What makes a good experiment for proof-of-principle QEC?

James Wootton
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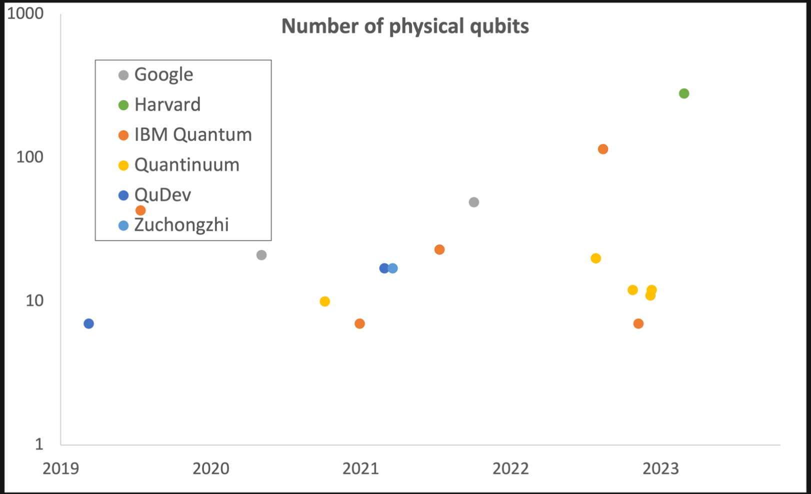
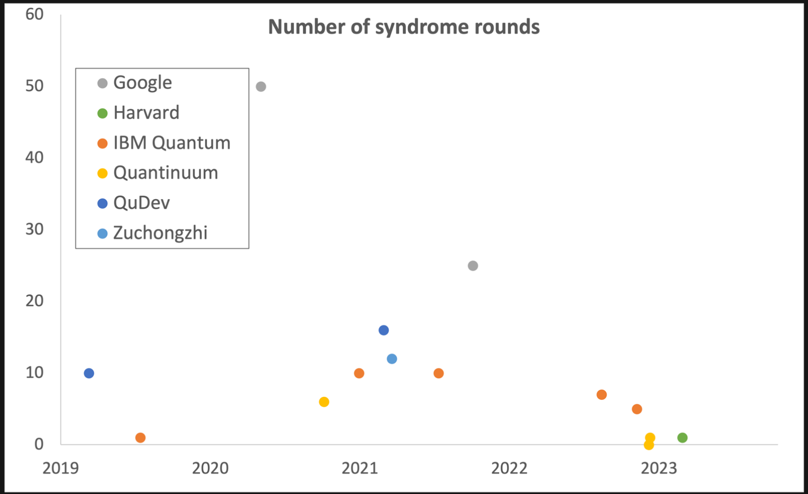
Numbers from recent QEC experiments

- Two important metrics in QEC experiments: how big and how long



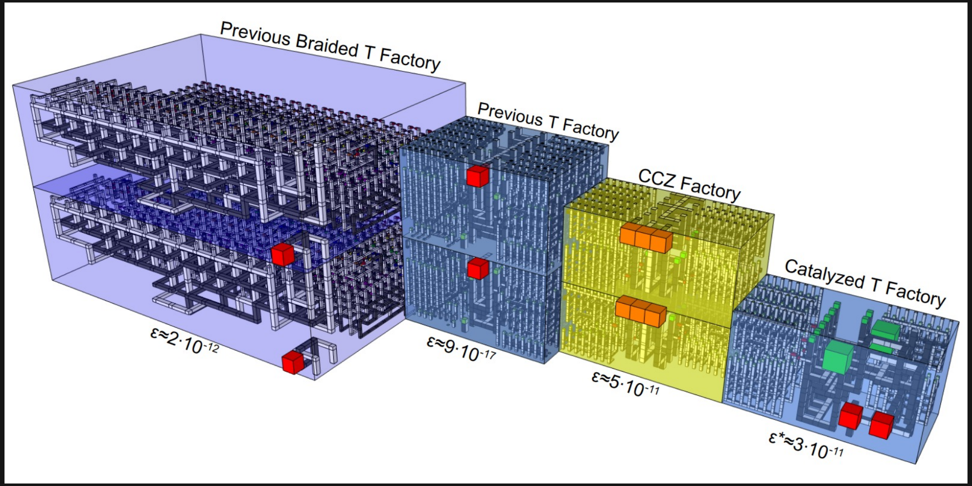


- Records here are
  - 280 physical qubits
  - 50 syndrome measurement rounds

Numbers from recent QEC experiments

- Great progress!

- But still far to go before fault-tolerance
  - $\gg$ 10 000 of physical qubits just to *store* a 2048 bit number
  - Logical circuit depth $\gg$ 100 to factor it
  - $\gg$ 10 syndrome rounds required for each



Gidney and Fowler, Quantum 3, 135 (2019)

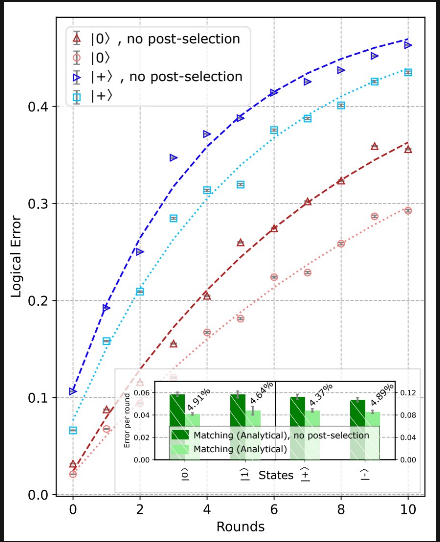
- Significant effort required for non-Clifford gates, such as magic state distillation

- Even with unrealistic optimism, we are orders of magnitude away!

Numbers from recent QEC experiments

- We currently see the logical qubits of experiments
  - Proof-of-principle for QEC
  - Logical error rate < physical error rate

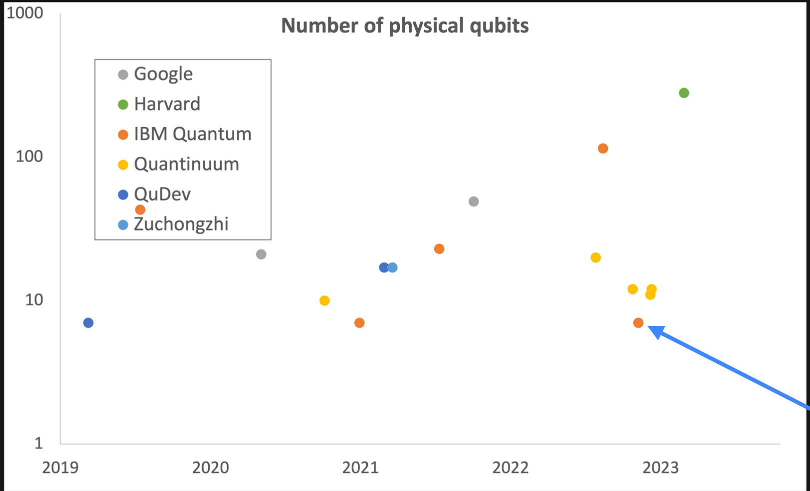
- Algorithms need the logical qubits of FTQC
  - Logical error rate < 10^{-10}
  - Fully satisfy DiVincenzo's criteria

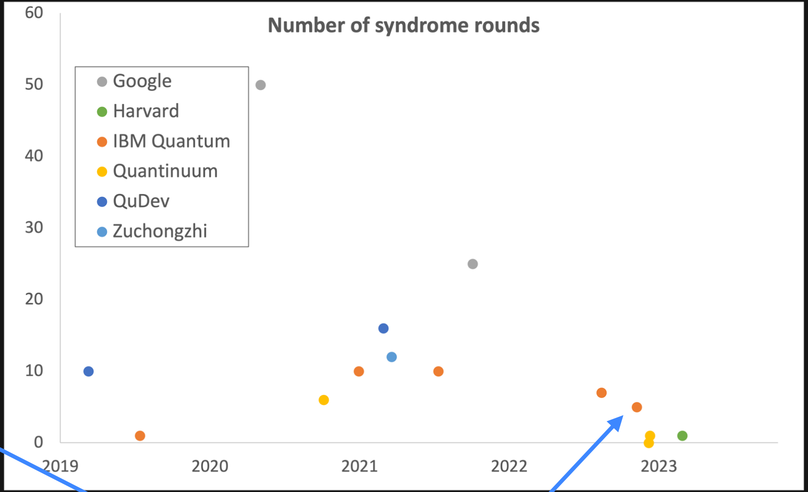


Sundaresen et al.,
Nat Commun 14, 2852 (2023)

1. A scalable physical system with well-characterized qubit
2. The ability to initialize the state of the qubits to a simple fiducial state
3. Long relevant decoherence times
4. A "universal" set of quantum gates
5. A qubit-specific measurement capability

Numbers from recent QEC experiments





- Moderate size and length, but with important innovations
  - High fidelity magic state preparation
  - Dynamic circuits to improve yield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Encoding a magic state with beyond break-even fidelity

Riddhi S. Gupta, Neereja Sundaresan, Thomas Alexander, Christopher J. Wood, Seth T. Merkel, Michael B. Healy, Marius Hillenbrand, Tomas Jochym-O'Connor, James R. Wootton, Theodore J. Yoder, Andrew W. Cross, Maika Takita & Benjamin J. Brown

Nature **625**, 259–263 (2024) | Cite this article

Numbers from recent QEC experiments

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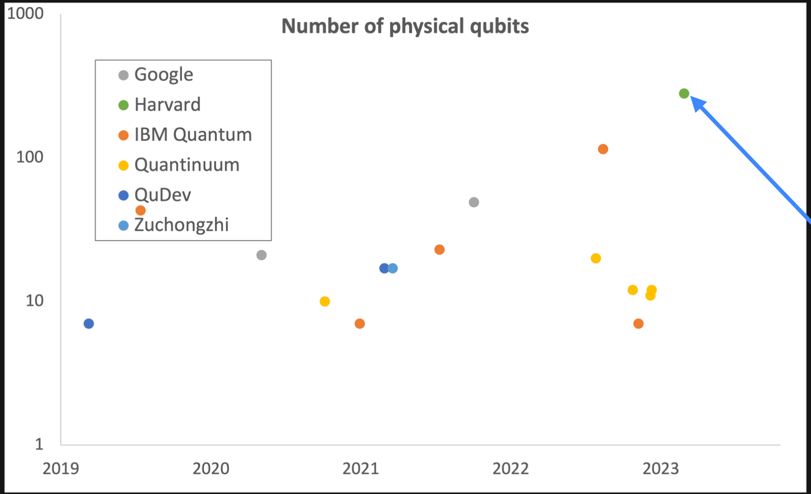
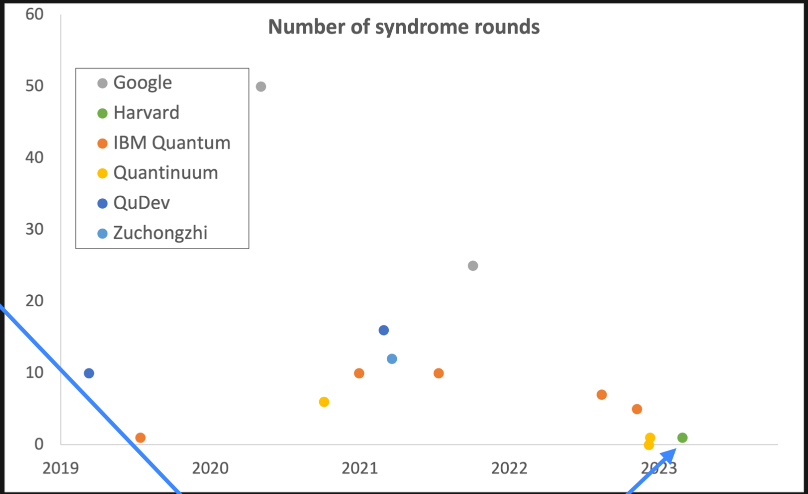
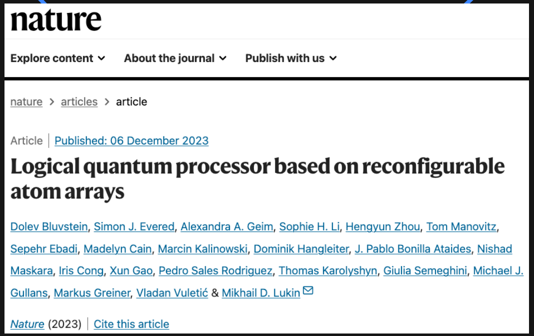




- Record-setting size
- Only a single syndrome measurement round



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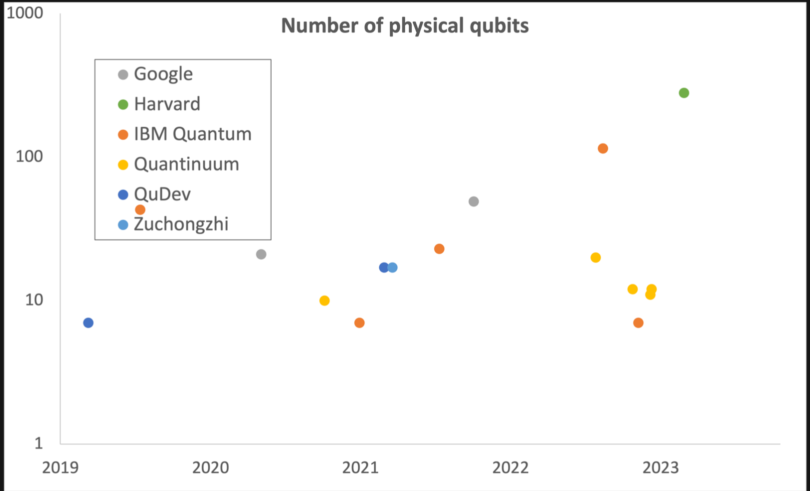
Article | Published: 06 December 2023

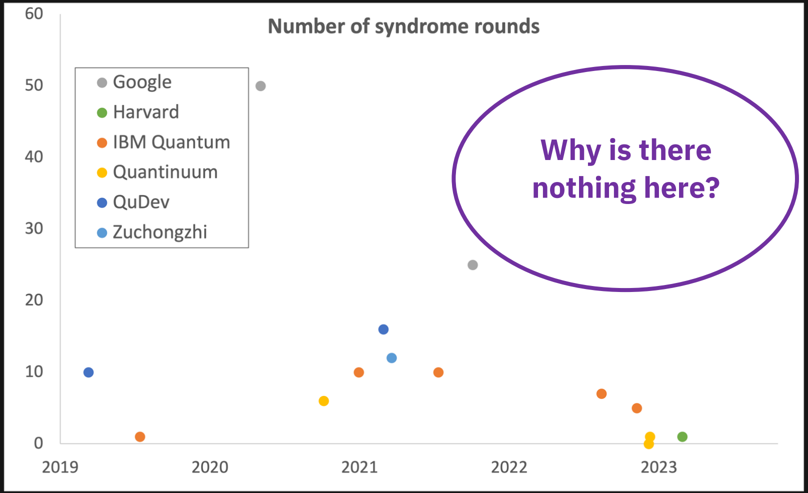
Logical quantum processor based on reconfigurable atom arrays

Dolev Bluvstein, Simon J. Evered, Alexandra A. Geim, Sophie H. Li, Hengyun Zhou, Tom Manovitz, Sepehr Ebadi, Madelyn Cain, Marcin Kalinowski, Dominik Hangleiter, J. Pablo Bonilla Ataides, Nishad Maskara, Iris Cong, Xun Gao, Pedro Sales Rodriguez, Thomas Karolyshyn, Giulia Semeghini, Michael J. Gullans, Markus Greiner, Vladan Vuletić & Mikhail D. Lukin

Nature (2023) | Cite this article

Numbers from recent QEC experiments

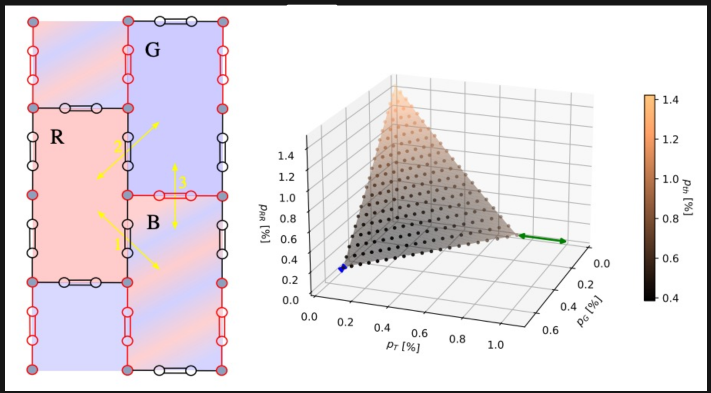




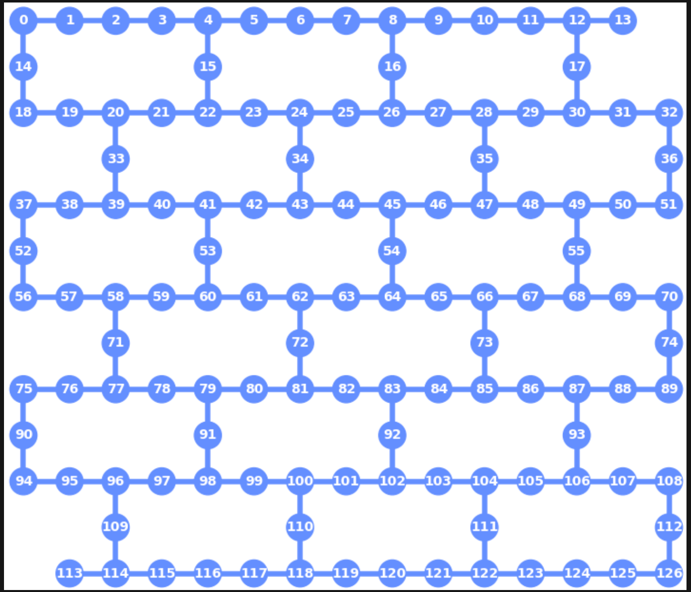
- Many experiments have sought to increase qubit number
- Less have tried to probe large numbers of syndrome measurement rounds
- Let’s push on to 100 and more rounds!

Why rounds are important too

- As an example, here's a preview of work in progress
- How should we best adapt QEC to sparse qubit connectivity?
  - Like IBM Quantum's current heavy hex layout
  - Or even more extreme examples for spin qubits



Bence Hetényi, James R. Wootton, arXiv:2306.17786

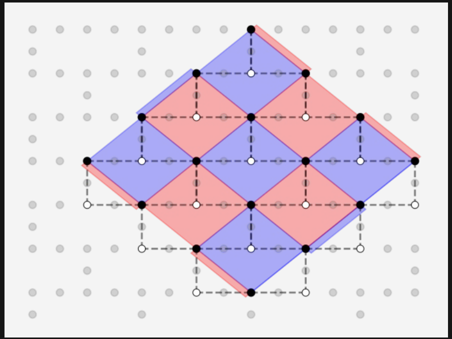


ibm_sherbrooke

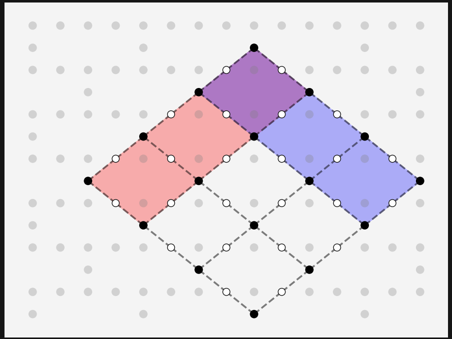
Why rounds are important too

- Sparse connectivity sometimes means idle qubits

3CX surface code

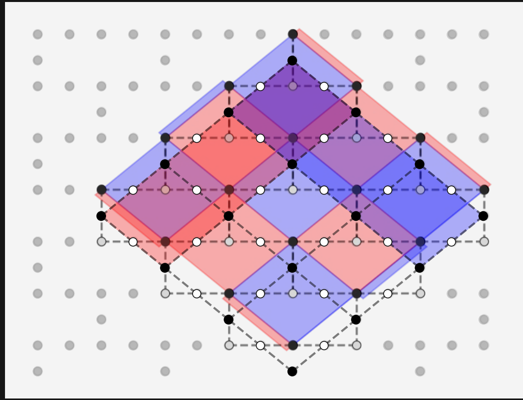


Bacon Shor



Bence Hetényi

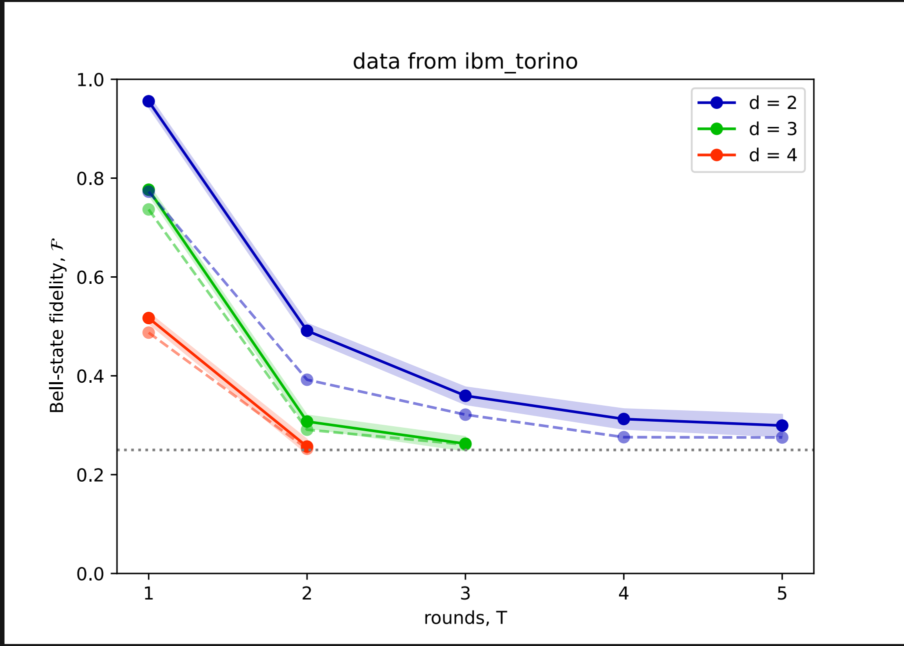
- But we can make this bug into a feature, implementing codes on top of each other
- Allows for
  - Transversal CNOT
  - Fault-tolerant entangling measurements



Why rounds are important too

- With this we
  - Prepare a logical Bell state
  - Do fault-tolerant tomography (XX, YY and ZZ)

- We can get very nice fidelities after one round (after cherry picking system size and post-selection)
- But multiple rounds show a fast decay
- With only one round, the lifetime is a complete unknown



So let's do more rounds!

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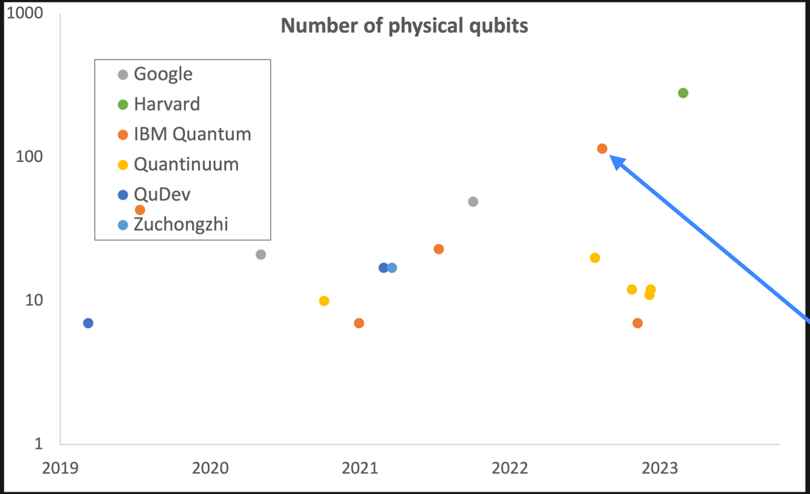
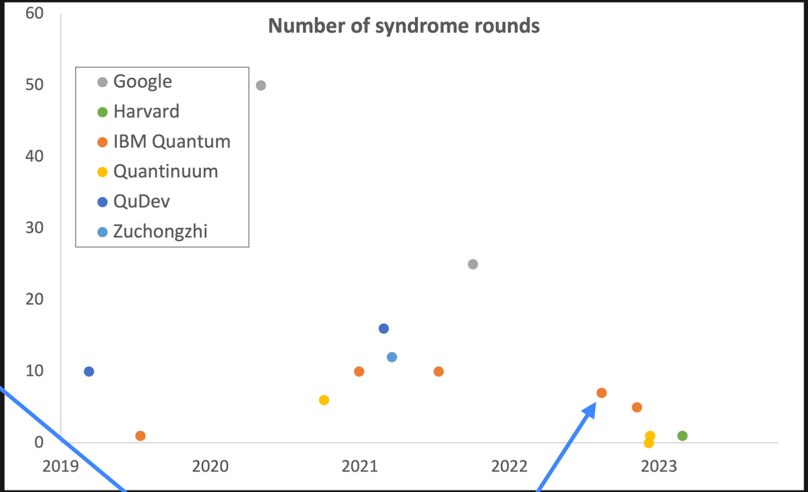




- A good option for this is repetition codes
  - Can be implemented on any platform
  - Give good benchmarking data

Enhanced repetition codes for the cross-platform comparison of progress towards fault-tolerance

Milan Liepelt,[1,2] Tommaso Peduzzi,[1] and James R. Wootton[1]

[1] *IBM Quantum, IBM Research – Europe, Zurich*

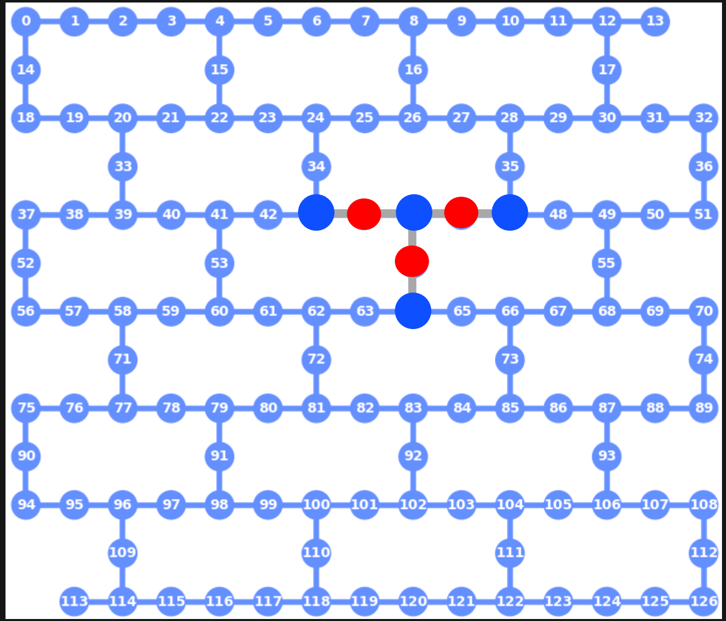
[2] *Department of Physics and the Swiss Nanoscience Institute, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*

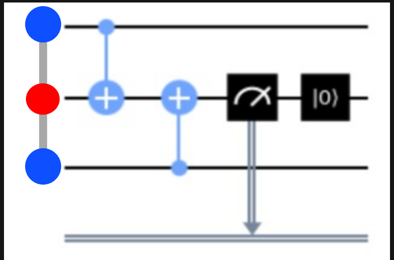
(Dated: August 21, 2023)

Achieving fault-tolerance will require a strong relationship between the hardware and the protocols used. Different approaches will therefore naturally have tailored proof-of-principle experiments to benchmark progress. Nevertheless, repetition codes have become a commonly used basis of experiments that allow cross-platform comparisons. Here we propose methods by which repetition code experiments can be expanded and improved, while retaining cross-platform compatibility. We also consider novel methods of analyzing the results, which offer more detailed insights than simple calculation of the logical error rate.

Repetition codes on heavy hex

- Using 127 qubit IBM Quantum device with
  - 52 code qubits
  - 68 auxiliary qubits
  - 10 syndrome measurement rounds
- 2 qubit parity measurements on each edge of the hexagons





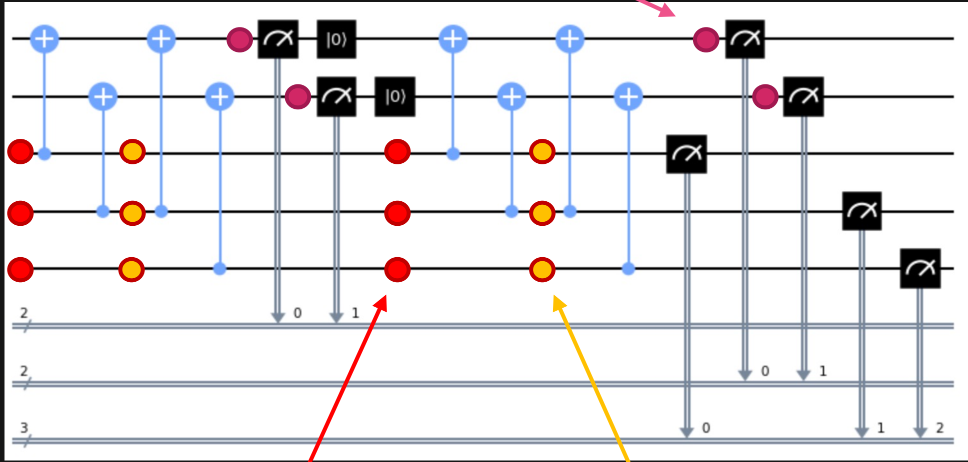

Tomasso Peduzzi


Milan Liepelt

Microscopic benchmarks

- Syndrome is designed to detect errors, and tell us when and where they happen
- Allows us to calculate probabilities of errors at every point in the circuit

Primarily measurement

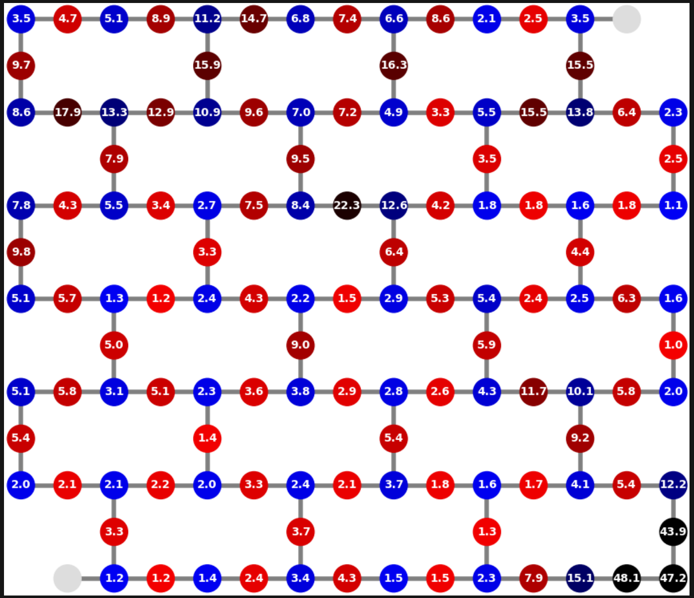


Primarily relaxation

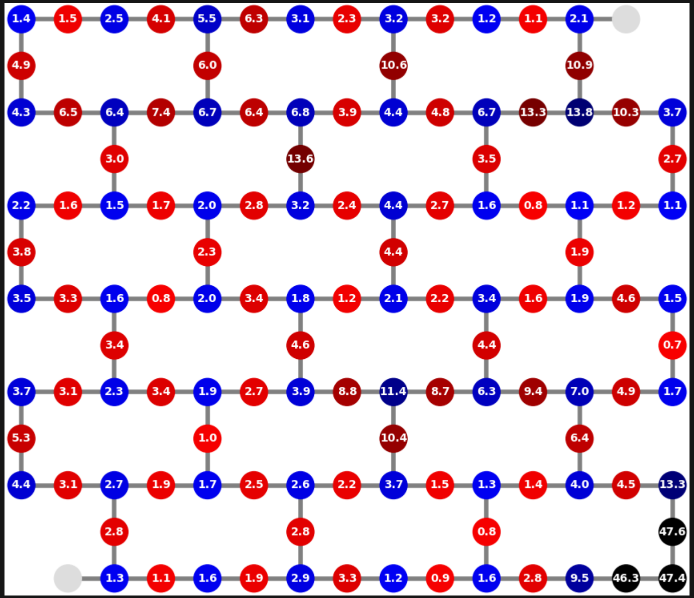
Primarily cnot errors

Microscopic benchmarks

- Averaging these errors for each qubits shows us the real noise experience by QEC codes



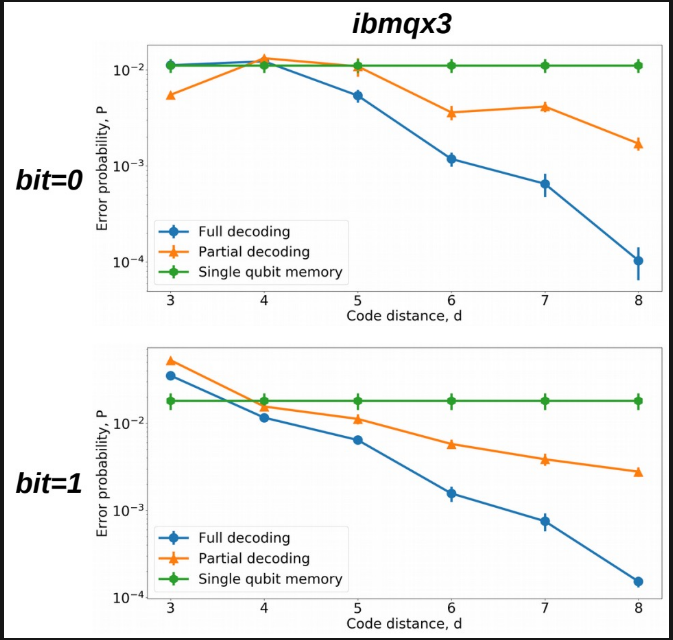
`resets=True`



`resets=False`

Macroscopic benchmarks

- Standard test of QEC quality is the logical error rate
  - Encode a known bit value
  - Run some syndrome measurement rounds
  - Read out encoded information
  - What is the probability of the correct outcome
- Requires many different code sizes to be run
  - Does performance improve for bigger codes?
  - How does it decay over many rounds
- But for large codes, errors become very difficult to find!

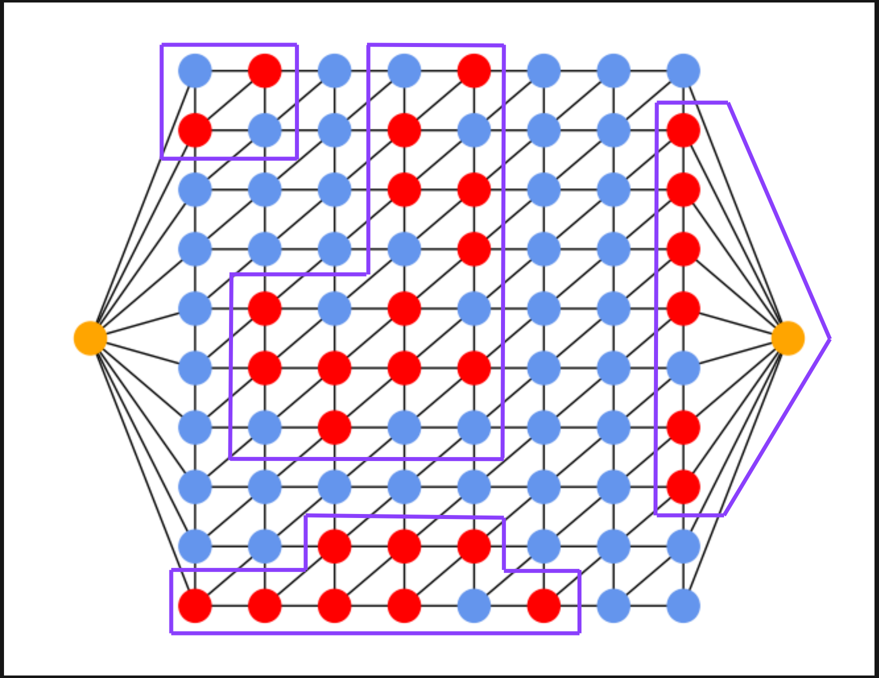


James R. Wootton, Daniel Loss arXiv:1709.00990

Macroscopic benchmarks

- Instead, we can look inside the decoder
- Reliable decoding requires reliable identification of errors
- Ambiguities caused when errors occur too close, too often
  - Look at error clusters identified by the decoder
  - Analyze the number of errors they contain
- Required software is open source

  github.com/qiskit/qiskit-qec



Macroscopic benchmarks

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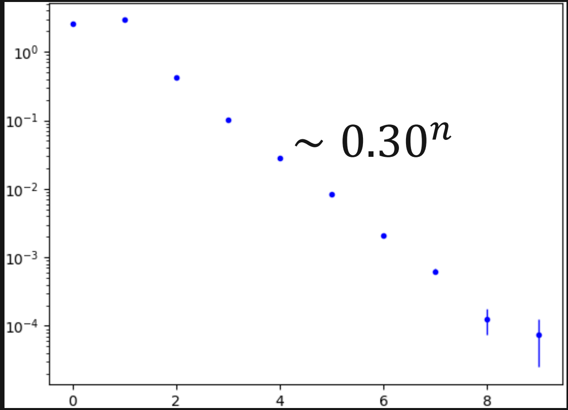
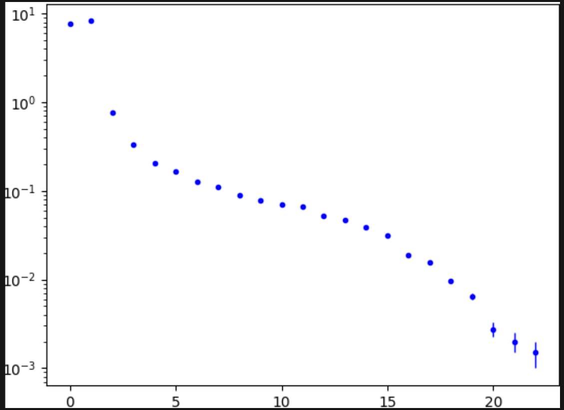
- We look at the number of errors in each cluster
- And look at how common clusters are
- See if there is the required exponential decay

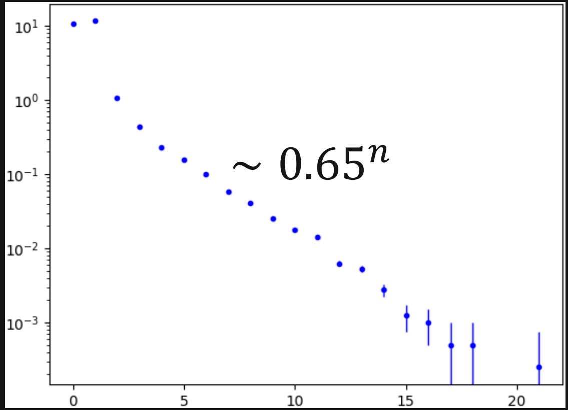
- Decay rate provides us with a good QEC comparison



p=1% (simulation)



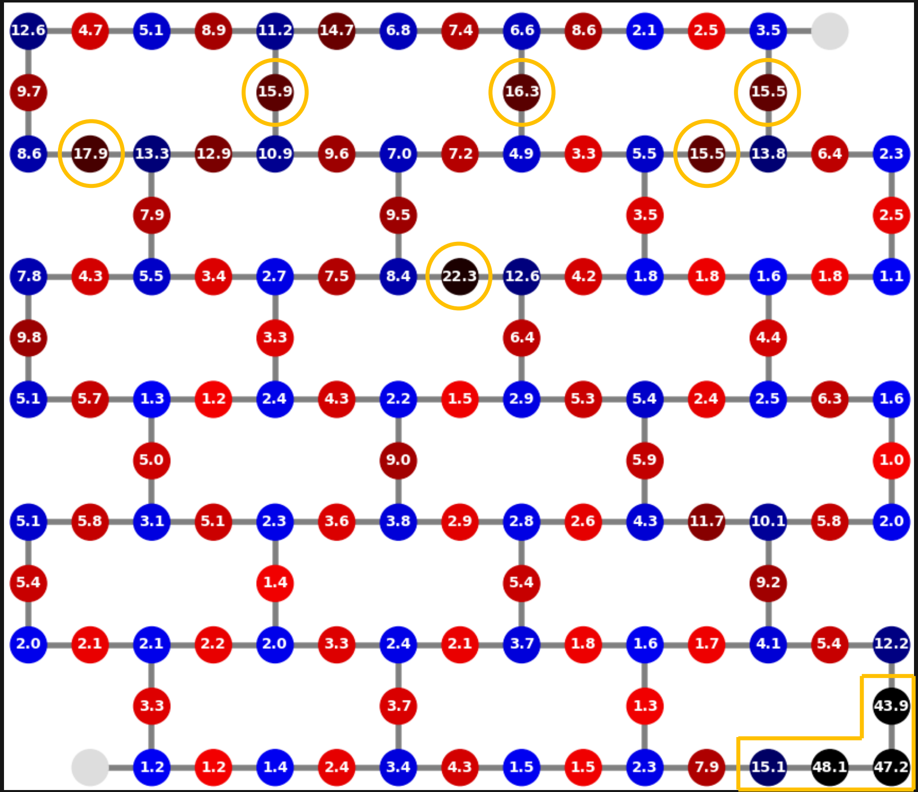
resets=True



resets=False

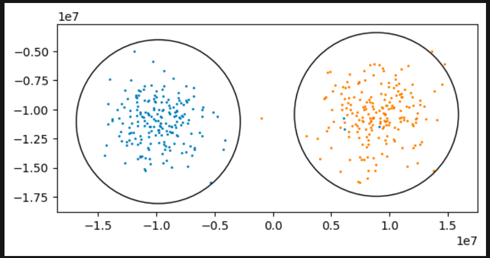
Towards 100 rounds

- One of the main obstacles: measurement noise
  - What is causing this?
  - How can we mitigate the effects?

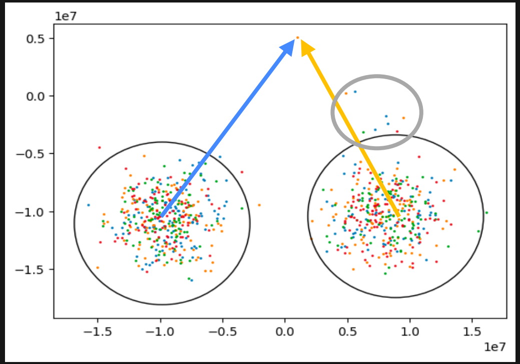


Looking under the hood of measurement

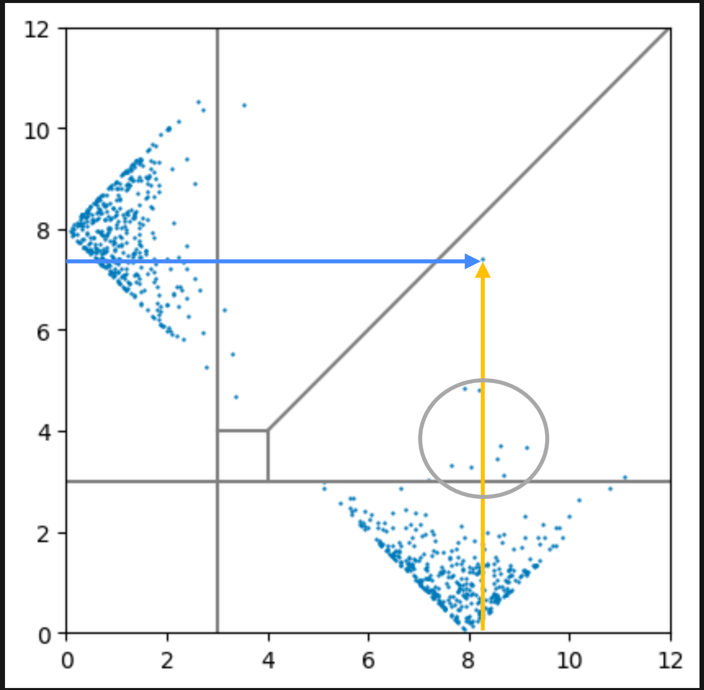
- More detailed form of measurement info: IQ point
- First, can we find a representation that allows easy comparison of qubits?



Calibration



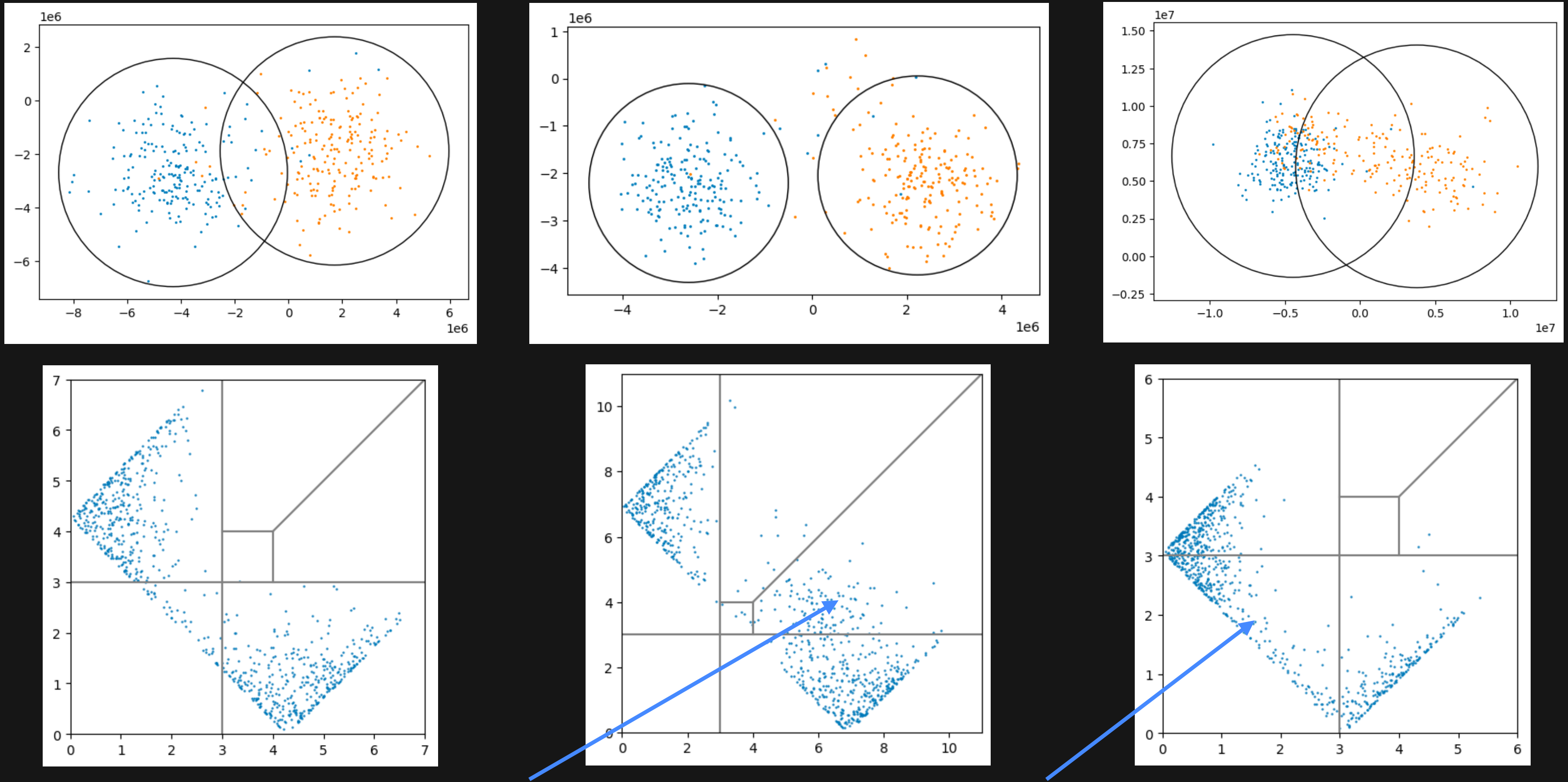
After multiple syndrome measurements



After multiple syndrome measurements (alternative representation)

Looking under the hood of measurement

5 9 59

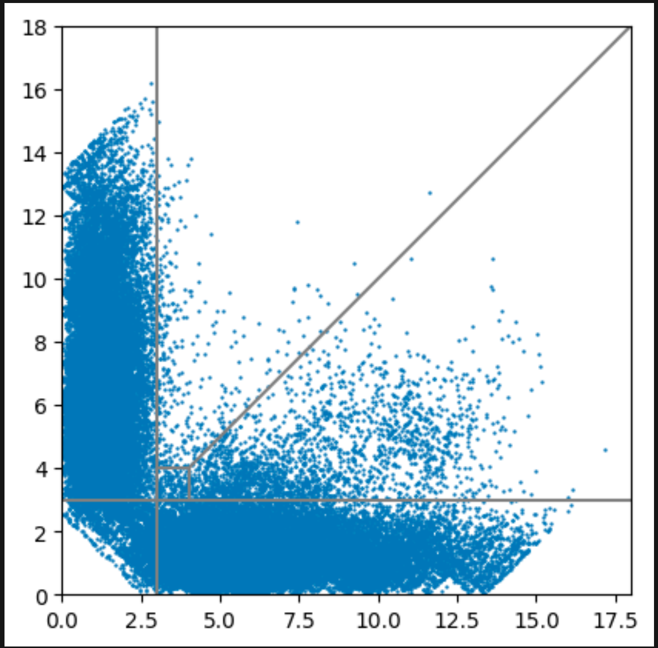


leakage

ambiguity

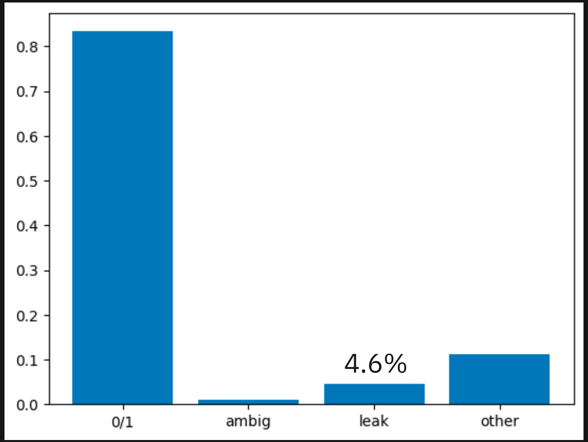
Results from a 127 qubit Eagle

- All points from the 50th round

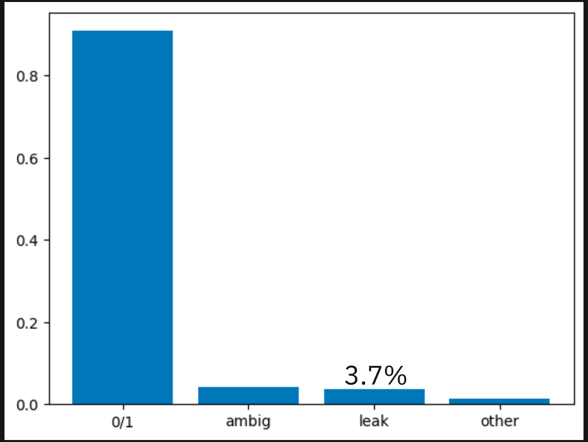


- Leakage on the order of a few percent

2 stdevs

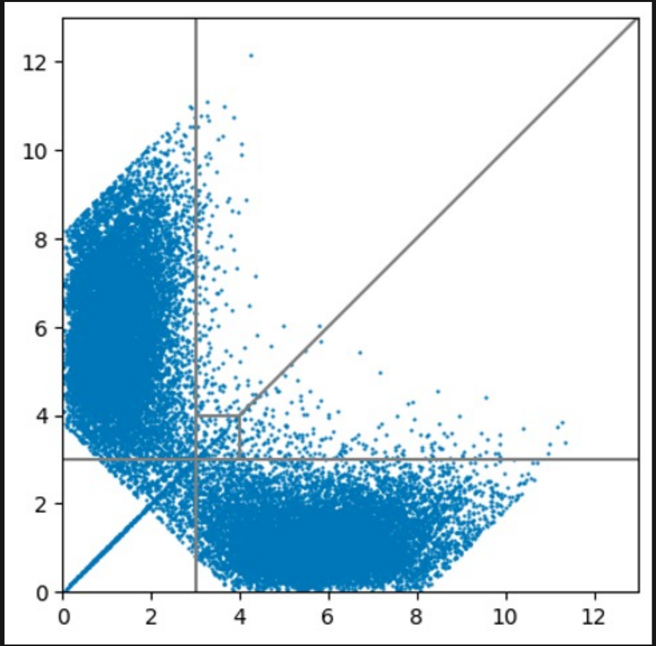


3 stdevs



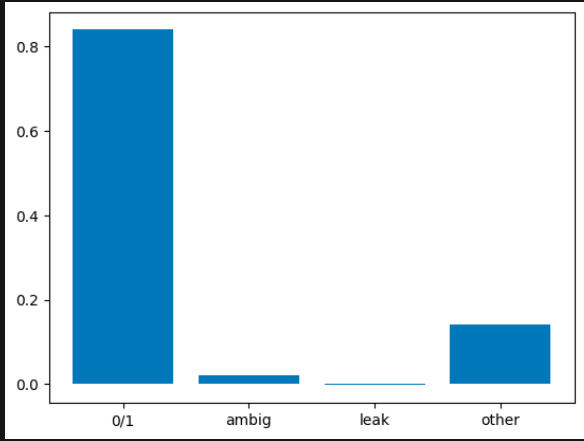
Results from a 133 qubit Heron

- All points from the 50th round

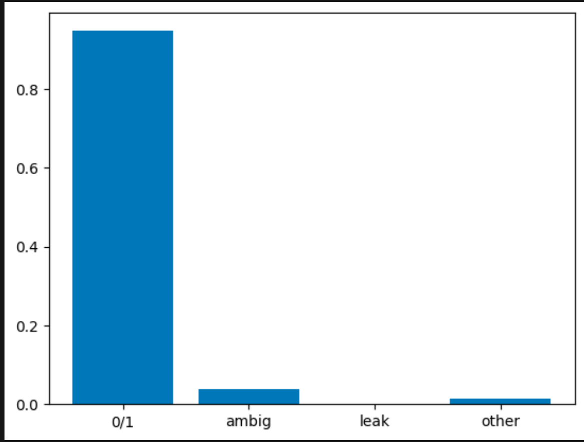


- Leakage barely apparent

2 stdevs

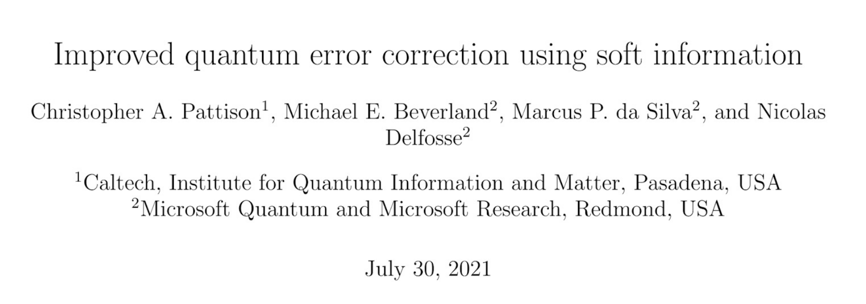


3 stdevs



Soft information decoding

- IQ data can also be used to inform the decoder
- Applying this to data from our devices results in big improvements

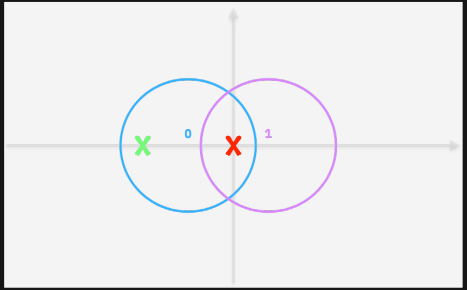


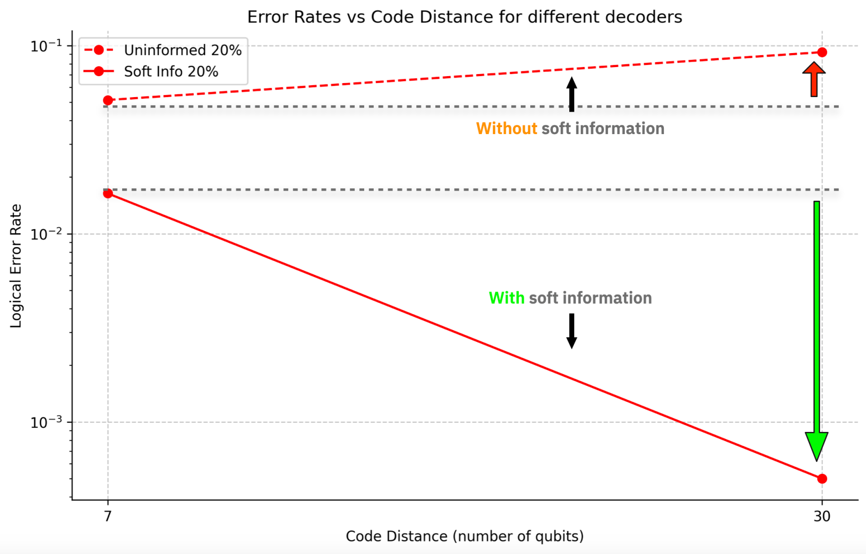
Improved quantum error correction using soft information

Christopher A. Pattison[1], Michael E. Beverland[2], Marcus P. da Silva[2], and Nicolas Delfosse[2]

[1]Caltech, Institute for Quantum Information and Matter, Pasadena, USA
[2]Microsoft Quantum and Microsoft Research, Redmond, USA

July 30, 2021





Maurice Hanisch

Conclusions

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- Let’s keep on making bigger and better QEC experiments

- But let’s not forget that time is important as space!

Thanks for your attention!