Superconductivity from confinement transition of a FL* metal with Z_2 topological and Ising nematic order

(arXiv:1603.03041)

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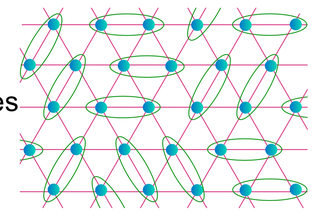
Z_2 spin liquids

- Quantum disordered ground states of certain Mott insulators
- No broken symmetry, topological degeneracy of ground states
- Schwinger boson or Abrikosov fermion mean-field theory:

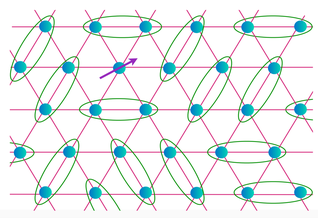


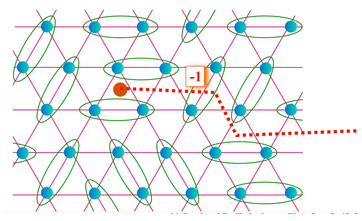
- $\vec{S} = \frac{1}{2} b^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} b_{i\beta}, \text{ or } \vec{S} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$

Read and Sachdev, PRL **66**, 1773 (1991)

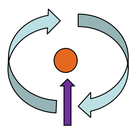
Wen, PRB **44**, 2662 (1991)

- $H^b_{MF} = -\sum_{i,j} (Q_{ij} \epsilon_{\alpha\beta} b^\dagger_{i\alpha} b^\dagger_{j\beta} + h.c.) + \sum_i \lambda_i (b^\dagger_{i\alpha} b_{i\alpha} - 1)$
- Excitations:





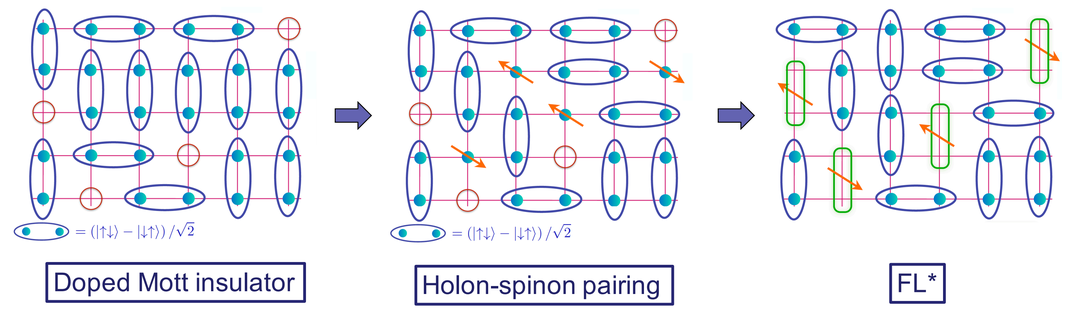
- 1. Fractionalized spin-half spinons 2. Visons or vortices of the Z_2 gauge field
- Spinons and visons are mutual semions



$\psi_s \to -\psi_s$

- J_1-J_2-J_3 Heisenberg model on the square lattice:
- Quantum fluctuations can drive a continuous phase transition from a spiral incommensurate antiferromagnet at (Q,0) or (0,Q) to a Z_2 spin liquid with Ising nematic order ➡ broken C_4 symmetry ➡ $|Q_{i,i+\hat{x}}|^2 - |Q_{i,i+\hat{y}}|^2 \neq 0$

Fractionalized Fermi liquid (Z_2 FL*)



- Metallic state with charge-e spin-half ***c*** fermions in the background of a Z_2 spin liquid

Punk, Allais and Sachdev, PNAS **112**, 9552 (2015)

- The size of the Fermi surface is determined by dopant density p

Senthil, Voijta and Sachdev, PRL **90**, 216403 (2003)

Paramekanti and Vishwanath, PRB **70**, 245118 (2004)

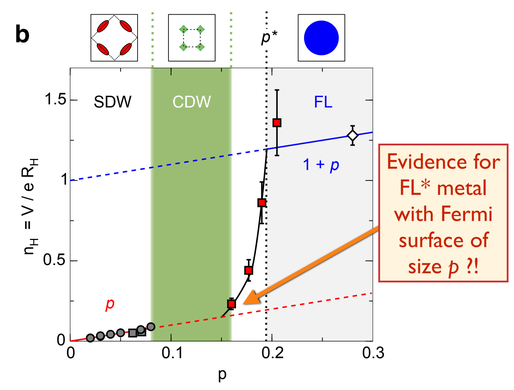
- No low energy fractionalized excitations
- The vortices of the internal Z_2 gauge field (visons) survive in the FL* metal, hence its topological character
- *Violates Luttinger's theorem* due to presence of emergent gauge excitations

Additional sectors of Z_2-FL*

	1_c	e_c	m_c	ϵ_c
S	1/2	0	1/2	0
Statistics	fermion	fermion	fermion	boson
Mutual semions	–	$m, \epsilon, m_c, \epsilon_c$	$e, \epsilon, e_c, \epsilon_c$	e, m, e_c, m_c
Q	1	1	1	1
Field operator	c	–	–	B

bosonic chargon

Hall effect measurements in YBCO



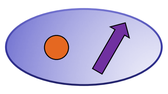
Badoux, Proust, Taillefer et al, Nature **531**, 9552 (2016)

Linking bosonic and fermionic descriptions

- Topological properties of Z_2 gauge theory:
- 4 kinds of topologically distinct excitations: e, m, ϵ and 1 (topologically trivial)
- Fusion rules:

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

Kitaev, Annals of Physics **321** (2006)



- In the context of Z_2 spin liquids:

$$e \to b \text{ (bosonic spinon)}$$
$$\epsilon \to f \text{ (fermionic spinon)}$$
$$m \to v \text{ (vison)}$$

- Symmetry fractionalization:

Essin and Hermele, PRB **87**, 104406 (2013)

Lu, Cho and Vishwanath, arXiv:1403.0575

- Symmetries act *projectively* on individual anyons
- For each symmetry (space-group, time-reversal) combination equivalent to identity, we can associate a Z_2 quantum number for each anyon
- From the Z_2 quantum numbers of the bosonic spinons and visons, we can determine the symmetry fractionalization quantum numbers of the fermionic spinons for a fully gapped Z_2 spin liquid
- Equivalence of bosonic and fermionic Z_2 spin liquids on the rectangular lattice:

Symmetry commutation	σ^e_O	σ^m_O	σ^t_O	σ^ϵ_O
$T_x^{-1}T_y^{-1}T_xT_y$	$(-1)^{p_1}$	-1	1	$\sigma^\epsilon_{T_xT_y} = (-1)^{p_1+1}$
$P_x^{-1}T_xP_xT_x$	$(-1)^{p_2}$	1	1	$\sigma^\epsilon_{P_xT_x} = (-1)^{p_2}$
$P_y^{-1}T_x^{-1}P_yT_x$	$(-1)^{p_3}$	-1	1	$\sigma^\epsilon_{P_yT_x} = (-1)^{p_3+1}$
$P_x^{-1}T_y^{-1}P_xT_y$	$(-1)^{p_4}$	-1	1	$\sigma^\epsilon P_xT_y = (-1)^{p_4+1}$
$P_y^{-1}T_yP_yT_y$	$(-1)^{p_5}$	1	1	$\sigma^\epsilon_{P_yT_y} = (-1)^{p_5}$
P_x^2	$(-1)^{p_6}$	1	-1	$\sigma^\epsilon_{P_x} = (-1)^{p_6+1}$
P_y^2	$(-1)^{p_7}$	1	-1	$\sigma^\epsilon_{P_y} = (-1)^{p_7+1}$
$P_x^{-1}P_y^{-1}P_xP_y$	1	-1	-1	$\sigma^\epsilon_{P_xP_y} = 1$
$\mathcal{T}^2$	-1	1	1	$\sigma^\epsilon_{\mathcal{T}} = -1$
$T_x^{-1}\mathcal{T}^{-1}T_x\mathcal{T}$	$(-1)^{p_8}$	1	1	$\sigma^\epsilon_{\mathcal{T}T_x} = (-1)^{p_8}$
$T_y^{-1}\mathcal{T}^{-1}T_y\mathcal{T}$	$(-1)^{p_9}$	1	1	$\sigma^\epsilon_{\mathcal{T}T_y} = (-1)^{p_9}$
$P_x^{-1}\mathcal{T}^{-1}P_x\mathcal{T}$	$(-1)^{p_6}$	1	-1	$\sigma^\epsilon_{\mathcal{T}P_x} = (-1)^{p_6+1}$
$P_y^{-1}\mathcal{T}^{-1}P_y\mathcal{T}$	$(-1)^{p_7}$	1	-1	$\sigma^\epsilon_{\mathcal{T}P_y} = (-1)^{p_7+1}$

- Can write down a Hamiltonian consistent with the projective symmetry realization for the fermionic spinons ➡ Pi-flux gapped spin liquid

Superconducting transition

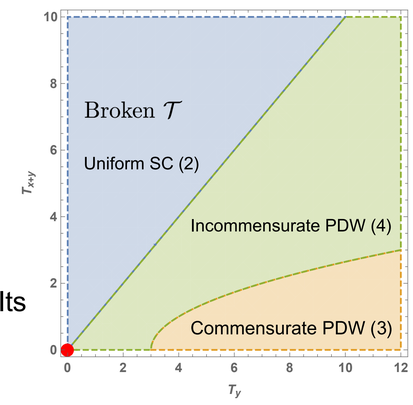
- Confinement transitions out of the Z_2 FL* :

Condense b ➡ SDW | Condense v ➡ Bond-DW | Condense B ➡ Superconductivity

Chubukov, Senthil and Sachdev, PRL **72**, 2089 (1994)

Patel, Chowdhury, Allais and Sachdev, PRB **93**, 165139 (2016)

- A Higgs transition induced by condensation of $B \sim f^\dagger_{i\alpha} c_\alpha$ or $\epsilon_{\alpha\beta} c_{i\alpha} f_{i\beta}$ results in confinement as B carries Z_2 gauge charge
- The pairing of ***f*** spinons induces a pairing of the ***c*** fermions, resulting in a superconductor
- Non-trivial transformation of B under translation results in spatial modulation of the superconducting order parameter (Pair-Density Wave or FFLO state)



Conclusions and Outlook

- Developed mapping between bosonic and fermionic Z_2 spin liquids on the rectangular lattice
- Formulated equivalent fermionic description of an energetically favorable gapped bosonic Z_2 spin liquid which can underlie a Z_2 FL* state
- Confinement transition out of this FL* can lead to a superconductor, usually a PDW
- *Open questions:* (work in progress)
  - Does a FL* metal describe the pseudogap phase?
  - Uniform d-wave superconductivity from Z_2 FL* ?
  - What about d-wave SC co-existing bond-DW and PDW as observed in recent STM experiments?

Fujita et al, PNAS **111**, 3026 (2014)
Hamidian et al, Nature **532**, 343 (2016)