Title: Neural Network Decoders for Measurement-Induced Phase Transitions

Speakers: Michael Gullans

Series: Perimeter Institute Quantum Discussions

Date: April 27, 2022 - 11:00 AM

URL: https://pirsa.org/22040010

Abstract: The sustained storage, transmission, or processing of quantum information will likely be a non-equilibrium process that requires monitoring the system and applying some form of feedback to produce fault-tolerance. In this talk, I will discuss a class of models based on random quantum circuits with intermediate measurements that display a similar phenomenology to standard models for fault-tolerance, including the existence of a threshold, but with several helpful simplifications. However, naïve realizations of the threshold require an exponential number of repetitions of the experiment to fully explore the output space of the intermediate measurements. Recently, it has been proposed that this problem can be circumvented by developing efficient entanglement "decoders" that have close parallels to quantum error correction decoders. We show how to leverage modern machine learning tools to devise a neural network decoder to detect the phase transition. We then study the complexity and scalability of this approach and discuss how it can be utilized to detect entanglement phase transitions in generic experiments.

Zoom Link: https://pitp.zoom.us/j/99123641139?pwd=VmkyR3BSNWF5bURVYmFVakp0ZkNRZz09

Neural Network Decoders for Measurement-Induced Phase Transitions

Michael Gullans

Joint Center for Quantum Information and Computer Science,
NIST/University of Maryland, College Park

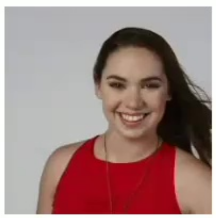
Perimeter Institute, April 27, 2022

UNIVERSITY OF MARYLAND JOINT CENTER FOR QUANTUM INFORMATION AND COMPUTER SCIENCE NIST NSF

References and Collaborations

David Huse

M. J. Gullans and D.A. Huse,
Phys. Rev. X 10, 041020 (2020).
Phys. Rev. Lett. 125, 070606 (2020).



Crystal Noel

Pradeep Niroula

Chris Monroe

C.A. Noel *et al.*, arXiv:2106.05881,
Nature Phys. (in press)

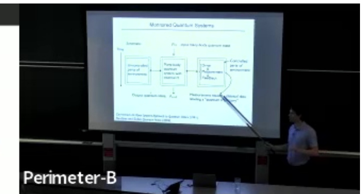
Hossein Dehghani

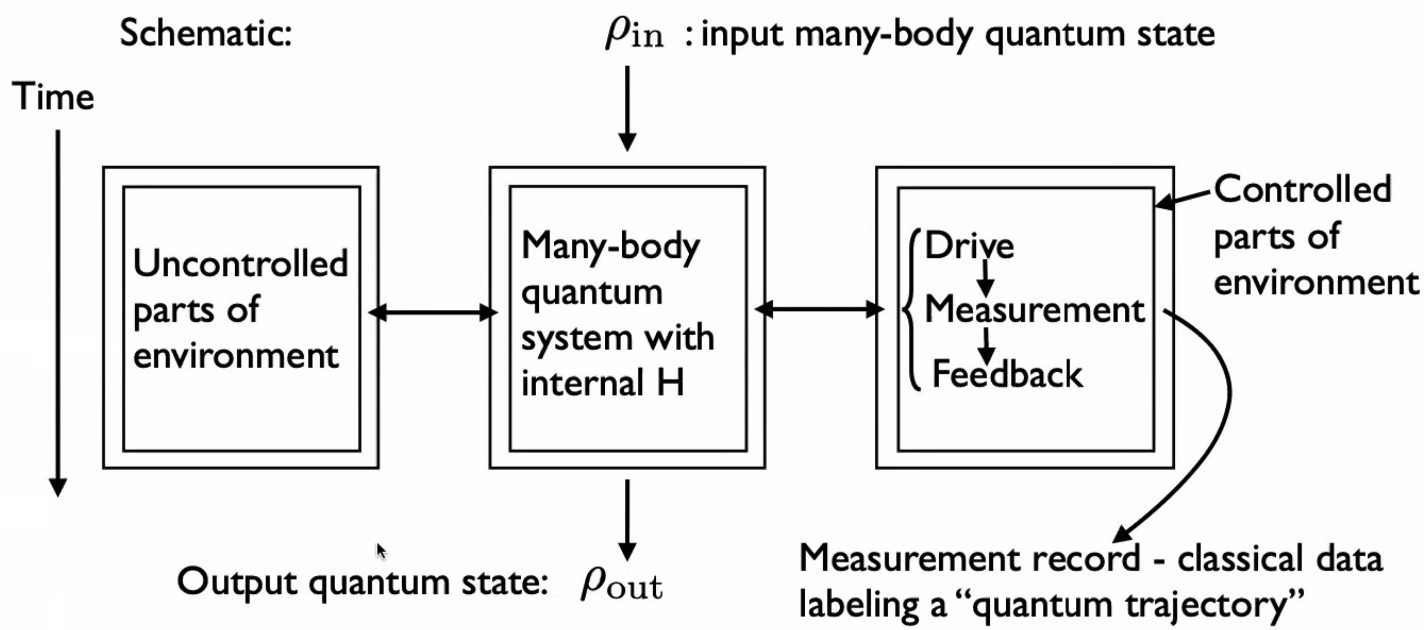
Ali Lavasani

Mohammad Hafezi

H. Dehghani *et al.*, arXiv:2204.10904

Monitored Quantum Systems

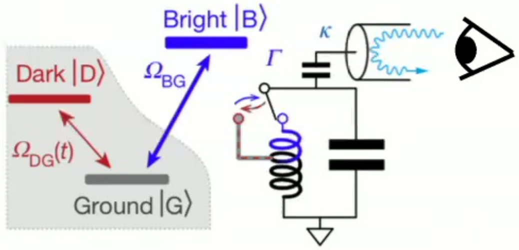


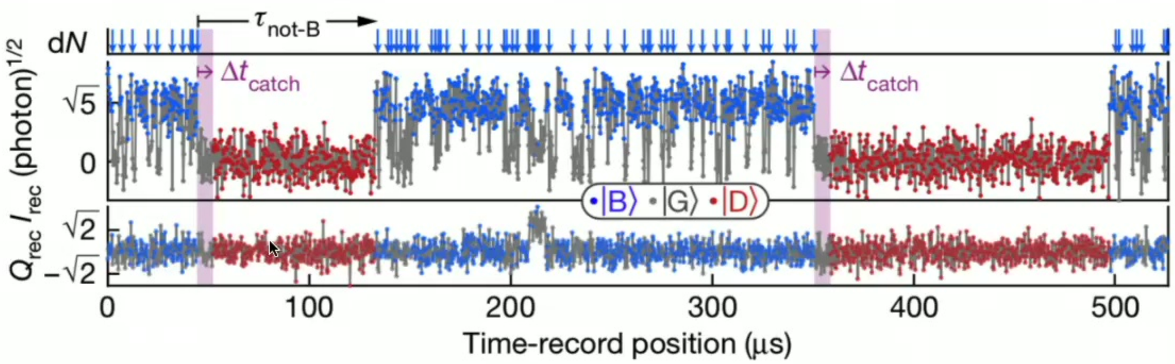


Carmichael, *An Open Systems Approach to Quantum Optics* (1991).
Gardiner and Zoller, *Quantum Noise* (2004).

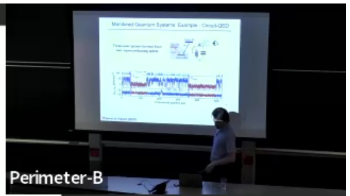
Monitored Quantum Systems: Example - Circuit-QED

Three-level system formed from two superconducting qubits

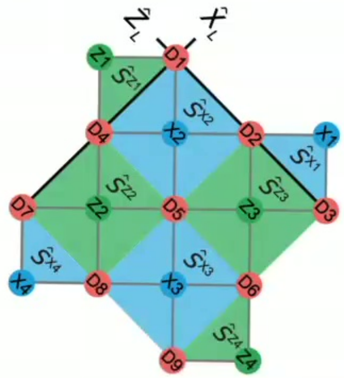


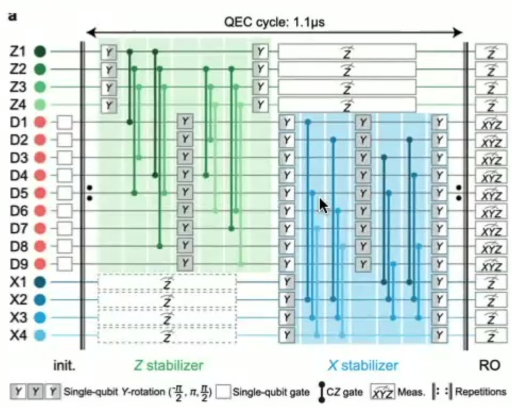


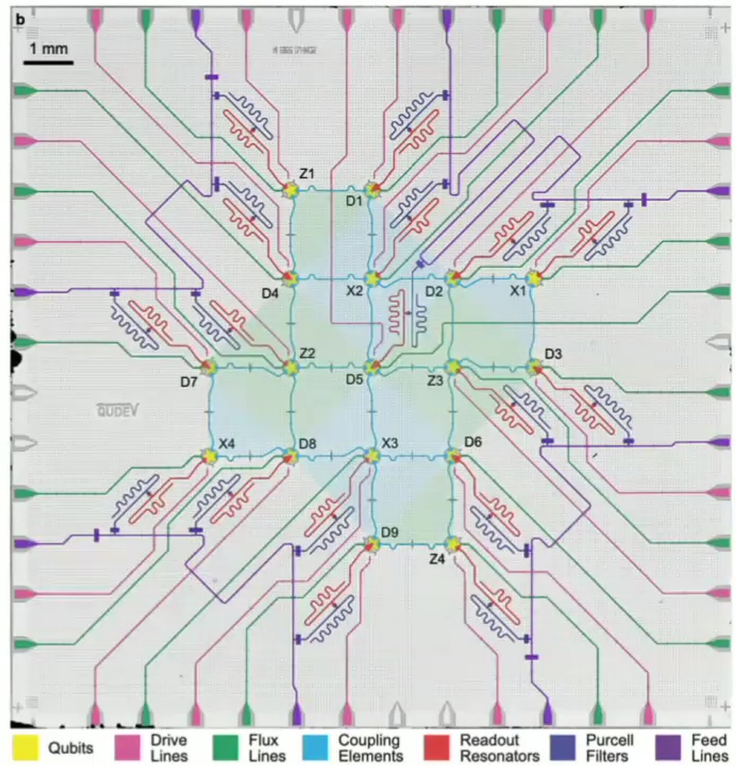
Minev *et al.*, Nature (2019).

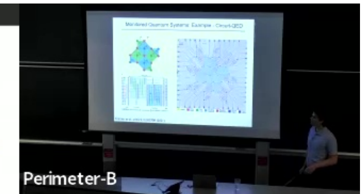


Monitored Quantum Systems: Example - Circuit-QED



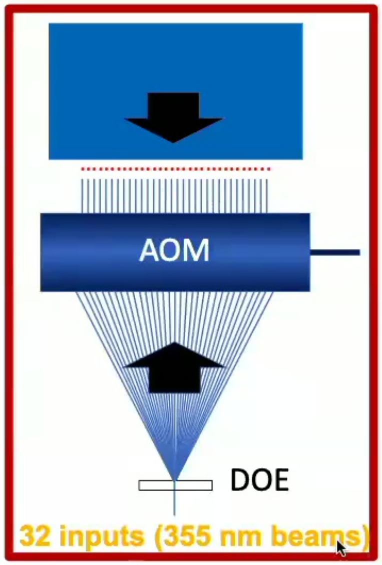


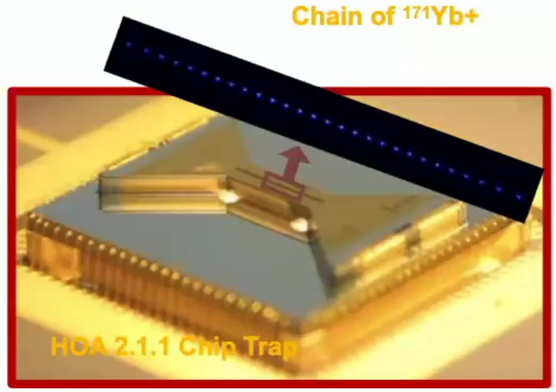


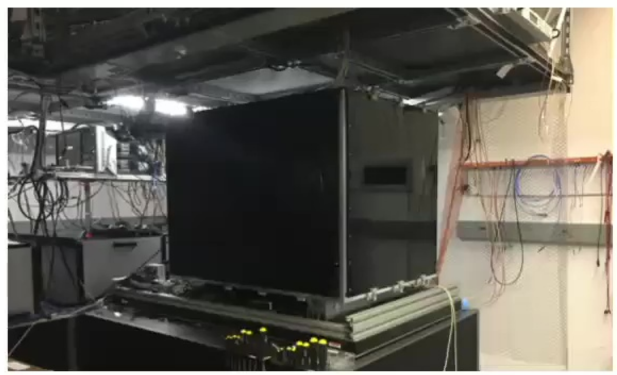


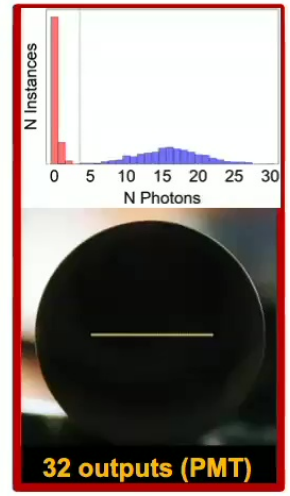
Krinner *et al.*, arXiv:2112.03708 (2021).

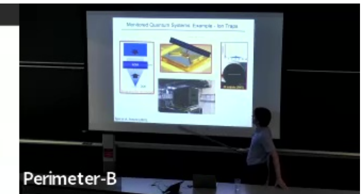
Monitored Quantum Systems: Example - Ion Traps









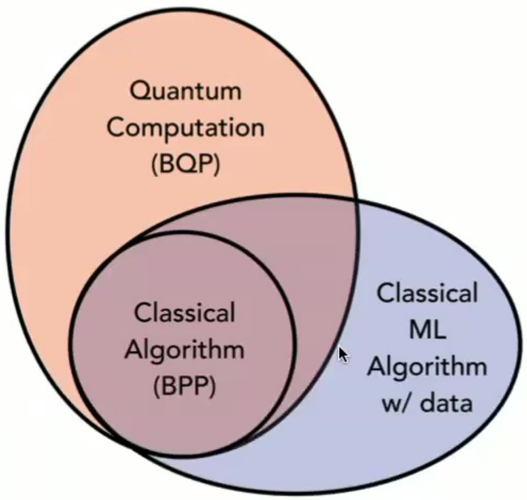


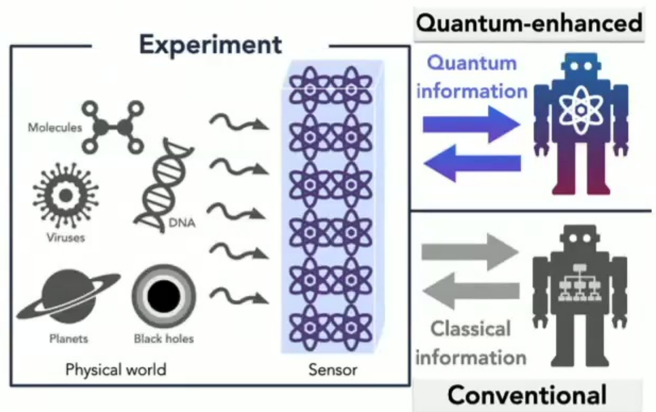
Egan *et al.*, Nature (2021).

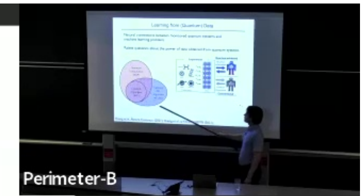
Learning from (Quantum) Data

Natural connections between monitored quantum systems and machine learning problems

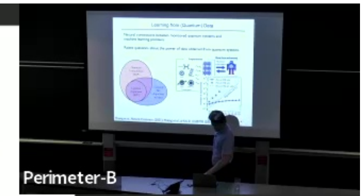
Raises questions about the power of data obtained from quantum systems







Huang *et al.*, Nature Commun. (2021); Huang *et al.*, arXiv:2112.00778 (2021).



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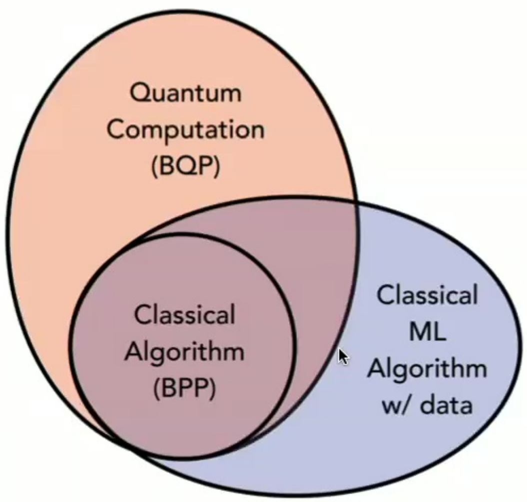
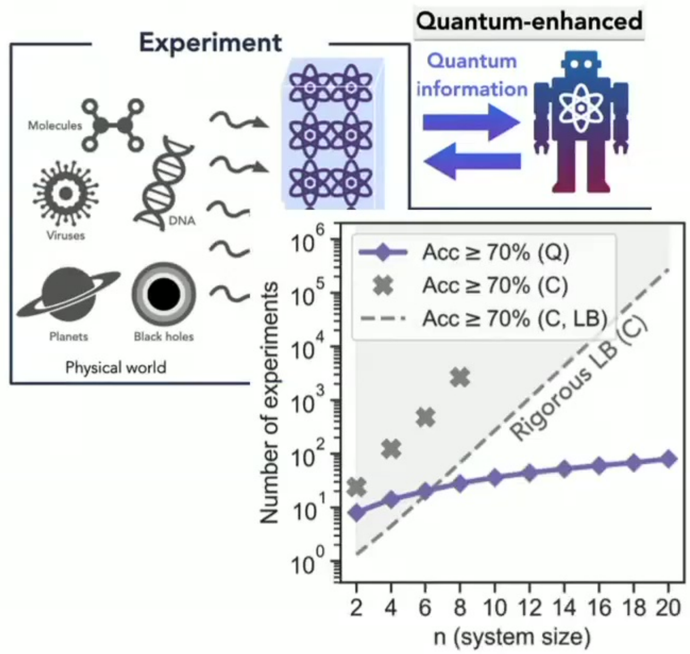
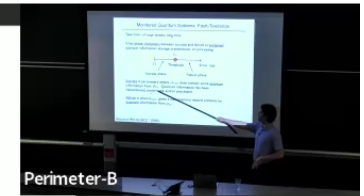




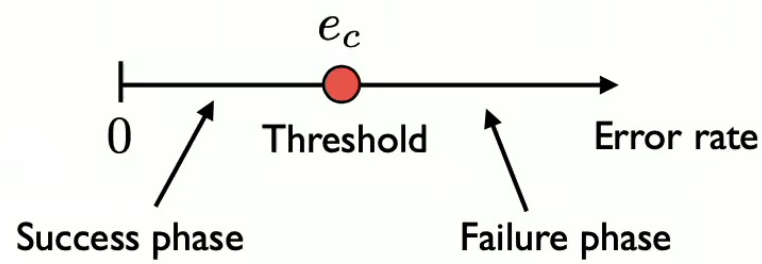
Huang *et al.*, Nature Commun. (2021); Huang *et al.*, arXiv:2112.00778 (2021).

Monitored Quantum Systems: Fault-Tolerance



Take limits of large system, long time

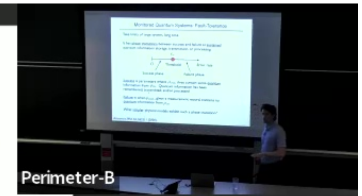
It has <u>phase transitions</u> between success and failure at <u>sustained</u> quantum information storage, transmission, or processing



<u>Success</u> is parameters where ρ_{out} does contain some <u>quantum</u> information from ρ_{in}. Quantum information has been remembered, transmitted, and/or processed

<u>Failure</u> is when ρ_{out} , given a measurement record, contains no <u>quantum</u> information from ρ_{in}.

Aharonov, PRA 62, 062311 (2000).



Monitored Quantum Systems: Fault-Tolerance

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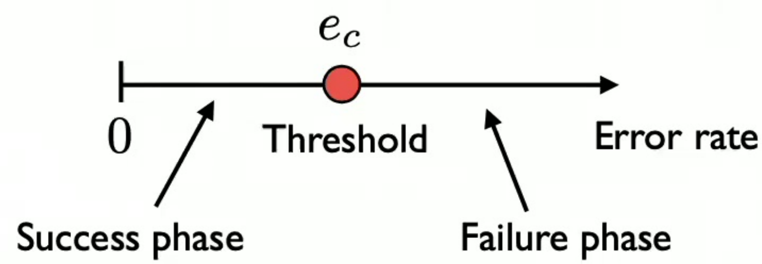

Success is parameters where ρ_{out} does contain some quantum information from ρ_{in}. Quantum information has been remembered, transmitted, and/or processed

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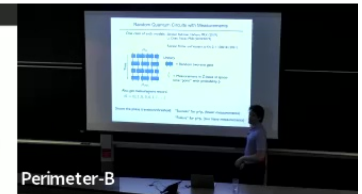
What simpler physical models exhibit such a phase transition?

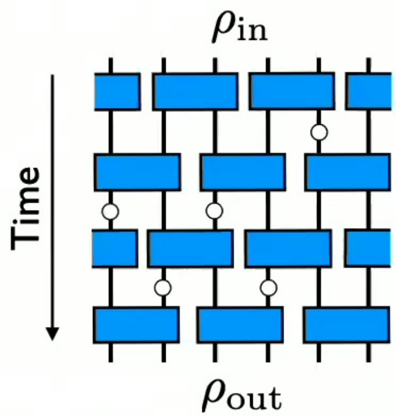
Aharonov, PRA 62, 062311 (2000).



Random Quantum Circuits with Measurements

One class of such models: Skinner, Ruhman, Nahum, PRX (2019).
Li, Chen, Fisher, PRB (2018/2019).

Review: Potter and Vasseur, arXiv:2111.08018 (2021).



Unitary

= Random two-site gate

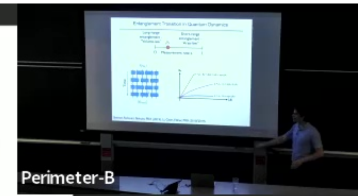
= Measurement in Z-basis at space-time "point" with probability p

Also get measurement record

$$\vec{m} = (0, 1, 0, 0, 0, 1, 1, \ldots)$$

Shows the phase transition/threshold: "Success" for $p<p_c$ (fewer measurements)

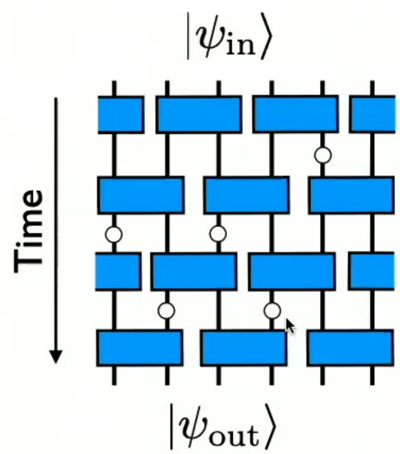
"Failure" for $p>p_c$ (too many measurements)

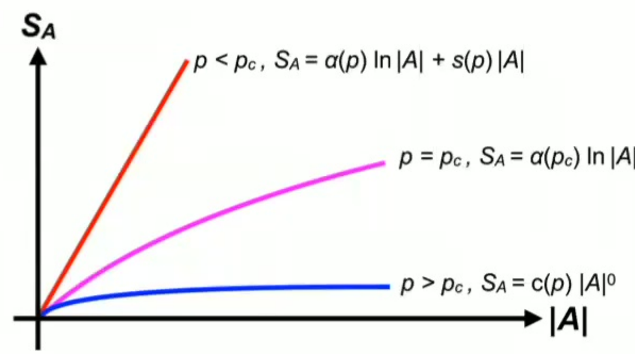


Entanglement Transition in Quantum Dynamics

Long-range entanglement - "Volume-law" p_c Short-range entanglement - "Area-law"

0 Measurement rate p 1





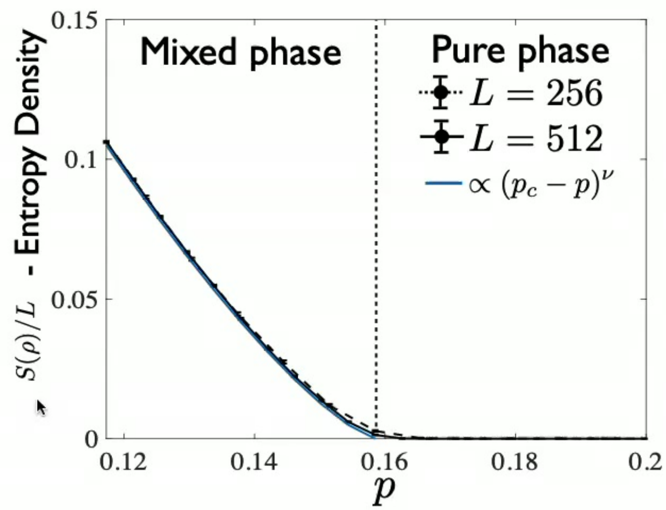
Skinner, Ruhman, Nahum, PRX (2019). Li, Chen, Fisher, PRB (2018/2019).

Purification or Coding Transition

Start in a mixed state

Stays mixed for times exp(L) p_c Purifies at constant rate

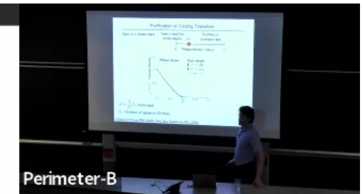
0 Measurement rate p 1



$\rho = \frac{1}{2^L}\mathbb{I}$ - Initial state

L - Number of qubits in 1D chain

Gullans and Huse, PRX (2020). Choi, Bao, Qi, Altman, PRL (2020).

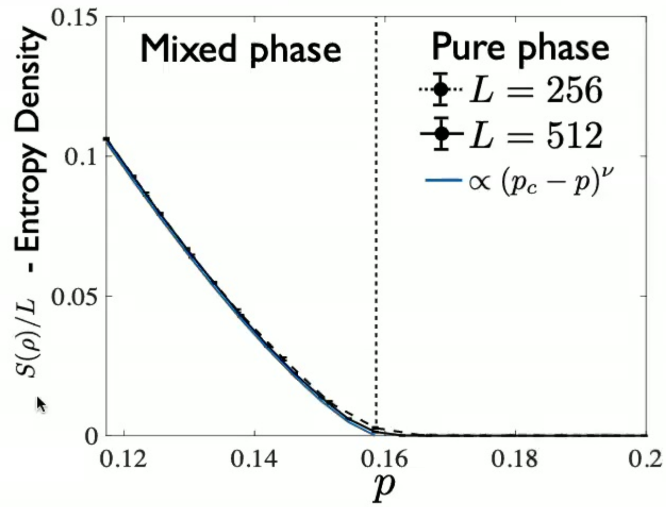


Purification or Coding Transition

Start in a mixed state

Stays mixed for times exp(L) — p_c — Purifies at constant rate

0 — Measurement rate p — 1



$\rho = \frac{1}{2^L}\mathbb{I}$ - Initial state

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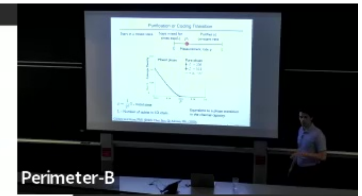
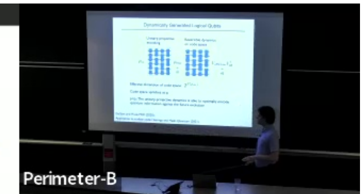
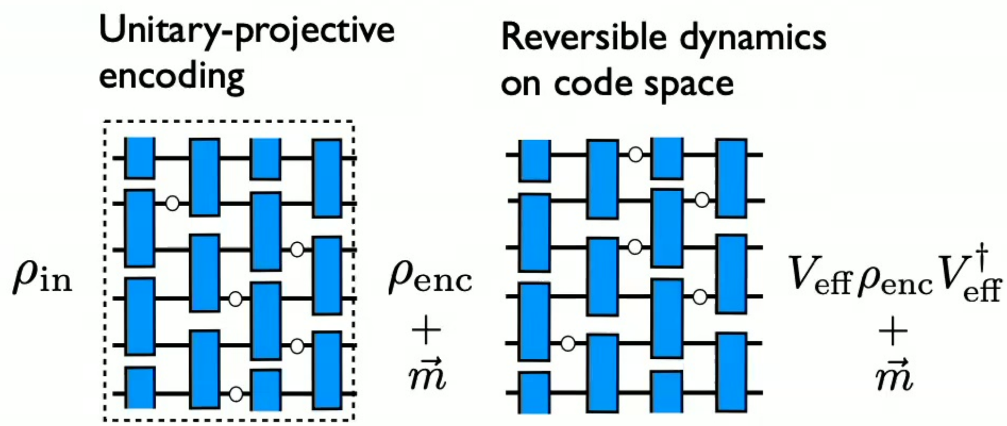
Equivalent to a phase transition in the channel capacity

Gullans and Huse, PRX (2020). Choi, Bao, Qi, Altman, PRL (2020).





Dynamically Generated Logical Qubits



Effective dimension of code space: $2^{S(\rho_{\vec{m}})}$

Code space vanishes at p_c

$p<p_c$: The unitary-projective dynamics is able to optimally encode quantum information against the future evolution

Gullans and Huse, PRX (2020).

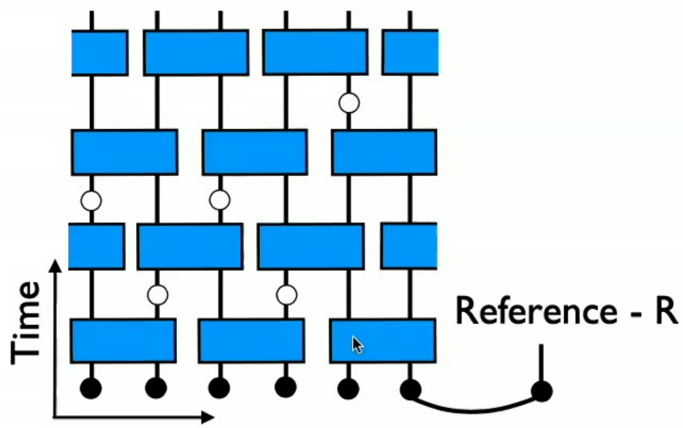
Application to surface code: Hastings and Haah, Quantum (2021).

Local Order Parameter for the Phase Transition

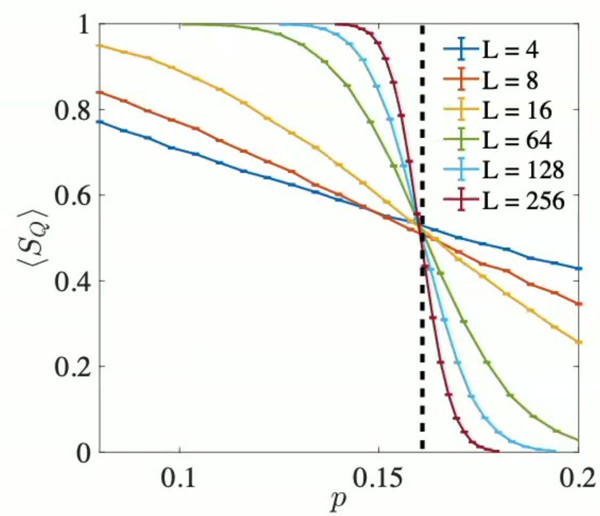
Entropy of a single entangled reference qubit acts as an order parameter

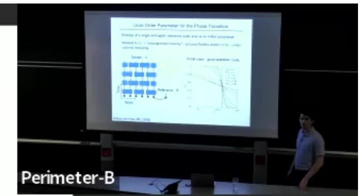
Related to F_e = "entanglement fidelity" - process fidelity metric in QI - under optimal decoding

System - S



Initial state - good stabilizer code





Gullans and Huse, PRL (2020).

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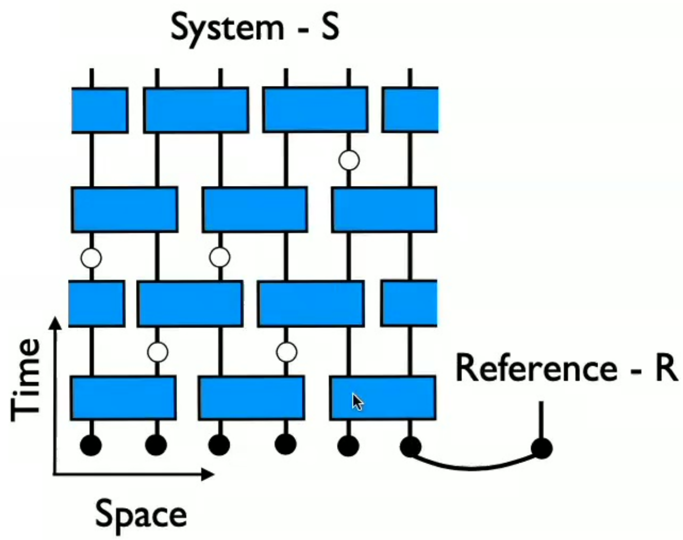

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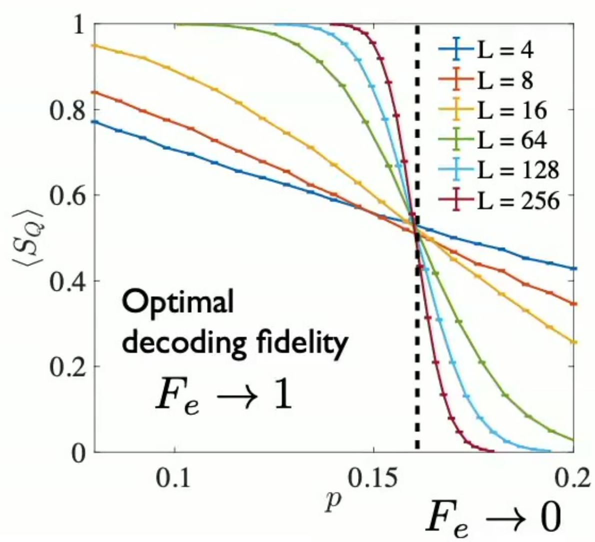
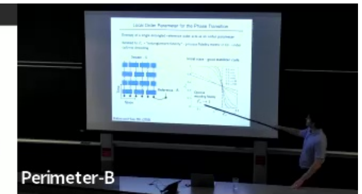
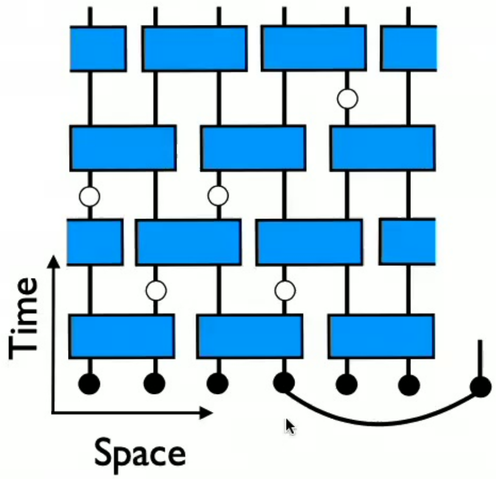


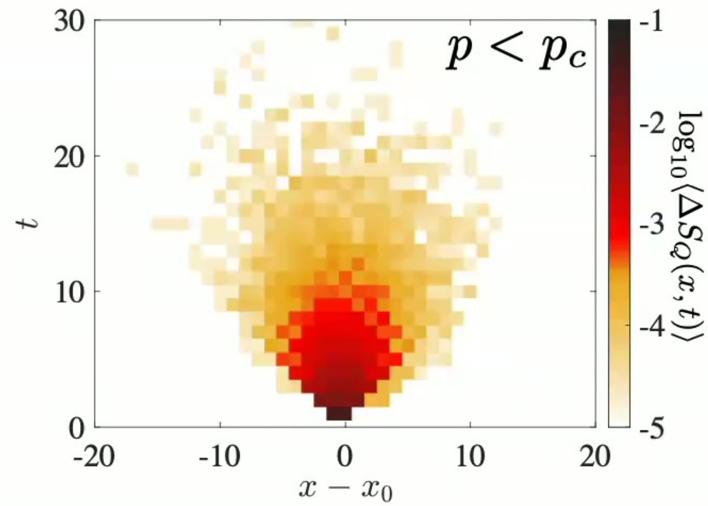
Gullans and Huse, PRL (2020).



Evidence for Scalability from Emergent Light Cone

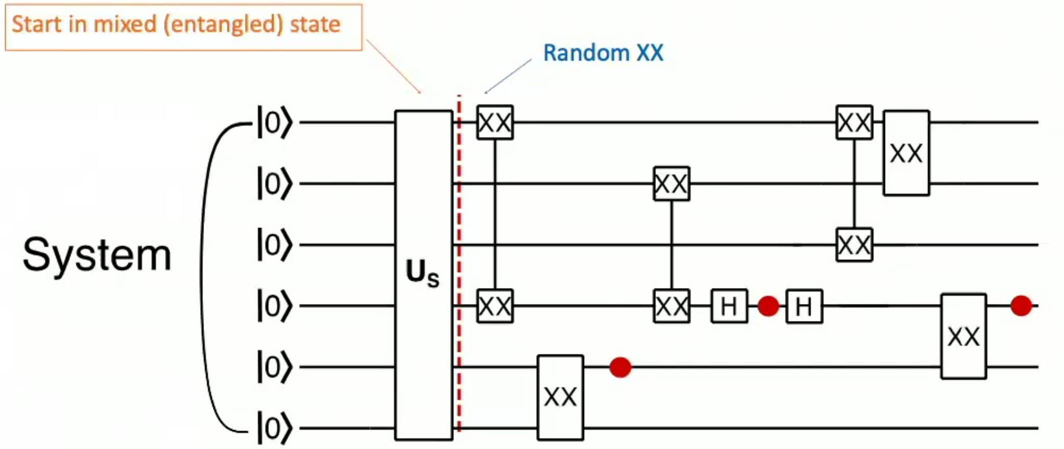
For locally entangled qubit only need access to measurements within a statistical light cone*





*Weak violations to locality arise from quantum teleportation: Li, Chen, Ludwig, Fisher, PRB (2021).

Implementation in Ion Trap System - All-to-All Circuits



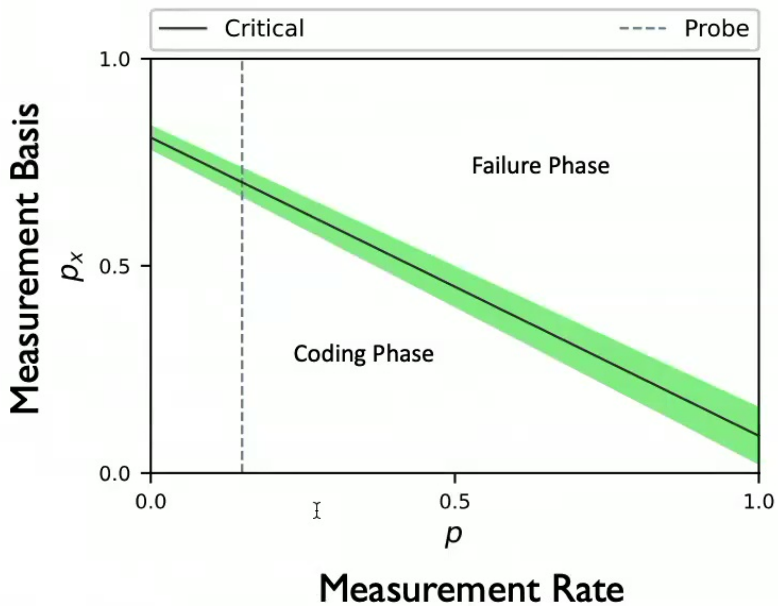
Exploit natural strengths of ion-chain architecture

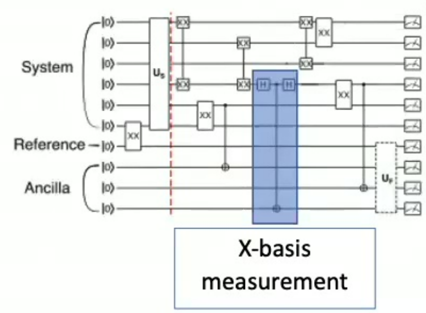
- High-fidelity Molmer-Sorensen gate $XX(\theta) = e^{-i\theta X_1 X_2}$
- All-to-all connectivity

Noel *et al.*, arXiv:2106.05881 (2021).

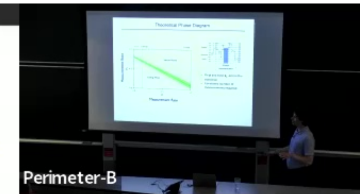
Ion-trap proposal for 1D model: Czischek *et al.*, PRA (2021).

Theoretical Phase Diagram





- Fix **p** and tune $\mathbf{p_x}$ across the transition
- Constrains number of measurements required



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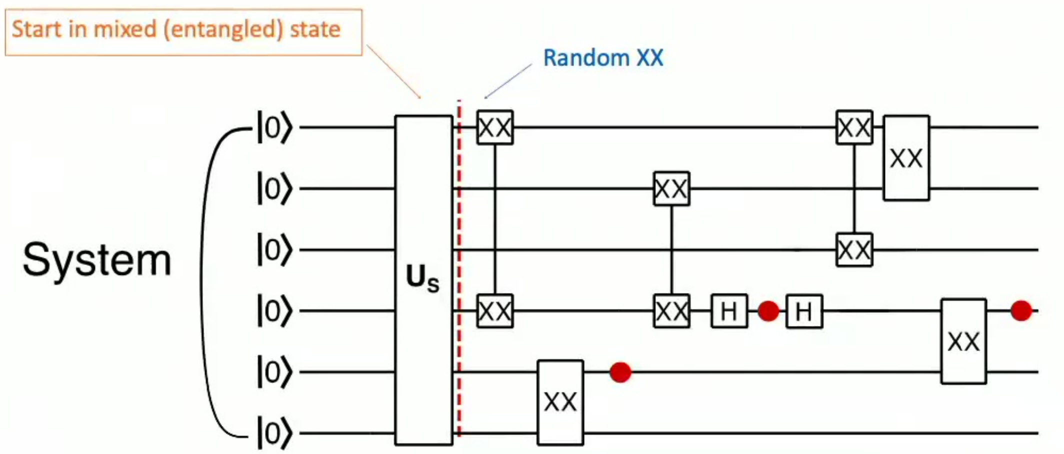

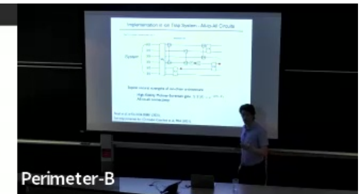

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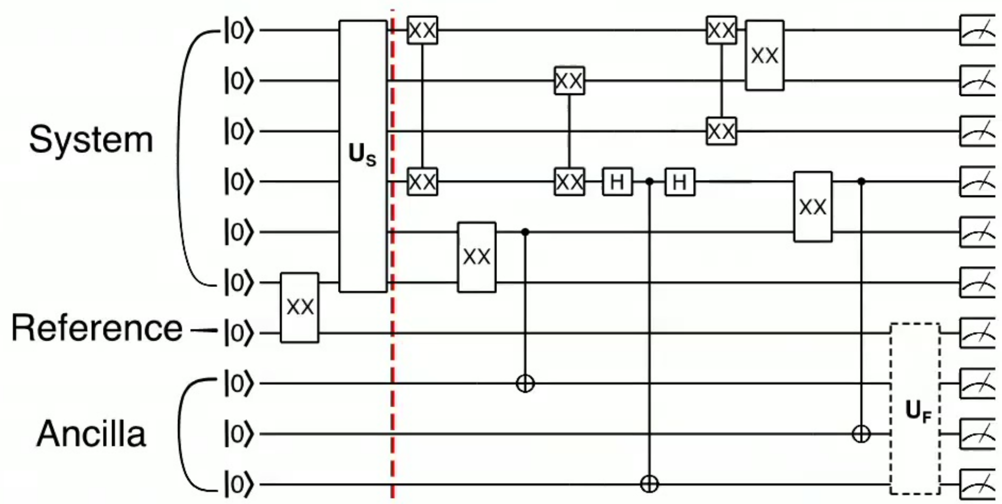
Deferred Measurements and Quantum Feedback

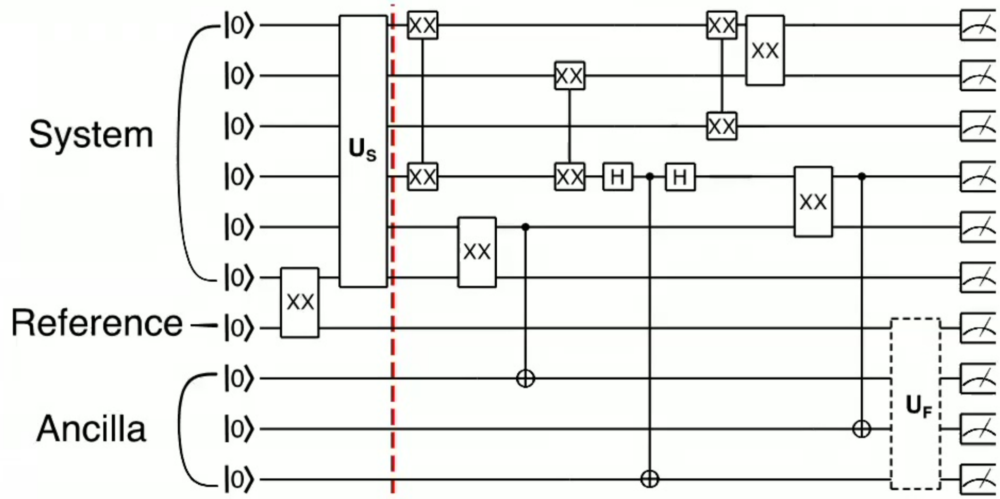


Use ancilla to defer measurements

Noel *et al.*, arXiv:2106.05881 (2021).

Related to black hole information recovery problem: Yoshida, arXiv:2109.08691 (2021).

Deferred Measurements and Quantum Feedback



Use ancilla to defer measurements

Analytically computed decoder for reference

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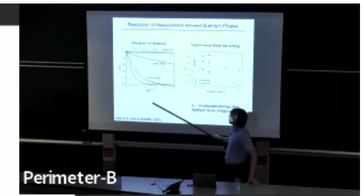
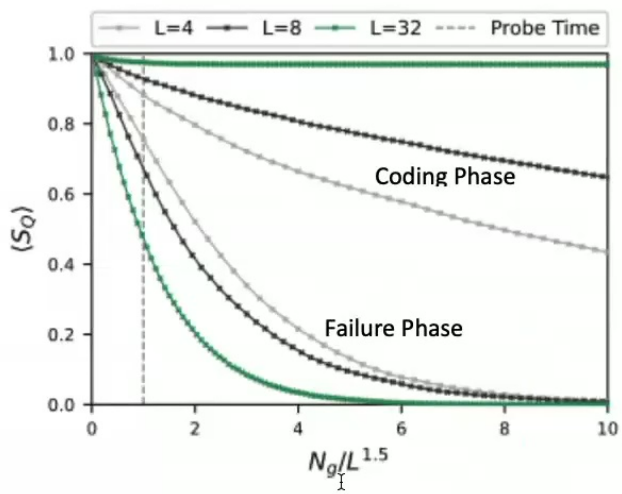
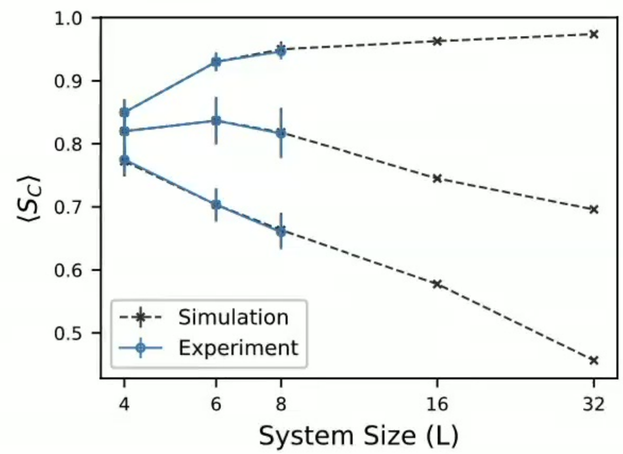
Realization of Measurement-Induced Quantum Phases



Simulation of dynamics



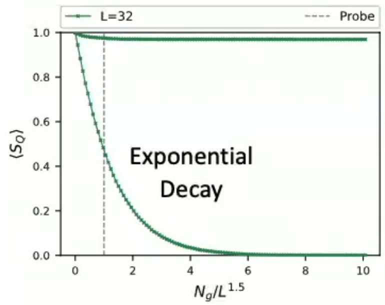
Experimental finite-size scaling



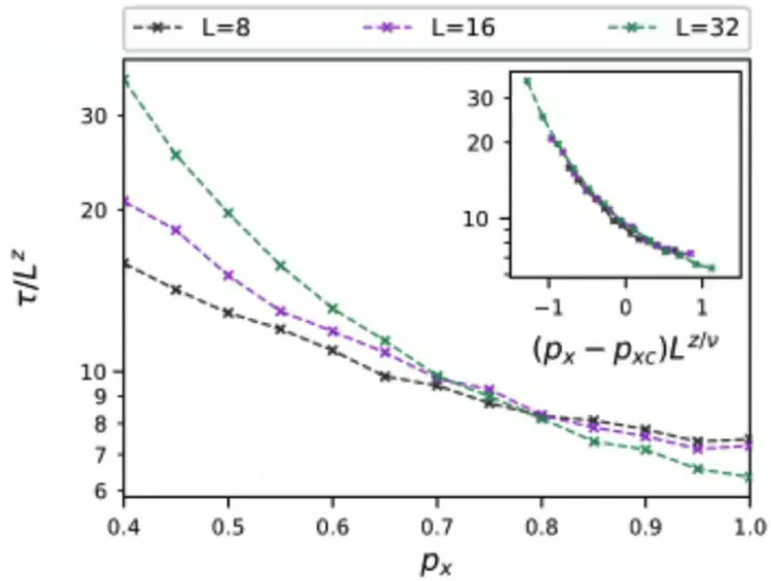
S_C - thresholded entropy after feedback (error mitigation)

Noel *et al.*, arXiv:2106.05881 (2021).

Requirements to Probe Criticality



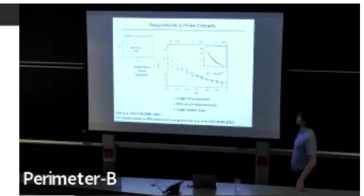
Exponential Decay Parameter



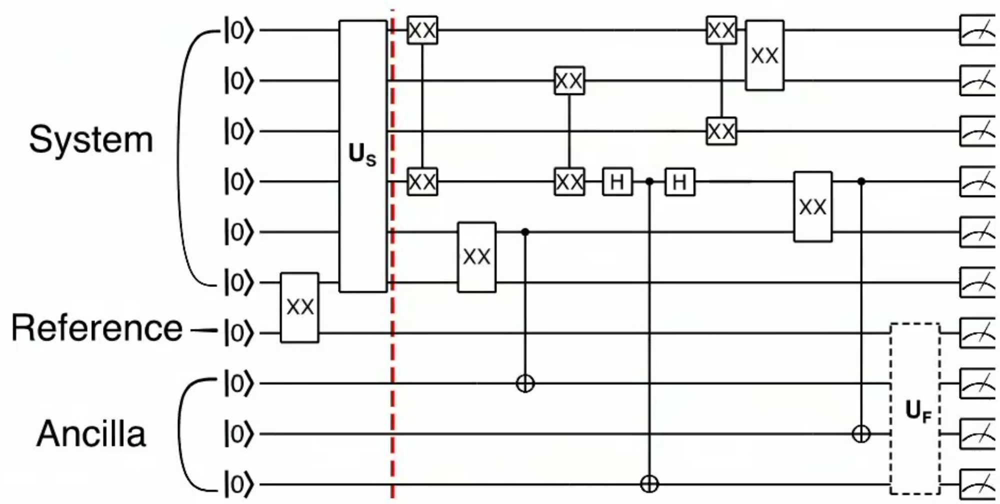
- Longer time evolution
- Mid-circuit measurements
- Larger system sizes

Noel *et al.*, arXiv:2106.05881 (2021).

1D criticality probed on IBM machine with tomography: Koh *et al.*, arXiv:2203.04338 (2022).



Deferred Measurements and Quantum Feedback



Use ancilla to defer measurements

Analytically computed decoder for reference

Noel *et al.*, arXiv:2106.05881 (2021).

Related to black hole information recovery problem: Yoshida, arXiv:2109.08691 (2021).

Beyond Stabilizer Circuits

Stabilizer circuits

- Experimentally accessible
- Robust to noise
- Decodable analytically Gottesman-Knill theorem or Yoshida protocol

Gate set is non-universal - generic circuits are a distinct universality class

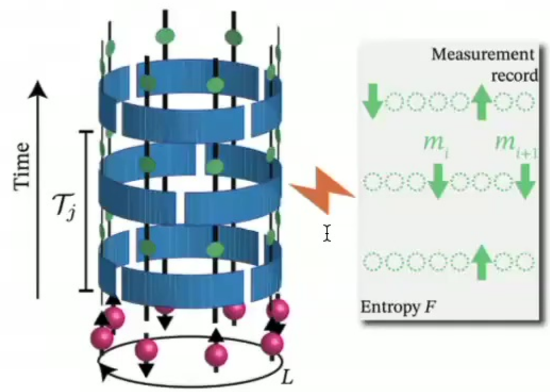
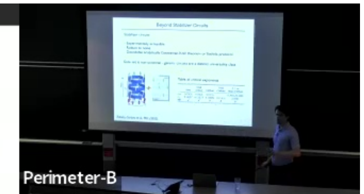


Table of critical exponents

	Haar	Dual unitary	Clifford	Dual Clifford	$d=\infty$ Haar/Clifford
c_{eff}	0.25(3)	0.24(2)	0.37(1)		0.2914/0.3652
x_1	$0.14(2)^{\dagger}$	$0.122(1)^{\dagger}$	0.120(5)	0.111(1)	0.1042
MF	✓	✓	✗	✗	✗

Zabalo, Gullans *et al.*, PRL (2022).

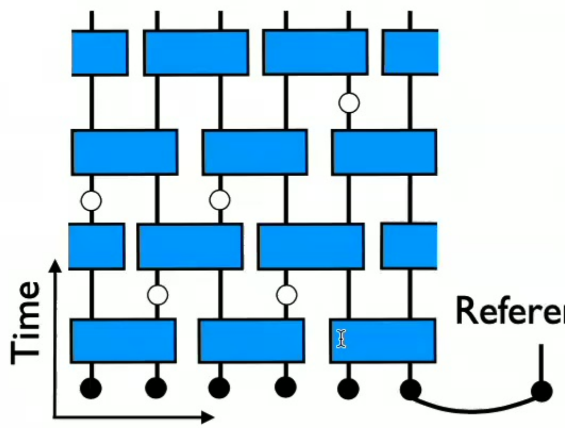


Local Order Parameter for the Phase Transition

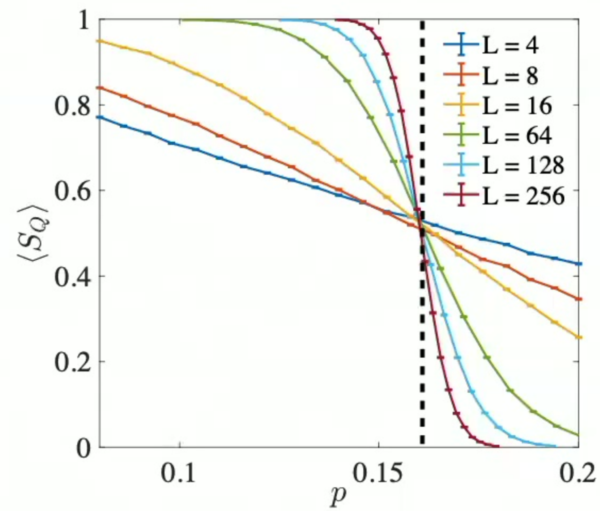
Entropy of a single entangled reference qubit acts as an order parameter

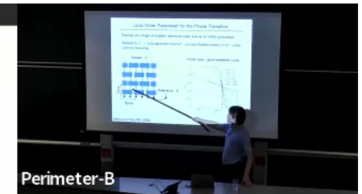
Related to F_e = "entanglement fidelity" - process fidelity metric in QI - under optimal decoding

System - S



Initial state - good stabilizer code

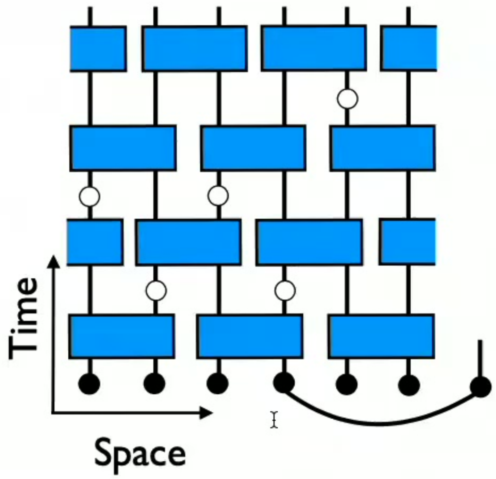


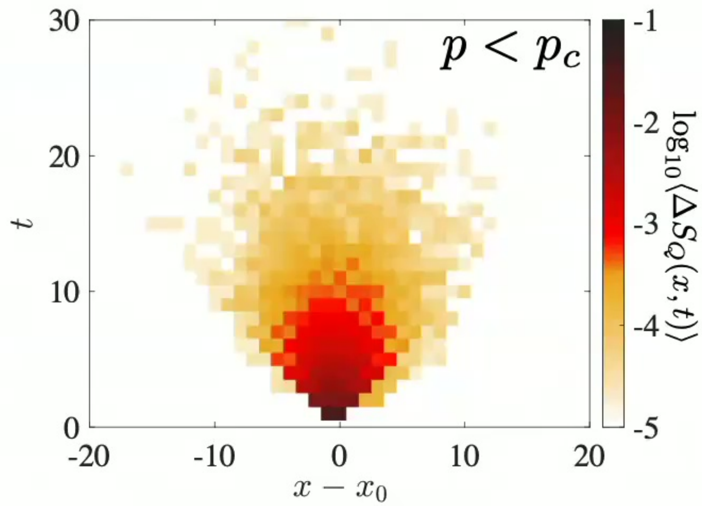


Gullans and Huse, PRL (2020).

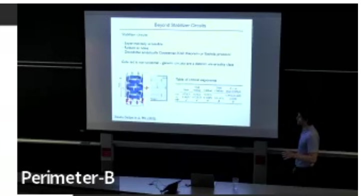
Evidence for Scalability from Emergent Light Cone

For locally entangled qubit only need access to measurements within a statistical light cone*





*Weak violations to locality arise from quantum teleportation: Li, Chen, Ludwig, Fisher, PRB (2021).



Beyond Stabilizer Circuits

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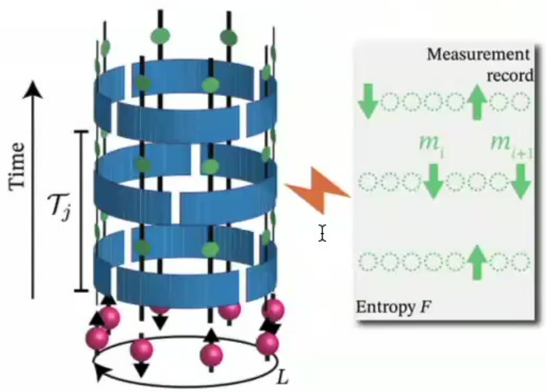
Gate set is non-universal - generic circuits are a distinct universality class



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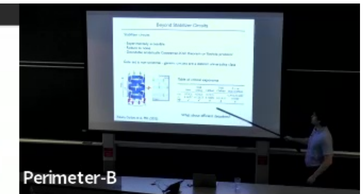

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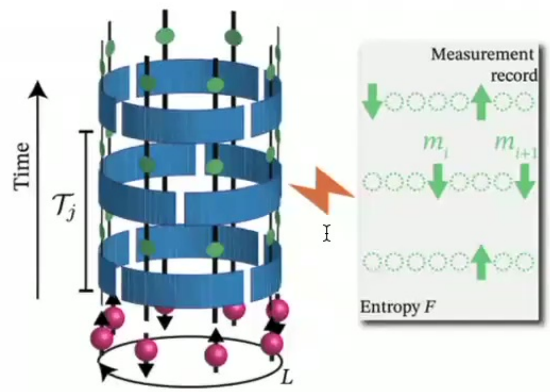

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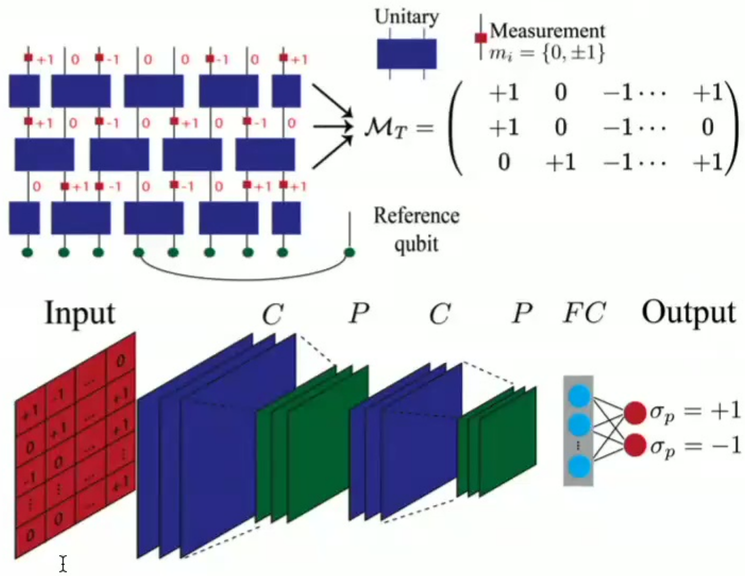
What about efficient decoders?

Zabalo, Gullans *et al.*, PRL (2022).

Neural Network Decoder

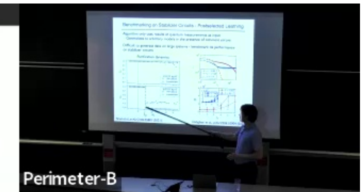
Treat decoding problem as an image classification problem



Decoder tries to find the Pauli expectation values of the reference qubit conditioned on measurement outcomes

$$F_{\mathcal{C}}(\mathcal{M}_T) = (\langle \sigma_X \rangle, \langle \sigma_Y \rangle, \langle \sigma_Z \rangle)$$

Dehghani *et al.*, arXiv:2204.10904 (2022).

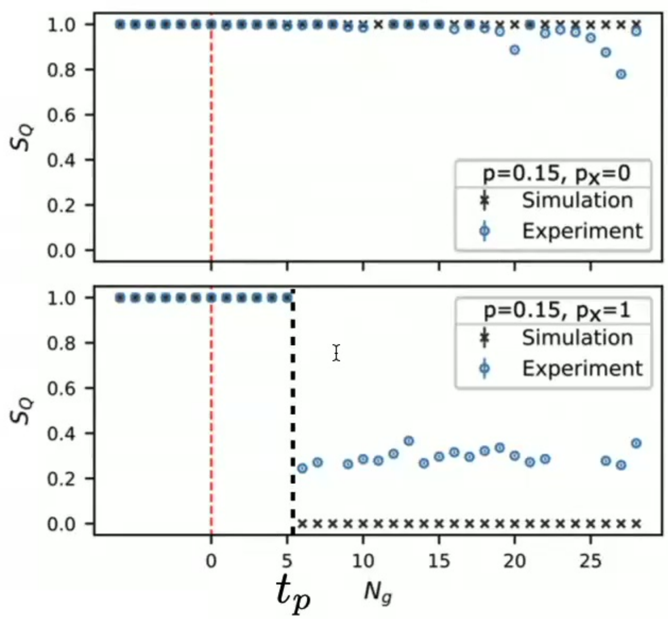


Benchmarking on Stabilizer Circuits - Postselected Learning

Algorithm only uses results of quantum measurements as input
- Generalizes to arbitrary models in the presence of coherent errors

Difficult to generate data on large systems - benchmark its performance on stabilizer circuits

Purification dynamics



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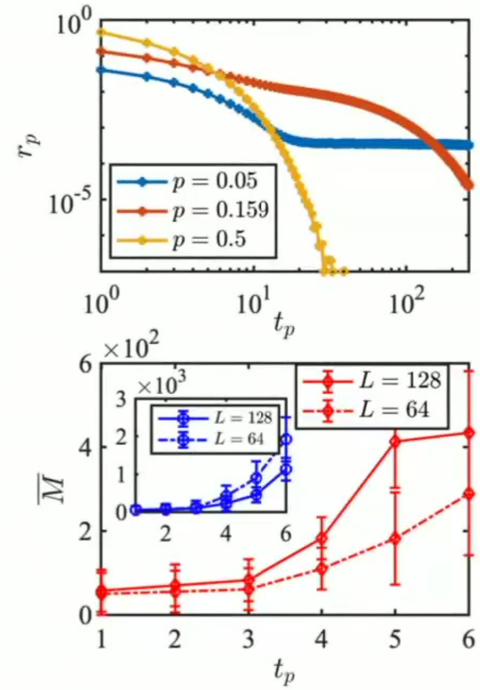

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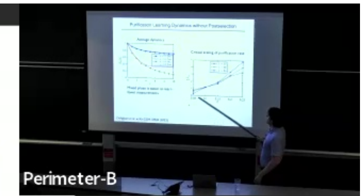
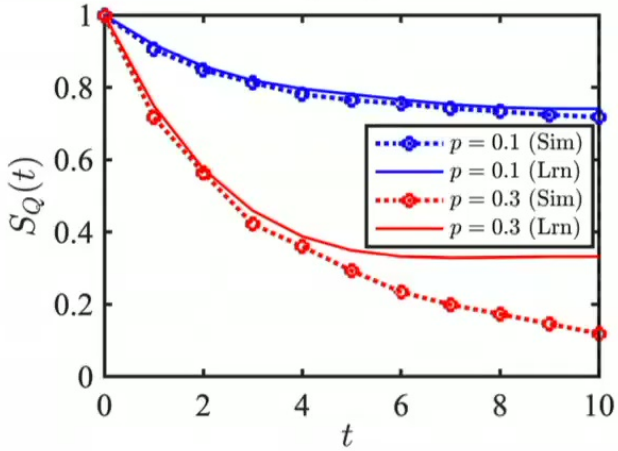
Purification Learning Dynamics without Postselection

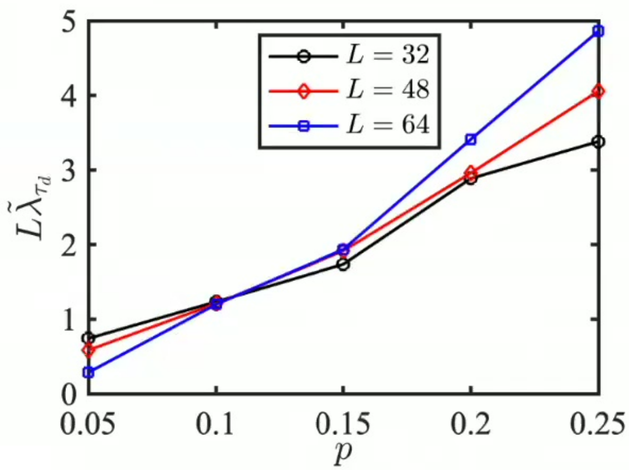


Average dynamics



Mixed phase is easier to learn - fewer measurements

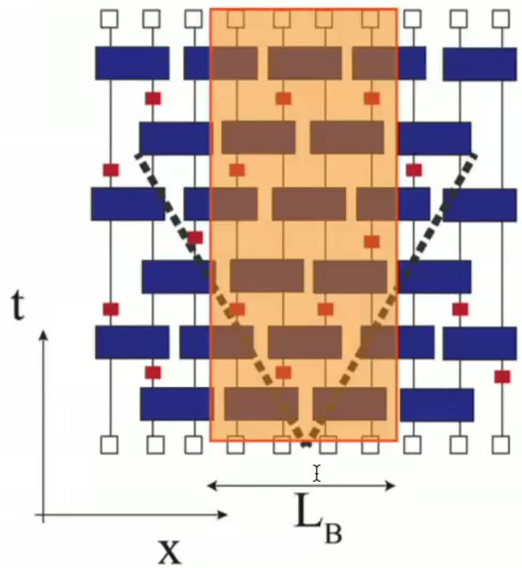
Critical scaling of purification rate

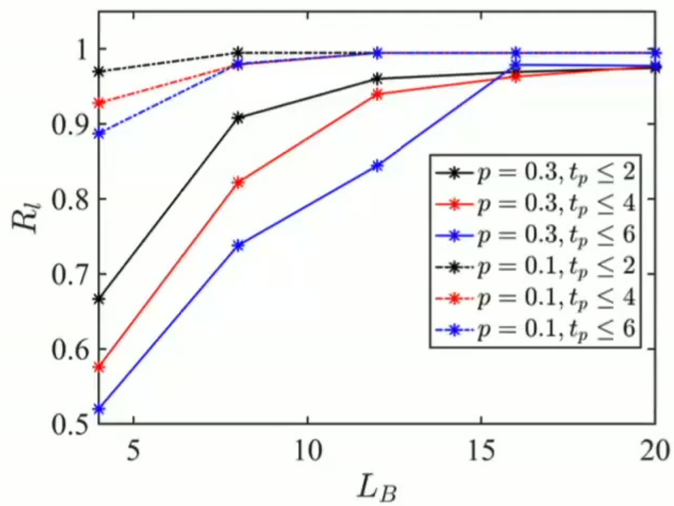


Dehghani *et al.*, arXiv:2204.10904 (2022).

Scalability of Learning

Train the neural network using sub-circuits of the full circuit





Learnability saturates when the sub-circuit extends beyond the lightcone

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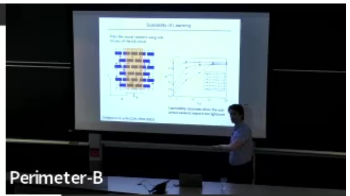

Open Questions

Some of the goals of this work:

- Examine more types of systems. Try to include more “realistic” features, uncontrolled environment, active error correction, …

- Find more ways to qualitatively and quantitatively characterize “success” phase(s). Are there more than one phase with different levels of “success”?

- Understand phase transitions: Can it be practical to operate <u>near</u> to phase transitions? Or does one have to go “deep” into the “success” phase to have good scalable quantum information systems?

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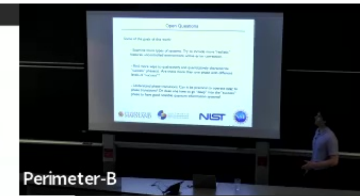

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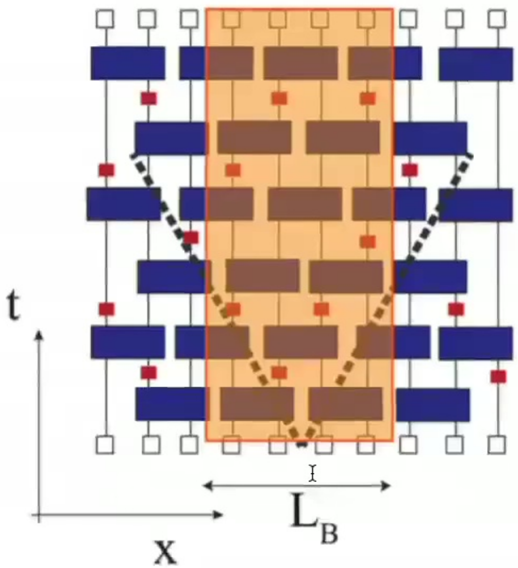

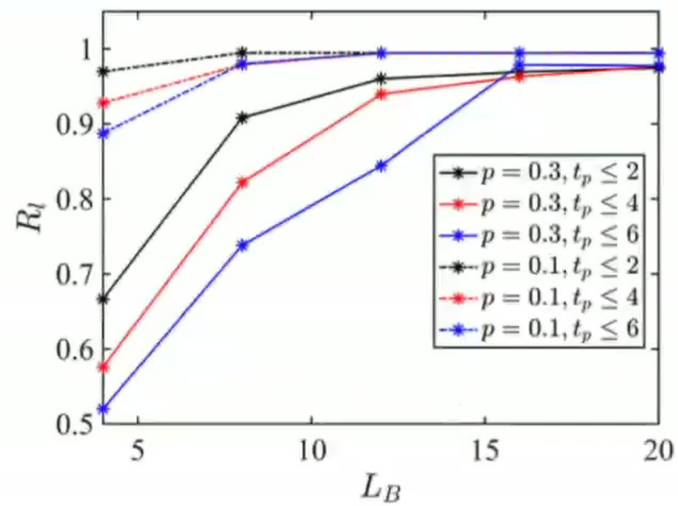

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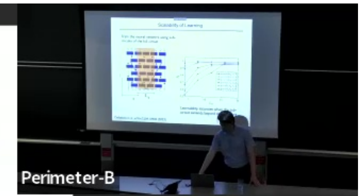

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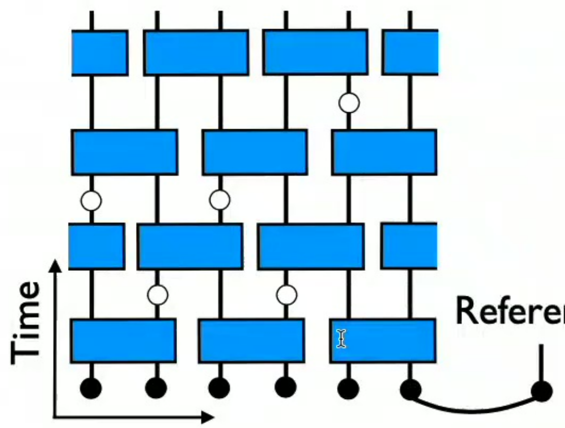

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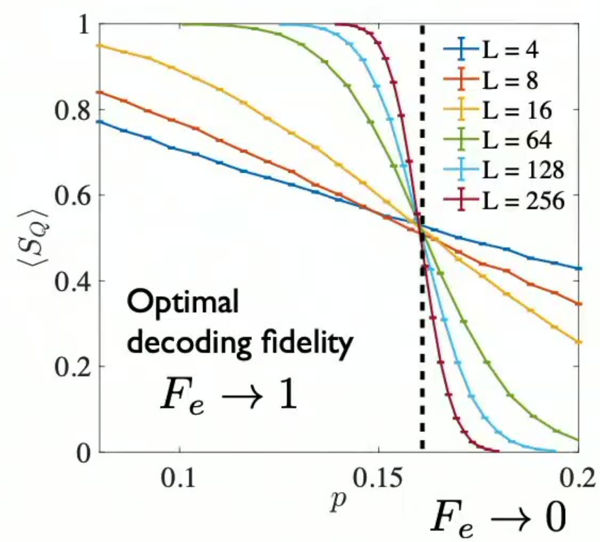

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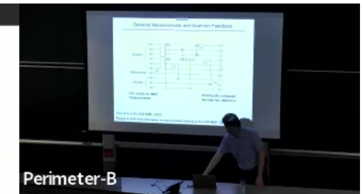
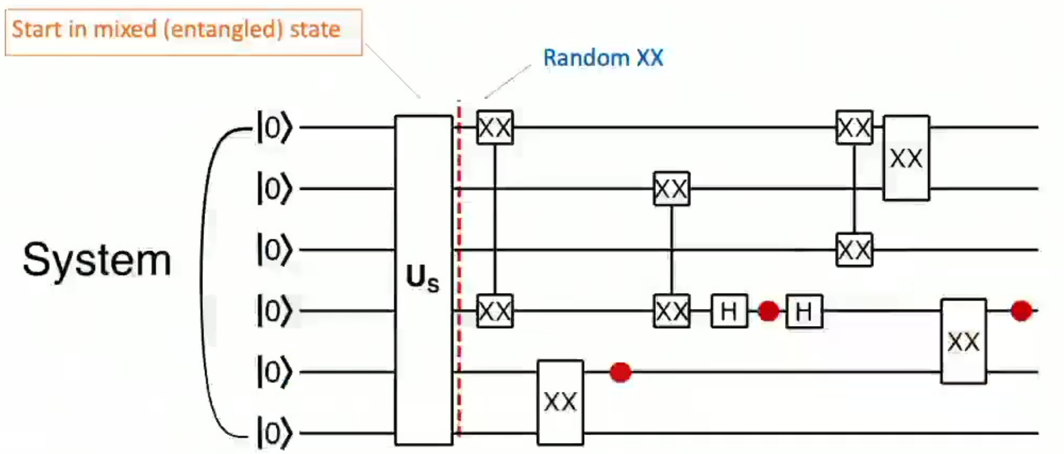


Implementation in Ion Trap System - All-to-All Circuits

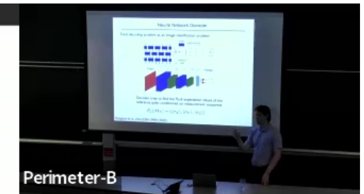


Exploit natural strengths of ion-chain architecture

- High-fidelity Molmer-Sorensen gate $XX(\theta) = e^{-i\theta X_1 X_2}$
- All-to-all connectivity

Noel *et al.*, arXiv:2106.05881 (2021).

Ion-trap proposal for 1D model: Czischek *et al.*, PRA (2021).



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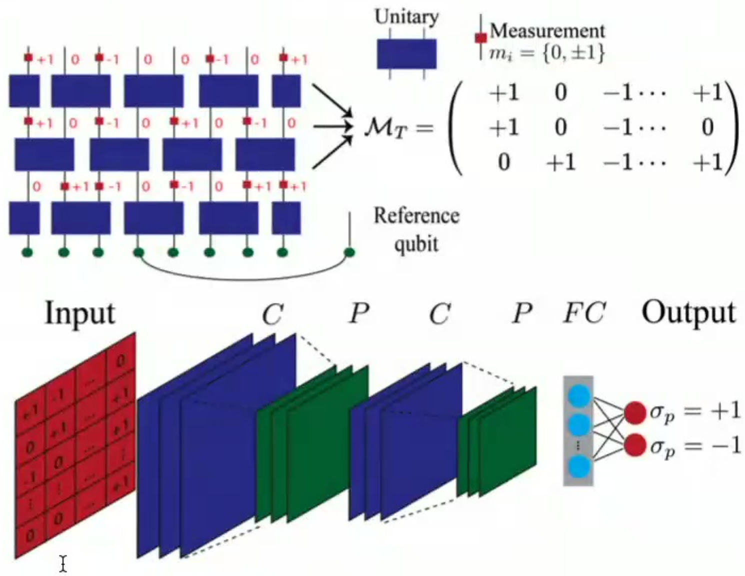

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