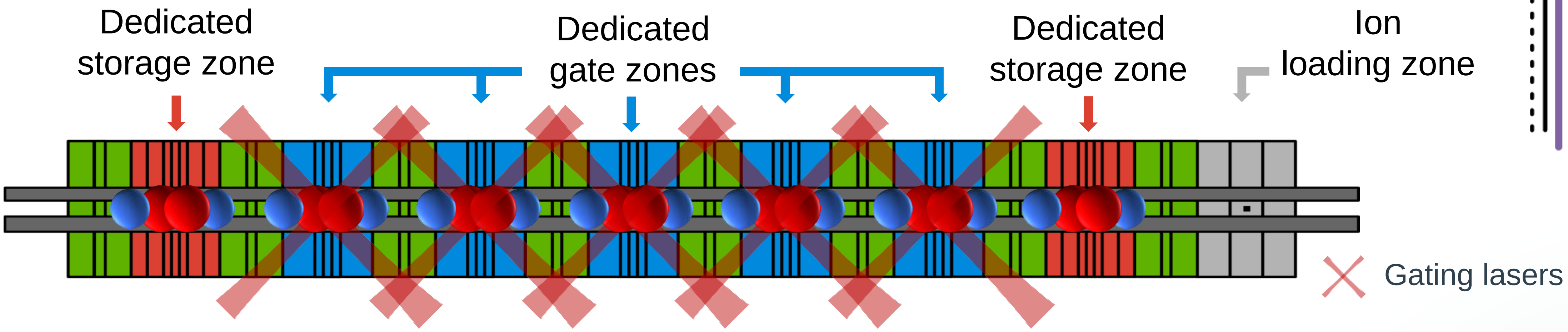
Scaling the QCCD Architecture for Trapped-Ion Quantum Computers

Presented by **Alistair Milne**

13th November 2024

QCCD Trapped-Ion Architecture

SYSTEM MODEL H1



H1 Generation Ion Trap Architecture

Quantum bits (qubits) are stored in the electronic states of identical Yb^{+} ions.

$^{171}Yb^{+}$ $|1\rangle$ $|0\rangle$ Hyperfine qubit

QCCD architecture enables using **gate zones**

- Single qubit gates, two qubit gates and state detection all performed using lasers

Cooling ions provide mid-circuit cooling, maintaining circuit fidelity throughout circuit.

$^{138}Ba^{+}$ Cooling ion

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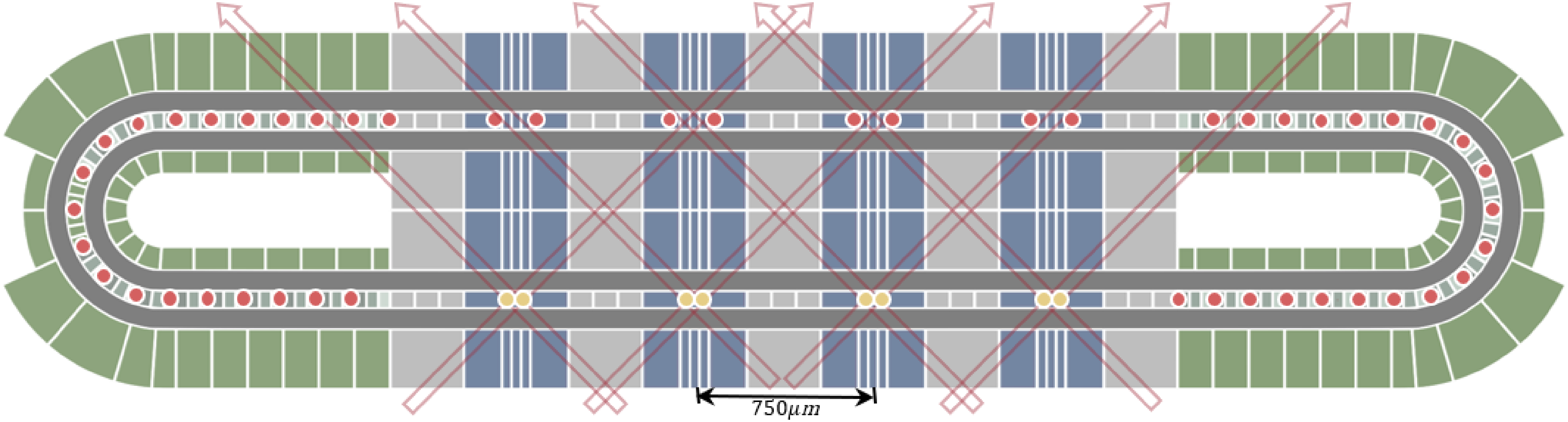
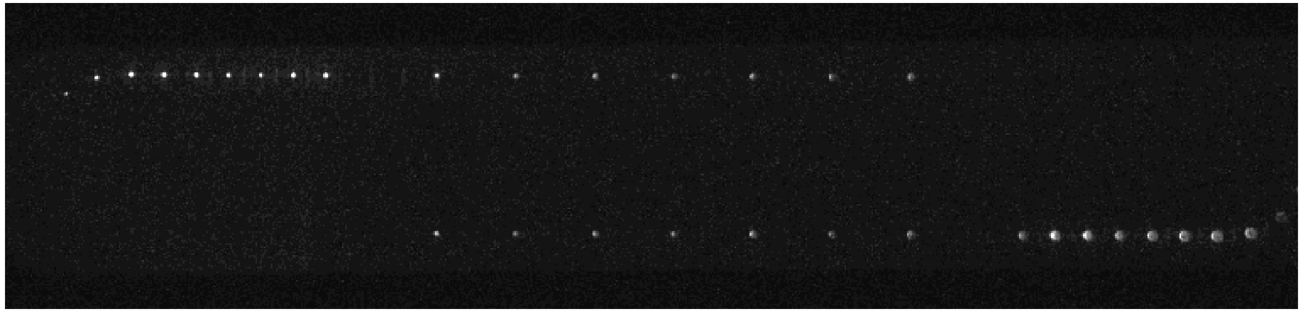
System Model H2: 56 qubit trapped-ion processor

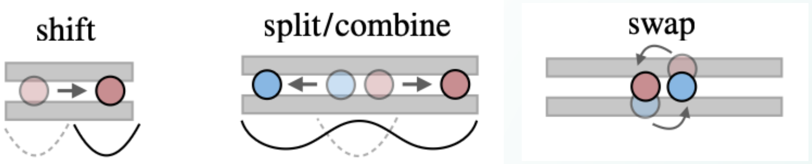




Shuttling qubits around the trap

Transport primitives

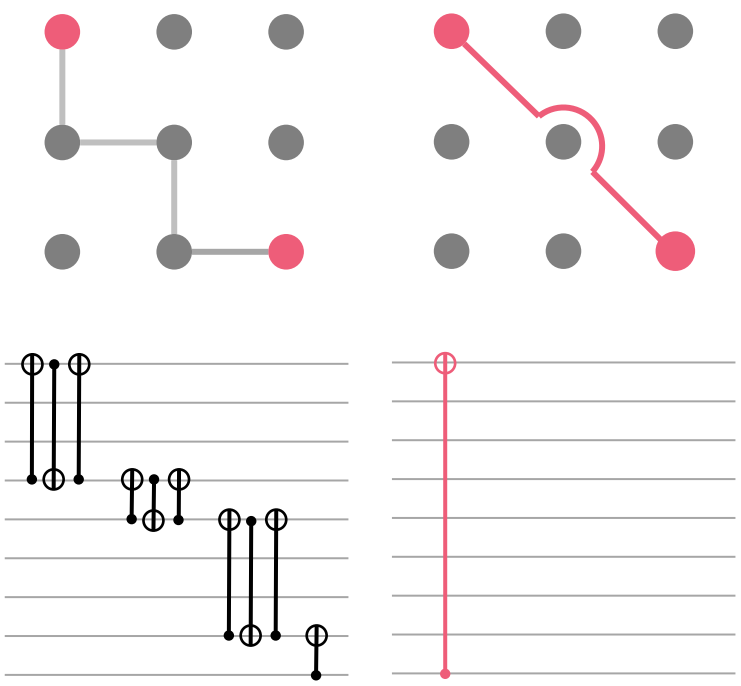
- Enable arbitrary sorting of ions and all-to-all connectivity



QCCD architecture: differentiating features

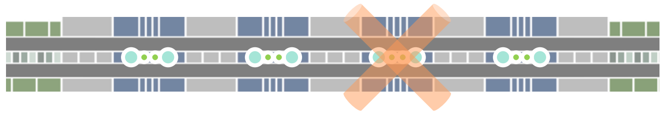
All-to-All Connectivity

Nearest Neighbor | All-to-All

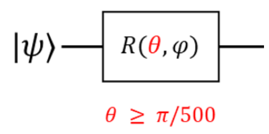


High-Fidelity Gates

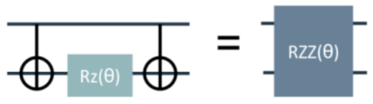
- 56 qubits, 1540 qubit pairings
- 4 gate zone calibrations
- Not 1540 qubit pair calibrations



Arbitrary Angle 1-qubit and 2-qubit gates

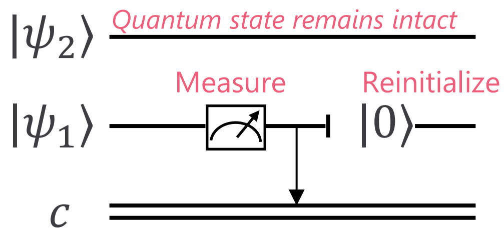


$$RZZ(\theta) = e^{-\frac{i\theta}{2}}\begin{pmatrix}1 & 0 & 0 & 0\\ 0 & e^{i\theta} & 0 & 0\\ 0 & 0 & e^{i\theta} & 0\\ 0 & 0 & 0 & 1\end{pmatrix}$$



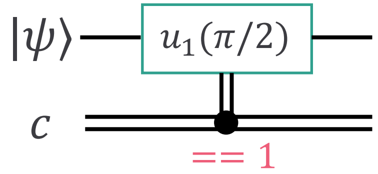
Qubit Measurement and Reuse

- Measurement and reuse



- Conditional logic

If c==1, perform gate
If c==0, do not



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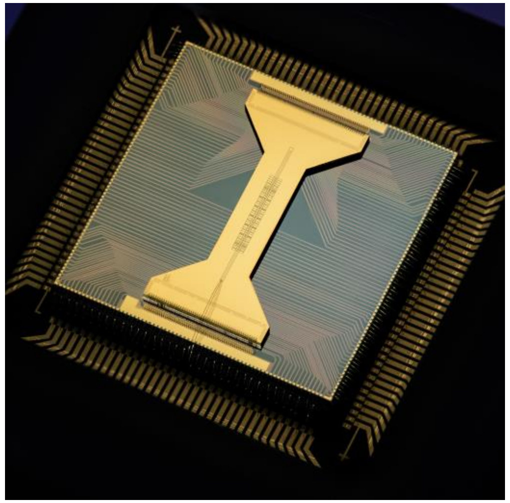
Quantinuum’s commercial systems

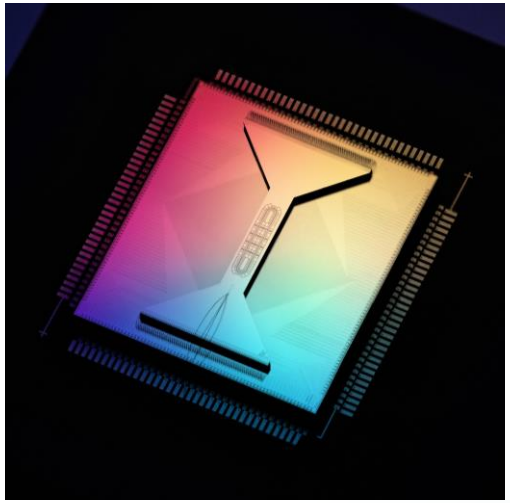
Hardware specifications and benchmarking data available at:

https://github.com/CQCL/quantinuum-hardware-specifications/

SYSTEM MODEL H1



SYSTEM MODEL H2



Qubits	20 fully-connected	56 fully-connected
1Q Gate Error	$2.1(3)\times10^{-5}$	$2.9(4)\times10^{-5}$
2Q Gate Error	$8.8(3)\times10^{-4}$	$1.28(8)\times10^{-3}$
SPAM Error	$2.5(1)\times10^{-3}$	$1.5(1)\times10^{-3}$
Measurement Crosstalk Error	$1.5(1)\times10^{-5}$	$7.4(8)\times10^{-6}$
Memory Error	$2.1(2)\times10^{-4}$	$5.0(5)\times10^{-4}$
Quantum Volume	1 048 576 (2^{20})	2 097 152 (2^{21})
Mirror Benchmarking (Qubits)	$1.4(2)\times10^{-3}$ (20)	$2.5(1)\times10^{-3}$ (56)
GHZ State Fidelity (Qubits)	81.6(8)% (20)	61.6(8)% (56)
Depth-1 Circuit Time	21 ms	70 ms

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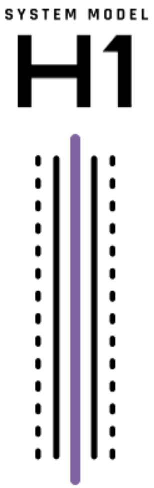

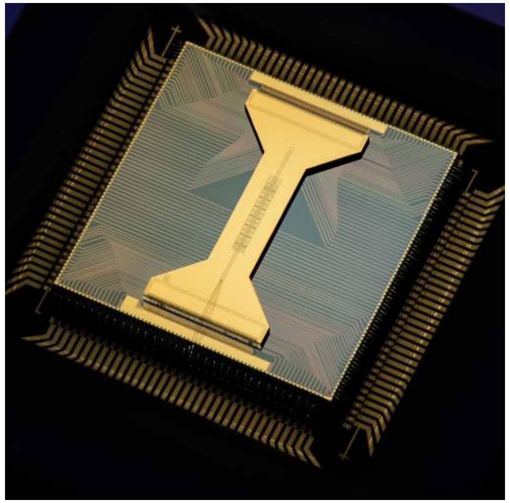

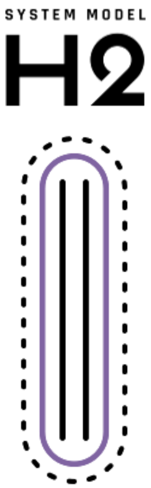

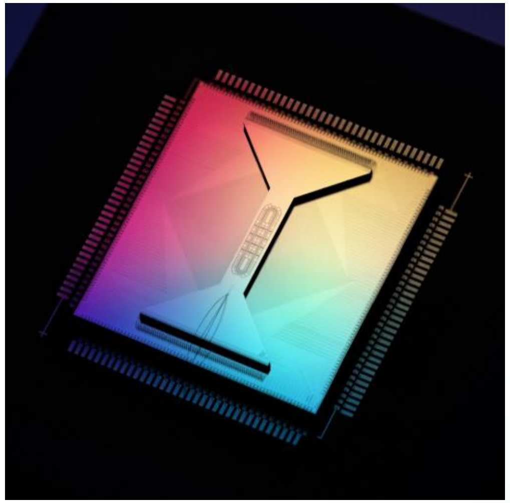

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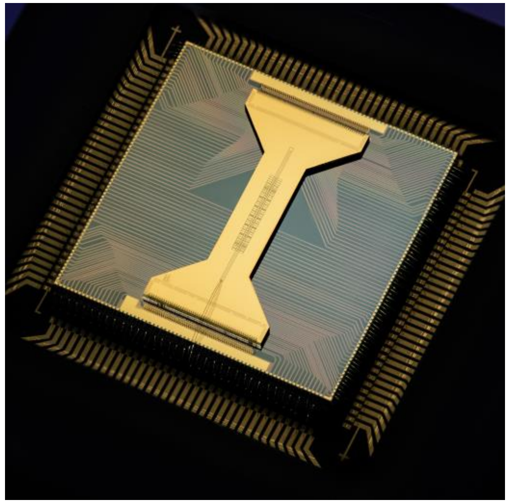
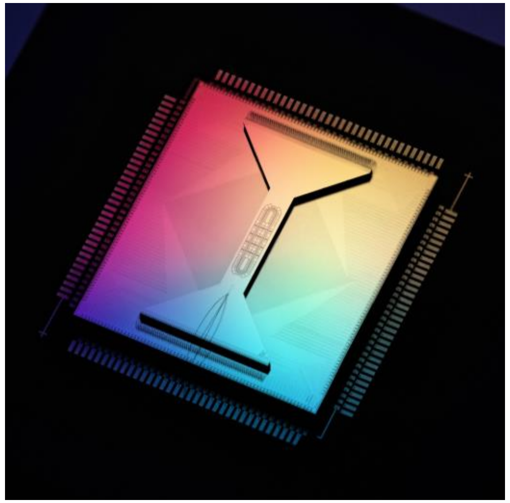


SYSTEM MODEL H2



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Development roadmap

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	2020	2023	2025	2027	2029
SYSTEMS:	SYSTEM MODEL H1	SYSTEM MODEL H2	QUANTINUUM HELIOS	QUANTINUUM SOL	QUANTINUUM APOLLO
PHYSICAL QUBITS:	20	56	96	192	1000's
PHYSICAL 2-QUBIT GATE ERROR:	1×10^{-3}	1×10^{-3}	$< 5 \times 10^{-4}$	$< 2 \times 10^{-4}$	1×10^{-4}
LOGICAL QUBITS:		> 12	~ 50	~ 100	100's
LOGICAL ERROR RATES:		1×10^{-3}	$< 10^{-4}$	$\sim 10^{-5}$	1×10^{-5} to 1×10^{-10}*

*analysis based on recent literature in new, novel error correcting codes predict that error could be as low as 1E-10 in Apollo (ref: arXiv:2403.16054, arXiv:2308.07915)

Development roadmap

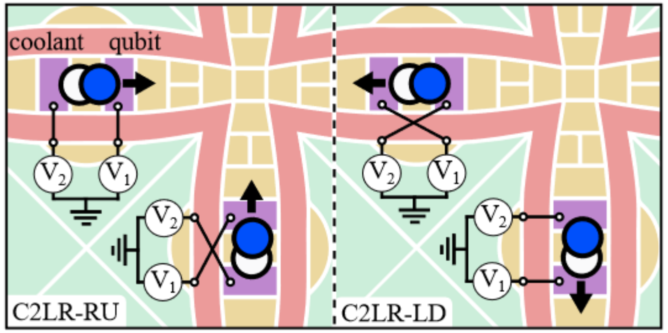
2020 — SYSTEM MODEL H1

2023 — SYSTEM MODEL H2

2025 — QUANTINUUM HELIOS

2027 — QUANTINUUM SOL

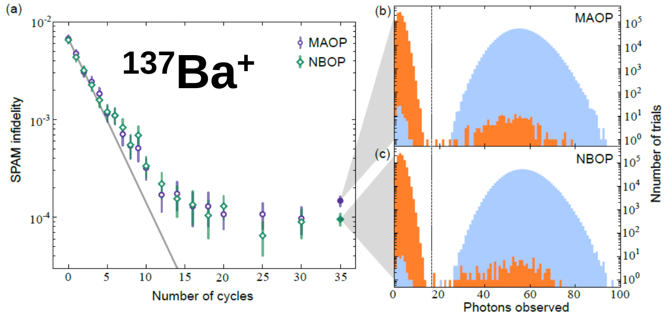
2029 — QUANTINUUM APOLLO



2D grid with scalable electronics

R. Delaney et al., Multispecies Ion Transport in a Grid Based Surface-Electrode Trap, arXiv:2403.00756 (2024)

Integrated photonics for beam delivery



New qubit with high SPAM fidelity

F. A. An *et al.*, Phys. Rev. Lett. 129, 130501 (2022)

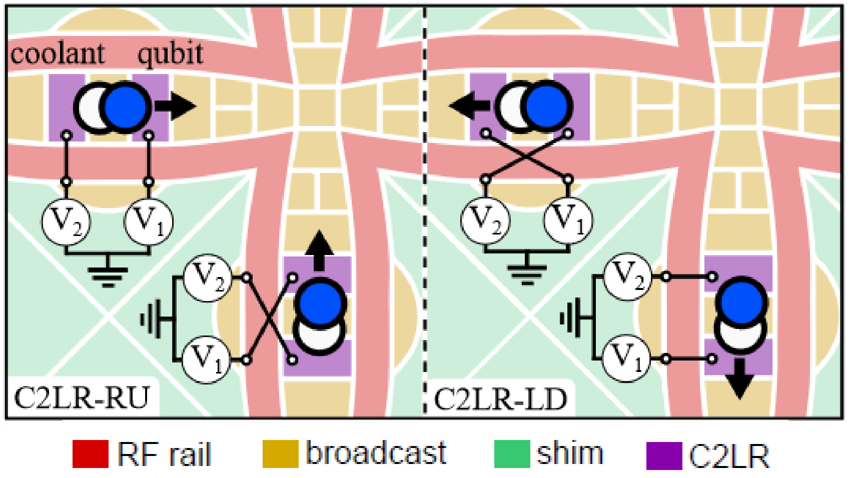
Universal, Fault-Tolerant Quantum Computing

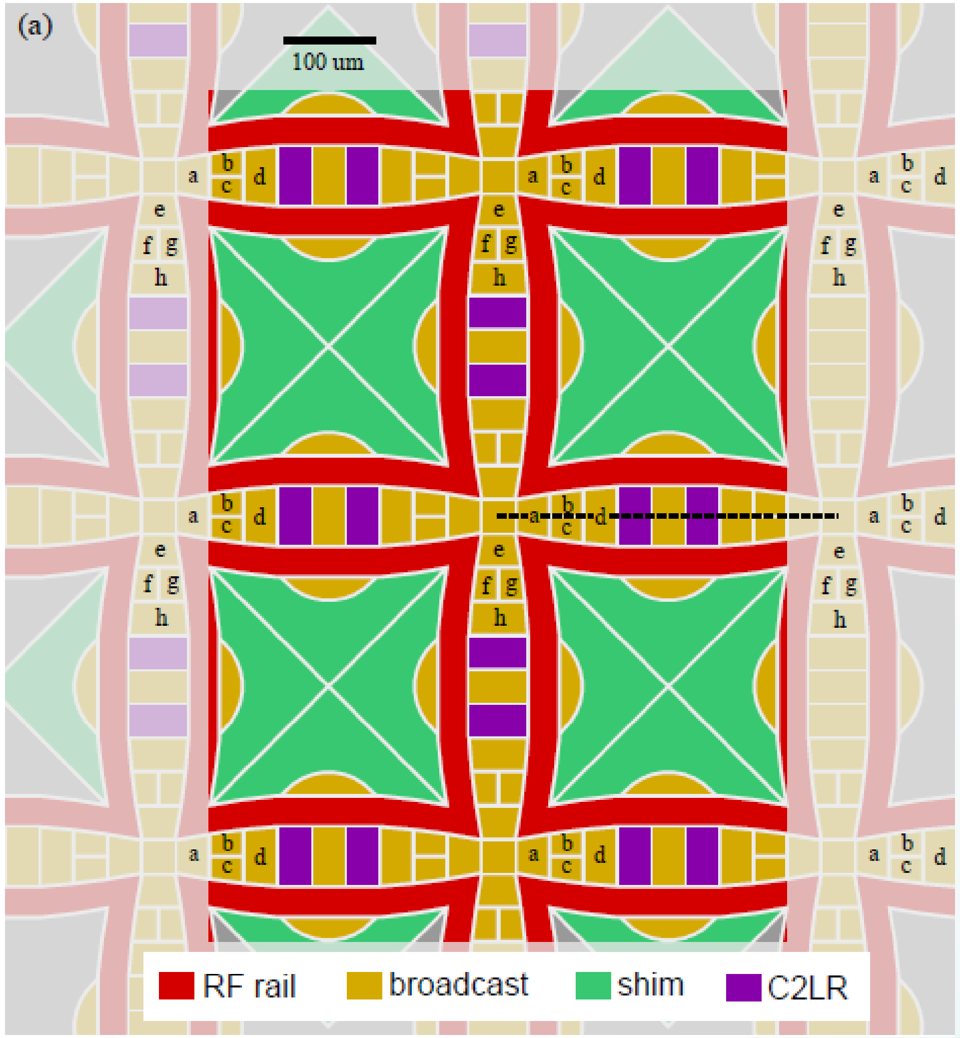
Noisy Intermediate-Scale Quantum (NISQ) Era

Scalable wiring for 2D grid

- 2D grid traps enable fast all-to-all connectivity
- Without a mitigation strategy, wiring scales linearly
- C2LR scheme: broadcast RF signals + 1 digital signal per zone

Fixed number of fast AWG channels
+
Digital switching signals
→ Scalable control electronics





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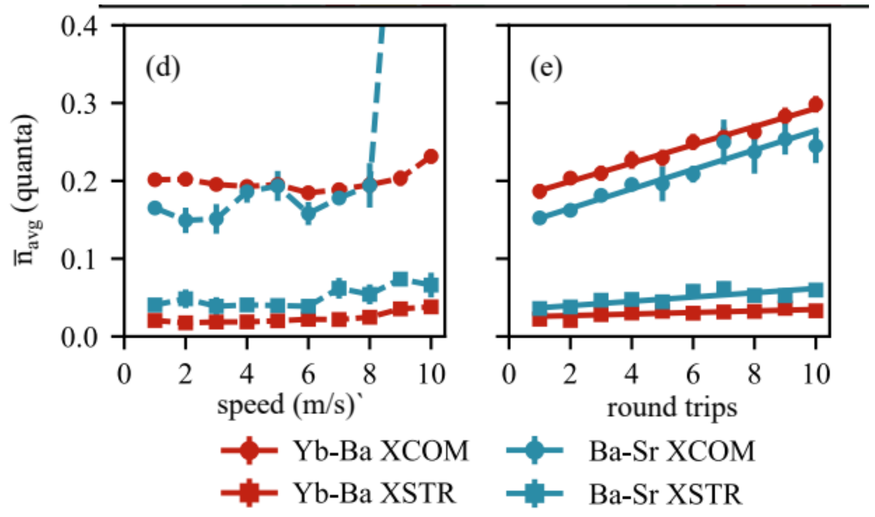

R. Delaney *et al.*, Multispecies Ion Transport in a Grid Based Surface-Electrode Trap, arXiv:2403.00756 (2024)

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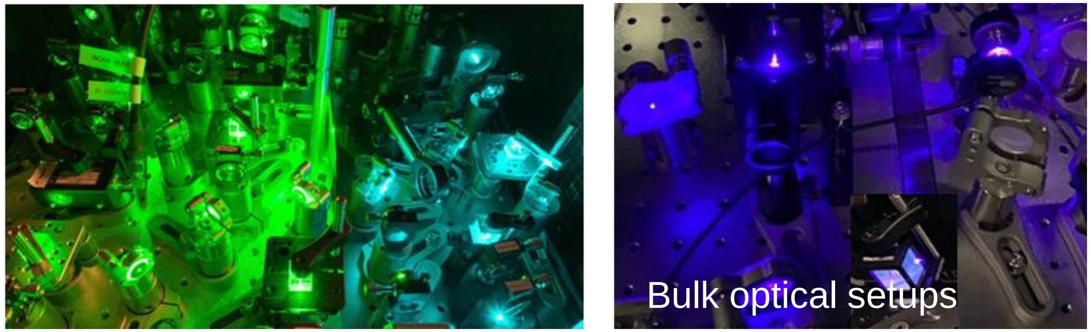
Photonics integration

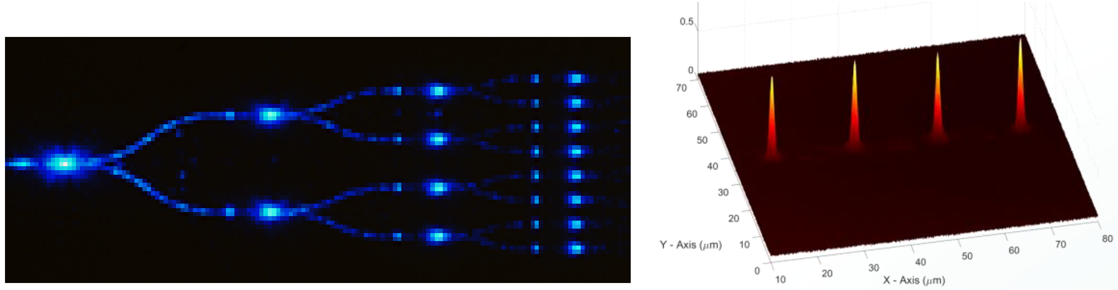
- **Free-space bulk + fiber optics:** large physical footprint, complex alignment

- **Photonics for beam delivery and conditioning**: decrease physical footprint and reduce alignment complexity

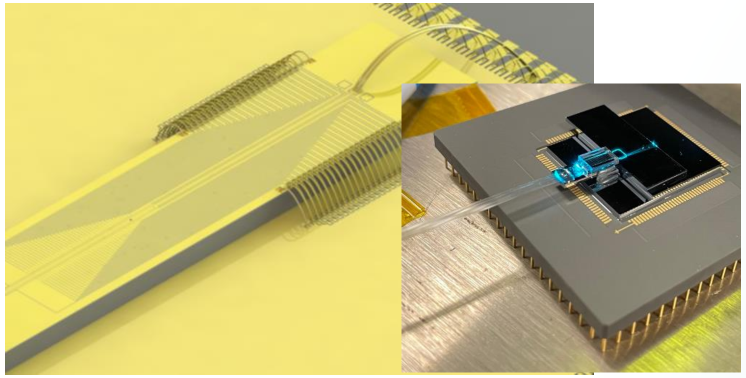
- **Integrated photonics in trap structure**, meta-materials for in-vacuum beam shaping and control

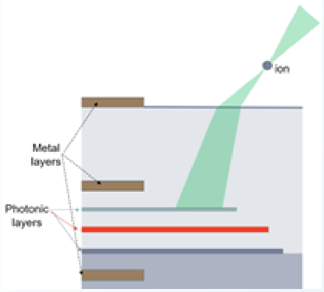


Bulk optical setups



Low-loss photonic waveguides, splitters, polarizers, couplers





Photonics layers

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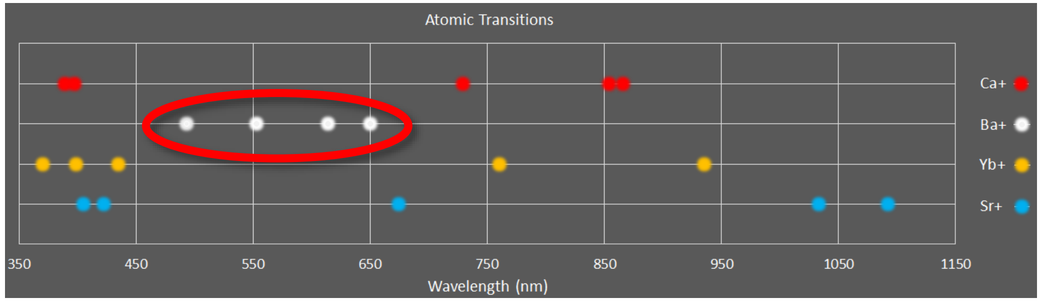
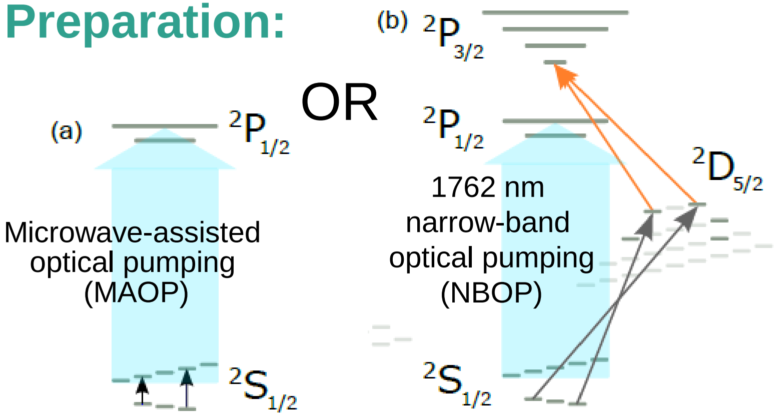
$^{137}Ba^{+}$: qubit for scale

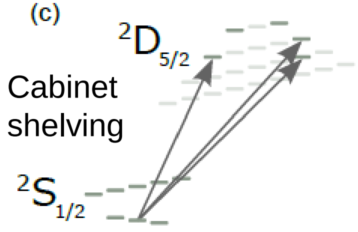
- Visible laser wavelengths more compatible with integrated photonics. No high-power UV required.
- Low SPAM error



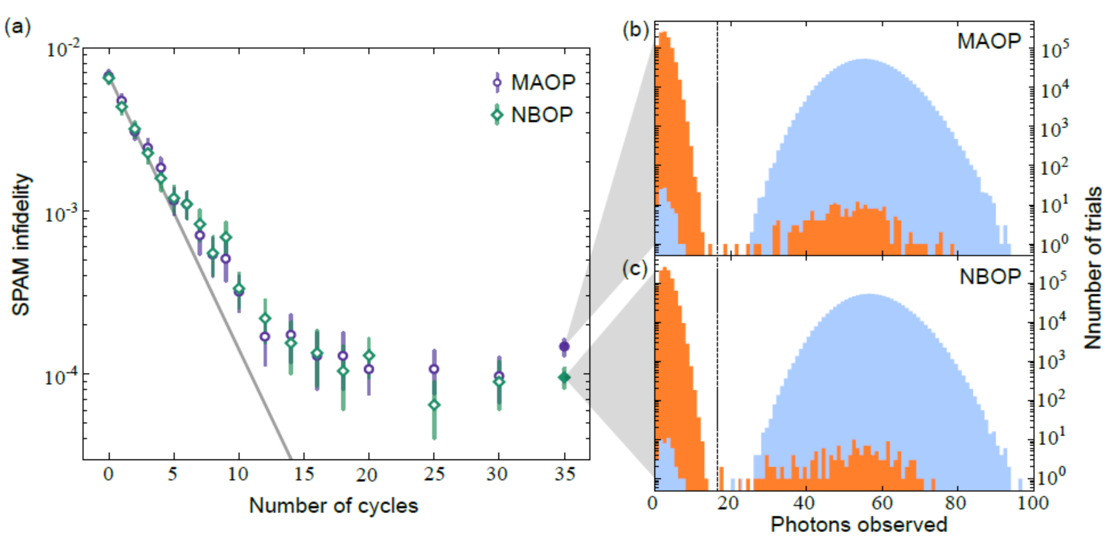
State Preparation:



Detection:



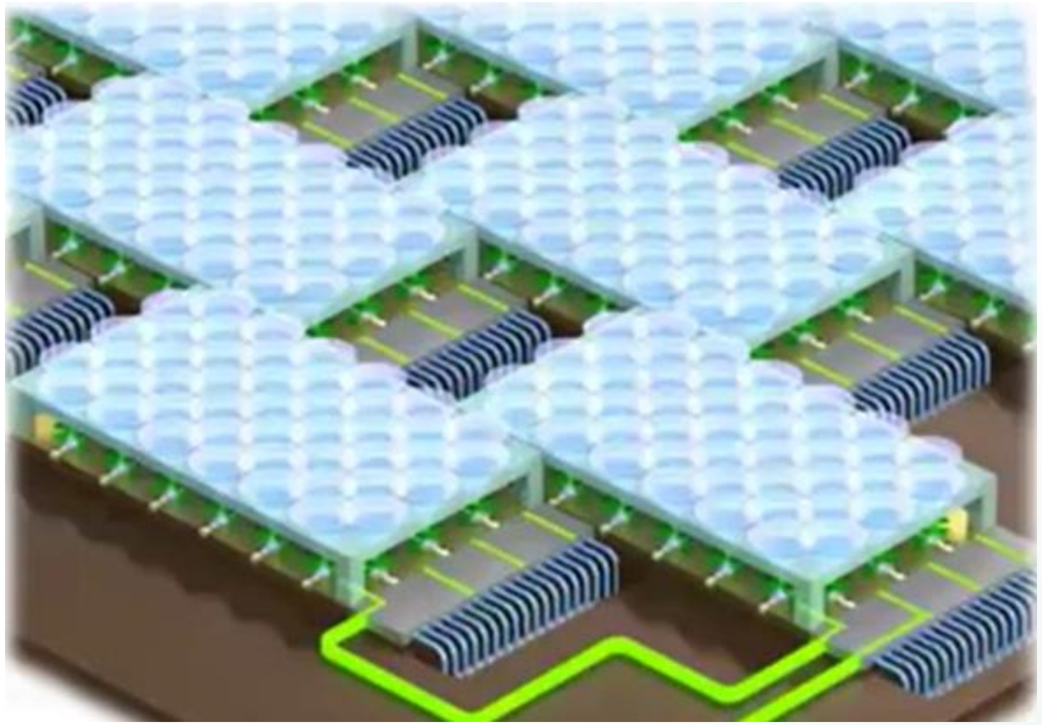
SPAM error: $9.6(1.4)\times10^{-5}$



An, Fangzhao Alex, *et al.* High fidelity state preparation and measurement of ion hyperfine qubits with I > 1/2, Phys. Rev. Lett. **129**, 130501 (2022).

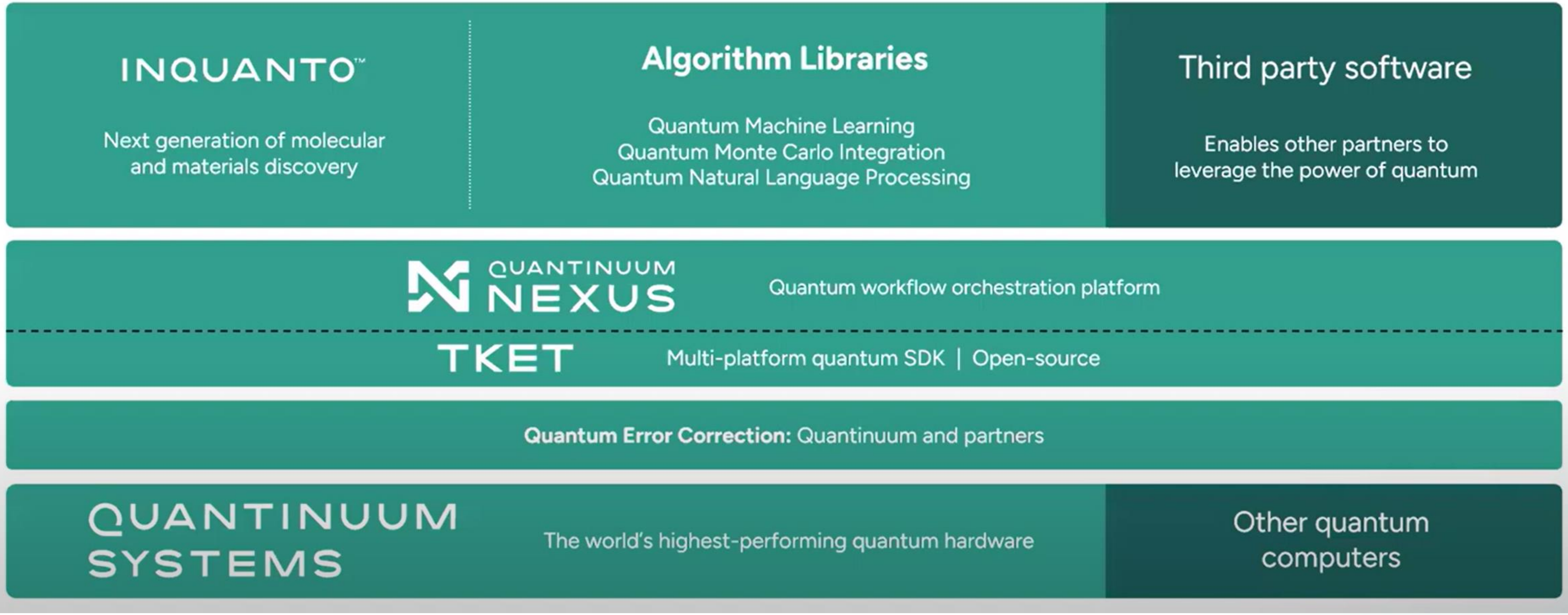
Modular architectures with trapped ions

- **Near term:** increase qubit density on single chip (50,000 qubits on a single square-inch dye)
- **Long term:** trap tiling to scale to millions of qubits (30 cm x 30 cm area)
- Qubits distributed between modules via ion transport
- Beams delivered via integrated photonics



Tiled trap modules

Quantinuum's Quantum Computing Infrastructure



Thank you

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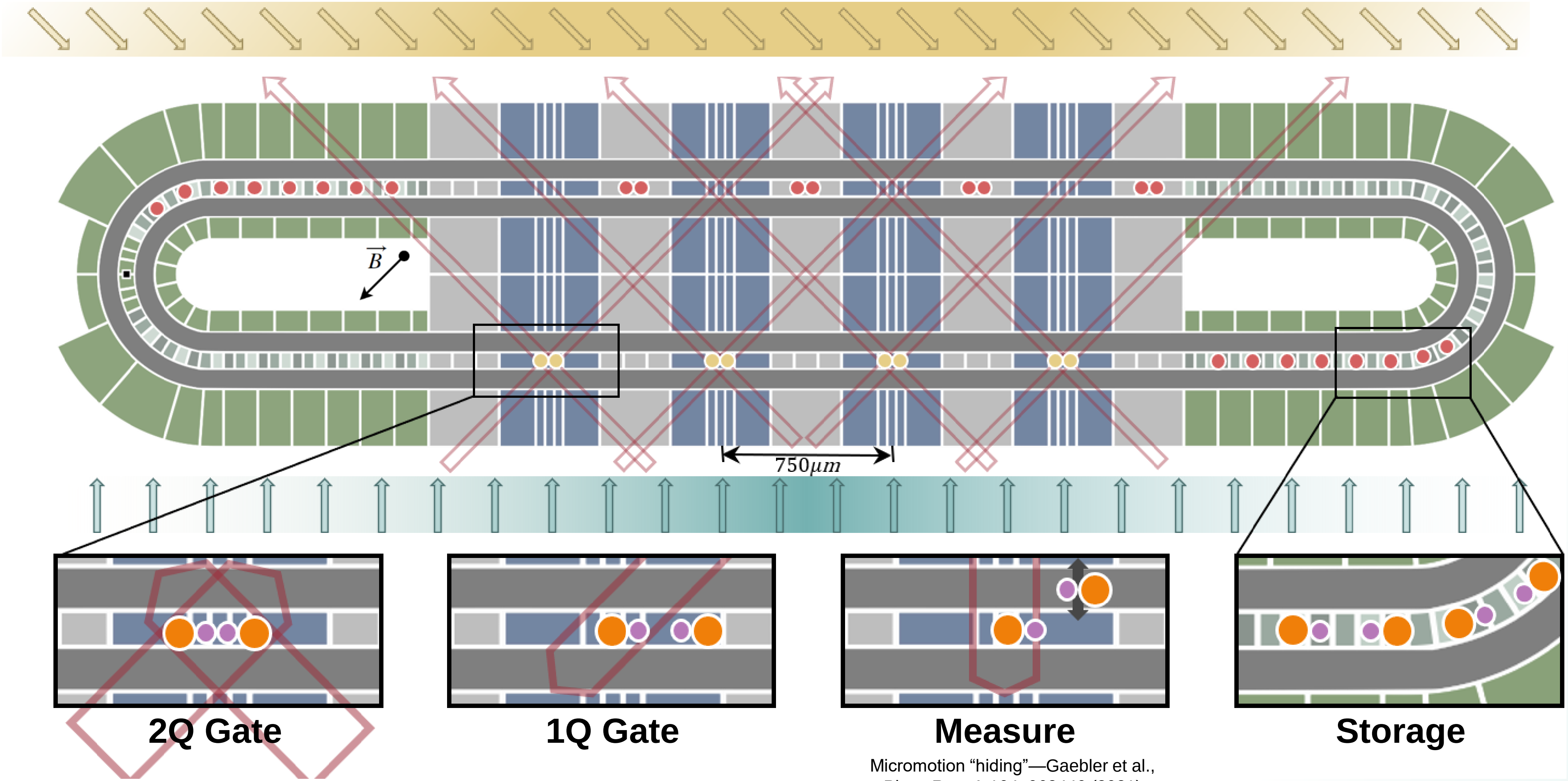
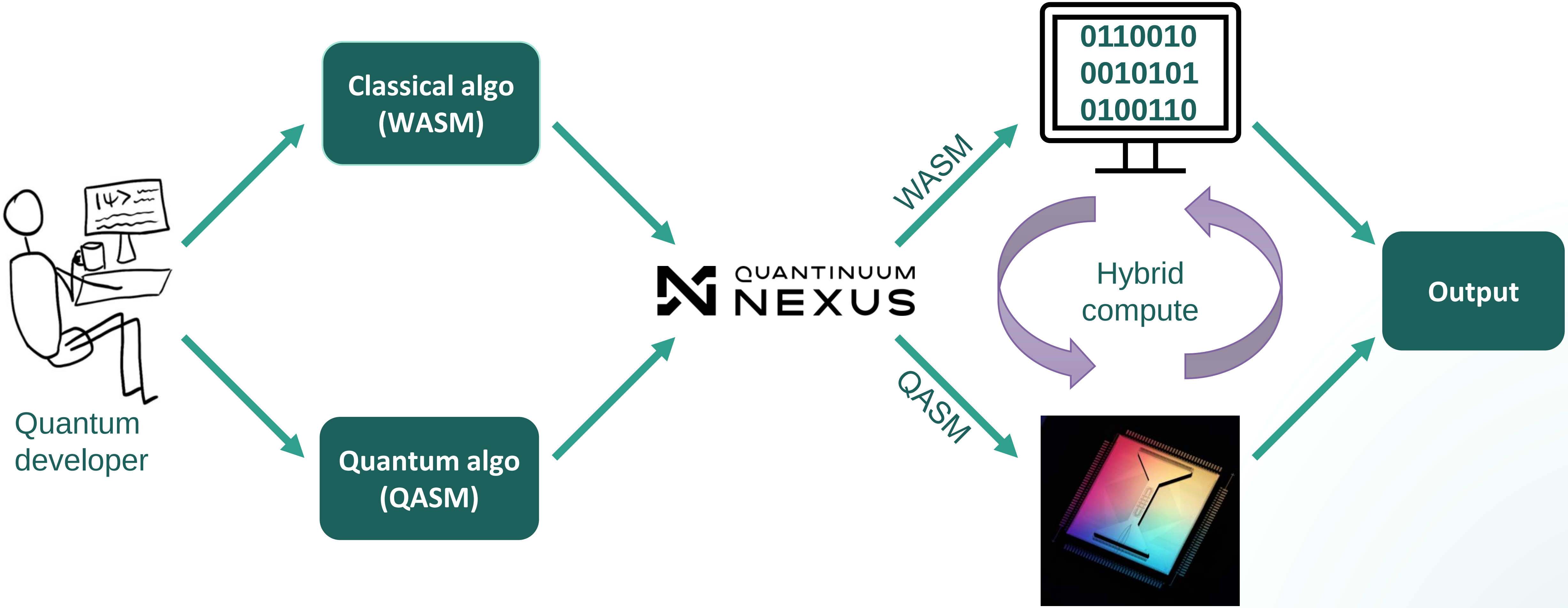
System Model H2: 56 qubit trapped-ion processor



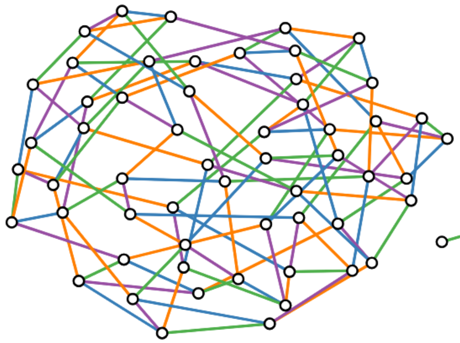
Micromotion "hiding"—Gaebler et al.,
Phys. Rev. A 104, 062440 (2021)

Fault-tolerant Quantum Computing Infrastructure

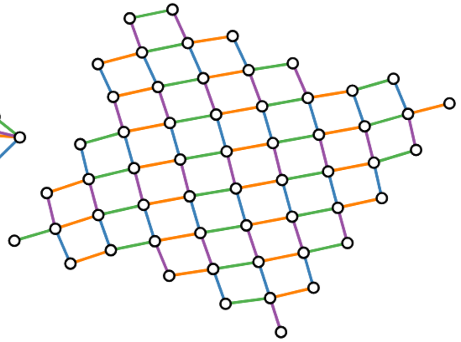


Exceeding classical computing: random circuit sampling

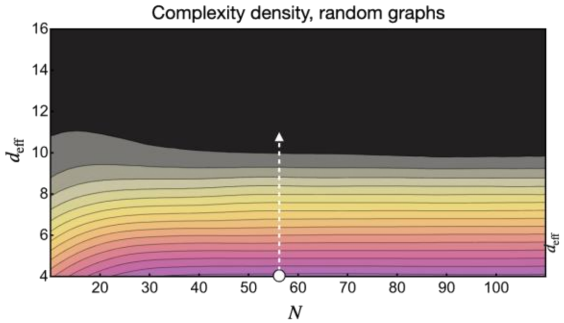
- All-to-all connectivity: much harder to classically simulate

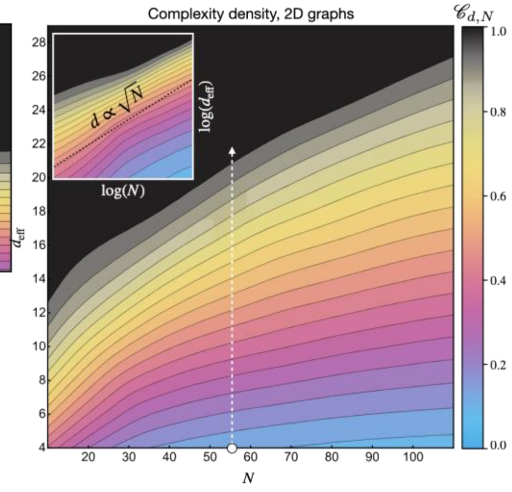


All-to-all



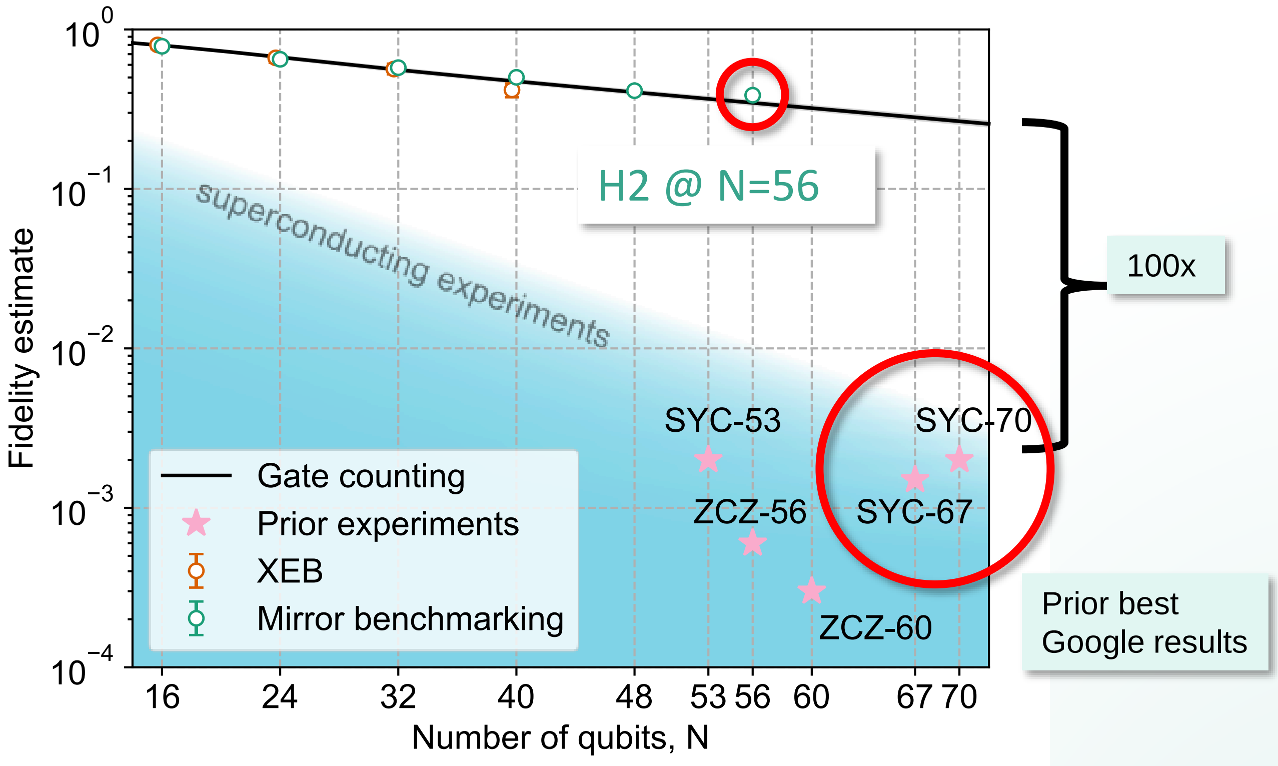
2D grid





M. DeCross *et al.*, The computational power of random quantum circuits in arbitrary geometries, arXiv:2406.02501 (2024)

- Executed with 100x better fidelity than previous demonstrations

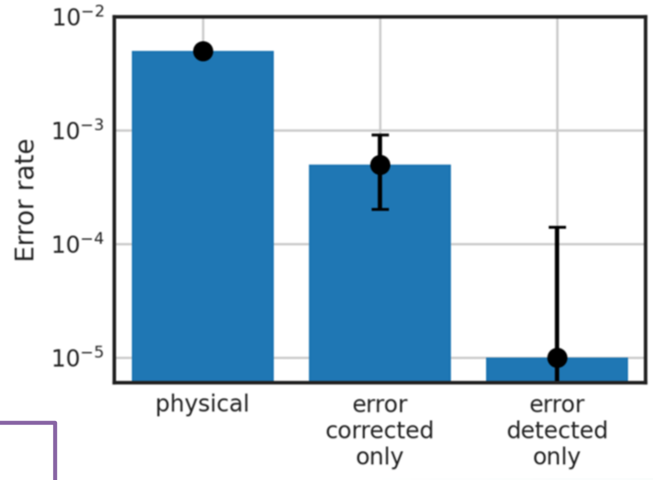


F. Arute, *et al.*, Nature **574**, 505 (2019). Q. Zhu, *et al.*, Science Bulletin **67**, 240 (2022)
A. Morvan, *et al.*, arXiv 2304.11119 (2023). M. DeCross et al., arXiv 2406.02501

Demonstration of logical qubits and repeated error correction with better-than-physical error rates

Bell state preparation: [[7,1,3]] Steane code

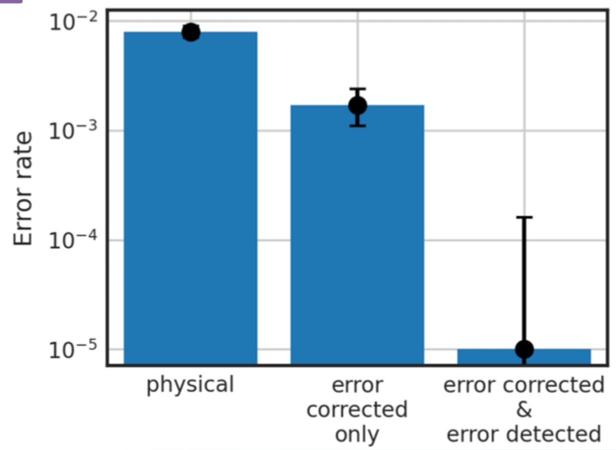
	runs	pre-accepted	post-accepted	corrections	errors	E_{xz} error rate	gain
unencoded baseline	274,400	—	—	—	1,367	$0.50\%^{+0.03\%}_{-0.03\%}$	—
encoded, pre-selection only	24,200	18,035	—	646	9	$0.05\%^{+0.04\%}_{-0.03\%}$	9.8
encoded, pre- and post-selection	24,200	18,035	17,389	—	0	$0.001\%^{+0.013\%}_{-0.001\%}$	500



$>10^4$ trials with 0 errors

Bell state preparation: [[12,2,4]] Carbon code

	runs	pre-accepted	post-accepted	corrections	errors	E_{xz} error rate	gain
unencoded baseline	16,000	16,000	—	—	125	$0.8^{+0.1}_{-0.1}\%$	—
encoded, pre-selection only	22,000	15,483	—	928	26	$0.17^{+0.07}_{-0.06}\%$	4.7
encoded, pre- and post-selection	22,000	15,483	15,409	854	0	$0.001\%^{+0.015\%}_{-0.001\%}$	800



M. P. da Silva *et al.*, arXiv 2404.02280

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Demonstration of quantum computation and error correction with a tesseract code

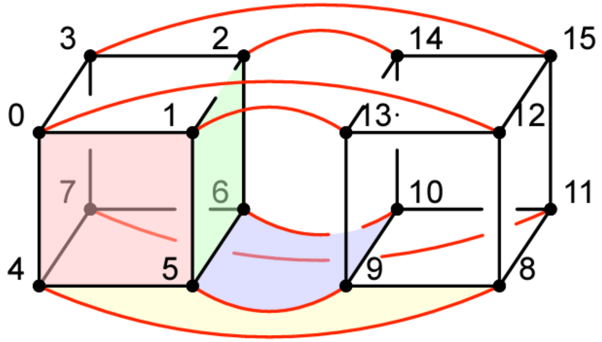

FIG. 1. The [[16, 6, 4]] color code on the 4D hypercube, or tesseract. Each of the 16 vertices is a qubit. Cubes are X and Z stabilizers, and squares are logical operators, e.g., 0145.

More complex structure (compared to 2D surface code)
Benefits from all-to-all connectivity

Experiment	Qubits	Baseline error rate	Encoded error rate	Gain
Path-4	4	1.5(2)%	$0.10^{+0.11}_{-0.06}$%	15×
Cube-8	8	2.3(3)%	$0.2^{+0.2}_{-0.1}$%	11×
$\|0^{12}\rangle + \|1^{12}\rangle$ Cat-12	12	2.4(3)%	$0.11^{+0.16}_{-0.08}$%	22×
Error correction 5×	4	2.7(4)%	$0.11^{+0.21}_{-0.09}$%	24×
	8	5.6(6)%	$0.7^{+0.7}_{-0.4}$%	8×

12-logical-qubit GHZ state prep with ~99.9% fidelity
(22x better than 12-physical-qubit GHZ state prep)

B. W. Reichardt *et al.,* arXiv 2409.04628

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