A Modular Scalable Fault-Tolerant Quantum Computer Based on Rydberg Arrays and Cavities

Massachusetts Institute of Technology

Josiah Sinclair, Joshua Ramette, Alyssa Rudelis, Dolev Bluvstein, Beili Hu, Edita Bytyqi, Luke Stewart, Mikhail Lukin, Vladan Vuletić

BIG MODULES CONNECT WAY BETTER

Rydberg atom arrays are a promising approach to quantum computing, leveraging large numbers of identical qubits and high fidelity operations [1,2].

Our goal: design a unit module with sufficient quantum i/o such that the system can be scaled up arbitrarily by simply adding more modules.

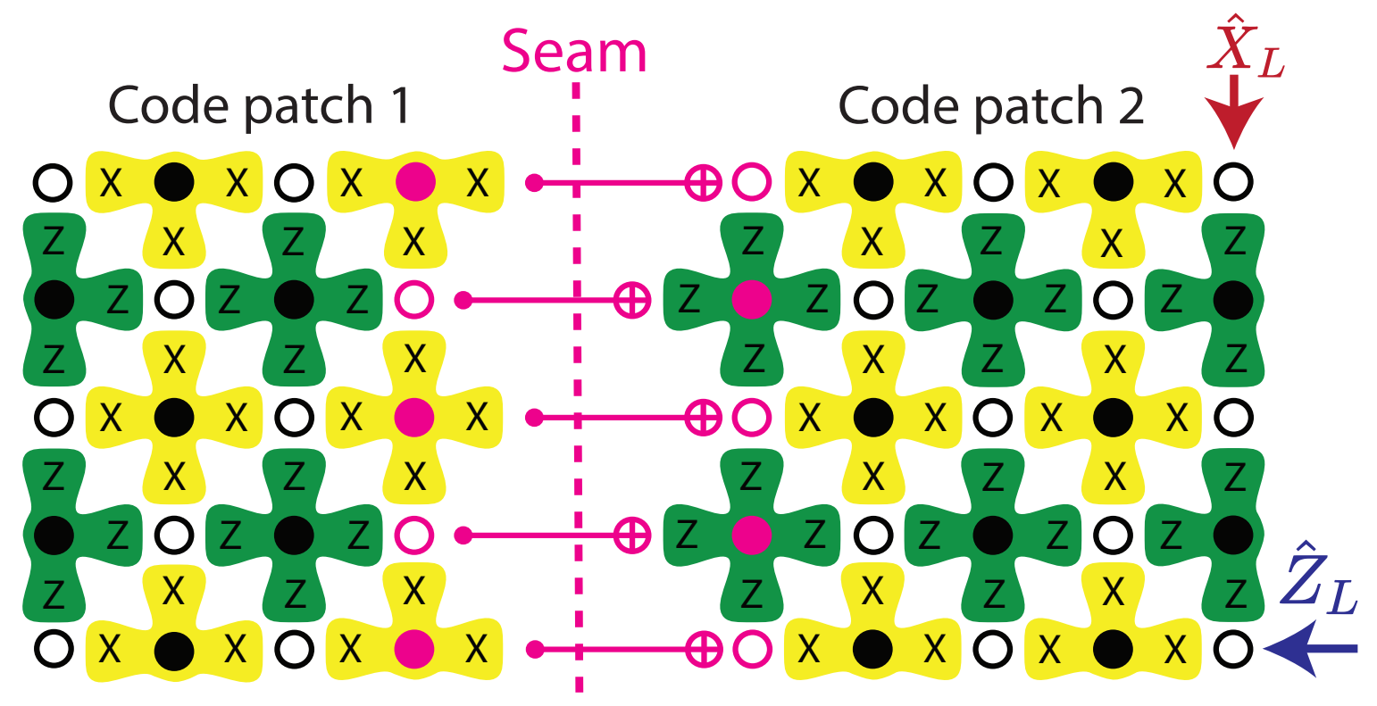
We show large modules (N > 100) have 2x higher local gate thresholds and 10x higher Bell pair thresholds compared to small modules (N=1-5).

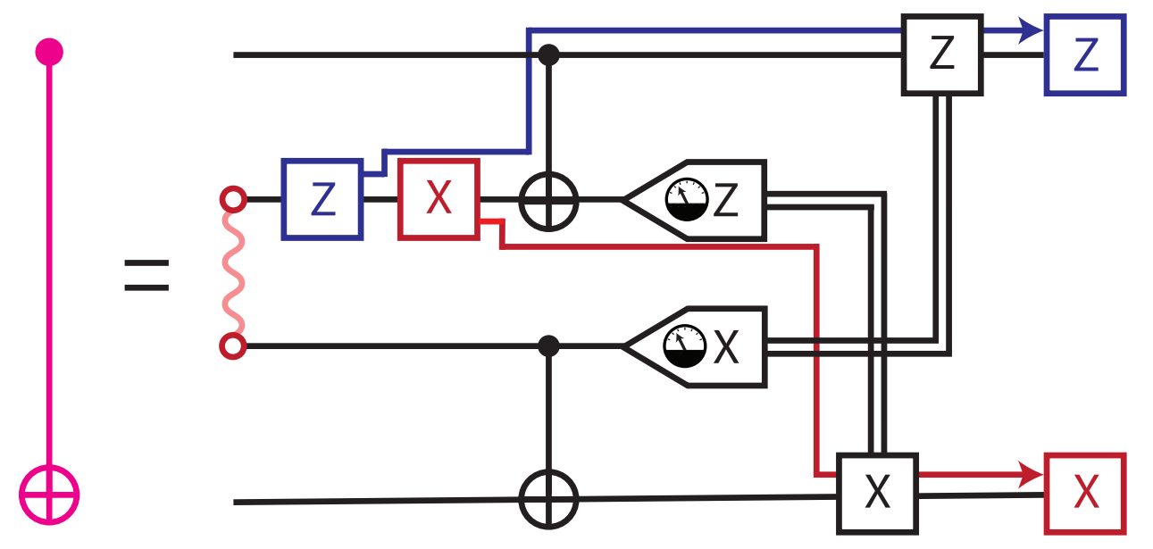
Bell pair generation rates (>40 kHz) and qubit readout rates (>1 MHz) required for fault-tolerant communication between large (N=1600) modules is possible with an optical cavity.

These results pave the way for a scalable, fault-tolerant architecture for quantum computing based on near-term Rydberg arrays augmented with optical cavities.

CONNECTING MODULES FAULT-TOLERANTLY

To compute across separated modules fault-tolerantly, need to be able to initialize and maintain a planar surface code [4] patch straddling both modules (i.e. stabilizer checks are done using teleported gates)





Seam is lower dimensional than bulk -> only bit flips occur -> protected by a repetition code with better thresholds [5] (applicable to all similar systems).

A simple model: logical error probability equals the sum of error rates for the bulk and the seam.

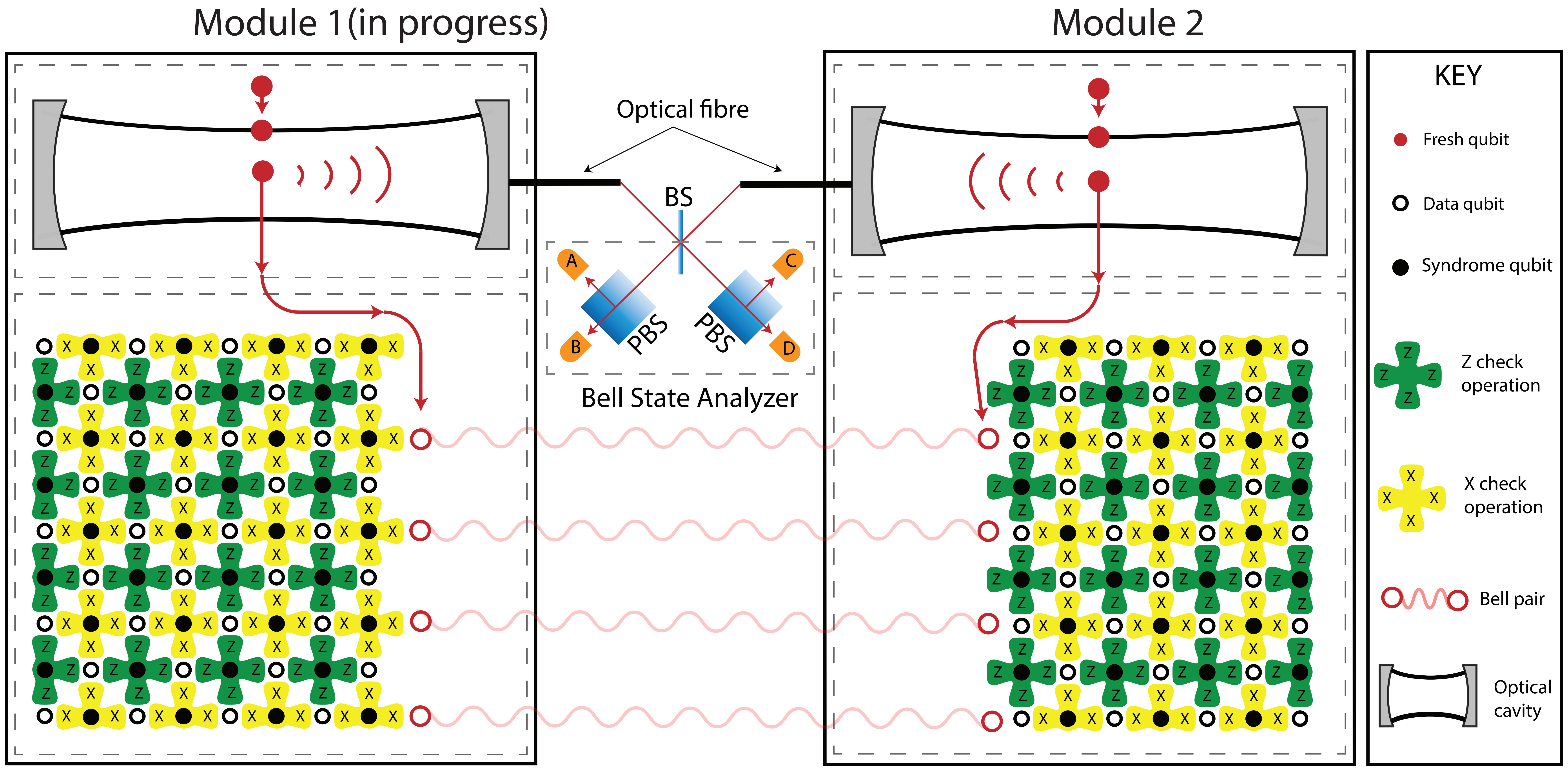
$$P_{error}^{tot} = \left(\frac{p_{bulk}}{p_{th}^{surf}}\right)^{d/2} + \left(\frac{p_{seam}}{p_{th}^{rep}}\right)^{d/2}$$

To determine code thresholds, we construct a detailed Rydberg error model:

$$p_{bulk} \approx 2p_{CX} \qquad p_{seam} \approx 0.5p_B + 2.5p_{CX} + p_M$$

$$q_{bulk} \approx 2p_{CX} + p_M \qquad q_{seam} \approx 0.5p_B + 2.5p_{CX} + 2p_M$$

APPLYING OUR RESULTS TO A NEW ARCHITECTURE



Surface code patches in each module are realized using an array of atoms, and connected using teleported gate.

Bell pairs required for teleported gates are generated using an optical cavity and transported to the seam (red arrows). Cavity can also be used for fast readout.

REASONABLE [IN PROGRESS] CAVITY PARAMETERS
C = 8.5 [3]
Length = 4 mm [40 mm]
Waist = 10 μm [45 μm]
τ = 0.12 μs [3 μs]

BELL PAIR RATES WITH REASONABLE [IN PROGRESS] CAVITY
Bell pair success probability = 0.19 [0.12]
Repetition time = 4 x τ = 0.48 μs [12 μs]
Mean entanglement time = 2.5 μs [93 μs]
Cycle time = 2L x 2.5 μs = 100 μs [231 μs] (L = 20 [L = 5])

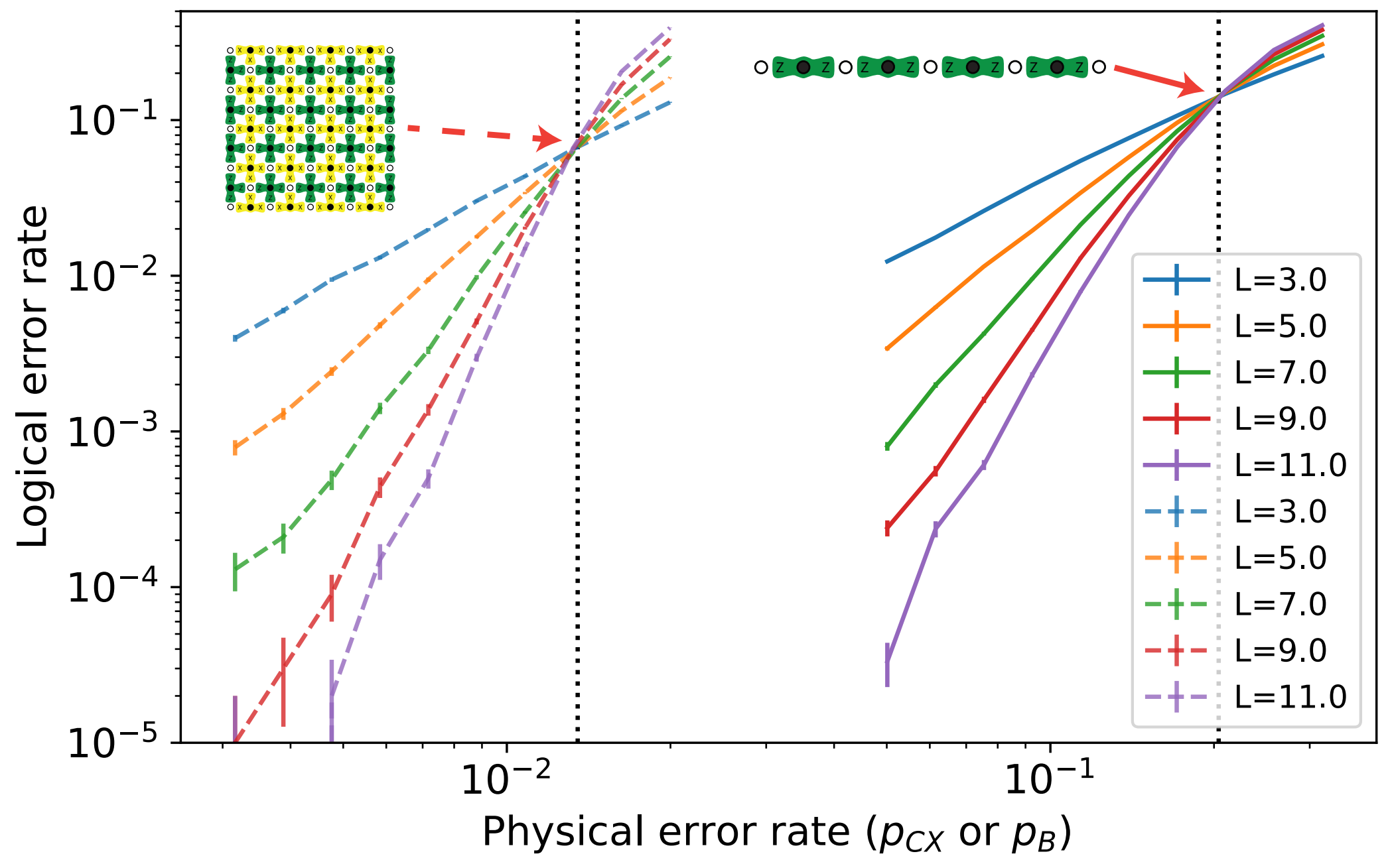


Fig. 1 According to our error model, surface code CNOT threshold is 1% (dashed) and seam Bell pair threshold is 20% (solid).

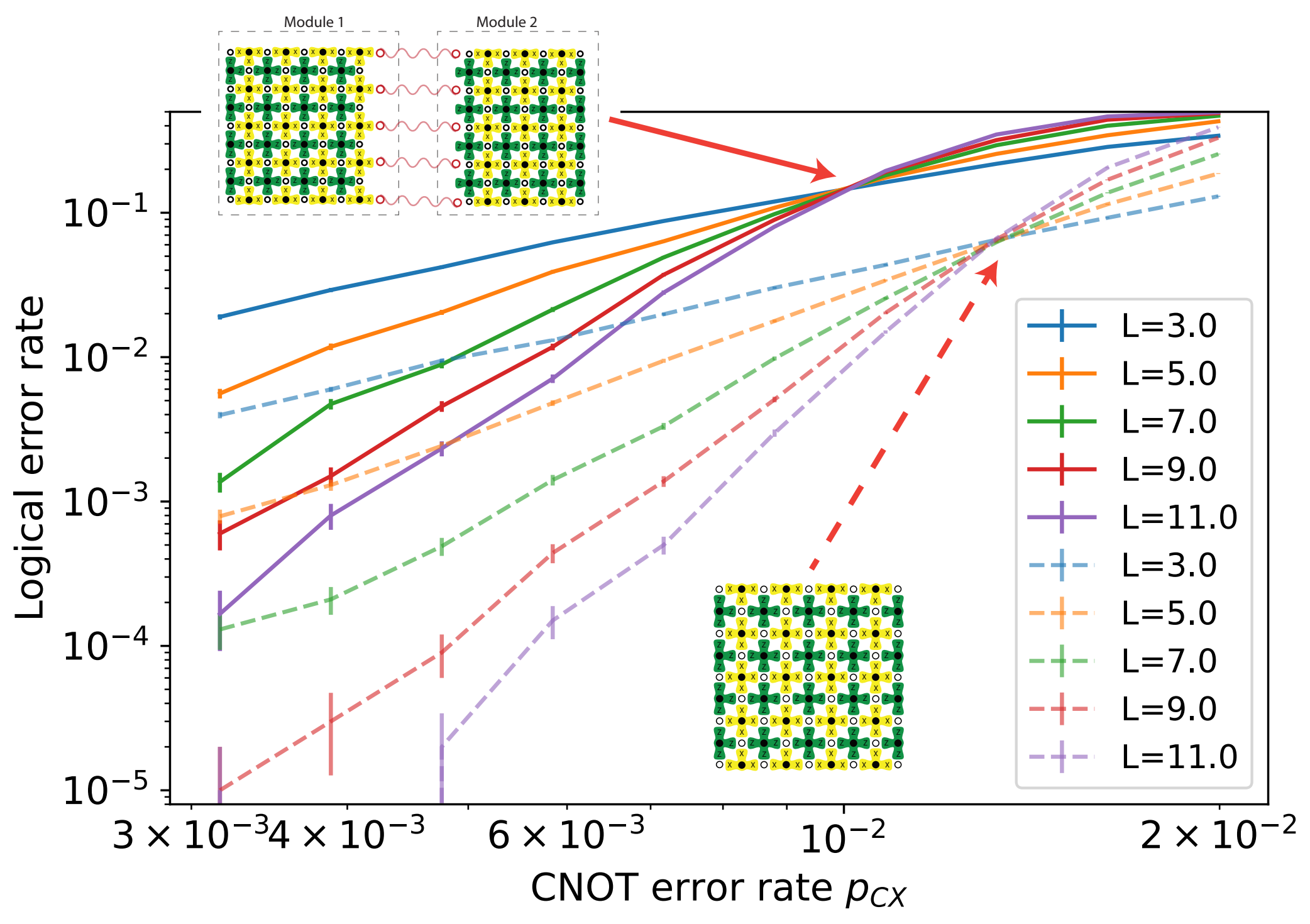


Fig. 2 Logical error suppression with noisy seam (solid) similar to noiseless seam (dashed). Noisy seam has Bell pair errors 10x CNOT error rate.

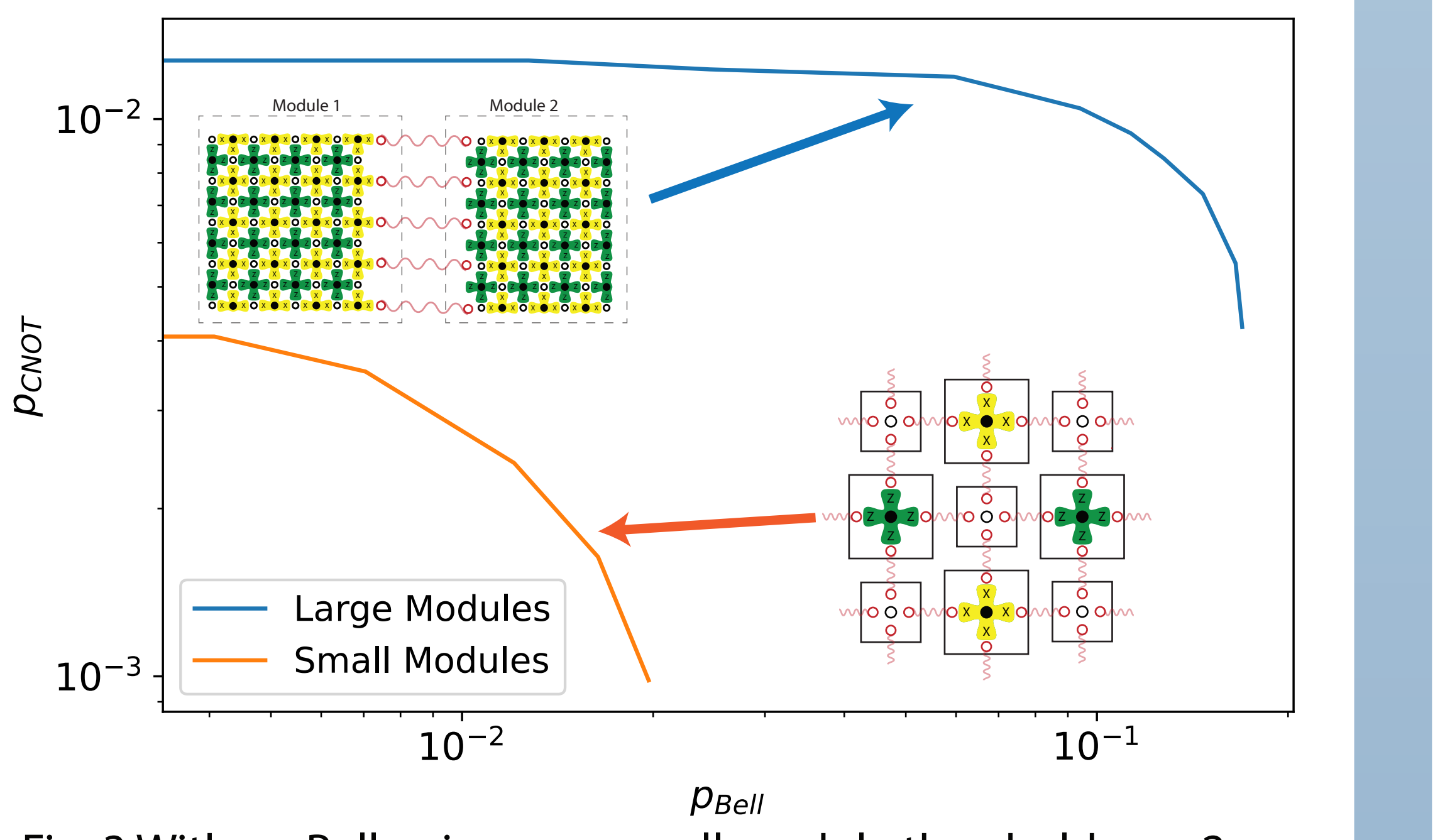


Fig. 3 With no Bell pair errors, small module thresholds are 2x worse than large module thresholds (large is > 100 qubits, small is 1-5 qubits). Large modules can also tolerate 10x noisier Bell pairs.

FAST SYNDROME READOUT WITH CAVITY

Syndrome qubits highly biased (1000:1) to be in "no error" state.

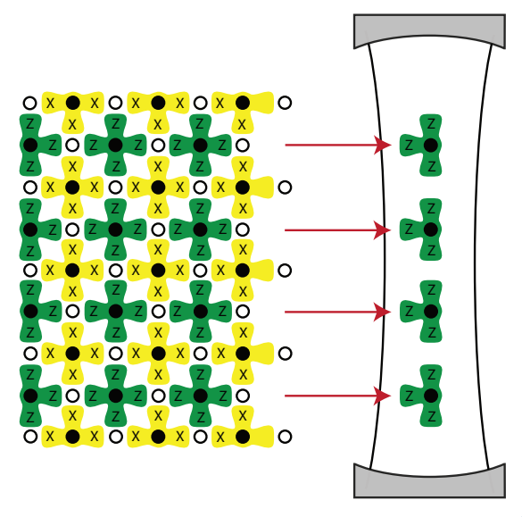
Speed up "search" by loading many syndrome qubits into cavity and checking if *any* are in error state.

If any are in error state, find them using a binary search.

$$\langle n_{searches} \rangle = 1 + Np\log_2(N)$$

With modest cavity parameters, should be able to read out 1000 syndrome qubits in 10-20 searches, requiring 5-10 μs total.

REASONABLE [IN PROGRESS] CAVITY READOUT PARAMETERS
Readout 2L unbiased qubits in 8 μs [5 μs] (L=20 [L=5])
Readout 2L^2 biased qubits in 6 μs [4 μs] (L=20 [L=5])



REFERENCES

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