Quantum error correction beyond the surface code

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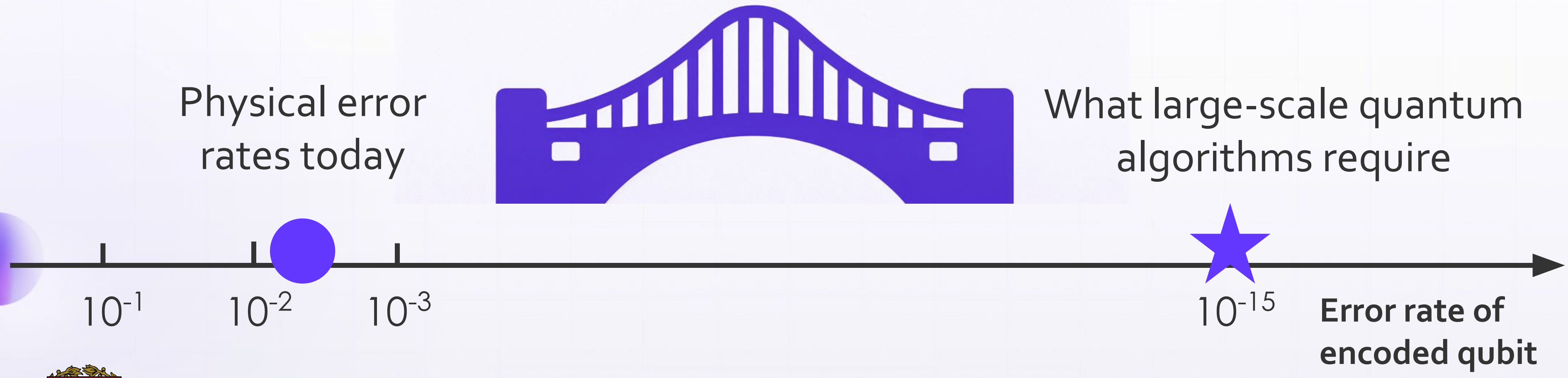
Joint work with Qian Xu*, Chris Pattison, Nithin Raveendran, Dolev Bluvstein, Jonathan Wurtz, Bane Vasic, Mikhail Lukin, Liang Jiang, Hengyun (Harry) Zhou. **Nat. Phys. 20, 1084-1090**

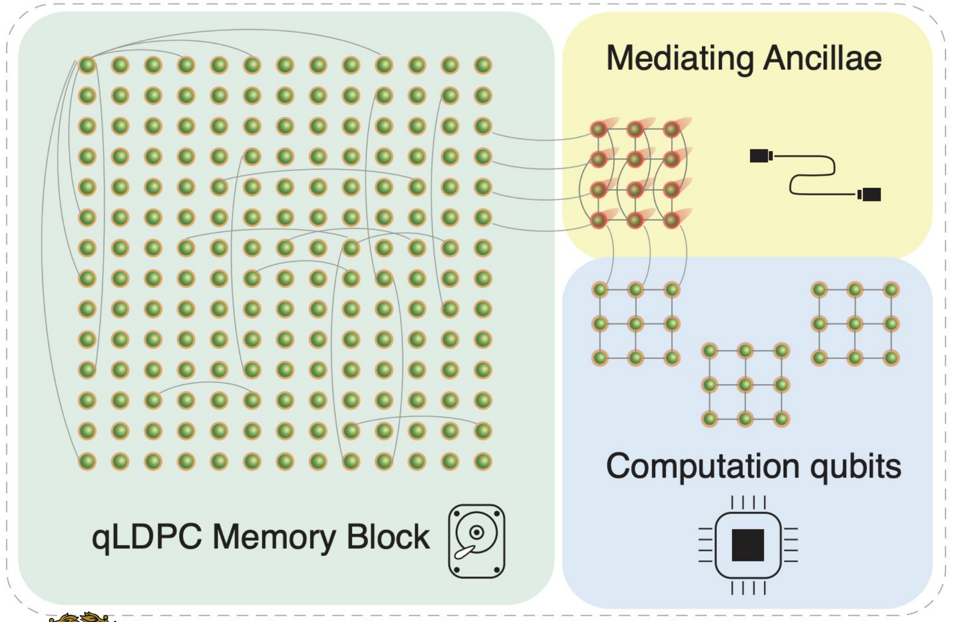
Challenge of Large-Scale Quantum Computation

Quantum error correction will bridge this gap!

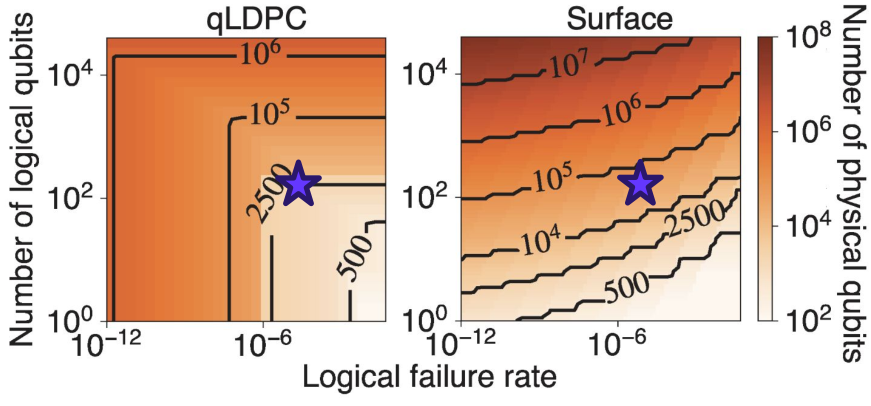


This Work: Bridging the Gap with qLDPC Codes

Implementation blueprint for memory & logical gates on a neutral atom quantum computer



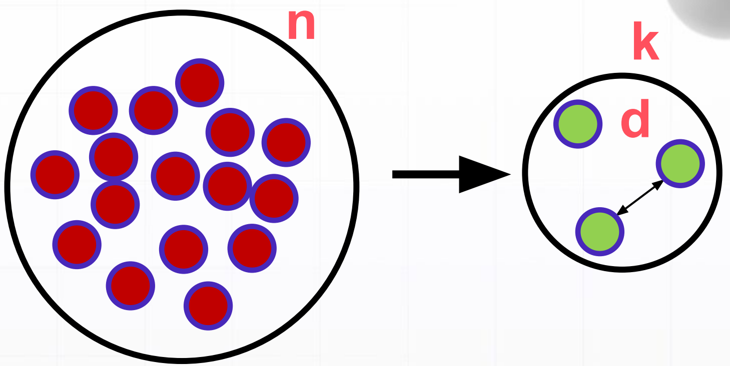
- Order of magnitude fewer physical qubits required, when replacing surface code with qLDPC code



Q. Xu*, JPBA*, C. Pattison ...,L. Jiang, H. Zhou, arXiv:2308.08648

Beyond the surface code?

- Good codes: $k = O(n), d = O(n)$
- Surface code: $k = O(1), d = O(\sqrt{n})$
- Best 2D-local codes: $kd^2 \leq O(n)$ (saturated by surface code)
- For improved properties: need non-locality!
- ... while preserving ldpc-ness (constant check weight + qubit degree)



> **The main message** is that magic state distillation is *not* the dominant cost in a surface-code-based quantum computer. Rather, the large overhead of surface codes is due to their low encoding rate, which implies that a large number of qubits is required to simply store all data qubits of the computation.

Litinski, Quantum (2019)

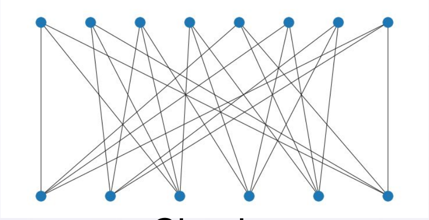
[[n, k, d]] quantum code:

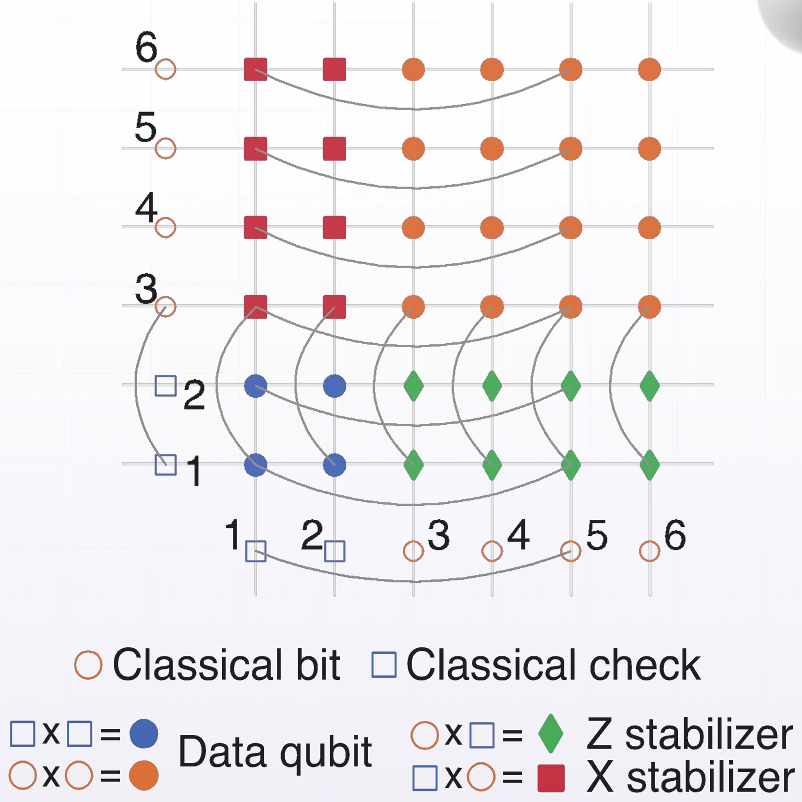
- n: number of physical qubits
- k: number of logical qubits
- d: code distance (error-correcting power)
- R=k/n : code rate

Bravyi, Terhal, Poulin, PRL 2010; Baspin, Krishna, PRL 2022

Product Structure of Some qLDPC Codes

- Hypergraph product code (HGP):
  - Construct quantum code by taking product between two classical codes
  - Example: surface code = HGP of two repetition codes
- Taking HGP of two classical codes with $[n, k = \Theta(n), d = \Theta(n)]$, we obtain a quantum code $[[n, \boldsymbol{k = \Theta(n)}, d = \Theta(\sqrt{n})]]$
  - In this work: random (3,4)-biregular graphs

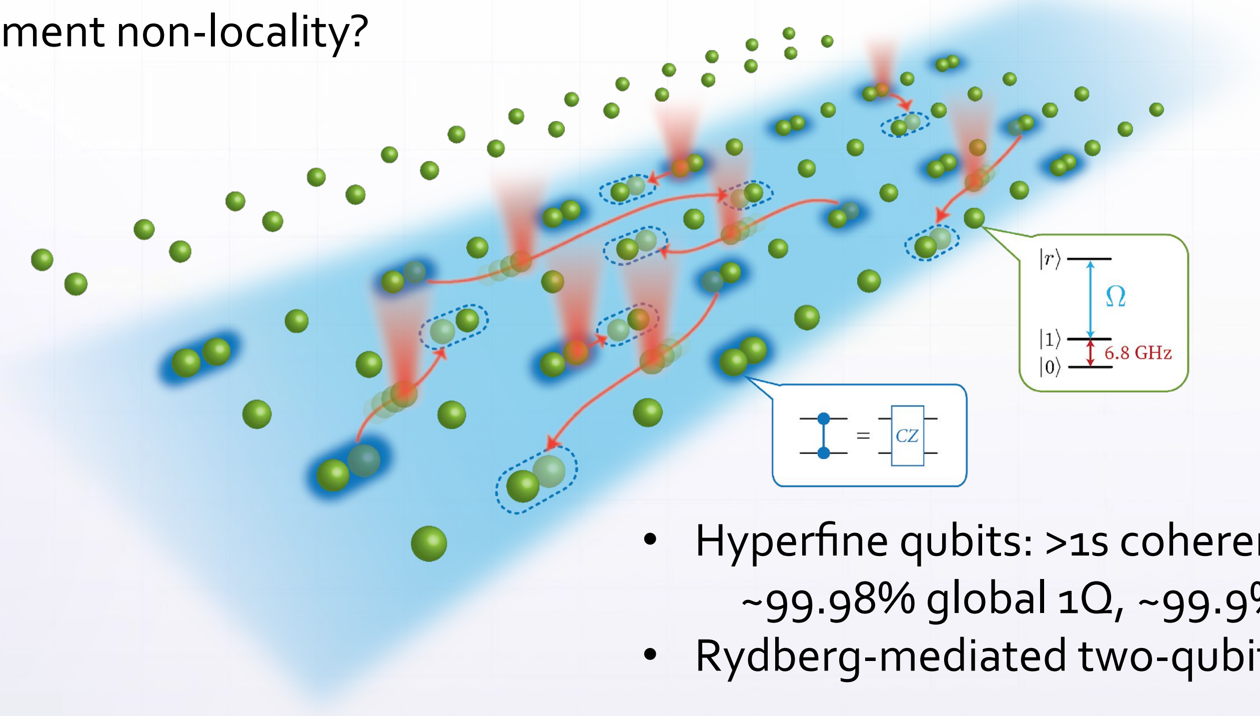




Tillich, Zémor, IEEE Trans. Inf. Th. 2014; Tremblay et al., PRL 2022

Dynamically Reconfigurable Architecture with Neutral Atoms

How to implement non-locality?

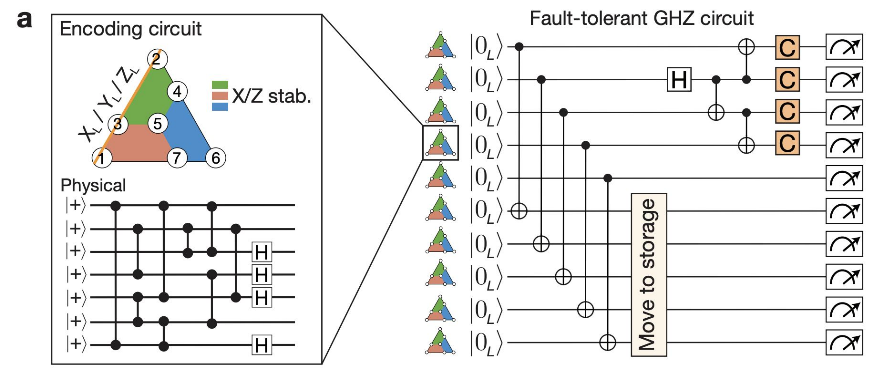


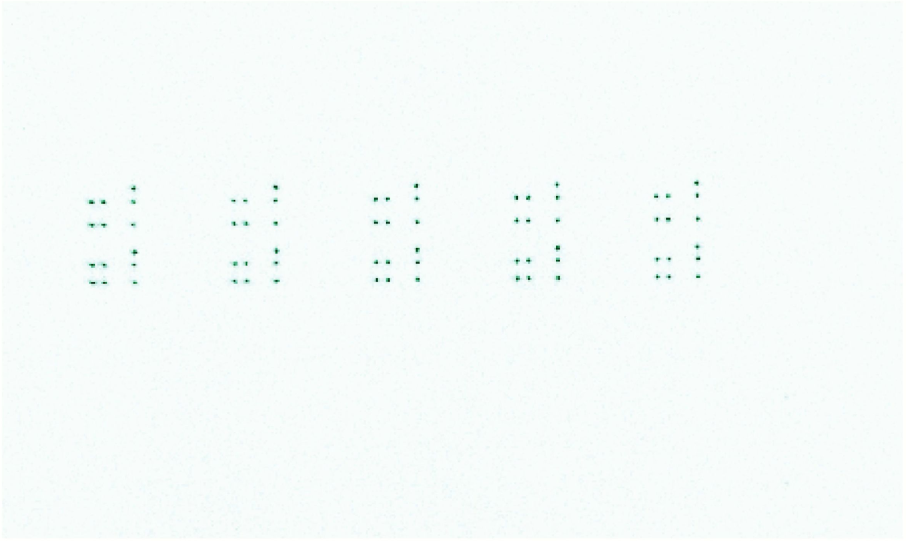
- Hyperfine qubits: >1s coherence,
  ~99.98% global 1Q, ~99.9% local 1Q
- Rydberg-mediated two-qubit gates ~99.5%

Bluvstein et al., Nature 2022; Evered*, Bluvstein*, Kalinowski*, Ebadi, Manovitz, HZ, ..., Nature 2023
See also complementary work from Thompson, Endres, Kaufman, Saffman, Browaeys, Bernien, Atom and others

Unique opportunities for error correction with reconfigurable atom arrays

Example: GHZ state with logical qubits



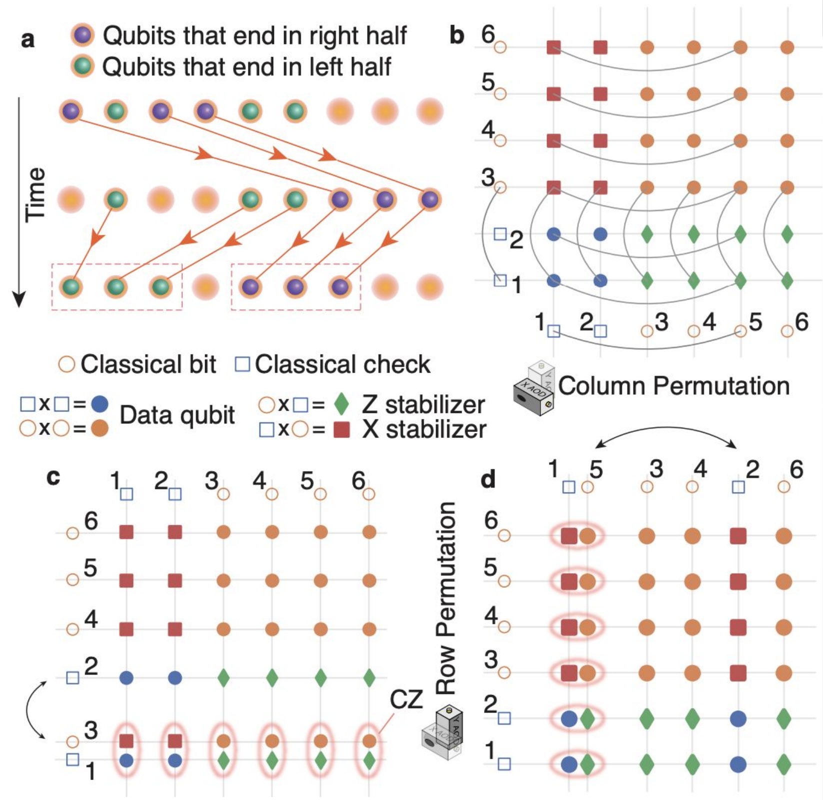


Enabling feature: efficient parallel classical control!

Bluvstein et al., Nature 625, 58-65 (2024)

Implementing the Product Structure of HGP codes

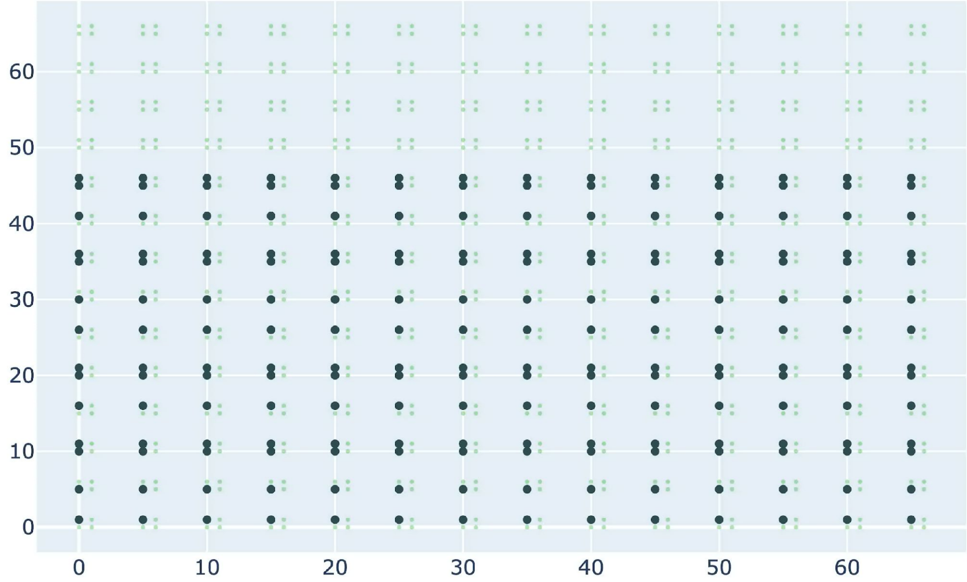
- Key insight: product structure of codes matches well with product structure of optical tools (AODs)
- For each check:
  - Permute columns, do CZ gates
  - Permute rows, do CZ gates
- Efficient 1D rearrangement:
  - L qubits in a line
  - At each step:
    - Move to the right half qubits that in the end configuration appear in the right half
  - Repeat within each new half
  - #moves = $O(\log L)$



Q. Xu*, JPBA*, C. Pattison ...,L. Jiang, H. Zhou, Nat. Phys. 20, 1084-1090

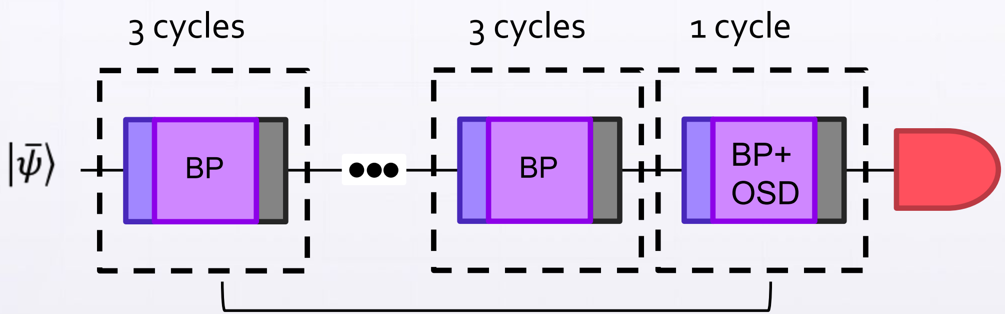
Full Layout for Hypergraph Product Code

- Very generic compilation and with current optical tools
- Movie generated using experimental software and commands!



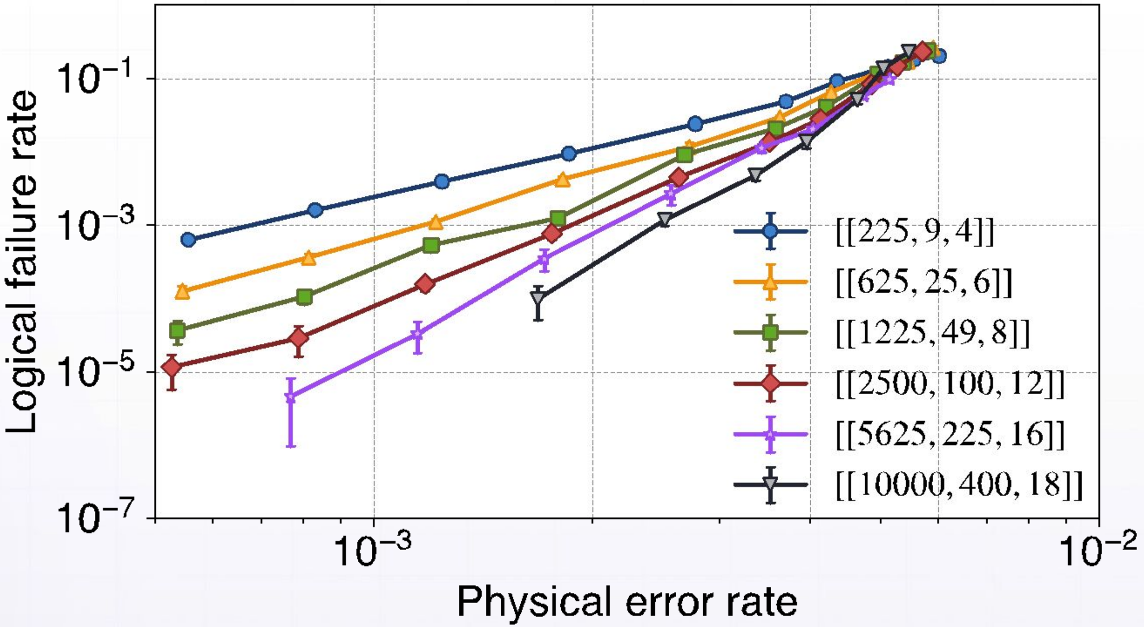
Circuit-Level Performance Evaluation

- Memory simulations: keep logical qubit alive for a long time
- HGP codes satisfy linear syndrome confinement:
  - "Qubits errors cannot grow without triggering more measurement syndromes"
- Confinement + bounded check weight:
  - Single-shot decoding
  - Single-ancilla syndrome extraction is fault-tolerant
  - We prove the existence of a threshold under these considerations!
- BP + BP-OSD decoding on circuit-level detector error model
  - Joint decoding of multiple rounds to improve performance



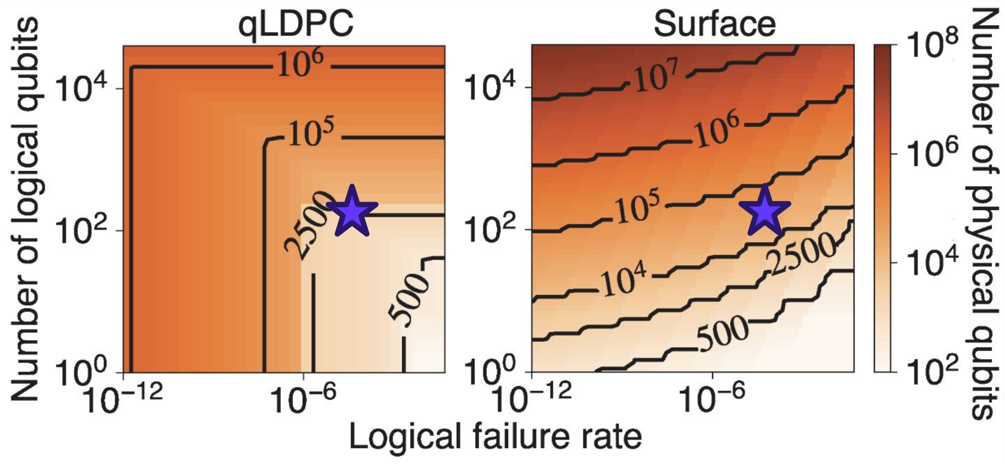
A. Quintavalle et al., PRX Quantum **2021**

Competitive Memory Circuit-Level Performance



- Error threshold ~ 0.6% under circuit-level depolarizing noise without idling errors
- Long neutral atom coherence times -> adding in realistic idling errors (that scale with code size) produces minimal changes

Competitive Circuit-Level Performance

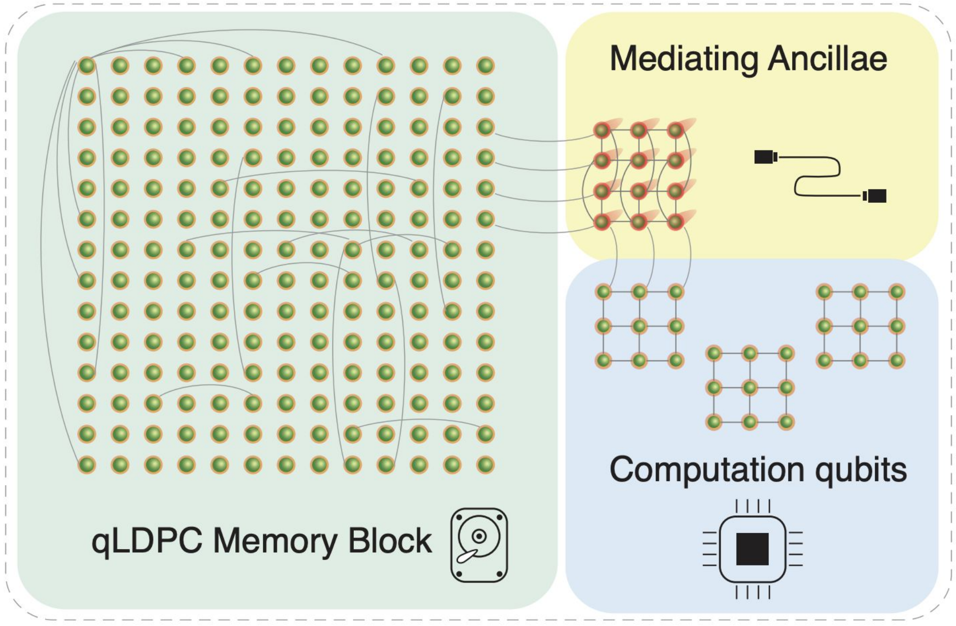


- qLDPC codes start out-performing surface codes at **several hundred physical qubits** and 0.1% error rates
- **Orders of magnitude** savings!
- <100k qubits enough for 1000 logical qubit computation!

Logical qubits	25	80	180	400
Logical failure rate	10^{-3}	10^{-4}	2×10^{-5}	6×10^{-6}
HGP code physical qubits (improvement over surface code)	1235 (1×)	4606 (2.8×)	10760 (4.0×)	19600 (6.9×)
LP code physical qubits (improvement over surface code)	851 (1.4×)	1367 (9.4×)	2670 (16.2×)	

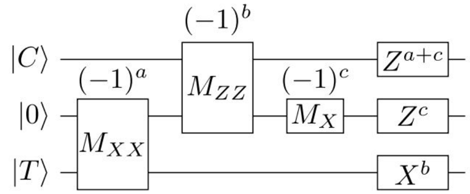
Computation with Logical Qubits

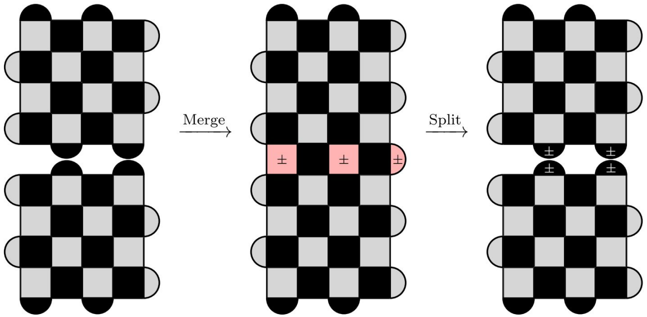
- qLDPC: memory
- Topological codes: processor
- Small enough number of computational qubits in parallel:
  - Can maintain constant overhead
- Our contribution:
  - Qubit efficient teleportation qldpc↔surface
  - First numerical simulations of computation with qLDPC codes



Lattice surgery

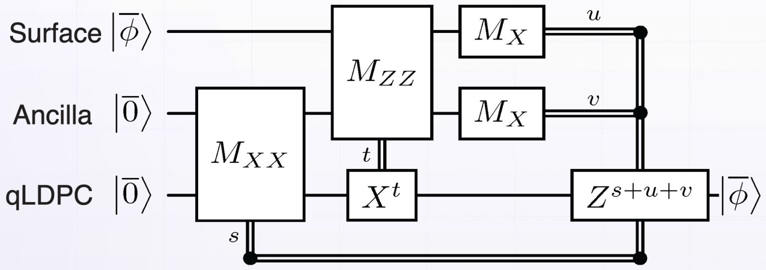
- Measurement-based gates: universal
  - Need: single and joint (logical) Clifford measurements
- Trick – for codes of similar boundary:
  - Merge codes
  - Logical measurement becomes stabilizer of new code
  - Measure stabilizer fault-tolerantly
  - Split codes
- Teleportation: also through measurement
  - Boundary of qLDPC and surface code can be very different
  - How to merge to perform joint measurement?

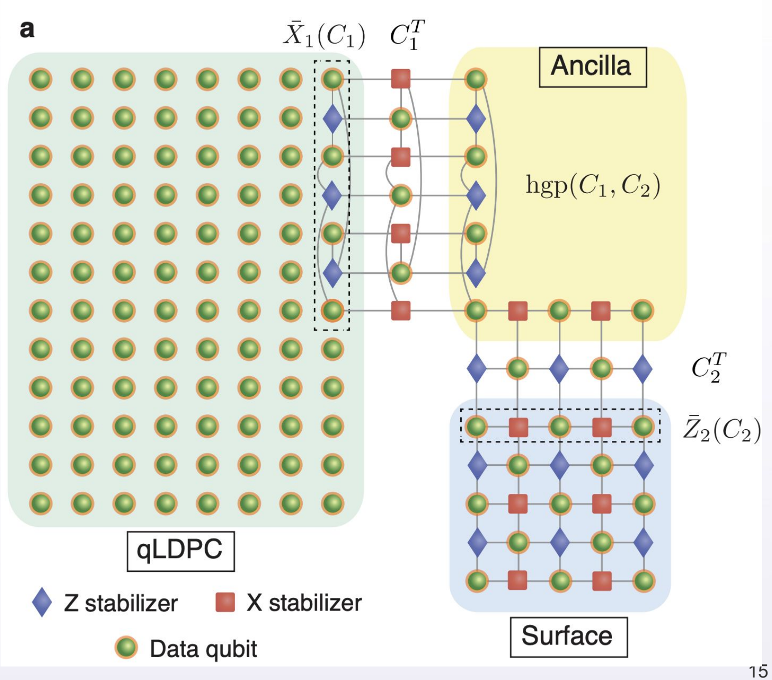




Teleportation through Lattice Surgery

- Mediate teleportation with ancilla block. Treat logicals as classical codes
- Ancilla block: HGP again!
- Logicals of same type:
  - Normal lattice surgery



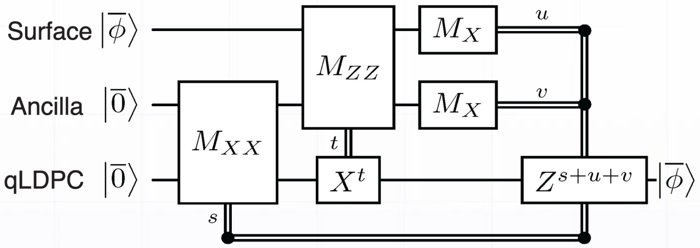


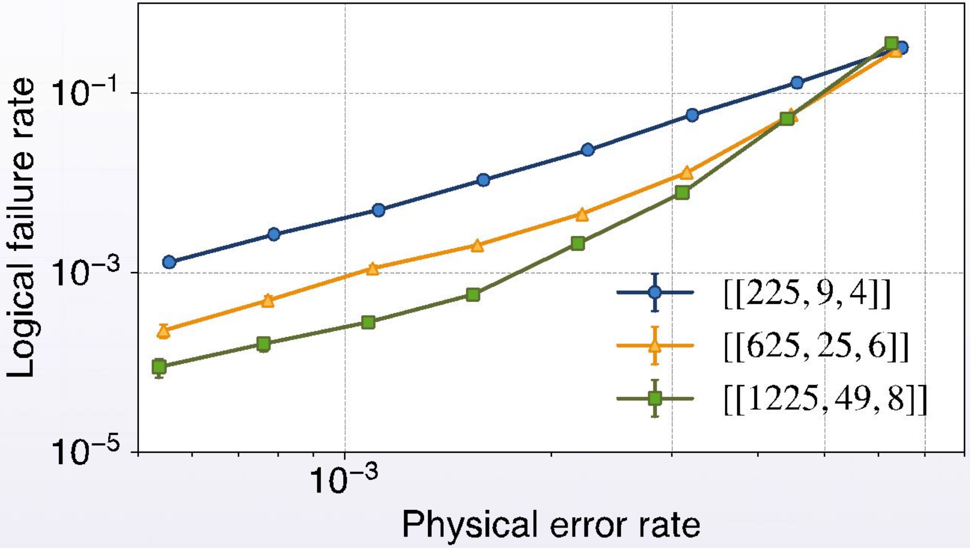
N.B. We prove this procedure is fault-tolerant

L. C. Cohen, et al., Sci. Adv. 8 eabn1717 (2022)

Lattice Surgery Performance

- Teleport logical qubits into surface code for computation
- Circuit-level simulations of teleportation process
- **Competitive threshold and error rates maintained**!



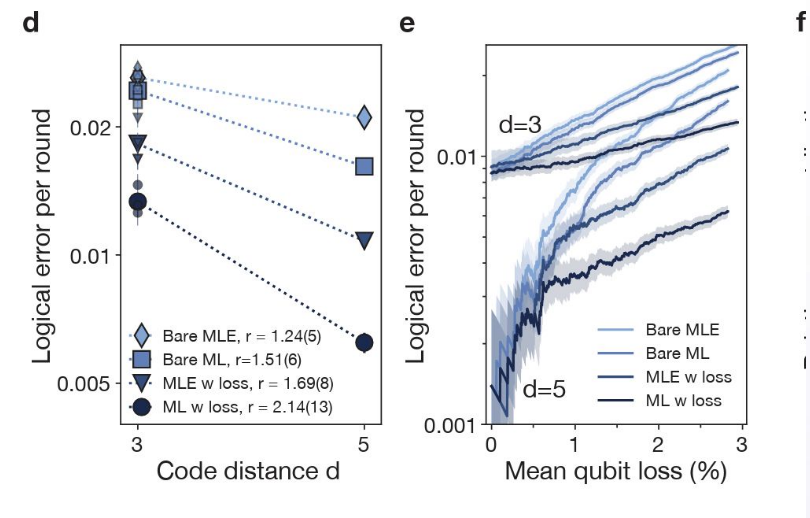


Outlook

Exploring LDPC challenges and opportunities on near-term hardware

- Space-time trade-offs
- Improving qLDPC computation
- How to incorporate QEM into these
  - QEM largely unexplored in neutral atom
  - Some ideas: QEC naturally projects nois
    needed?), extrapolation based on posts

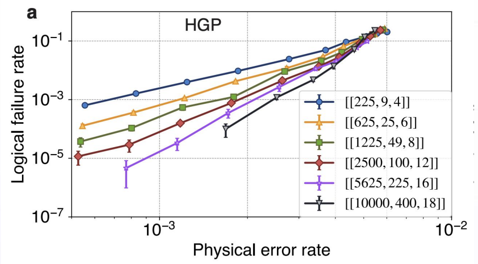
2x below surface-code threshold

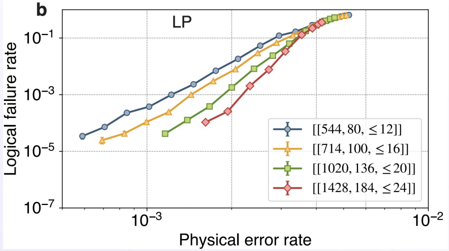


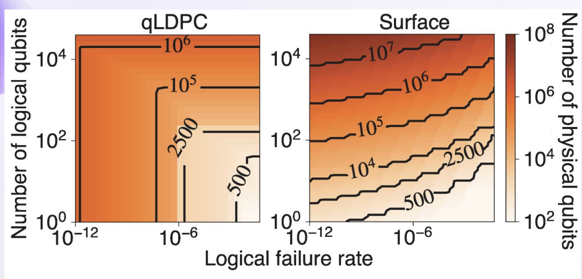
D. Bluvstein*, A. Geim*, S. Li, S. Evered, **JPBA**, et al., arxiv:2506.20661 (2025)

Summary

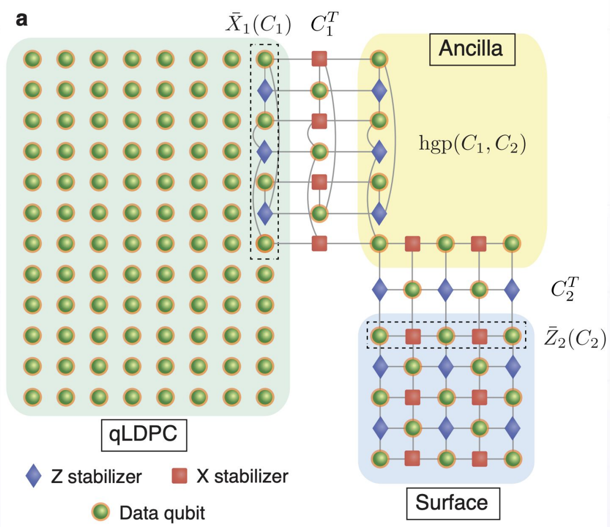
Memory

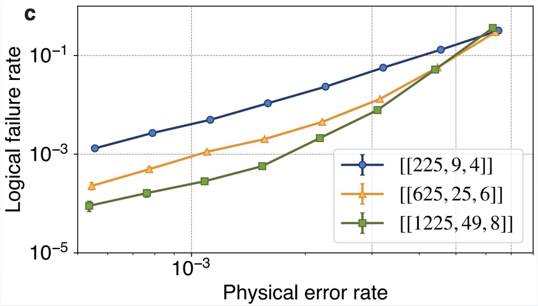




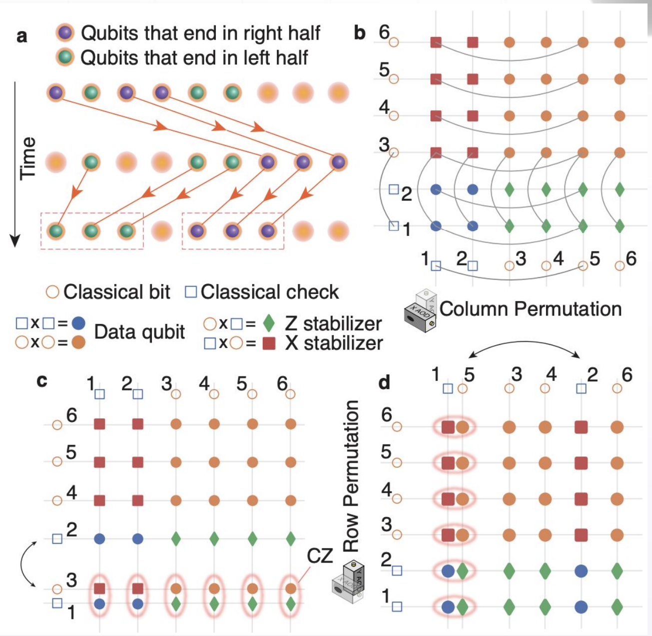


Gates



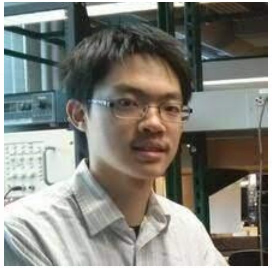


Practical implementation



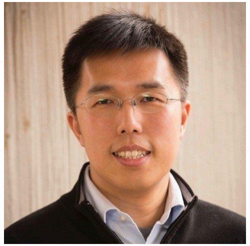
Collaborators

Qian Xu
(U.Chicago)



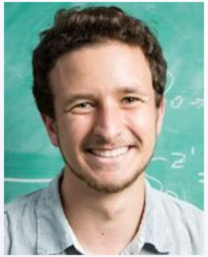
Harry Zhou
(Harvard, QuEra)

Chris Pattison
(Caltech)



Liang Jiang
(U.Chicago)

Mikhail Lukin
(Harvard)



Dolev
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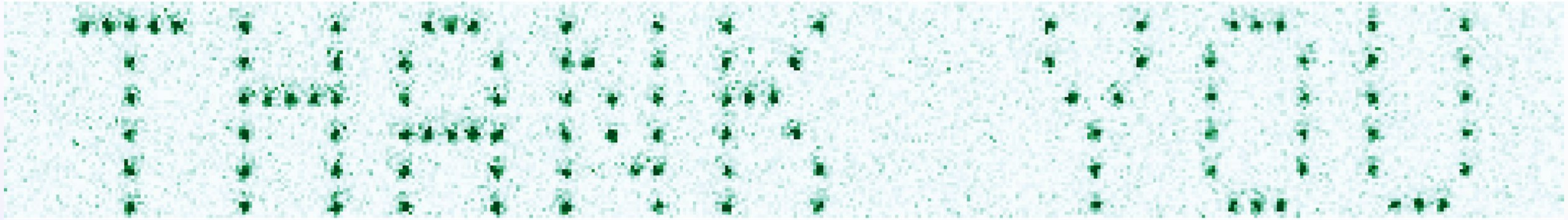
Raveendran
(Arizona)

Jonathan Wurtz
(QuEra)

Bane Vasic
(Arizona)

Thanks also to other members of Harvard atom array team.


THANK YOU