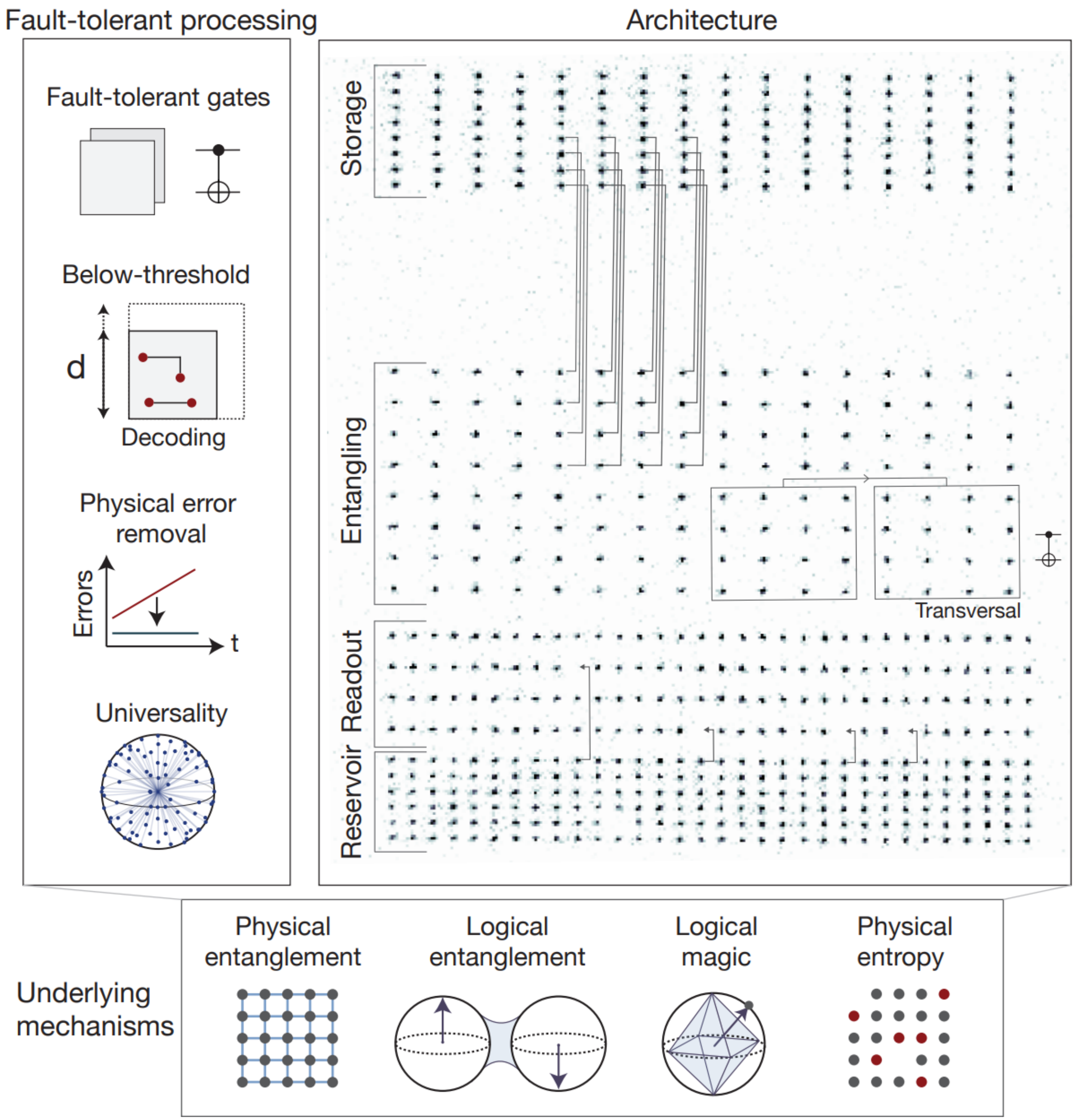
A fault-tolerant neutral-atom architecture for universal quantum computation



Alexandra (Sasha) Geim
Lukin Group, Harvard University
Math Picture seminar, 03/03/2026

Bluvstein*, AAG* *et al.* (*Nature*, 2025)

Challenge of quantum

Promise of *computational advantage* in quantum systems, but need to counteract *errors* and *decoherence*

Example – noisy classical communication

- Encode info. in many digital bits: 0’s and 1’s
- Logical state is also digital: 0 or 1

Classical bits: **digitized** + corrected via **dissipation**

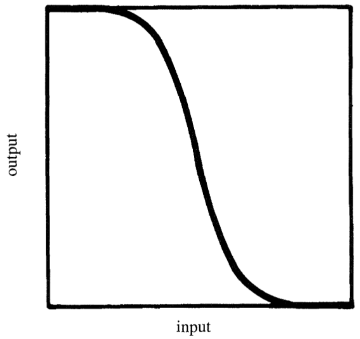


Figure 1. Idealized response of a digital inverting circuit.

Landauer 1995

The physical nature of information

Rolf Landauer [1]

3. Quantum parallelism: A return to analog computation

An analog computer can do much more per step than a digital computer. But an analog computer, in which a physical variable such as a voltage can take on any value within a permitted range, does not allow for easy error correction. Therefore, in the analog computer errors, due to unintentional imperfections in the machinery, build up quickly and the procedure can go through only a few successive steps before the errors accumulate prohibitively. A digital computer, by contrast, allows only a *0* or *1*. That permits us to restore signals toward their intended values, before they drift far away from that. In typical digital logic the signal

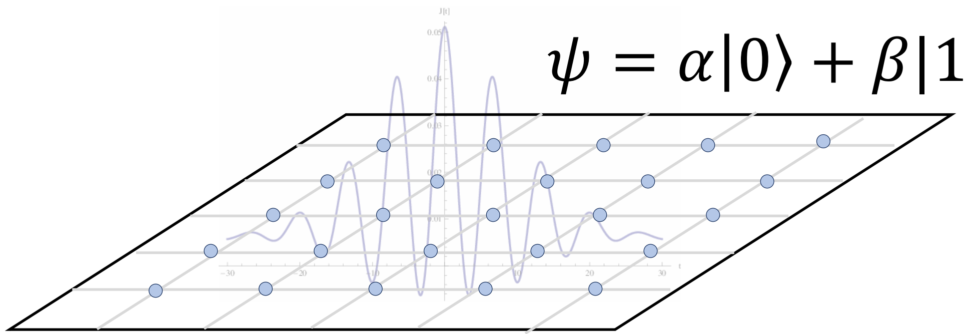
How to combine this intrinsically irreversible digital error correction with quantum computation?

Early debates on physics of information: Landauer, Bennett, Benioff, Fredkin, Toffoli, Shor...

Quantum error correction

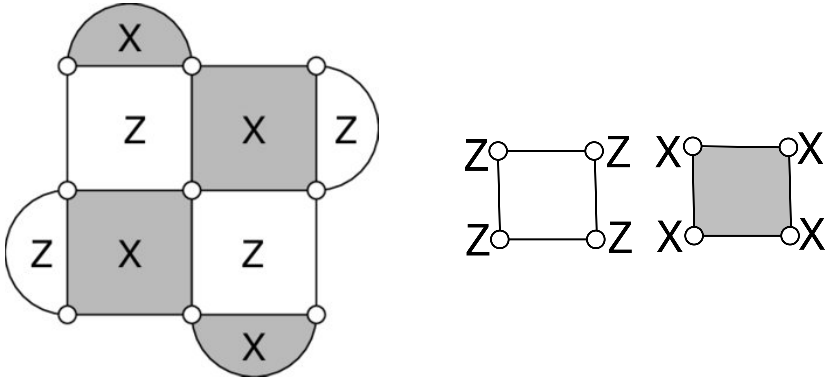
QEC allows for unitary logical computation constructed from dissipative physical states

- Encoded across many **physical** qubits (e.g., toric, colour, high-rate,...)
  - **Dissipation** via projective measurement (stabilizer checks)
  - Digitized, correctable errors (bit flips and phase flips)
- **Logical** computation remains **unitary** and **analog**
  - Enabled by underlying physical entanglement



$$\psi = \alpha|0\rangle + \beta|1\rangle$$

Logical qubit



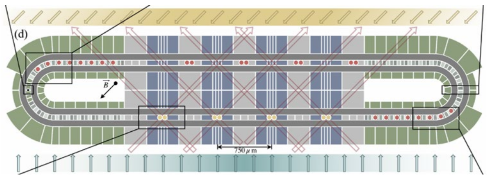
Pioneering works: Shor, Steane, Calderbank, Kitaev, Preskill, Gottesman ...

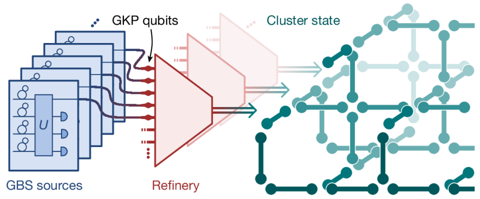
QEC architecture: the challenge

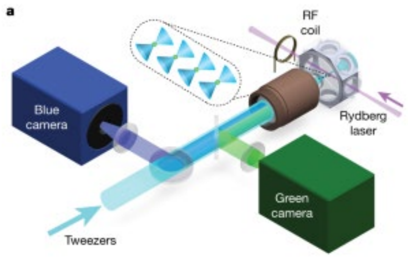
Ability to correct errors, at the cost of *complexity* and *constraints*

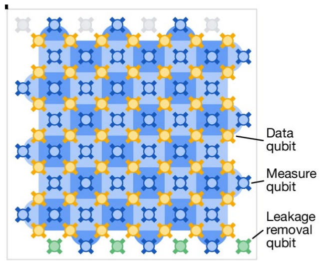
- Requirements: qubit overhead, low error rates, restricted logic operations, control complexity, long run times, …

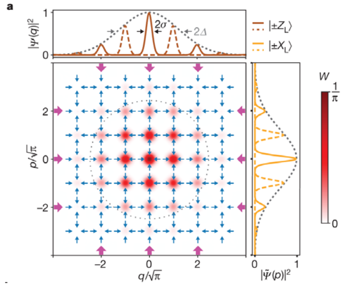
Hardware + control





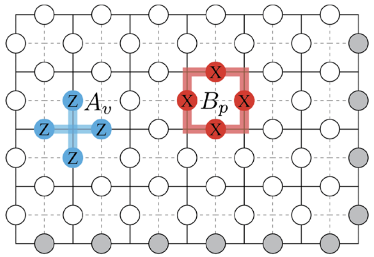


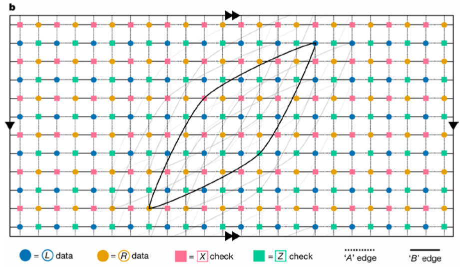




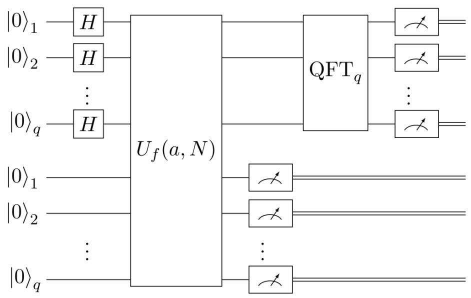
Ions, s.c. qubits, photons, atoms, molecules, solid state…

Logical encoding + decoding





Algorithm design



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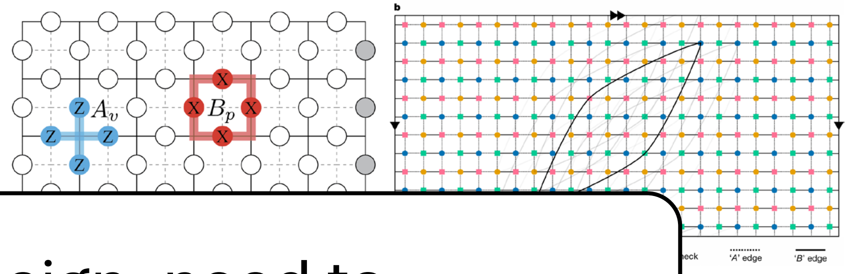
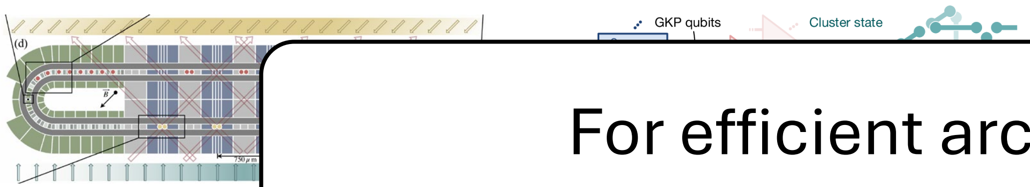
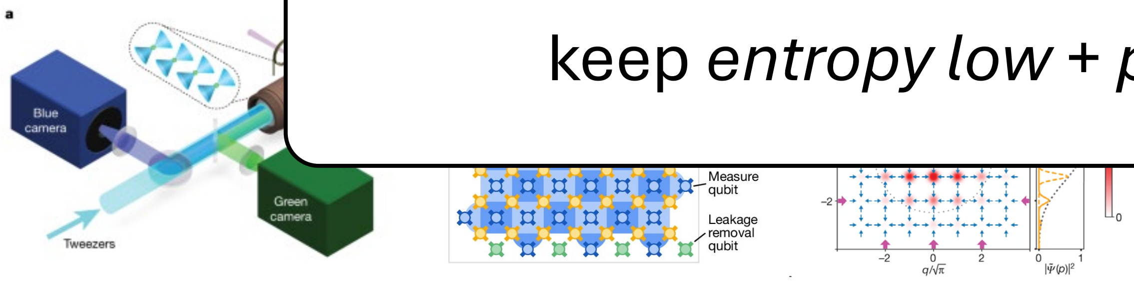
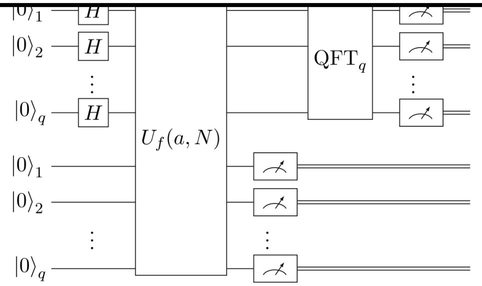


Hardware + control



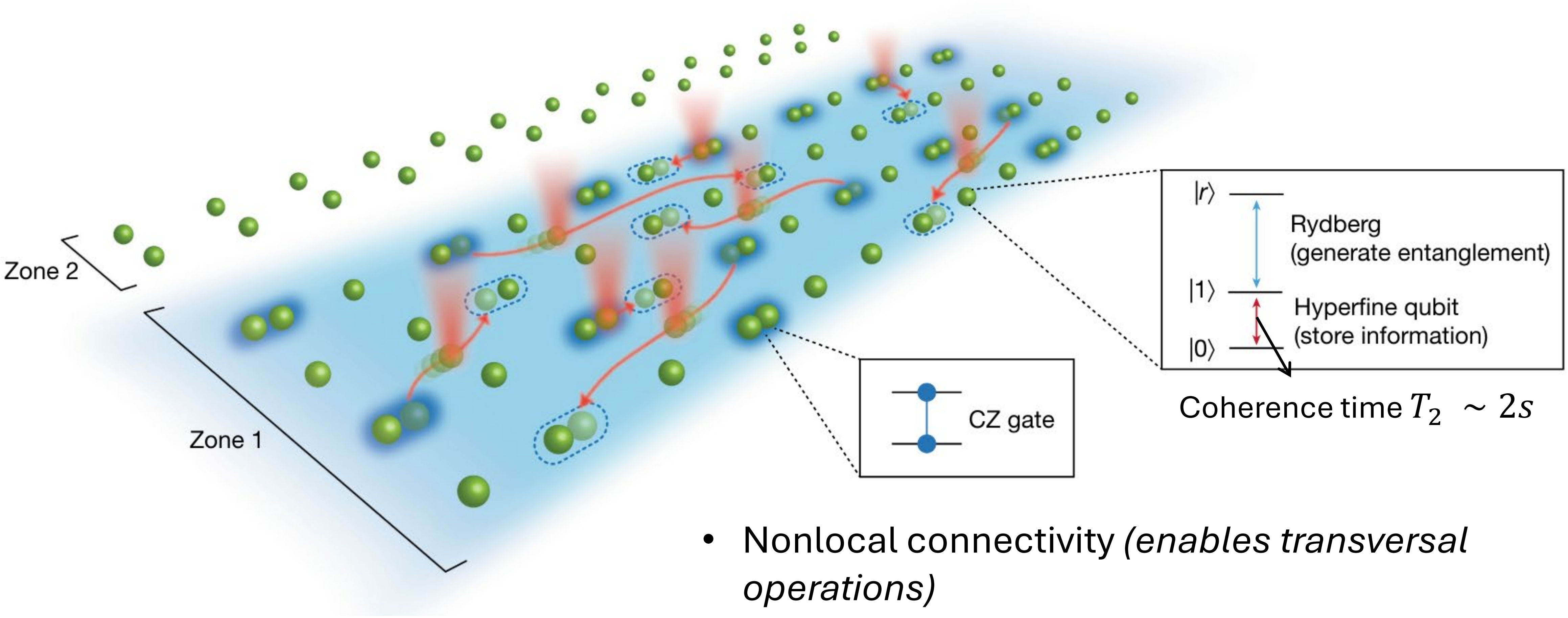
For efficient architecture design, need to understand the *core mechanisms* of QEC which keep *entropy low* + *protect algorithm* output





Ions, s.c. qubits, photons, atoms, molecules, solid state…

Our approach: reconfigurable atom arrays

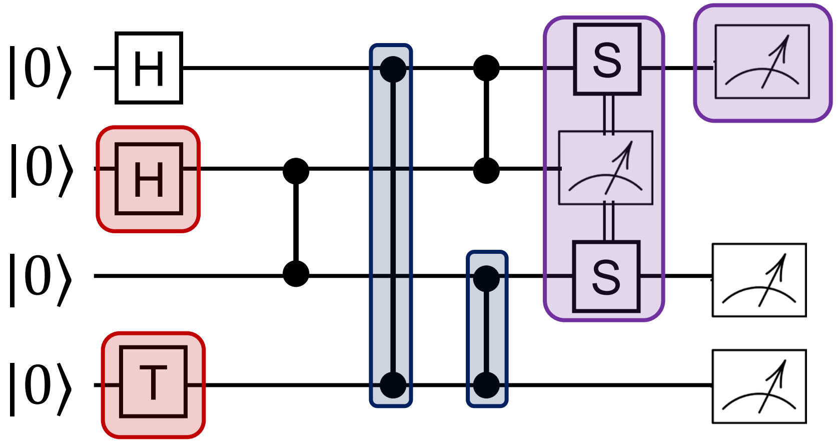


Bluvstein *et al. Nature* **604,** 451-456 (2022)

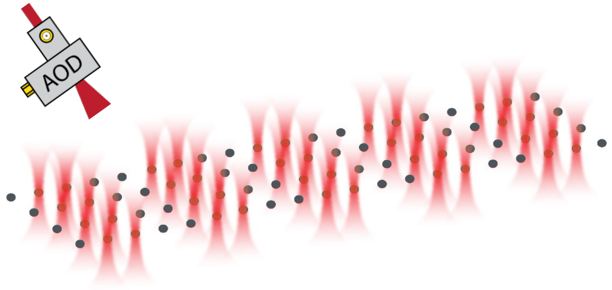
- Nonlocal connectivity *(enables transversal operations)*
- Efficient parallel control
- High fidelity operations

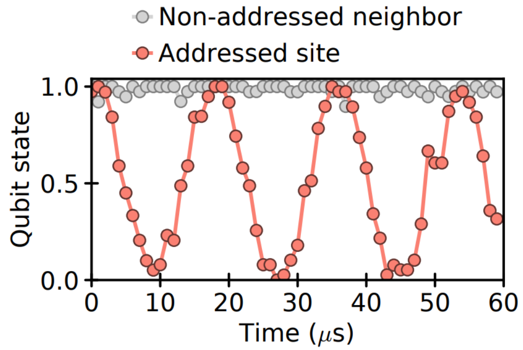
Programming high-fidelity circuits

Example quantum circuit:



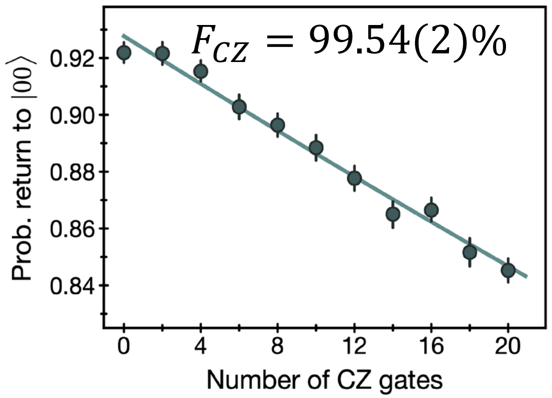
Fully programmable single-qubit gates



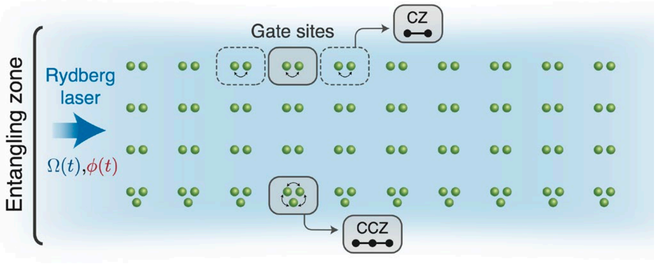


Global >99.99%, Local ~99.9%

Entangling gates

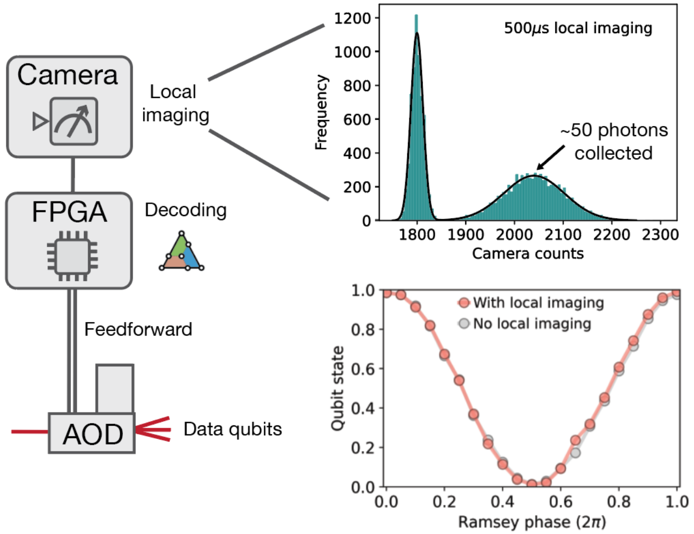


Atomic motion programs (nonlocal) connectivity



*fidelities are continuing to improve!
Published state-of-the-art is 99.71(5)% (Endres group in Sr)

Readout + mid-circuit feedforward



This talk

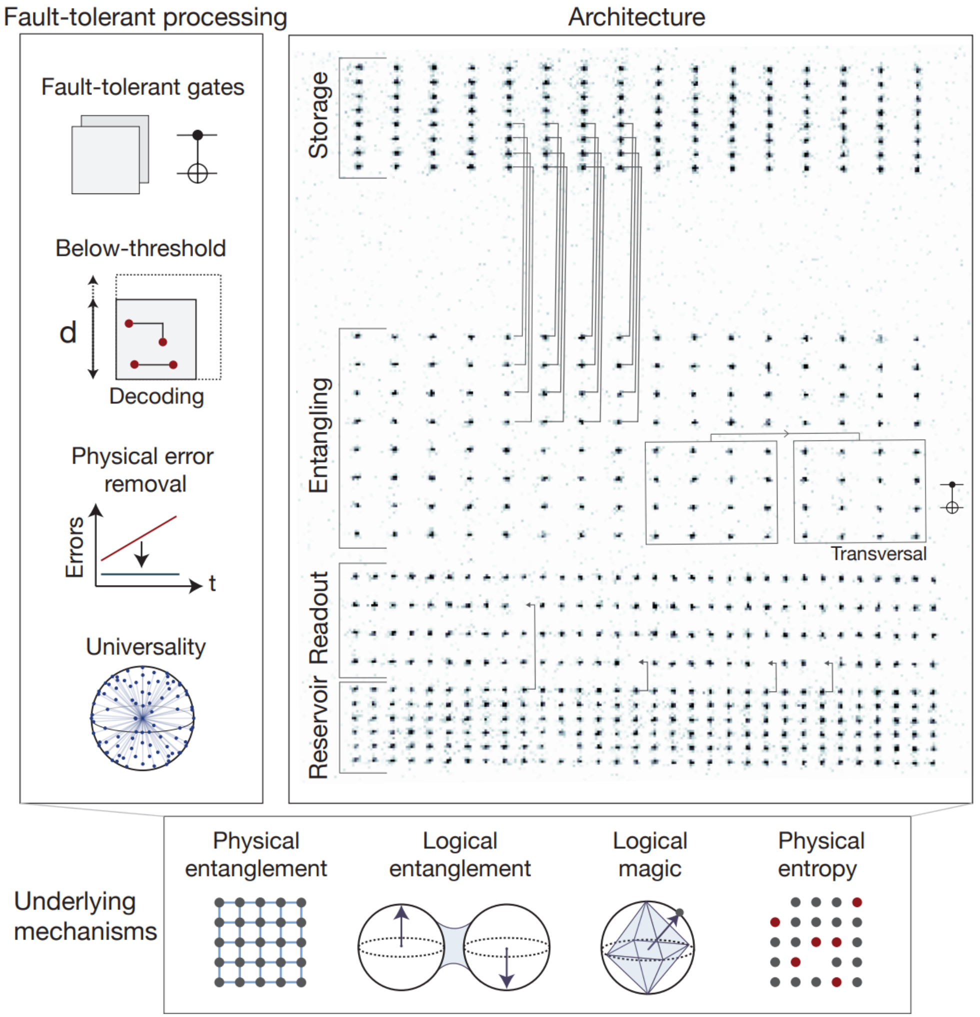
Exploring key components for universal, fault-tolerant quantum computation

1. Entropy removal and below-threshold performance

2. Stabilizer measurement in logic operations

3. Universality with discrete gates

4. Architecture for deep circuit computation



Bluvstein*, AAG* *et al.* (*Nature*, 2025)

Neutral atom logical processor

Zoned architecture with up to ~450 atomic qubits

Storage

- Idle logical qubits are stored, safe from errors

Entangling

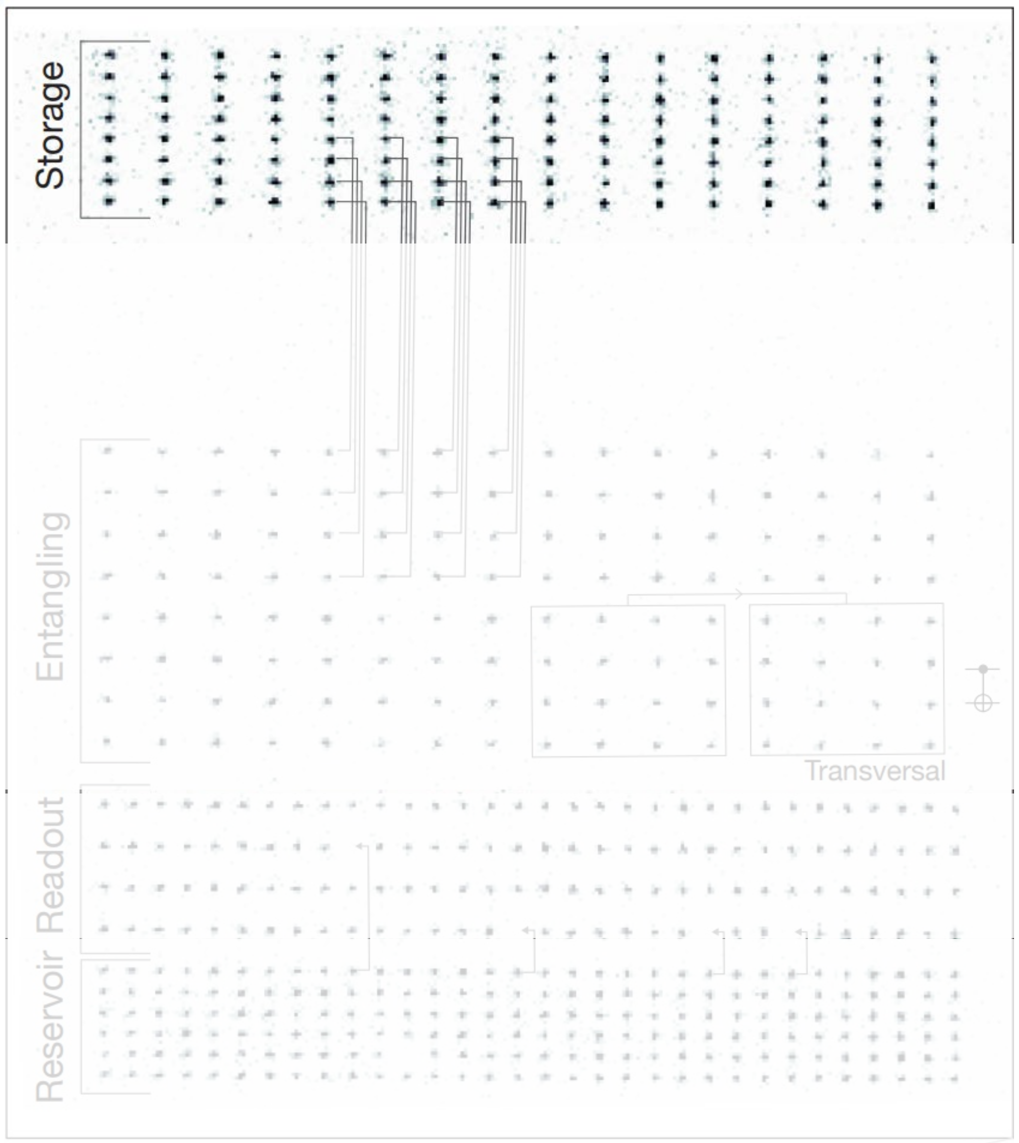
- Long-range connectivity via atom motion
- Parallel 2Q gates
- Fully-programmable SQ gates

Readout

- Mid-circuit measurement and qubit re-use

Reservoir

- Refill lost qubits (towards continuous operation)

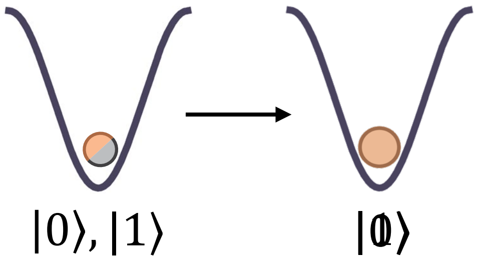


New approach to qubit readout (Gen IV upgrade)

Conventional readout:

Spin-to-loss conversion

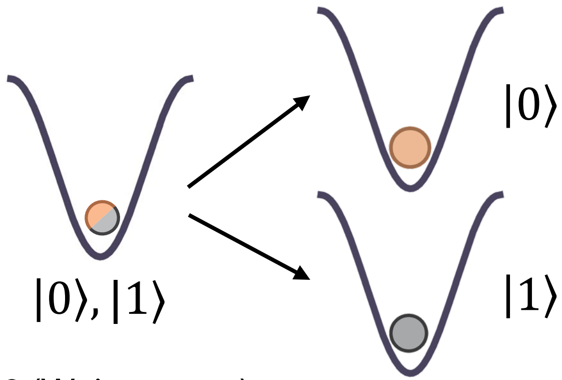
- Imaging mixes qubit states
- Solution: use spin-to-loss conversion



Lossless, state-resolved readout:

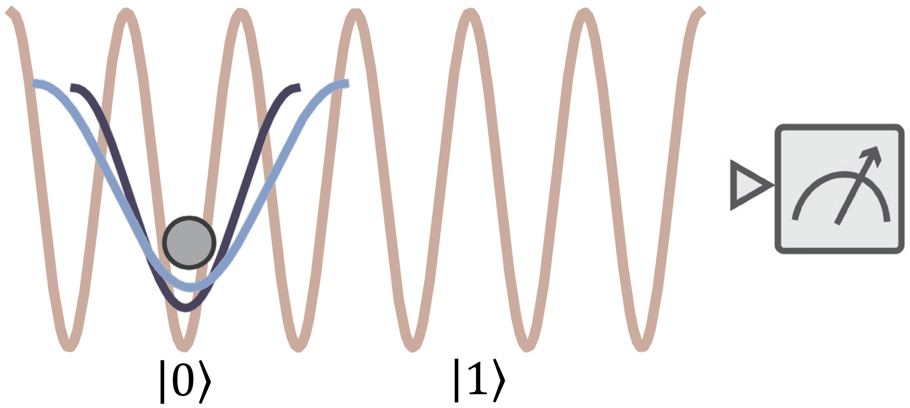
Spin-to-position conversion

- Directly distinguish {0,1,loss}
- Can re-use the atom



Inspired by Wu et al *Nature Physics* 2019 (Weiss group)

1D optical lattice for spin-selective pinning



Enables **loss detection**
and now retain the atom*

*can be re-cooled, reinitialized and re-used… see later

New approach to qubit readout (Gen IV upgrade)

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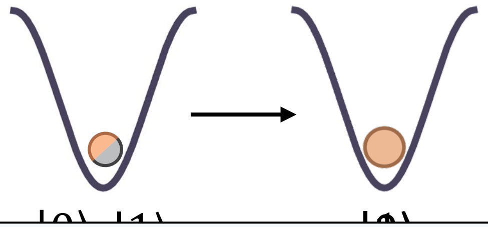

Lossless, state-resolved readout:

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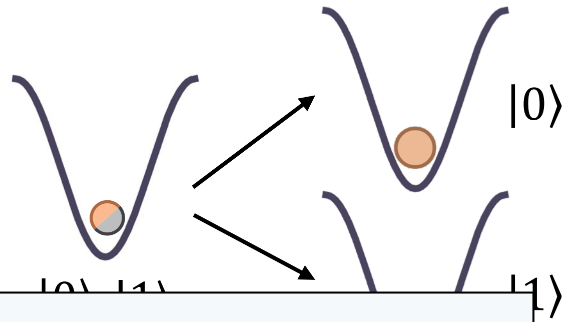
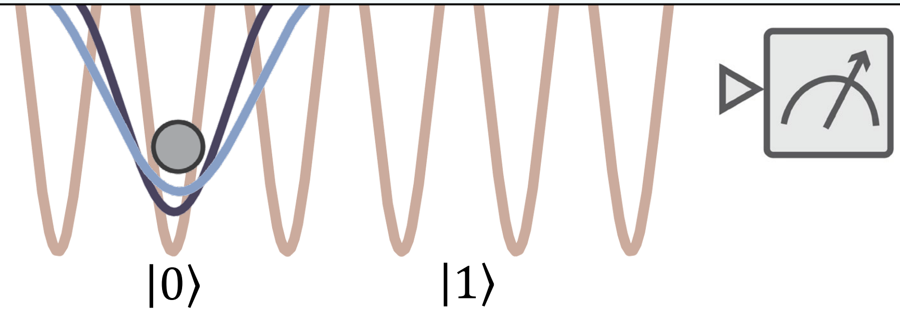


Rabi oscillations measured with spin-to-position conversion

(note: just readout, not in coherent positional state)



Enables **loss detection**
and now retain the atom*

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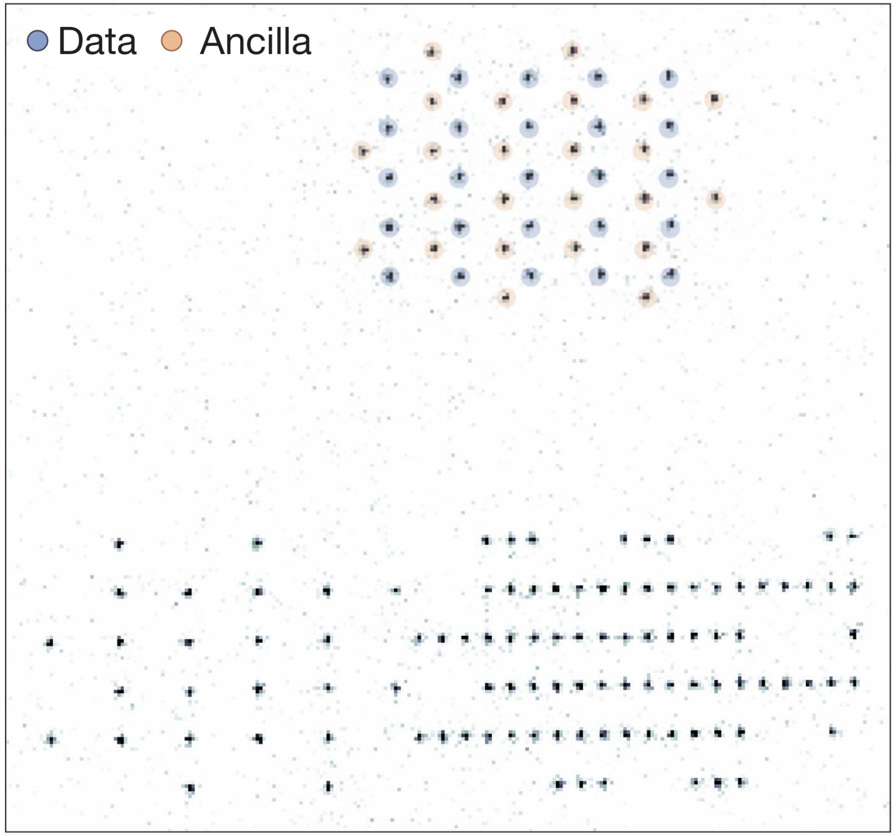
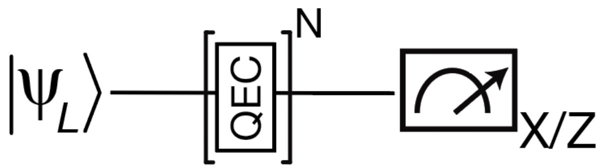
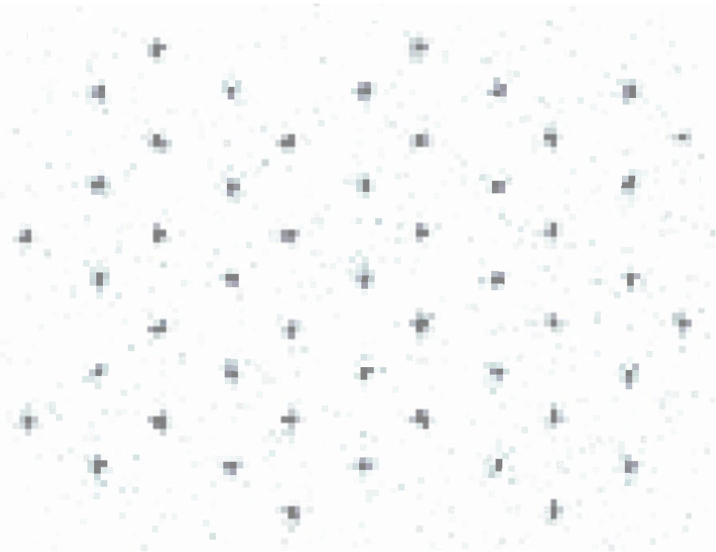
Repeated QEC with the surface code



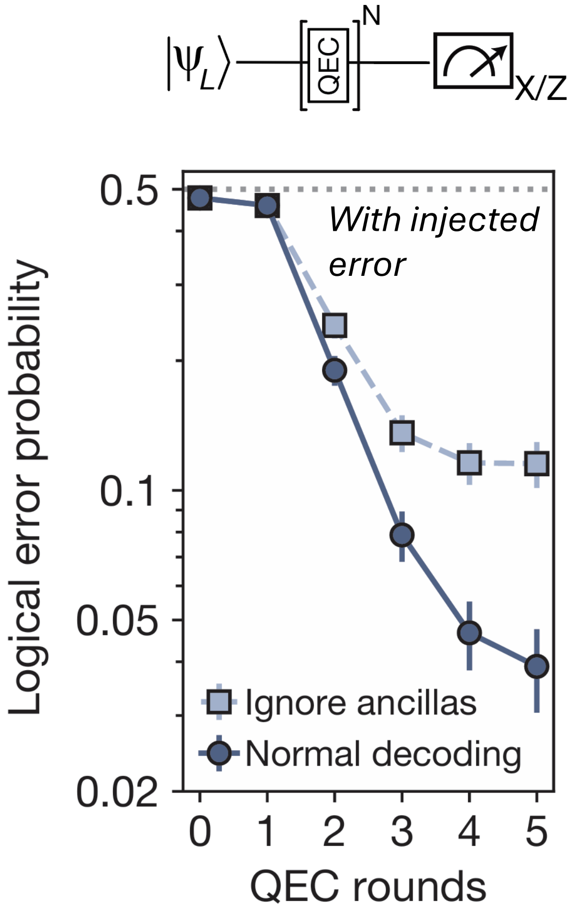
d=5 surface code w/ five ancilla blocks

Up to 5 rounds of QEC



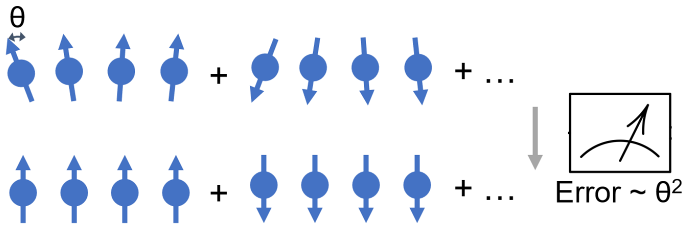


Role of repeated QEC

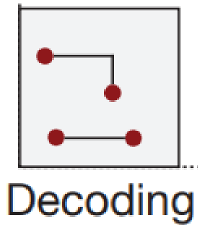


Two mechanisms for suppressing error

(1) **Zeno** effect, projective measurement



(2) **Tracking** errors, removing entropy

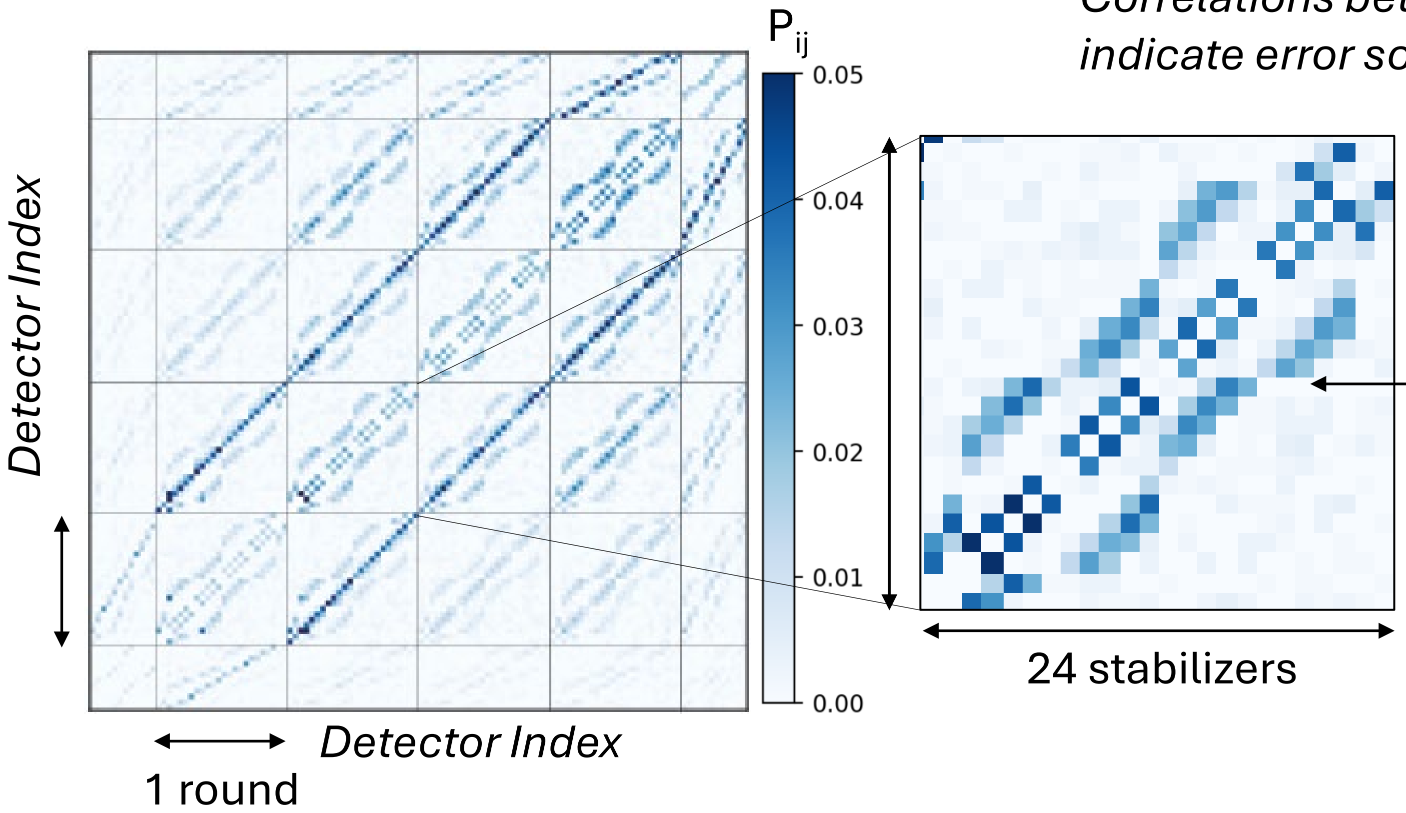


Note – no physical qubit corrections needed for universal computation as Pauli's tracked in software

Effect of loss in repeated QEC

5 rounds repeated QEC
P_{ij} matrix (correlation b.w. detectors)

Correlations between stabilizers indicate error sources



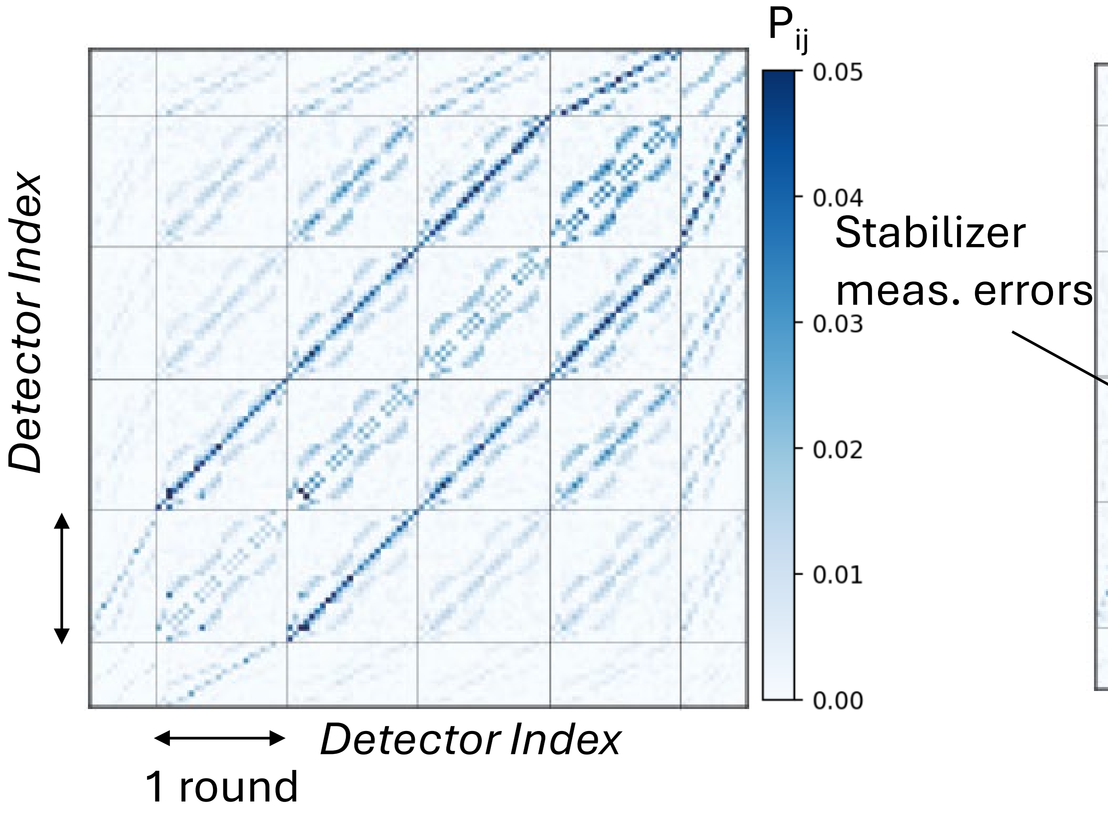
Physical qubit errors lead to correlations between adjacent stabilizers / detectors (space-like correlations)

Detector effectively = stabilizer
“Flags” if an error occurred (product of stabilizers)

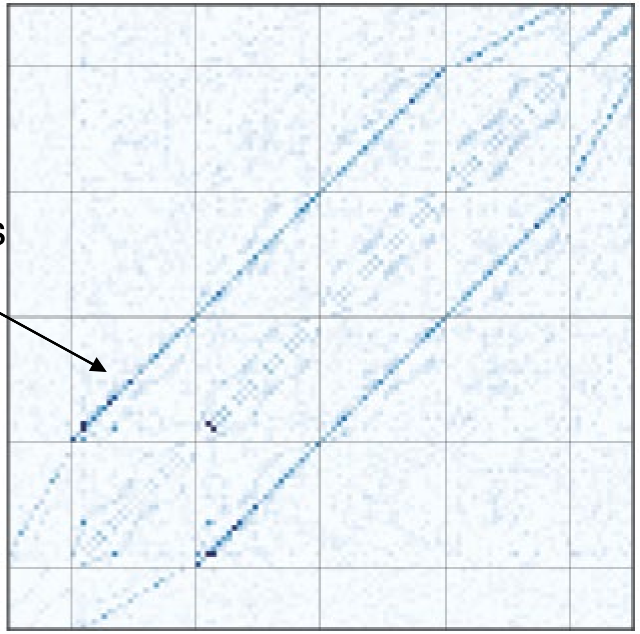
Building off foundational work in repeated QEC from superconducting qubit community

Effect of loss in repeated QEC

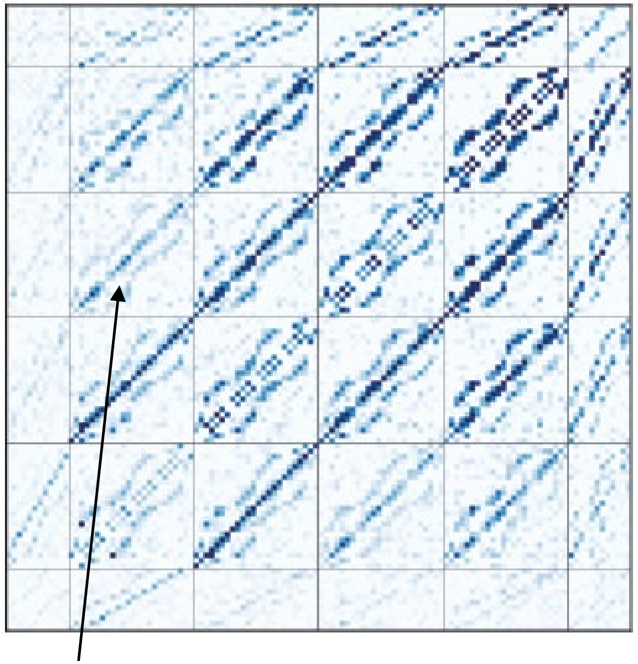
5 rounds repeated QEC
P_{ij} matrix (correlation b.w. detectors)



5% of shots with least loss



5% of shots with most loss



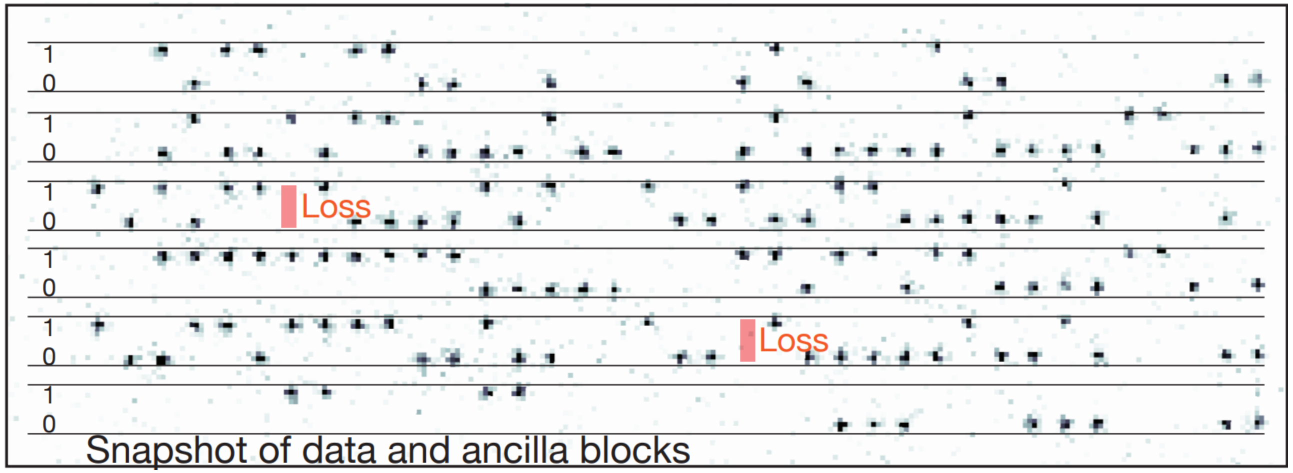
Significant time-like correlations between detectors ...

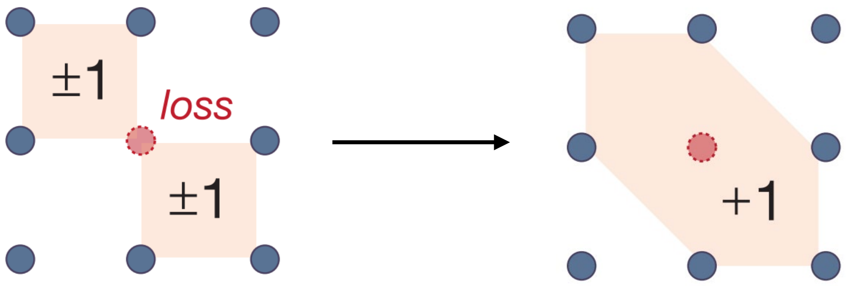
Atom loss plays a major role in neutral atom repeated QEC *(dominant source is 2Q gate loss error)*

Long theoretically predicted "blinking" pattern from lost qubit, resulting in subsystem code behavior. See e.g. Kribs et al PRL 2005

Loss detection in repeated QEC

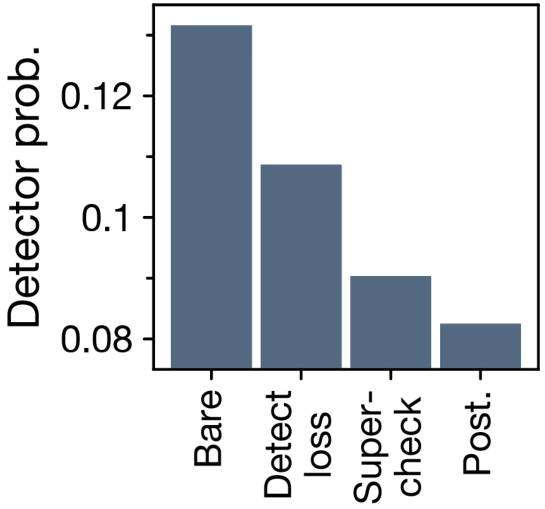
d=5 surface code with 4 rounds of stabilizer measurement

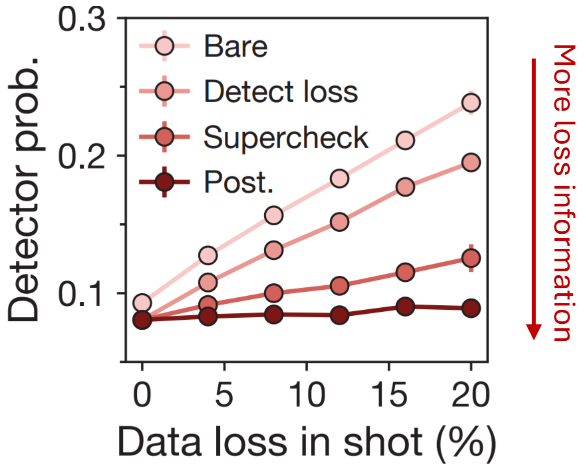




Superchecks: *recover information from anti-commuting stabilizers for decoding*

- **Detectors** compare stabilizer measurements between rounds → flag errors
- Loss info. reduces unknown errors (info of error *location*)

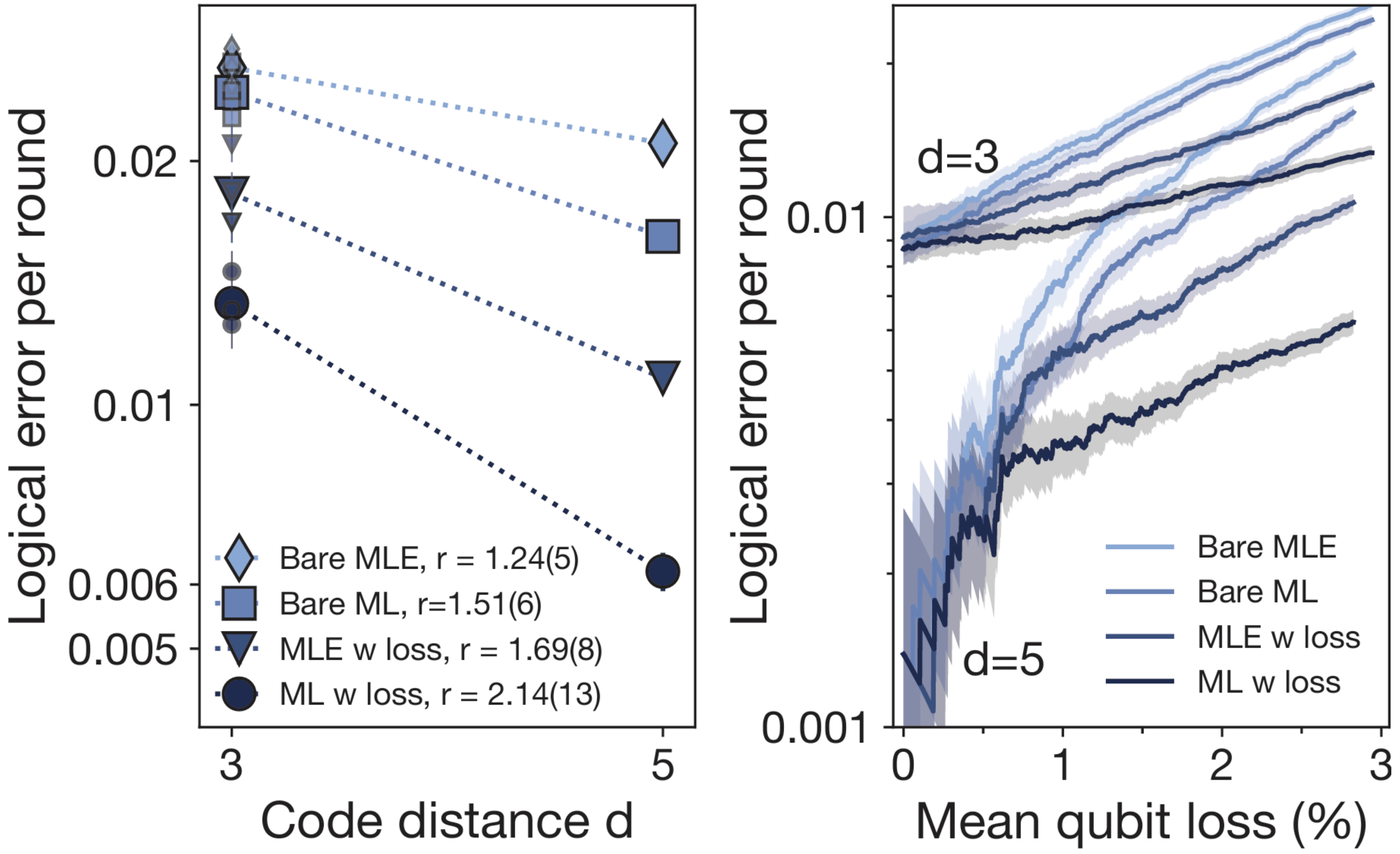




Erasure ideas: *Jeff Thompson, Shruti Puri. See also experiments by Endres and superconducting qubit community.*

Theory: *Stace et al PRL 2009, Baranes, Cain, et al arXiv: 2502.20558. Also Chow et al arXiv:2405.10434, Yu et al arXiv:2411.04664*

Repeated QEC below threshold using loss detection



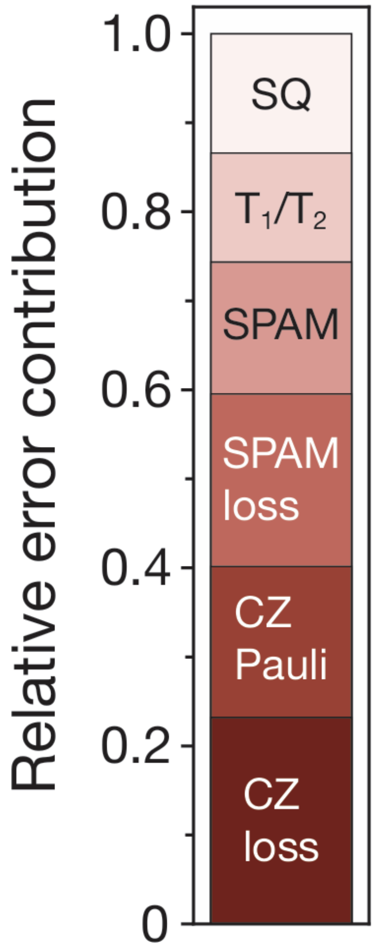
- **Most-likely error (MLE)** decoder, using experiment error model with loss information
- **Machine learning (ML)** decoder trained on simulation and experiment
- **2.14(13)x** below threshold for this specific characterization circuit
  - ~10% reduction w/ transversal gates and correlated decoding
  - ~15% reduction in infinite depth limit

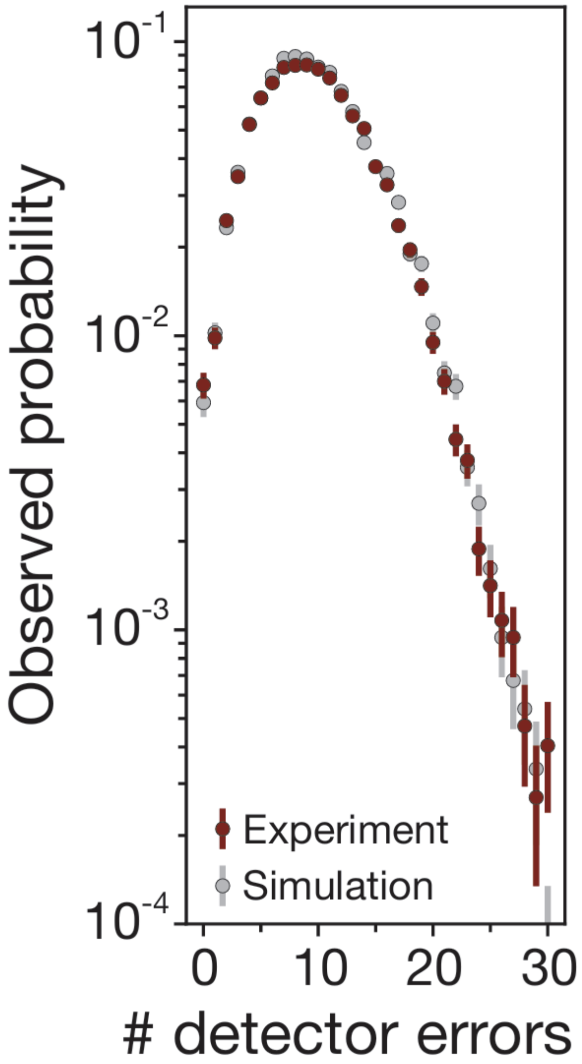
Comparable performance to Google Nature 2024 (but fewer rounds)

Major decoding effort!

ML decoding is extremely useful and currently *~4-5 orders of magnitude* faster than algorithmic decoders
See e.g., also Melko, Google, many others …

Repeated QEC below threshold using loss detection





- Error distribution agrees with simple simulations
- Small correlated error between gates in benchmarking not present in circuits
  - Due to decay to adjacent Rydberg P states
  - ~400us between gates removes correlations
- Leakage strongly dominated by loss. Captured with lattice (delayed erasure).
- ~2x below threshold, desire at least ~5x.
  - Fix single-qubit “bugs”
  - Improve 2Q gate with increased laser power + calibration

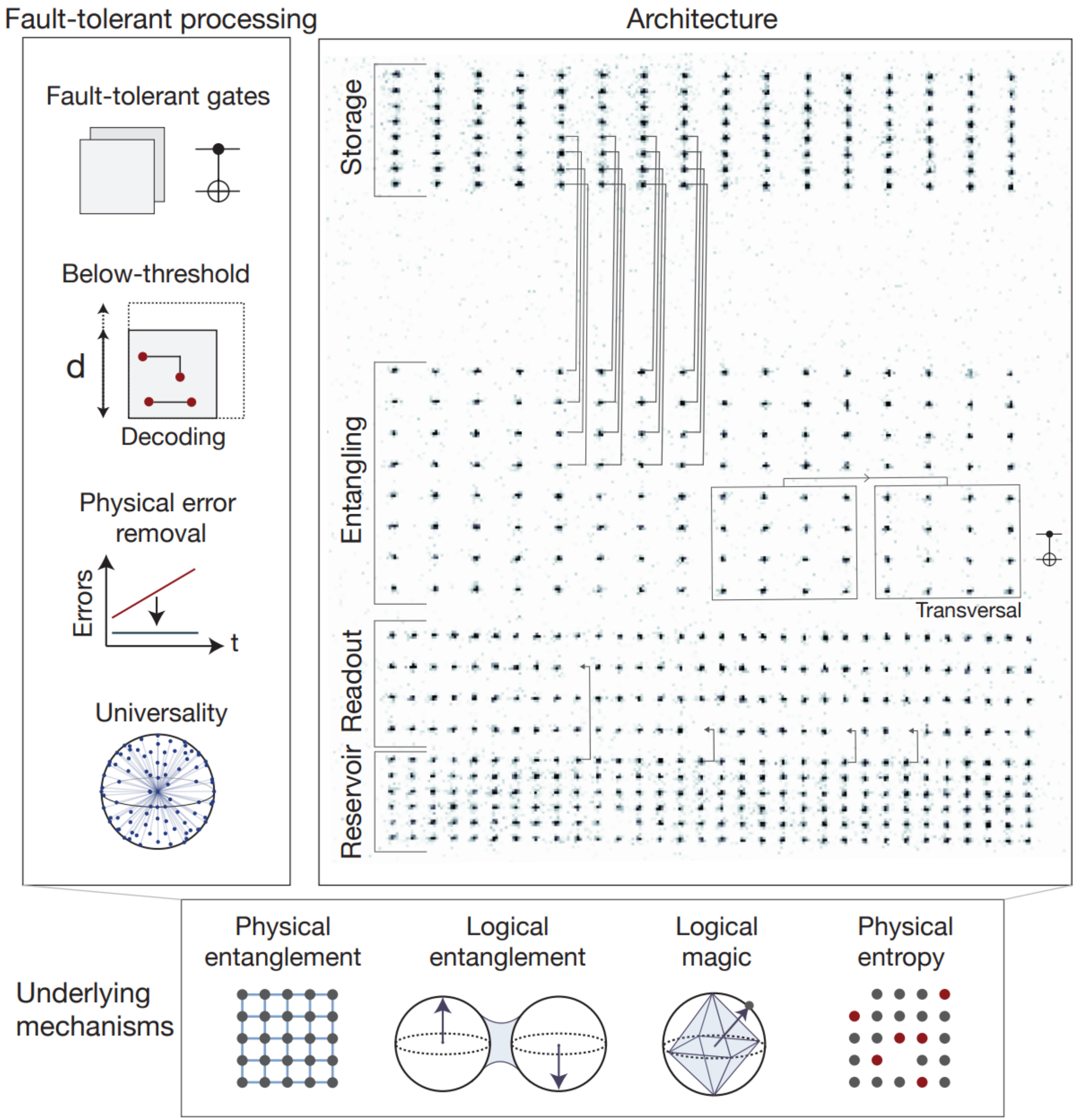
This talk

1. Entropy removal and below-threshold performance

2. Stabilizer measurement in logic operations

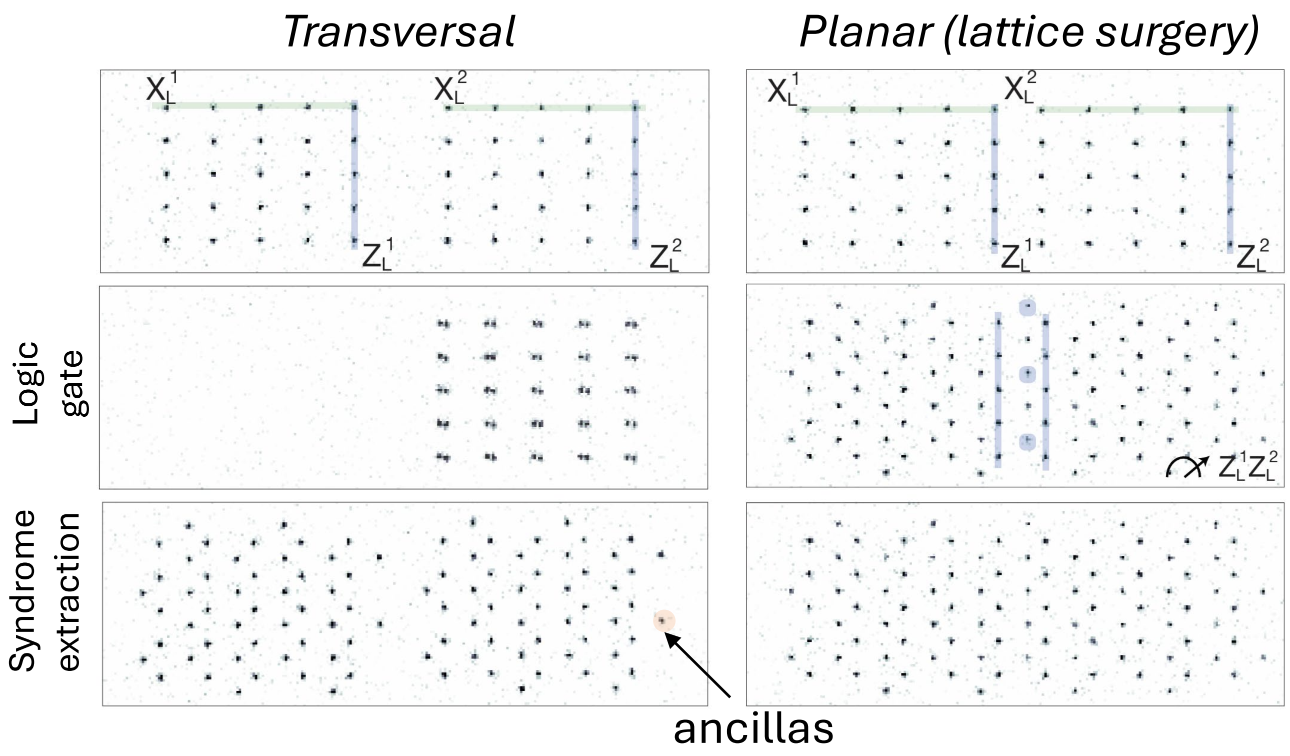
3. Universality with discrete gates

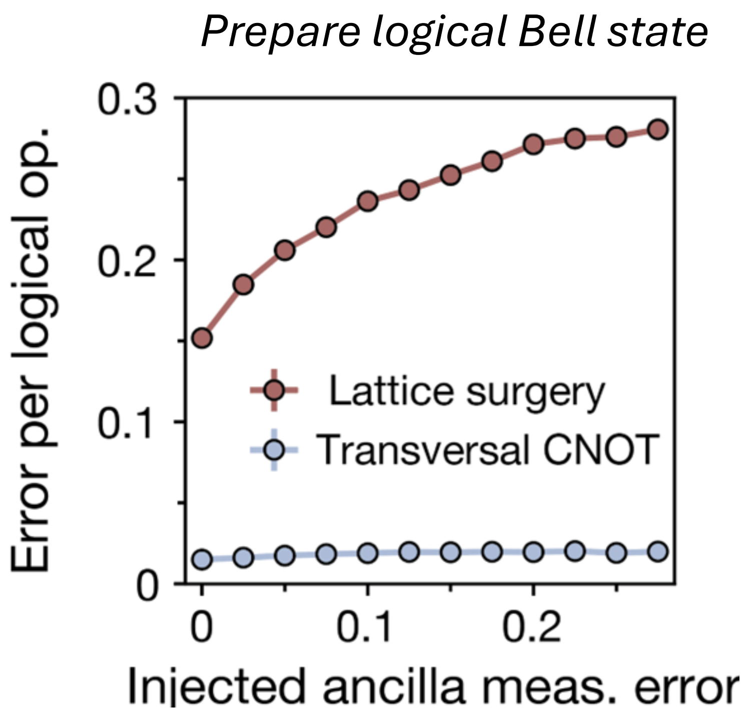
4. Architecture for deep circuit computation



Bluvstein*, AAG* *et al.* (*Nature*, 2025)

Role of stabilizer measurement in logic operations





Logic gates realized *directly* between data qubits

Stabilizer measurements *remove entropy from data qubits*

→Measurement errors benign

Logic gates realized *via ancilla stabilizer measurements*

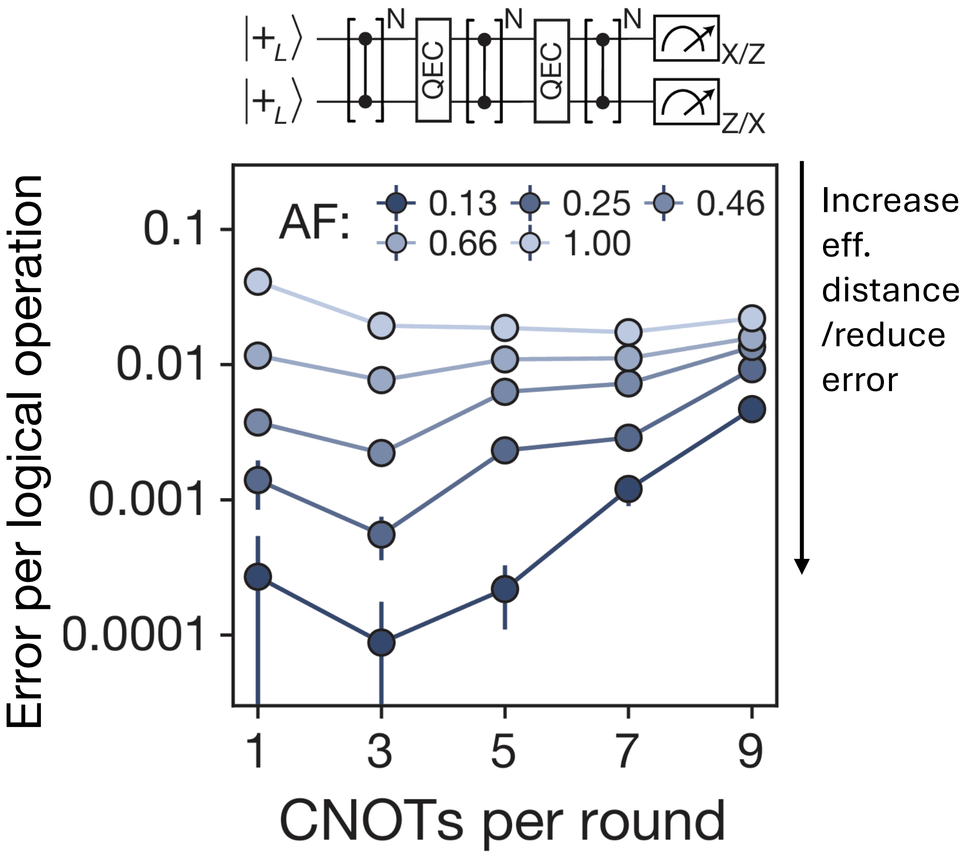
Stabilizer measurements *performing logic as well as entropy removal*

→ Measurements must be correct: repeat d times for fault-tolerance

Transversal setting:

Only needed to balance rate of entropy creation + entropy removal

Balancing entropy removal with performing logic



Optimal is ~3 CNOTs per round, consistent with theoretical predictions
Cain … Bluvstein, Lukin, arXiv:2403.03272, Zhou*, Zhao*, Cain, Bluvstein et al arXiv: 2406.17653

Continued experiment <-> theory insights: decode *logical stabilizer*, not individual logical qubits …
Cain*, Bluvstein*, Zhao*,…AAG,…Zhou arXiv:2505.13587

"Logical gate fidelity" is not a single number: depends on the *internal entropy* (~density of errors)

By leveraging efficient transversal gates + correlated decoding, reduce required QEC rounds from *O(d)* to *O(1)* *(~10-100x speed-up for large scale computation)*

This talk

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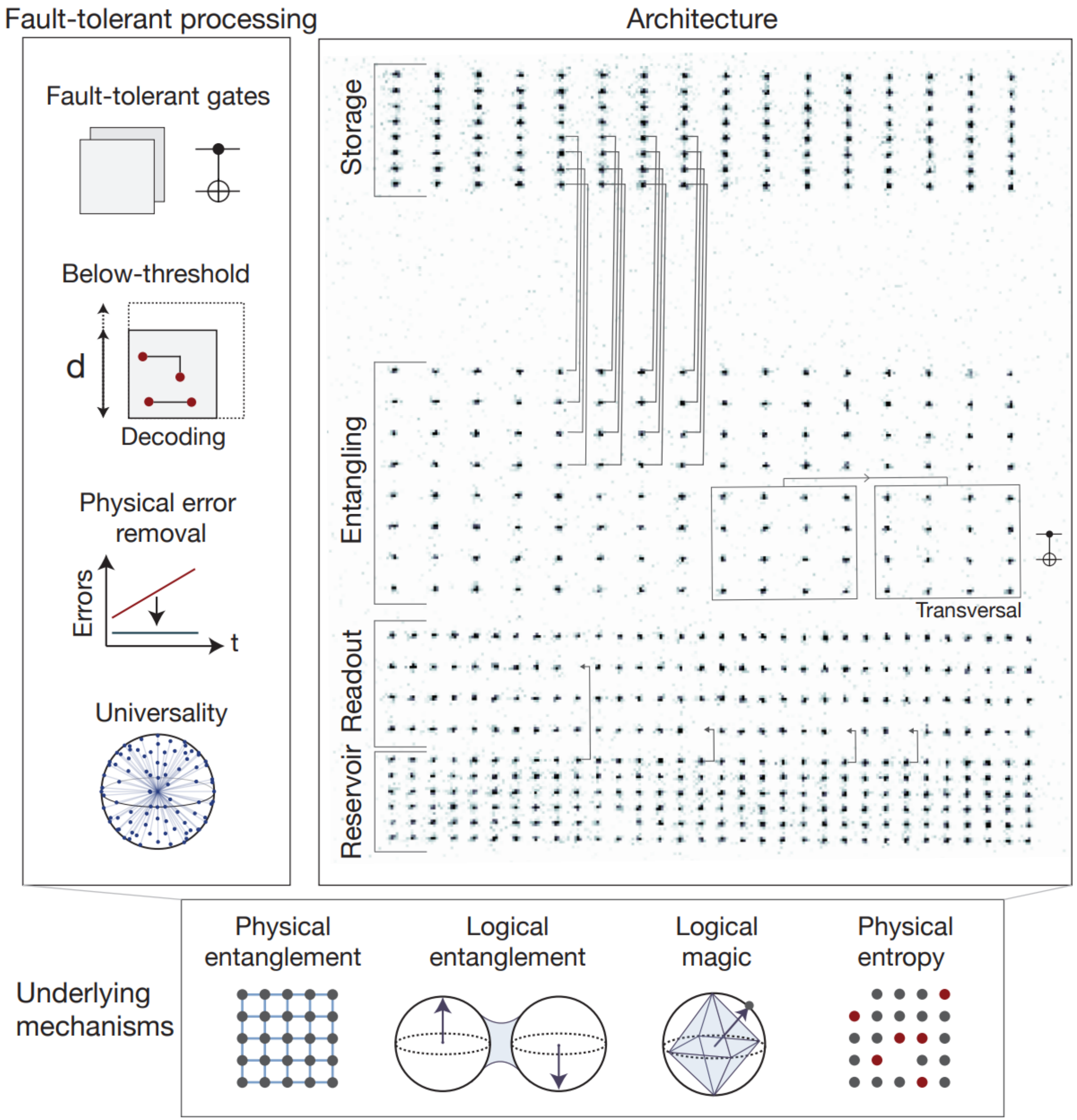


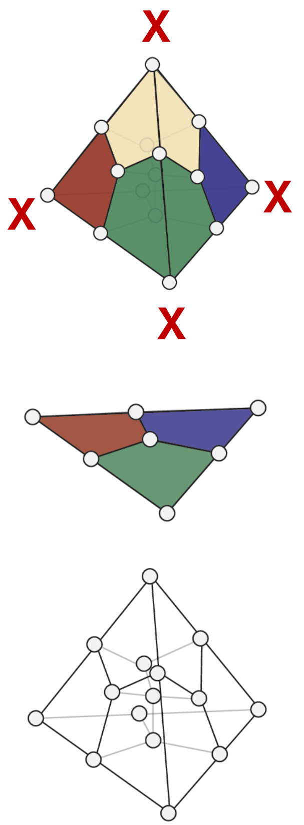
Bluvstein*, AAG* *et al.* (*Nature*, 2025)

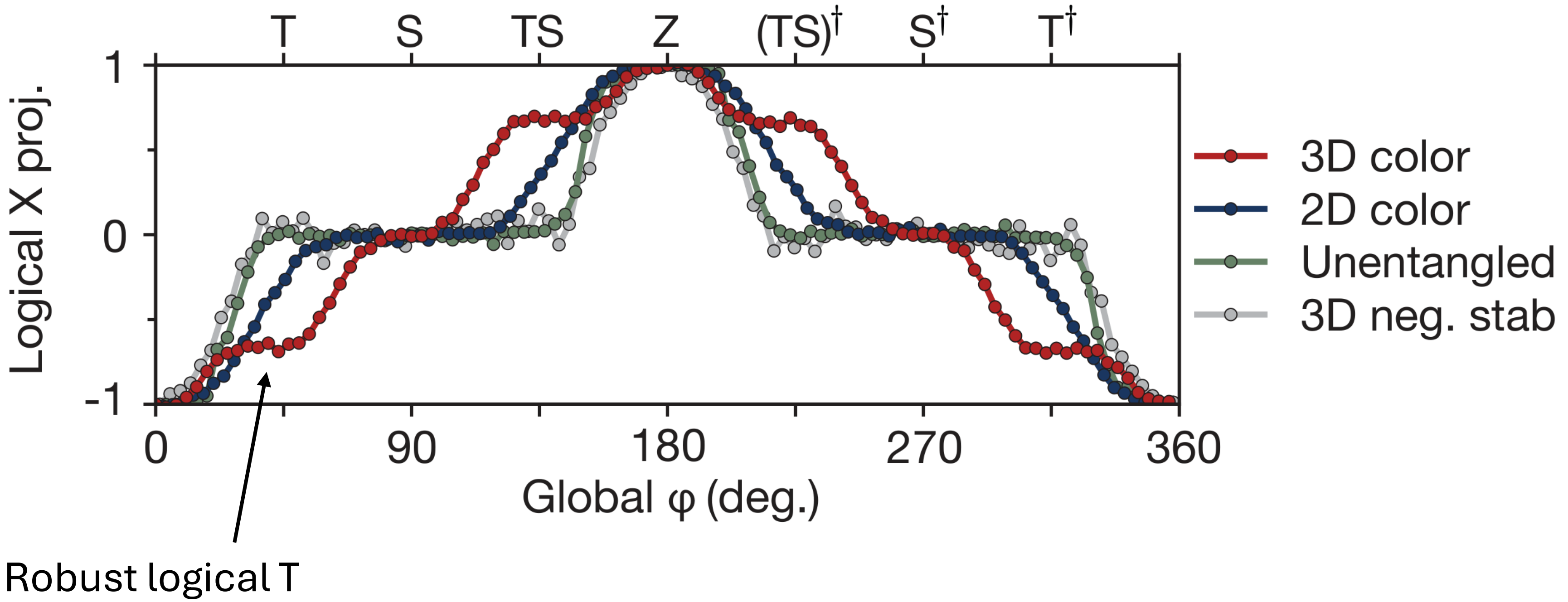
Mechanisms for universality

Eastin-Knill "no-go" theorem: single code cannot have a transversal universal gate set

→ Need *teleportation* between codes for universality

3D Reed-Muller code [[15,1,3]] has transversal T (45-degree rotation)

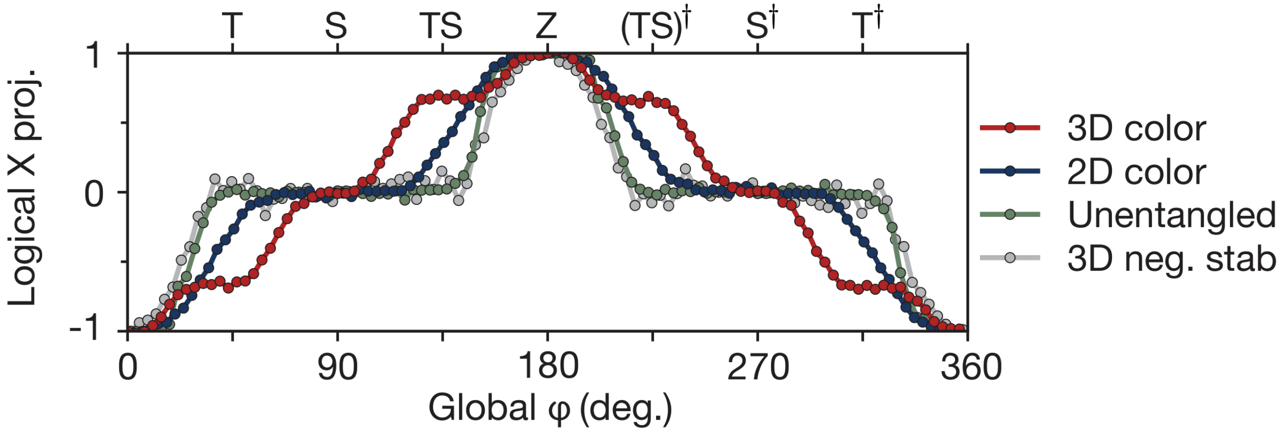


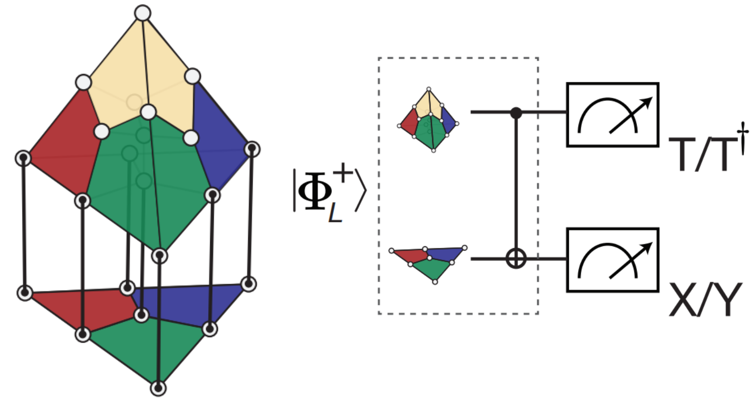


Correct *physical entanglement* structure, i.e., +1 stabilizer signs now *necessary* for logic (cannot just track)

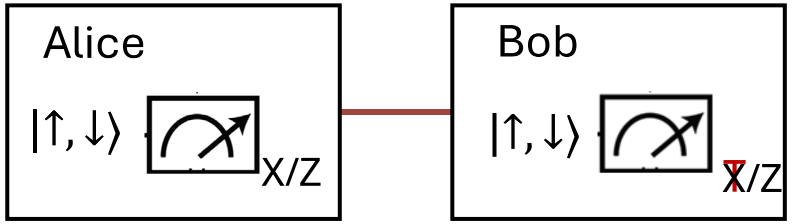
Link between physical entanglement and logical magic

Unlike transversal Clifford circuits, physical entanglement is *required* for logical magic



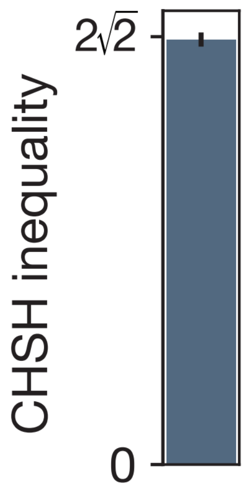


Error-corrected Bell test



Bell test requires T basis
→requires entanglement for QEC

Saturates quantum bound

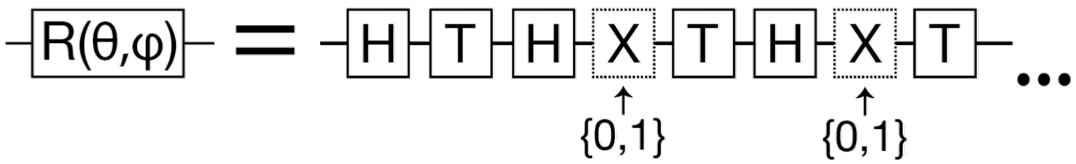


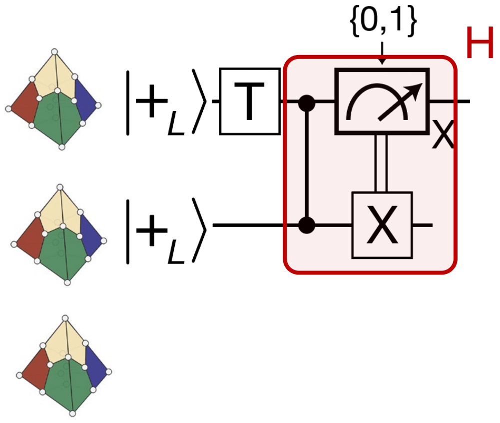
- Computational hardness <-> need for physical entanglement
- Measurement of 3D code underpins logical non-Clifford
- Teleport into circuit (code switching, T factories,...)

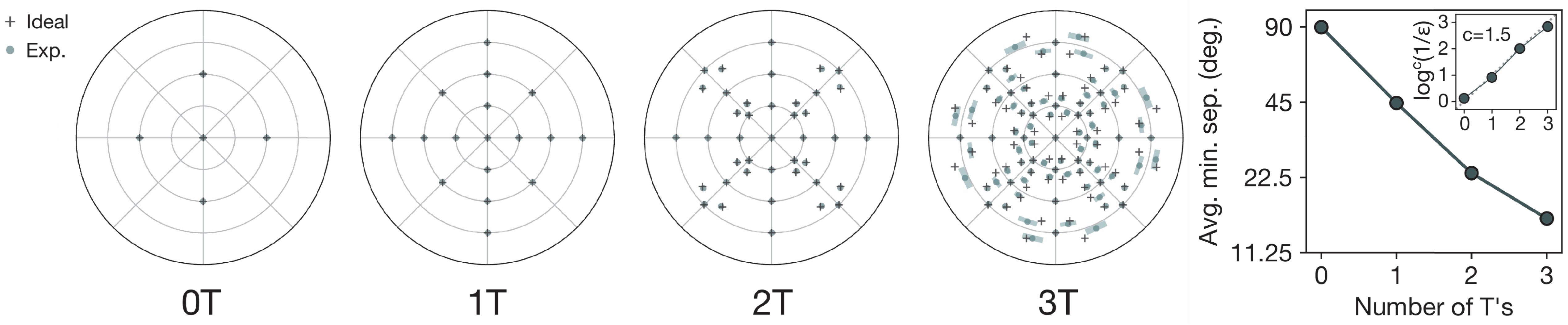
Universality through measurement

With transversal gates, transversal teleportation is a key algorithmic primitive

Solovay-Kitaev theorem: arbitrary angles with polylogarithmic overhead







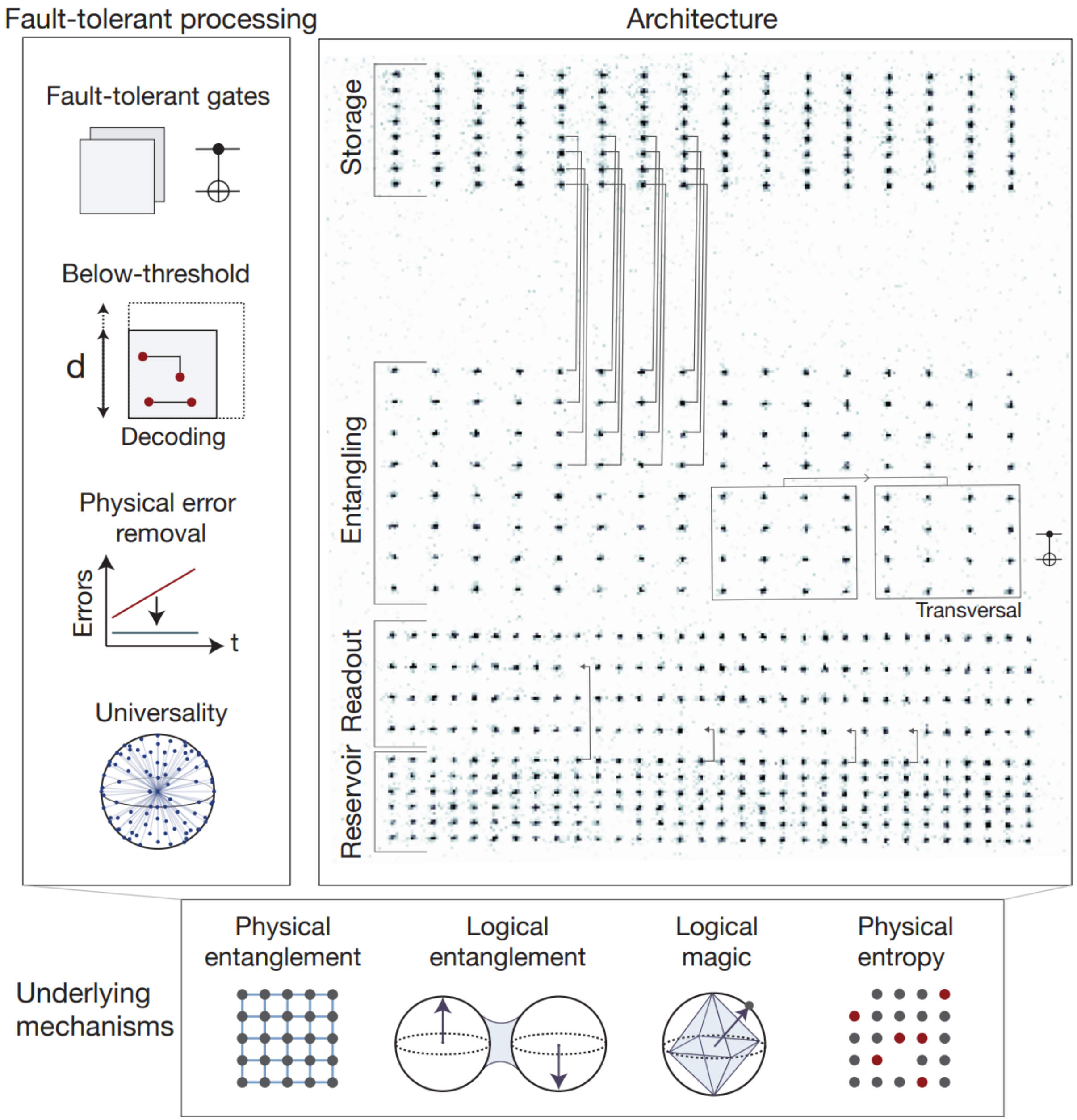
This talk

1. Entropy removal and below-threshold performance

2. Stabilizer measurement in logic operations

3. Universality with discrete gates

4. Architecture for deep circuit computation



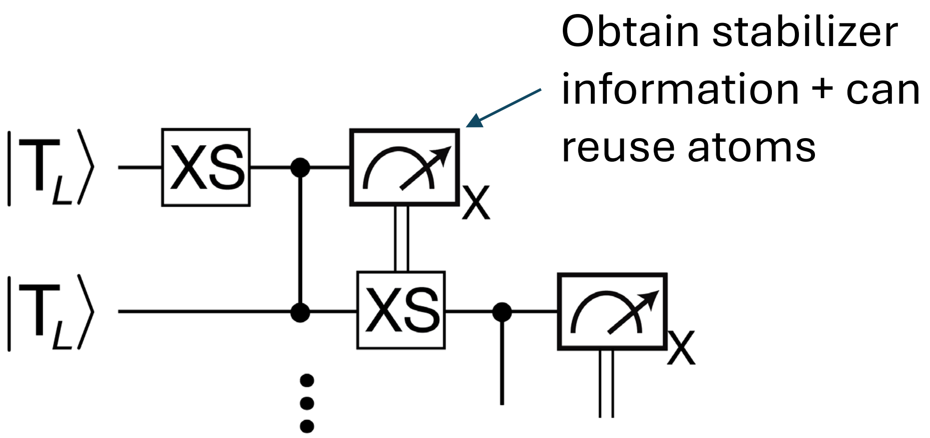
Bluvstein*, AAG* *et al.* (*Nature*, 2025)

Leveraging teleportation for entropy removal

Need to remove *all types* of entropy for deep computations

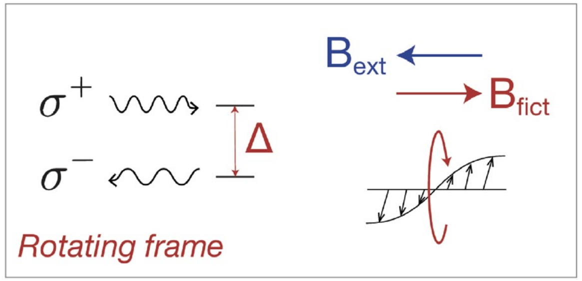
(1) Physical qubit state (X and Z errors)   (2) Atomic state (motional state, loss, leakage)

Algorithm level:
Teleportation natively accomplishes physical qubit reset

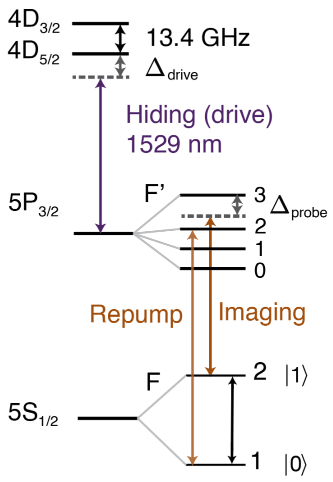


Hardware level: AMO tools for deep circuits

Local cooling + imaging in finite B-field



1529-nm shielding to preserve coherence during imaging

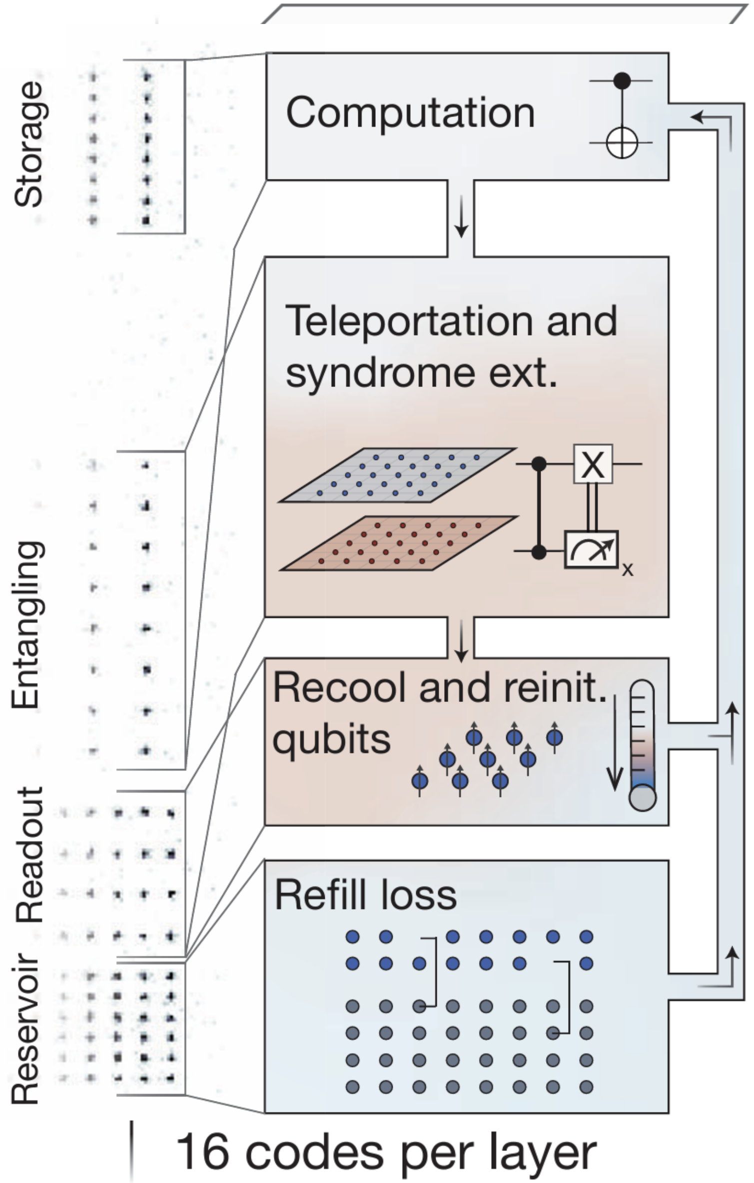


→ Enable steady state operation

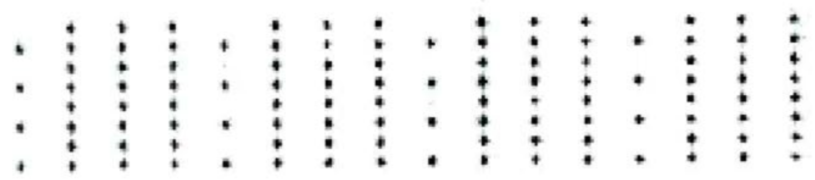
Chow *et al*. arXiv:2312.06438 (EIT cooling), Hu *et al.* arXiv:2408.15329 (1529-nm shielding)

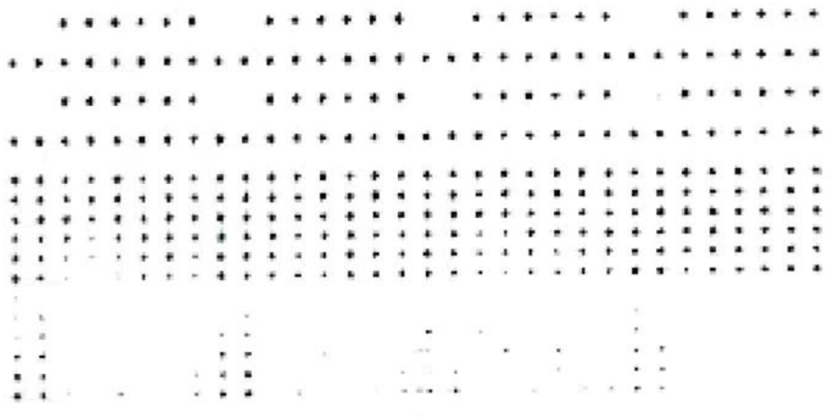
Leveraging teleportation for entropy removal

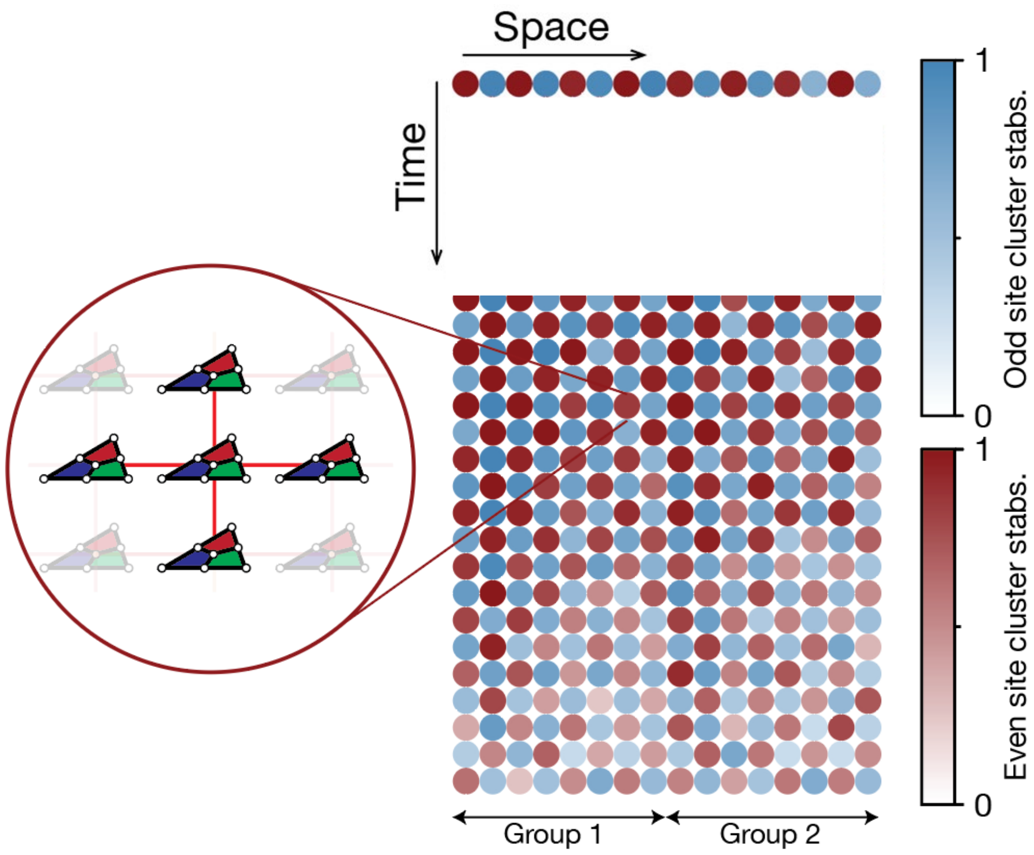
"Fridge" to remove entropy from computation



One A-B teleportation layer to make a 2D logical cluster state

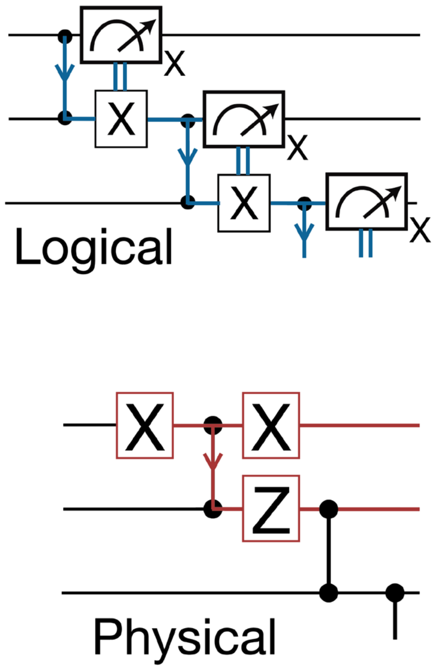


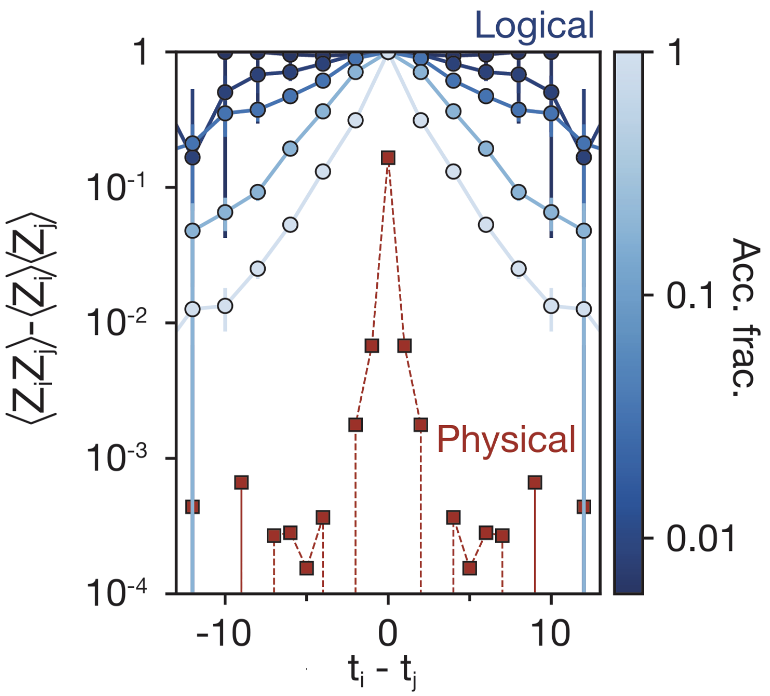


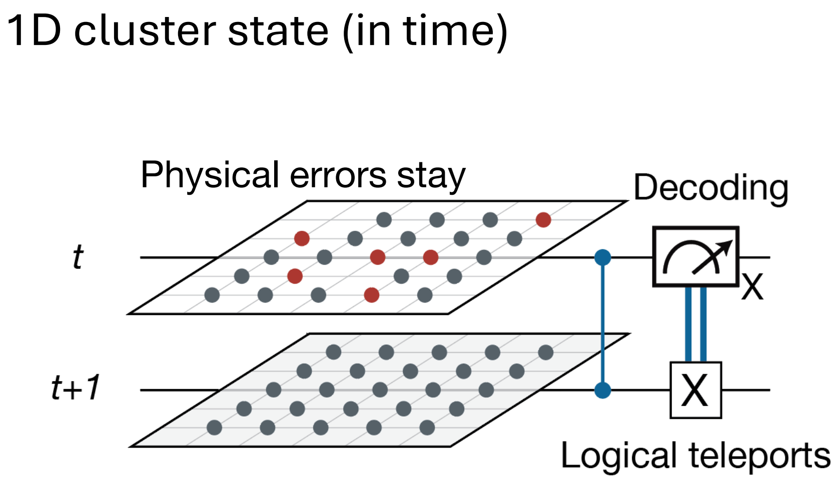


Experimental 2D cluster state stabilizers with Steane codes

Deep circuits via logical teleportations







Unitary evolution on logical level via teleportation
Algorithm leads to correlations

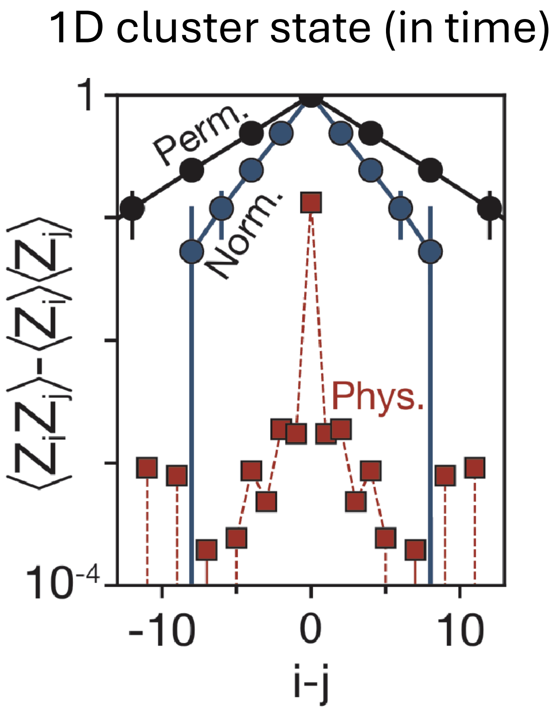
Dissipation on physical level by measurement
Stabilizer errors quickly dissipated and correlations rapidly decay

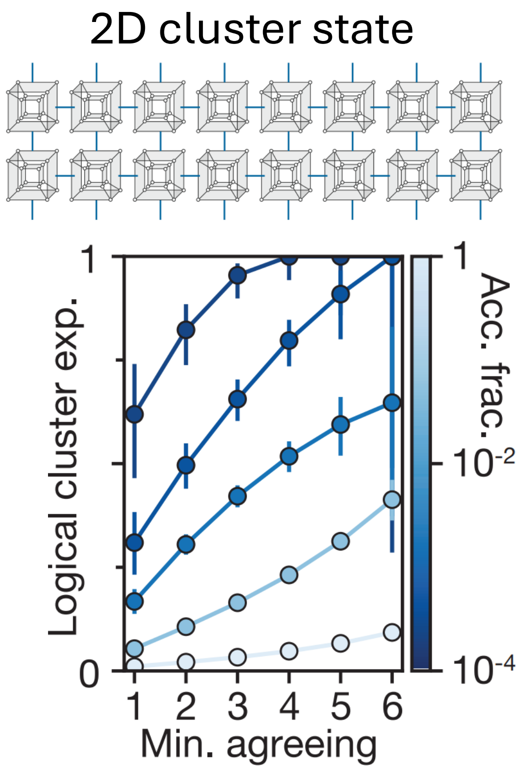
Teleportation enables:

- **Universality** with transversal gates
- Native **removal** of all types of **entropy**
- Simple and very general approach

Exploring deep circuits with logical teleportations

Teleportation is independent of the details of the code → extend to *high-rate codes*





Using [[16,6,4]] (part of quantum Reed-Muller code family)

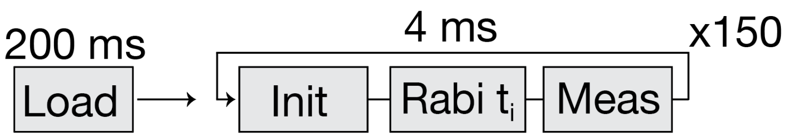
Physical entanglement inherent to high-rate codes enables **new types operations**:

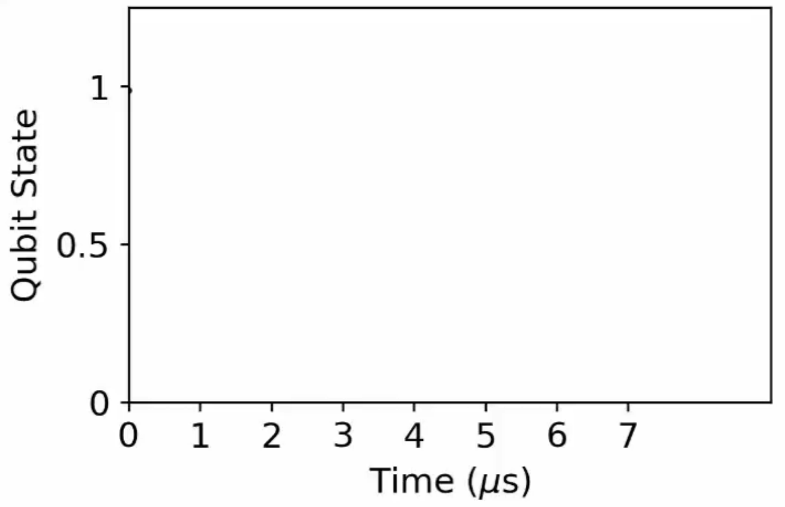
- *Permutations* within a code block performs *logical CNOT* → redistribute in-block entanglement
- Operators supported on the same physical qubits → leverage correlations for error detection

All using ML decoding which we find is very practical for such near-term algorithms see e.g., Bonilla Ataides*, Gu* *arXiv* 2509.11370.
Theory + exp. on permutation CNOTs: Quantinuum *arXiv* 2404.02280 and *arXiv* 2409.04628; Koh *et al.* *arXiv* 2601.20927;

Outlook: qubit re-use for fast calibrations

Qubit reuse enables fast calibration, including 1Q and 2Q gates

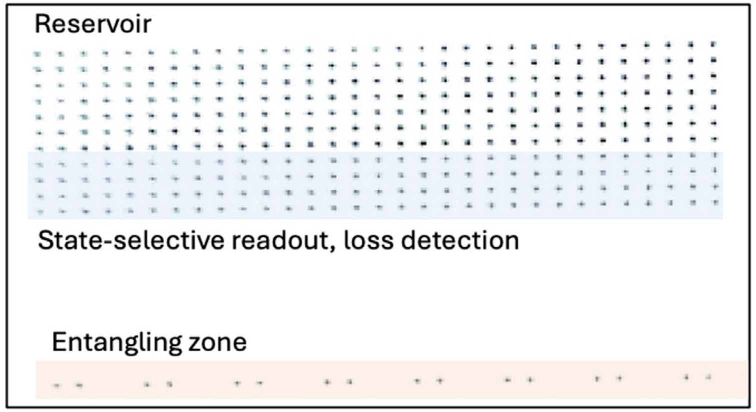


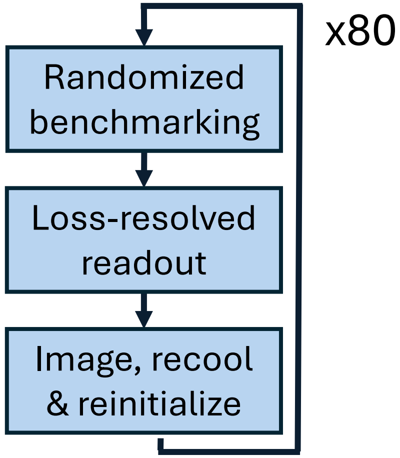


Real time!

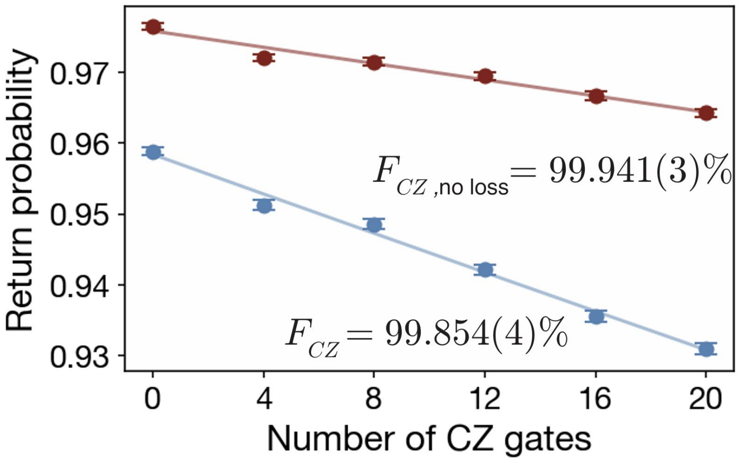
~200Hz cycle rate for Rabi oscillations
(here using global imaging)

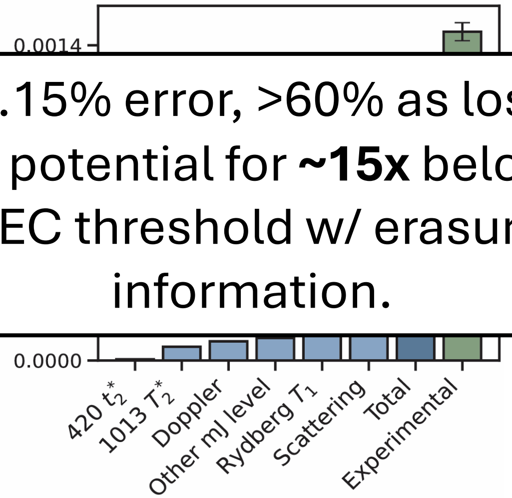
1D zone enables exploring high Rabi frequency gates; ~30 Hz cycle rate





Preliminary, raw fidelity: 99.85%
Loss postselected: 99.94%





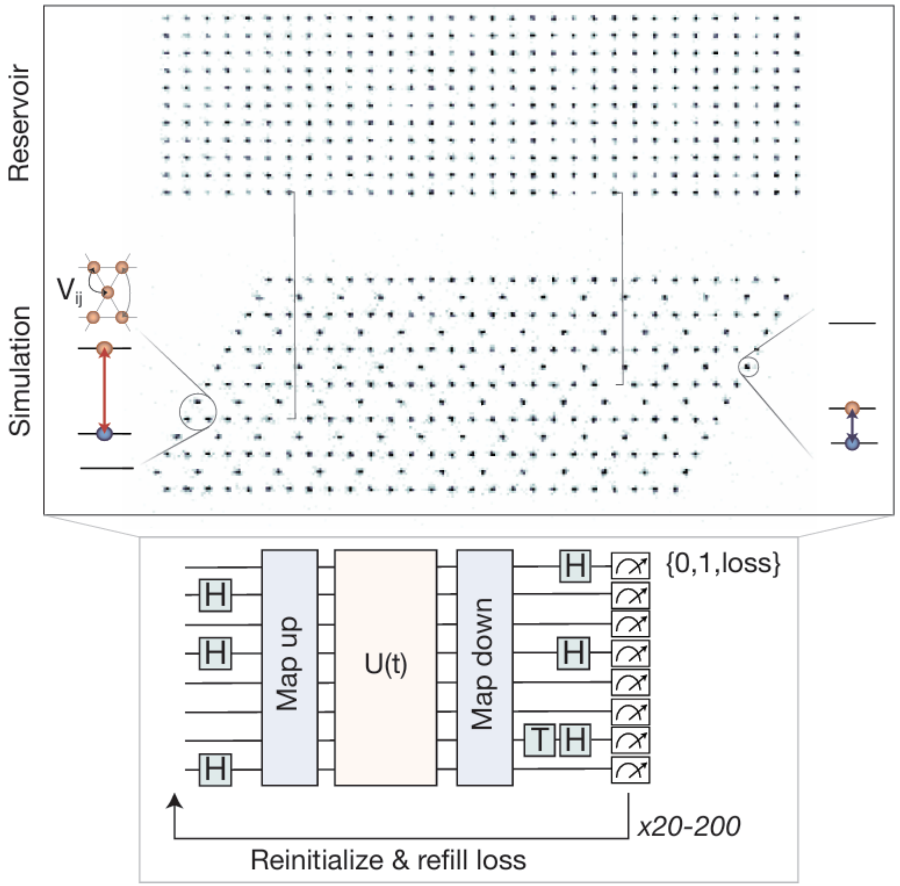
~0.15% error, >60% as loss → potential for **~15x** below QEC threshold w/ erasure information.

Evered*, Xu*, Li*, AAG et al., in prep

Previous state-of-the-art: 99.71(5)% with Sr from Endres group at Caltech. Related work at Princeton, MPQ, JILA, Infleqtion, Atom Computing, ...

Outlook: qubit re-use for quantum simulation

Analog-digital simulations:
coherently map between hyperfine + Rydberg

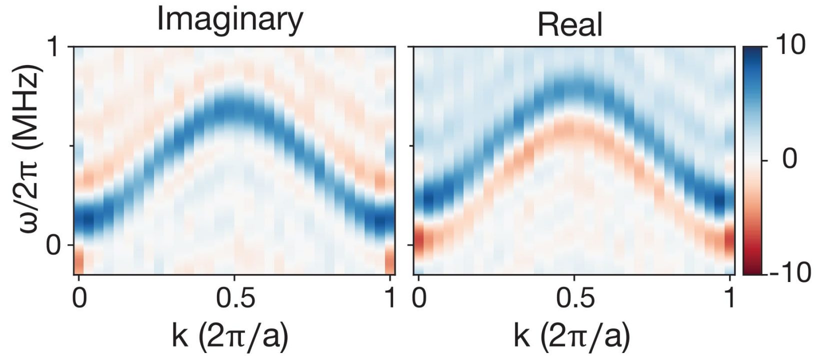


Rydberg qubit → interacting, many-body evolution

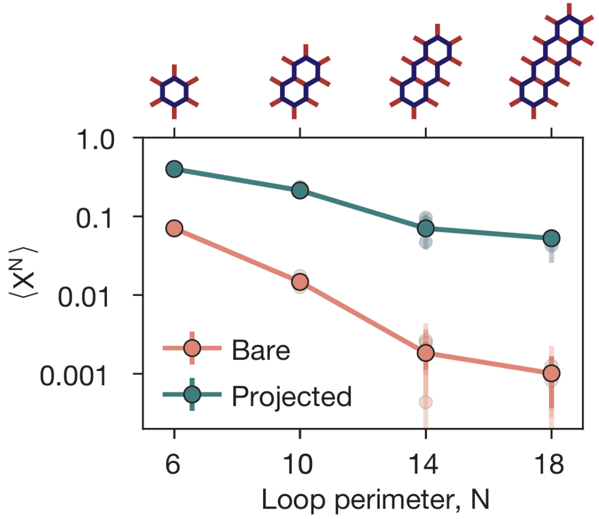
Hyperfine qubit → long-lived, high-fidelity 1Q/2Q gates

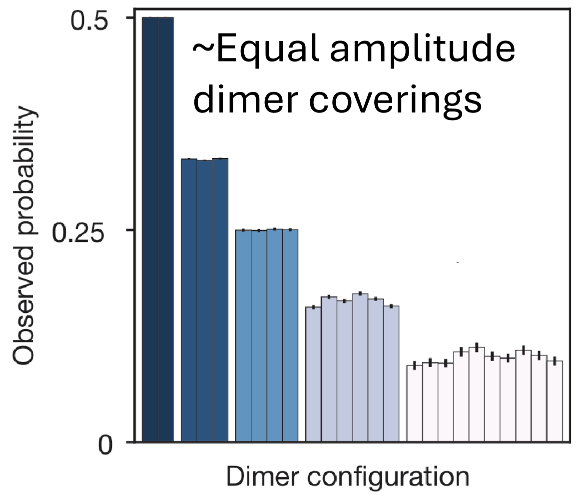
Floquet engineering

Here, engineer 1D hopping and probe low-energy excitations w/ digital gates



U(1) Rokhsar-Kivelson state (QSL)



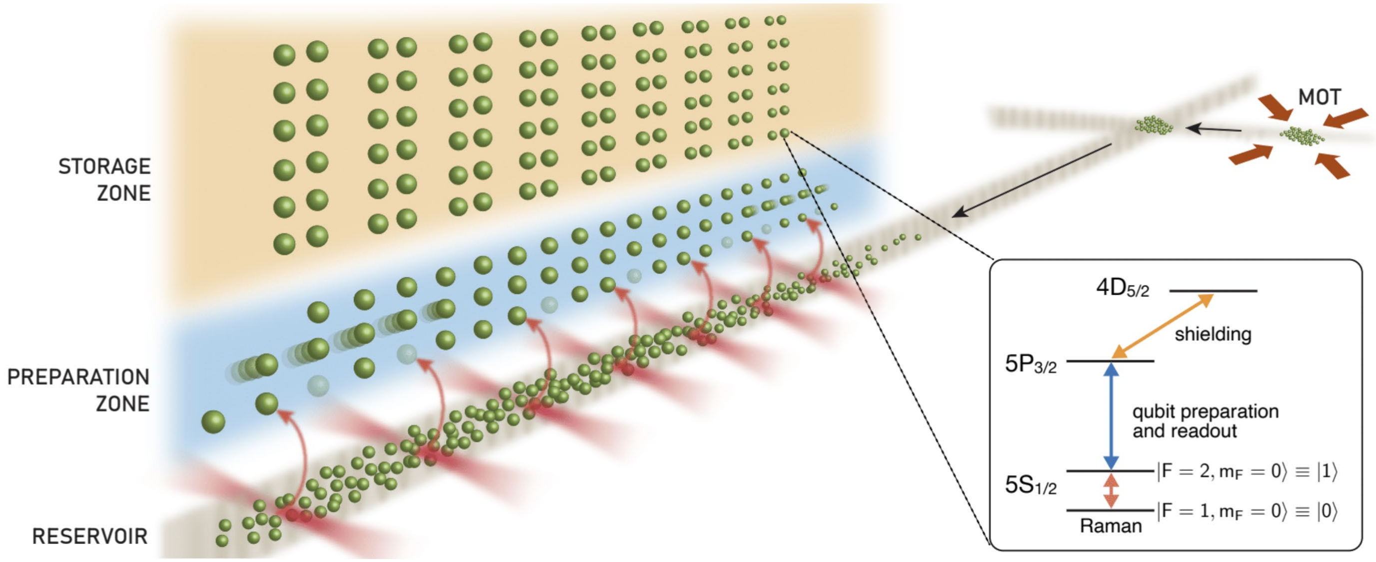


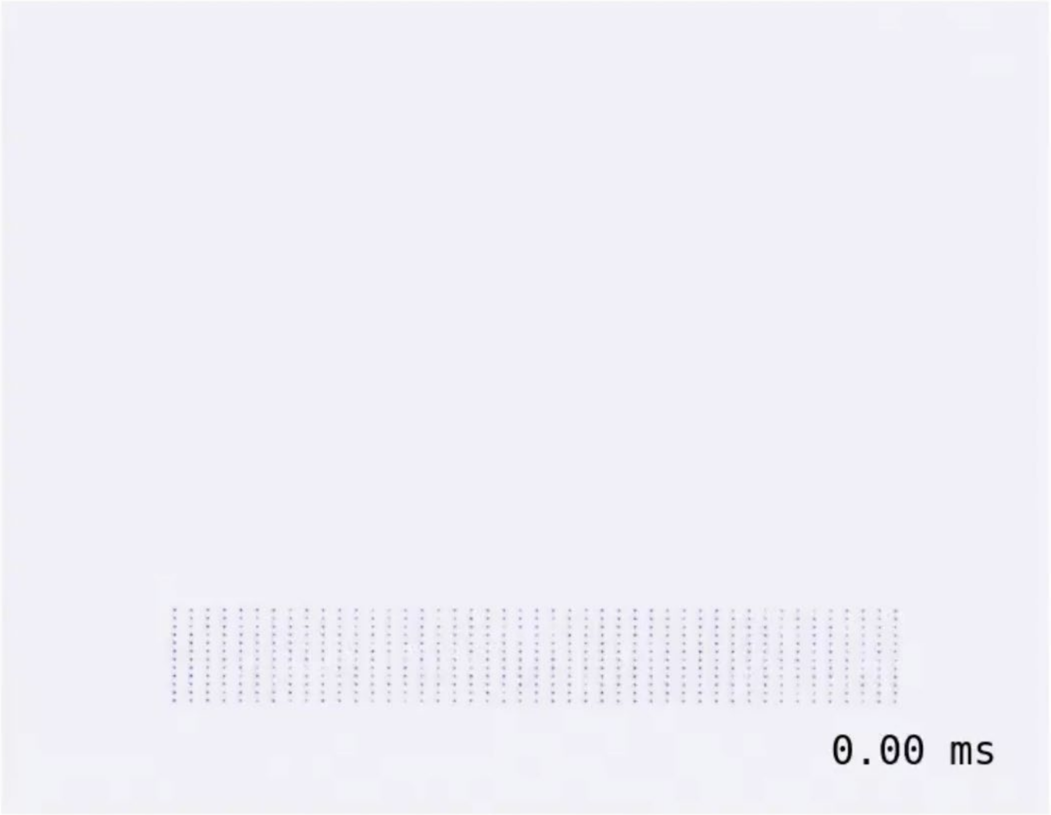
New ability to directly measure coherence & entanglement of complex many-body state

AAG *et al.* arXiv 2602.18555

Outlook: fast, continuous atomic physics experiments

Continuous operation with 3000 atoms
Atom Array II (Lukin group)

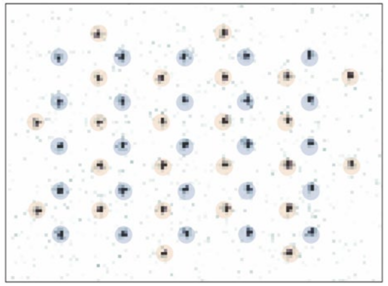




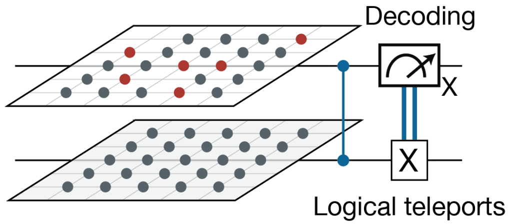
Exciting opportunities to leverage new AMO tools for large-scale, efficient QEC architectures!

Summary and outlook

Starting to explore **foundations of algorithms with QEC**:

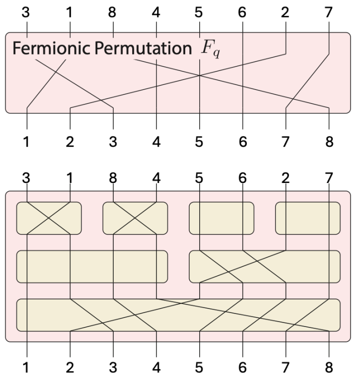


Interplay between quantum logic + entropy removal

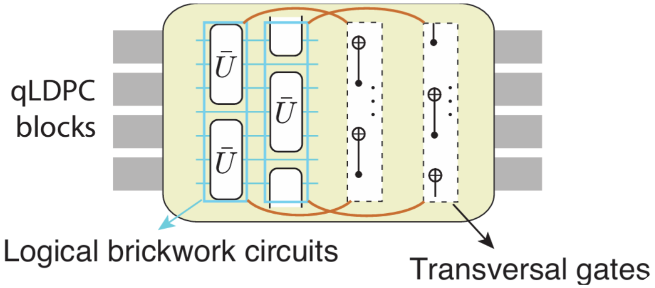


Teleportation for universality + physical qubit reset

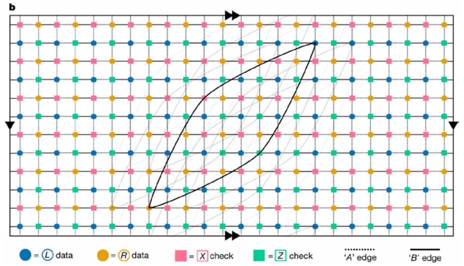
Developing **new approaches to circuit and code design:**



Maskara *et al*. arXiv 2509.08898;
Constantinides *et al*. arXiv 2510.05099



Xu *et al*. arXiv 2510.06159



Bravyi *et al*. Nature (2024)

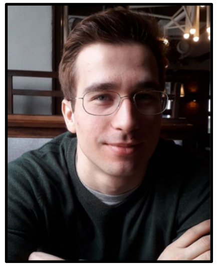
In the next few years, entering a regime of useful fault-tolerant computation:

- Error rates to achieve ~5-10x below-threshold performance
- Co-design of error-correcting codes, circuit compilation and hardware
- Continuous operation for deep circuits with 10-100k atoms
- Exploring new experimental platforms and controls (atomic species, qubit encodings, erasure, optical tools,...)

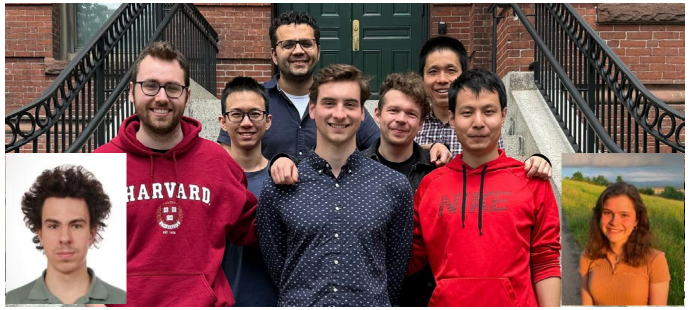
...and along the way learn techniques for quantum simulation, sensing, precision measurement,...

Muqing Xu, Simon Evered, Tom Manovitz, Dolev Bluvstein, AAG, Sophie Li

Marcin Kalinowski



Atom Array II: *Elias Trapp, Luke Stewart, Tim Guo, Simon Hollerith, Tout Wang, Allen Chiu, Mohamed Abobeih, Pavel Stroganov, Lisa Marie Peters, Xingjian Lyu*



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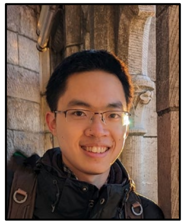
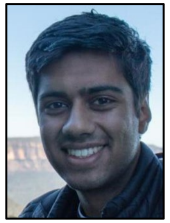


N. Maskara



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