Mixed-State Long-Range Order and Criticality from Measurement and Feedback

Tsung-Cheng (Peter) Lu

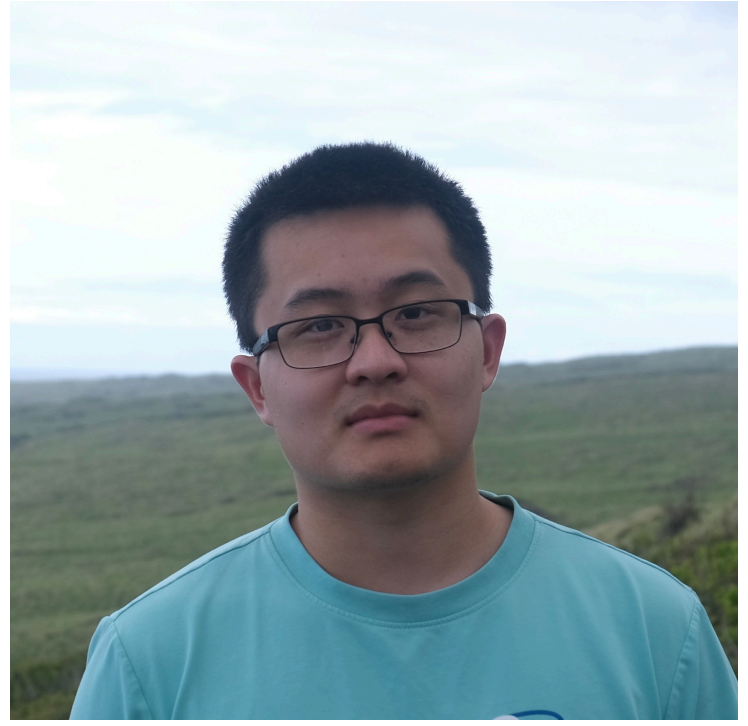
(Perimeter Institute)

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

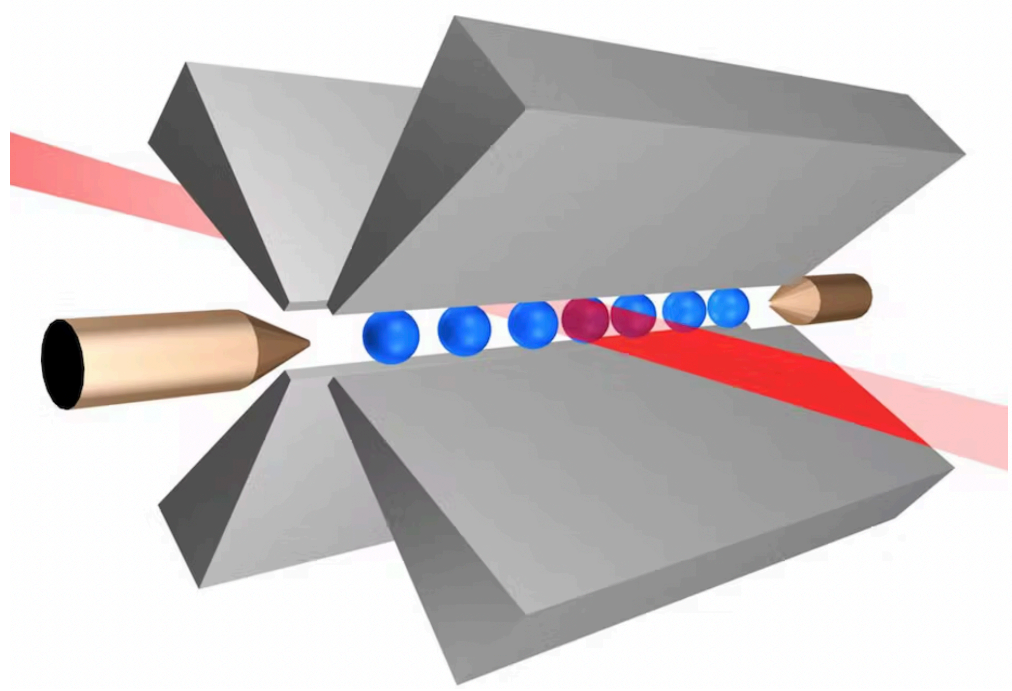
Zhehao Zhang (UCSB)

Sagar Vijay (UCSB)

Tim Hsieh (Perimeter)

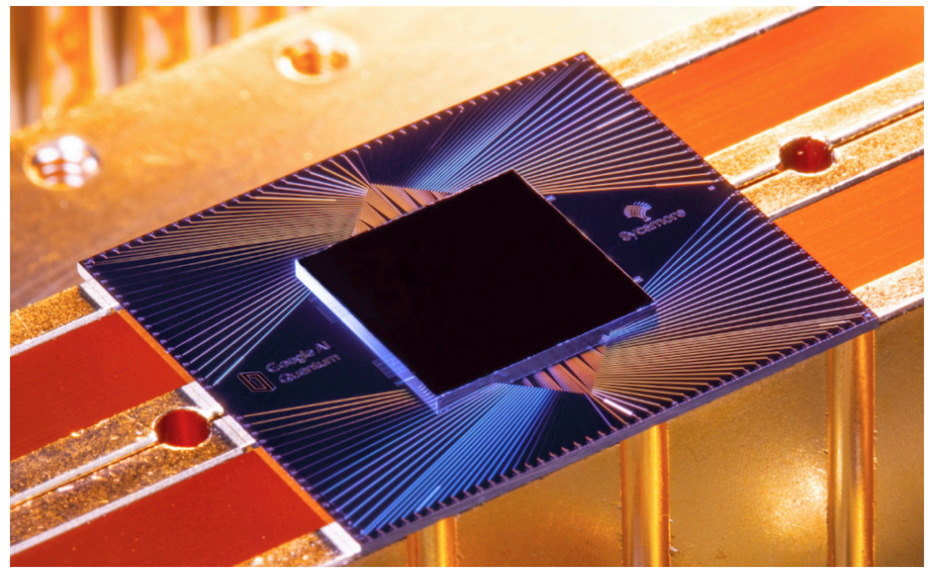


Noisy Intermediate-Scale Quantum Systems



Trapped-ion quantum computer

E.g. Duke/IonQ
Quantinuum

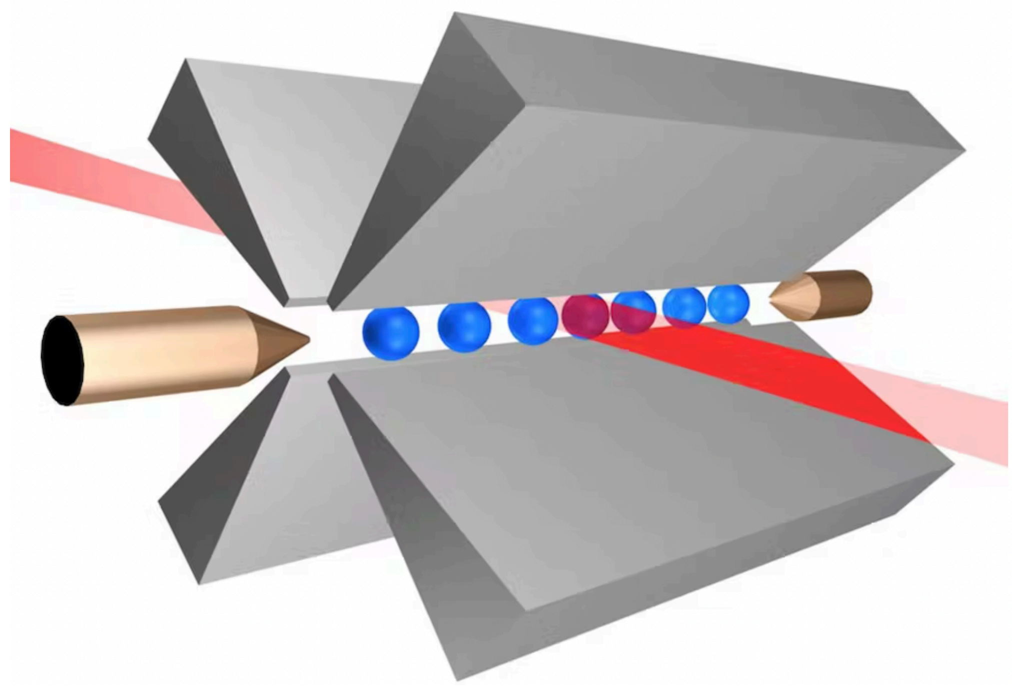


Superconducting qubits

E.g. Google
IBM

Qubits, unitary gates, mid-circuit measurement available

Noisy Intermediate-Scale Quantum Systems



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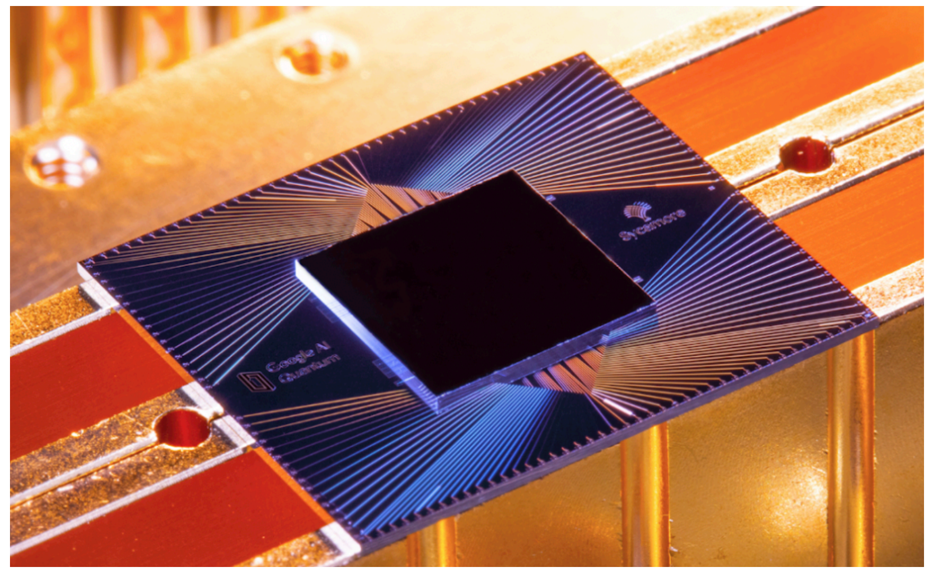

Superconducting qubits

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Qubits, unitary gates, mid-circuit measurement available

Can we artificially engineer non-trivial many-body states?

(which may be challenging to find in nature)

(Long-range entangled)
Non-trivial states

Example 1
Topological order

No local order parameters

Fractionalized quasiparticles (anyons)

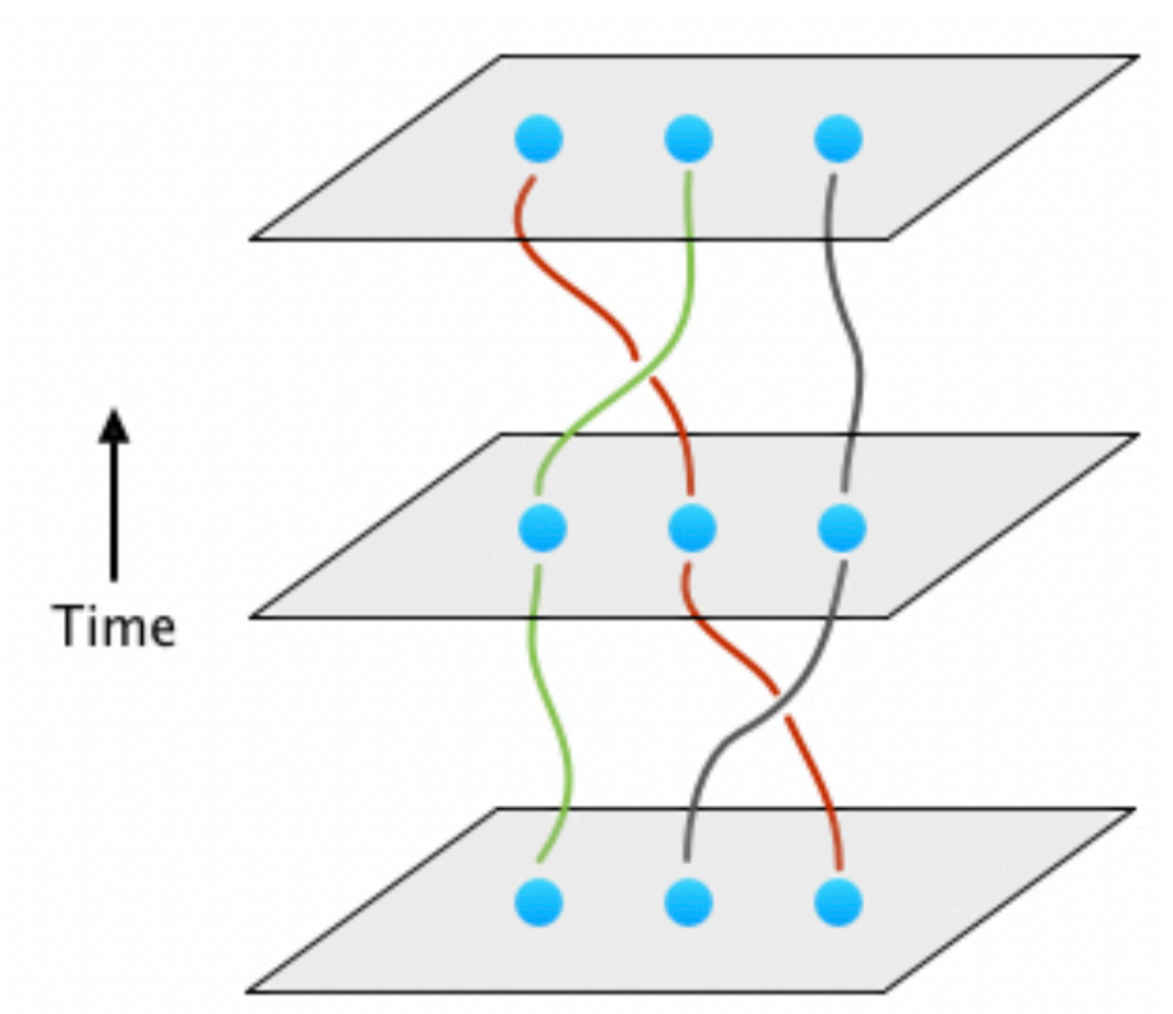

Fig. from Quanta Magazine

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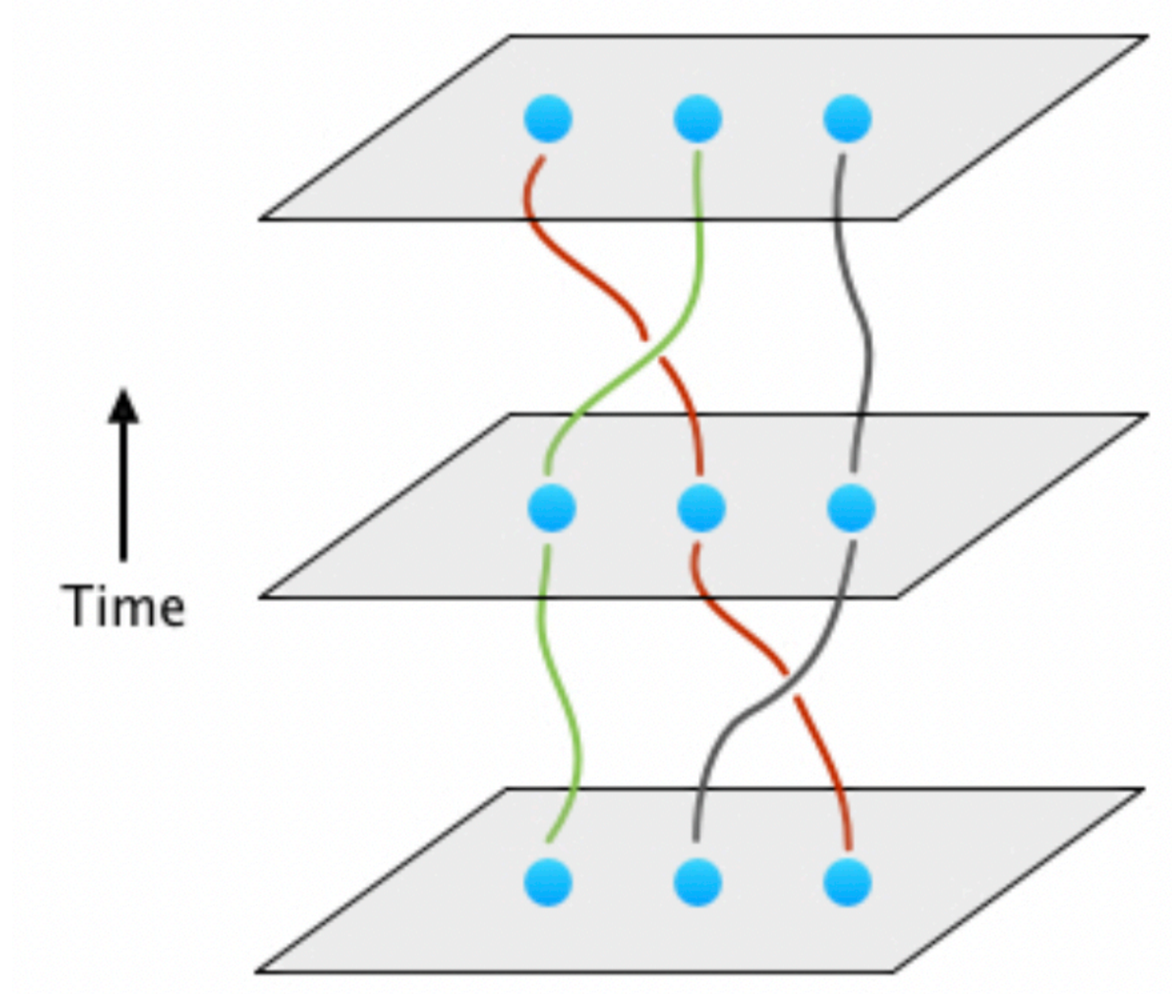


Fig. from Quanta Magazine

Example 2
Quantum critical states

Phase transitions between quantum orders

Quantum correlations at all scales

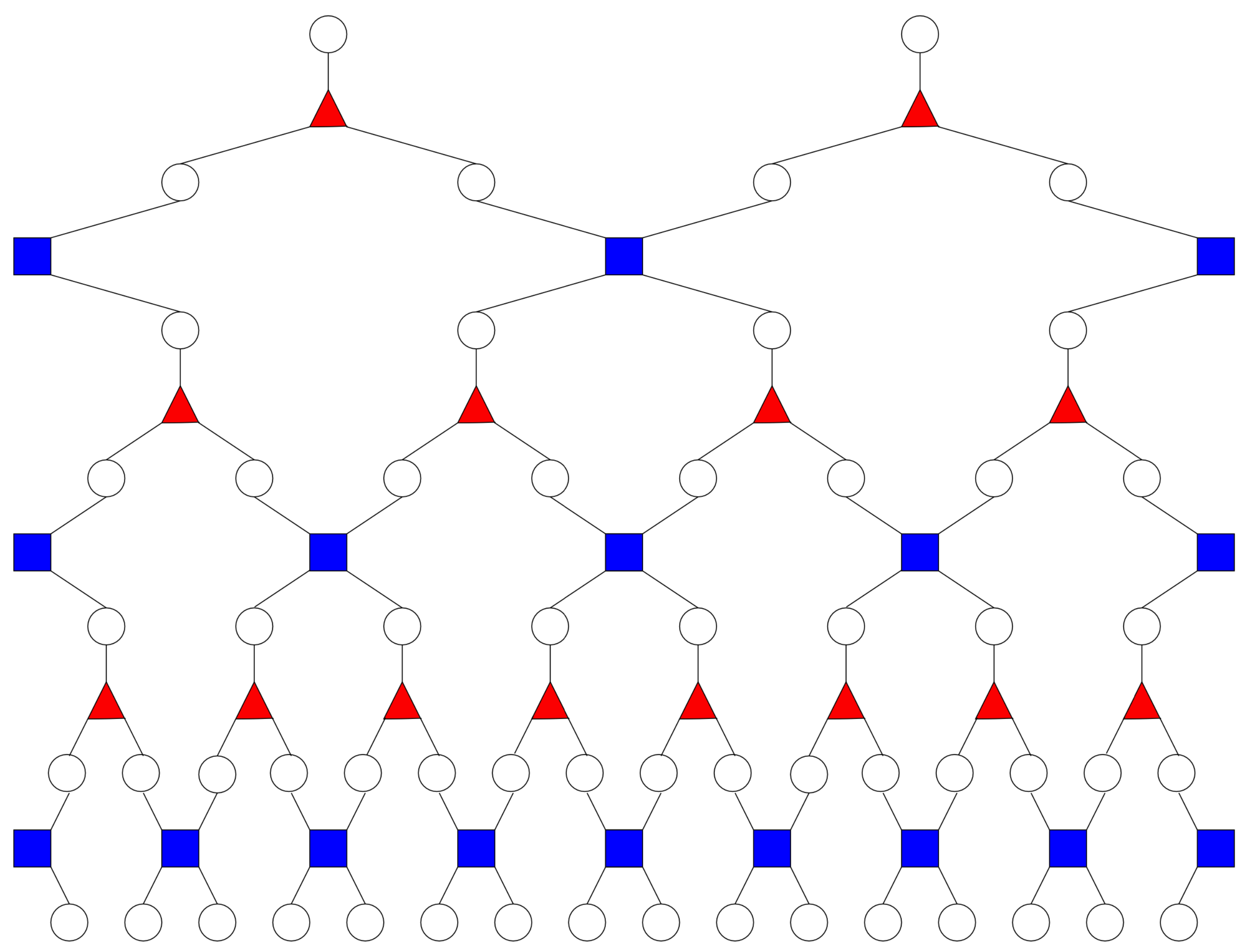


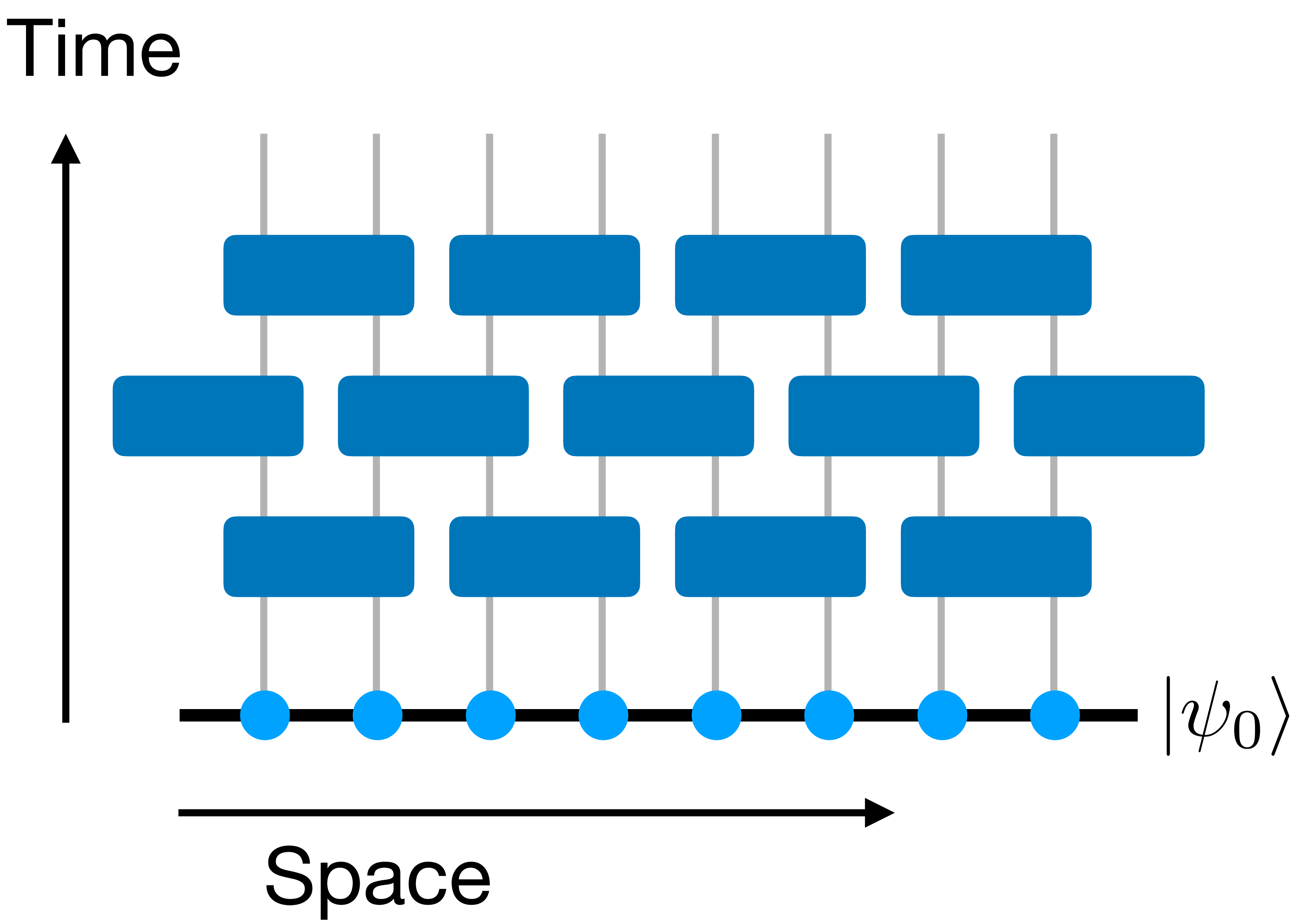
Fig. from Swingle

(Long-range entangled)
Non-trivial states

Example 1
Topological order

Example 2
Quantum critical states

Local unitary circuits



Preparation Time ≳ O(L), Lieb-Robinson bound

(Long-range entangled)
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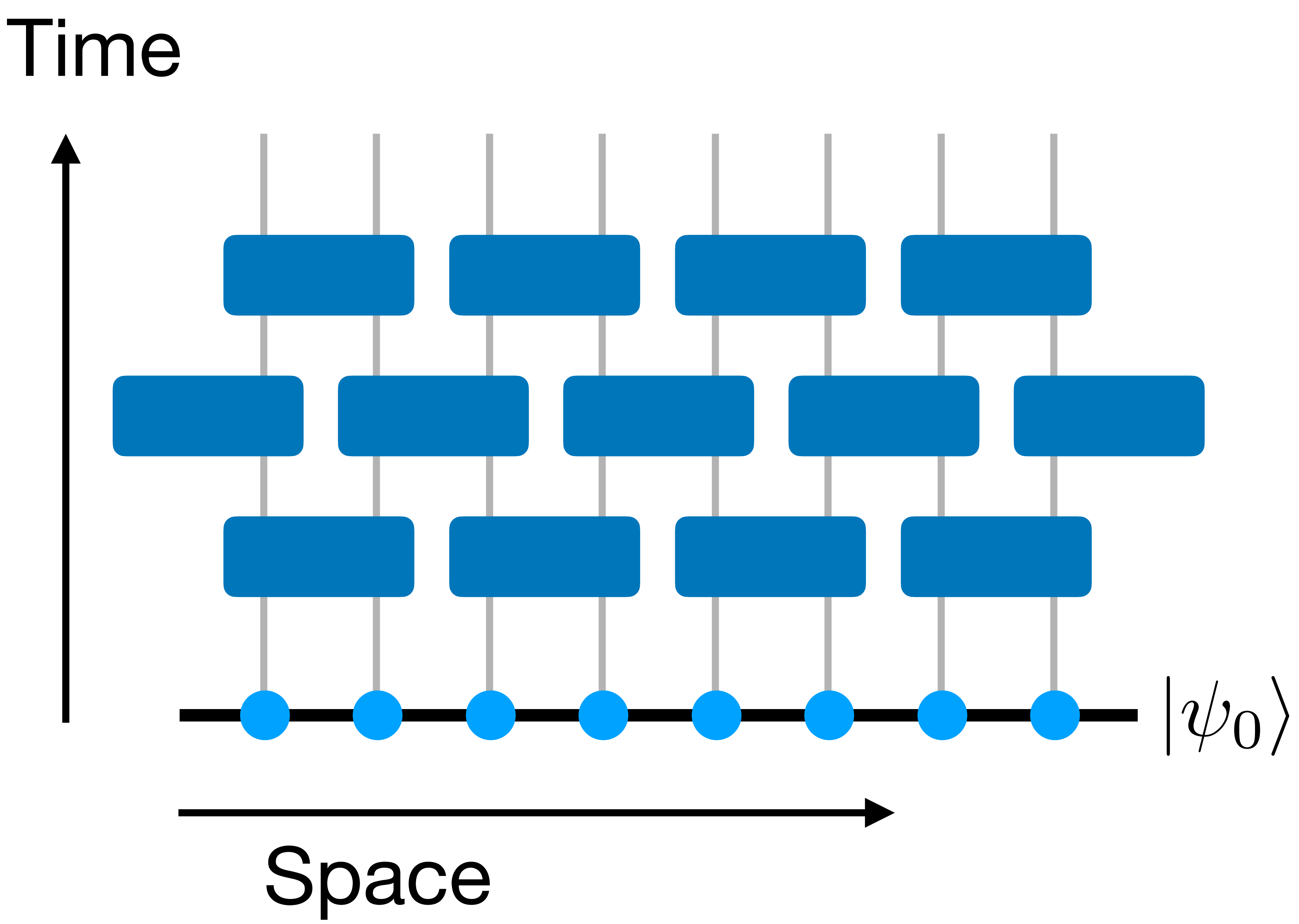

Preparation Time ≳ O(L), Lieb-Robinson bound

undesirable in near-term quantum computers

Workaround?

(Long-range entangled)
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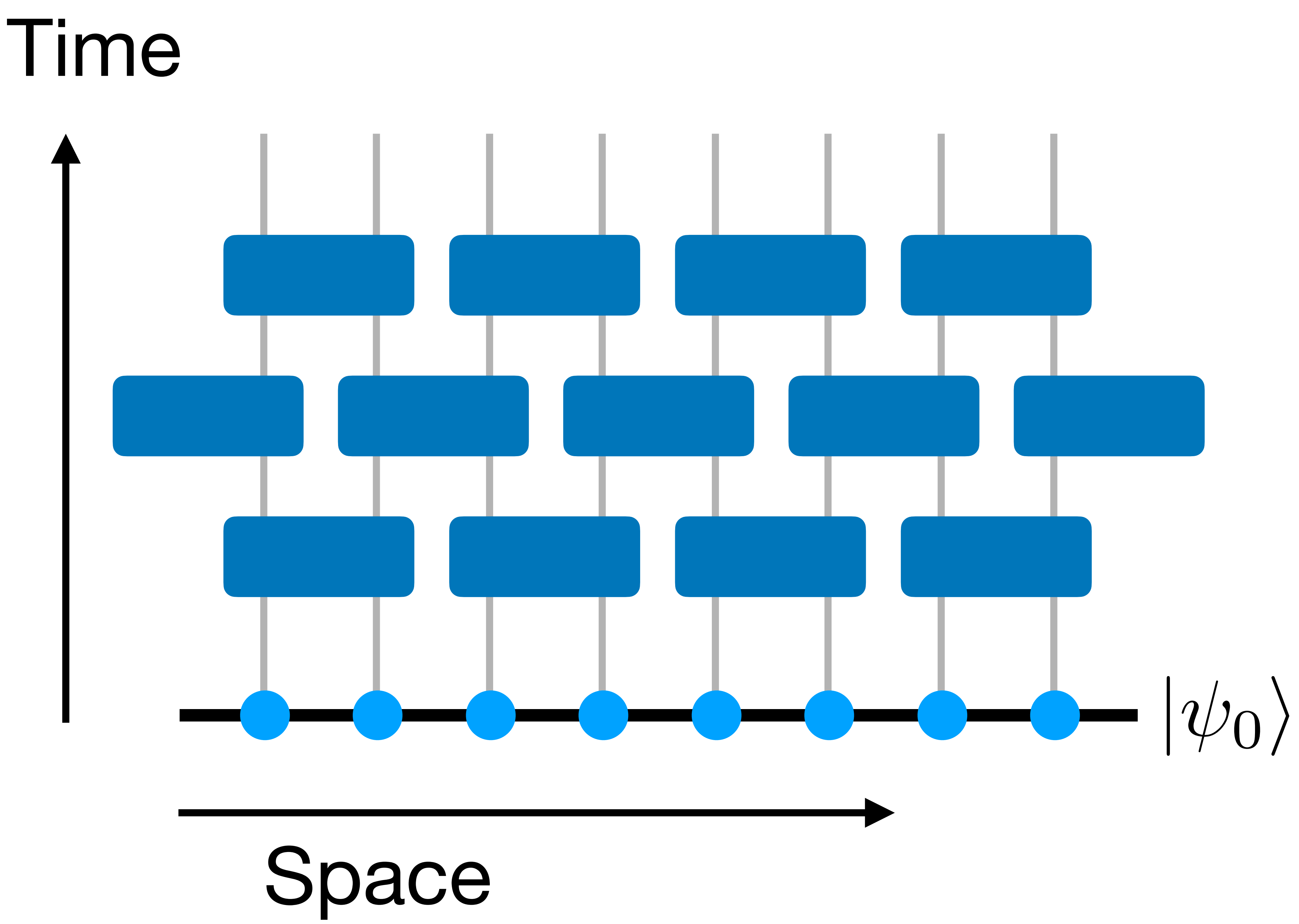


Preparation Time ≳ O(L), Lieb-Robinson bound

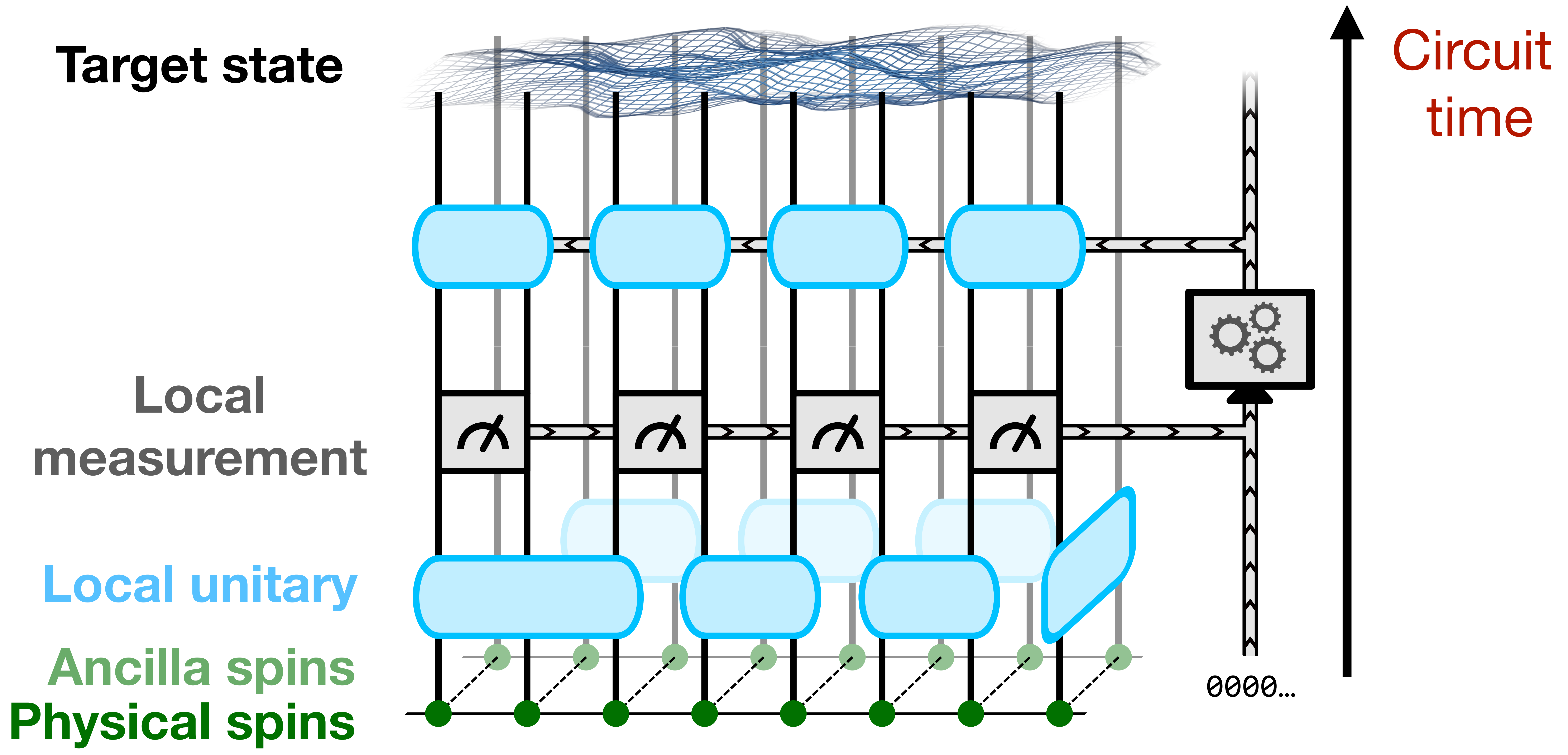
undesirable in near-term quantum computers

Workaround?

With local **measurement** (non-unitary),
many LRE states are possible in O(1) time !

Adaptive protocols

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



The applied unitary gates are **adaptive** (depend on global measurement outcomes)

Adaptive protocols - (partial) literature

Theory

GHZ state — (2001) Briegel, Raussendorf

Toric code — (2005) Raussendorf, Bravyi, Harrington

(2021) Piroli, Styliaris, Cirac

Non-abelian (solvable group) T.O. {
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(2022) Lu, Lessa, Kim, Hsieh arXiv: 2206.13527 (PRX Quantum)

Tensor-network, parton construction, entanglement renormalization

Certain (chiral) non-abelian T.O. in O(1) depth

Levin-Wen string nets, CFT gapless (critical) state in O(Log L) depth

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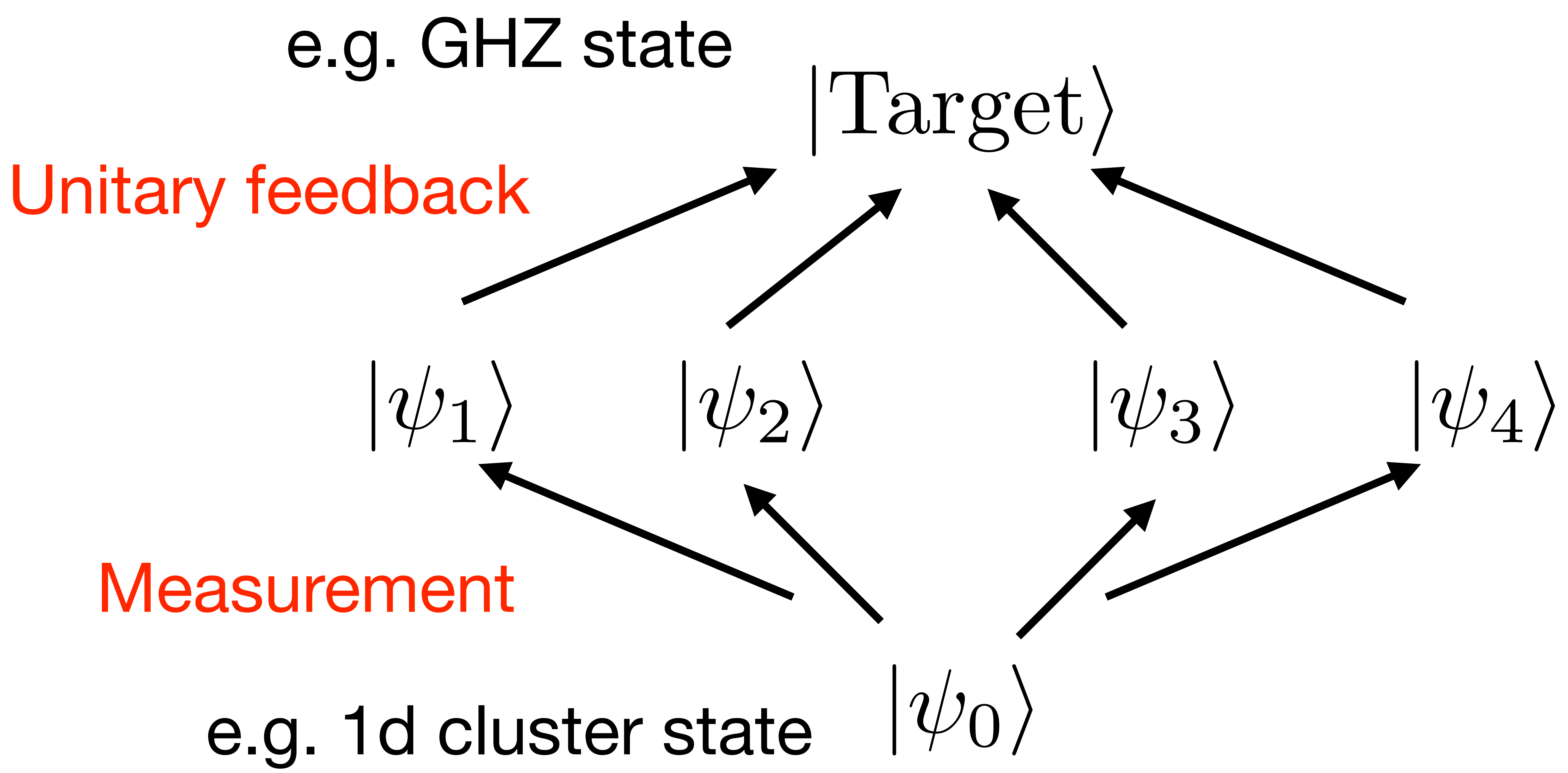
Experiment

Toric code {
- (2023) Quantinuum, **Perimeter**, UC Davis
- (2023)Quantinuum, Harvard, Caltech

Non-abelian T.O. ← (2023)Quantinuum, Harvard, Caltech

Stability of adaptive protocols?



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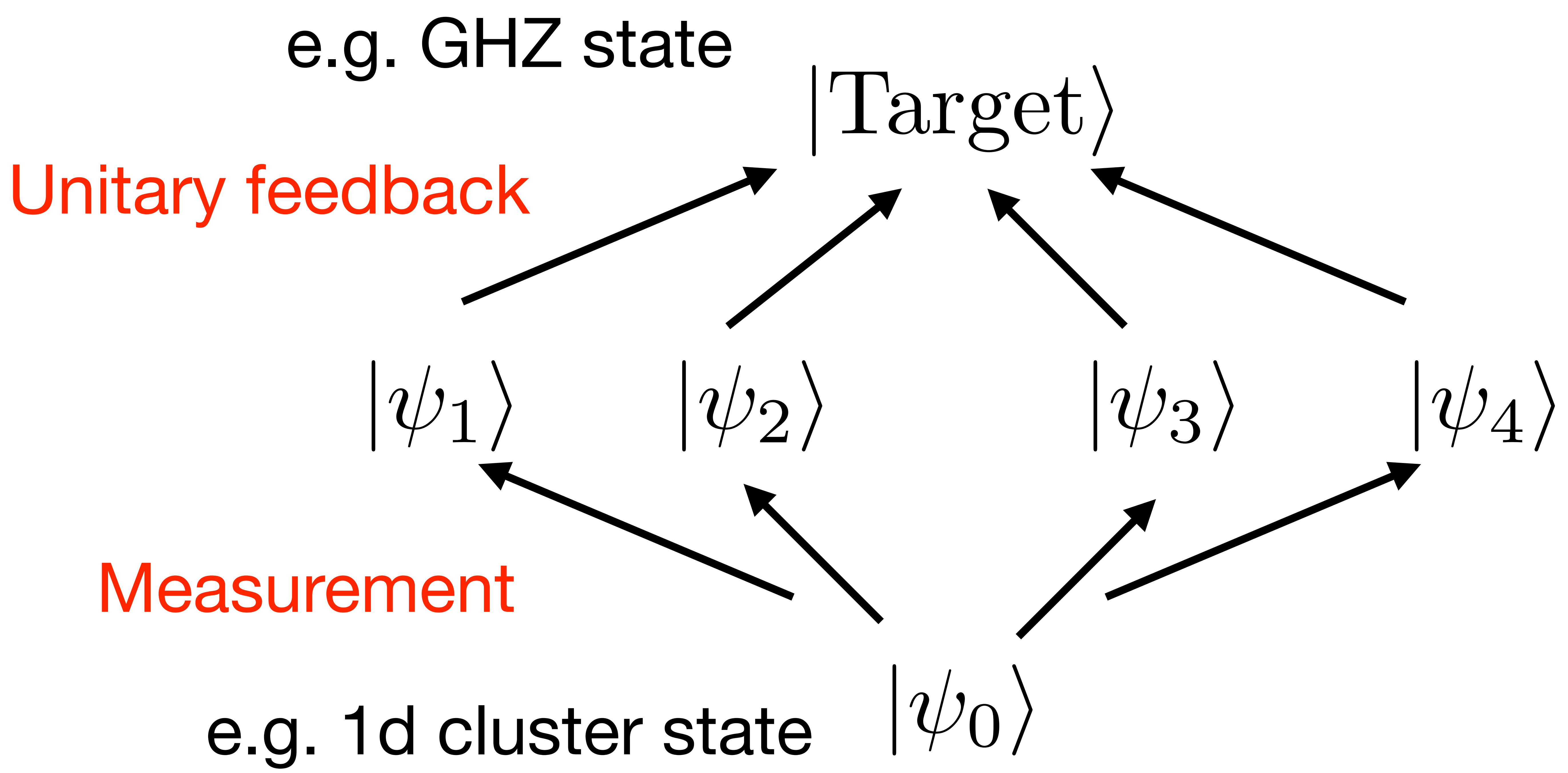

Fine-tuning required

When perturbing initial state, pure-state trajectories may not converge

→ Realizing a mixed state ρ

Long-range entangled?

This talk

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

Simple pure states

e.g. short-range entangled

—— O(1)-depth channel ——→

Non-trivial (LRE) mixed states

Quantum order/criticality coexisting with classical fluctuations

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e.g. short-range entangled

O(1)-depth channel →

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In contrast

$$\rho \sim e^{-\beta H}$$

Typically short-range entangled

e.g. 2d toric code, Hastings (2011)

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Route to non-trivial mixed-state phases of matter

Recent interest:
(pure) many-body states (e.g. SPT, topological order) under decoherence

de Groot, Turzillo, Schuch (2022); Lee, You, Xu (2022);
Zhang, Qi, Bi (2022); Ma, Wang (2022); Fan, Bao, Altman, Vishwanath (2023) …

This talk

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

Simple pure states e.g. short-range entangled	O(1)-depth channel →	Non-trivial (LRE) mixed states Quantum order/criticality coexisting with classical fluctuations

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

Z_2 x Z_2 SPT order (symmetry-protected topological) → Z_2 long-range (topological) order

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

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

Emergence of order/criticality is a **universal** property of the input phase hence demonstrating robustness

Application with SPT

G - SPT
(Symmetry Protected Topological)

constant-depth
⟷
unitary circuit

Product states

Only when the gates breaks G symmetry

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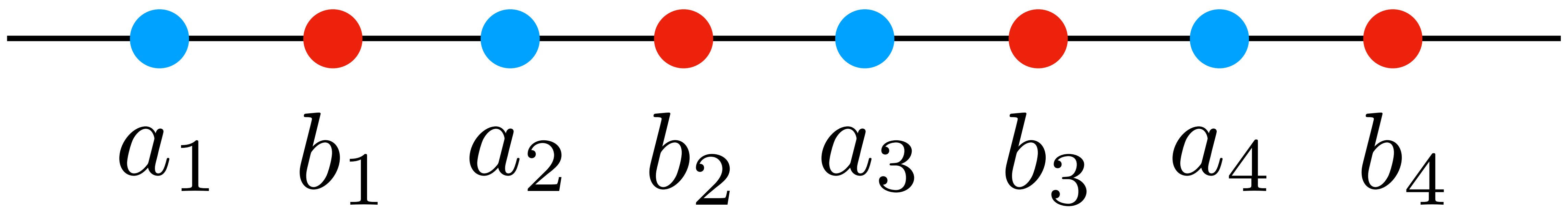
$G = Z_2 \times Z_2$
Cluster-state SPT



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

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

Application with SPT

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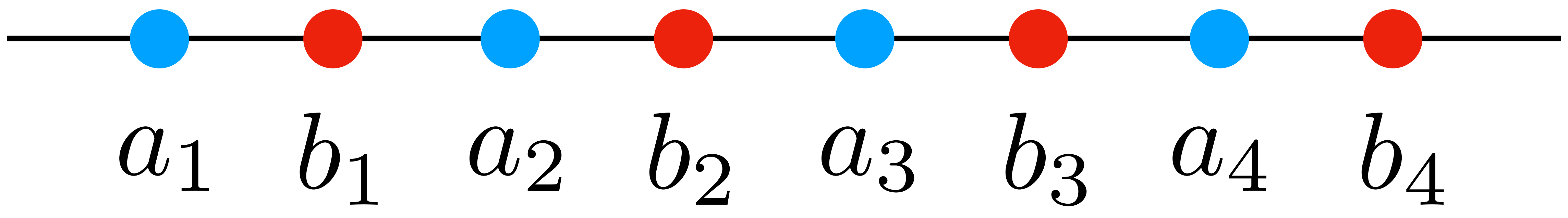

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Symmetry $\prod_i X_{a,i} \quad \prod_i X_{b,i}$

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

See e.g. Pollmann,Turner (2012)

Application with SPT

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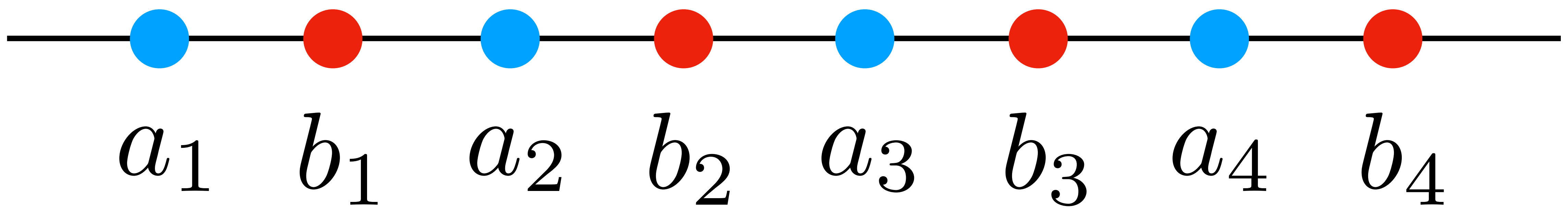
constant-depth ⟷ unitary circuit

Product states

Only when the gates breaks G symmetry

G = Z_2 x Z_2

Cluster-state SPT



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

$$-g\sum_i O_i$$

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

See e.g. Pollmann,Turner (2012)

Application with SPT

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

SPT $|\psi_0\rangle$

↓

(GHZ-like) mixed state

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

e.g. GHZ state $|000...\rangle + |111...\rangle$

$c = 1$

Application with SPT

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Precise meaning of non-trivial (LRE) mixed state Hastings, PRL (2011)

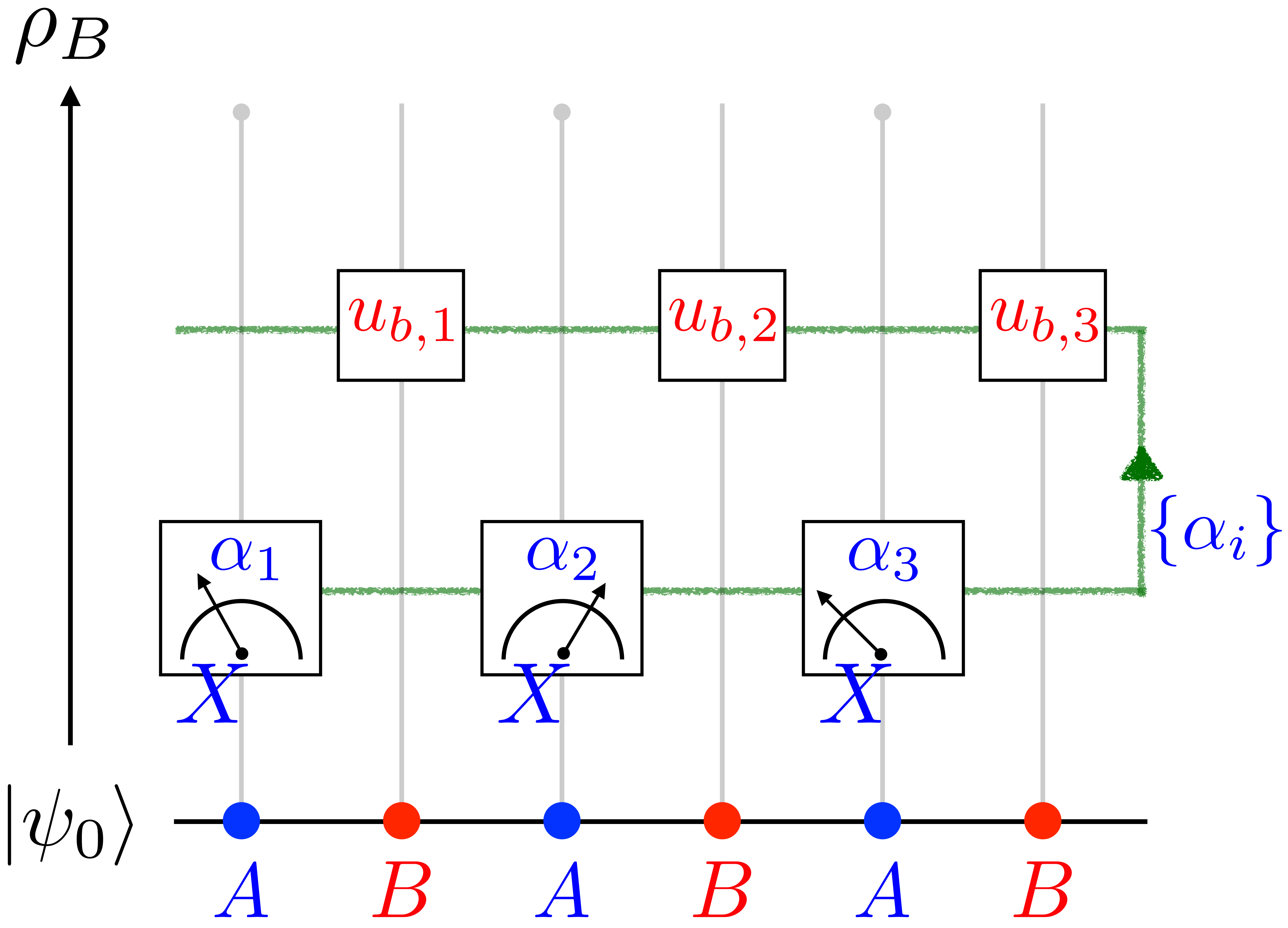
$$\rho_B \neq \sum_n p_n |\mathrm{SRE}_n\rangle\langle \mathrm{SRE}_n|$$

$|\mathrm{SRE}_n\rangle$ is connected to $\uparrow\uparrow\uparrow\uparrow \ldots$ using local unitary in constant time

Depth-2 protocol

Mixed-state ensemble

$$\left\{ p_\alpha, |\psi_\alpha\rangle = \frac{U_\alpha P_\alpha |\psi_0\rangle}{\sqrt{\langle\psi_0|P_\alpha|\psi_0\rangle}} \right\}$$



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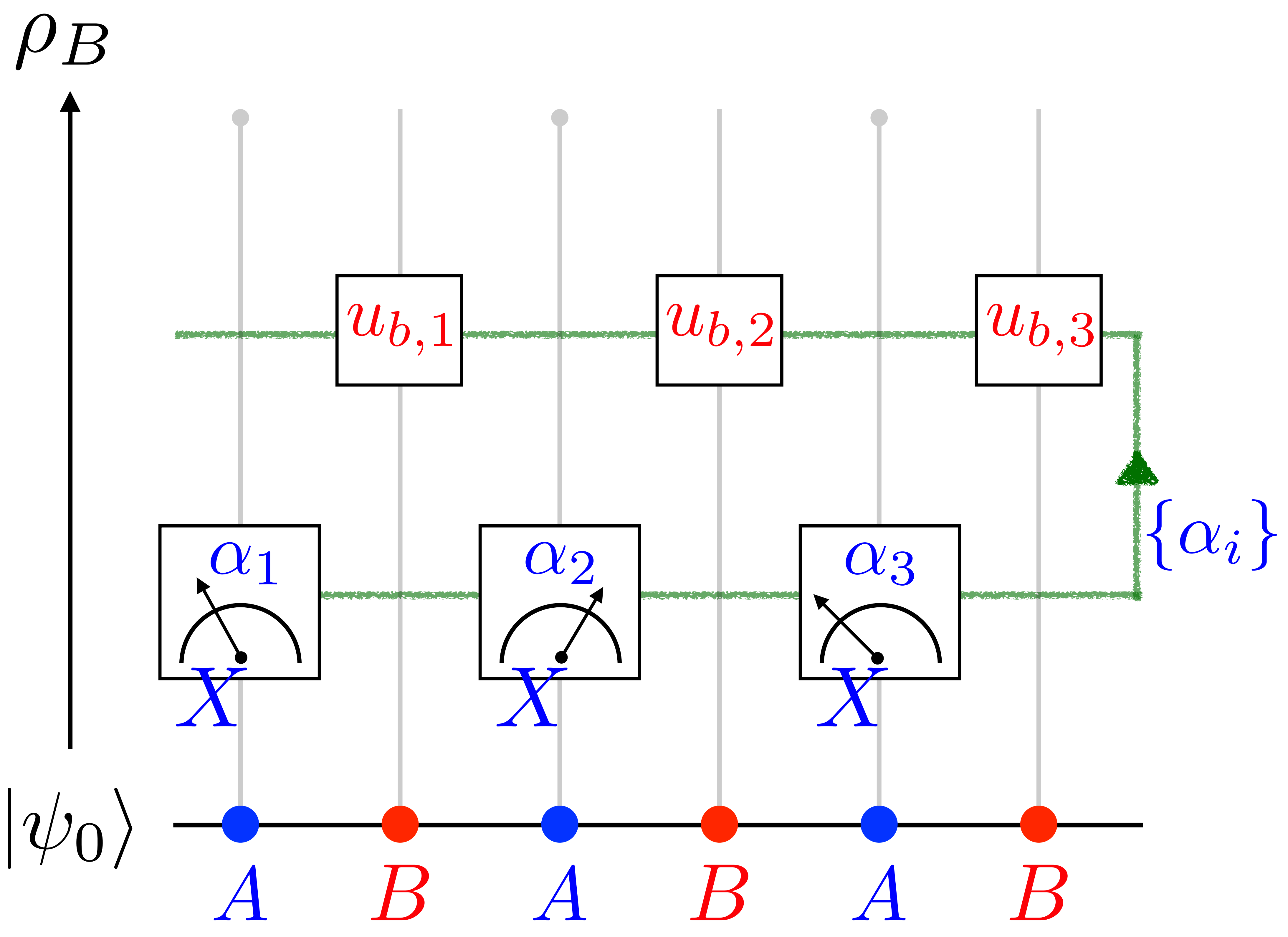

$$\rho_B = \mathrm{tr}_A \left(|\psi\rangle\langle\psi| \right)$$

Purification $|\psi\rangle = \sum_\alpha U_\alpha P_\alpha |\psi_0\rangle$

A controlled unitary U

cannot be realized using finite-depth unitary circuits

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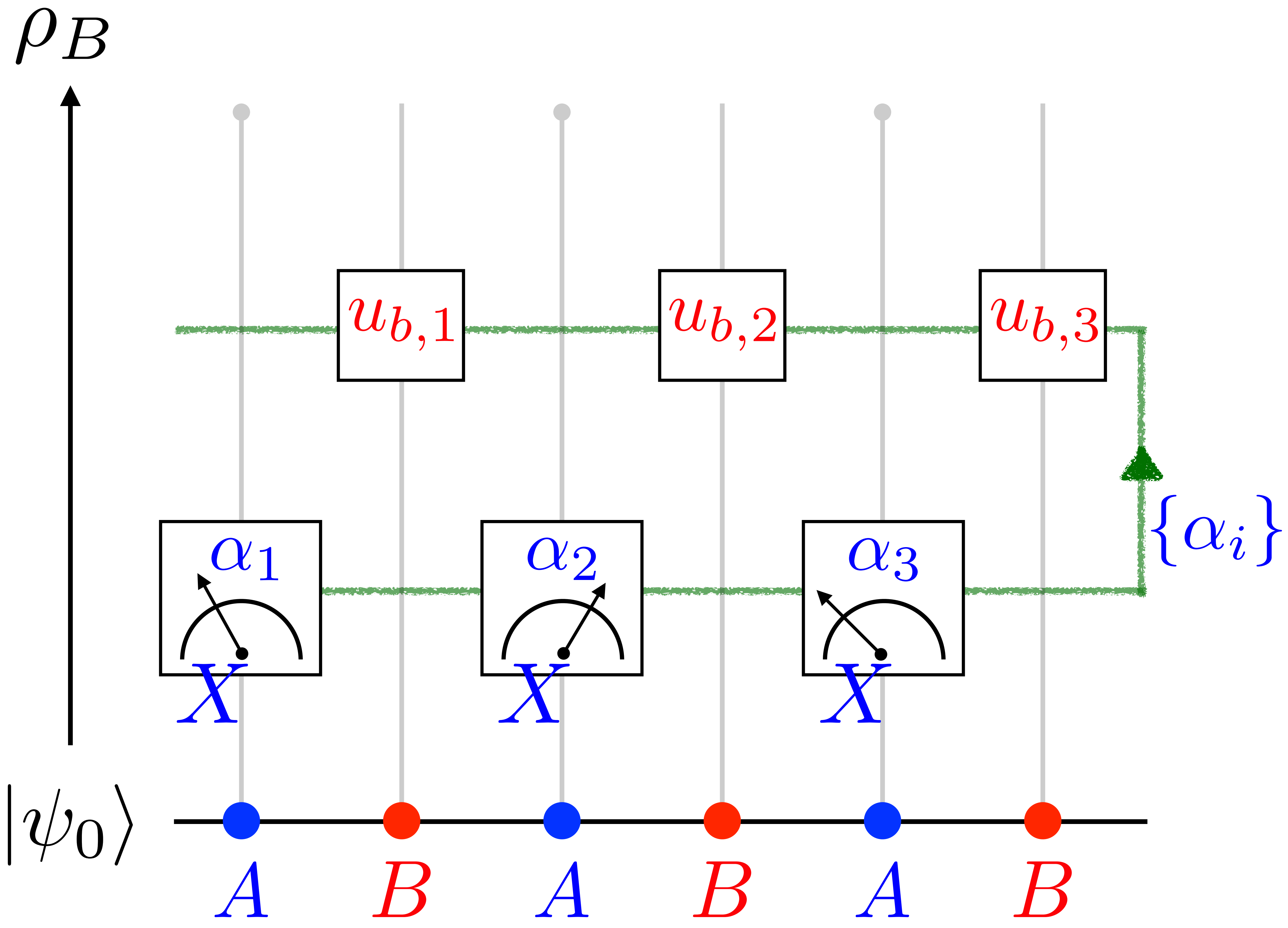

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A controlled unitary U

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

$$U_\alpha^\dagger Z_{b,i} U_\alpha = (\alpha_1\alpha_2\cdots\alpha_i) Z_{b,i}$$

Depth-2 protocol

Mixed-state ensemble

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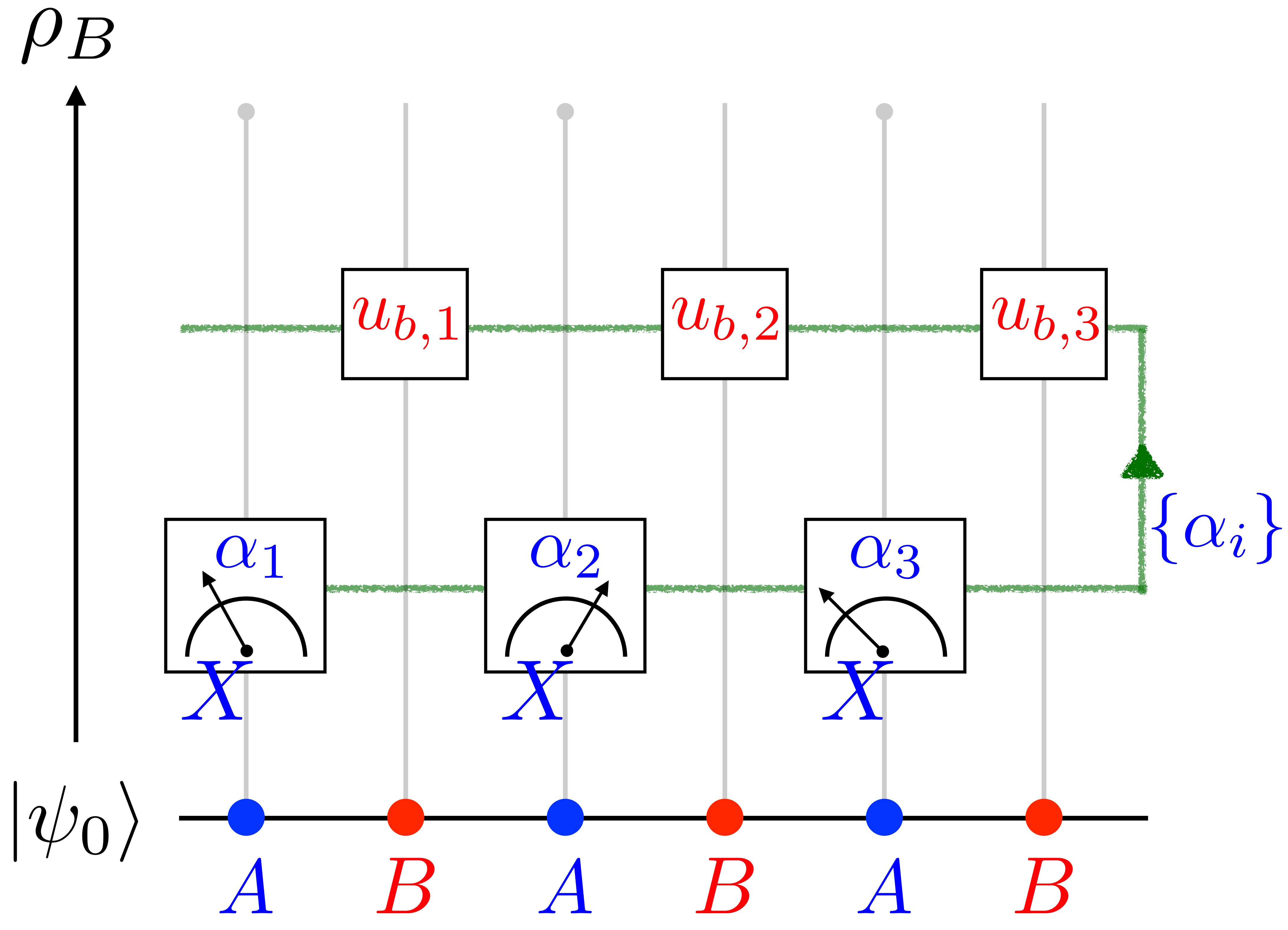

$$\rho_B = \mathrm{tr}_A \left(|\psi\rangle\langle\psi| \right)$$

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

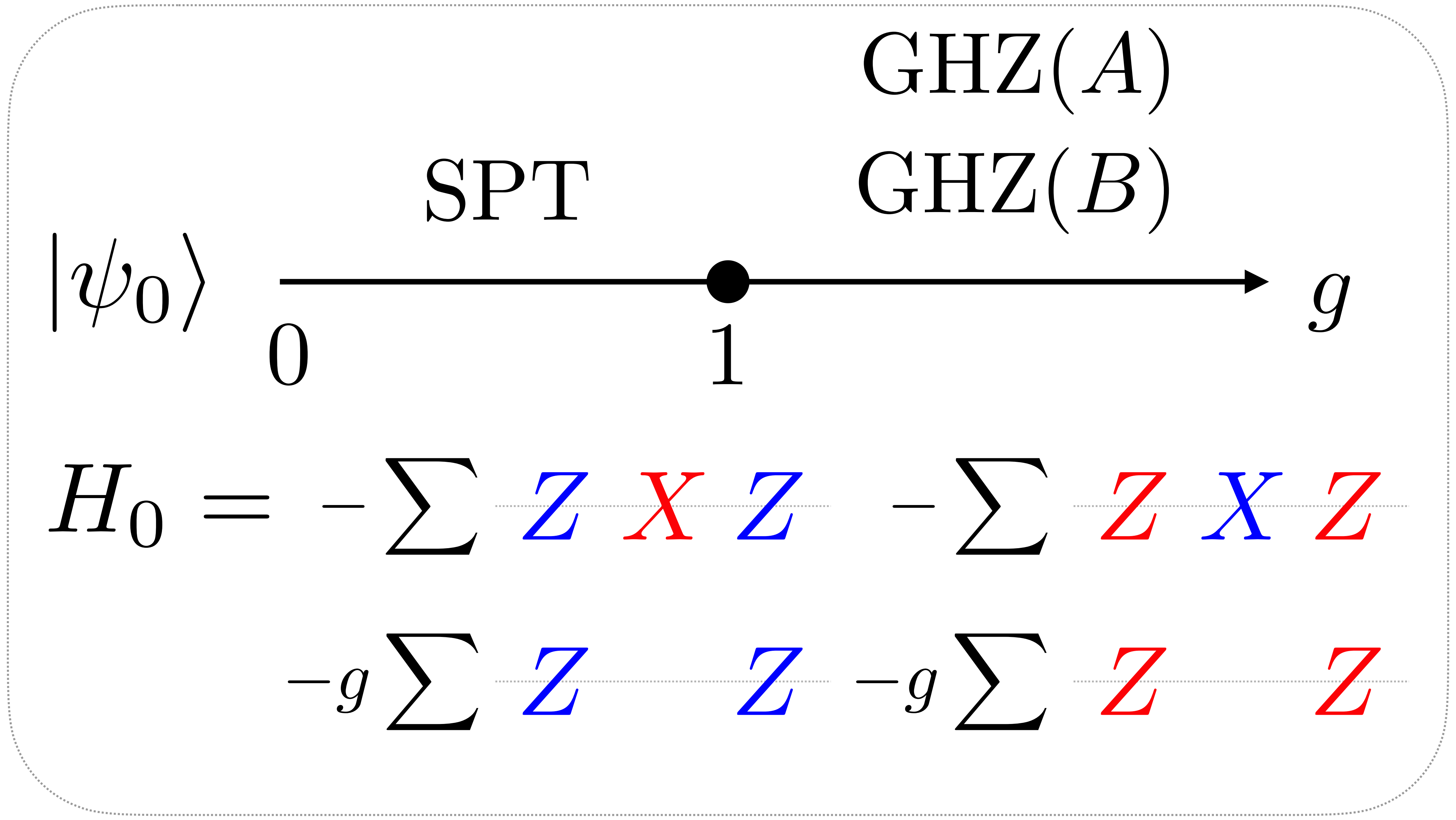
$$U_\alpha^\dagger Z_{b,i} U_\alpha = (\alpha_1 \alpha_2 \cdots \alpha_i) Z_{b,i}$$

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

Hidden string order -> long-range order

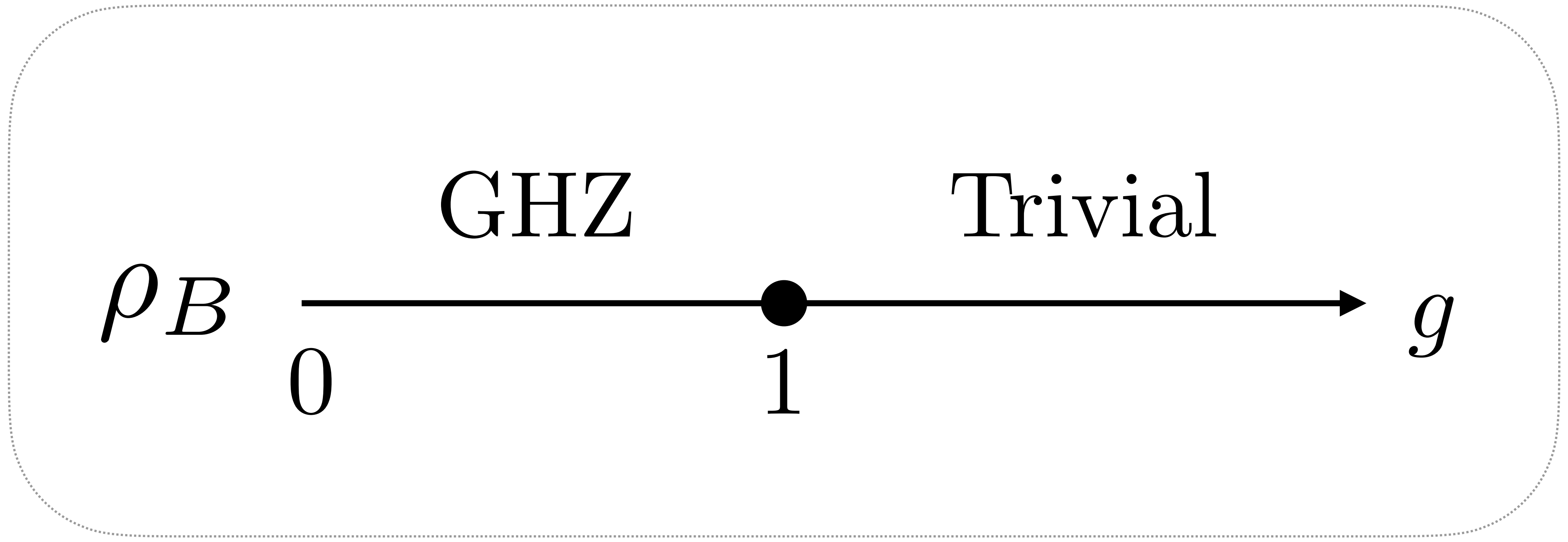

GHZ(A)
GHZ(B)
SPT
|ψ0⟩
0
1
g
H0 = −∑ Z X Z −∑ Z X Z
−g∑ Z Z −g∑ Z Z
Measurement
+ Feedback
GHZ
Trivial
ρB
0
1
g

GHZ(A)
GHZ(B)
SPT
$|\psi_0\rangle$
0
1
g
$H_0 = -\sum ZXZ \quad -\sum ZXZ$
$-g\sum Z \quad Z \quad -g\sum Z \quad Z$
Measurement
+ Feedback
ρ_B
GHZ
Trivial
Purification
Controlled unitary
$U = \sum_\alpha U_\alpha P_\alpha$
$|\psi\rangle$
$H = -\sum Z \quad Z \quad -\sum Z \quad Z$
$-g\sum ZXZ \quad -g\sum ZXZ$



Measurement

+ Feedback



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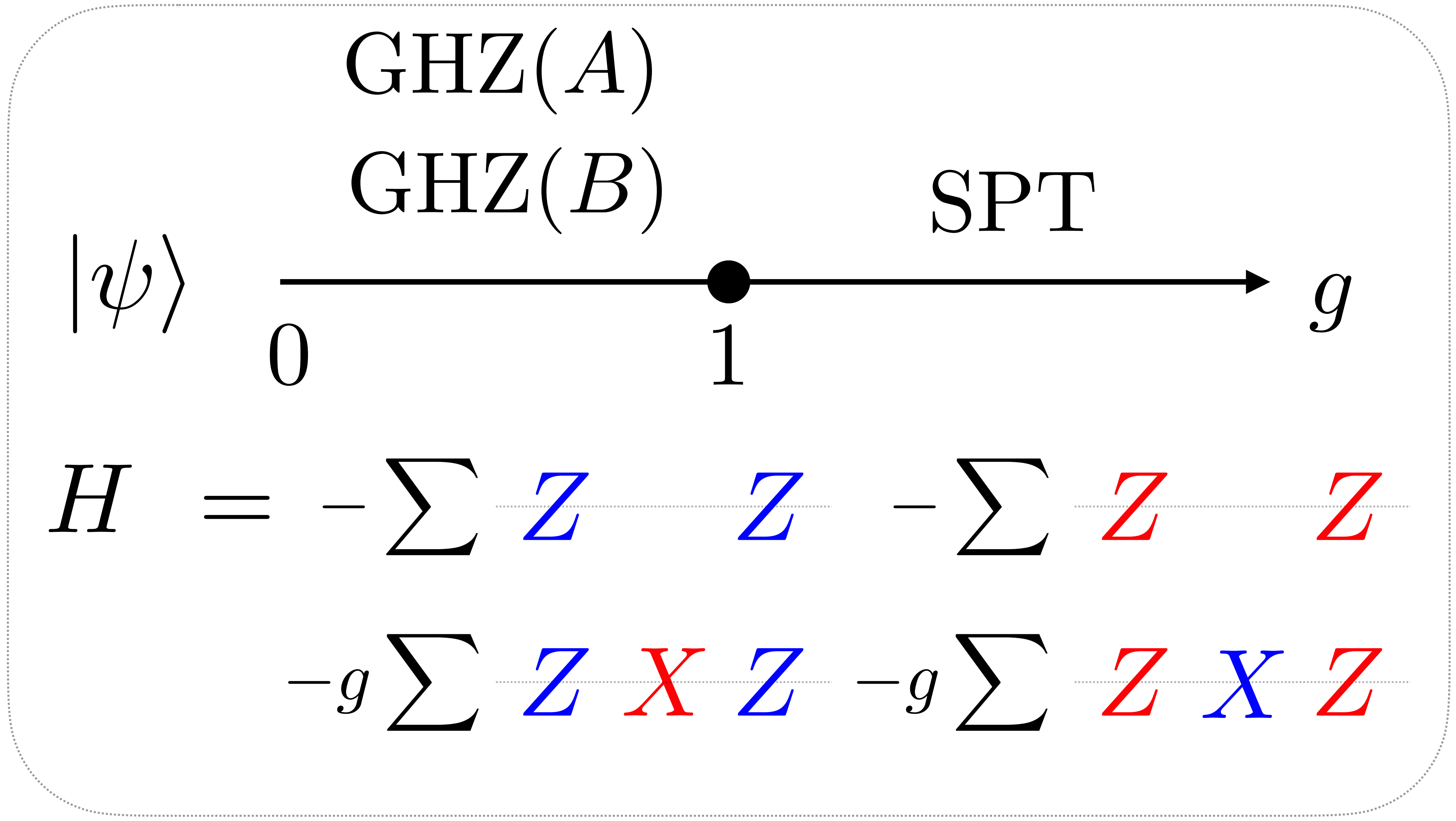
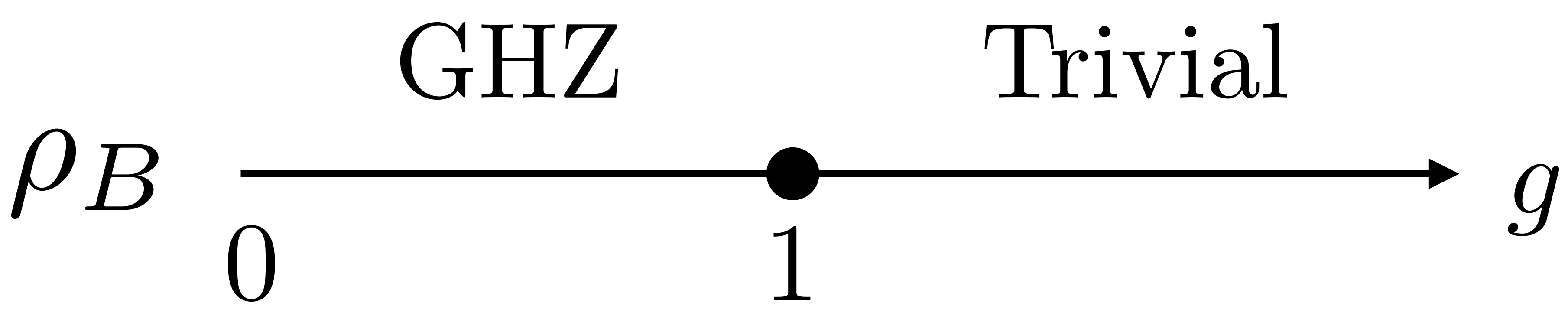


Kennedy-Tasaki transformation (1992)

Haldane SPT -> 2 Z_2 long-range order

More recent refs: Li, Oshikawa, Zheng (2023)

Mixed-state quantum criticality (g=1)



Order operator

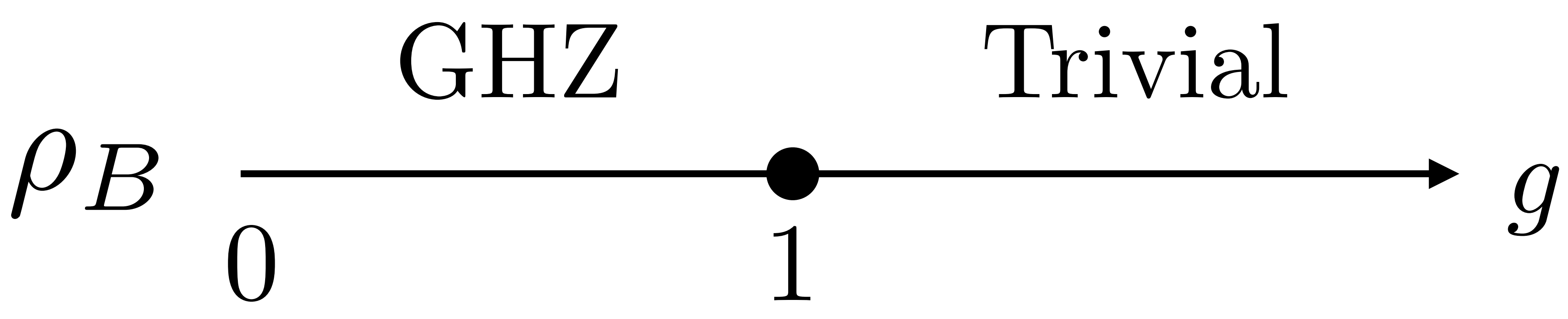
$$\langle Z_{b,i} Z_{b,j} \rangle \sim \frac{1}{|i-j|^{\eta}}$$

Disorder operator

$$\langle X_{b,i} X_{b,i+1} \ldots X_{b,j} \rangle \sim \frac{1}{|i-j|^{2\eta}}$$

twice of Ising CFT

Mixed-state quantum criticality (g=1)



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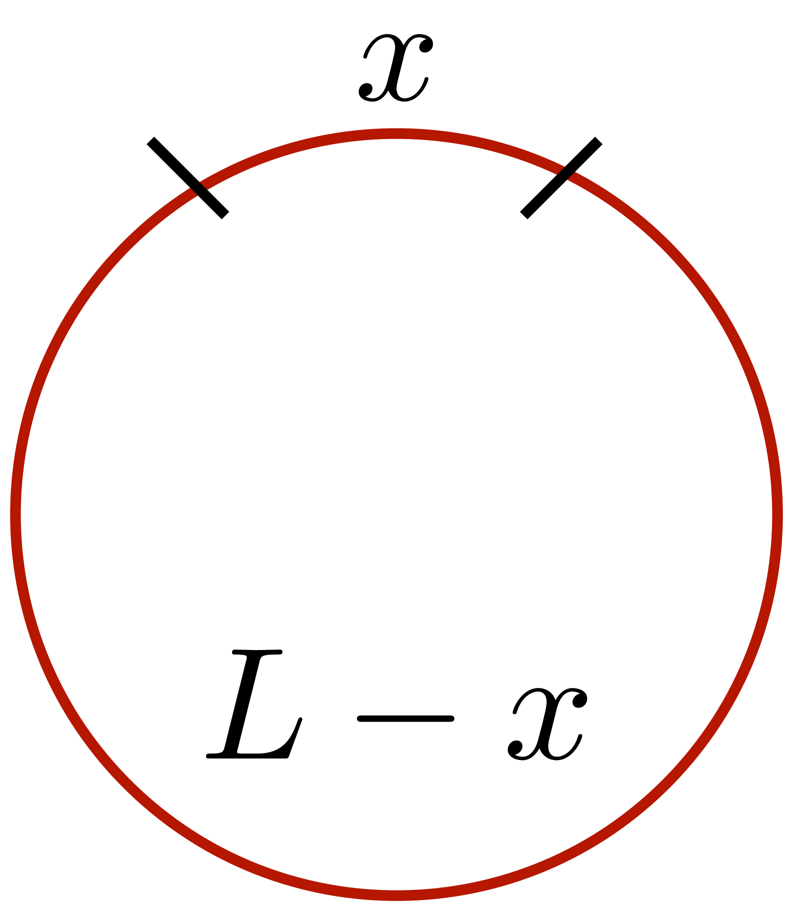
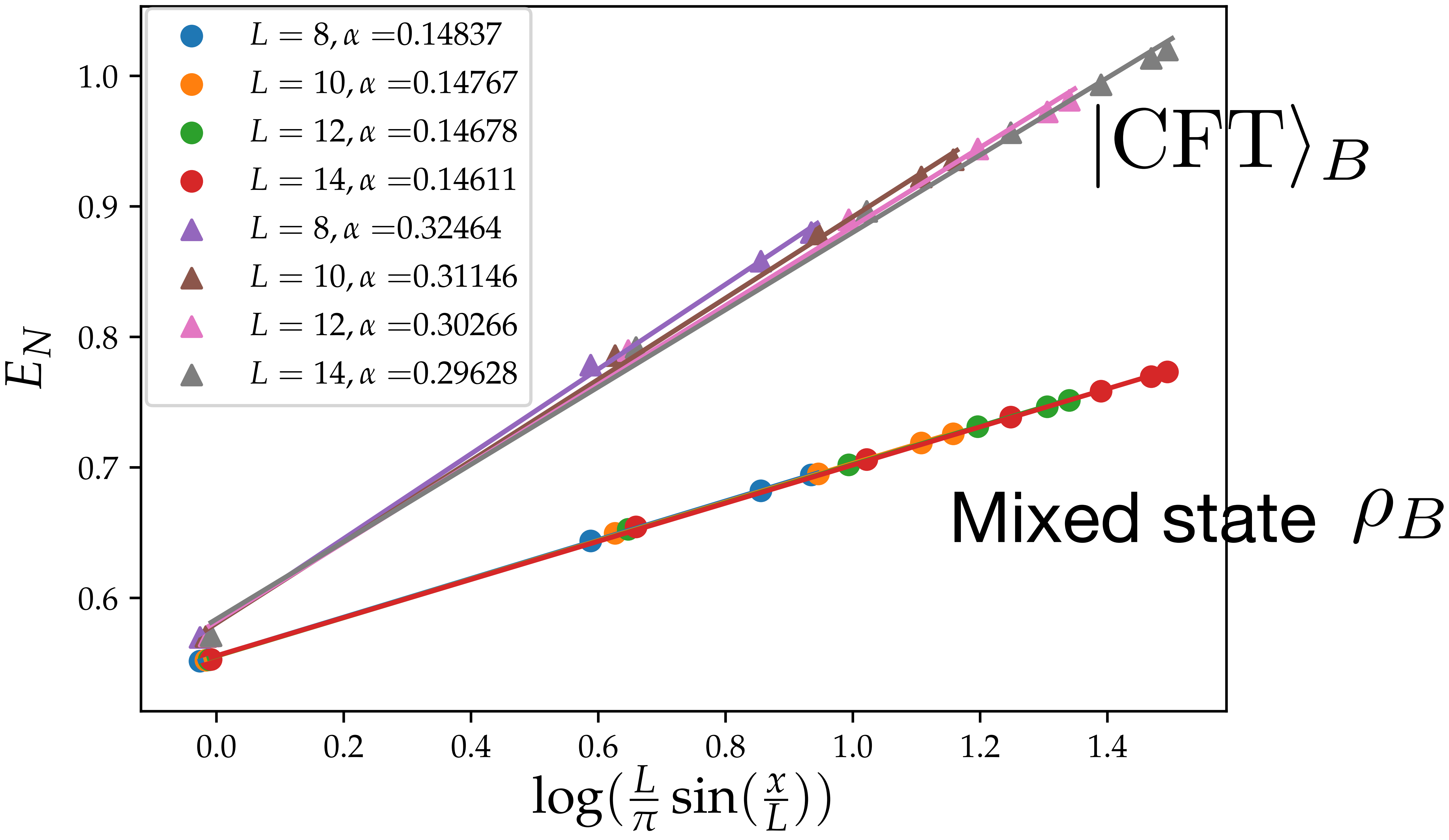
twice of Ising CFT

B sublattice



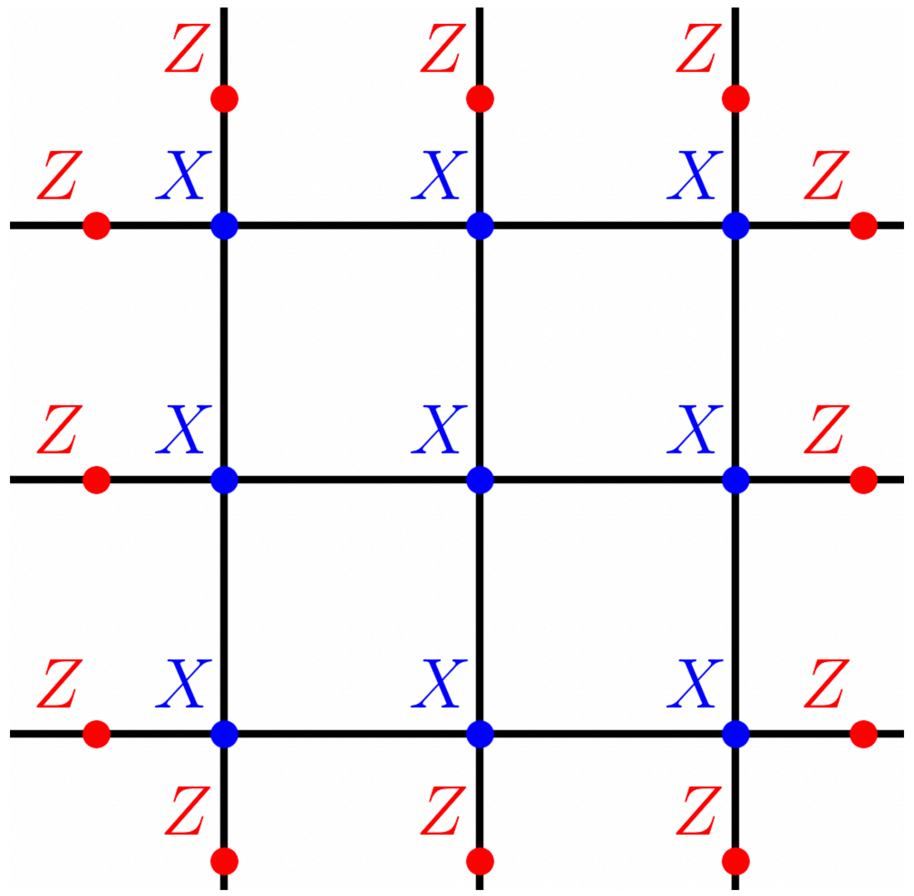


Mixed-state entanglement (Entanglement negativity) Vidal, Werner (2001)

$$E_N(\alpha, \beta) = \alpha \log\left[\frac{L}{\pi}\sin\left(\frac{\pi x}{L}\right)\right] + \beta$$

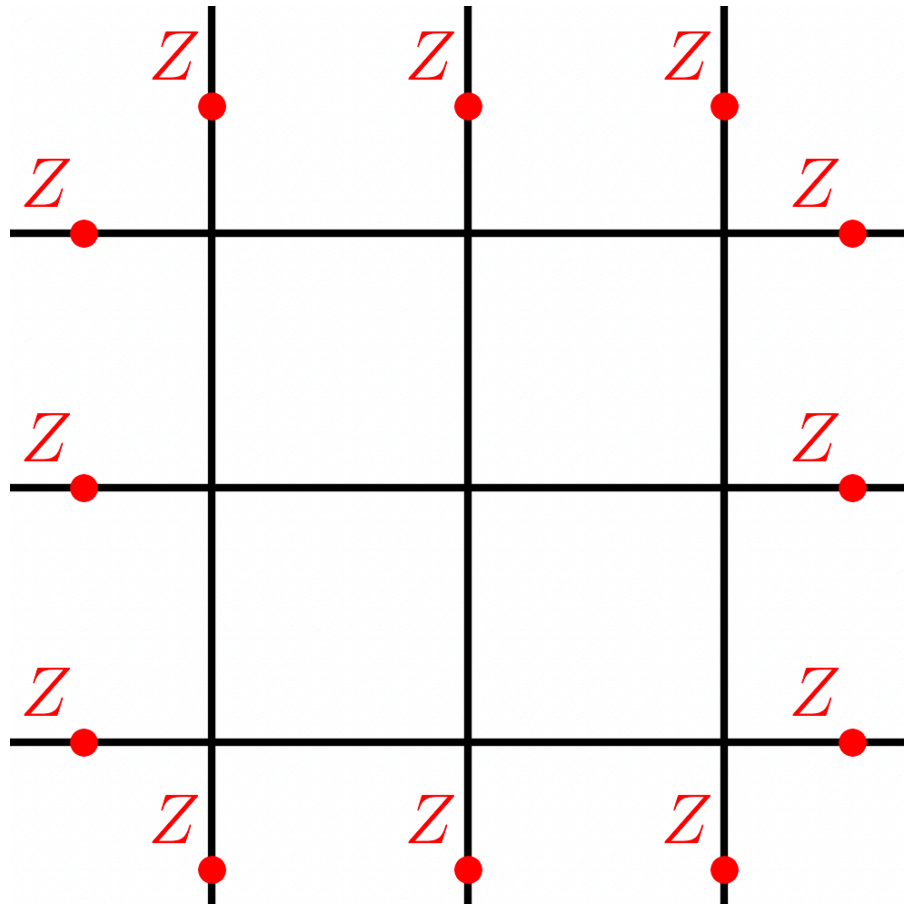
Generalization

Higher-dim.
$\mathbb{Z}_2$ q-form x $\mathbb{Z}_2$ p-form **SPTs** → Mixed-state $\mathbb{Z}_2$ **Topological Order**



Perimeter Law

$$\sim e^{-c|\tilde{\gamma}|}$$



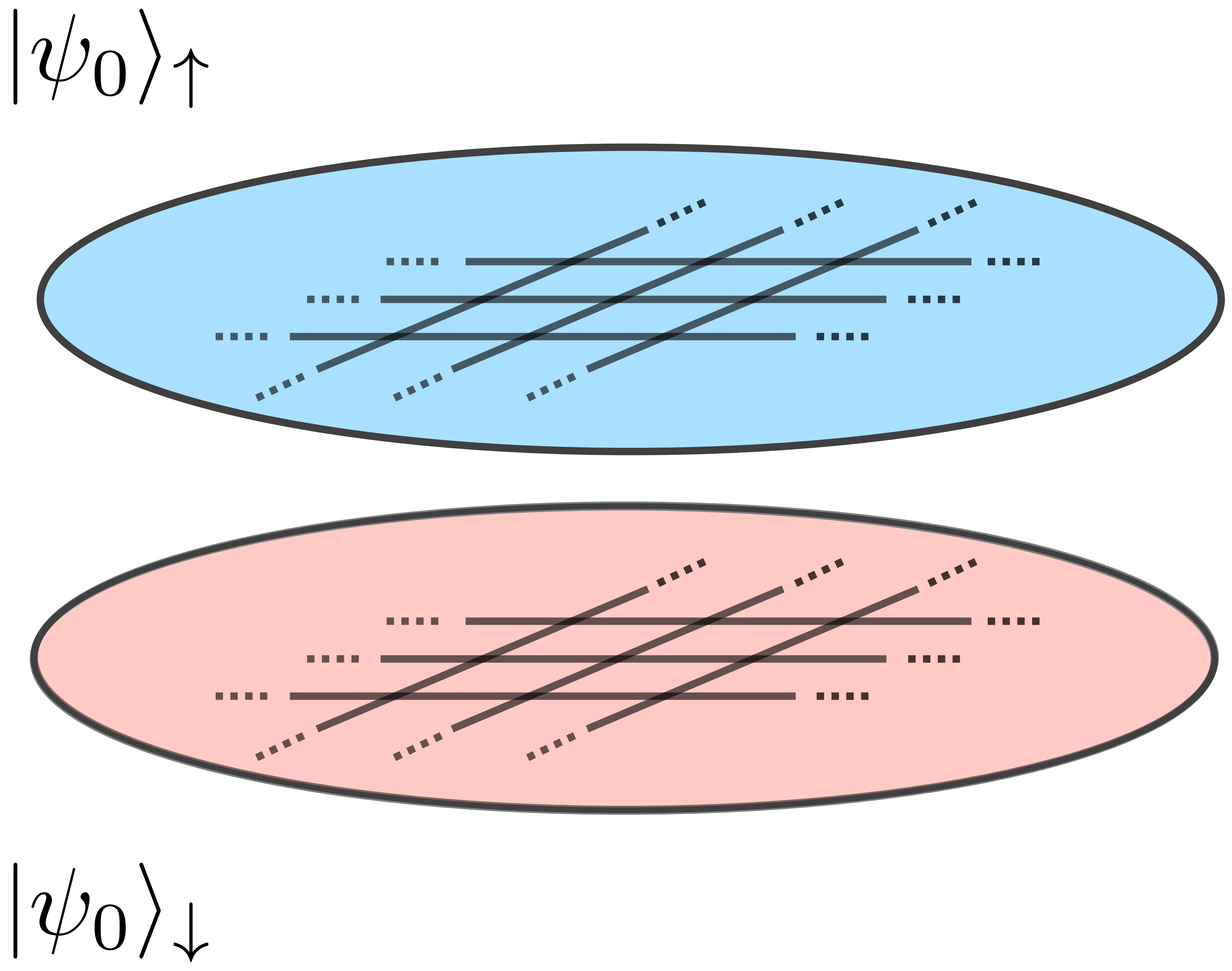
Perimeter Law

$$\sim e^{-c|\tilde{\gamma}|}$$

(Generalize to abelian G x H symmetry)

Adaptive protocol by measuring **fermions**

Motivated from Gutzwiller projection (1963)

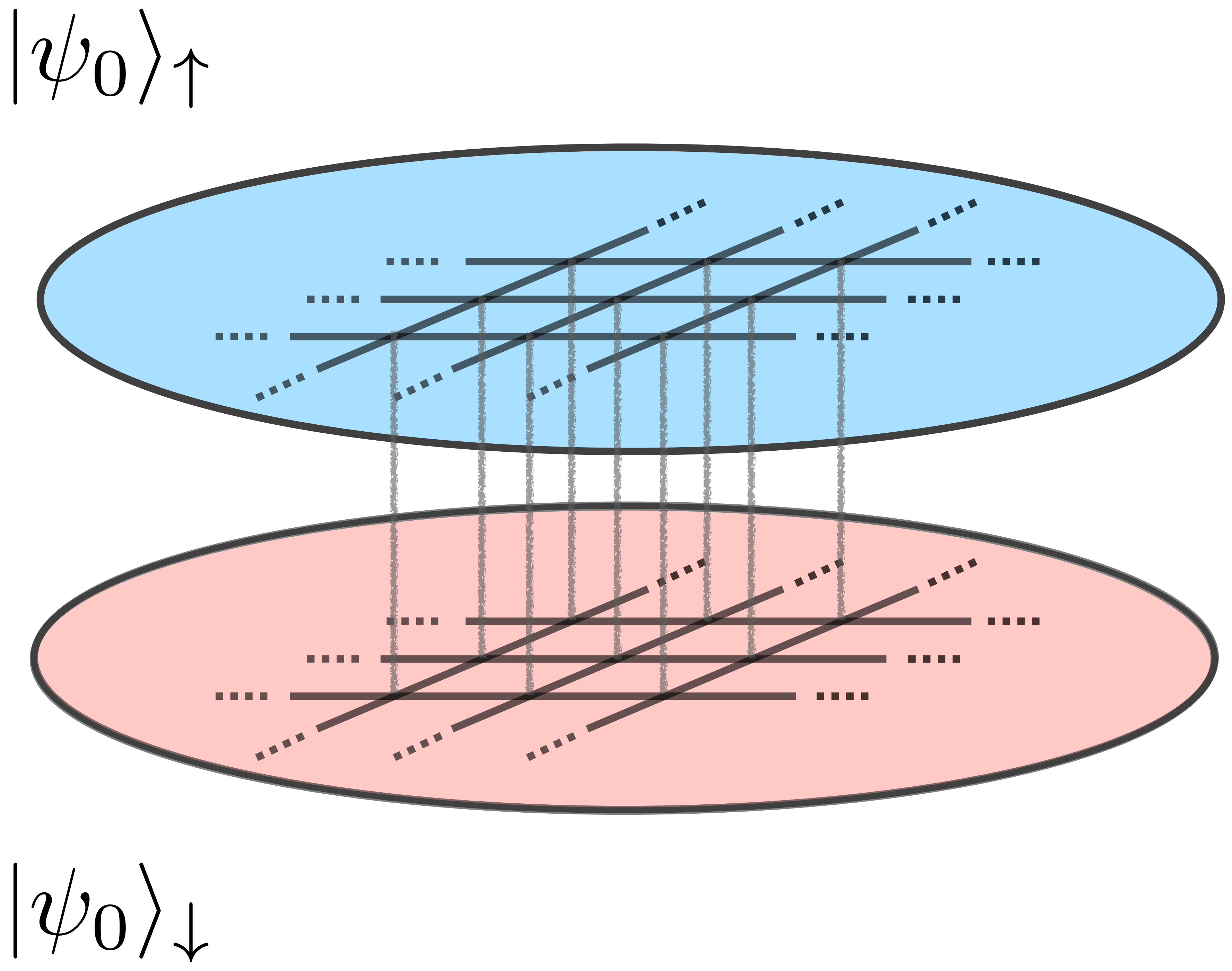


Free fermion (Gaussian state)

$$|\psi_{0,\uparrow}\rangle \otimes |\psi_{0,\downarrow}\rangle$$

Adaptive protocol by measuring fermions

Motivated from Gutzwiller projection (1963)



Free fermion (Gaussian state)

$$|\psi_{0,\uparrow}\rangle \otimes |\psi_{0,\downarrow}\rangle$$

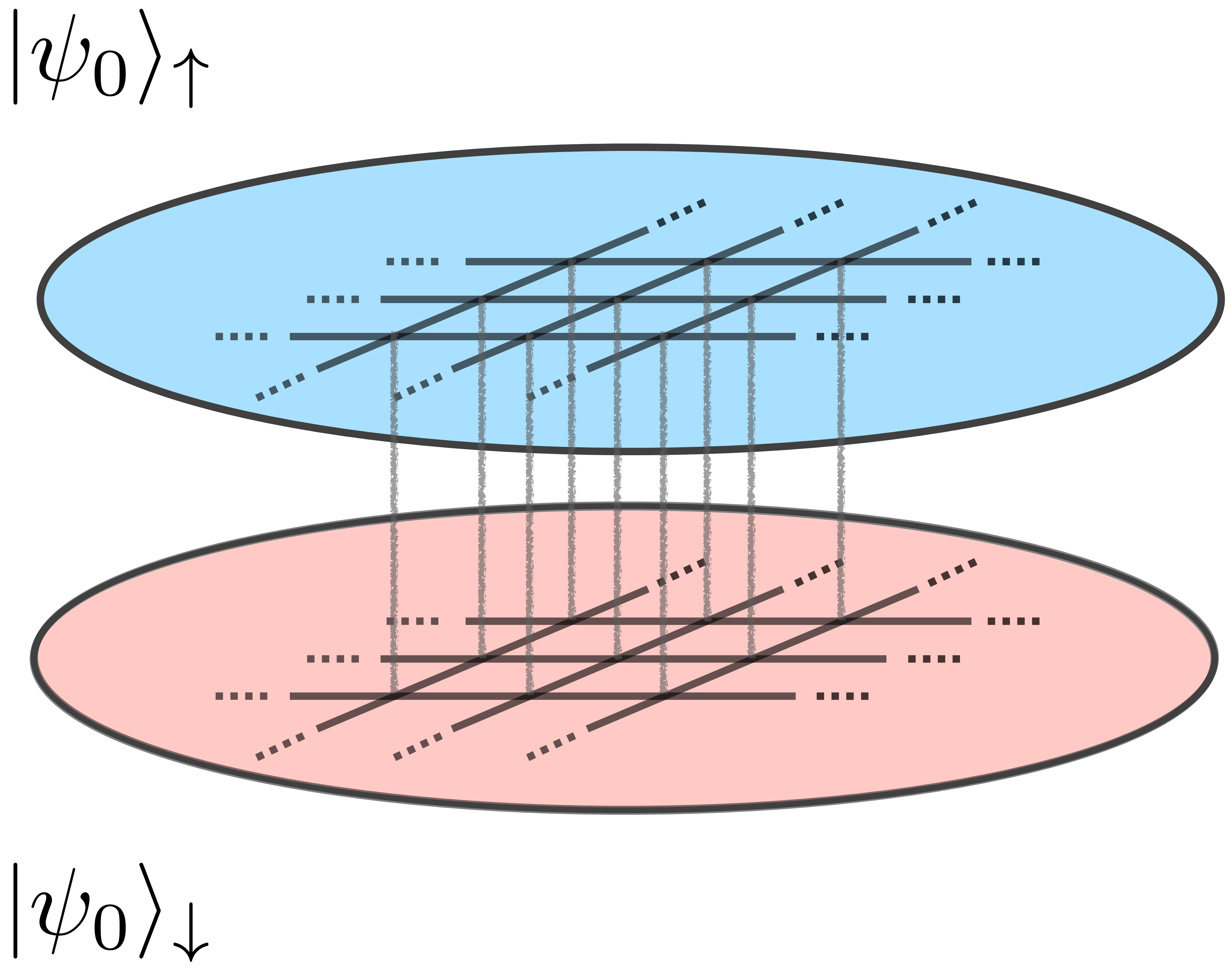
$$|\psi_g\rangle = P_g|\psi_{0,\uparrow}\rangle \otimes |\psi_{0,\downarrow}\rangle$$

↓

Projecting to
single-occupation per site

Adaptive protocol by measuring fermions

Motivated from Gutzwiller projection (1963)



Free fermion (Gaussian state)

$$|\psi_{0,\uparrow}\rangle \otimes |\psi_{0,\downarrow}\rangle$$

$$|\psi_g\rangle = P_g|\psi_{0,\uparrow}\rangle \otimes |\psi_{0,\downarrow}\rangle$$

↓

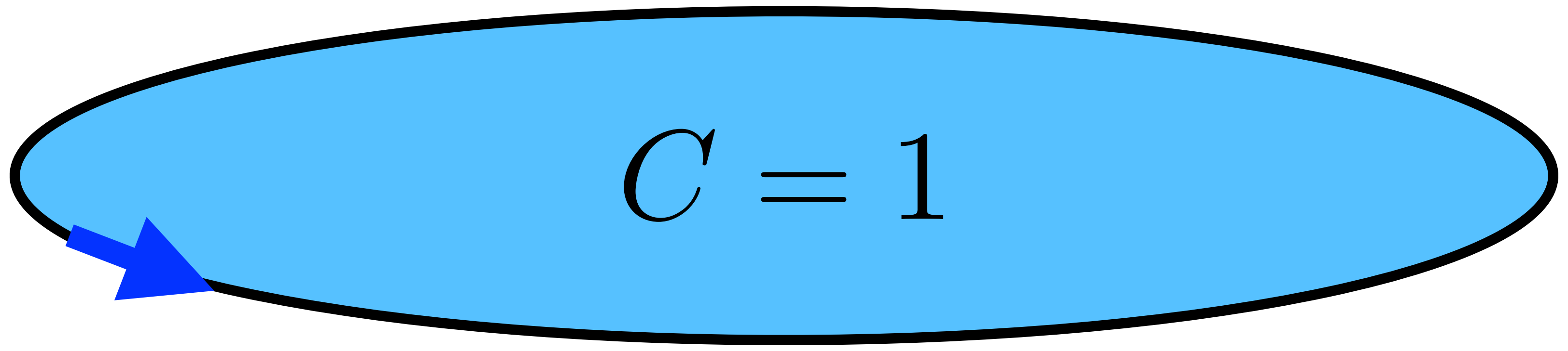
Projecting to
single-occupation per site

Gutzwiller projection by measuring fermion number?

Cannot control the measurement outcome

Mixed-state quantum criticality from gapped states of matter

2d Chern insulators   Review: Hasan, Kane (2010)



$|\psi_0\rangle$

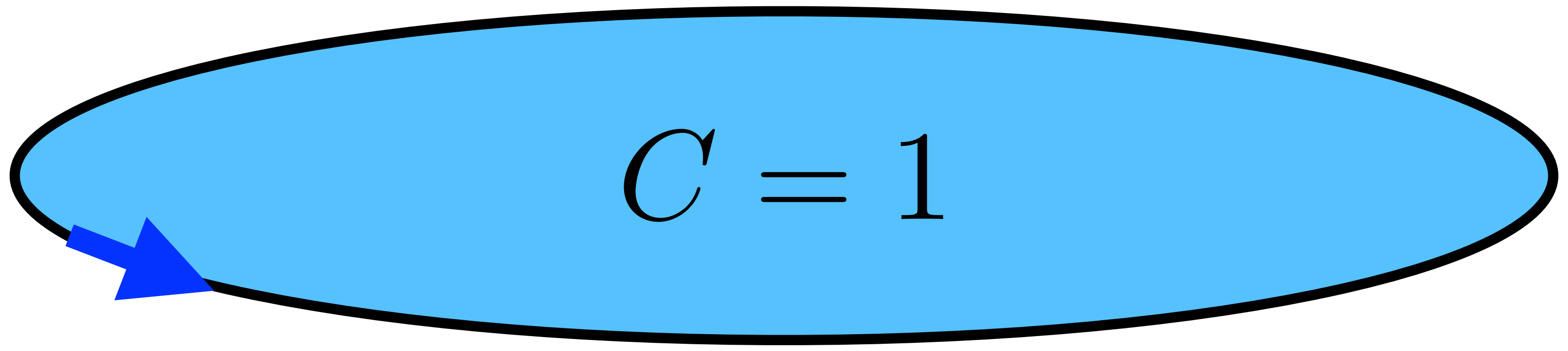
Chiral current

Trivial bulk correlation

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

Mixed-state quantum criticality from gapped states of matter

2d Chern insulators



$|\psi_0\rangle$

Chiral current

Trivial bulk correlation

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Off-diagonal long-range order

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

Flux attachment - > bosons

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

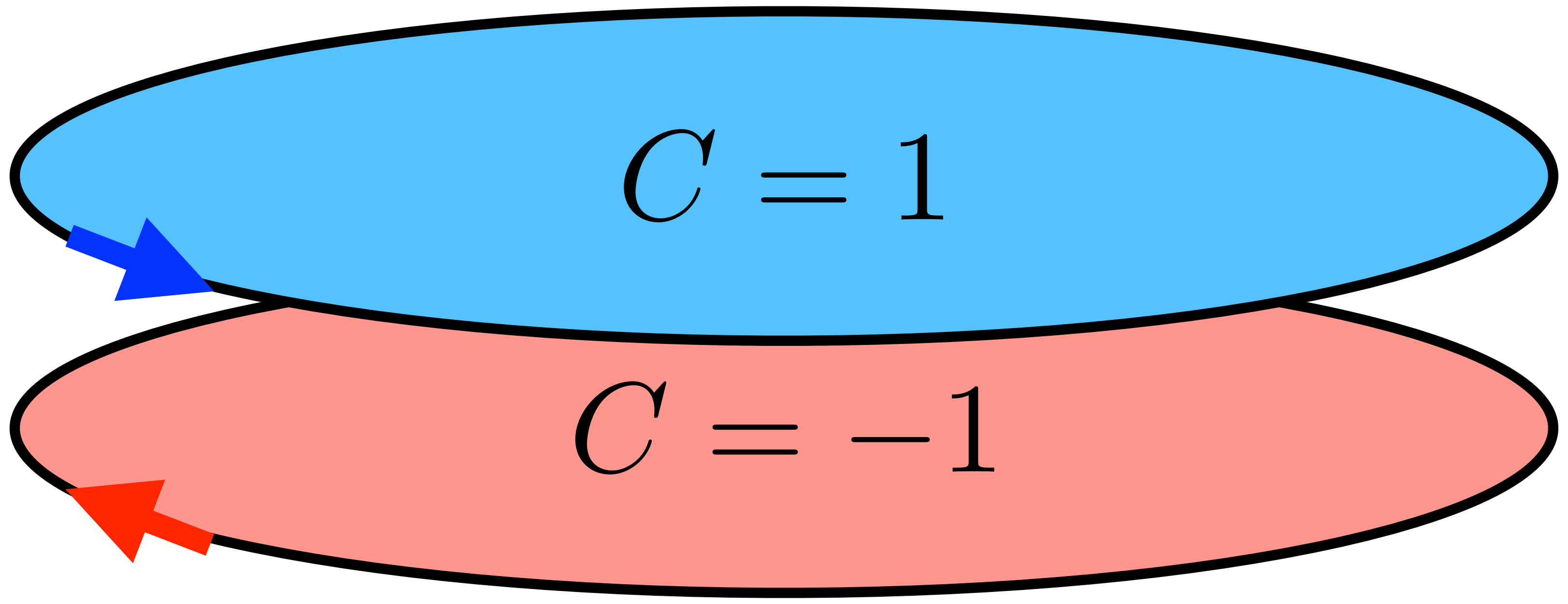
$$\eta(\mathbf{x}) = e^{i\int d^2x'\hat{n}(\mathbf{x}')\mathrm{arg}(\mathbf{x}-\mathbf{x}')}$$

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

Flux attachment from measurement + feedback !

Mixed-state quantum criticality from gapped states of matter

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



$$S^+(\mathbf{x}) = c^\dagger_\uparrow(\mathbf{x})c_\downarrow(\mathbf{x})$$

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

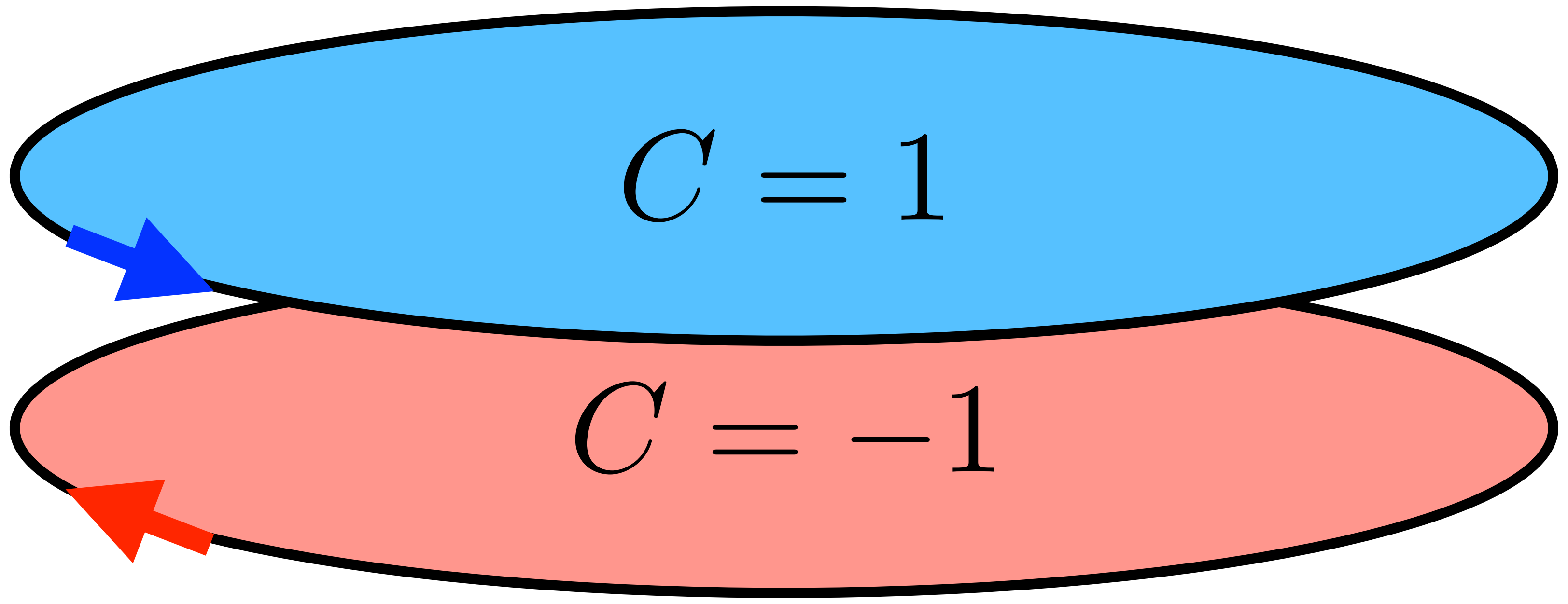
$$\hat{\phi}_\downarrow(\mathbf{x}) = -\int d^2x'\hat{n}_\downarrow(\mathbf{x}')\arg(\mathbf{x}-\mathbf{x}')$$

$$\langle\psi_0|\underline{e^{i[\hat{\phi}_\uparrow(\mathbf{x})-\hat{\phi}_\downarrow(\mathbf{x})]}S^+(\mathbf{x})S^-(\mathbf{x}')e^{-i[\hat{\phi}_\uparrow(\mathbf{x}')-\hat{\phi}_\downarrow(\mathbf{x}')]}}|\psi_0\rangle$$

$$\sim \langle\psi_0|_\uparrow\tilde{c}_\uparrow(\mathbf{x}')\tilde{c}^\dagger_\uparrow(\mathbf{x})|\psi_0\rangle_\uparrow\langle\psi_0|_\downarrow\tilde{c}_\downarrow(\mathbf{x})\tilde{c}^\dagger_\downarrow(\mathbf{x}')|\psi_0\rangle_\downarrow \sim \frac{1}{|\mathbf{x}-\mathbf{x}'|^{2\alpha}}$$

Mixed-state quantum criticality from gapped states of matter

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



$|\psi_0\rangle_\uparrow$

$|\psi_0\rangle_\downarrow$

(1) measuring onsite fermion number

(2) unitary $n = \{n_1, n_2, \cdots\}$

$$U_n = \prod_{\mathbf{x}} e^{-i\phi(\mathbf{x})S^z(\mathbf{x}\ )}$$

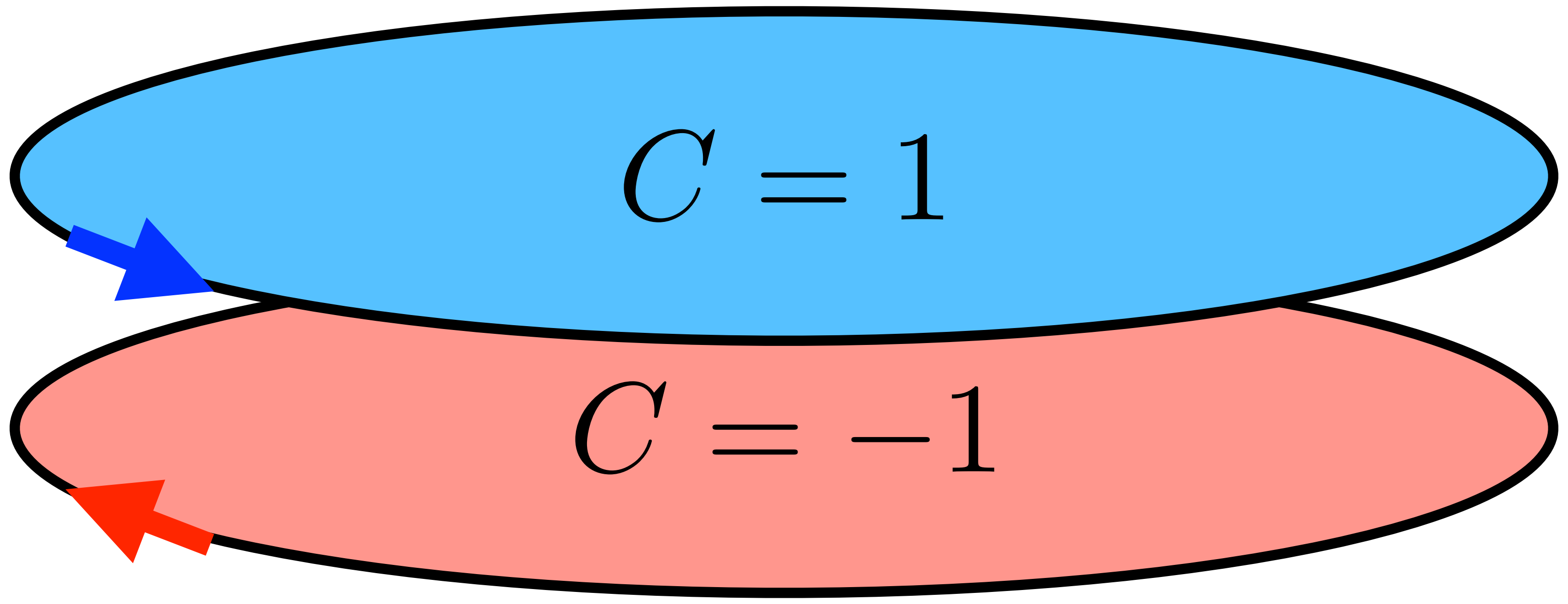
$$\phi(\mathbf{x}) = \sum_{\mathbf{x}'} n(\mathbf{x}')\arg(\mathbf{x}-\mathbf{x}')$$

$$U_n^\dagger S^+(\mathbf{x}) U_n = e^{i[\phi_\uparrow(\mathbf{x})-\phi_\downarrow(\mathbf{x})]} S^+(\mathbf{x})$$

$$U_n^\dagger S^-(\mathbf{x}') U_n = e^{-i[\phi_\uparrow(\mathbf{x}')-\phi_\downarrow(\mathbf{x}')]} S^-(\mathbf{x}')$$

Mixed-state quantum criticality from gapped states of matter

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



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$$e^{i[\hat{\phi}_\uparrow(\mathbf{x}) - \hat{\phi}_\downarrow(\mathbf{x})]} S^+(\mathbf{x}) S^-(\mathbf{x}') e^{-i[\hat{\phi}_\uparrow(\mathbf{x}') - \hat{\phi}_\downarrow(\mathbf{x}')]}$$

↓

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

Summary - adaptive protocol

Measurement + feedback unitary + classical communication

—> efficient manipulation of many-body states

Low-depth realization of mixed-state order and criticality

Pure		**Mixed**
$Z_2 \times Z_2$ SPT	———>	Long-range (topological) order
Gapped Chern insulator (exp. decaying correlation)	———>	Mixed-state quantum criticality (algebraic correlation)
1d fermion (algebraic correlation)	———>	1d fermion (enhanced algebraic correlation)

Summary - adaptive protocol

Measurement + feedback unitary + classical communication

—> efficient manipulation of many-body states

Low-depth realization of mixed-state order and criticality

Open questions

(1) Non-local transformation & flux attachment

More non-trivial orders/criticality?

(2) Limitations of measurement + feedback

(3) Mixed-state phases of matter - characterization & diagnostic