Dynamics of field-driven phases of the Kitaev model

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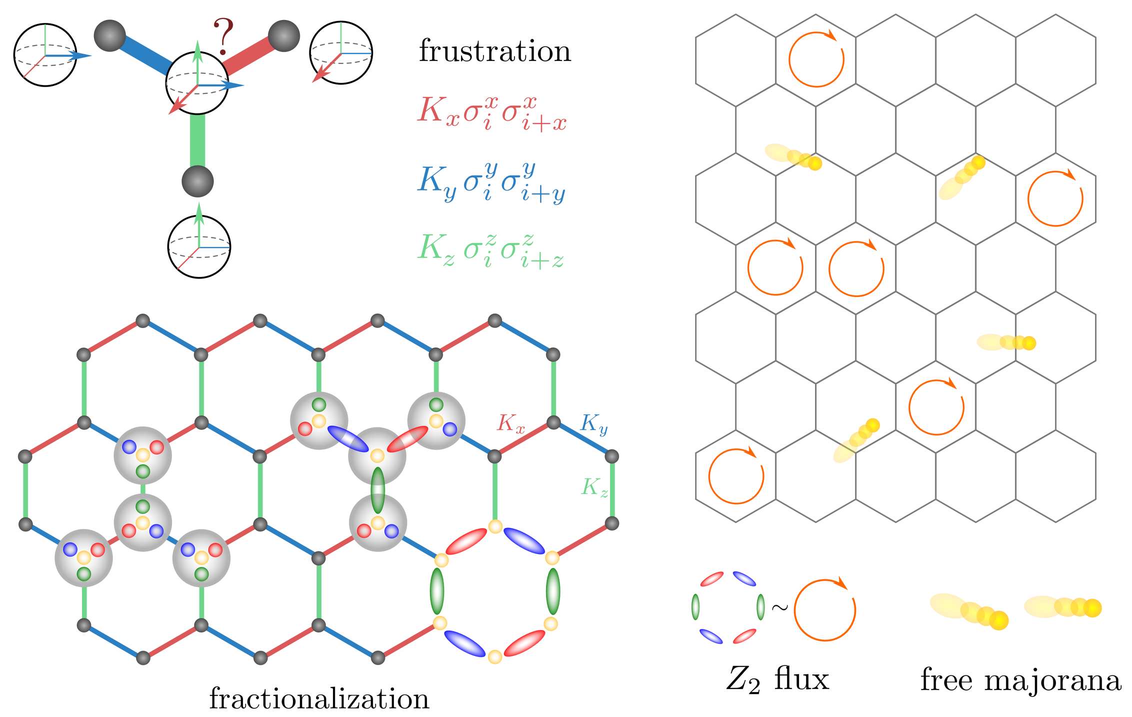
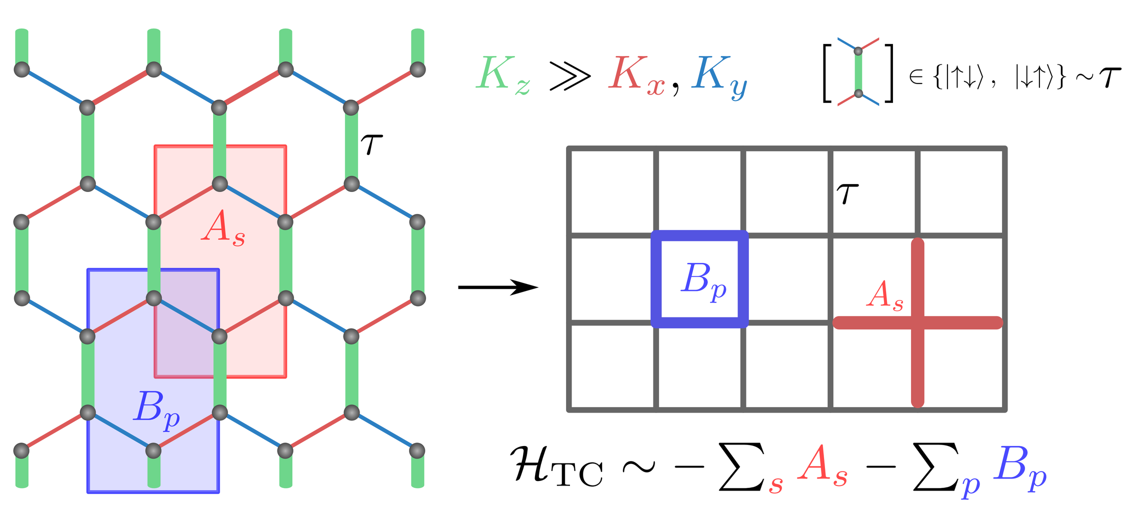
Introduction



The bond-dependent exchange in the Kitaev model leads to frustrated interaction. Each spin fractionalizes into four partons, giving rise to a Z_2 gauge structure and free majoranas

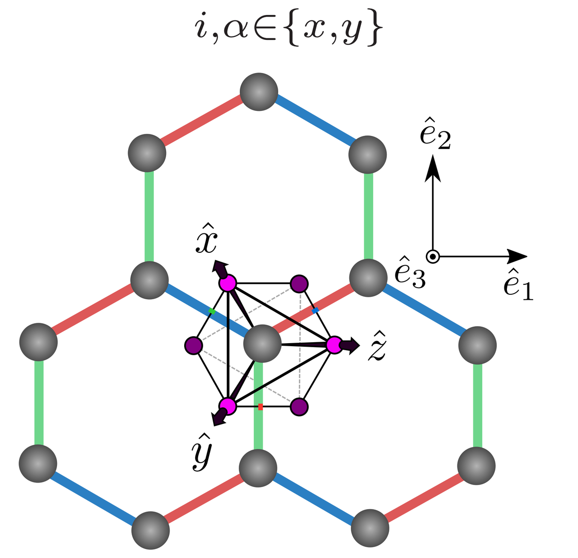


At the anisotropic limit, e.g. $K_z \gg K_x, K_y$, majoranas are highly gapped. The model becomes the Z_2 Toric code (TC) at the low energy sector, with $A_s = \prod_{i\in s} \tau_i^x$ and $B_p = \prod_{i\in p} \tau_i^z$.

Objectives

Phases and characteristic dynamics induced by external field along different directions and varying energy scales of anisotropic exchange interactions, i.e. as a function of $(\vec{h}, K_z)$:

$$\mathcal{H} = K \sum_{i,\alpha\in\{x,y\}} \sigma_i^\alpha \sigma_{i_\alpha}^\alpha + K_z \sum_i \sigma_i^z \sigma_{i_z}^z - \vec{h}\cdot\sum_i \vec{\sigma}_i$$



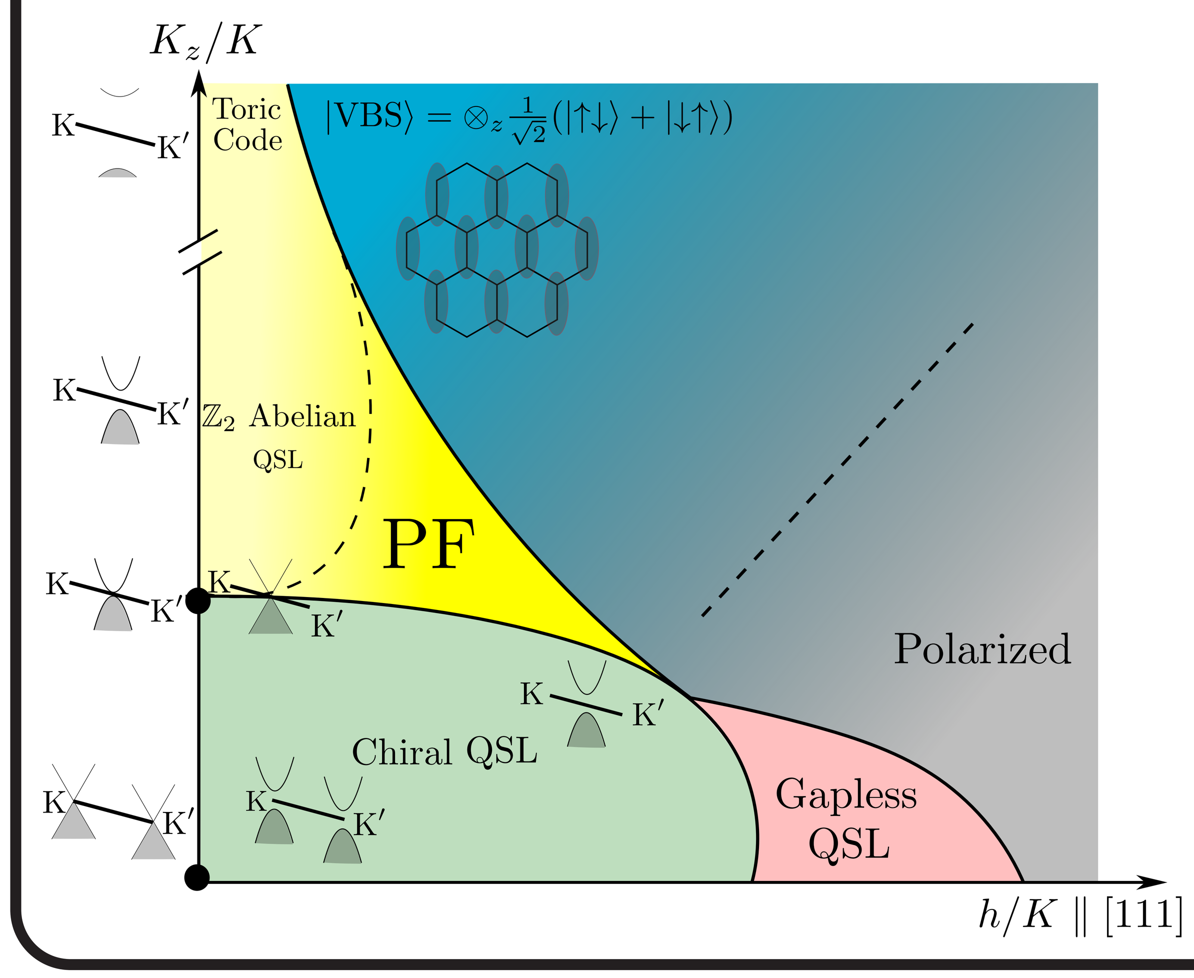
Focus on directions:

$\vec{h}$ in [111]$\parallel \hat{e}_3$
$\vec{h}$ in [001] $\parallel \hat{z}$

with varying antiferromagnetic exchange $K_z, K > 0$.

In $RuCl_3$, [001] points from Ru to its Cl ligand.

Kitaev model under $\vec{h}\parallel$[111]



PHASES	EXCITATIONS OF KITAEV MODEL UNDER [111] FIELD
KQSL	Gapless majoranas Gapped Z_2 fluxes
CSL	Majoranas at $\sim h^3/K$ Gapped non-Abelian anyons
Abelian QSL	Abelian anyons [1,e,m,ϵ] Only ϵ disperses (in 1D)
VBS	Gapped $(\lvert\uparrow\downarrow\rangle - \lvert\downarrow\uparrow\rangle)$ at $\sim h^2/K_z$ Gapped $(\lvert\uparrow\uparrow\rangle, \lvert\downarrow\downarrow\rangle)$ at $\sim K_z/K$
Gapless QSL	Neutral Fermi surface of fermions
Polarized	Spin waves at $\sim h/K$
PF*	Damped ϵ fermions Gapped hybridized fermions

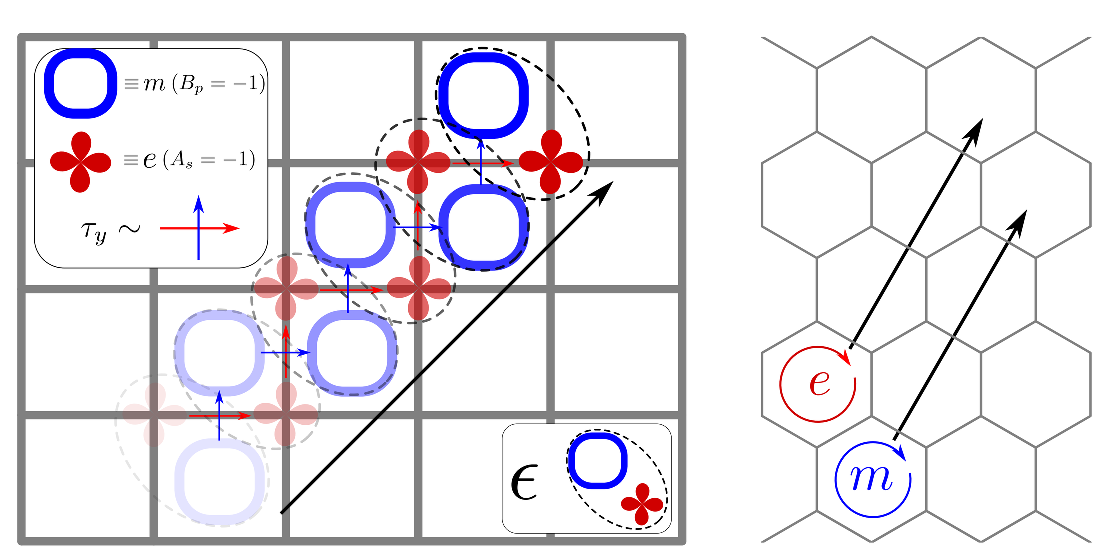
Dynamics of ϵ anyon

At $K_z/K \gg 2$, the second order perturbation in [111] field gives the effective Hamiltonian:

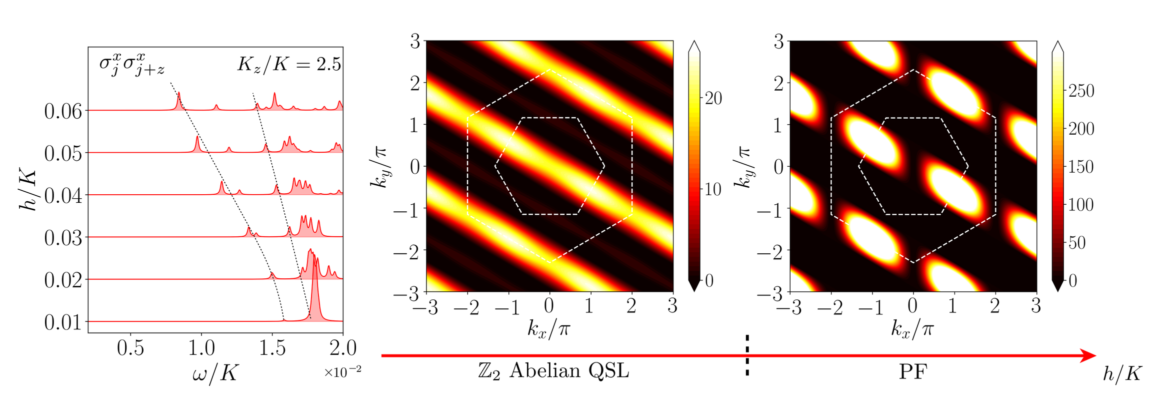
$$\mathcal{H} \simeq -J_{\mathrm{TC}}\left[\sum_s A_s + \sum_p B_p\right] - \frac{h^2}{K_z}\sum_i \tau_i^y$$

Only ϵ anyon disperses in *fixed* directions [1]:

$$\varepsilon(\vec{k}) = 4J_{\mathrm{TC}} - \frac{4h^2}{K_z}\cos\left(\frac{\sqrt{3}}{2}k_x + \frac{3}{2}k_y\right)$$



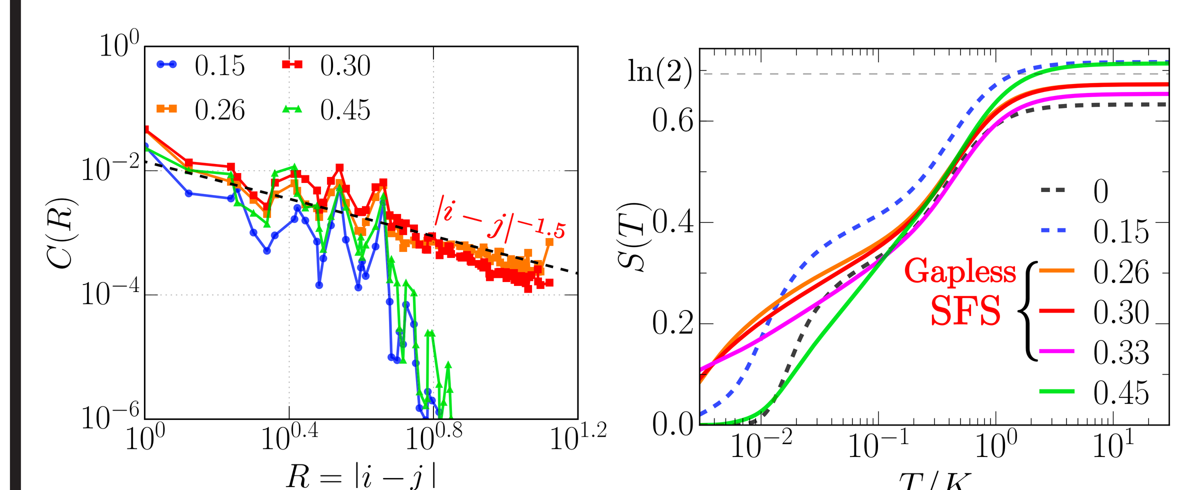
Sharp signature of fractionalization and gauge-matter hybridization in scattering experiment:



$S(\omega)$ and $S(\vec{k},\omega)$ of the lowest excitated mode given by the two spin flip operator $\sigma_i^x\sigma_{i+z}^x$.

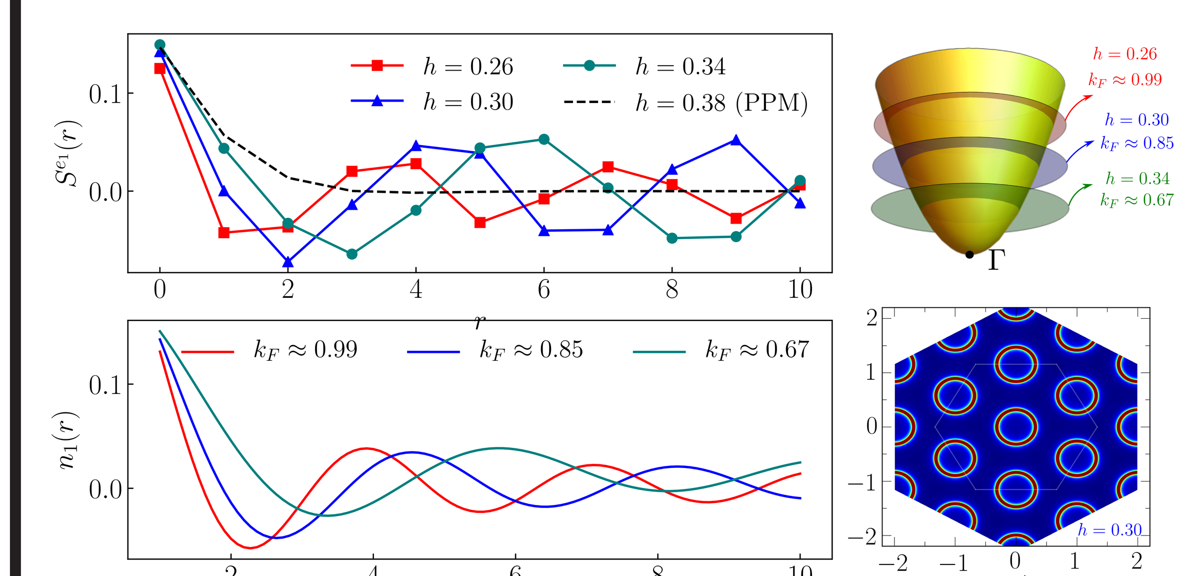
Spinon Fermi surface

The gapless QSL induced by an intermediate field has emergent spinon Fermi surface [2].

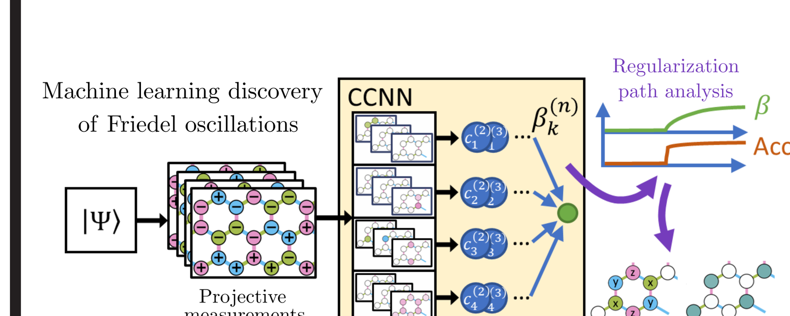


Friedel oscillations of spinons:

$$\langle S^{e_1}(r)\rangle \sim \langle n_1(r)\rangle \sim \frac{k_F}{\pi}\left[1 - \frac{\sin(2k_F r)}{2k_F r}\right] + C$$



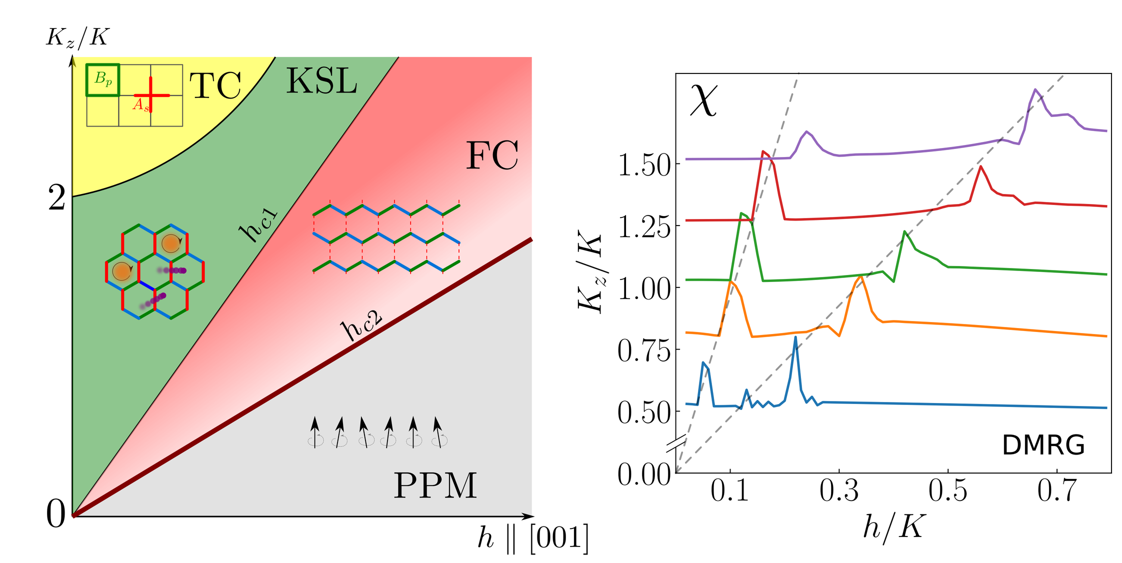
Evidence from machine learning:



K. Zhang, S. Feng, Y. Lensky, N. Trivedi and E. Kim. Preprint (2023)

Ising criticality by $\vec{h}\parallel$[001]

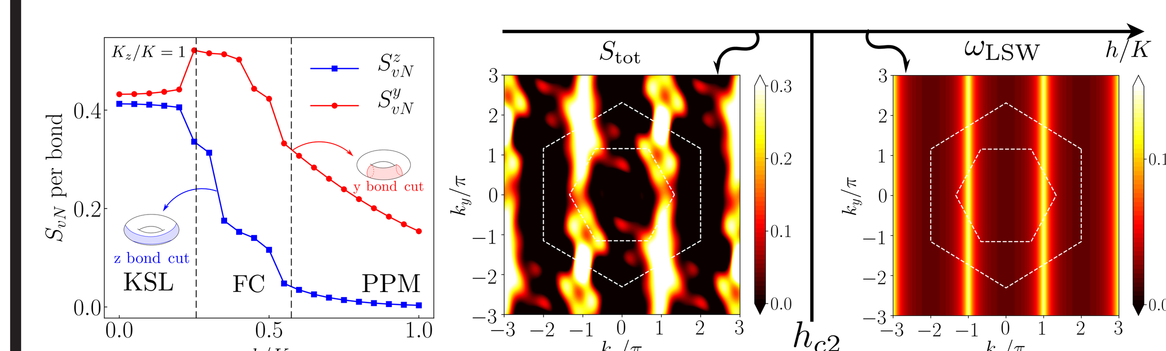
Under [001] field, the intermediate gapless phase becomes much larger, the effective dimension is reduced, and the phase boundary at h_{c2} features decoupled Ising critical chains.



By parton mean field theory for free fermion f and bond fermion χ_z, z-bond exchange reads

$$K_z\left(b_{i,A}^z b_{i,A+\hat{z}}^z c_{i,A} c_{i,A+\hat{z}}\right) \simeq K_z(2n_i^f - 1)(1 - 2n_i^z)$$

$\lim_{h\to h_{c2}^-} n_i^z = \frac{1}{2} \Rightarrow$ decoupled compass chains



At $h = h_{c2}$ where K_z effectively vanishes, a compass chain is mapped to Ising critical point

$$\mathcal{H} \simeq \sum_i \sigma_i^x\sigma_{i+1}^x + \sigma_{i+1}^y\sigma_{i+2}^y \sim -\sum_i \tilde{\sigma}_i^z\tilde{\sigma}_{i+1}^z - \tilde{\sigma}_i^x$$

Weak coupling in FC is captured by $\mathcal{H}$(FC)

$$\sum_{a=\mathrm{L,R}} \int dx \gamma_a \partial_x \gamma_a - \tilde{h}\int dx (\gamma_L\partial_x\gamma_L)(\gamma_R\partial_x\gamma_R)$$

which remains gapless until an $\tilde{h}_c > 0$.

References

[1] Shi Feng, Adhip Agarwala, Subhro Bhattacharjee, and Nandini Trivedi. Anyon dynamics in field-driven phases of the anisotropic kitaev model. *arXiv:2206.12990*, 2022.

[2] Niravkumar D. Patel and Nandini Trivedi. Magnetic field-induced intermediate quantum spin liquid with a spinon fermi surface. *Proceedings of the National Academy of Sciences*, 116(25):12199–12203, 2019.