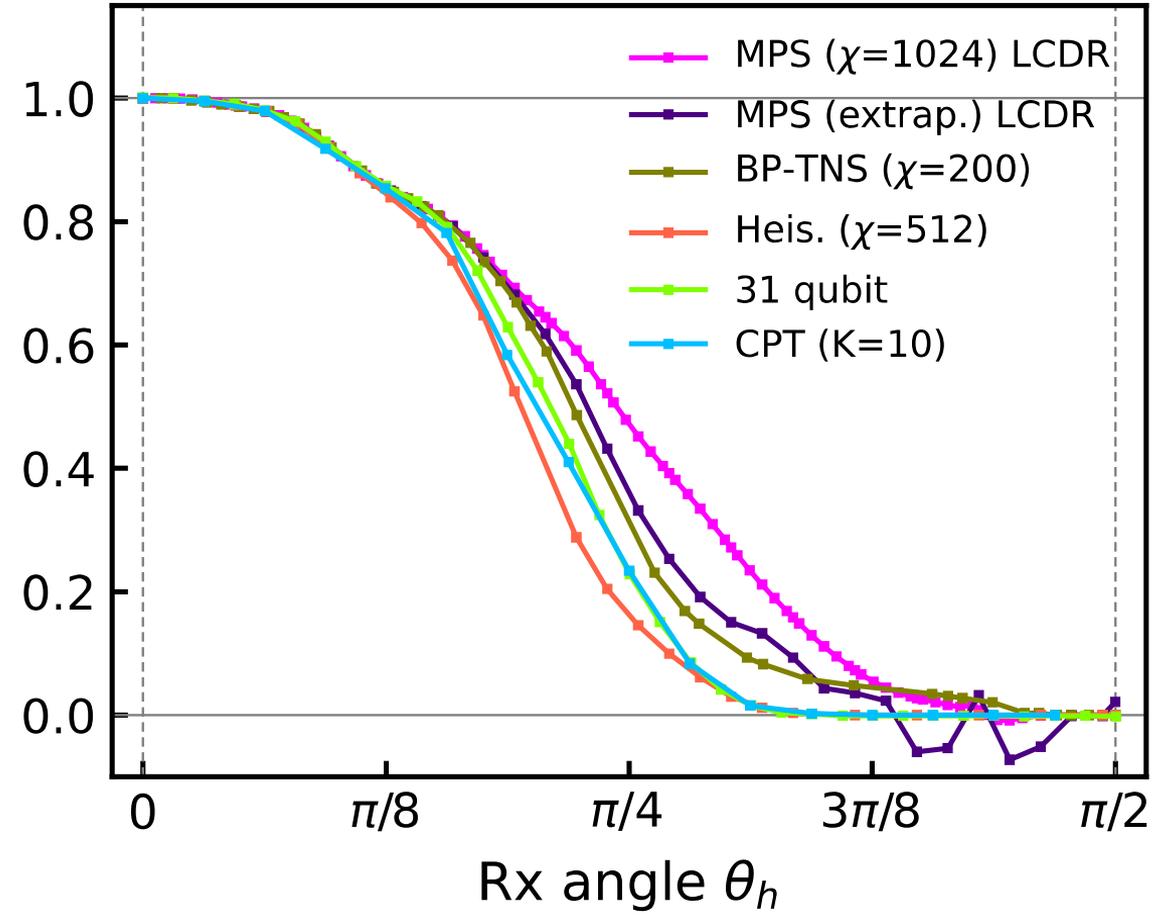
127Q



Depth 60

# Classical benchmarking of ZNE beyond exact verification

$$\langle Z_{62} \rangle$$



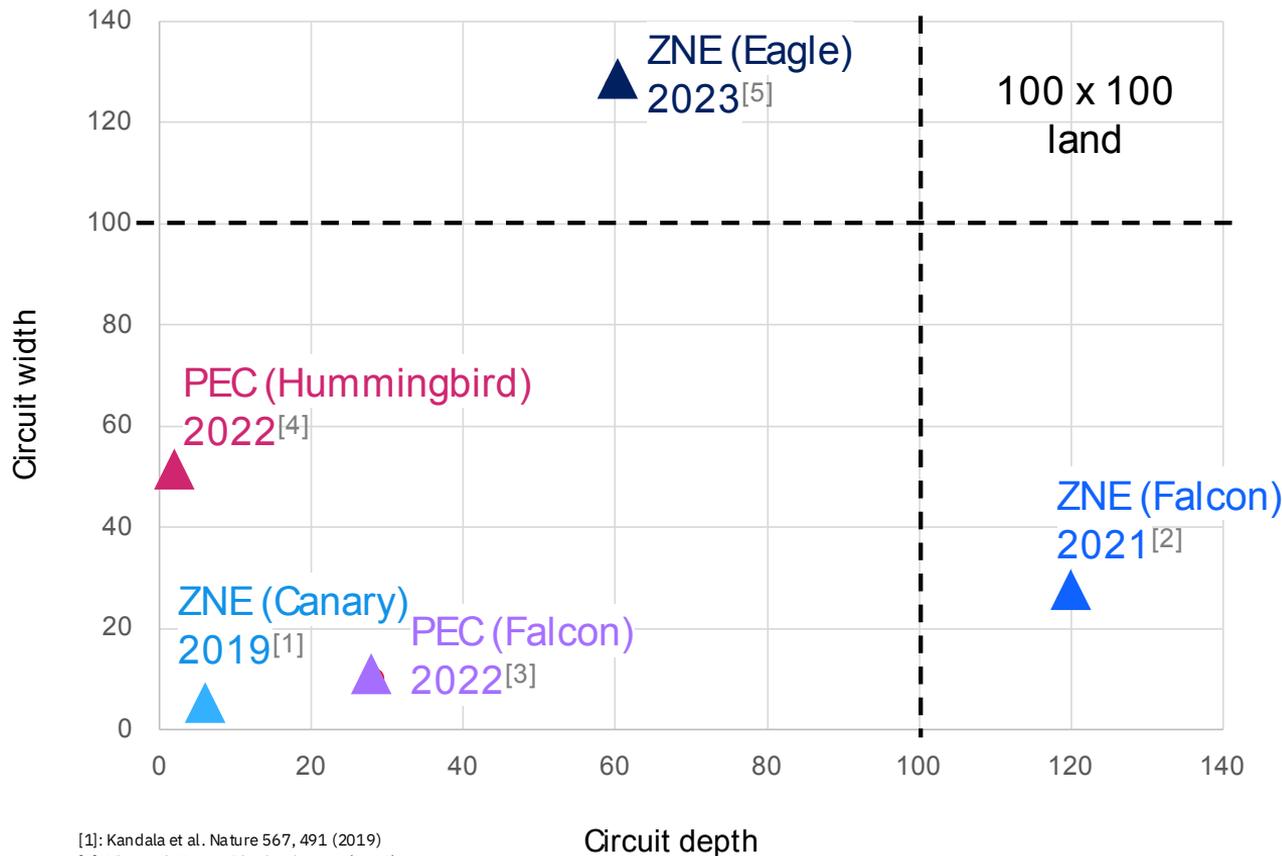
arXiv:2306.14887 (BP-TNS)  
arXiv:2306.16372 (CPT)  
arXiv:2306.15970 (31 qubit)  
arXiv:2306.17839 (MPS extrap., Heis.)

*Quantum computers today can provide reliable results at a scale that is beyond exact, brute-force classical computation.*

*(this is not a quantum advantage claim)*

# Mapping the path to useful quantum computing

100x100 land is where we predict we can start looking for quantum advantage



[1]: Kandala et al. Nature 567, 491 (2019)

[2]: Kim et al. Nature Physics, in prep (2021)

[3]: van den Berg et al. arXiv:2201.09866 (2022)

[4]: Temme et al. <https://research.ibm.com/blog/gammabar-for-quantum-advantage>

[5]: Kim et al., Nature **618**, 500–505 (2023), O. Shtanko, et al. arXiv:2307.07552 (2023)

# After all, what does this experiment look like?

#qubits x #entangling gates	127 x 60
qubit mapping	manual
2 qubit placement	manual = hardware topology
2 qubit gate / 1 qubit gate	logical (CNOT, RX, S, Sqrt(Y),...)
gate error mitigation	Probabilistic Error Amplification (PEA) + Zero Noise Extrapolation (ZNE)
read error mitigation	Twirled Readout Error eXtinction (TRES)

# References

- Kim, Y., Eddins, A., Anand, S. *et al.* Evidence for the utility of quantum computing before fault tolerance. *Nature* **618**, 500–505 (2023). <https://doi.org/10.1038/>
- Evidence for the Utility of Quantum Computing before Fault Tolerance | Qiskit Seminar Series, <https://www.youtube.com/watch?v=hIUydsivY9k>

Break

*We then have a hands-on session.*

Thank you