Paramagnon fractionalization theory of the cuprate pseudogap

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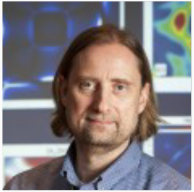

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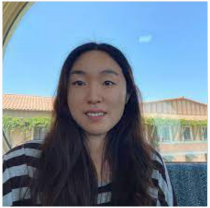

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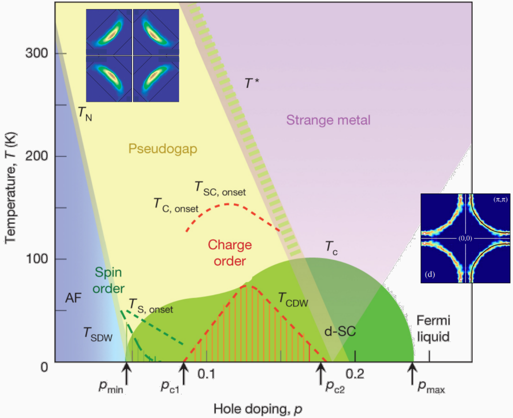
Long-standing mystery in cuprates - the nature of the pseudogap



View the pseudogap metal as a quantum state, which could be stable at $T = 0$ under suitable conditions

> Goal: construct a mean-field theory that captures both FL and psuedo-gap metals

Keimer et al., "From Quantum Matter to High-Temperature Superconductivity in Copper Oxides".

Paramagnon theory of the Hubbard model

Starting point: Hubbard-Stratonovich transformation in particle-hole channel

$$H_U = -\sum_{i<j} t_{ij} \left[c^\dagger_{i\alpha} c_{i\alpha} + c^\dagger_{j\alpha} c_{i\alpha} \right] + \sum_i \left[-\mu(n_{i\uparrow} + n_{i\downarrow}) + U n_{i\uparrow} n_{i\downarrow} \right]$$

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$$U\left(n_{i\uparrow} - \frac{1}{2}\right)\left(n_{i\downarrow} - \frac{1}{2}\right) = -\frac{2U}{3}\mathbf{S}_i^2 + \frac{U}{4}$$

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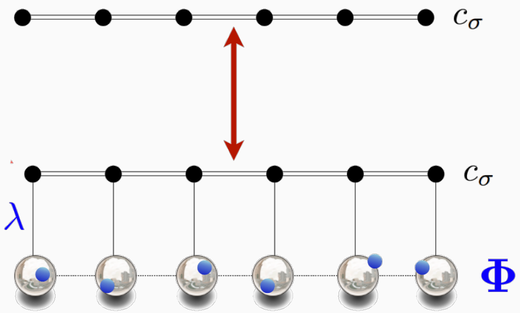
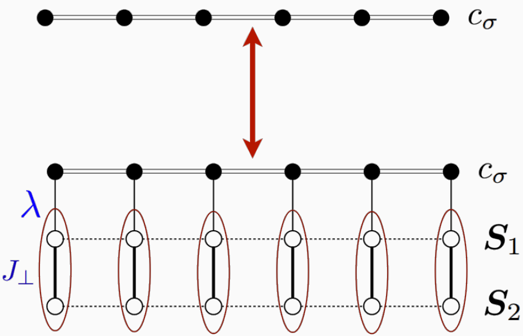
$$\exp \left(\frac{2U}{3} \sum_i \int \mathrm{d}\tau \, \mathbf{S}_i^2 \right) = \int \mathcal{D} \mathbf{\Phi}_i(\tau) \exp \left(-\sum_i \int \mathrm{d}\tau \left[\frac{3}{8U} \mathbf{\Phi}_i^2 + \mathbf{\Phi}_i \cdot c^\dagger_{i\alpha} \frac{\boldsymbol{\sigma}_{\alpha\beta}}{2} c_{i\beta} \right] \right)$$

Paramagnon theory of the Hubbard model



$$H = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c_{\mathbf{p}\alpha}^\dagger c_{\mathbf{p}\alpha} - \lambda \sum_i c_{i\alpha}^\dagger \frac{\sigma_{\alpha\beta}}{2} c_{i\beta} \cdot \mathbf{\Phi}_i + \frac{J_\perp}{2} \mathbf{P}_{\mathbf{\Phi}i}^2 + \sum_i V(\mathbf{\Phi}_i)$$

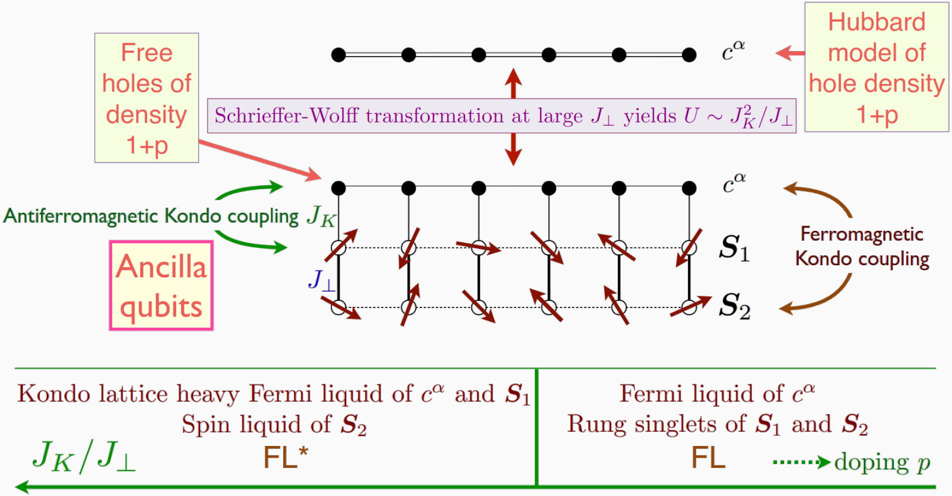
Paramagnon theory of the Hubbard model



$$H = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^\dagger_{\mathbf{p}\alpha} c_{\mathbf{p}\alpha} - \lambda \sum_i c^\dagger_{i\alpha} \frac{\sigma_{\alpha\beta}}{2} c_{i\beta} \cdot \mathbf{\Phi}_i + \frac{J_\perp}{2} \mathbf{P}^2_{\mathbf{\Phi} i} + \sum_i V(\mathbf{\Phi}_i)$$

Represent $\ell = 0\,, 1$ excitations as antiferromagnetic spin pair, $\mathbf{\Phi}_i = \frac{1}{\sqrt{3}} \left(\mathbf{S}_{2i} - \mathbf{S}_{1i} \right)$

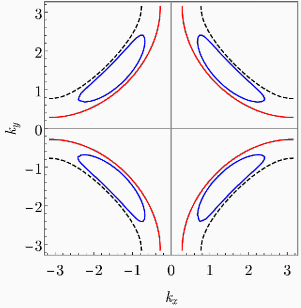
Mean-field phase diagram of the pseudogap metal

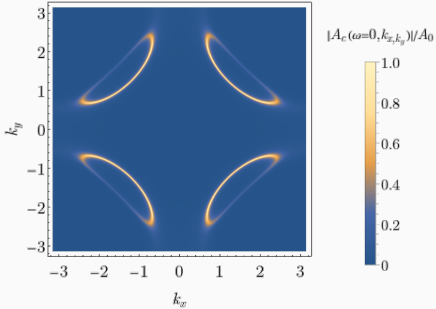


FL* phase qualitatively captures pseudogap features

$$\mathbf{S}_{n,i} = f^{\dagger}_{n,i,\alpha} \frac{\sigma_{\alpha\beta}}{2} f_{n,i,\beta} \qquad \sum_{\alpha} f^{\dagger}_{n,i,\alpha} f_{n,i,\alpha} = 1$$

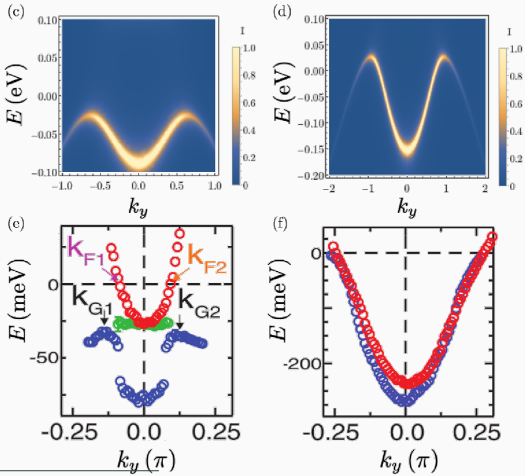
Non-zero hybridization between c and f_1 leads to FL* phase.





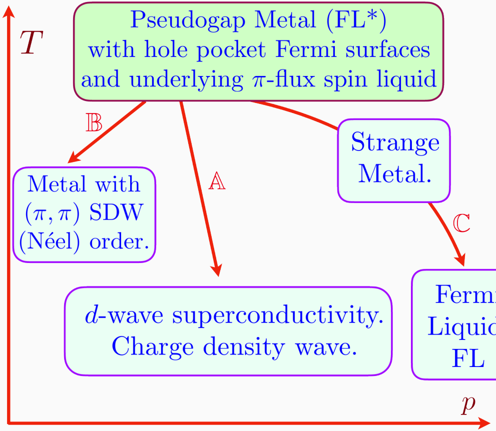
$$H = -\sum_{i,j} t_{ij} c^{\dagger}_{i\sigma} c_{j\sigma} + \sum_{i,j} t_{1,ij} f^{\dagger}_{1i\sigma} f_{1j\sigma} + \sum_{i} B \left(c^{\dagger}_{i\sigma} f_{1i\sigma} + f^{\dagger}_{1i\sigma} c_{i\sigma} \right)$$

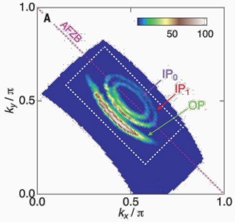
FL* phase qualitatively captures pseudogap features

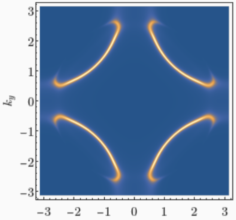


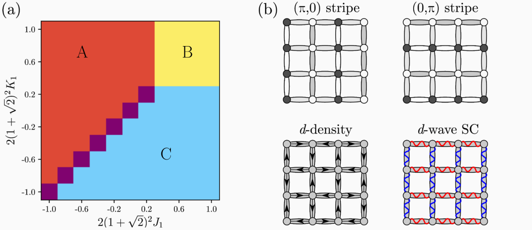
He et al., "From a Single-Band Metal to a High-Temperature Superconductor via Two Thermal Phase Transitions".

Instabilities to ordered phases described by second ancilla layer



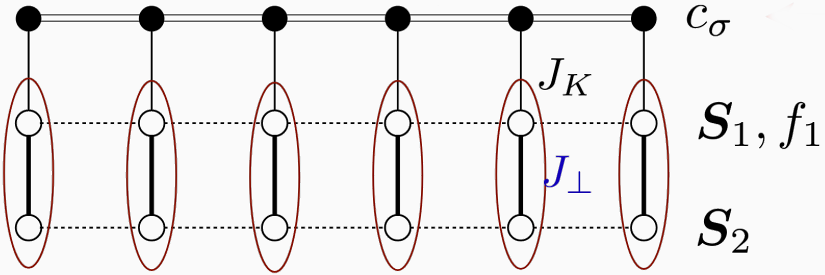






Kunisada et al., "Observation of Small Fermi Pockets Protected by Clean CuO2 Sheets of a High-Tc Superconductor".

Paramagnon fractionalization admits trial wavefunctions



$$|\psi_0\rangle = |\text{Slater}[c\,, f_1\,, f_2]\rangle$$

$$|\psi\rangle = [\text{Projection on to rung singlets}]\,|\psi_0\rangle$$

$$\text{FL} \;:\; |\psi_0\rangle = |\psi_c\rangle \otimes |f_1\,, f_2\rangle$$

$$\text{FL}^* \;:\; |\psi_0\rangle = |\psi_c\,, f_1\rangle \otimes |f_2\rangle$$

How energetically favorable is FL*?