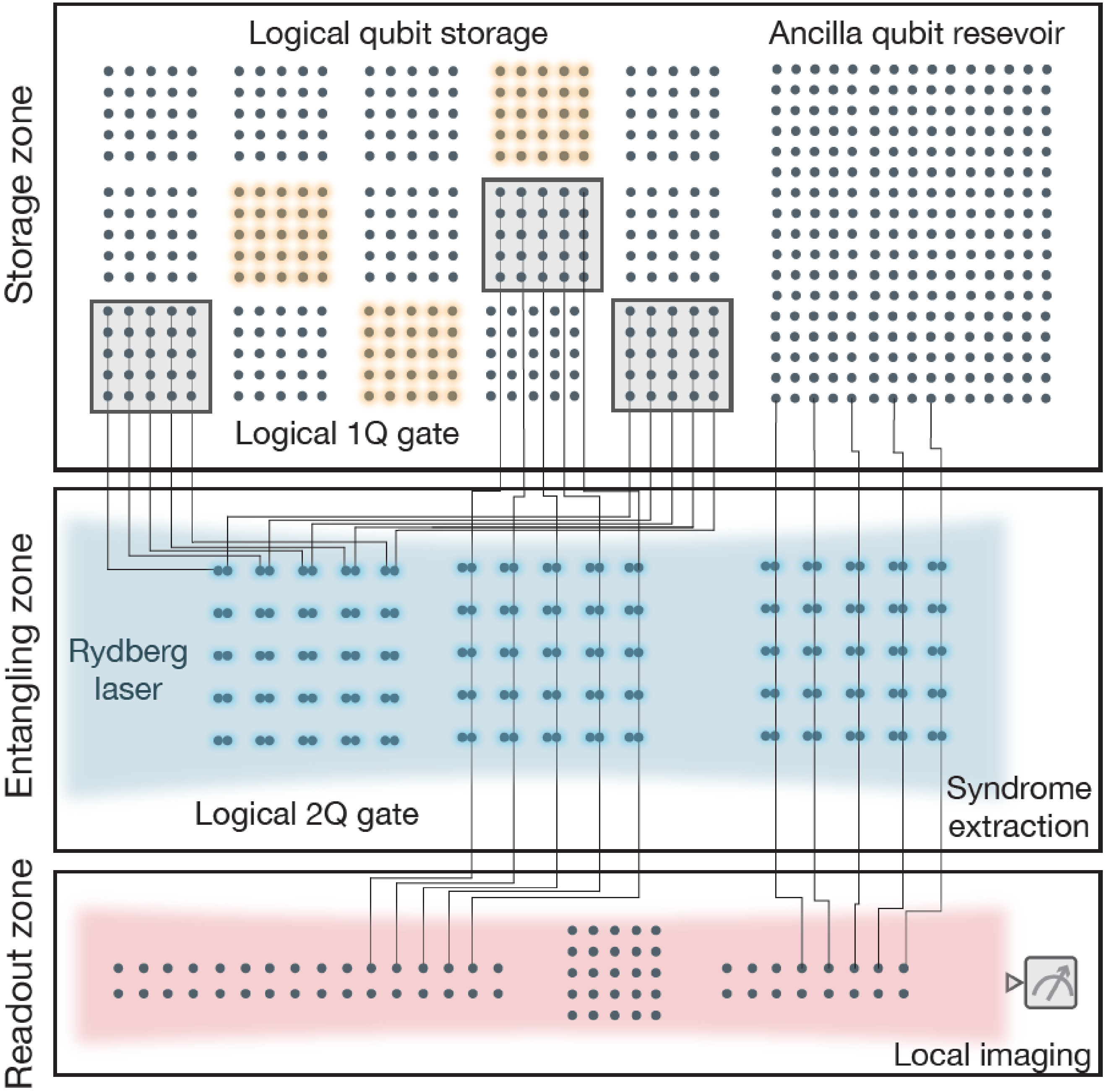
Logical quantum processor based on reconfigurable atom arrays

Dolev Bluvstein
Harvard atom array team
Lukin, Greiner, and Vuletic collaboration
Mathematical picture language seminar
April 16 2024



Frontiers of experimental quantum information

~2010s, exploring small-scale quantum computations with physical qubits
(physical qubit: atoms, ions, defects, superconductors …)

“Age of quantum discovery”

Many-body systems and new quantum phenomena

Error correction frontier

First 1-2 *logical* qubits / gates

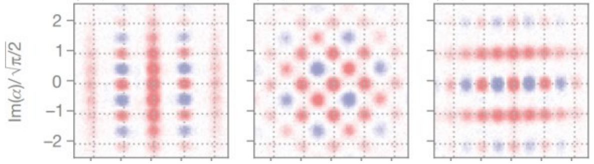
Fighting decoherence is the central challenge in large-scale quantum computation

Quantum error correction is the only known realistic route to suppress gate errors to the required levels for useful algorithms ($10^{-3} \rightarrow 10^{-10}$)

…before QEC, people thought quantum computing would be fundamentally impossible

n
e)

Xanadu Nature 2022
(see also USTC Science 2020)



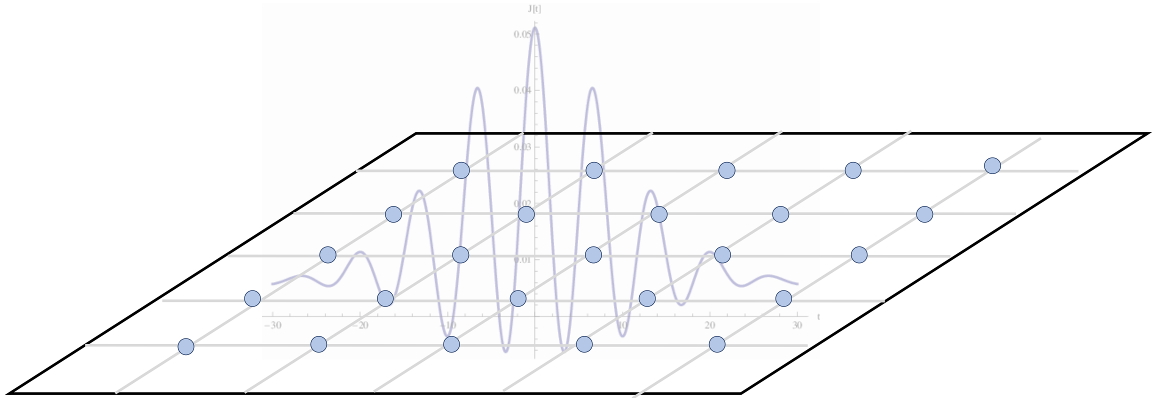
Yale 2023
(Bosonic)

Quantum error correction

- Classical error-correction: make copies! 0 → 000
- Quantum error-correction: *conceptual challenges*
  - no-cloning theorem ☹, can't duplicate quantum information
  - How to check for error without collapsing state?

So how to do quantum error correction?

- Use *entanglement* to store information *nonlocally* to encode a *logical qubit*
- *By being delocalized, logical qubit degree of freedom hard to accidentally manipulate*
- *Measuring products of qubits (stabilizers) detects errors while preserving encoded q. info*

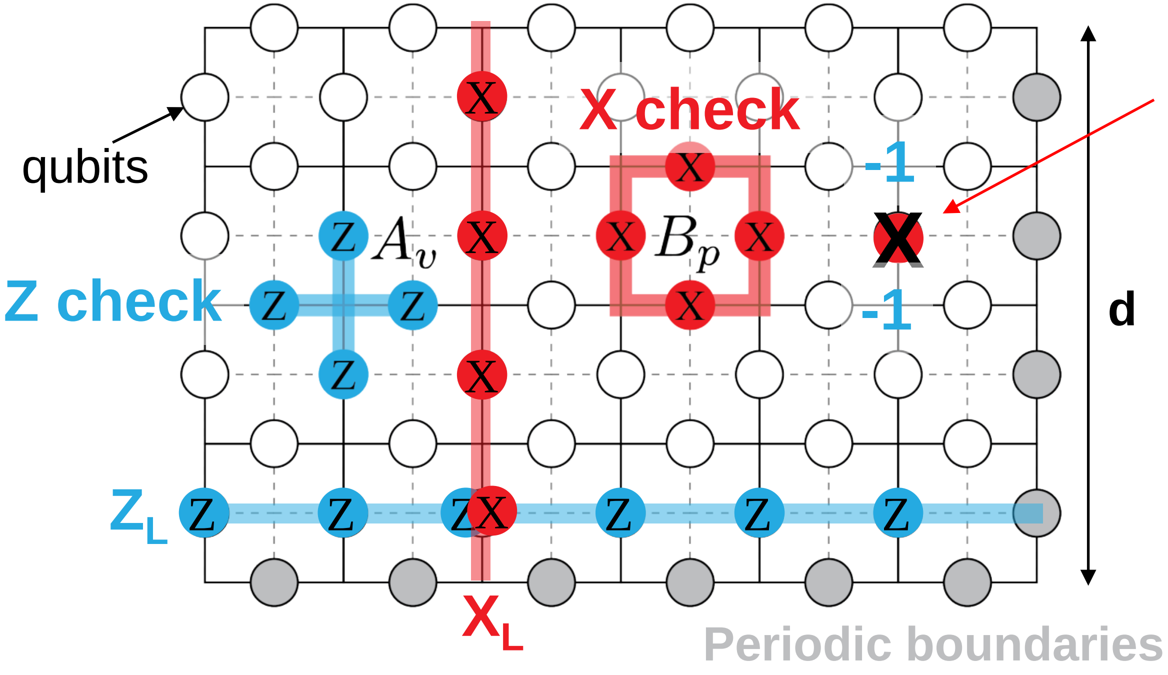


Logical qubit

Shor 95, Steane 96, Kitaev 97, Preskill, Laflamme, Calderbank, Gottesman …

QEC example: the toric code

Error-free state is with all X and Z
“stabilizer” products (checks) = +1



(technically two logical qubits for the torus)

Physical qubit errors will cause checks to show an error happened at a specific location – infer (decode), and undo.

As lattice size (**code distance d**) increases: more opportunities for errors, but more checks – *threshold behavior*

Logical error probability ~ $\left(\frac{p}{p_{th}}\right)^{\frac{d+1}{2}}$

→ $p_{th} \approx 1\%$
→ Offers realistic route to extremely small errors

- It was the theoretical breakthrough of quantum error correction that really allowed the field of quantum computing to take off
- And it is understood that eventually, we will need to switch to performing algorithms with *logical qubits,* instead of physical qubits

Quantum error correction is *challenging*

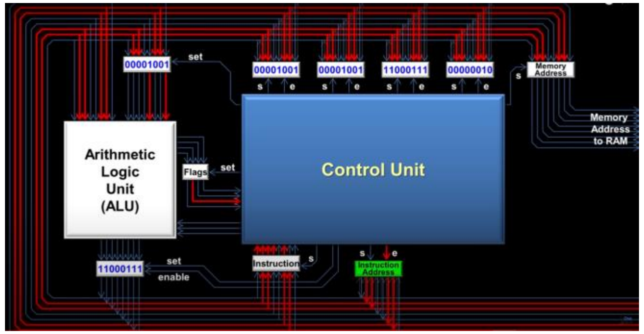
(Optimistic) estimates^1 for large-scale problems: million physical qubits and logical error rate 10^{-10}

Efficient classical control is a major challenge

Classical computers: ~1000 wires for ~billion bits

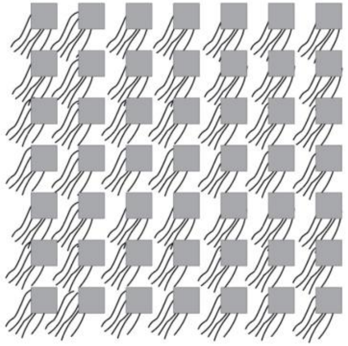
Quantum computers: several “wires” per qubit

Classical architecture



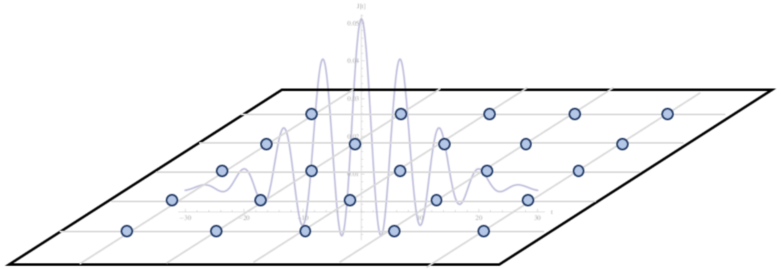
“How a CPU works” by InOneLesson

Quantum architecture



Challenge 1: “Wire problem” poses significant challenge to large-scale control.

Challenge 2: Once logical qubit is delocalized, it becomes *hard to operate on.*

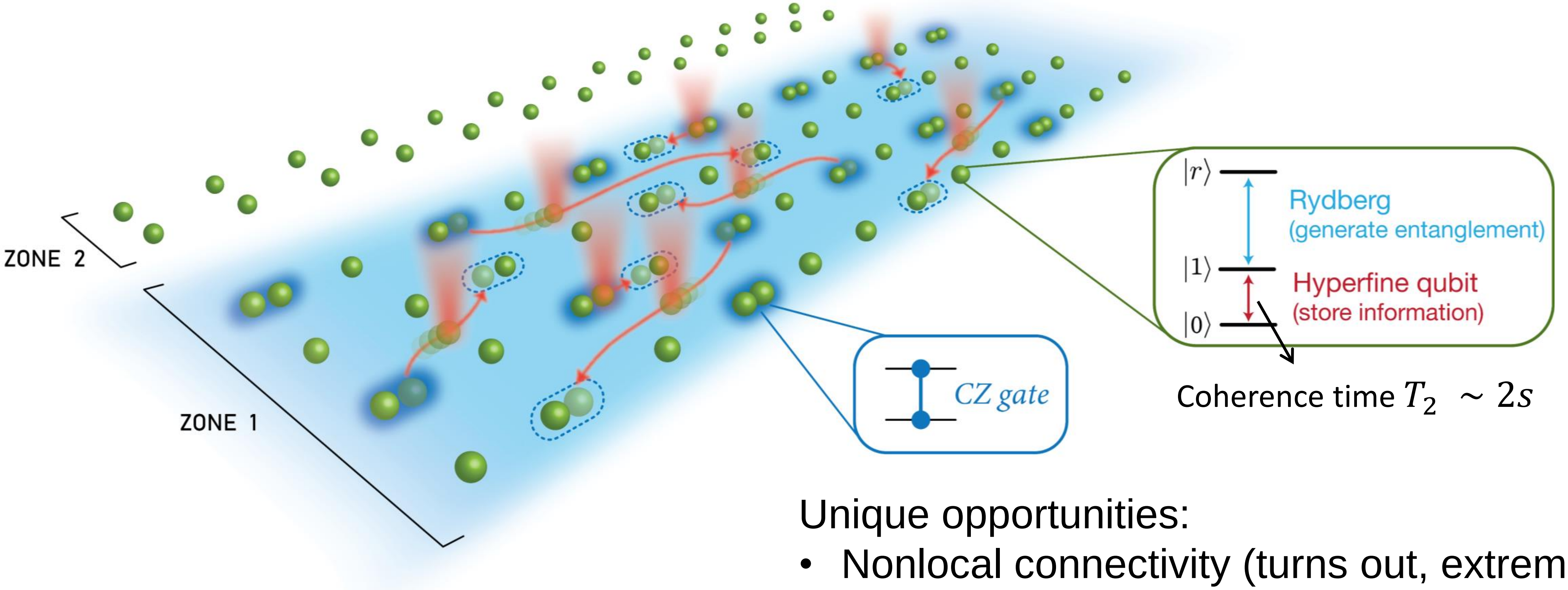


Logical qubit

Large overheads + complexity of *operating* on logical qubits have focused studies to ~1-2 logical qubits / gates

1: Gidney Ekera Quantum 2021

Our approach: reconfigurable atom arrays



Coherence time $T_2 \sim 2s$

DB *et al. Nature* **604,** 451-456 (2022)

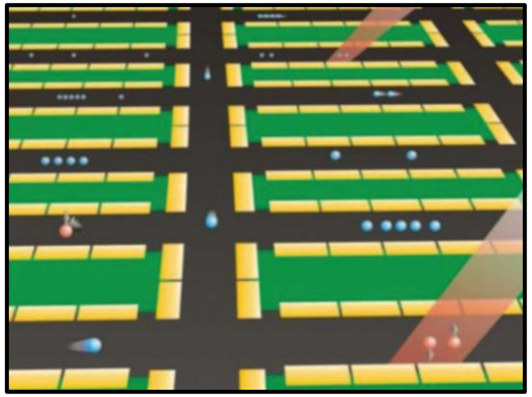
Unique opportunities:

- Nonlocal connectivity (turns out, extremely useful for error correction)
- Parallel, efficient classical control

Pioneering work and recent exciting developments: Weiss, Saffman, Browaeys, Grangier, Regal, Endres, Kaufman, Bernien, Thompson, Ni, Bakr, Bloch, Covey ... See also optical lattice parallelism (Deutsch)

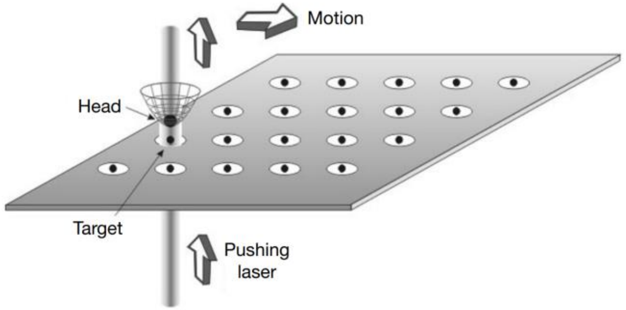
We are building off tremendous progress from the community…

Ions: 20+ year vision of shuttling-based architecture (+ recent expts) – nonlocal connectivity



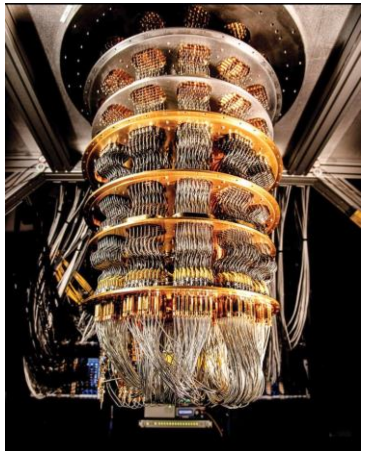
Monroe, Kim

Wineland 1998, recent Quantinuum expts…



Cirac, Zoller Nature 2000

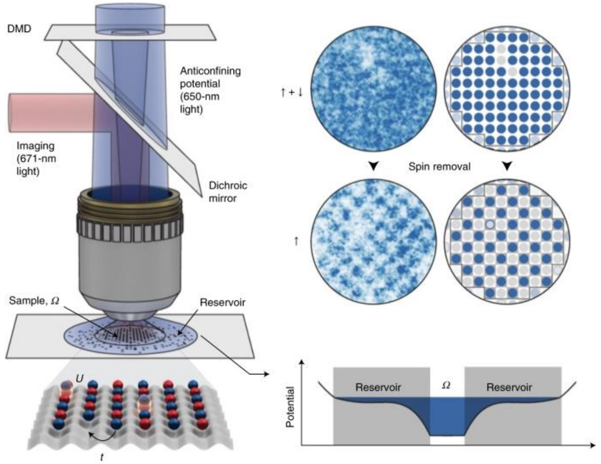
Superconducting qubits: early experience with controlling moderately large systems (50-70 qubits) – taught importance of the “wire problem” of control



Yale, Google, IBM, Wallraff, Oliver …

Decades of cold atom research

- Pioneering work in neutral atom tweezer community
- Ultracold atoms / optical lattice quantum simulators (the true pioneers of parallel, efficient control)



Greiner, Gross, Bakr, Bloch, Deutsch …

1. Programming a quantum circuit with neutral atoms

2. Logical quantum processing

Neutral atoms

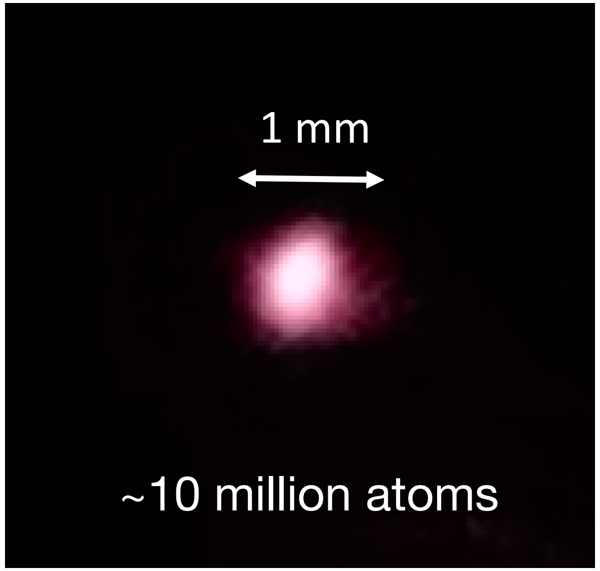


Image of atoms in a magneto optical trap (MOT)

Cold, identical neutral atom qubits are essentially unlimited

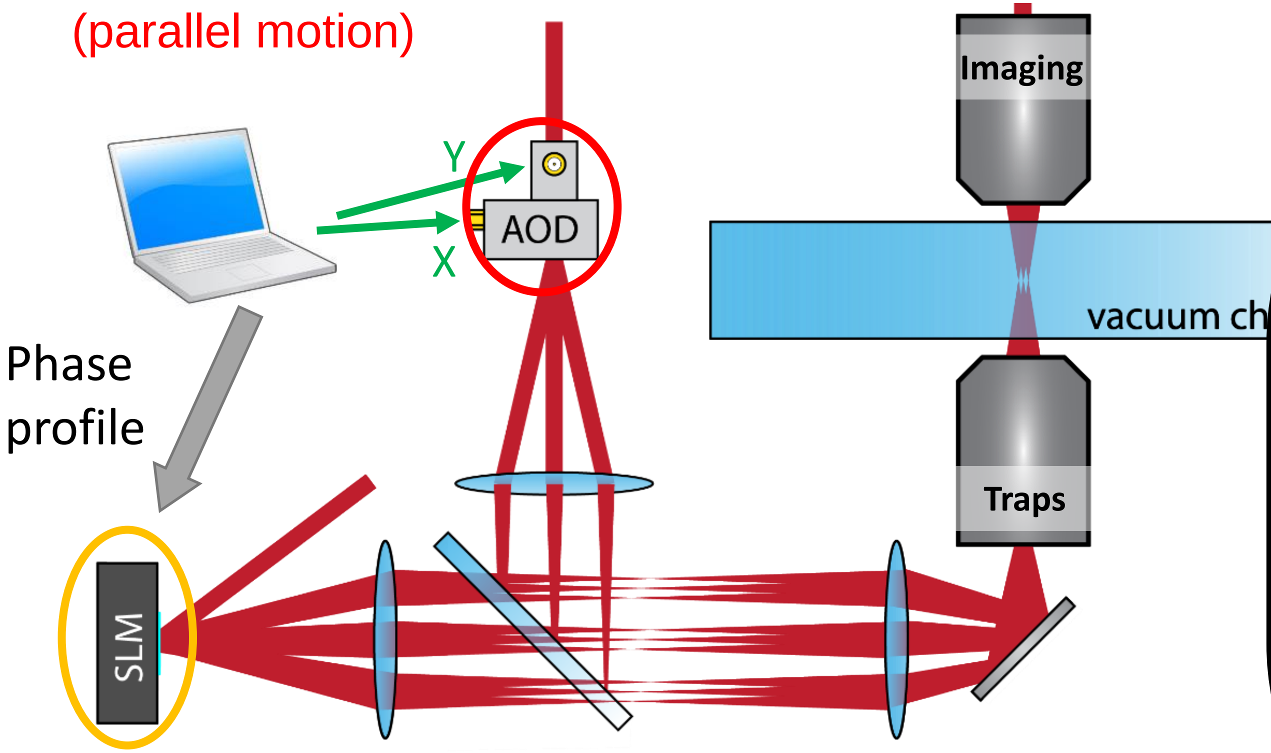
The key challenge is efficient classical control

Thousand neutral atoms in 2D tweezer arrays

Efficient classical control of many qubit positions

Crossed Acousto-Optic Deflectors

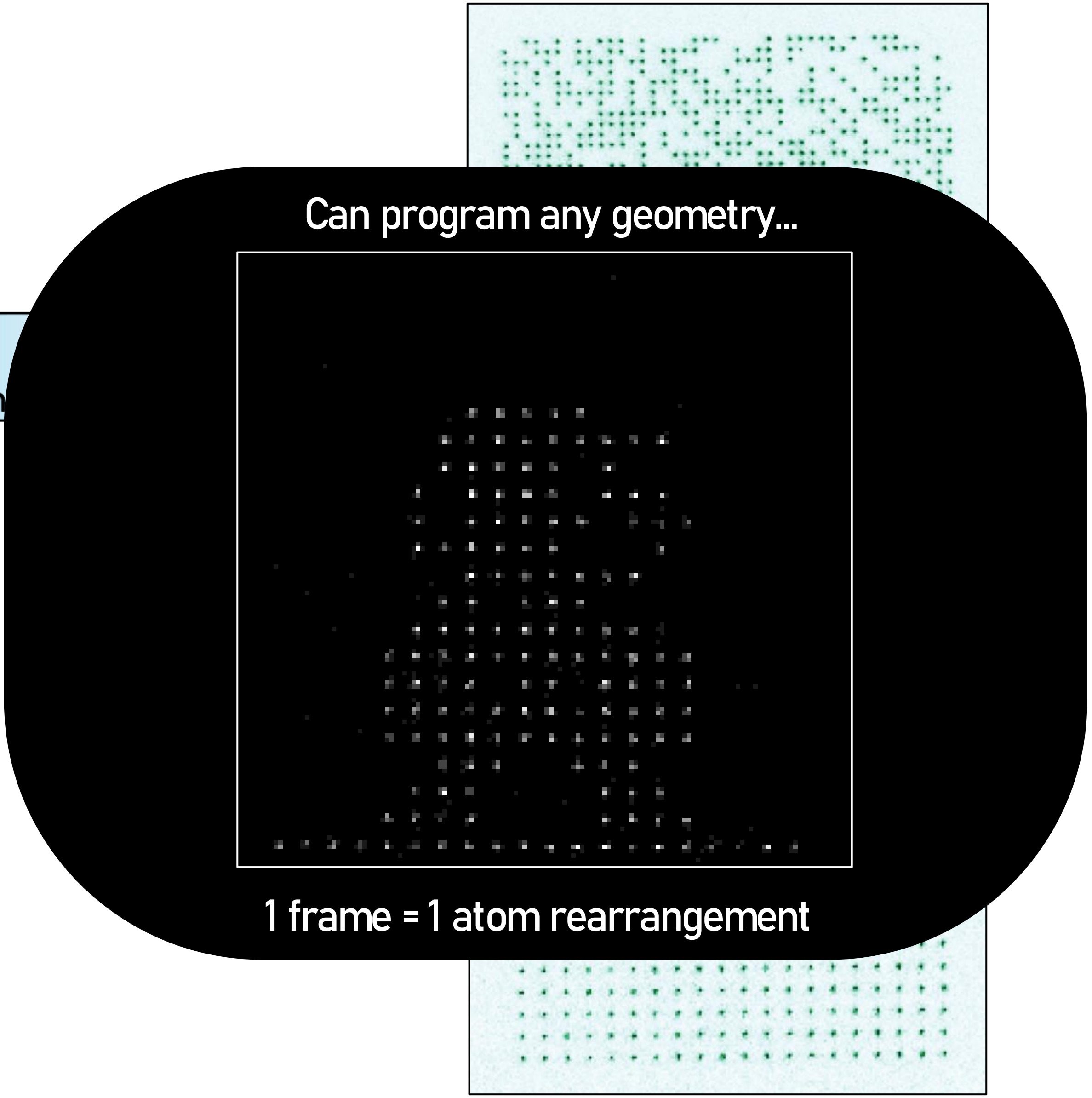
(parallel motion)



Spatial Light Modulator

(efficient programmable generation of many tweezers)

>1000 atoms



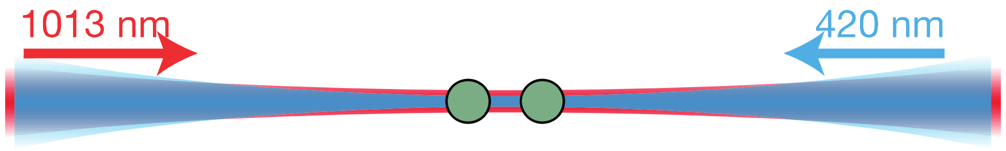
Can program any geometry...

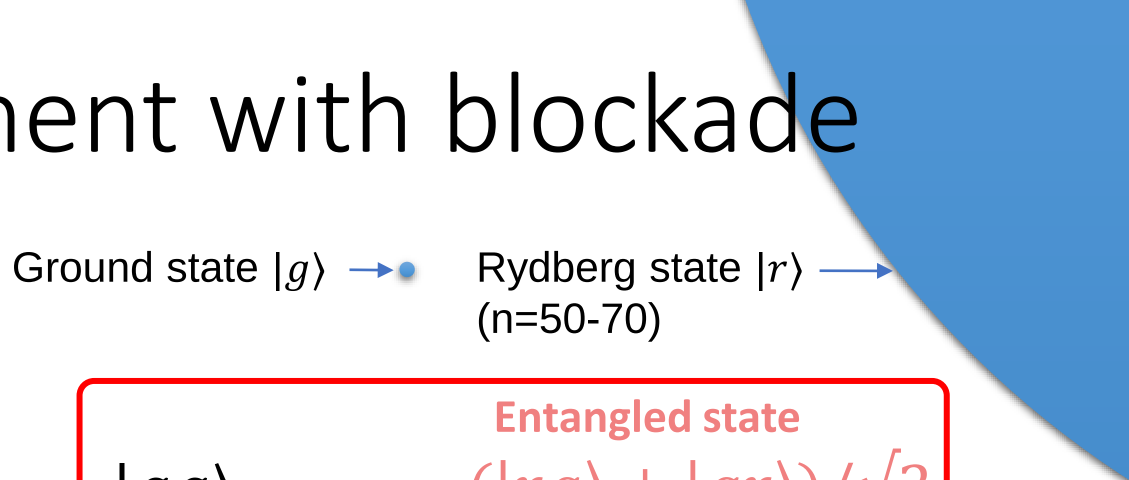
1 frame = 1 atom rearrangement

Ebadi et al Nature 2021

Related work: Scholl et al Nature 2021 (Browaeys),
Endres, Kaufman, Bernien, Saffman, Thompson, Ni, Bakr, Bloch …

Rydberg atoms and entanglement with blockade





Ground state $|g\rangle$ →

Rydberg state $|r\rangle$ →
(n=50-70)

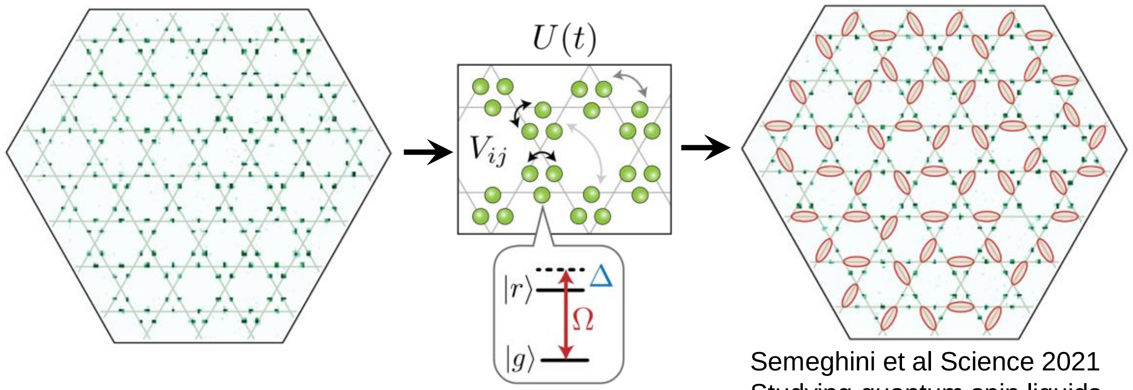
Two atoms: $|rr\rangle$ shifts by Van der Waals interaction ($\propto 1/R^6$)

→ adjacent atoms cannot be simultaneously excited, **Rydberg blockade**

Entangled state

$$|gg\rangle \longrightarrow (|rg\rangle + |gr\rangle)/\sqrt{2}$$

Analog (Hamiltonian evolution)



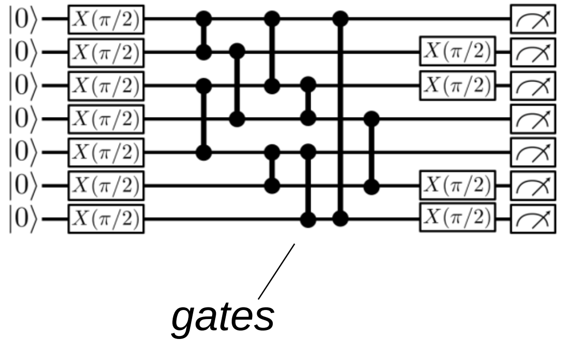
Semeghini et al Science 2021
Studying quantum spin liquids

- Position atom, turn on global excitation laser (run Hamiltonian), study quantum dynamics

Also: Phase transitions (Ebadi et al Nature 2021)
Nonequilibrium dynamics (Bluvstein et al Science 2021)
Combinatorial optimization (Ebadi et al Science 2022)

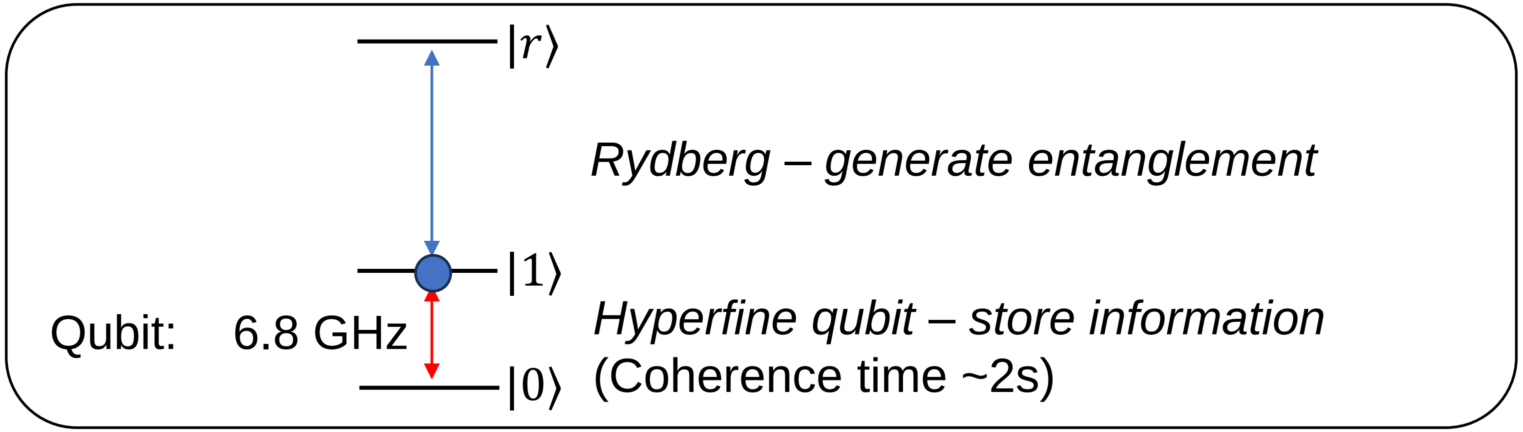
Digital

Quantum circuit:



- Controllable quantum operations (gates) to realize *universal quantum computation*
- Although more degrees of freedom, *still want efficient classical control*

Neutral atom quantum circuits: two-qubit gates



$|r\rangle$

Rydberg – generate entanglement

$|1\rangle$

Qubit: 6.8 GHz

Hyperfine qubit – store information
(Coherence time ~2s)

$|0\rangle$

Rydberg state $|r\rangle$
(n=50-70)

Ground state $|1\rangle$

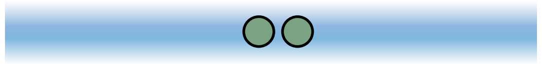
Levine-Pichler CZ gate:

$$\begin{array}{lcl} |00\rangle & \rightarrow & |00\rangle \\ \begin{array}{l}|01\rangle\\|10\rangle\end{array} & \begin{array}{c}\rightarrow\\\rightarrow\end{array} & \left.\begin{array}{l}|01\rangle\\|10\rangle\end{array}\right\}\ \Omega \\ |11\rangle & \rightarrow & \left.-|11\rangle\right\}\ \sqrt{2}\Omega \end{array}$$

Due to Rydberg blockade, if both in $|1\rangle$, entangled coupling to $\frac{|1r\rangle+|r1\rangle}{\sqrt{2}}$ generates a different *accumulated phase*

Harry Levine

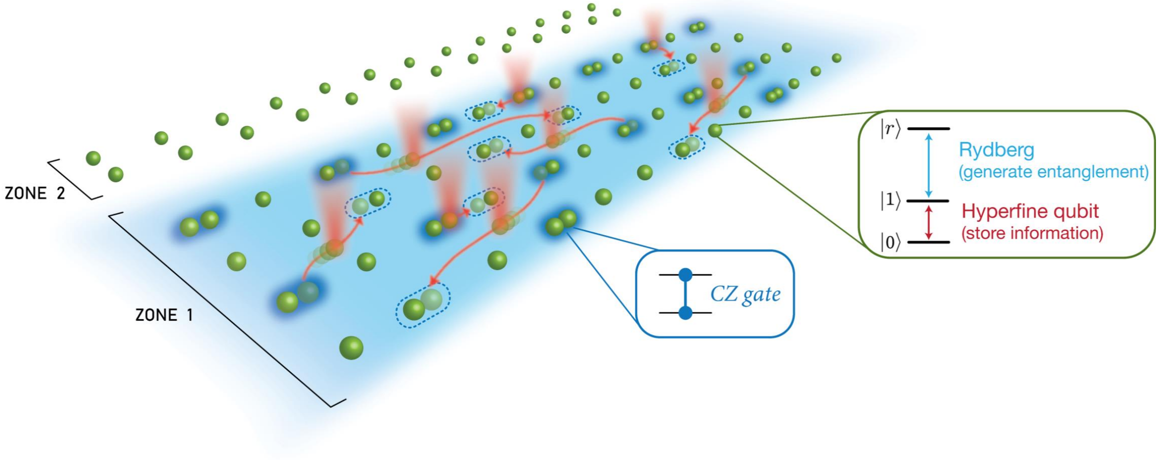
Global Rydberg laser drive



Levine, et. al. *PRL* **123**, 170503 *(2019)*

Rabi frequency Ω

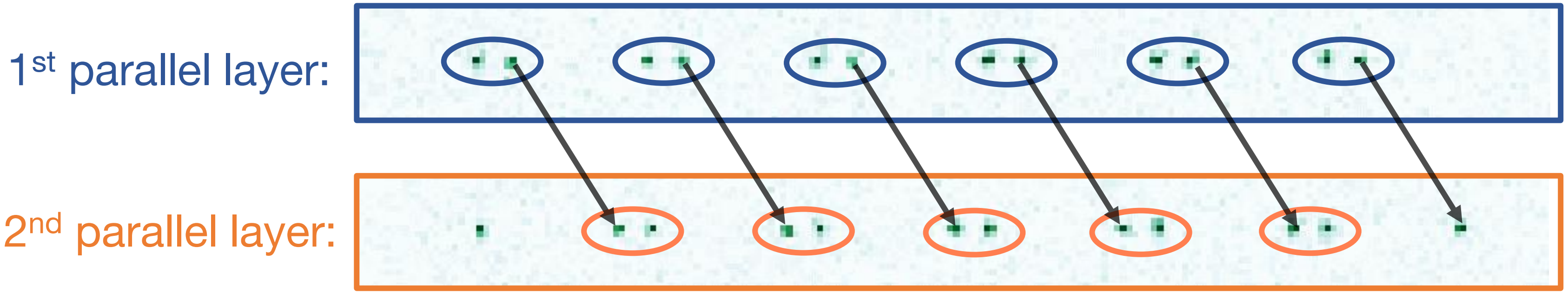
- Global pulses
- Blockade: if two atoms are next to each other, they will do a CZ gate!



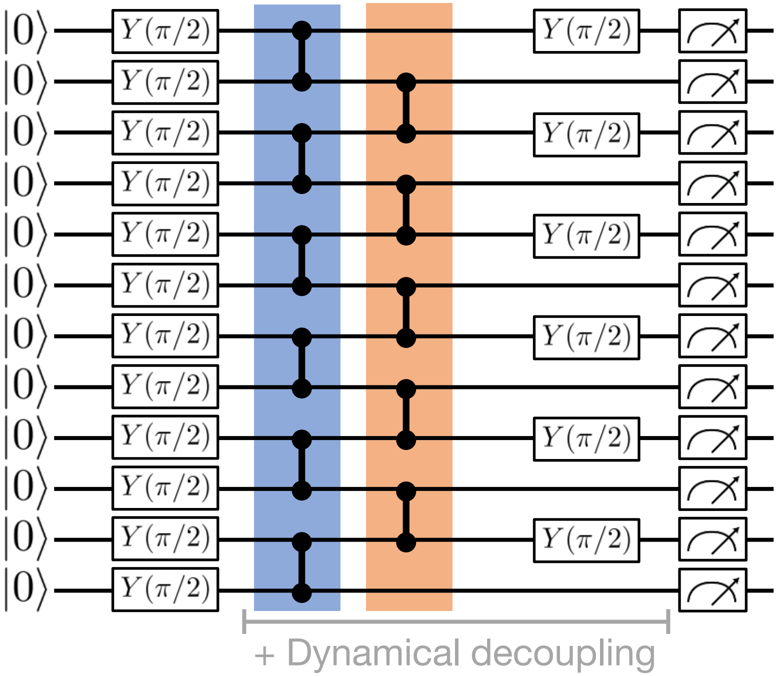
Programming a circuit with parallel controls: 12-atom cluster state

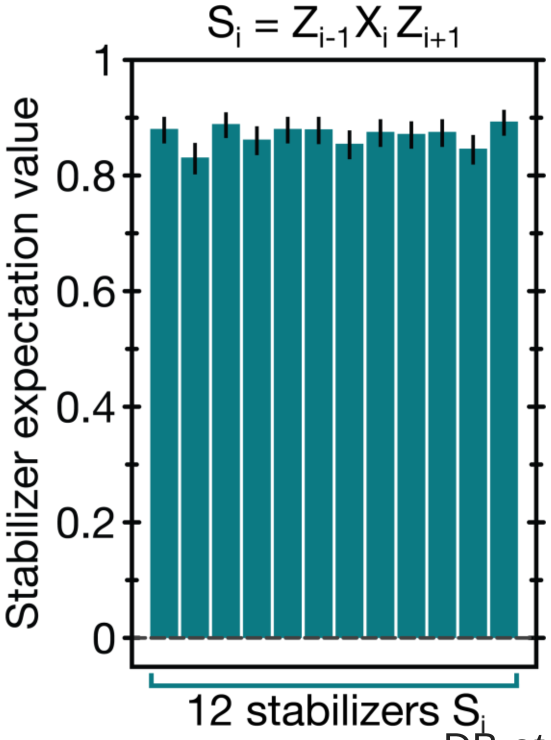
Position defines gate (blockade) → efficient control over many qubit positions gives efficient control over complex quantum circuits

SLM AOD



First coherent moving: Beugnon Nat Phys 2007
See also: Schlosser Quant Inf Proc 2011





Shows successful creation of the state

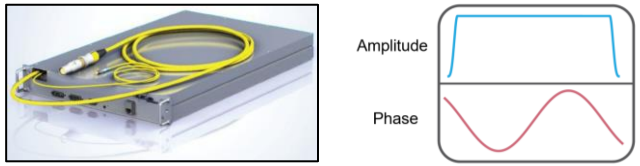
Fidelity limited by (old) 2Q gate fidelity ~97.5%

Related work: Graham et al Nature 2022

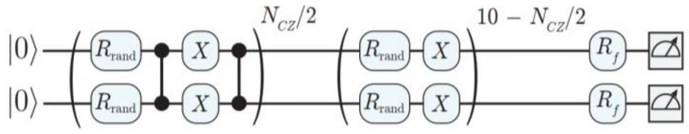
DB *et al. Nature* **604,** 451-456 (2022)

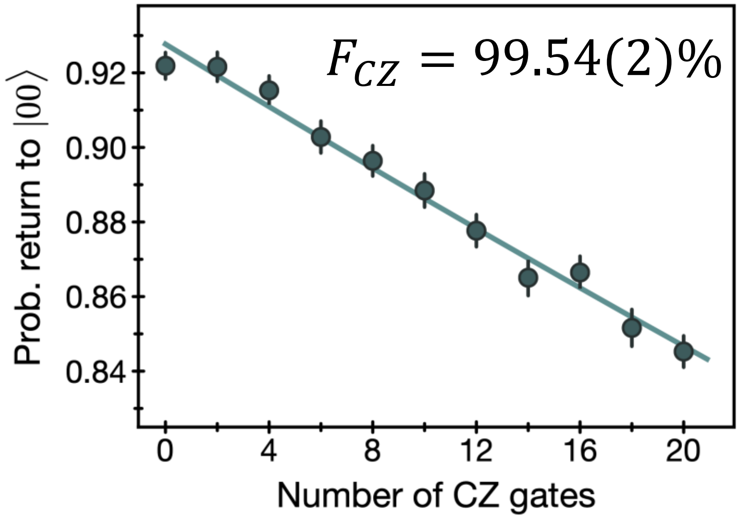
Universal, high-fidelity digital circuits: technical upgrades (2023)

99.5% 2Q gates on 60 qubits in parallel



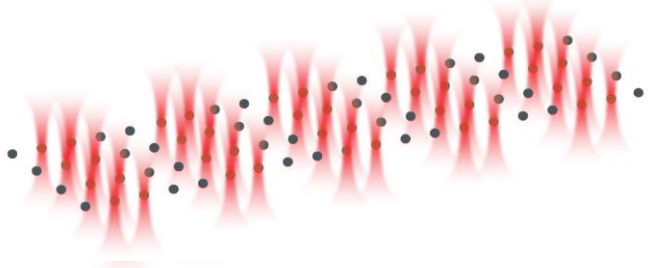
High power laser, improved gate technique (Jandura, Pupillo Quantum 2022)

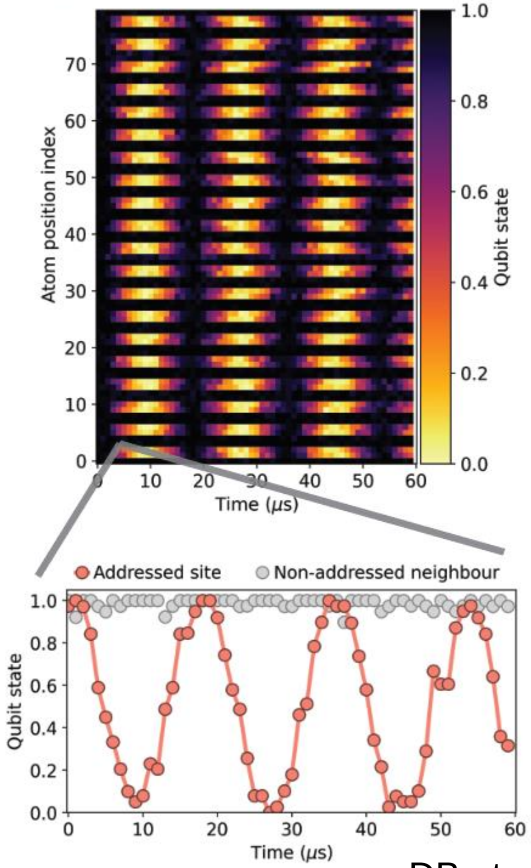




S Evered*, DB*, M Kalinowski* et al Nature 2023
See also Thompson, Endres papers (with erasure!)

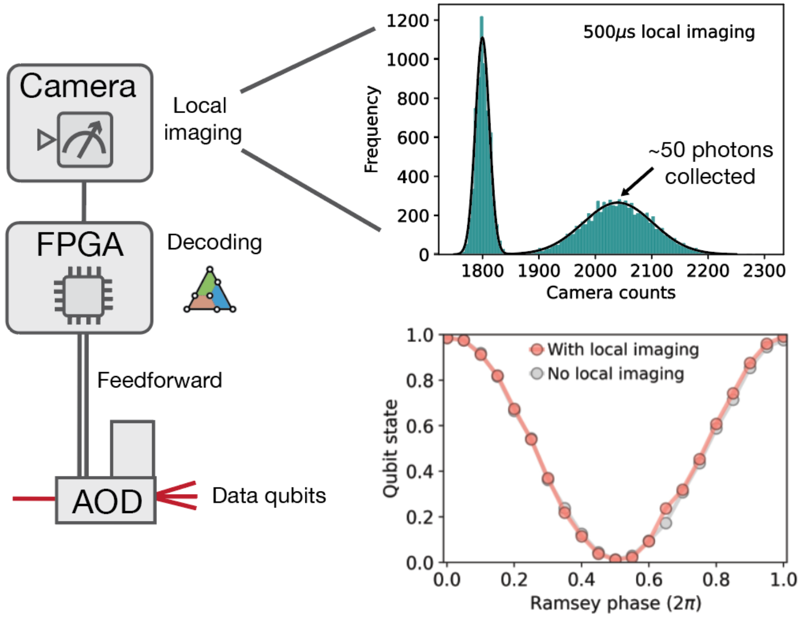
Fully programmable, parallel 1Q gates

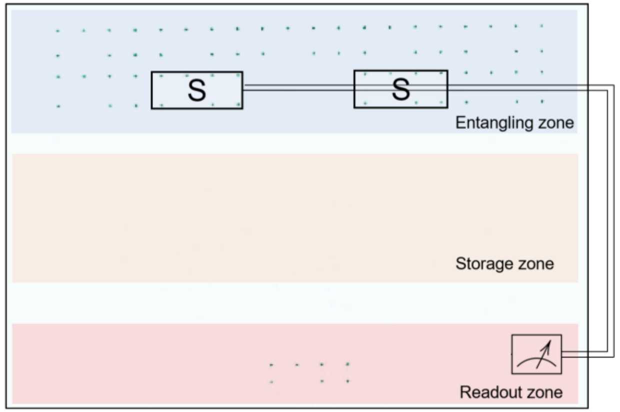




DB et al Nature 2023

Mid-circuit readout and feedforward





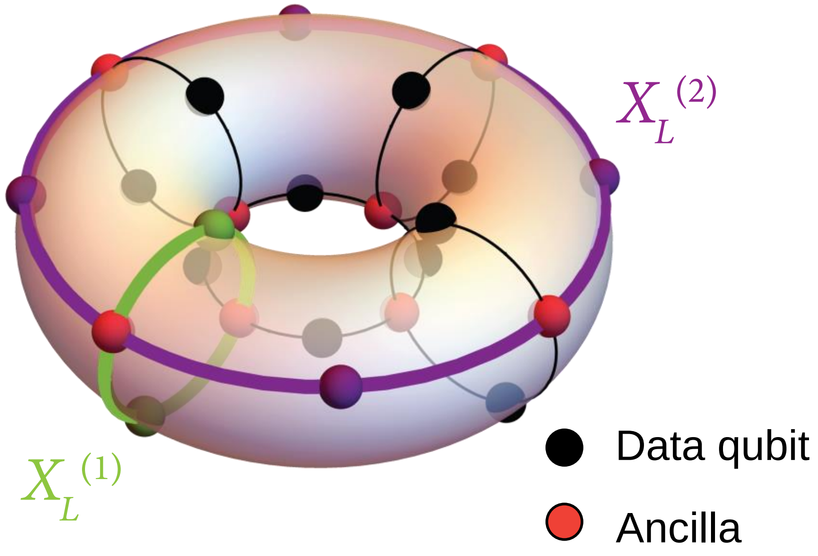
Harvard-MIT-QuEra collaboration
See also very nice works: Stamper-Kurn, Bernien, Saffman, Thompson, Kaufman, Atom Computing

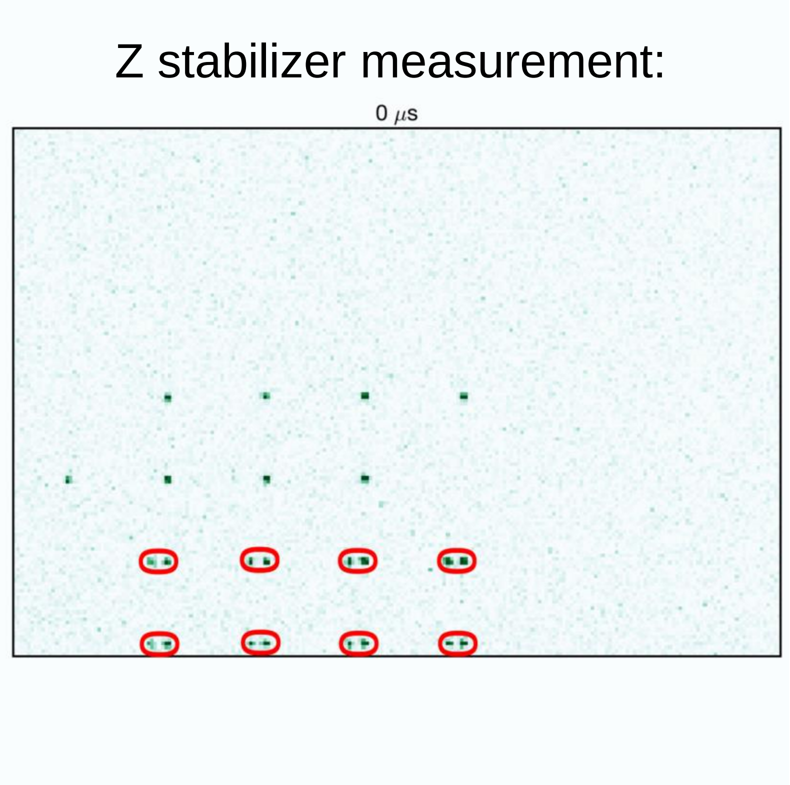
Exploring quantum error correction with neutral atom devices

2022: Toric code (on a torus)

Realizing error correction codes with nonlocal connectivity

Circuit is simply programmed by specifying SLM profile and AOD waveform
Parallel control over many qubits with O(1) classical controls

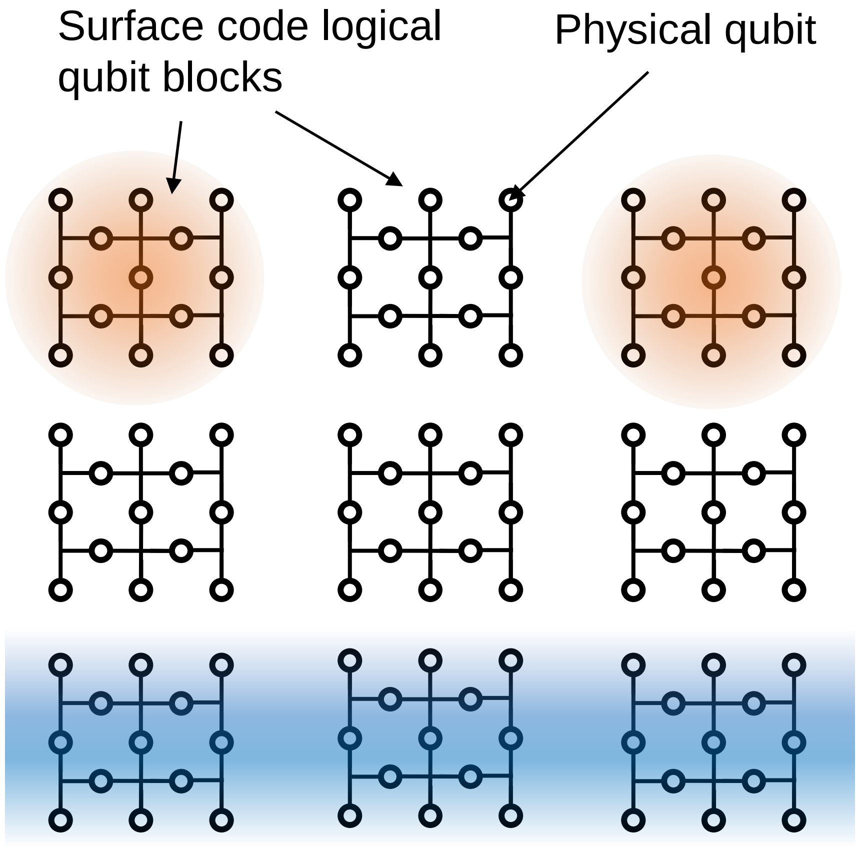




Kitaev toric code 1997

DB *et al. Nature* **604,** 451-456 (2022)

Parallel logical qubit processing with O(1) controls



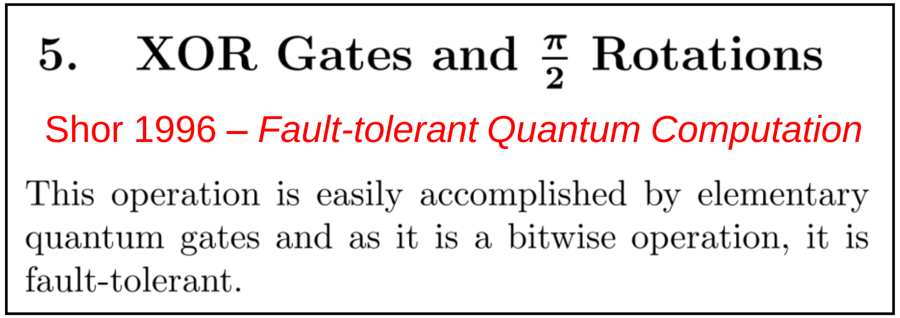
Transversal single-qubit gate

Transversal entangling gate

Shor 1996, Dennis et al 2001

Single *logical* qubit control, instead of single *physical* qubit control

Naturally multiplexes with optics



5. XOR Gates and $\frac{\pi}{2}$ Rotations

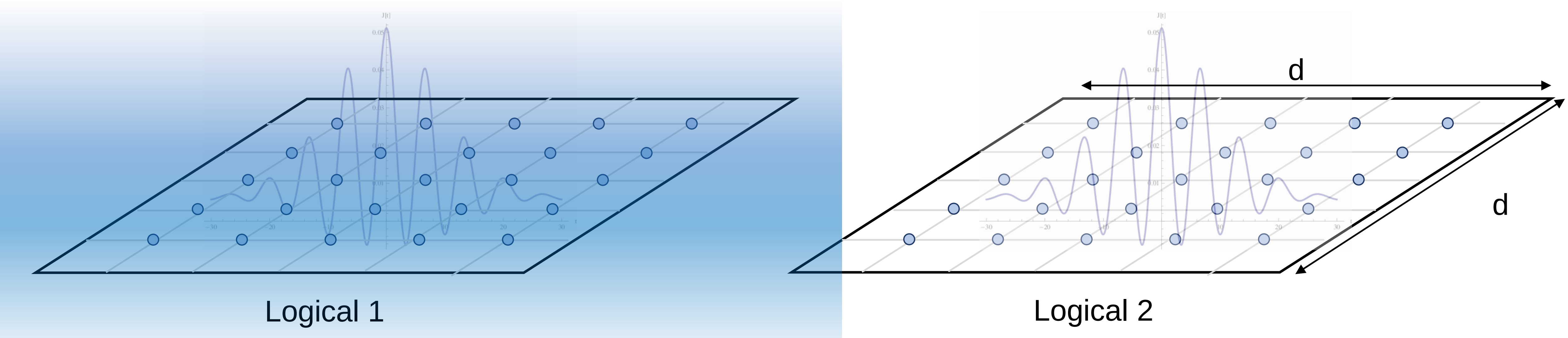
Shor 1996 – *Fault-tolerant Quantum Computation*

This operation is easily accomplished by elementary quantum gates and as it is a bitwise operation, it is fault-tolerant.

Efficient, parallel computation with logical qubits

Transversal CNOT based on parallel motion

By being delocalized, logical qubit degree of freedom hard to accidentally ***or intentionally*** *manipulate*



Transversal CNOT: directly interact the delocalized degrees of freedom

- *Inherently fault-tolerant* – d rounds of correction not required between each gate unlike lattice-based approaches
    - *Fault-tolerant: errors cannot spread within code block*

- *Long-range, direct connections between logical qubits* – can have significant savings for large-scale algorithms

- *Efficient control: all physical qubits receive the same instruction and act like one big atom*

First generation logical processor based on zoned architecture

Key focus: parallel control of many logical qubits with only a few wires

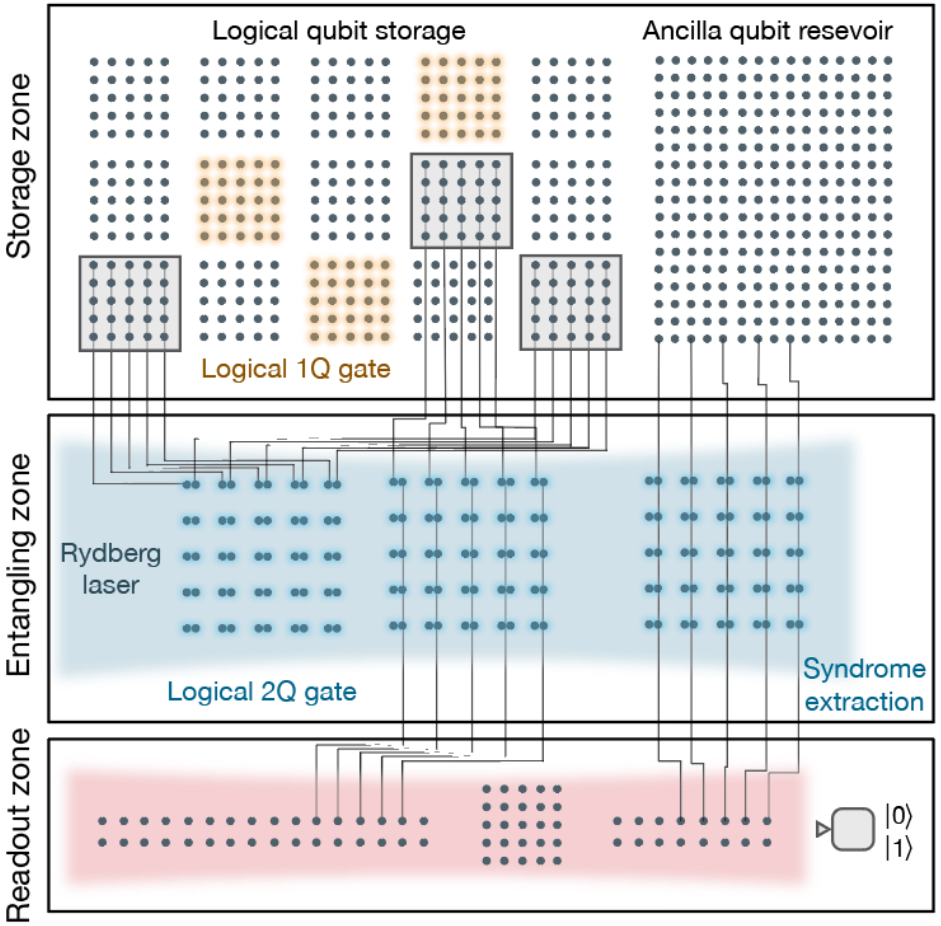
Transversal gates: inherently fault-tolerant

Storage zone: idle logical qubits are stored, safe from errors

Entangling zone: transversal operations with few global beams

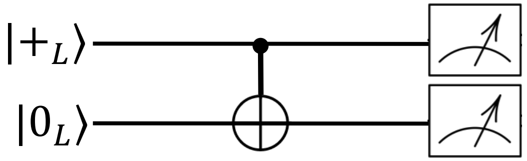
Readout zone: measure qubits without disturbing active qubits

Long-range connectivity: opportunities for exotic codes

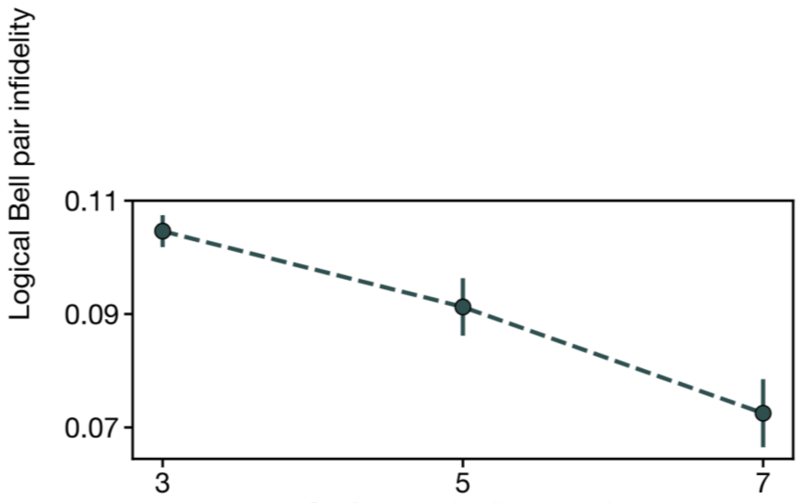


Bluvstein et al Nature 2023

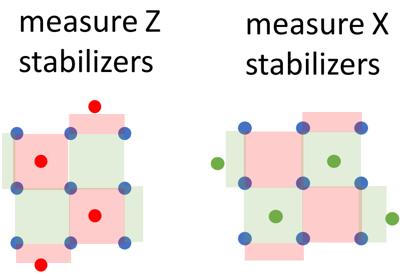
Example: logical CNOT with surface code



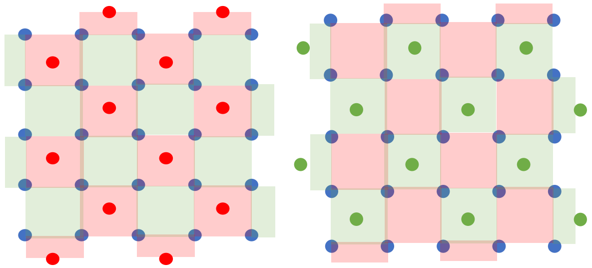
Note: effective threshold of entire circuit higher due to nearby time boundaries - future work will involve trying to *increase the number of applied transversal CNOTs* with repeated correction



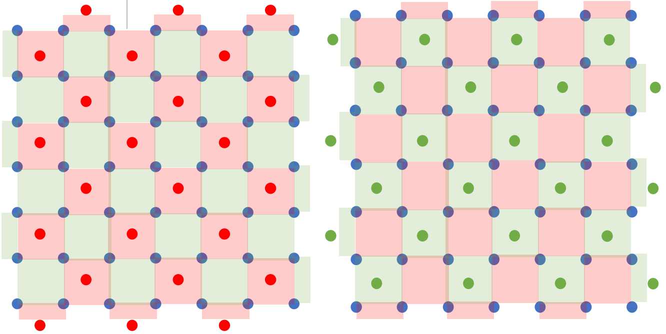
1. Improved gate performance with increased code size
2. Decoding logical qubits *jointly* improves logical algorithm performance – M Cain … DB, Lukin



d = 3



d = 5



d =7

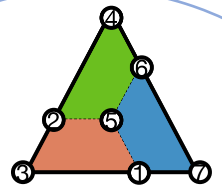
- Key QEC property: operations should improve with system size (code distance *d*)
- Here, state preparation non-Fault-Tolerant (nFT) beyond d=3, but still allows probing behavior of transversal CNOT

Prior work: memory with single d=3,5 codes (Google, Nature, 2023), entanglement of two d=2 surface codes via lattice surgery (Innsbruck, Nature , 2021), Yale gates

Bluvstein et al Nature 2023

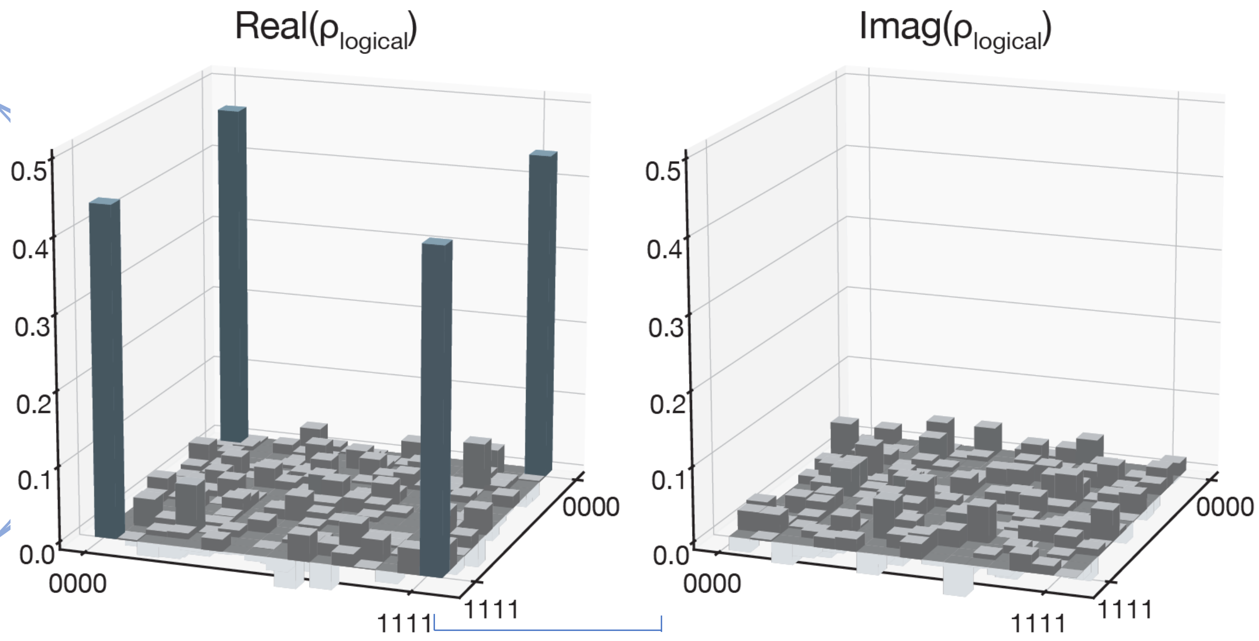
Fault-tolerant algorithms: GHZ state

GHZ (or “cat”) state: $|0_L 0_L 0_L 0_L\rangle + |1_L 1_L 1_L 1_L\rangle$

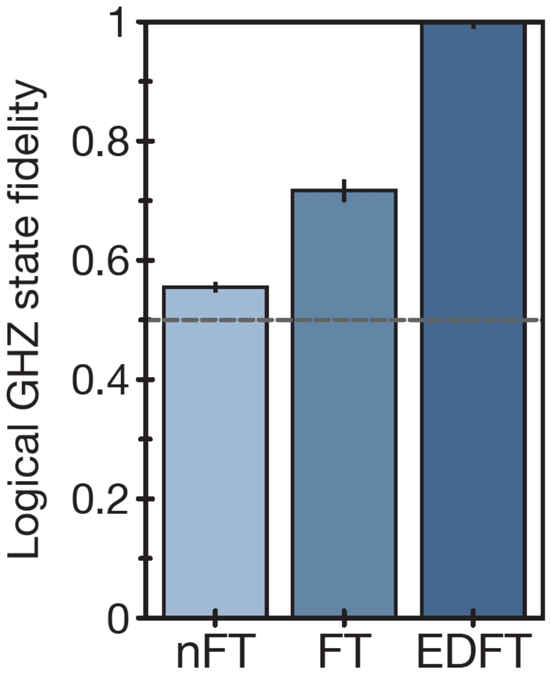


Color code logical qubit

Similar to surface code, but more logical operations allowed



“Steane error correction” – improves logical initialization to 99.9%



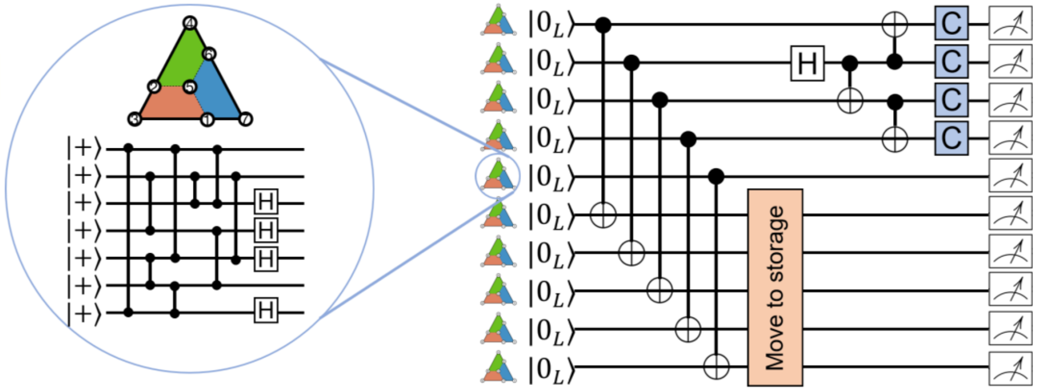
Measurements in all 81 logical bases

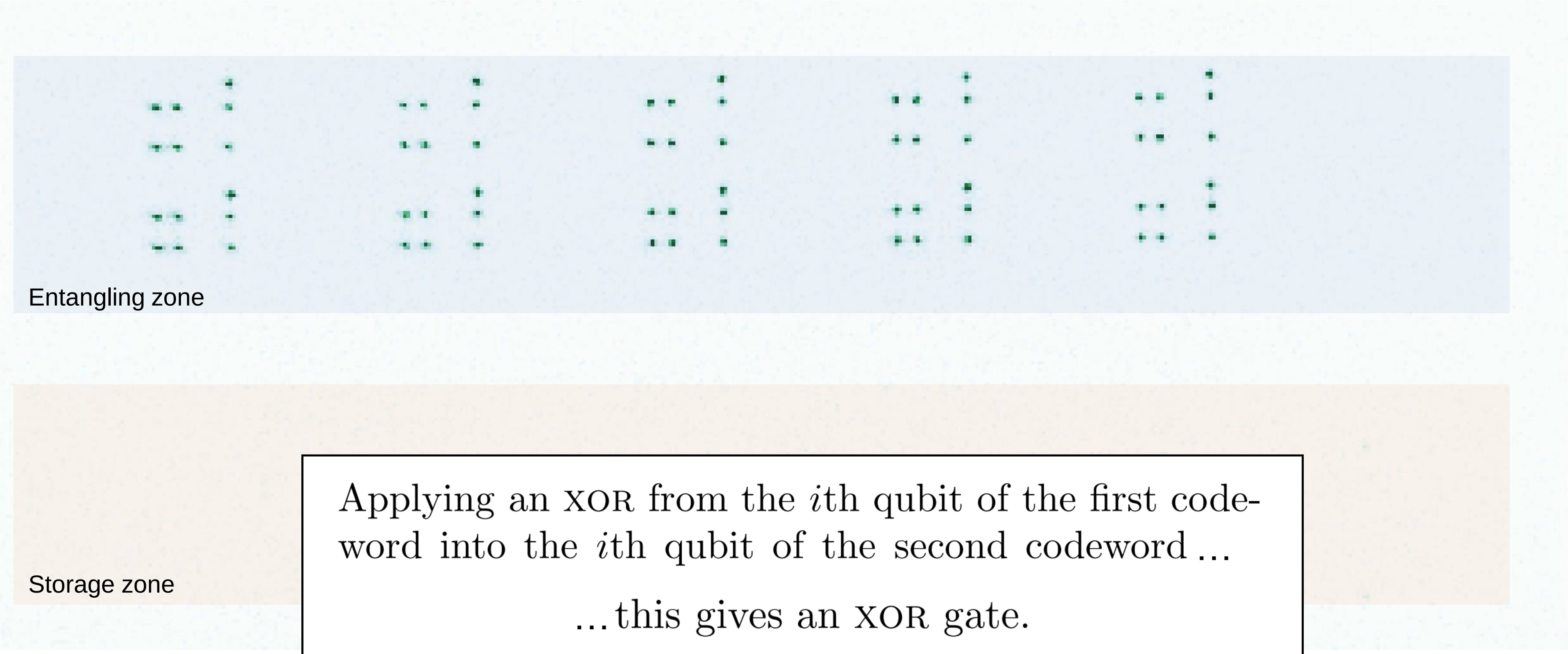
nFT: non-Fault-tolerant algorithm. Don’t postselect on ancilla logicals.
FT: Fault-tolerant algorithm. Postselect on ancilla logicals.
EDFT: Fault-tolerant algorithm with error detection. Postselect on all stabilizers correct.

Exploring early fault-tolerant computations

Bluvstein et al Nature 2023

GHZ circuit





Applying an XOR from the ith qubit of the first codeword into the ith qubit of the second codeword …

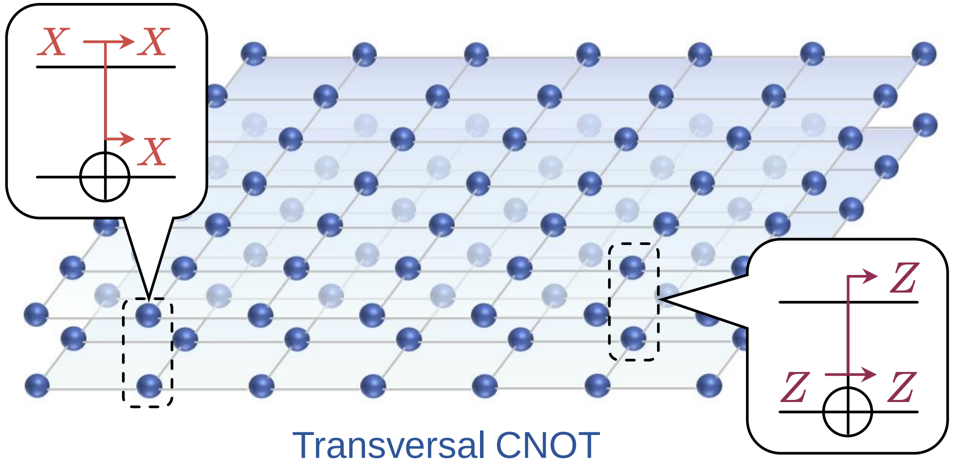
… this gives an XOR gate.

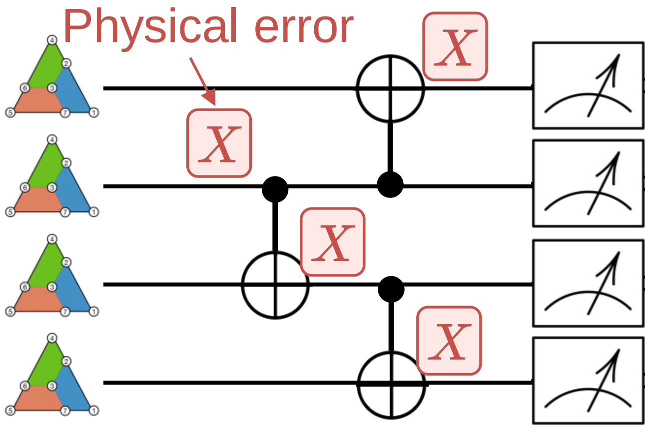
Shor 1996 – *Fault-tolerant Quantum Computation*

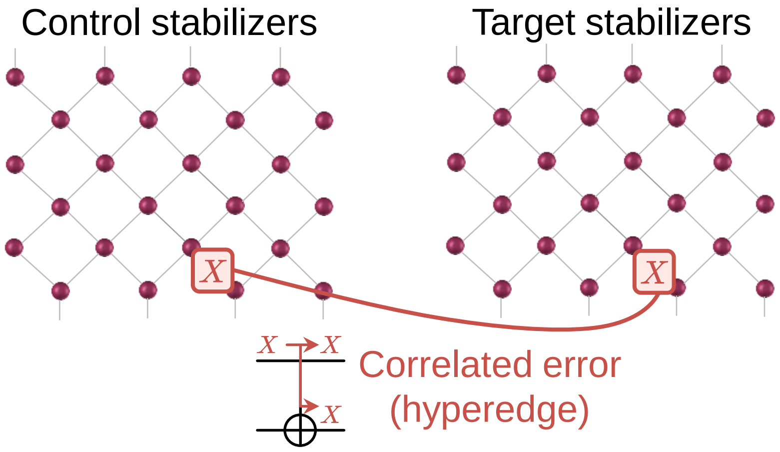
Bluvstein et al Nature 2023

Correlated decoding

Madelyn Cain, C Zhao, H Zhou … Jaffe, DB, Lukin – arXiv:2403.03272







When two logical qubits do a gate, add edges / hyperedges to their decoding graph

Correlated syndromes between multiple logical qubits provides significant information

- improved decoding performance (eg, Steane QEC)
- “undoing” error propagation by tracking

However, new errors build in time … *need to remove entropy*

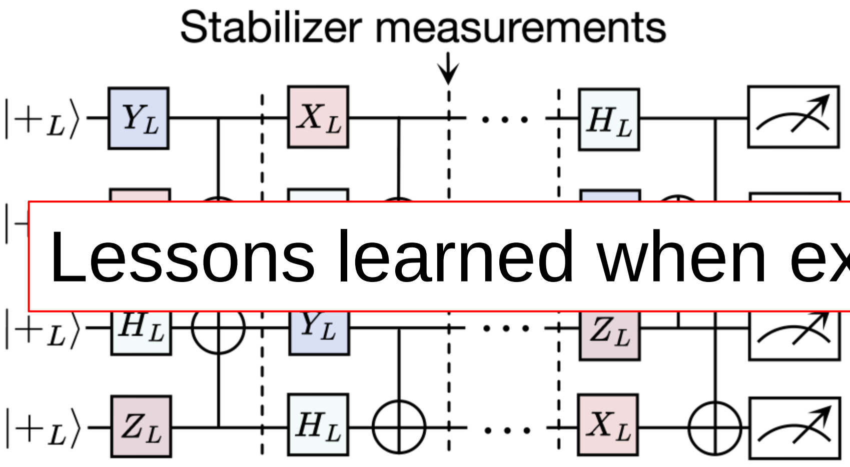
see also
Gidney, C. Quantum 5, 497 (2021),
Delfosse, N. & Paetznick, A. arXiv:2304.05943v2 (2023),
McEwen, M., Bacon, D. Gidney, C. arXiv:2302.02192 (2023)

Correlated decoding → ~1 round per CNOT

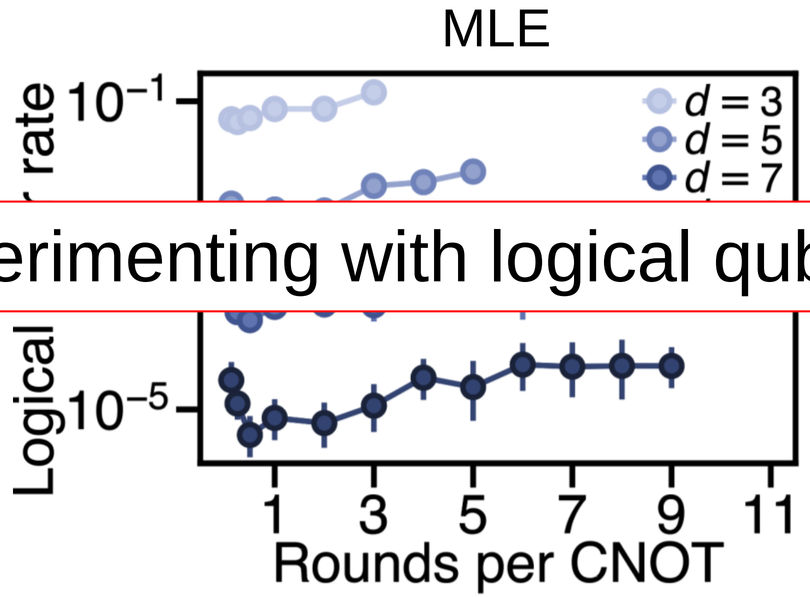
Madelyn Cain, C Zhao, H Zhou … Jaffe, DB, Lukin – arXiv:2403.03272

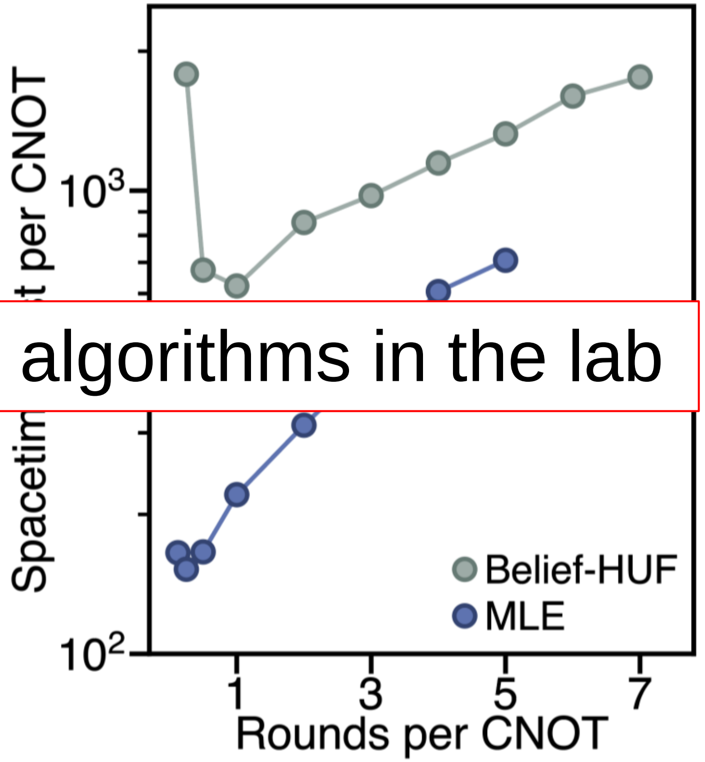
Key insights:

- Only need ~1 round of stabilizer measurement per transversal CNOT to remove the newly created entropy
- “d rounds” is a “bug” from measurement errors. Since they propagate deterministically, can verify as circuit proceeds.



Variable number n_r syndrome extraction rounds per CNOT



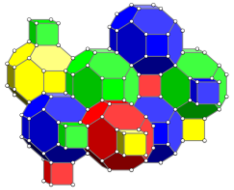


Lessons learned when experimenting with logical qubit algorithms in the lab

Space-time reduction by factor of ~d

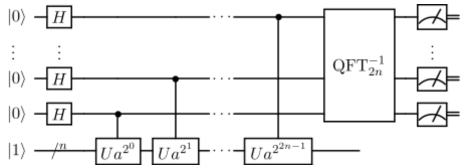
Building logical processors in the lab

Error-correcting code

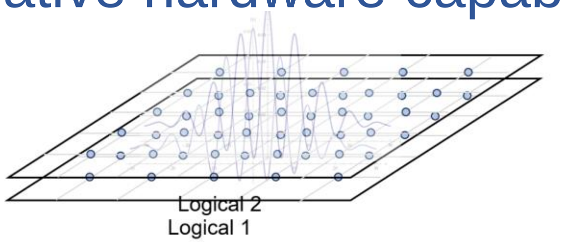


Co-design

Algorithm



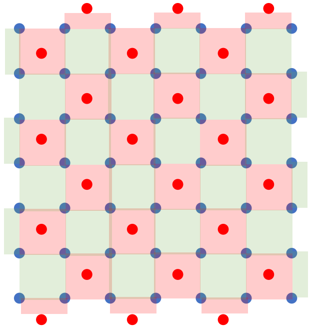
Native hardware capabilities



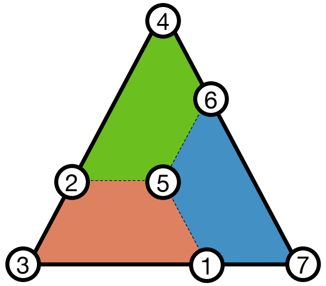
Entering the era of early fault-tolerant quantum computation ...
Search for as many breakthroughs as possible …

Challenges with error-corrected computation

non-Cliffords and universality



Surface code



Color code

- QEC codes have a *discrete gate set* available
- 2D codes can do *Cliffords* {H, S, CNOT} easily, but cannot do *non-Cliffords* {T, CCZ} *easily*
- non-Clifford gate needed to complete *universal gate set*
  - *Actually, non-Clifford needed for any classically hard computation…*

Control-Control-Z gate (CCZ)
Non-Clifford gate

Computational complexity grows exponentially with number of non-Cliffords applied[1]
(State-of-the-art "Clifford + T" simulators[2] can handle ~16 CCZ's)

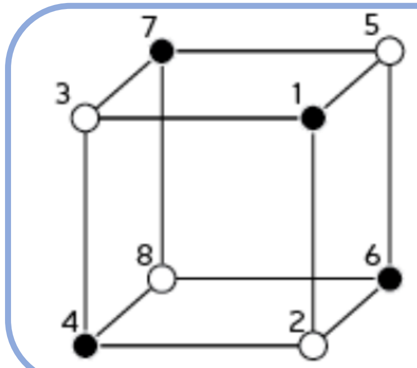
Amount of non-Clifford = "magic"
See many works on magic from Jaffe group, e.g. Bu, Jaffe, Wei, arXiv:2402.05780

[1] Generically
[2] Simulators that take advantage of small number of non-Cliffords

Gottesman-Knill theorem

Fault-tolerant compiling: programming complex logical circuits

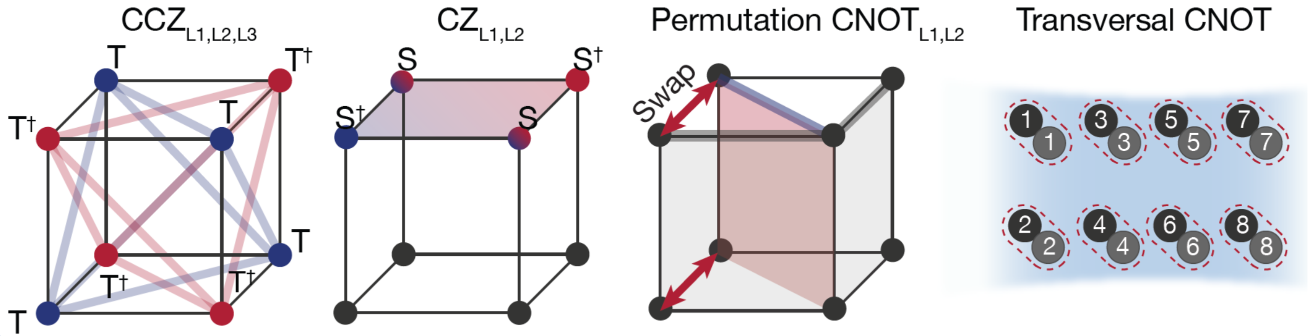
3D codes lose the transversal H, but gain transversal non-Cliffords



[[8,3,2]] code – small 3D code

“The smallest interesting colour code”, Earl Campbell blog

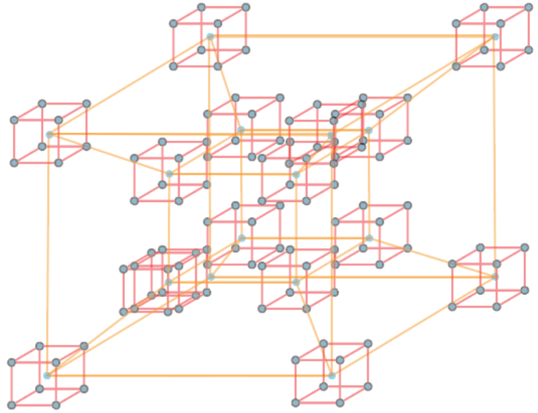
Vasmer, Kubica PRX Quantum 2022
See also arXiv:2309.08663, arXv:2309.09893



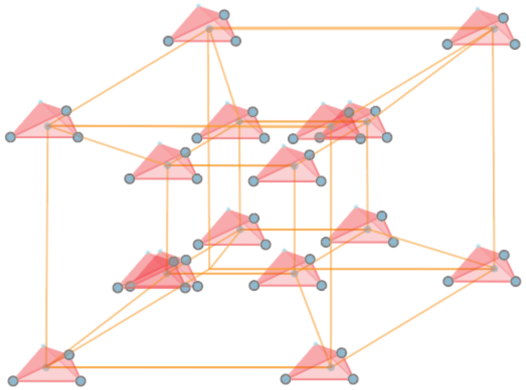
48 logical qubits, 228 logical two-qubit gates, 48 logical CCZs

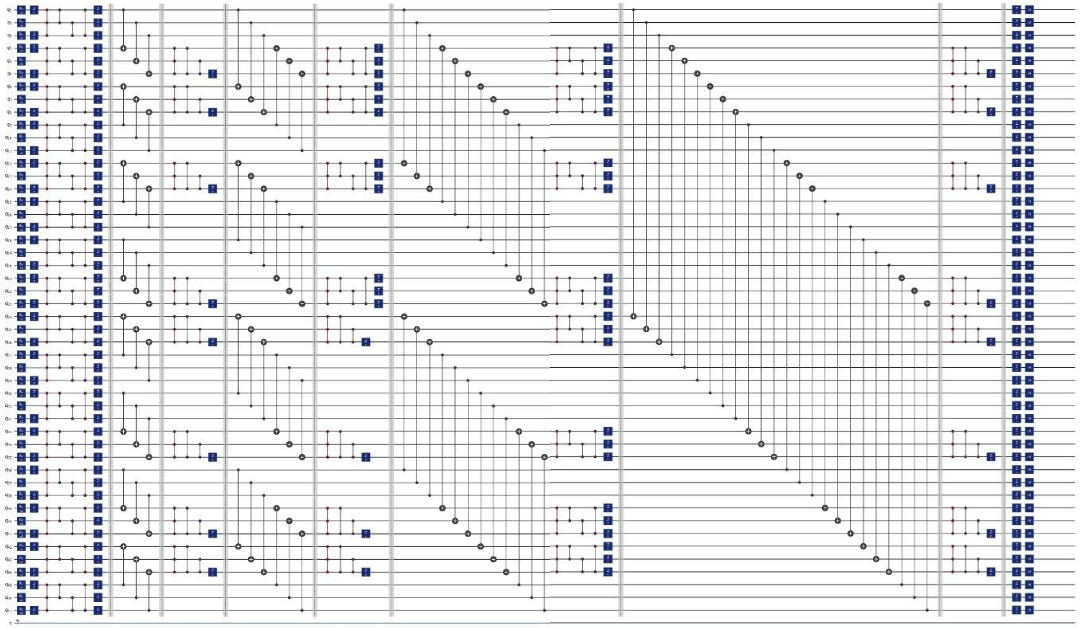
Scrambling / supremacy circuits: utilize nonlocal connectivity of ***logical qubits*** *and make hypercubes of* ***logical qubits***

Physical connectivity



Logical connectivity





Logical circuit

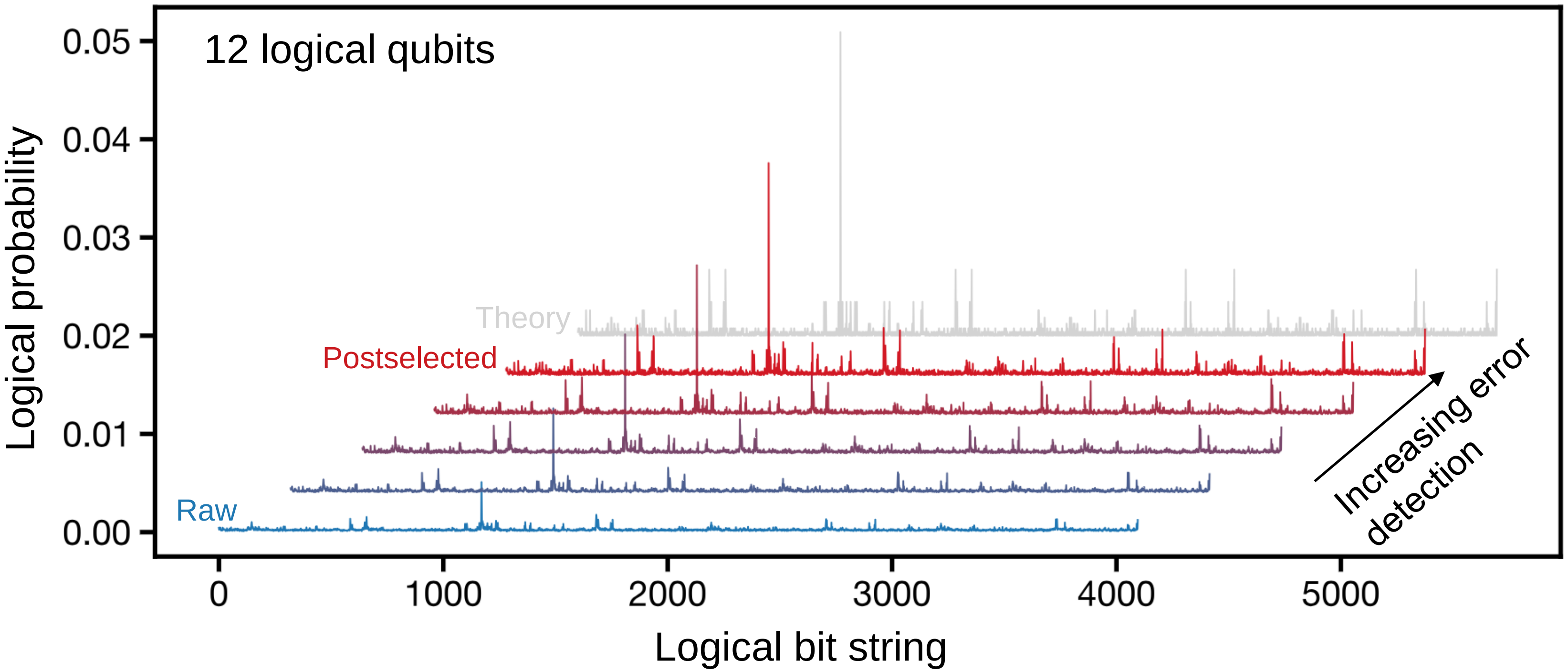
IQP circuit (+CNOT) – Bremner et al arXiv:1005.1407 – see also Paletta et al arXiv: 2307.10729, Mezher et al arXiv: 2005.11539
D Hangleiter, M Kalinowski*, DB* … Kubica, Lukin, Gullans, in prep – further analysis, extension, and connection to IQP*

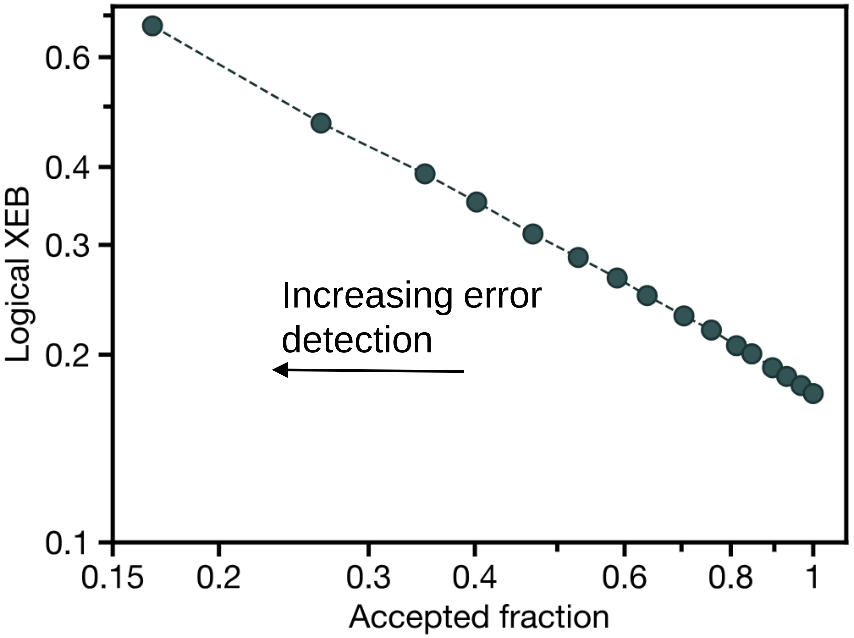
Bluvstein et al Nature 2023

Complex quantum circuits with logical qubits – sampling

$|\psi\rangle$

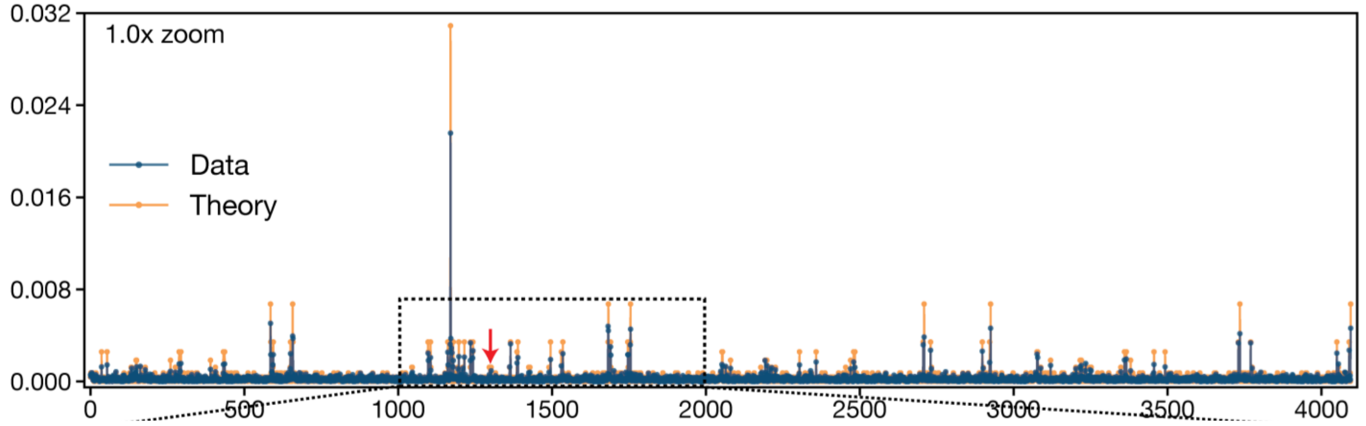
- Sampling: Take snapshots of many-body wavefunction and compare to expected distribution (simulations)
- XEB: sampling score (weighted sum normalized from 0 to 1).





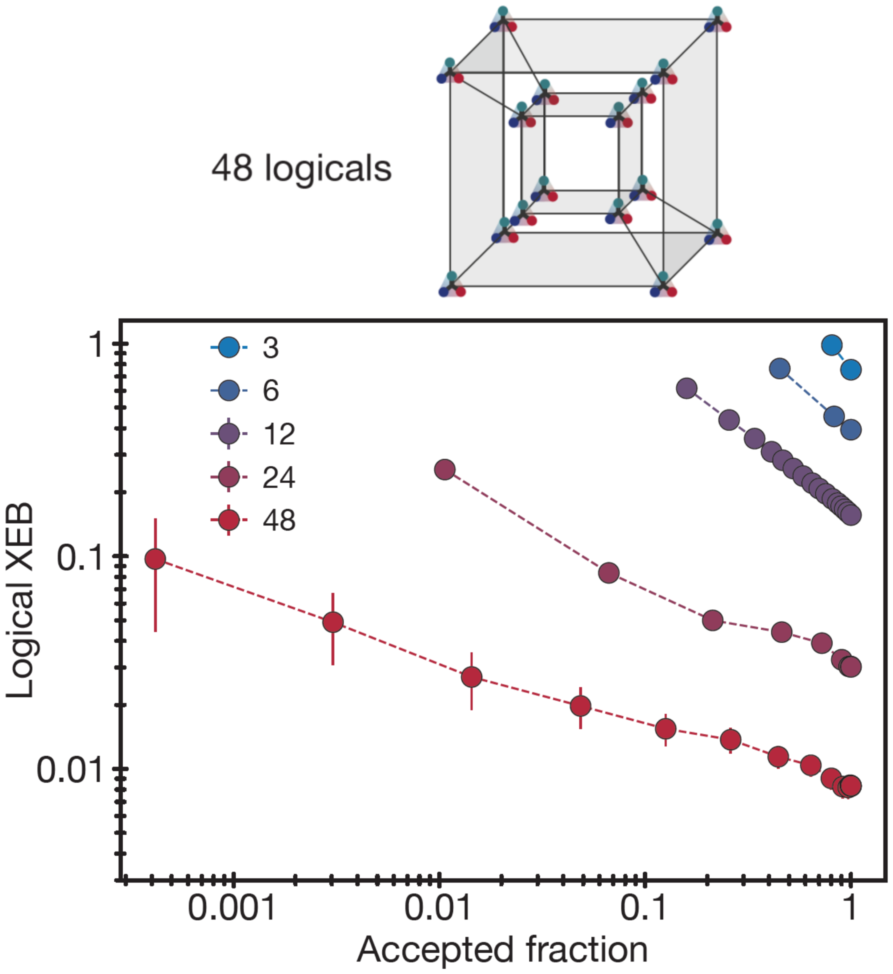
Google Nature 2019
Google arXiv: 2304.11119
Pan group PRL 2021
See also photon groups, USTC , Xanadu ..

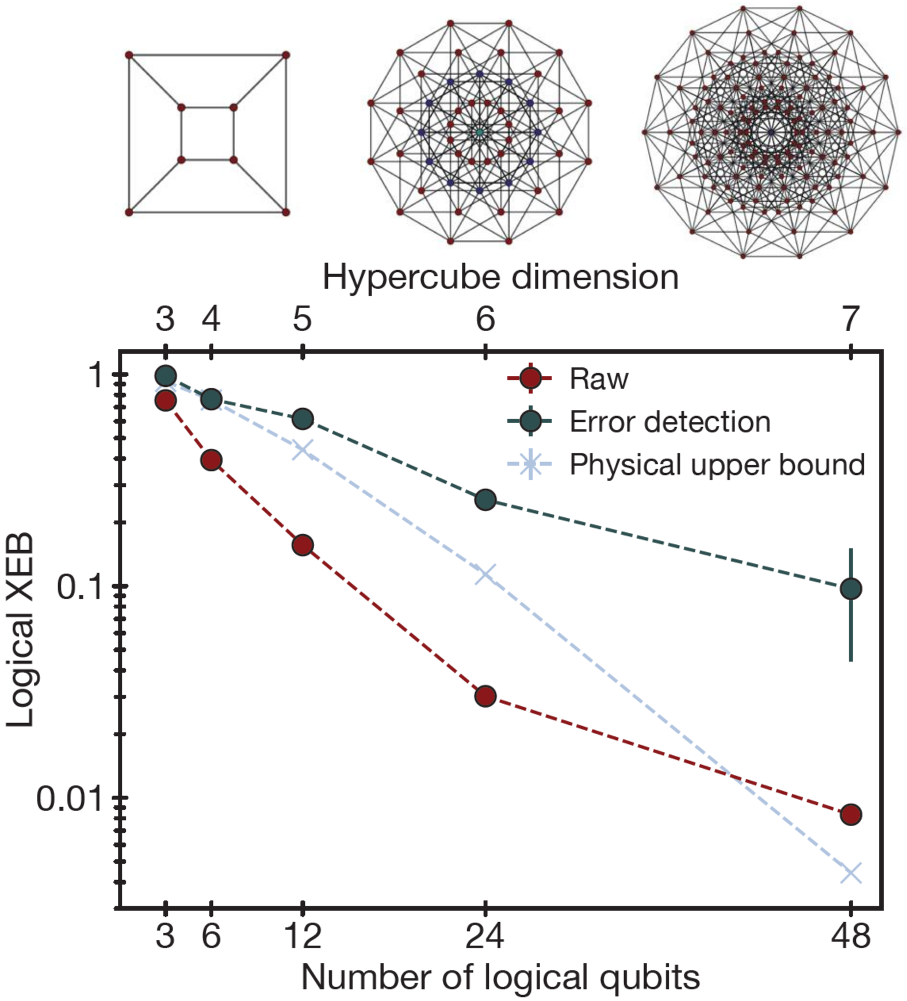
Complex quantum circuits with logical qubits – sampling



Complex logical circuits – scaling to large sizes

Up to 48 logical qubits, 228 logical two-qubit gates, 48 logical CCZs

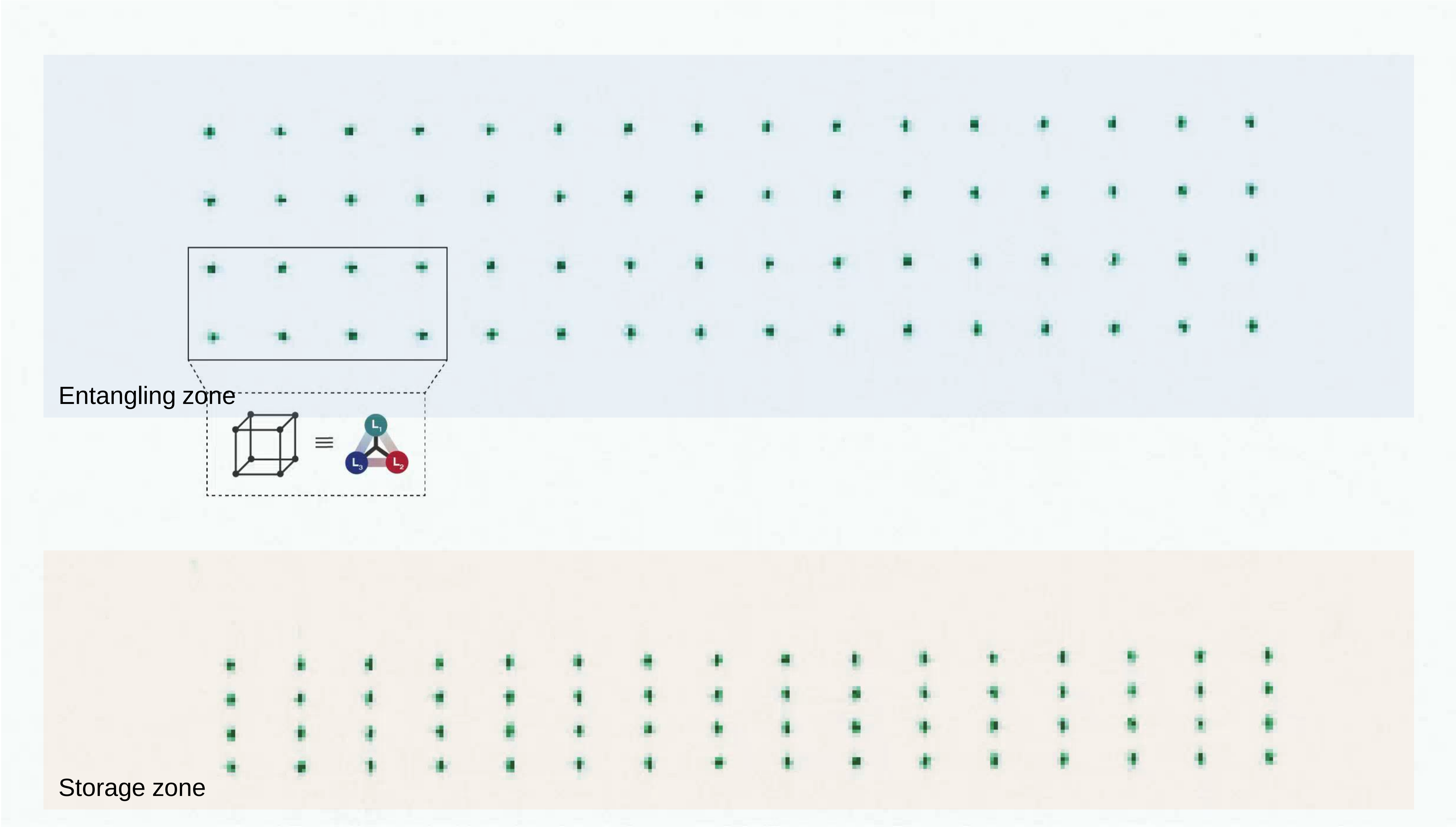




- Finite XEB – successful sampling. XEB score improves with increased error detection
- Postselected logical XEB up to ~10x higher than previous physical implementations (at cost of measurement time)

Bluvstein et al Nature 2023

Seven-dimensional hypercube circuit



Inspired by conversations with Jason Cong and Daniel Tan
See also Kuriyattil et al PRX Quantum 2023

Bluvstein et al Nature 2023

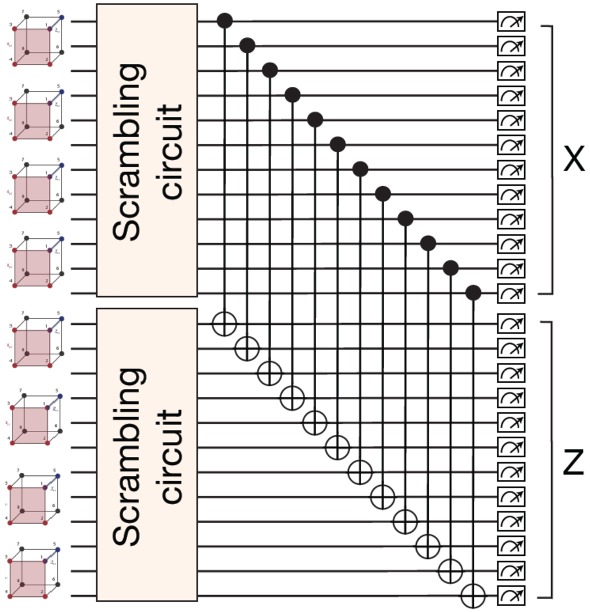
“Fault-tolerant compiling” of quantum simulations

Bell basis measurement: extremely powerful tool in quantum information

- Entanglement entropy – Daley, Pichler et al PRL 2012
- Simultaneous extraction of all 4^N Pauli strings (absolute values) – Huang Science 2022

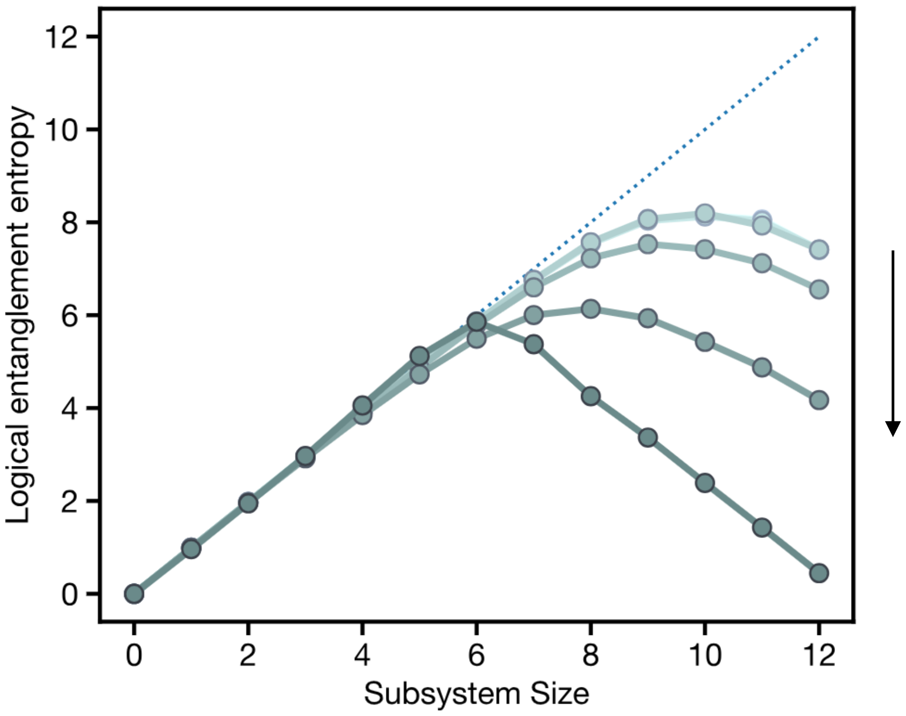
Fully compatible with logical qubits and transversal CNOT!

Bell basis measurement



Two copies of 12 logical circuit, followed by transversal CNOTs for Bell basis measurement

Scrambling and thermalization dynamics



Increasing error detection

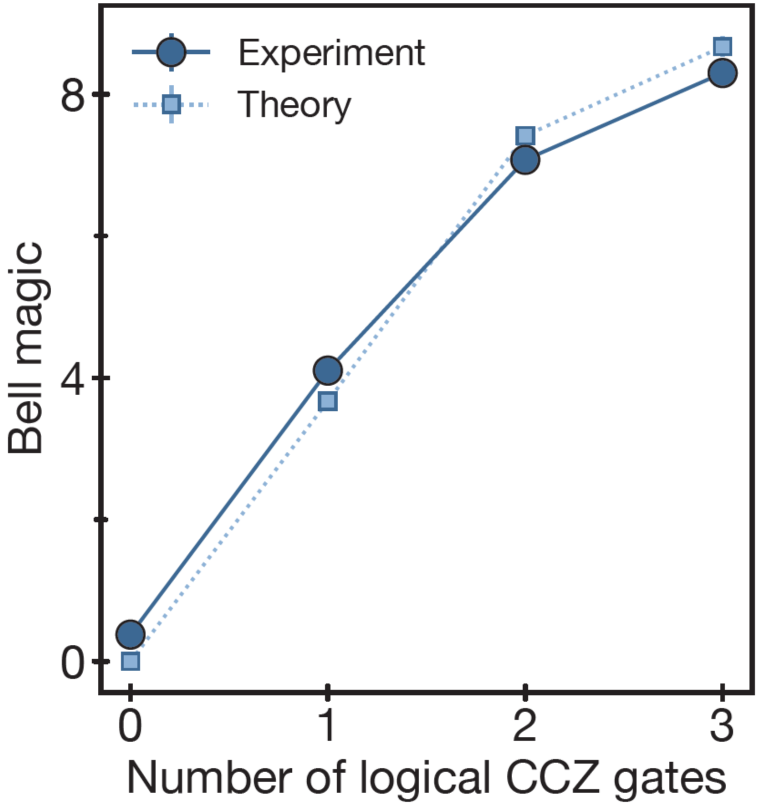
Error-correction allows us to see clean Page curve behavior with limited decoherence

Logical qubits can already be used for various interesting physics and quantum information explorations

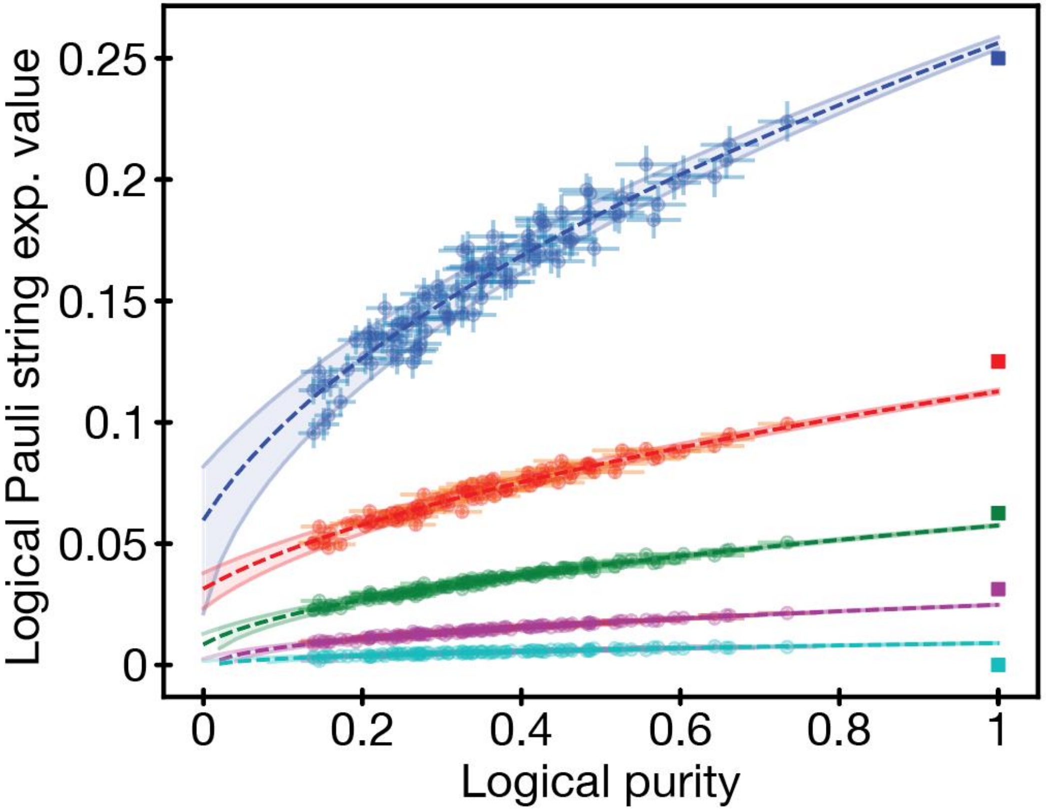
Bluvstein et al Nature 2023

Measuring Magic, Pauli extraction, zero-noise extrapolation

Bell difference sampling



Extracting all 4^12 Pauli string (absolute values)



Predicted values (squares)

Five discrete expectation values for this circuit, grouped together

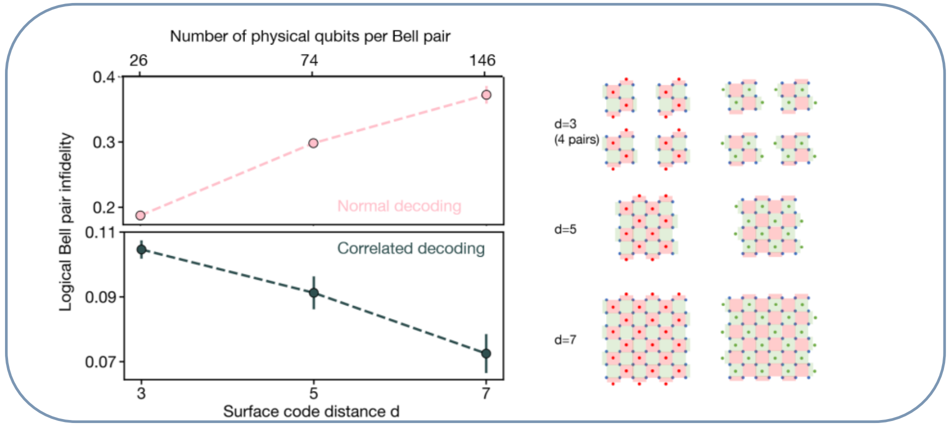
Sliding-scale error detection *… zero-noise extrapolation*

Combination of encoded qubits with two-copy measurements offers interesting possibilities and error mitigation strategies in quantum simulation

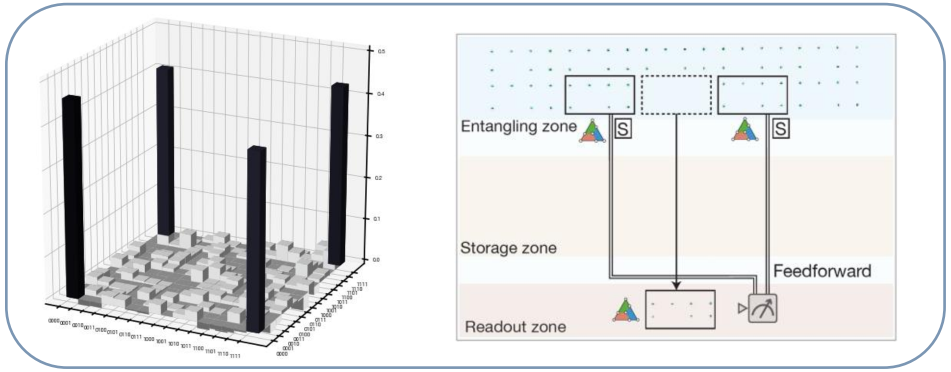
Bluvstein et al Nature 2023

Summary: Quantum information processing with logical qubits

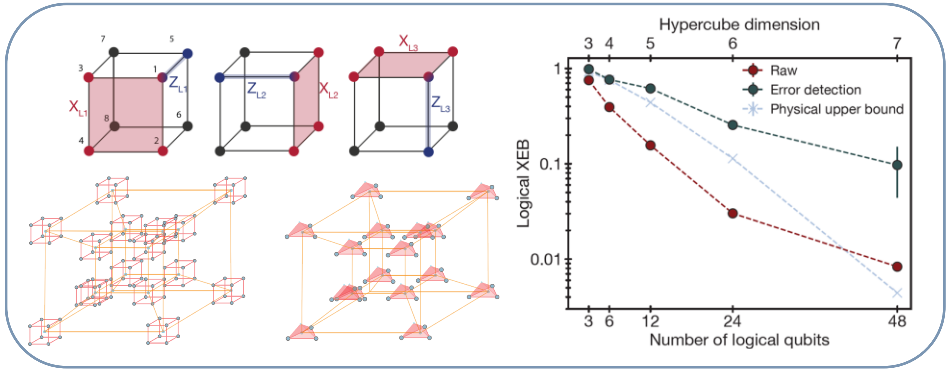
- Quantum operations improve with code size (surface codes as large as d=7)



- Fault-tolerant algorithms and characterizing zoned processor



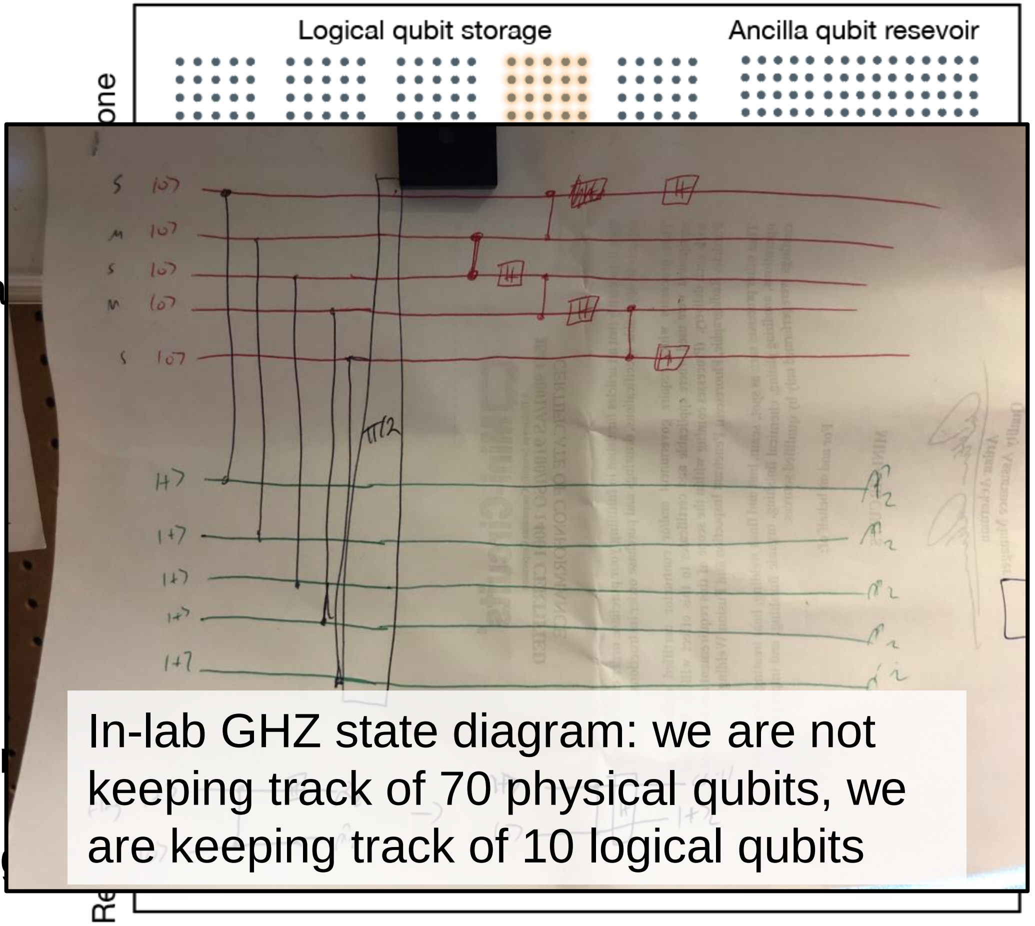
- Complex scrambling circuits with small 3D codes and hundreds of logical entangling gates



So, what did we learn, and where do we go from here?

Lessons from our first-generation logical processor

- Control over single *logical* qubits as the fundamental units can dramatically reduce costs of a logical processor
- Instead of considering individual logical qubits, consider algorithms as a whole (e.g. correlated decoding)
- Logical qubits (many-body systems) are not literally qubits, and sometimes don’t behave exactly the way you’d expect
  - ☹ Bell state fidelity ≠ SPAM x gate fidelity
  - ☺ *Inherently digital operation*, coherent logical errors suppressed
- There are genuine examples where logical qubits can already outperfor physical qubits at interesting problems
  - The discrete gate set is a curse, but also a blessing if you can desi your problem around it
  - Many more opportunities for early-generation logical algorithms



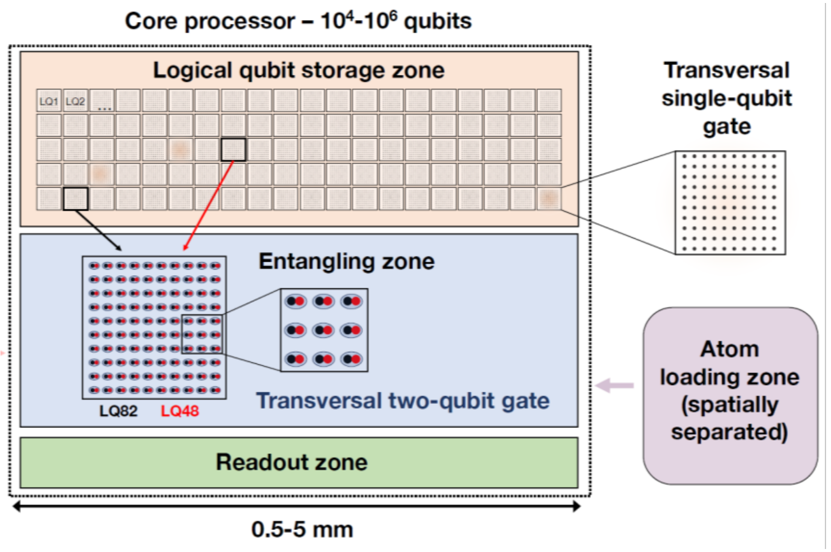
In-lab GHZ state diagram: we are not keeping track of 70 physical qubits, we are keeping track of 10 logical qubits

Medium-scale logical processors: unique opportunity for atoms

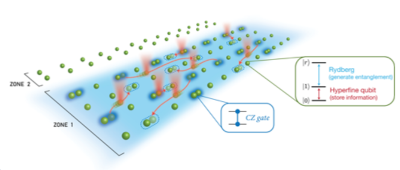
Open theory questions:

1. What algorithms should we study with 100 logical qubits and 1M logical gates?
2. How do we structure these algorithms for efficient QEC implementation? *Fault-tolerant compiling*

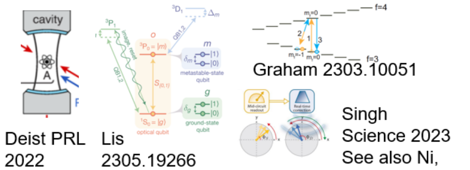
→A path to 100 logical qubit device with ~10^{-5} logical error



Nonlocal connectivity, transversal logic gates, zoned architecture



Mid-circuit readout:
Cavities, Shelving, Dual species, zones



Graham 2303.10051

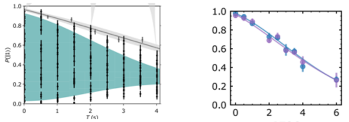
Deist PRL 2022

Lis 2305.19266

Singh Science 2023
See also Ni, semeghini

Also Schleier-Smith, Vuletic

Alkaline-earth; long T2, esp nuclear



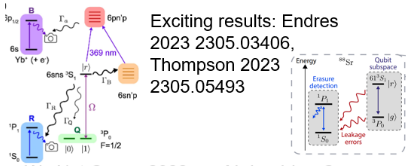
Jenkins PRX 2022

Ma PRX 2022

Atom Computing, Endres, Covey …

Moving will work great for nuclear spins!

Erasure conversion
Idea: Thompson group, Puri



Exciting results: Endres 2023 2305.03406, Thompson 2023 2305.05493

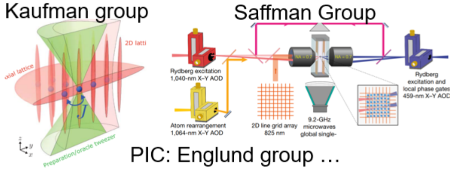
Wu Nat Comm 2022
Sahay 2302.03063

Noise bias Cong et al PRX 2022

Various approaches to local addressing, lattices, clever optical technologies …

Kaufman group

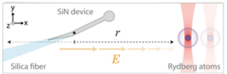
Saffman Group



PIC: Englund group …

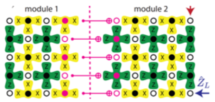
Reloading: Bernien group, atom computing…

Optical networking



Covey, Bernien groups …

Ocola 2210.12879



Vuletic group

Ramette, Sinclair 2302.01296

Very nice initial continuous reloading (2024): Atom computing 2401.16177, Zeiher 2402.04994

A medium-scale QEC device:
New tool for scientific discoveries
Accelerating the path to large scale QC

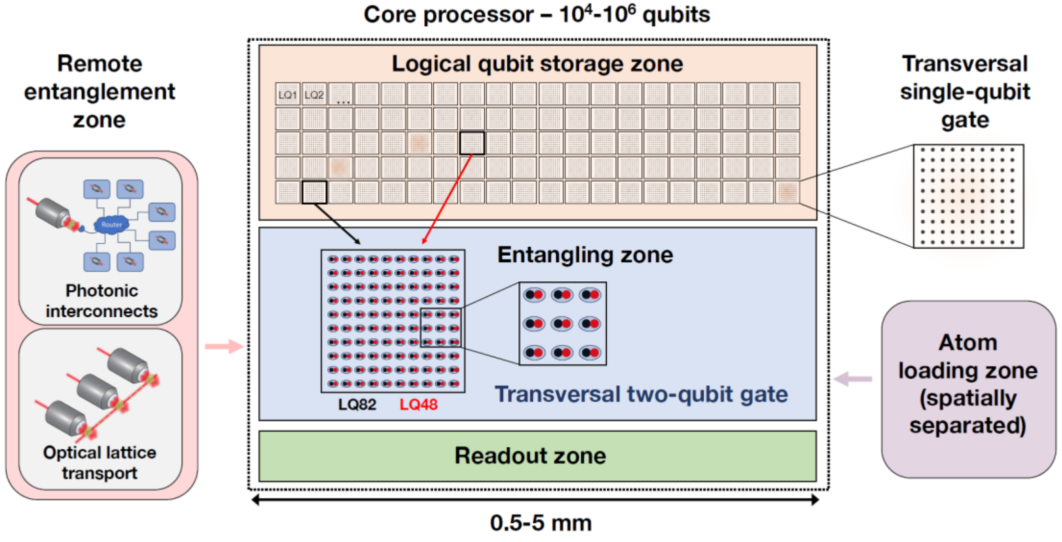
In the coming years, such devices will unlock completely new studies of quantum mechanics

Diverse opportunities with neutral atoms

How to get to large-scale processor, e.g. >1000 logicals?

- *Optimistic estimates[1]: 1 million qubits, 10^{-10} error rate, day-long computation*

- *Possible avenues:*
  - LDPC[2] codes and other clever tricks: favorable scaling
  - Power-efficient trapping: e.g., 2D or 3D optical lattices for trapping 1 million atoms
  - Connected modules: photonic interconnects through cavities or free-space



Core processor – 10^4-10^6 qubits

Remote entanglement zone

Photonic interconnects

Optical lattice transport

Logical qubit storage zone

Transversal single-qubit gate

Entangling zone

Transversal two-qubit gate

Atom loading zone (spatially separated)

Readout zone

0.5-5 mm

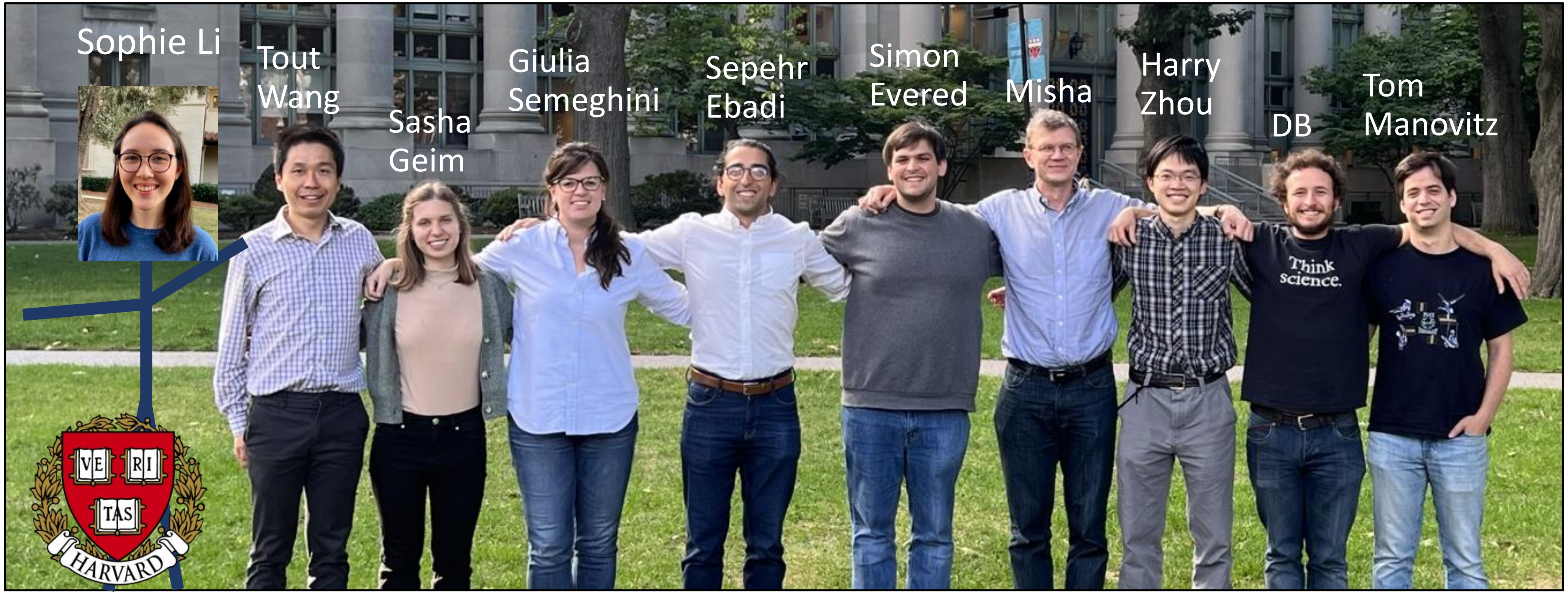
Should pursue all possible breakthroughs – hardware, code & algorithm design!

Experimentation with early generation logical devices will likely reshape the way we think these large-scale processors should be built (theory & hardware)

---

[1]: Gidney Ekera Quantum 2021

[2]: Q Xu*, P Bonilla* et al., arXiv: 2308.08648 (collaboration of Lukin & Jiang groups + QuEra (H Zhou)) – see also Bravyi et al



★ *Atom Array II:*

Tout Wang, Tim Guo, Allen Chiu, Pavel Stroganov, Mohamed Abobeih, Simon Hollerith, Sebastian Geier

★ *Collaboration with QuEra*

P Sales Rodriguez

T Karolyshyn

PIs

M. Lukin

V. Vuletic

M. Greiner

Theory collaborators

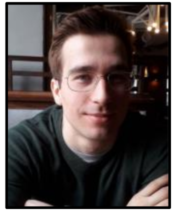
N. Maskara

M. Cain

I. Cong

JP Bonilla Ataides

M. Kalinowski

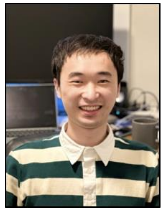


M. Gullans

D. Hangleiter

X. Gao

C. Zhao



A. Jaffe

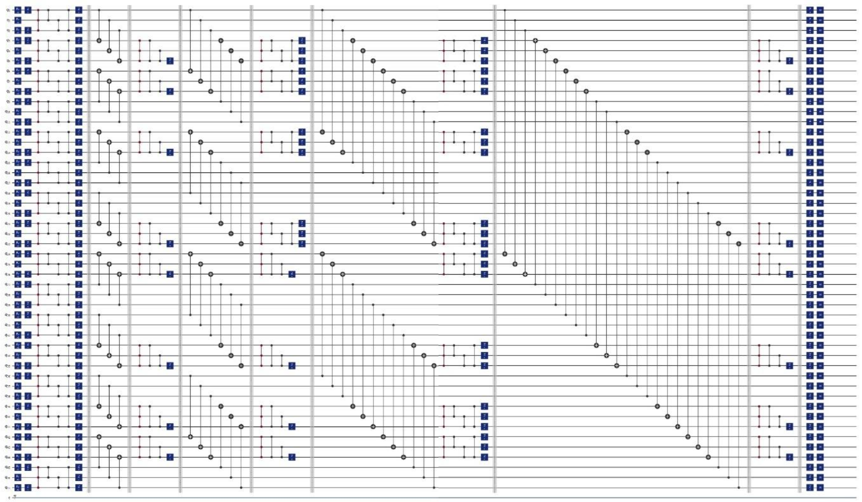
N. Meister

Funding: QuEra, NSF, CUA, Vannevar Bush, AFOSR MURI, DARPA, IARPA, NDSEG, Hertz

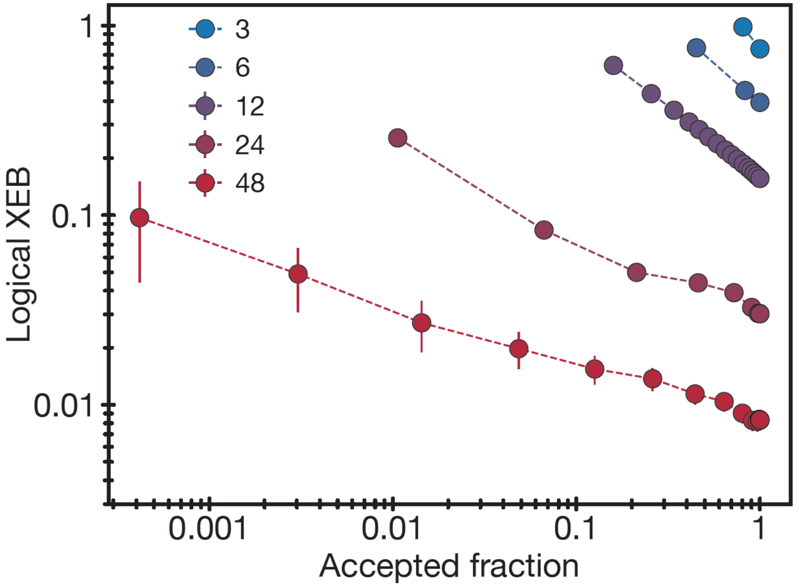
Outlook: towards quantum advantage with logical qubits

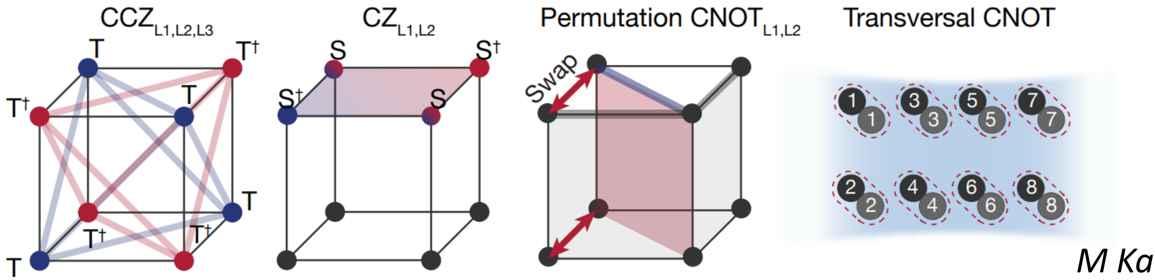
- Present work: we intentionally structure our exact circuit so that they are susceptible to an “attack” using tensor contraction of two wavefunctions each with n/2 qubits, partitioned by the final CNOT layer
  - Leads to 2^(n/2) simulation cost
  - This “attack” is broken by applying additional CNOT layers, recovering 2^n scaling

- Nice recent work by IBM / IonQ arXiv:2402.03211 finds another “attack” for our exact circuit by using “minimal covering sets” or “minimal vertex covers” of the CCZs
  - Leads to 2^(n/3) simulation cost
  - This “attack” is broken by implementing permutation CNOTs, recovering 2^n scaling
  - Permutation CNOT is fault-tolerant and directly achievable in our atom array system – is just a parallel reshuffling of qubits



Logical circuit





M Kalinowski, M Gullans, D Hangleiter (and others), in preparation