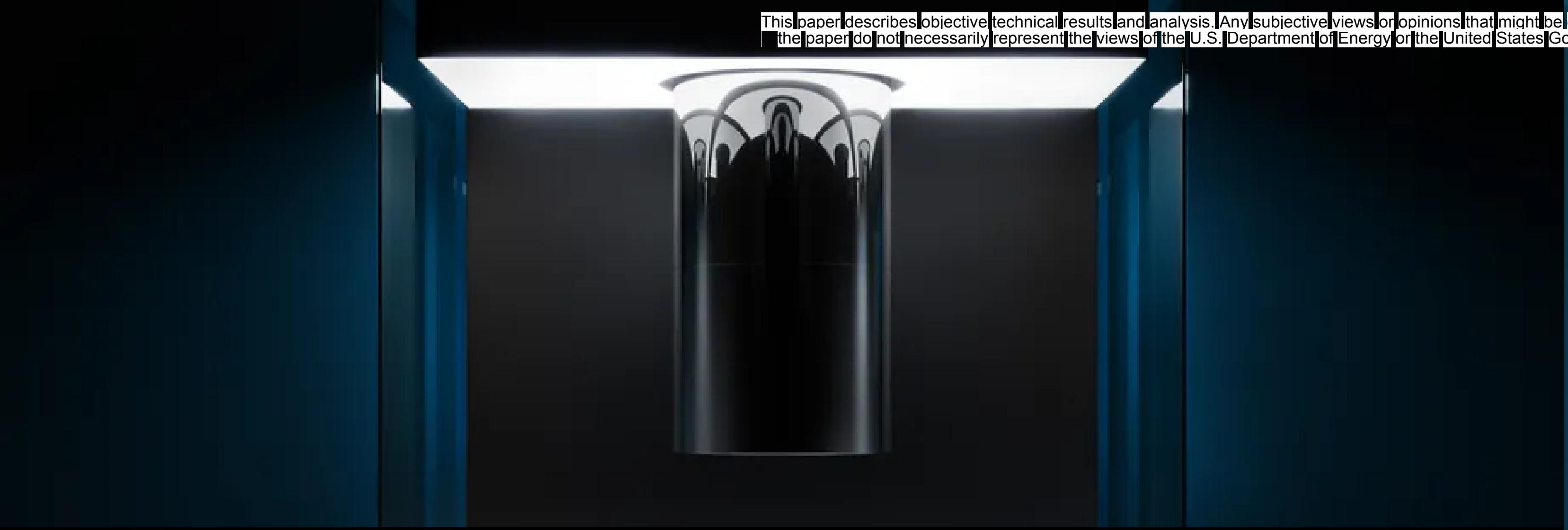
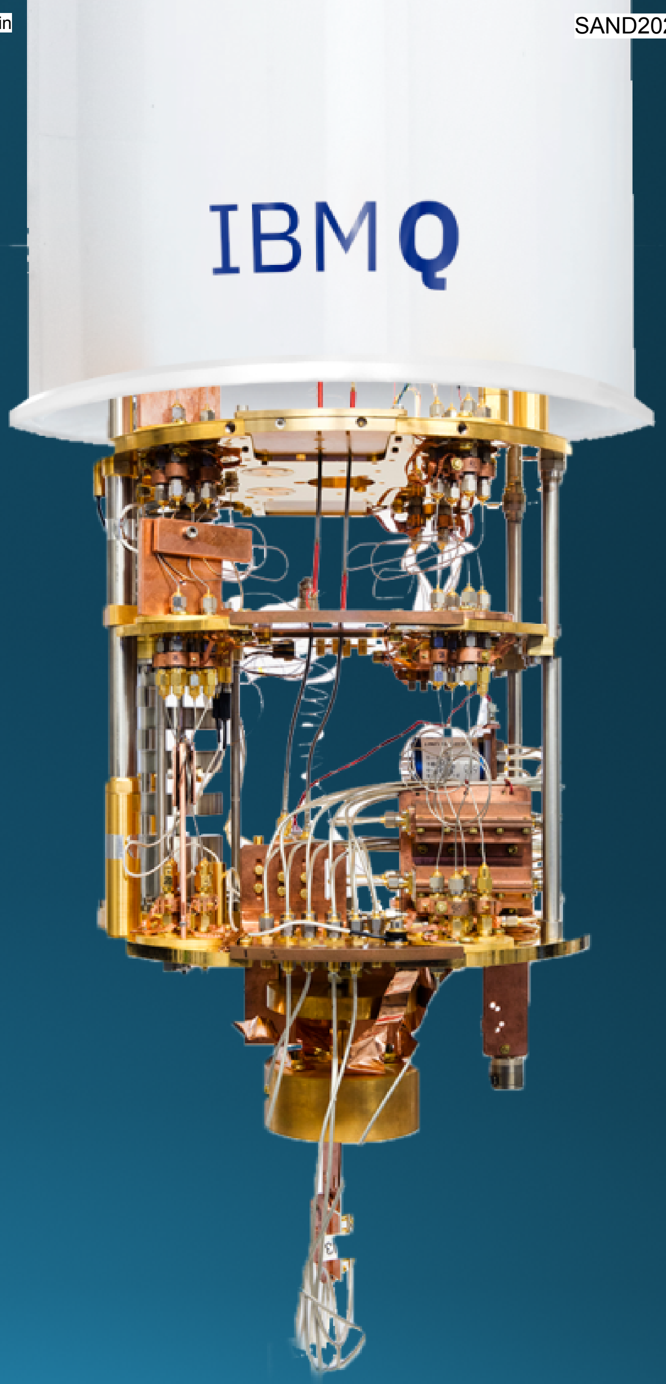
SAND2022-1790C



Characterization and Benchmarking of Quantum Computers



Megan Dahlhauser,

Travis Humble

OAK RIDGE National Laboratory

BREDESEN CENTER

Sandia National Laboratories

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arXiv:2201.02243

Images Credit: IBM

Spectrum of Approaches

More detailed descriptions
More metrics analyzed

Information Gain

Gate Set Tomography [1]

Noise Reconstruction [2]

Empirical Direct Characterization [3]

Scalability

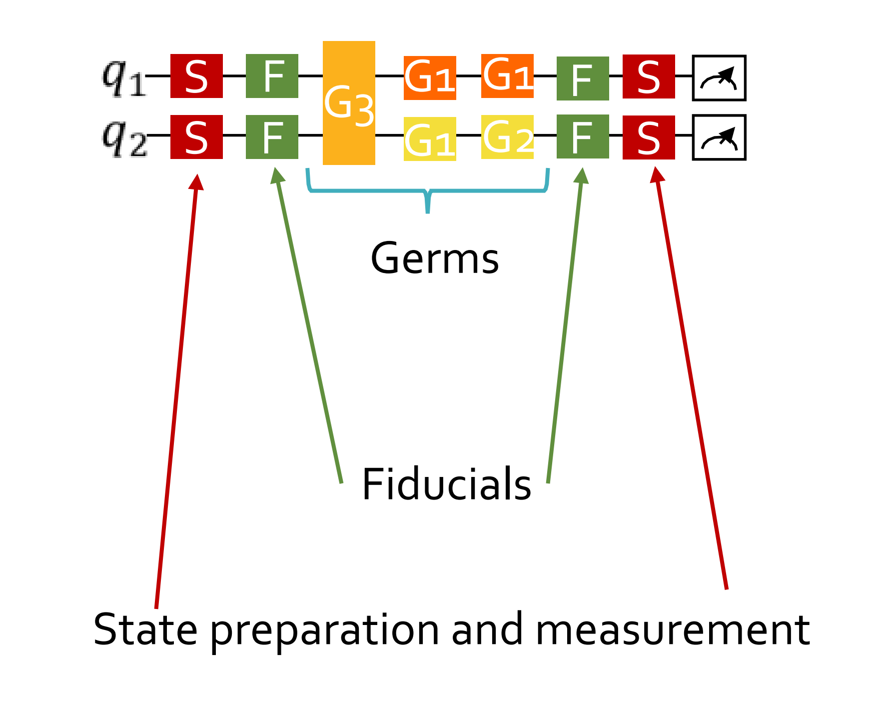
Fewer experiments needed
Faster information return

[1] R. Blume-Kohout et al. “Demonstration of qubit operations below a rigorous fault tolerance threshold with gate set tomography,” Nature Communications, vol. 8, p. 14485, Feb 2017.
[2] R. Harper et al. “Efficient learning of quantum noise,” Nature Physics, Aug 2020.
[3] M. L. Dahlhauser and T. S. Humble, “Modeling noisy quantum circuits using experimental characterization,” Phys. Rev. A, vol. 103, p. 042603, Apr 2021.

Gate Set Tomography (GST)

- Developed by team at Sandia and implemented in pyGSTi software
- Tomography: collect information from multiple axes, e.g. CT scan
- Fully characterizes a gate set at once
- Scales exponentially in system size
- Prohibitive for many qubits
- Yields Pauli Transfer Matrix of each gate in experiment:

$$PTM_{i,j} = \frac{1}{d}\mathrm{Tr}\{P_i \Lambda(P_j)\}$$



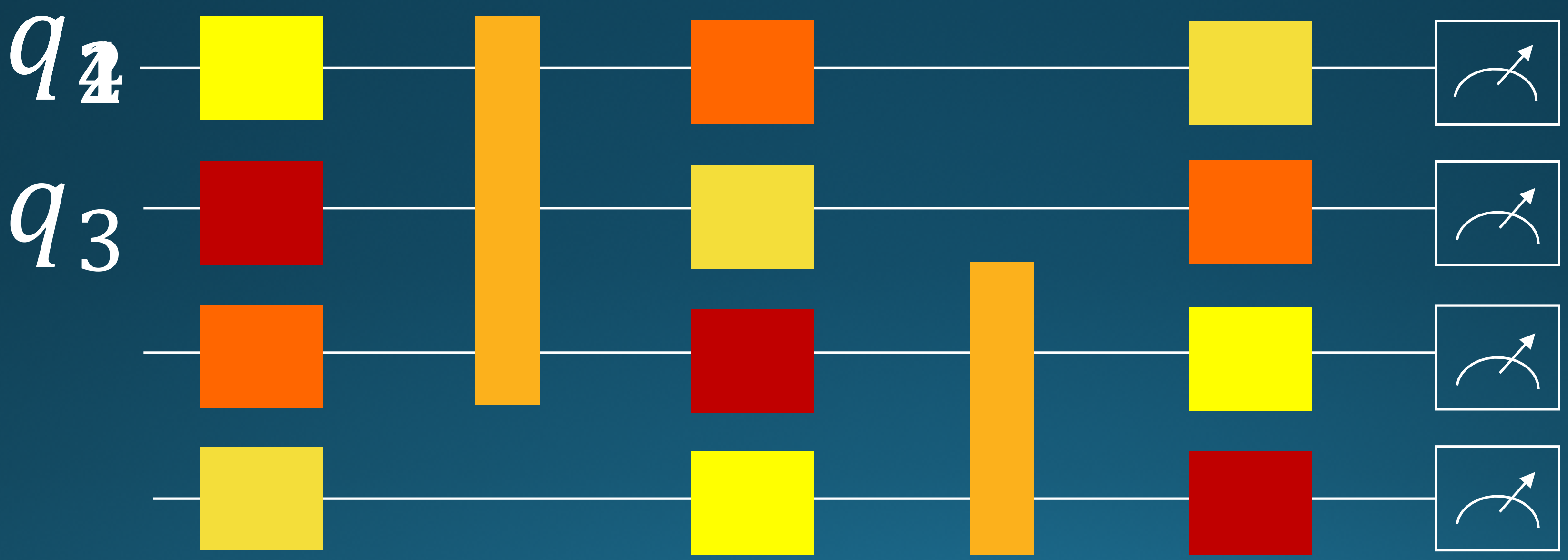
[1] R. Blume-Kohout et al. "Demonstration of qubit operations below a rigorous fault tolerance threshold with gate set tomography," Nature Communications, vol. 8, p. 14485, Feb 2017

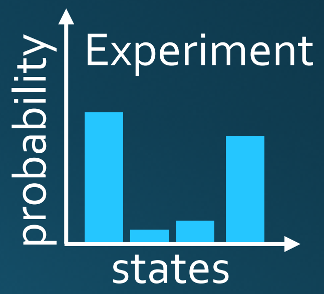
[2] E. Nielsen, L. Saldyt, Rob, J. Gross, T. Proctor, K. Rudinger, T. L. Scholten, msarovar, K. Young, D. Nadlinger, pyIonControl, and R. Blume-Kohout, "pygstio/pygsti: Version 0.9.9.2," June 2020.

Randomized Compiling (RC)

Developed by the company Quantum Benchmark and implemented in True-q software

A circuit with single- and multi-qubit gates



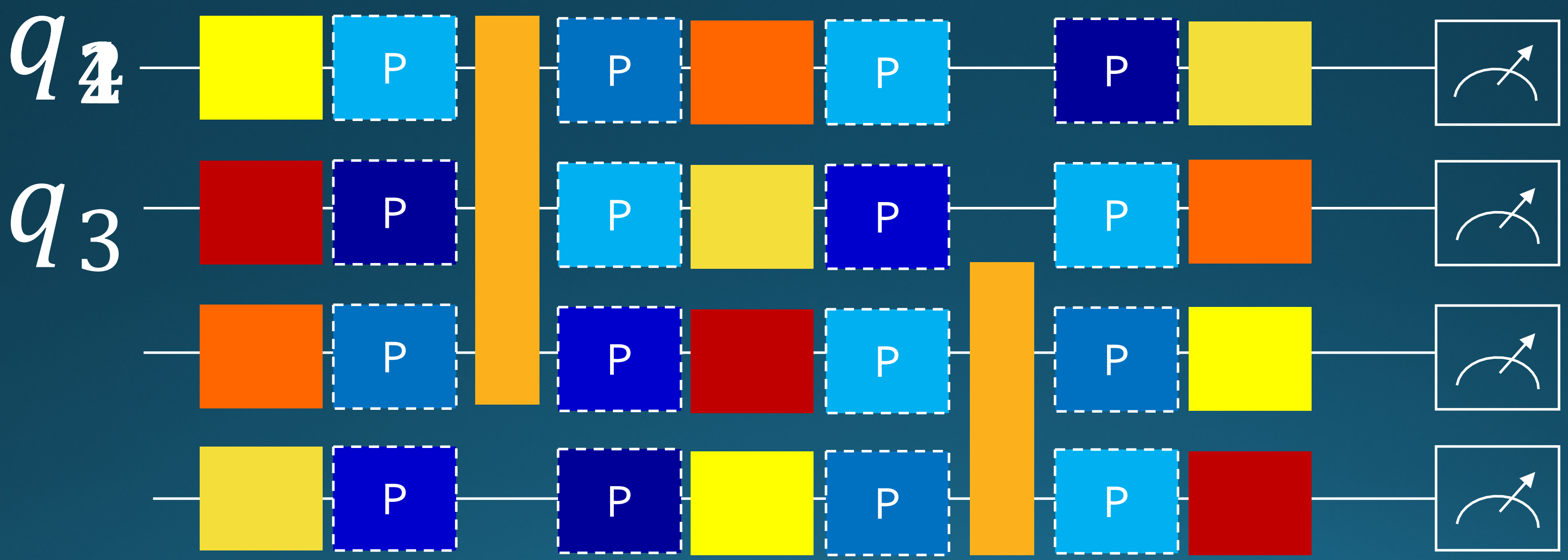


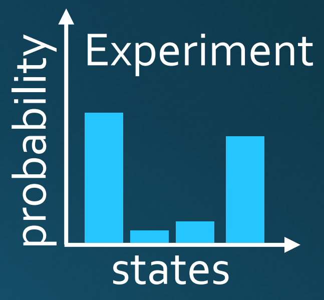
[1] J. J. Wallman and J. Emerson, “Noise tailoring for scalable quantum computation via randomized compiling,” Phys. Rev. A, vol. 94, p. 052325, Nov 2016.
[2] S. J. Beale, A. Carignan-Dugas, D. Dahlen, J. Emerson, I. Hincks, A. Jain, D. Hufnagel, E. Ospadov, J. Saunders, J. J. Wallman, and A. Winick, “True-q,”

Randomized Compiling (RC)

Developed by the company Quantum Benchmark and implemented in True-q software

Insert Pauli gates around multi-qubit gates





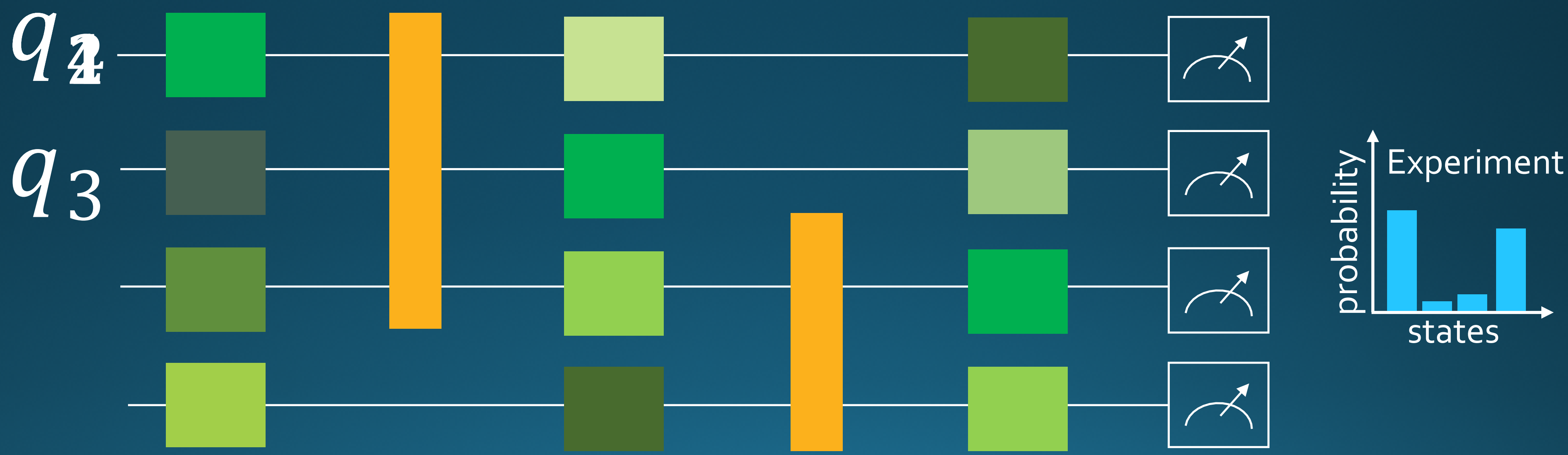
[1] J. J. Wallman and J. Emerson, “Noise tailoring for scalable quantum computation via randomized compiling,” Phys. Rev. A, vol. 94, p. 052325, Nov 2016.

[2] S. J. Beale, A. Carignan-Dugas, D. Dahlen, J. Emerson, I. Hincks, A. Jain, D. Hufnagel, E. Ospadov, J. Saunders, J. J. Wallman, and A. Winick, “True-q,”

Randomized Compiling (RC)

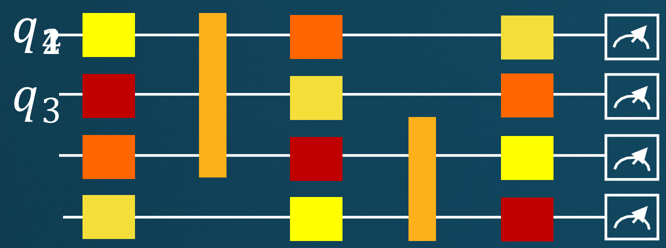
Developed by the company Quantum Benchmark and implemented in True-q software

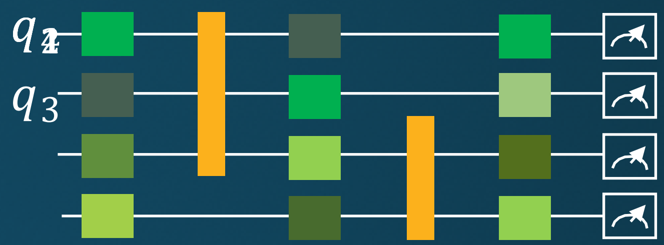
Compile Pauli gates with single-qubit gates



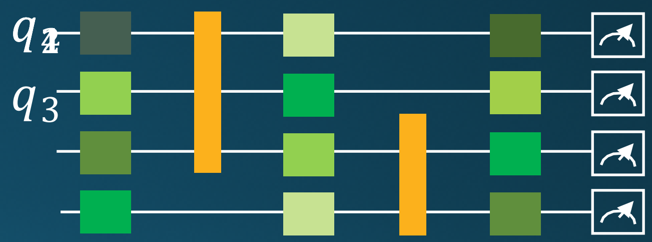
[1] J. J. Wallman and J. Emerson, “Noise tailoring for scalable quantum computation via randomized compiling,” Phys. Rev. A, vol. 94, p. 052325, Nov 2016.
[2] S. J. Beale, A. Carignan-Dugas, D. Dahlen, J. Emerson, I. Hincks, A. Jain, D. Hufnagel, E. Ospadov, J. Saunders, J. J. Wallman, and A. Winick, “True-q,”

Randomized Compiling (RC)



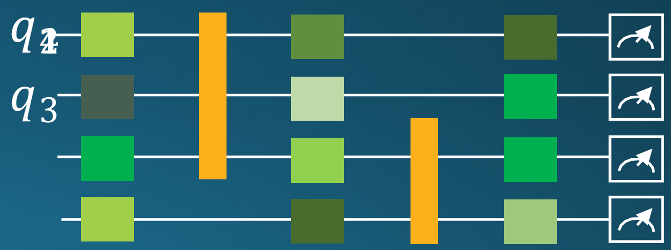


In the absence of noise: results are the same
In the presence of noise: results may be better or worse



Benefits: noise is transformed to a stochastic Pauli channel:

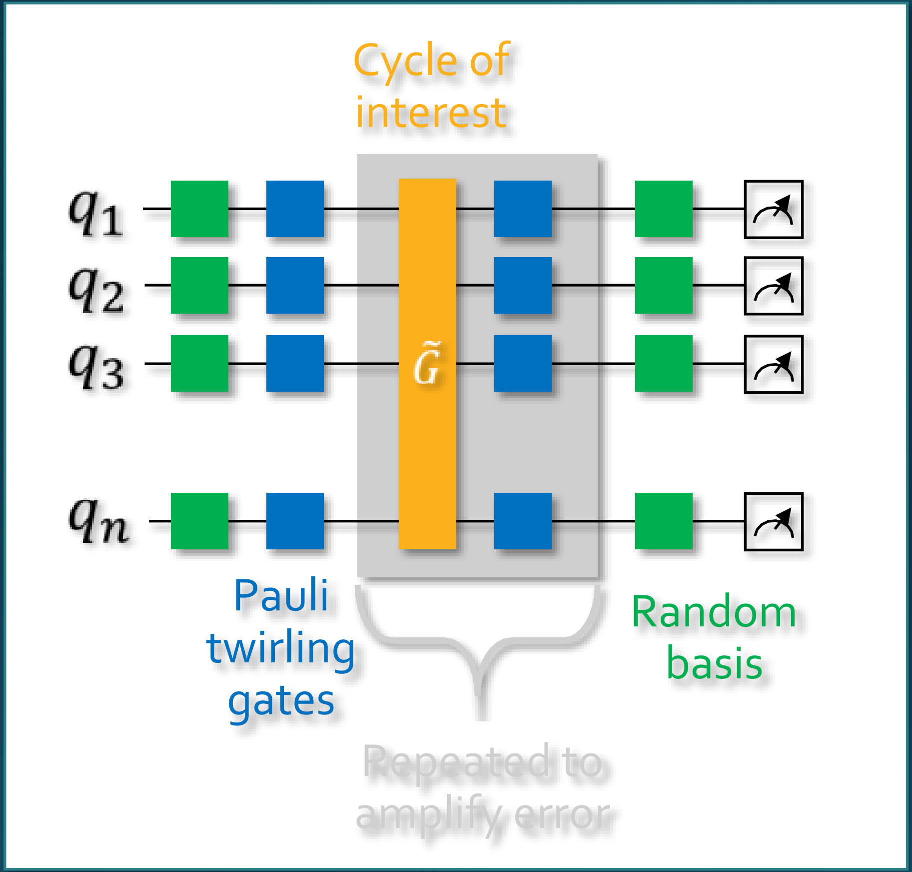
$$\varepsilon_{SP}(\rho) = \sum_{P \in \mathbf{P}} c_P P \rho P^\dagger$$



which might improve runtime performance, performance stability, and predictability

[1] J. J. Wallman and J. Emerson, "Noise tailoring for scalable quantum computation via randomized compiling," Phys. Rev. A, vol. 94, p. 052325, Nov 2016.
[2] S. J. Beale, A. Carignan-Dugas, D. Dahlen, J. Emerson, I. Hincks, A. Jain, D. Hufnagel, E. Ospadov, J. Saunders, J. J. Wallman, and A. Winick, "True-q,"

K-body Noise Reconstruction (KNR)



Developed by the company Quantum Benchmark (now Keysight) and implemented in True-q software

Transforms the Pauli decay rates into error probabilities

$$\boldsymbol{f}_G = \boldsymbol{W}_{G,P^n}\boldsymbol{p}$$

Relates vector of fidelities $\boldsymbol{f}_G$ to vector of Pauli error rates $\boldsymbol{p}$ via Walsh-Hadamard transform $\boldsymbol{W}_{G,P^n}$

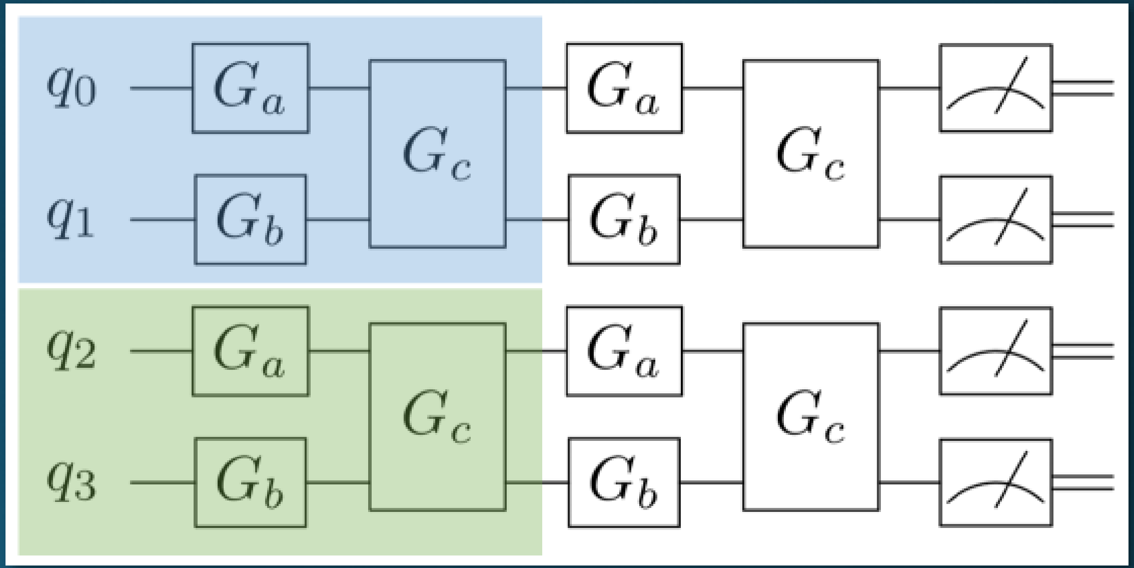
Output: **probability distribution of errors** present in the cycle or subset of the cycle

Can use probability distribution to generate noise model for device

[1] R. Harper, S. T. Flammia, and J. J. Wallman, “Efficient learning of quantum noise,” Nature Physics, Aug 2020.
[2] S. J. Beale, A. Carignan-Dugas, D. Dahlen, J. Emerson, I. Hincks, A. Jain, D. Hufnagel, E. Ospadov, J. Saunders, J. J. Wallman, and A. Winick, “True-q,” June 2020.

Empirical Direct Characterization (EDC)

- Developed by us
- Approach to noisy quantum circuit modeling based on experimental characterization
- Uses subcircuit decomposition to create coarse-grained noise estimates
- Highly efficient and scalable
- Scales as $2q + 2c + 1$ for q qubits and c components



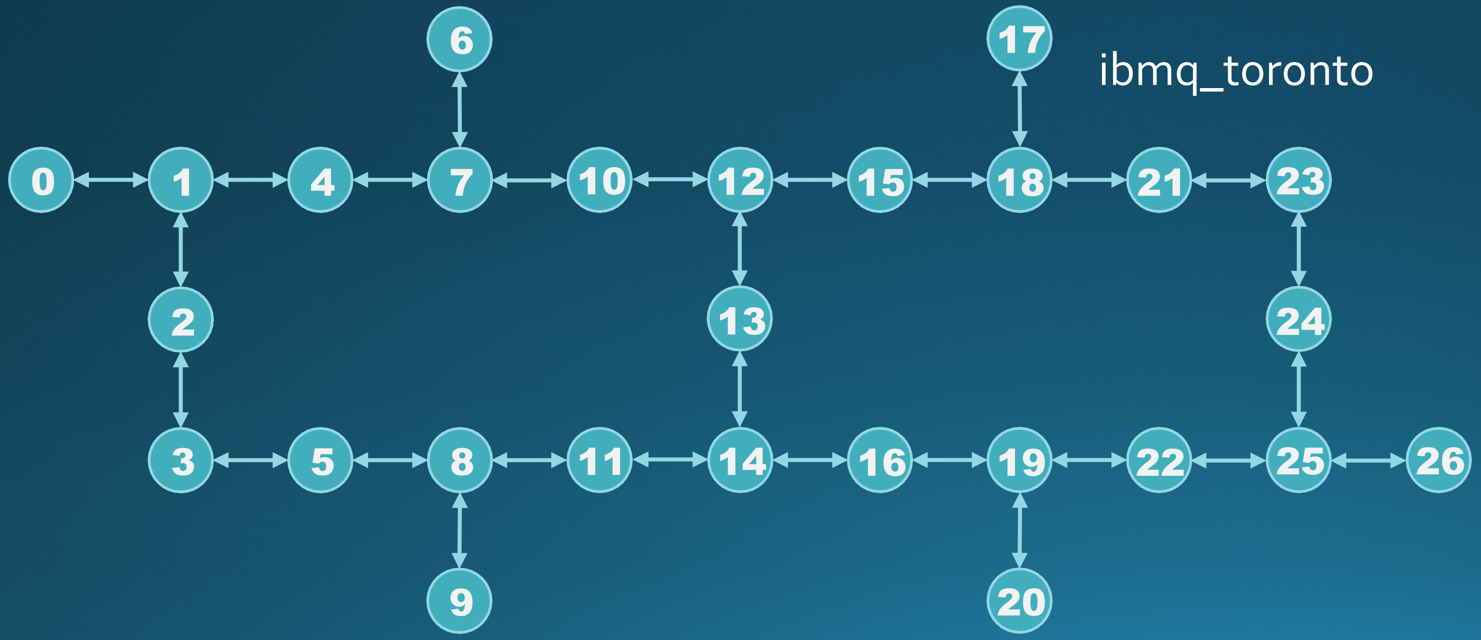
M. L. Dahlhauser and T. S. Humble, "Modeling noisy quantum circuits using experimental characterization," Phys. Rev. A, vol. 103, p. 042603, Apr 2021.

Experiment Details

ORNL Quad
Credit: ORNL

Experiment QPU

- Run quantum circuits on ibmq_toronto
- 27-qubit superconducting QPU
- Online since August 2020
- Access through the cloud using Qiskit
- Code publicly available on our repo



ibmq_toronto

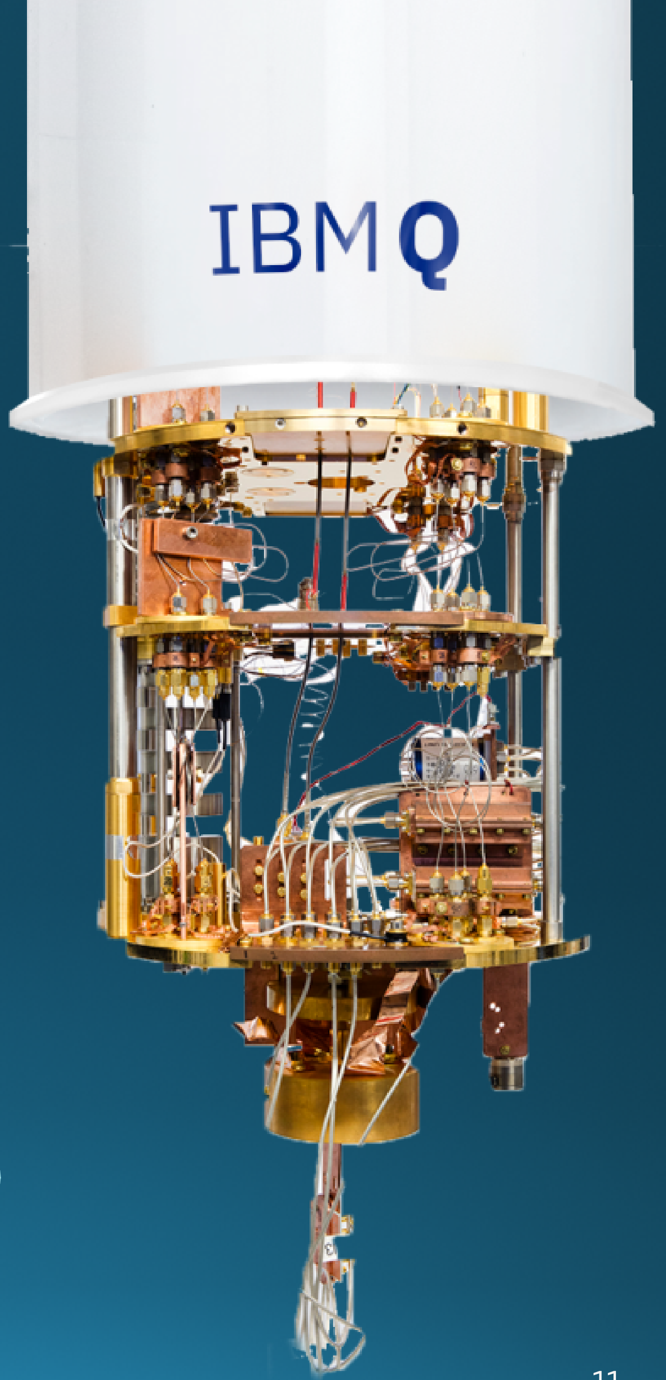
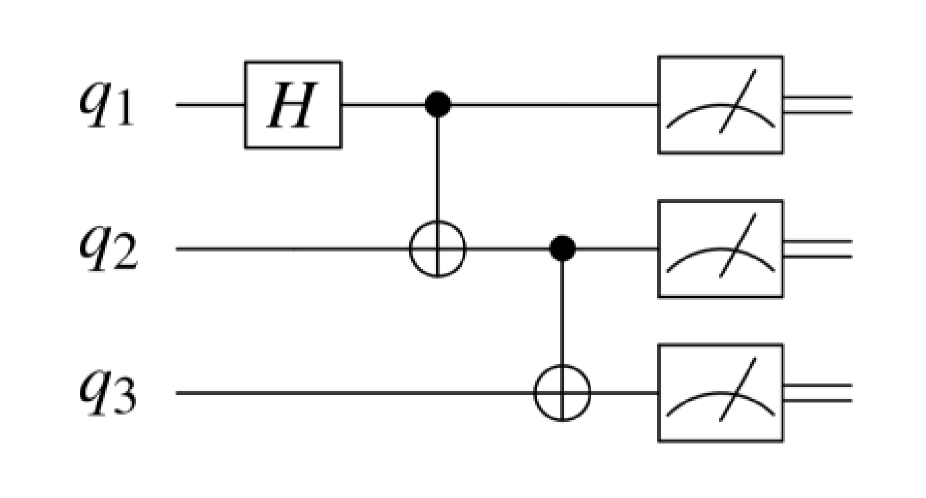


Image Credit: IBM

H. Abraham et al. "Qiskit: An opensource framework for quantum computing," 2019. DOI 10.5281/zenodo.2562110

GHZ-State Preparation Circuits



n-qubit GHZ for $n = \{2, 3, \ldots, n\}$

$$|GHZ(n)\rangle = \frac{|0\rangle^{\otimes n} + |1\rangle^{\otimes n}}{\sqrt{2}}$$

Properties:

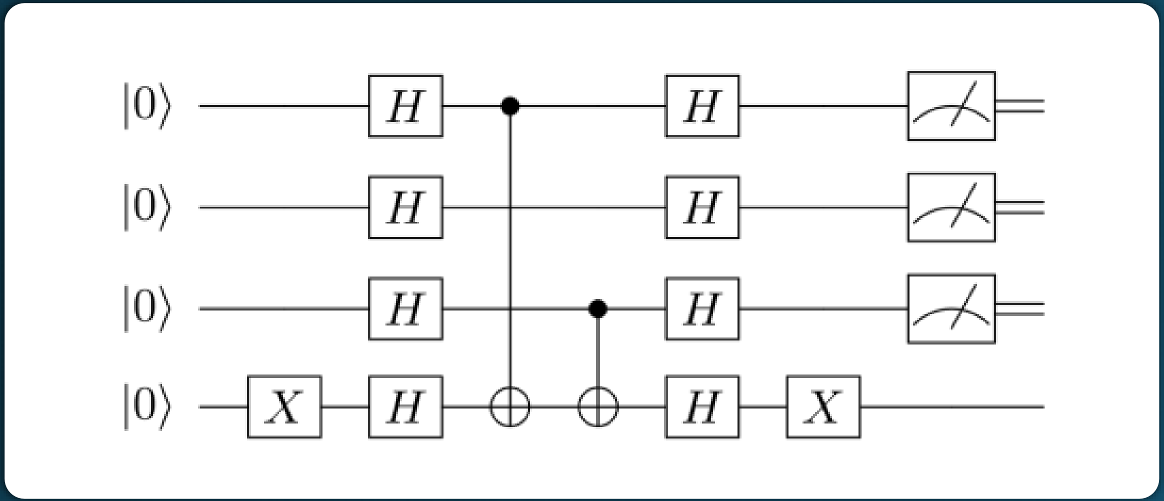
- Creates equal superposition state
- Entangles *n* qubits

Benefits:

- Maximum Hamming distance between two "correct" states
- Common gate set
- Extensible to any size register

arXiv:2201.02243

Bernstein-Vazirani Circuits



- Encode each binary secret string from zero to 2^n
- For each one in the binary string, add CNOT with control qubit on corresponding string location

Properties:

- Quantum algorithm that learns a secret string in one query
- Variable circuit depth

Benefits

- 2^n circuits for n-bit encoding
- Yields one expected outcome
- Common gate set

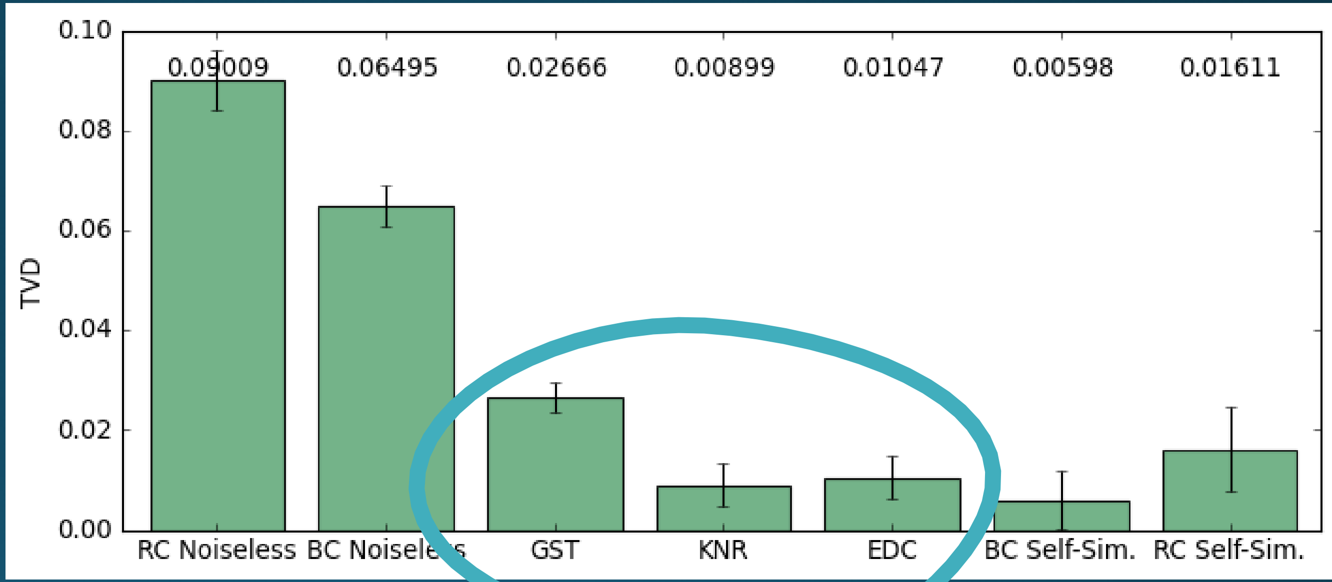
arXiv:2201.02243

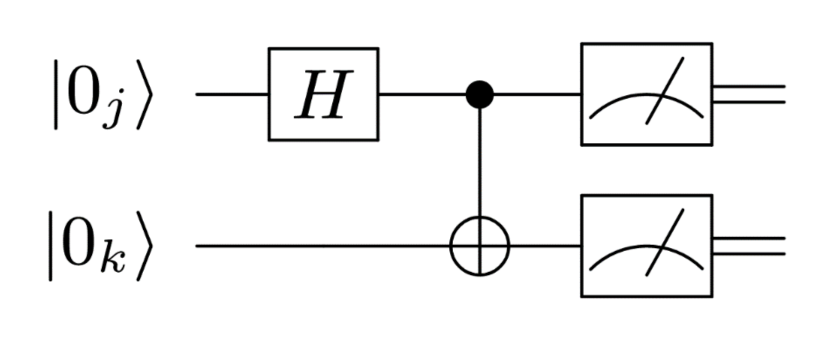
Results

Greve Hall
Credit: UTK

Bell State Test

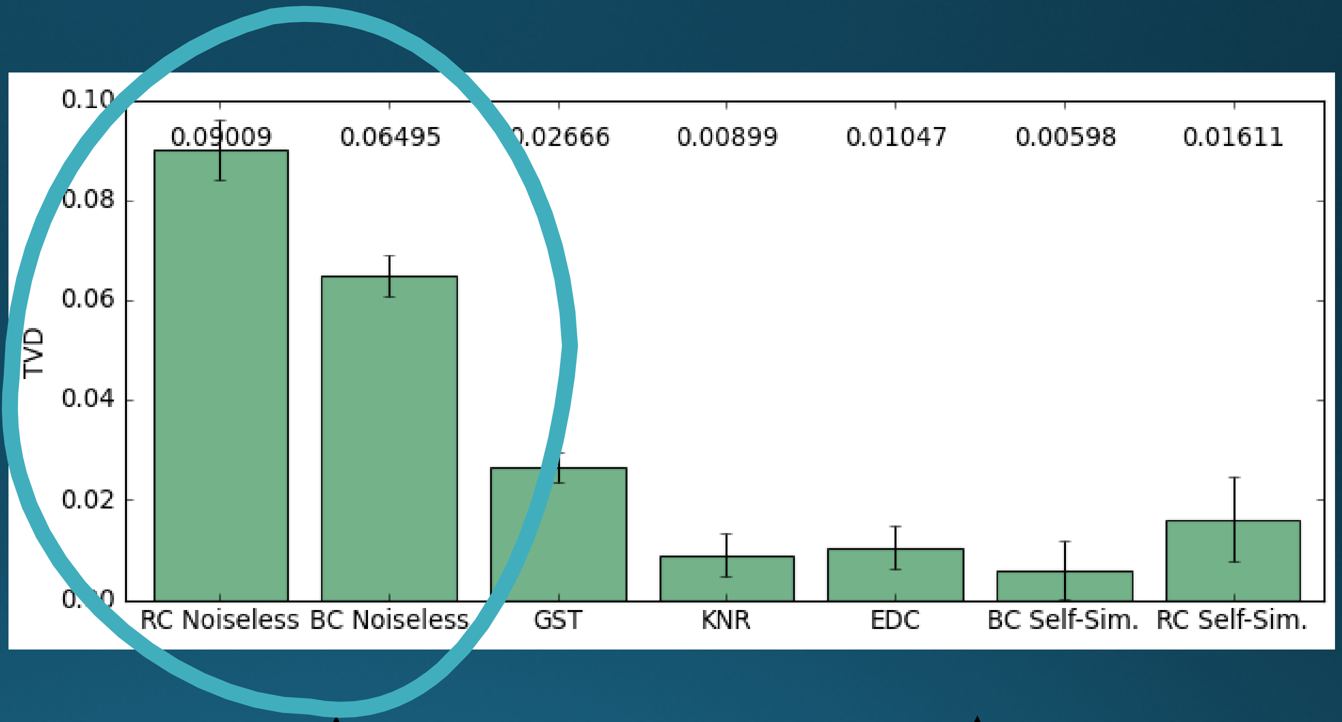
- KNR and EDC are closest to experiment
- GST is outside of error bars of KNR and EDC

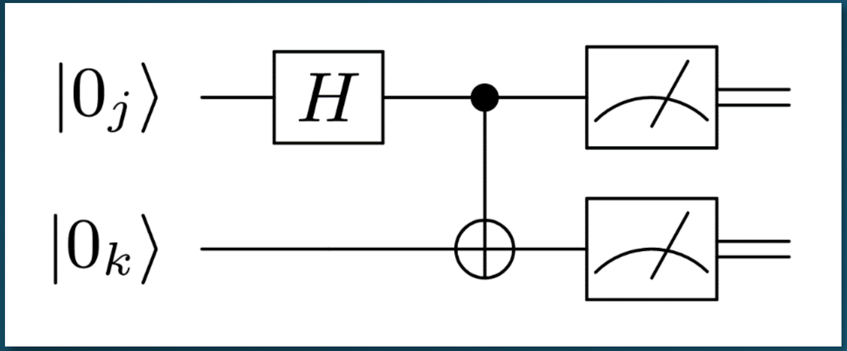




Bell State Test

- Noiseless represents TVD between the experiment and an ideal Bell state preparation

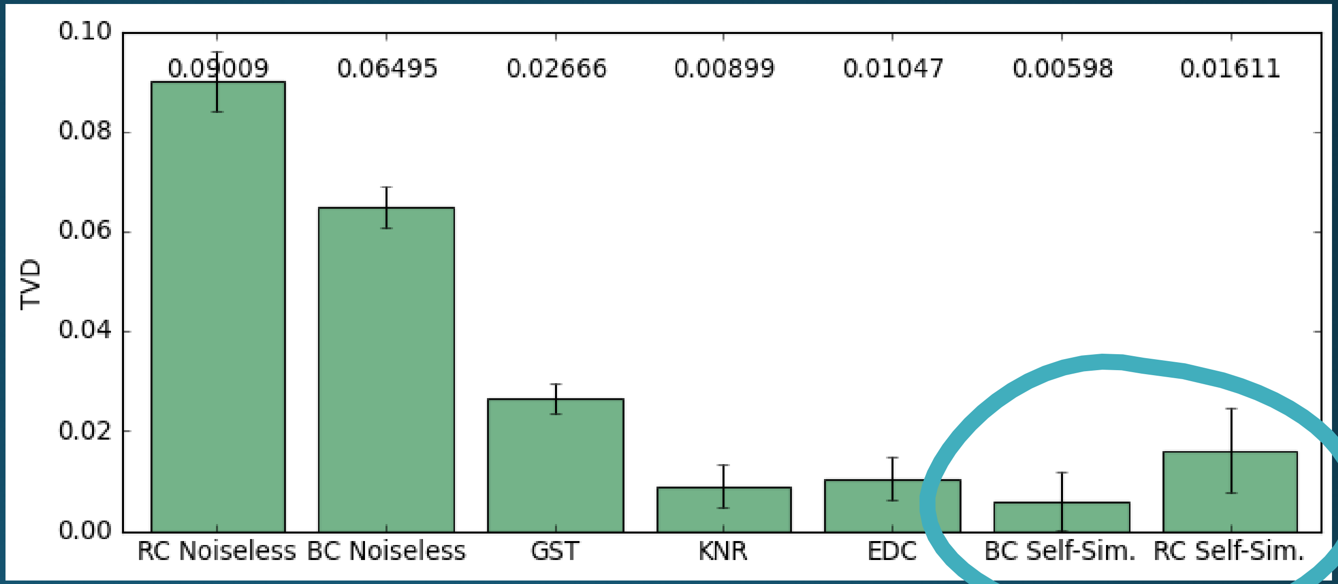


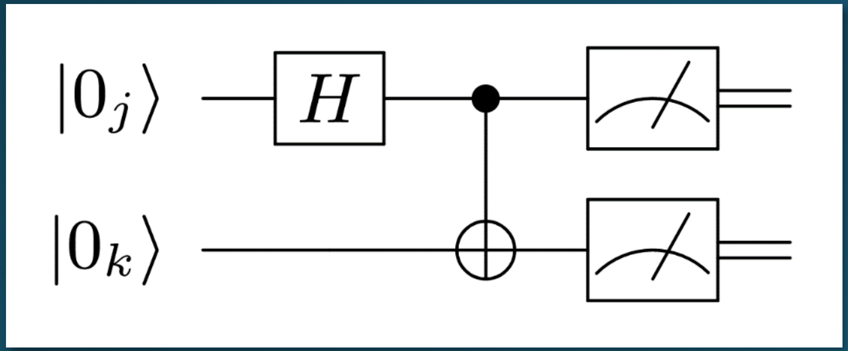


arXiv:2201.02243

Bell State Test

- Self-simulation tests the TVD between two experiments run on ibmq_toronto in the same time window
- Best case simulation example
- KNR and EDC are within error bars of these

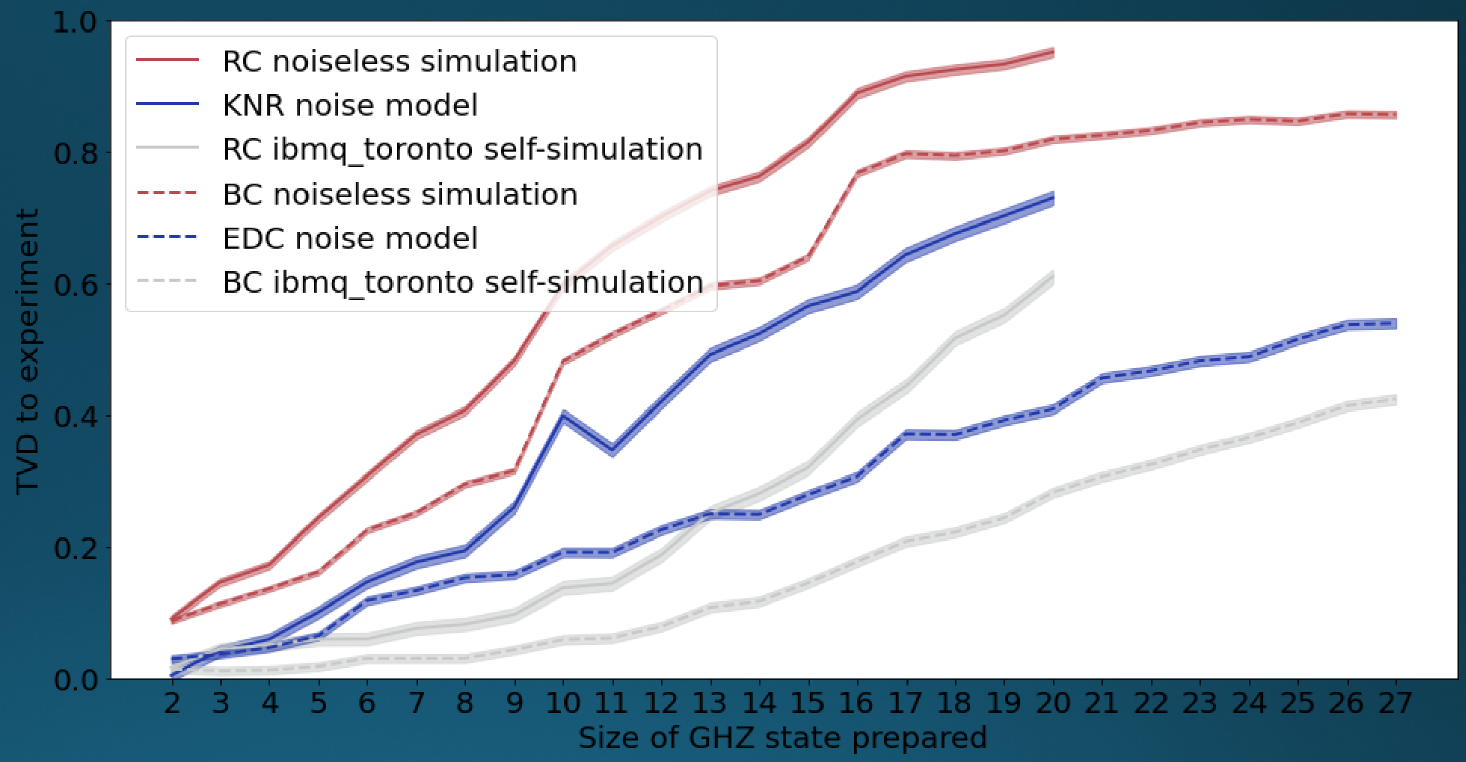




arXiv:2201.02243

GHZ Benchmark

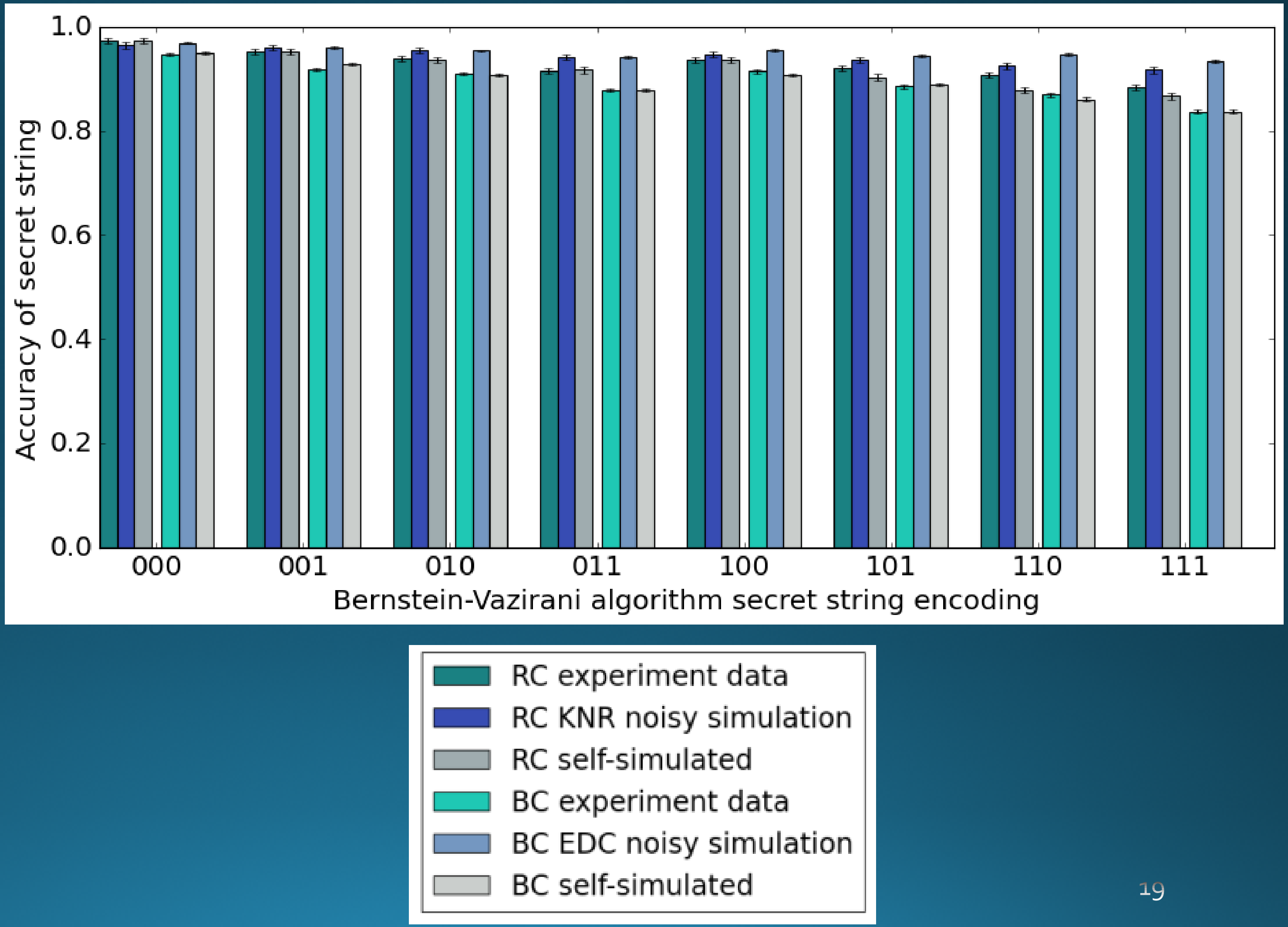
- BC = bare circuits (not randomly compiled)
- BC GHZ circuits consistently prepare a more accurate state than RC GHZ circuits
- EDC achieves the lowest TVD consistently except the 2-qubit state only
- TVD of EDC scales best with register size



arXiv:2201.02243

Bernstein-Vazirani (BV) Benchmark

- RC BV circuits achieve higher accuracy than BC BV circuits
- Accuracy decreases with additional CNOTs
- KNR consistently came closest to experiment accuracy
- KNR is about as good as self-simulation for some secret strings
- Both methods tend to overestimate accuracy



arXiv:2201.02243

Conclusions

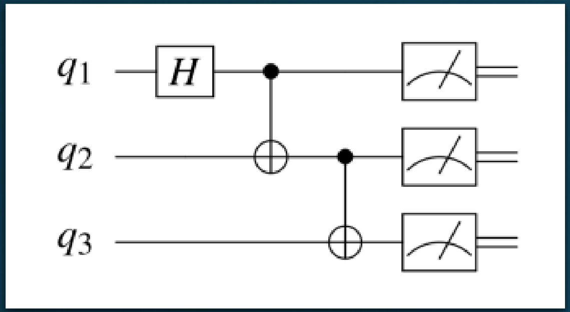
Credit: ORNL

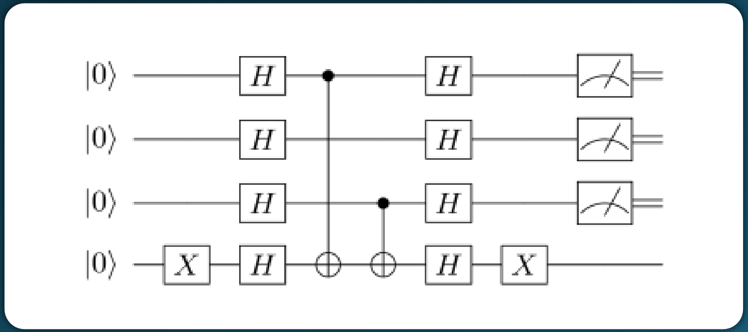
Conclusions

Increased noise model detail does not correlate with improved accuracy

Noise model performance degrades for larger qubit registers

Conclusions





Best characterization method depends on the application

Structure, size, context of circuit are primary contributing factors

Conclusions

KNR could be applied to BV circuits to predict QPU performance

No model described all noise present in the system

Non-Markovian noise present in CNOT gates might be the additional error

Select References

1. M. L. Dahlhauser and T. S. Humble, "Modeling noisy quantum circuits using experimental characterization," Phys. Rev. A, vol. 103, p. 042603, Apr 2021.
2. "IBM Quantum." https://quantum-computing.ibm.com/, 2021.
3. J. J. Wallman and J. Emerson, "Noise tailoring for scalable quantum computation via randomized compiling," Phys. Rev. A, vol. 94, p. 052325, Nov 2016.
4. S. J. Beale, A. Carignan-Dugas, D. Dahlen, J. Emerson, I. Hincks, A. Jain, D. Hufnagel, E. Ospadov, J. Saunders, J. J. Wallman, and A. Winick, "True-q," June 2020.
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8. R. Harper, S. T. Flammia, and J. J. Wallman, "Efficient learning of quantum noise," Nature Physics, Aug 2020.
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10. H. Abraham et al. "Qiskit: An opensource framework for quantum computing," 2019. DOI 10.5281/zenodo.2562110

Summit Supercomputer
Credit: ORNL

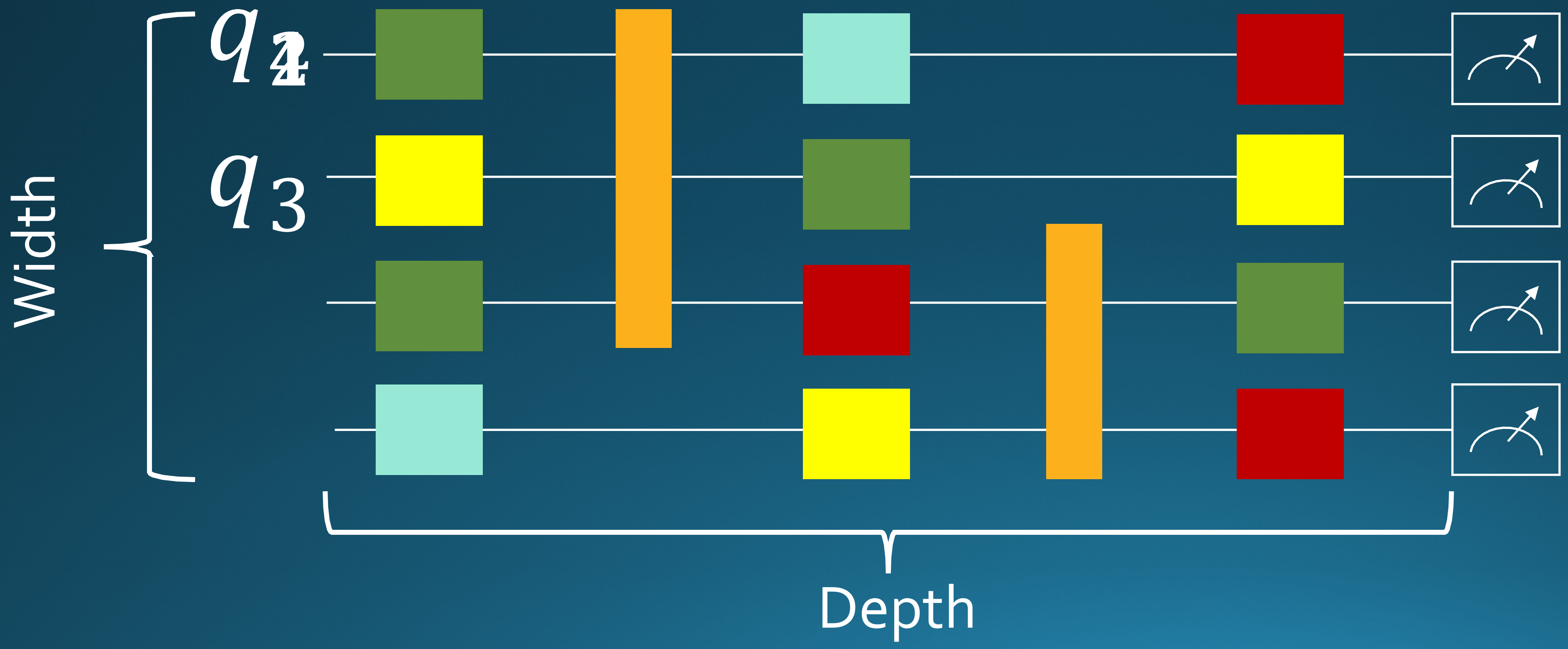
Thank you!

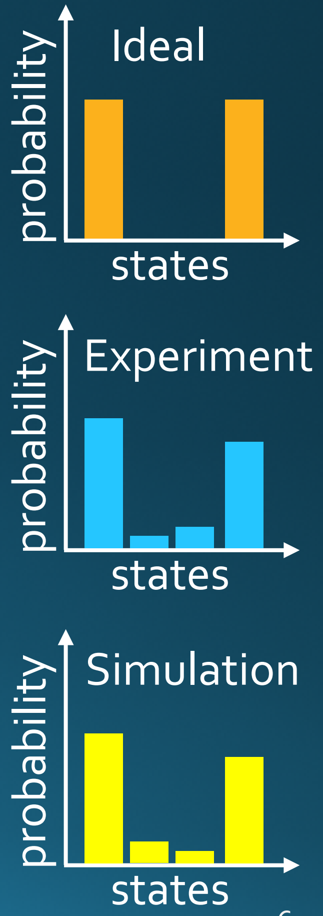
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

arXiv:2201.02243

QPU Experimentation

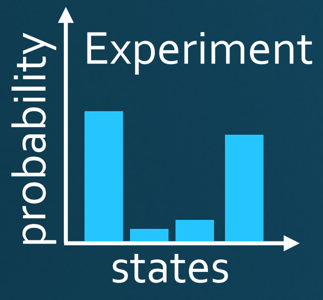
A circuit with single- and multi-qubit gates

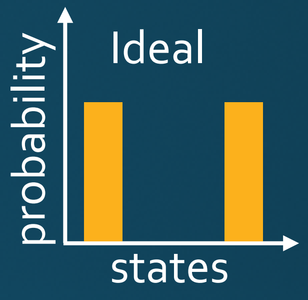




arXiv:2201.02243

Total Variation Distance (TVD)





Probability distributions *A* and *B*

Number of times state *i* is measured

$$TVD(A,B) = \frac{1}{2}\sum_i \left|\frac{h_i^A}{N} - \frac{h_i^B}{N}\right|$$

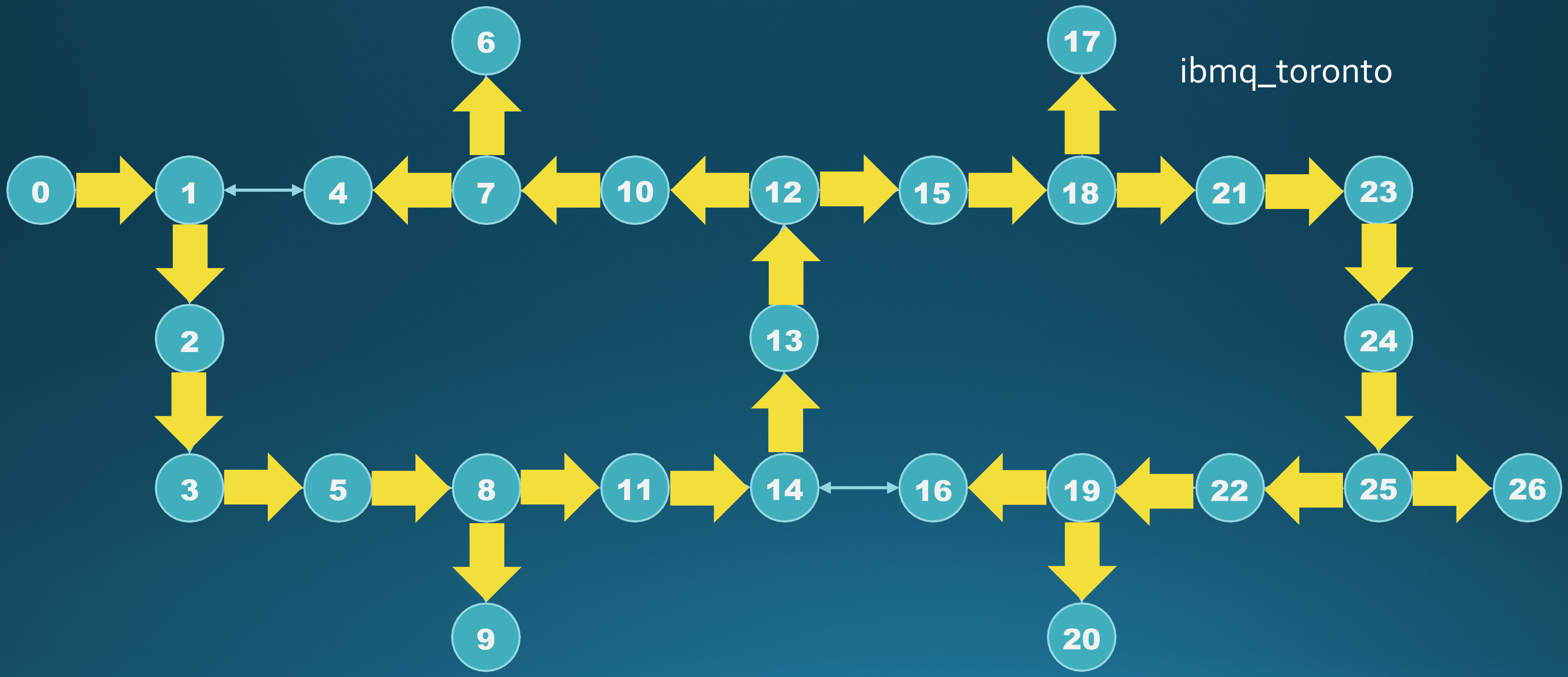
State result index

Total number of samples

Low TVD: close, good agreement; minimum zero
High TVD: far, bad agreement; maximum one

arXiv:2201.02243

GHZ Mapping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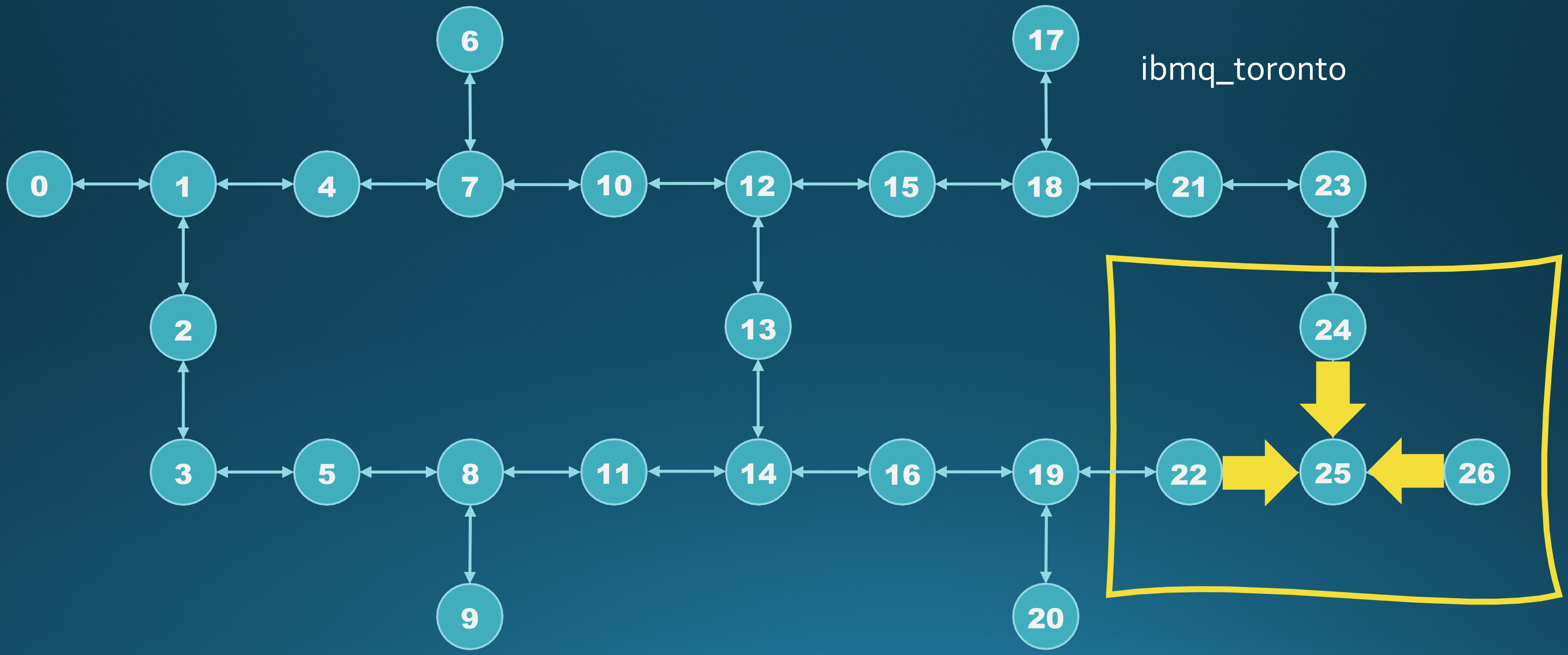
BV Mapping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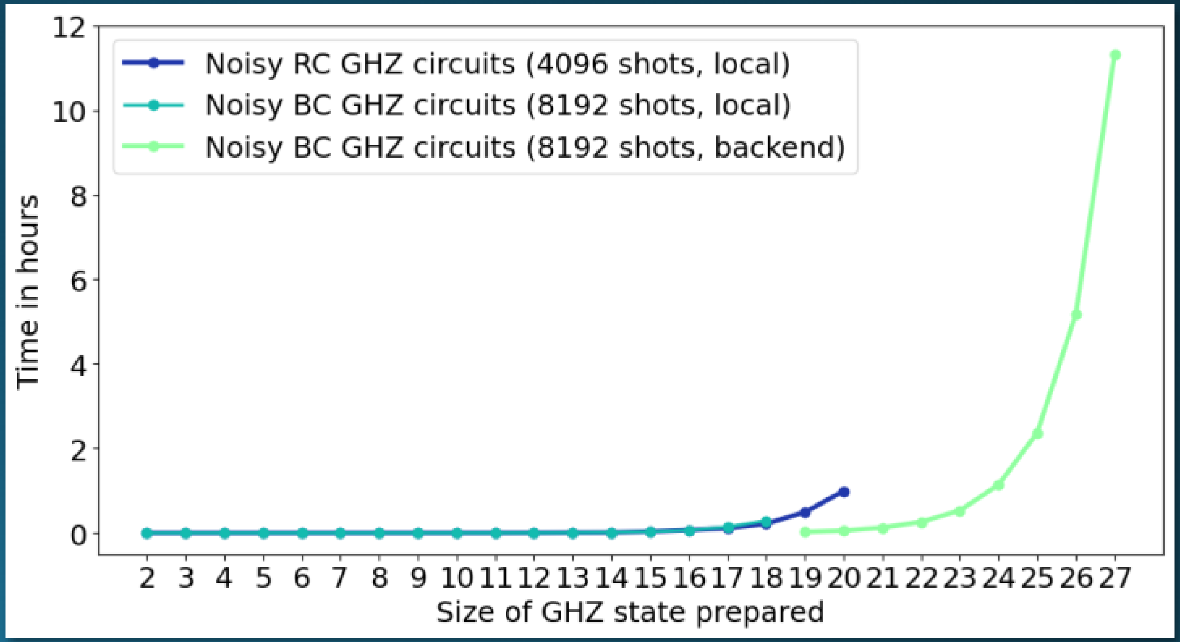
Classical Resources

Local calculations: personal laptop with 16 GB RAM and Intel Core i7 processor
Backend calculations: IBM classical computer dedicated to quantum circuit simulations accessed through cloud

Method	Details	Time Taken
GST	Calculate results	70.13 hours
KNR	Simulate noisy RC GHZ circuits (2-20 qubits, local)	1.95 hours
EDC	Simulate noisy BC GHZ circuits (2-18 qubits, local)	33.53 minutes
EDC	Simulate noisy BC GHZ circuits (19-27 qubits, backend)	21.02 hours
KNR	Simulate noisy RC BV circuits (4 qubits, local)	1 minute
EDC	Simulate noisy BC BV circuits (4 qubits, local)	1 minute



Quantum Resources

Quantum circuits run on ibmq_toronto during a 12-hour window of reserved computation time FEB 2021

Method	Details	Circuits	Time
GST	2-qubit gate set $\{R_X\left(\frac{\pi}{2}\right), R_Y\left(\frac{\pi}{2}\right), R_Z\left(\frac{\pi}{2}\right), I, CNOT\}$	20094	2.28 hours
KNR (GHZ)	Per-gate cycles (20)	10440	17 minutes
RC GHZ	2-20-qubit GHZ circuits compiled into 32 each	608	12 minutes
KNR (BV)	Time step cycles (5)	1980	6 minutes
RC BV	All 3-bit string encodings compiled into 32 each	256	6 minutes
EDC	27-qubit characterizations	205	11 minutes
BC GHZ	2-27-qubit GHZ circuits	26	
BC BV	All 3-bit string encodings	8	