Title: Fractionalized Topological Insulators in Frustrated Magnets

Date: May 03, 2012 05:00 PM

URL: http://pirsa.org/12050042

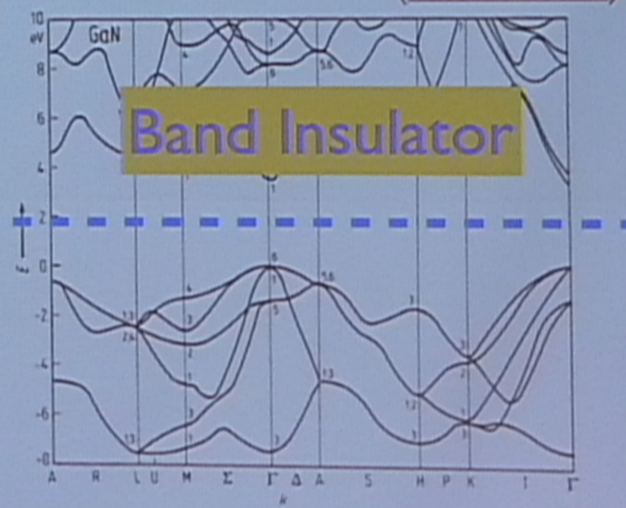
Abstract: Spin liquid phases in frustrated magnets may arise in a variety of forms. Here we discuss the possibility of topological insulators of spinons or the fractionalized excitations in spin liquids. These phases should be characterized by "both" of the two popular and different definitions of topological orders, namely the long-range entanglement and the symmetry-protected topological order. We show an explicit construction of such a state in frustrated magnets on the pyrochlore lattice and discuss novel properties such as the finite surface thermal conductivity.

Electronic phases: Weak Coupling (U/t<<1)

The Hubbard Hamiltonian

$$\mathcal{H} = - \sum_{ij,\sigma\sigma'} t_{ij}^{\sigma\sigma'} c_{i\sigma}^{\dagger} c_{j\sigma'} + U \sum_{i} n_{i\uparrow} n_{i\downarrow}$$

(www.ioffe.ru)



The Bloch Hamiltonian

$$\mathcal{H}_B = \sum_{k,\alpha} \epsilon_\alpha(\mathbf{k}) c_{\mathbf{k}\alpha}^{\dagger} c_{\mathbf{k}\alpha}$$

Topological Band Insulator...(II)

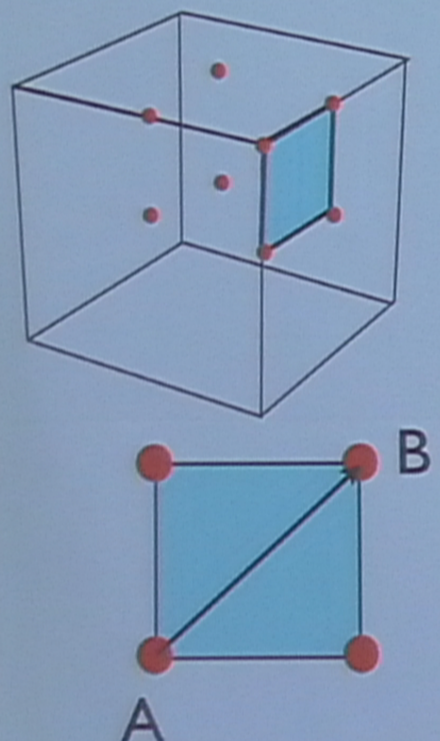
Fu, Kane, Mele; Roy; Moore , Balents (2006)

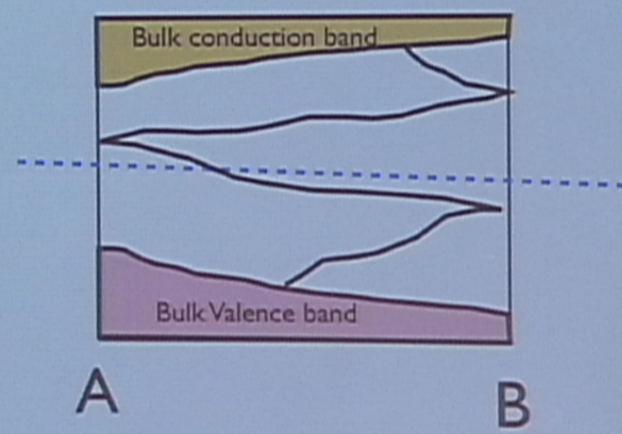
A characteristic feature of to distinguish the different BI is to look at surface states.

Possibility-II

Surface states cross the chemical potential ODD number of times

Topological Band Insulator





(Spin rotation is broken, by SOC[say])

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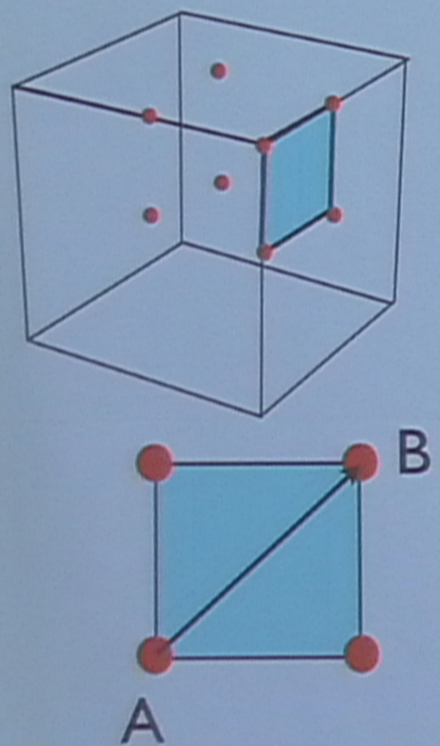

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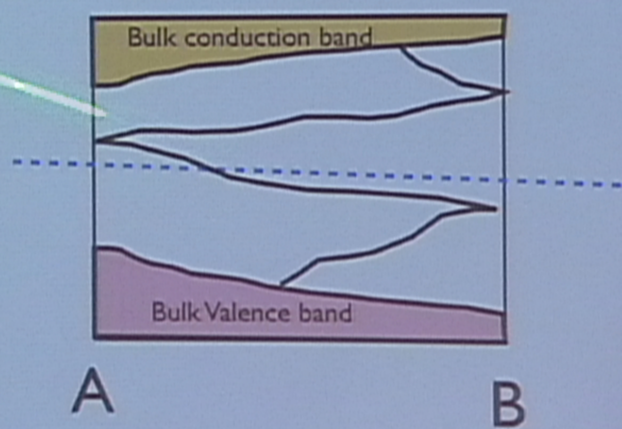

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Electronic Phases: Strong coupling (U/t>>1)

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- At half filling

- Spin rotation symmetry present

Heisenberg Model

$$\mathcal{H}_h = \sum_{ij} J_{ij} \mathbf{S}_i \cdot \mathbf{S}_j + \cdots$$

$$J = 4t_{ij}^2/U$$

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Quantum Spin Liquids: Fermionic Mean Field Theory for U(1) spin liquids

Wen (2002)

$$\mathbf{S} = \frac{1}{2} f^\dagger \boldsymbol{\sigma} f \qquad f \rightarrow \text{fermionic spinons}$$

U(1) SL: Band Theory for the spinons

constraint

for $J > 0$ $\qquad f_i^\dagger f_i = 1$

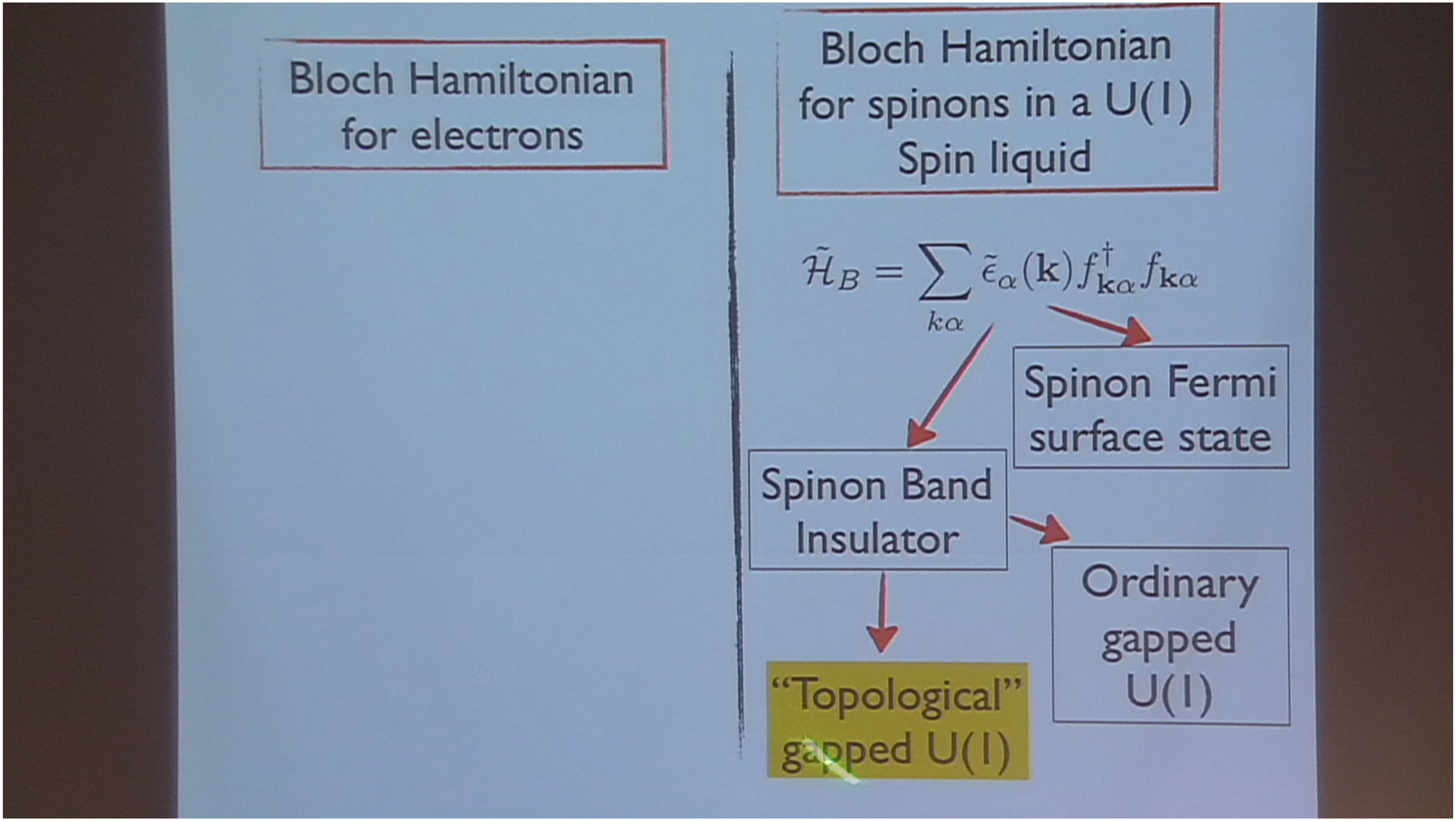
Relax this to
1 particle/site
on average

$$J \sum_{ij} \mathbf{S}_i \cdot \mathbf{S}_j \xrightarrow{\text{MF}} -J \sum_{ij} \chi_{ij} f_i^\dagger f_j \xrightarrow{\text{Fourier}} \sum_{\mathbf{k}\alpha} \tilde{\epsilon}_\alpha(\mathbf{k}) f_{\mathbf{k}\alpha}^\dagger f_{\mathbf{k}\alpha}$$

Solve self-consistently for the parameters

Beyond MFT

1. Numerical projection : $\mathcal{P}|\Psi_{MF}\rangle$
2. Consider the effect of gauge fluctuations


Bloch Hamiltonian for electrons
Bloch Hamiltonian for spinons in a U(1) Spin liquid
$\tilde{\mathcal{H}}_B = \sum_{k\alpha} \tilde{\epsilon}_\alpha(\mathbf{k}) f^\dagger_{\mathbf{k}\alpha} f_{\mathbf{k}\alpha}$
Spinon Fermi surface state
Spinon Band Insulator
Ordinary gapped U(1)
"Topological" gapped U(1)

FM Exchange and emergent SO Coupling

Shindou, Momoi (2009)

In this case the stable decoupling channels are the triplet p-h and p-p channels

Further Consequence of breaking spin rotation symmetry

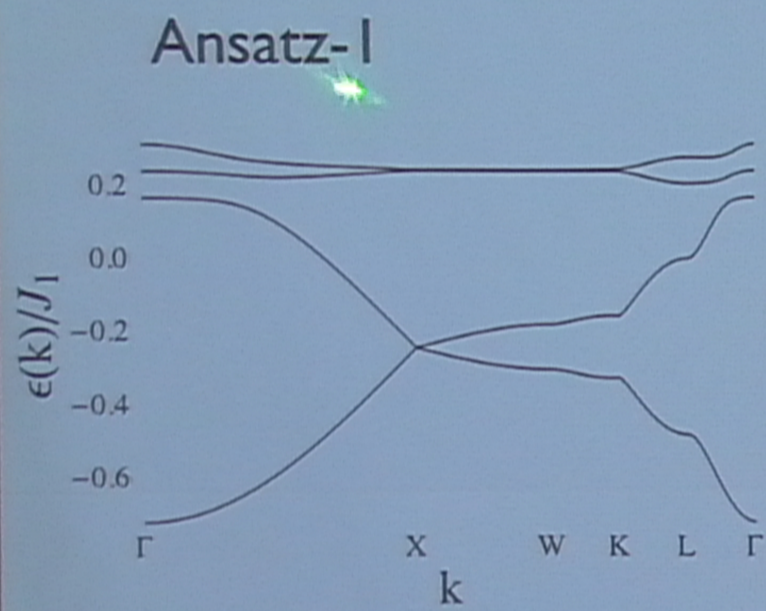
Shindou, Momoi (2009)

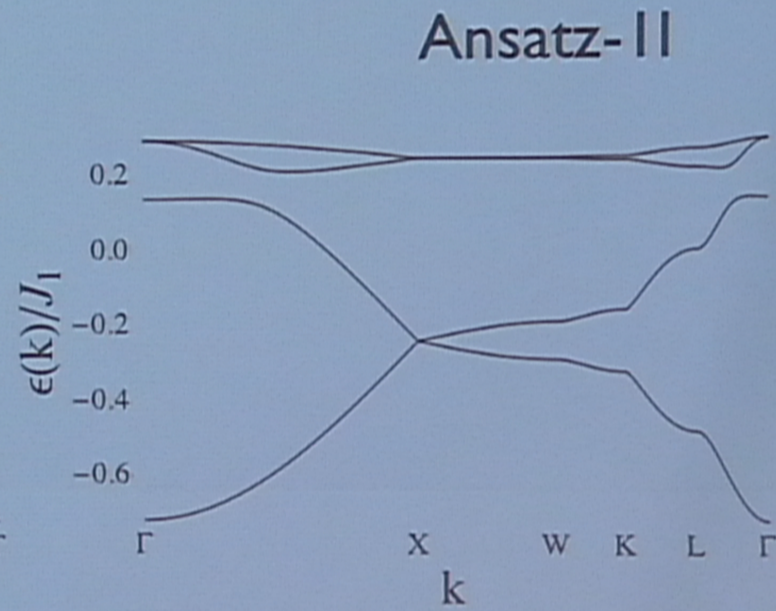
Non-zero bond spin nematic order

$$\langle \mathcal{Q}_{ij}^{ab} \rangle = \langle \frac{1}{2}\left(S_i^a S_j^b + S_j^b S_i^a\right) - \frac{\delta_{ab}}{3}\mathbf{S}_i \cdot \mathbf{S}_j \rangle = -\frac{1}{2}\left[E_{ij,a}E^*_{ij,b} - \frac{\delta_{ab}}{3}|\mathbf{E}_{ij}|^2\right] \neq 0$$

$$\langle \mathcal{J}_{ij} \rangle = \langle \mathbf{S}_i \times \mathbf{S}_j \rangle = \frac{i}{2}\left[\mathbf{E}^*_{ij}\chi_{ik}\chi_{kj} - \mathbf{E}_{ij}\chi_{jk}\chi_{ki}\right] \neq 0$$

Spinon Band and Topological Indices





Ansatz-I breaks some point group symmetries of the lattice

Beyond Mean field

- Incorporate gauge fluctuations
- In 3D compact pure U(1) gauge theory allows deconfimenemt.
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Summary

- A gapped U(1) spin liquid with non-trivial band topology for the spinons in 3D.
- Spin-rotation invariant microscopic models.
- Emergent SO coupling.
- Rich low energy spectrum.
- Interesting phase transitions (????)

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