# Majorana metal from a chiral spin liquid

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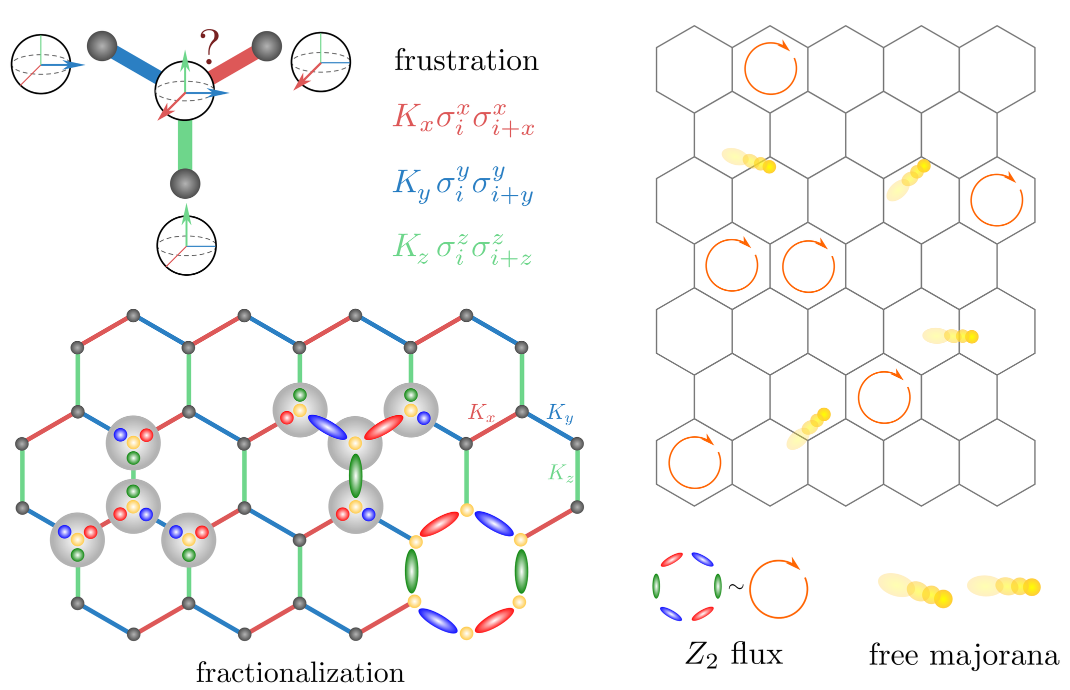
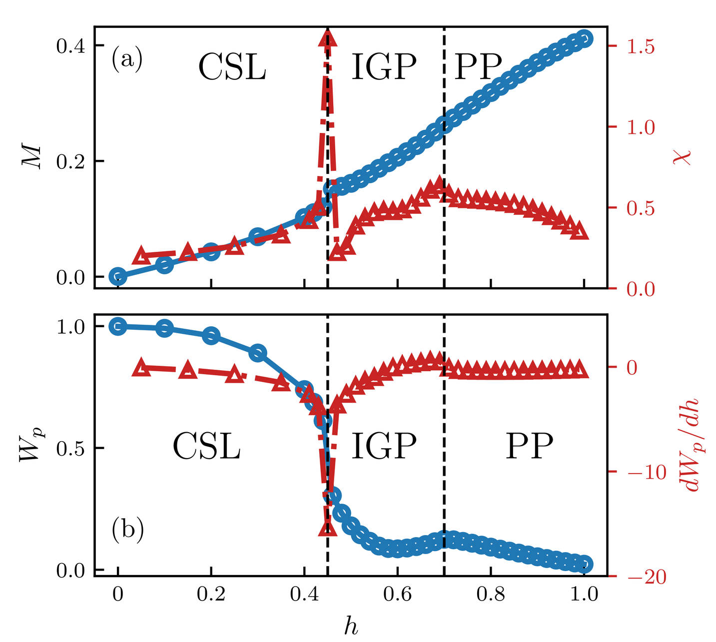
## Introduction

### Model

$$H_{\text{Kitaev}} = \sum_{i,\alpha\in\{x,y,z\}} \sigma_i^\alpha \sigma_{i_\alpha}^\alpha \quad (\text{p}-\text{wave spinon SC})$$




Phase diagram of $H = H_{\text{Kitaev}} - h\sum_{i,\alpha}\sigma_i^\alpha$




$M$ : Magnetization

$W_p$ : $Z_2$ flux

$W_p = +1$ : flux vac.

$W_p = -1$ : excited

**Fluxes fluctuate strongly in IGP**

**CSL**: Chiral Spin Liquid (Gapped Majorana topological Insulator)

**IGP**: Intermediate Gapless phase (Superconducting Majorana Metal)

### Question

What is the nature of the emergent IGP?
The mechanism for gapless spectrum?

Deconfined fermions (spinons) in QSLs

$$\mathbf{S}_i = \frac{1}{2} f_{i,\alpha}^\dagger \boldsymbol{\sigma}_{\alpha\beta} f_{i,\beta}, \quad \alpha,\beta \in \{\uparrow,\downarrow\}$$

$Z_2$ real (Majorana) fermion $f_i^\dagger f_j + \Delta f_i^\dagger f_j^\dagger + \text{H.c.}$

Relation to gapped spinons with topological order?

Neutral Fermi surface?

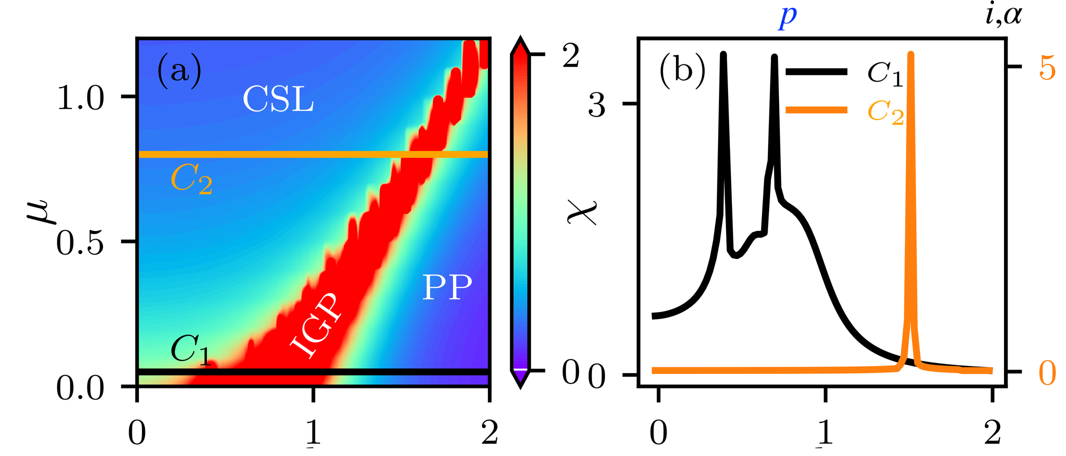
U(1) complex spinon?
or
A Fermi surface of $Z_2$ real (Majorana) fermion?

Reference: A. Kitaev, Annals of Physics 321 , 2 (2006).

## Metal from Flux disorder

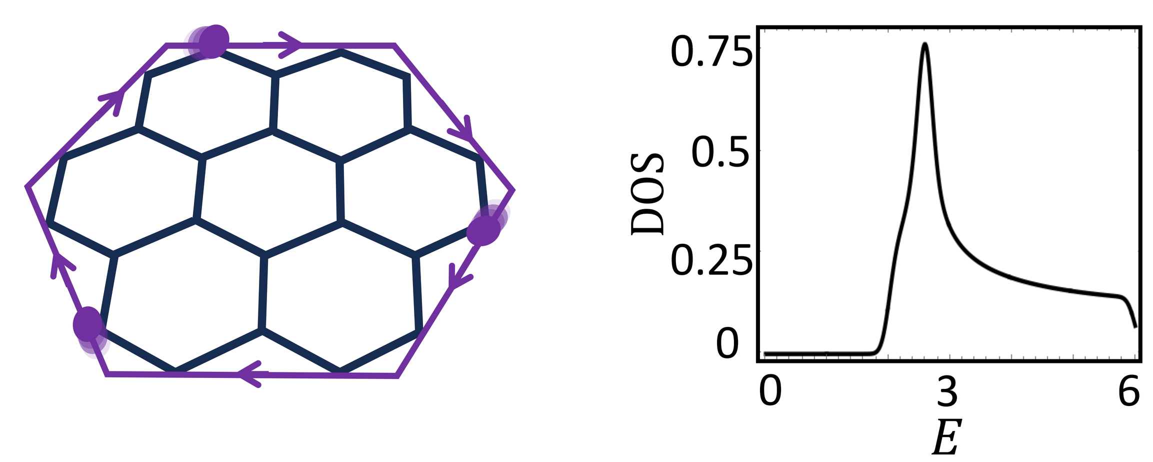
### A guess

Let's penalize flux: $H' = H_{\text{Kitaev}} - \mu\sum_p W_p - h\sum_{i,\alpha}\sigma_i^\alpha$




Flux should be responsible!

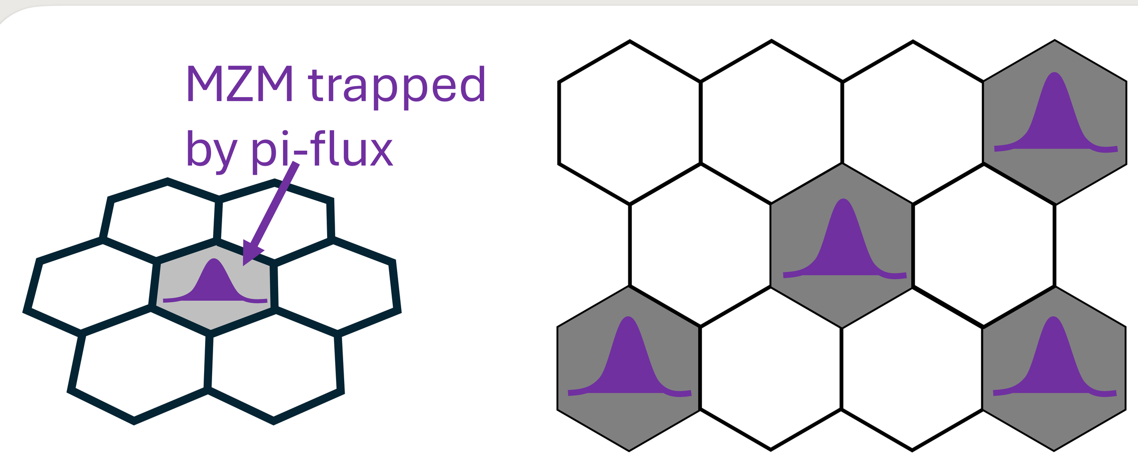
### From a chiral spinon insulator ...




p-wave spinon superconductor (SC)
~ chiral Majorana fermions ($c = f^\dagger + f$)

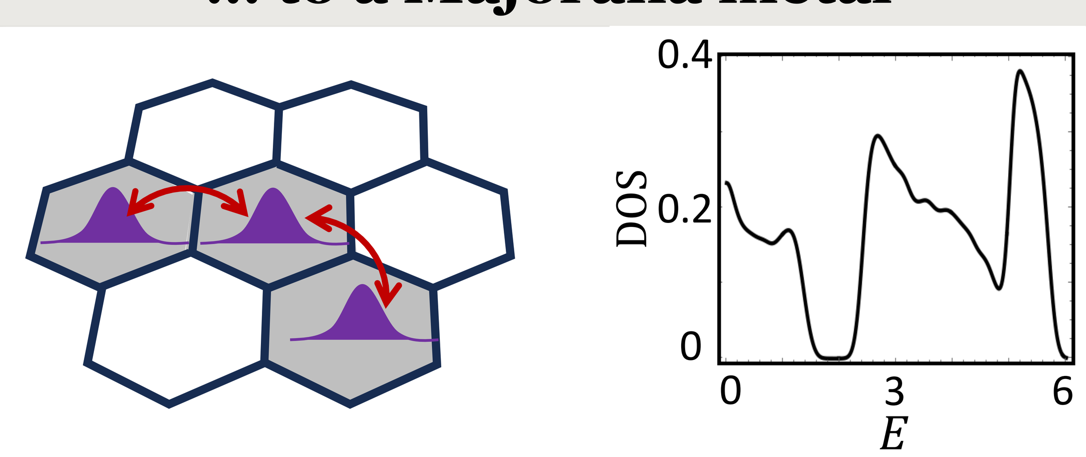
$$\sum_{ij} t_{ij} f_i^\dagger f_j + \Delta f_i^\dagger f_j^\dagger + \text{H.c.} \sim \sum_{ij} t_{ij} c_i c_j + \text{H.c.}$$

### ... via flux disorder ...




An ensemble of flux configurations
Each flux traps a Majorana mode

### ... to a Majorana metal




Proliferation of fluxes leads to large overlap between tapped Majorana modes ➡️ Majorana metal!

Reference: C. R. Laumann *el al*, Phys. Rev. B 85, 161301 (2012)

## Majorana Fermi surface from Kitaev spin liquid

### A mean field ansatz

Flux and Majorana fermions become entangled

$$|\Psi_{\text{IGP}}\rangle = \sum_F \psi_F |F\rangle \otimes |M_F\rangle$$

$$\rho_M = \text{Tr}_F |\Psi_{\text{IGP}}\rangle\langle\Psi_{\text{IGP}}| = \sum_F |\psi_F|^2 |M_F\rangle\langle M_F|$$

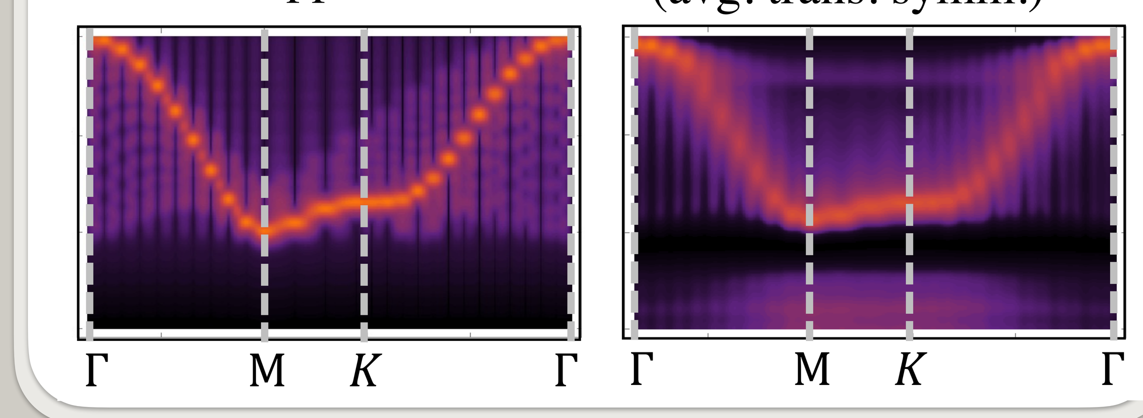
Majorana fermions traveling through flux disorder

The effective ensemble of tight-binding Majorana

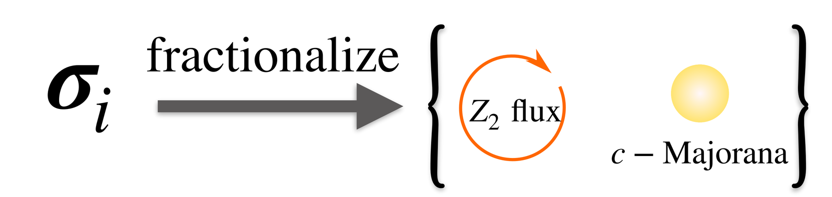
$$H \approx \sum T_{ij} c_i c_j + \text{H.c.}, \quad \text{for random } T_{ij}$$

Emergent superconducting Majorana metal of class D

Reference: C. R. Laumann *el al*, Phys. Rev. B 85, 161301 (2012)



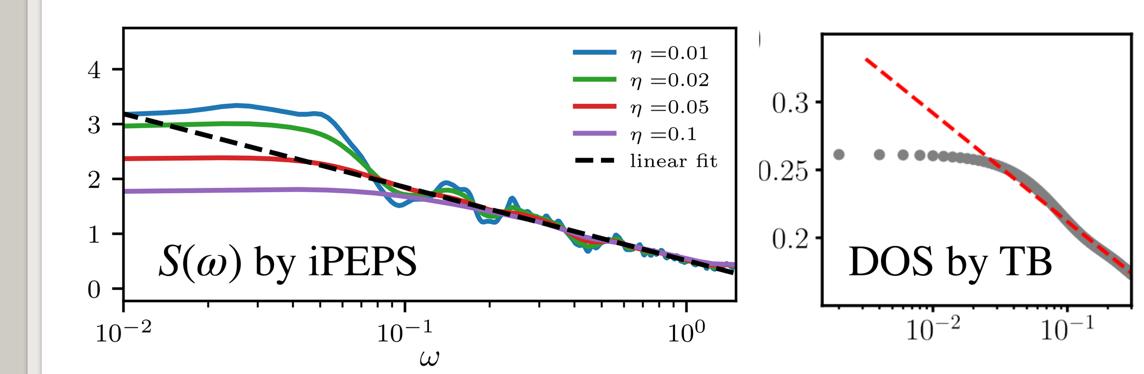

### Majorana and spin response

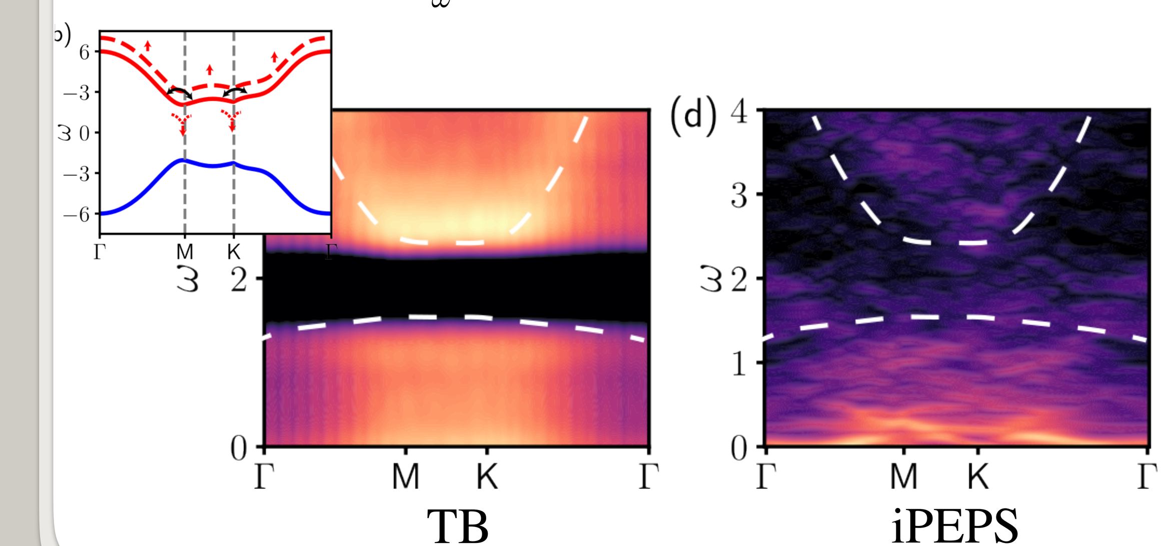



Flux has 'glassy' dynamics,
response is governed by Majorana fermions

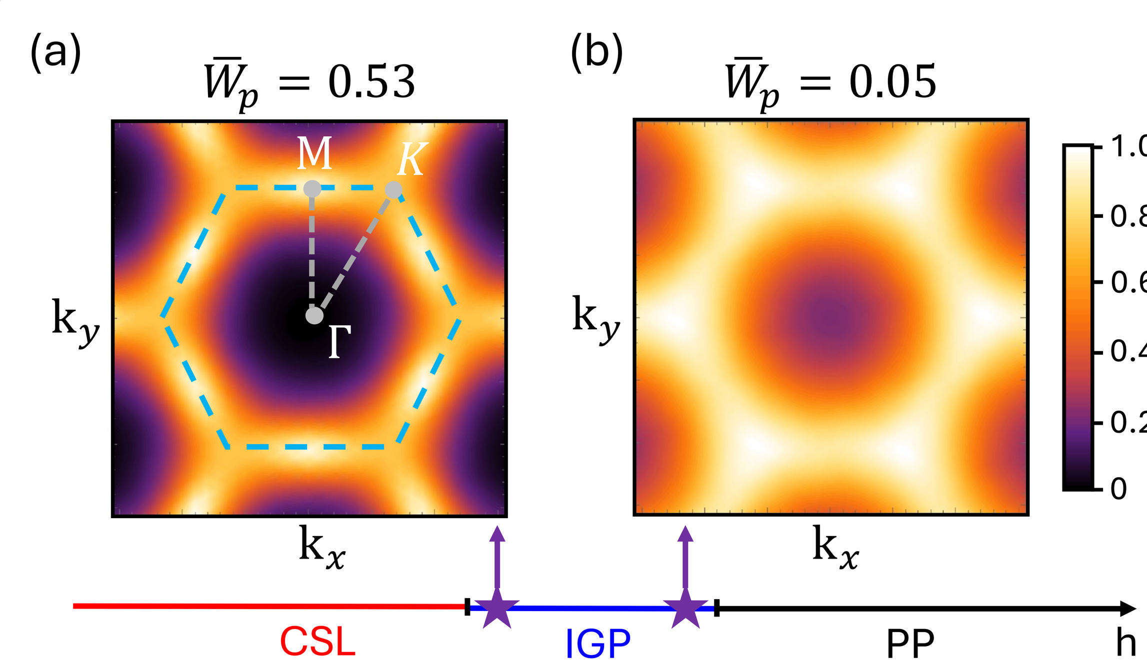
Relating the many-body spectrum to TB Majoranas

$$\langle \boldsymbol{\sigma}_i(t)\cdot\boldsymbol{\sigma}_j(0)\rangle \sim \langle\langle M_F | c_i(t) c_j | M_F\rangle\rangle_F$$



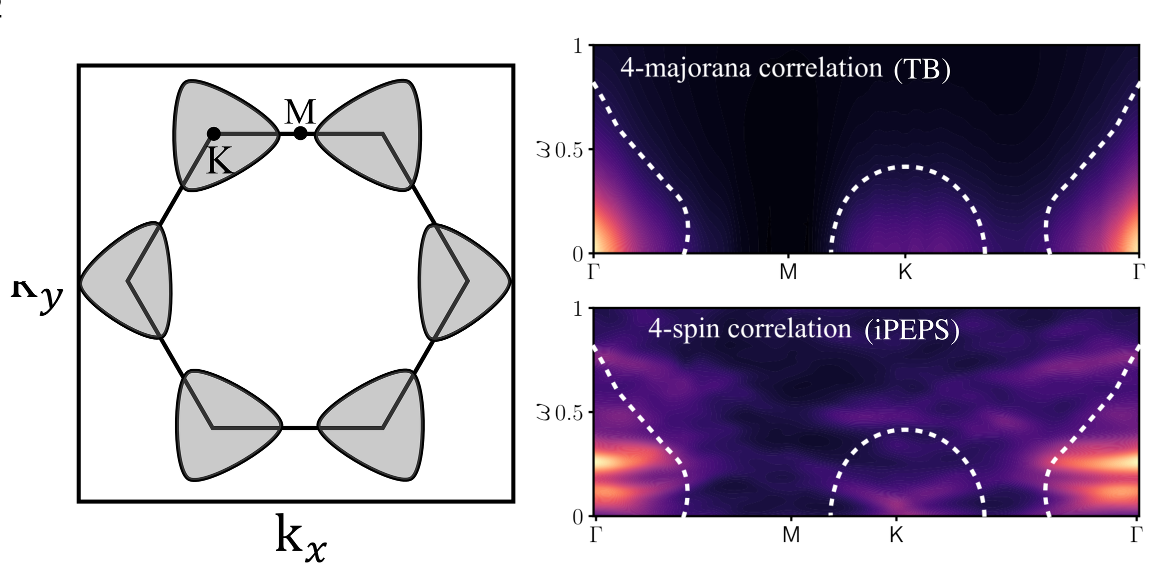

### Majorana 'Fermi surface'




Low-energy spectrum of the Four-Majorana dynamics governed by the shape of Majorana FS reproduces the four-spin dynamics by iPEPS

dimer operators : $D_i^\alpha \equiv \sigma_i^\alpha \sigma_{i+z}^\alpha$

$$\langle \boldsymbol{D}_i(t)\cdot\boldsymbol{D}_j\rangle \sim \langle\langle M_F | c_i(t) c_{i+z}(t) c_j c_{j+z} | M_F\rangle\rangle_F$$




Within the **IGP** (Superconducting Majorana Metal), the shape of the Majorana FS at zero energy can be tuned by magnetic field, which controls the intensity of $Z_2$ flux fluctuation.

### References

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