An SPT-LSM theorem for weak SPTs with non-invertible symmetry

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Quantum phases and symmetry

A fundamental problem in quantum condensed matter physics is to understand quantum phases

1. How do we diagnose different quantum phases?
2. What are the allowed possible quantum phases?

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2. What are the allowed possible quantum phases?

Sometimes, phases are characterized by a symmetry

- Superfluids by U(1) boson number conservation

- Topological insulators by $\mathrm{U}(1)_f$ and $\mathbb{Z}_2^{\mathrm{T}}$ symmetries

For such phases, symmetries provide answers to questions (1) and (2).

Generalized symmetries

There has been a recent flurry of interest in generalizing the notion of symmetries

- Ordinary symmetries transform local operators in an invertible manner (e.g., $c_r^\dagger \to \mathrm{e}^{\mathrm{i}\theta} c_r^\dagger$)
- So-called generalized symmetries modify this definition

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Non-invertible symmetries have non-invertible transformations

[Bhardwaj, Tachikawa 2017; Chang, Lin, Shao, Wang, Yin 2018; ⋯]

- Can arise at critical points from Kramers-Wannier dualities
  [⋯ ; Choi, Córdova, Hsin, Lam, Shao 2021; ⋯ ; Seiberg, Shao 2023; **SP**, Delfino, Lam, Aksoy 2024]
- Can emerge in ordered phases (are symmetries of nonlinear sigma models) [**SP** 2023; **SP**, Zhu, Beaudry, X-G Wen 2023]

Generalized symmetries

Q: Why should we consider these as symmetries?

Generalized symmetries

Q: Why should we consider these as symmetries?

A: They pass the duck test!

If it looks like a duck, swims like a duck, and quacks like a duck, then it probably is a duck.

- Have conservation laws
- Can constrain phase diagrams (be anomalous)
- Can characterize SSB and SPT phases

Quantum phases + generalized symmetry

Which quantum phases are characterized by generalized symmetries?

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Which quantum phases are characterized by generalized symmetries?

Build-a-phase recipe

(1) Choose your generalized symmetries adjectives

$$a_1 - a_2 - a_3 - \cdots \text{ Symmetry}$$

(2) Specify SSB and SPT pattern

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Ordered phases *Topological insulators*

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Ordered phases *Topological insulators*

Topological order *Maxwell phases* *Higgs phases* *Fracton phases*

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Ordered phases

Topological insulators

Topological order

Maxwell phases

Higgs phases

Fracton phases

Phases we have yet to name!

Quantum phases + generalized symmetry

Which quantum phases are characterized by generalized symmetries?

Why care?

1. Provides a novel and unifying perspective of quantum phases
2. Guides us towards new quantum phases and models
3. Further develops a classification of quantum phases based on symmetries (a "generalized Landau paradigm")

TL;DR for this talk

In this talk, we explore Symmetry Protected Topological (SPT) phases characterized by non-invertible symmetries

- Find a new class of entangled weak SPTs characterized by projective non-invertible symmetries

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In this talk, we explore Symmetry Protected Topological (SPT) phases characterized by non-invertible symmetries

- Find a new class of entangled weak SPTs characterized by projective non-invertible symmetries

Outline:

1. Review SPTs (from a symmetry defect perspective)
2. Simple example of an entangled weak SPT characterized by a projective non-invertible symmetry
3. General discussion on (SPT-)LSM theorems from projective non-invertible symmetries

What are SPTs

An SPT phase is a gapped quantum phase described by a symmetry with a unique ground state on all closed spatial manifolds [Chen, Gu, Liu, Wen 2011; Wang, Senthil 2013; Else, Nayak 2014; ⋯]

- Interesting physics can arise on boundaries and interfaces between SPTs (e.g., topological order, gapless excitations)

SPTs are characterized in the bulk by their response to static probes

- Background gauge fields and symmetry defects

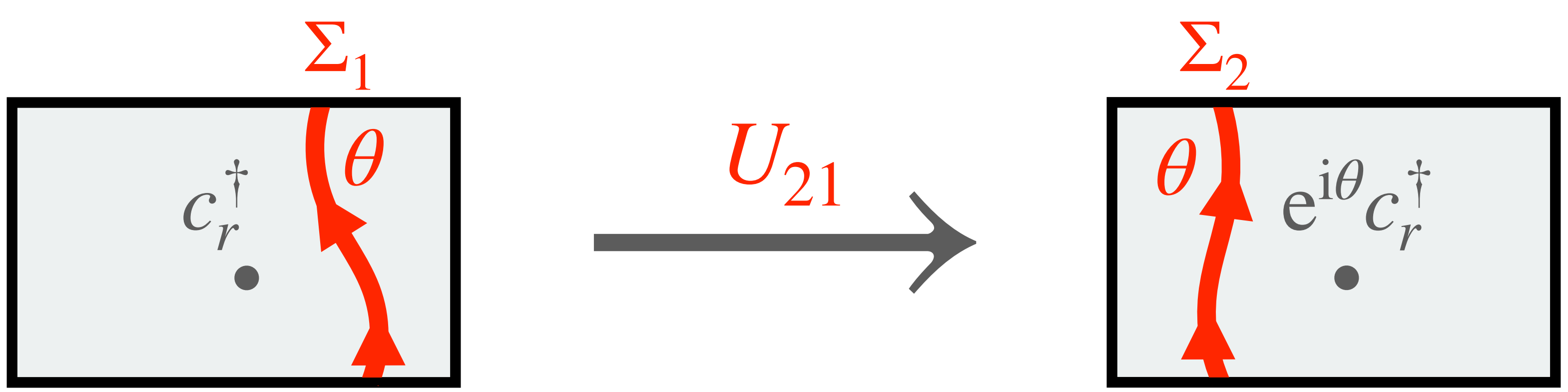
Symmetry defects

Symmetry defects (domain walls) are localized modifications to the Hamiltonian $H^{(\Sigma)}_{\text{defect}} = H + \delta H(\Sigma)$ and other operators

- Moved using unitary operators (are topological defects)

$$H^{(\Sigma_2)}_{\text{defect}} = U_{21} H^{(\Sigma_1)}_{\text{defect}} U^{\dagger}_{21}$$

- Implement the symmetry transformation across space



- Twisted boundary conditions $(T_{\perp})^{L}$ = Symmetry operator

Example: $\mathbb{Z}_2 \times \mathbb{Z}_2$ SPTs

1d periodic lattice with two qubits on each site $j \sim j + L$ acted on by Pauli operators X_j, Z_j and $\tilde{X}_j$, $\tilde{Z}_j$.

$$H_p = -\sum_{j=1}^{L} (X_j + \tilde{X}_j)$$

$$|\mathrm{GS}_p\rangle = |+ + \cdots +\rangle$$

$$H_c = -\sum_{j=1}^{L} \left(\tilde{Z}_{j-1} X_j \tilde{Z}_j + Z_j \tilde{X}_j Z_{j+1}\right)$$

$$|\mathrm{GS}_c\rangle = \tilde{Z}_{j-1} X_j \tilde{Z}_j |\mathrm{GS}_c\rangle = Z_j \tilde{X}_j Z_{j+1} |\mathrm{GS}_c\rangle$$

- Both models have a unique symmetric gapped ground state
- There is a $\mathbb{Z}_2 \times \tilde{\mathbb{Z}}_2$ symmetry $U = \prod_j X_j$ and $\tilde{U} = \prod_j \tilde{X}_j$ with $U|\mathrm{GS}_\bullet\rangle = \tilde{U}|\mathrm{GS}_\bullet\rangle = |\mathrm{GS}_\bullet\rangle$

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H_p and H_c are both in a $\mathbb{Z}_2 \times \tilde{\mathbb{Z}}_2$ SPT phase

Distinguishing $\mathbb{Z}_2 \times \mathbb{Z}_2$ SPTs

Are H_p and H_c in different $\mathbb{Z}_2 \times \tilde{\mathbb{Z}}_2$ SPT phases?

We can check by inserting a U symmetry defect at $\langle L, 1 \rangle$

➤ Gives rise to U-twisted boundary conditions: $Z_{j+L} = -Z_j$

1. H_p is unaffected, so its ground state still satisfies

$$U\,|\mathrm{GS}_{p;U}\rangle = +\,|\mathrm{GS}_{p;U}\rangle \qquad \tilde{U}\,|\mathrm{GS}_{p;U}\rangle = +\,|\mathrm{GS}_{p;U}\rangle$$

2. H_c becomes $H_c + 2\,Z_L\,\tilde{X}_L\,Z_1$, and its ground state satisfies

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Different domain wall decorations imply that H_p and H_c are in different $\mathbb{Z}_2 \times \tilde{\mathbb{Z}}_2$ SPT phases

[Chen, Lu, Vishwanath 2013; Gaiotto, Johnson-Freyd 2017; Wang, Ning, Cheng 2021]

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Example: $\mathbb{Z}_2$ weak SPTs

1d periodic lattice with a qubit on each site $j \sim j + L$

$$H_+ = -\sum_j X_j \quad \text{vs.} \quad H_- = +\sum_j X_j$$

- Both have a unique gapped ground state $|\mathrm{GS}_\pm\rangle = \otimes_j |\pm\rangle$
- Symmetries: $\mathbb{Z}_2 \times \mathbb{Z}_L$ with $U = \prod_j X_j$ and $T: j \to j+1$

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SPTs characterized by translations are called weak SPTs

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Let's insert a $U = \prod_j X_j$ symmetry defect at $\langle L, 1 \rangle$

- Neither H_+ or H_- are modified by $Z_{j+L} = -Z_j$
- Translation operator becomes $T = X_1 T_{\text{defect-free}}$ $(T^L = U)$

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	Even L	Even L, $\mathbb{Z}_2$ symmetry defect
$U\lvert\text{GS}_\pm\rangle =$	$+\lvert\text{GS}_\pm\rangle$	$+\lvert\text{GS}_\pm\rangle$
$T\lvert\text{GS}_\pm\rangle =$	$+\lvert\text{GS}_\pm\rangle$	$\pm\lvert\text{GS}_\pm\rangle$

Different $\mathbb{Z}_2$ weak SPTs

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Are H_+ and H_- in different $\mathbb{Z}_2$ weak SPT phases?

Translation defect carries $\mathbb{Z}_2$ symmetry charge in $|\mathrm{GS}_-\rangle$

- Inserting a translation defect is done by

$$T^L = 1 \to T^L = T \implies L \to L-1$$

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	Even L	Even L, $\mathbb{Z}_2$ symmetry defect	Odd L
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A curious Hamiltonian

1d periodic lattice with a single qubit and $\mathbb{Z}_4$ qudit on each site $j \sim j + L$ [**SP**, Lam, Aksoy arXiv:2409.18113]

- σ^x, σ^z act on qubits: $(\sigma^x)^2 = (\sigma^z)^2 = 1$ and $\sigma^z\sigma^x = -\sigma^x\sigma^z$
- X, Z act on $\mathbb{Z}_4$ qudits: $X^4 = Z^4 = 1$ and $ZX = \mathrm{i}\,XZ$

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$$H = -\sum_j \sigma_j^x\, C_{j+1}\, \sigma_{j+1}^x + \frac{1}{4} \sum_j (Z_j - Z_j^\dagger)\, \sigma_j^z\, (Z_{j+1} - Z_{j+1}^\dagger)$$

- C acts as $X \to X^\dagger$ and $Z \to Z^\dagger$
- Is a sum of commuting terms and has a unique gapped ground state

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- C
- Is
gr

$$|\,\mathrm{GS}\rangle = \sum_{\substack{\{\varphi_j = 0,1\}\\ \{\alpha_j = 0,2\}}} \mathrm{i}^{\sum_j \alpha_j(\varphi_j - \varphi_{j-1})} \bigotimes_j |\,\sigma^x_j = (-1)^{\varphi_j},\ Z_j = \mathrm{i}^{\alpha_j+1}\rangle$$

Some curious symmetries

$$H = -\sum_j \sigma_j^x\, C_{j+1}\, \sigma_{j+1}^x + \frac{1}{4}\sum_j (Z_j - Z_j^\dagger)\, \sigma_j^z\, (Z_{j+1} - Z_{j+1}^\dagger)$$

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What are the symmetries of H?

- $\mathbb{Z}_L$ lattice translations T: $j \to j+1$
- Three $\mathbb{Z}_2$ symmetry operators

$$U = \prod_j X_j^2, \qquad R_1 = \prod_j \sigma_j^z, \qquad R_2 = \prod_j Z_j^2$$

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- 🤷 symmetry operator

$$R_{\mathsf{E}} = \frac{1}{2} \left(1 + R_1\right) \left(1 + R_2\right) \prod_j Z_j^{\prod_{k=1}^{j-1} \sigma_k^z}$$

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What are the symmetries of H?

- $\mathbb{Z}$
- T

R_E is a non-invertible symmetry operator

- $R_\mathsf{E} |\psi\rangle = 0$ if $R_1 |\psi\rangle = -|\psi\rangle$ or $R_2 |\psi\rangle = -|\psi\rangle$
- R_E have zero-eigenvalues $\Longrightarrow$ R_E is non-invertible

- 🤷‍♂️ symmetry operator

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A curious SPT

These symmetry operators obey

$$U^2 = 1, \quad R_i^2 = 1, \quad R_{\mathsf{E}}^2 = 1 + R_1 + R_2 + R_1 R_2, \quad R_{\mathsf{E}} R_i = R_i R_{\mathsf{E}} = R_{\mathsf{E}}$$

$$U\, R_{\mathsf{E}} = (-1)^L R_{\mathsf{E}}\, U$$

- Form a (projective) $\mathbb{Z}_2 \times \mathsf{Rep}(D_8)$ symmetry

Dihedral group of order 8 $D_8 \simeq \langle r, s \mid r^2 = s^4 = 1, rsr = s^3 \rangle$

- Four 1d reps $\mathbf{1}$, $\mathbf{P}_1$, $\mathbf{P}_2$, $\mathbf{P}_3 = \mathbf{P}_1 \otimes \mathbf{P}_2$ and one 2d irrep E

$$\mathbf{P}_i \otimes \mathbf{P}_i = \mathbf{1} \qquad \mathsf{E} \otimes \mathsf{E} = \mathbf{1} \oplus \mathbf{P}_1 \oplus \mathbf{P}_2 \oplus \mathbf{P}_3 \qquad \mathsf{E} \otimes \mathbf{P}_i = \mathbf{P}_i \otimes \mathsf{E} = \mathsf{E}$$

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Ground state satisfies

$$T|\mathrm{GS}\rangle = +|\mathrm{GS}\rangle \qquad U|\mathrm{GS}\rangle = +|\mathrm{GS}\rangle \qquad R_1|\mathrm{GS}\rangle = +|\mathrm{GS}\rangle$$

$$R_2|\mathrm{GS}\rangle = \begin{cases} +|\mathrm{GS}\rangle, & L \text{ even} \\ -|\mathrm{GS}\rangle, & L \text{ odd} \end{cases} \qquad R_{\mathsf{E}}|\mathrm{GS}\rangle = \begin{cases} +2|\mathrm{GS}\rangle, & L \text{ even} \\ 0, & L \text{ odd} \end{cases}$$

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➤ Form a (projective) $\mathbb{Z}_2 \times \mathsf{Rep}(D_8)$ symmetry

H is in a $\mathbb{Z}_2 \times \mathsf{Rep}(D_8)$ weak SPT phase

➤ Translation defects carry $\mathsf{Rep}(D_8)$ symmetry charge in $|\mathrm{GS}\rangle$

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A curious projective algebra

This SPT is characterized by a projective symmetry:

$$U\,R_{\mathsf{E}} = -R_{\mathsf{E}}\,U \qquad (\text{odd } L)$$

Projective unitary symmetries $U_1 U_2 = \mathrm{e}^{\mathrm{i}\theta} U_2 U_1$ forbid SPTs

➤ Assume non-degenerate symmetric ground state:

1. $\langle\psi|\,U_1 U_2\,|\psi\rangle = \langle\psi|\psi\rangle = 1$
2. $\langle\psi|\,U_1 U_2\,|\psi\rangle = \mathrm{e}^{\mathrm{i}\theta}\langle\psi|\,U_2 U_1\,|\psi\rangle = \mathrm{e}^{\mathrm{i}\theta}$

} *Contradicts assumption*

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Projective non-invertible symmetries <u>are compatible</u> with SPTs

- Loophole: symmetry operator has zero-eigenvalues
- $UR_{\mathsf{E}} = (-1)^L R_{\mathsf{E}}U$ enforces $R_{\mathsf{E}}|\mathrm{GS}_{\mathrm{SPT}}\rangle = 0$ when L is odd

The surprising lack of an 't Hooft anomaly

Inserting U or R_{E} symmetry defects leads to the projective algebras

U *symmetry defect*	R_{E} *symmetry defect*
$R_{\mathsf{E}}\,T = -\,T\,R_{\mathsf{E}}$	$T\,U = -\,U\,T$

For invertible symmetries, such projective algebras imply an 't Hooft anomaly (e.g., the type III anomaly $(-1)^{\int_{M_3} a\cup b\cup c}$)

[Matsui 2008; Yao, Oshikawa 2020; Seifnashri 2023; Kapustin, Sopenko 2024]

➤ This is not true for non-invertible symmetries!

The surprising lack of an ’t Hooft anomaly

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Fails because of $R_{\mathsf{E}} = 0$ loophole

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... 2023; Kapustin, Sopenko 2024]

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The surprising lack of an ’t Hooft anomaly

Inserting U or R_{E} symmetry defects leads to the projective algebras

U symmetry defect	*R_{E} symmetry defect*
$R_{\mathsf{E}} T = - T R_{\mathsf{E}}$	$T U = - U T$

Fails because of $R_{\mathsf{E}} = 0$ loophole

Fails because the degeneracy is encoded in the defect’s quantum dimension

For invertib… metries, such projectiv… bras imply an ’t … the type … 2023; Kapustin, …

- This is not true for non-inv…

Projective $Z(G) \times \mathsf{Rep}(G)$ symmetry

The projective $\mathbb{Z}_2 \times \mathsf{Rep}(D_8)$ symmetry is a special case of a more general projective $Z(G) \times \mathsf{Rep}(G)$ symmetry

- $Z(G)$ is the center of a finite group G
- $\mathsf{Rep}(G)$ is the fusion category of representations of G

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The projective $\mathbb{Z}_2 \times \mathsf{Rep}(D_8)$ symmetry is a special case of a more general projective $Z(G) \times \mathsf{Rep}(G)$ symmetry

- $Z(G)$ is the center of a finite group G
- $\mathsf{Rep}(G)$ is the fusion category of representations of G

$Z(G)$ symmetry operator U_z, with $z \in Z(G)$, satisfies

$$U_{z_1} U_{z_2} = U_{z_1 z_2}$$

$\mathsf{Rep}(G)$ symmetry operator R_Γ, with Γ an irrep of G, satisfies

$$R_{\Gamma_a} \times R_{\Gamma_b} = R_{\Gamma_a \otimes \Gamma_b} = R_{\oplus_c N_{ab}^c \Gamma_c} = \sum_c N_{ab}^c R_{\Gamma_c}$$

- Non-invertible symmetry when G is non-Abelian

Projective $Z(G) \times \mathsf{Rep}(G)$ symmetry

The projectivity arises through the relation

$$R_\Gamma U_z = (\mathrm{e}^{\mathrm{i}\phi_\Gamma(z)})^L \, U_z R_\Gamma \quad \text{with } \mathrm{e}^{\mathrm{i}\phi_\Gamma(z)} = \mathrm{Tr}[\Gamma(z)] \, / \, d_\Gamma$$

Projective $Z(G) \times \mathsf{Rep}(G)$ symmetry

The projectivity arises through the relation

$$R_\Gamma U_z = (\mathrm{e}^{\mathrm{i}\phi_\Gamma(z)})^L U_z R_\Gamma \quad \text{with } \mathrm{e}^{\mathrm{i}\phi_\Gamma(z)} = \mathrm{Tr}[\Gamma(z)] / d_\Gamma$$

e.g., $\mathrm{e}^{\mathrm{i}\phi_\Gamma(z)}$ when $G = \mathbb{Z}_2$ $(Z(\mathbb{Z}_2) = \mathbb{Z}_2)$

z \ Γ	$\mathbf{1}$	sign
$+1$	$+1$	$+1$
-1	$+1$	-1

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e.g., $e^{i\phi_\Gamma(z)}$ when $G = D_8$ $(Z(D_8) = \mathbb{Z}_2)$

z \ Γ	$\mathbf{1}$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	E
$+1$	$+1$	$+1$	$+1$	$+1$	$+1$
-1	$+1$	$+1$	$+1$	$+1$	-1

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$+1$	$+1$	$+1$	$+1$	$+1$	$+1$
-1	$+1$	$+1$	$+1$	$+1$	-1

Explicit expressions of U_z and R_Γ for the Hilbert space $\bigotimes_j \mathbb{C}^{|G|}$

$$U_z = \sum_{\{g_j\}} |zg_1, \cdots, zg_L\rangle\langle g_1, \cdots, g_L| \qquad R_\Gamma = \sum_{\{g_j\}} \mathrm{Tr}[\Gamma(g_1 \cdots g_L)]\, |g_1, \cdots, g_L\rangle\langle g_1, \cdots, g_L|$$

Projective $Z(G) \times \mathsf{Rep}(G)$ symmetry

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e.g., $e^{i\phi}$

Projective algebras also arise from inserting symmetry defects [**SP**, Lam, Aksoy arXiv:2409.18113]

$z \in Z(G)$ *defect*	$\Gamma \in \mathsf{Rep}(G)$ *defect*
$R_\Gamma T^{(z)}_{\mathrm{tw}} = e^{i\phi_\Gamma(z)} T^{(z)}_{\mathrm{tw}} R_\Gamma$	$T^{(\Gamma)}_{\mathrm{tw}} U_z = e^{i\phi_\Gamma(z)} U_z T^{(\Gamma)}_{\mathrm{tw}}$

Explic

$\bigotimes_j \mathbb{C}^{|G|}$

$$U_z = \sum_{\{g_j\}} |z g_1, \cdots, z g_L\rangle\langle g_1, \cdots, g_L| \qquad R_\Gamma = \sum_{\{g_j\}} \mathrm{Tr}[\Gamma(g_1 \cdots g_L)] \, |g_1, \cdots, g_L\rangle\langle g_1, \cdots, g_L|$$

(SPT)-LSM theorems

$$R_\Gamma U_z = (\mathrm{e}^{\mathrm{i}\phi_\Gamma(z)})^L U_z R_\Gamma$$

There is an Lieb-Schultz-Mattis (LSM) theorem when $\mathrm{e}^{\mathrm{i}\phi_\Gamma(z)}$ is non-trivial for a unitary R_Γ

[⋯; Matsui 2008; Chen, Gu, Wen 2010; Yao, Oshikawa 2020; Ogata, Tasaki 2021; Seifnashri 2023; Kapustin, Sopenko 2024]

- The LSM theorem forbids SPT phases
- The ground state always has long-range entanglement

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- The LSM theorem forbids SPT phases
- The ground state always has long-range entanglement

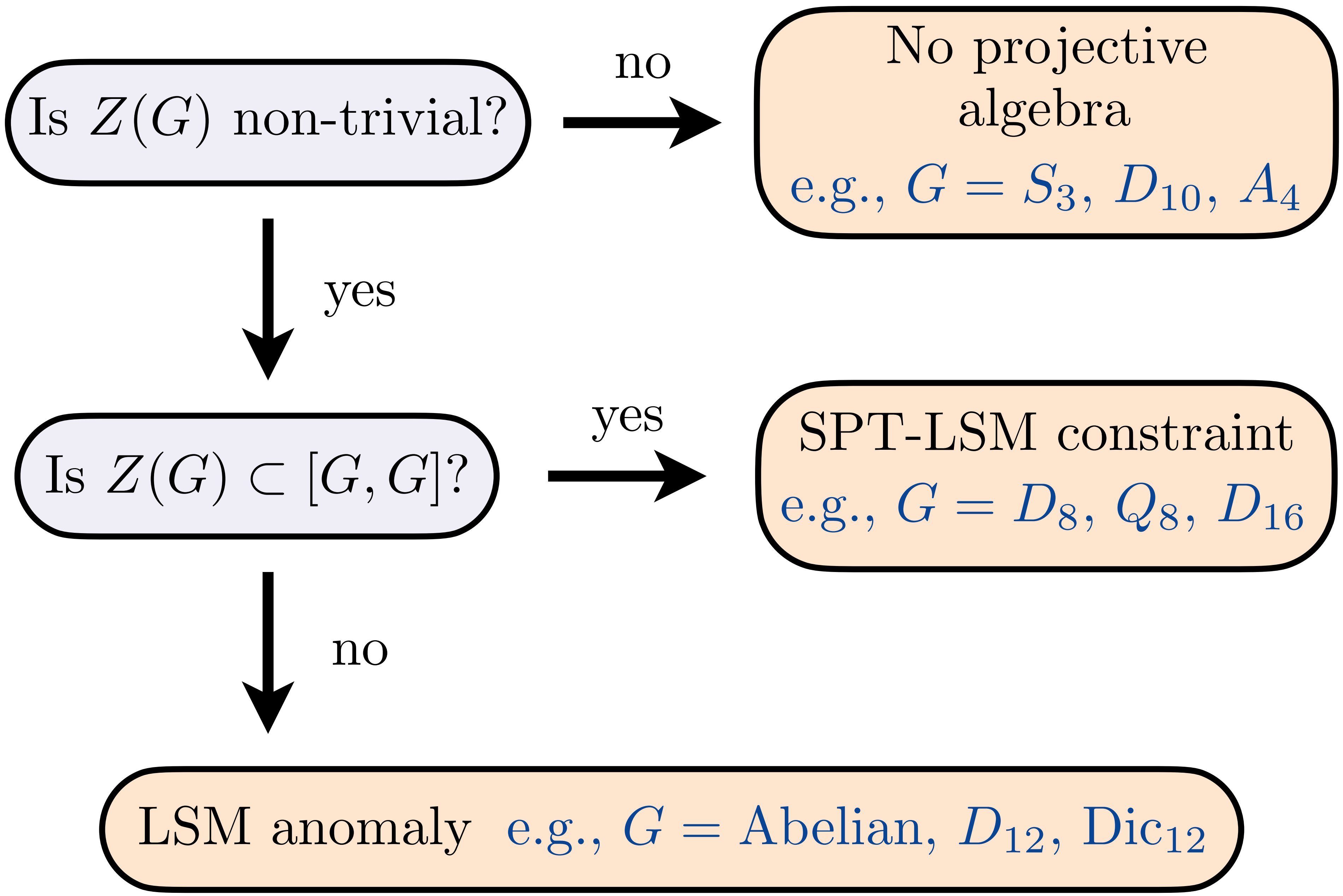
When there is no LSM theorem, the projective algebra gives rise to an SPT-LSM theorem

- Any SPT state must have non-zero entanglement

[Lu 2017; Yang, Jiang, Vishwanath, Ran 2017; Lu, Ran, Oshikawa 2017; ⋯]

(SPT)-LSM theorems

Whether there is an (SPT)-LSM theorem depends on G:



Non-invertible weak SPT

If there is an SPT phase, $R_\Gamma U_z = (\mathrm{e}^{\mathrm{i}\phi_\Gamma(z)})^L U_z R_\Gamma$ forces its ground state to satisfy $R_\Gamma|\mathrm{GS}\rangle = 0$ for nontrivial $(\mathrm{e}^{\mathrm{i}\phi_\Gamma(z)})^L$

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Two possibilities:

1. An SPT state satisfies $R_\Gamma|\mathrm{GS}\rangle = 0$ for all system sizes L
2. For $L = L^*$ where all $(\mathrm{e}^{\mathrm{i}\phi_\Gamma(z)})^{L^*} = 1$, an SPT state satisfies $R_\Gamma|\mathrm{GS}\rangle = \lambda_\Gamma|\mathrm{GS}\rangle$, but $R_\Gamma|\mathrm{GS}\rangle = 0$ for $L \neq L^*$

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The first is incompatible with $1+1$D TQFT, where $\langle R_\Gamma \rangle = d_\Gamma$

[Chang, Lin, Shao, Wang, Yin 2018]

➤ Reasonable to assume that this SPT state at some $L = L^*$ is described by a TQFT in the IR

Non-invertible weak SPT

If there is an SPT phase, $R_\Gamma U_z = (\mathrm{e}^{\mathrm{i}\phi_\Gamma(z)})^L U_z R_\Gamma$ forces its ground state to satisfy $R_\Gamma|\mathrm{GS}\rangle = 0$ for nontrivial $(\mathrm{e}^{\mathrm{i}\phi_\Gamma(z)})^L$

Tw

1.

2.

At $L = L^*$, SPTs satisfy $R_\Gamma|\mathrm{GS}\rangle = \lambda_\Gamma|\mathrm{GS}\rangle$

At $L = L^* + 1$, SPTs satisfy $R_\Gamma|\mathrm{GS}\rangle = 0$

- ➤ All SPT states have translation defects dressed by non-trivial $\mathsf{Rep}(G)$ symmetry charge
- ➤ $\nexists$ a trivial SPT $\Longrightarrow$ SPT-LSM theorem

The $= d_\Gamma$

[Chang, Lin, Shao, Wang, Yin 2018]

➤ Reasonable to assume that this SPT state at some $L = L^*$ is described by a TQFT in the IR

SPT-LSM theorem

To prove this SPT-LSM theorem, we

1. Use that the $Z(G)$ symmetry is on-site:

$$U_z = \prod_j U_j^{(z)} \quad \text{which satisfies} \quad R_\Gamma U_j^{(z)} = \mathrm{e}^{\mathrm{i}\phi_\Gamma(z)}\, U_j^{(z)} R_\Gamma$$

2. Assume that any unique gapped ground state $|\mathrm{GS}\rangle$ satisfies $R_\Gamma|\mathrm{GS}\rangle \neq 0$ for some system size $L = L^*$

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We prove this assumption for product states in $\bigotimes_j \mathbb{C}^{|G|}$, *where*

$$R_\Gamma = \sum_{\{g_j\}} \mathrm{Tr}[\Gamma(g_1 \cdots g_L)]\,|g_1, \cdots, g_L\rangle\langle g_1, \cdots, g_L|$$

but it is true as long as there is an IR TQFT description

SPT-LSM theorem

If there is a unique gapped $|\mathrm{GS}\rangle$ that is a product state:

- $U_z|\mathrm{GS}\rangle = |\mathrm{GS}\rangle \Longrightarrow U_j^{(z)}|\mathrm{GS}\rangle = |\mathrm{GS}\rangle$

Using the assumption, $R_\Gamma|\mathrm{GS}\rangle = \lambda_\Gamma|\mathrm{GS}\rangle$ at $L = L^*$:

1. $R_\Gamma U_j^{(z)}|\mathrm{GS}\rangle = R_\Gamma|\mathrm{GS}\rangle = \lambda_\Gamma|\mathrm{GS}\rangle$
2. $R_\Gamma U_j^{(z)}|\mathrm{GS}\rangle = \mathrm{e}^{\mathrm{i}\phi_\Gamma(z)} U_j^{(z)} R_\Gamma|\mathrm{GS}\rangle = \lambda_\Gamma \mathrm{e}^{\mathrm{i}\phi_\Gamma(z)}|\mathrm{GS}\rangle$

$\Big\}$ *Contradiction*

SPT-LSM theorem

If there is a unique gapped $|\mathrm{GS}\rangle$ that is a product state:

- $U_z|\mathrm{GS}\rangle = |\mathrm{GS}\rangle \implies U_j^{(z)}|\mathrm{GS}\rangle = |\mathrm{GS}\rangle$

Using the assumption, $R_\Gamma|\mathrm{GS}\rangle = \lambda_\Gamma|\mathrm{GS}\rangle$ at $L = L^*$:

$$\left.\begin{aligned}&1.\ \ R_\Gamma U_j^{(z)}|\mathrm{GS}\rangle = R_\Gamma|\mathrm{GS}\rangle = \lambda_\Gamma|\mathrm{GS}\rangle\\ &2.\ \ R_\Gamma U_j^{(z)}|\mathrm{GS}\rangle = \mathrm{e}^{\mathrm{i}\phi_\Gamma(z)}U_j^{(z)}R_\Gamma|\mathrm{GS}\rangle = \lambda_\Gamma \mathrm{e}^{\mathrm{i}\phi_\Gamma(z)}|\mathrm{GS}\rangle\end{aligned}\right\} \mathit{Contradiction}$$

$\implies$ Cannot be an SPT state that is a product state at $L = L^*$

SPT-LSM theorem

If there is a unique gapped $|\mathrm{GS}\rangle$ that is a product state:

- $U_z|\mathrm{GS}\rangle = |\mathrm{GS}\rangle \implies U_j^{(z)}|\mathrm{GS}\rangle = |\mathrm{GS}\rangle$

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$\Big\}$ *Contradiction*

$\implies$ Cannot be an SPT state that is a product state at $L = L^*$

$\implies$ By locality, there cannot be an SPT state that is a product state for any L

SPT-LSM theorem

If there is a unique gapped $|\mathrm{GS}\rangle$ that is a product state:

➤ $U_z|\mathrm{GS}\rangle = |\mathrm{GS}\rangle \implies U_j^{(z)}|\mathrm{GS}\rangle = |\mathrm{GS}\rangle$

Usin

1. R

diction

2. R

Therefore, the projective non-invertible symmetry prevents a product state SPT

➤ All SPTs must have non-zero entanglement

$\implies$ Cannot be an SPT state that is a product state at $L = L^*$

$\implies$ By locality, there cannot be an SPT state that is a product state for any L

Outlook

We found a new class of entangled weak SPTs characterized by a projective $Z(G) \times \mathsf{Rep}(G)$ non-invertible symmetry

1. An exactly solvable model in a weak SPT phase characterized by a projective $\mathbb{Z}_2 \times \mathsf{Rep}(D_8)$ symmetry
2. General discussion on decorated domain wall pattern of these $Z(G) \times \mathsf{Rep}(G)$ weak SPTs $\Longrightarrow$ an SPT-LSM theorem

New quantum phases and models can be discovered using generalized symmetries as a guide!

SP, Lam, Aksoy arXiv:2409.18113

Back-up slides

LSM anomaly in the XY model

Many-qubit model on a periodic chain with Hamiltonian

$$H = \sum_{j=1}^{L} J\,\sigma_j^x\,\sigma_{j+1}^x + K\,\sigma_j^y\,\sigma_{j+1}^y$$

- There is an LSM anomaly involving the $\mathbb{Z}_2^x \times \mathbb{Z}_2^y \times \mathbb{Z}_L$ symmetry [Chen, Gu, Wen 2010; Ogata, Tasaki 2021]

$$U_x = \prod_j \sigma_j^x, \quad U_y = \prod_j \sigma_j^y, \quad \text{and lattice translations } T$$

- Manifests through the projective algebras [Cheng, Seiberg 2023]

Translation defects	$\mathbb{Z}_2^x$ *defect*	$\mathbb{Z}_2^y$ *defect*
$U_x U_y = (-1)^L U_y U_x$	$U_y T = -\,T\,U_y$	$T\,U_x = -\,U_x T$

GROUP BASED QUDITS

A *G*-qudit is a $|G|$-level quantum mechanical system whose states are $|g\rangle$ with $g \in G$

- G is a finite group, e.g. $\mathbb{Z}_2$, S_3, D_8, SmallGroup(32,49)

Group based Pauli operators [Brell 2014]

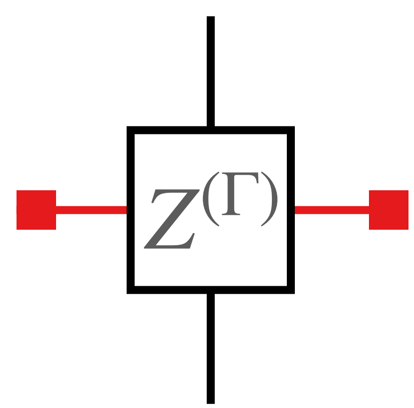
- X operators labeled by group elements

$\bar{g} \equiv g^{-1}$

$$\overrightarrow{X}^{(g)} = \sum_h |gh\rangle\langle h| \qquad \overleftarrow{X}^{(g)} = \sum_h |h\bar{g}\rangle\langle h|$$

- Z operators are MPOs labeled by irreps $\Gamma : G \to \mathrm{GL}(d_\Gamma, \mathbb{C})$

$$[Z^{(\Gamma)}]_{\alpha\beta} = \sum_h [\Gamma(h)]_{\alpha\beta} |h\rangle\langle h| \equiv \alpha$$



$\beta \qquad (\alpha, \beta = 1,2,\cdots, d_\Gamma)$

GROUP BASED QUDITS

Example: $G = \mathbb{Z}_2$ where $g \in \{1, -1\}$ and $\Gamma \in \{\mathbf{1}, \mathbf{1}'\}$

$$\overrightarrow{X}^{(1)} = \overleftarrow{X}^{(1)} = [Z^{(\mathbf{1})}]_{11} = 1$$

$$\overrightarrow{X}^{(-1)} = \overleftarrow{X}^{(-1)} = \sigma^x \qquad [Z^{(\mathbf{1}')}]_{11} = \sigma^z$$

Group based Pauli operators satisfy

1. $\overrightarrow{X}^{(g)}\,\overrightarrow{X}^{(h)} = \overrightarrow{X}^{(gh)}$, $\overleftarrow{X}^{(g)}\,\overleftarrow{X}^{(h)} = \overleftarrow{X}^{(gh)}$, and $\overrightarrow{X}^{(g)}\,\overleftarrow{X}^{(h)} = \overleftarrow{X}^{(h)}\,\overrightarrow{X}^{(g)}$
2. $\overrightarrow{X}^{(g)}\,\overrightarrow{X}^{(h)} = \overrightarrow{X}^{(h)}\,\overrightarrow{X}^{(g)}$ iff g and h commute
3. $\overrightarrow{X}^{(g)}\,[Z^{(\Gamma)}]_{\alpha\beta} = [\Gamma(\bar{g})]_{\alpha\gamma}[Z^{(\Gamma)}]_{\gamma\beta}\,\overrightarrow{X}^{(g)}$
4. Unitarity: $\overrightarrow{X}^{(g)\dagger} = \overrightarrow{X}^{(\bar{g})}$, $\overleftarrow{X}^{(g)\dagger} = \overleftarrow{X}^{(\bar{g})}$, $[Z^{(\Gamma)\dagger}\,Z^{(\Gamma)}]_{\alpha\beta} = \delta_{\alpha\beta}$

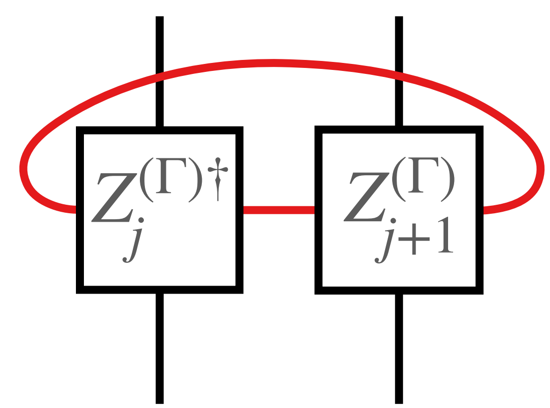
GROUP BASED XY MODEL

Group based Pauli operators are useful for constructing quantum lattice models [Brell 2014; Albert *et. al.* 2021; Fechisin, Tantivasadakarn, Albert 2023]

Group based XY model: Consider a periodic 1d lattice of L sites. On each site j resides a G-qudit and its Hamiltonian

$$H_{XY} = \sum_{j=1}^{L} \left(\sum_{\Gamma} J_\Gamma \operatorname{Tr}\left(Z_j^{(\Gamma)\dagger} Z_{j+1}^{(\Gamma)} \right) + \sum_{g} K_g \overleftarrow{X}_j^{(g)} \overrightarrow{X}_{j+1}^{(g)} \right) + \text{hc}$$

$$\operatorname{Tr}\left(Z_j^{(\Gamma)\dagger} Z_{j+1}^{(\Gamma)} \right) = \sum_{\{g\}} \chi_\Gamma(\bar{g}_j g_{j+1}) \, | \{g\} \rangle \langle \{g\} | \equiv$$



- For $G = \mathbb{Z}_2$, this is the ordinary quantum XY model

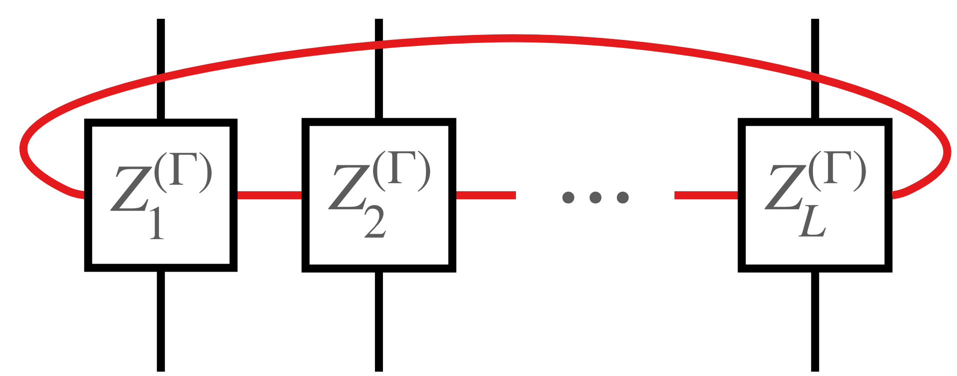
SYMMETRY OPERATORS

$$H_{XY} = \sum_{j=1}^{L} \left(\sum_{\Gamma} J_\Gamma \operatorname{Tr}\left(Z_j^{(\Gamma)\dagger} Z_{j+1}^{(\Gamma)} \right) + \sum_g K_g \overleftarrow{X}_j^{(g)} \overrightarrow{X}_{j+1}^{(g)} \right) + \text{hc}$$

$\mathbb{Z}_L$ lattice translations: $T\mathcal{O}_j T^\dagger = \mathcal{O}_{j+1}$

Various internal symmetries:

- $Z(G)$ symmetry $U_z = \prod_j \overrightarrow{X}_j^{(z)}$ with $z \in Z(G)$
- Rep(G) symmetry $R_\Gamma = \operatorname{Tr}\left(\prod_{j=1}^{L} Z_j^{(\Gamma)} \right) \equiv$



$$R_{\Gamma_a} \times R_{\Gamma_b} = R_{\Gamma_a \otimes \Gamma_b} = R_{\oplus_c N_{ab}^c \Gamma_c} = \sum_c N_{ab}^c R_{\Gamma_c}$$

PROJECTIVE ALGEBRA FROM DEFECTS

$$U_z = \prod_j \vec{X}_j^{(z)} \qquad R_\Gamma = \mathrm{Tr}\left(\prod_{j=1}^{L} Z_j^{(\Gamma)}\right)$$

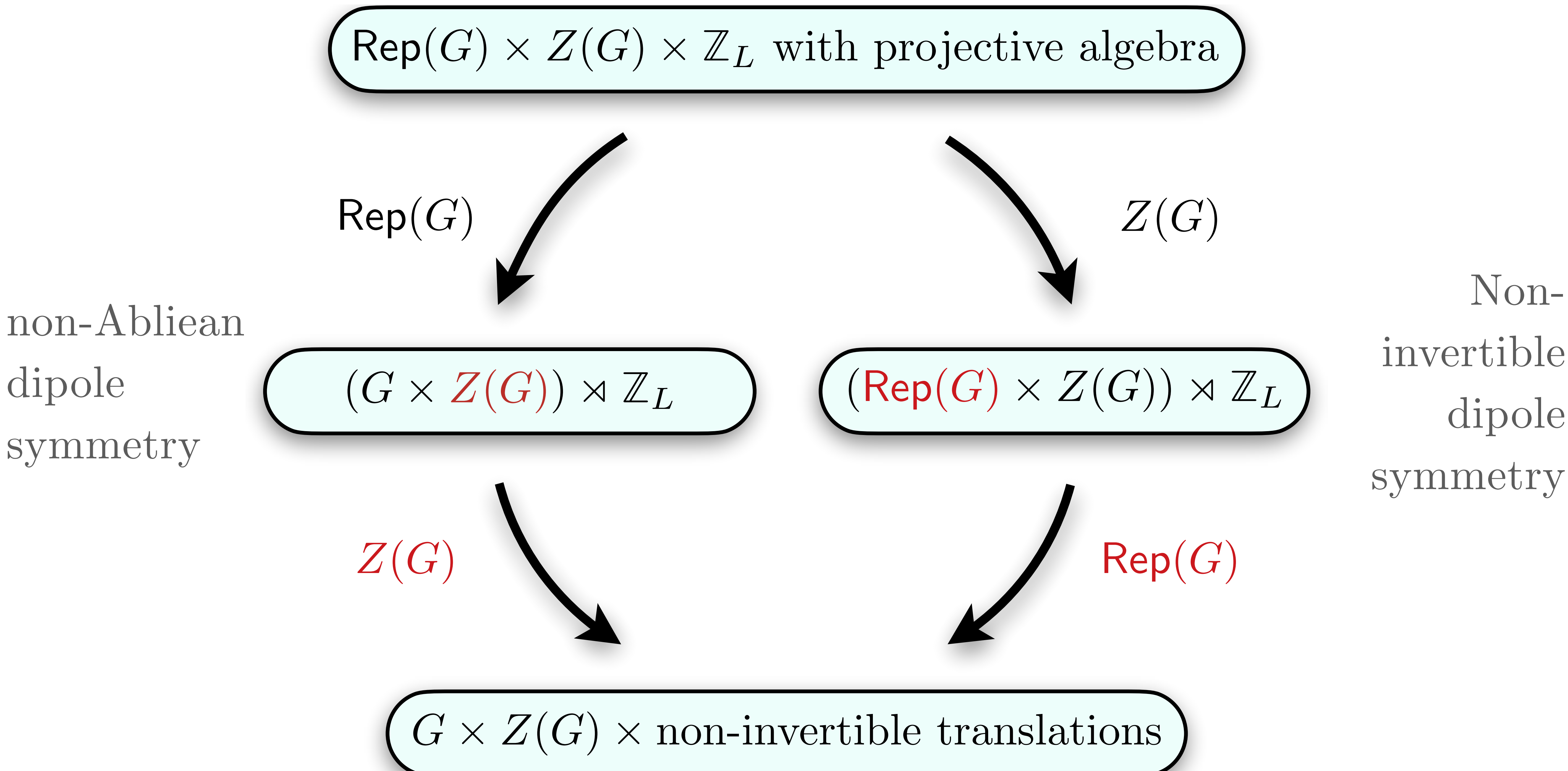
$$T_{\mathrm{tw}}^{(z)} = \vec{X}_I^{(z)}\, T \qquad T_{\mathrm{tw}}^{(\Gamma)} = \hat{Z}_I^{(\Gamma)}\,(T \otimes \mathbf{1})$$

Letting $\mathrm{e}^{\mathrm{i}\phi_\Gamma(z)} \equiv \chi_\Gamma(z)/d_\Gamma$

Translation defects	$z \in Z(G)$ *defect*	$\Gamma \in \mathsf{Rep}(G)$ *defect*
$R_\Gamma U_z = (\mathrm{e}^{\mathrm{i}\phi_\Gamma(z)})^L\, U_z R_\Gamma$	$R_\Gamma T_{\mathrm{tw}}^{(z)} = \mathrm{e}^{\mathrm{i}\phi_\Gamma(z)} T_{\mathrm{tw}}^{(z)} R_\Gamma$	$T_{\mathrm{tw}}^{(\Gamma)}\, U_z = \mathrm{e}^{\mathrm{i}\phi_\Gamma(z)} U_z\, T_{\mathrm{tw}}^{(\Gamma)}$

- Generalizes the $G = \mathbb{Z}_2$ projective algebra of the ordinary quantum XY model

GAUGING WEB



$\mathsf{Rep}(G) \times Z(G) \times \mathbb{Z}_L$ with projective algebra
$\mathsf{Rep}(G)$
$Z(G)$
non-Abliean dipole symmetry
$(G \times Z(G)) \rtimes \mathbb{Z}_L$
$(\mathsf{Rep}(G) \times Z(G)) \rtimes \mathbb{Z}_L$
Non-invertible dipole symmetry
$Z(G)$
$\mathsf{Rep}(G)$
$G \times Z(G) \times$ non-invertible translations