Title: The rise and fall of mixed-state entanglement: measurement, feedback, and decoherence

Speakers: Peter Lu

Collection: Physics of Quantum Information

Date: May 27, 2024 - 3:30 PM

URL: https://pirsa.org/24050030

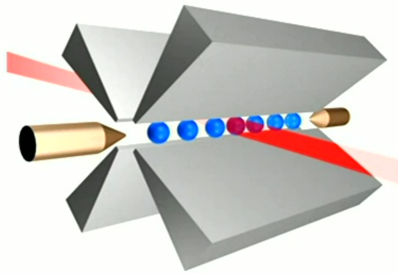
Abstract: Long-range entangled mixed states are exotic many-body systems that exhibit intrinsically quantum phenomena despite extensive classical fluctuations. In the first part of the talk, I will show how they can be efficiently prepared with measurements and unitary feedback conditioned on the measurement outcome. For example, symmetry-protected topological phases can be universally converted into mixed states with long-range entanglement, and certain gapped topological states such as Chern insulators can be converted into mixed states with critical correlations in the bulk. In the second part of the talk, I will discuss how decoherence can drive interesting mixed-state entanglement transitions. By focusing on the toric codes in various space dimensions subject to certain types of decoherence, I will present the exact results of entanglement negativity, from which the universality class of entanglement transitions can be completely characterized.

The rise and fall of
mixed-state long-range entanglement
measurement, feedback, and decoherence

Tsung-Cheng Peter Lu

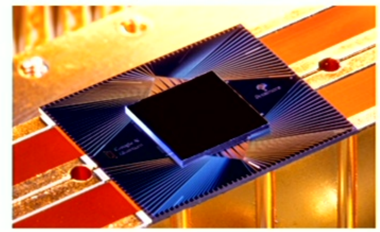
PERIMETER INSTITUTE

New possibilities via quantum devices



Trapped-ion quantum computer

E.g. Duke/IonQ
Quantinuum



Superconducting qubits

E.g. Google
IBM

What should we do with them?

New possibilities via quantum devices

Condensed matter
physicists

Realize interesting states of matter!

Traditional approach

Herbertsmithite
(A spin liquid candidate)

New (bottom-up) approach

$$|\psi\rangle = U|0\rangle^{\otimes N}$$

Realizing the target state
with quantum operations

New possibilities via quantum devices

Condensed matter physicists

Realize interesting states of matter!

Quantum information physicists

Perform quantum computing!

Quantum computing can beat classical computing

New possibilities via quantum devices

Condensed matter
physicists

Realize interesting states of matter!

Quantum information
physicists

Perform quantum computing!

Quantum computing can beat classical computing

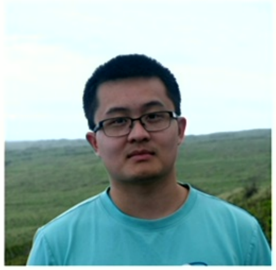
(Mixed-state)
Long-range entangled quantum matter

Outline

Part I: State preparation

i.e. how to efficiently create long-range entanglement?

arXiv: 2303.15507 (PRX Quantum), joint work with



Zhehao Zhang (UCSB)

Sagar Vijay (UCSB)

Tim Hsieh (Perimeter)

Part II: Stability of quantum matter subject to decoherence

i.e. how does decoherence kill long-range entanglement?

arXiv:2404.06514, TCL

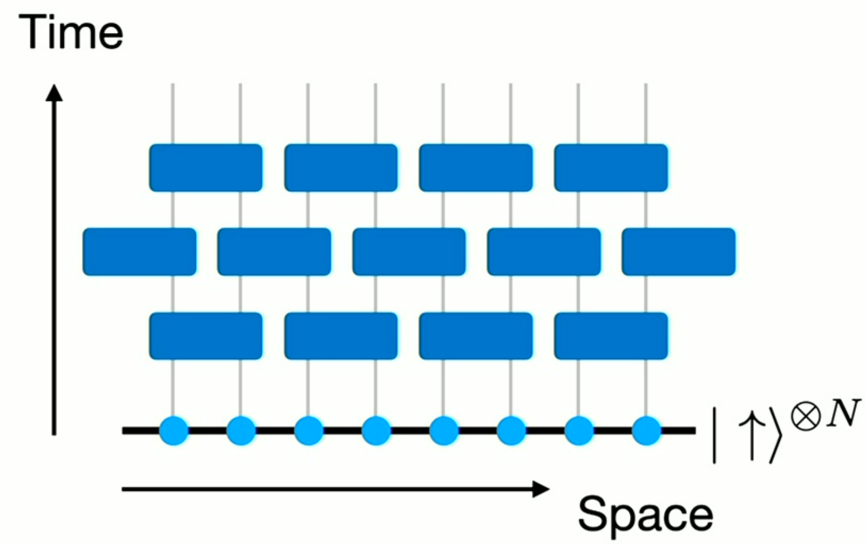
State preparation - bottleneck of quantum devices

Local unitary circuits

Realizing LRE requires
time growing with the system size

[Lieb, Robinson (1972)] [Bravyi, Hastings, Verstraete (2006)]

Not scalable since qubits decohere quickly

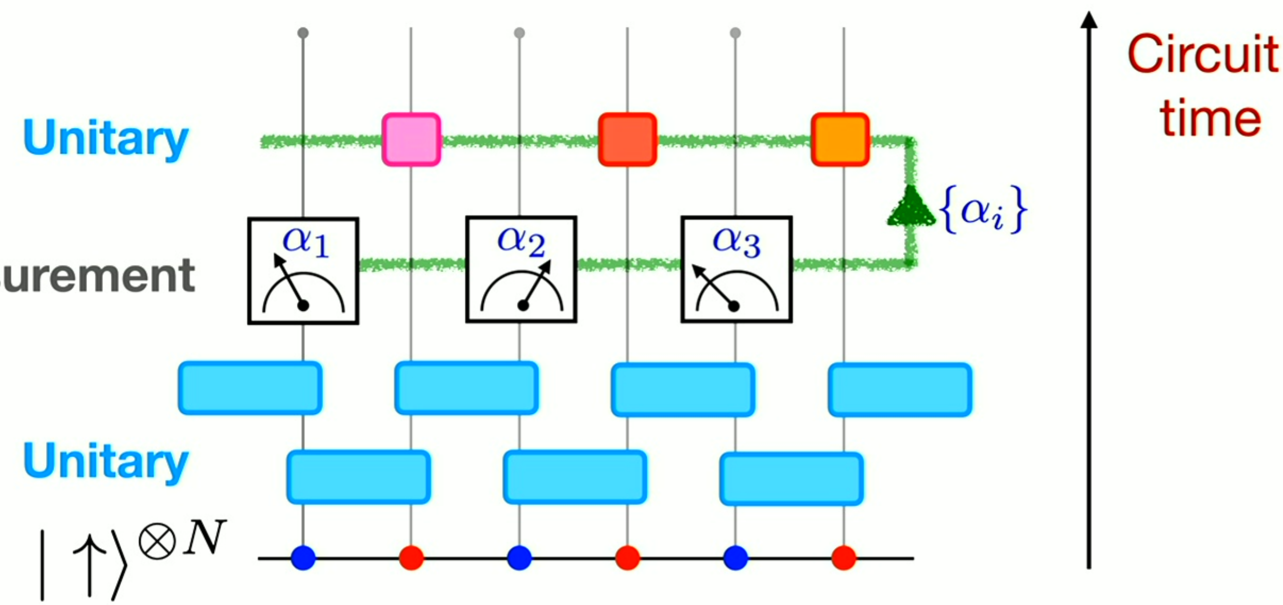


Measurement - LRE possible in O(1) time!

e.g. topological orders

Measurement-based approach

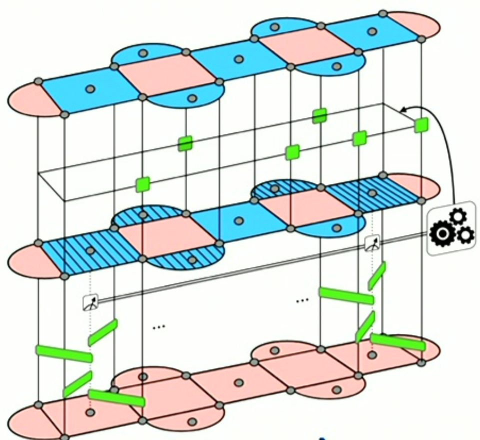
Local quantum operation (unitary gates & measurement) & **Non-local** classical communication



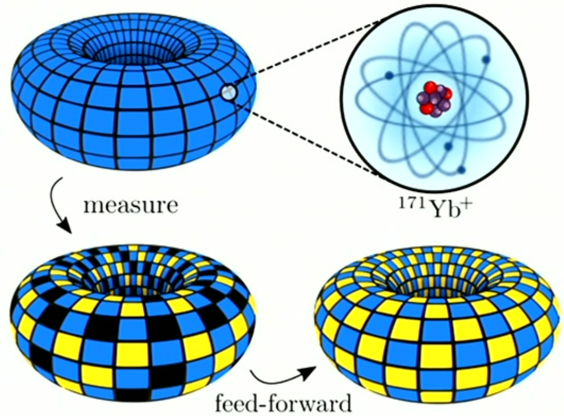
Briegel, Raussendorf (2001); Raussendorf, Bravyi, Harrington (2005); Piroli, Styliaris, Cirac (2021); Tantivasadakarn, Thorngren, Vishwanath, Verresen (2021) ; Bravyi, Kim, Kliesch, Koenig (2022); TCL, Lessa, Kim, Hsieh (2022), ….

Experimental realization

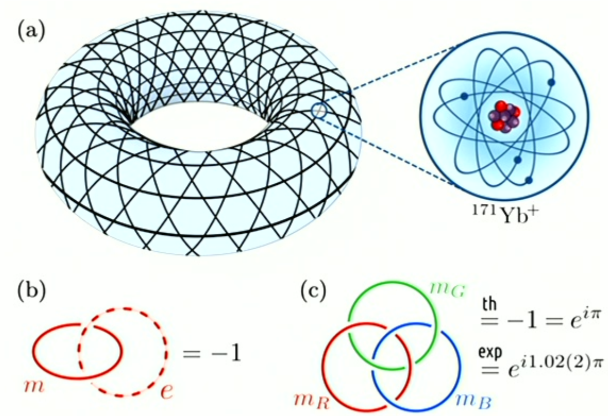
Quantinuum, UC Davis, Perimeter
arXiv:2302.03029 (2023)



Quantinuum, Caltech, Harvard
arXiv:2302.01917 (2023)



Quantinuum, Caltech, Harvard,
arXiv:2305.03766 (Nature 2023)



Abelian topological orders

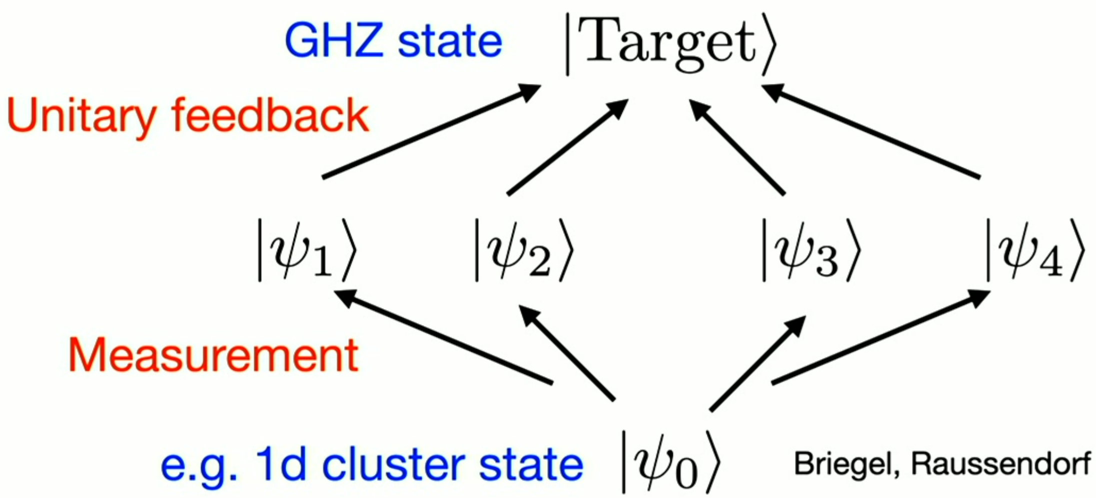
Non-abelian topological orders

New directions with measurement

- What LRE states can be efficiently prepared via measurement & feedback

- Are the measurement-feedback protocols stable?
(e.g. imperfect unitary or measurement)

Motivating example



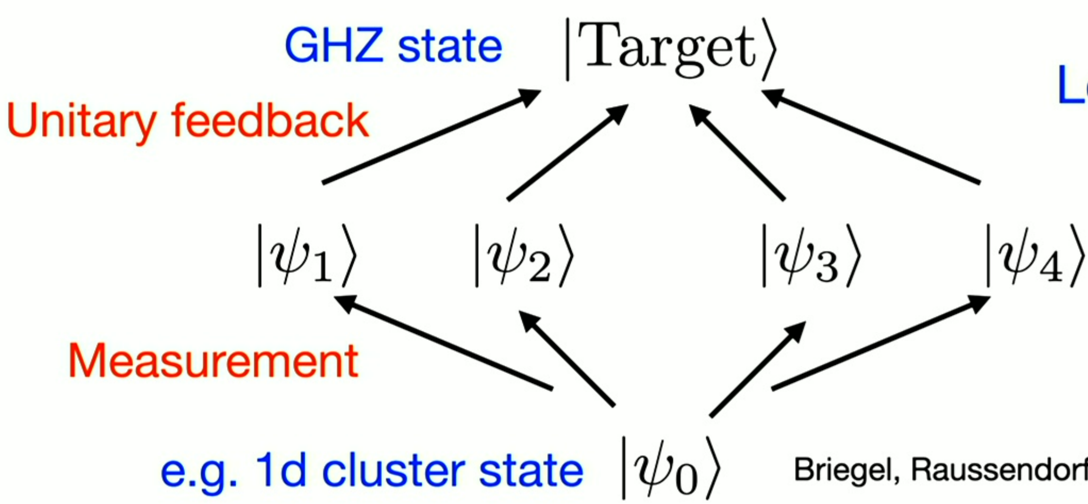
Briegel, Raussendorf (2001)

New directions with measurement

- What LRE states can be efficiently prepared via measurement & feedback

- Are the measurement-feedback protocols stable?
(e.g. imperfect unitary or measurement)

Motivating example



Briegel, Raussendorf (2001)

If perturbing the initial state?

Long-range entangled mixed-state?

What do it mean?

Experimental diagnostic?

(Deterministic) non-local quantum channels

via measurement + feedback

arXiv: 2303.15507 (PRX Quantum), **TCL**, Zhang, Vijay, Hsieh

input states (with certain universal properties)	→	Long-range orders/criticality (insensitive to microscopic details of input) (Generically mixed)

$Z_2 \times Z_2$ SPT order (symmetry-protected topological) → Z_2 long-range (topological) order

Gapped, pure state (Chern insulators) → Quantum critical mixed states

(Deterministic) non-local quantum channels

via measurement + feedback

arXiv: 2303.15507 (PRX Quantum), **TCL**, Zhang, Vijay, Hsieh

input states (with certain universal properties)	→	Long-range orders/criticality (insensitive to microscopic details of input) (Generically mixed)

Quan. Info. Robust protocols for generating long-range entanglement

Quan. Matter Non-trivial mixed-state matter in O(1) depth
In contrast, thermal Gibbs (mixed) states are generically trivial

(Exception - 4d toric code)

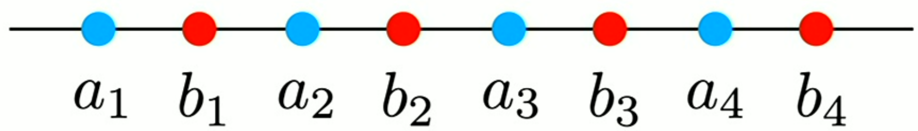
Application with SPT

(Symmetry Protected Topological)

Inspired by Briegel, Raussendorf (2001); Tantivasadakarn, Thorngren, Vishwanath, Verresen (2021)

$G = Z_2 \times Z_2$

Cluster-state SPT



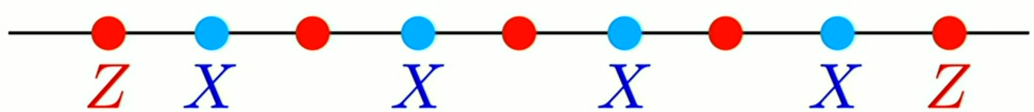
$$H = -\sum_i Z_{a,i} X_{b,i} Z_{a,i+1} - \sum_i Z_{b,i-1} X_{a,i} Z_{b,i}$$

Symmetry $\prod_i X_{a,i} \quad \prod_i X_{b,i}$

String order

See e.g. Pollmann, Turner (2012)

$$\langle Z_{b,i} \left(\prod_{k=i+1}^{j} X_{a,k} \right) Z_{b,j} \rangle = 1$$



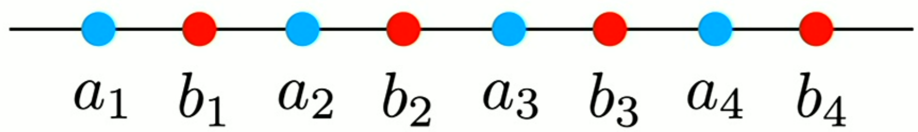
Application with SPT

(Symmetry Protected Topological)

Inspired by Briegel, Raussendorf (2001);
Tantivasadakarn, Thorngren, Vishwanath, Verresen (2021)

$G = Z_2 \times Z_2$

Cluster-state SPT



$$H = -\sum_i Z_{a,i} X_{b,i} Z_{a,i+1} - \sum_i Z_{b,i-1} X_{a,i} Z_{b,i}$$

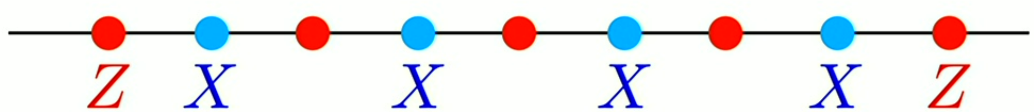
Symmetry $\prod_i X_{a,i}$ $\prod_i X_{b,i}$

$$-g \sum_i O_i$$ Symmetry-preserving perturbation

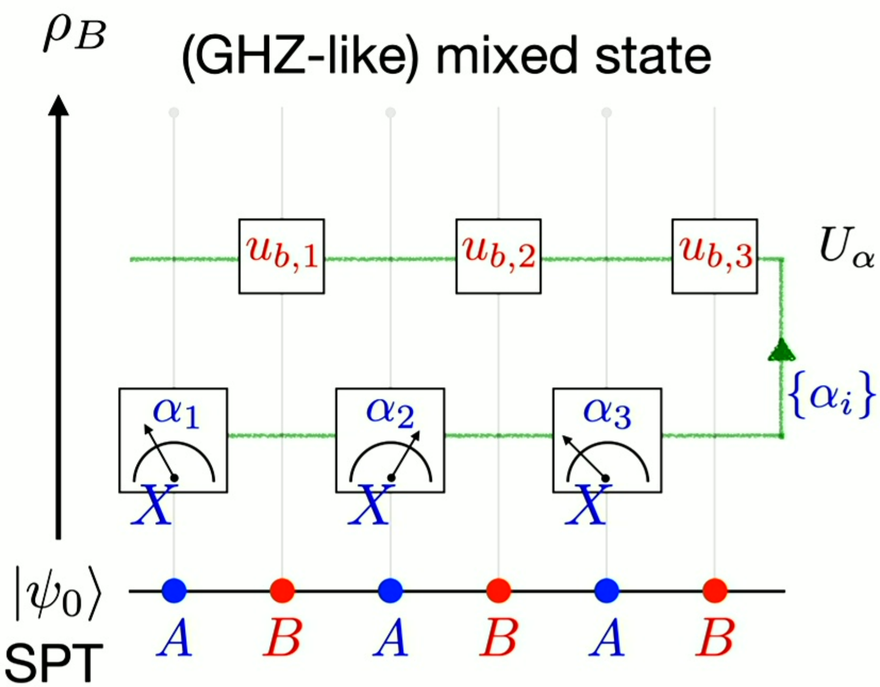
String order

See e.g. Pollmann, Turner (2012)

$$\langle Z_{b,i} \left(\prod_{k=i+1}^{j} X_{a,k} \right) Z_{b,j} \rangle = c = O(1)$$



SPT to mixed-state long-rang entanglement

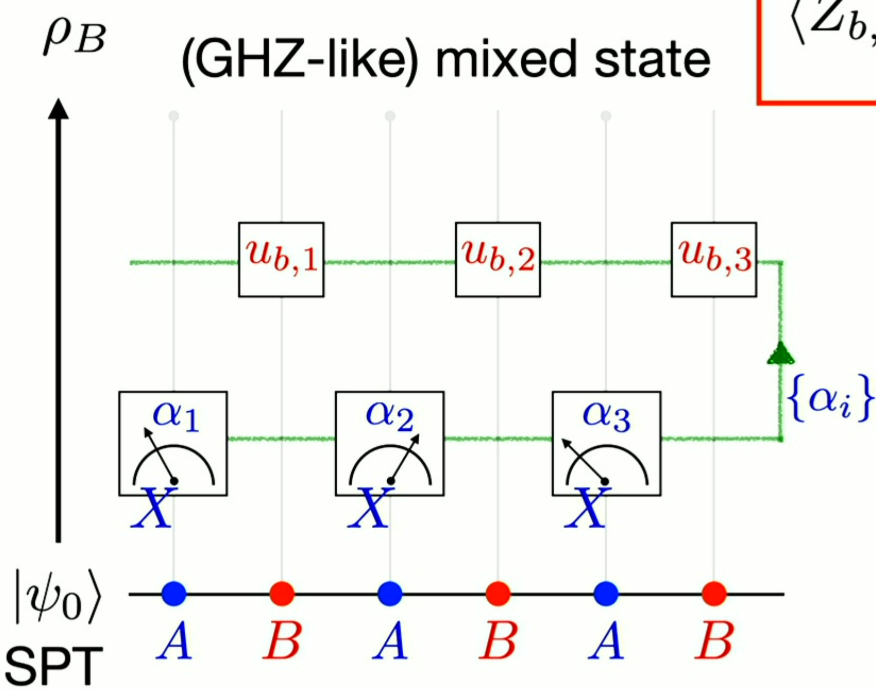


$$U_\alpha = \prod_i X_{b,i}^{\frac{1-\prod_{j=1,2,\dots}^{i} \alpha_j}{2}}$$

$$\langle Z_{b,i} \left(\prod_{k=i+1}^{j} X_{a,k} \right) Z_{b,j} \rangle = c = O(1) > 0$$

SPT to mixed-state long-rang entanglement

(GHZ-like) mixed state



$$\langle Z_{b,i} Z_{b,j} \rangle = c = O(1) > 0, \; \langle \prod_i X_{b,i} \rangle = 1$$

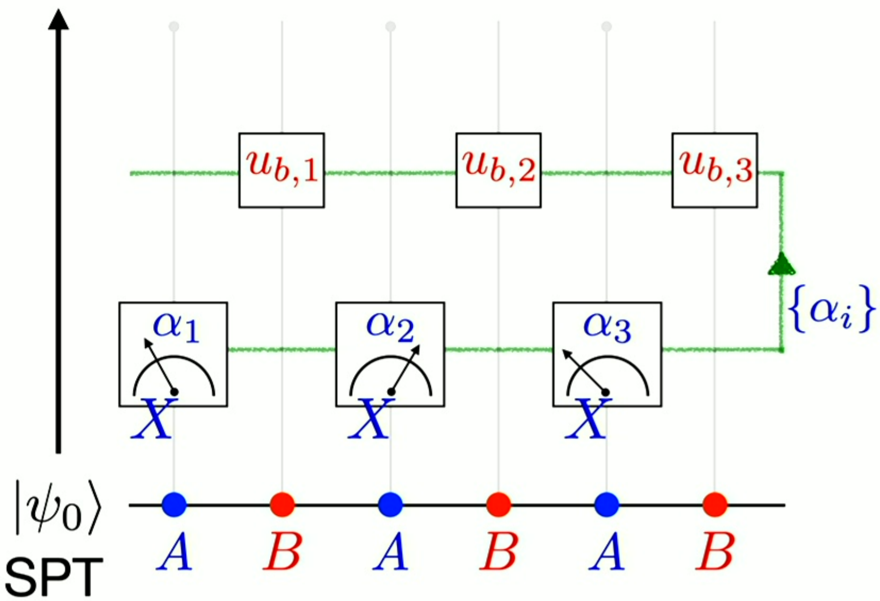
$$\rho_B \neq \sum_n p_n |\mathrm{SRE}_n\rangle\langle \mathrm{SRE}_n|$$

Hasting (2011)

$$\langle Z_{b,i} \left(\prod_{k=i+1}^{j} X_{a,k} \right) Z_{b,j} \rangle = c = O(1) > 0$$

SPT to mixed-state long-rang entanglement

$$\rho_B = \mathrm{tr}_A \left(|\psi\rangle\langle\psi|\right)$$



$$|\psi\rangle = U|\psi_0\rangle$$

$$U = \sum_\alpha (U_\alpha)_B \otimes (|\alpha\rangle\langle\alpha|)_A$$

$$U_\alpha = \prod_i X_{b,i}^{\frac{1-\prod_{j=1,2,\cdots}^{i} \alpha_j}{2}}$$

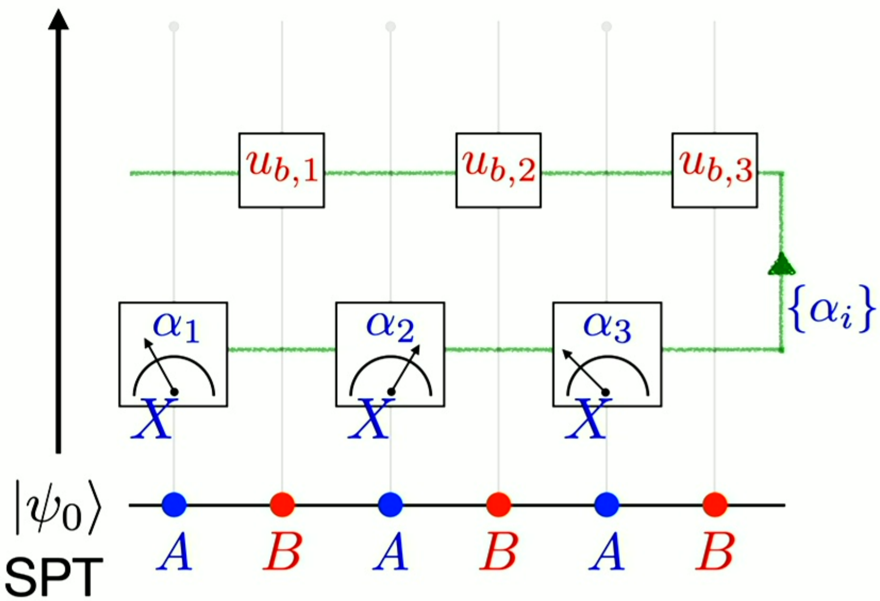
A controlled unitary
implementing non-local transformation

$$U\left[Z_{b,i}(\prod_{k=i+1}^{j} X_{a,k})Z_{b,j}\right]U^\dagger = Z_{b,i}Z_{b,j}$$

Hidden string order -> long-range order

SPT to mixed-state long-rang entanglement

$$\rho_B = \mathrm{tr}_A \left(|\psi\rangle\langle\psi|\right)$$



$$|\psi\rangle = U|\psi_0\rangle$$

$$U = \sum_\alpha (U_\alpha)_B \otimes (|\alpha\rangle\langle\alpha|)_A$$

$$U_\alpha = \prod_i X_{b,i}^{\frac{1-\prod_{j=1,2,\dots}^{i} \alpha_j}{2}}$$

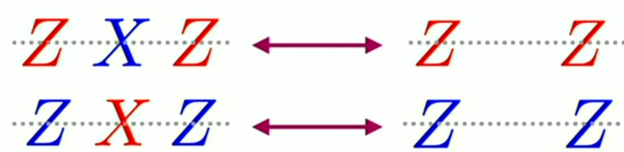
A controlled unitary implementing non-local transformation

$$U\left[Z_{b,i}\left(\prod_{k=i+1}^{j} X_{a,k}\right)Z_{b,j}\right]U^\dagger = Z_{b,i}Z_{b,j}$$

Hidden string order -> long-range order

Kennedy-Tasaki transformation (1992)

Haldane SPT -> 2 Z_2 long-range order



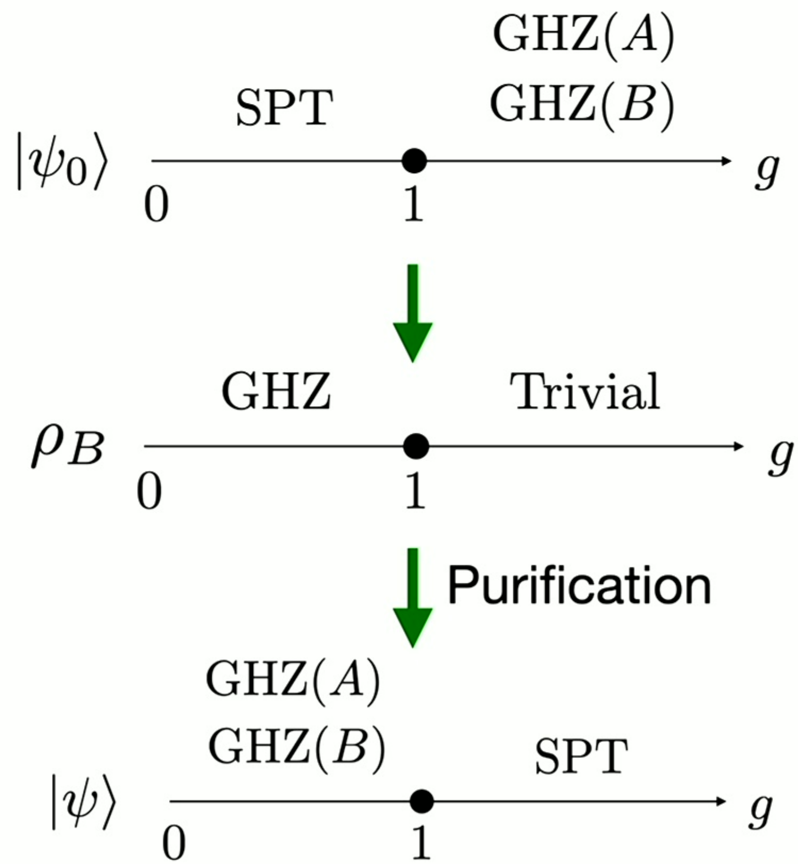
Example

$$H_0 = -\sum ZXZ - \sum ZXZ$$
$$-g\sum Z\cdots Z - g\sum Z\cdots Z$$

Controlled unitary

$$U = \sum_\alpha U_\alpha P_\alpha$$

$$H = -\sum Z\cdots Z - \sum Z\cdots Z$$
$$-g\sum ZXZ - g\sum ZXZ$$

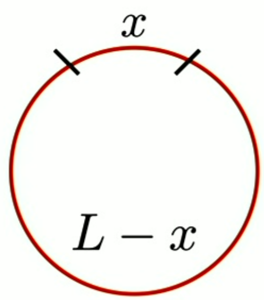


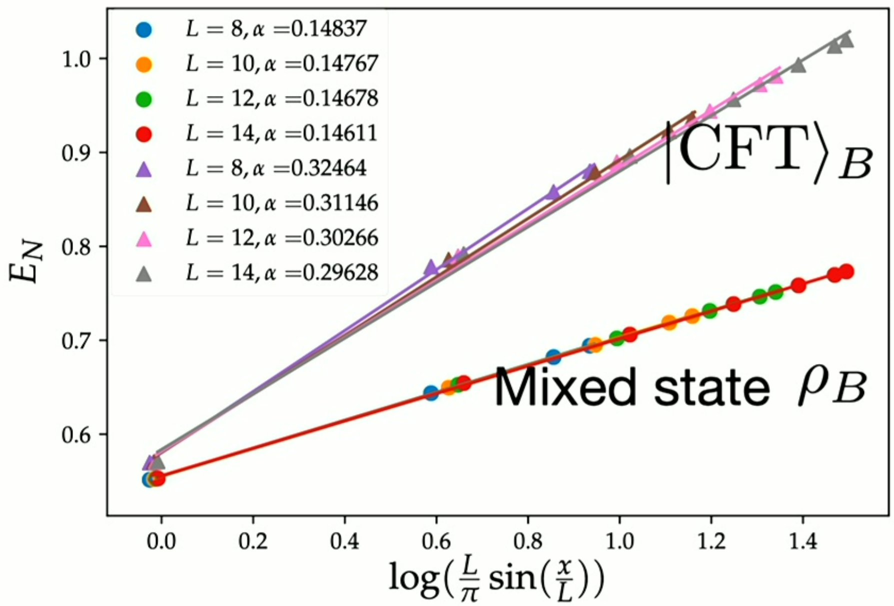
Mixed-state quantum criticality

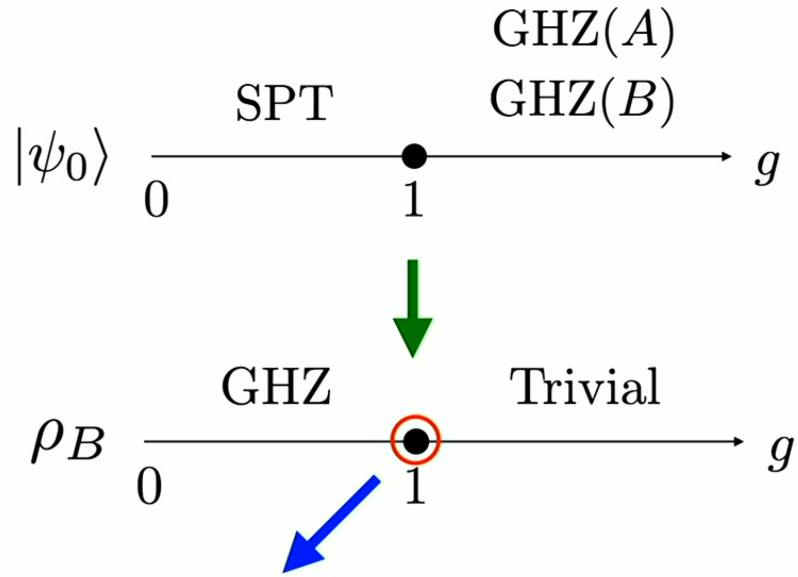
B sublattice

Mixed-state entanglement
(Entanglement negativity)

Vidal, Werner (2001)







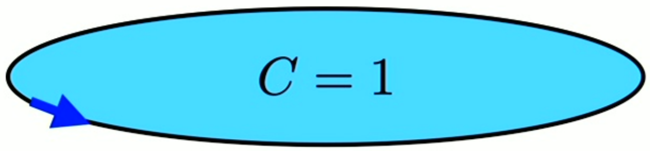
Log scaling entanglement negativity

in contrast, area-law negativity in
Gibbs state of local Hamiltonians

Sherman et.al. (2016)

Mixed-state quantum criticality from gapped states of matter

2d Chern insulators



$|\psi_0\rangle$

Chiral current

Trivial bulk correlation

$$\langle\psi_0|c(\mathbf{x})c^\dagger(\mathbf{x}')|\psi_0\rangle \sim e^{-\frac{|\mathbf{x}-\mathbf{x}'|}{\xi}}$$

Fermion correlation

Off-diagonal long-range order

Girvin, MacDonald (1987);
Kvorning, Spånslätt, Chan, Ryu (2019)

$$b^\dagger(\mathbf{x}) = \eta(\mathbf{x})c^\dagger(\mathbf{x})$$

boson ↓ Fermion

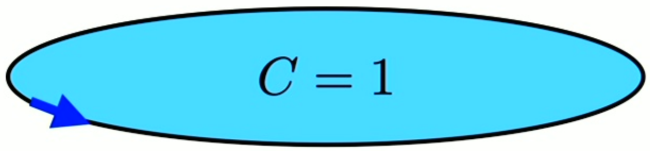
$$\eta(\mathbf{x}) = e^{i\int d^2x'\,\hat{n}(\mathbf{x}')\arg(\mathbf{x}-\mathbf{x}')}$$

Flux attachment

$$\langle\psi_0|b(\mathbf{x})b^\dagger(\mathbf{x}')|\psi_0\rangle \sim \frac{1}{|\mathbf{x}-\mathbf{x}'|^\alpha}$$

Mixed-state quantum criticality from gapped states of matter

2d Chern insulators



$|\psi_0\rangle$

Chiral current

Trivial bulk correlation

$$\langle\psi_0|c(\mathbf{x})c^\dagger(\mathbf{x}')|\psi_0\rangle \sim e^{-\frac{|\mathbf{x}-\mathbf{x}'|}{\xi}}$$

Fermion correlation

Off-diagonal long-range order

Girvin, MacDonald (1987);
Kvorning, Spånslätt, Chan, Ryu (2019)

$$b^\dagger(\mathbf{x}) = \eta(\mathbf{x})c^\dagger(\mathbf{x})$$

boson ↓ Fermion

$$\eta(\mathbf{x}) = e^{i\int d^2x'\,\hat{n}(\mathbf{x}')\arg(\mathbf{x}-\mathbf{x}')}$$

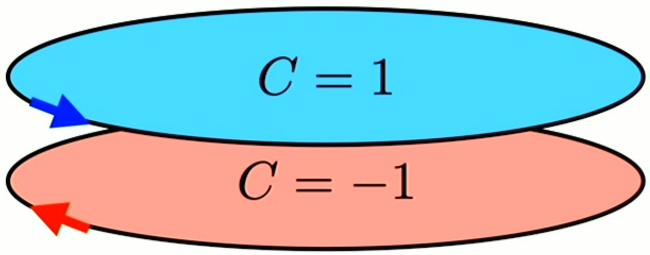
Flux attachment

$$\langle\psi_0|b(\mathbf{x})b^\dagger(\mathbf{x}')|\psi_0\rangle \sim \frac{1}{|\mathbf{x}-\mathbf{x}'|^\alpha}$$

Flux attachment via measurement + feedback !

Mixed-state quantum criticality from gapped states of matter

2d Chern insulators $|\psi_{0,\uparrow}\rangle \otimes |\psi_{0,\downarrow}\rangle$



$|\psi_0\rangle_\uparrow$

$|\psi_0\rangle_\downarrow$ $\quad S^+(\mathbf{x}) = c_\uparrow^+(\mathbf{x})c_\downarrow(\mathbf{x})$

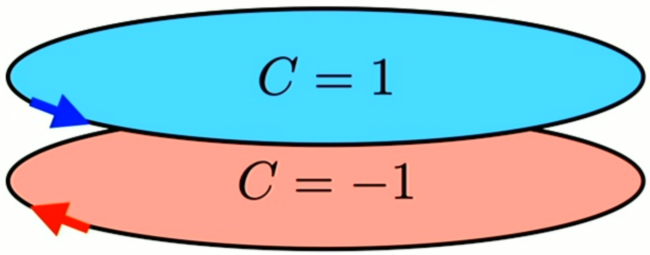
$$|\psi_0\rangle \qquad \left\langle e^{i[\hat{\phi}_\uparrow(\mathbf{x})-\hat{\phi}_\downarrow(\mathbf{x})]} S^+(\mathbf{x}) S^-(\mathbf{x}') e^{-i[\hat{\phi}_\uparrow(\mathbf{x}')-\hat{\phi}_\downarrow(\mathbf{x}')]} \right\rangle_0 \sim \frac{1}{|\mathbf{x}-\mathbf{x}'|^{2\alpha}}$$

$$\hat{\phi}_\uparrow(\mathbf{x}) = \int d^2x' \hat{n}_\uparrow(\mathbf{x}') \arg(\mathbf{x}-\mathbf{x}')$$

$$\hat{\phi}_\downarrow(\mathbf{x}) = -\int d^2x' \hat{n}_\downarrow(\mathbf{x}') \arg(\mathbf{x}-\mathbf{x}')$$

Mixed-state quantum criticality from gapped states of matter

2d Chern insulators $|\psi_{0,\uparrow}\rangle \otimes |\psi_{0,\downarrow}\rangle$



$|\psi_0\rangle_\uparrow$

$|\psi_0\rangle_\downarrow$ $\quad S^+(\mathbf{x}) = c_\uparrow^+(\mathbf{x})c_\downarrow(\mathbf{x})$

$$|\psi_0\rangle \qquad \left\langle e^{i[\hat{\phi}_\uparrow(\mathbf{x})-\hat{\phi}_\downarrow(\mathbf{x})]} S^+(\mathbf{x}) S^-(\mathbf{x}') e^{-i[\hat{\phi}_\uparrow(\mathbf{x}')-\hat{\phi}_\downarrow(\mathbf{x}')]} \right\rangle_0 \sim \frac{1}{|\mathbf{x}-\mathbf{x}'|^{2\alpha}}$$

$$\downarrow \qquad\qquad ||$$

$$\rho \qquad \left\langle S^+(\mathbf{x}) S^-(\mathbf{x}') \right\rangle_\rho$$

Measuring fermion numbers
+ feedback unitary

Occupation number measurement
via quantum gas microscope

e.g. review by Gross, Bakr
Nature Phys (2021)

Non-local channel using measurements

arXiv: 2303.15507 (PRX Quantum), **TCL**, Zhang, Vijay, Hsieh

Long-range entangled mixed-states

Kennedy-Tasaki transformation SPT -> long-range (topological) order

(generalized to higher dimension and more symmetries)

Flux attachment Gapped states -> critical states

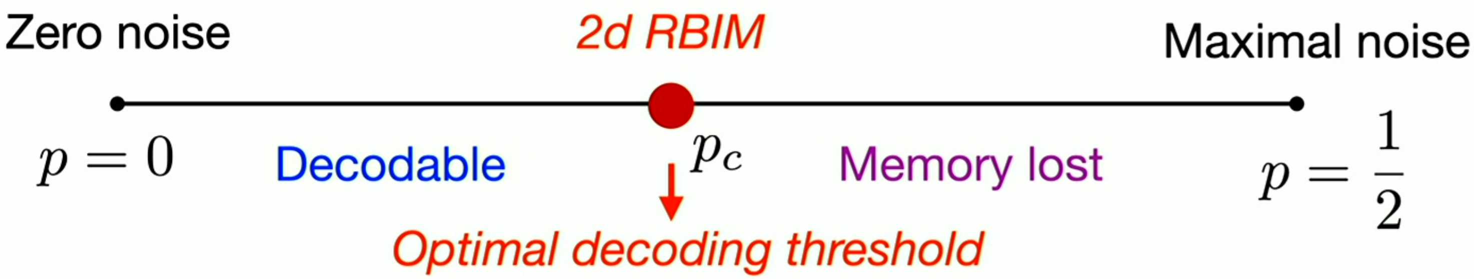
Classification and entanglement structures remains to be better understood

See Ralph Jason Costales's poster for partial progress

Part II: Stability of LRE states

arXiv:2404.06514, **TCL**

Topological codes (e.g. toric code) protect information up to a critical noise rate



Intrinsic property of the noisy mixed state? Fan, Bao, Altman, Vishwanath (2023)

also, Lee, Jian, Xu (2023)

Mixed-state topological order survives up to p_c?

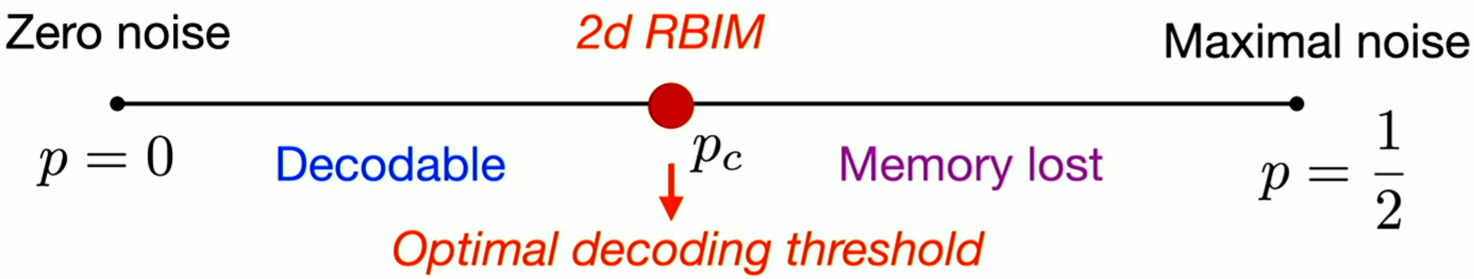
Mixed-state phases of matter?

$\mathrm{Tr}[\rho O]$ smooth function of p

Part II: Stability of LRE states

arXiv:2404.06514, **TCL**

Topological codes (e.g. toric code) protect information up to a critical noise rate



Intrinsic property of the noisy mixed state? Fan, Bao, Altman, Vishwanath (2023)

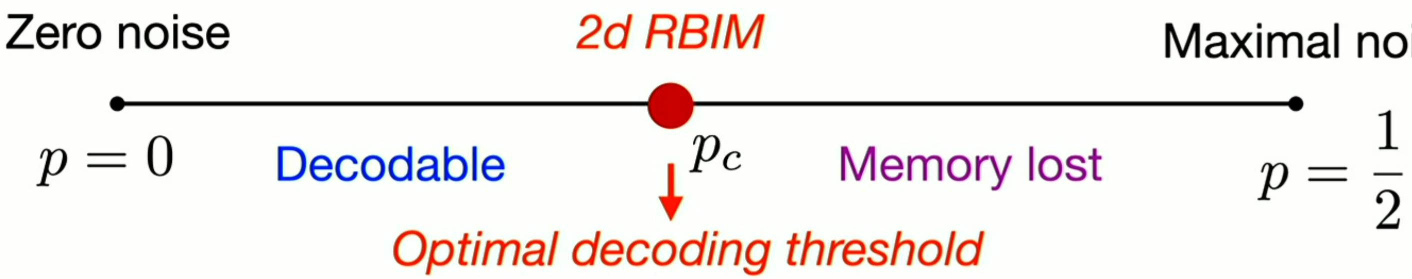
also, Lee, Jian, Xu (2023)

- Mixed-state phase and channel (Sang, Zou, Hsieh, 2023) (Sang, Hsieh, 2024)
- Separability transition (Chen, Grover, 2023, 2024)

Part II: Stability of LRE states

arXiv:2404.06514, **TCL**

Topological codes (e.g. toric code) protect information up to a critical noise rate



Intrinsic property of the noisy mixed state? Fan, Bao, Altman, Vishwanath (2023)

also, Lee, Jian, Xu (2023)

- Direct diagnosis via mixed-state entanglement remains missing

Fan et.al. - Renyi negativity different critical p with different universality

$$R_{2n} = \frac{1}{2-2n} \log \frac{\mathrm{tr}(\rho^\Gamma)^{2n}}{\mathrm{tr}\rho^{2n}}$$

$$\lim_{n \to \frac{1}{2}} R_{2n} = E_N = \log |\rho^\Gamma|_1$$ **Entanglement negativity ??**

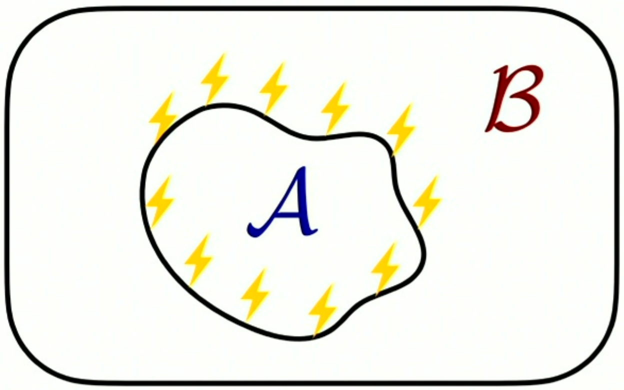
Boundary decoherence

arXiv:2404.06514, **TCL**

Exact results of mixed-state entanglement
& universality of the entanglement transition

Boundary decoherence

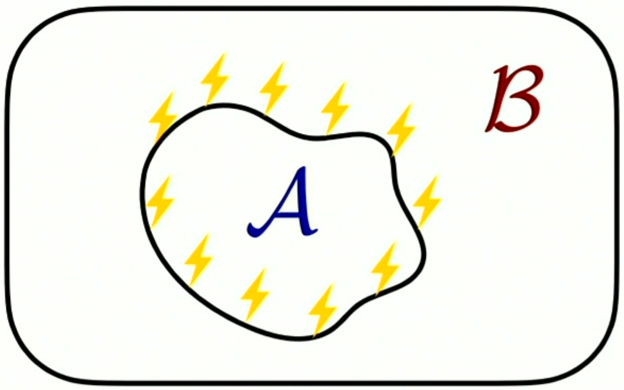
arXiv:2404.06514, **TCL**



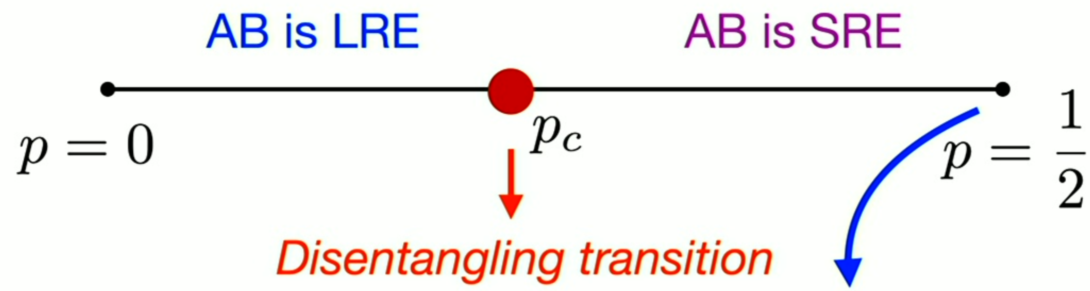
Toric code under boundary decoherence
(Proliferates boundary anyons)

Boundary decoherence

arXiv:2404.06514, **TCL**



Toric code under boundary decoherence
(Proliferates boundary anyons)

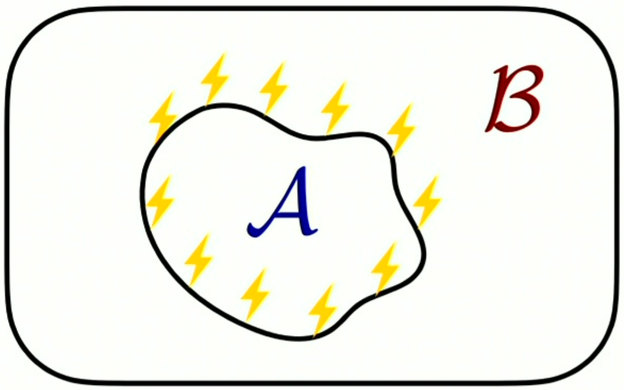


$$\rho = \sum_i p_i \ \rho_{A,i} \otimes \rho_{B,i}$$

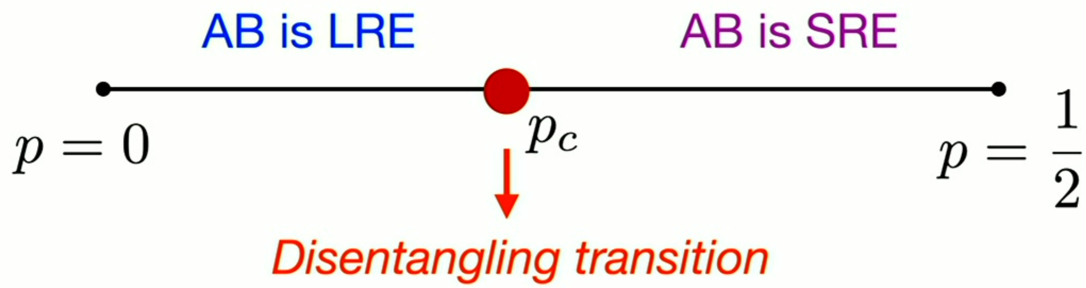
Bulk topo. order in A,B

Boundary decoherence

arXiv:2404.06514, **TCL**



Toric code under boundary decoherence
(Proliferates boundary anyons)



Entanglement negativity

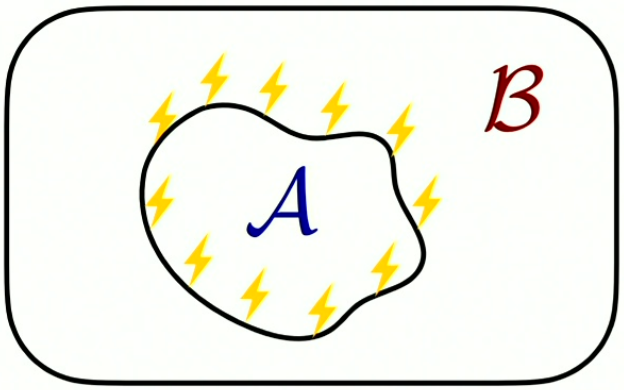
Peres (1996), Horodecki (1996), Vidal, Werner (2001)

$$E_N = \log|\rho^\Gamma|_1 = \log\left(\sum_i |\lambda_i|\right)$$

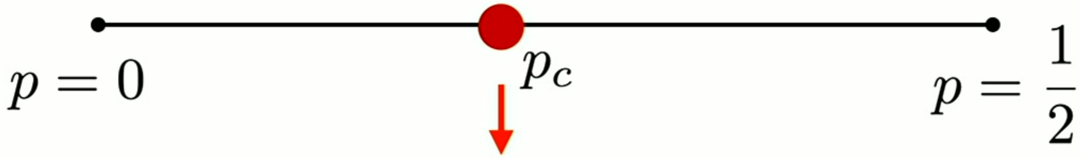
$\{\lambda_i\}$ Negativity spectrum

Boundary decoherence

arXiv:2404.06514, **TCL**



Toric code under boundary decoherence
(Proliferates boundary anyons)



Disentangling transition

Entanglement negativity

Peres (1996), Horodecki (1996), Vidal, Werner (2001)

$$E_N = \alpha L - \boxed{E_{\text{topo}}}$$

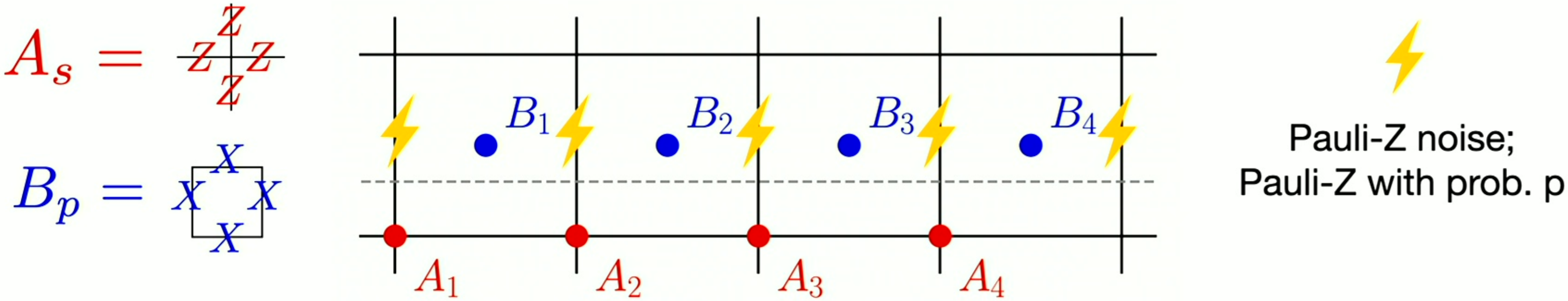
Topological negativity: LRE diagnostic

Diagnostic for Finite-T Topo. order

TCL, Hsieh, Grover, PRL (2020)

TCL, Vijay (PRR,2022)

2d toric code

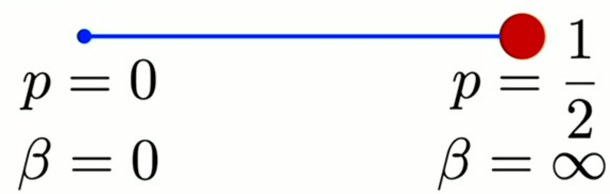


$$E_N = \log Z_{1\mathrm{d,Ising}} - \log \tilde{Z}_{1\mathrm{d,Ising}}$$

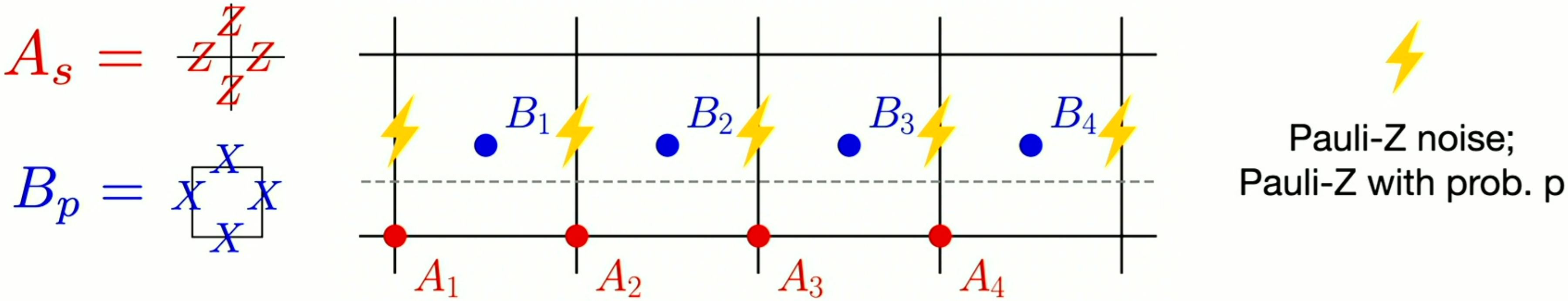
$$\tanh \beta = \frac{p}{1-p}$$

$$\sum_{\{\sigma_i\}} e^{\beta \sum_{i=1}^{L} \sigma_i \sigma_{i+1}}$$

$$\sum_{\{\sigma_i\}} e^{\beta \sum_{i=1}^{L} \sigma_i \sigma_{i+1}} \delta\left(\sigma_i \sigma_{i+1} = 1\right) = 2e^{\beta L}$$



2d toric code



$$E_N = \log Z_{\text{1d,Ising}} - \log \tilde{Z}_{\text{1d,Ising}}$$

$$\tanh \beta = \frac{p}{1-p}$$

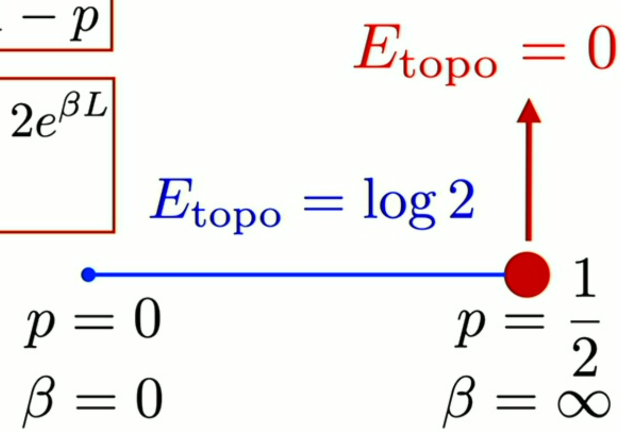
$$\sum_{\{\sigma_i\}} e^{\beta \sum_{i=1}^{L} \sigma_i \sigma_{i+1}}$$

$$\sum_{\{\sigma_i\}} e^{\beta \sum_{i=1}^{L} \sigma_i \sigma_{i+1}} \delta\left(\sigma_i \sigma_{i+1} = 1\right) = 2e^{\beta L}$$

$$E_N = \alpha L - E_{\text{topo}}$$

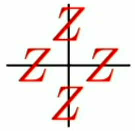
$$\alpha \to \log(2-2p)$$

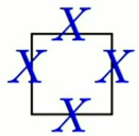
$$E_{\text{topo}} = \log\left(\frac{2}{1+\left(\frac{p}{1-p}\right)^L}\right)$$

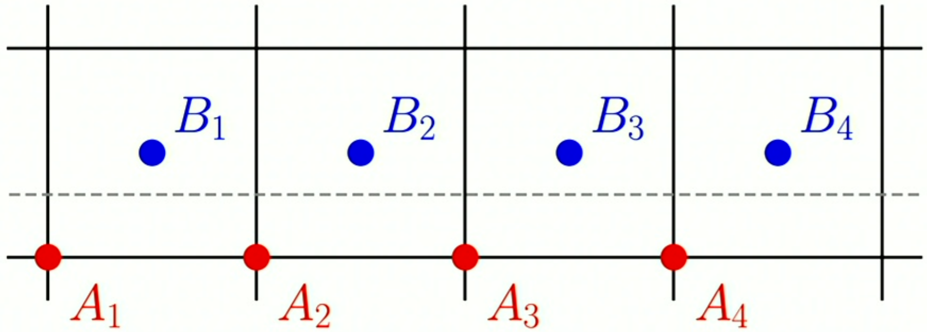


Negativity spectrum (pure-state toric code)

TCL, *Vijay (PRR 2023)*

$A_s =$ 

$B_p =$ 



Two Z_2 symmetries

$$\rho^\Gamma(\{A_i, B_i\}) \propto \chi(\{A_i, B_i\}) = \pm 1$$

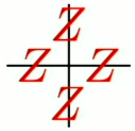
$$A_i, B_i = \pm 1$$

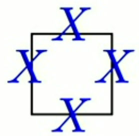
$$\prod_i A_i = \prod_i B_i = 1$$

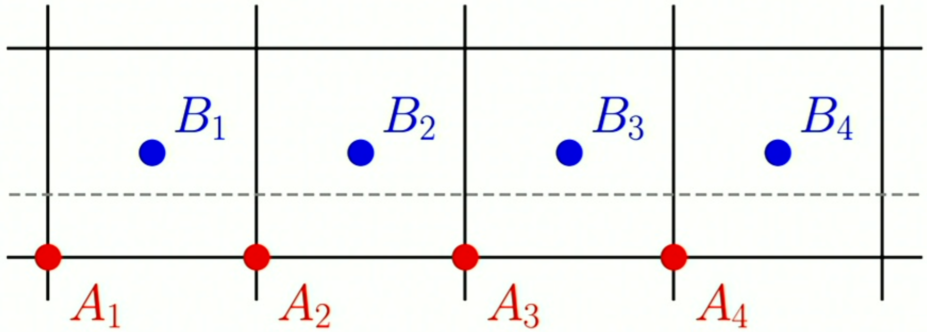
$A_i = -1$ e anyons $\quad B_i = -1$ m anyons

Negativity spectrum (pure-state toric code)

TCL, Vijay (PRR 2023)

$A_s =$ 

$B_p =$ 



Two Z_2 symmetries

$$\rho^\Gamma(\{A_i, B_i\}) \propto \chi(\{A_i, B_i\})$$
$$= \pm 1$$

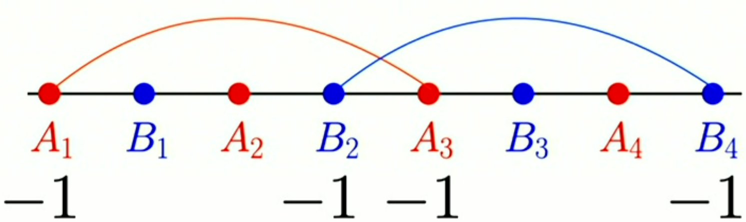
$A_i, B_i = \pm 1$

$$\prod_i A_i = \prod_i B_i = 1$$

$A_i = -1$ e anyons

$B_i = -1$ m anyons

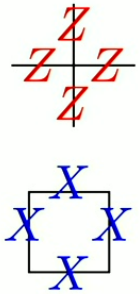
$\chi = -1$

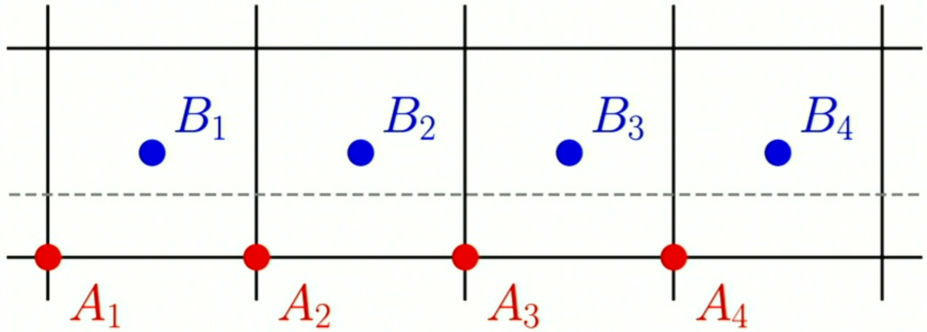


Negativity spectrum (pure-state toric code)

TCL, Vijay (PRR 2023)

$A_s =$ / $B_p =$





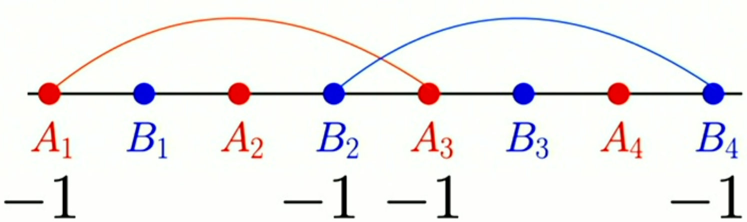
Two Z_2 symmetries

$$\rho^{\Gamma}(\{A_i, B_i\}) \propto \chi(\{A_i, B_i\}) = \pm 1$$

$$A_i, B_i = \pm 1$$

$$\prod_i A_i = \prod_i B_i = 1$$

$$\chi = -1$$



Partial transpose proliferates the boundary anyons and reveals the braiding phase between e, m anyons

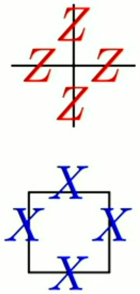
$$|\text{1d cluster}\rangle = \sum_{\{A_i, B_i\}} \chi(\{A_i, B_i\}) |A_1, B_1, A_2, B_2 ...\rangle_X$$

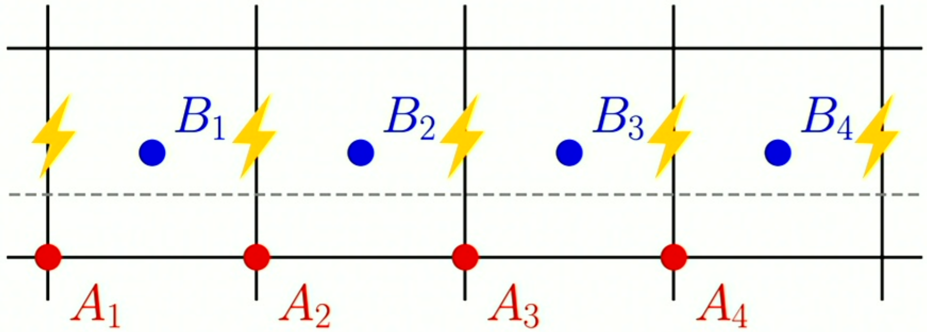
Z_2 x Z_2 SPT

Negativity spectrum

Negativity spectrum (boundary decohered)

$A_s =$, $B_p =$





Pauli-Z noise;
Pauli-Z with prob. p

$$\rho^{\Gamma}(\{A_i, B_i\}) \propto \chi(\{A_i, B_i\}) \; e^{\beta \sum_{i=1}^{L} A_i}$$

$$\prod_{i=1}^{L} A_i = 1$$

$$\tanh \beta = \frac{p}{1-p}$$

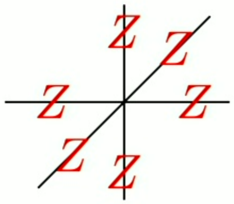
Gibbs weight of finite-T 1d Ising

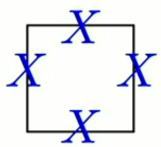
$$A_i = \sigma_i \sigma_{i+1}$$

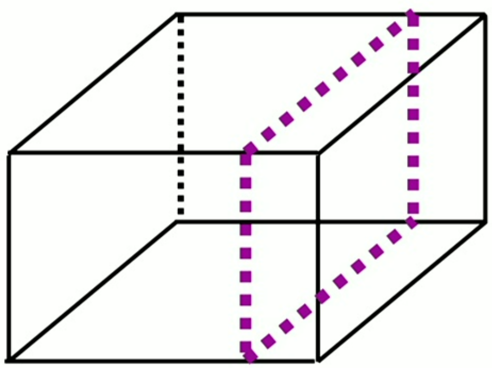
Domain-wall variable

Negativity spectrum computable for any stabilizer models

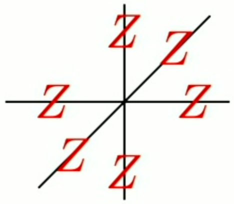
3d toric code with boundary decoherence

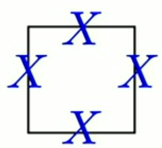
$A_s =$ 

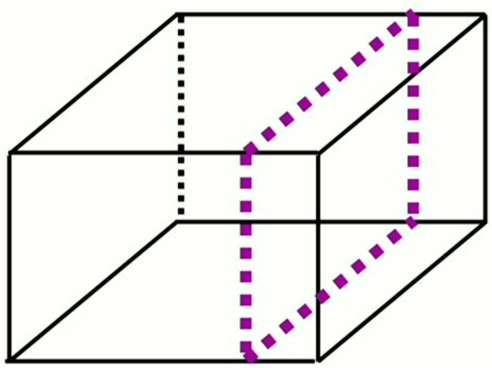
$B_p =$ 



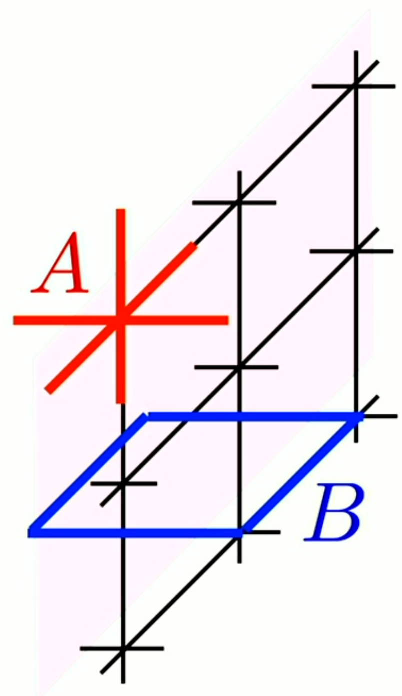
3d toric code with boundary decoherence

$A_s =$ 

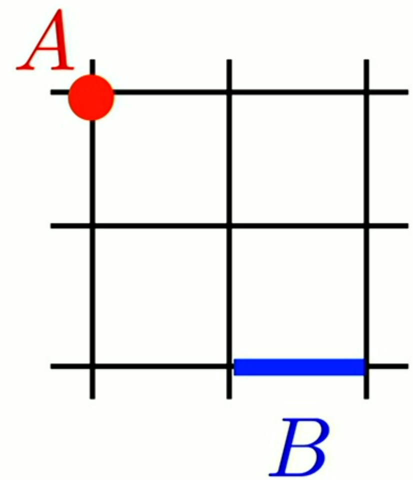
$B_p =$ 



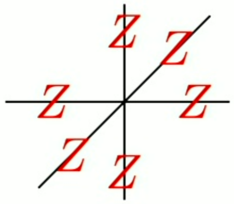
2d boundary

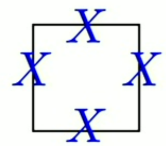


2d cross-section

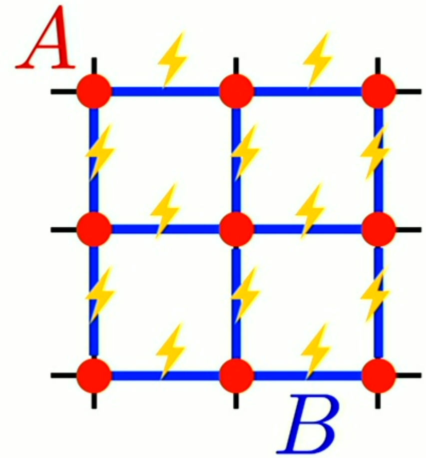


3d toric code with boundary decoherence

$A_s =$ 

$B_p =$ 

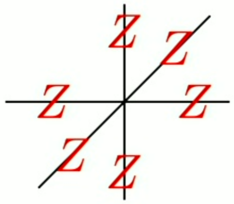
2d cross-section

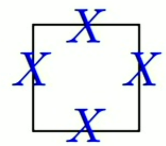


X noise; Pauli-X with prob. p

Excite A_s vertex charges

3d toric code with boundary decoherence

$A_s =$ 

$B_p =$ 

$$E_N = \log \underline{Z_{\text{2d,Ising}}} - \log \underline{\tilde{Z}_{\text{2d,Ising}}}$$

$$\sum_\sigma e^{\beta \sum_{\langle ij \rangle} \sigma_i \sigma_j} \qquad 2e^{2\beta L^2}$$

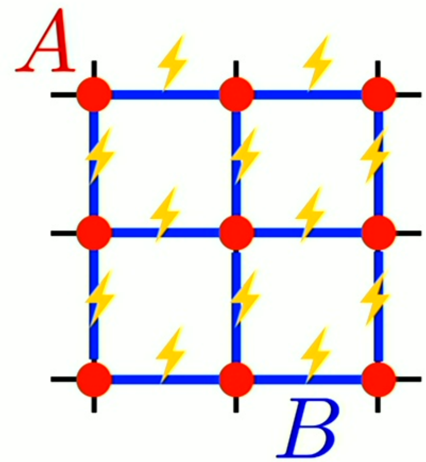
$$\boxed{\tanh \beta = \frac{p}{1-p}}$$

$E_{\text{topo}} = \log 2$ $\qquad$ $E_{\text{topo}} = 0$

$p = 0$ $\qquad$ $p_c \approx 0.29$ $\qquad$ $p = \frac{1}{2}$

2d Ising

2d cross-section



X noise; Pauli-X with prob. p

Excite A_s vertex charges

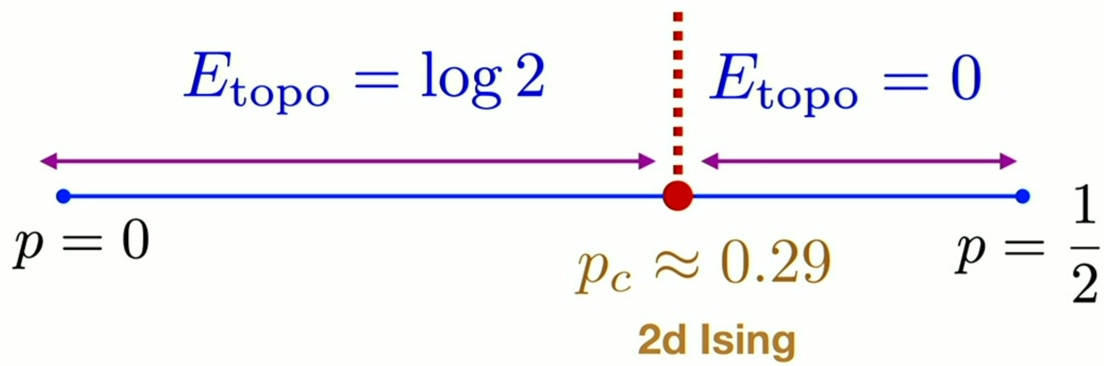
Boundary decoherence

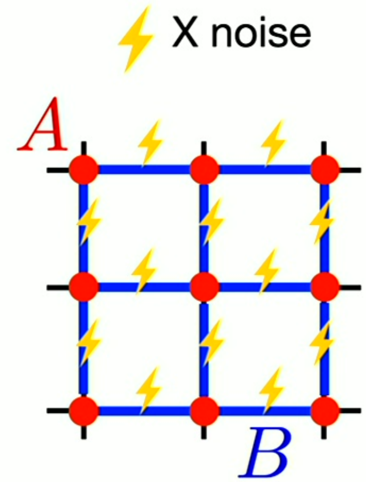
Formalism applied to any qubit stabilizer models

e.g. 4d toric code

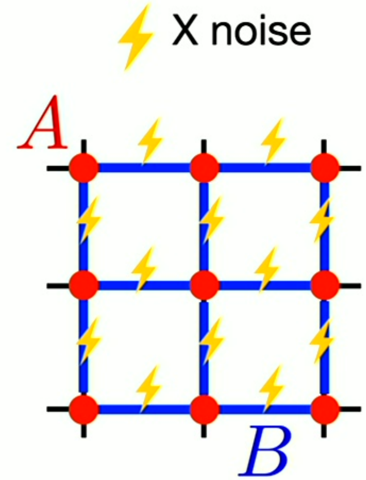
These exact results of entanglement negativity lead to **new puzzles**…

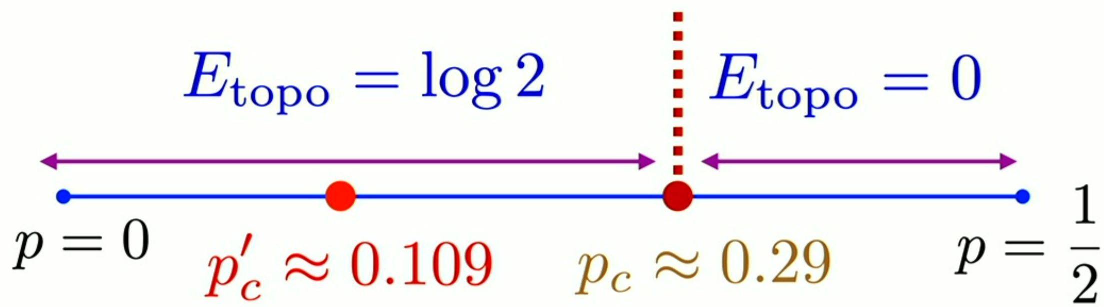
3d toric code revisited





3d toric code revisited





2d Random-bond Ising

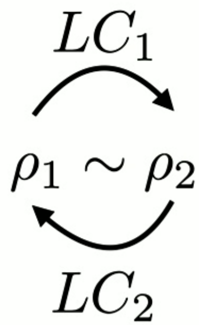
2d Ising

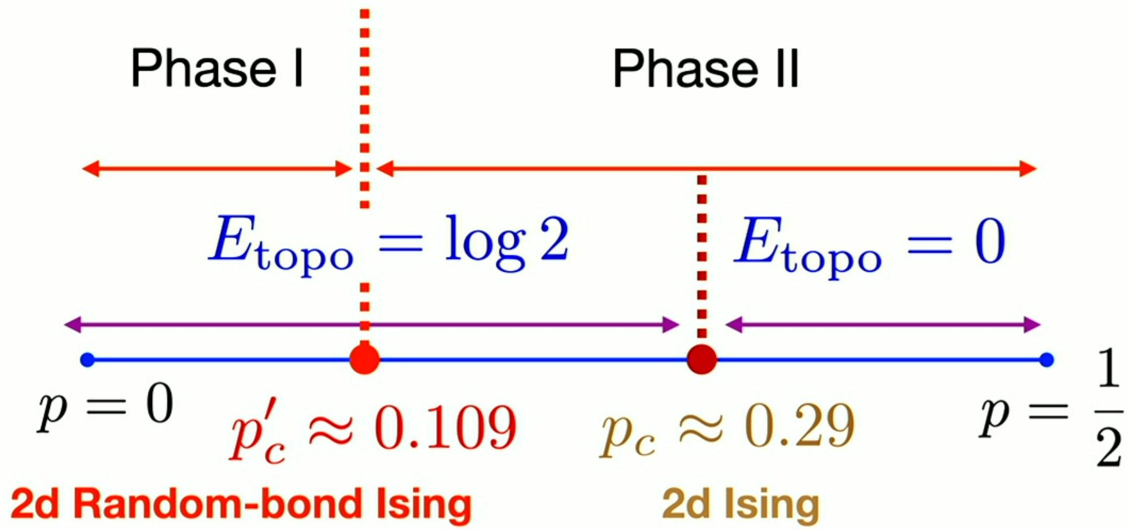
Syndrome distribution
same as uniformly decohered **2d toric**

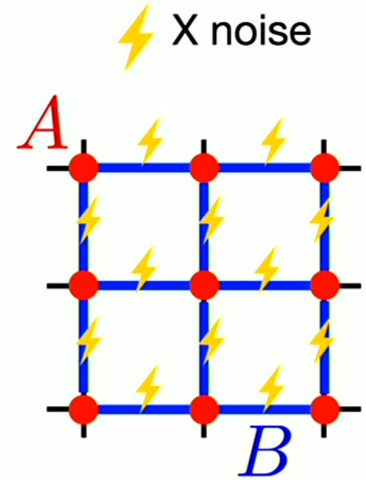
$$-\mathrm{tr}\rho \log \rho$$

3d toric code revisited

Based on arXiv:2404.07251, Sang & Hsieh





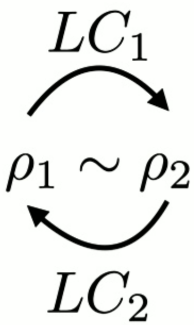


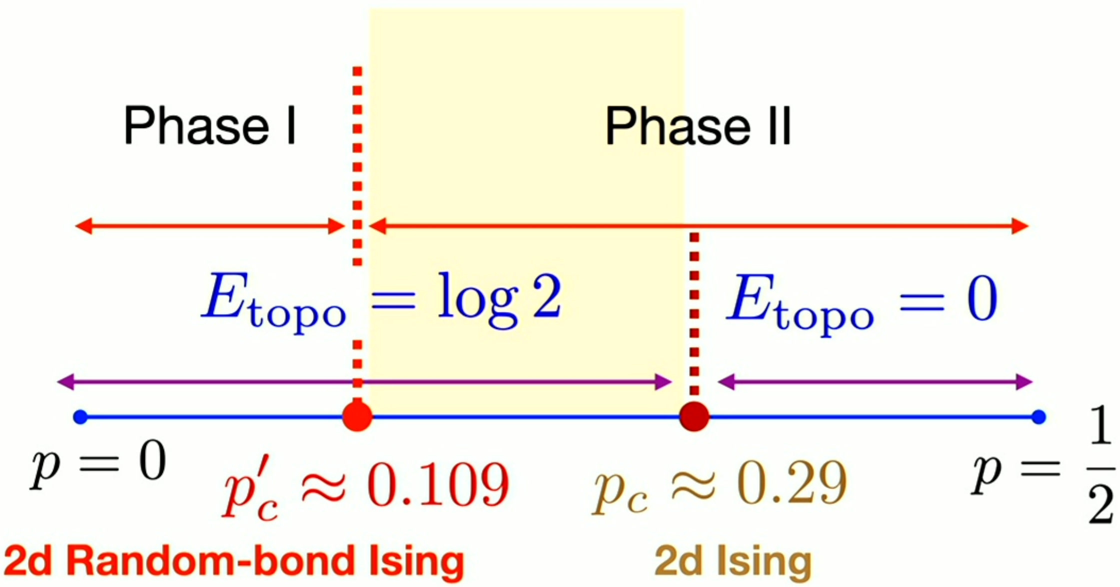
Syndrome distribution
same as uniformly decohered **2d toric**

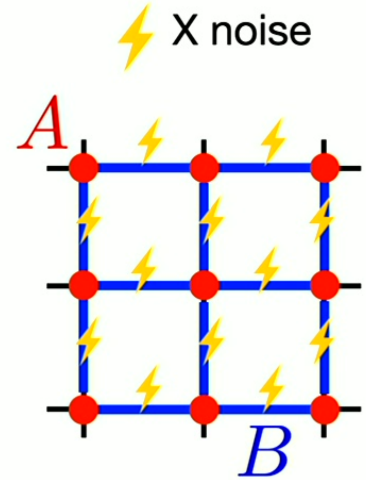
$$-\mathrm{tr}\rho \log \rho$$

3d toric code revisited

Based on arXiv:2404.07251, Sang & Hsieh







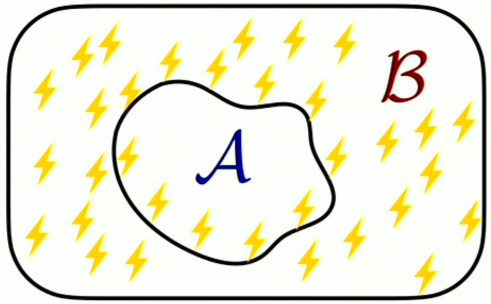
Syndrome distribution
same as uniformly decohered **2d toric**

$-\mathrm{tr}\rho \log \rho$

$p_c' < p < p_c$ Spurious entanglement?

(quasi) local channel creates
non-zero topological negativity?

Decohered toric code (noise everywhere)



Zero noise — *2d RBIM* — Maximal noise

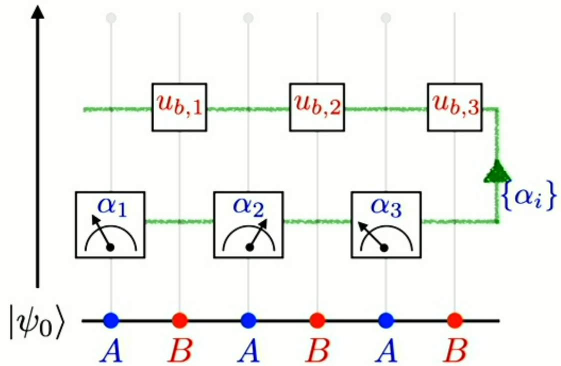
$p = 0$ — Decodable — p_c — Memory lost — $p = \frac{1}{2}$

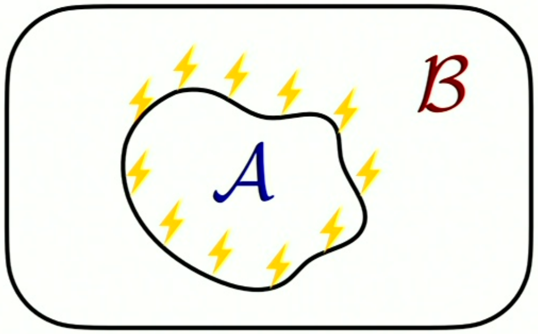
Optimal decoding threshold

Does negativity witness the decoding transition?

Perhaps require other (better) entanglement measure?

Summary





Creating LRE via measurement-feedback

TCL, Zhang, Vijay, Hsieh (PRX Quantum, 2023)

- Limitation of measurements & feedback? Gapped pure state -> critical pure states?
- Our prepared mixed states - classification & entanglement structure?

Destroying LRE via decoherence

TCL, arXiv:2404.06514 (2024)

- Boundary separability perspective
- Negativity transition in the 2d toric code (noise everywhere)
- Boundary decoherence in various quantum matter