Utility Scale Experiment I

2024/07/05

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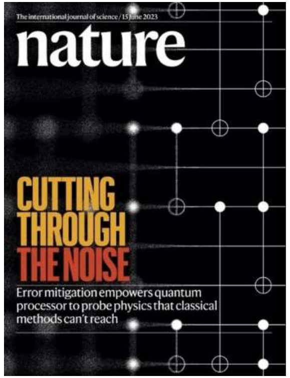
Outline

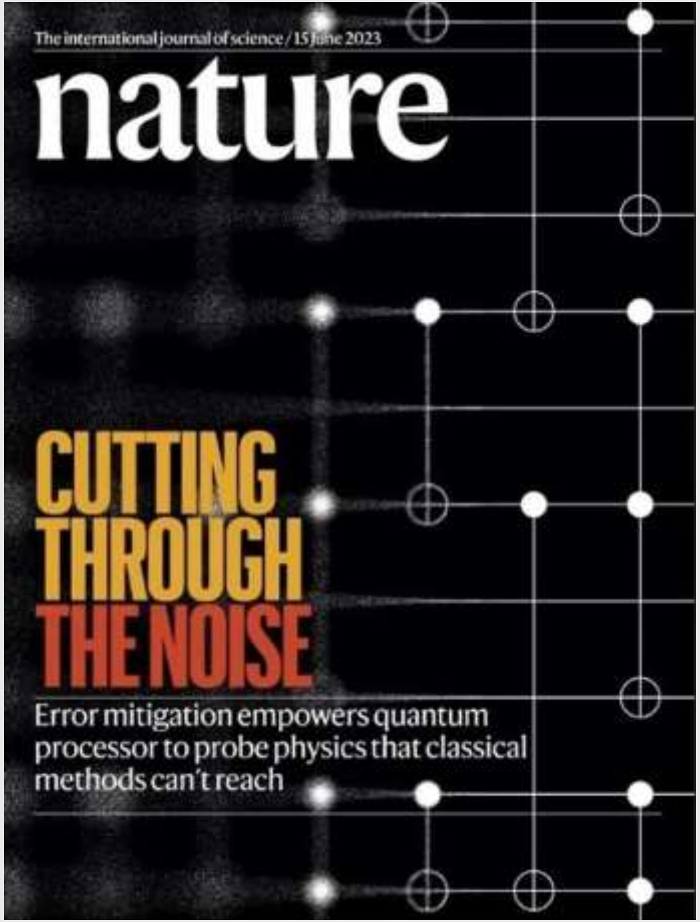
- Introduction of the Utility Paper
  - published in Nature Vol 618, 15 June 2023
  - ushered in an era of Quantum Utility

<Break>

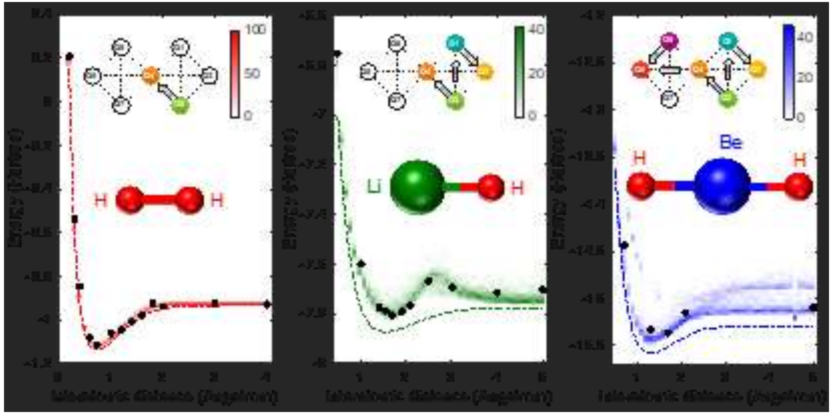
- Jupyter notebook with
  - a simpler experiment based on the Utility paper
  - your assignment



A new era has begun: Quantum Utility



6 Years ago..



H
H
Li
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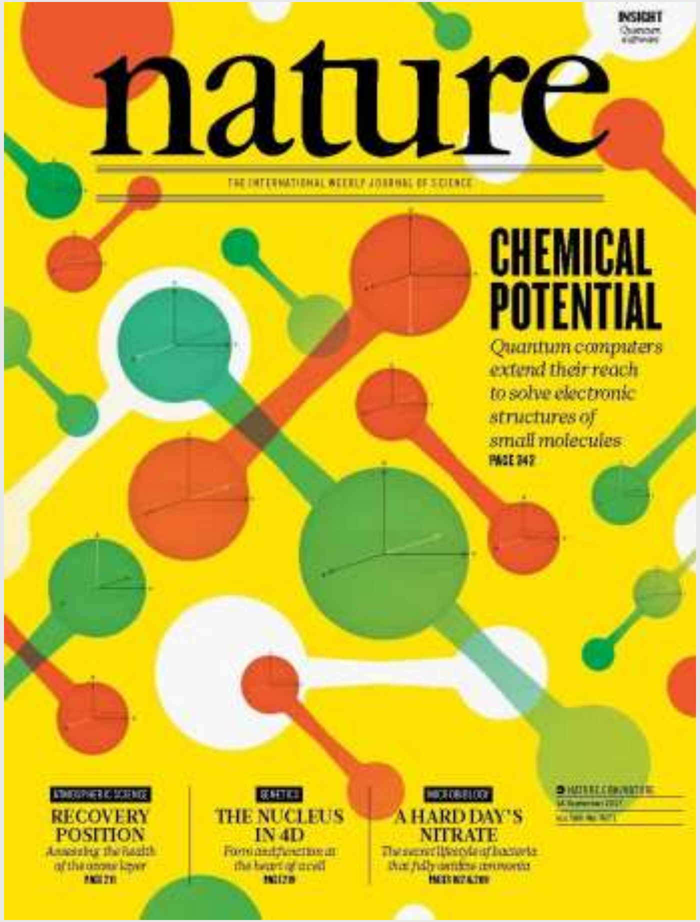
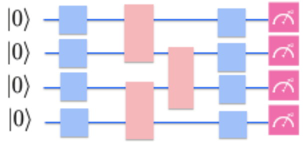
H
Be
H

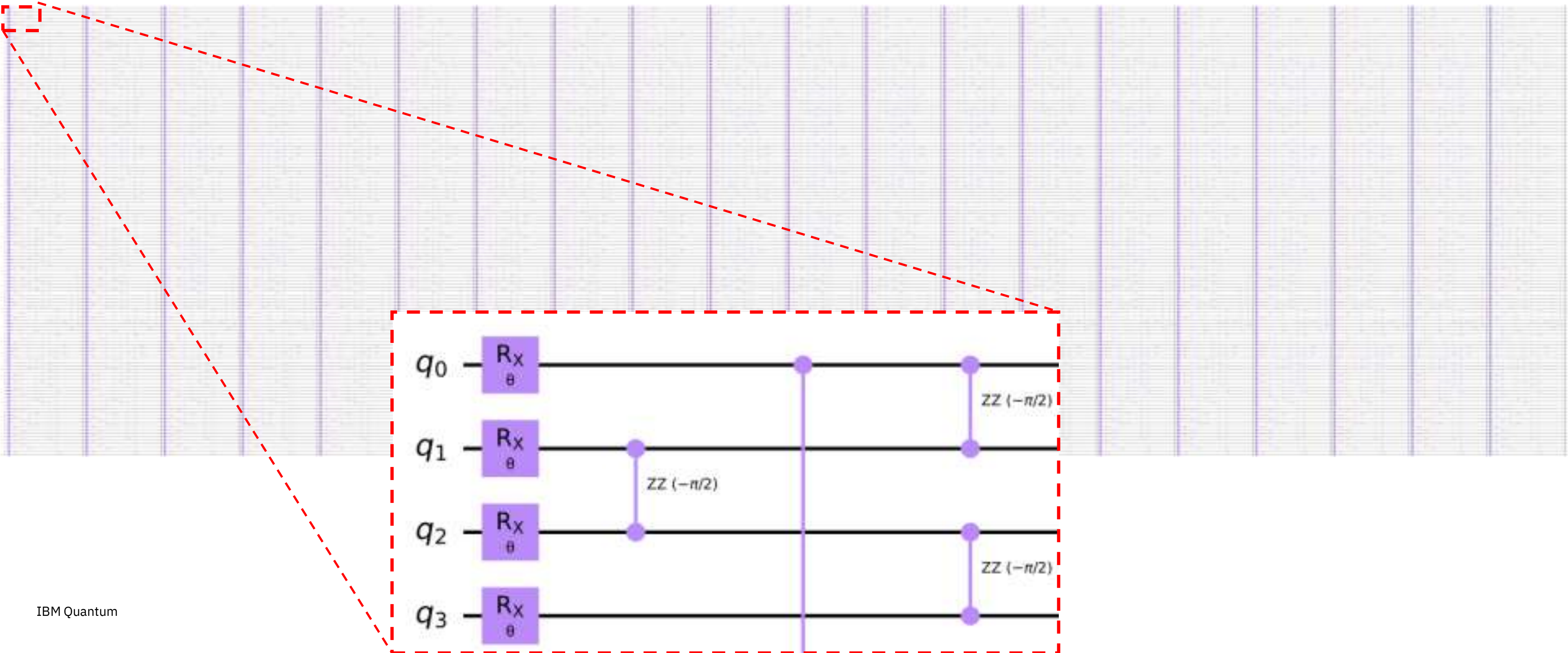


nature
CHEMICAL POTENTIAL
Quantum computers extend their reach to solve electronic structures of small molecules
RECOVERY POSITION
THE NUCLEUS IN 4D
A HARD DAY'S NITRATE

127 qubit x 60 entangling layers



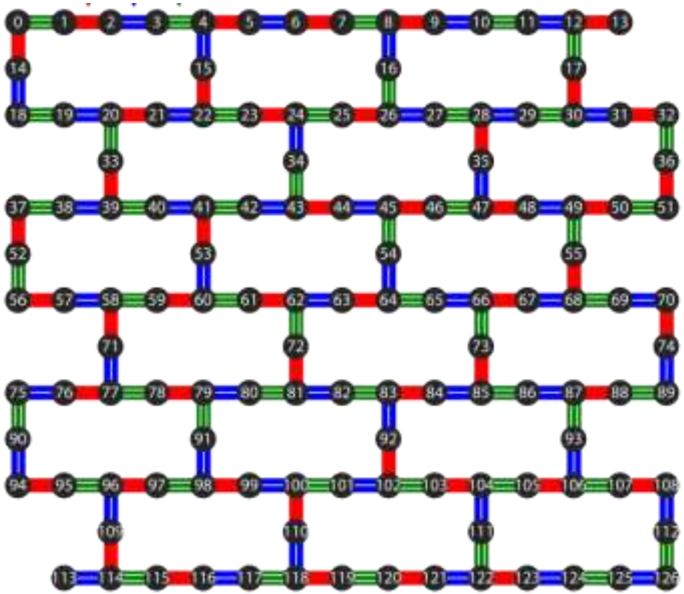
2017: 4 qubit, depth 2



The experiment

- Spin lattice shares hardware topology (127Q device)

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



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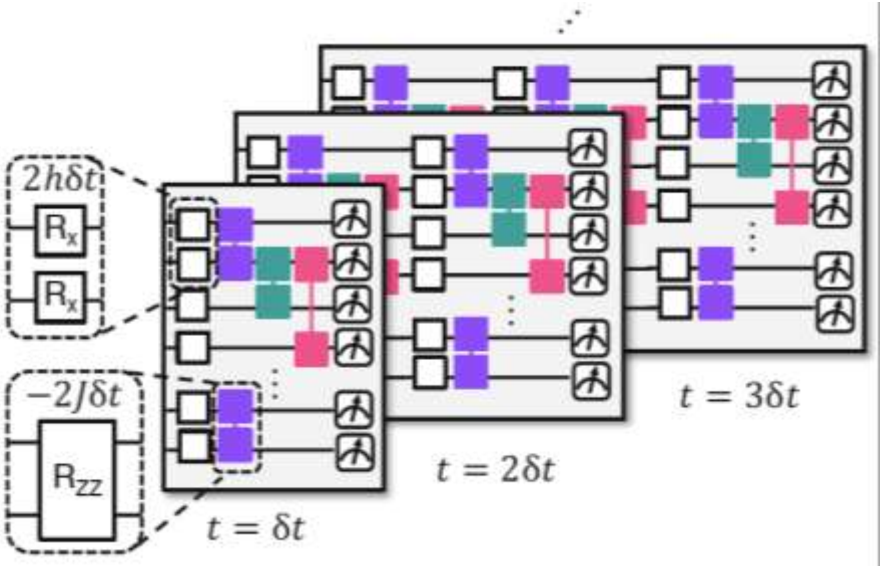
$$H = -J \sum_{(i,j)\in E} Z_i Z_j + h \sum_{i\in V} X_i$$

- (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



The experiment

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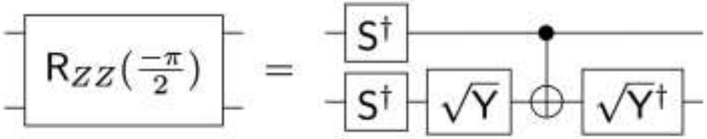
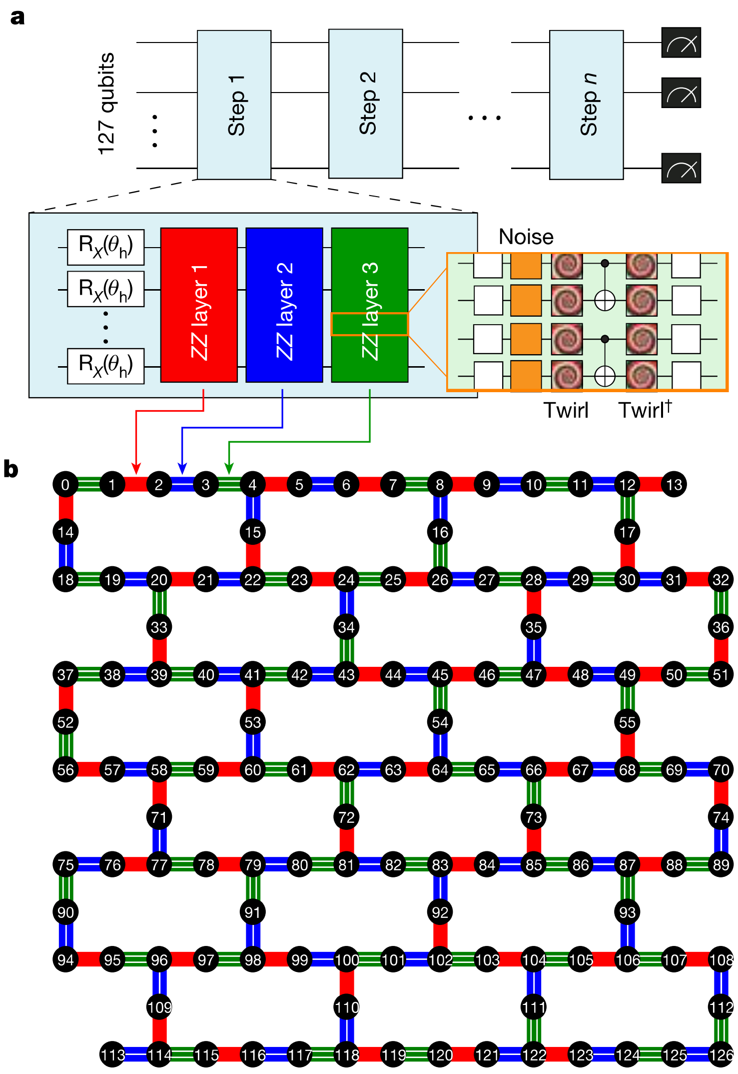
  - We can express $\mathbf{R_{ZZ}}(-\frac{\boldsymbol{\pi}}{\mathbf{2}})$ with one CNOT 

  - Change single qubit gate rotation $(\boldsymbol{\theta_h})$ to explore different parameter range of the circuit


a
127 qubits
Step 1
Step 2
Step n
$R_X(\theta_h)$
ZZ layer 1
ZZ layer 2
ZZ layer 3
Noise
Twirl
Twirl†
b

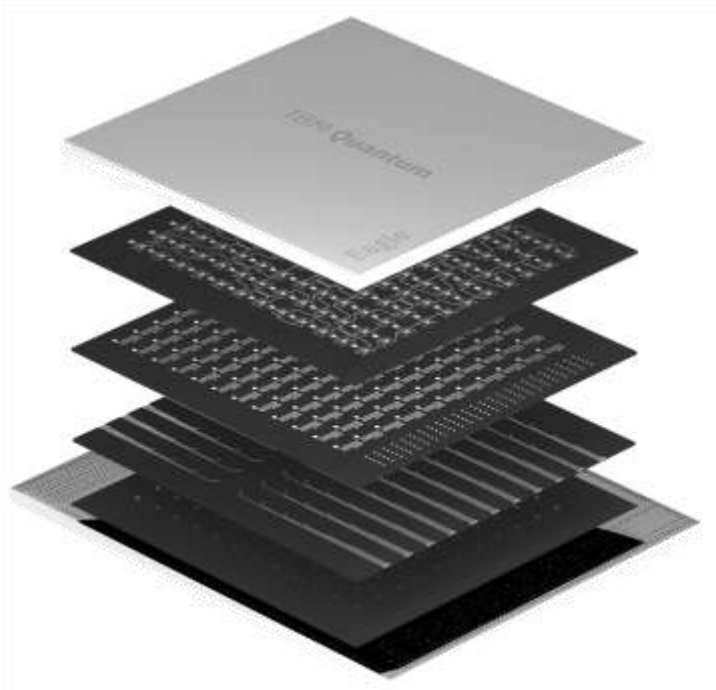
What made this experiment possible?

- Building a 127 qubit system

2019
Falcon
27 Qubits

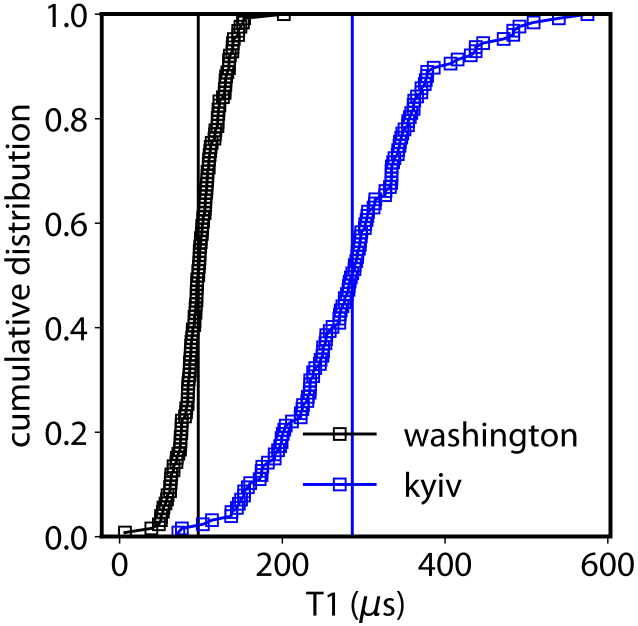
2020
Hummingbird
65 Qubits

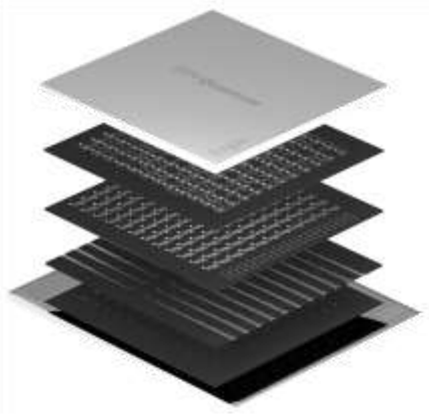
2021
Eagle
127 Qubits



What made this experiment possible?

- Building a 127 qubit system
- Coherence improvements

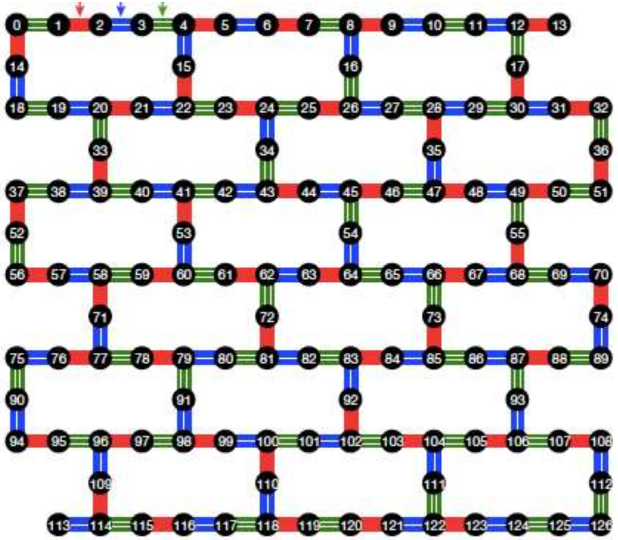


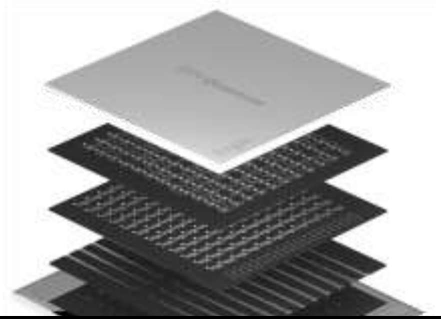


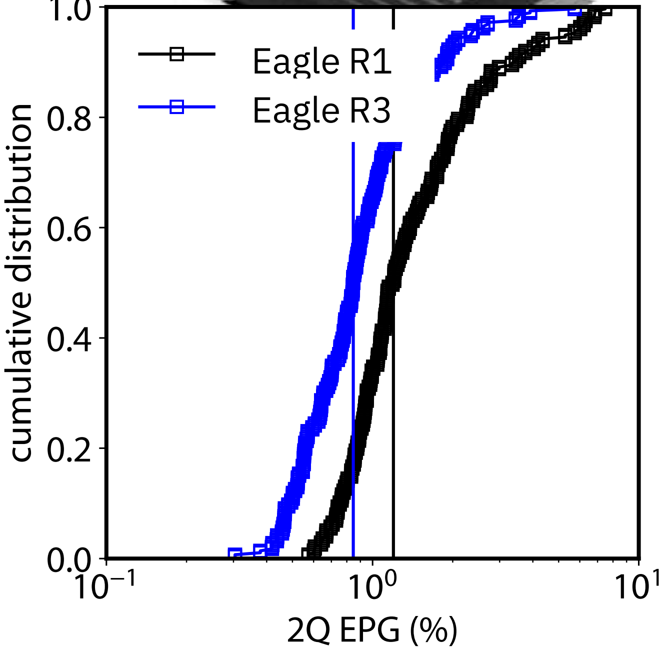
What made this experiment possible?

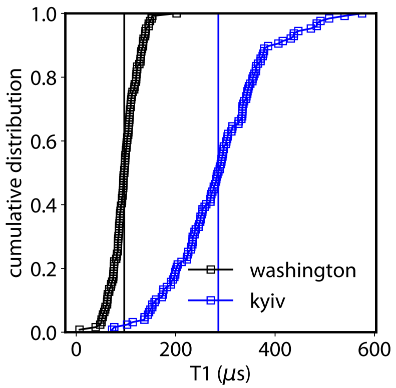
IBM **Quantum**

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









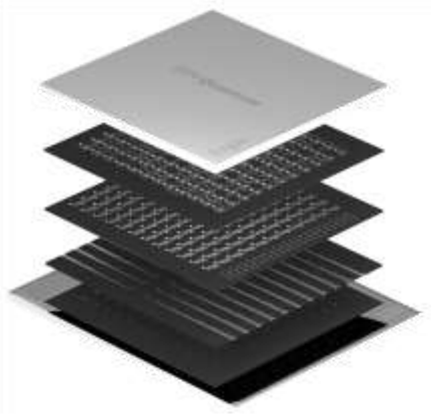
What made this experiment possible?

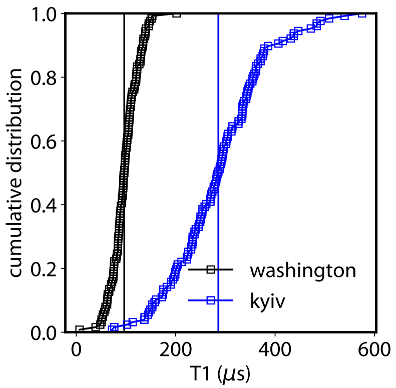
IBM **Quantum**

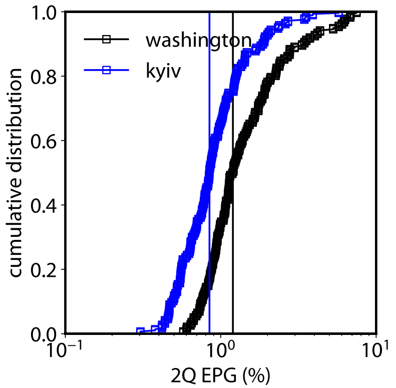
- Building a 127 qubit system
- Coherence improvements
- Advances in device calibration
- Noise modeling & error mitigation

(1) Scalable noise characterization

(2) More accurate noise amplification







An efficiently learnable noise model

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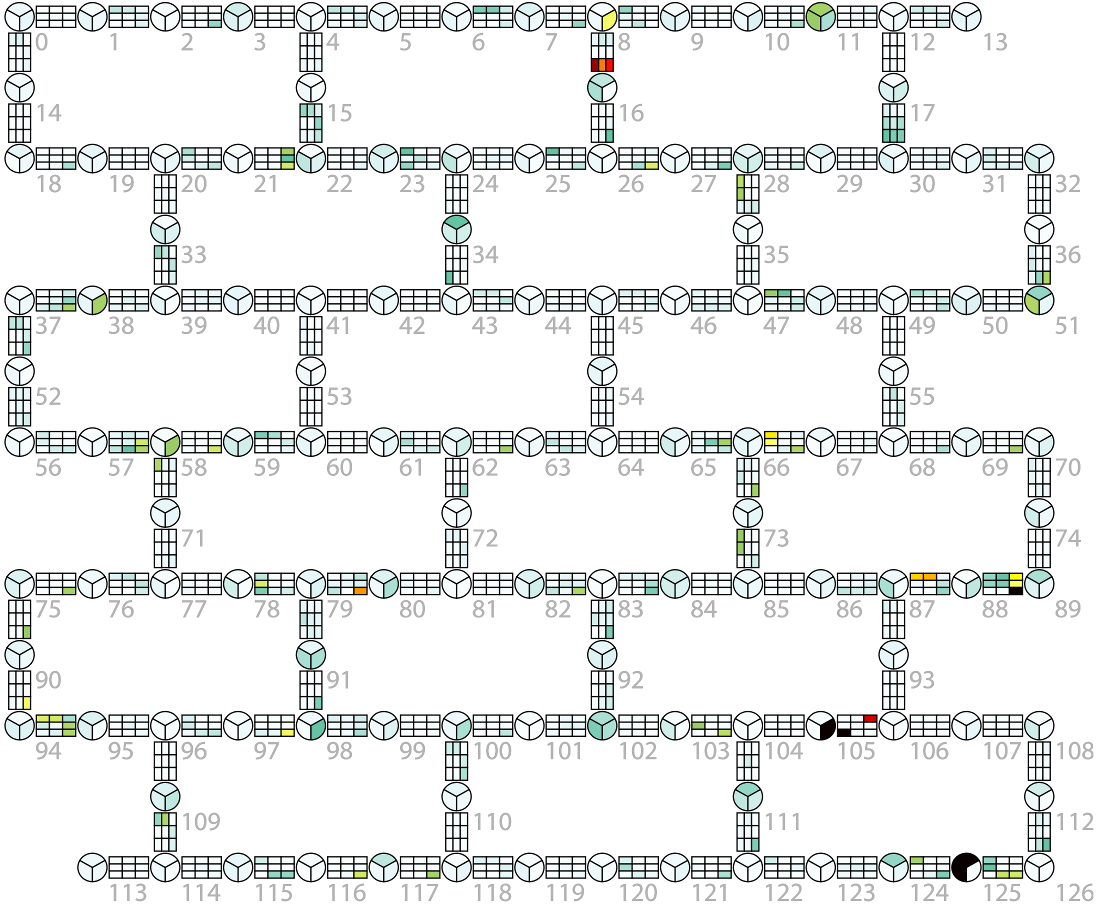
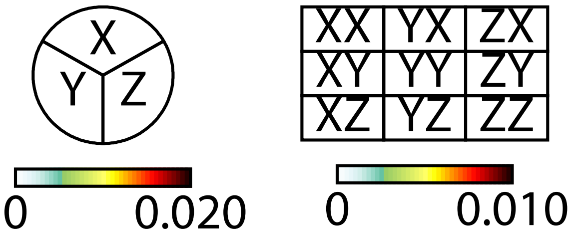


Reduced model complexity:

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



ZNE using probabilistic error amplification

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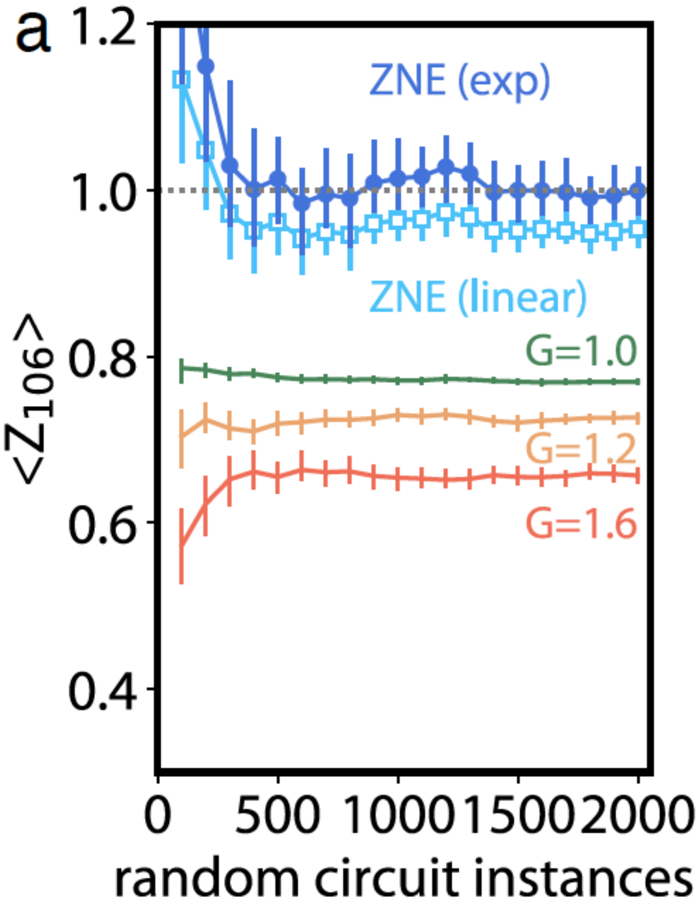
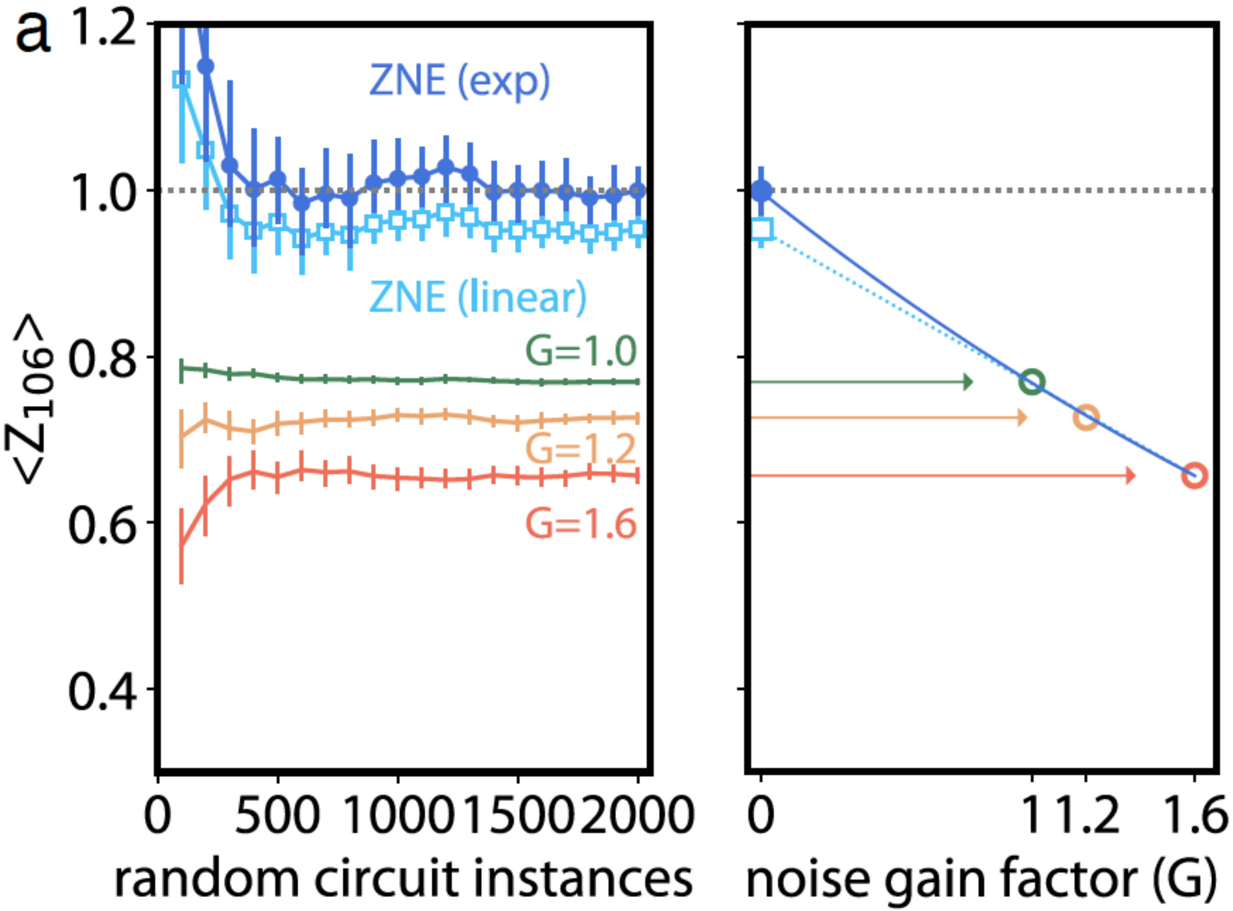


Exponential extrapolation:

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

ZNE using probabilistic error amplification

IBM **Quantum**



Exponential extrapolation:

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127 qubit x 15 entangling layers

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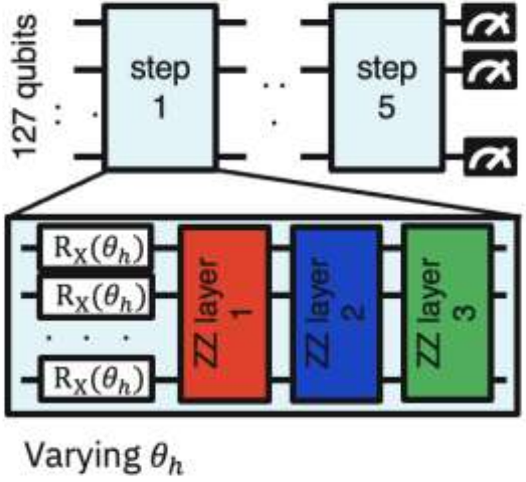
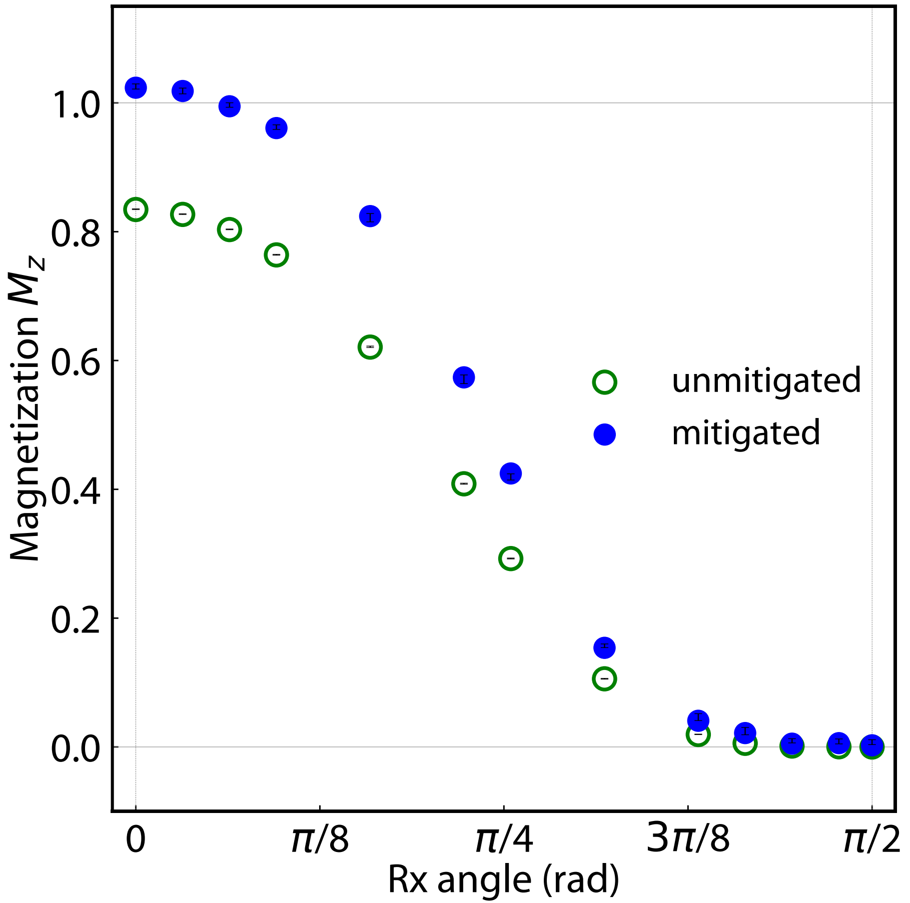
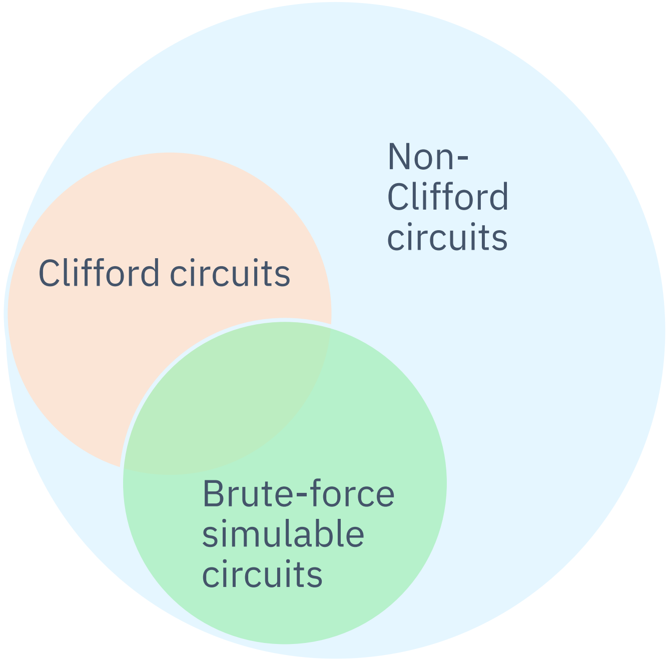
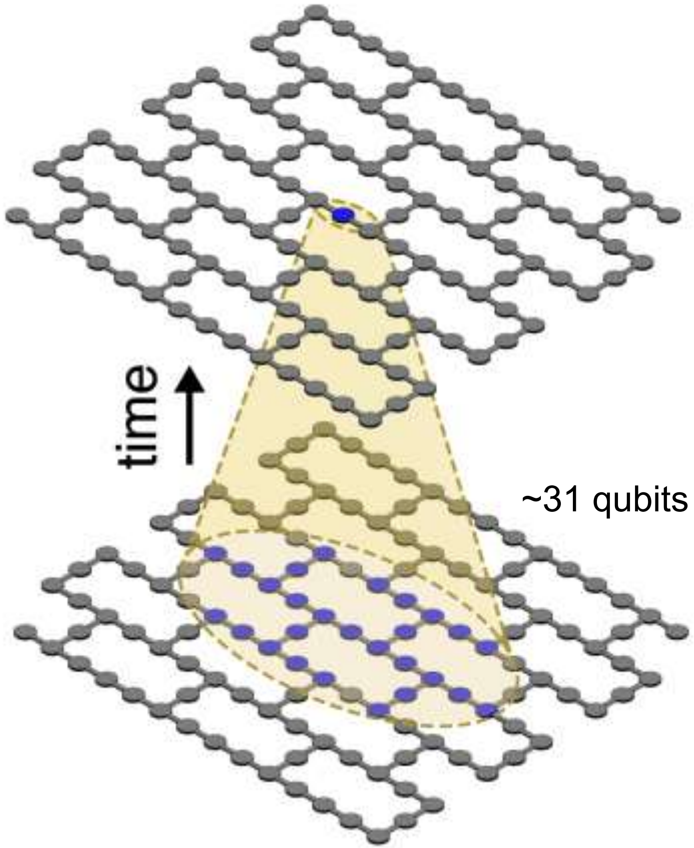


$$\langle M_z \rangle = \frac{1}{127} \sum_i \langle M_{z,i} \rangle$$



127 qubit x 15 entangling layers

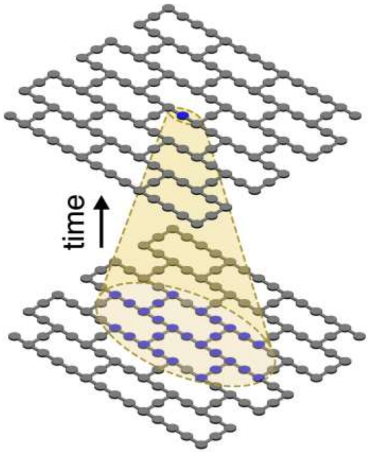


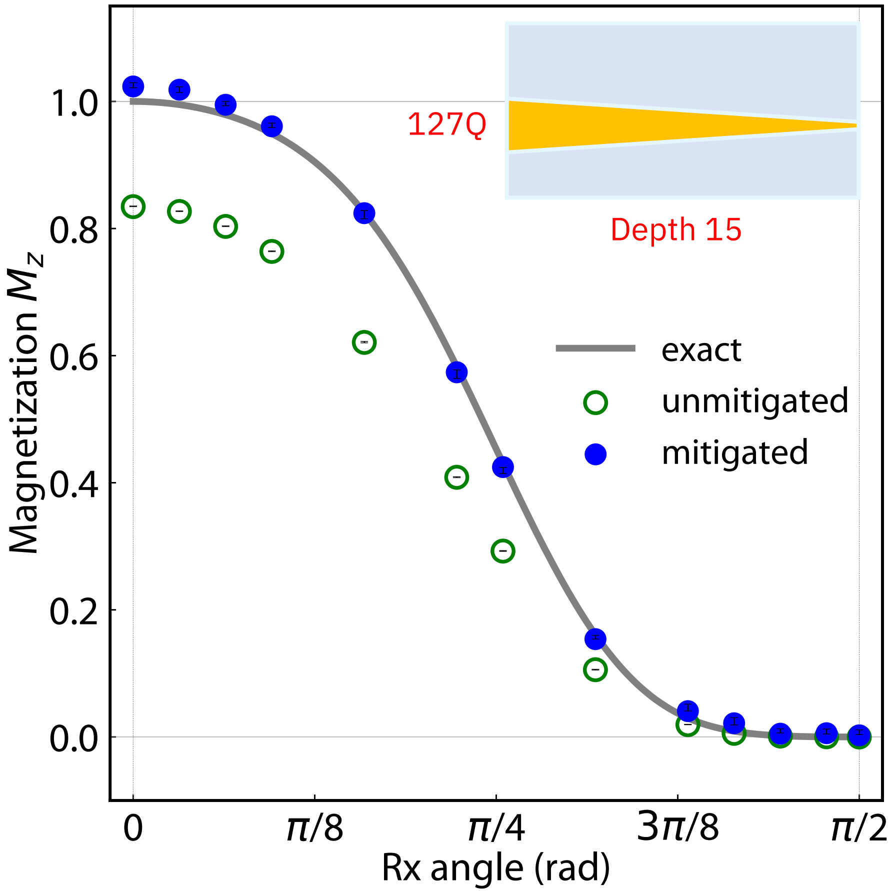


127 qubit x 15 entangling layers

IBM **Quantum**

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



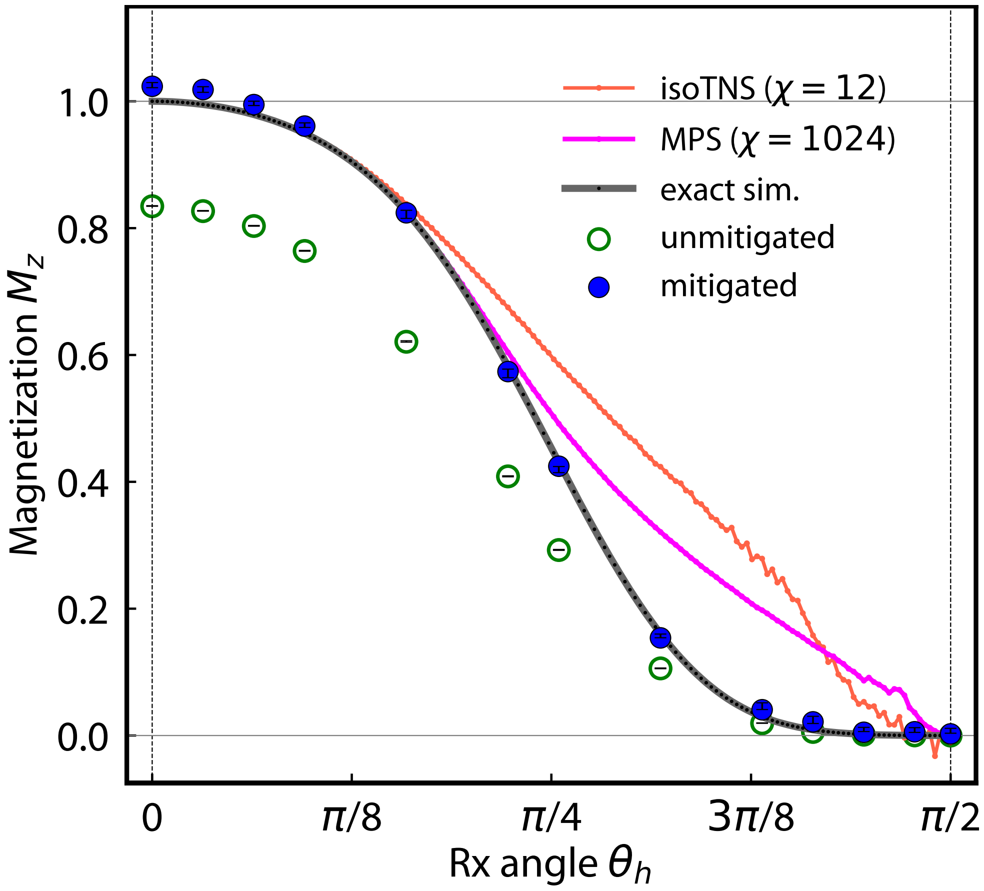


127 qubit x 15 entangling layers

IBM **Quantum**

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

- MPS and isoTNS methods begin to fail in the limit of increasing entanglement



Beyond exactly verifiable circuit

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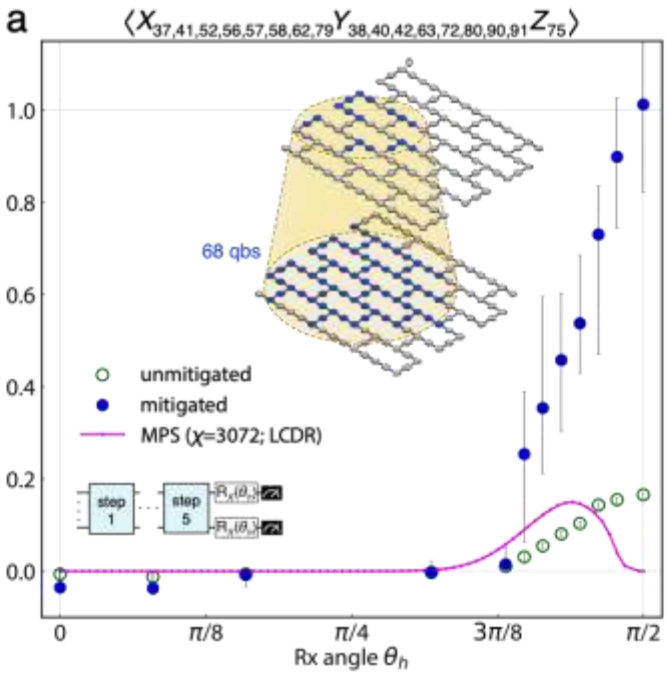
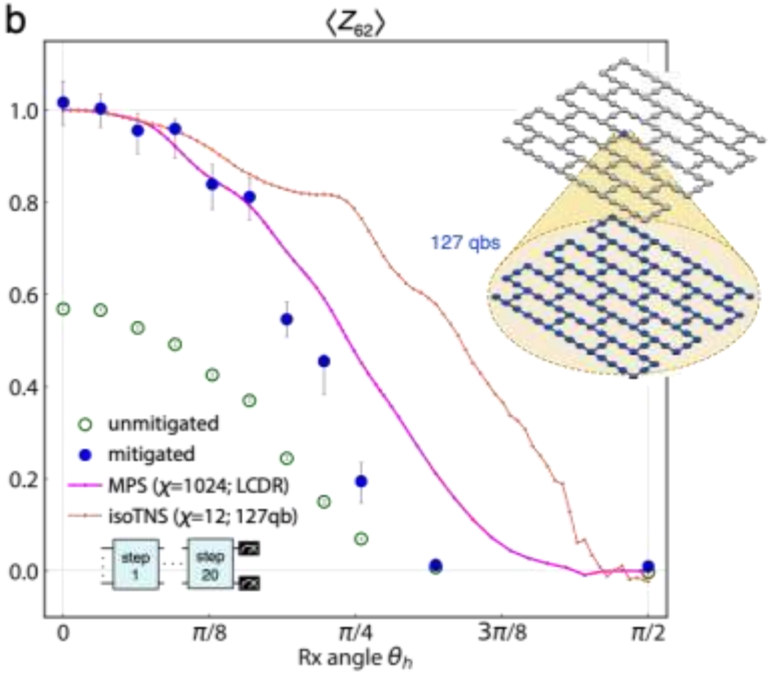
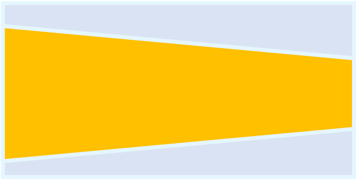


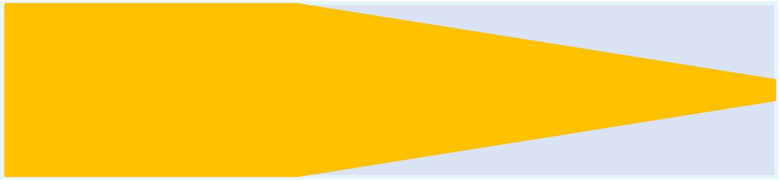


127Q



Depth 15

127Q



Depth 60

Classical benchmarking of ZNE beyond exact verification

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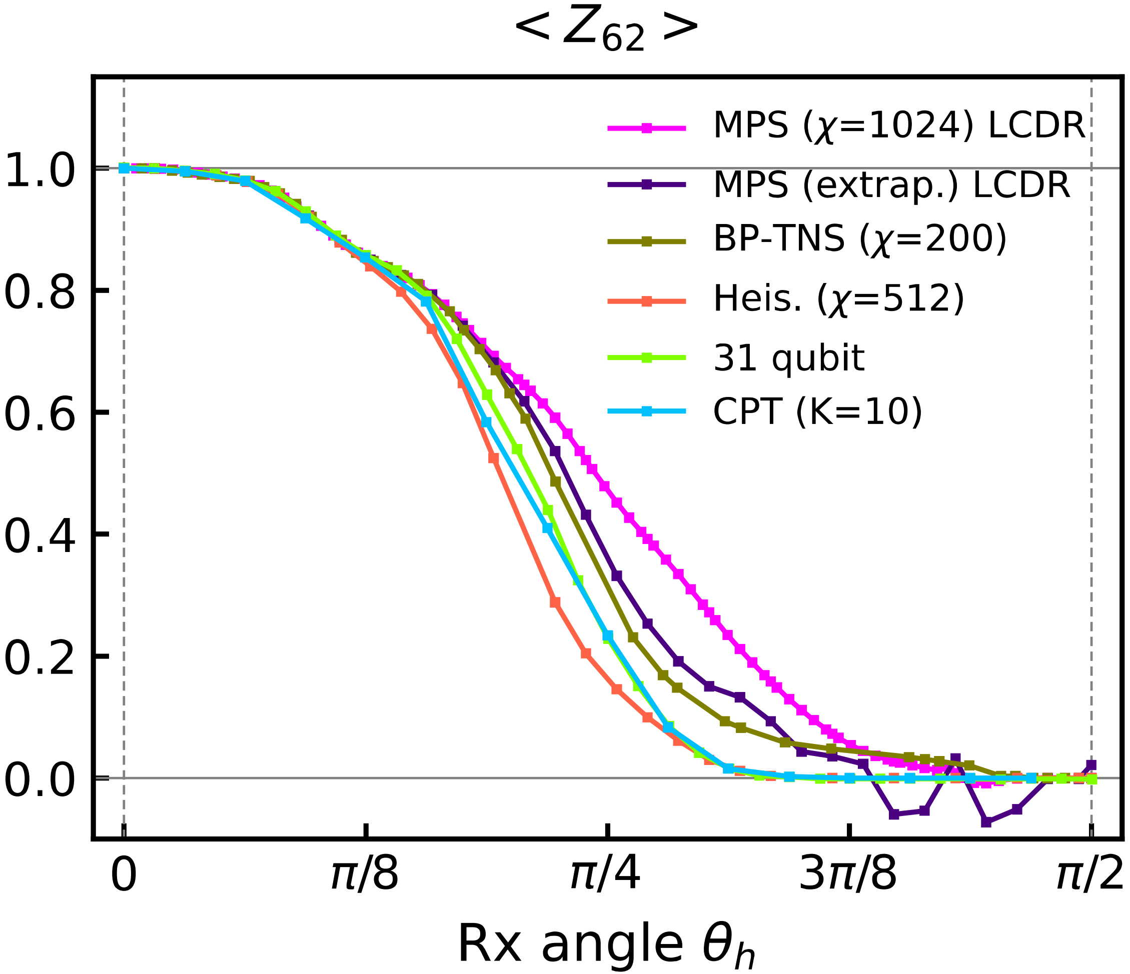


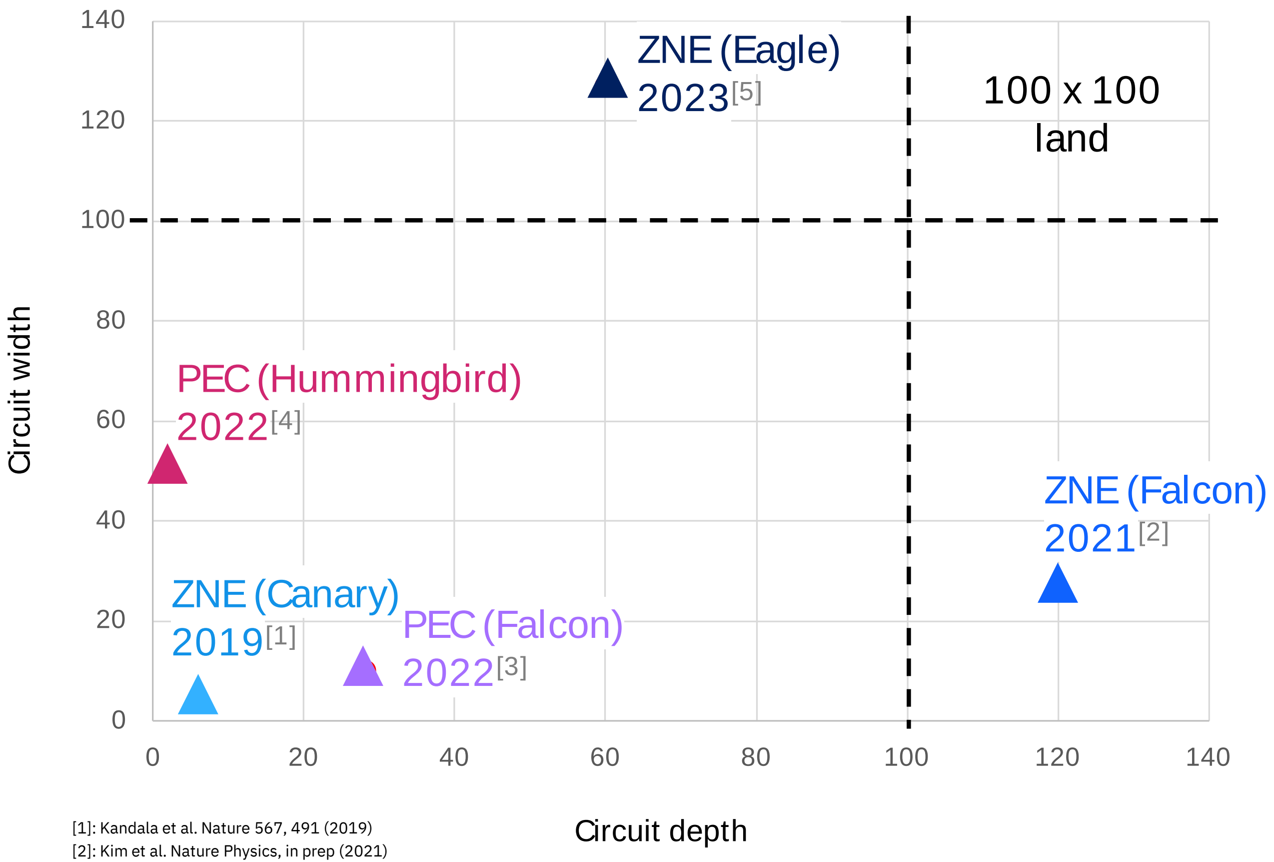
arXiv:2306.14887 (BP-TNS)
arXiv:2306.16372 (CPT)
arXiv:2306.15970 (31 qubit)
arXiv:2306.17839 (MPS extrap., Heis.)

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?

IBM **Quantum**

#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 (TREX)

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