Laboratoire de Physique Théorique et Modèles Statistiques

Boundary transitions from a single round of measurements on gapless quantum states

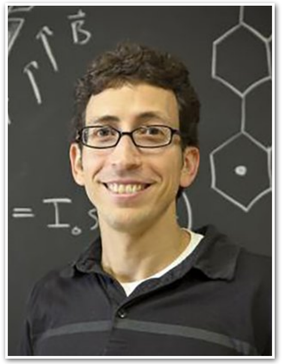
Sara Murciano

Workshop Interfaces & Symmetries, YITP

6 March 2026

Yue Liu

David Mross

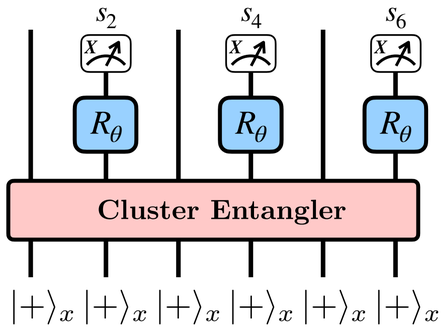


Jason Alicea

Phys. Rev. Research 7, 023293, 2025.

Measurement-generated novel quantum phenomena

Preparation of long-range entangled states from cluster state



Piroli, Styliaris, Cirac, Phys. Rev. Lett. 127, 220503 (2021).

Tantivasadakarn, Thorngren, Vishwanath, Verresen.
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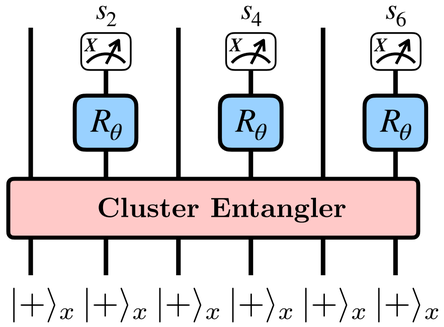

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Measurement-altered criticality

1D Tomonaga-Luttinger Liquids

Altered Correlations

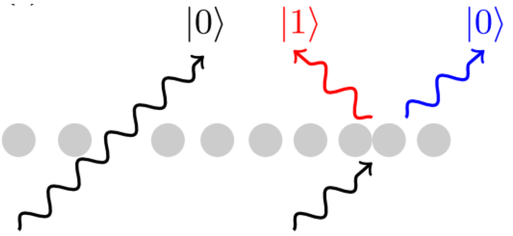
Measurements Conspire Nonlocally to Restructure Critical Quantum States

Samuel J. Garratt,[1] Zack Weinstein,[1] and Ehud Altman[1,2]

Altered Entanglement

New critical states induced by measurement

Xinyu Sun,[1] Hong Yao,[1,*] and Shao-Kai Jian[2,†]



Transverse-Field Ising Model

Nonlocality and entanglement in measured critical quantum Ising chains

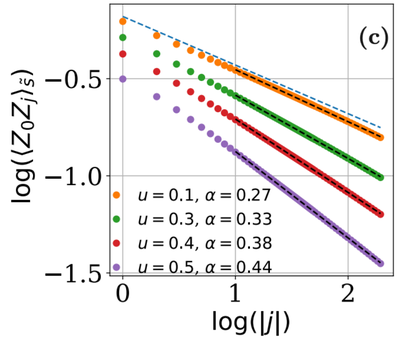
Zack Weinstein,[1,*] Rohith Sajith,[1,*] Ehud Altman,[1,2] and Samuel J. Garratt[1]

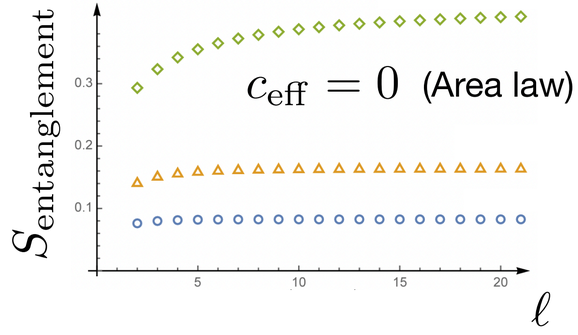
Entanglement in a one-dimensional critical state after measurements

Zhou Yang,[1] Dan Mao,[1] and Chao-Ming Jian[1]

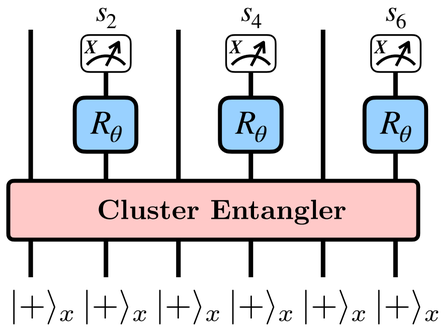
Measurement-altered Ising quantum criticality

Sara Murciano,[1,2,*] Pablo Sala,[1,2,*] Yue Liu,[1] Roger S. K. Mong,[3] and Jason Alicea[1,2]

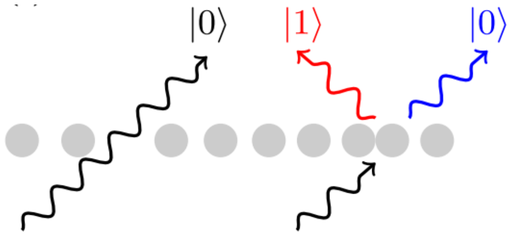




Preparation of long-range entangled states from cluster state



Measurements in a gapless parent state of the 1D cluster state



Measurement-altered criticality

Outline:

- Review about the canonical cluster state
- Gapless parent of the 1D cluster state
- Weak measurements on the gapless parent state
- Conclusions and outlook

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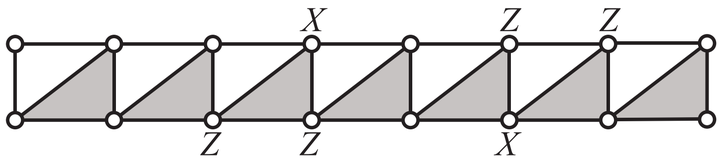
Canonical cluster state: a review



$y = 1$

$y = 2$

$$H_{\text{cluster}} = -\sum_{j=1}^{N-1} (Z_{j,1} X_{j,2} Z_{j+1,1} + Z_{j,2} X_{j+1,1} Z_{j+1,2})$$

Symmetry Protected Topological (SPT) phase:

$$G_1 = \prod_{j=1}^{N} X_{j,1} \qquad G_2 = \prod_{j=1}^{N} X_{j,2}$$

R. Raussendorf and H. J. Briegel, Phys. Rev. Lett. 86, 5188 (2001).

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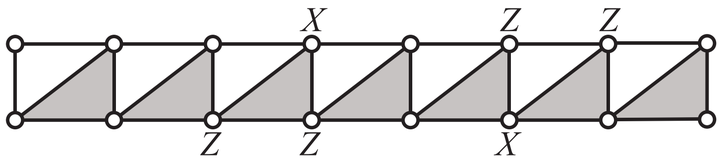

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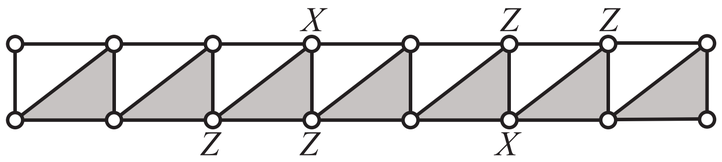

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String order parameter:

$$\mathcal{S}_{j,k} \equiv \begin{bmatrix} Z_j & & & & Z_k \\ X_j & X_{j+1} & \cdots & X_{k-1} & \end{bmatrix} = 1$$

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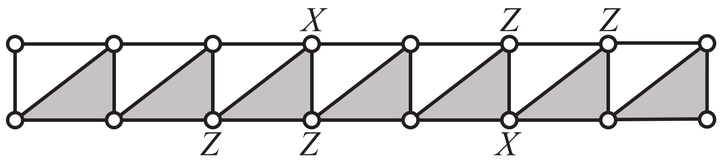

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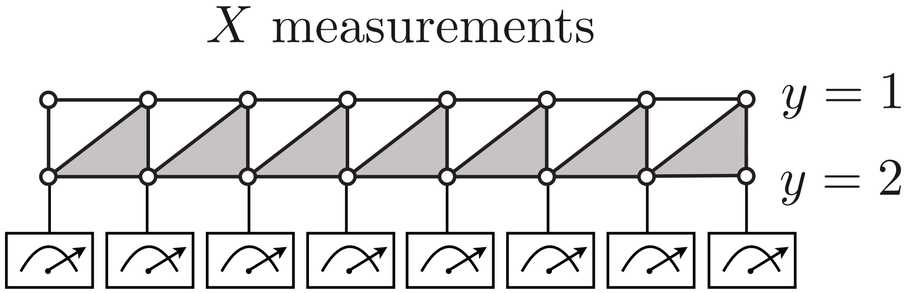
but $\langle Z_{j,1} Z_{k,1} \rangle = 0$

short-range!

R. Raussendorf and H. J. Briegel, Phys. Rev. Lett. 86, 5188 (2001).

Conversion into a GHZ state



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Post-measurement state: $|\psi\rangle_{\boldsymbol{s}} \propto \mathcal{P}_{\boldsymbol{s}} |\psi_0\rangle \equiv \prod_{j=1}^{N} \left(\frac{1+s_j X_{j,2}}{2}\right) |\psi_0\rangle$

$$\langle Z_{j,1} Z_{k,1} \rangle_{\boldsymbol{s}} = \frac{\langle \psi_0 | \mathcal{P}_{\boldsymbol{s}} Z_{j,1} Z_{k,1} \mathcal{P}_{\boldsymbol{s}} \mathcal{S}_{j,k} | \psi_0 \rangle}{\langle \psi_0 | \mathcal{P}_{\boldsymbol{s}} | \psi_0 \rangle} = s_j \cdots s_{k-1}$$

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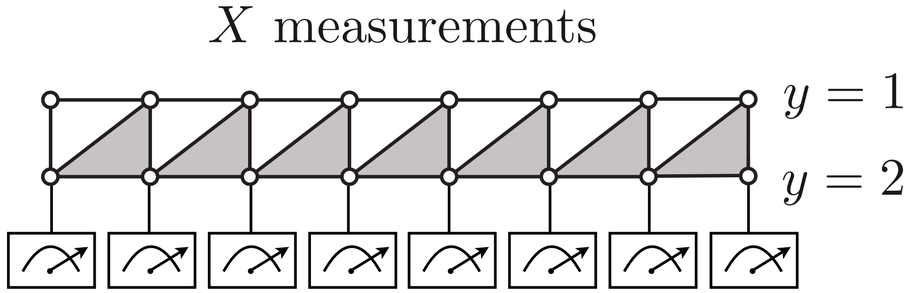

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controlled unitary feedback: $U_{\boldsymbol{s}} |\psi\rangle_{\boldsymbol{s}}$

$s_j = 1$

$\sum_{\boldsymbol{s}} p_{\boldsymbol{s}} \langle Z_{j,1} Z_{k,1} \rangle_{\boldsymbol{s}} \, s_j \cdots s_{k-1} = 1$

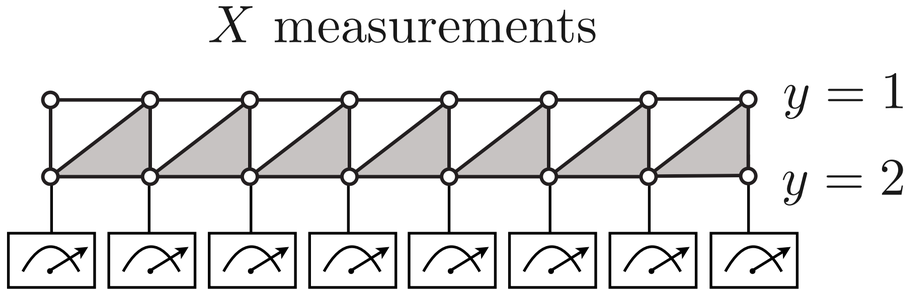
Reminder:
$\sum_{\boldsymbol{s}} p_{\boldsymbol{s}} \langle Z_{j,1} Z_{k,1} \rangle_{\boldsymbol{s}} = \langle Z_{j,1} Z_{k,1} \rangle_0$

correlations characteristic of a GHZ state

$$|\text{GHZ}\rangle = \frac{1}{\sqrt{2}} (|\uparrow \cdots \uparrow\rangle + |\downarrow \cdots \downarrow\rangle)$$

R. Raussendorf and H. J. Briegel, Phys. Rev. Lett. 86, 5188 (2001).

Conversion into a GHZ state



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long-range order!

$$\langle Z_{j,1} Z_{k,1} \rangle_{\boldsymbol{s}} = \frac{\langle \psi_0 | \mathcal{P}_{\boldsymbol{s}} Z_{j,1} Z_{k,1} \mathcal{P}_{\boldsymbol{s}} \mathcal{S}_{j,k} | \psi_0 \rangle}{\langle \psi_0 | \mathcal{P}_{\boldsymbol{s}} | \psi_0 \rangle} = s_j \cdots s_{k-1}$$

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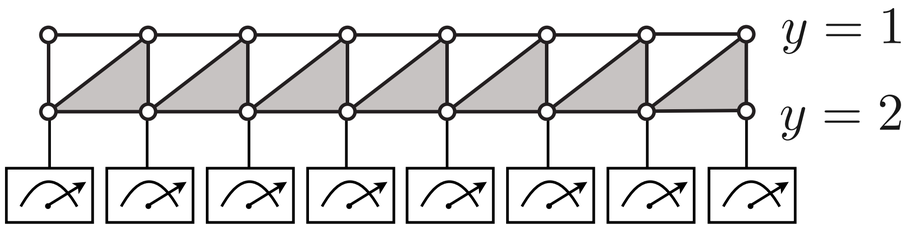
Conversion into a GHZ state: is it robust?

weak 'tilted' measurement



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Post-measurement state: $|\psi\rangle_{\boldsymbol{s}} \propto e^{2\beta \sum_j s_j (\cos\omega X_{j,2} + \sin\omega Z_{j,2})} |\psi_0\rangle$

β: measurement strength
ω: measurement angle

$$\langle Z_{j,1}Z_{k,1}\rangle_{\text{uni}} \approx (\tanh 2\beta \cos\omega)^{|j-k|} \equiv e^{-|j-k|/\xi}$$

long-range order only appears when
the measurement is projective
and when the tilt angle is $\omega = 0$

Lee, Ji, Bi, Fisher, arXiv:2208.11699, 2022.

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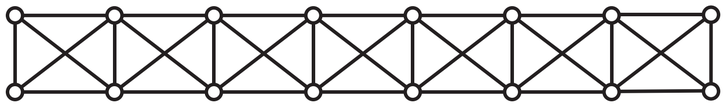
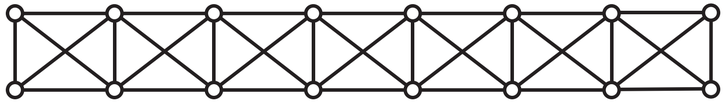
Gapless parent of the cluster state



$$H = -\sum_{j=1}^{N-1} [\cos\alpha(Z_{j,1}X_{j,2}Z_{j+1,1} + Z_{j,2}X_{j+1,1}Z_{j+1,2}) + \sin\alpha(Z_{j,2}X_{j,1}Z_{j+1,2} + Z_{j,1}X_{j+1,2}Z_{j+1,1})].$$

Gapless parent of the cluster state



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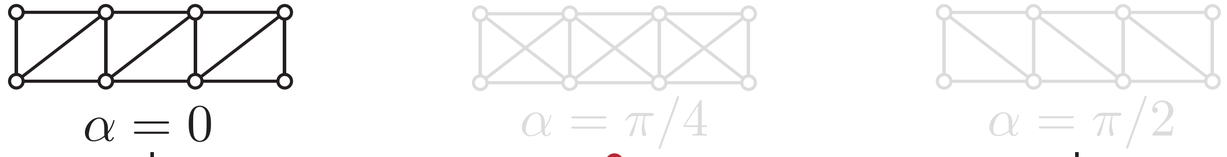

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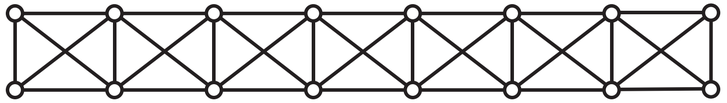

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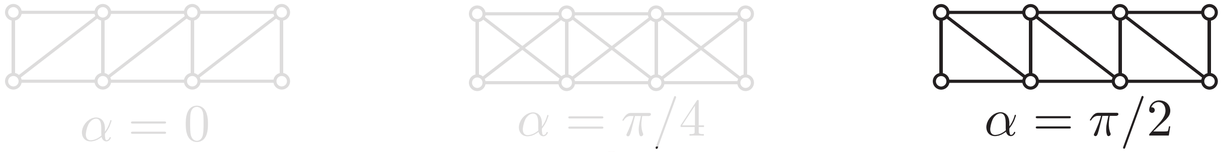
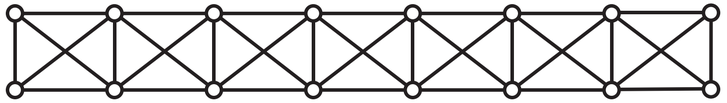


$\alpha = 0$ $\alpha = \pi/4$ $\alpha = \pi/2$

Gapped SPT Gapped SPT

$c = 2$ gapless

Gapless parent of the cluster state



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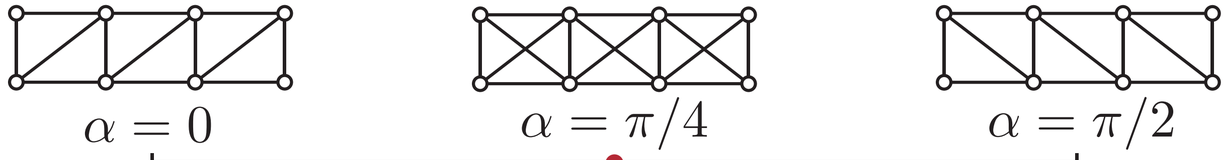
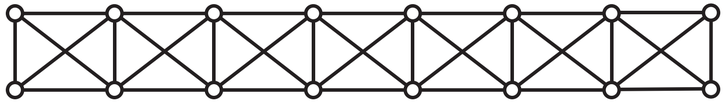
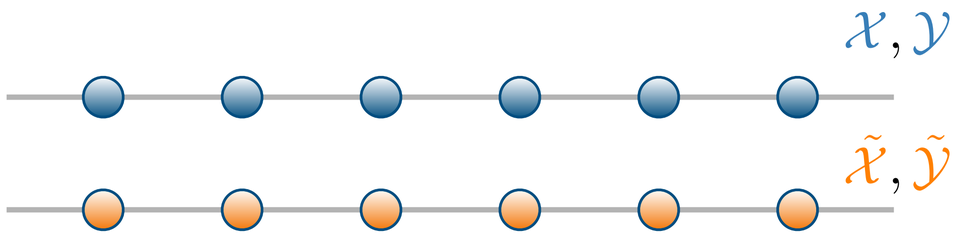


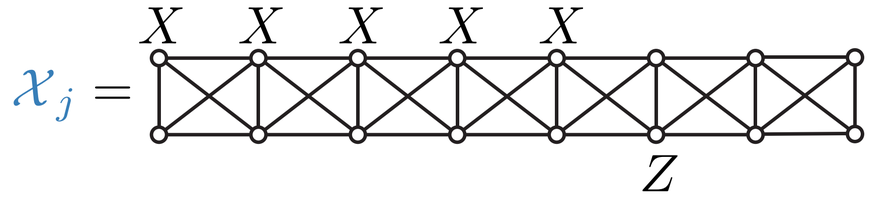
interchain reflection symmetry

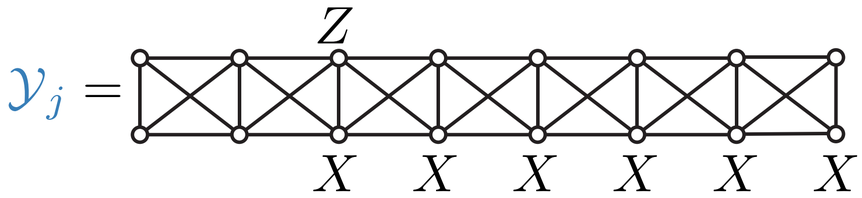
Gapless parent of the cluster state

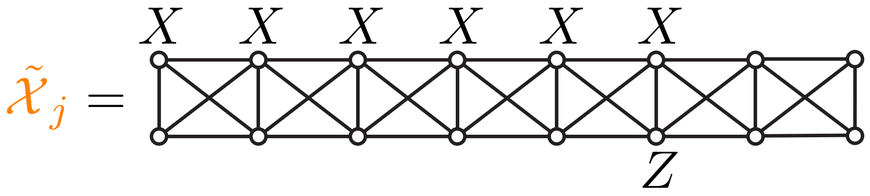


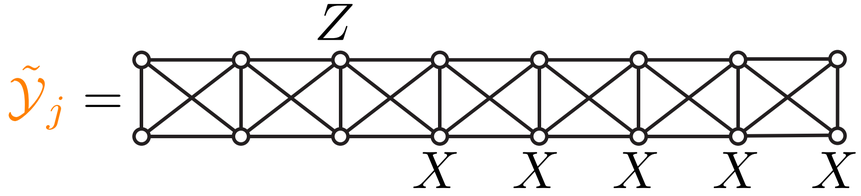


New set of Pauli operators:







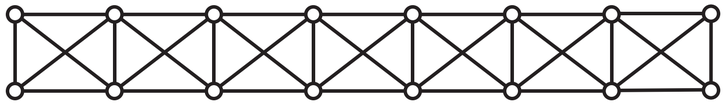


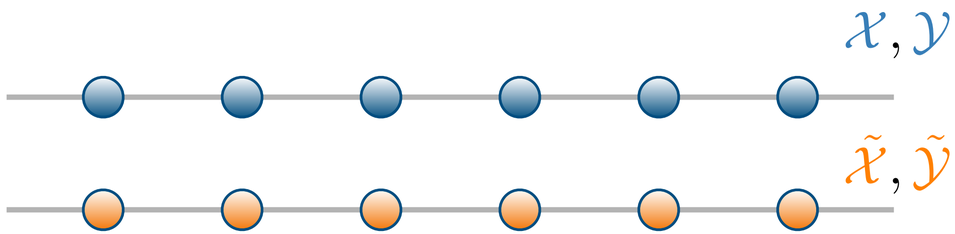
$$H = -\sum_{j=1}^{N-1} [(\sin\alpha \mathcal{X}_j \mathcal{X}_{j+1} + \cos\alpha \mathcal{Y}_j \mathcal{Y}_{j+1}) + (\cos\alpha \tilde{\mathcal{X}}_j \tilde{\mathcal{X}}_{j+1} + \sin\alpha \tilde{\mathcal{Y}}_j \tilde{\mathcal{Y}}_{j+1})]$$

two decoupled $\mathcal{XY}$ models
$\alpha = \pi/4$: gapless system
with $c = 2$

T. Kennedy and H. Tasaki,
Commun. Math. Phys.147,431 (1992).

Gapless parent of the cluster state





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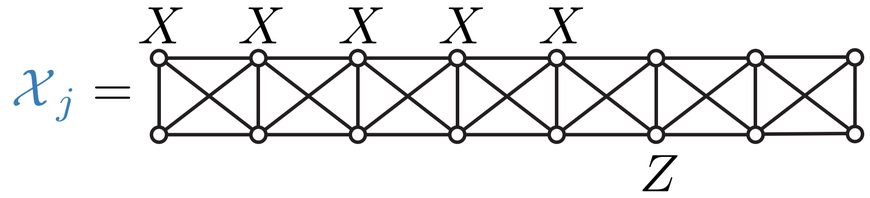
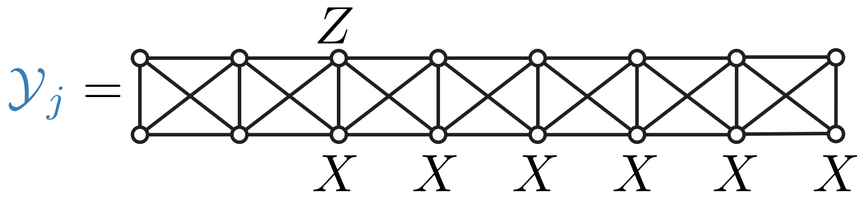
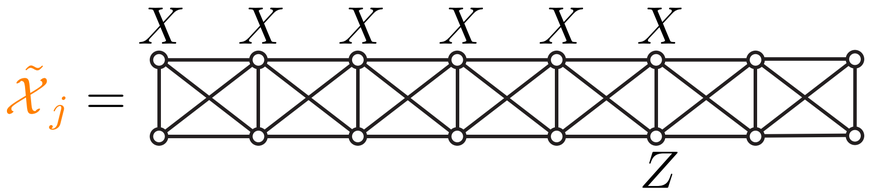
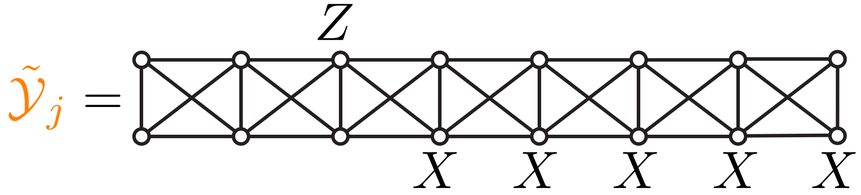






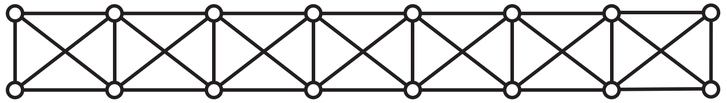


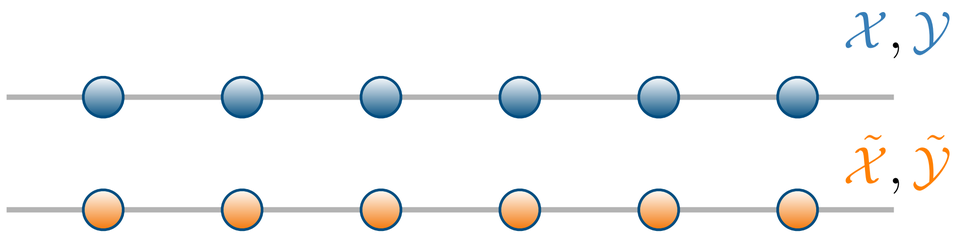
$$H = -\sum_{j=1}^{N-1} [(\sin\alpha \mathcal{X}_j \mathcal{X}_{j+1} + \cos\alpha \mathcal{Y}_j \mathcal{Y}_{j+1}) \qquad \alpha = 0$$
$$+(\cos\alpha \tilde{\mathcal{X}}_j \tilde{\mathcal{X}}_{j+1} + \sin\alpha \tilde{\mathcal{Y}}_j \tilde{\mathcal{Y}}_{j+1})]$$

T. Kennedy and H. Tasaki,
Commun. Math. Phys.147,431 (1992).

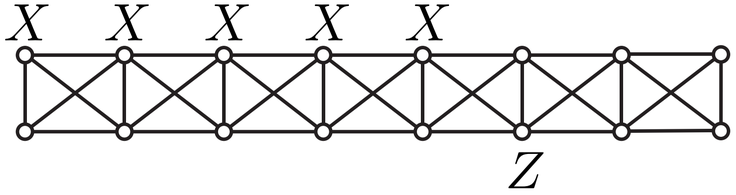
L. Li, M. Oshikawa, and Y. Zheng,
Phys. Rev. B 108, 214429 (2023).

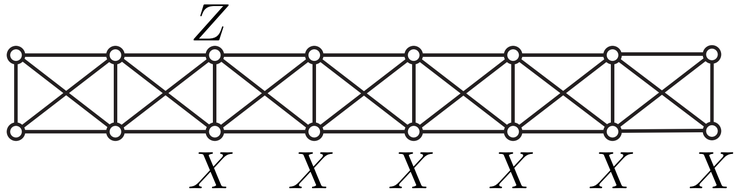
Gapless parent of the cluster state

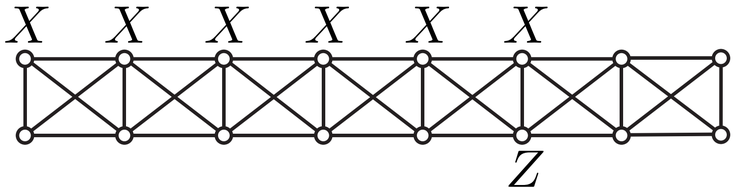


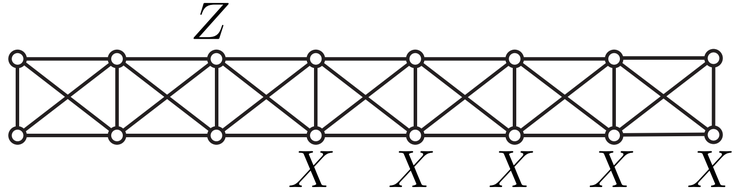


New set of Pauli operators:

$\mathcal{X}_j =$ 

$\mathcal{Y}_j =$ 

$\tilde{\mathcal{X}}_j =$ 

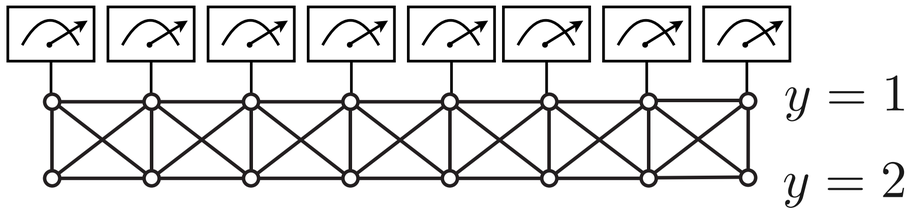
$\tilde{\mathcal{Y}}_j =$ 

$$H_\Delta = -\sum_j \Big[(\mathcal{X}_j \mathcal{X}_{j+1} + \mathcal{Y}_j \mathcal{Y}_{j+1} + \Delta \mathcal{Z}_j \mathcal{Z}_{j+1}) + \left(\tilde{\mathcal{X}}_j \tilde{\mathcal{X}}_{j+1} + \tilde{\mathcal{Y}}_j \tilde{\mathcal{Y}}_{j+1} + \Delta \tilde{\mathcal{Z}}_j \tilde{\mathcal{Z}}_{j+1} \right) \Big]$$

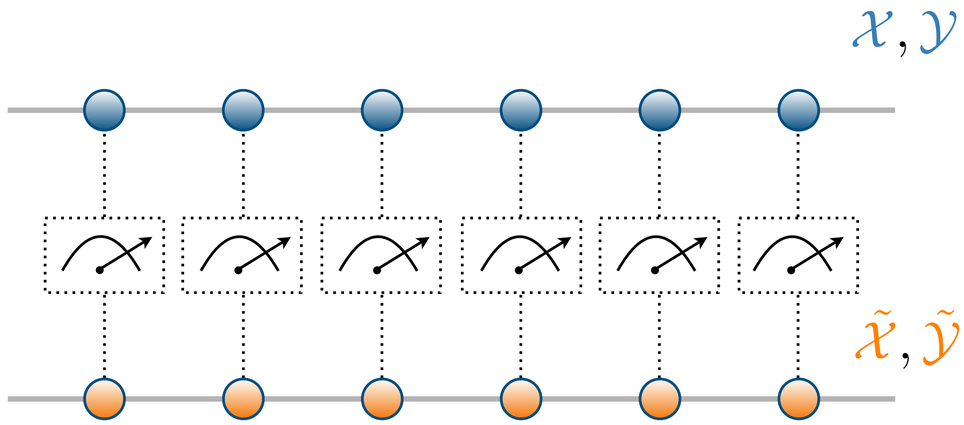
$\alpha = \pi/4$ + symmetry-preserving terms generating $\mathcal{Z}\mathcal{Z}$-type operators

Gapless parent of the cluster state

Original	$X_{j,1}$	$X_{j,2}$	$Z_{j,1}Z_{j+1,1}$	$Z_{j,1}$
New	$\mathcal{X}_j\tilde{\mathcal{X}}_j$	$\mathcal{Y}_j\tilde{\mathcal{Y}}_j$	$\mathcal{Y}_j\tilde{\mathcal{Y}}_{j+1}$	$\begin{pmatrix} & \mathcal{Y}_{j+1} & \cdots & \mathcal{Y}_N \\ \tilde{\mathcal{Y}}_j & \tilde{\mathcal{Y}}_{j+1} & \cdots & \tilde{\mathcal{Y}}_N \end{pmatrix}$



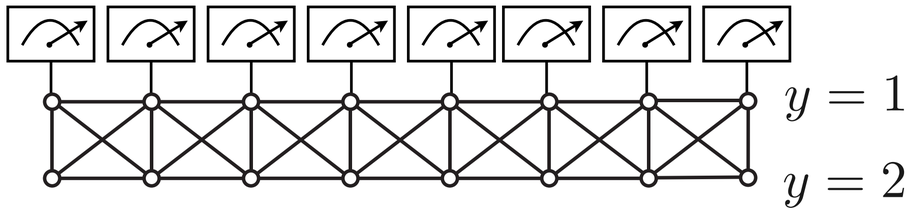
$=$



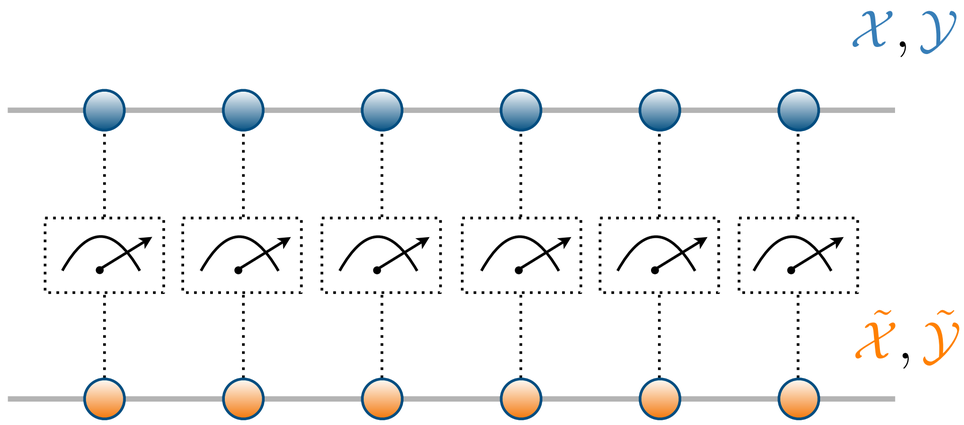
$$H_\Delta = -\sum_j \Big[(\mathcal{X}_j\mathcal{X}_{j+1} + \mathcal{Y}_j\mathcal{Y}_{j+1} + \Delta\mathcal{Z}_j\mathcal{Z}_{j+1}) + \left(\tilde{\mathcal{X}}_j\tilde{\mathcal{X}}_{j+1} + \tilde{\mathcal{Y}}_j\tilde{\mathcal{Y}}_{j+1} + \Delta\tilde{\mathcal{Z}}_j\tilde{\mathcal{Z}}_{j+1}\right) \Big]$$

Gapless parent of the cluster state

Original	$X_{j,1}$	$X_{j,2}$	$Z_{j,1}Z_{j+1,1}$	$Z_{j,1}$
New	$\mathcal{X}_j\tilde{\mathcal{X}}_j$	$\mathcal{Y}_j\tilde{\mathcal{Y}}_j$	$\mathcal{Y}_j\tilde{\mathcal{Y}}_{j+1}$	$\begin{pmatrix} & \mathcal{Y}_{j+1} & \cdots & \mathcal{Y}_N \\ \tilde{\mathcal{Y}}_j & \tilde{\mathcal{Y}}_{j+1} & \cdots & \tilde{\mathcal{Y}}_N \end{pmatrix}$



$=$



Can we still prepare long-range order from this gapless Hamiltonian?

Is it robust far from projective measurements and is there a privileged measurement direction?

Is the decoding protocol still valid?

Outline:

- Review about the canonical cluster state
- Gapless parent of the 1D cluster state
- Weak measurements on the gapless parent state
- Conclusions and outlook

Tomonaga-Luttinger liquid

Gapless parent state $\longrightarrow$ 2 decoupled $\mathcal{XXZ}$ spin chains with $\Delta \in [-1, 1]$ $\longrightarrow$ Tomonaga-Luttinger liquid (TLL)

Tomonaga-Luttinger liquid

Gapless parent state $\longrightarrow$ 2 decoupled $\mathcal{XXZ}$ spin chains with $\Delta \in [-1, 1]$ $\longrightarrow$ Tomonaga-Luttinger liquid (TLL)

$$S_{\mathrm{TLL}} = \frac{K}{2\pi} \int_{x,\tau} \left[(\partial_x \theta)^2 + (\partial_\tau \theta)^2 \right]$$

$\downarrow$ phase

$K = \frac{\pi}{2 \arccos \Delta}$
Luttinger parameter

Operator/Field	Power-law correlations
$\mathcal{X}_j + i\mathcal{Y}_j \sim$ density $\uparrow$ $e^{-i\theta} + ic_1(-1)^j \left[e^{-i(2\phi+\theta)} - e^{i(2\phi-\theta)} \right]$	$\langle \mathcal{X}_0 \mathcal{X}_j \rangle \sim \lvert j \rvert^{-\frac{1}{2K}}$
	$\langle \mathcal{Y}_0 \mathcal{Y}_j \rangle \sim \lvert j \rvert^{-\frac{1}{2K}}$
$\mathcal{Z}_j \sim -\frac{2}{\pi} \partial_x \phi + c_2(-1)^j \cos(2\phi)$	$C_1 \lvert j \rvert^{-2} + C_2(-1)^j \lvert j \rvert^{-2K}$

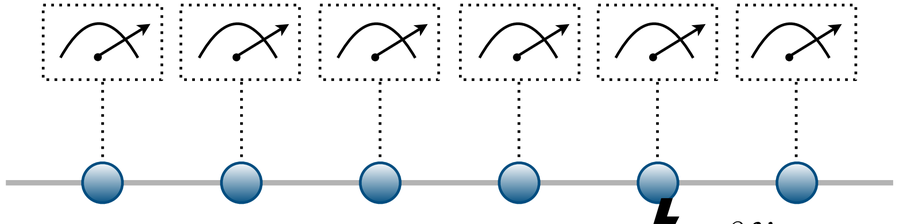
Entanglement

$$\rho_A = \mathrm{Tr}_B \left| \psi_c \right\rangle \left\langle \psi_c \right| \quad \Longrightarrow$$

$$S_A^{(n)} = \frac{1}{1-n} \log \mathrm{Tr}[\rho_A^n] \sim c \frac{n+1}{6n} \log \ell$$

with **central charge** $c = 1$

Weak measurement on a single XXZ spin chain



s_j: measurement outcome
β: measurement strength
$(\beta \to \infty)$: projective limit

$$\frac{e^{s_j \beta \mathcal{X}_j}}{\sqrt{2\cosh 2\beta}}$$

For Z-basis measurements, see:
S. J. Garratt, Z. Weinstein, E. Altman,
Phys. Rev. X 13, 021026 (2023).

Post-measurement state: $\quad |\psi_{\boldsymbol{s}}\rangle = \frac{1}{\mathcal{N}} e^{\beta \sum_j s_j \mathcal{X}_j} |\psi_c\rangle$

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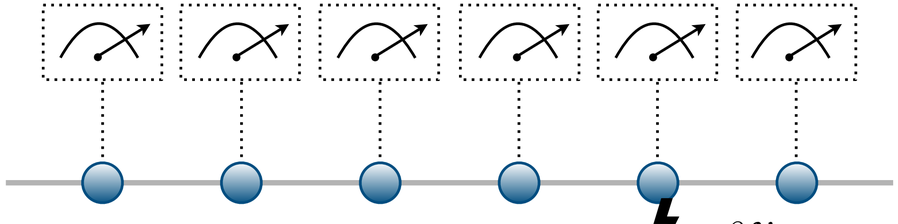

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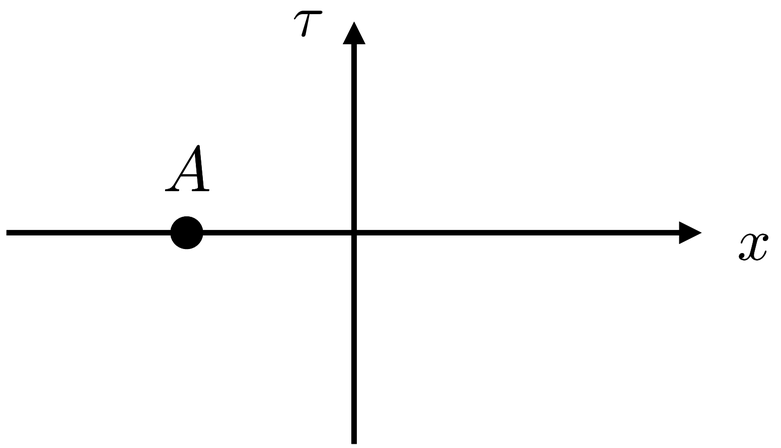
$$\langle \psi_c | A | \psi_c \rangle \to \int \mathcal{D}\theta e^{-S_c} A_{\rm cont}(x, \tau = 0)$$



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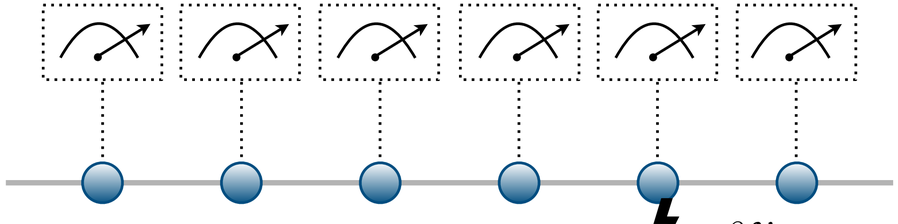

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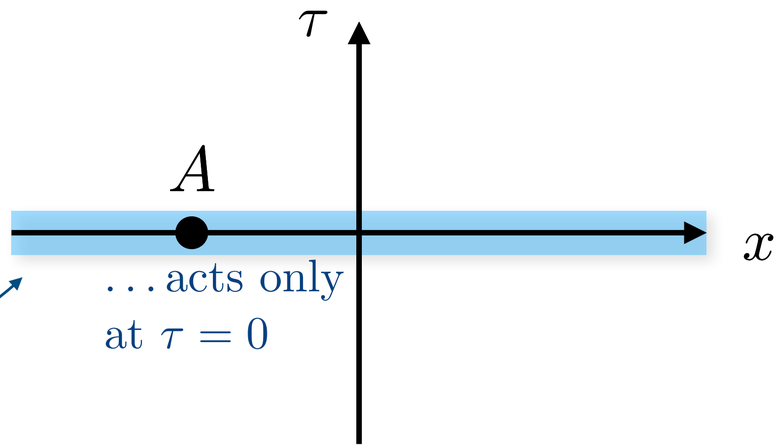
$$\mathcal{M} \sim e^{\beta \sum_j O_j + \cdots}$$

$$\langle \psi_c | \mathcal{M} A \mathcal{M} | \psi_c \rangle \to \int \mathcal{D}\theta e^{-S_c - S_{\text{meas}}} A_{\text{cont}}(x, \tau = 0)$$

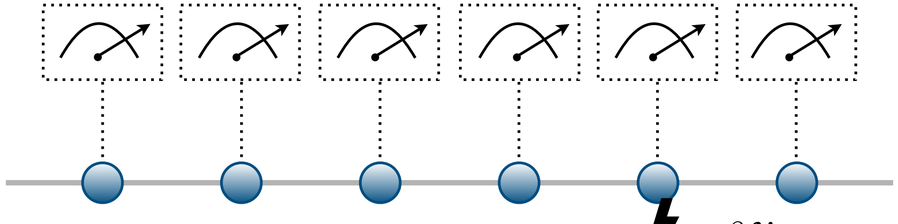
Correction from weak measurement...



Weak measurement ~ "imaginary time" quantum impurity!

S. J. Garratt, Z. Weinstein, E. Altman, Phys. Rev. X 13, 021026 (2023).

Weak measurement on a single XXZ spin chain



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$$\frac{e^{s_j \beta \mathcal{X}_j}}{\sqrt{2\cosh 2\beta}}$$

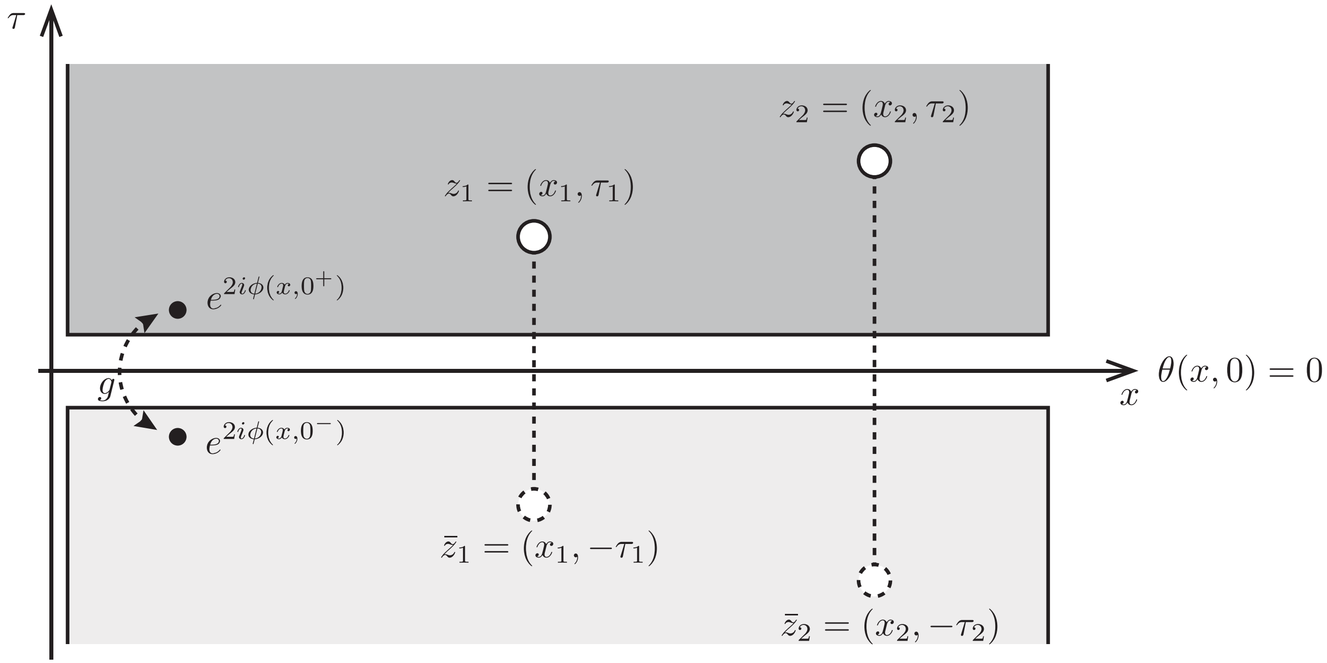
Post-measurement state: $|\psi_{\rm uni}\rangle = \frac{1}{\mathcal{N}} e^{\beta \sum_j \mathcal{X}_j} |\psi_c\rangle$

$$S' = S_{\rm TLL} + \beta \int_x \cos\theta|_{\tau=0}$$

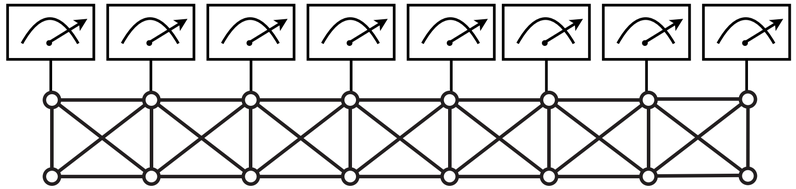
"Impurity" action is **RELEVANT** for $K > 1/4$.
How are critical properties modified?

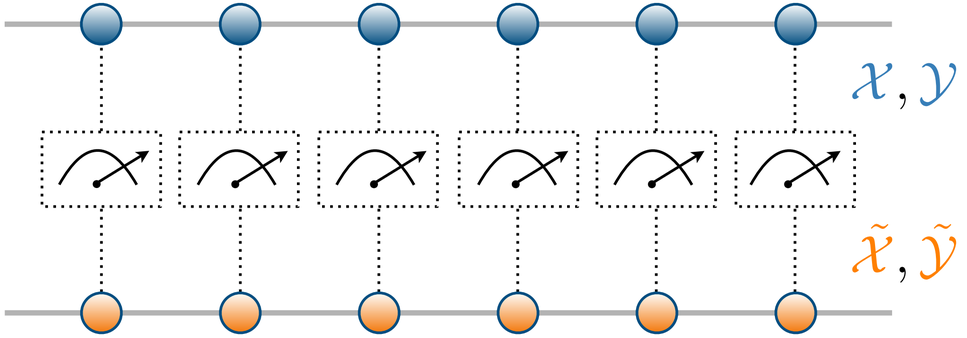
$$\langle \mathcal{X}_0 \mathcal{X}_x \rangle_c \propto x^{-1/(2K)} \to x^{-\min(4,8K)}$$

$$\langle \mathcal{Y}_0 \mathcal{Y}_x \rangle_c \propto x^{-1/(2K)} \to x^{-2}$$



Weak measurement on the gapless parent state (X-basis)



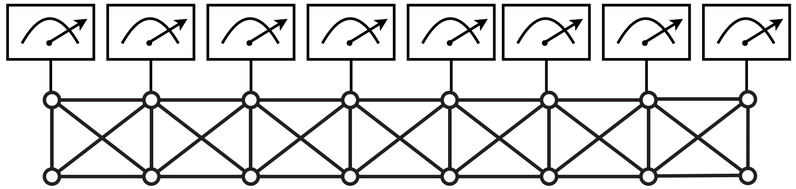


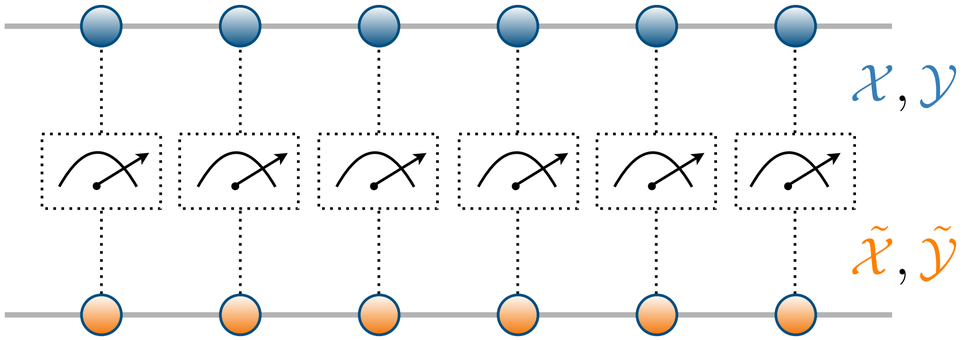
Post-measurement state: $|\psi_{\rm uni}\rangle = \frac{1}{\mathcal{N}} e^{\beta \sum_j X_{j,1}} |\psi_\Delta\rangle \to \frac{1}{\mathcal{N}} e^{\beta \sum_j \mathcal{X}_j \tilde{\mathcal{X}}_j} |\psi_c\rangle |\tilde{\psi}_c\rangle$

$$S' = S_{\rm TLL}[\theta] + S_{\rm TLL}[\tilde{\theta}] + \beta \int_x \cos(\theta)\cos(\tilde{\theta})|_{\tau=0}$$

"Impurity" action is **RELEVANT** for $K > 1/2$.

Weak measurement on the gapless parent state (X-basis)





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$$S' = S_{\rm TLL}[\theta] + S_{\rm TLL}[\tilde{\theta}] + \beta \int_x \cos(\theta)\cos(\tilde{\theta})|_{\tau=0}$$

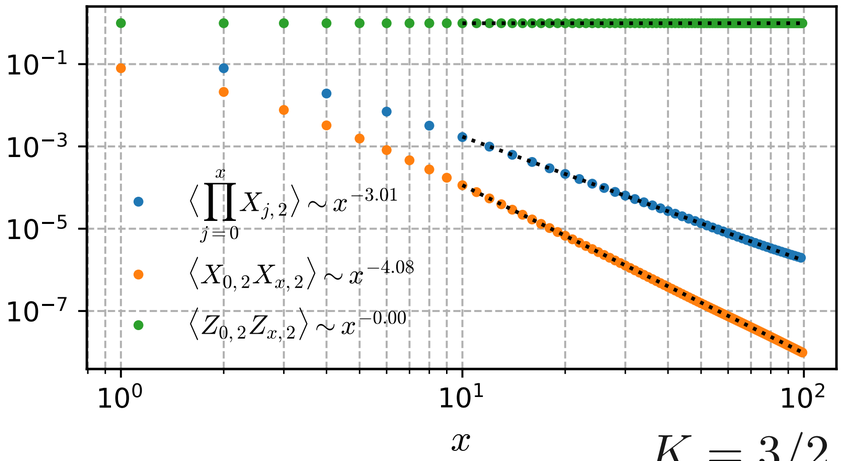
"Impurity" action is **RELEVANT** for $K > 1/2$.

$$\langle X_{0,2} X_{x,2} \rangle_{\rm uni} \sim |x|^{-\min(4,4K)}$$

order parameter $\langle Z_{0,2} Z_{x,2} \rangle_{\rm uni} \sim$ const.

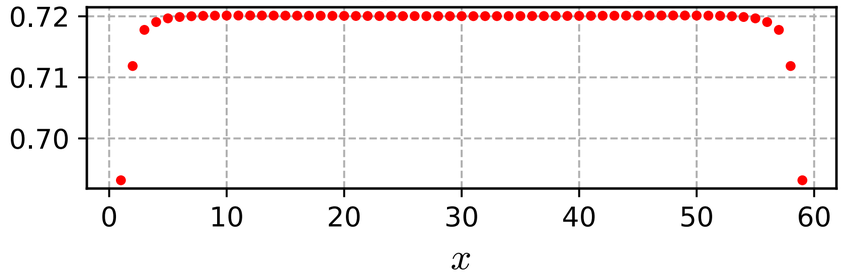
disorder parameter $\langle \prod_{i=j}^{k} X_{i,2} \rangle_{\rm uni} \sim |j-k|^{-2K}$

Correlation functions

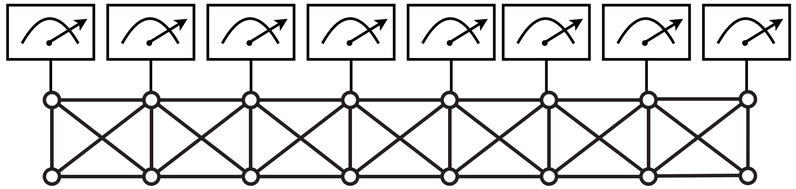


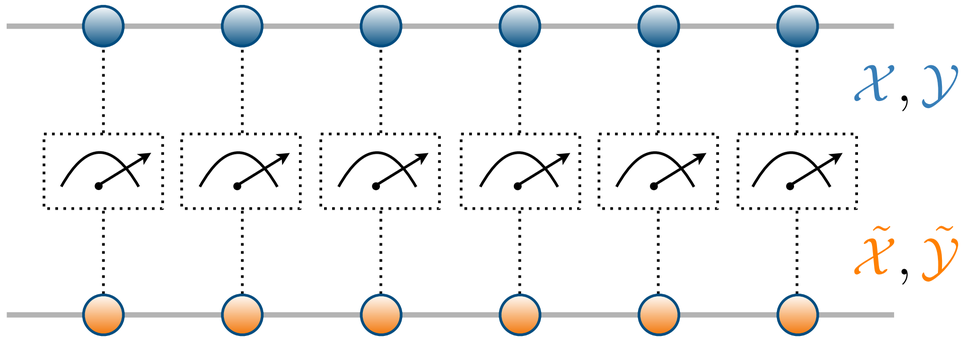
$K = 3/2$

Entanglement entropy



A decoding protocol





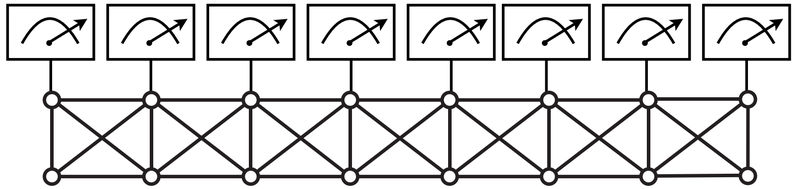
Reminder:

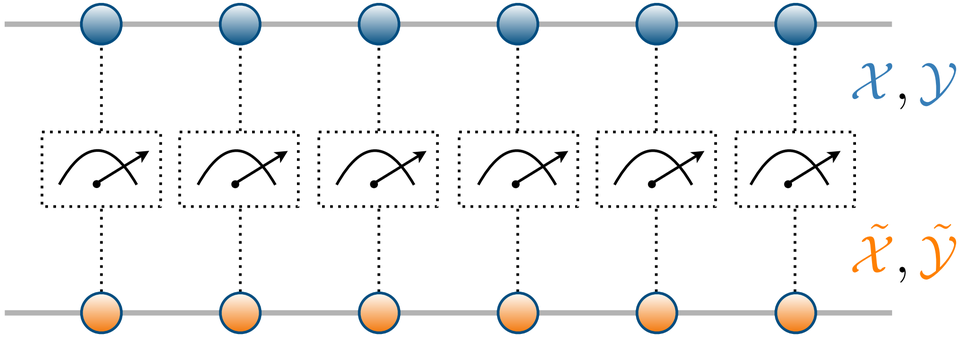
$$\sum_{\boldsymbol{s}} p_{\boldsymbol{s}} \langle Z_{j,2} Z_{k,2} \rangle_{\boldsymbol{s}} = \langle Z_{j,2} Z_{k,2} \rangle_0 \sim |j-k|^{-1/2}$$

$$\sum_{\boldsymbol{s}} p_{\boldsymbol{s}} \langle Z_{j,2} Z_{k,2} \rangle_{\boldsymbol{s}} \, s_j s_{j+1} \cdots s_{k-1} \sim |j-k|^{-1/(2K)}$$

Same decoding protocol used for canonical cluster state yields power-law behavior (not GHZ)!

Weak measurement on the gapless parent state (Z-basis)

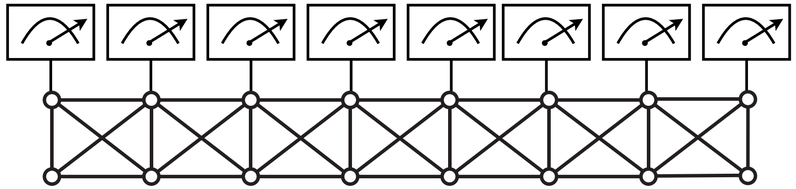


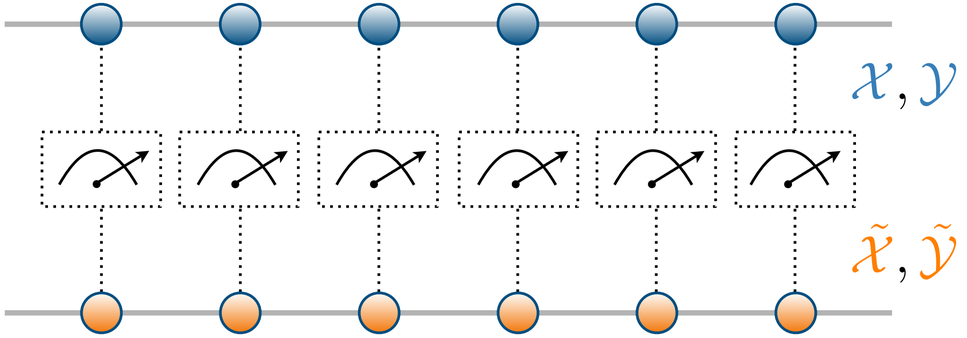


Post-measurement state: $|\psi_{\text{uni}}\rangle = \frac{1}{\mathcal{N}} e^{\beta \sum_j z_{j,1}} |\psi_\Delta\rangle \to Z_{j,1} = \begin{pmatrix} & y_{j+1} & \cdots & y_N \\ \tilde{y}_j & \tilde{y}_{j+1} & \cdots & \tilde{y}_N \end{pmatrix}$

Numerically, we find that the scaling dimension of $Z_{j,1}$ is $1/4$, so the measurement is always relevant.

Weak measurement on the gapless parent state (Z-basis)





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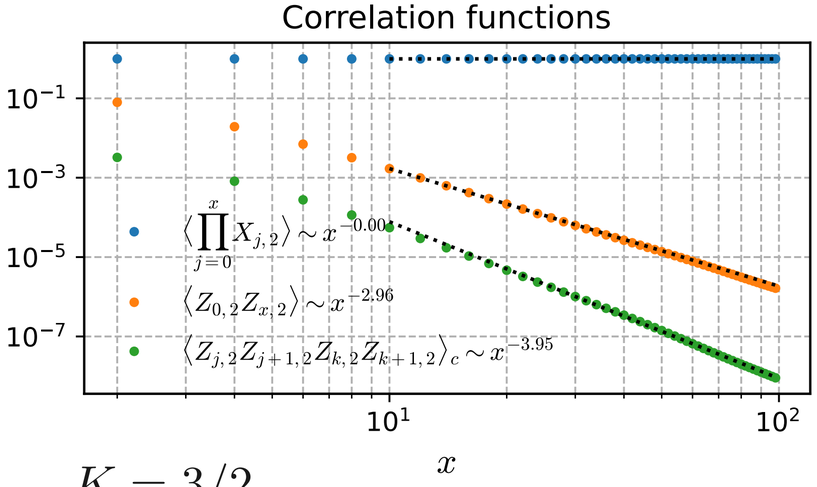
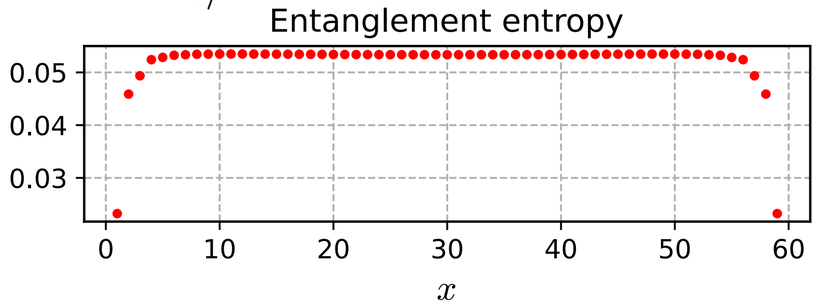


$K = 3/2$



Numerically, we find that the scaling dimension of $Z_{j,1}$ is $1/4$, so the measurement is always relevant.

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order parameter $\langle Z_{0,2} Z_{x,2} \rangle_{\rm uni} \sim |x|^{-2K}$

disorder parameter $\langle \prod_{i=j}^{k} X_{i,2} \rangle_{\rm uni} \sim$ const.

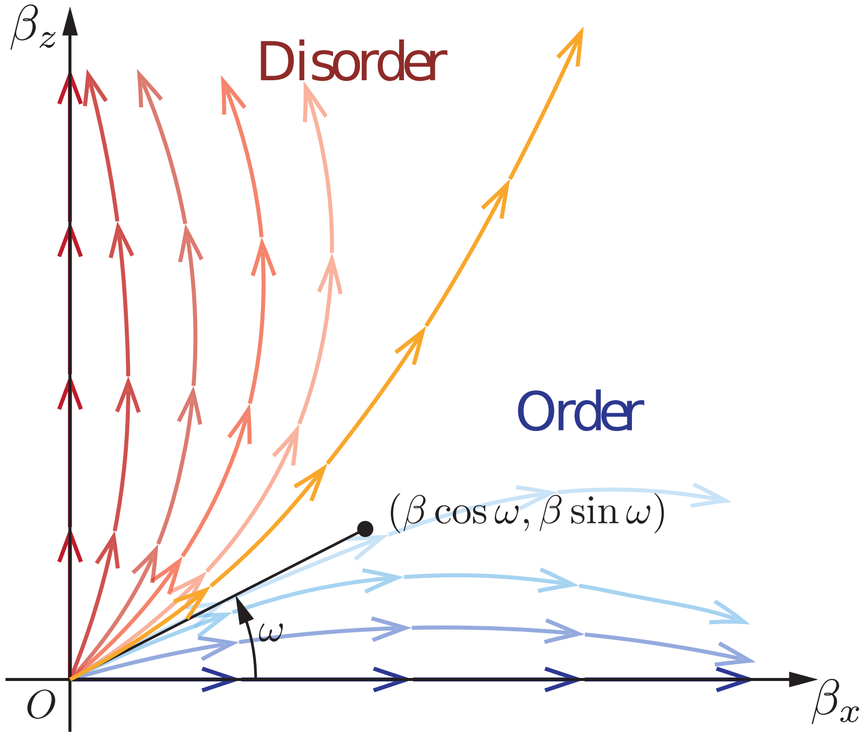
Tilted weak measurements

Post-measurement state: $|\psi_{\text{uni}}\rangle = \frac{1}{\mathcal{N}} e^{\beta \sum_j [\cos(\omega) X_{j,1} + \sin(\omega) Z_{j,1}]} |\psi_\Delta\rangle\,, \qquad \omega \in [0, \frac{\pi}{2}]$

Tilted weak measurements

Post-measurement state: $|\psi_{\text{uni}}\rangle = \frac{1}{\mathcal{N}} e^{\beta \sum_j [\cos(\omega) X_{j,1} + \sin(\omega) Z_{j,1}]} |\psi_\Delta\rangle\,, \qquad \omega \in [0, \frac{\pi}{2}]$

$\omega = 0, \pi/2$ are two stable fixed points for $K > 1$ $\Rightarrow$ intermediate fixed point for some critical value ω_c



Tilted weak measurements

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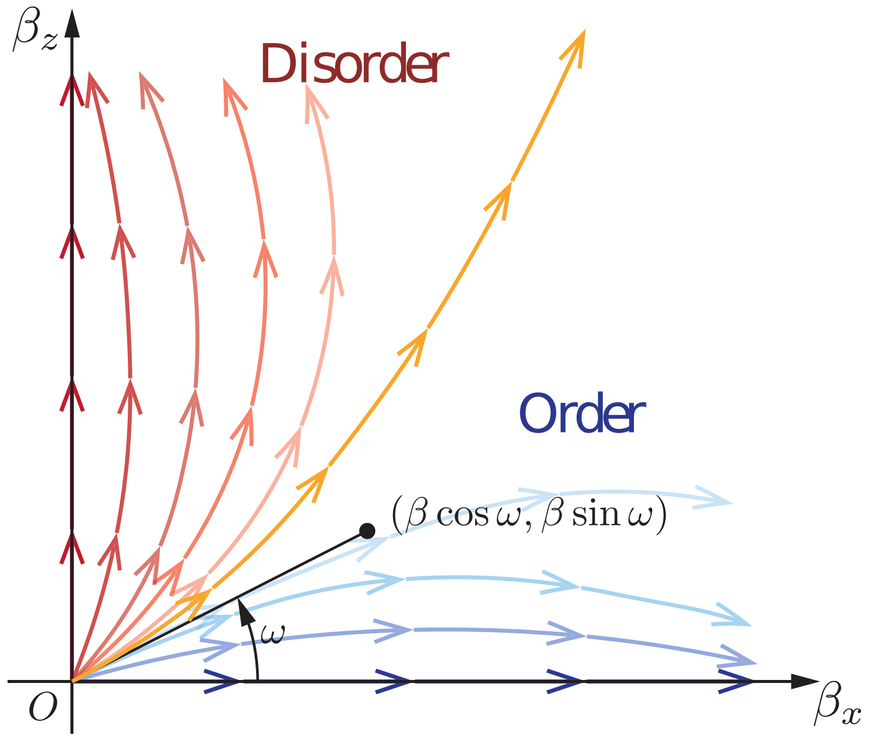

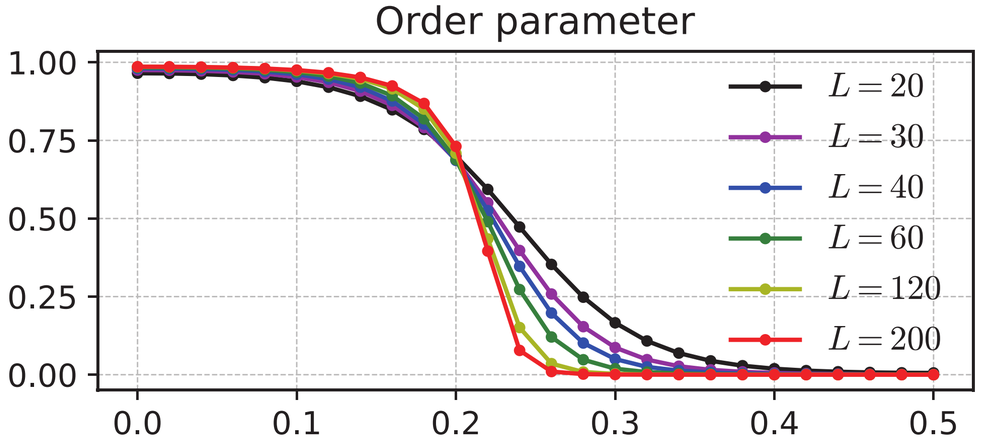

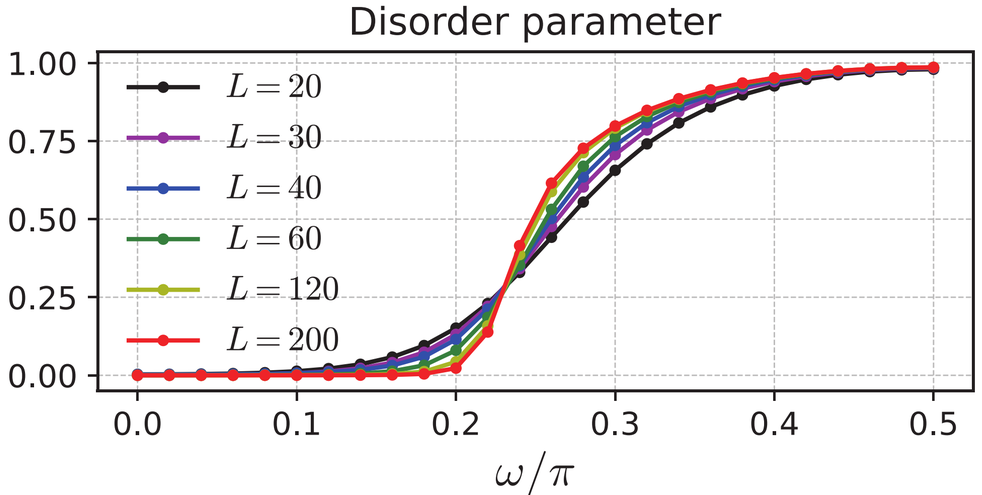

$K = 3/2$

Tilted weak measurements

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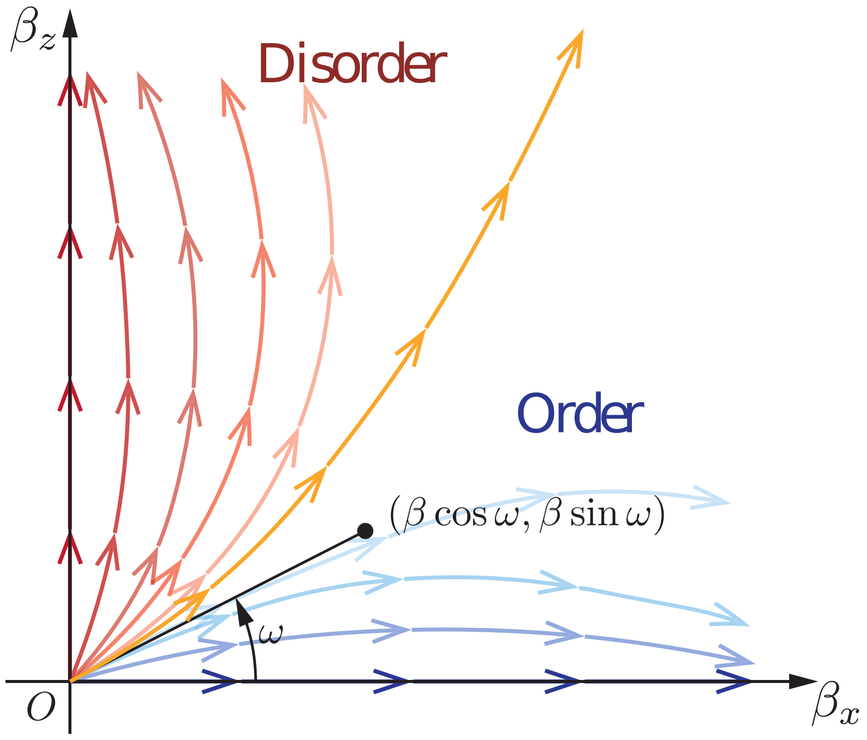

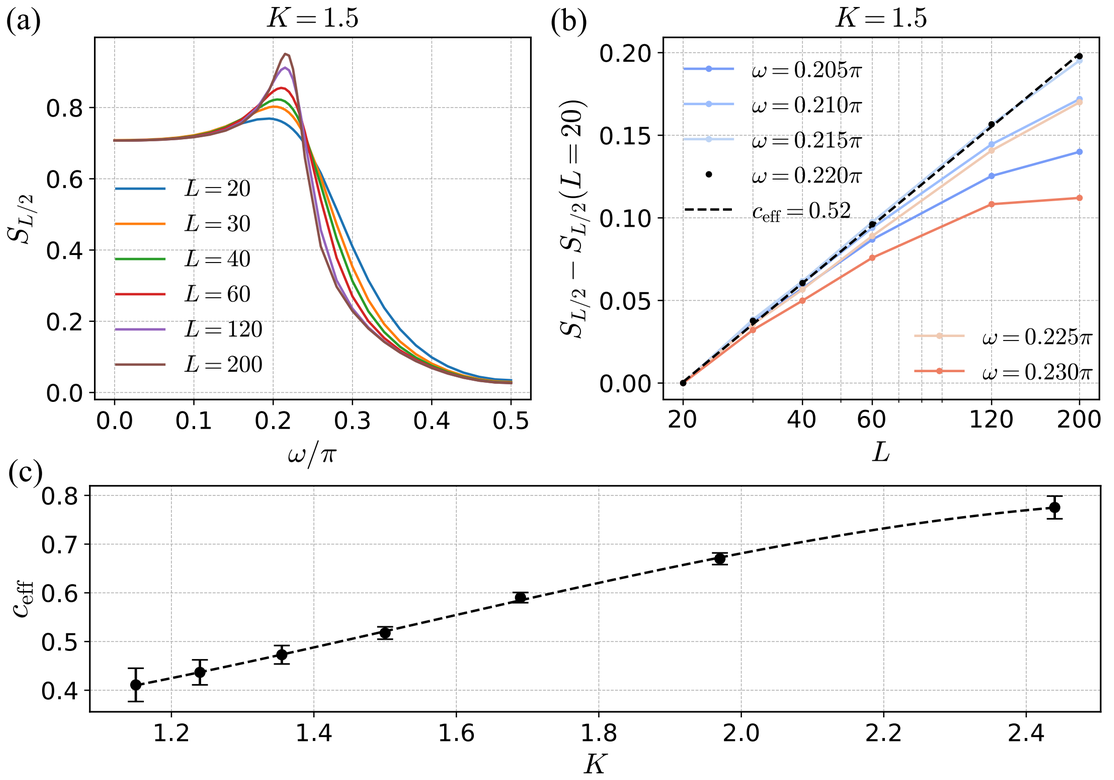

Tilted weak measurements (symmetry-preserving)

Post-measurement state: $|\psi_{\rm uni}\rangle = \frac{1}{\mathcal{N}} e^{\beta \sum_j [\cos(\omega) X_{j,1} + \sin(\omega) Z_{j,1} Z_{j+1,1}]} |\psi_\Delta\rangle\,, \qquad \omega \in [0, \frac{\pi}{2}]$

$\omega = 0, \pi/2$ are two stable fixed point for $K > 1/2$ $\quad \Longrightarrow \quad$ intermediate fixed point for some critical value ω_c

$$S' = S_{\rm TLL}[\theta_+] + S_{\rm TLL}[\theta_-] + \beta \int_x \left[\sin\left(\frac{\pi}{4} - \omega\right) \cos(\theta_+)|_{\tau=0} + \cos\left(\frac{\pi}{4} - \omega\right) \cos(\theta_-)|_{\tau=0} \right]$$

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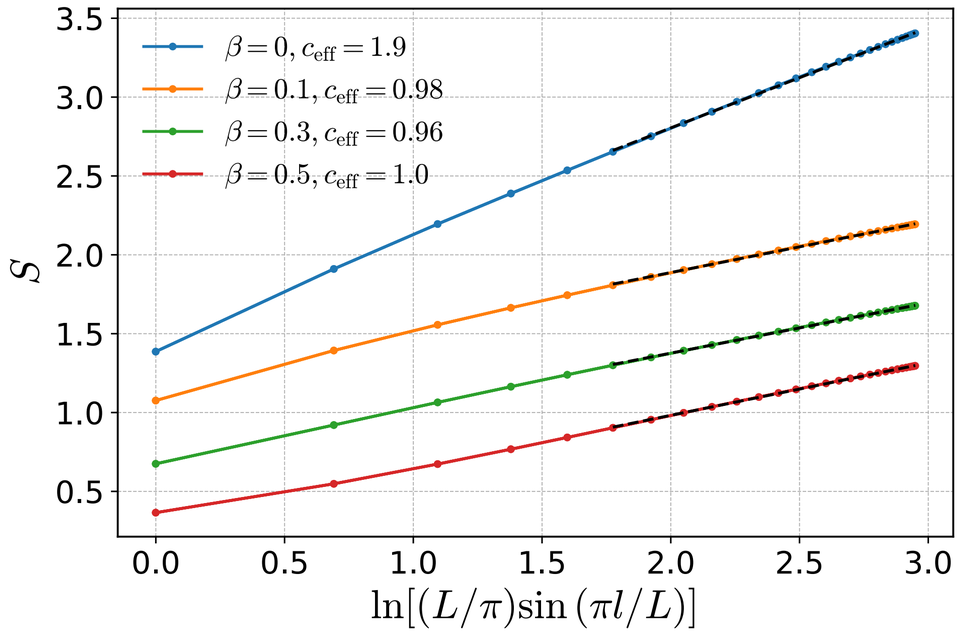
$\omega = \pi/4$: intermediate fixed point, with a gapless sector θ_+



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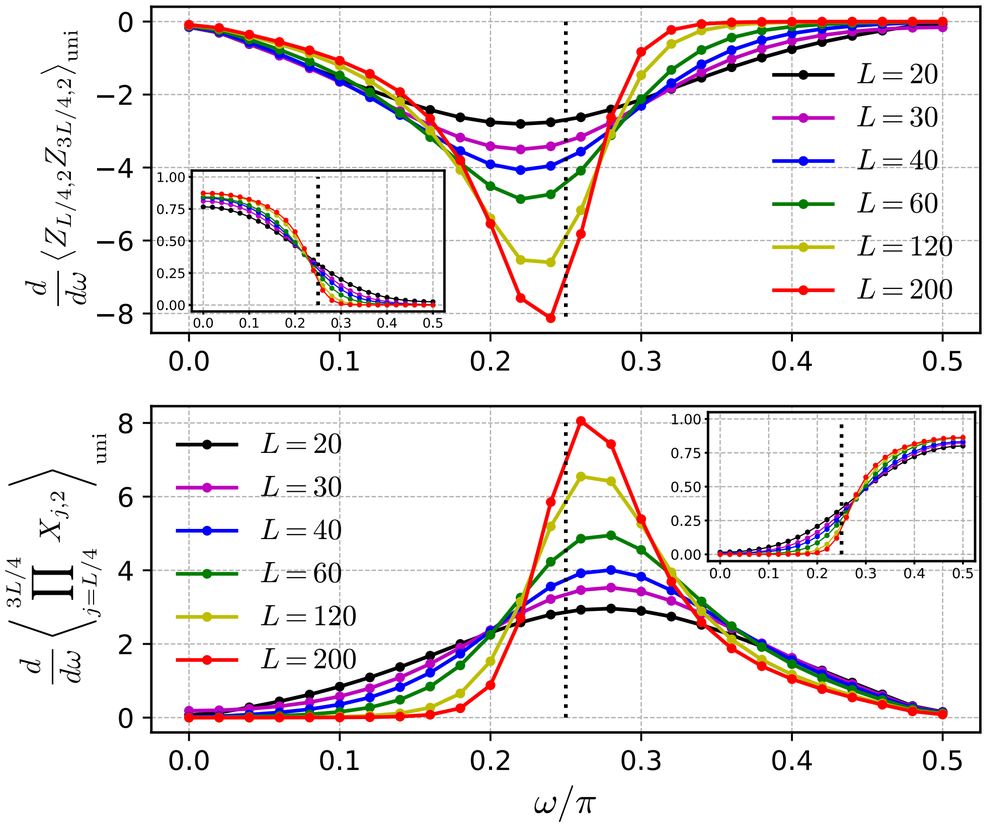


Outline:

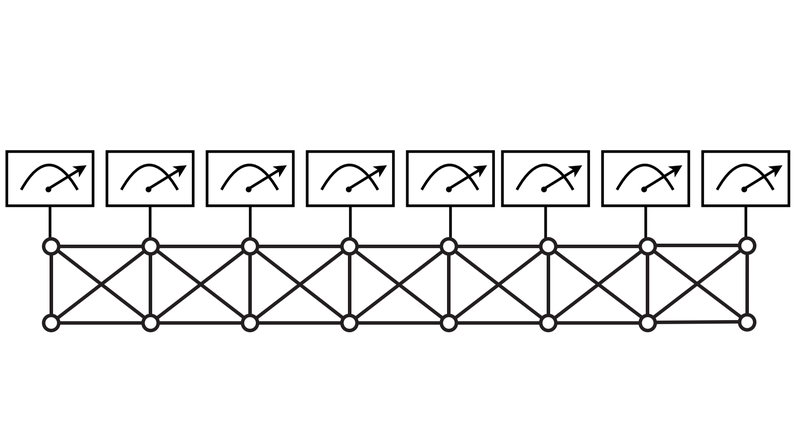
- Review about the canonical cluster state
- Gapless parent of the 1D cluster state
- Weak measurements on the gapless parent state
- Conclusions and outlook

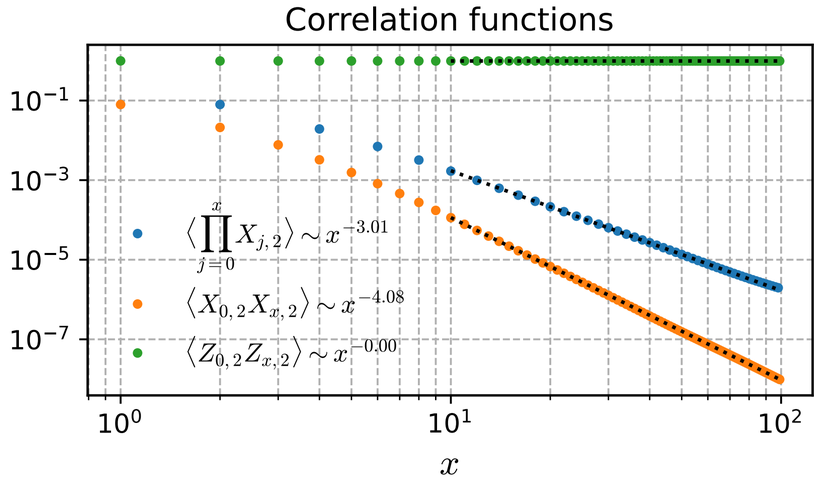
Conclusions…

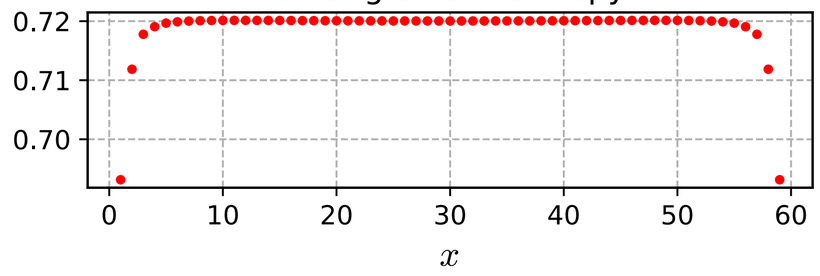
Can we still prepare long-range order from this gapless Hamiltonian?

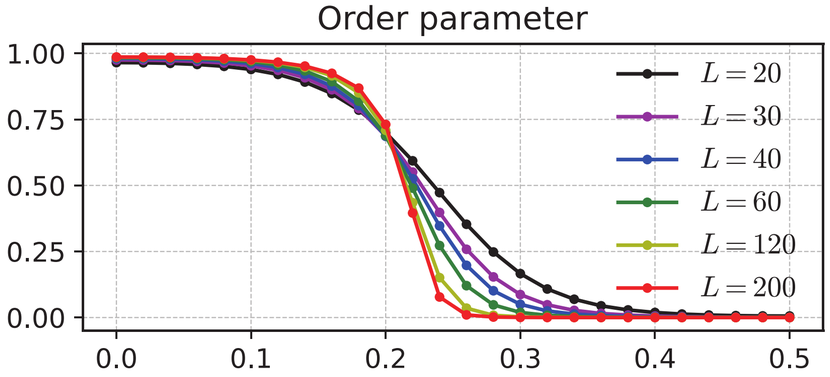
Is it robust far from projective measurements and is there a privileged measurement direction?

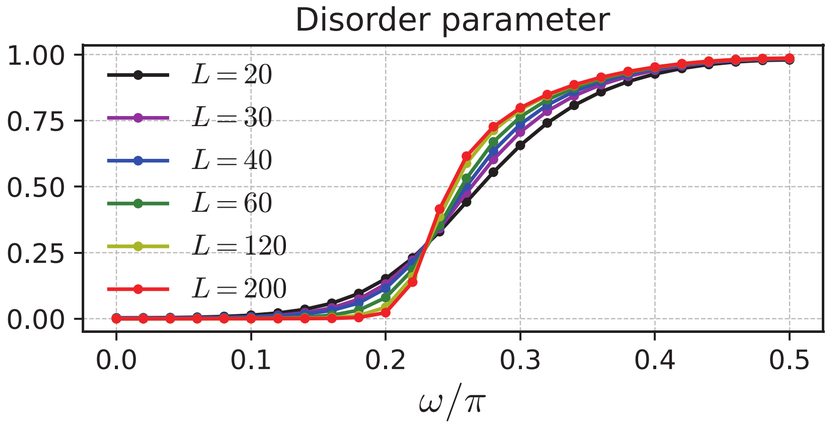
Is the decoding protocol still valid?











...outlook

REVIEW

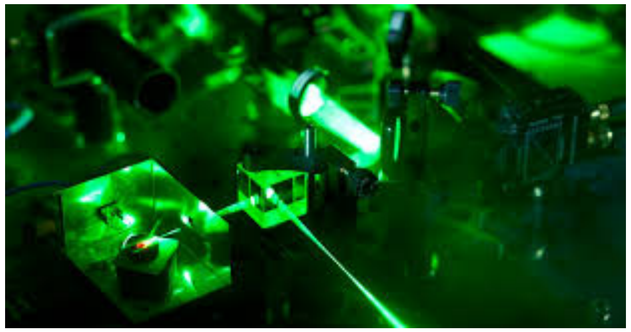
Quantum-Enhanced Measurements: Beating the Standard Quantum Limit

Vittorio Giovannetti,[1] Seth Lloyd,[2*] Lorenzo Maccone[3]

Quantum mechanics, through the Heisenberg uncertainty principle, imposes limits on the precision of measurement. Conventional measurement techniques typically fail to reach these limits. Conventional bounds to the precision of measurements such as the shot noise limit or the standard quantum limit are not as fundamental as the Heisenberg limits and can be beaten using quantum strategies that employ "quantum tricks" such as squeezing and entanglement.

Roadmap in criticality & quantum sensing:

- Measurements and quantum critical metrological gain:
  application of states with long-range order and power-law decay?



...outlook

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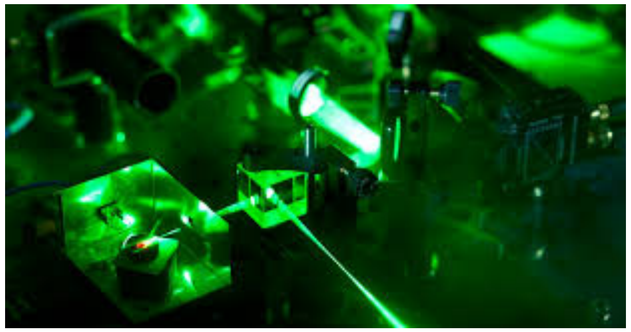

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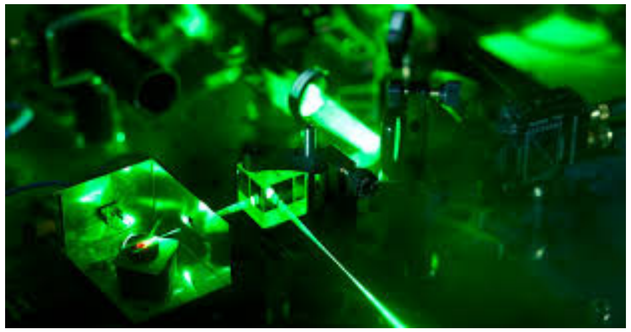
- Use measurements to produce different critical states?
- Theory side: Higher-dimensions, critical (but non-conformal) field theories, fuzzy sphere ...



Thanks!