Superconductivity from confinement transition of a FL* metal with $Z_2$ topological and Ising nematic order
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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:
  \[
  S = \frac{1}{2} a_i^\dagger a_i b_i^\dagger b_i, \quad \text{or} \quad S = \frac{1}{2} a_i^\dagger a_i f_i^\dagger f_i
  \]
- Examinations:
  1. Fractionalized spin-half spinons
  2. Visons or vortices of the $Z_2$ gauge field
  - Spinons and visons are mutual semions
  - $J_{s-c} \sim J_{c-s} $ Heisenberg model on the square lattice
  - Quantum fluctuations can drive a continuous phase transition from a spiral the fermionic gapped state

**Fractionalized Fermi liquid (Z$_2$ FL*)**
- Metallic state with charge $\pi$-spin-half $c$ fermions in the background of a $Z_2$ spin liquid
  - Pure, Alice and Sachdev, PNAS 112, 9502 (2015)
- The size of the Fermi surface is determined by dopant density $p$
  - Senffl, Vojta and Sachdev, PRL 96, 216403 (2006)
- No low energy fractionalized excitations
  - Panagopoulos and Vishwanath, PRL 78, 245101 (2002)
- 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

**Linking bosonic and fermionic descriptions**
- **Topological properties of $Z_2$ gauge theory**
  - 4 kinds of topologically distinct excitations: $e$, $m$, $\epsilon$ and 1 (topologically trivial)
- **Fusion rules**:
  - $\epsilon \times \epsilon = m \times m = e \times \epsilon = e \times e = \epsilon$
  - $1 \times 1 = 1$, $e \times 1 = m$, $m \times 1 = m$, $\epsilon \times 1 = \epsilon$
  - $\epsilon \times m = \epsilon$, $m \times \epsilon = m$, $m \times m = e$
- **In the context of $Z_2$ spin liquids**:
  - $e \rightarrow b$ (bosonic spinon)
  - $e \rightarrow f$ (fermionic spinon)
  - $m \rightarrow (\text{vison})$
- **Symmetry fractionalization**:
  - 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**:
  - Can write down a Hamiltonian consistent with the projective symmetry realization for the fermionic spinons $\leftrightarrow$ Pf-flux gapped spin liquid

> Figure: K. Fujita and J. C. Seamus Davis