Title: Field-induced neutral Fermi surfaces and QCD3 quantum criticalities

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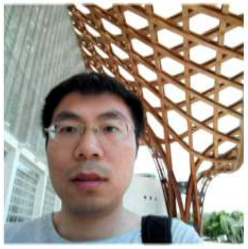
Abstract: We perform both numerical and theoretical studies on the phase diagram of the Kitaev materials in the presence of a magnetic field. We find that a new quantum spin liquid state with neutral Fermi surfaces emerges at intermediate field strengths, between the regimes for the non-Abelian chiral spin liquid state and for the trivial polarized state. We discuss the exotic field-induced quantum phase transitions from this new state with neutral Fermi surfaces to its nearby phases. We also theoretically study the field-induced quantum phase transitions from the non-Abelian chiral spin liquid to the symmetry-broken zigzag phase and to the trivial polarized state. Utilizing the recently developed dualities of gauge theories, we find these transitions can be described by critical bosons or gapless fermions coupled to emergent non-Abelian gauge fields, and the critical theories are of the type of a QCD3-Chern-Simons theory. We propose that all these exotic quantum phase transitions can potentially be direct and continuous in the Kitaev materials, and we present sound evidence for this proposal. Therefore, besides being systems with intriguing quantum magnetism, Kitaev materials may also serve as table-top experimental platforms to study the interesting dynamics of emergent strongly interacting quarks and gluons in 2+1 dimensions. Finally, we address the experimental signatures of these phenomena.

Field-induced neutral Fermi surface and QCD_3 quantum criticalities in Kitaev materials

Liujun Zou



Yin-Chen He

LZ and He, arXiv: 1809.09091

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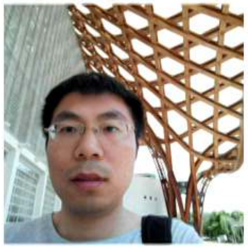

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CAUTION

Motivations

- Explore exotic quantum phases and phase transitions
- Realize interesting physics in real materials
- Understand 2+1 d strongly coupled theories
- …

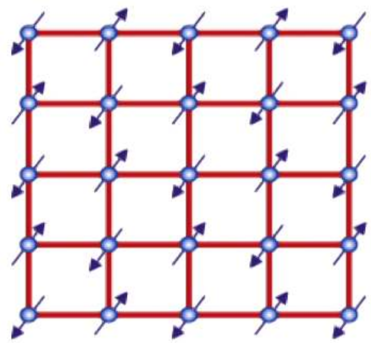
Outline

- Introduction
- Field-induced neutral Fermi surface
- QCD_3-Chern-Simons quantum criticalities
- Discussion

Basics of traditional condensed matter

- Quantum phases are often distinguished by their patterns of spontaneous symmetry breaking (SSB)
- The low-lying excitations can often be understood as long-lived quasiparticles
- Quantum phase transitions are described in terms of fluctuating local order parameters

Example: antiferromagnet



- Pattern of SSB: spin rotation and translation
- Excitations: magnons
- Phase transition: Neel order parameter

Beyond the conventional paradigm: Quantum spin liquids (QSL)

- QSL: a spin system with nontrivial pattern of entanglement in the ground state (not associated with SSB)

- gapped: anyonic quasiparticles (bosonic topological order)
- gapless
  - nonlocal quasiparticles
  - no well-defined quasiparticle

EX 1: gapped Z_2 QSL

- Nontrivial excitations: m, ϵ and their bound state

~ local excitation

- Similarity with an ordinary superconductor:

$$\epsilon \longleftrightarrow \text{electron}$$
$$m \longleftrightarrow \pi\text{-flux}$$

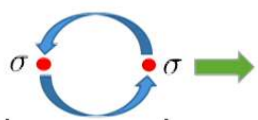
- Difference: ϵ and m are emergent

EX 2: gapped Ising topological order (ITO)

- Nontrivial excitations: σ and ϵ

~ local excitation

~ local excitation or ϵ



$\exp\left(-i\frac{\pi}{4}\right)$ or $\exp\left(i\frac{3\pi}{4}\right)$

- Similarity with a p+ip superconductor:

$\epsilon \longleftrightarrow$ electrons

$\sigma \longleftrightarrow \pi$-flux

chiral edge $\longleftrightarrow$ chiral edge

quantized thermal Hall $\longleftrightarrow$ quantized thermal Hall

EX 3: gapless Neutral Fermi surface (NFS)

neutral local excitation ~ 

NFS

- Similarity with a Fermi liquid:

  NFS $\longleftrightarrow$ Fermi surface of electrons
- Differences:

  1. f is neutral, but interact with an emergent U(1) gauge field
  2. No well-defined quasiparticle in NFS
  3. NFS is stable against weak attractive interactions

Why elusive experimentally?

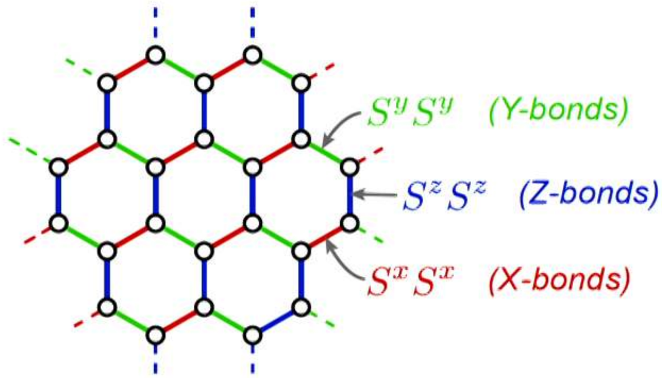
- Requires strong and specific structure of interactions

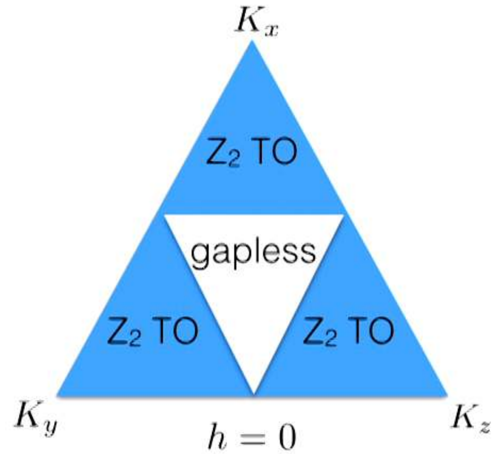
→ build and realize realistic models

- Lack of a smoking-gun signature

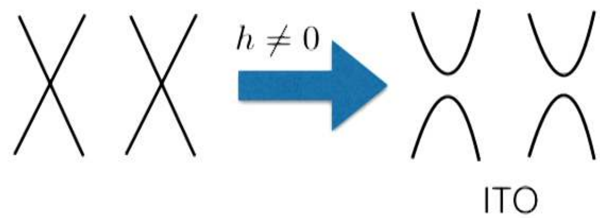
→ develop effective detecting methods

Kitaev model





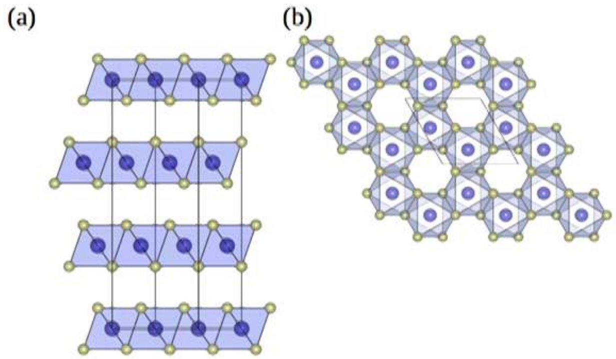
$$H_{\mathrm{K}} = \sum_{\langle ij \rangle \in \alpha} K_\alpha S_i^\alpha S_j^\alpha - \sum_i \vec{h} \cdot \vec{S}_i$$



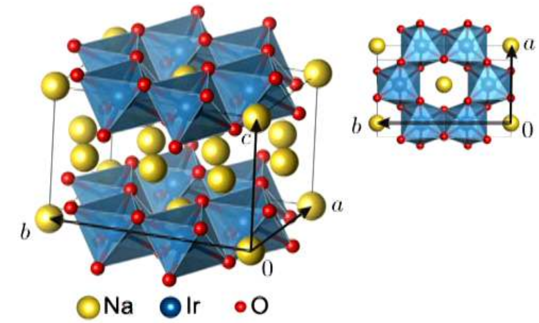
Phase 1: Z2 TO
Phase 2: ITO
Phase 3: trivial paramagnet

Kitaev, arXiv: cond-mat/0506438

Kitaev materials



$\alpha - \mathrm{RuCl_3}$

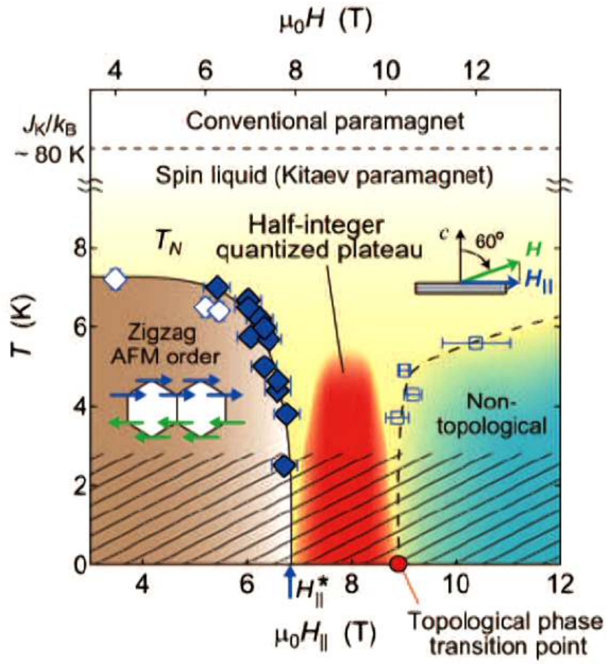


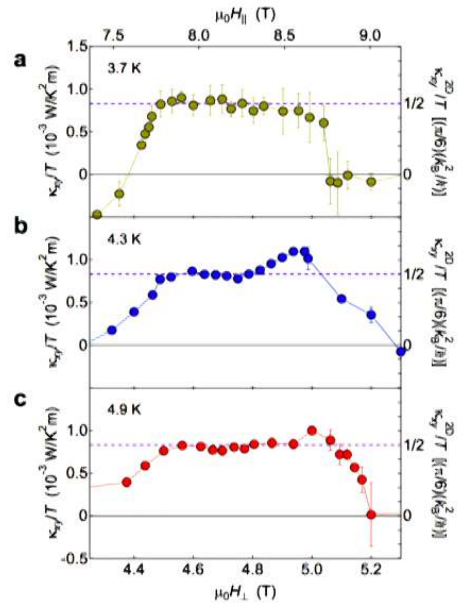
$\mathrm{Na_2IrO_3}$

Jackli and Khaliullin

Review: Trebst, arXiv: 1701.07056
Winter et al, arXiv: 1706.06113

$\alpha - \mathrm{RuCl}_3$





Kasahara, Matsuda, et al, arXiv: 1805.05022.

Ye, et al, arXiv: 1805.10532

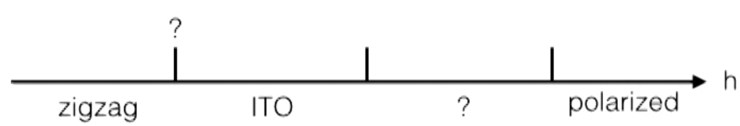
Vinkler-Aviv, Rosch, arXiv: 1805.11587

Cookmeyer, Moore, arXiv: 1807.03857

An ITO may indeed be realized in Kitaev meterials

Main questions

- Is the transition between the ITO and the trivial state direct, or is there an intermediate phase?
- Is there a critical theory to describe the transition between the ITO and the zigzag phase?



LZ and He, arXiv: 1809.09091

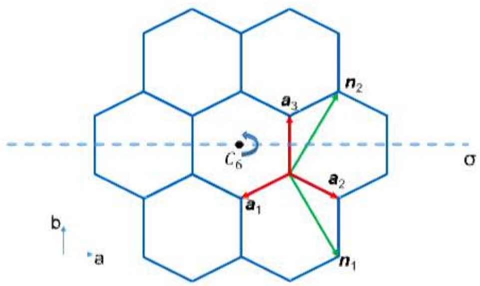
Quantum phase transitions

- Universality class
- Intricate interplay among all moving parts
- Unified understanding of the phases and crossover

Model and symmetry

- Is the transition between the ITO and the trivial state direct, or is there an intermediate phase?
- Model Hamiltonian:

$$H = K \sum_{\langle ij \rangle \in \alpha} S_i^\alpha S_j^\alpha - \vec{h} \cdot \sum_i \vec{S}_i$$



small h: ITO
large h: trivial

- Symmetries:

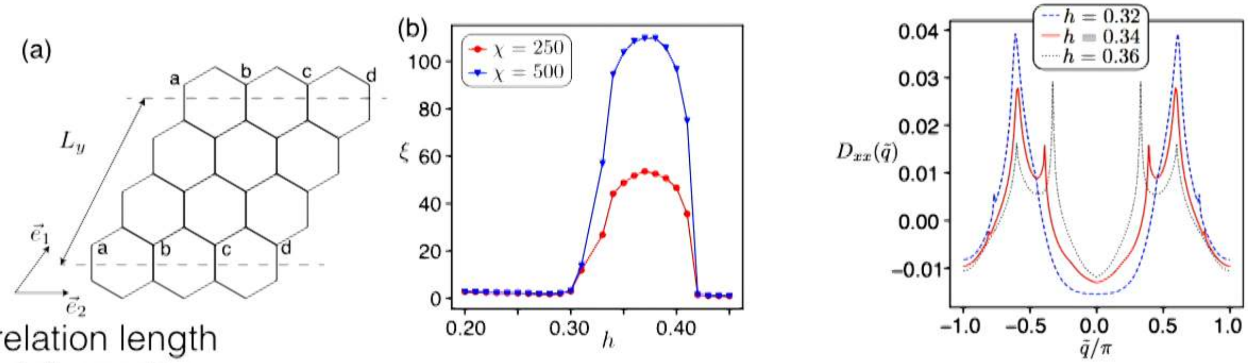
$$T_{1,2} : \vec{S}_{\vec{r}} \to \vec{S}_{\vec{r}+\vec{n}_{1,2}}$$

$$C_6^* : S_{\vec{r}}^x \to S_{C_6\vec{r}}^z, S_{\vec{r}}^y \to S_{C_6\vec{r}}^x, S_{\vec{r}}^z \to S_{C_6\vec{r}}^y$$

$$\mathcal{T}\sigma^* : S_{\vec{r}}^x \to S_{\sigma\vec{r}}^y, S_{\vec{r}}^y \to S_{\sigma\vec{r}}^x, S_{\vec{r}}^z \to S_{\sigma\vec{r}}^y$$

LZ and He, arXiv: 1809.09091

Numerical results: gapless NFS



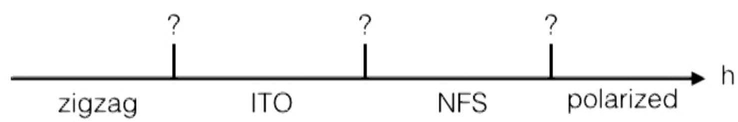
ξ : correlation length
χ : bond dimension
D_{xx} : spin structure factor

- Weak and strong fields: ξ independent on χ → gapped phase
- Intermediate fields: ξ increases dramatically with χ → gapless phase
- $2k_f$ singularities → NFS

LZ and He, arXiv: 1809.09091

A unified picture?

- Want a unified understanding of various phases



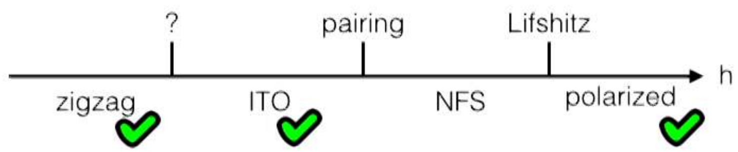
- NFS as a parent state

shrinking the NFS → confinement → trivial state

pairing → gap out the NFS → ITO

LZ and He, arXiv: 1809.09091

Where are we? Where to go?



LZ and He, arXiv: 1809.09091

Outline

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- QCD_3-Chern-Simons quantum criticalities
- Discussion

What's the game?

- Topological aspect:

  Remove the topological order, $\{1, \sigma, \epsilon\}$

- Symmetry aspect:

  Obtain the correct symmetries

- Dynamical aspect:

  Examine the existence of relevant perturbations

LZ and He, arXiv: 1809.09091

Why nontrivial?

- Usual strategy: anyon condensation

condense a bosonic anyon

↓

confines all other anyons

Why nontrivial?

- Usual strategy: anyon condensation

condense a bosonic anyon

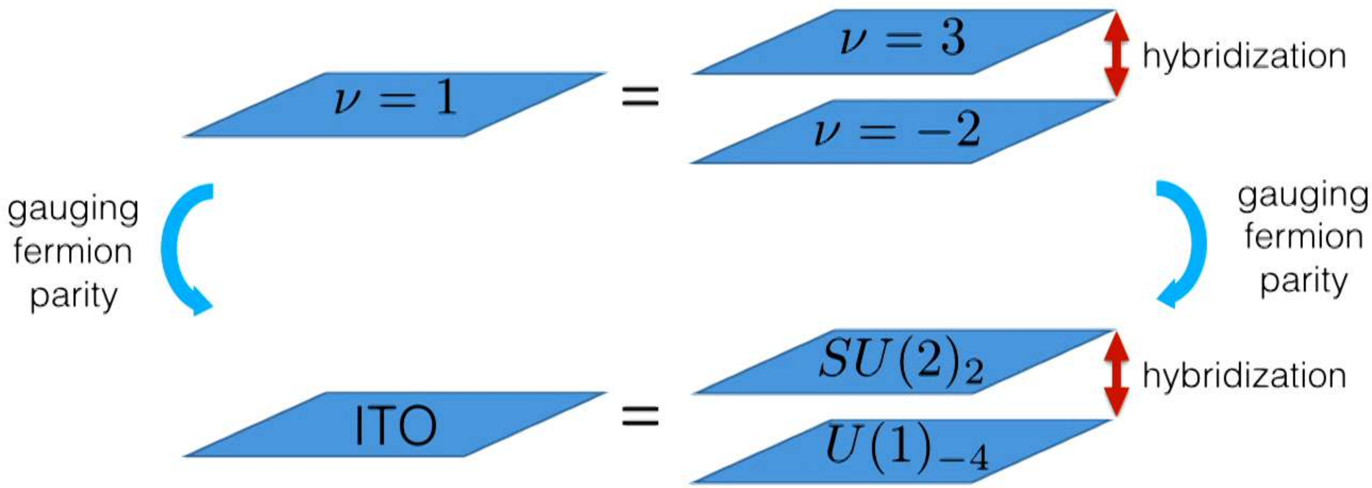
no boson to condense

confines all other anyons

- Find proper dual descriptions of the phases

1=3+(-2)

Kitaev, arXiv: cond-mat/0506438



$$\text{ITO} \longleftrightarrow \frac{SU(2)_2 \times U(1)_{-4}}{Z_2}$$

Seiberg, Witten, arXiv: 1602.04251

LZ and He, arXiv: 1809.09091

Topological aspect

$$\mathcal{L} = \mathcal{L}_{[\Phi,\mathbf{b}]} + \mathcal{L}_{\mathrm{CS}} + \mathcal{L}_{\mathrm{Maxwell-Yang-Mills}}$$

$$\mathcal{L}_{\mathrm{CS}} = -\frac{2}{4\pi}\mathrm{Tr}\left(bdb - \frac{2i}{3}b^3\right) + \frac{4}{4\pi}\tilde{b}d\tilde{b}$$

$\mathbf{b} = b + \tilde{b}\mathbf{1}$: a U(2) gauge field

$\mathcal{L}_{[\Phi,\mathbf{b}]}$: minimal coupling

- gapped Φ : Chern-Simons description of ITO
- condense Φ: short-range entangled state
- But which short-range entangled state?

LZ and He, arXiv: 1809.09091

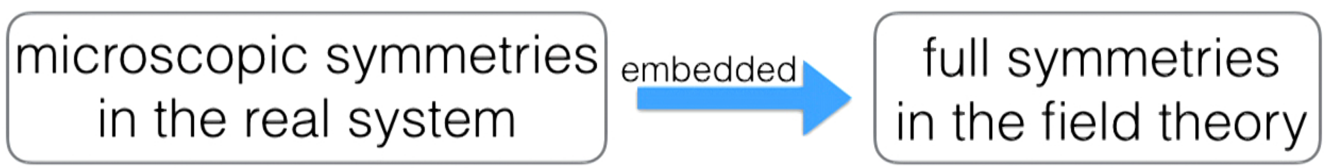
Symmetry aspect

- Microscopic symmetries:

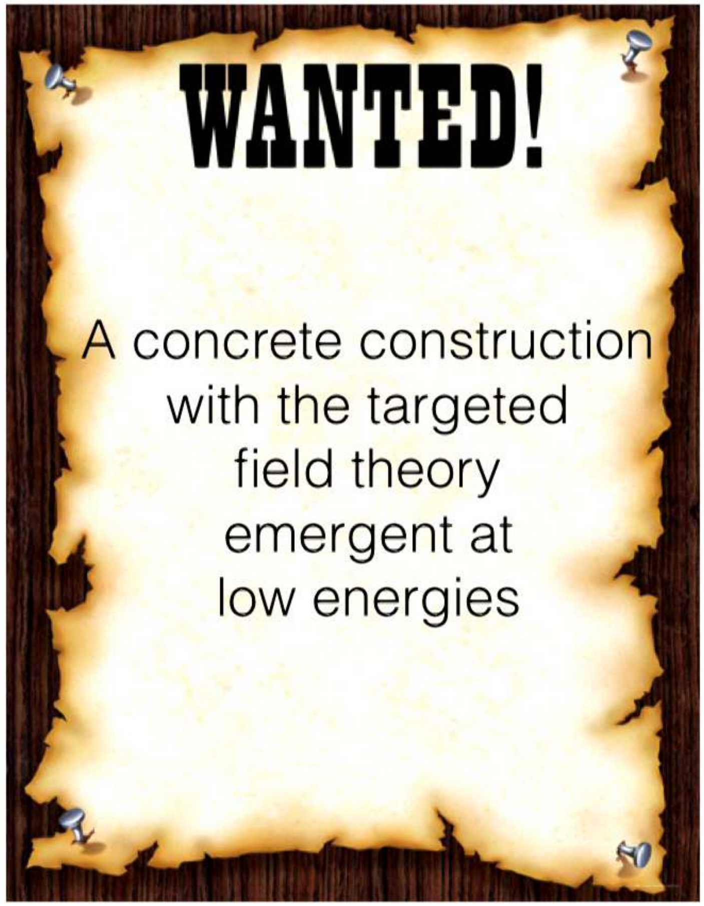
  lattice symmetries, etc

- Symmetries in the field theory:

  Poincare, CPT, U(1) flux conservation, SU(N_f) flavor



- Embedding pattern: depends on microscopic details



LZ and He, arXiv: 1809.09091

Fermionic dual theory

- Why fermionic? More flexible mean field states.
- Dual Lagrangian (level-rank duality):

$$\mathcal{L} = \sum_{I=1}^{N_f} \bar{\Psi}_I i(\partial\!\!\!/ - i a\!\!\!/)\Psi_I + m \sum \bar{\Psi}_I \Psi_I + \mathcal{L}_{\text{top}},$$

$$\mathcal{L}_{\text{top}} = \frac{2 - N_f/2}{4\pi} \mathrm{Tr}\left[\mathbf{a} d\mathbf{a} - \frac{2i}{3}\mathbf{a}^3\right] + (4 - N_f)\,\mathrm{CS}_g$$

$$+ \frac{2}{4\pi}\beta d\beta - \frac{1}{2\pi}\beta d(B - (\mathrm{Tr}\mathbf{a})).$$

Hsin, Seiberg, arXiv: 1607.07457

Radicevic, Tong, Turner, arXiv: 1608.04732

$\mathbf{a}$: another U(2) gauge field

N_f : number of flavors

CS_g : background gravitational Chern-Simons term

β : another U(1) gauge field

LZ and He, arXiv: 1809.09091

Parton construction

- Parton construction:

$$S^+ = \underbrace{c_1^\dagger c_2^\dagger}_{U(1)} \overbrace{\underbrace{f_1^\dagger f_2^\dagger}_{SU(2)}}^{U(1)}$$

- Mean field descriptions (w/ concrete Hamiltonians):

	$f_{1,2}$	$c_{1,2}$	Phase
1	$C=2$	$C=-1$	ITO
2	$C=1$	$C=-1$	zigzag
3	$C=0$	$C=-1$	polarized

$N_f = 2$ (rows 1 → 3); $N_f = 1$ (rows 1 → 2)

C: Chern number

LZ and He, arXiv: 1809.09091

Dynamical aspect

- Are there relevant perturbations other than the tuning parameters?

- The most obvious relevant perturbations:

$$\bar{\Psi}\gamma^{\mu}\Psi, \quad \frac{1}{2\pi}d(\mathrm{Tr}\mathbf{a}), \quad \mathcal{M}, \quad \bar{\Psi}\vec{\tau}\Psi, \quad \bar{\Psi}\vec{\tau}\gamma^{\mu}\Psi$$

τ: flavor matrix

- They are all forbidden by microscopic symmetries.

→ possible direct continuous transitions

LZ and He, arXiv: 1809.09091

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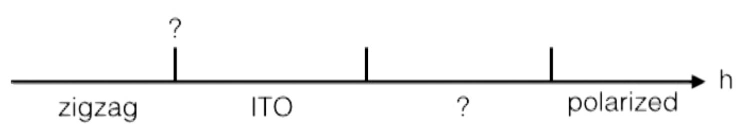
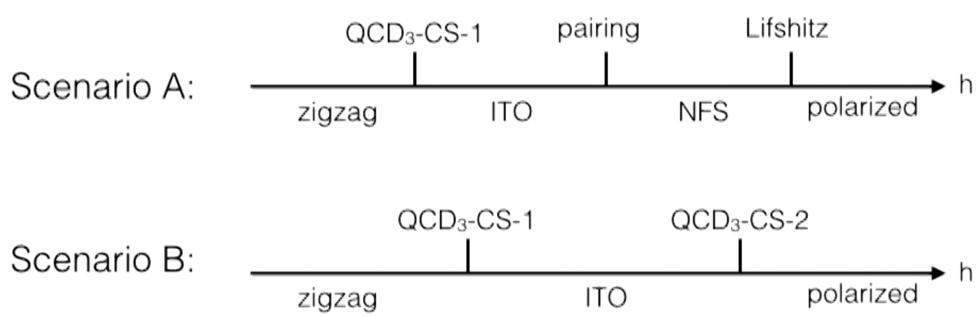


LZ and He, arXiv: 1809.09091

Summary

- Possible neutral Fermi surface with intermediate field strengths
- Possible exotic direct and continuous quantum phase transitions out the Ising topological order described by QCD_3-Chern-Simons theories



Discussion

- Experimental detection of the neutral Fermi surface

  Thermodynamics and thermal transport?
  Neutron scattering?
  Magnetic oscillation and charge oscillation?

- Numerics on more realistic models

- More on the critical theories

- A grand unification theory?

- Other platforms?