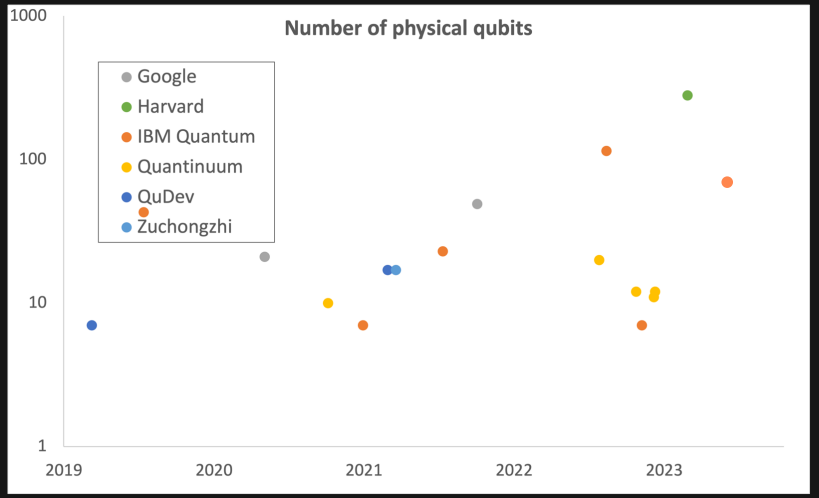
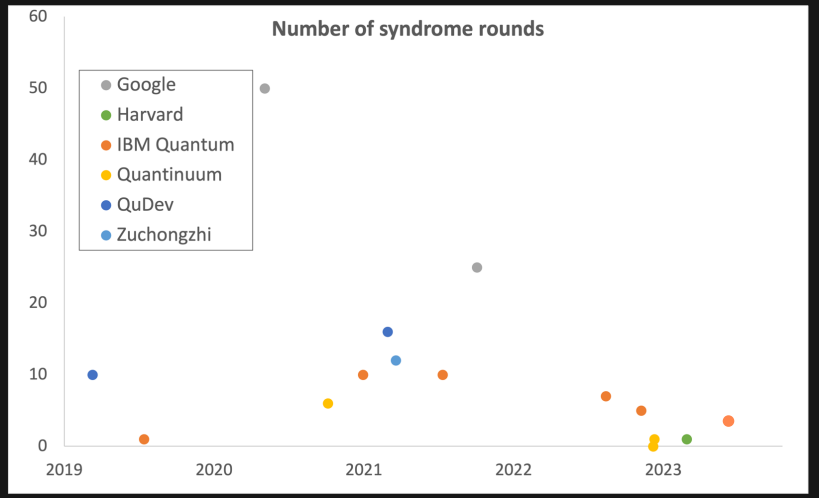
Proof-of-principle experiments for QEC

James Wootton
IBM Quantum, IBM Research - Zurich

Numbers from recent QEC experiments

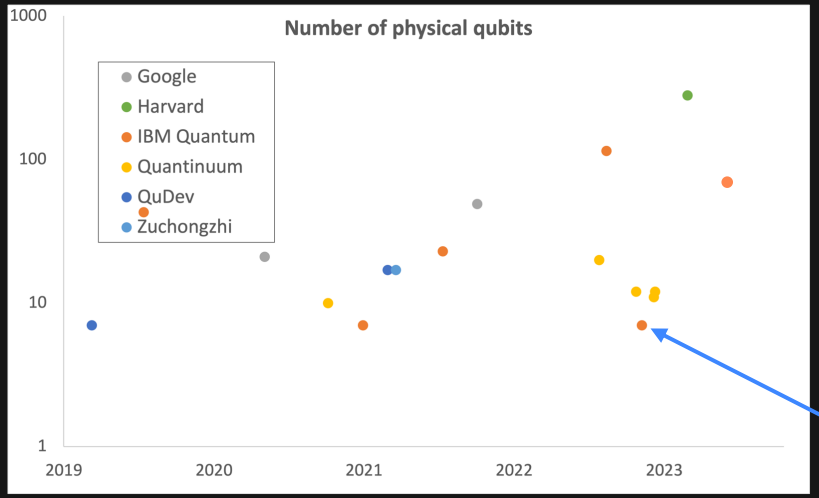
- Two important metrics in QEC experiments: how big and how long

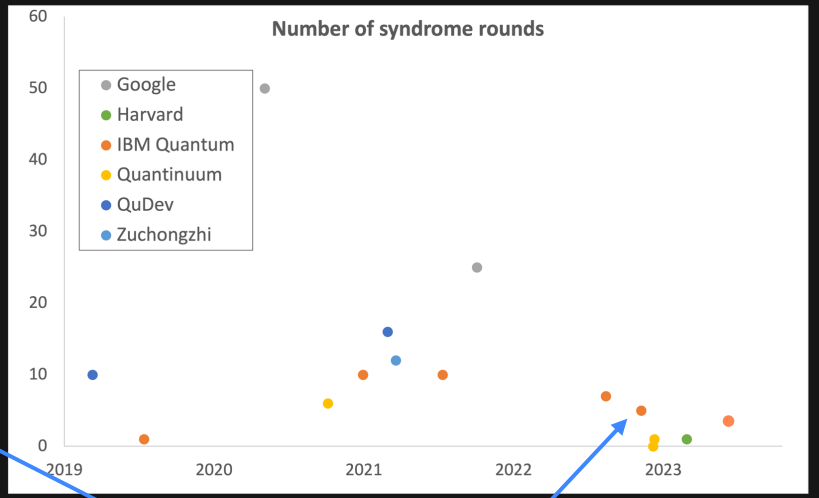




- Records here are
  - 280 physical qubits
  - 50 syndrome measurement rounds

Numbers from recent QEC experiments





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

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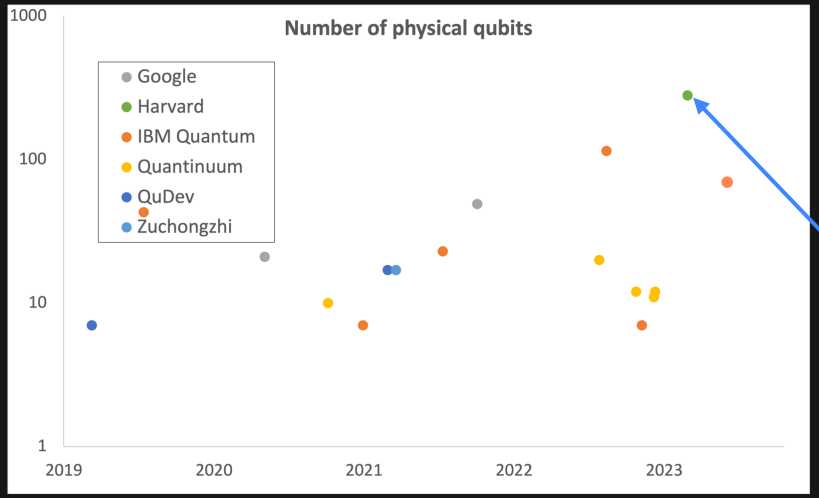
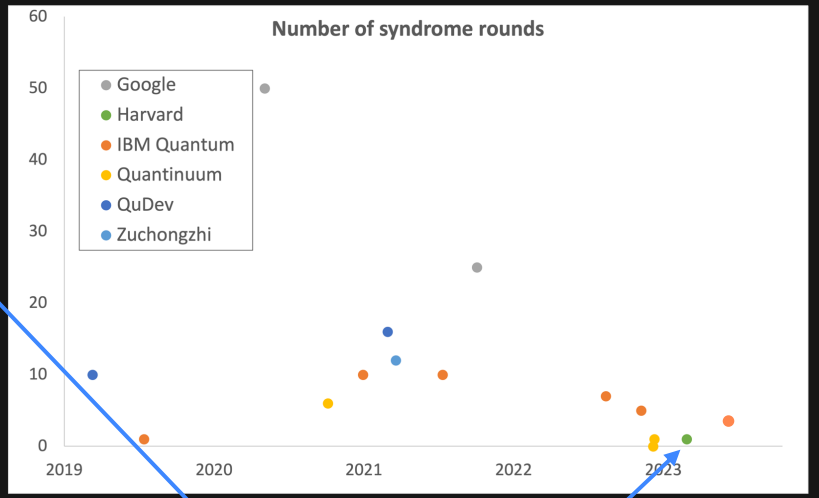
Encoding a magic state with beyond break-even fidelity

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 ✉

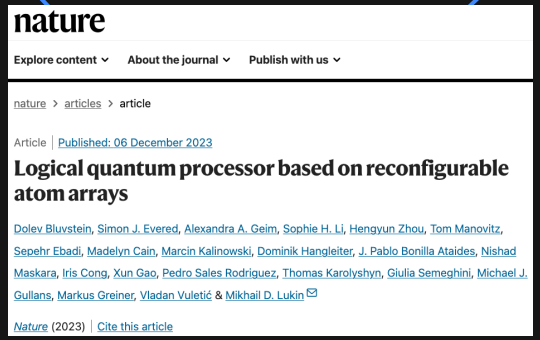
Nature **625**, 259–263 (2024) | Cite this article

Numbers from recent QEC experiments





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



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Article | Published: 06 December 2023

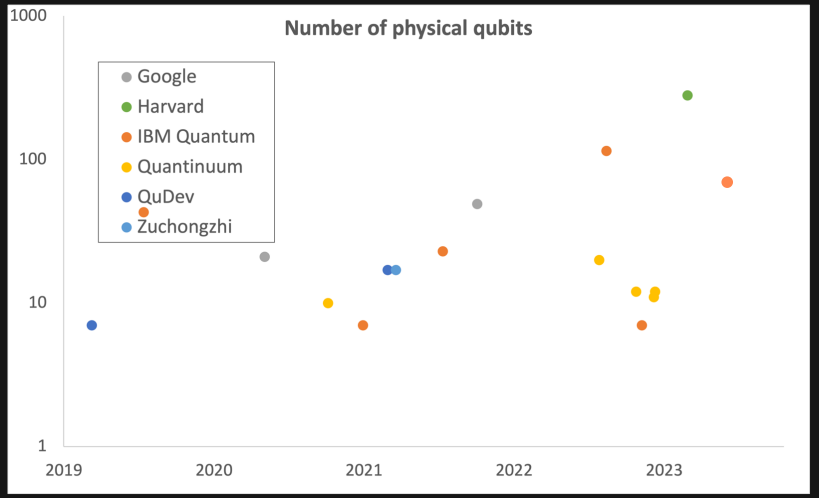
Logical quantum processor based on reconfigurable atom arrays

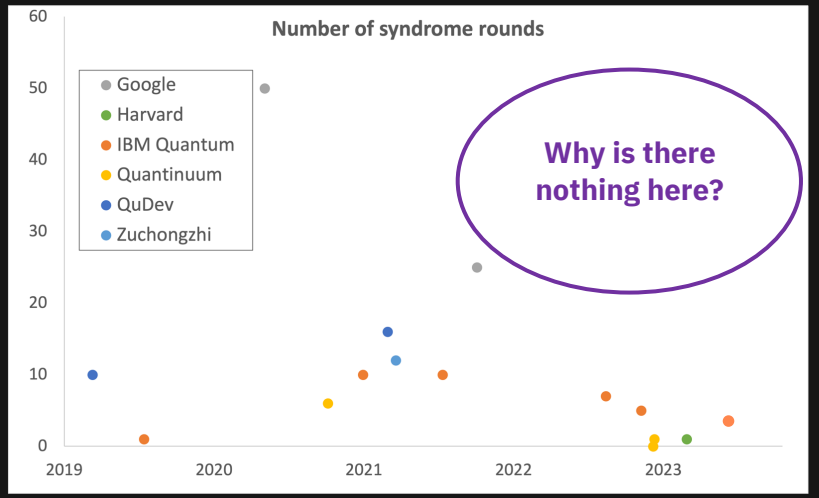
Dolev Bluvstein, Simon J. Evered, Alexandra A. Geim, Sophie H. Li, Hengyun Zhou, Tom Manovitz, Sepehr Ebadi, Madelyn Cain, Marcin Kalinowski, Dominik Hangleiter, J. Pablo Bonilla Ataides, Nishad Maskara, Iris Cong, Xun Gao, Pedro Sales Rodriguez, Thomas Karolyshyn, Giulia Semeghini, Michael J. Gullans,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

Nature (2023) | Cite this article

Numbers from recent QEC experiments

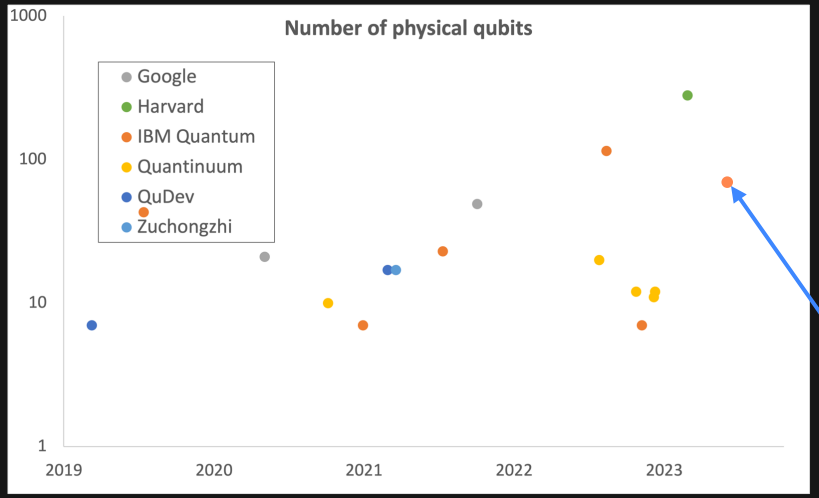
IBM **Quantum**

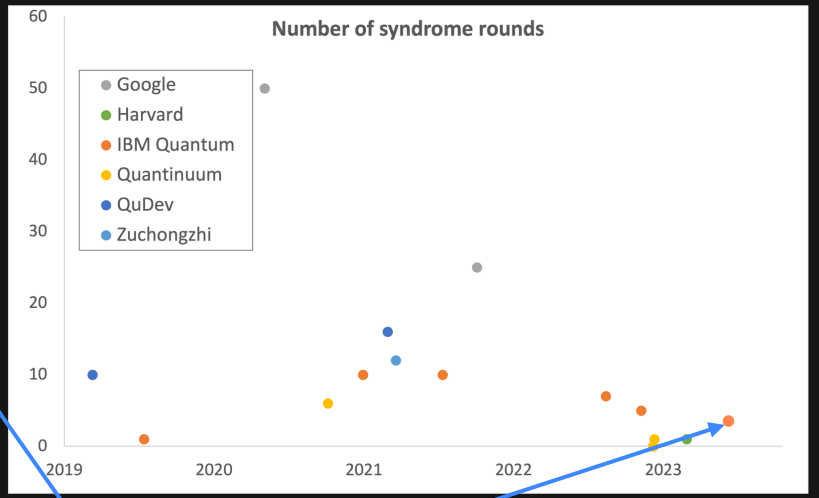




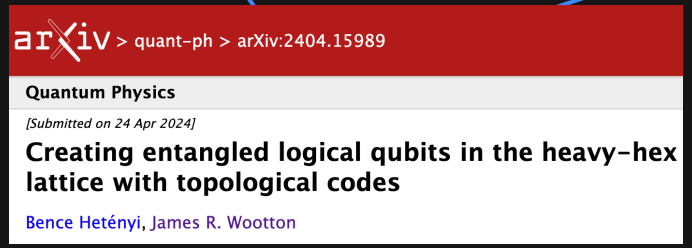
- Many experiments have sought to increase qubit number
- Less have tried to probe large numbers of syndrome measurement rounds
- Let’s push on to 100 and more rounds!

Why rounds are important too





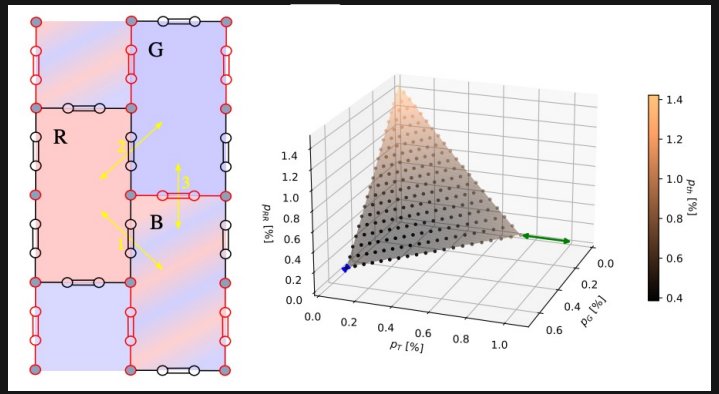
- Bell state between two logical qubits
  - Nice results for single round
  - But we look at multiple rounds too...



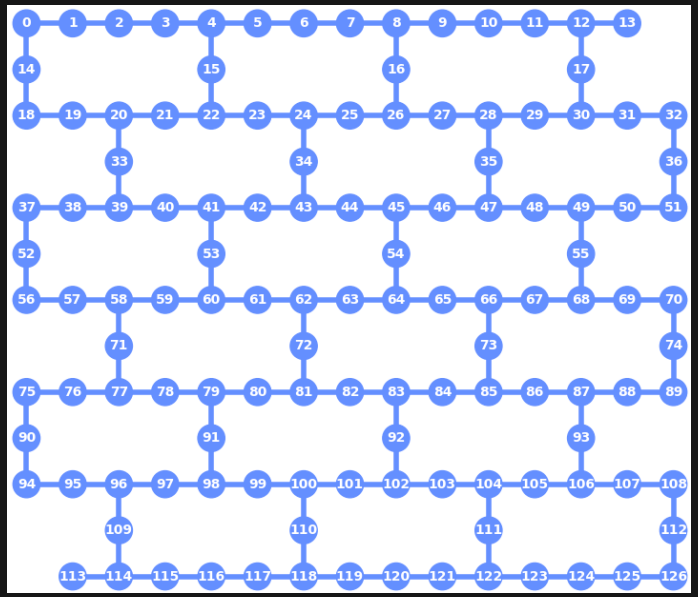
Bence Hetényi

Why rounds are important too

- 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

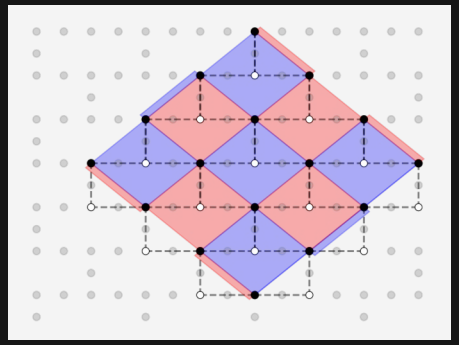


ibm_sherbrooke

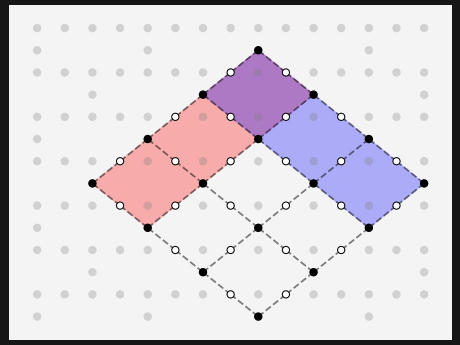
Why rounds are important too

- Sparse connectivity sometimes means idle qubits

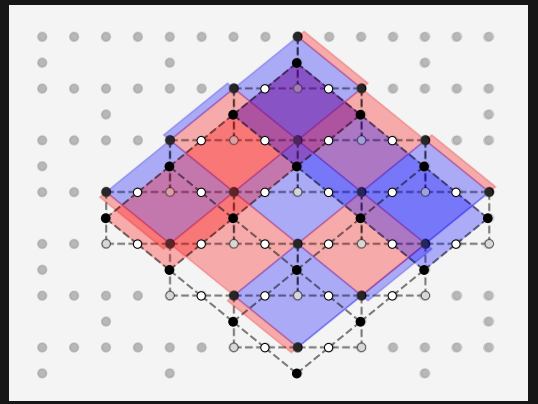
3CX surface code



Bacon Shor



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

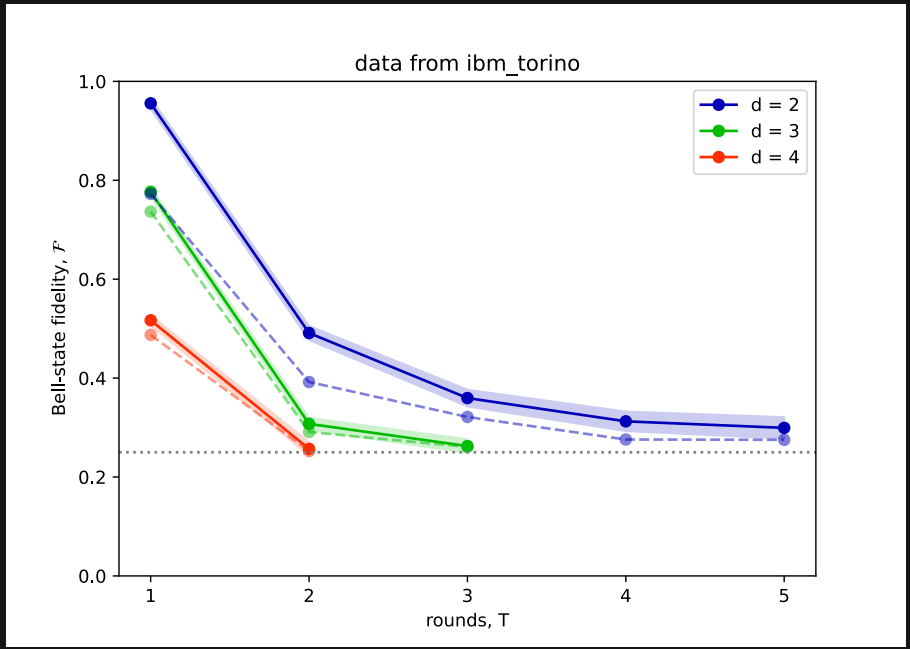


Why rounds are important too

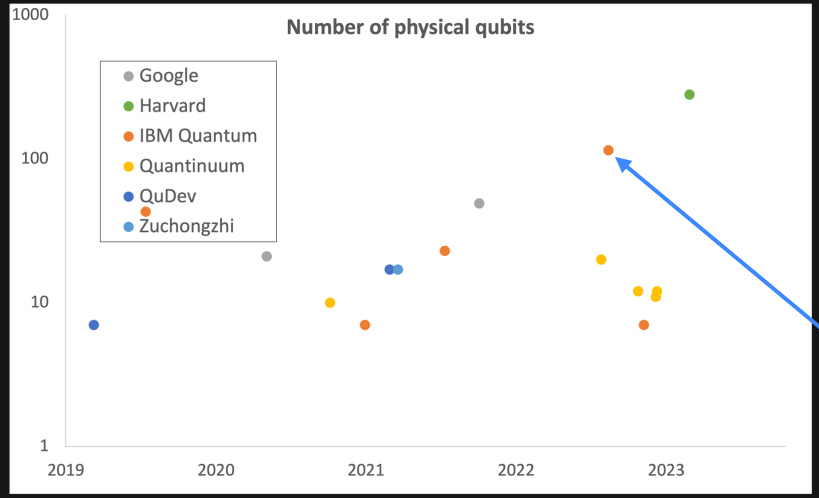
- With this we
  - Prepare a logical Bell state
  - Do fault-tolerant tomography (XX, YY and ZZ)

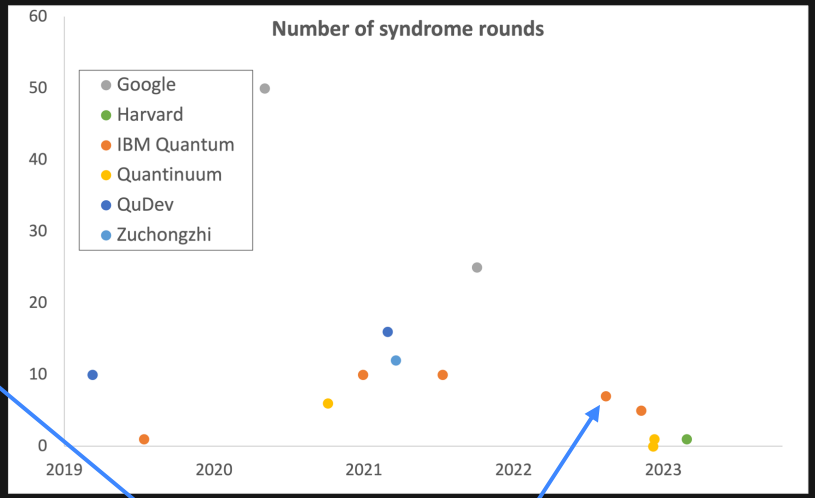
- We can get very nice fidelities after one round (after cherry picking system size and post-selection)
- But multiple rounds show a fast decay

- With only one round, the lifetime is a complete unknown



So let’s do more rounds!





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

Journal of Physics A: Mathematical and Theoretical

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

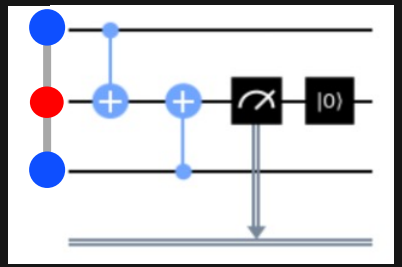
Milan Liepelt[1], Tommaso Peduzzi[1] and James Wootton[1]

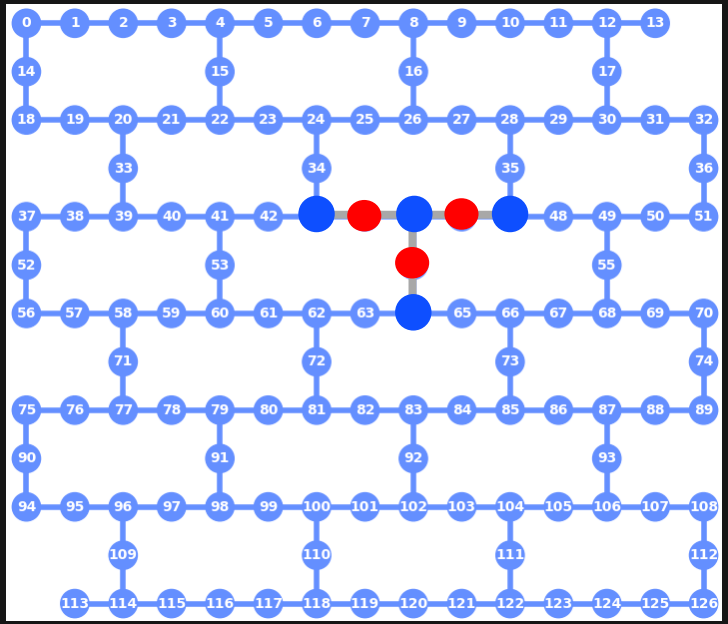
Accepted Manuscript online 24 May 2024 • © 2024 The Author(s). Published by IOP Publishing Ltd

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

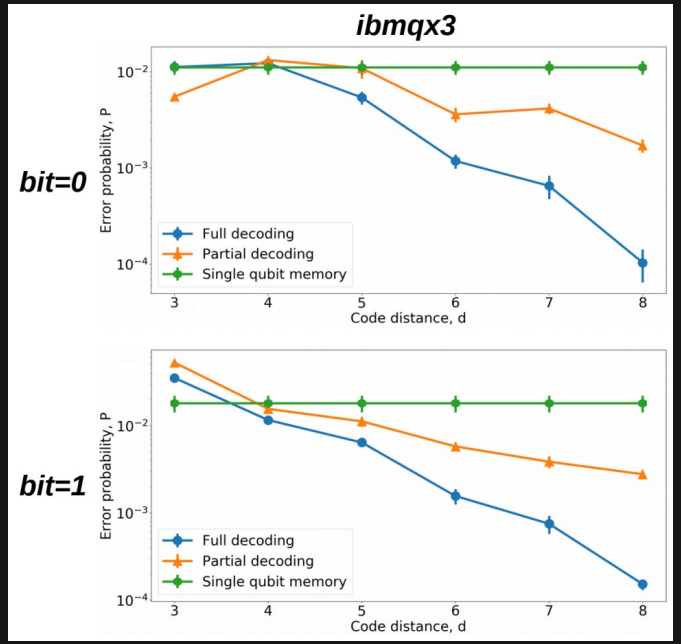

Milan Liepelt

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

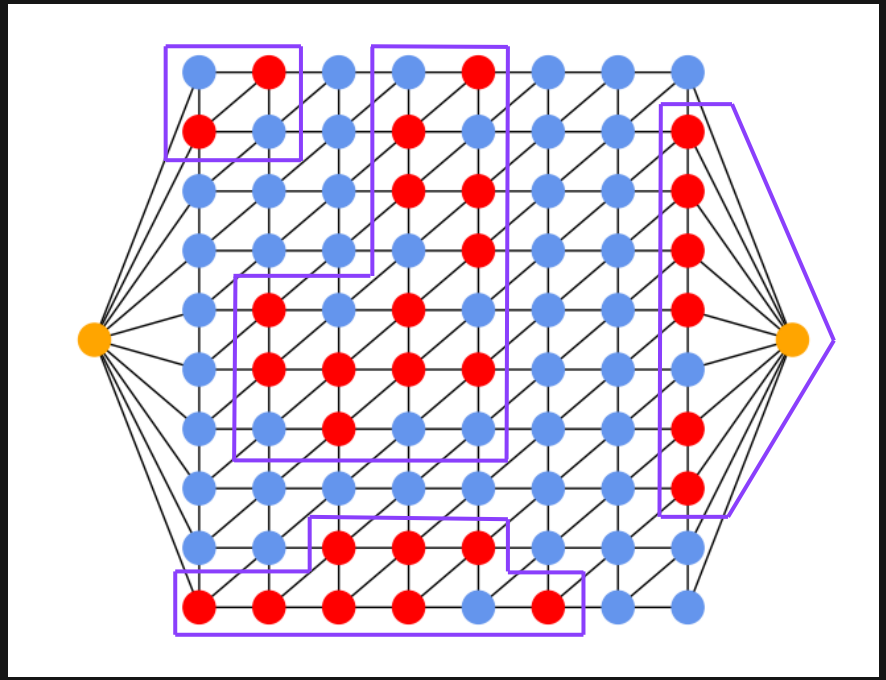
- But for large codes, errors become very difficult to find!



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

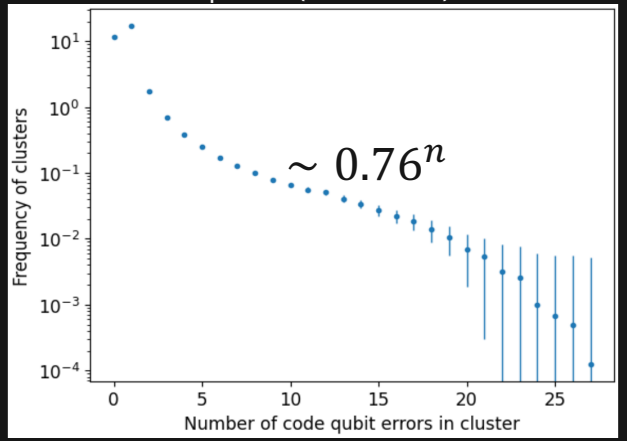


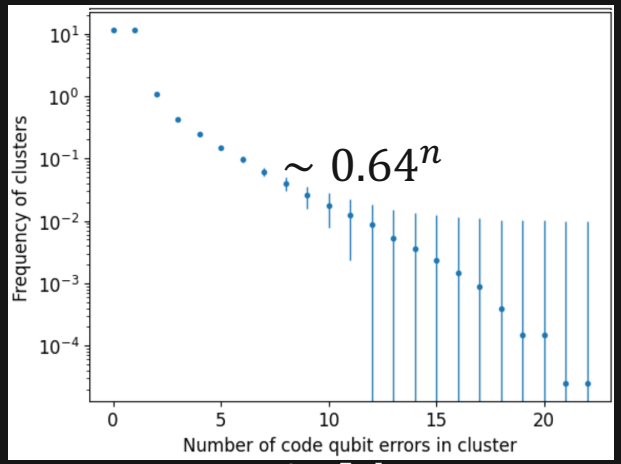
Macroscopic benchmarks

- 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

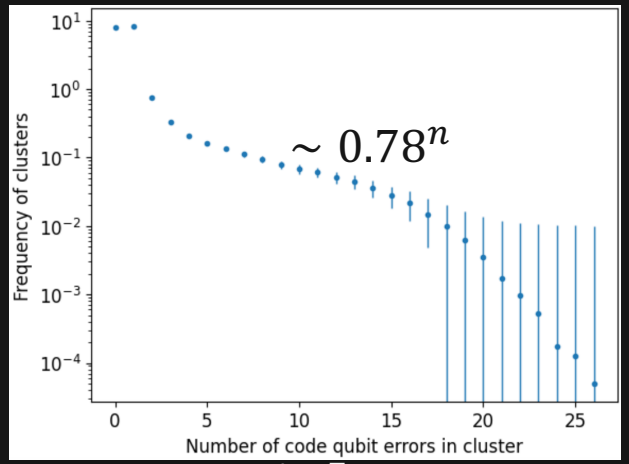
- Decay rate provides us with a good QEC comparison

p=3% (simulation)





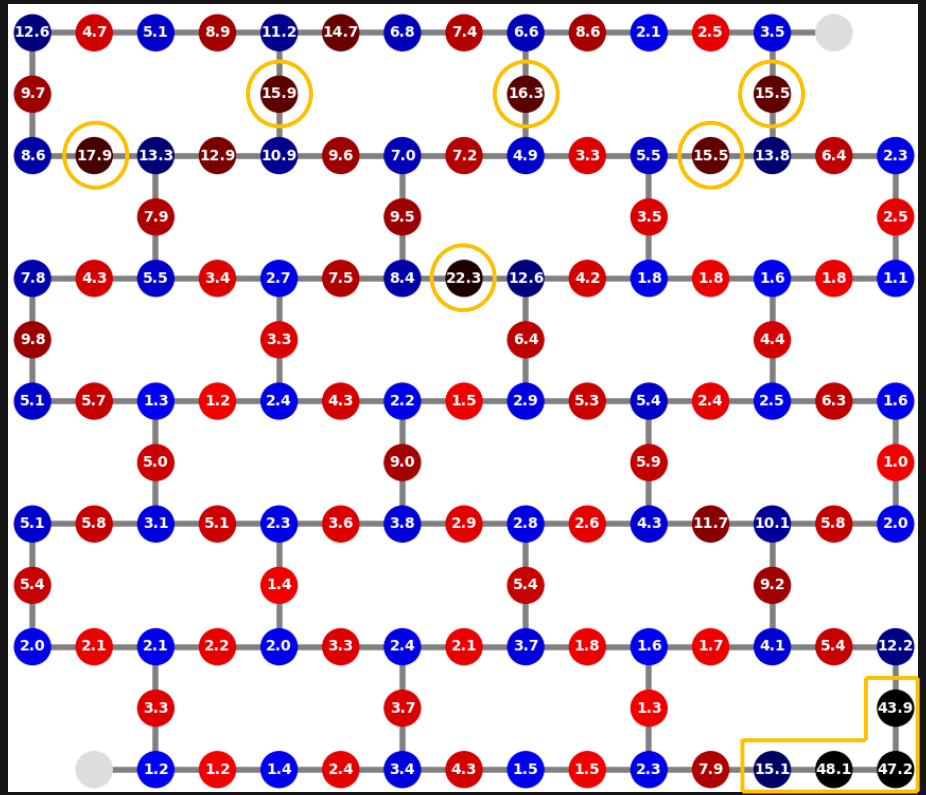
resets=False



resets=True

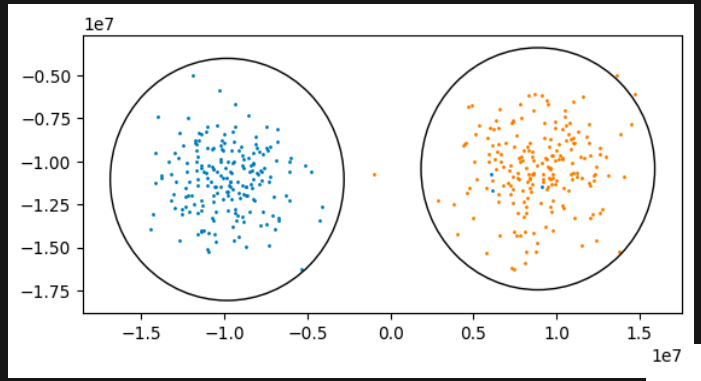
Towards 100 rounds

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

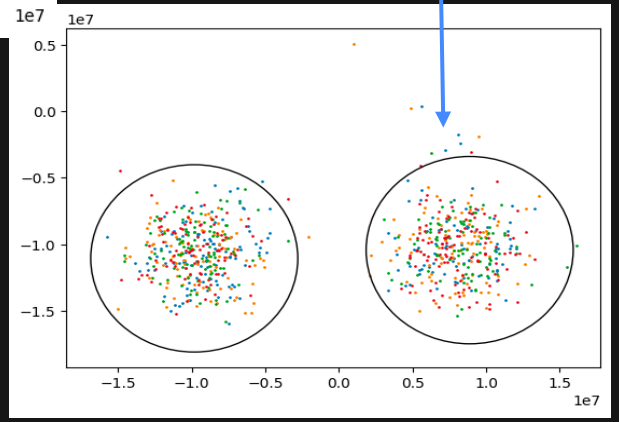


Looking under the hood of measurement

- More detailed form of measurement info: IQ point
- Classification of 0 and 1 based on calibration data



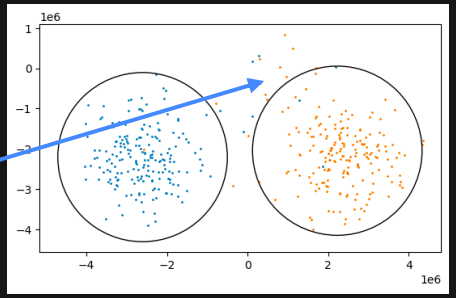
Calibration data



After several syndrome rounds

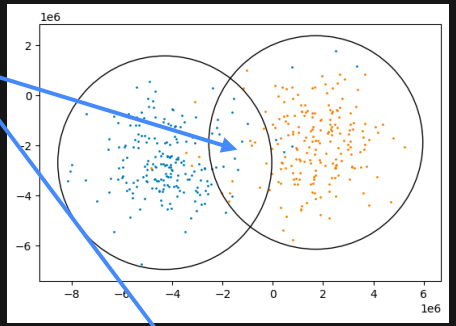
leakage

9



ambiguity

5



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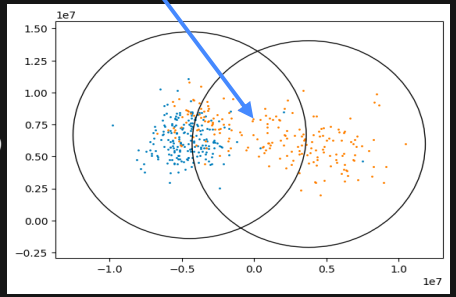


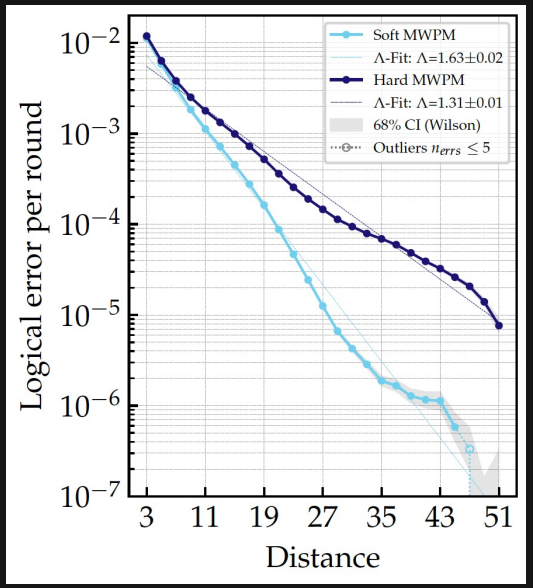
127 qubit Eagle over 100 rounds

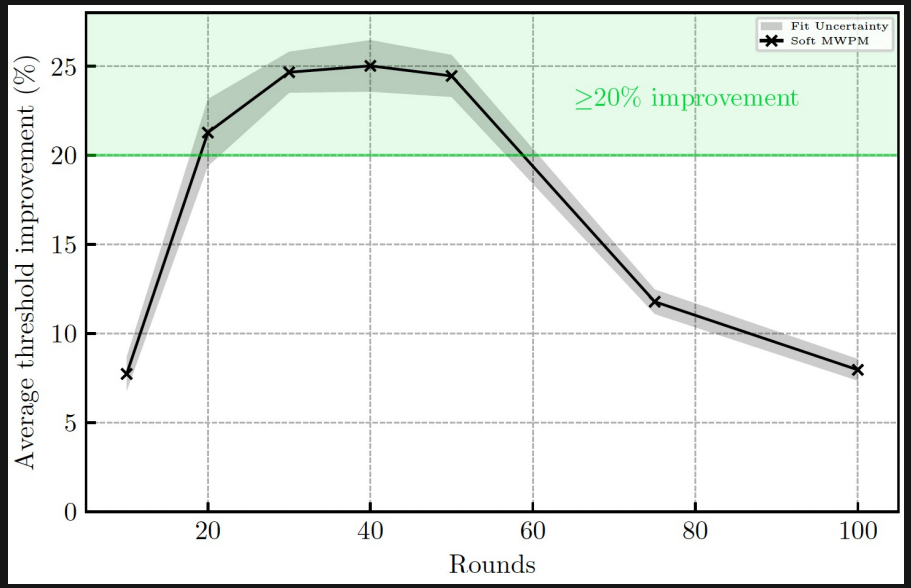
IBM **Quantum**

- IQ data can also be used to inform the decoder
  - ➢ Dynamic reweighting with soft information
- Applying this to data from our devices results in large improvements

Maurice Hanisch

Bence Hetényi





Conclusions

- Let’s keep on making bigger and better QEC experiments
- But let’s not forget that time is important as space!
- Our upcoming papers set the record at 100 rounds
- Hopefully you’ll beat us soon!

Thanks for your attention!