Quantum fluctuating antiferromagnetism: A route to intertwining topological order & discrete broken symmetries

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Pseudogap phase in high T_c cuprates

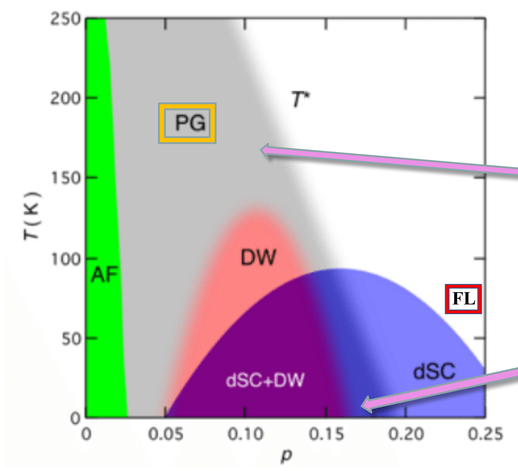


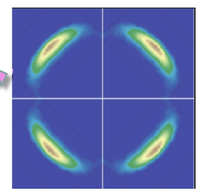
Figure credits: K. Fujita *et al*, Nature Physics **12**, 150–156 (2016)
M. Plate *et al*, PRL. 95, 077001 (2005)

Pseudogap Metal:

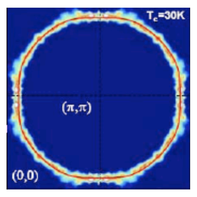
Displays Fermi arcs.

Behaves like a Fermi liquid, with a Fermi surface of size *p* instead of *1 + p*.

Hall effect experiments show that it is also present at high magnetic fields and low temperatures.



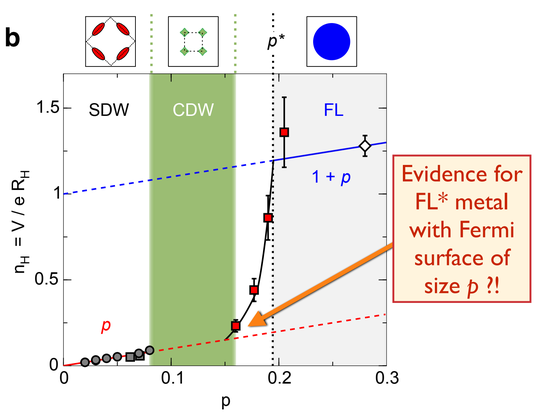
Conventional Fermi liquid: Large hole Fermi surface of size 1 + p.



- Hall conductivity provides strong evidence of Fermi surface reconstruction near optimal doping
- Is there a quantum critical point under the superconducting dome?
- What is the nature of phase transition?

Symmetry breaking or topological?

Hall effect measurements in YBCO

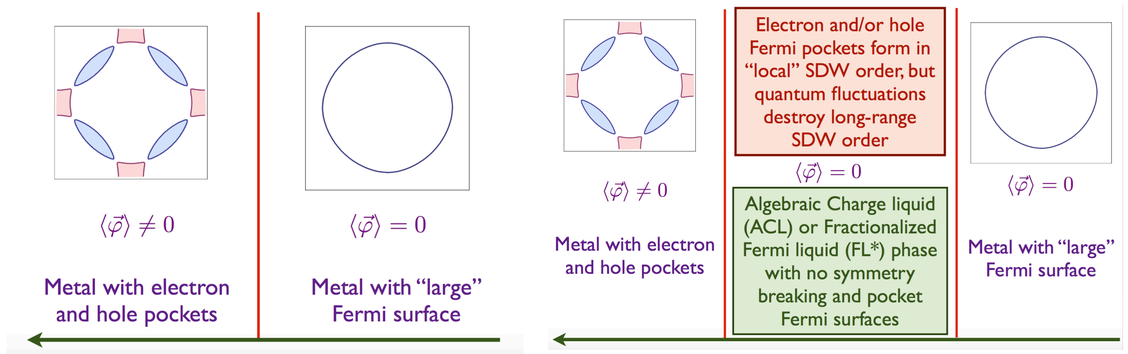


Badoux, Proust, Taillefer et al., Nature **531**, 210 (2016)

Evidence for FL* metal with Fermi surface of size *p* ?!

Possibility 1: Symmetry breaking: Spin density wave (SDW) order

Possibility 2: Topological order (No long range symmetry breaking)

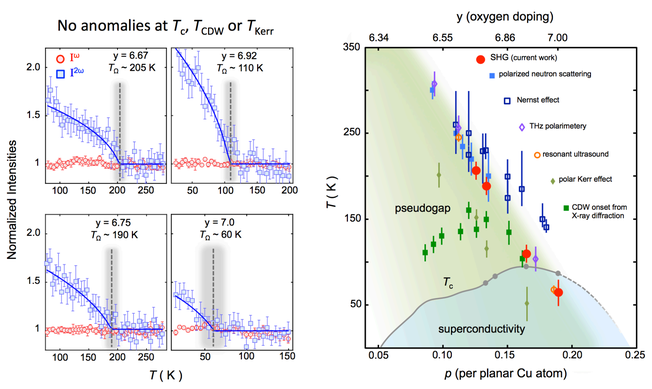


Topological metal violates Luttinger's Theorem

M. Oshikawa, PRL **84**, 3370 (2000)
T. Senthil *et al*, PRL **90**, 216403 (2003)
Paramekanti *et al*, PRB **70**, 245118 (2004)

Additional broken symmetries in the pseudogap phase

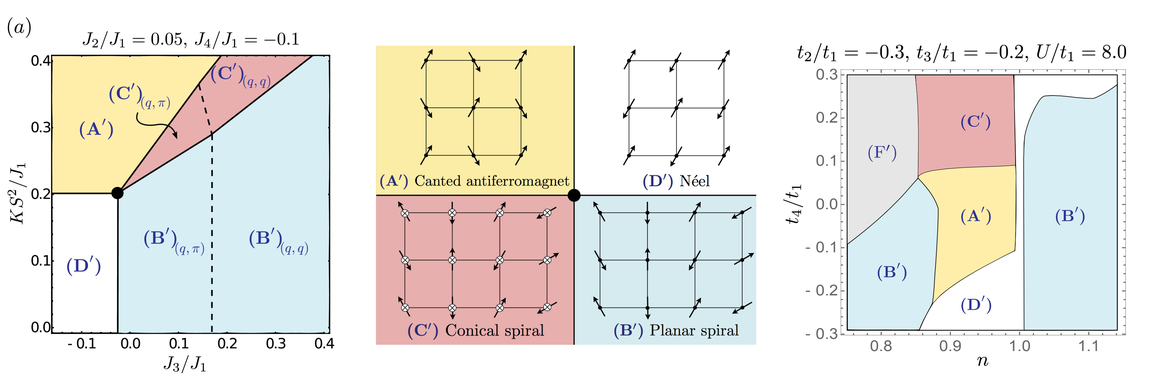
- Nematic order, broken C_4 symmetry
  Daou *et al*, Nature **463**, 519 (2010)
- Broken inversion symmetry C_2
- Broken time reversal $\boldsymbol{\theta}$ (?)
- $\boldsymbol{\theta}$ C_2 seems to be preserved
  Zhao, Belvin, Hsieh *et al*, Nature Physics **13**, 250 (2017)



Can discrete symmetry breaking be intertwined with topological order?

Do such phases appear naturally proximate to a Neel antiferromagnet?

Long range AF order close to Neel phase



Phases of classical frustrated Heinsenberg model with ring exchange K

Identical SDW phases in metal

Z_2 topological order in insulators

Key idea: **Quantum disorder the spins: Spin-rotation and translation invariance regained. Discrete symmetries remain broken.**

CP^1 model with emergent U(1) gauge field

$\mathbf{n} = z_\alpha^* \vec{\sigma}_{\alpha\beta} z_\beta$ with $\alpha, \beta = \uparrow, \downarrow$, $|z_\alpha|^2 = 1$ (X.Yang and F.Wang, 2016, X.-G Wen, 2002)

Condense charge 2 Higgs fields

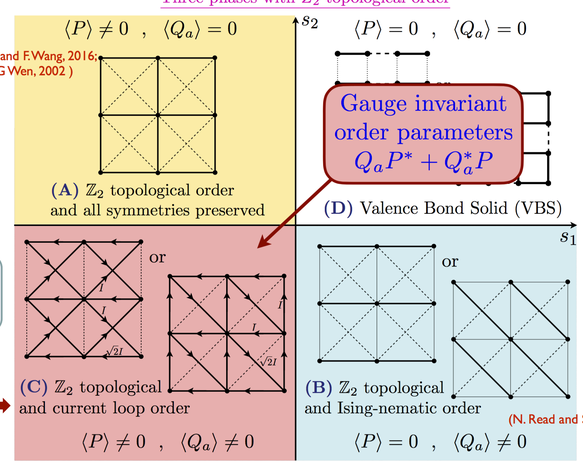
$P \sim \varepsilon_{\alpha\beta} z_\alpha \partial_t z_\beta \quad , \quad Q_a \sim \varepsilon_{\alpha\beta} z_\alpha \partial_a z_\beta$

$$\mathcal{L} = \frac{1}{g}|(\partial_\mu - i a_\mu) z_\alpha|^2 + s_1 |P|^2 + s_2 |Q_a|^2$$

Odd under C_2 and θ, but even under θ C_2 – same symmetries as loop currents

Phase diagram at large g with $\langle z_\alpha \rangle = 0$

Three phases with Z_2 topological order



Z_2 topological order in metals

Spin fermion model: Electrons coupled to O(3) AF order parameter

$$\mathcal{H}_c = -\sum_{i,\rho} t_\rho \left(c^\dagger_{i,\alpha} c_{i+\boldsymbol{v}_\rho,\alpha} + c^\dagger_{i+\boldsymbol{v}_\rho,\alpha} c_{i,\alpha} \right) - \mu \sum_i c^\dagger_{i,\alpha} c_{i,\alpha} + \mathcal{H}_{\rm int}$$

$$\mathcal{H}_{\rm int} = -\lambda \sum_i \eta_i \Phi^\ell(i) c^\dagger_{i,\alpha} \sigma^\ell_{\alpha\beta} c_{i,\beta} + V_\Phi$$

Transform to '*rotating reference frame*' defined by local orientation of the O(3) order parameter

$$\begin{pmatrix} c_{i\uparrow} \\ c_{i\downarrow} \end{pmatrix} = R_i \begin{pmatrix} \psi_{i,+} \\ \psi_{i,-} \end{pmatrix}$$

Fermionic chargons

Sachdev *et al*, PRB **80**, 155129 (2009)

$$\mathcal{H}_{\rm int} = -\lambda \sum_i \eta_i H^a(i) \psi^\dagger_{i,s} \sigma^a_{ss'} \psi_{i,s'} + V_H$$

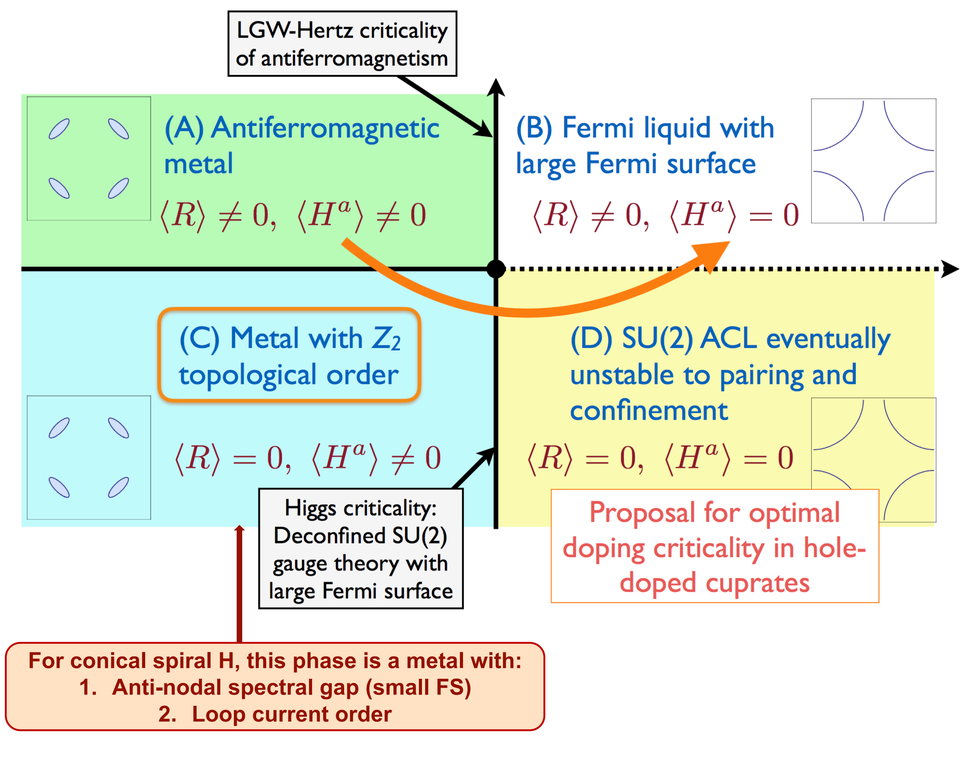
$$\sigma^\ell \Phi^\ell(i) = R_i \, \sigma^a H^a(i) \, R_i^\dagger$$

Higgs field

Higgs field = AFM order for the chargons

Global phase diagram

Chowdhury *et al*, PRB **91**, 115123 (2015)
Sachdev *et al*, PTEP 12C102 (2016)



For conical spiral H, this phase is a metal with:
1. **Anti-nodal spectral gap (small FS)**
2. **Loop current order**

Conclusions and open questions

- **SU(2) gauge theory of metals with Z_2 topological order can explain the concurrent appearance of anti-nodal gap and discrete broken symmetries in the hole-doped cuprates.**
- **Topologically ordered phases energetically proximate to the Neel state have the desired broken symmetries.**
- How does one relate the parameters of the theory to the microscopic hopping/interaction parameters measured in experiments?
- What are the signatures of topological order in numerics, like cluster DMFT on the 2d Hubbard model?
- Is time-reversal symmetry broken in the hole-doped cuprates? If not, how does one get a topological metal with broken inversion inversion but intact time-reversal?
- What about phase transitions to superconductivity/density wave-phases?