Confinement transition out of a FL* metal with Z_2 topological and Ising-nematic order

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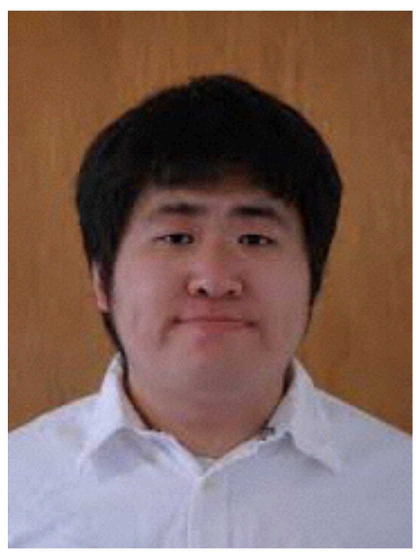
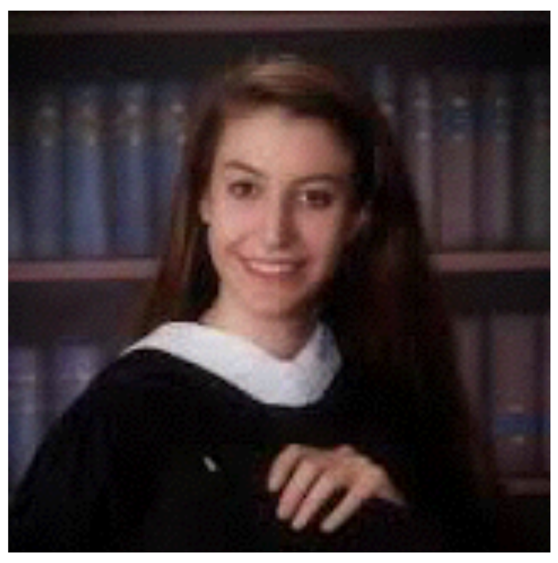



1. Z_2 spin liquid on the square lattice

N. Read and S. Sachdev, PRL **66**, 1773 (1991)

- Start with the semiclassical ground state of the J_1-J_2-J_3 antiferromagnet on the square lattice which has co-planar spiral antiferromagnetic order at the wavevector $(Q, 0)$.
- Quantum fluctuations across a continuous phase transition lead to a spin liquid state with Z_2 topological order and long-range Ising-nematic order
- This state can be efficiently described by Schwinger boson mean field theory.

$$H^b_{MF} = -\sum_{ij}(Q_{ij}\epsilon_{\alpha\beta}b^\dagger_{i\alpha}b^\dagger_{j\alpha} + h.c.) + \sum_i \lambda_i b^\dagger_{i\alpha}b_{i\alpha}$$

$$|\Psi^b\rangle = P_G \ \exp\left[\sum_{ij}\xi_{ij}\epsilon_{\alpha\beta}b^\dagger_{i\alpha}b^\dagger_{j\beta}\right]|0\rangle$$

- Excitations of the Z_2 spin liquid are
  (i) bosonic spinons $z_\alpha \sim b_\alpha + b^\dagger_\alpha$ and
  (ii) bosonic visons, which are Z_2 vortices in the Q_{ij}.
- The bosonic spinons and visons are mutual semions.

2. From bosonic to fermonic spinons

Purely topological properties of Z_2 spin liquids:

- 4 kinds of excitations, e, m, ϵ and the trivial local excitation 1
- Have the following fusion rules:

$$e \times e = m \times m = \epsilon \times \epsilon = 1$$
$$1 \times 1 = 1, e \times 1 = e, m \times 1 = m, \epsilon \times 1 = \epsilon$$
$$e \times m = \epsilon, e \times \epsilon = m, m \times \epsilon = e$$

- In the context of spin liquids, e and ϵ are bosonic and fermionic spinons, and m is the vison, 1 is a local excitation with integer spin

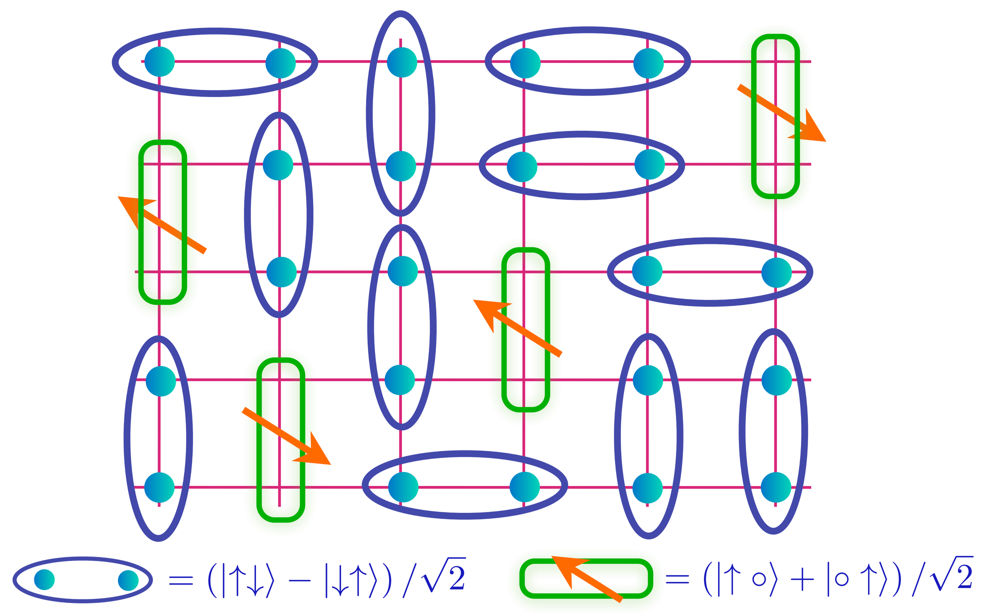
From the projective transformations of bosonic spinons (e particle) and the vison (the m particle) under space-group symmetries of the antiferromagnet, we can determine the projective symmetry transformations of the fermionic spinons (ϵ particle). Finally, we can determine the effective Hamiltonian of the fermionic spinons f_α.

A.M. Essin and M. Hermele, PRB **87**, 104406 (2013)
Y.-M. Lu, G.Y. Cho, A. Vishwanath, 1403.0575

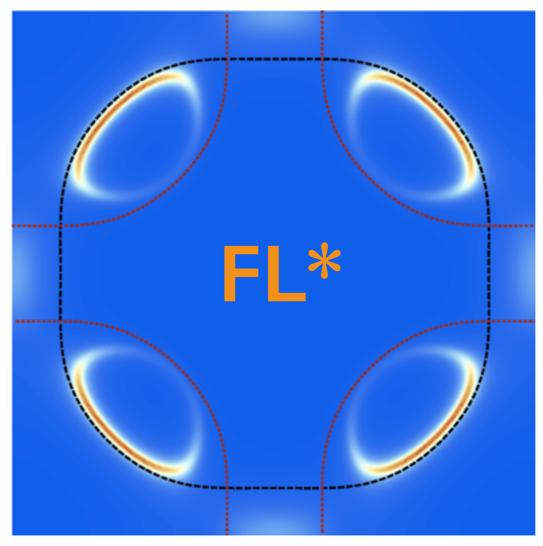
Symmetry relations for spin liquids on the rectangular lattice

Commutation relation	Bosonic PSG	Fermionic PSG	Vison PSG	Twist factor	Relation
$T_x^{-1}T_y^{-1}T_xT_y$	$(-1)^{p_1}$	$\eta_{T_xT_y}$	-1	1	$(-1)^{p_1+1} = \eta_{T_xT_y}$
$P_x^{-1}T_xP_xT_x$	$(-1)^{p_2}$	$\eta_{P_xT_y}$	1	1	$(-1)^{p_2} = \eta_{P_xT_x}$
$P_y^{-1}T_x^{-1}P_yT_x$	$(-1)^{p_3}$	$\eta_{P_yT_x}$	-1	1	$(-1)^{p_3+1} = \eta_{P_yT_x}$
$P_x^{-1}T_y^{-1}P_xT_y$	$(-1)^{p_4}$	$\eta_{P_xT_y}$	-1	1	$(-1)^{p_4+1} = \eta_{P_xT_y}$
$P_y^{-1}T_yP_yT_y$	$(-1)^{p_5}$	$\eta_{P_yT_y}$	1	1	$(-1)^{p_5} = \eta_{P_yT_y}$
P_x^2	$(-1)^{p_6}$	η_{P_x}	1	-1	$(-1)^{p_6+1} = \eta_{P_x}$
P_y^2	$(-1)^{p_7}$	η_{P_y}	1	-1	$(-1)^{p_7+1} = \eta_{P_y}$
$P_x^{-1}P_y^{-1}P_xP_y$	1	$\eta_{P_xP_y}$	-1	-1	$1 = \eta_{P_xP_y}$
$\mathcal{T}^2$	-1	-1	1	1	$1 = 1$
$T_x^{-1}\mathcal{T}^{-1}T_x\mathcal{T}$	$(-1)^{p_8}$	$\eta_{\mathcal{T}T_x}$	1	1	$(-1)^{p_8} = \eta_{\mathcal{T}T_x}$
$T_y^{-1}\mathcal{T}^{-1}T_y\mathcal{T}$	$(-1)^{p_9}$	$\eta_{\mathcal{T}T_y}$	1	1	$(-1)^{p_9} = \eta_{\mathcal{T}T_y}$
$P_x^{-1}\mathcal{T}^{-1}P_x\mathcal{T}$	$(-1)^{p_6}$	$\eta_{\mathcal{T}P_x}$	1	-1	$(-1)^{p_6+1} = \eta_{\mathcal{T}P_x}$
$P_y^{-1}\mathcal{T}^{-1}P_y\mathcal{T}$	$(-1)^{p_7}$	$\eta_{\mathcal{T}P_y}$	1	-1	$(-1)^{p_7+1} = \eta_{\mathcal{T}P_y}$

3. FL* metal from a Z_2 spin liquid



M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

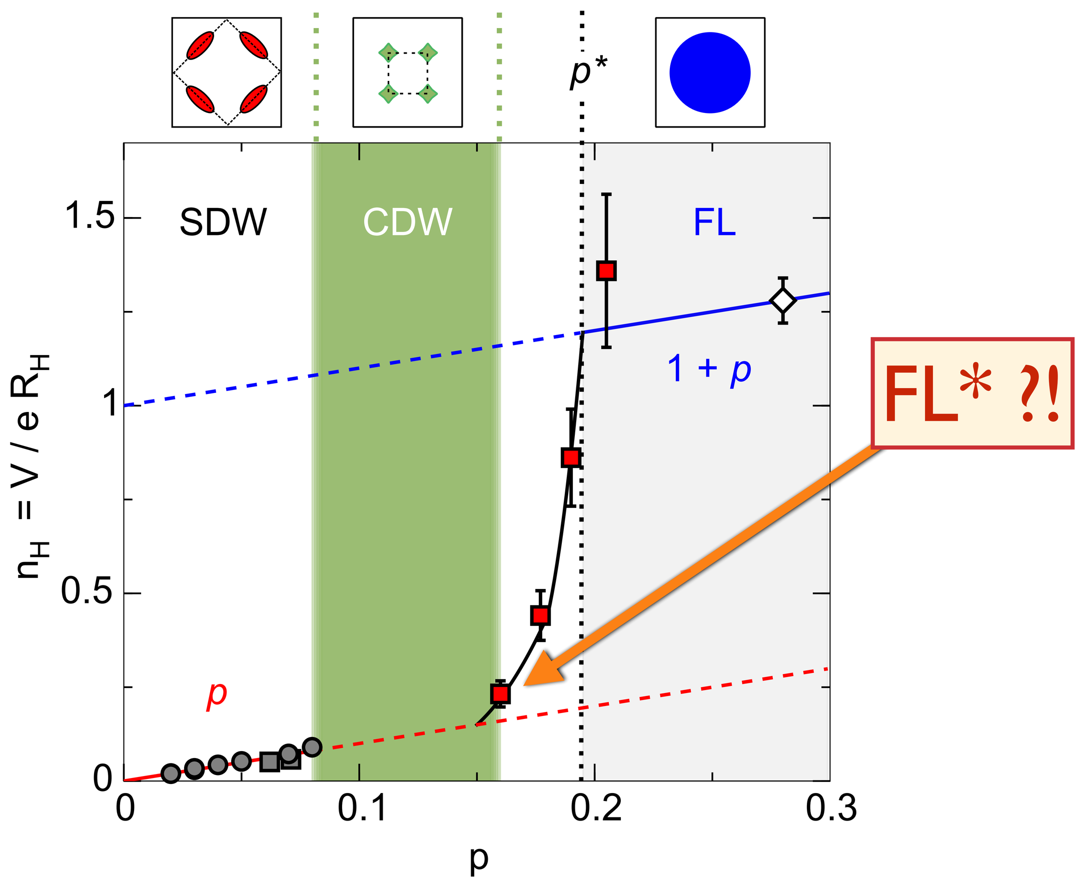


Y. Qi and S. Sachdev, PRB **81**, 115129 (2010)

- Dopants in a FL* metal are fermions, c_α, with charge $+e$ and spin $S = 1/2$ (the green dimers). So there need not be any low energy fractionalized excitations.
- The dopants form a Fermi surface of size equal to the dopant density p.
- The emergent gauge excitations of the Z_2 spin liquid, *i.e.* visons, survive in the FL* metal. Note that the green and blue dimers together have the same topological properties as the undoped dimer model.
- The violation of the Luttinger theorem in the FL* metal is justified by the presence of emergent gauge excitations (*i.e.* topological order).

Recent evidence for pseudogap metal as FL* in YBCO

Proust-Taillefer-UBC collaboration, Badoux et al. arXiv:1511.08162



4. Confinement transition of a FL* metal

- Confinement can be induced by the condensation of the bosonic bilinear $B \sim f^\dagger_\alpha c_\alpha$ or $\epsilon_{\alpha\beta}f_\alpha c_\beta$.
- This is a "Higgs" transition leading to confinement because B carries electric Z_2 charge.
- The B-condensed (Higgs) state is a superconductor because the pairing of the f_α fermions in the Z_2 spin liquid now induces a pairing of the c_α fermions. This pairing can have $d_{x^2-y^2} + s$ symmetry.
- The c_α fermions have trivial space group transformations, and so the projective space group transformations of B can be deduced from those of the fermionic spinons f_α.
- In many cases, the projective transformations of B also imply density-wave order in the superconductor. This implies there can be a direct second-order transition from the FL* metal to a confining Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) state.