The underdoped cuprates as fractionalized Fermi liquids (FL*)

R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil,
Physical Review B **75** , 235122 (2007)
R. K. Kaul, Y. B. Kim, S. Sachdev, and T. Senthil, *Nature Physics* **4**, 28 (2008)
S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, *Physical Review B* **80**, 155129 (2009)
Y. Qi and S. Sachdev, *Physical Review B* **81**, 115129 (2010)
E.G. Moon and S. Sachdev, arXiv:1010.xxxx

Talk online: sachdev.physics.harvard.edu

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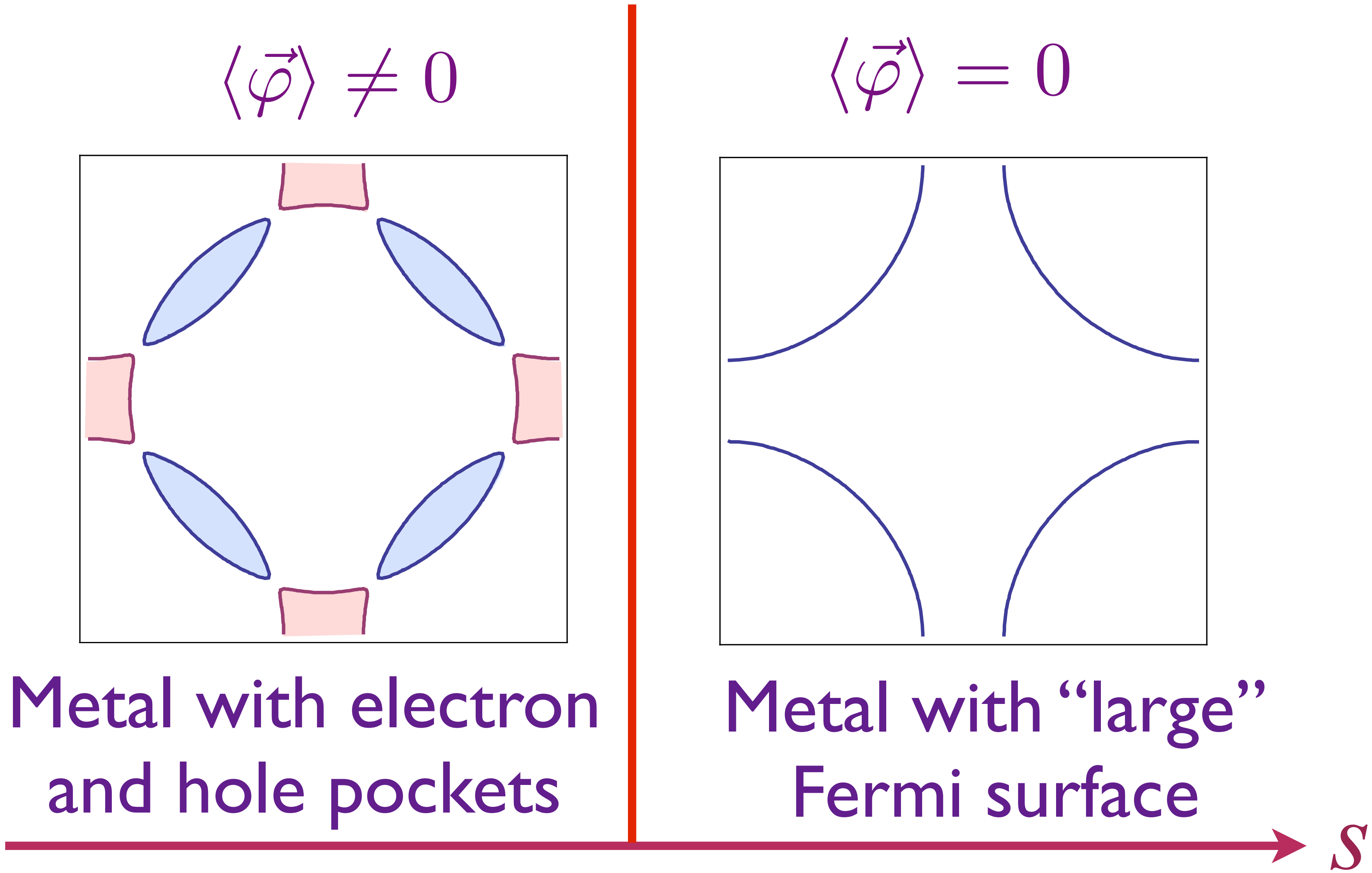
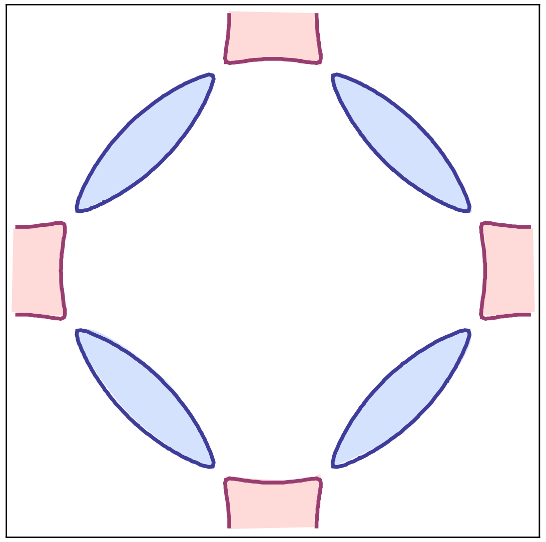
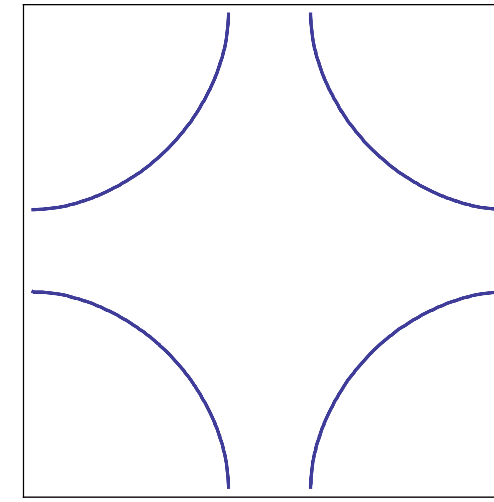
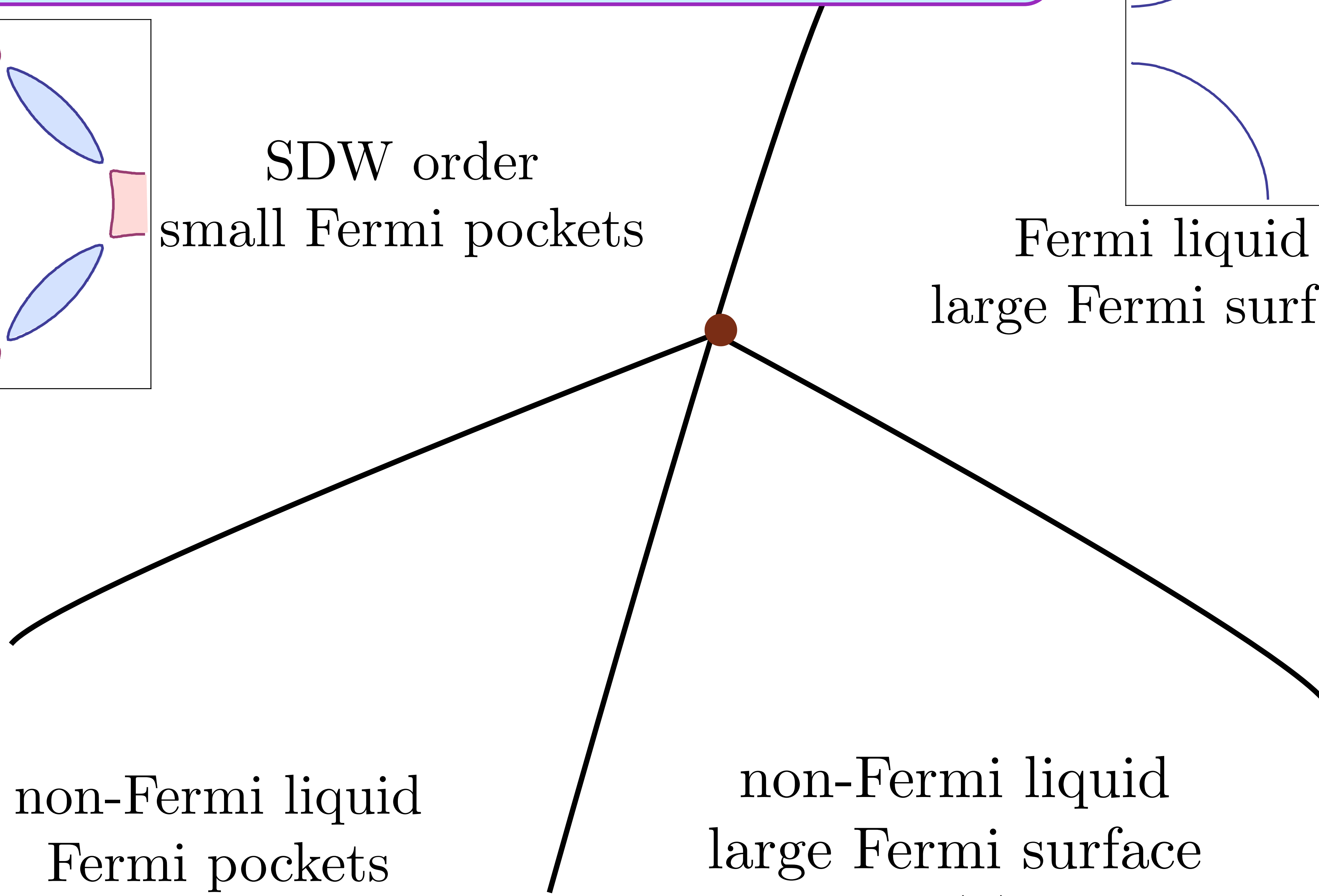
Quantum criticality of the onset of antiferromagnetism in a metal



SU(2) gauge theory: separating Fermi surface change from SDW order



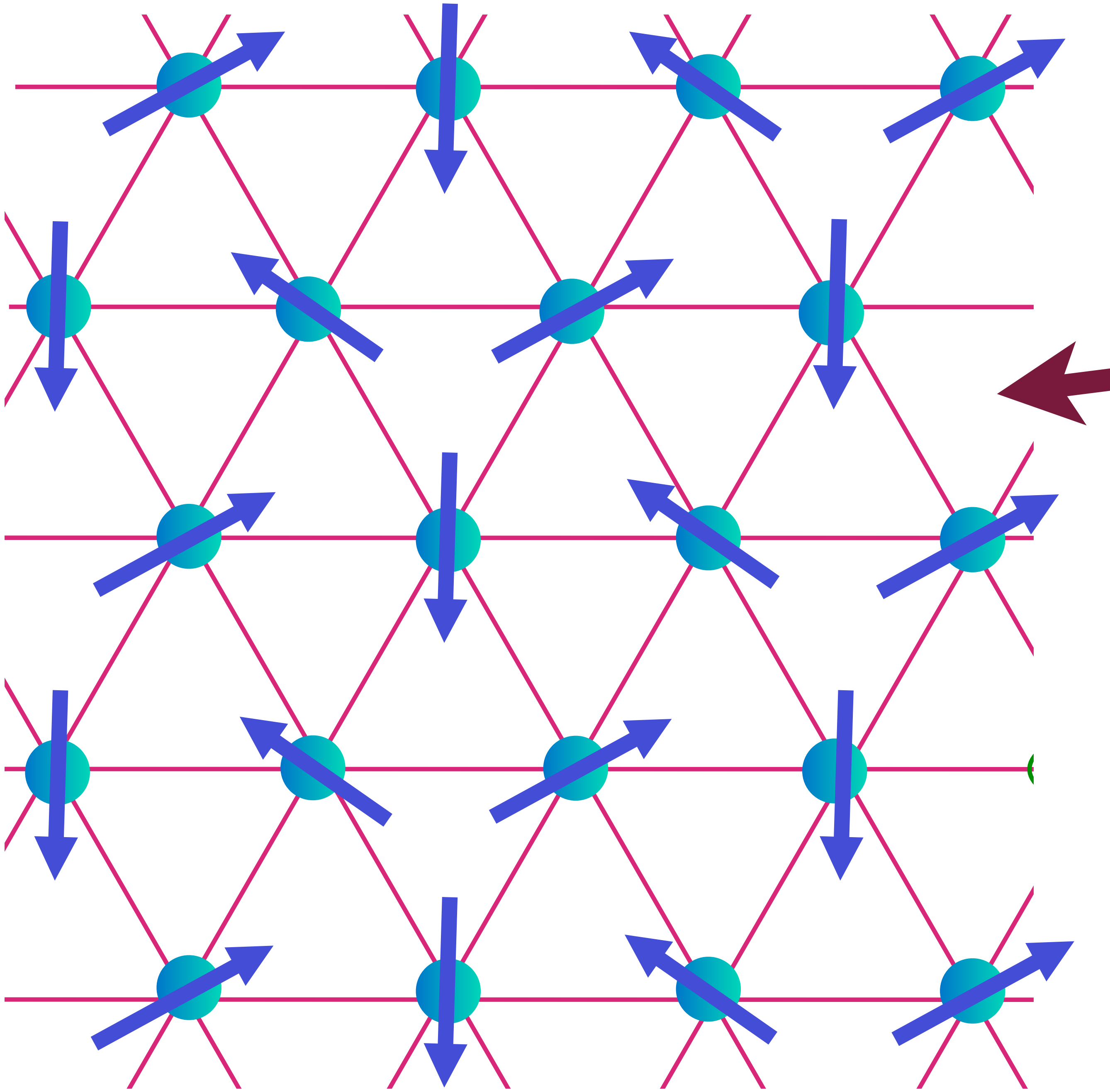




Leads to a FL* state: has Fermi pockets without translations symmetry breaking

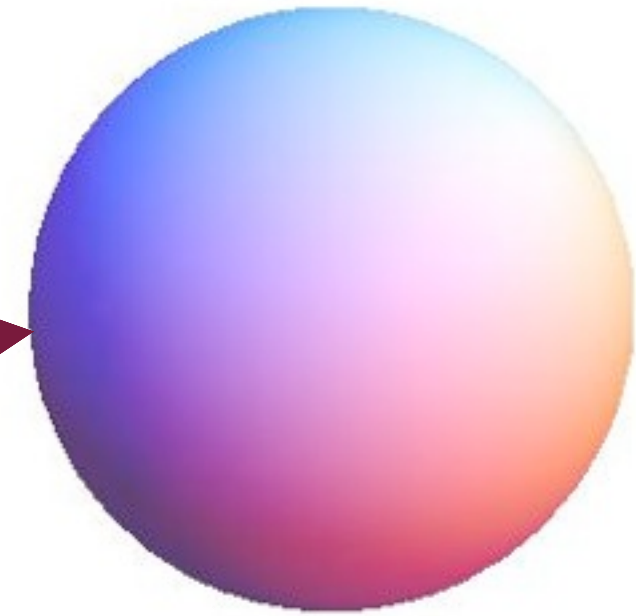
S. Sachdev, M.A. Metlitski, Y. Qi, and C. Xu, *Physical Review B* **80**, 155129 (2009)

Kondo lattice model



Kondo exchange

J_K

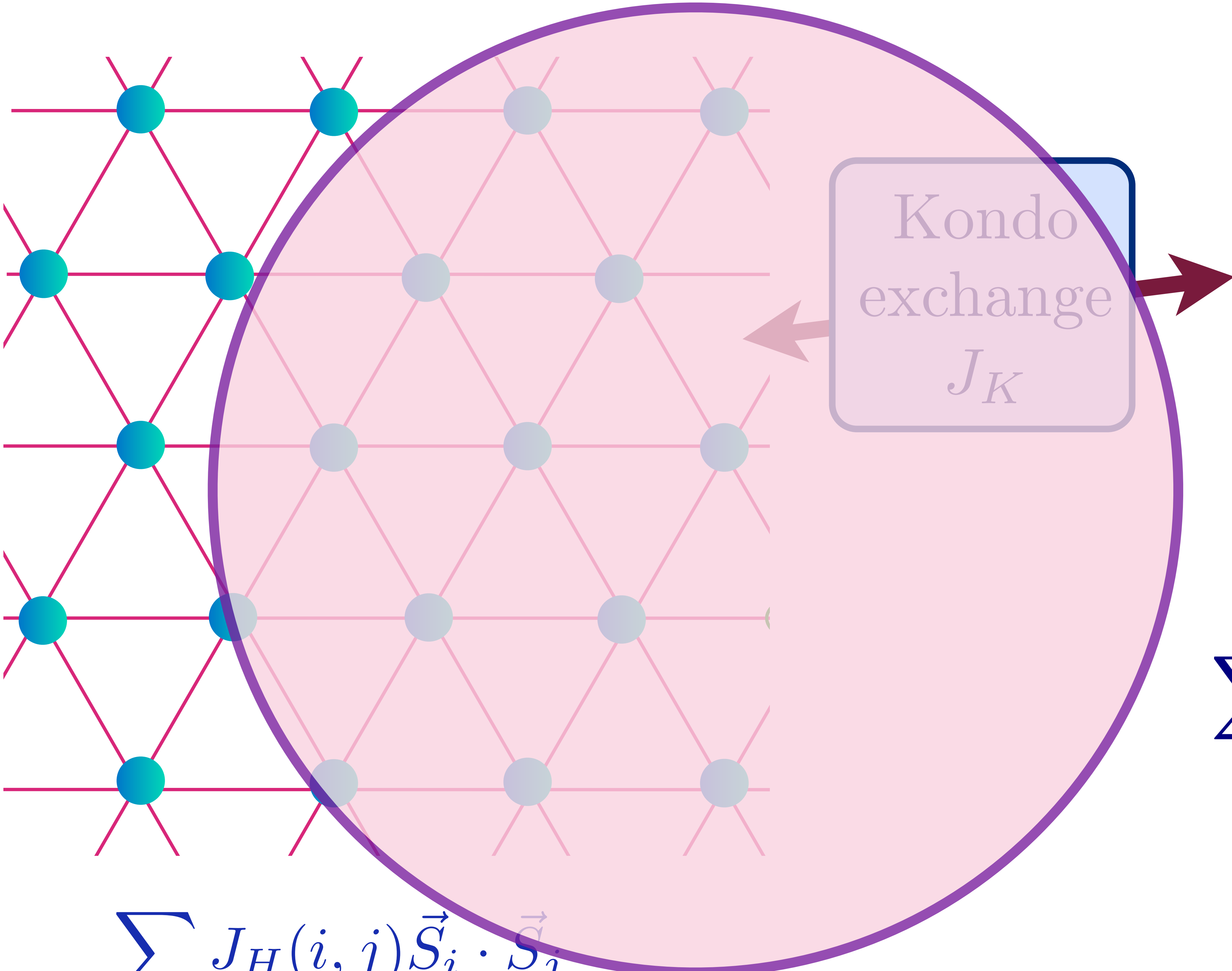


Conduction electrons

$$\sum_{\mathbf{k}} \varepsilon_{\mathbf{k}} c^{\dagger}_{\mathbf{k}\alpha} c_{\mathbf{k}\alpha}$$

$$\sum_{i<j} J_H(i,j) \vec{S}_i \cdot \vec{S}_j$$

Kondo lattice model



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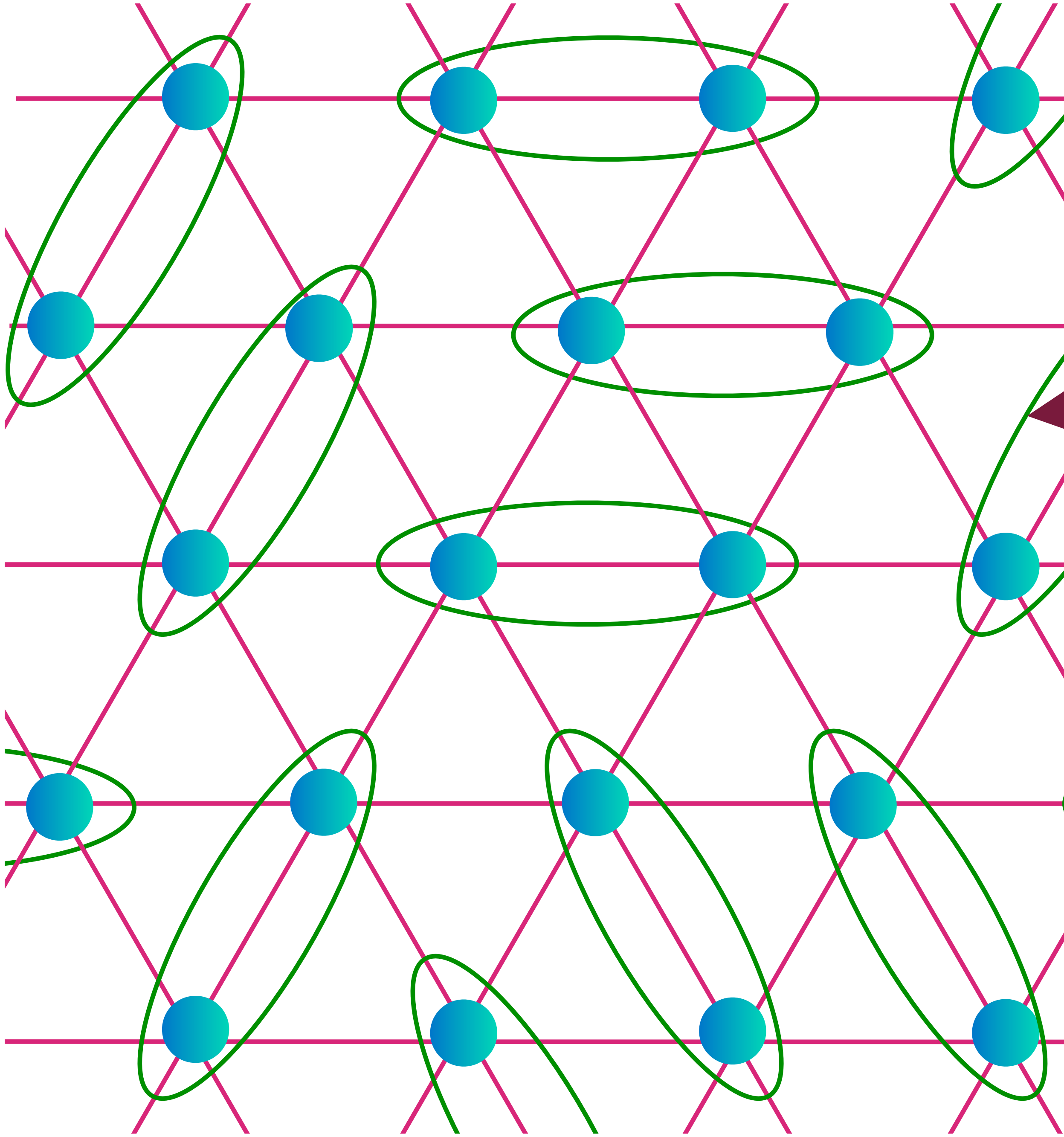
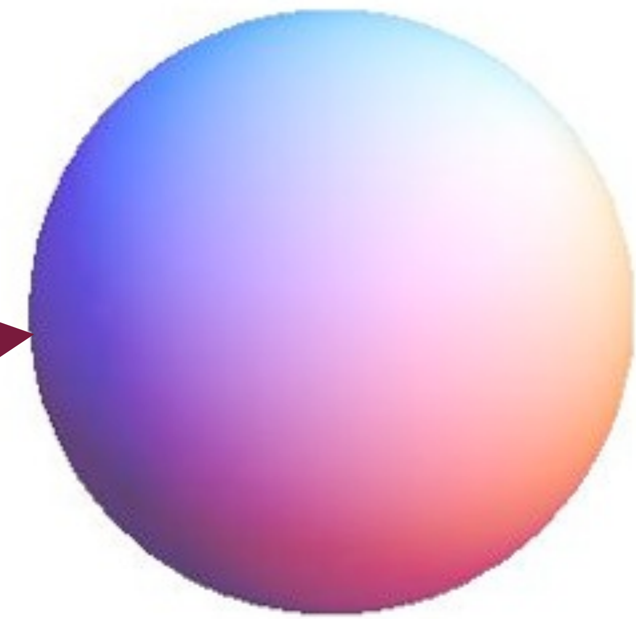
Large Fermi surface Fermi liquid (FL)

Kondo lattice model



Kondo exchange J_K



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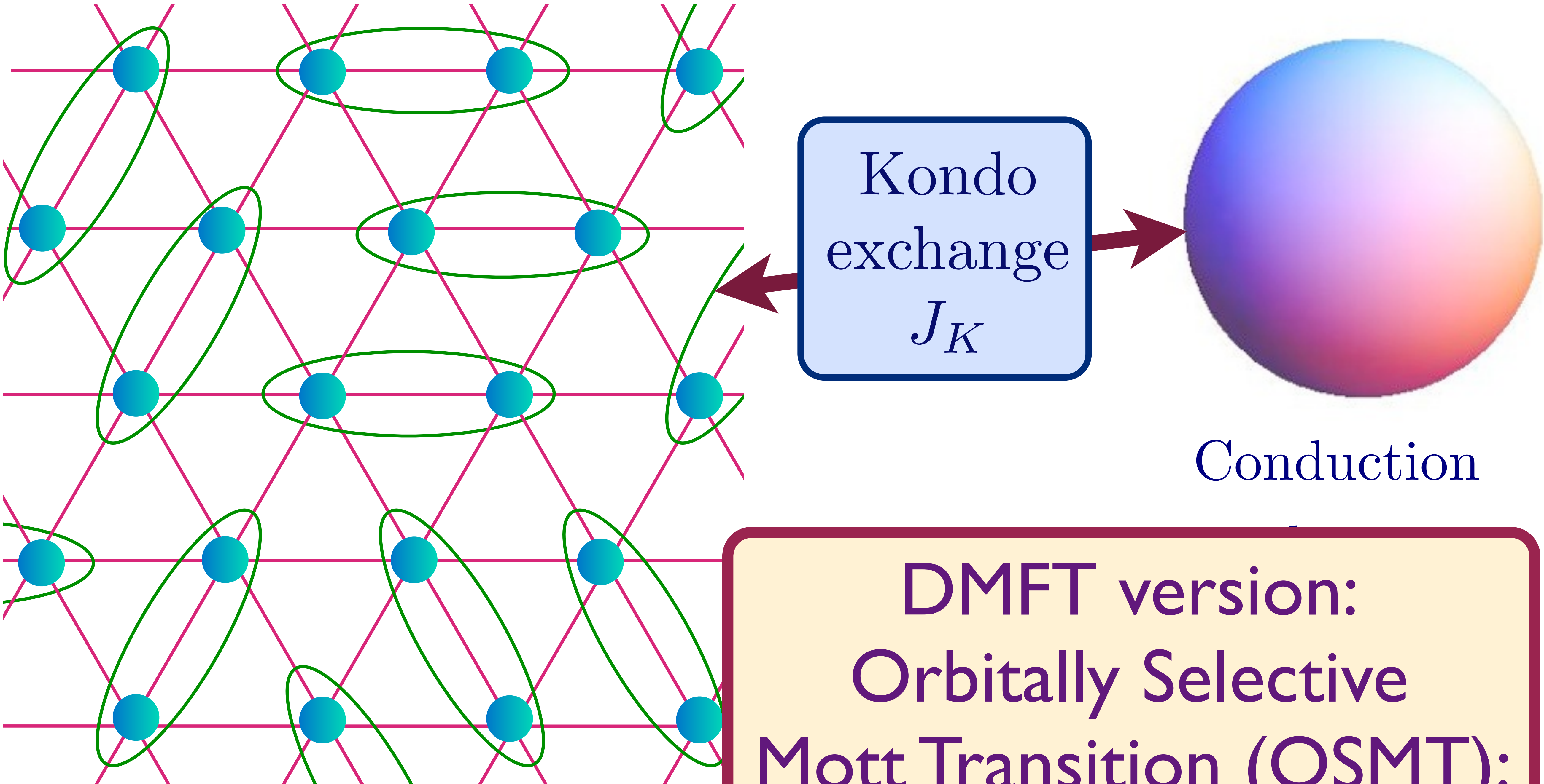
Fractionalized Fermi liquid (FL*)

T. Senthil, S. Sachdev, and M. Vojta, *Phys. Rev. Lett.* **90**, 216403 (2003).
T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004).

Kondo lattice model



$$\sum_{i<j} J_H(i,j)\vec{S}_i \cdot \vec{S}_j$$

DMFT version:
Orbitally Selective
Mott Transition (OSMT):
gauge fields of FL*
are missing

T. Senthil, S. Sachdev, and

T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004).

FL* from a one-band model of cuprates

Begin with SDW ordered state, and rotate to a frame polarized along the local orientation of the SDW order $\hat{\vec{\varphi}}$

$$\begin{pmatrix} c_\uparrow \\ c_\downarrow \end{pmatrix} = R \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix} \quad ; \quad R^\dagger \hat{\vec{\varphi}} \cdot \vec{\sigma} R = \sigma^z \quad ; \quad R^\dagger R = 1$$

H. J. Schulz, *Physical Review Letters* **65**, 2462 (1990)

B. I. Shraiman and E. D. Siggia, *Physical Review Letters* **61**, 467 (1988).

J. R. Schrieffer, *Journal of Superconductivity* **17**, 539 (2004)

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$$\text{With} \quad R = \left(\begin{array}{cc} z_\uparrow & -z_\downarrow^* \\ z_\downarrow & z_\uparrow^* \end{array} \right) \quad \text{or} \quad \hat{\vec{\varphi}} = z_\alpha^* \vec{\sigma}_{\alpha\beta} z_\beta$$

we obtain a gauge theory of bosonic neutral spinons z_α, spinless, charged fermions $\psi_\pm$, and an emergent gauge field.

FL* from a one-band model of cuprates

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These particles can bind into two species of gauge neutral, electron-like quasiparticles:

$$F_{i\alpha} \sim z_{i\alpha} \psi_{i+} \quad , \quad G_{i\alpha} \sim \varepsilon_{\alpha\beta} z_{i\beta}^* \psi_{i-}.$$

This species doubling is a key characteristic of the "topological order" of the underlying U(1) spin liquid.

FL* from a one-band model of cuprates

Use symmetry and physical arguments to constrain the effective Hamiltonian for the F_α and G_α

$$
\begin{aligned}
H_{\text{eff}} &= -\sum_{ij} t_{ij}(F^\dagger_{i\alpha}F_{j\alpha} + G^\dagger_{i\alpha}G_{j\alpha}) \\
&+ \lambda \sum_i (-1)^{i_x+i_y}(F^\dagger_{i\alpha}F_{i\alpha} - G^\dagger_{i\alpha}G_{i\alpha}) \\
&- \sum_{i<j} \tilde{t}_{ij}\ (F^\dagger_{i\alpha}G_{j\alpha} + G^\dagger_{i\alpha}F_{j\alpha}) \\
&+ \Delta(\cos k_x - \cos k_y) \text{ pairing in the superconductor}
\end{aligned}
$$

FL* from a one-band model of cuprates

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\end{aligned}
$$

Underlying band structure

FL* from a one-band model of cuprates

Use symmetry and physical arguments to constrain the effective Hamiltonian for the F_α and G_α

Potential from local antiferromagnetism

$$
\begin{aligned}
H_{\rm eff} \;=\; & -\sum_{ij} t_{ij}(F^\dagger_{i\alpha}F_{j\alpha} + \\
& + \; \lambda \sum_i (-1)^{i_x+i_y}(F^\dagger_{i\alpha}F_{i\alpha} - G^\dagger_{i\alpha}G_{i\alpha}) \\
& - \; \sum_{i<j} \tilde{t}_{ij}\;(F^\dagger_{i\alpha}G_{j\alpha} + G^\dagger_{i\alpha}F_{j\alpha}) \\
& + \; \Delta(\cos k_x - \cos k_y) \text{ pairing in the superconductor}
\end{aligned}
$$

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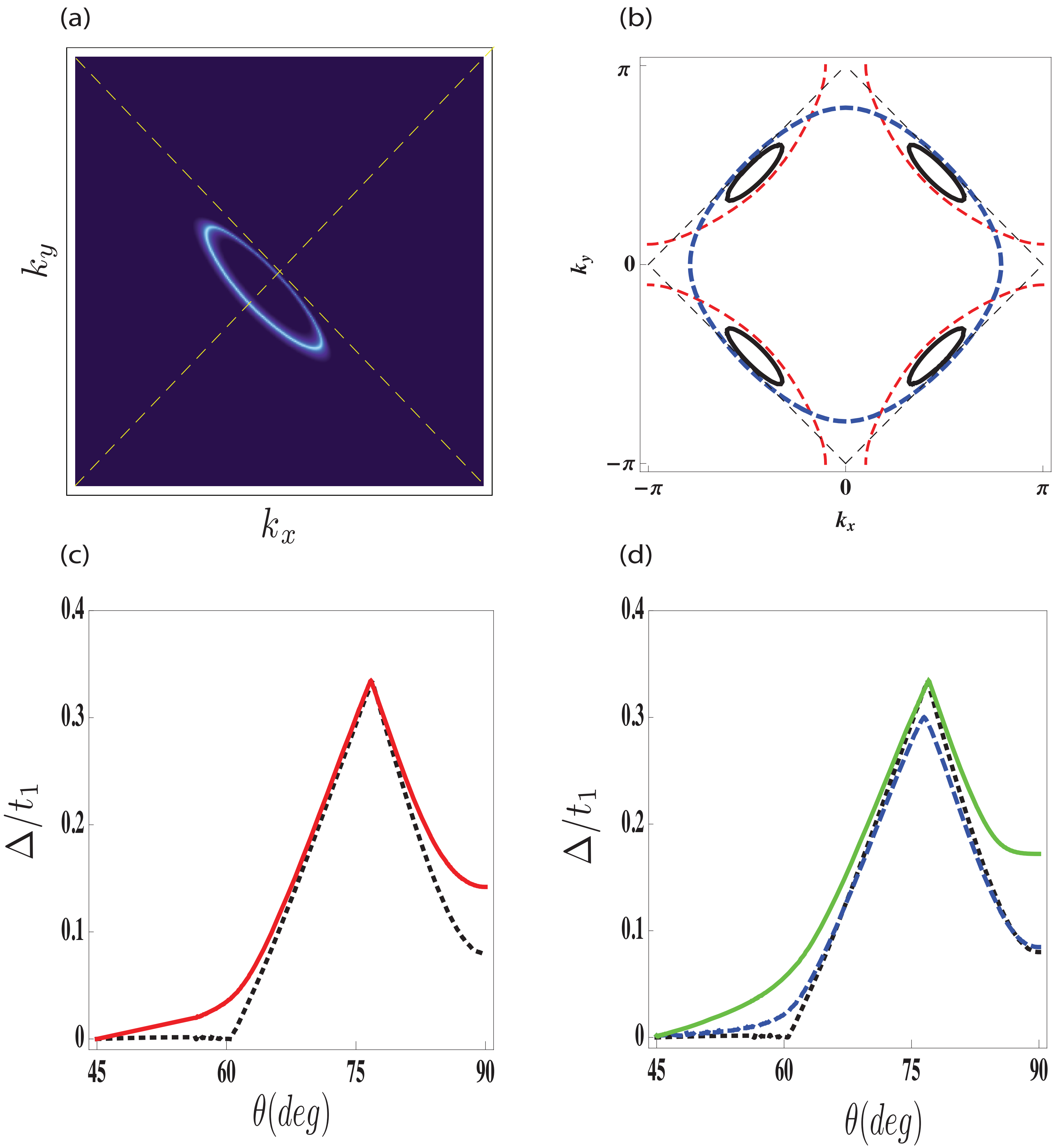
&+ \Delta(\cos k_x - \cos k_y) \text{ pairing in the superconductor}
\end{aligned}
$$

Mixing between 2 species: descends from the Shraiman-Siggia term

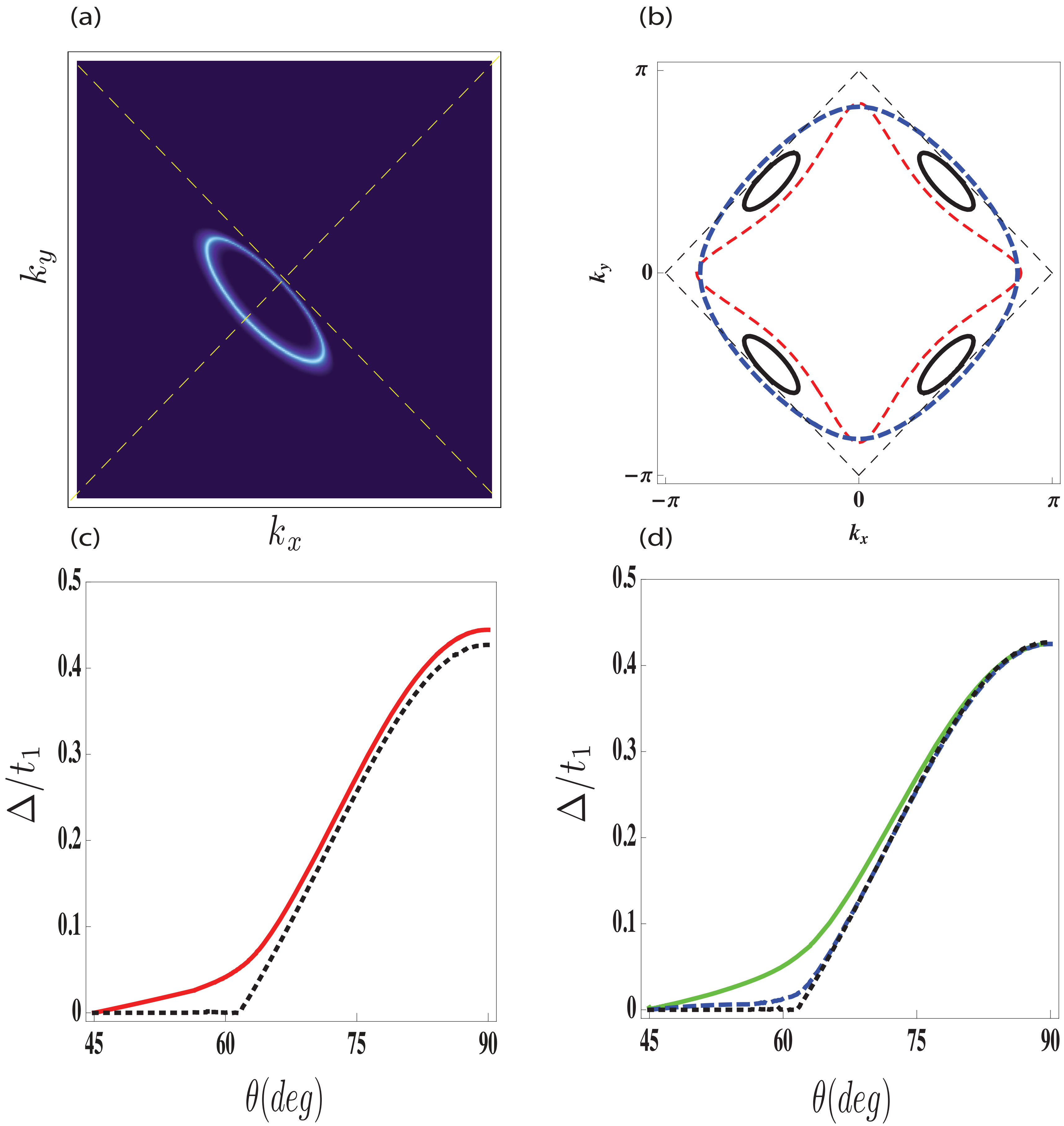
Weaker local antiferromagnetism



Normal state electron spectrum

Angular dependence of electronic gap in normal state and in superconductor

Stronger local antiferromagnetism



Normal state electron spectrum

Angular dependence of electronic gap in normal state and in superconductor

Normal state with electron pockets