Superconductivity from confinement transition of FL* metals with Z_2 topological order

Phys. Rev. B **94**, 024502 (2016), Phys. Rev. B **94**, 205117 (2016)

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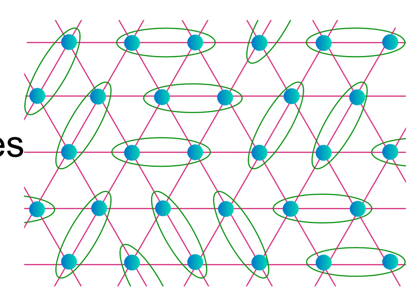
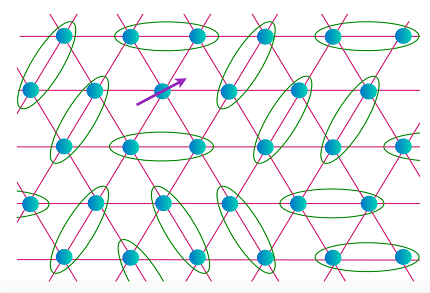
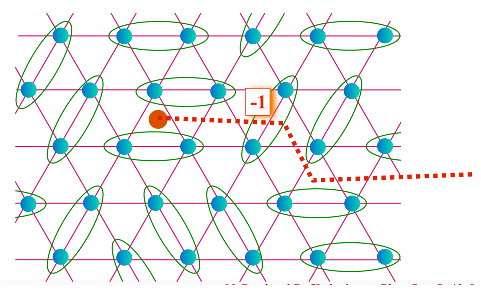
Z_2 spin liquids

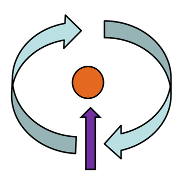


- Quantum disordered ground states of certain Mott insulators
- No broken symmetry, topological degeneracy of ground states
- Schwinger boson or Abrikosov fermion mean-field theory:
- $\vec{S} = \frac{1}{2} b^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} b_{i\beta}$, or $\vec{S} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$ — 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



$\psi_s \to -\psi_s$

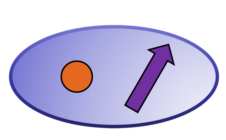
- J_1-J_2-J_3 Heisenberg model on the square lattice:
- Quantum fluctuations can drive a continuous phase transition from a spiral incommensurate antiferromagnet at (Q,0) or (0,Q) to a Z_2 spin liquid with Ising nematic order ⟹ broken C_4 symmetry → $|Q_{i,i+\hat{x}}|^2 - |Q_{i,i+\hat{y}}|^2 \neq 0$

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)

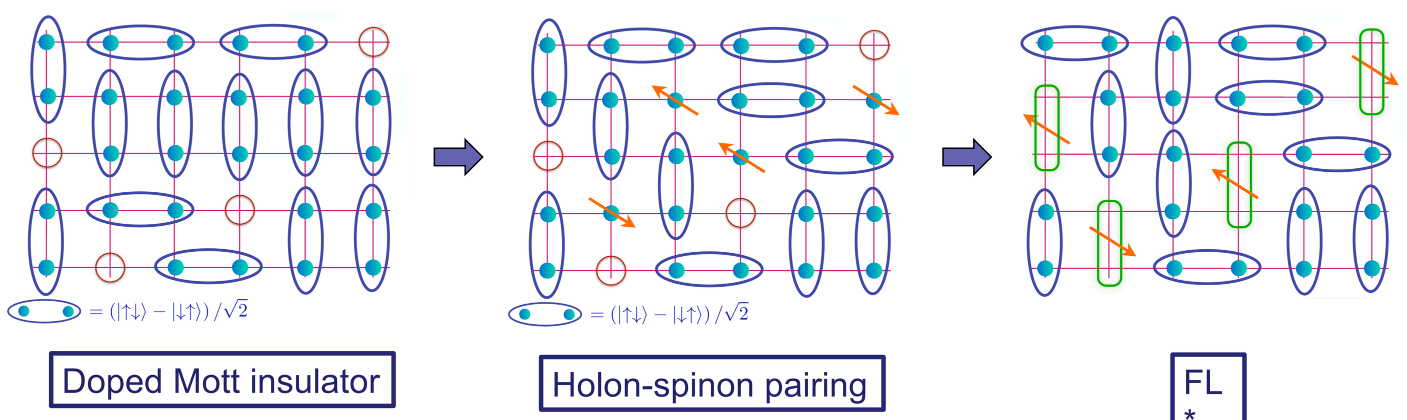


- In the context of Z_2 spin liquids: $e \to b$ (bosonic spinon), $\epsilon \to f$ (fermionic spinon), $m \to v$ (vison)
- Symmetry fractionalization: — Essin and Hermele, PRB **87**, 104406 (2013); Lu, Cho and Vishwanath, arXiv:1403.0575
- Symmetries act *projectively* on individual anyons
- For each 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

Fractionalized Fermi liquid (Z_2 FL*)



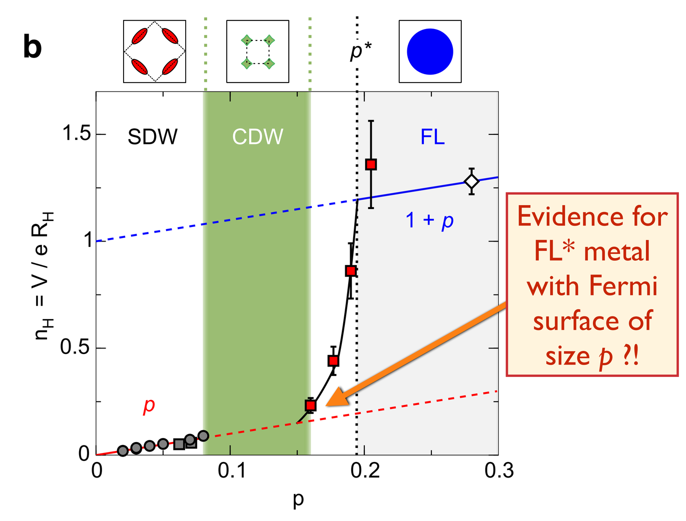
- Metallic state with charge-e spin-half ***c*** fermions in the background of a Z_2 spin liquid — Punk, Allais and Sachdev, PNAS **112**, 9552 (2015)
- The size of the Fermi surface is determined by dopant density p
- No low energy fractionalized excitations — Senthil, Vojta and Sachdev, PRL **90**, 216403 (2003); Paramekanti and Vishwanath, PRB **70**, 245118 (2004)
- 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



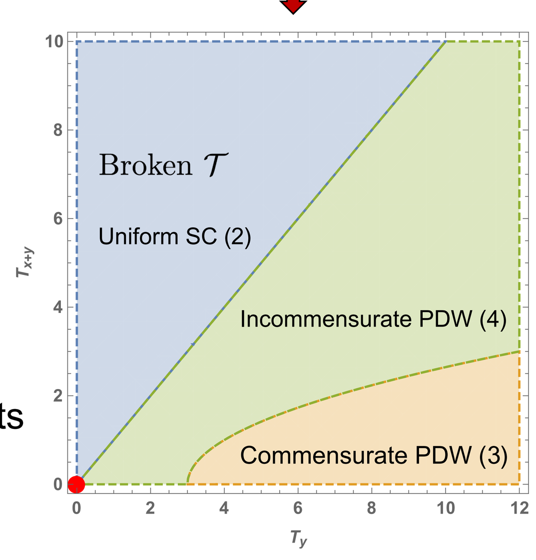
Badoux, Proust, Taillefer et al, Nature **531**, 9552 (2016)

Superconducting transition

Confinement transitions out of the Z_2 FL* :

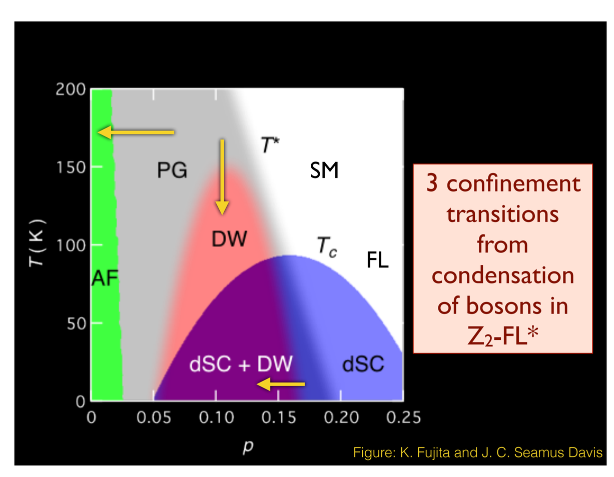
Condense b ⟹ SDW	Condense v ⟹ Bond-DW	Condense B ⟹ Superconductivity
Chubukov, Senthil and Sachdev, PRL **72**, 2089 (1994)	Patel, Chowdhury, Allais and Sachdev, PRB **93**, 165139 (2016)	

- 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)



D-wave SC, Density waves and Hall effect

- Consider a 'plain vanilla' Z_2 FL* with trivial PSG for fermionic spinons
- D-wave spinon-pairing leads to uniform d-wave SC
- Modified boson dispersions can lead to co-existing uniform SC with bond density waves and pair density waves at the same axial wave-vector **Q**, as observed in recent STM experiments. — Fujita et al, PNAS **111**, 3026 (2014); Hamidian et al, Nature **532**, 343 (2016)



- Hall No. also shows a jump at the optimal doping critical point in the metallic state at T=0
- *Open questions:*
  - How does the jump in the Hall No. smoothen at finite T?
  - Which experiments can distinguish the Z_2 FL* from other candidate *topological metals* or field-induced magnetism?