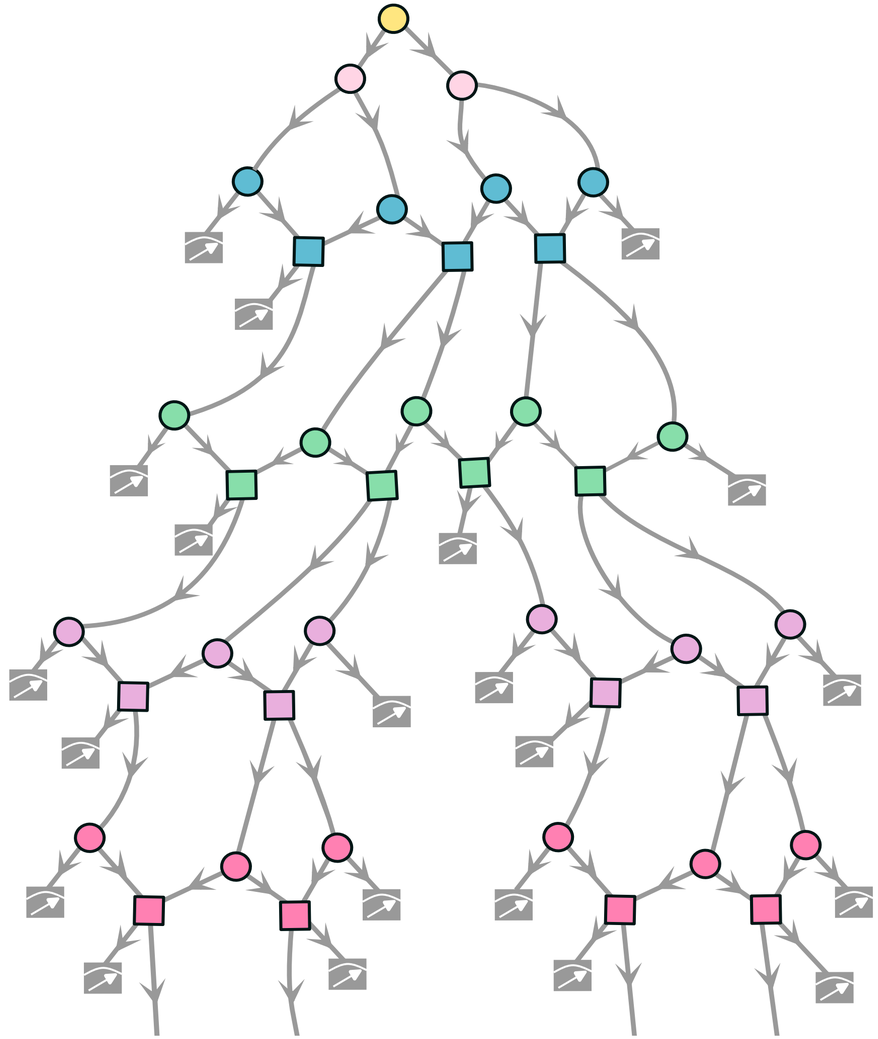
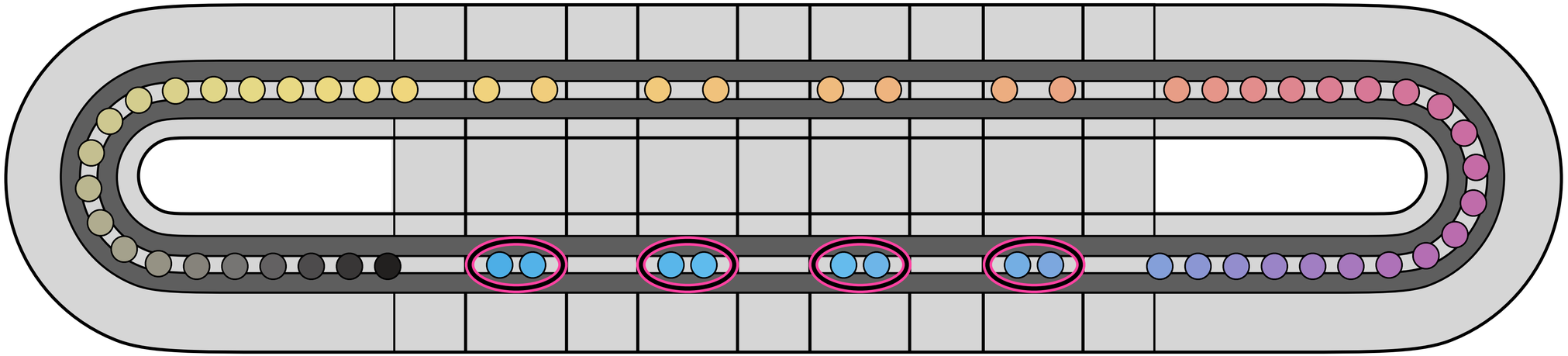
Dynamic quantum circuits in the QCCD architecture

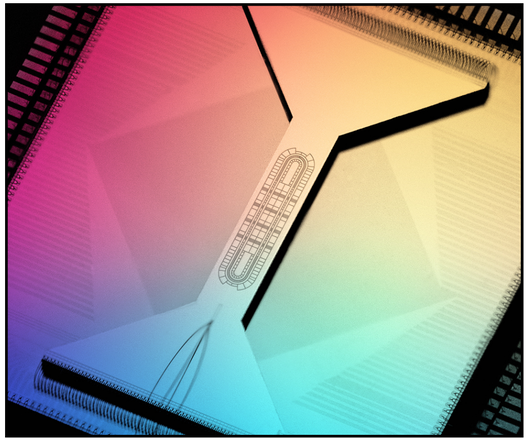
ERASE Townhall @ Yale
Michael Foss-Feig, Quantinuum



Overview of H2

Current configuration: 56 qubits (112 ions), 4 operational gates zones





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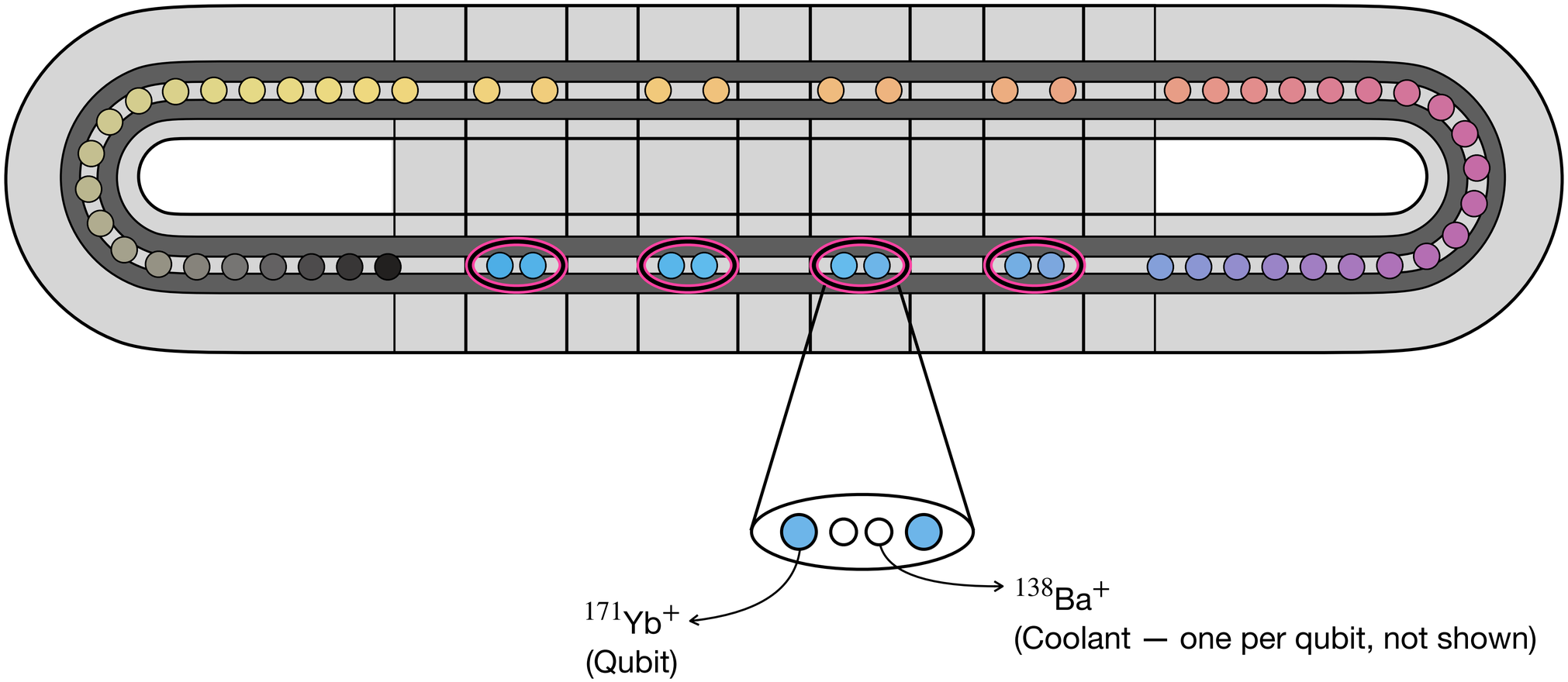

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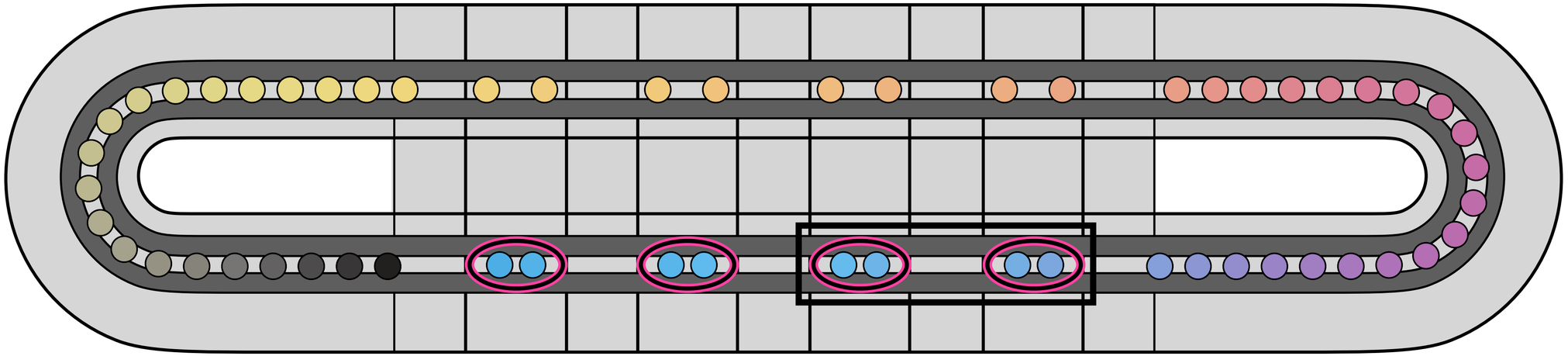

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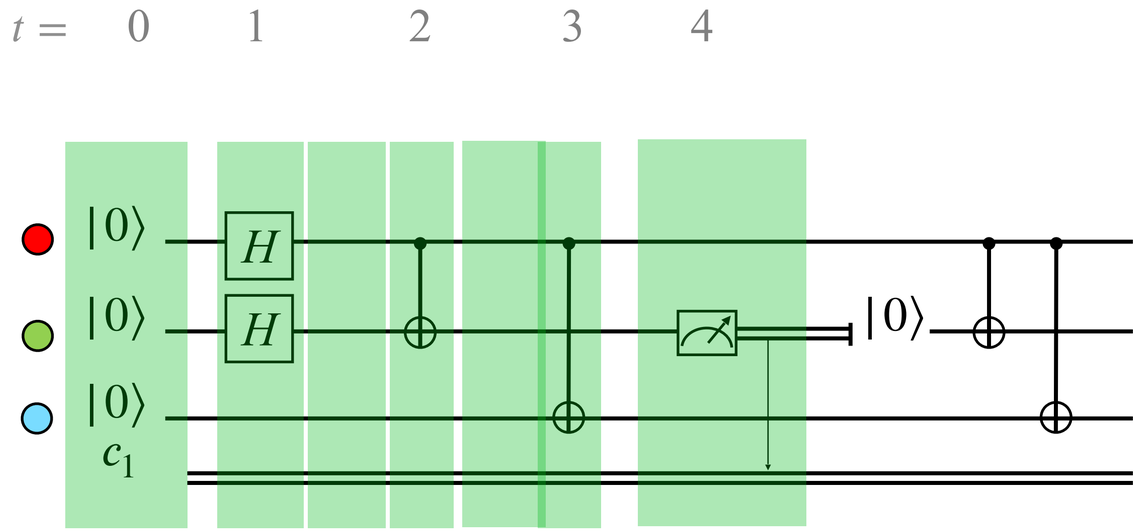
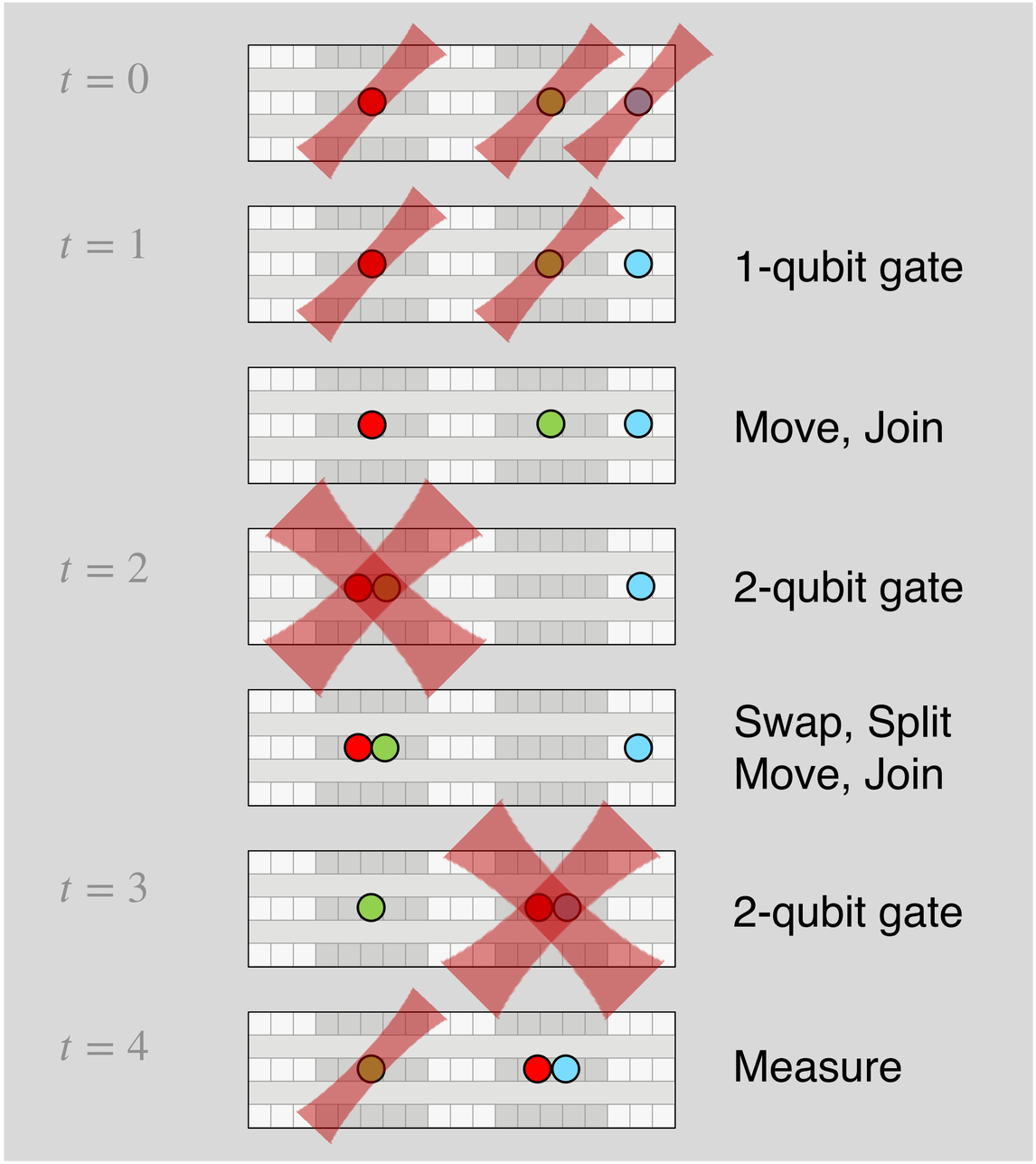
Quantum Circuit





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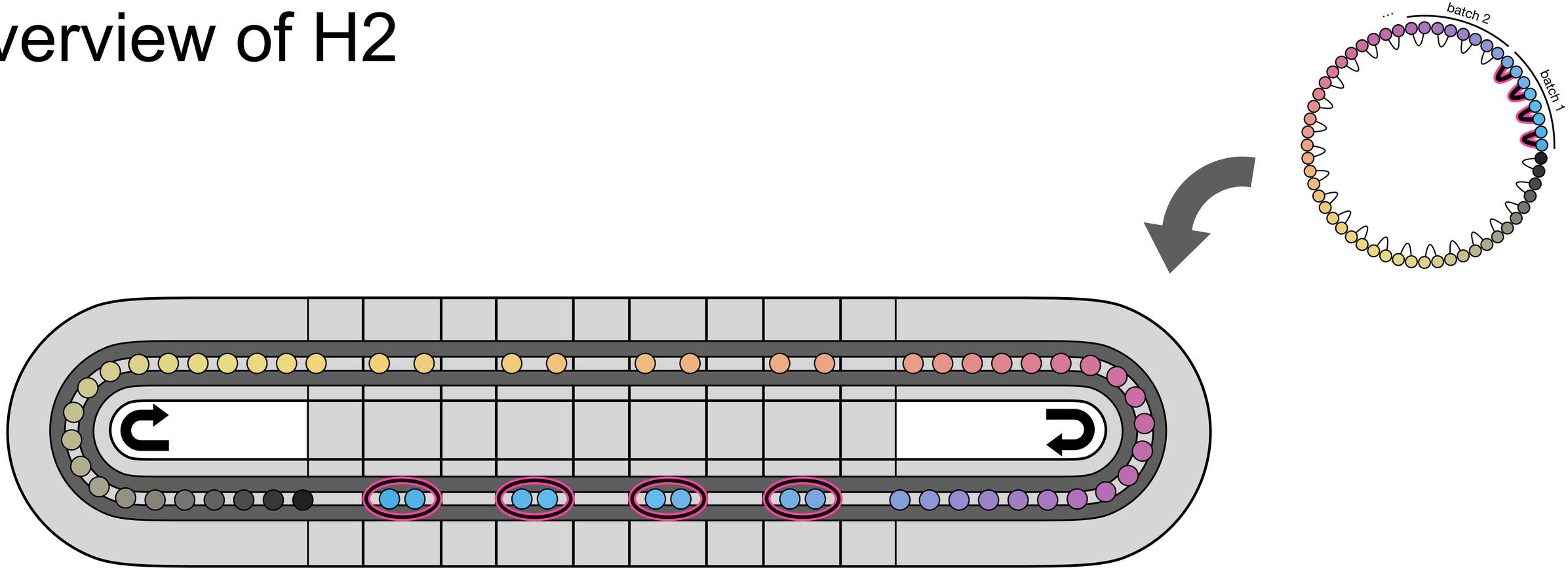

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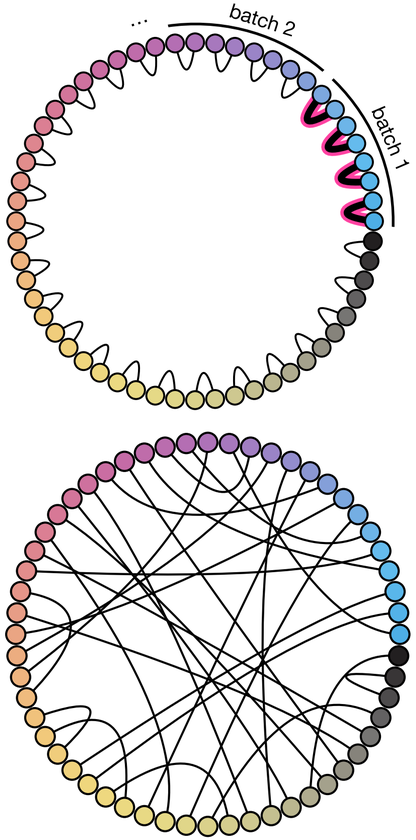

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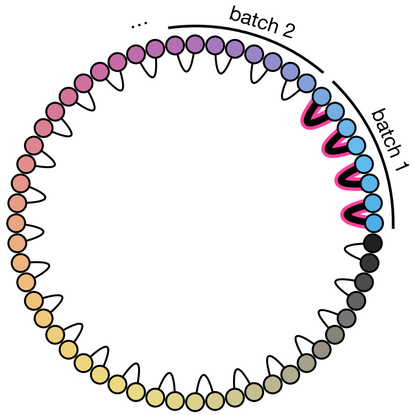

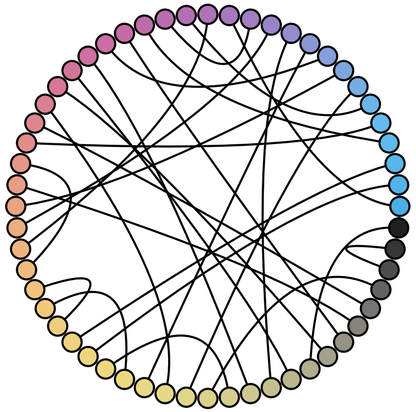

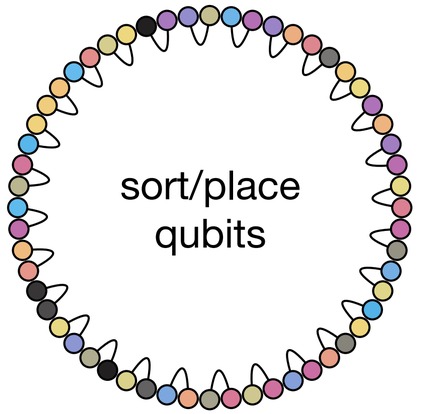

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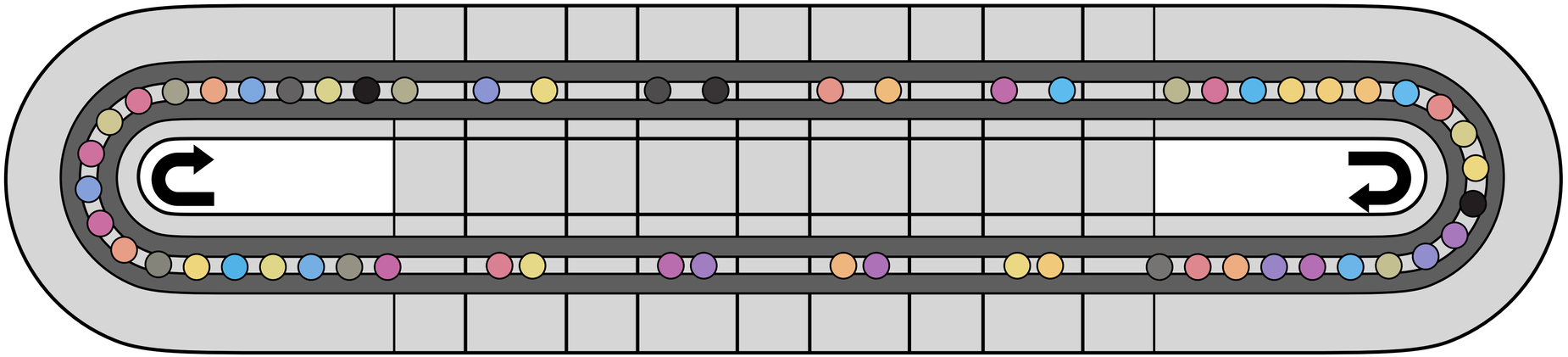

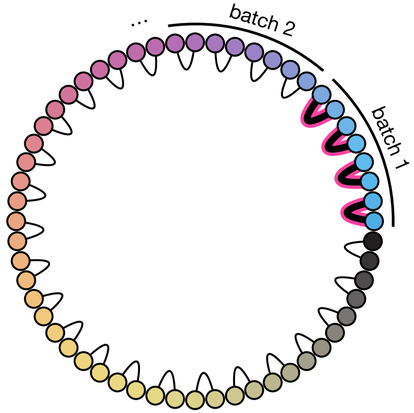

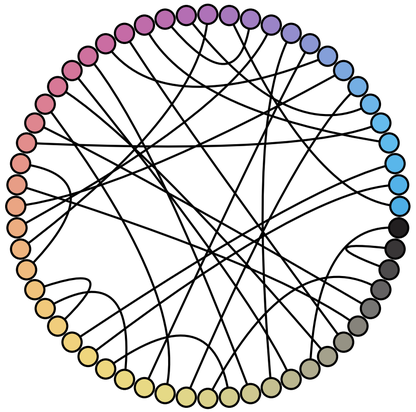

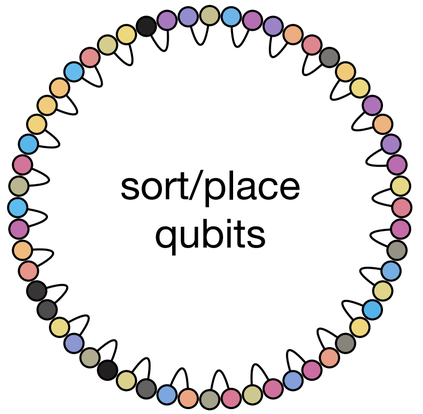

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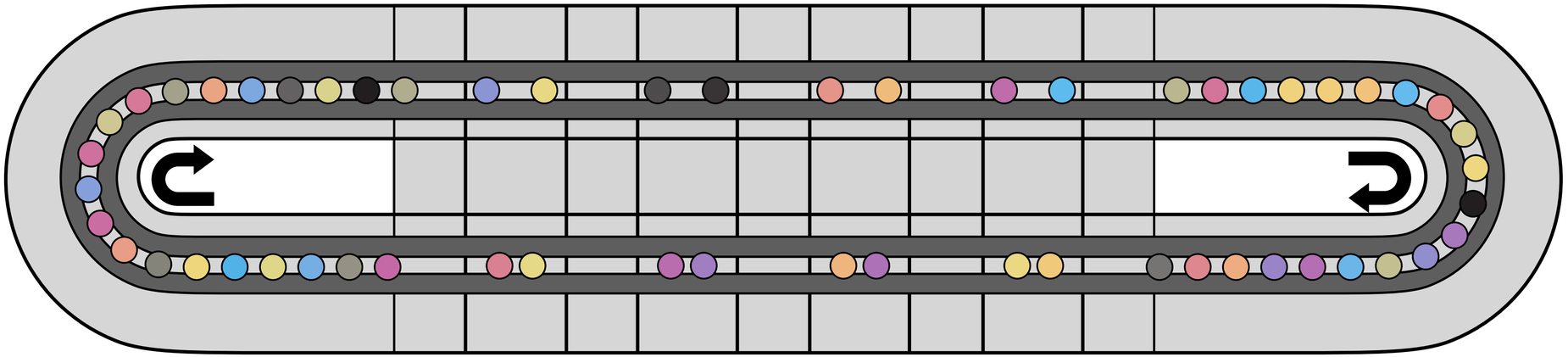

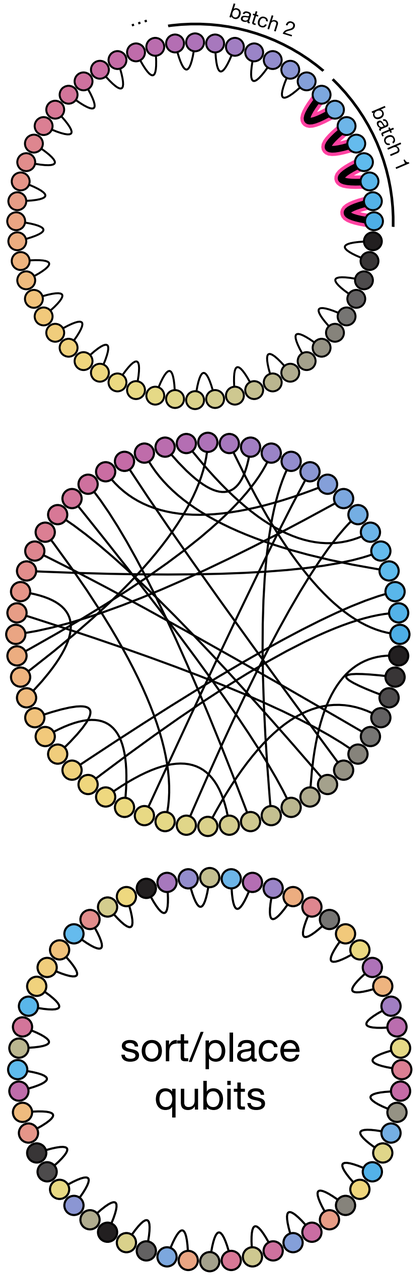

Advantages of the QCCD architecture:

- High connectivity (arbitrary at present!)

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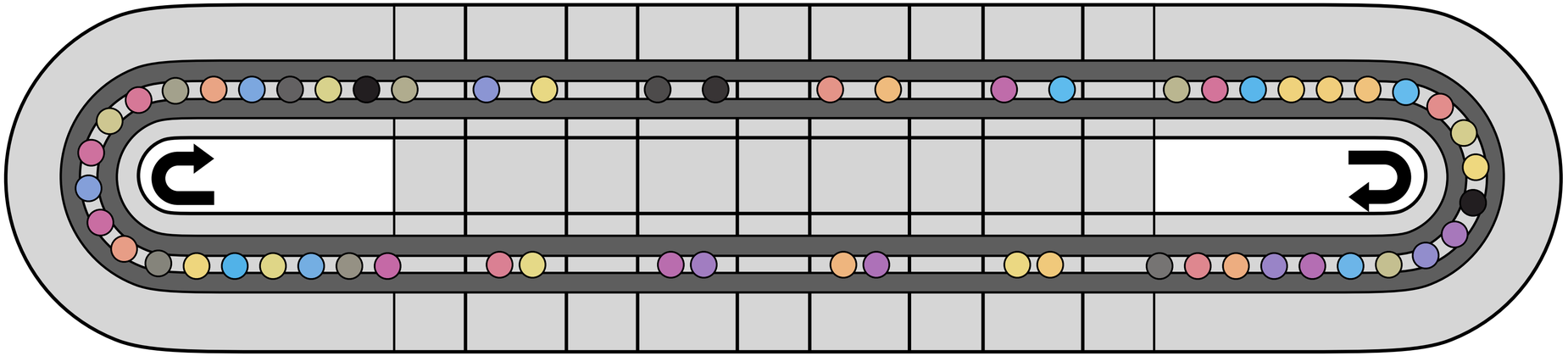

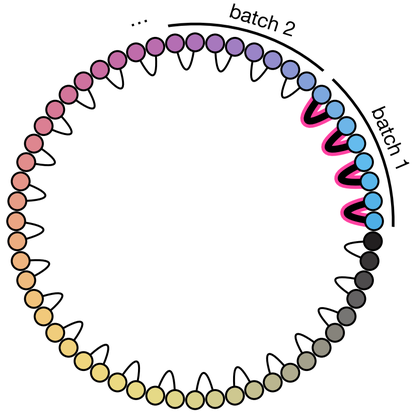

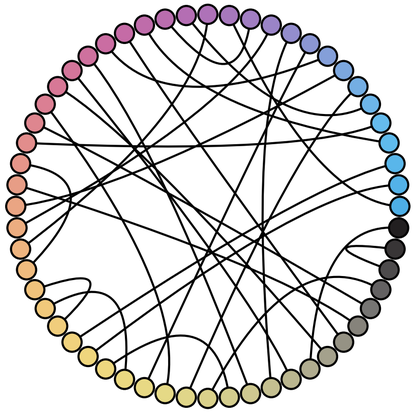

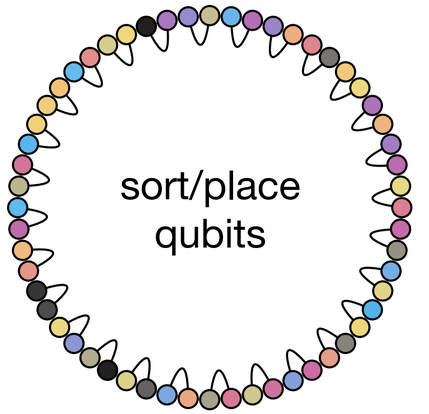

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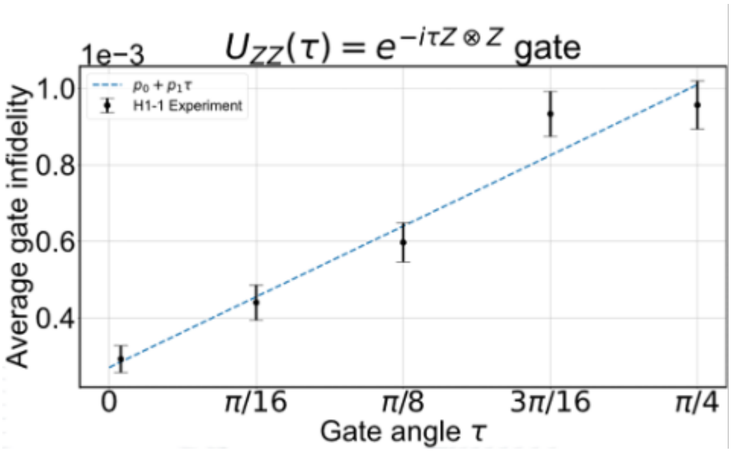

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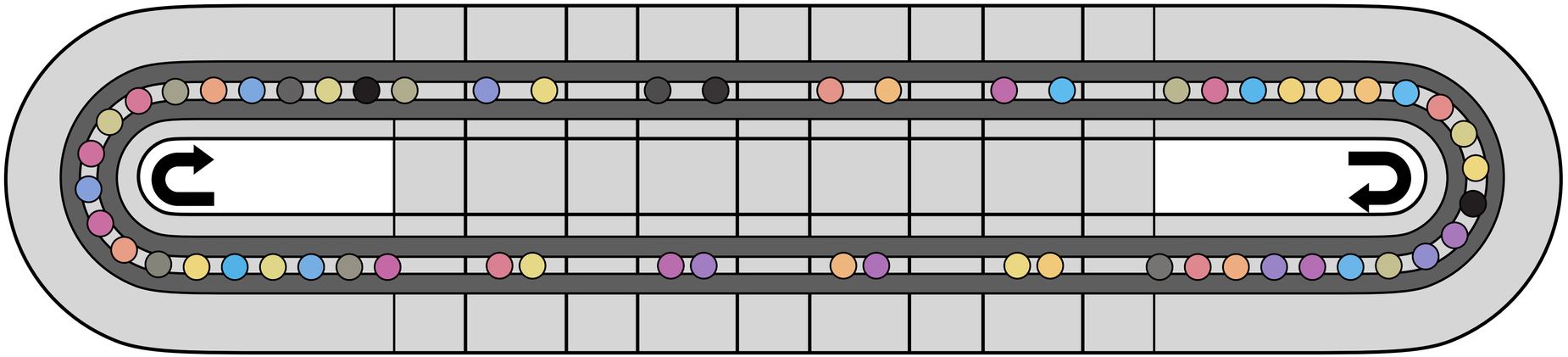

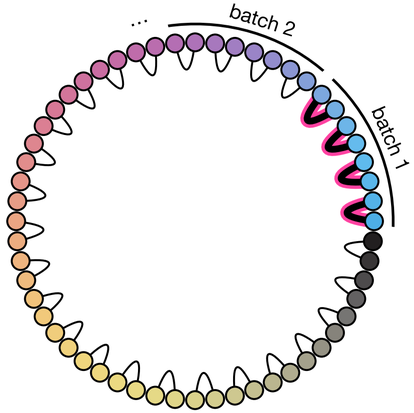

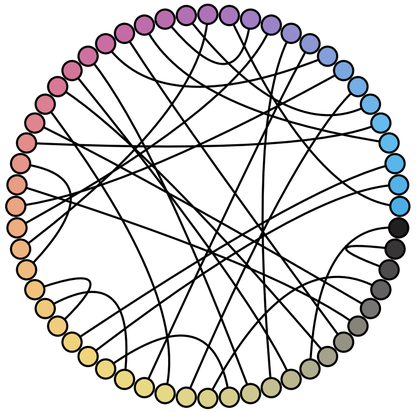

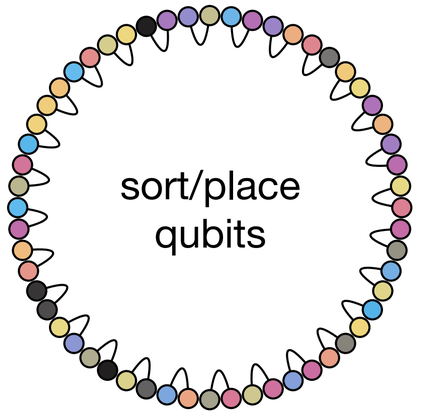

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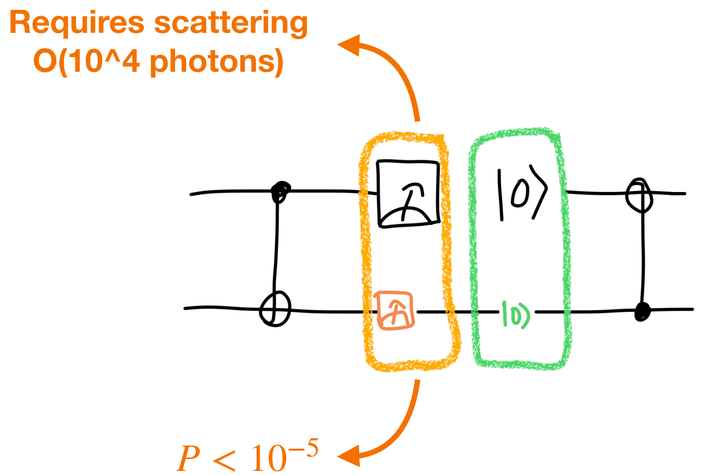
- Low cross-talk



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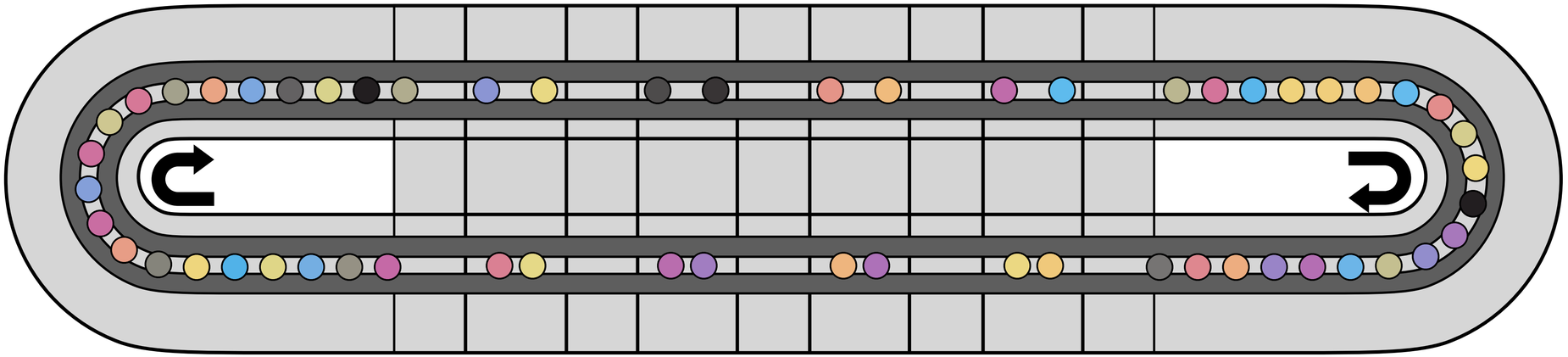

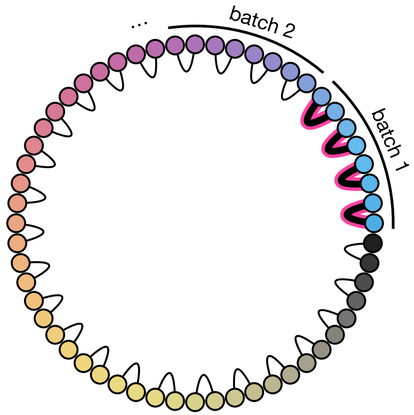

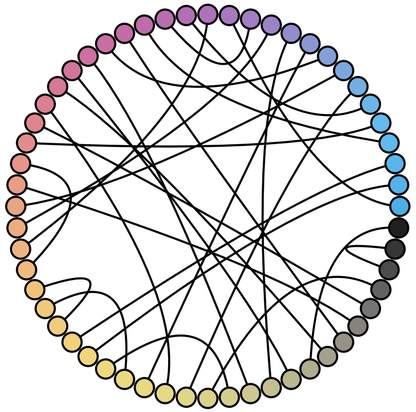

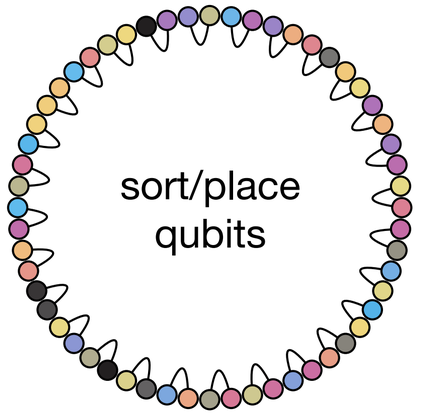

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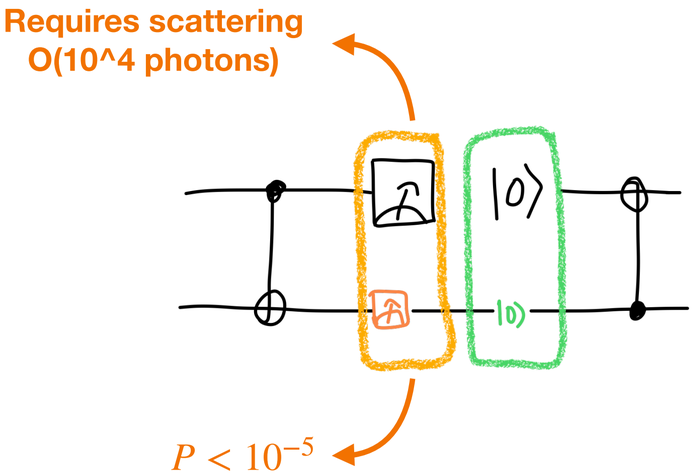
Primary disadvantage:

- It is (relatively) slow



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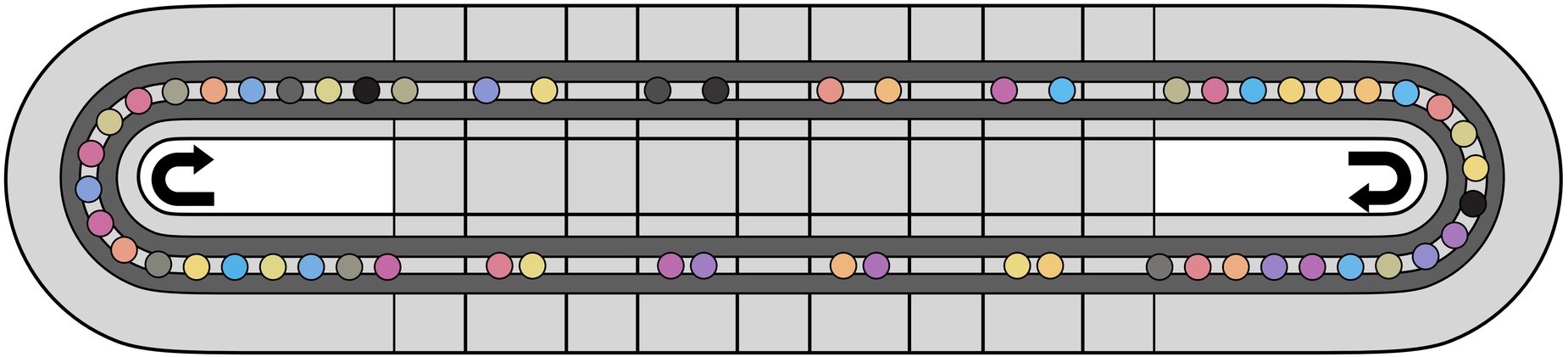

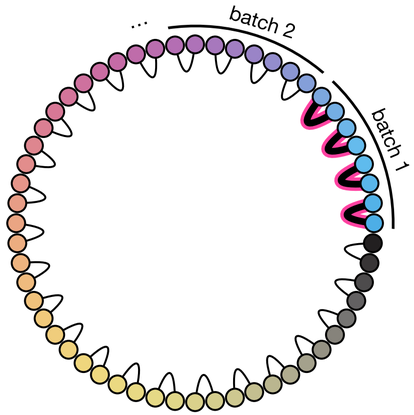

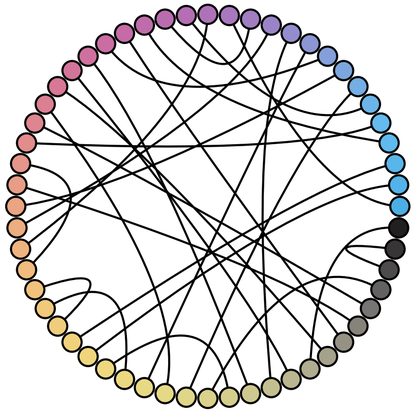

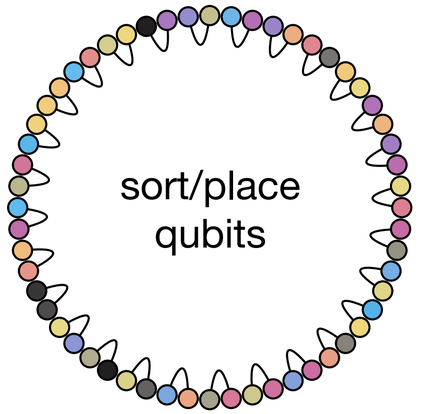

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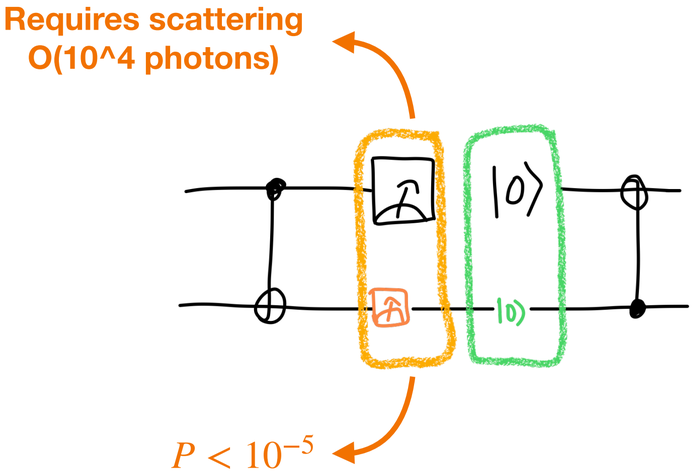
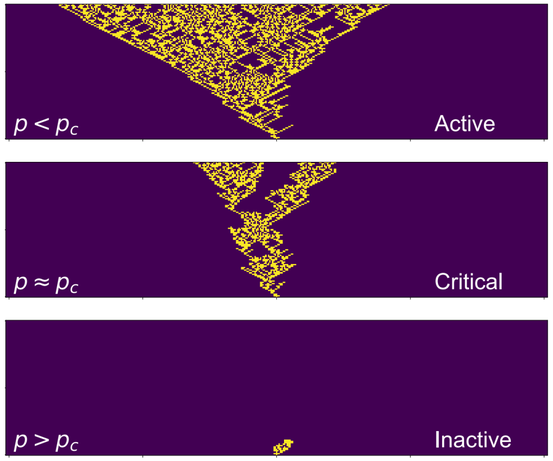


Non-equilibrium phase transition

arXiv 2209.12889

Classical



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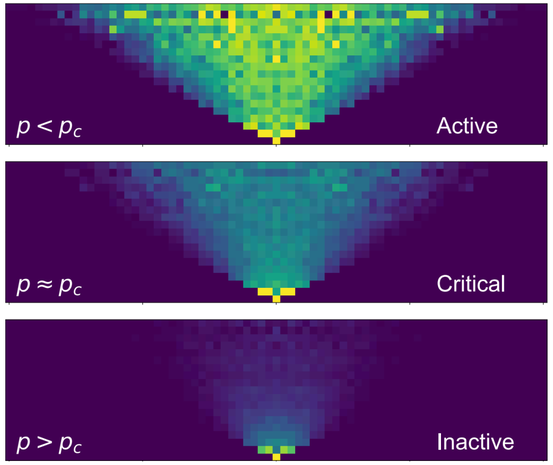

Long-range entanglement from adaptive circuits

Quantum tensor networks

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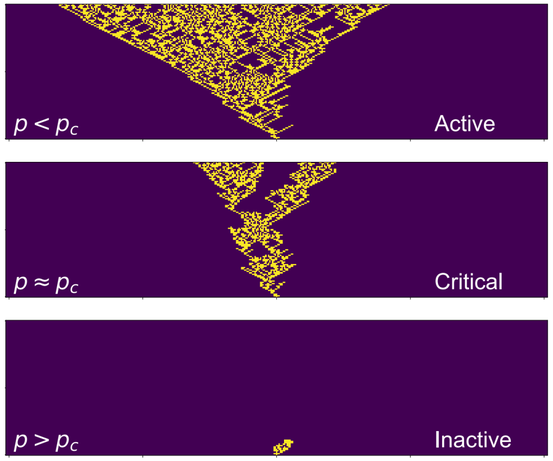

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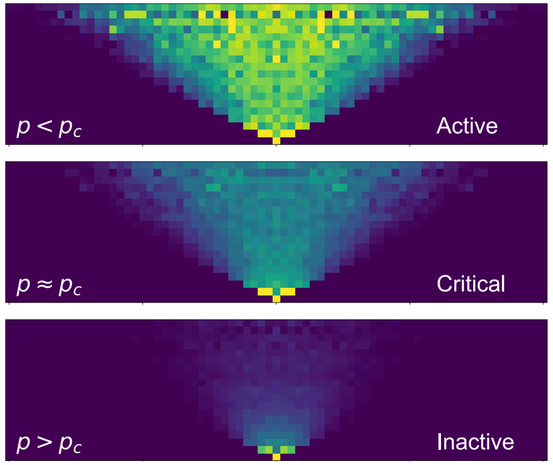

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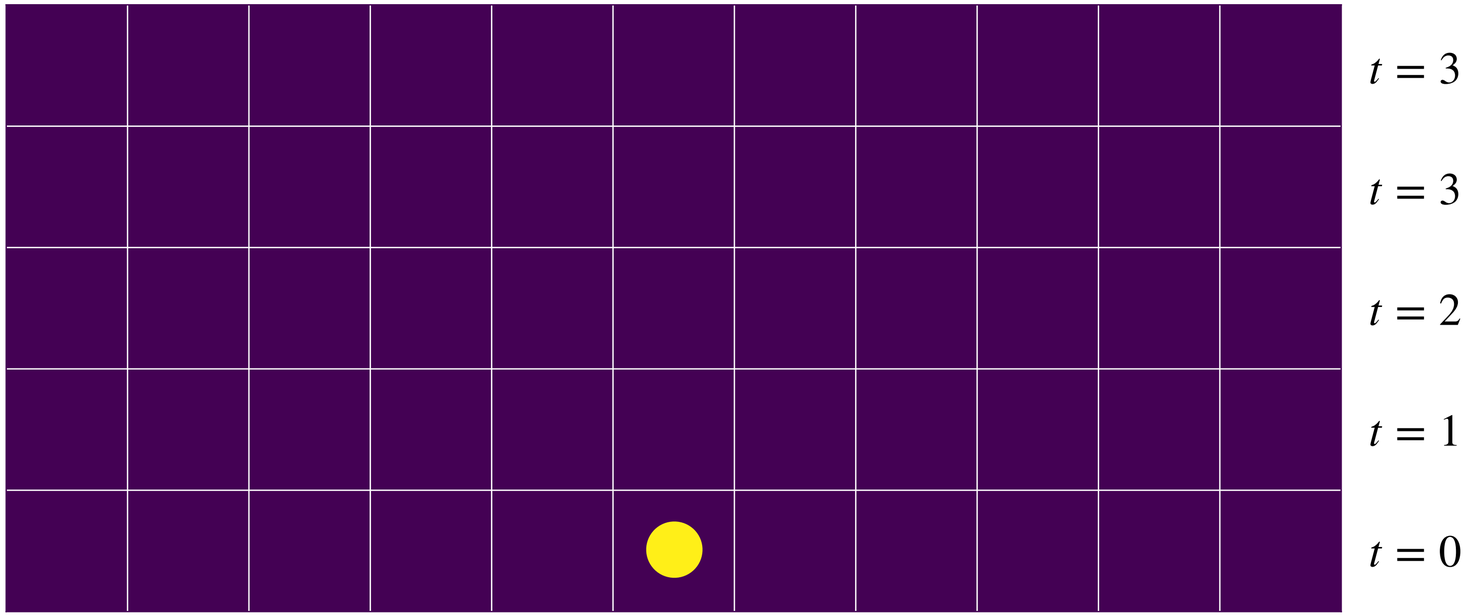

Infect neighbor with probability Q

Get better with probability P

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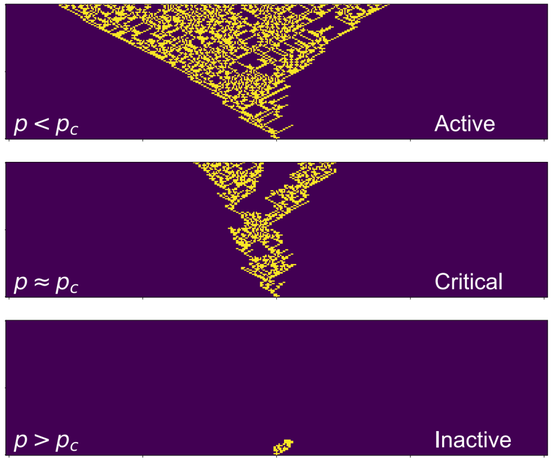

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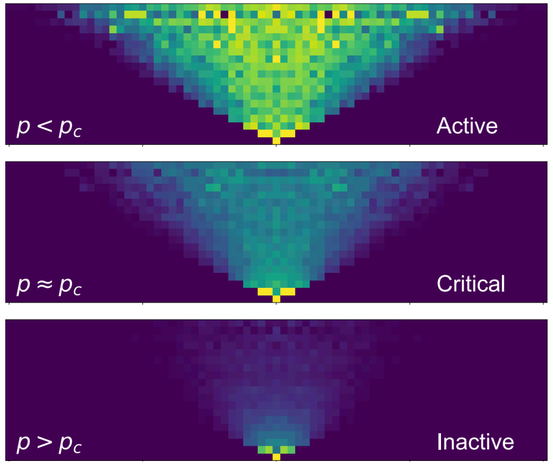

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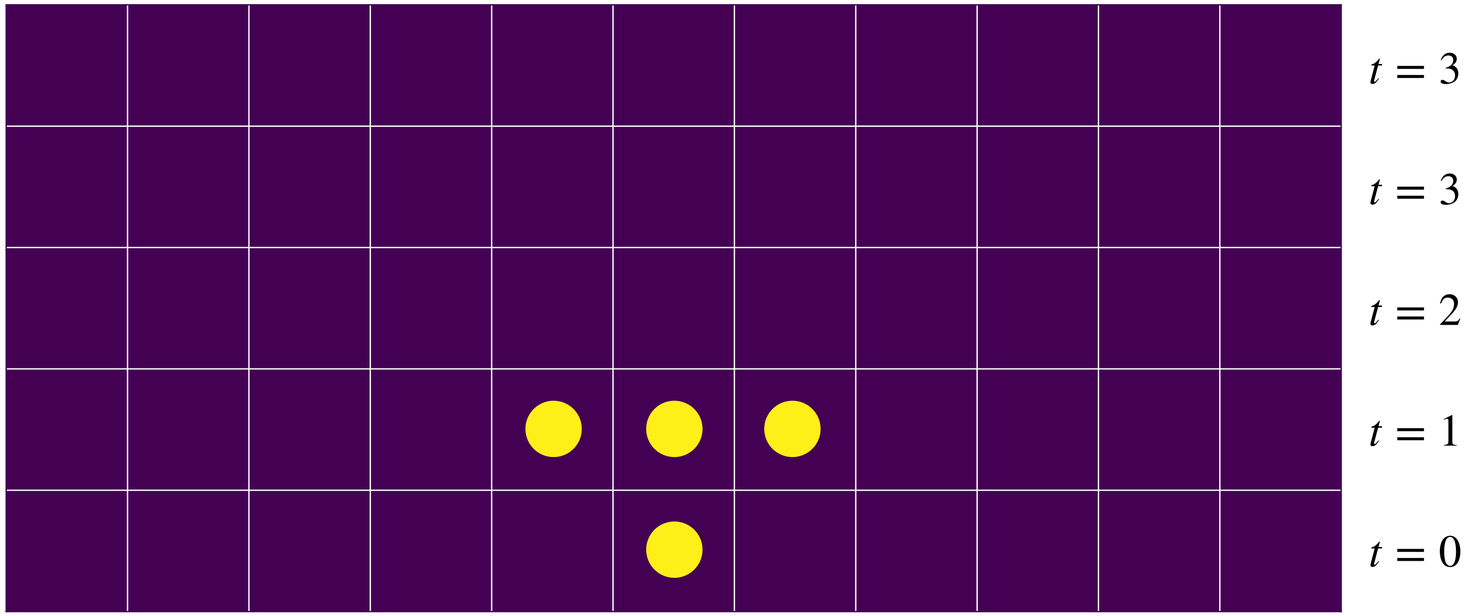

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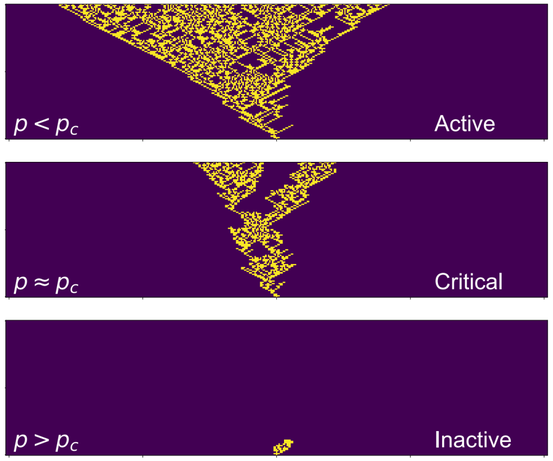

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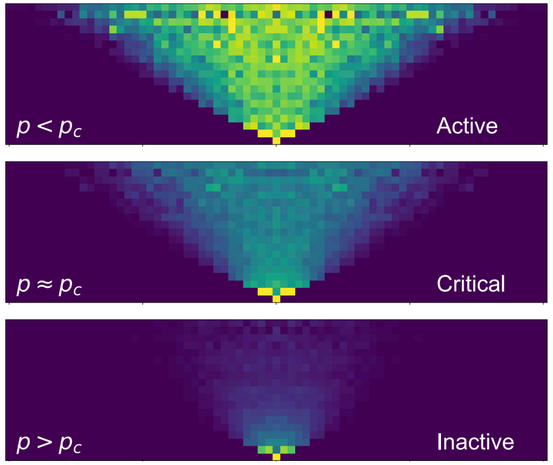

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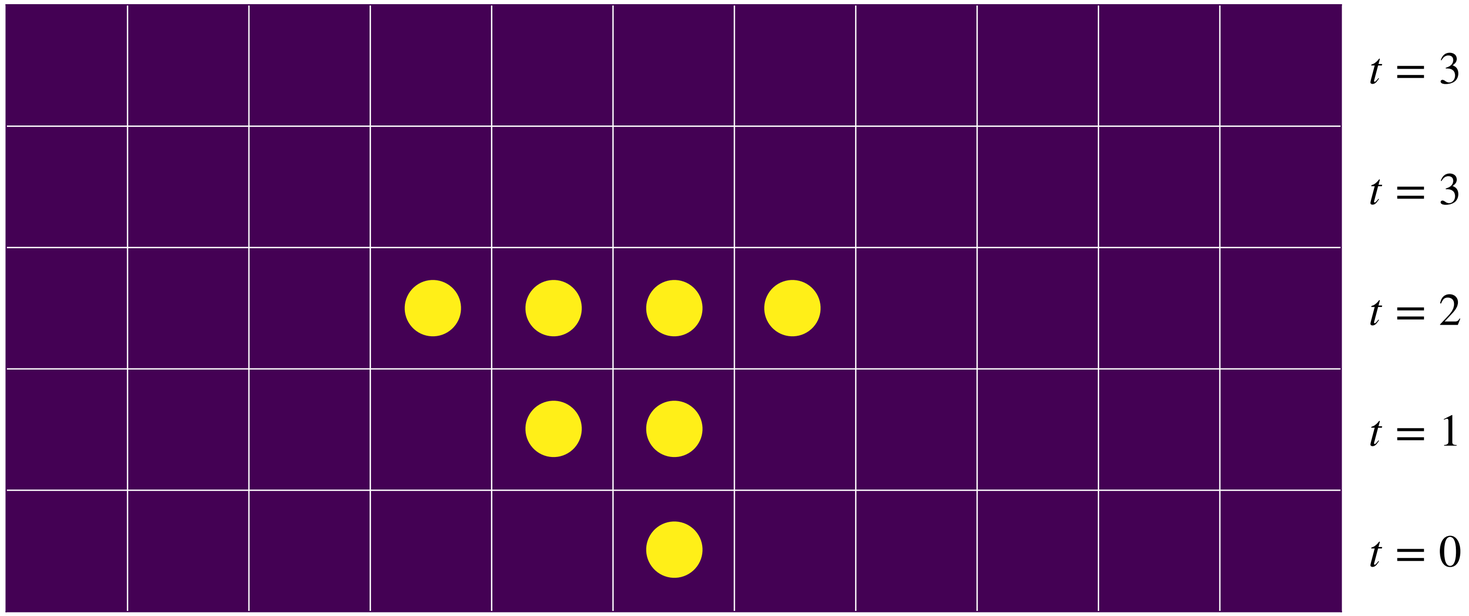

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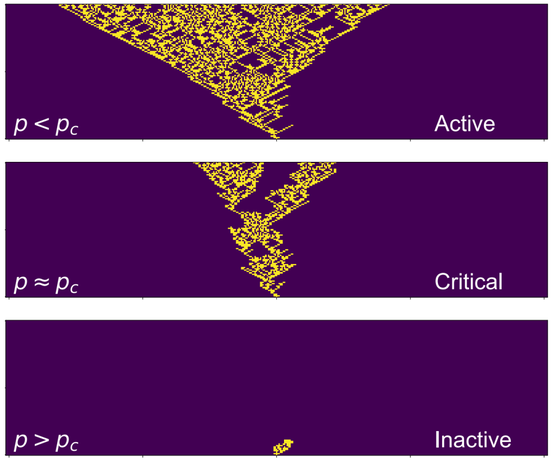

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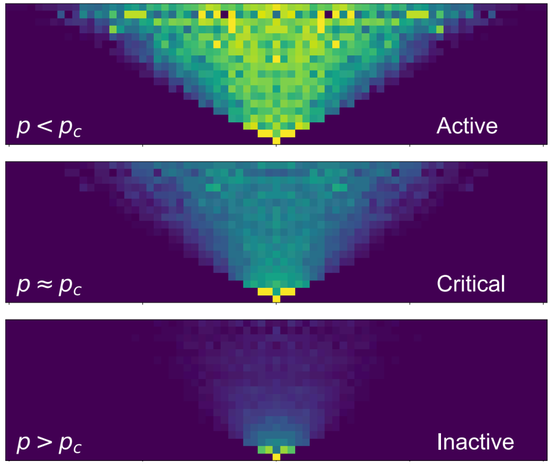

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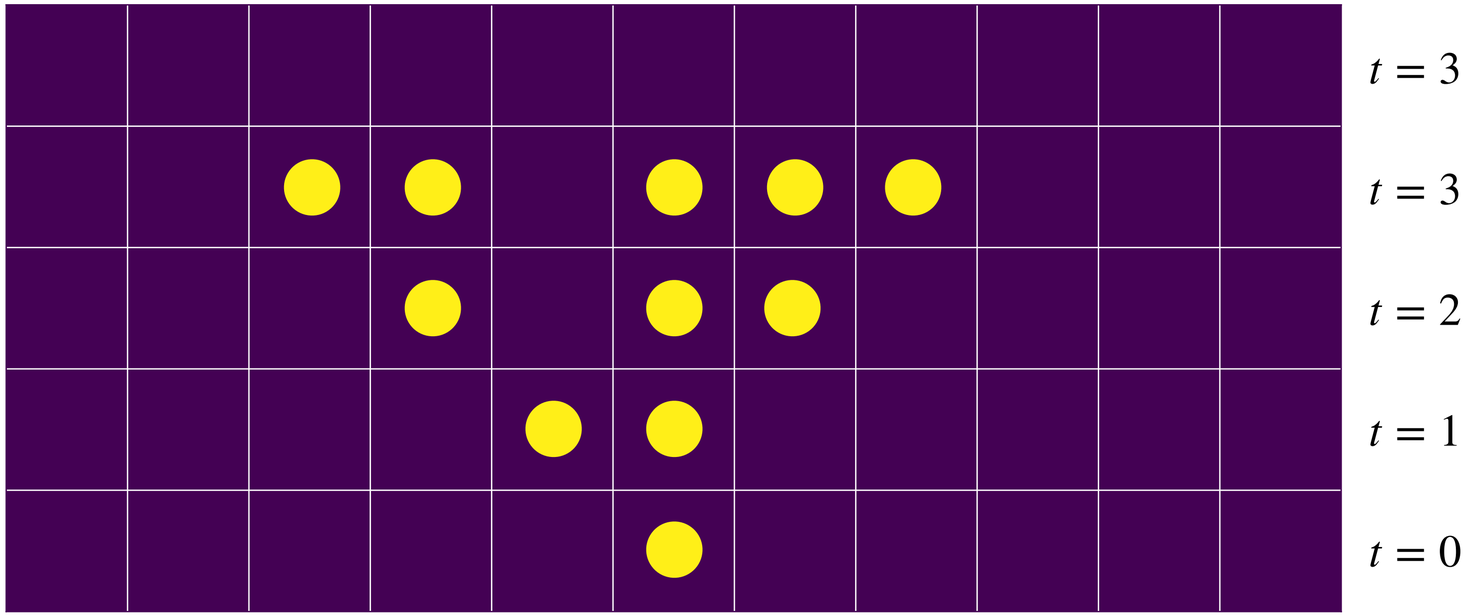

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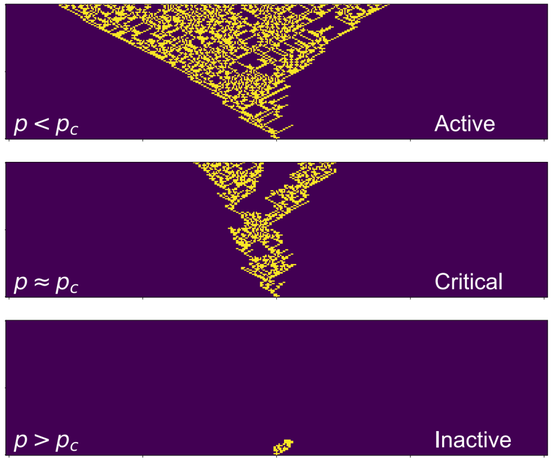

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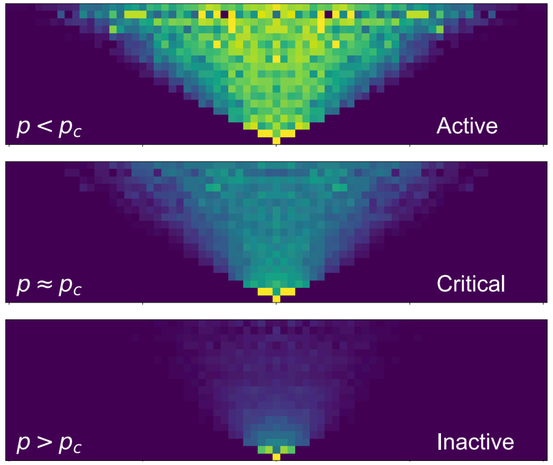

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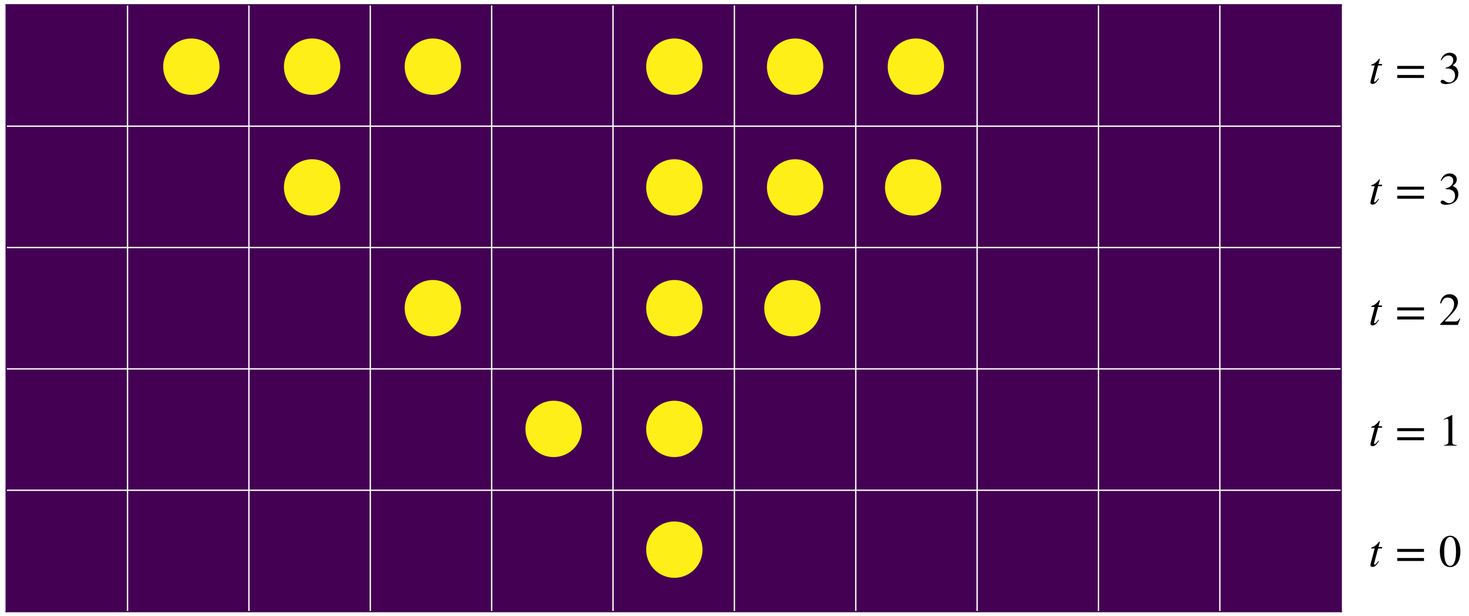

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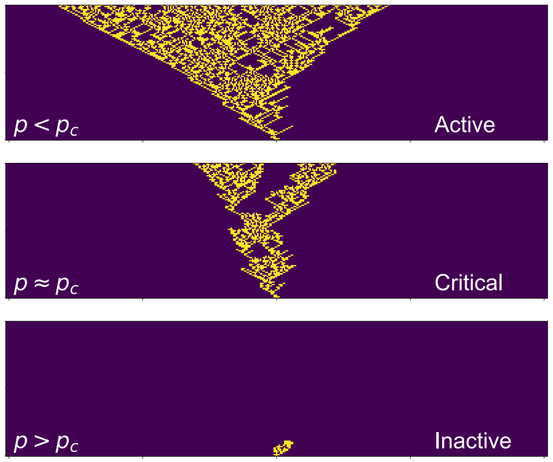

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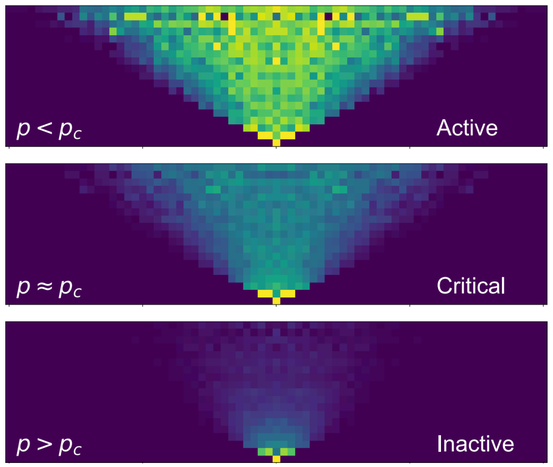

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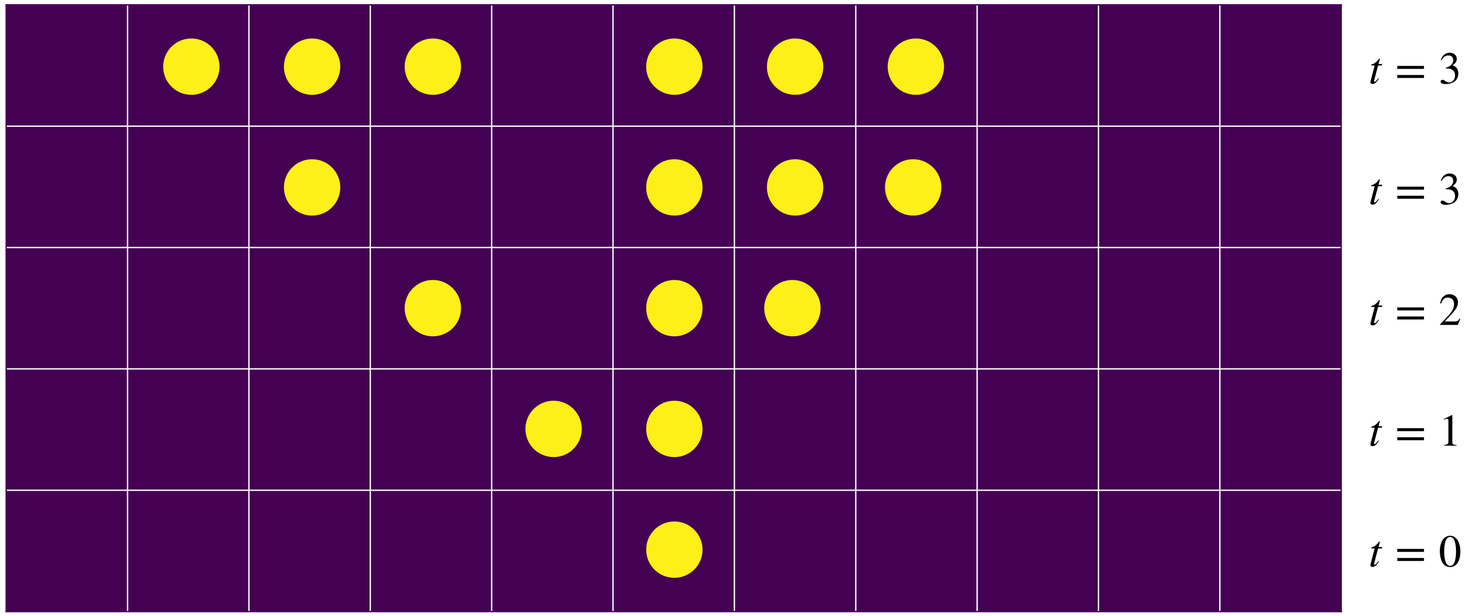
Quantum tensor networks

As a function of $p = P/Q$, there is a phase transition between an absorbing state ($p > p_c$: disease dies out) and an active state ($p < p_c$: pandemic)



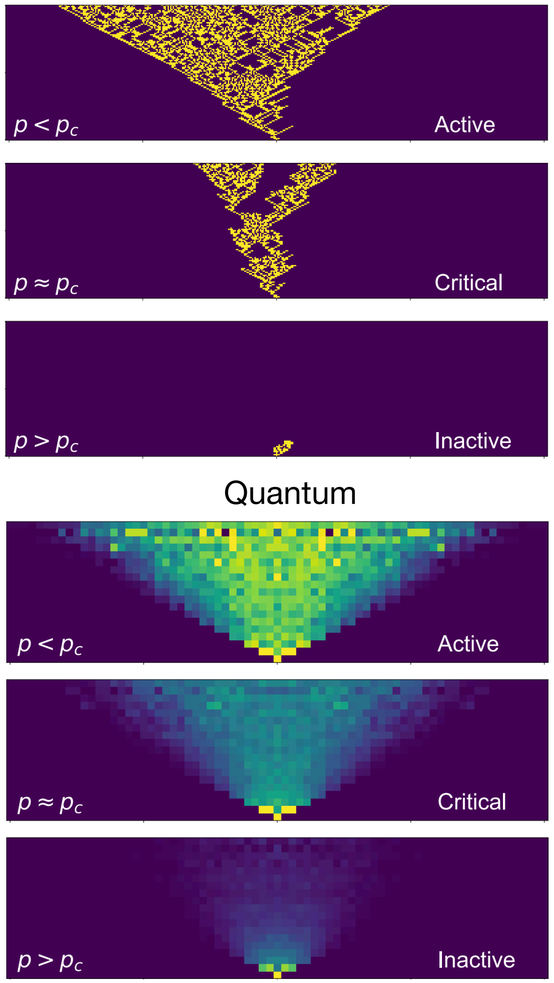
Infect neighbor with probability Q

Get better with probability P

Non-equilibrium phase transition

arXiv 2209.12889

Classical



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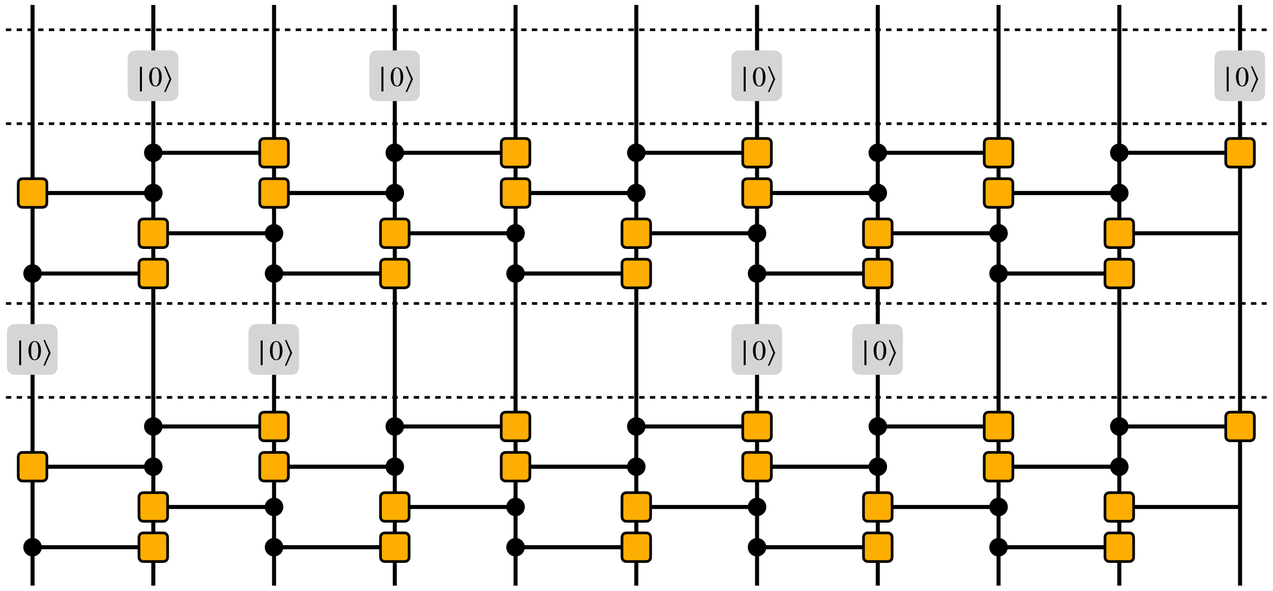

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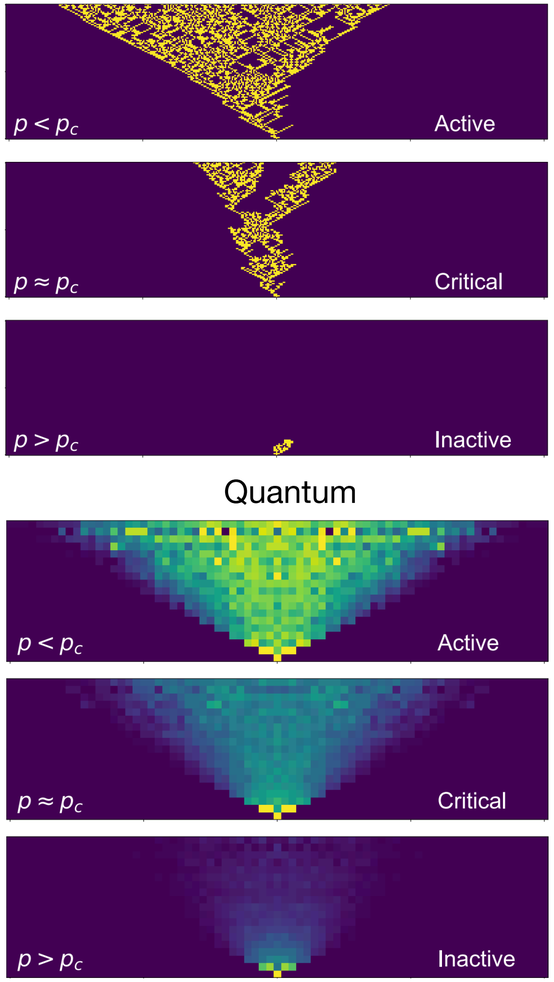

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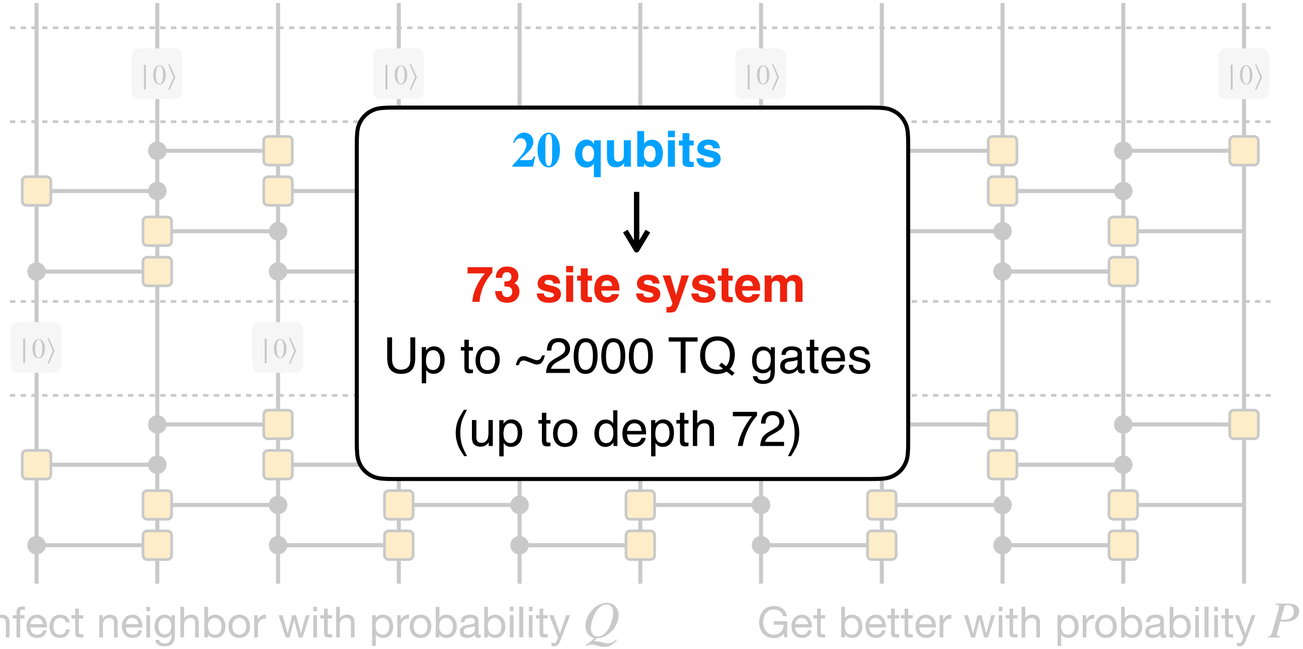

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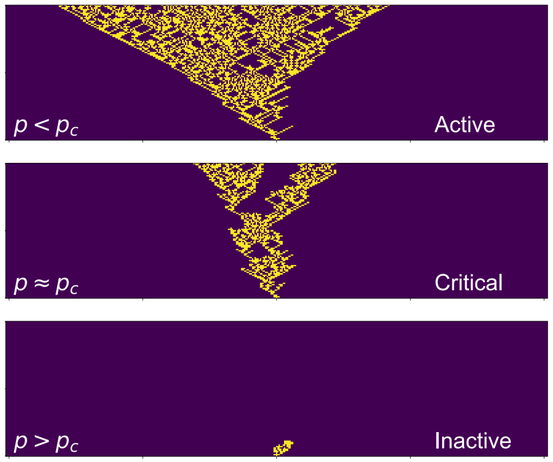

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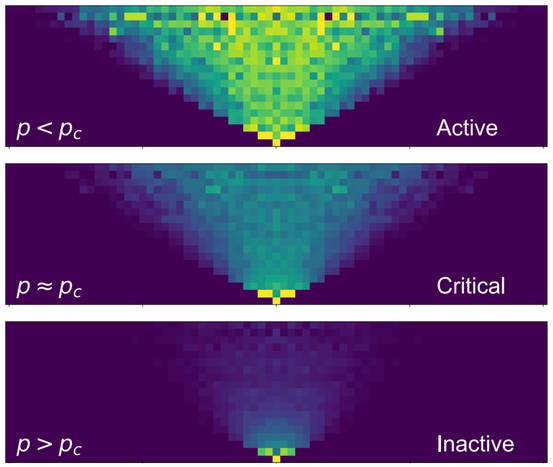

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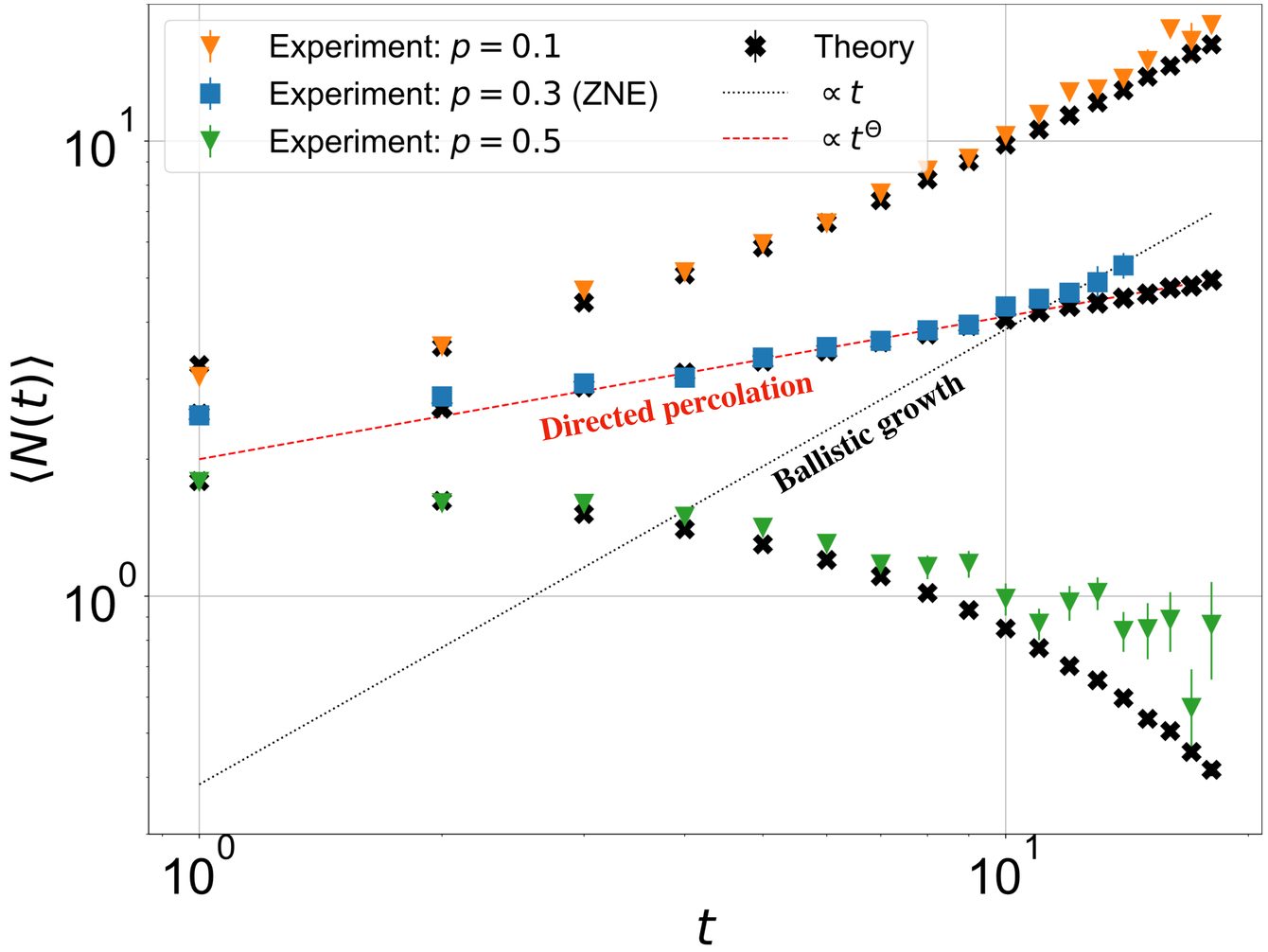

Quantum tensor networks

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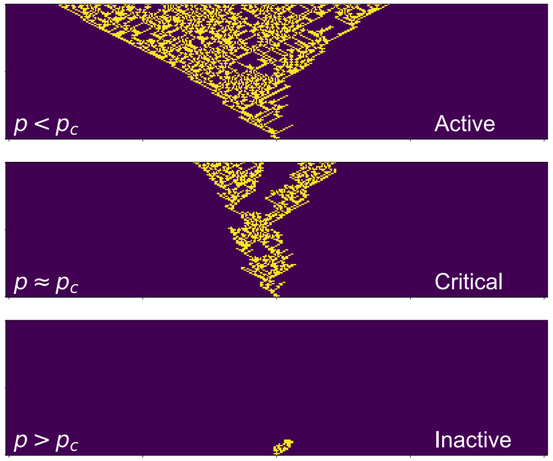
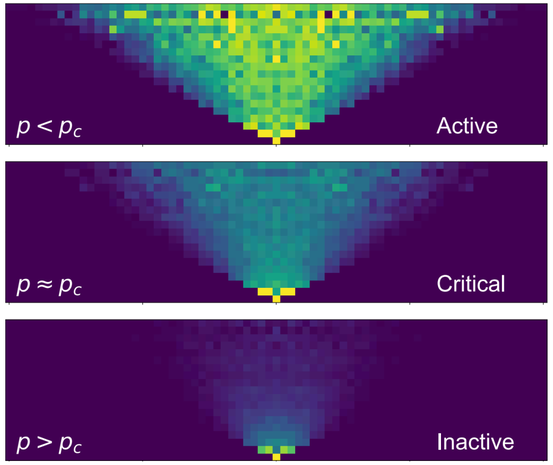
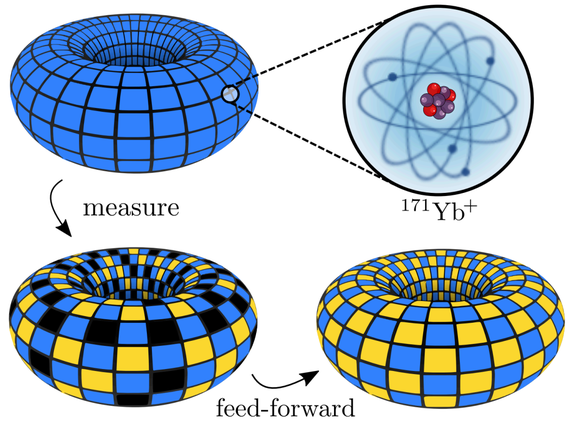


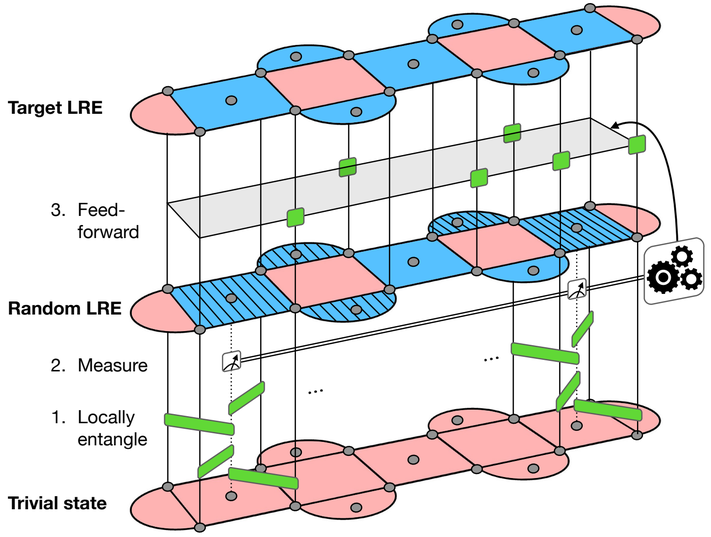
Quantum



Long-range entanglement from adaptive circuits

arXiv 2302.01917, 2302.03029, arXiv:2305.03766





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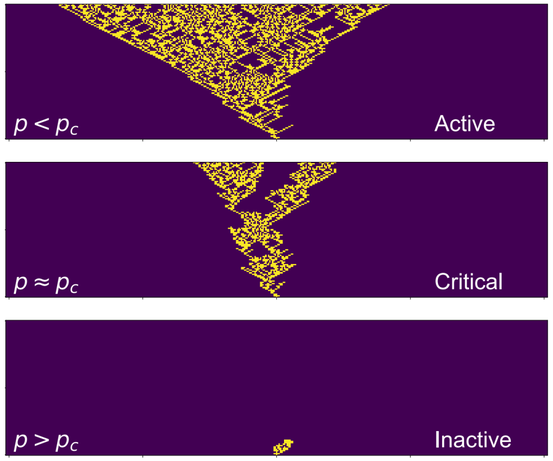

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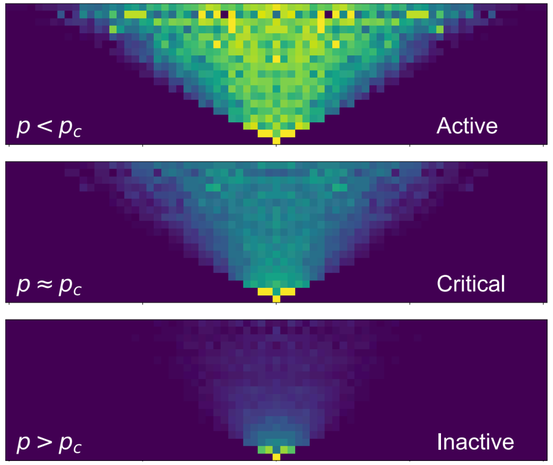

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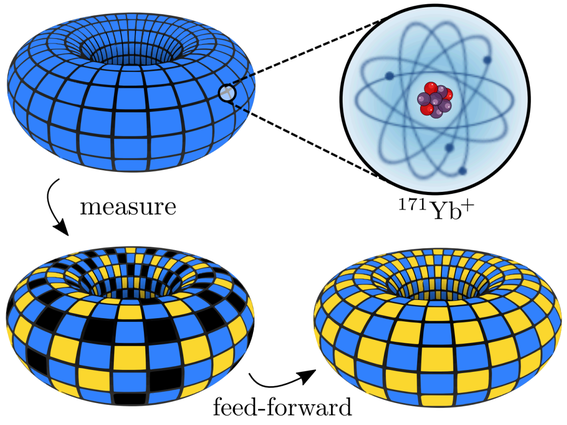
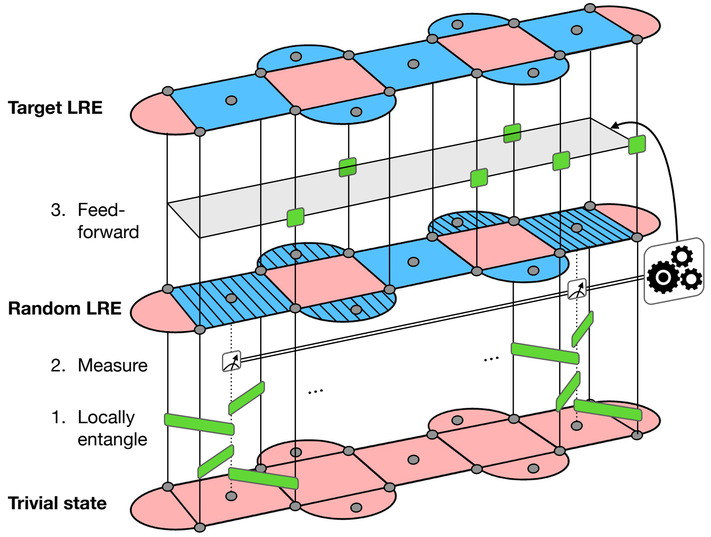
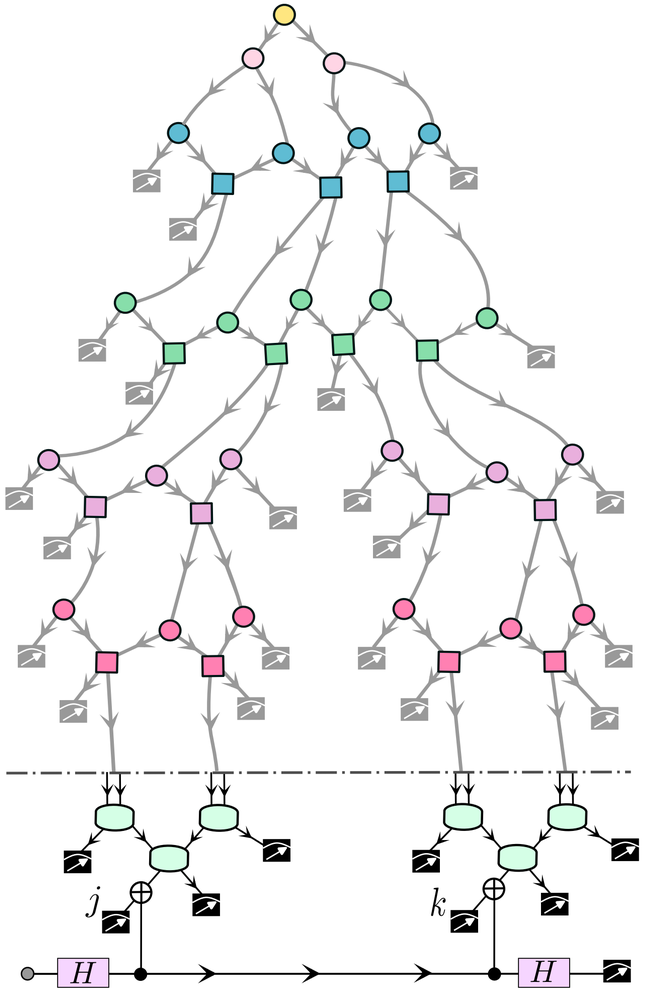




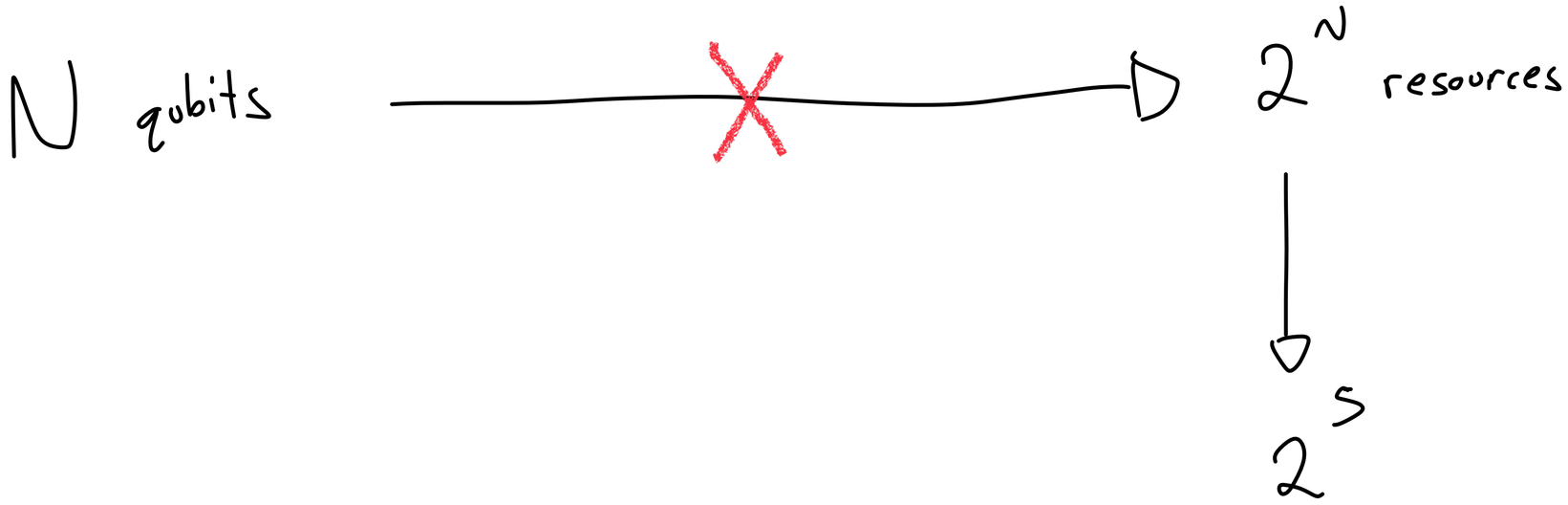
Quantum tensor networks

arXiv 2305.01650



Quantum tensor networks

Key insight from classical tensor network methods:



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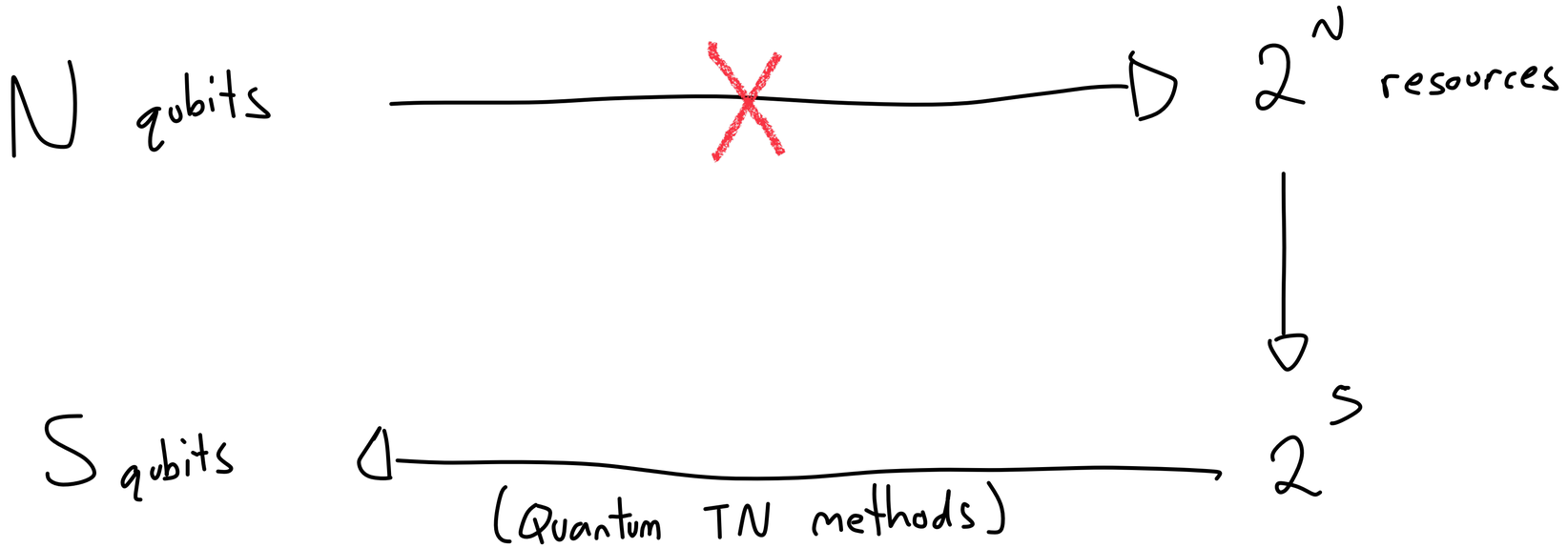

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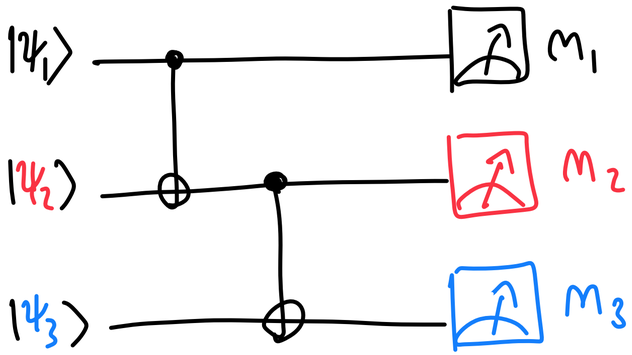

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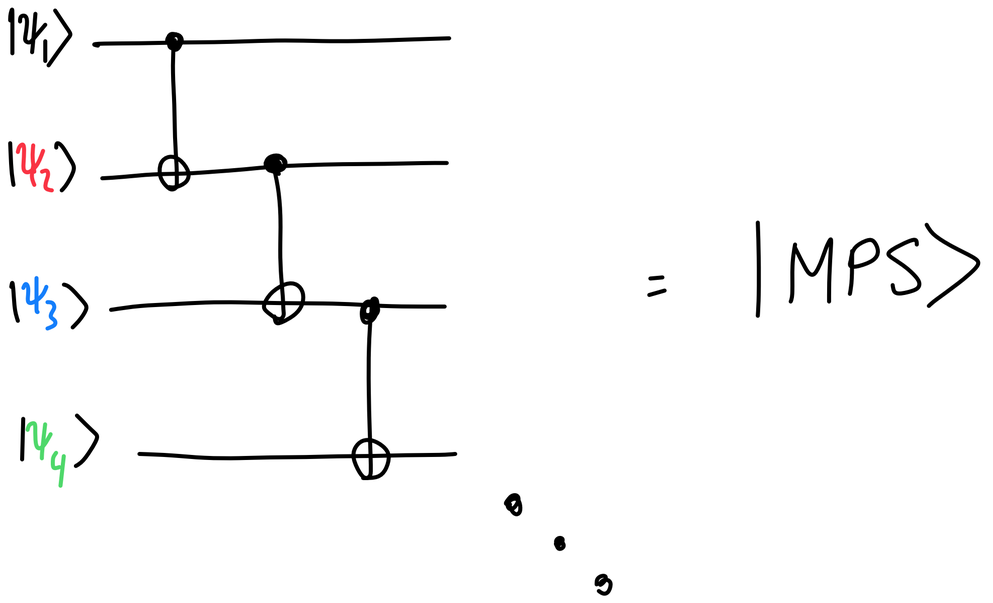

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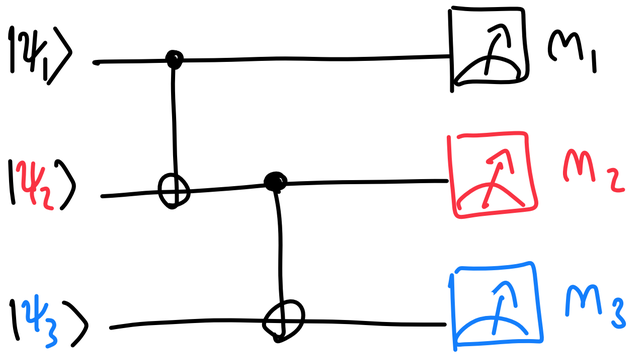

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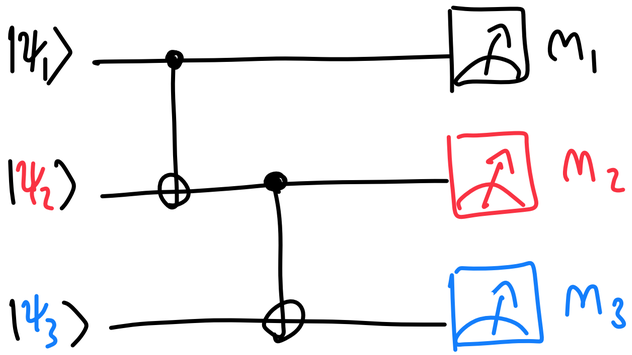

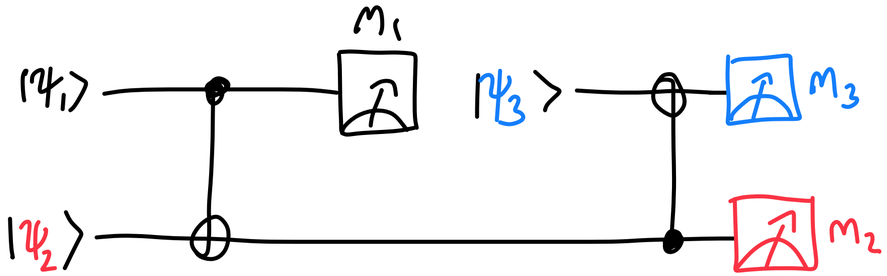

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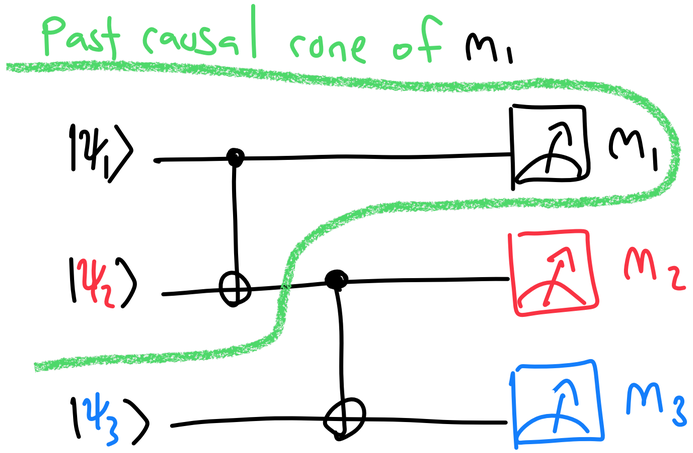

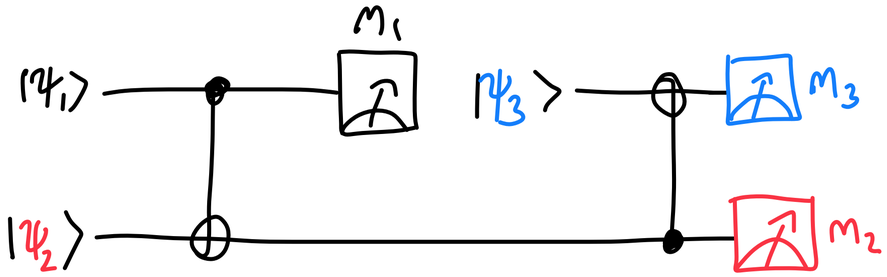

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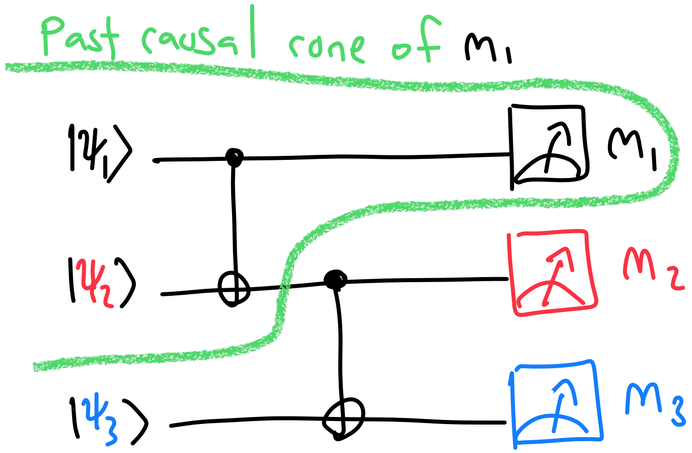

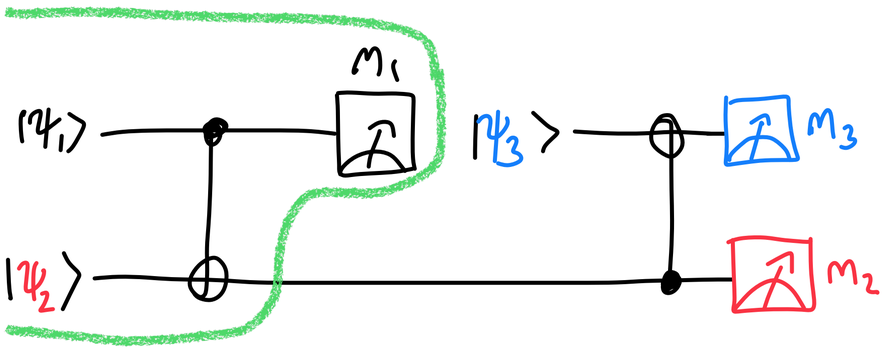

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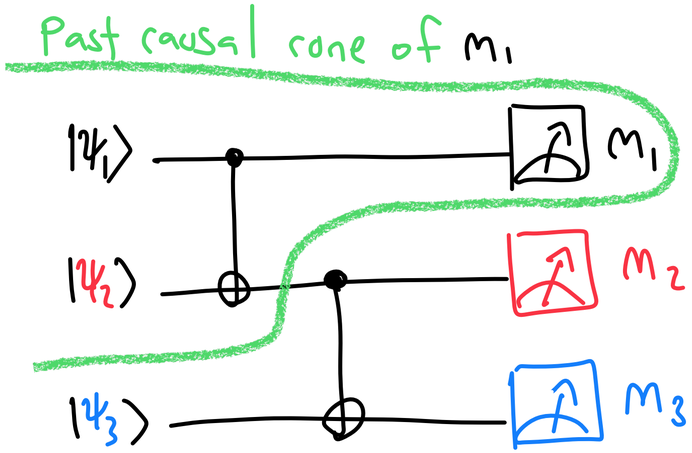
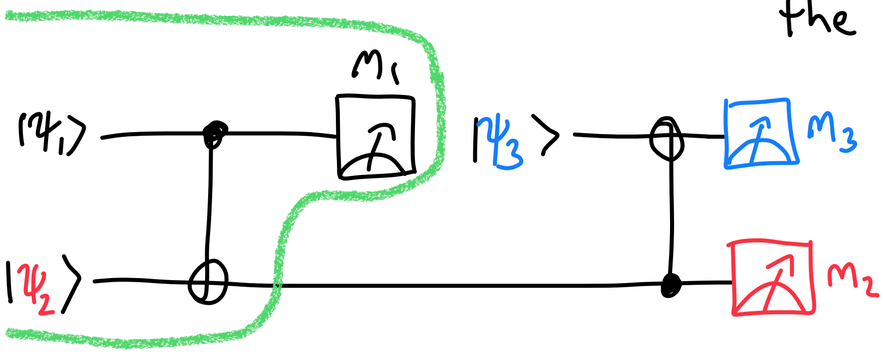


m_1, m_2, m_3 are sampled from the exact same distribution



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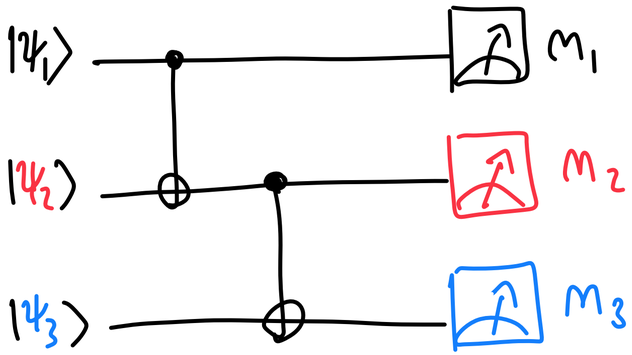
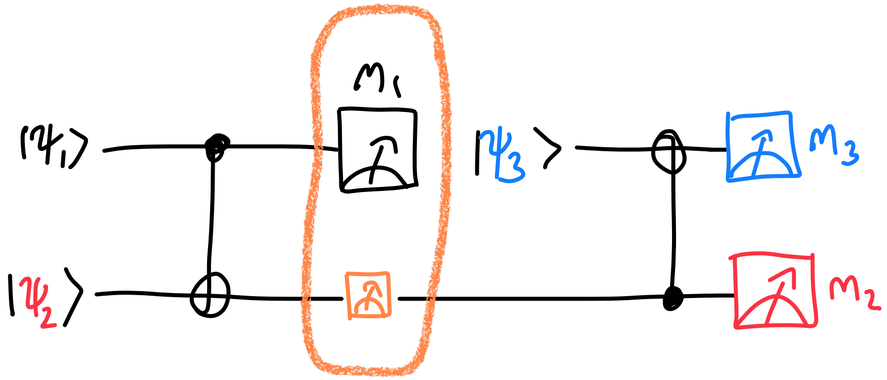
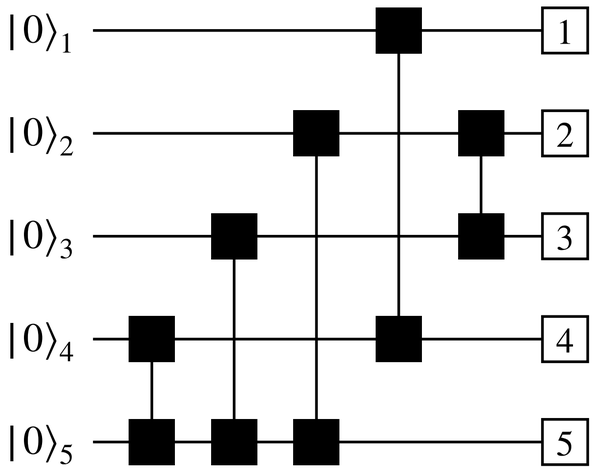




Automation via qubit reuse compilation

arXiv:2210.08039



Greedy heuristic for choosing measurement order:

Every time you measure a qubit, pick the one who's causal cone initialization requires the smallest number of new qubits

Automation via qubit reuse compilation

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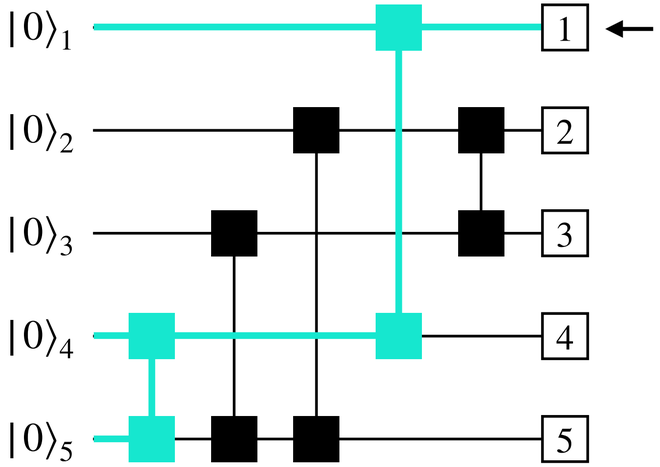

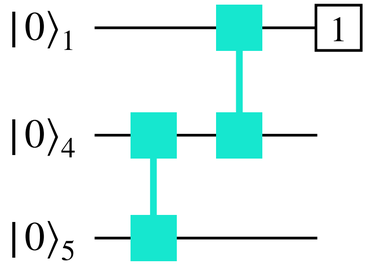

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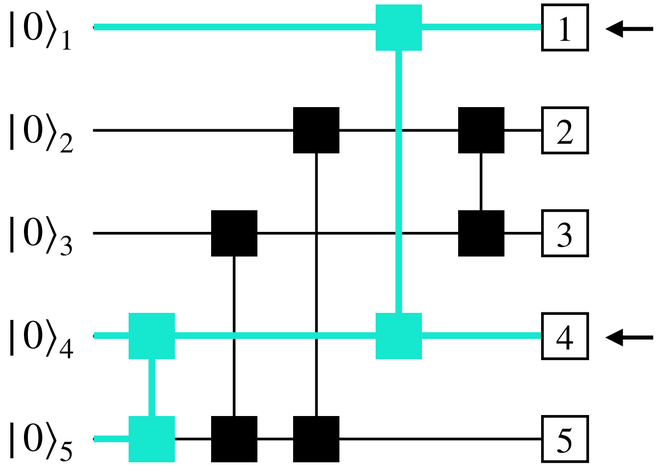

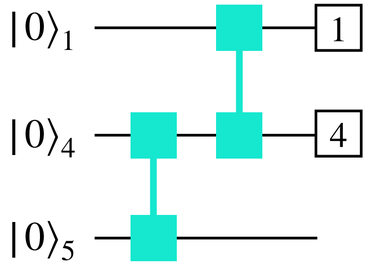

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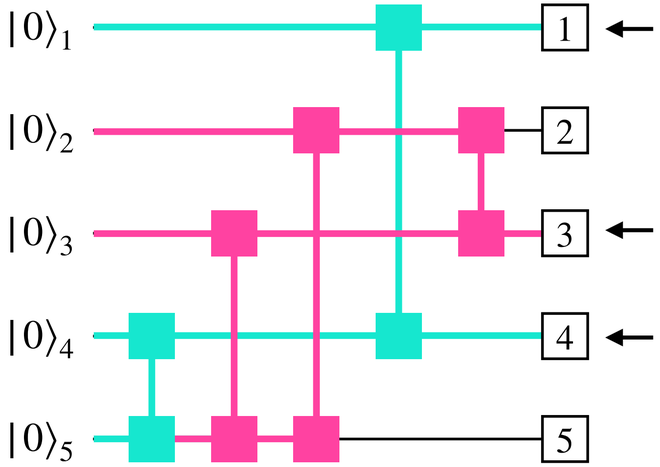

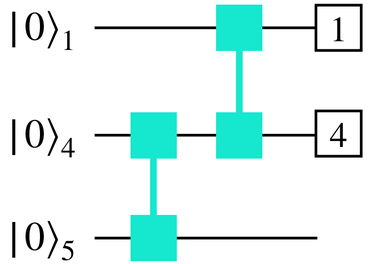

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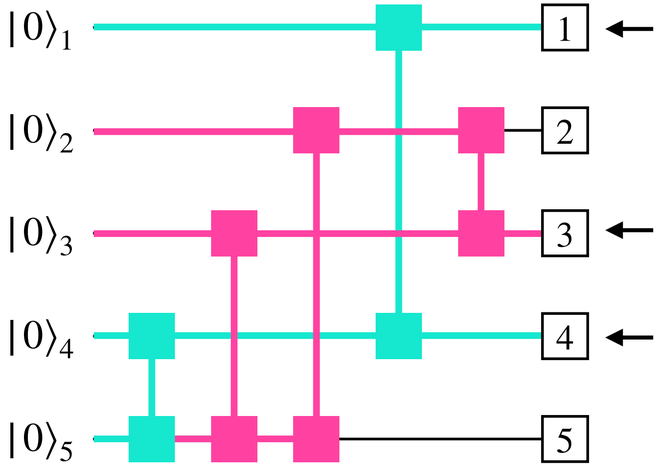

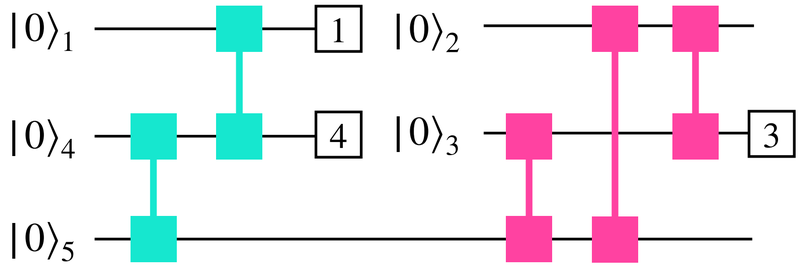

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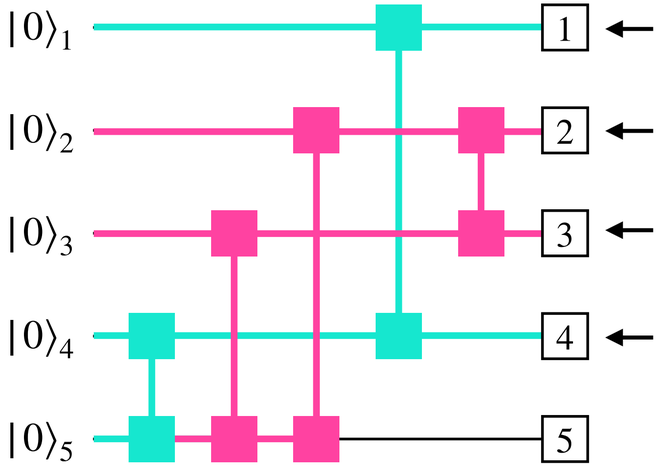

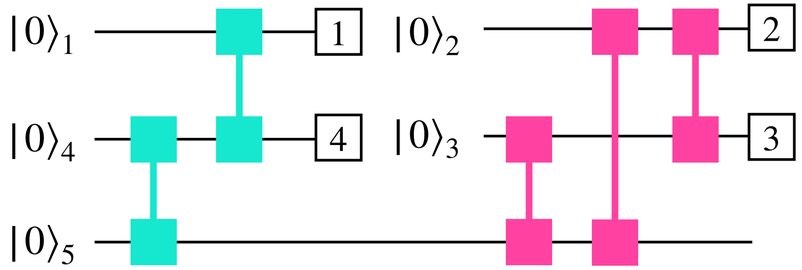

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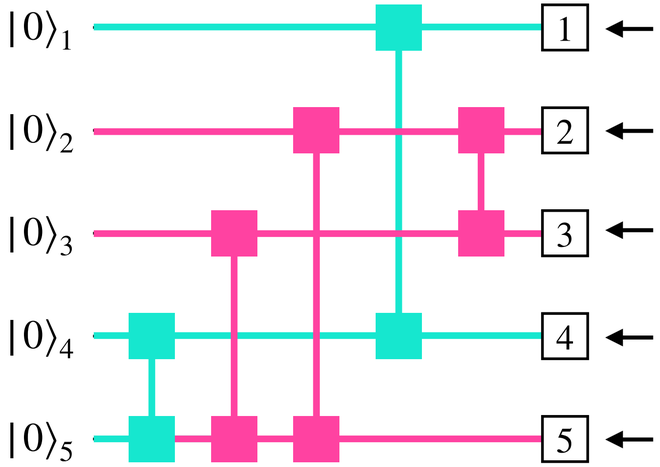

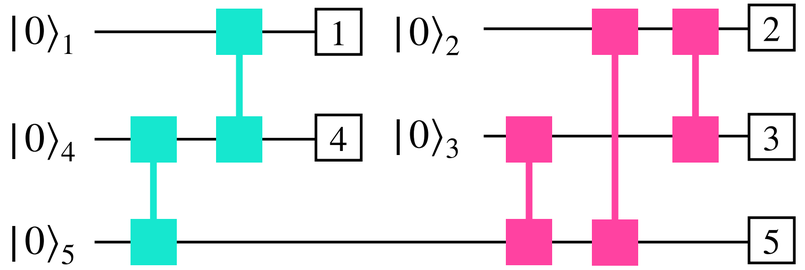

5 qubits → 3 qubits

MERA on a quantum computer

arXiv 2305.01650

$$H = -\sum_j X_j X_{j+1} - \lambda \sum_j Z_j$$

MERA on a quantum computer

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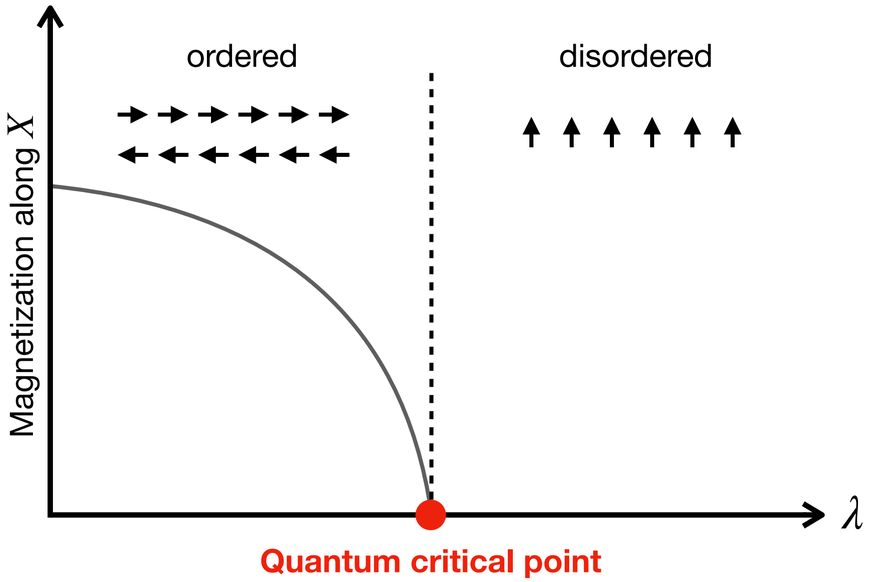


$\langle X_j X_k \rangle \sim \frac{1}{|j-k|^\eta} \quad (\eta = \frac{1}{4})$

MERA on a quantum computer

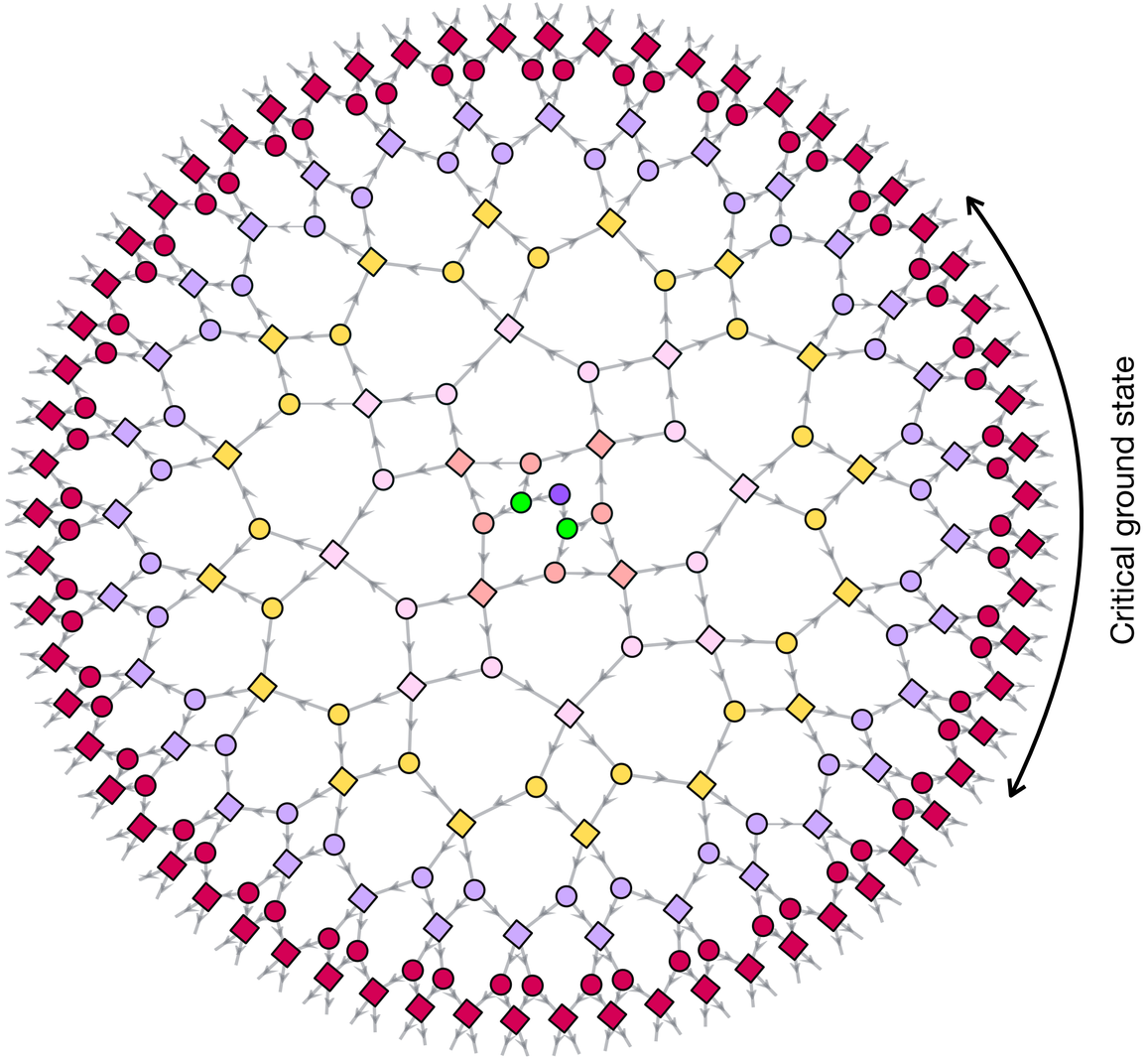
arXiv 2305.01650

20 qubits

↓

128 site system

Only 160 TQ gates



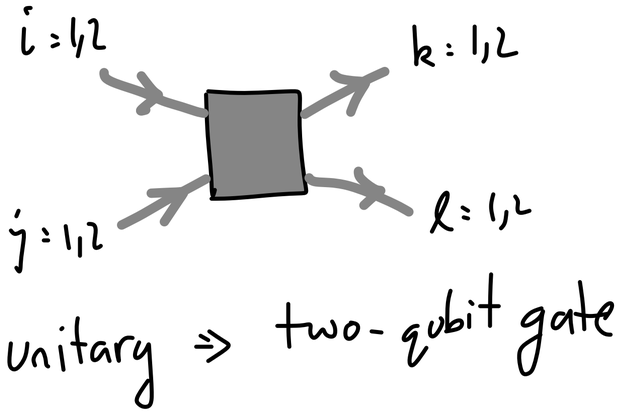
arxiv.org/abs/cond-mat/0512165

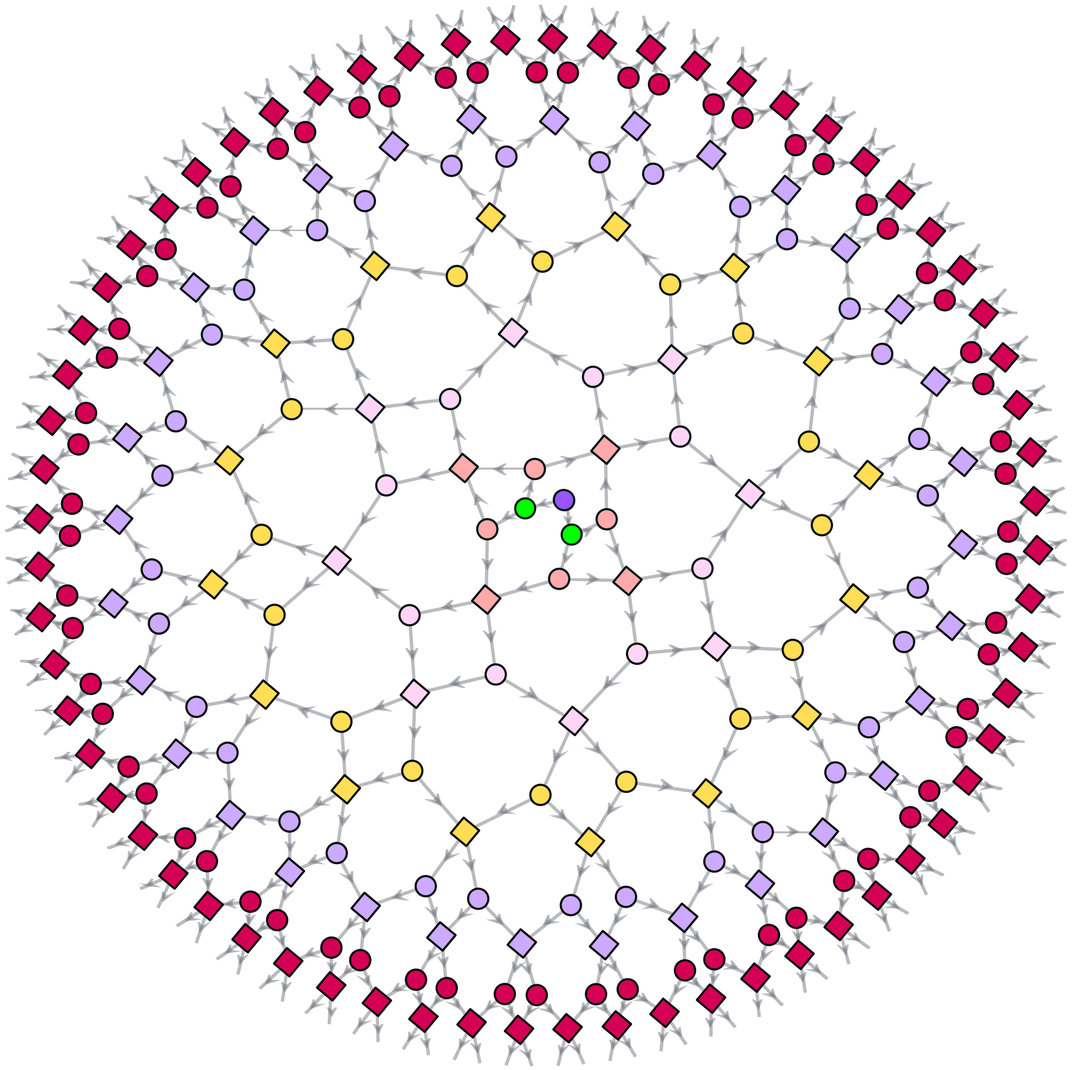
arxiv.org/abs/quant-ph/0610099

QUANTINUUM

MERA on a quantum computer

arXiv 2305.01650





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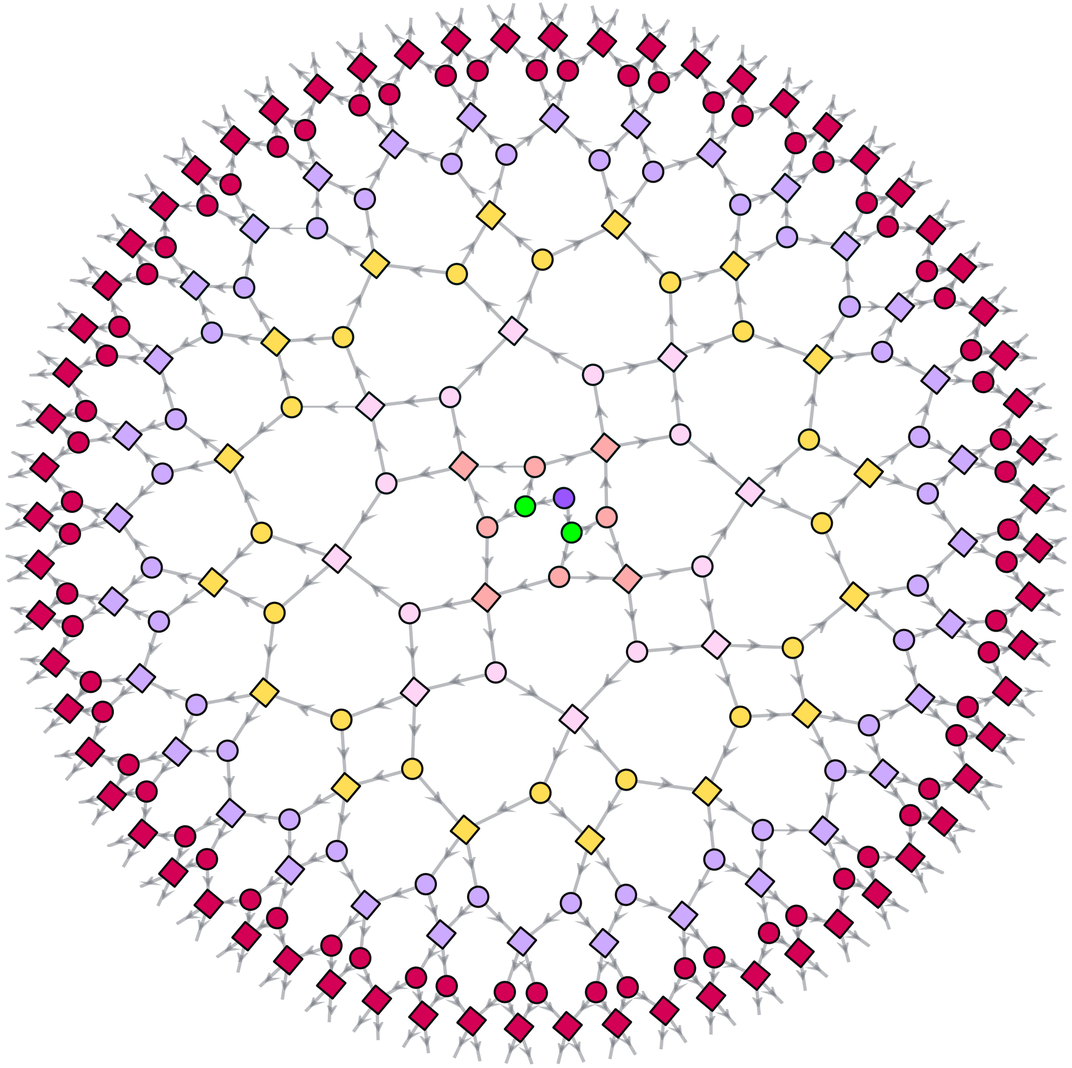
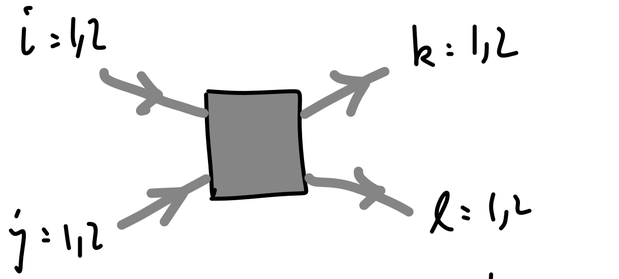
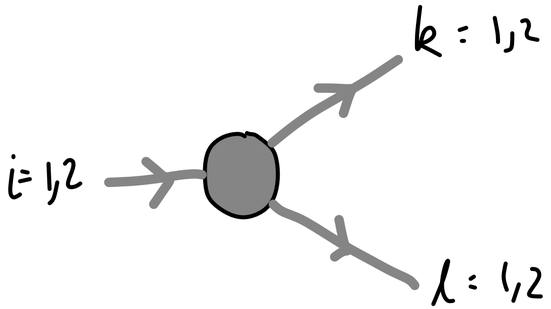




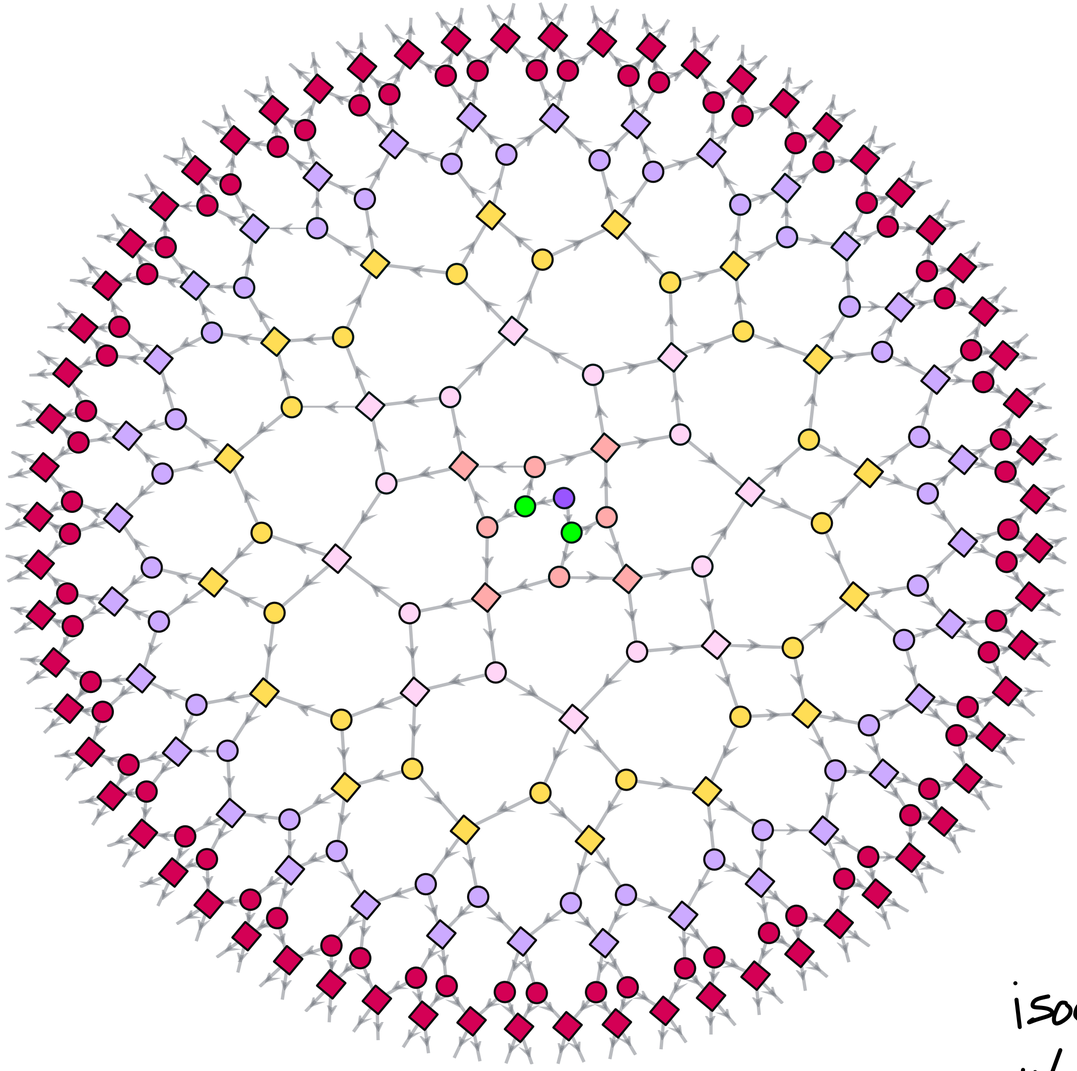
unitary ⇒ two-qubit gate

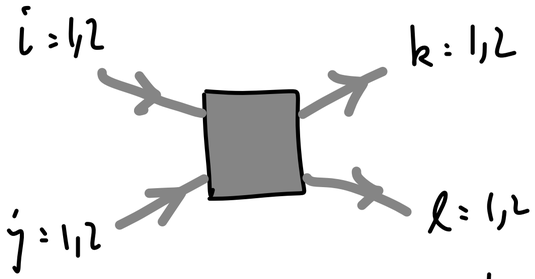


isometry → ?

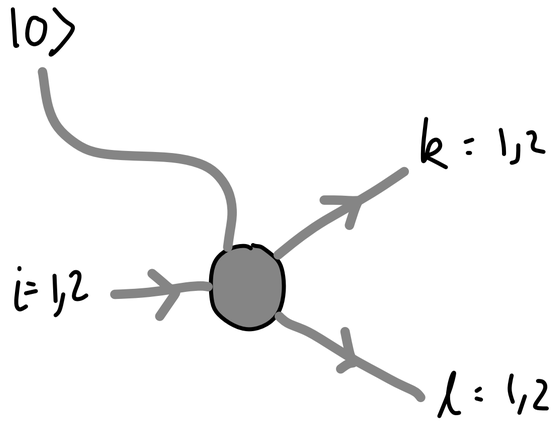
MERA on a quantum computer

arXiv 2305.01650





unitary ⇒ two-qubit gate



isometry ⇒ two-qubit gate
w/ one input fixed

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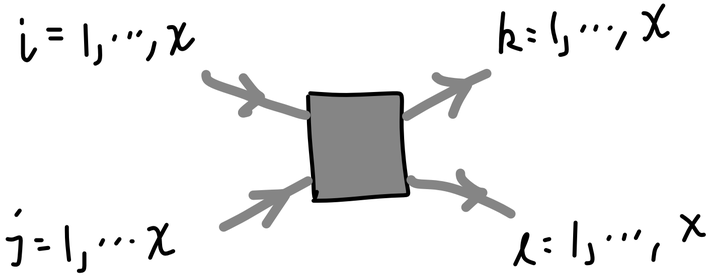

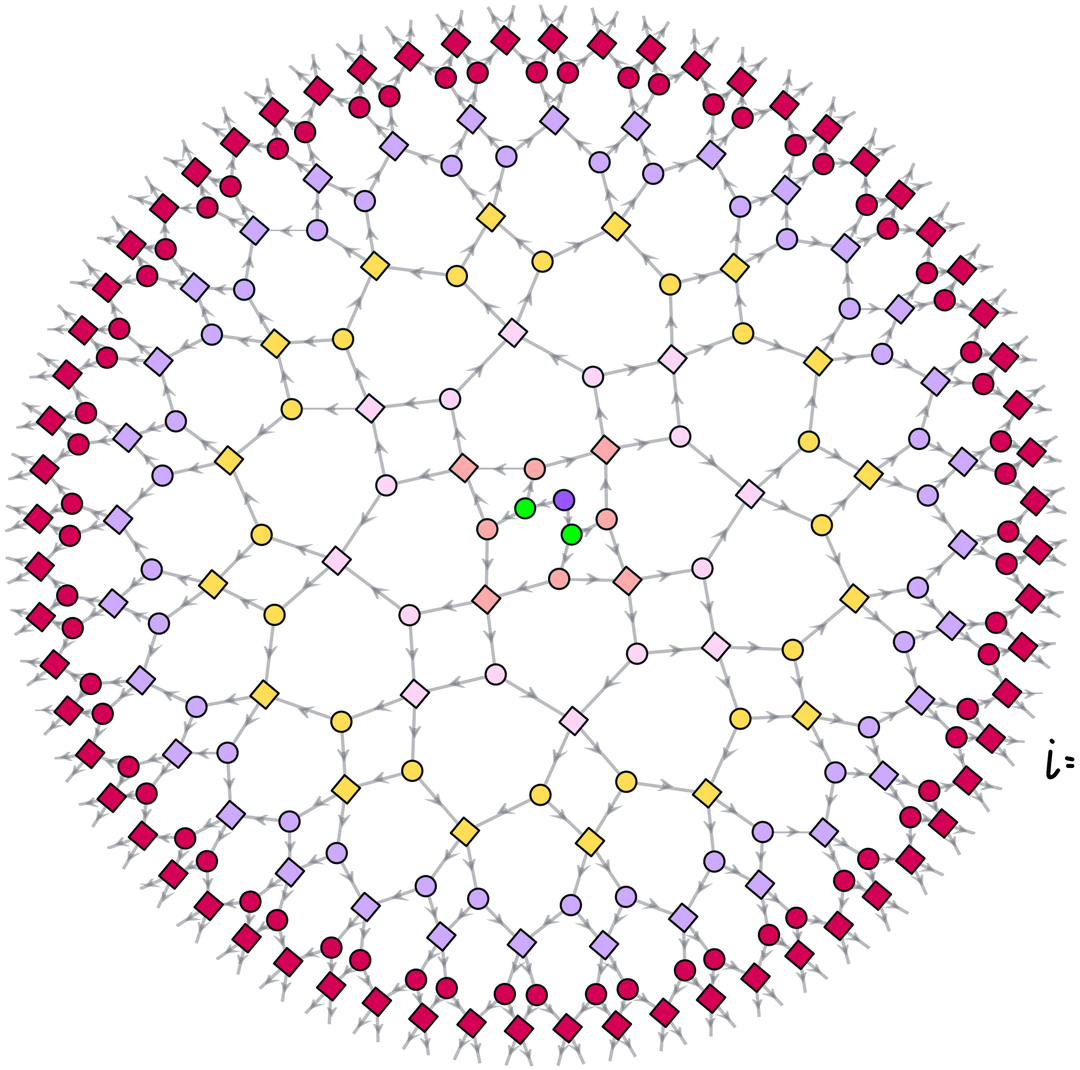

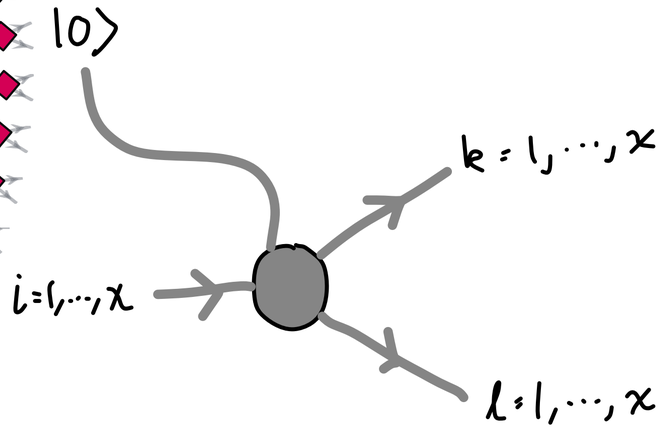

QUANTINUUM

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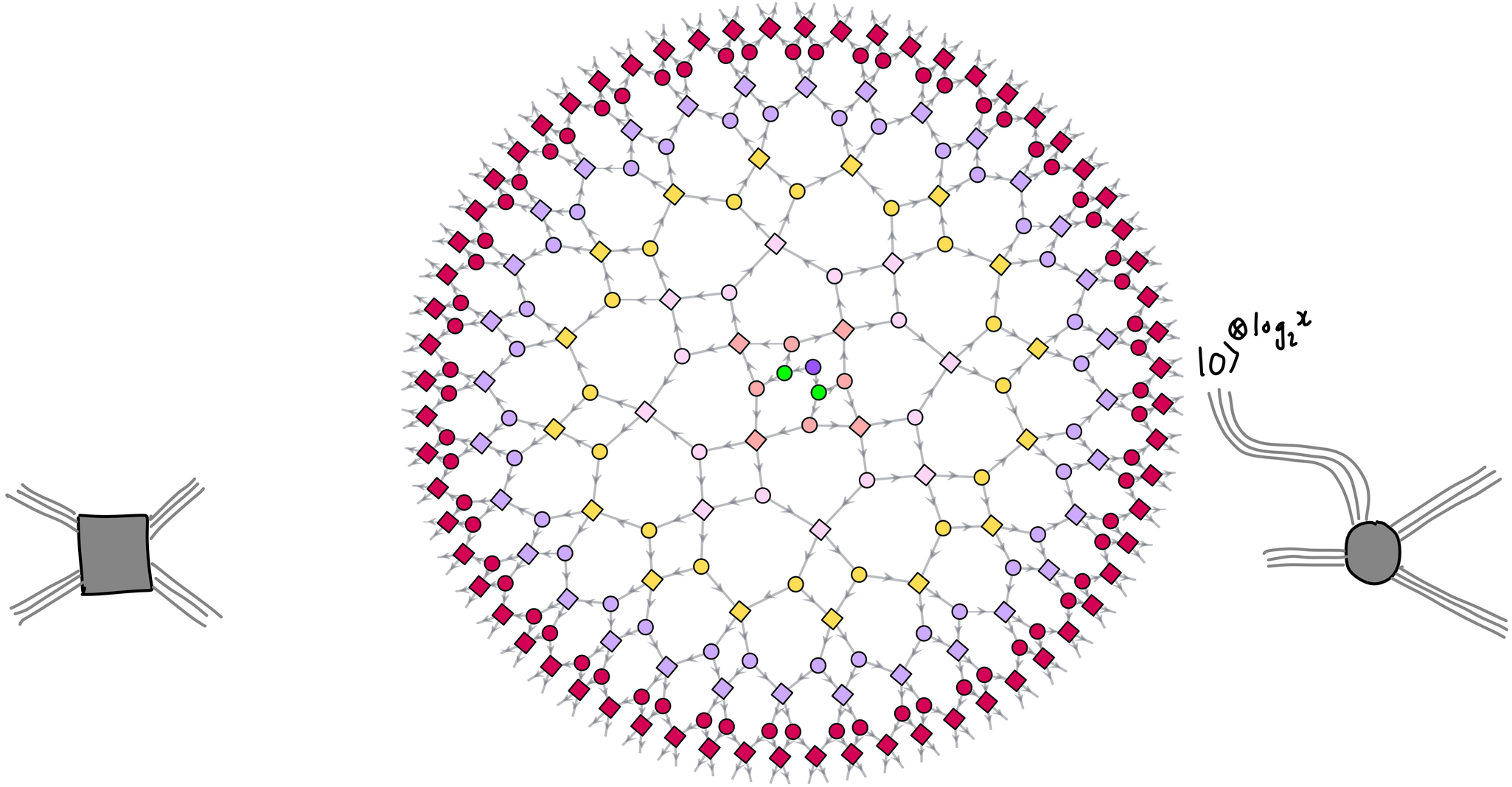

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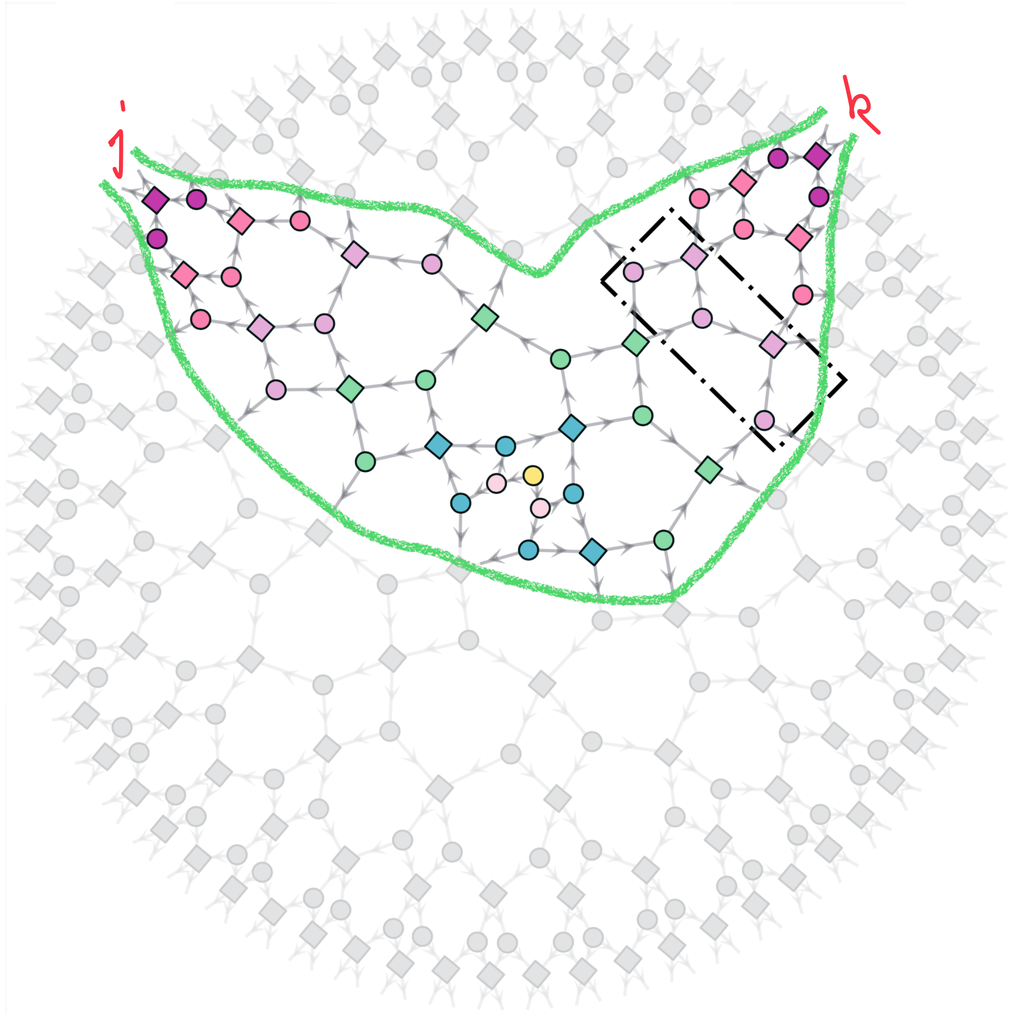

$$\langle X_j X_k \rangle \sim \frac{1}{|j-k|^{\eta}} \quad (\eta = \tfrac{1}{4})$$

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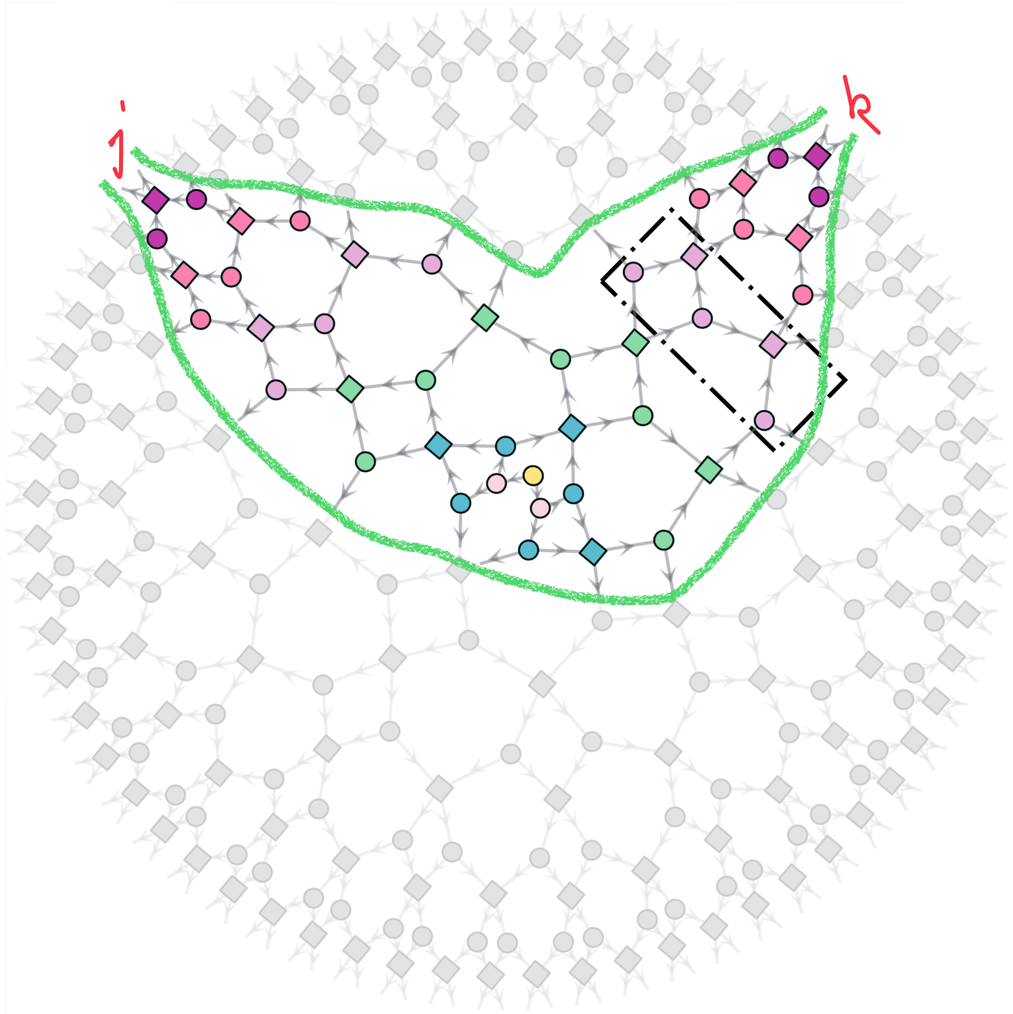

Bounded causal cones lead to “tame” classical contraction cost:

1D cost $\sim \chi^8$

2D cost $\sim \chi^{16}$

Things that would be nice to do but are very hard:

- High bond dimension
- dMERA
- MERA + time evolution (transport, thermalization, etc.)

All of these can be done on a quantum computer with exponentially less resources in space and time

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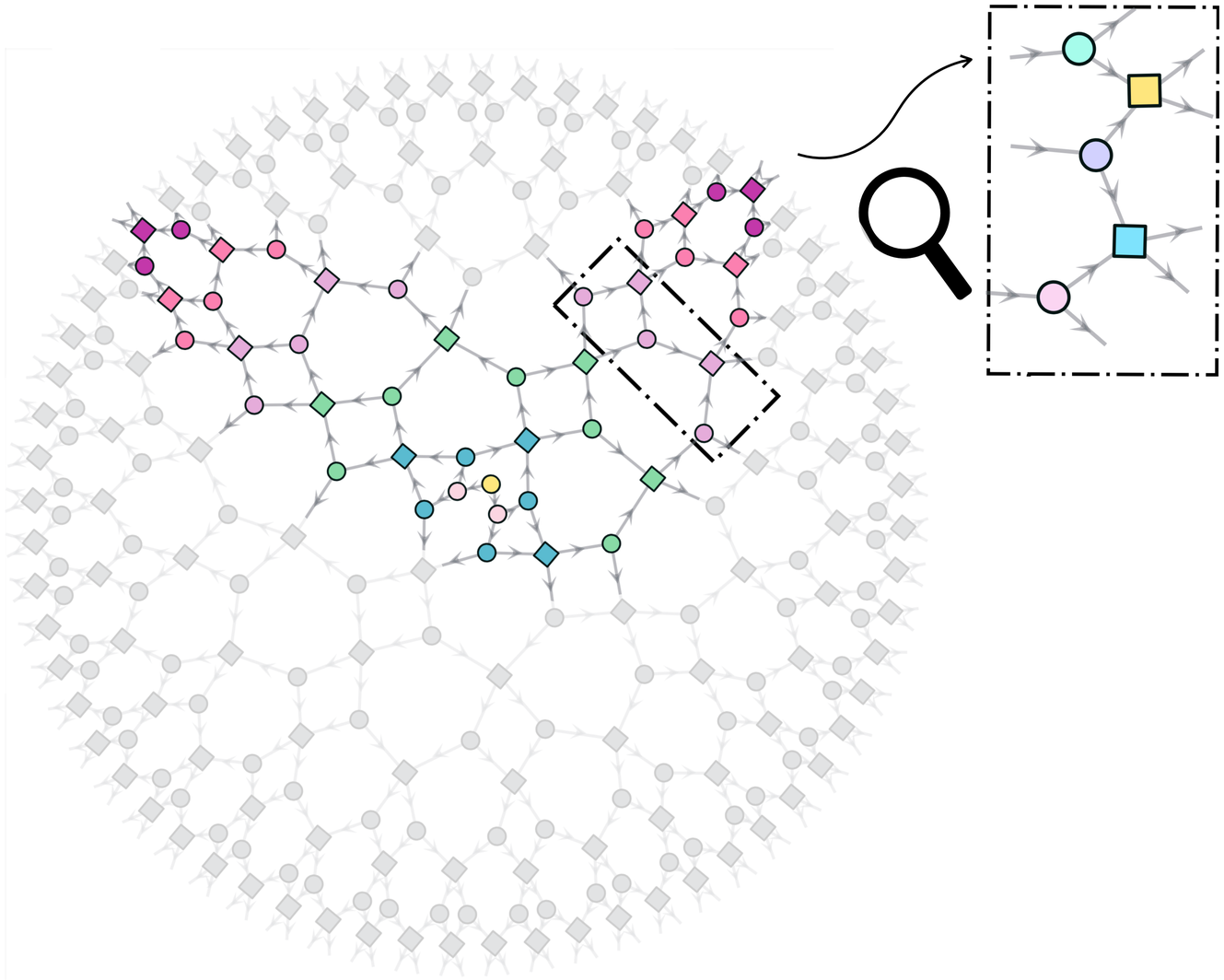

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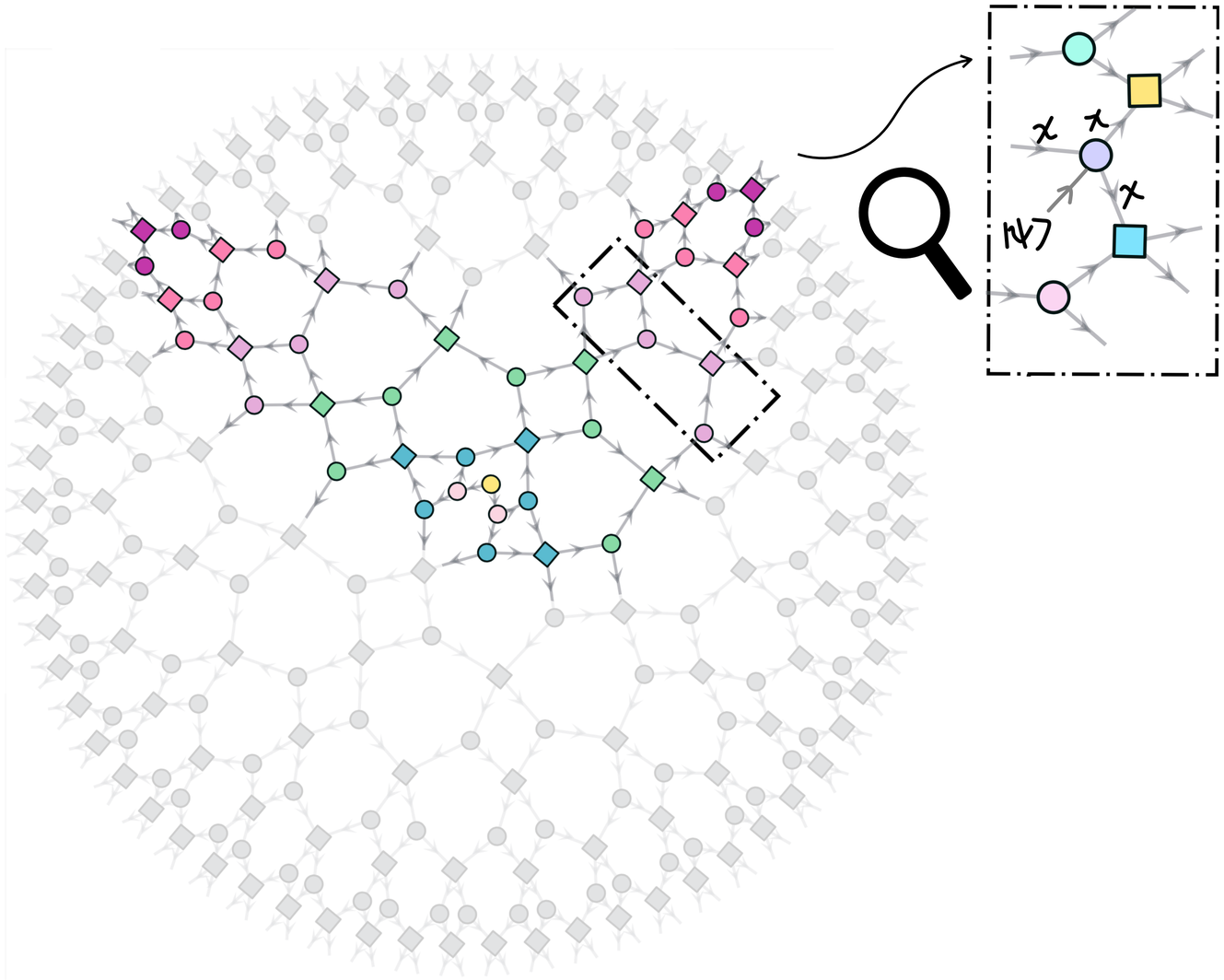

$|\Psi\rangle$ in a χ-dim Hilbert space

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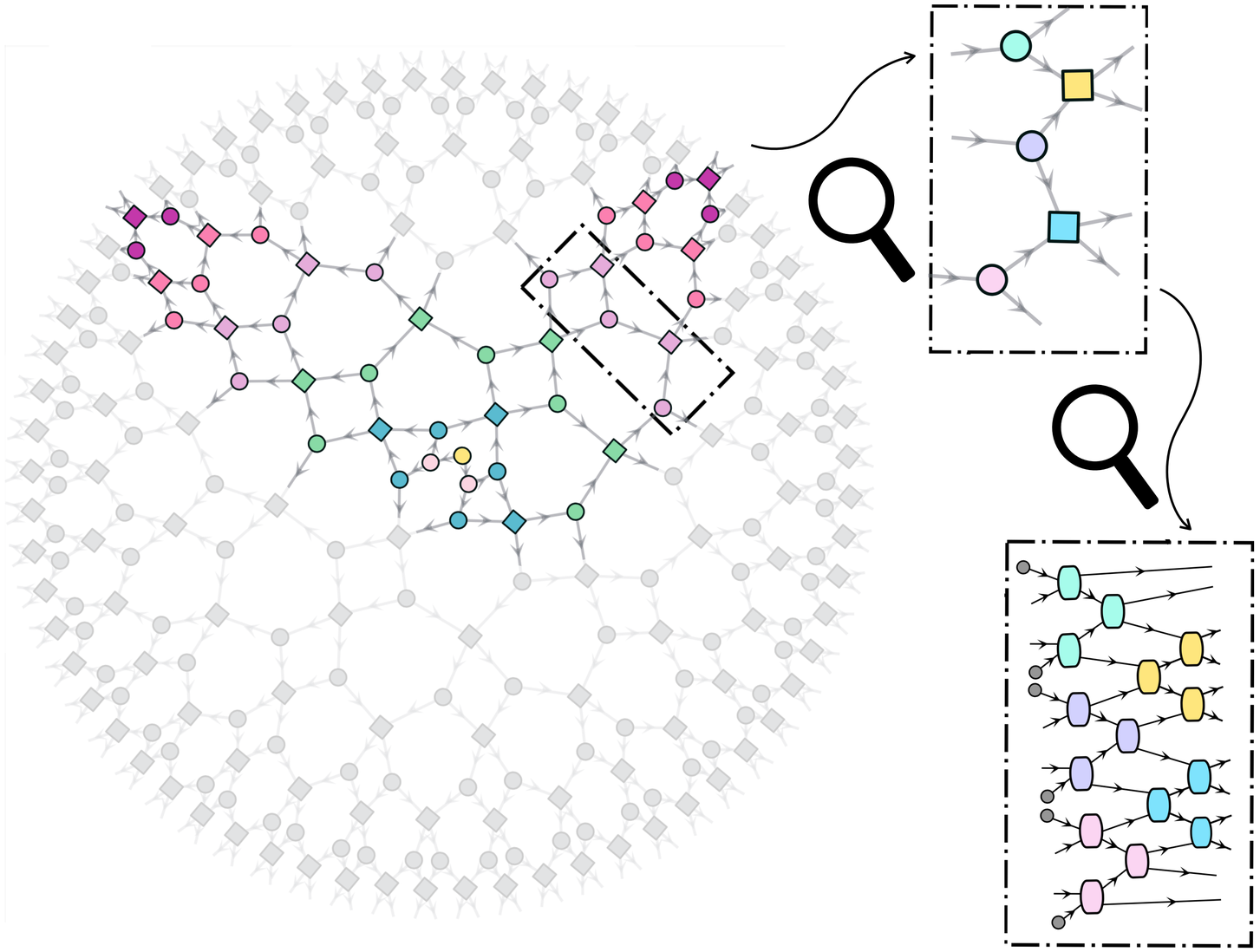

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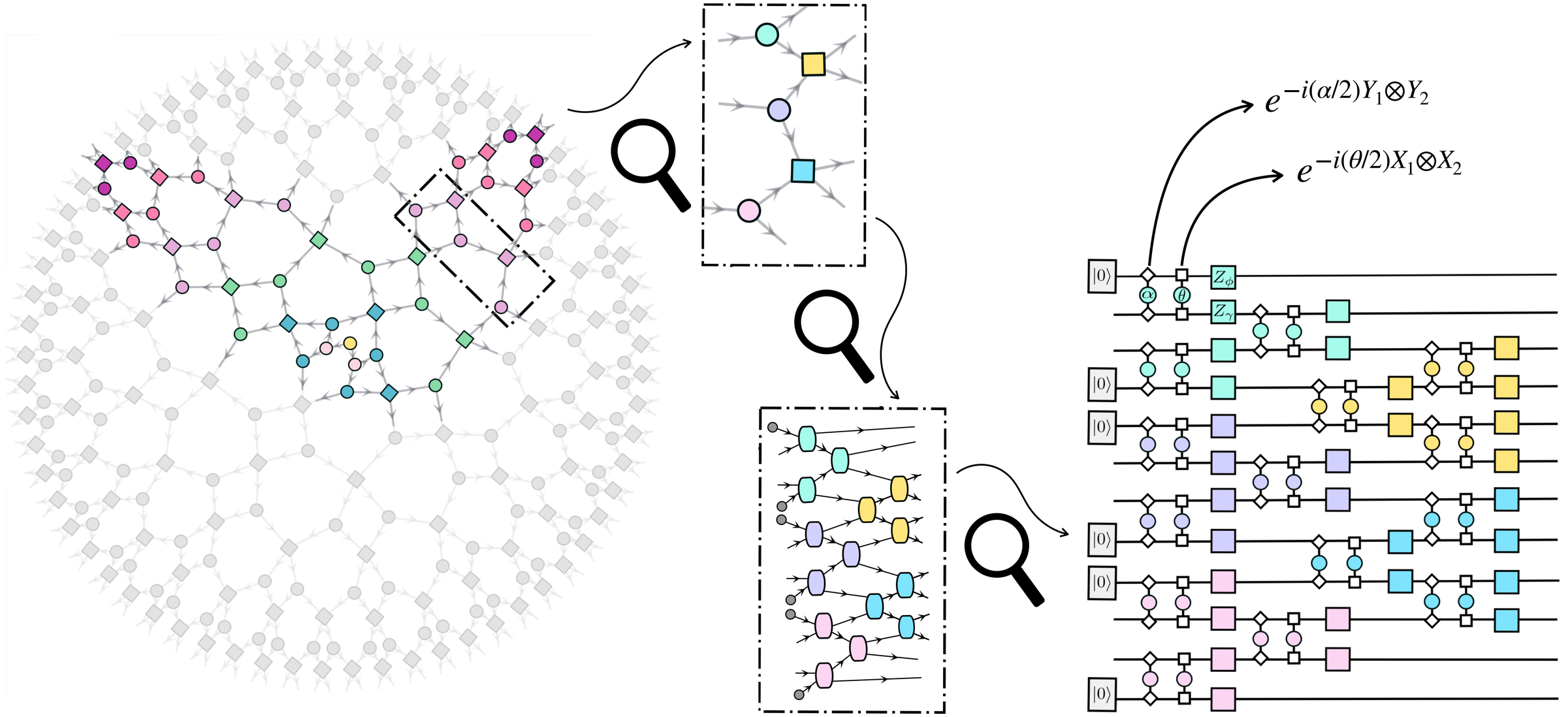

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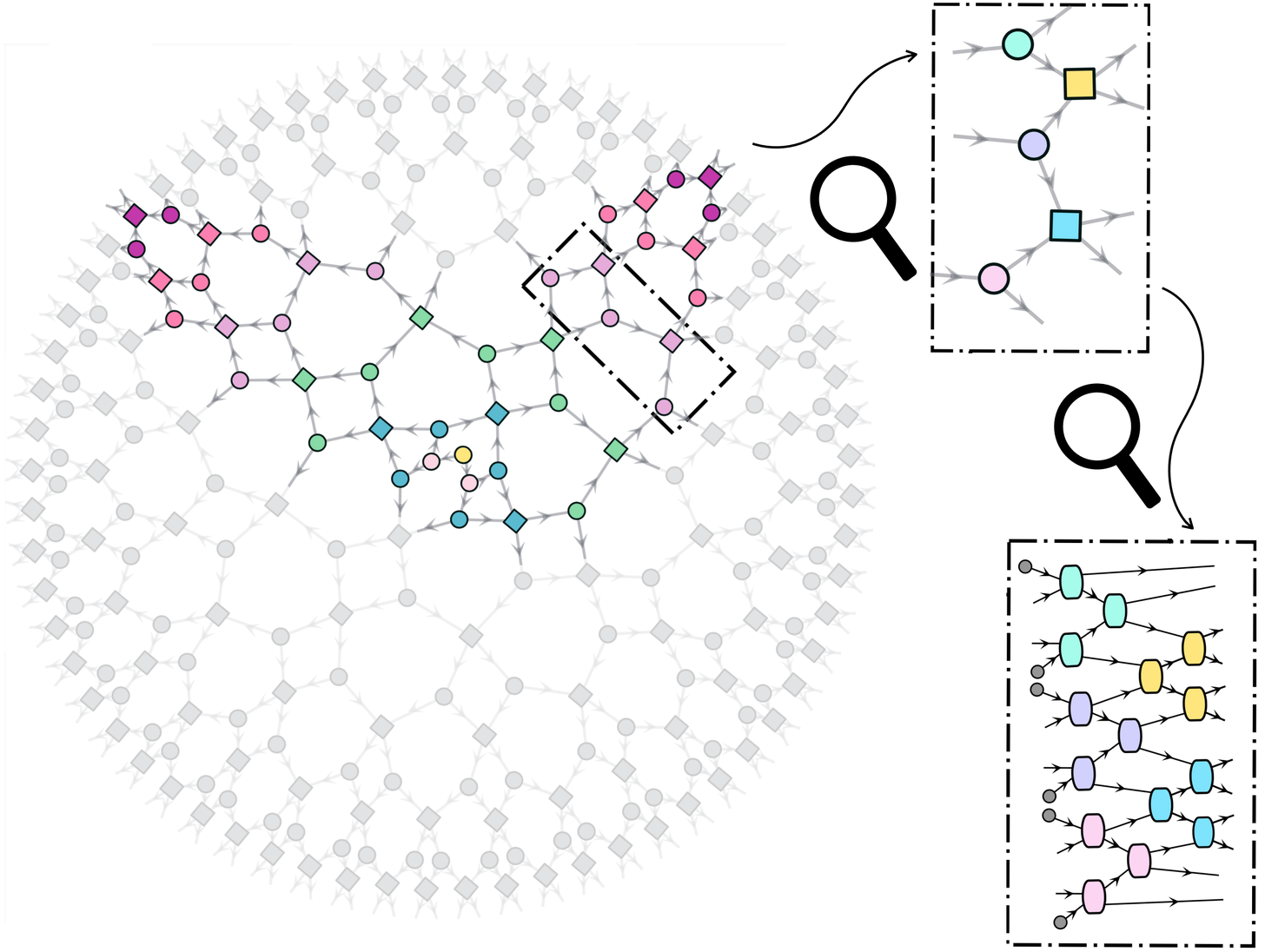
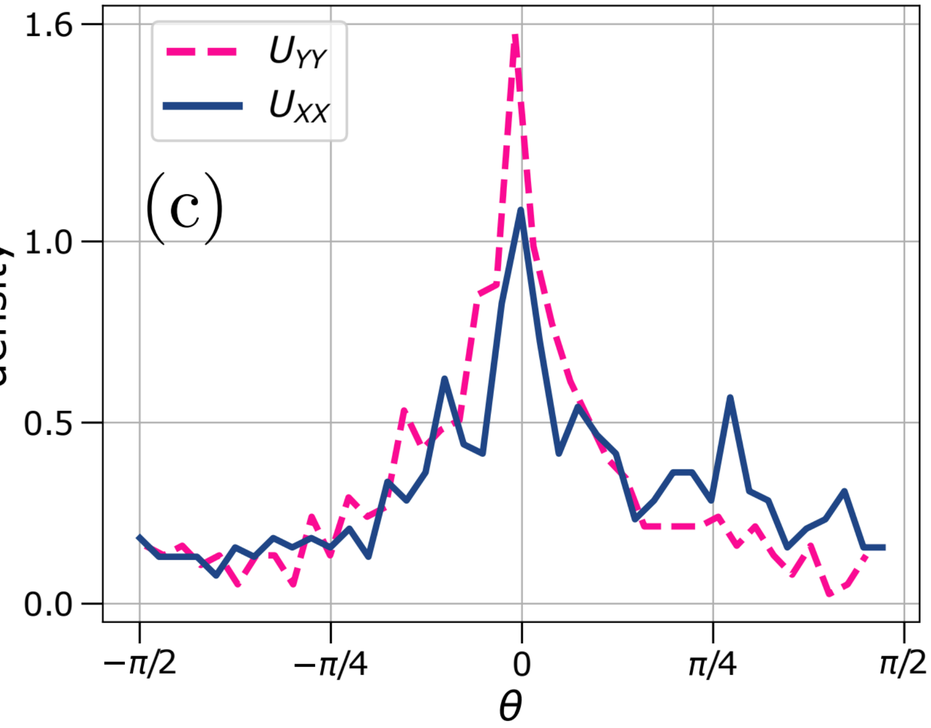


- All output qubits have common “predecessors” at higher scale (deeper in the bulk) → circuits demand high connectivity (even in 1D).
- Weakly entangling gates are extremely helpful



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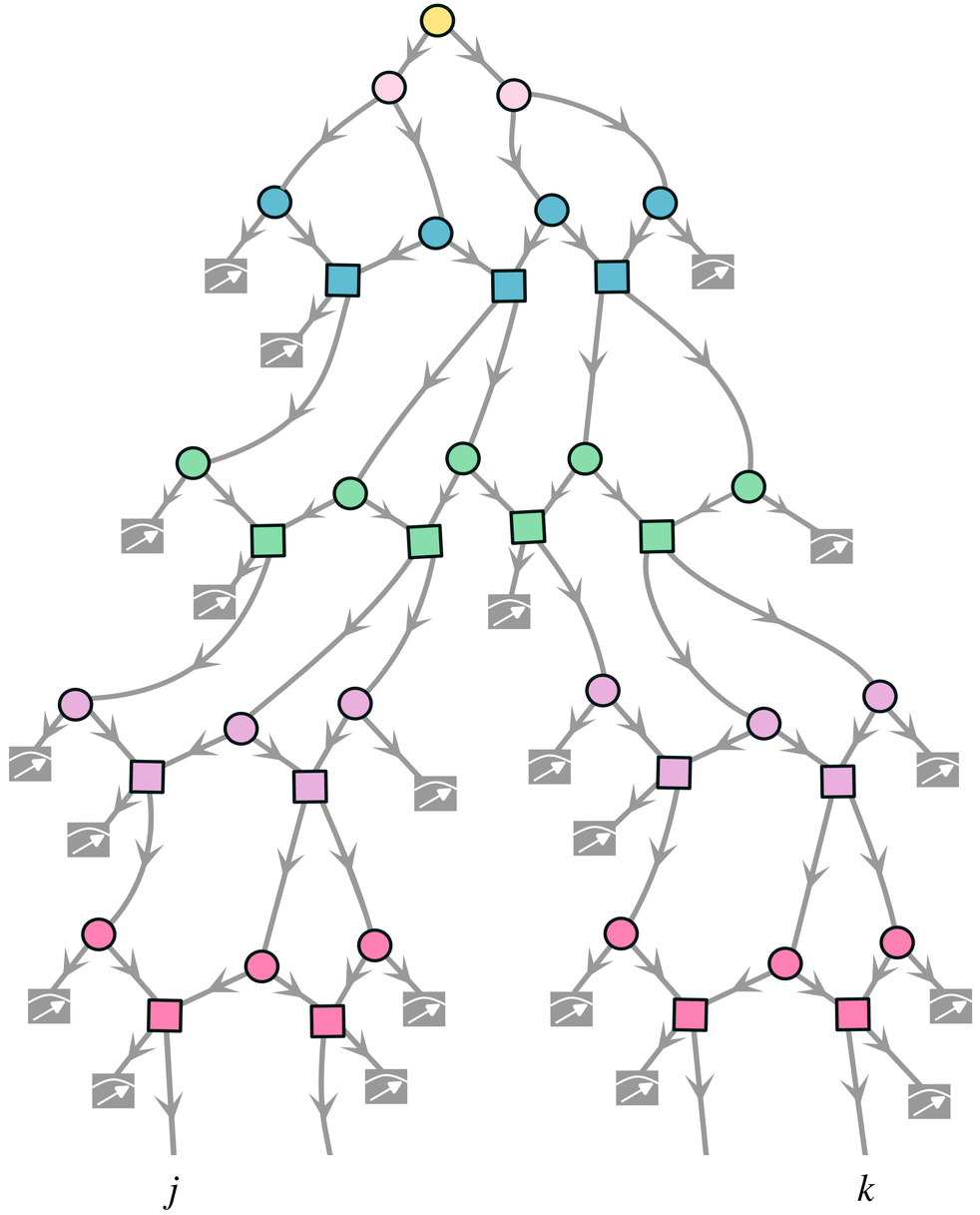
How many qubits? Count isometries



MERA on a quantum computer

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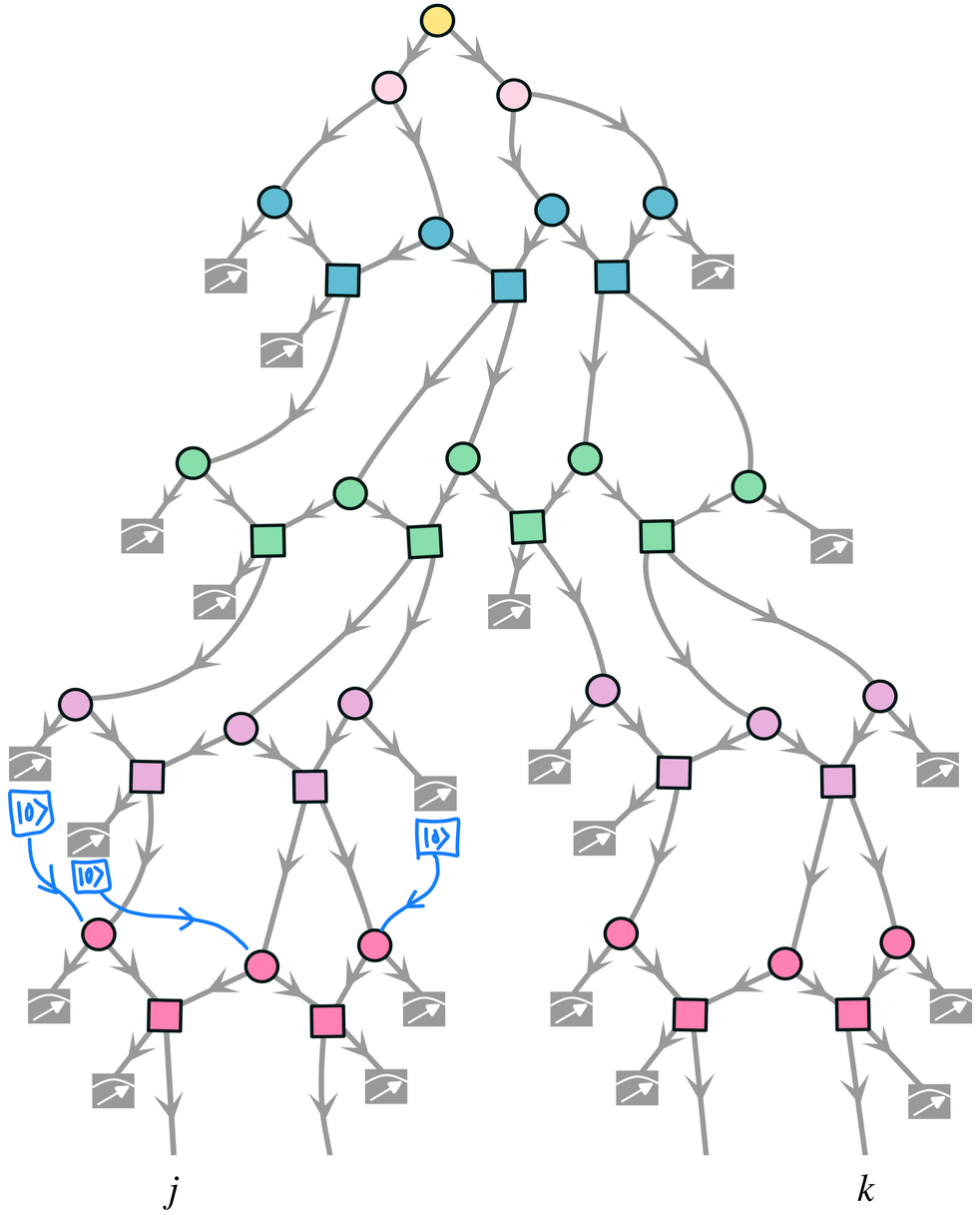
✗ How many qubits? Count isometries

✓ Set by $\chi \times$ (constant width of causal cone)



MERA on a quantum computer

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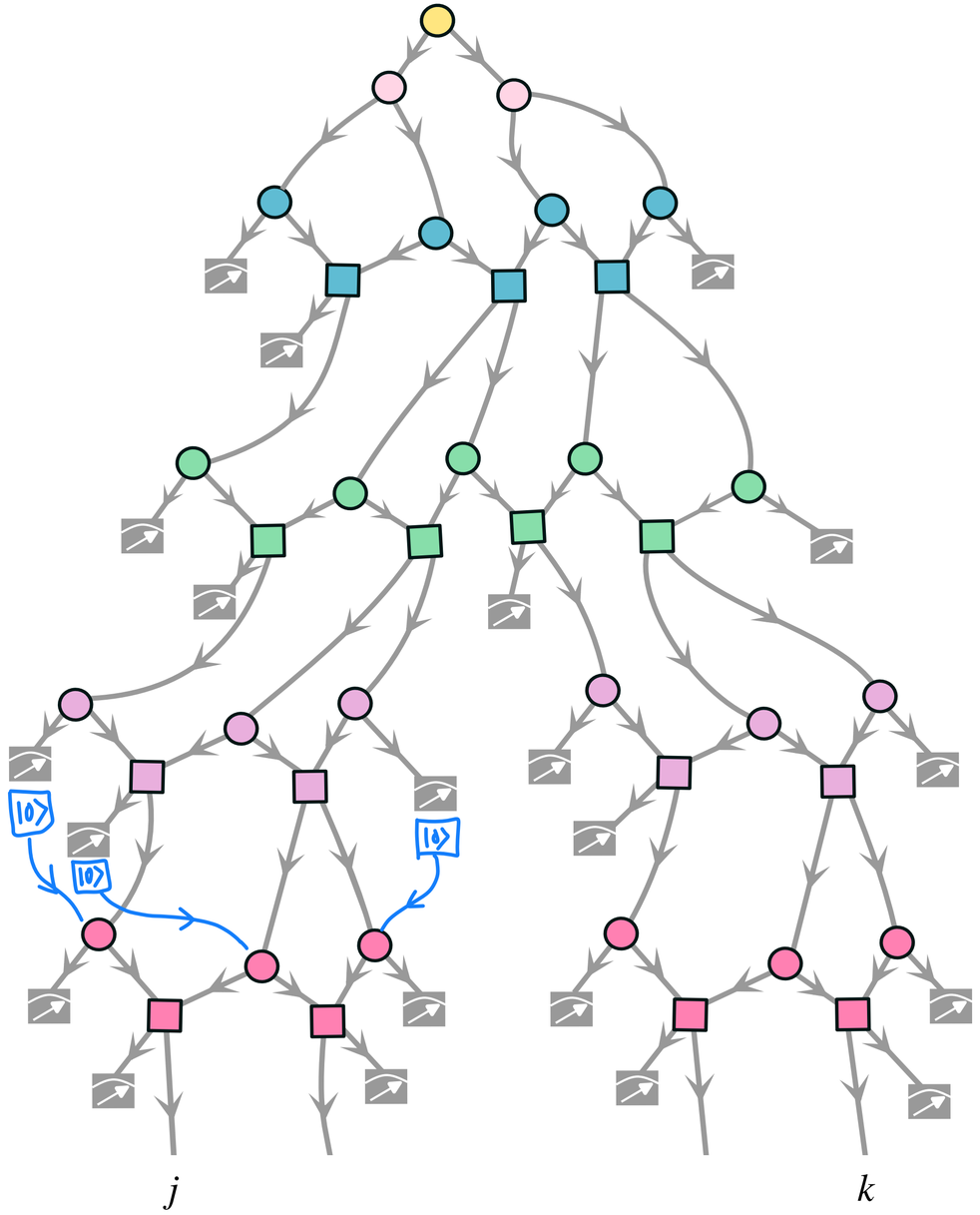
✗ How many qubits? Count isometries

✓ Set by $\chi \times$ (constant width of causal cone)

- Can even sample the full MERA output w/ ~ log L multiplicative overhead



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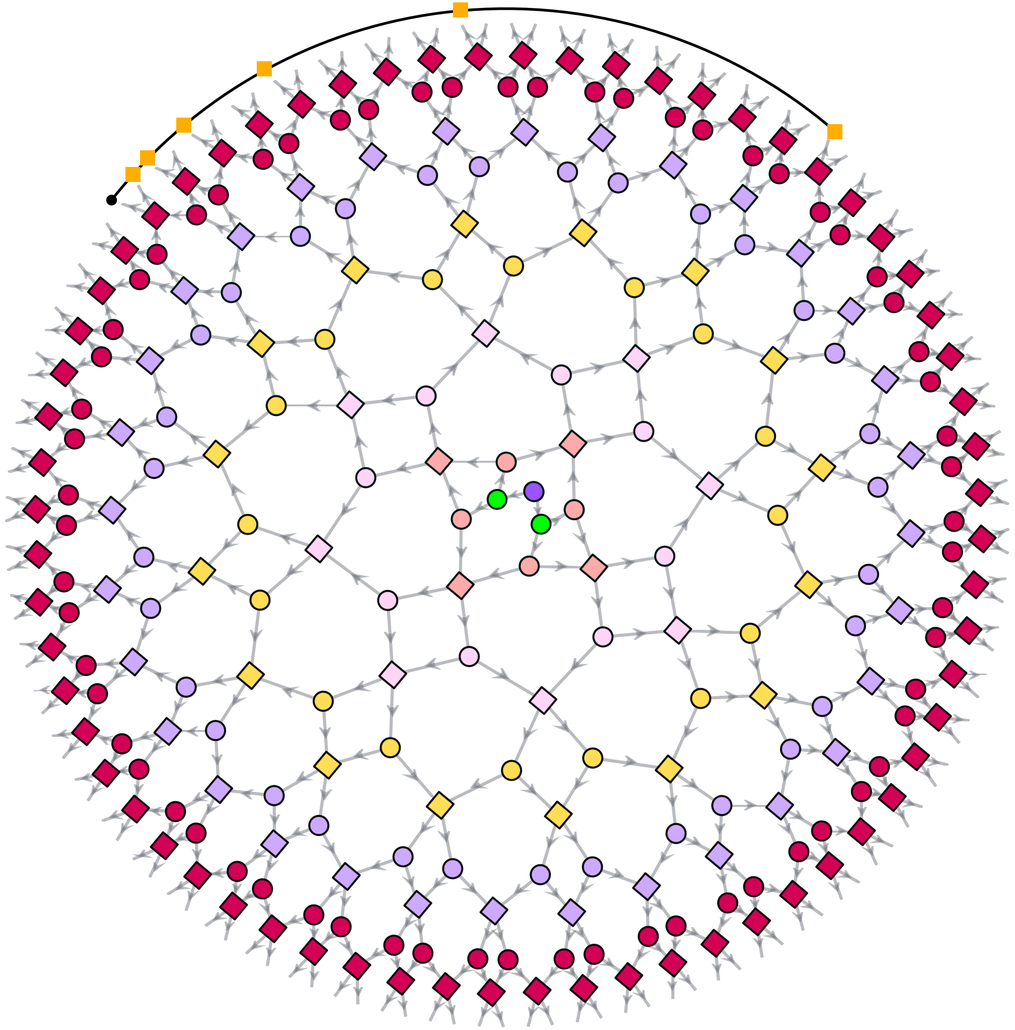
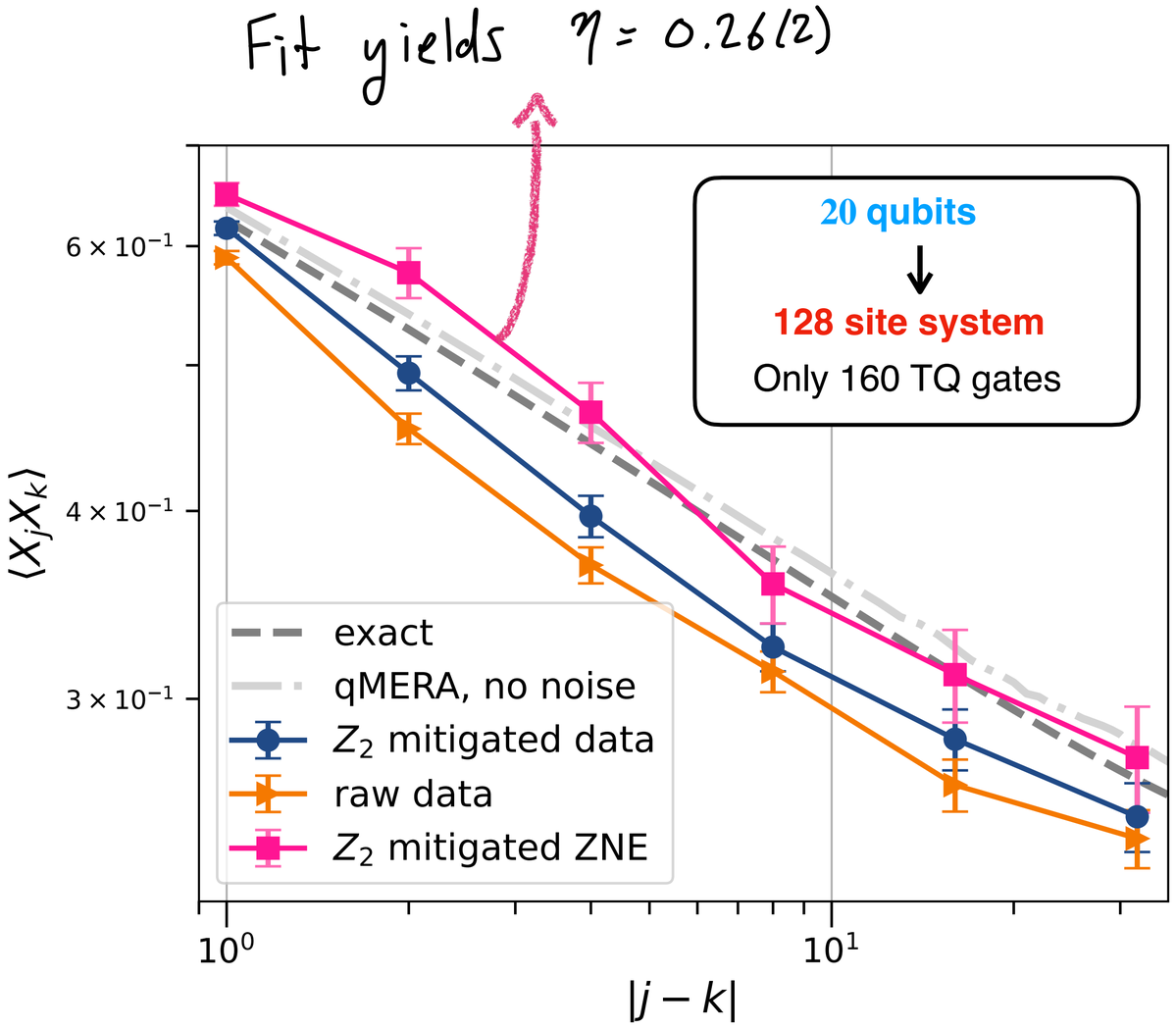
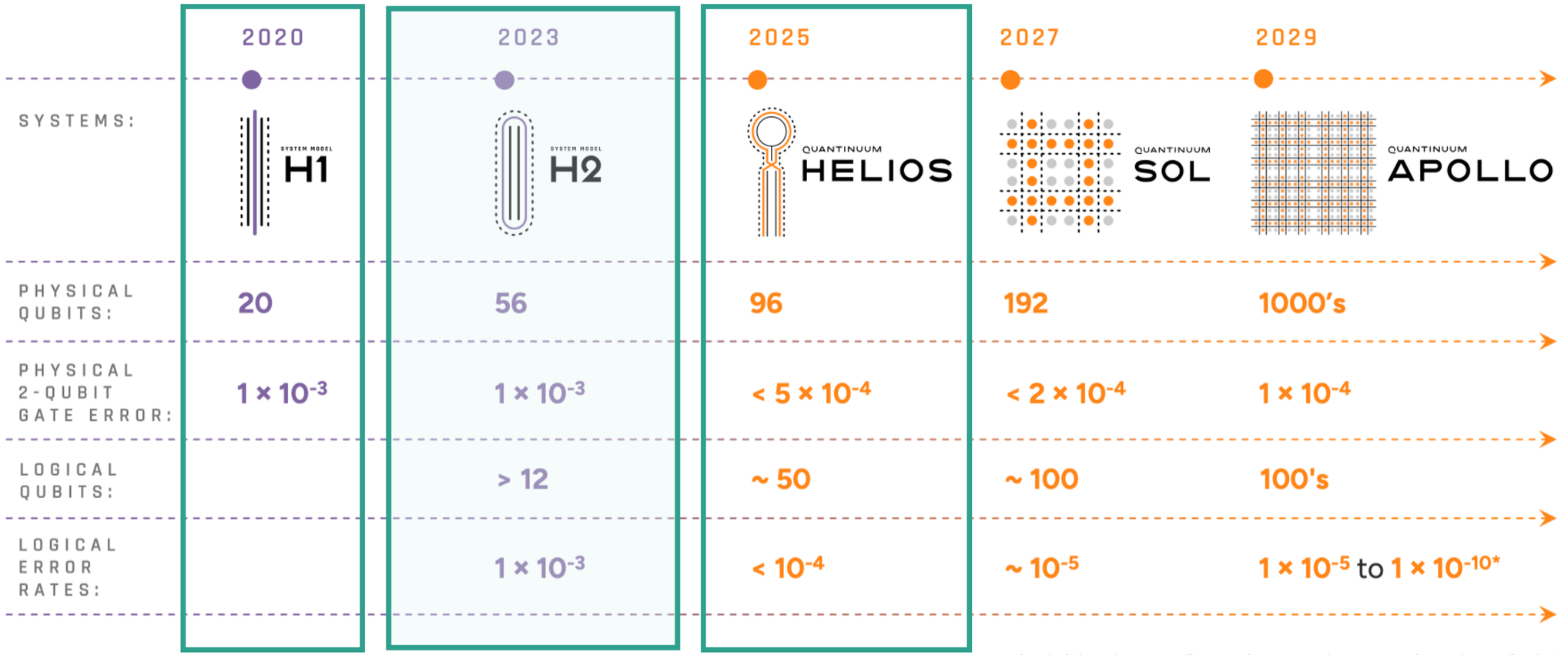




Quantinuum Systems Roadmap



*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)

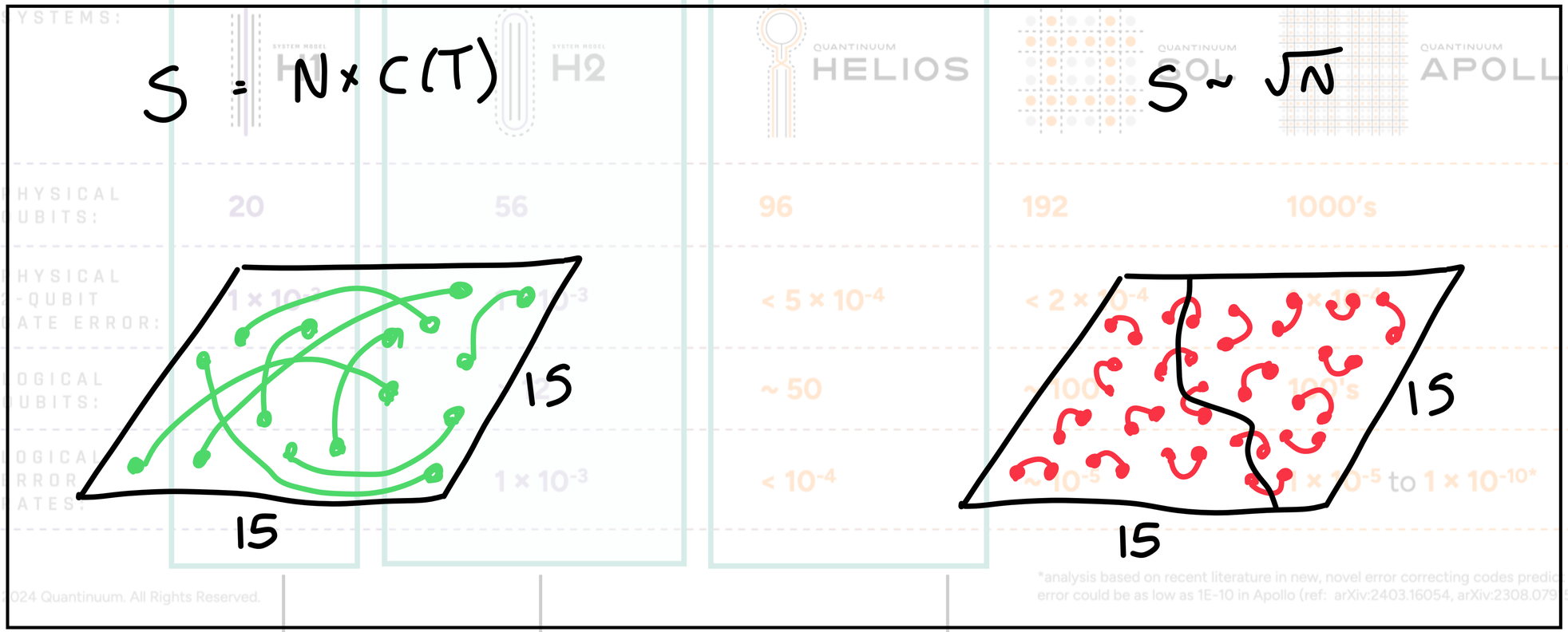
Experimental results in this talk

Several examples of classically difficult "calculations"

arXiv:2406.02501
arXiv:2503.20870

Coming this year

Quantinuum Systems Roadmap



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