Title: A measured approach toward long-range entangled matter

Speakers: Timothy Hsieh

Series: Colloquium

Date: November 08, 2023 - 2:00 PM

URL: https://pirsa.org/23110055

Abstract: Long-range entangled quantum matter encompasses a wealth of fascinating phenomena including fractionalization and criticality. I will show how quantum dynamics involving measurements can both enable new kinds of long-range entangled states and facilitate their realization on quantum simulators. In the first part, I will illustrate how competing measurements along with unitary time evolution can give rise to distinct universality classes of non-equilibrium criticality. In the second part, I will show how measurements and unitary evolution conditioned on the measurement outcomes ("adaptive quantum circuits") enable efficient preparation of long-range entangled matter. Finally, I will demonstrate how environmental measurement (decoherence) can remarkably enrich quantum critical pure states, giving rise to renormalization group flows between quantum channels with important implications on the entanglement structure of the resulting critical mixed states.

Zoom link https://pitp.zoom.us/j/97087115629?pwd=NHdlWG9oM0xHUDIzU05sUWRKdWlFdz09

Long-range entangled quantum matter

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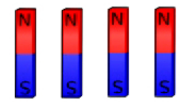
“Far” from classical product-like state 

Example 1: quantum critical states

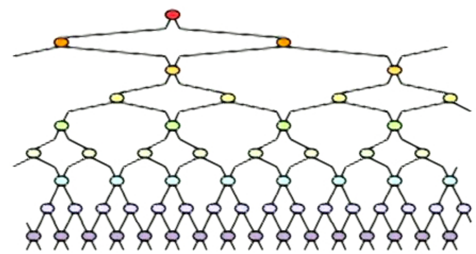


Fig. adapted from Vidal

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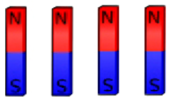
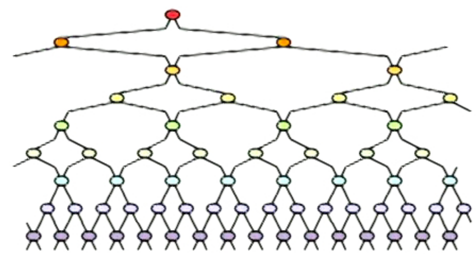
"Far" from classical product-like state 

Example 1: quantum critical states

Phase transitions between competing quantum orders (e.g. ferromagnet and paramagnet)



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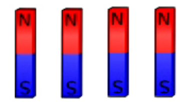
"Far" from classical product-like state 

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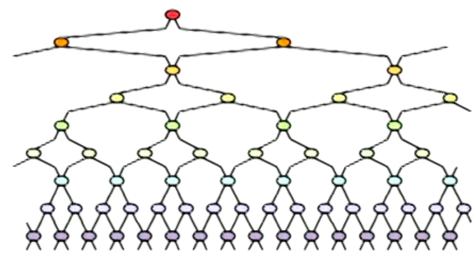

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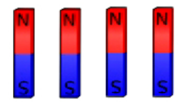
Phase transitions between competing quantum orders (e.g. ferromagnet and paramagnet)

Quantum correlations at all length scales

Long-range entangled quantum matter

"Far" from classical product-like state 

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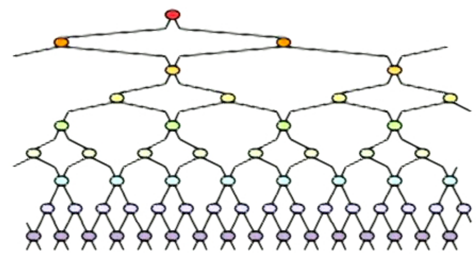

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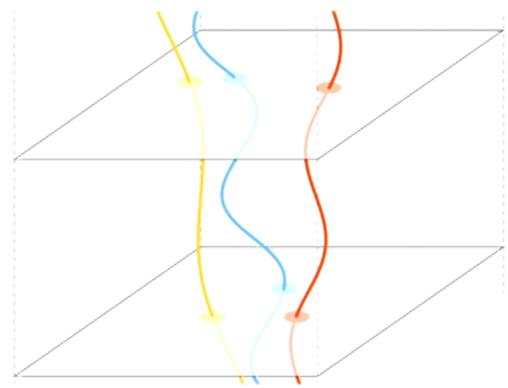
Phase transitions between competing quantum orders (e.g. ferromagnet and paramagnet)

Quantum correlations at all length scales

Example 2: topological order

No local order parameter



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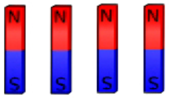
"Far" from classical product-like state 

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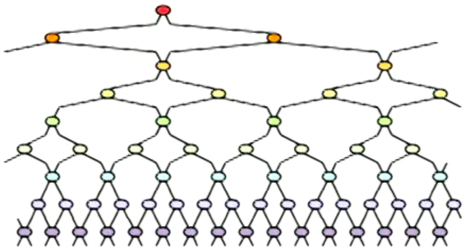
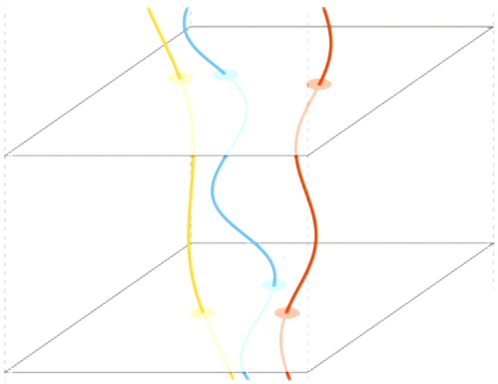


Fig. adapted from Vidal

Example 2: topological order

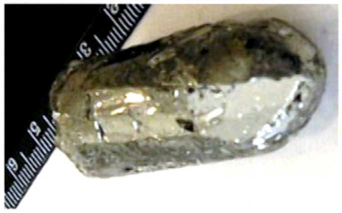
No local order parameter

Fractionalized excitations "anyons"

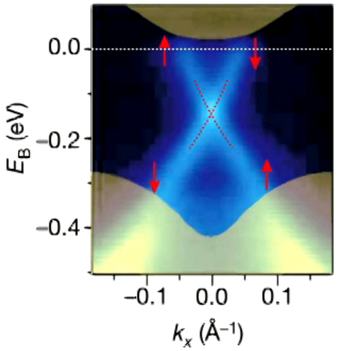


Topological quantum materials

Topological
insulators



Bi_2Se_3



D. Hsieh et.al. (2009)

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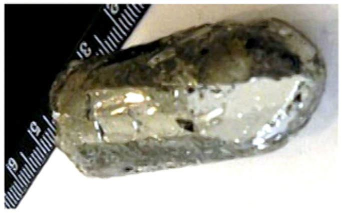

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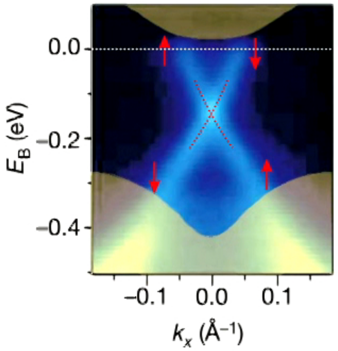

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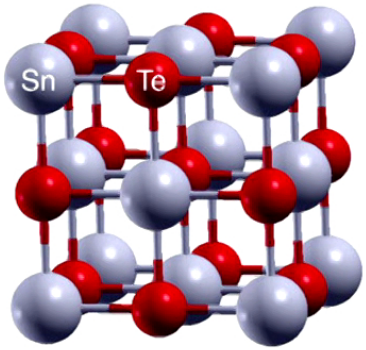
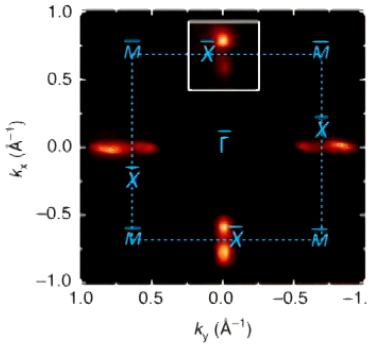
Topological
crystalline insulators





S. Xu et.al. (2012)

TH, H. Lin, J. Liu, W. Duan, A. Bansil, and L. Fu
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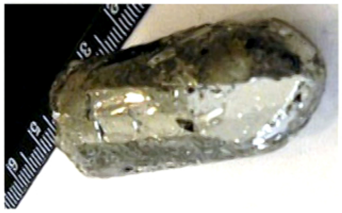

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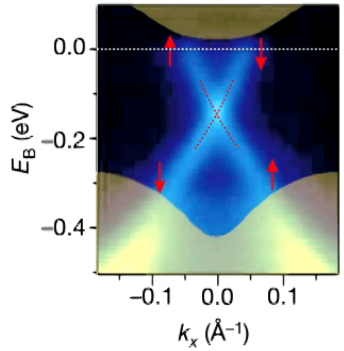

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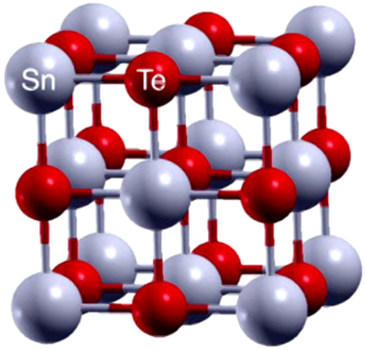

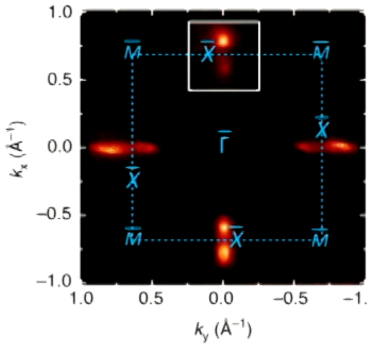

S. Xu et.al. (2012)

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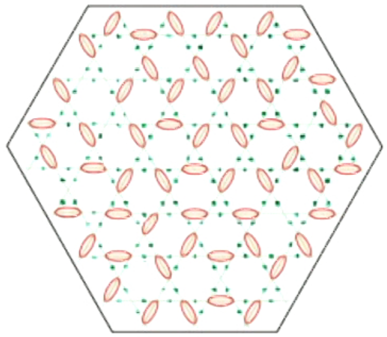
But long-range entangled matter much more elusive

Rise of the (Quantum) Machines

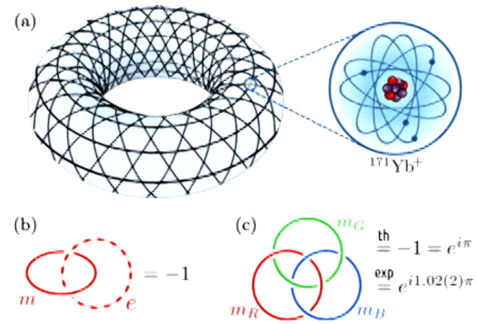
Rydberg array

Semeghini, et.al. (2021)



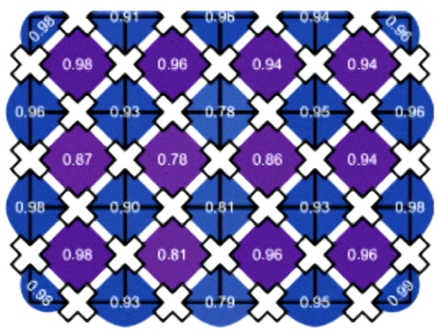
Trapped Ions

Iqbal, et.al. (2023)

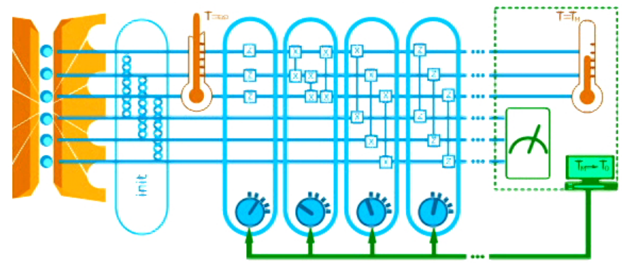


Superconducting qubits

Satzinger, et.al. (2021)



Quantum critical and thermofield double states on trapped ion computer:



Zhu, Johri, Linke, Landsman, Alderete, Nguyen, Matsuura, TH, and Monroe (2020)

W. Ho and TH (2019)

J. Wu and TH (2019)

Long-range entangled quantum matter

Far from classical product-like state

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Far from classical product-like state

Cannot be prepared from trivial product states using
local unitary quantum circuits of constant depth

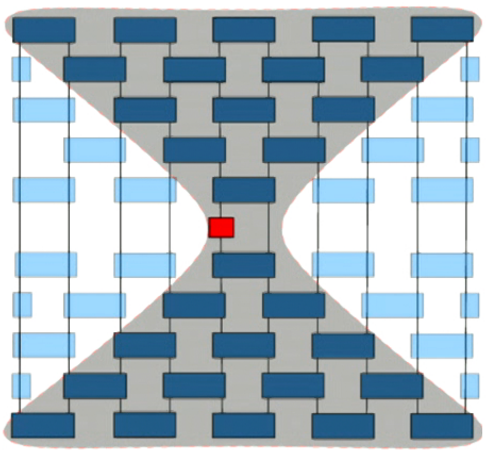

Figure from Xu, Swingle (2020)

Finite speed at which correlations can propagate

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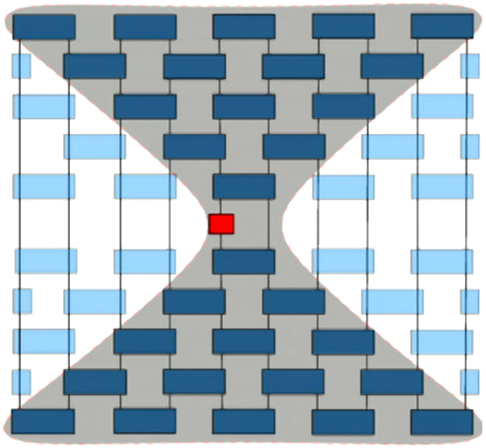

Figure from Xu, Swingle (2020)

Finite speed at which correlations can propagate

Need depth / time scaling with system size to produce requisite long range correlation

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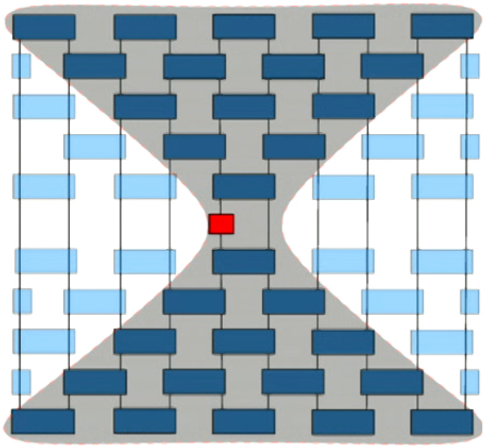


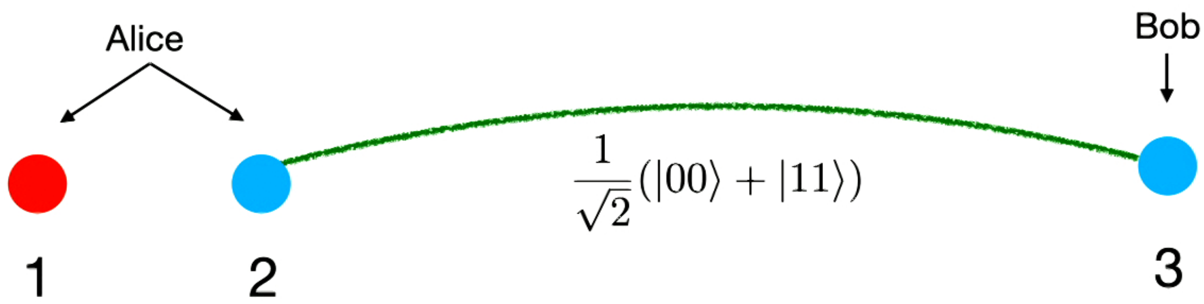
Figure from Xu, Swingle (2020)

Finite speed at which correlations can propagate

Need depth / time scaling with system size to produce requisite long range correlation

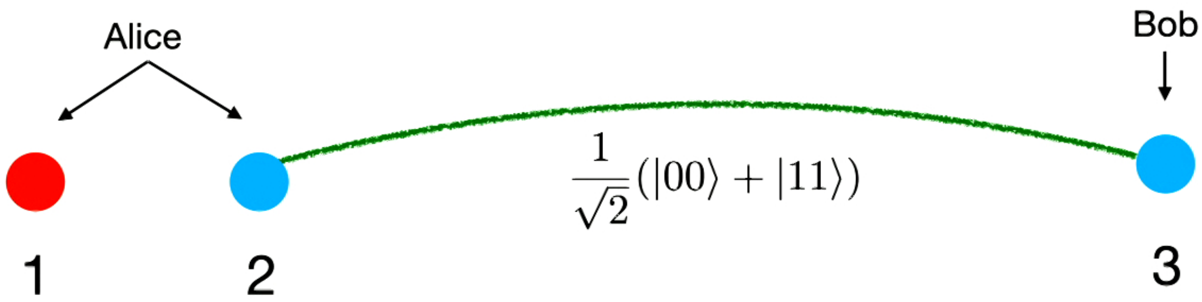
Use local measurements
(and possibly non-local classical communication)

Quantum Teleportation



Bennett, Brassard, Crepeau,
Jozsa, Peres, Wootters (1993)

Quantum Teleportation



Bennett, Brassard, Crepeau,
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Alice performs Bell pair (ZZ, XX) measurement on her qubits

Quantum Teleportation

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Quantum Teleportation

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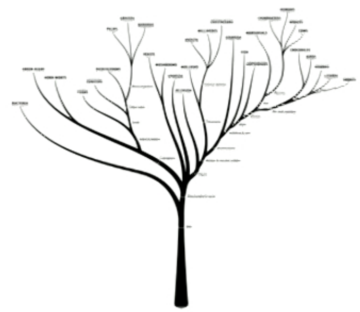
Alice performs Bell pair (ZZ, XX) measurement on her qubits

After Alice tells Bob which outcome (classical info), Bob can apply Pauli operator to recover Alice's qubit

This talk: measurements in many-body systems



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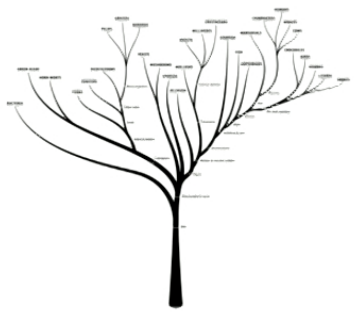
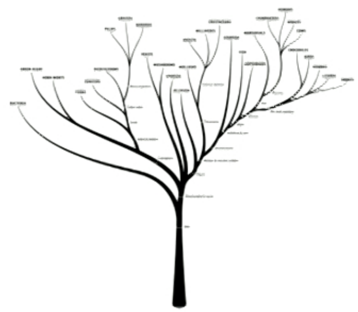


Part I: Competition between different measurements can give rise to novel long-range entangled states

Part II: Measurement + feedback can prepare many classes of long-range entangled states more efficiently than local unitary protocols

This talk: measurements in many-body systems



Part I: Competition between different measurements can give rise to novel long-range entangled states

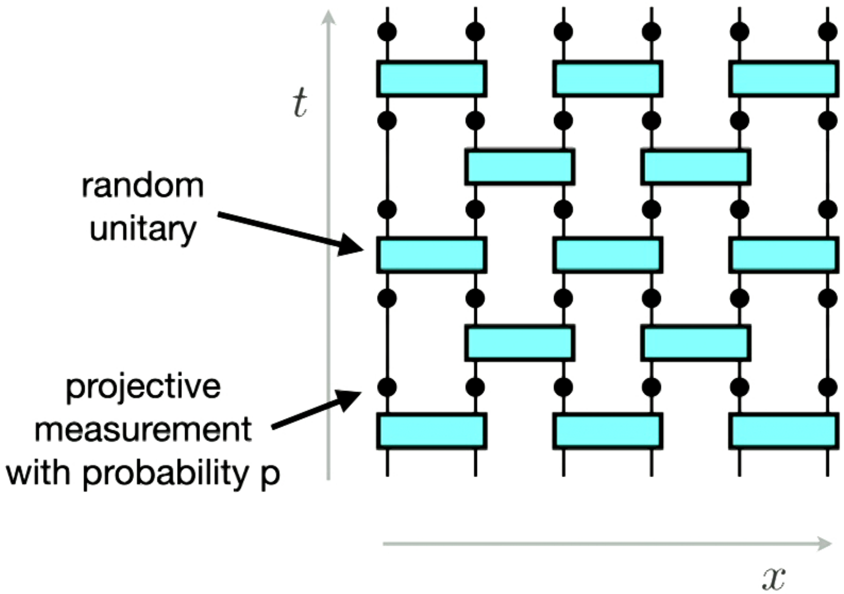
Part II: Measurement + feedback can prepare many classes of long-range entangled states more efficiently than local unitary protocols

Part III: Noise (measurement + forgetting outcome) can transform existing long-range entanglement

Measurement-driven quantum phases and transitions

Shengqi Sang and TH
Phys. Rev. Research 3, 023200 (2021)

Hybrid Quantum Circuits



Y. Li, X. Chen, MPA Fisher PRB 98, 205136 (2018)
B. Skinner, J. Ruhman, A. Nahum PRX 9, 031009 (2019)
X. Cao, A. Tillloy, A. De Luca SciPost 7 24 (2019)
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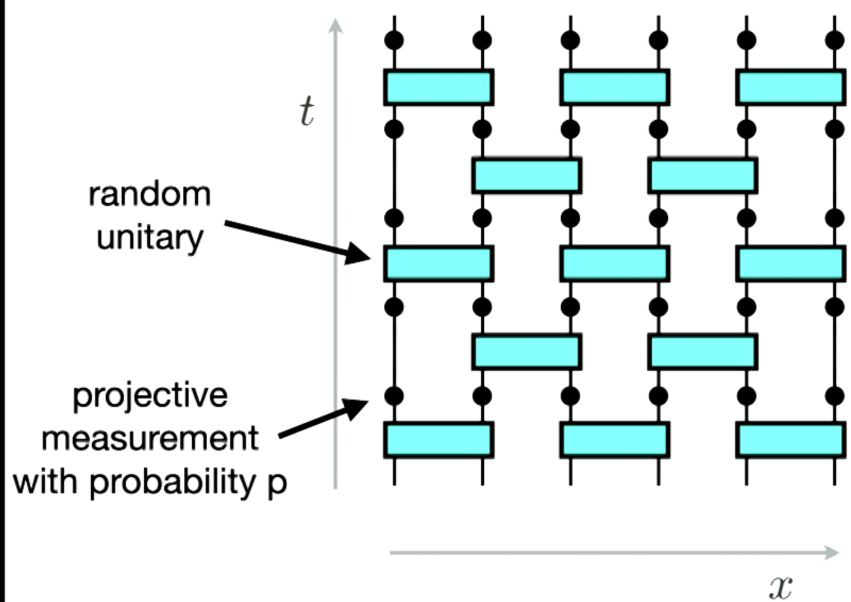

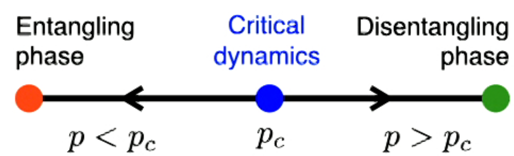

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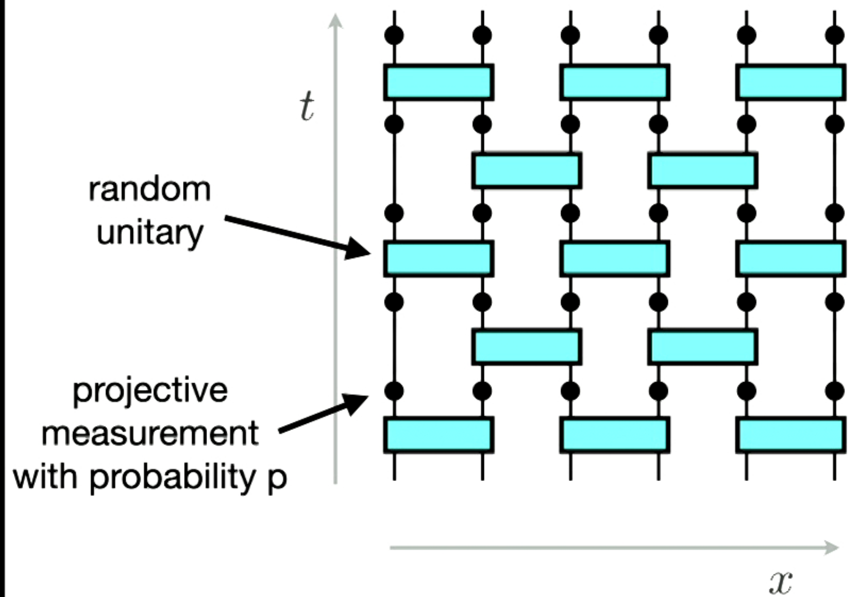

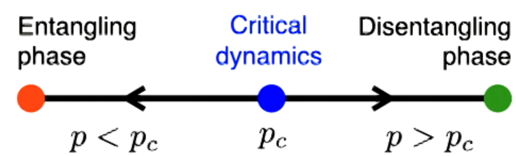

Volume law entanglement

$S_A \propto L_A$

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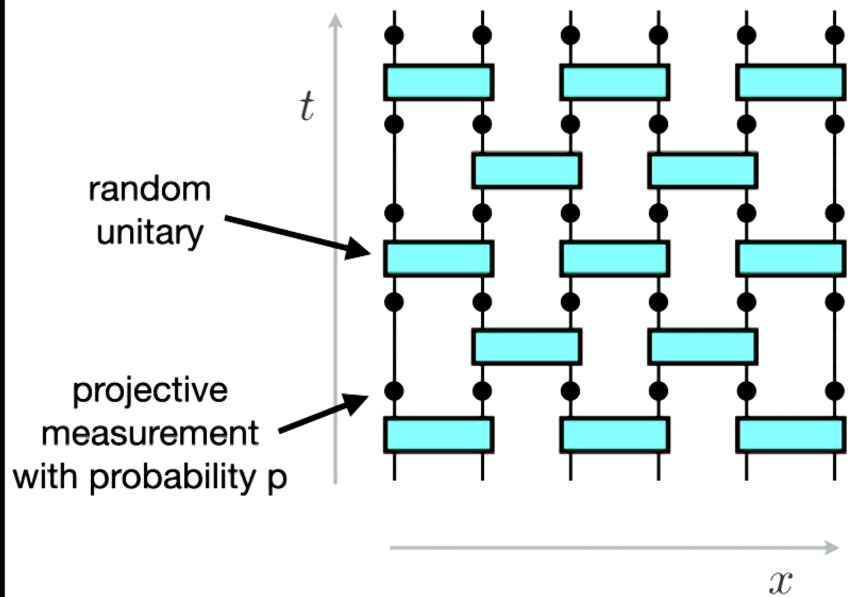

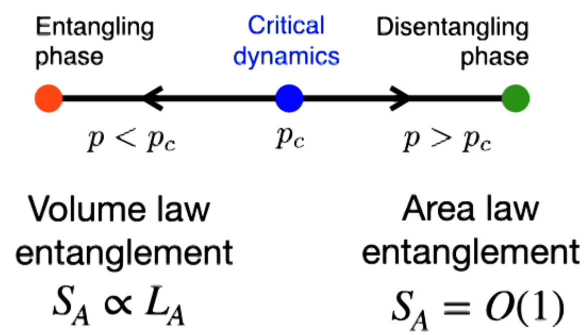

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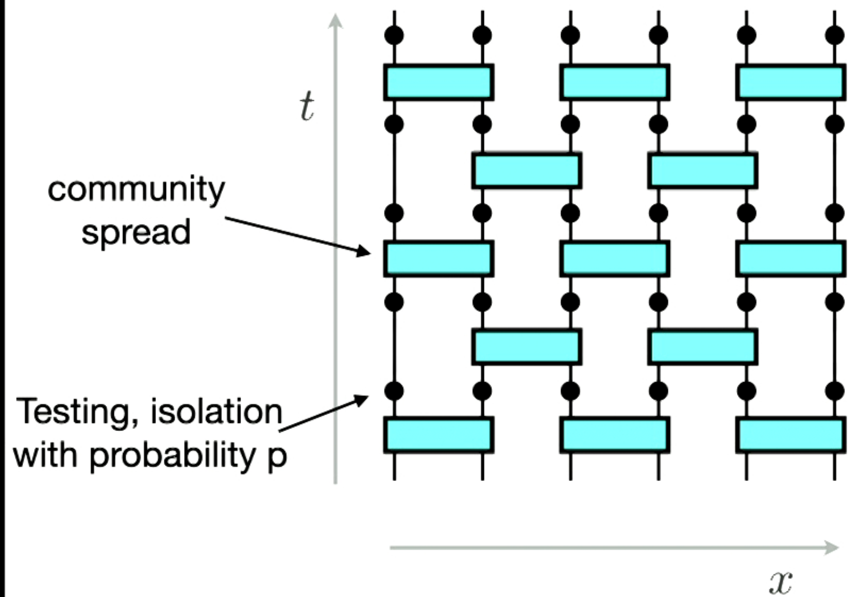
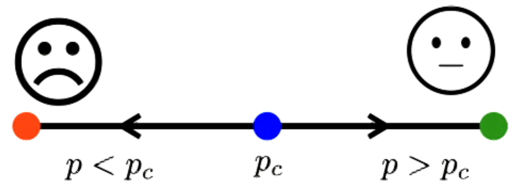
Practical Relevance





Measurement-only dynamics: a toy model

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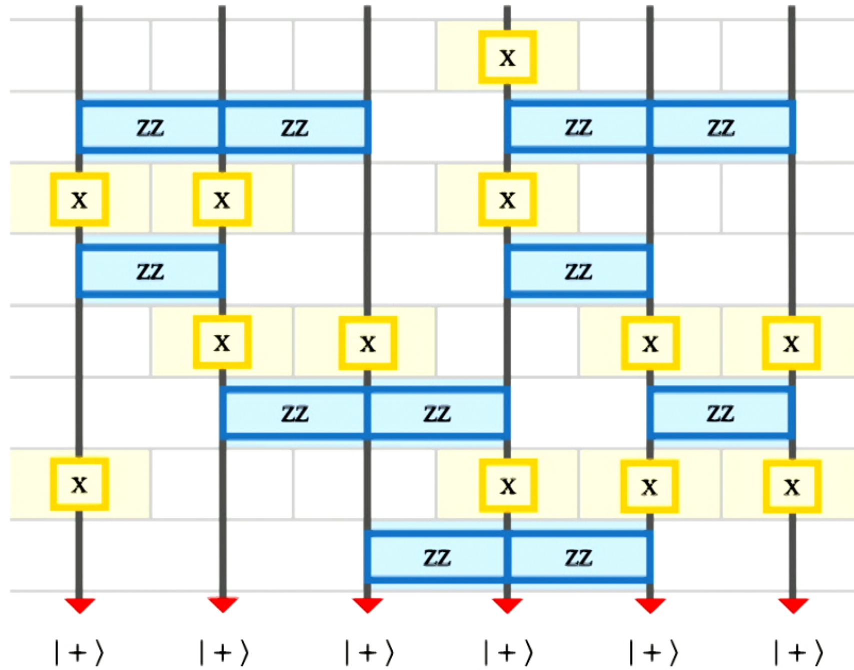

$X|+\rangle = |+\rangle$

See also
Skinner and Nahum,
Ippoliti, et.al.
Lavasani, et.al.
for related models

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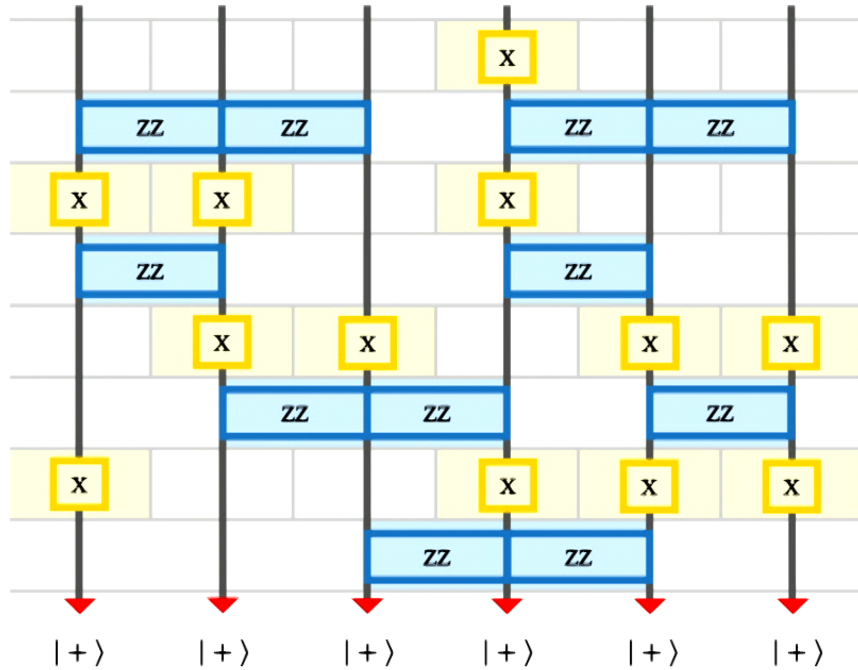

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Randomly measure ZZ and X; competition drives criticality

Extreme limits

ZZ measurement only: steady state has random $Z_i Z_{i+1} = \pm 1$ for every pair of qubits

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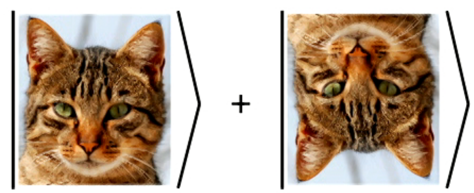
"random cat state" $$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\downarrow \dots \uparrow\rangle + |\downarrow\uparrow\uparrow \dots \downarrow\rangle)$$



X measurement only: remains a paramagnetic product state

Order Parameter and Phase Diagram

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Random cat aka spin glass: $\frac{1}{\sqrt{2}}(|\uparrow\downarrow\downarrow \dots \uparrow\rangle + |\downarrow\uparrow\uparrow \dots \downarrow\rangle)$

Order Parameter and Phase Diagram

Random cat aka spin glass: $\frac{1}{\sqrt{2}}(|\uparrow\downarrow\downarrow \ldots \uparrow\rangle + |\downarrow\uparrow\uparrow \ldots \downarrow\rangle)$

Quantify long-range order using spin glass or Edwards Anderson type order parameter:

$$O = \frac{1}{L}\sum_{i,j=1}^{L} \langle\psi|Z_i Z_j|\psi\rangle^2$$

Constant (paramagnet)
or linear with system size L (spin glass)?

Order Parameter and Phase Diagram

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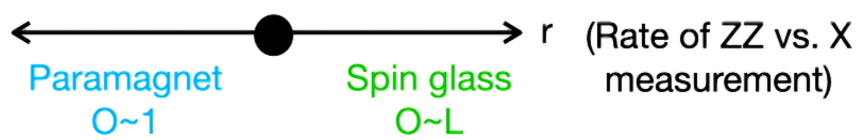

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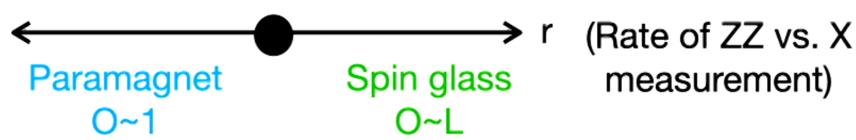
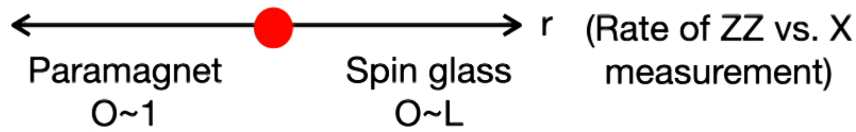


Ising symmetry essential for stability of spin glass (e.g. Z measurement would collapse cat)

Measurement-only phase transition



Represent each spin as pair of Majorana fermions (“Jordan-Wigner transformation”)

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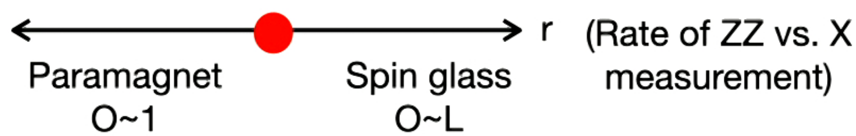

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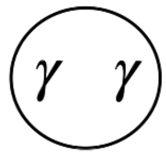
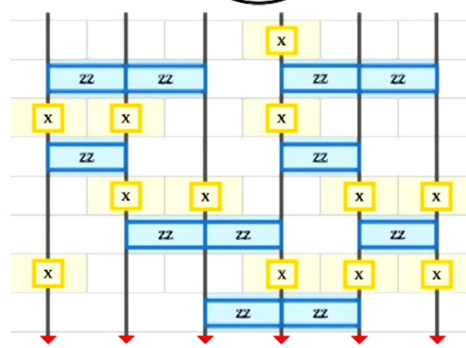
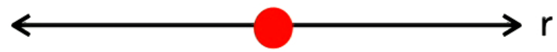


Majorana picture		Qubit picture	
$i\gamma_{2k-1}\gamma_{2k}$ measurement		X measurement	x
$i\gamma_{2k}\gamma_{2k+1}$ measurement		ZZ measurement	zz
identity gate	) (	identity gate	



Measurement-only phase transition

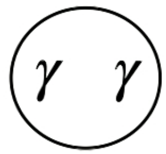


(Rate of ZZ vs. X measurement)

Paramagnet
O~1

Spin glass
O~L

Represent each spin as pair of Majorana fermions ("Jordan-Wigner transformation")



Majorana picture		Qubit picture	
$i\gamma_{2k-1}\gamma_{2k}$ measurement		X measurement	x
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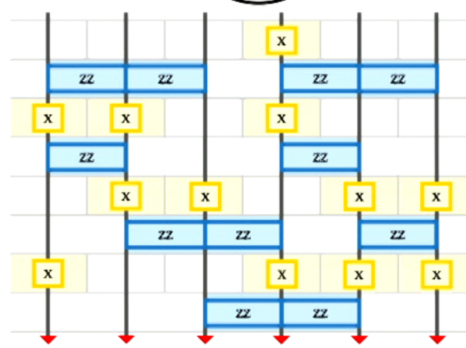

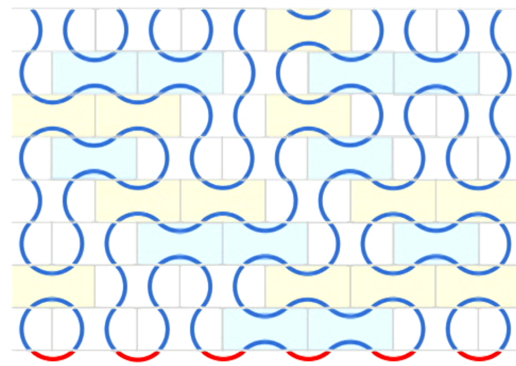

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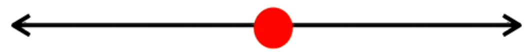

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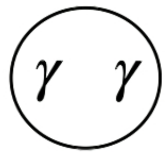
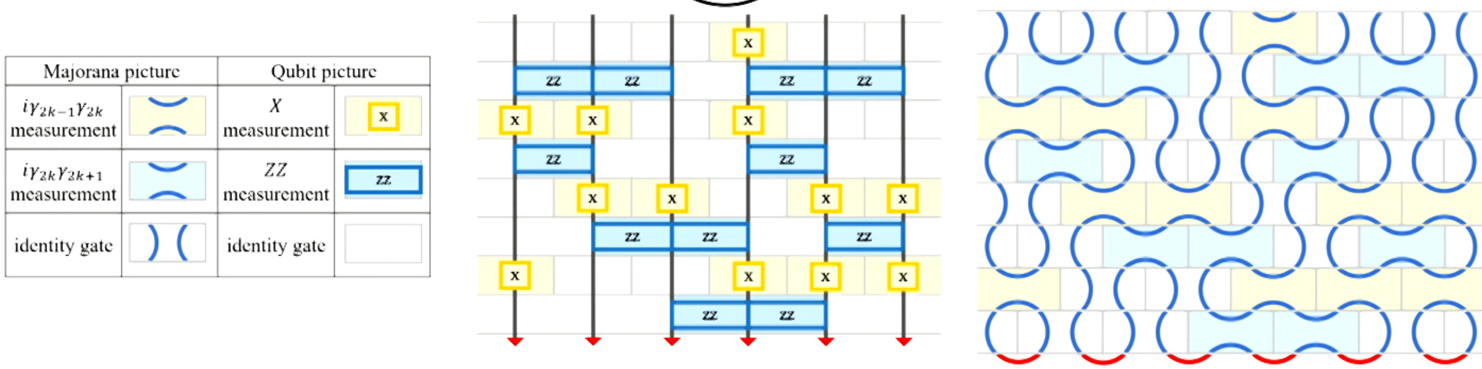
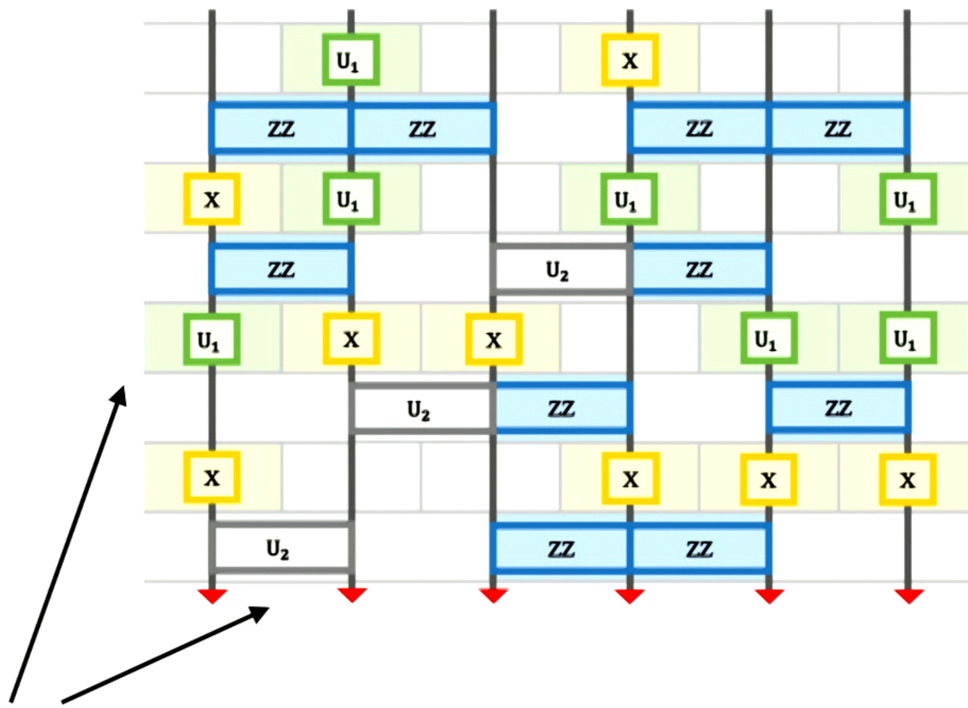




Classical loop model in critical percolation universality class Skinner, Nahum (2019)

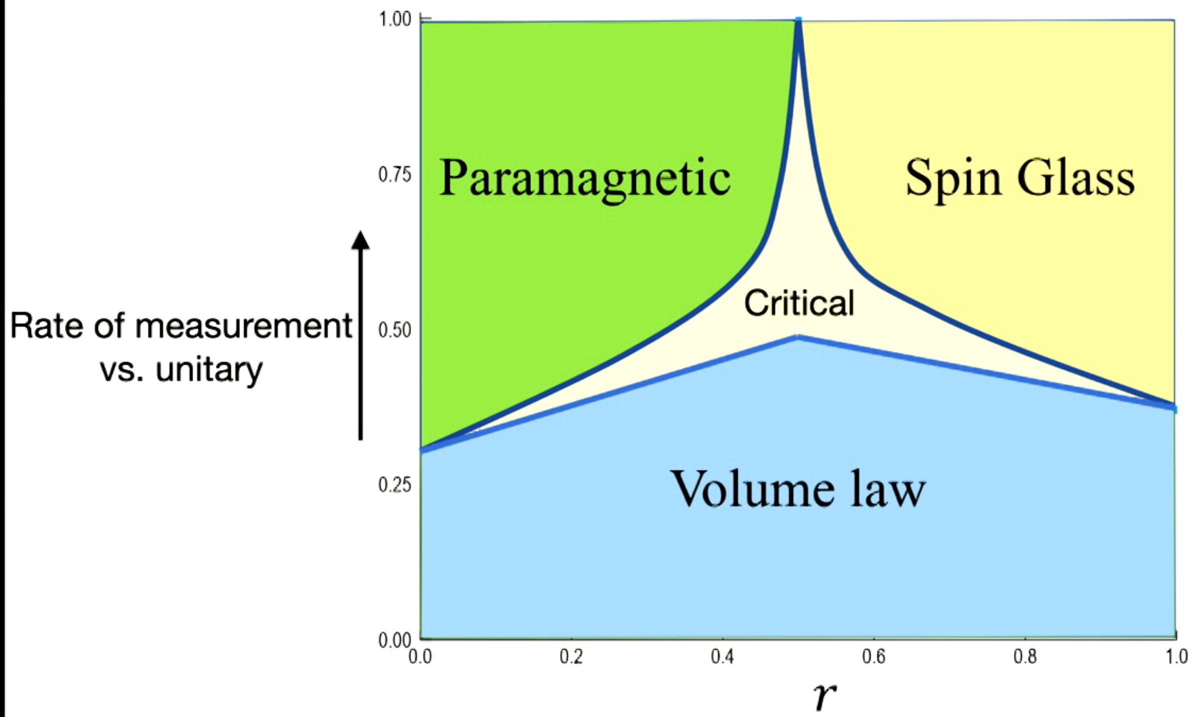
Entanglement of subregion of size L_A ~ $\frac{\sqrt{3}}{2\pi} \log L_A$

Measurements and Unitaries



Random unitary gates
preserving Ising symmetry

Phase Diagram



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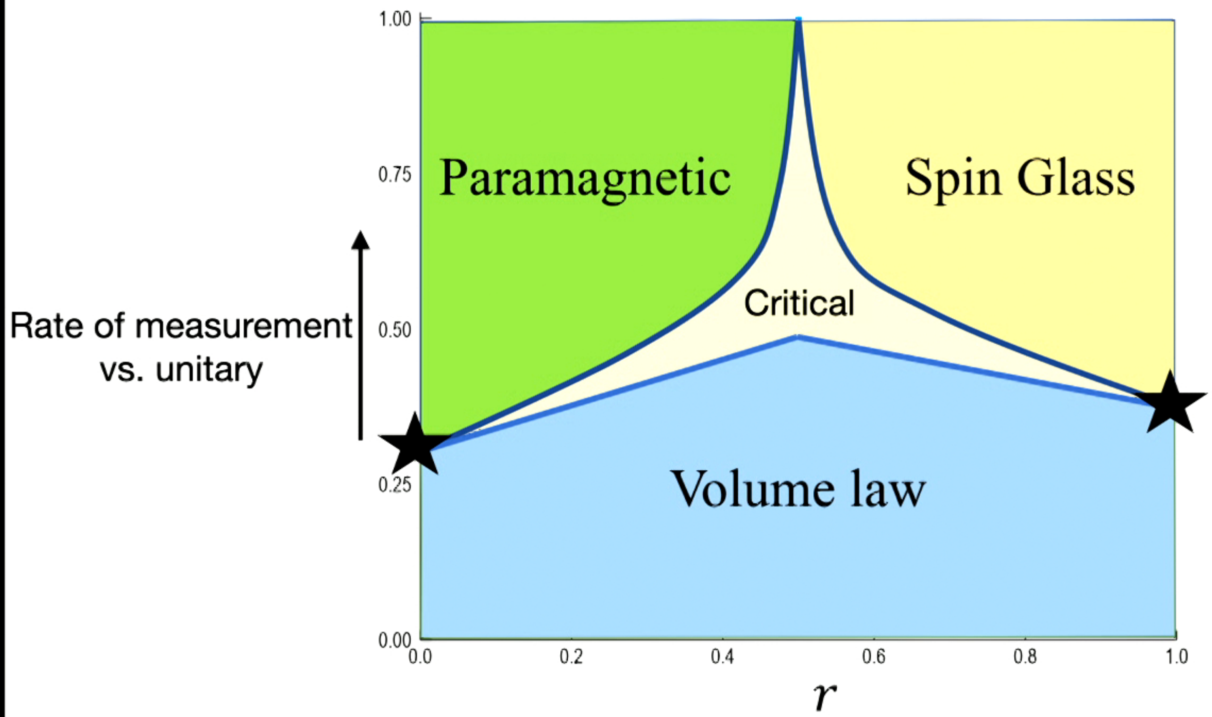
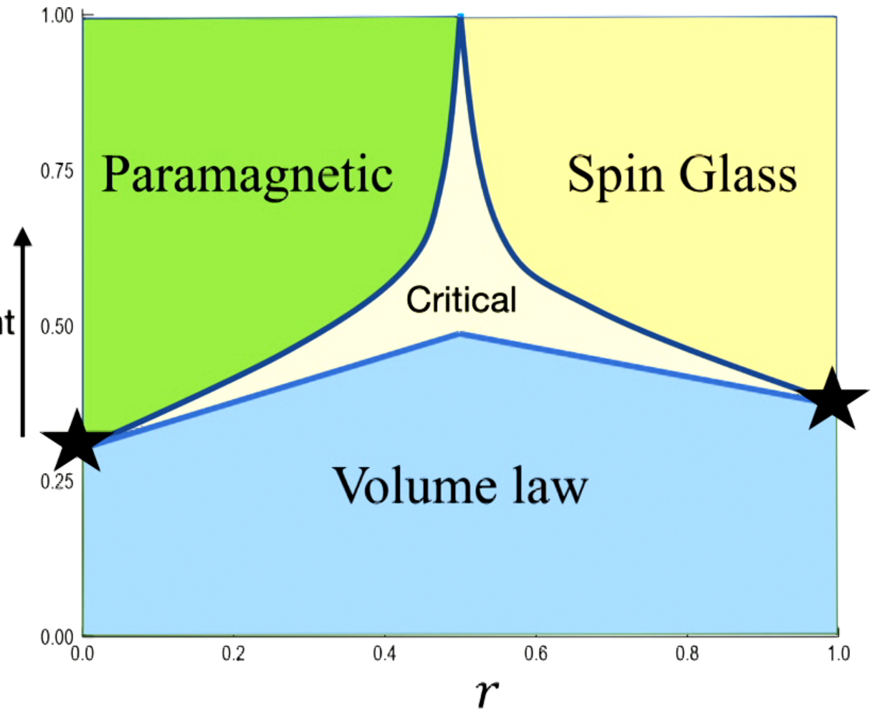


New non-equilibrium universality classes enabled by measurements

Phase Diagram

Rate of measurement vs. unitary



New non-equilibrium universality classes enabled by measurements

Measurement as a shortcut to long-range entangled matter

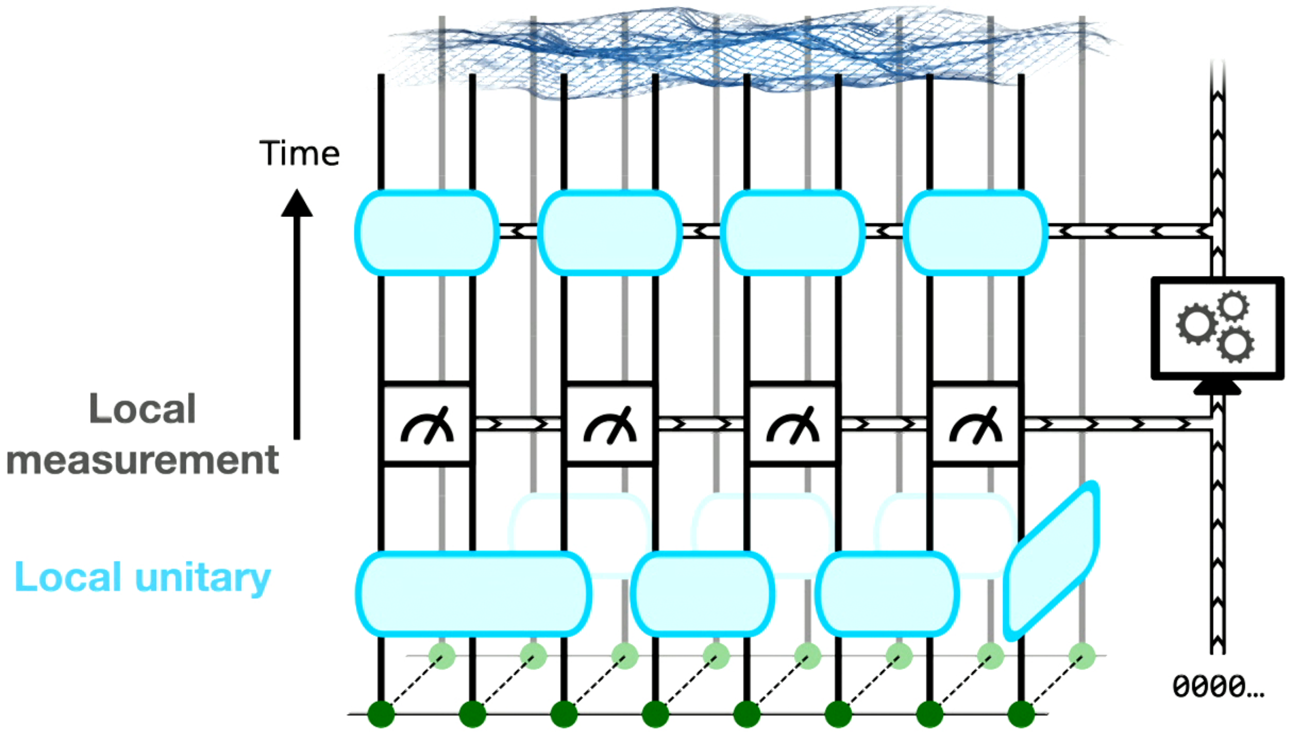
Tsung-Cheng (Peter) Lu
(Perimeter)

Leonardo Lessa
(Perimeter)

Isaac Kim
(UC Davis)

PRX Quantum 3, 040337 (2022)

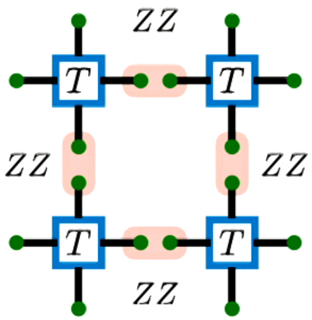
Local adaptive circuit



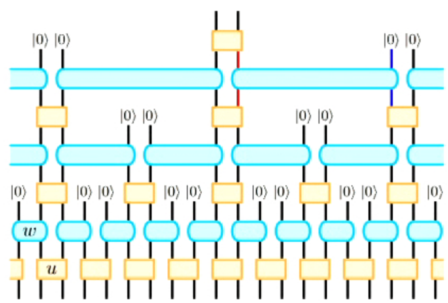
Local adaptive circuits for long-range entangled states

Our work: three general approaches based on distinct physical insights

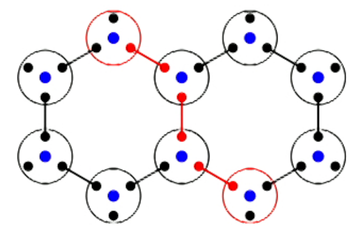
Tensor networks



Renormalization



Partons



Prior work with similar motivation: Briegel and Raussendorf (2001), Piroli, Styliaris, Cirac (2021), Tantivasadakarn, Thorngren, Vishwanath, Verresen (2021)

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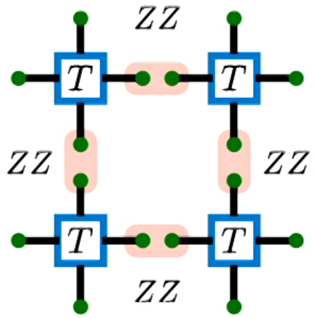
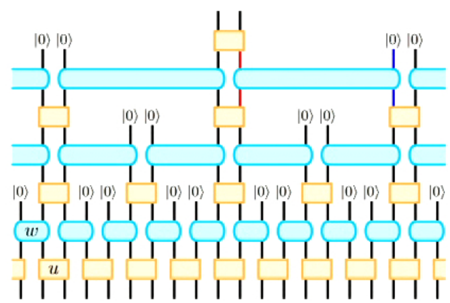


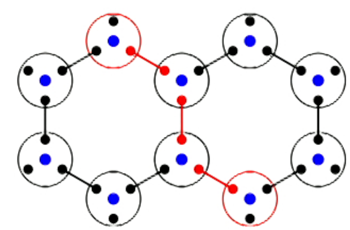
Modular, experiment-friendly

Renormalization



Quantum critical states
and non-abelian topological order

Partons



Chiral topological order

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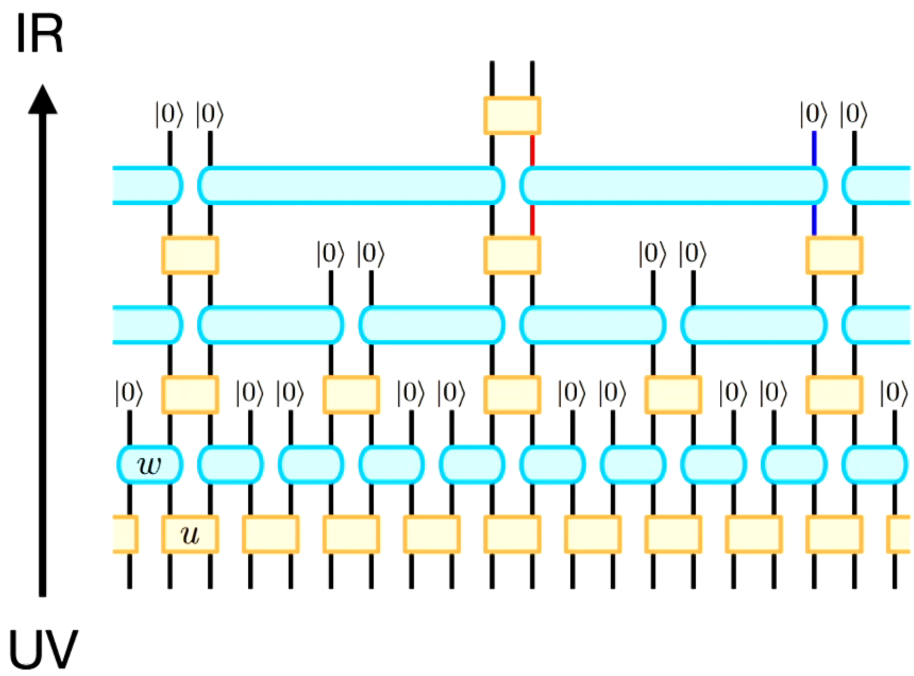
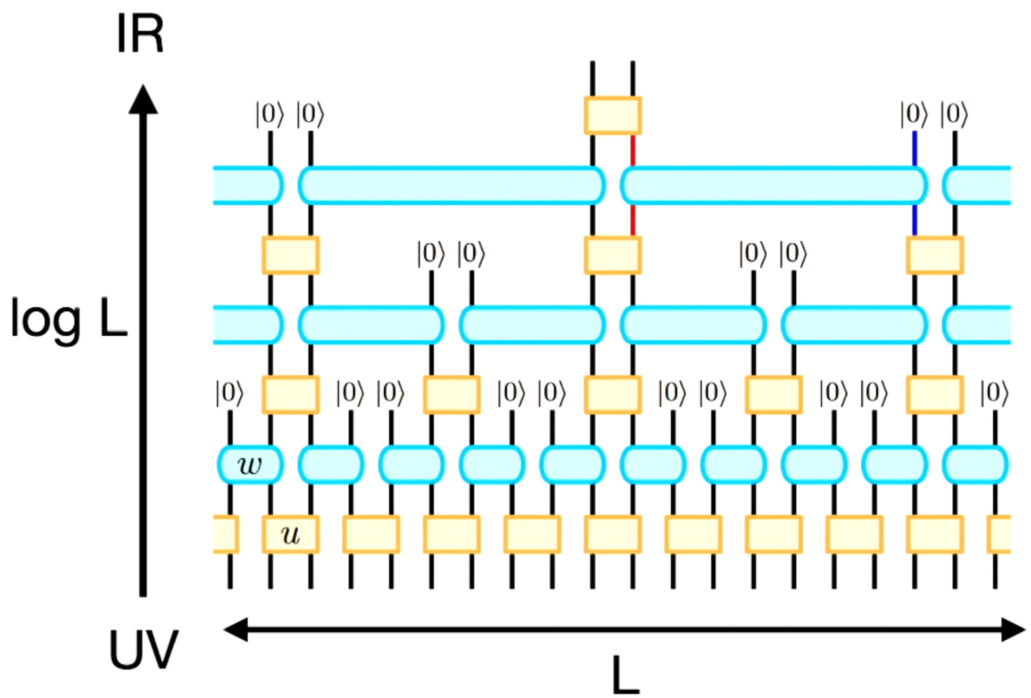
Entanglement Renormalization



Multiscale entanglement renormalization ansatz (MERA)

Vidal (2007)

Entanglement Renormalization



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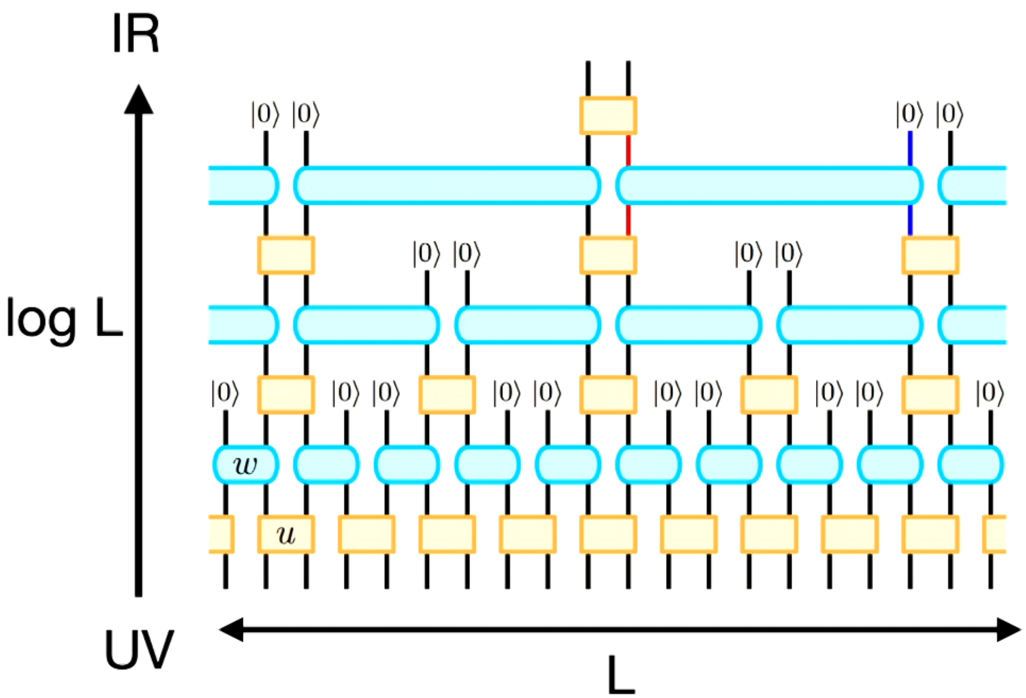

Non-local unitary circuit preparing state at finer length scales

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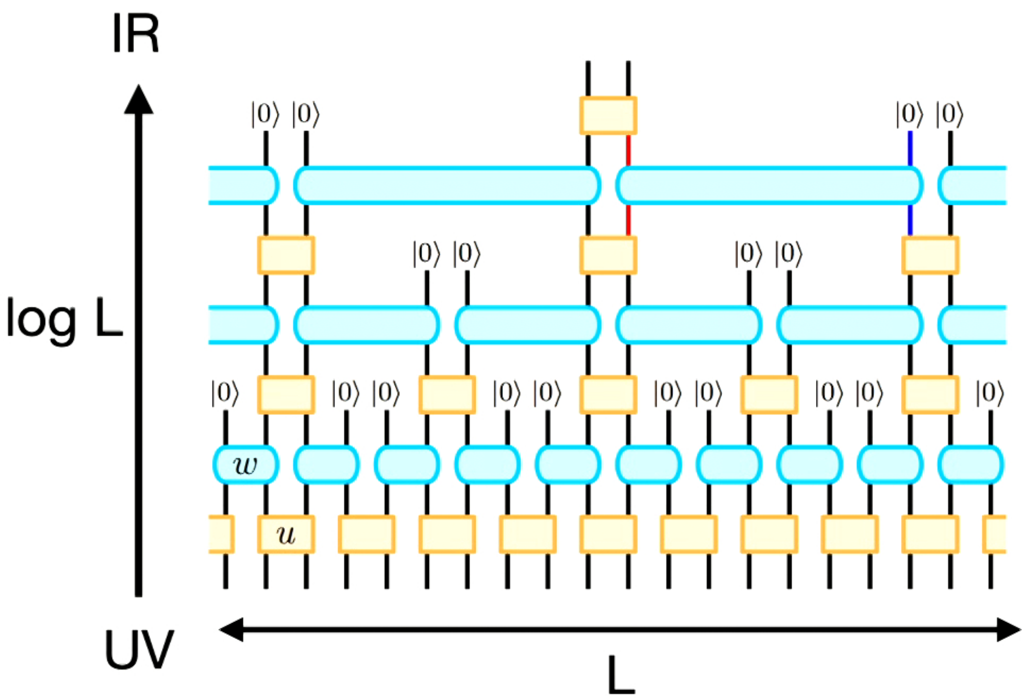

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Each non-local unitary gate can be realized as finite depth adaptive circuit using teleportation

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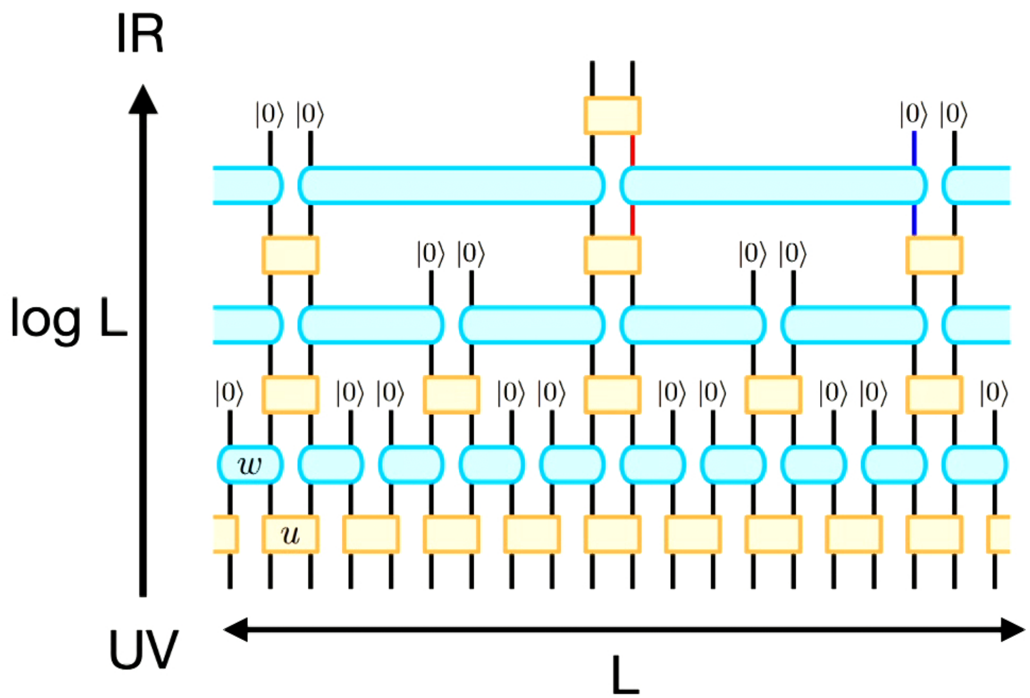

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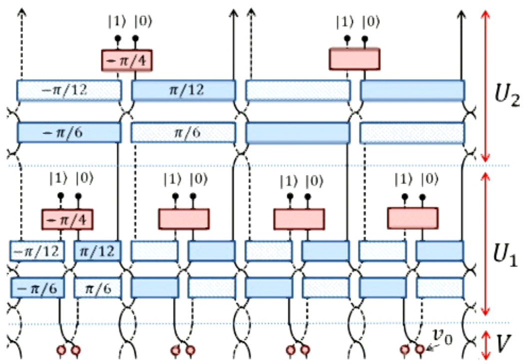
Gives log depth local adaptive circuit

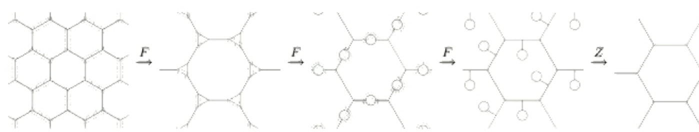
Adaptive circuits via renormalization

MERA: approximates 1d quantum critical states



Evenbly, White (2016)

exactly captures many topological orders (all string net models, quantum doubles)



Aguado, Vidal (2008)
Konig, Reichardt, Vidal (2009)

Local adaptive circuits with only depth ~log L for preparing all of the above!
(contrast with ~L typically required using local unitary circuit)

Adaptive Circuits:
Experiments and Mixed States

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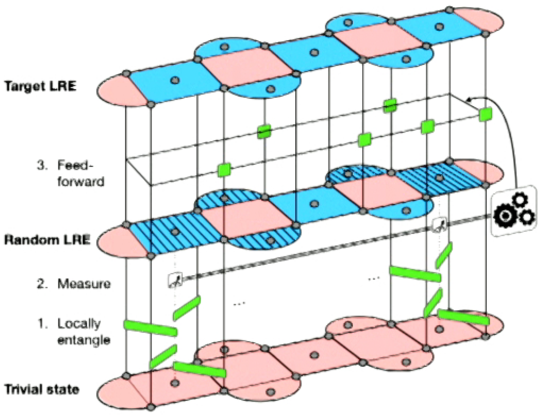
Experimental realization
with Quantinuum (trapped ion quantum computing)

arXiv:2302.03029 (2023)



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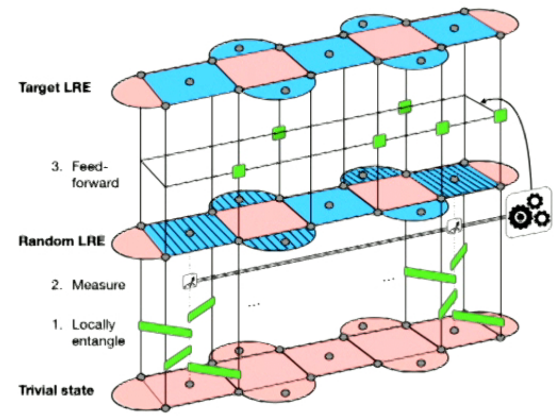
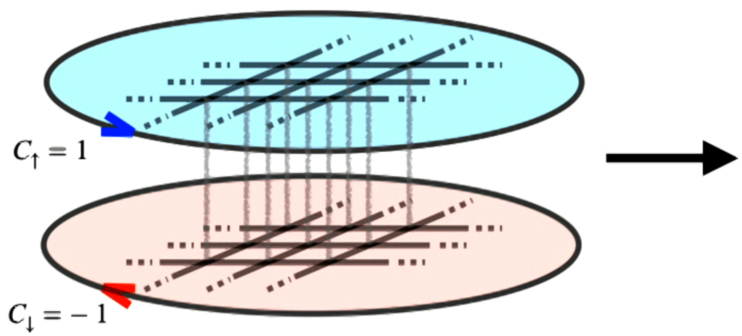
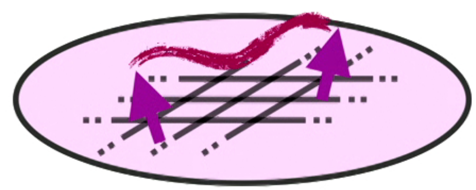


Control trajectories
to prepare interesting mixed states

T-C. Lu, Z. Zhang, S. Vijay, and TH
PRX Quantum 4, 030138 (2023)





$$S^+(\mathbf{x})S^-(\mathbf{x}') \sim \frac{1}{|\mathbf{x}-\mathbf{x}'|^{2\alpha}}$$

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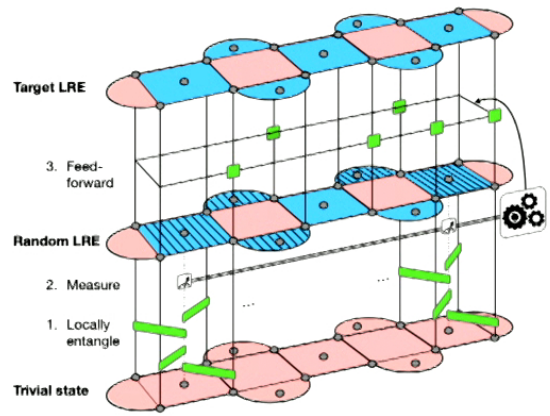

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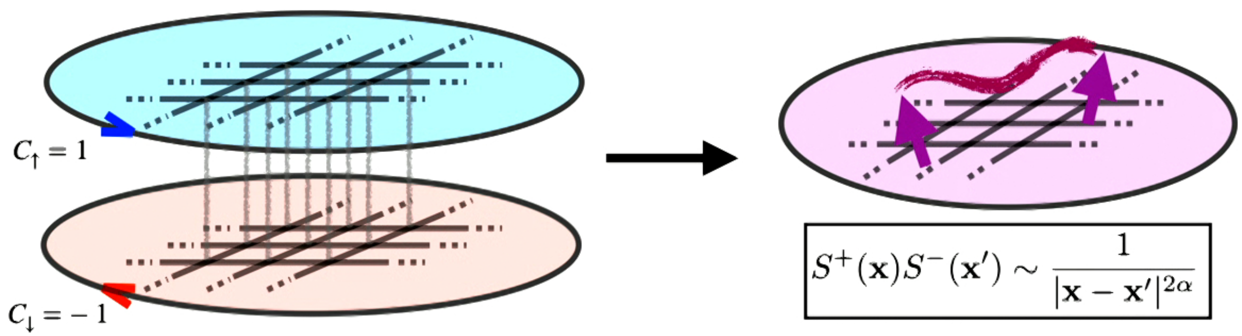

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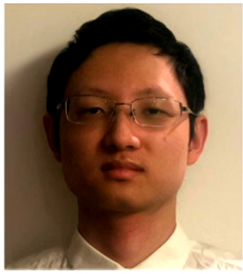
Channeling Quantum Criticality



Yijian Zou
(Perimeter)

Shengqi Sang
(Perimeter)

PRL 130, 250403 (2023)

Channeling Quantum Criticality

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How is the long-range entanglement in quantum critical states affected by noise?

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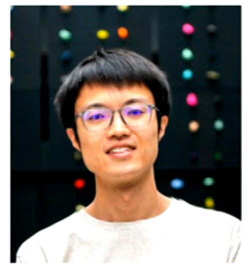

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Renormalization group (RG) flows for quantum channels describing noise

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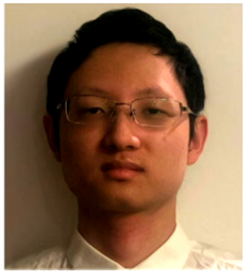

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Dictate entanglement structure / separability of resulting mixed states

Setup

Local quantum channel $\mathcal{N} = \otimes_{j=1}^{L} \mathcal{N}_j$

Dephasing in $\overrightarrow{v}$ direction with strength p:

$$\mathcal{D}_{p,\vec{v}}(\rho) = \left(1 - \frac{p}{2}\right) \rho + \frac{p}{2} \sigma_{\vec{v}} \ \rho \ \sigma_{\vec{v}}$$

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Critical state described by conformal field theory

Mapping channels to boundary conditions of $CFT^{\otimes 2n}$

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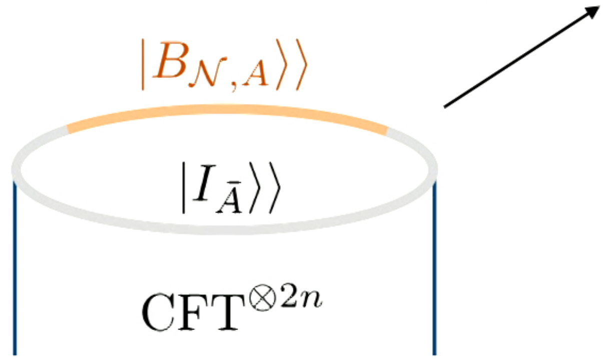
Renyi entropy of subsystem $S_A^{(n)}(\rho) := \frac{1}{1-n}\log \mathrm{Tr}(\rho_A^n)$



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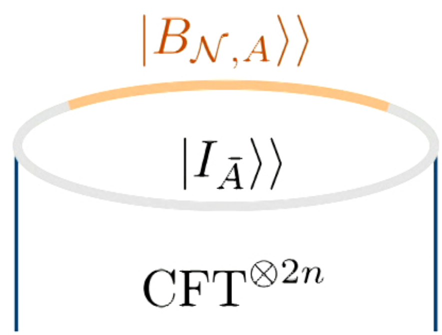


$$\mathrm{Tr}(\rho_A^n) = \mathrm{Tr}(\rho^{\otimes n}\tau_{n,A}) = \mathrm{Tr}(\mathcal{N}(|\psi\rangle\langle\psi|)^{\otimes n}\tau_{n,A}) = \mathrm{Tr}((|\psi\rangle\langle\psi|)^{\otimes n} B_{\mathcal{N},A})$$

Permutation operator

$\mathcal{N}^{*\otimes n}(\tau_{n,A})$

$$= \langle\langle(\psi \otimes \psi^*)^{\otimes n}|B_{\mathcal{N},A} I_{\bar{A}}\rangle\rangle$$

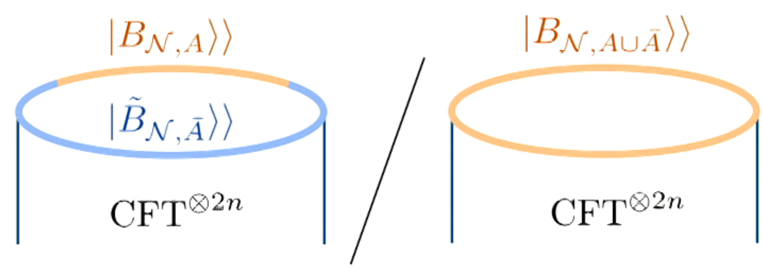
Operators as states
in doubled Hilbert space

Mapping channels to boundary conditions of $CFT^{\otimes 2n}$

Renyi entanglement negativity (a measure of quantum correlations for mixed states)

$$N_A^{(n)}(\rho) := \frac{1}{1-n} \log \frac{\mathrm{Tr}(\{\rho^{T_A}\}^n)}{\mathrm{Tr}(\rho^n)}$$

$$N_A^{(n)}(\rho) = \frac{1}{1-n} \log \frac{\langle\langle (\psi \otimes \psi^*)^{\otimes n} | B_{\mathcal{N},A} \tilde{B}_{\mathcal{N},\bar{A}} \rangle\rangle}{\langle\langle (\psi \otimes \psi^*)^{\otimes n} | B_{\mathcal{N},A\cup\bar{A}} \rangle\rangle}$$



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Channel with larger g can flow to channel with smaller g

RG flows for dephased 1d critical transverse-field Ising model

$$H = -\sum_{i=1}^{L} \sigma_{x,i}\sigma_{x,i+1} - \sum_{i=1}^{L} \sigma_{z,i}$$

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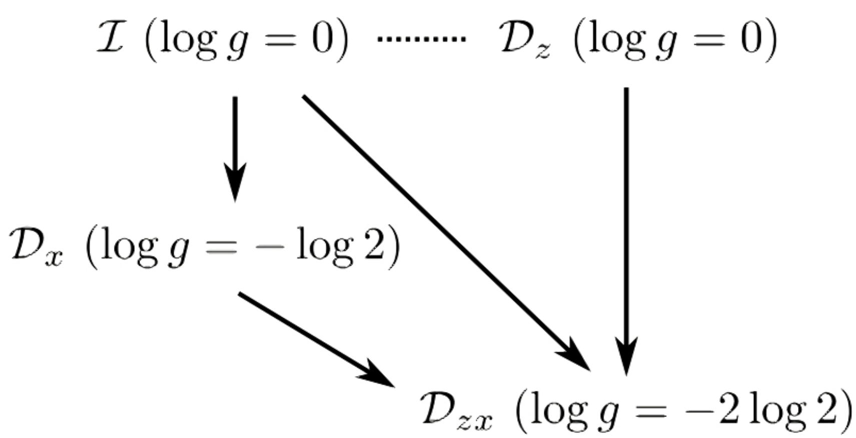

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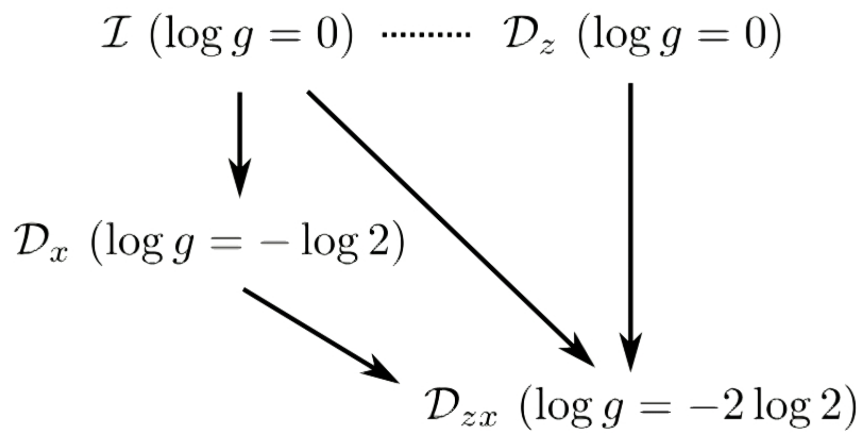
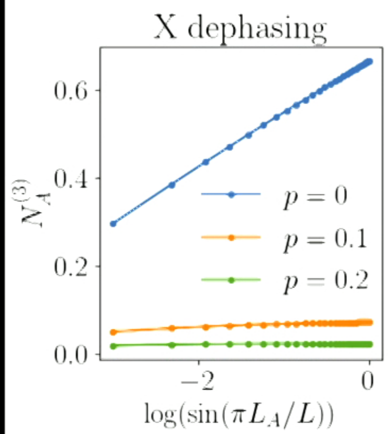


(Renyi) Entanglement Negativity

Relevant



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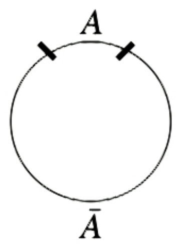

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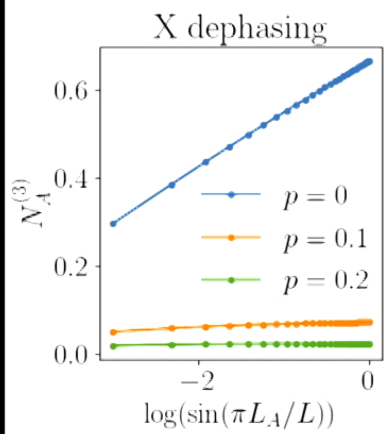

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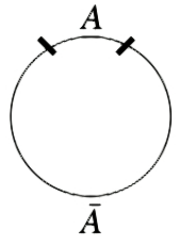
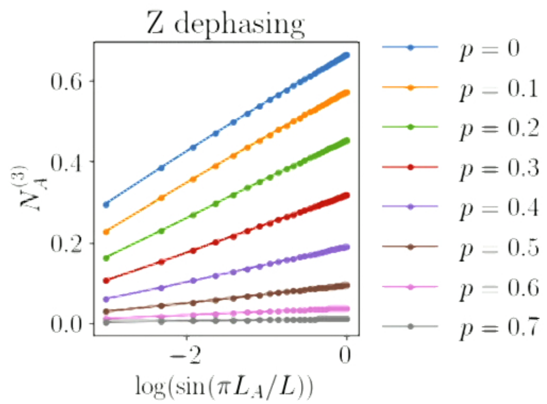
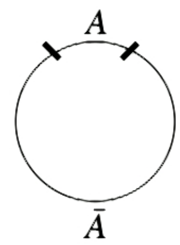


Marginal

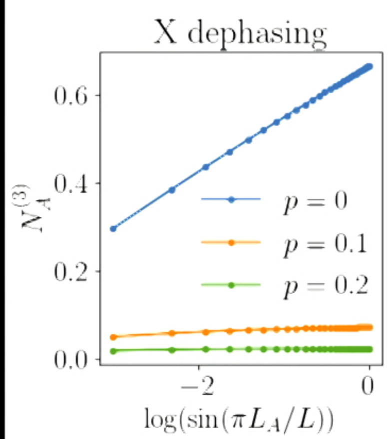


(Renyi) Entanglement Negativity

$$\rho = \mathcal{N}(|\psi\rangle\langle\psi|)$$



Relevant



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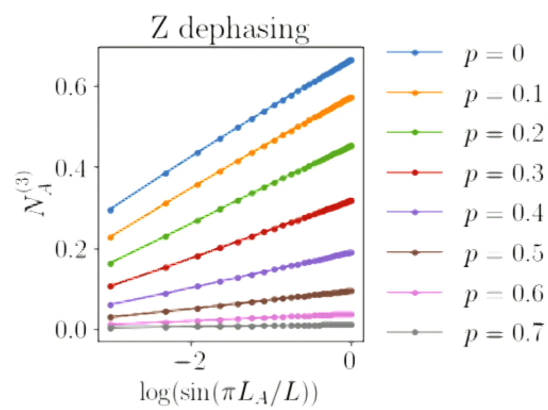
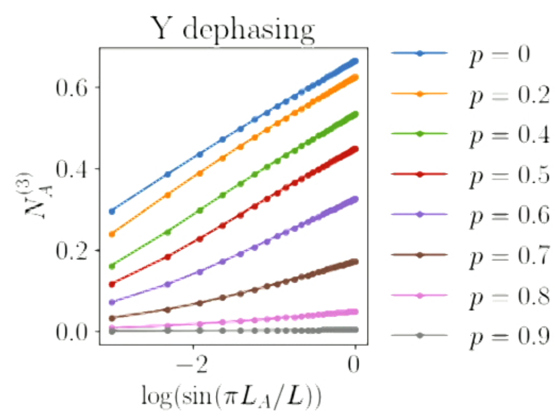
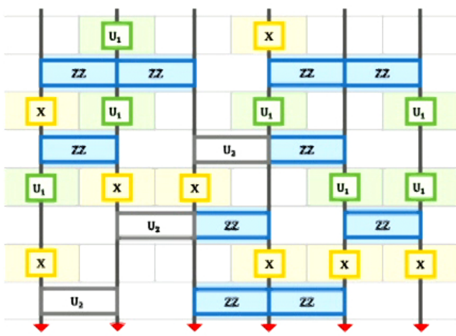


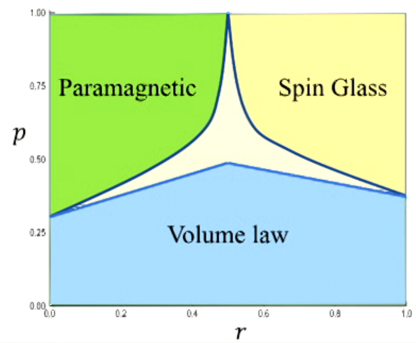
Irrelevant



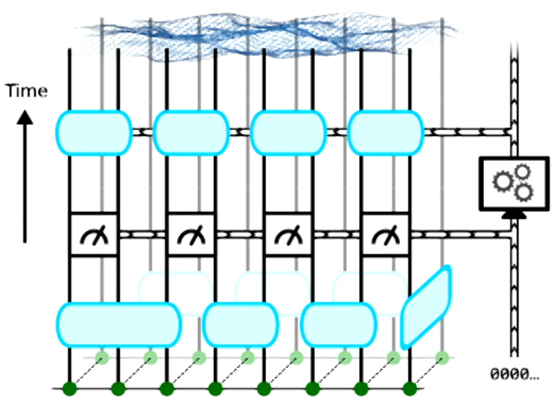
Continuously varying
log coefficient

Measurement-enabled long range entangled matter

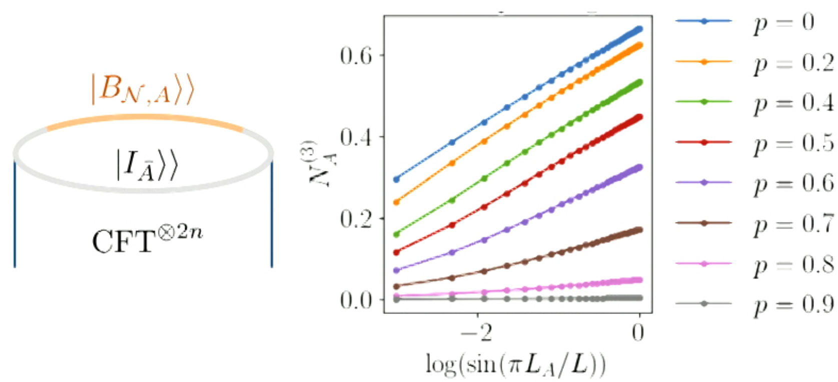




Sang and TH
Phys. Rev. Research 3, 023200 (2021)



Lu, Lessa, Kim, and TH
PRX Quantum 3, 040337 (2022)



Zou, Sang, and TH
PRL 130, 250403 (2023)

The open quantum frontier

Measurement and decoherence driven
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Collaboration with experiments: Zhu et.al. (2020) Foss-Feig et.al. (2023)

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Dynamics involving measurement and feedback (quantum-classical interfaces)
for generating novel mixed states?

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