Title: Chiral spin liquid and emergent anyons in a Kagome lattice Mott insulator

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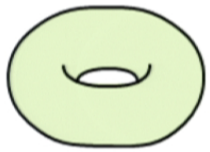
Abstract: Topological phases in frustrated quantum spin systems have fascinated researchers for decades. One of the earliest proposals for such a phase was the chiral spin liquid put forward by Kalmeyer and Laughlin in 1987 as the bosonic analogue of the fractional quantum Hall effect. Elusive for many years, recent times have finally seen a number of models that realize this phase. However, these models are somewhat artificial and unlikely to be found in realistic materials.
Here, we take an important step towards the goal of finding a chiral spin liquid in nature by examining a physically motivated model for a Mott insulator on the Kagome lattice with broken time-reversal symmetry. We first provide a theoretical justification for the emergent chiral spin liquid phase in terms of a network model perspective. We then present an unambiguous numerical identification and characterization of the universal topological properties of the phase, including ground state degeneracy, edge physics, and anyonic bulk excitations, by using a variety of powerful numerical probes, including the entanglement spectrum and modular transformations.

Emergence in complex systems



$\vec{S}_i \cdot (\vec{S}_j \times \vec{S}_k)$

Chiral spin liquid
and
emergent anyons
in a Kagome lattice Mott insulator

Lukasz Cincio and Guifre Vidal

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

with support from

JOHN TEMPLETON FOUNDATION

OUTLINE

- Anyon hunter's wish list:

  Ground state degeneracy
  S and T matrices
  Edge spectrum

- Hubbard model with magnetic field on Kagome

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$$H = J_{HB} \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j + h_z \sum_i S_i^z + J_\chi \sum_{i,j,k \in \Delta} \vec{S}_i \cdot (\vec{S}_j \times \vec{S}_k) + \cdots$$

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- Chiral spin liquid and emergent anyons

(Lukasz)

  Ground state degeneracy
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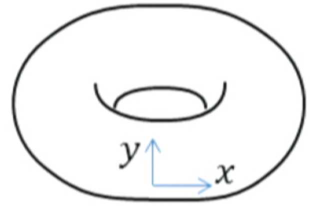
Anyon hunter's wish list

- Ground state degeneracy on the torus

X.-G. Wen, 1989



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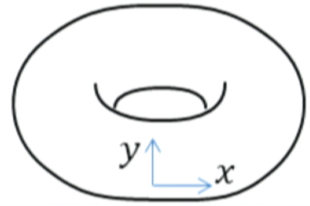
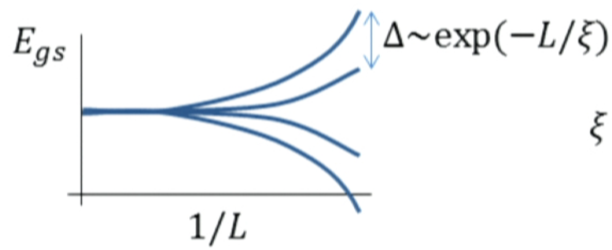


example: toric code has 4 ground states

Finite size L breaks ground state degeneracy



ξ correlation length

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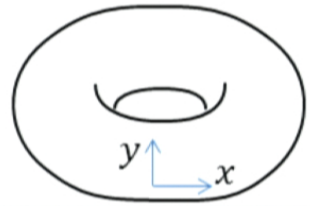

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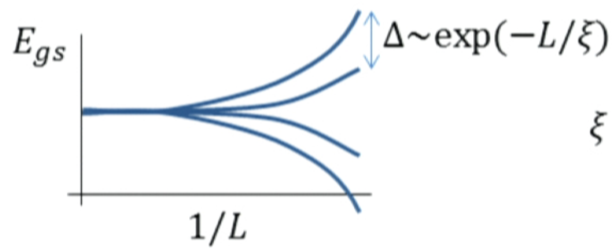

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In particular, if $L_x \gg L_y \gg \xi$

each "ground state" has a well-defined anyon flux i in x-direction

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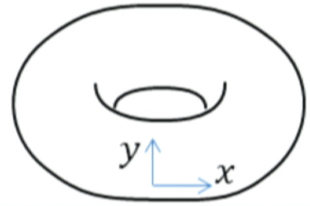

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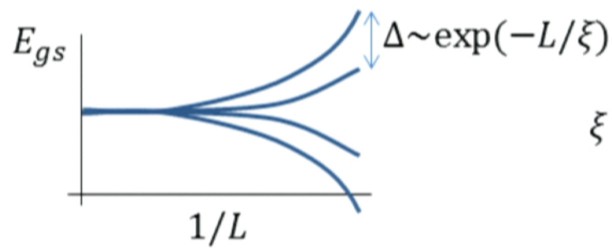

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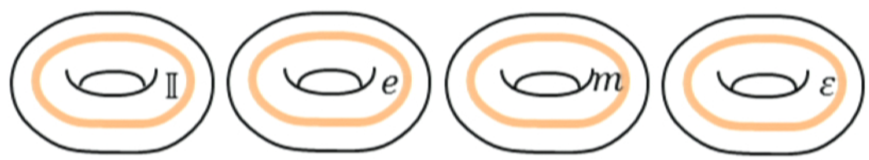
example: toric code $i = \mathbb{I}, e, m, \varepsilon$



Anyon hunter's wish list

- S and T matrices (generators of modular group)

Suppose we could create quasi-particles and exchange them,

self statistics

$|\Psi\rangle \rightarrow e^{i\phi}|\Psi\rangle$ anyon

$|\Psi\rangle \rightarrow |\Psi\rangle$ boson

$|\Psi\rangle \rightarrow -|\Psi\rangle$ fermion

mutual statistics

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topological T matrix

$$T_{ii} = \frac{1}{d_i}$$

$$T = e^{-i\frac{2\pi}{24}c}\begin{bmatrix} \theta_{\mathbb{I}} & & & \\ & \theta_e & & \\ & & \theta_m & \\ & & & \theta_\varepsilon \end{bmatrix}$$

topological spin θ_i

topological central charge c

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topological central charge c

$$T = \begin{bmatrix}1 & & & \\ & 1 & & \\ & & 1 & \\ & & & -1\end{bmatrix}$$

$c = 0$

$\theta_\varepsilon = -1$

$|\Psi\rangle \to -|\Psi\rangle$

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$$S = \frac{1}{D}\begin{bmatrix} d_{\mathbb{I}} & d_e & d_m & d_\varepsilon \\ d_e & x & x & x \\ d_m & x & x & x \\ d_\varepsilon & x & x & x \end{bmatrix}$$

quantum dimensions d_i

total quantum dimension $\mathrm{D} \equiv \sqrt{\sum_i d_i^2}$

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$2S_{em} = -1$

$|\Psi\rangle \to -|\Psi\rangle$

fusion rules $i \times j \to k$

$$N_{ij}^k = \sum_r \frac{S_{im}S_{jm}S^*_{mk}}{S_{1m}}$$

Verlinde formula

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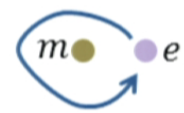

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$m \times e \rightarrow \varepsilon$

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S,T matrices can be extracted from ground state overlaps

Y. Zhang, T. Grover, A. Turner, M. Oshikawa, A. Vishwanath, PRB 2012

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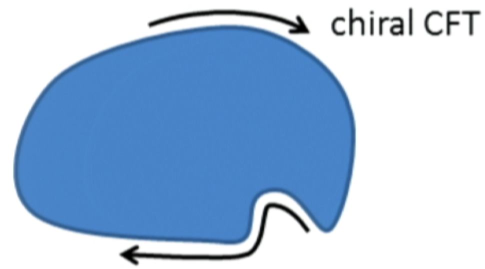
example: on square lattice

$S_{ij} =$ 

Anyon hunter's wish list

- Edge theory

Identify the protected gapless edge state



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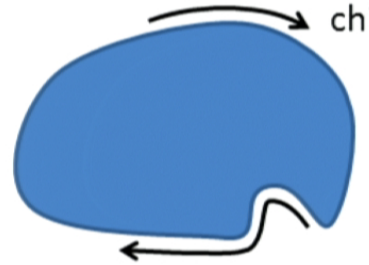
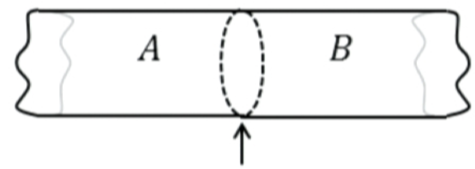


H. Li, F. D. M. Haldane, PRL 2008
X.-L. Qi, H. Katsura, A. W. W. Ludwig, PRL 2012

physical edge

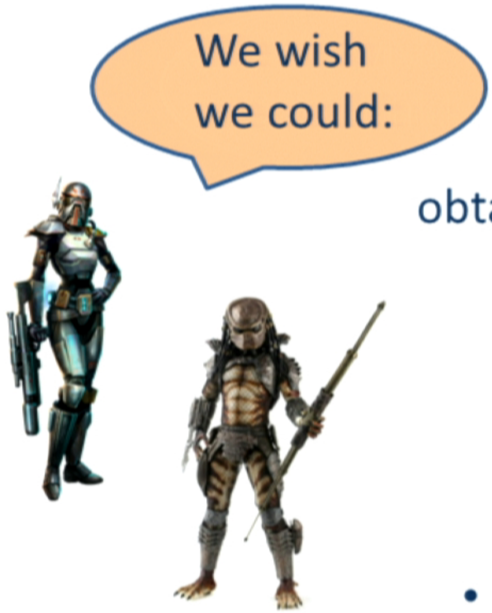
effective edge Hamiltonian H_{edge}

B. Swingle, T. Senthil, PRB 2012
A. Chandran, V. Khemani, S.L. Sondhi, arXiv 2013

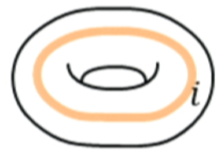


entanglement cut

density matrix for part A $\rho_A = e^{-H_{entanglement}}$



obtain a complete set of ground states on a torus

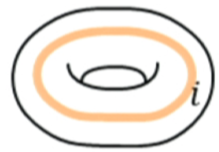


and then extract

- S,T modular matrices (topological excitations)
- entanglement spectrum (edge theory)

We wish
we could:

obtain a complete set of <u>ground states</u> on a torus



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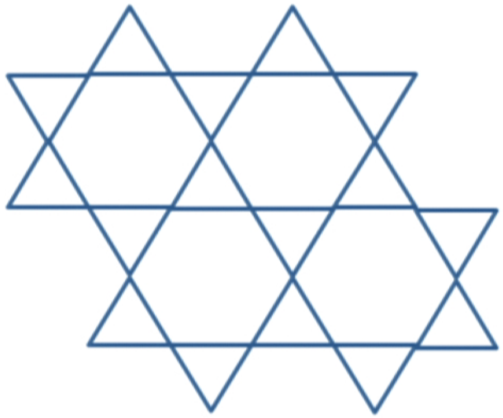
Hubbard model with magnetic field on the Kagome lattice



$$H = -\sum_{\langle i,j\rangle,\sigma}\left(t_{ij}c^{\dagger}_{i\sigma}c_{j\sigma} + t^{*}_{ij}c^{\dagger}_{j\sigma}c_{i\sigma}\right) + \mathrm{U}\sum_{i} n_{i\uparrow}n_{i\downarrow} + \frac{h_z}{2}\sum_{i}(n_{i\uparrow} - n_{i\downarrow})$$

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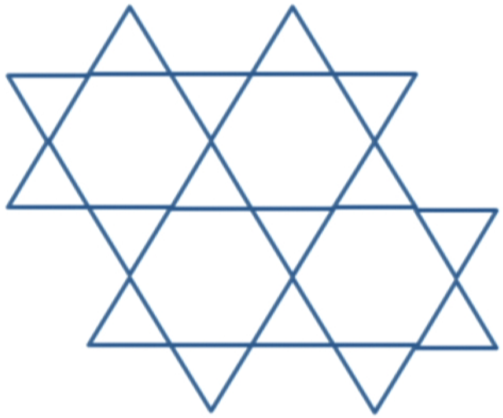

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$$+ \frac{h_z}{2} \sum_{i} (n_{i\uparrow} - n_{i\downarrow})$$

effect of magnetic field:

- Zeeman term h_z
- flux Φ through each elementary triangle

$$t_{ij} t_{jk} t_{ki} = t^3 \exp(i\Phi)$$

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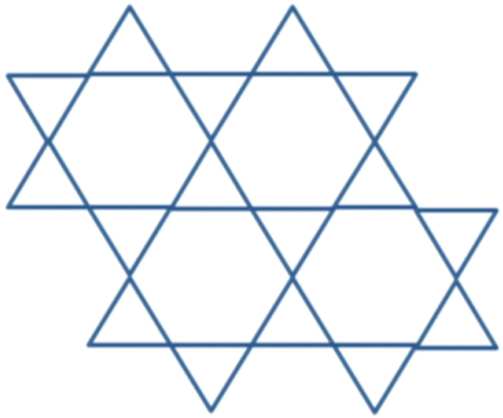

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effect of magnetic field:

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- Half filling $\langle n\rangle = 1$
- Perturbation theory in t/U (large U limit)

O.I. Motrunich, PRB 2006

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$J_{HB} \sim \frac{t^2}{U}$

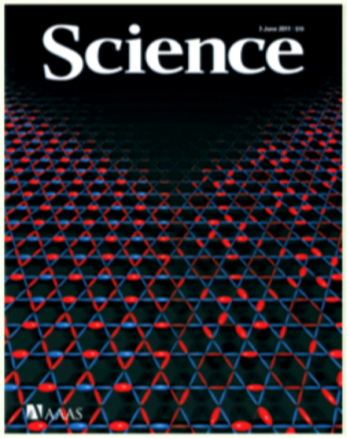
$J_\chi \sim \Phi \frac{t^3}{U^2}$

subleading

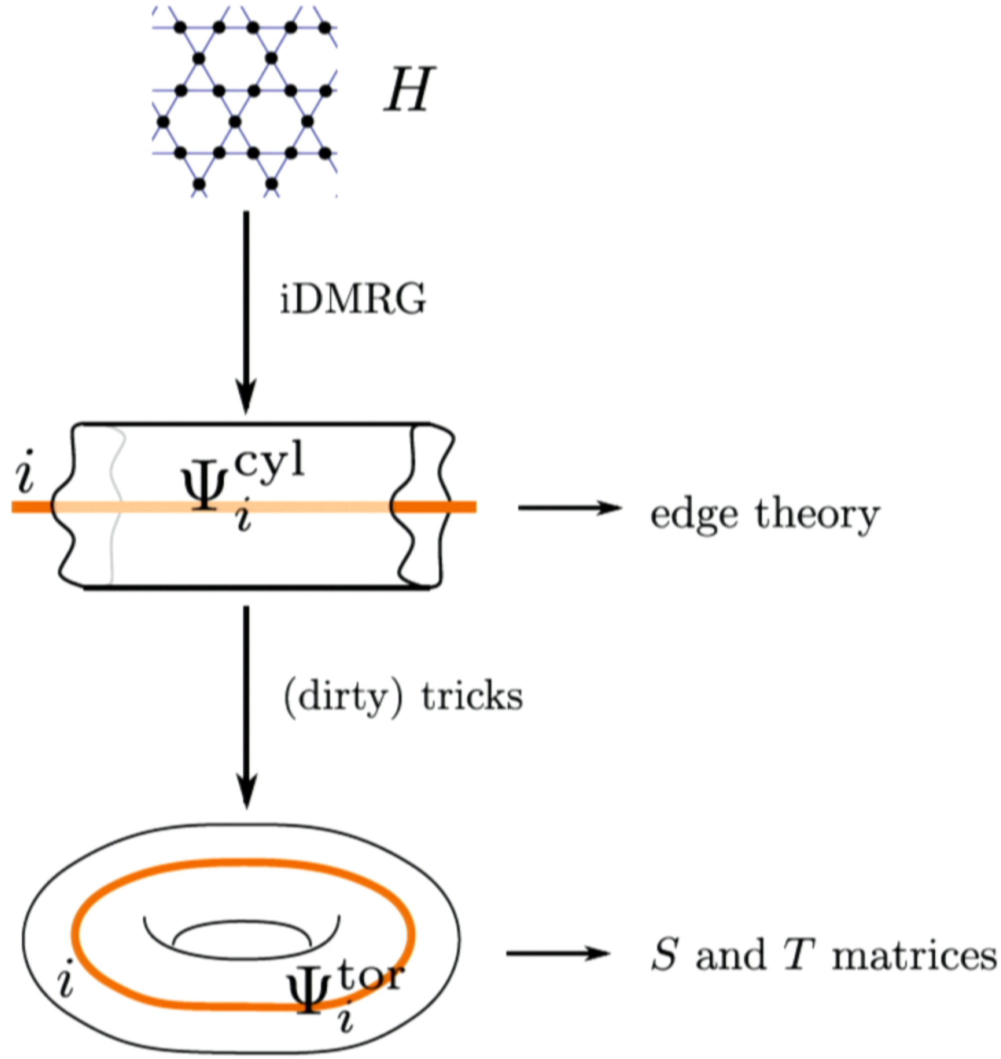
$h_z = 0, \Phi = 0$

$$H = \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$

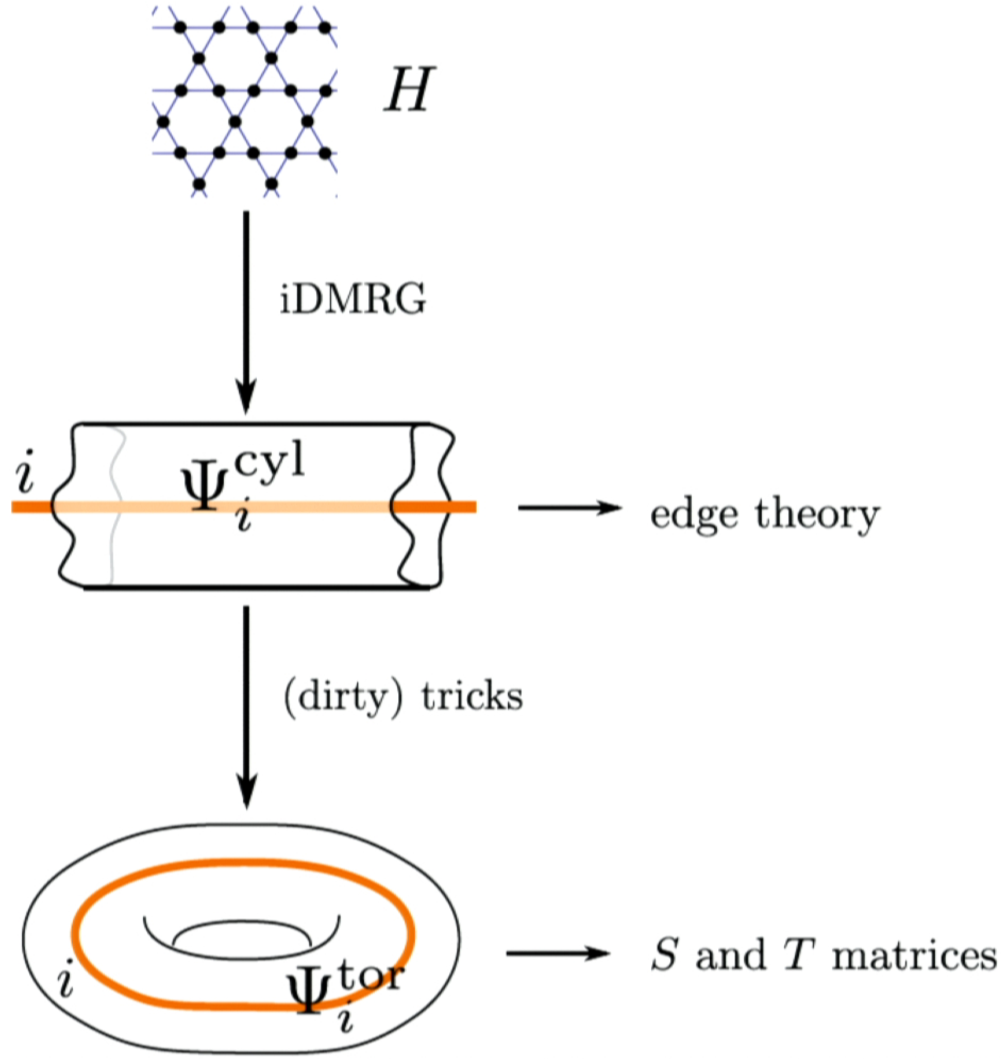
"Spin-liquid ground state of the
$s = 1/2$ Kagome Heisenberg Antiferromagnet"
S. Yan, D. A. Huse, S. R. White, Science (2011)



Anyon hunter's weapon

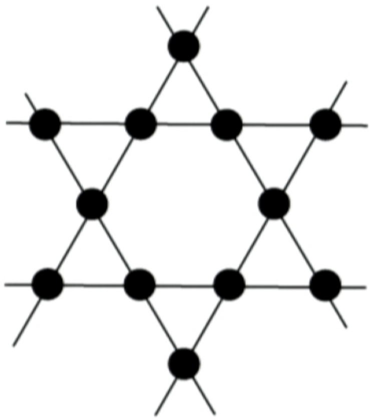


ANYON HUNTER'S WEAPON



MODEL

$$H = \cos\theta \sum_{\langle i,j\rangle} \vec{S}_i \cdot \vec{S}_j + \sin\theta \sum_{i,j,k\in\triangle} \vec{S}_i \cdot (\vec{S}_j \times \vec{S}_k) + h_z \sum_i S_i^z$$



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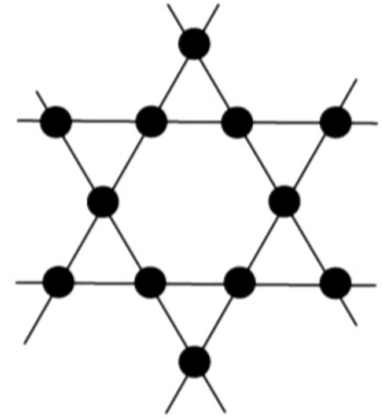
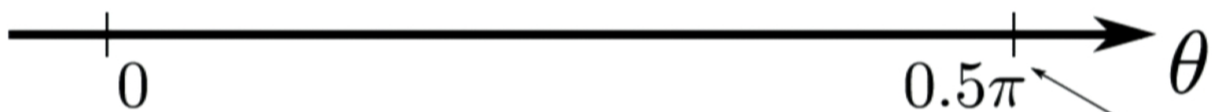
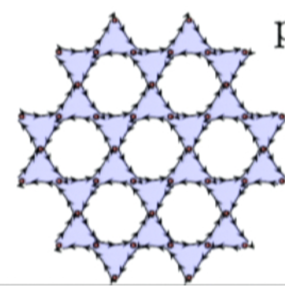


- so far ($h_z = 0$):





purely chiral point

$$H = \sum_{i,j,k \in \triangle} \vec{S}_i \cdot (\vec{S}_j \times \vec{S}_k)$$

speculation:
chiral spin liquid

network model
argument

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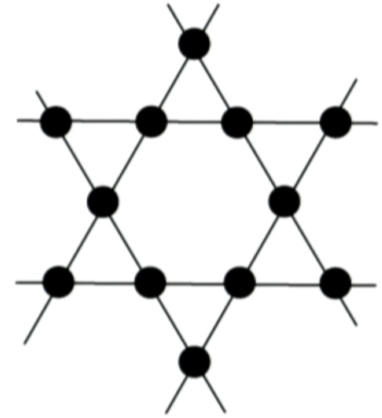

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Heisenberg point

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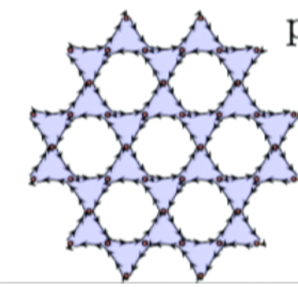
possible $\mathbb{Z}_2$ spin liquid

S. Yan, D. A. Huse, S. R. White, Science (2011)
H.-C. Jiang, Z. Wang, L. Balents, Nature Physics (2012)
S. Depenbrock, I. P. McCulloch, U. Schollwöck, PRL (2012)



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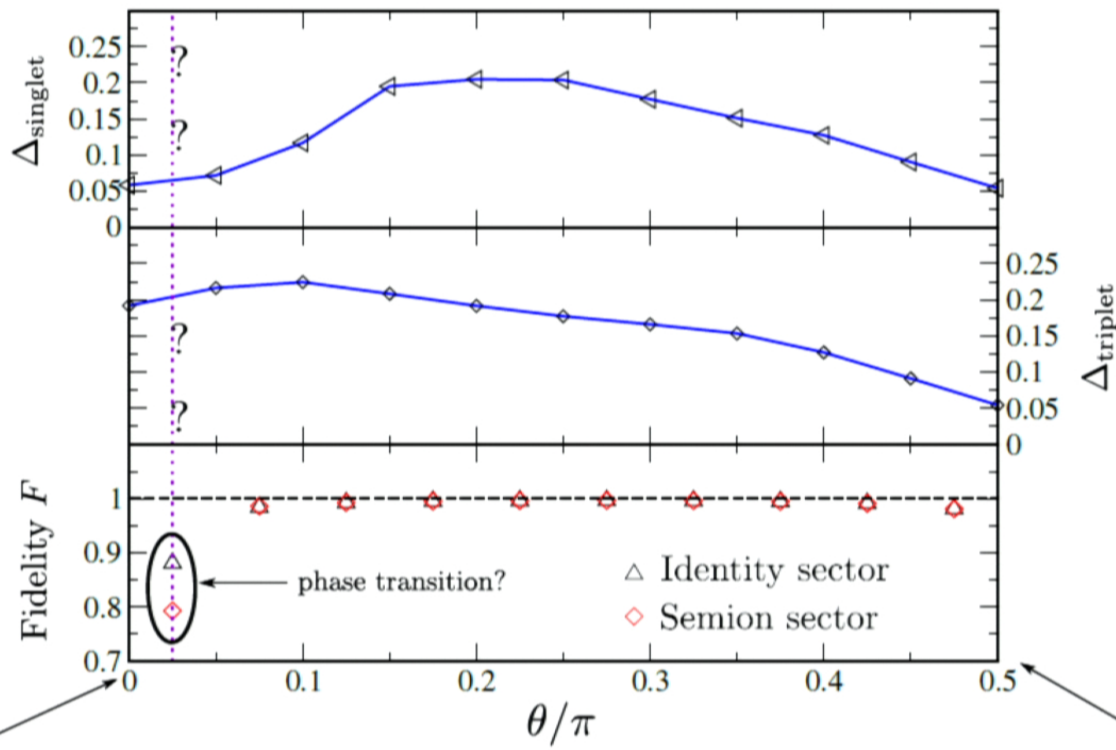
GAPS AND FIDELITY



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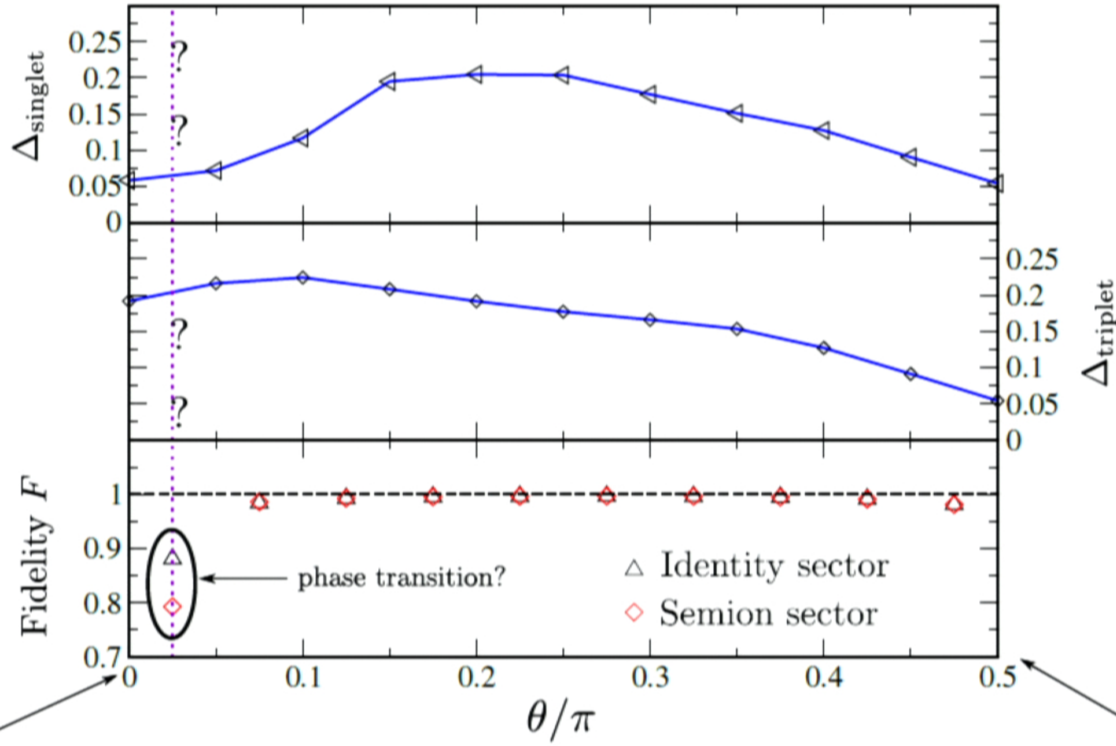

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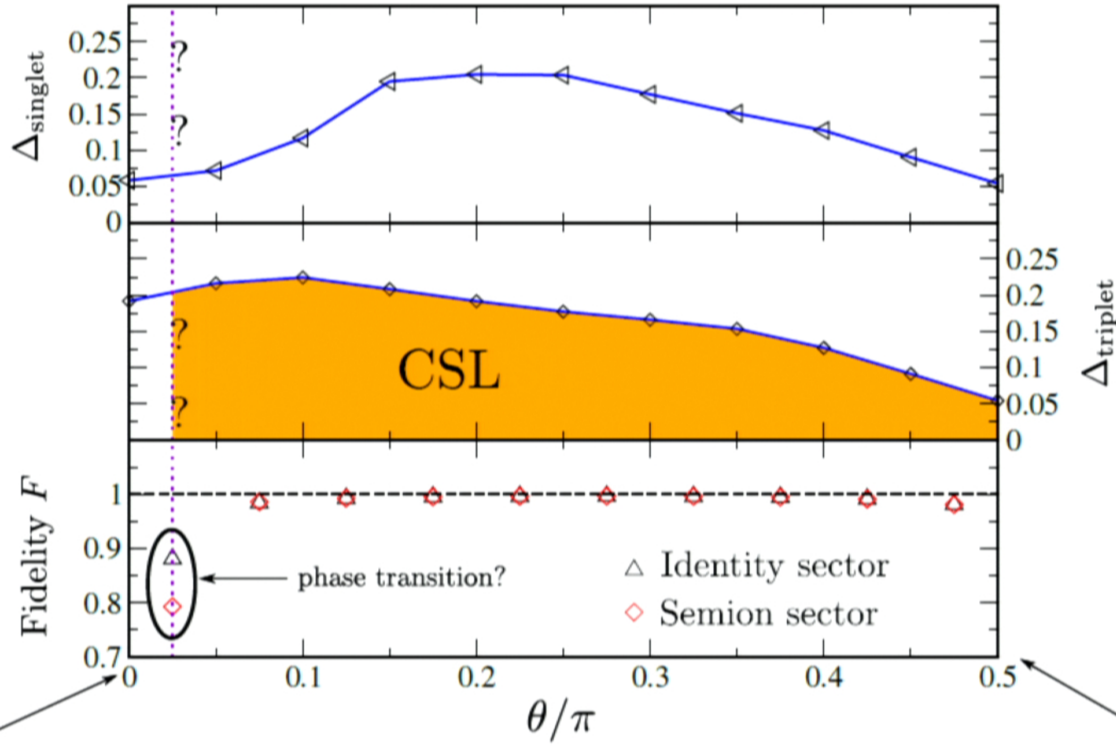
θ–h_z PHASE DIAGRAM



Heisenberg point

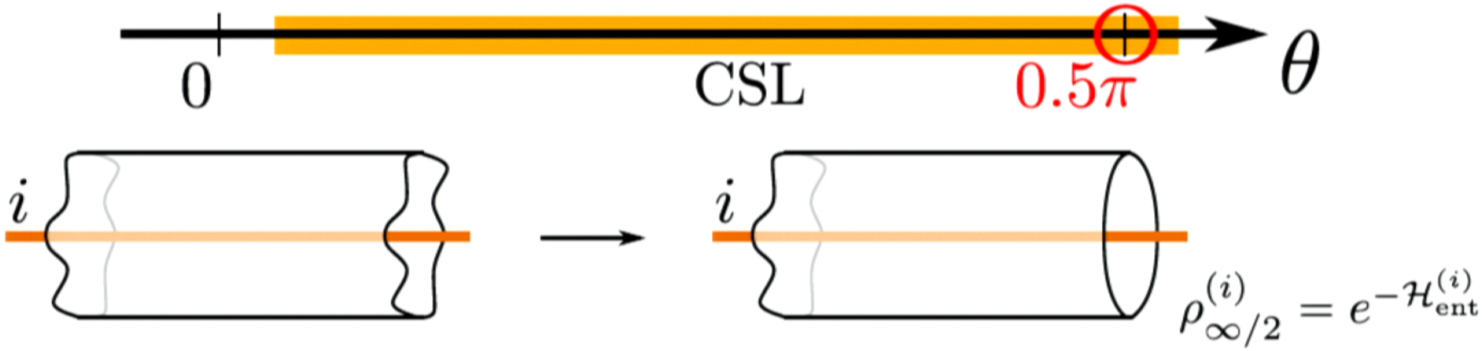
$$H = \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$

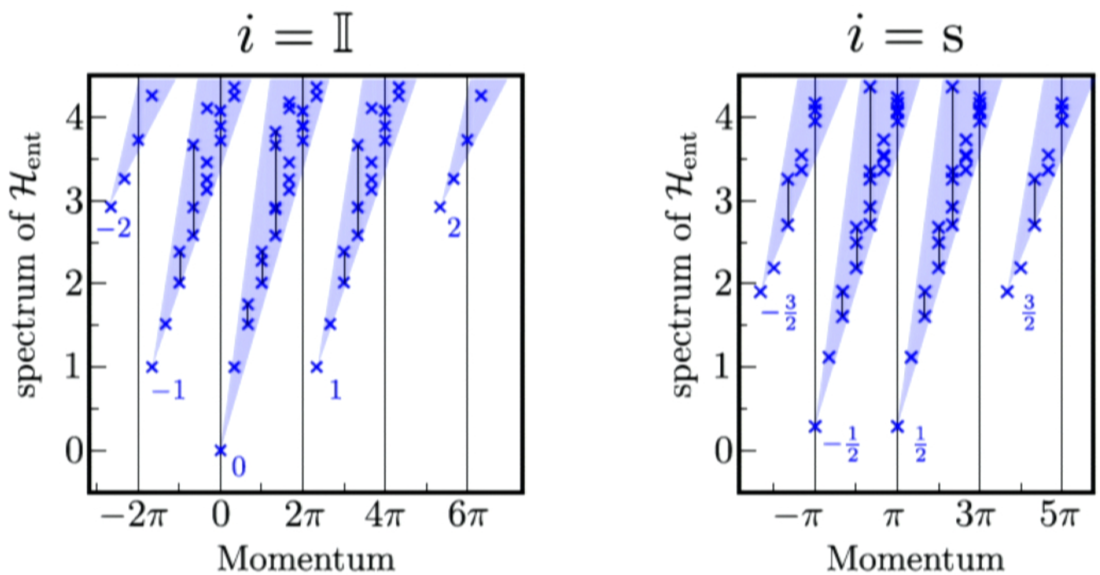
pure chiral point

$$H = \sum_{i,j,k \in \triangle} \vec{S}_i \cdot (\vec{S}_j \times \vec{S}_k)$$

- Fidelity: $F(\theta) = \langle \Psi_a(\theta - \epsilon) | \Psi_a(\theta + \epsilon) \rangle$
- $h_c \geq \Delta_{\text{triplet}}$

ENTANGLEMENT SPECTRUM





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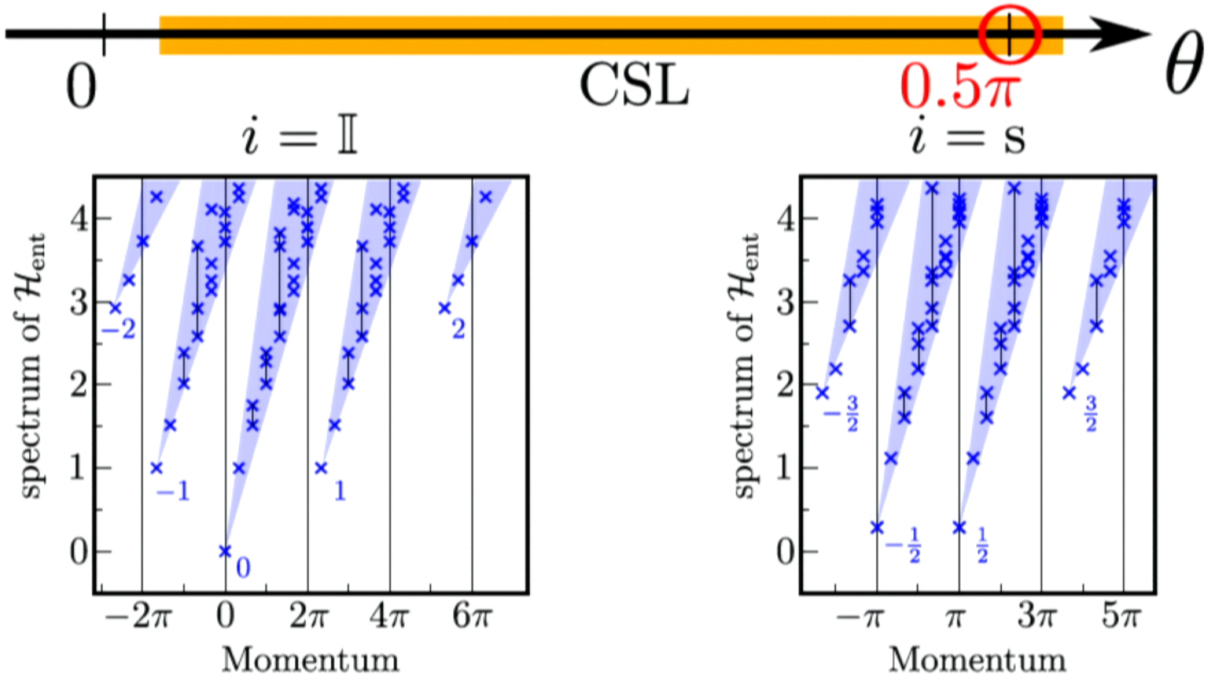

identification: chiral $SU(2)_1$ Wess-Zumino-Witten CFT

- sequence of degeneracies in momentum: 1-1-2-3-5-...
- SU(2) multiplets
- **integer** reps. of the spin (identity) and **half-integer** (semion)

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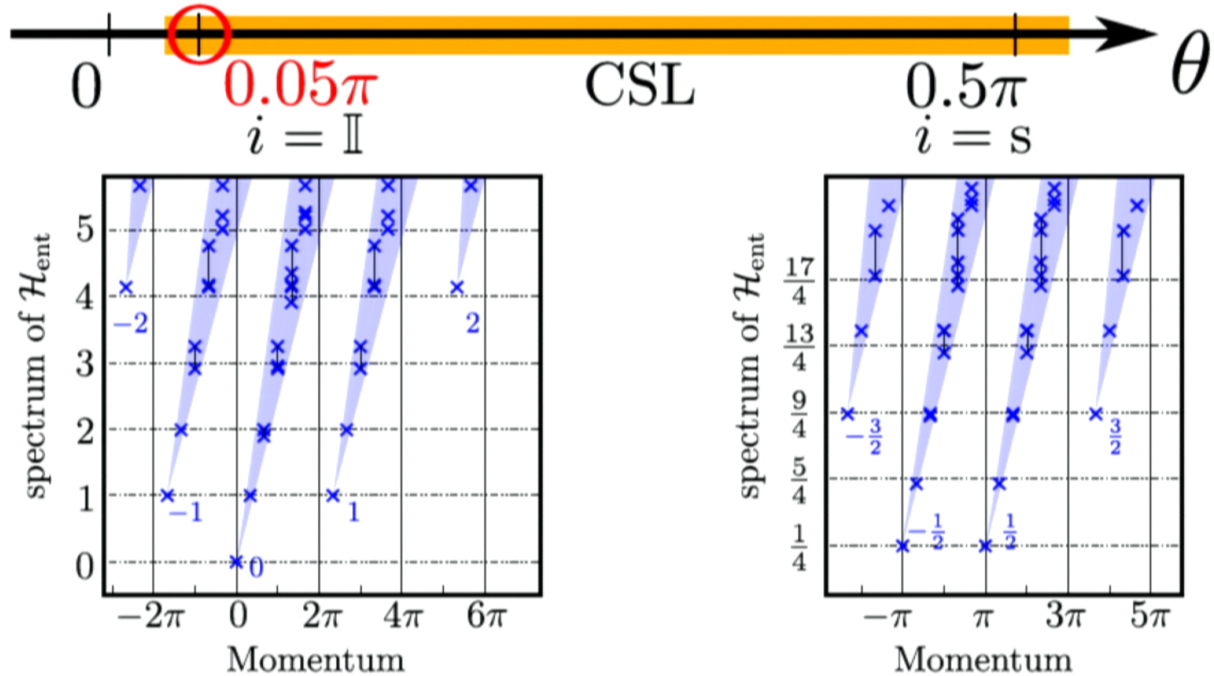

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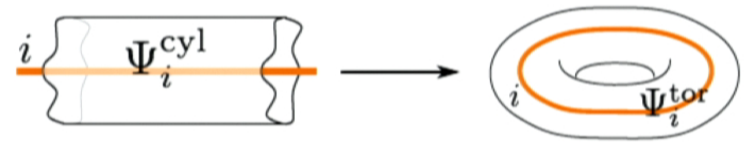
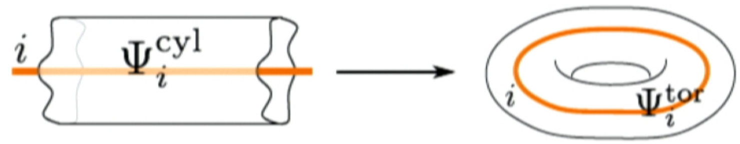
S AND T MATRICES



S and T matrices



$$S = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} + \frac{10^{-3}}{\sqrt{2}}\begin{bmatrix} -4 & -5 \\ -4 & 4+6i \end{bmatrix}$$

$$T = e^{-i\frac{2\pi}{24}\cdot 1}\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix} \times \left(e^{i\frac{2\pi}{24}0.012}\begin{bmatrix} 1 & 0 \\ 0 & e^{-i0.002\pi} \end{bmatrix} \right)$$

chiral semion
(exact)

deviation

S AND T MATRICES

$$S = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} + \frac{10^{-3}}{\sqrt{2}}\begin{bmatrix} -4 & -5 \\ -4 & 4+6i \end{bmatrix}$$

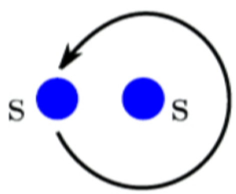
- quantum dimensions

  $d_{\mathbb{I}} = 1,\ d_{\mathrm{s}} = 1$

- total quantum dimension

  $D = \sqrt{2}$

- mutual statistics



$$|\Psi\rangle \longrightarrow -|\Psi\rangle$$

- fusion rules

  $\mathrm{s} \times \mathrm{s} = \mathbb{I}$

S AND T MATRICES

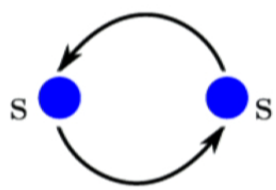
$$T = e^{-i\frac{2\pi}{24}\cdot 1}\begin{bmatrix} 1 & 0 \\ 0 & i \end{bmatrix} \quad \times \left(e^{i\frac{2\pi}{24}0.012}\begin{bmatrix} 1 & 0 \\ 0 & e^{-i0.002\pi} \end{bmatrix} \right)$$

- topological central charge

  $c = 1$

- topological spin

  $\theta_{\mathrm{s}} = i$



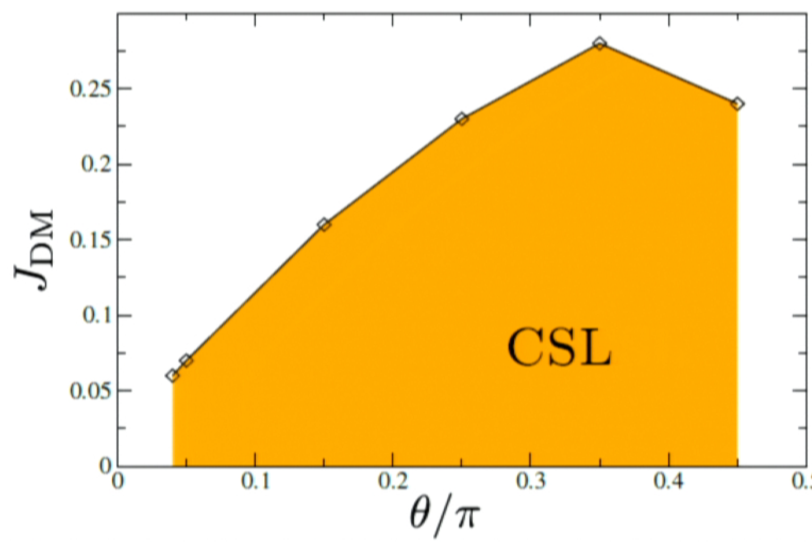
self statistics

$|\Psi\rangle \longrightarrow i \cdot |\Psi\rangle$

PERTURBATIONS

$$H = \cos\theta \sum_{\langle i,j\rangle} \vec{S}_i \cdot \vec{S}_j + \sin\theta \sum_{i,j,k\in\triangle} \vec{S}_i \cdot (\vec{S}_j \times \vec{S}_k) + H_{\text{int}}$$

- Dzyaloshinskii-Moriya interaction $H_{\text{int}} = J_{\text{DM}} \sum_{i<j} \hat{z} \cdot (\vec{S}_i \times \vec{S}_j)$



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- $H_{\text{int}} = J_{\text{NNN}} \sum_{\langle\langle i,j \rangle\rangle} \vec{S}_i \cdot \vec{S}_j$ $\quad J_{\text{NNN}} \in [-0.1, 0.27]$

- $H_{\text{int}} = J_z \sum_{\langle i,j \rangle} S_i^z S_j^z$ $\quad J_z \in [-1.2, 0]$

$(\theta = 0.15\pi)$

PERTURBATIONS

$$H = \cos\theta \sum_{\langle i,j\rangle} \vec{S}_i \cdot \vec{S}_j + \sin\theta \sum_{i,j,k\in\triangle} \vec{S}_i \cdot (\vec{S}_j \times \vec{S}_k) + H_{\text{int}}$$

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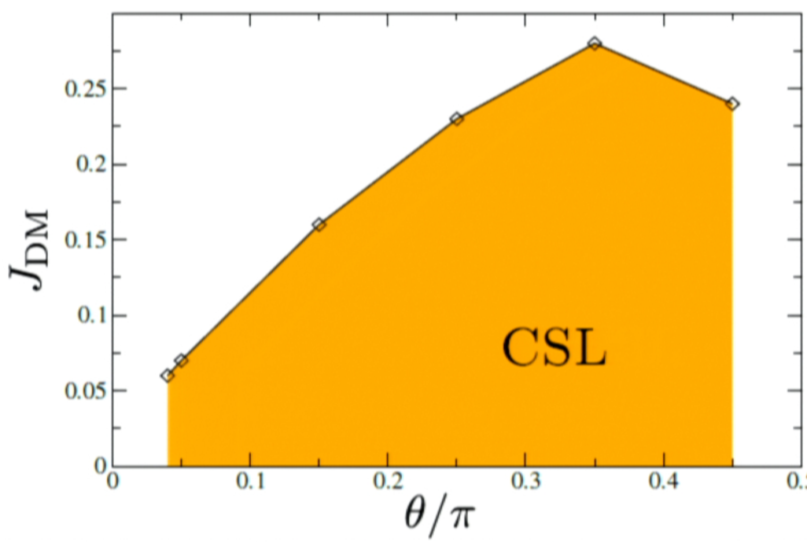
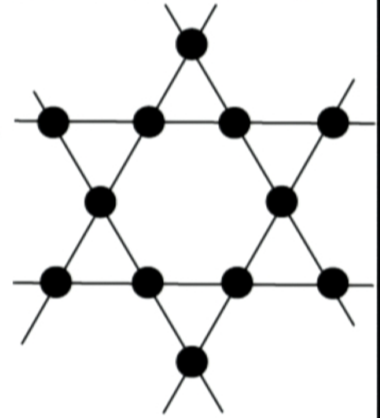


CONCLUSIONS



- Hubbard model with magnetic field on Kagome lattice

$$H = -\sum_{\langle i,j\rangle,\sigma}(t_{i,j}c^\dagger_{i\sigma}c_{j\sigma} + t^*_{i,j}c^\dagger_{j\sigma}c_{i\sigma}) + U\sum_i n_{i\uparrow}n_{i\downarrow} + \frac{h_z}{2}(n_{i\uparrow} - n_{i\downarrow})$$

- t/U expansion

$$H = \cos\theta\sum_{\langle i,j\rangle}\vec{S}_i\cdot\vec{S}_j + \sin\theta\sum_{i,j,k\in\triangle}\vec{S}_i\cdot(\vec{S}_j\times\vec{S}_k) + h_z\sum_i S^z_i$$

CONCLUSIONS

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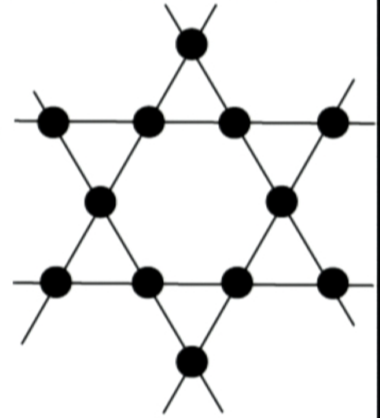

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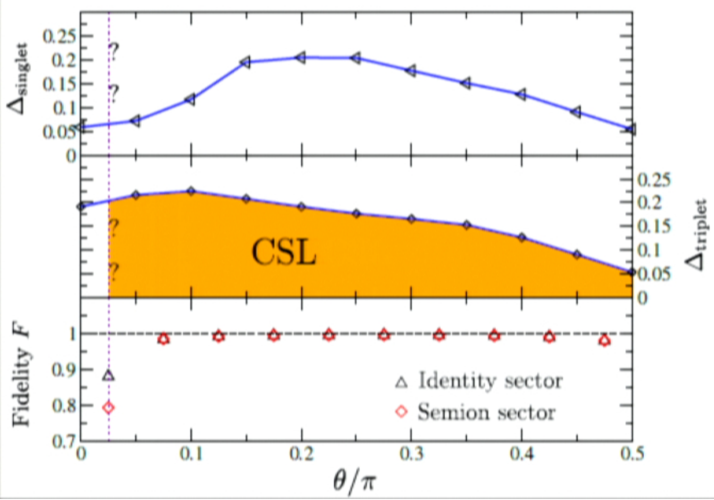
θ–h_z phase diagram



CONCLUSIONS

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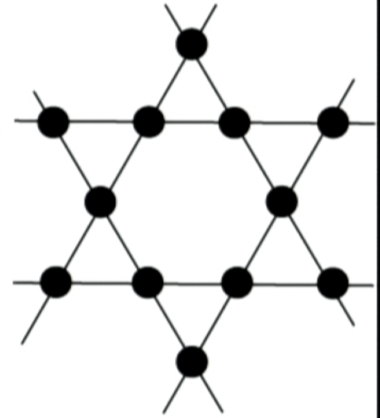

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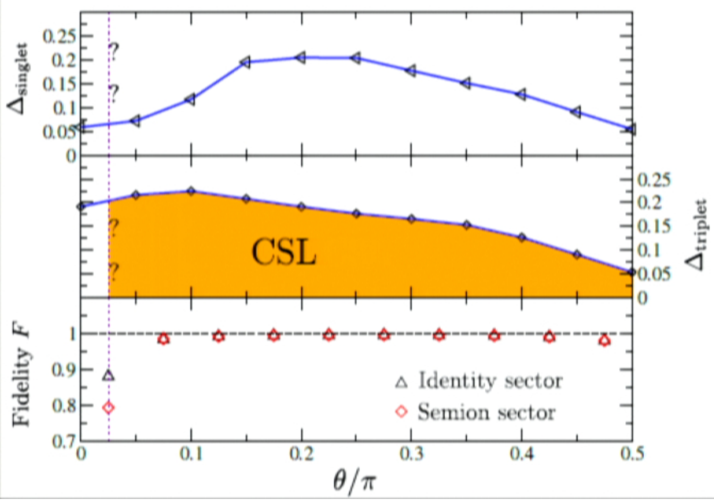
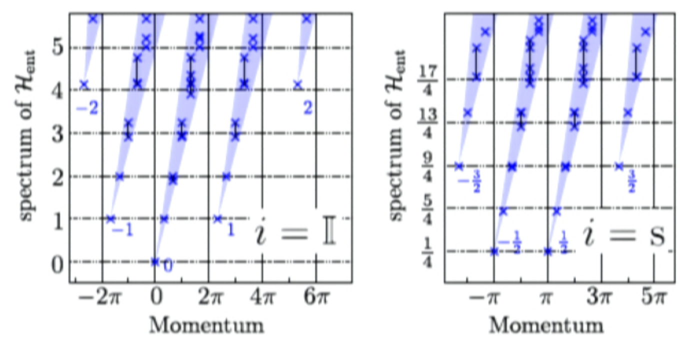
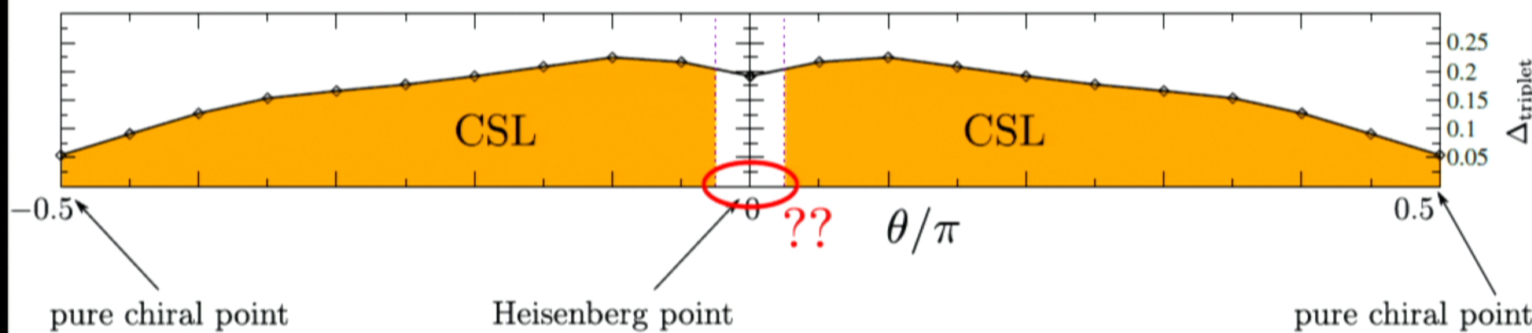


entanglement spectrum

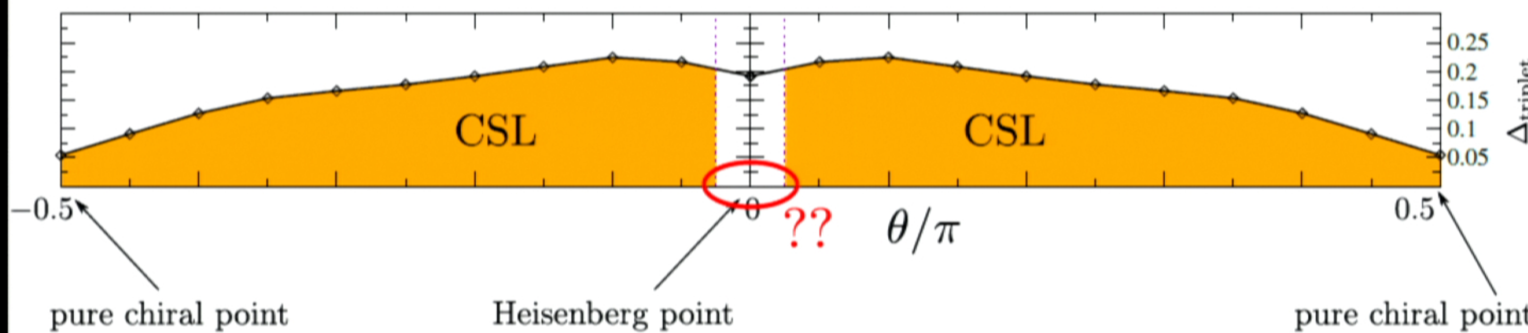


- edge theory: chiral $SU(2)_1$ WZW

WORK IN PROGRESS



WORK IN PROGRESS



THANK YOU!