Quantum critical metals near the onset of antiferromagnetism: superconductivity and other instabilities

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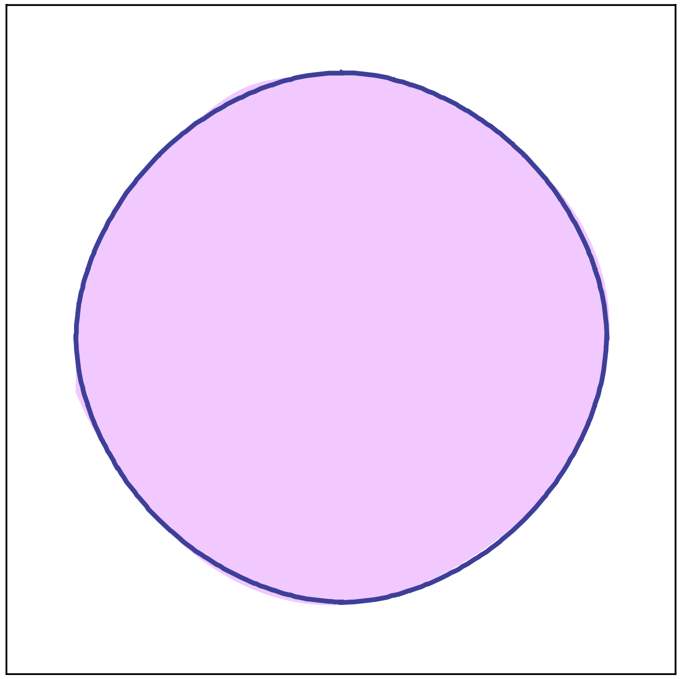
Fermi surface+antiferromagnetism

Metal with "large"
Fermi surface



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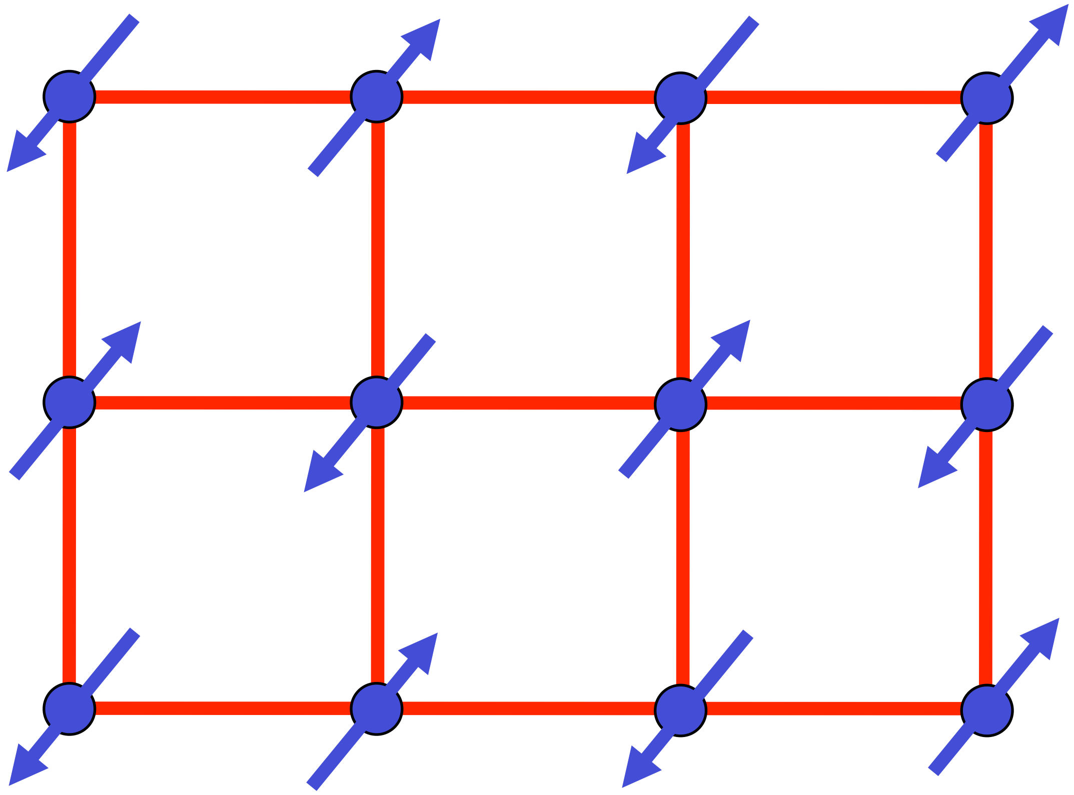

The electron spin polarization obeys

$$\left\langle \vec{S}(\mathbf{r},\tau) \right\rangle = \vec{\varphi}(\mathbf{r},\tau) e^{i\mathbf{K}\cdot\mathbf{r}}$$

where $\mathbf{K}$ is the ordering wavevector.

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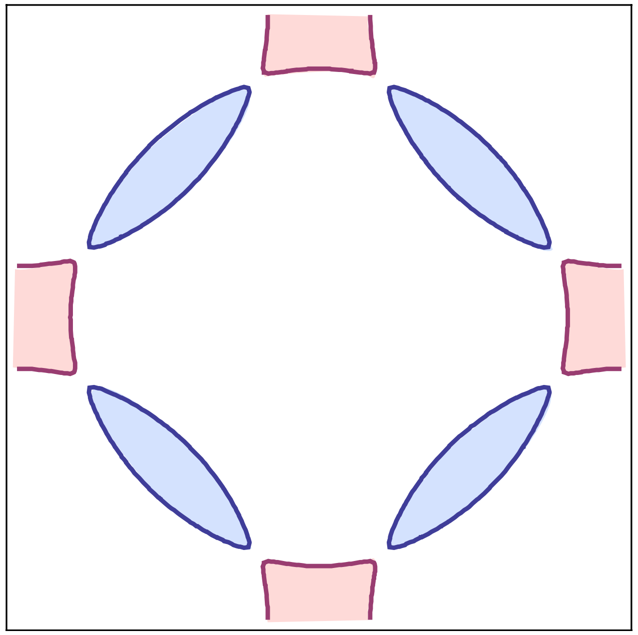

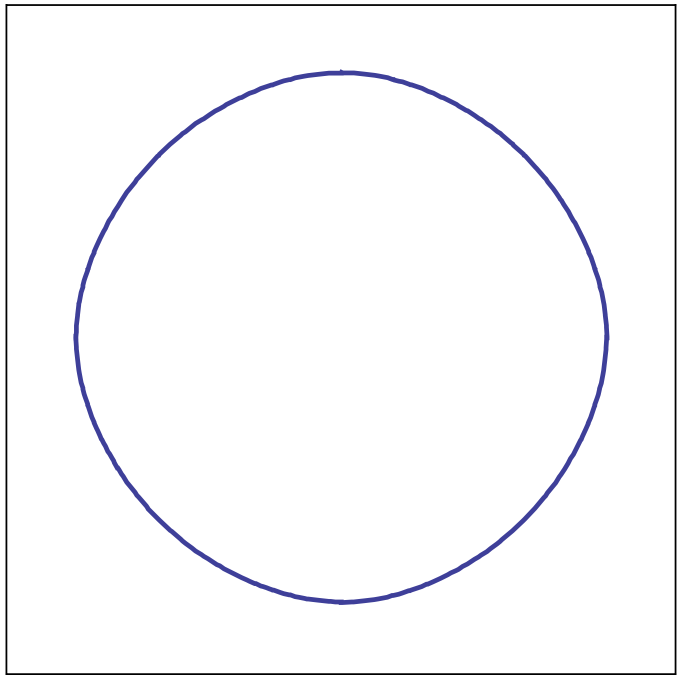

$\langle \vec{\varphi} \rangle \neq 0$

$\langle \vec{\varphi} \rangle = 0$

Metal with electron and hole pockets

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Increasing interaction

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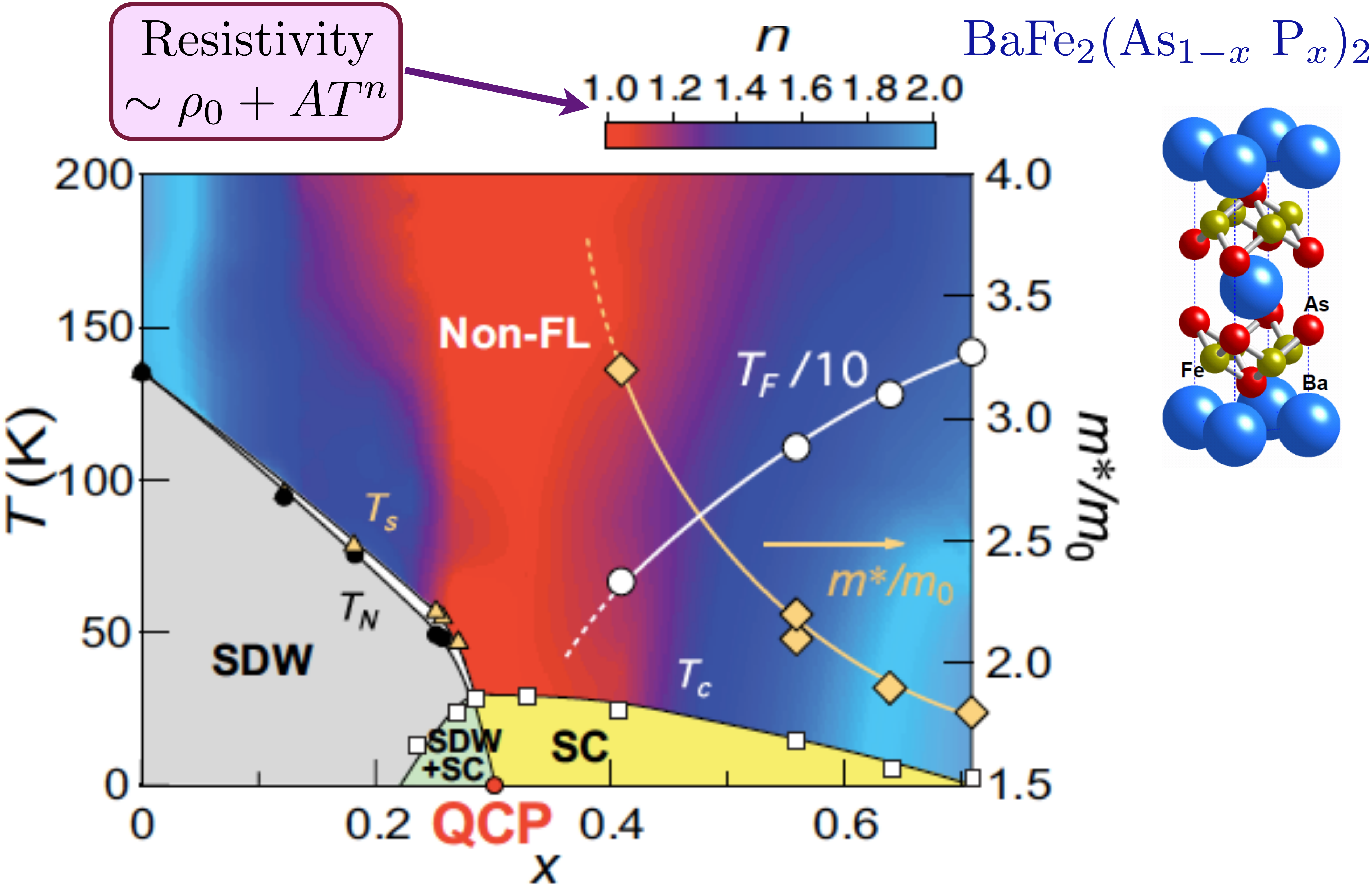

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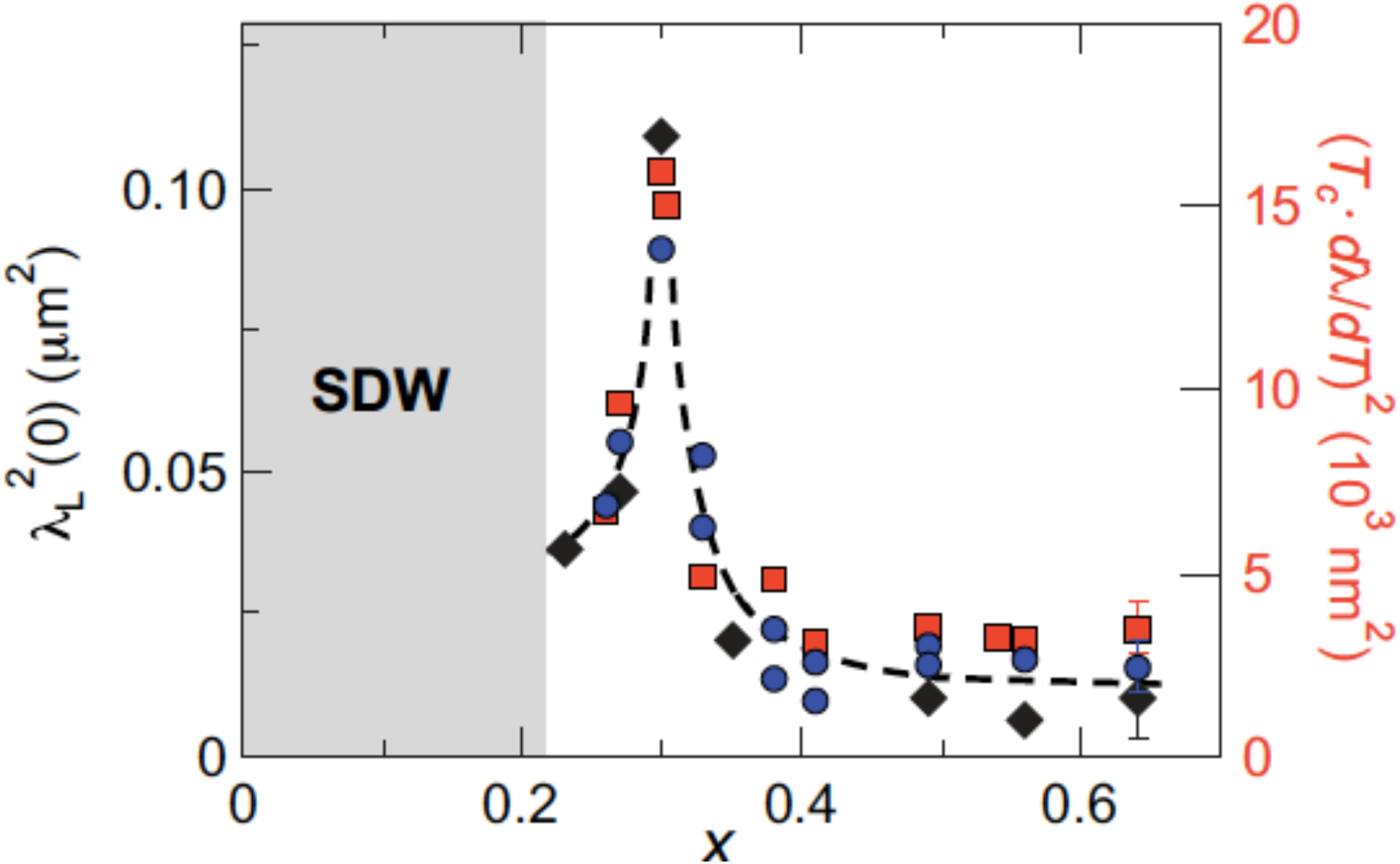

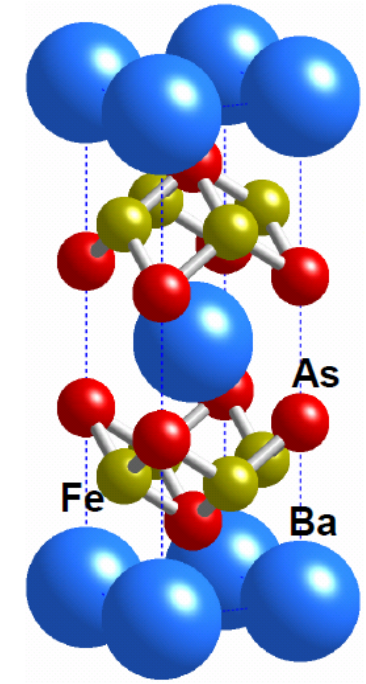

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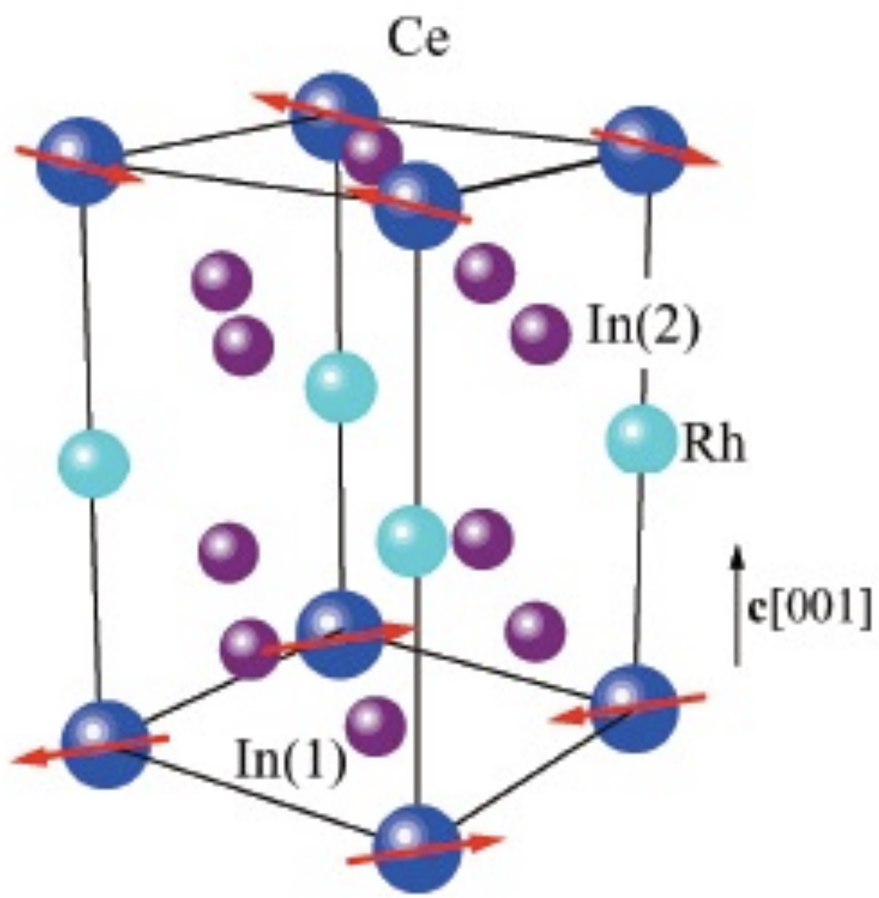
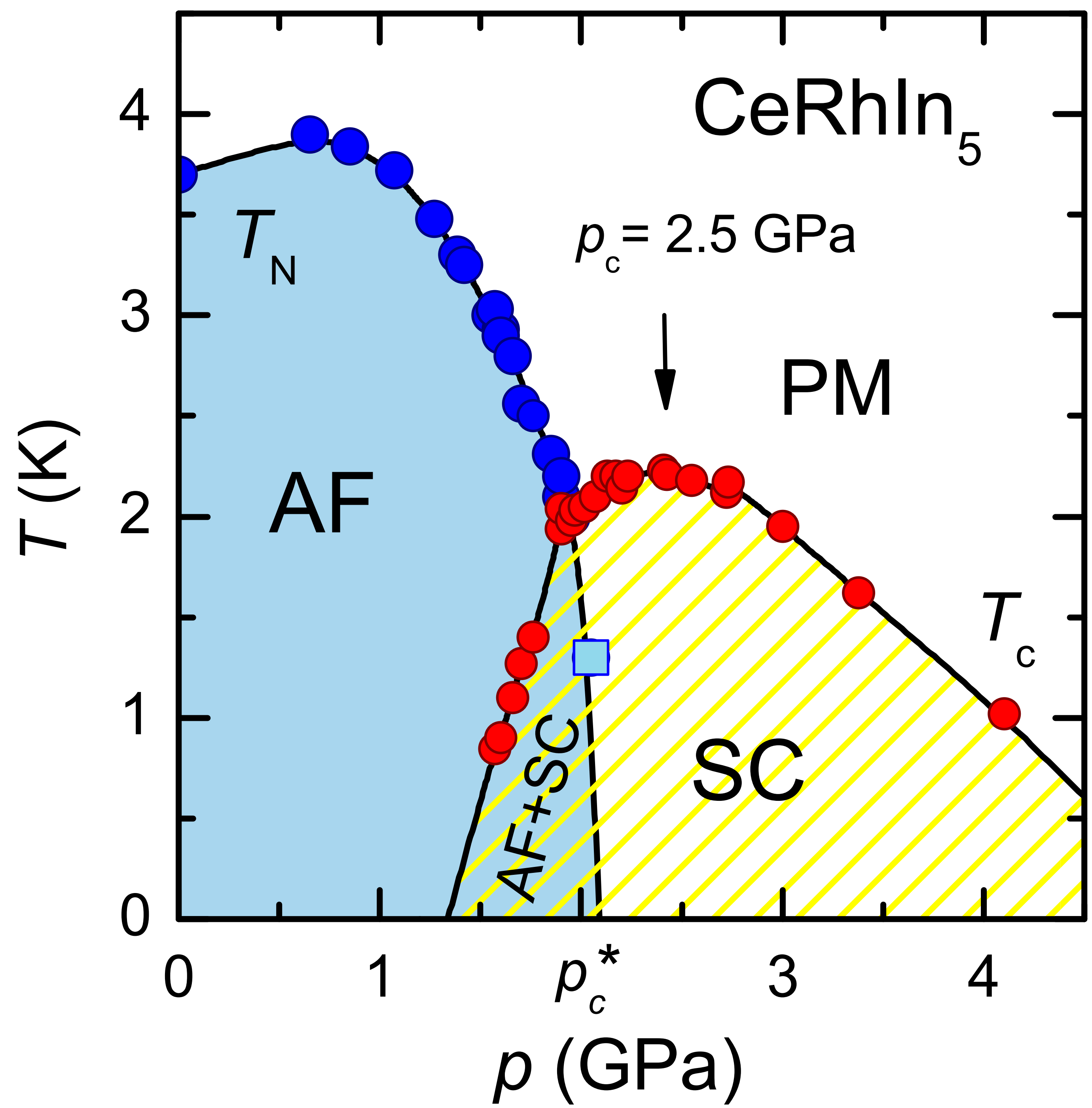
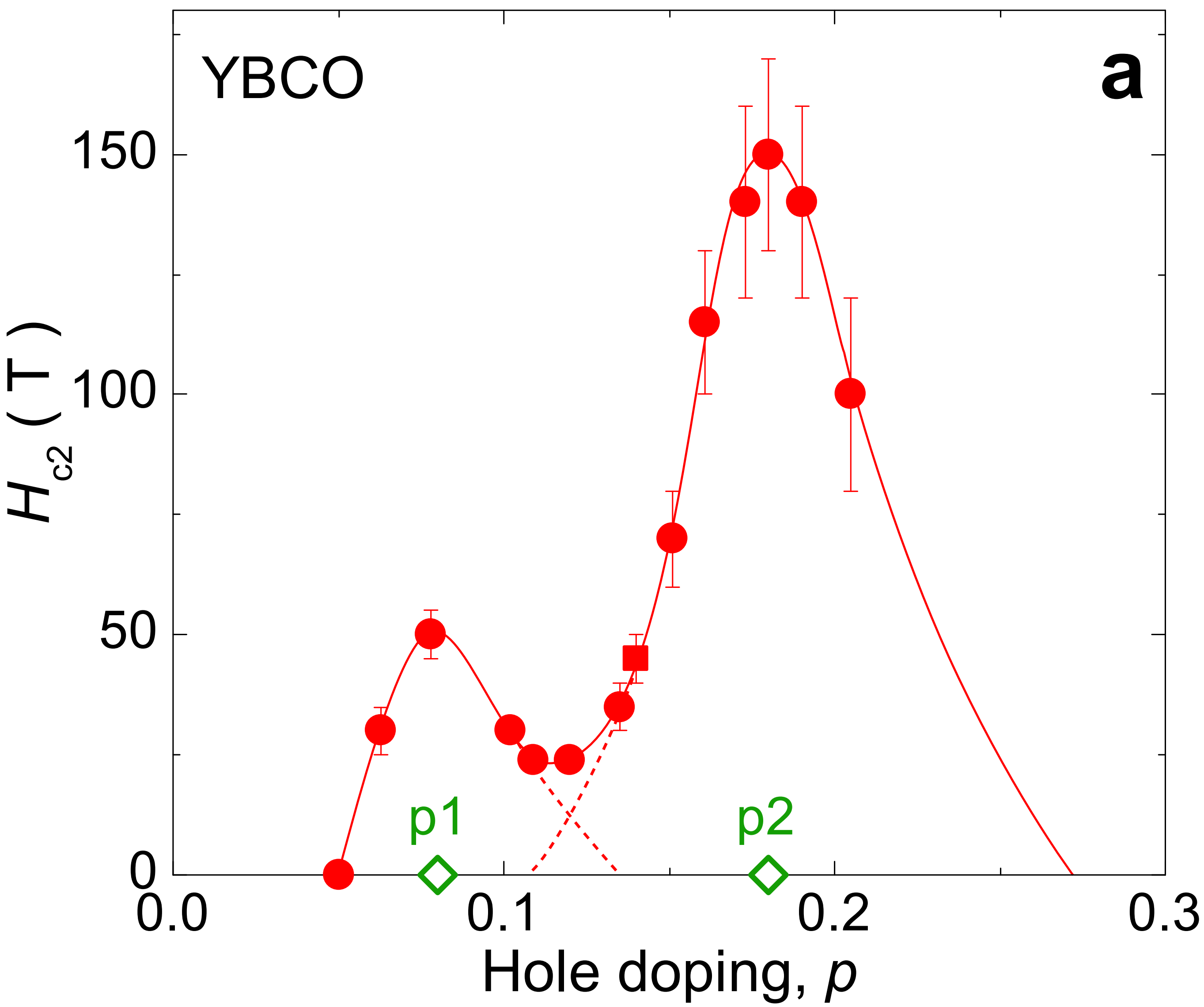
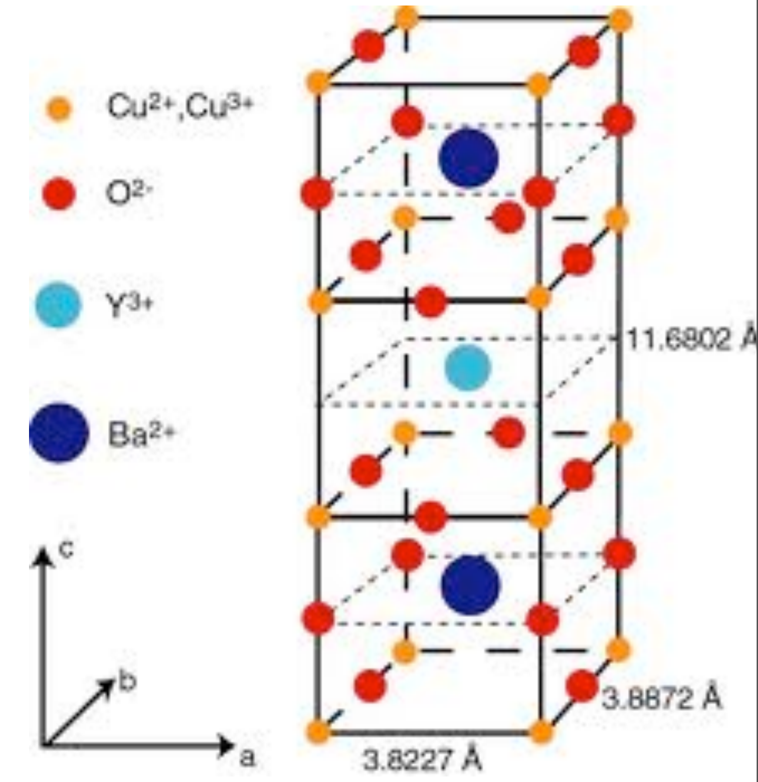
Lower T_c superconductivity in the heavy fermion compounds

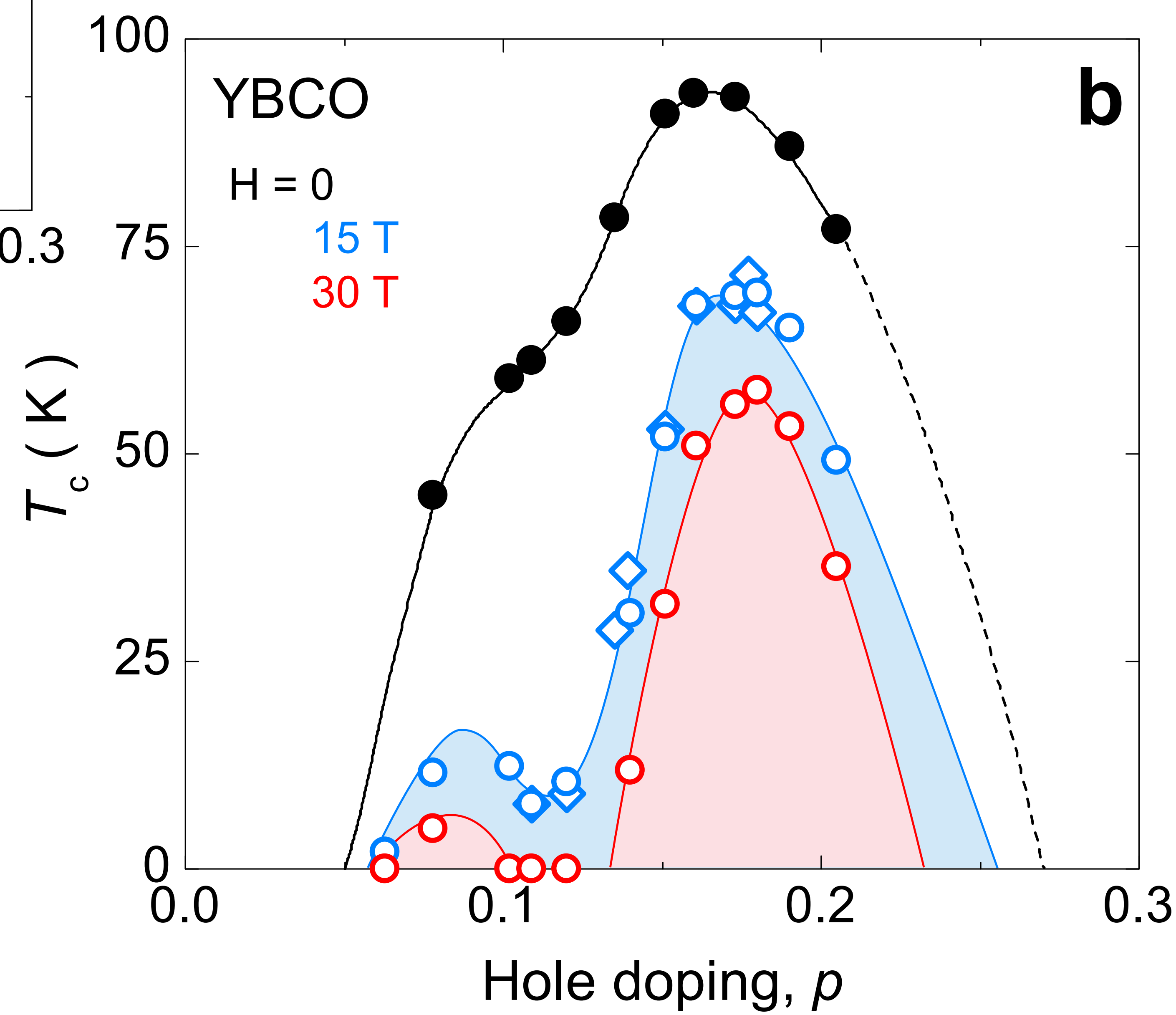




G. Knebel, D. Aoki, and J. Flouquet, arXiv:0911.5223.
Tuson Park, F. Ronning, H. Q. Yuan, M. B. Salamon, R. Movshovich, J. L. Sarrao, and J. D. Thompson, *Nature* **440**, 65 (2006)

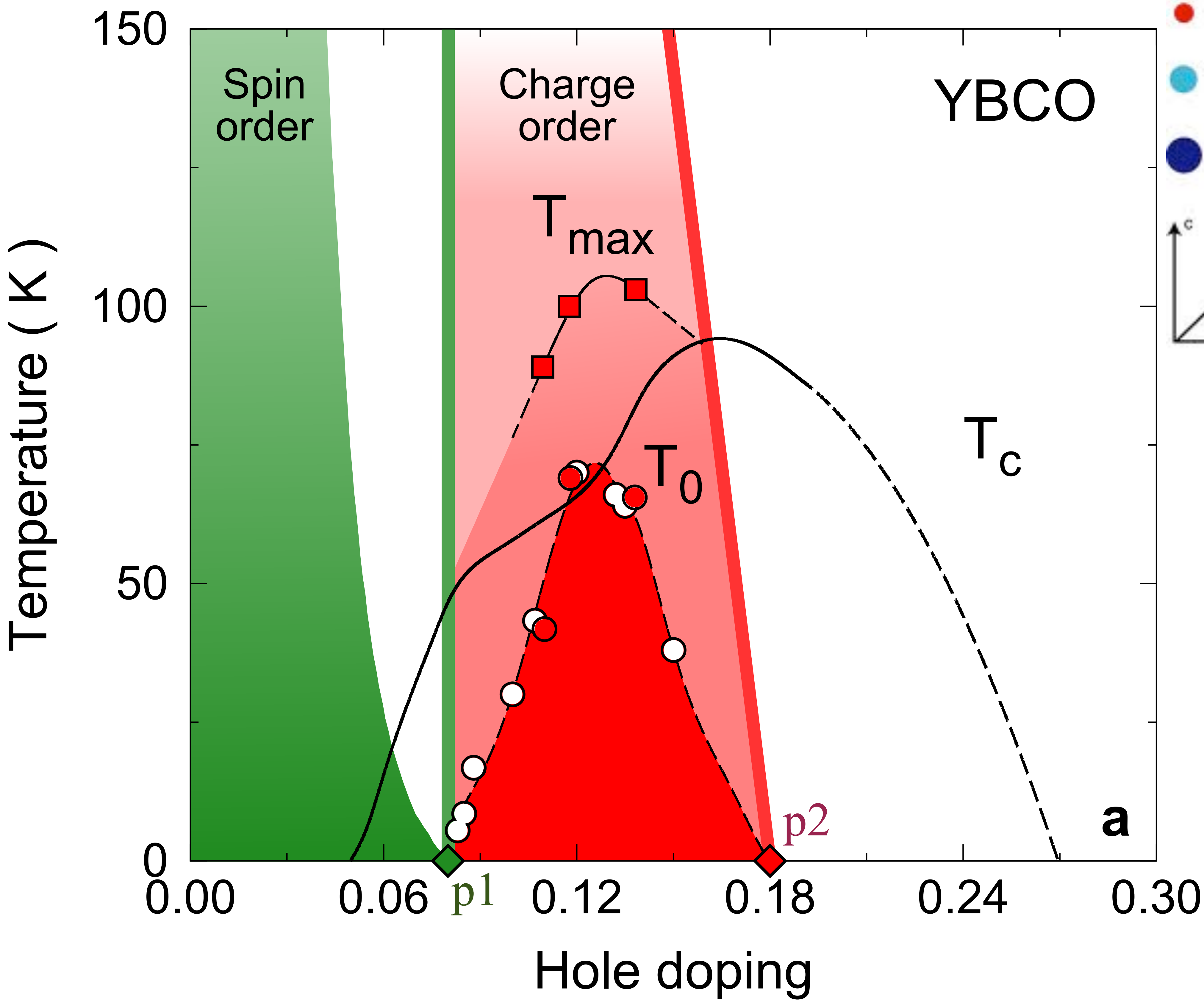


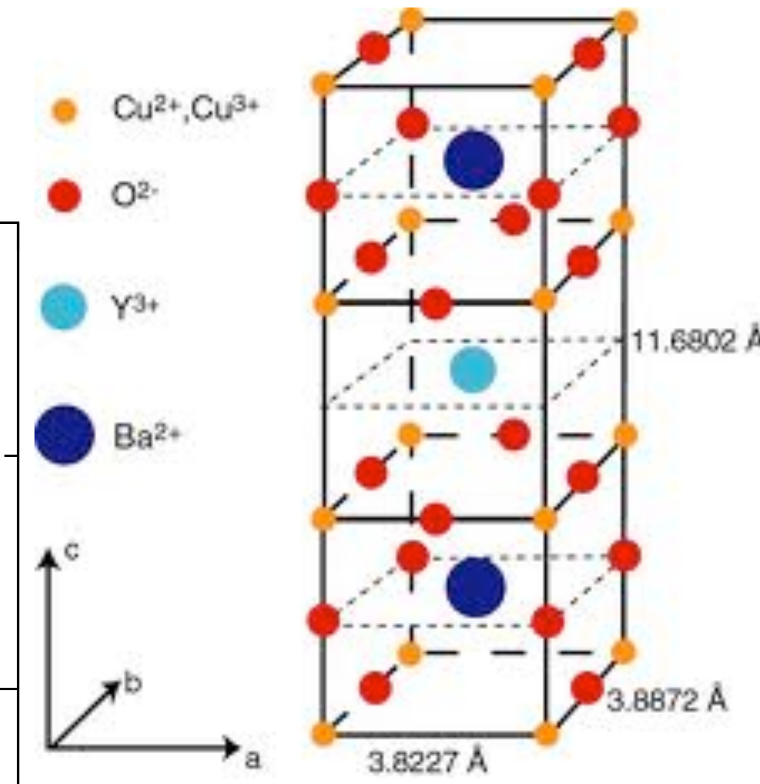




Hole-doped cuprates

G. Grissonnanche et al., preprint





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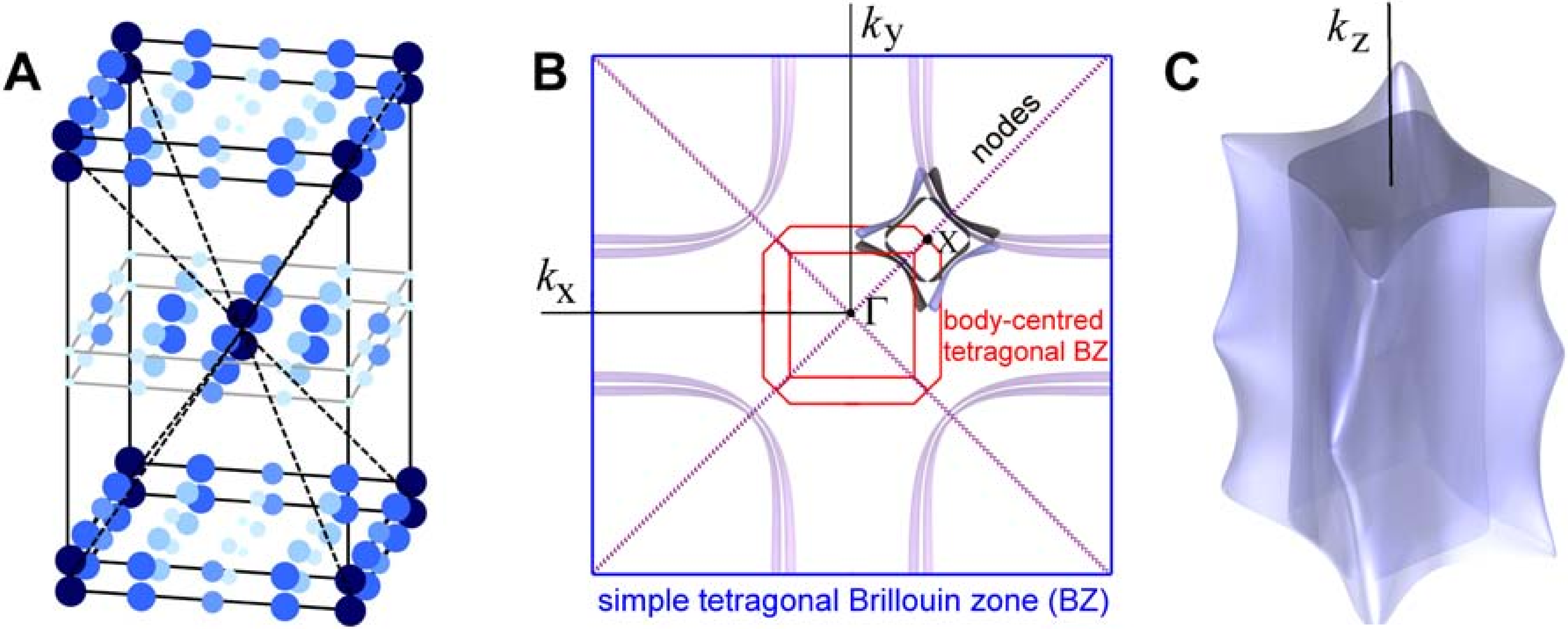

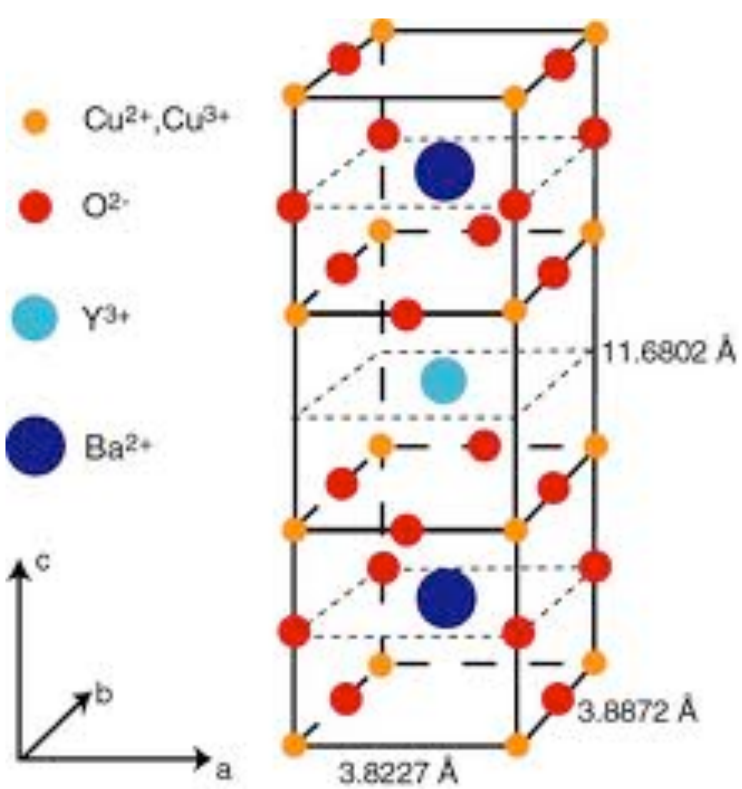

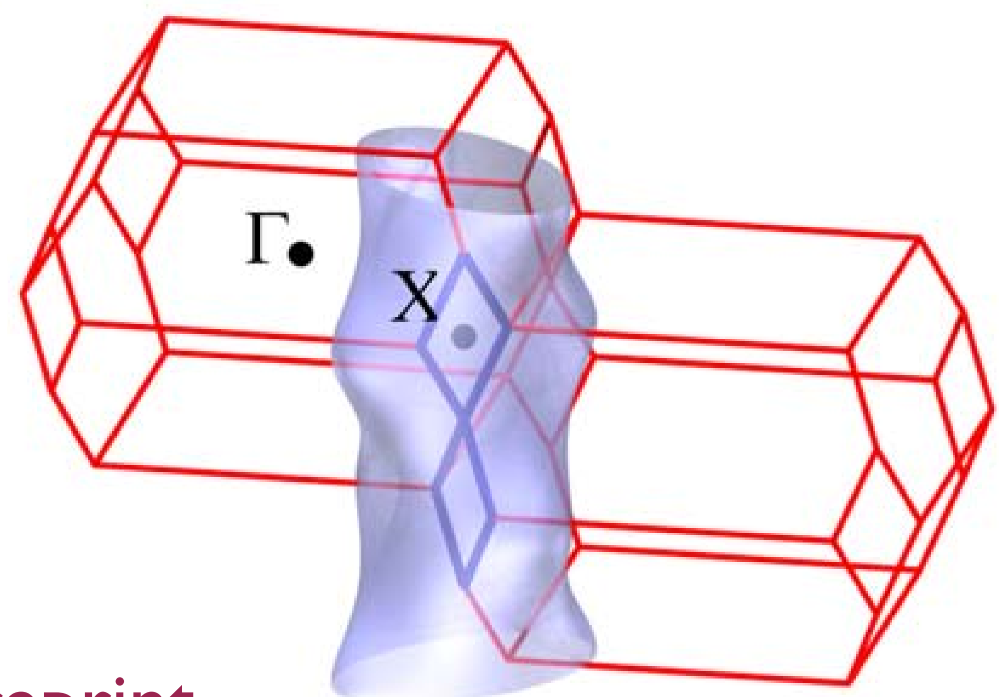

S. Sebastian et al., preprint

Outline

1. Weak coupling theory of SDW ordering,
   and d-wave superconductivity

2. Universal critical theory of SDW ordering

3. Emergent pseudospin symmetry, and
   quadrupolar density wave

4. Quantum Monte Carlo
   without the sign problem

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The Hubbard Model

$$H = -\sum_{i<j} t_{ij} c^\dagger_{i\alpha} c_{j\alpha} + U \sum_i \left(n_{i\uparrow} - \frac{1}{2} \right) \left(n_{i\downarrow} - \frac{1}{2} \right) - \mu \sum_i c^\dagger_{i\alpha} c_{i\alpha}$$

$t_{ij} \rightarrow$ "hopping". $U \rightarrow$ local repulsion, $\mu \rightarrow$ chemical potential

Spin index $\alpha = \uparrow, \downarrow$

$$n_{i\alpha} = c^\dagger_{i\alpha} c_{i\alpha}$$

$$c^\dagger_{i\alpha} c_{j\beta} + c_{j\beta} c^\dagger_{i\alpha} = \delta_{ij} \delta_{\alpha\beta}$$
$$c_{i\alpha} c_{j\beta} + c_{j\beta} c_{i\alpha} = 0$$

The Hubbard Model

Decouple *U* term by a Hubbard-Stratanovich transformation

$$\mathcal{S} = \int d^2r d\tau \left[\mathcal{L}_c + \mathcal{L}_\varphi + \mathcal{L}_{c\varphi}\right]$$

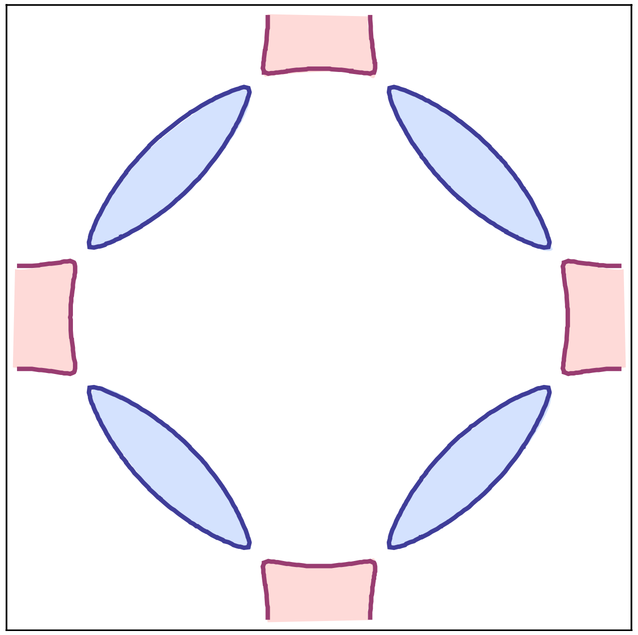
$$\mathcal{L}_c = c_a^\dagger \varepsilon(-i\boldsymbol{\nabla}) c_a$$

$$\mathcal{L}_\varphi = \frac{1}{2}(\boldsymbol{\nabla}\varphi_\alpha)^2 + \frac{r}{2}\varphi_\alpha^2 + \frac{u}{4}\left(\varphi_\alpha^2\right)^2$$

$$\mathcal{L}_{c\varphi} = \lambda\, \varphi_\alpha\, e^{i\mathbf{K}\cdot\mathbf{r}}\, c_a^\dagger\, \sigma_{ab}^\alpha\, c_b.$$

"Yukawa" coupling between fermions and antiferromagnetic order:
$\lambda^2 \sim U$, the Hubbard repulsion

Fermi surface+antiferromagnetism



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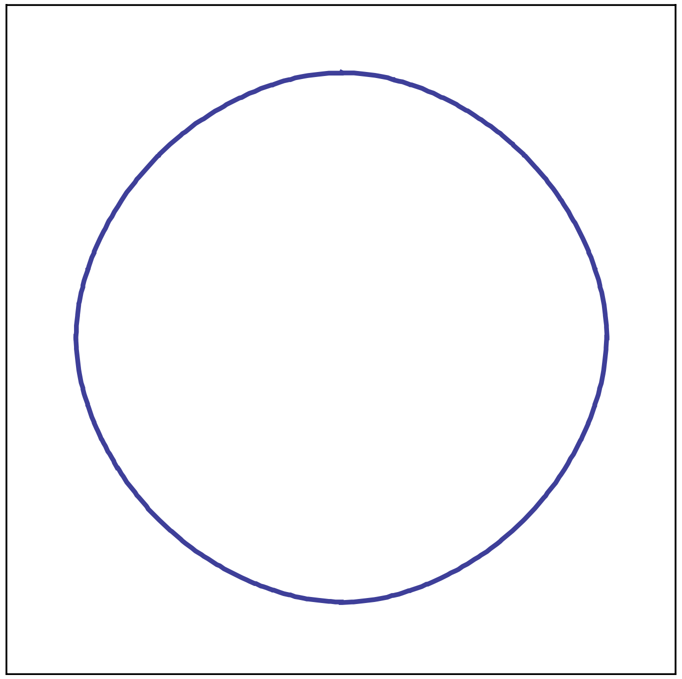

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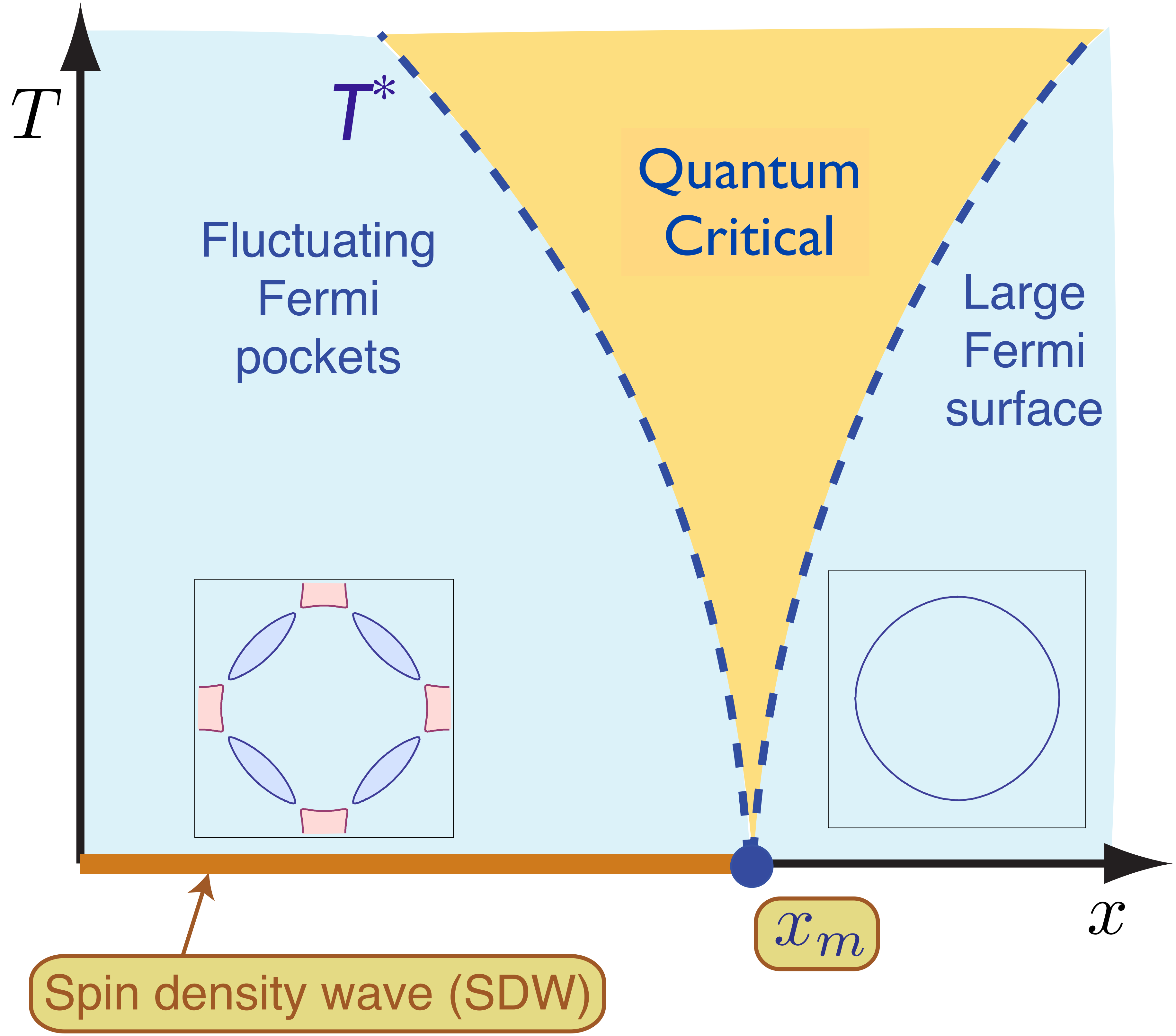
Theory of quantum criticality in the cuprates



Underlying SDW ordering quantum critical point in **metal** at $x = x_m$

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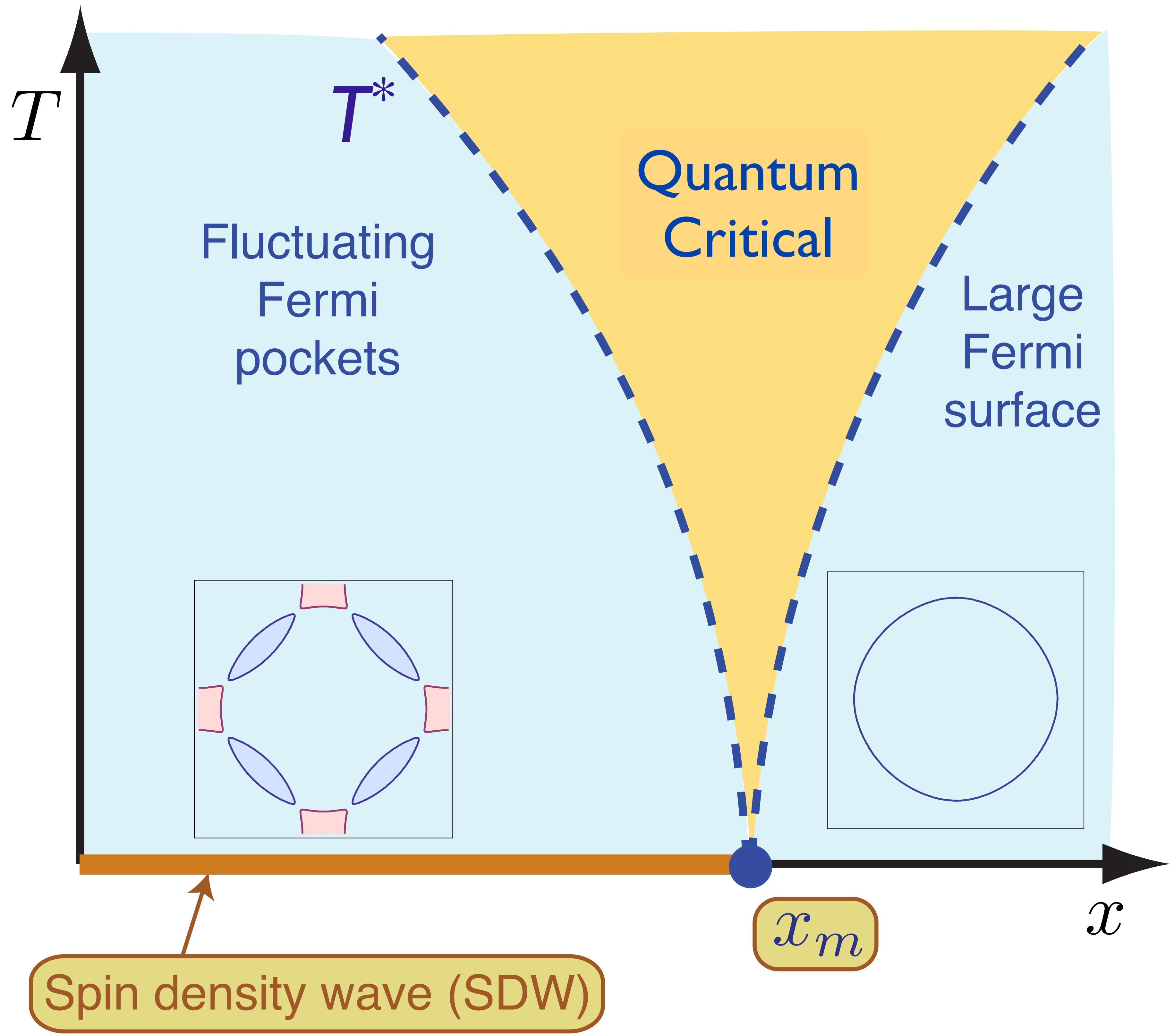

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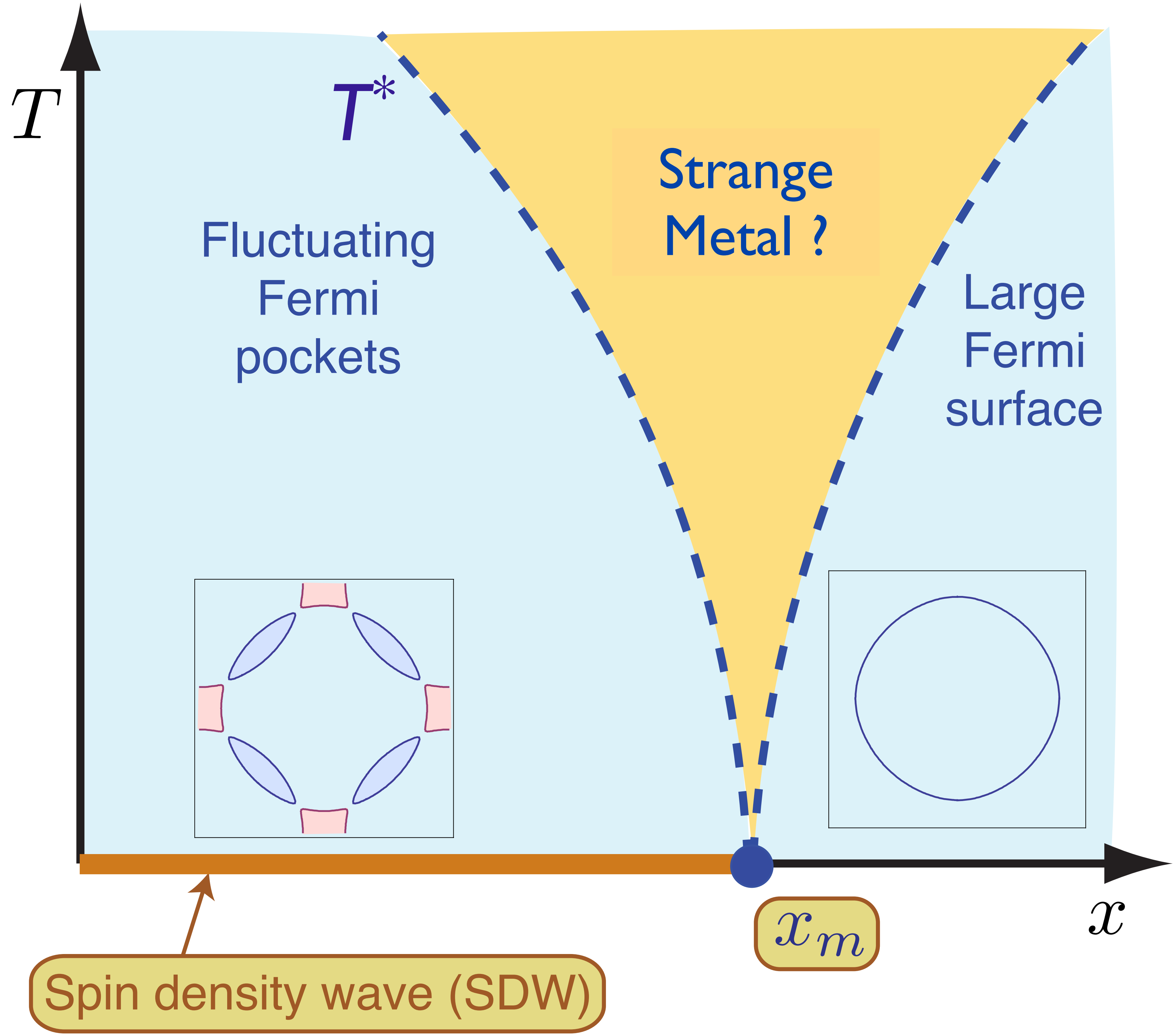


Relaxation and equilibration times $\sim \hbar/k_B T$ are robust properties of strongly-coupled quantum criticality

Pairing by SDW fluctuation exchange

We now allow the SDW field $\vec{\varphi}$ to be dynamical, coupling to electrons as

$$H_{\text{sdw}} = -\sum_{\mathbf{k},\mathbf{q},\alpha,\beta} \vec{\varphi}_{\mathbf{q}} \cdot c^{\dagger}_{\mathbf{k},\alpha} \vec{\sigma}_{\alpha\beta} c_{\mathbf{k}+\mathbf{K}+\mathbf{q},\beta}.$$

Exchange of a $\vec{\varphi}$ quantum leads to the effective interaction

$$H_{ee} = -\frac{1}{2} \sum_{\mathbf{q}} \sum_{\mathbf{p},\gamma,\delta} \sum_{\mathbf{k},\alpha,\beta} V_{\alpha\beta,\gamma\delta}(\mathbf{q}) c^{\dagger}_{\mathbf{k},\alpha} c_{\mathbf{k}+\mathbf{q},\beta} c^{\dagger}_{\mathbf{p},\gamma} c_{\mathbf{p}-\mathbf{q},\delta},$$

where the pairing interaction is

$$V_{\alpha\beta,\gamma\delta}(\mathbf{q}) = \vec{\sigma}_{\alpha\beta} \cdot \vec{\sigma}_{\gamma\delta} \frac{\chi_0}{\xi^{-2} + (\mathbf{q}-\mathbf{K})^2},$$

with $\chi_0 \xi^2$ the SDW susceptibility and ξ the SDW correlation length.

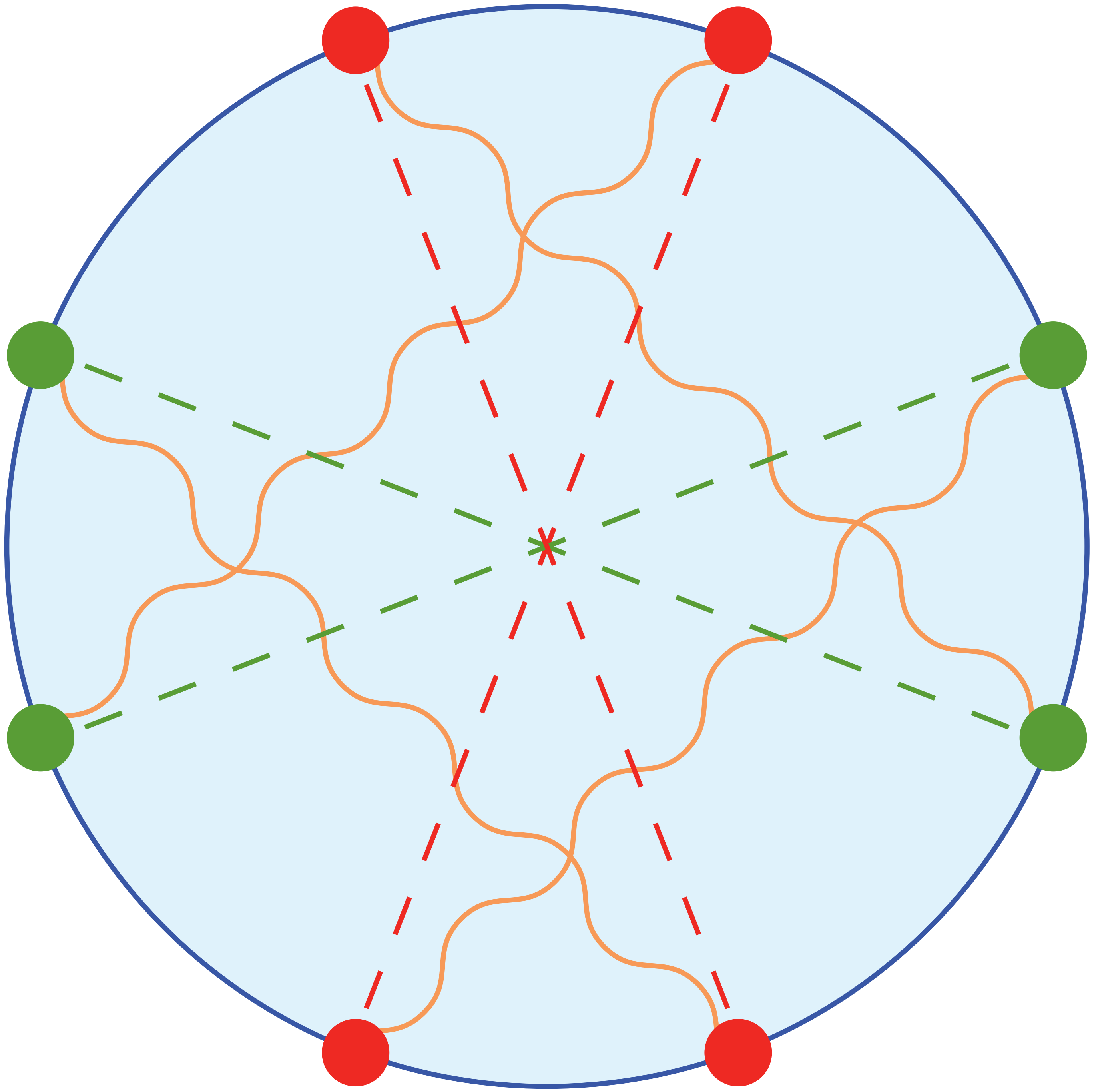
BCS Gap equation

In BCS theory, this interaction leads to the 'gap equation' for the pairing gap $\Delta_{\mathbf{k}} \propto \langle c_{\mathbf{k}\uparrow} c_{-\mathbf{k}\downarrow} \rangle$.

$$\Delta_{\mathbf{k}} = -\sum_{\mathbf{p}} \left(\frac{3\chi_0}{\xi^{-2} + (\mathbf{p} - \mathbf{k} - \mathbf{K})^2} \right) \frac{\Delta_{\mathbf{p}}}{2\sqrt{\varepsilon_{\mathbf{p}}^2 + \Delta_{\mathbf{p}}^2}}$$

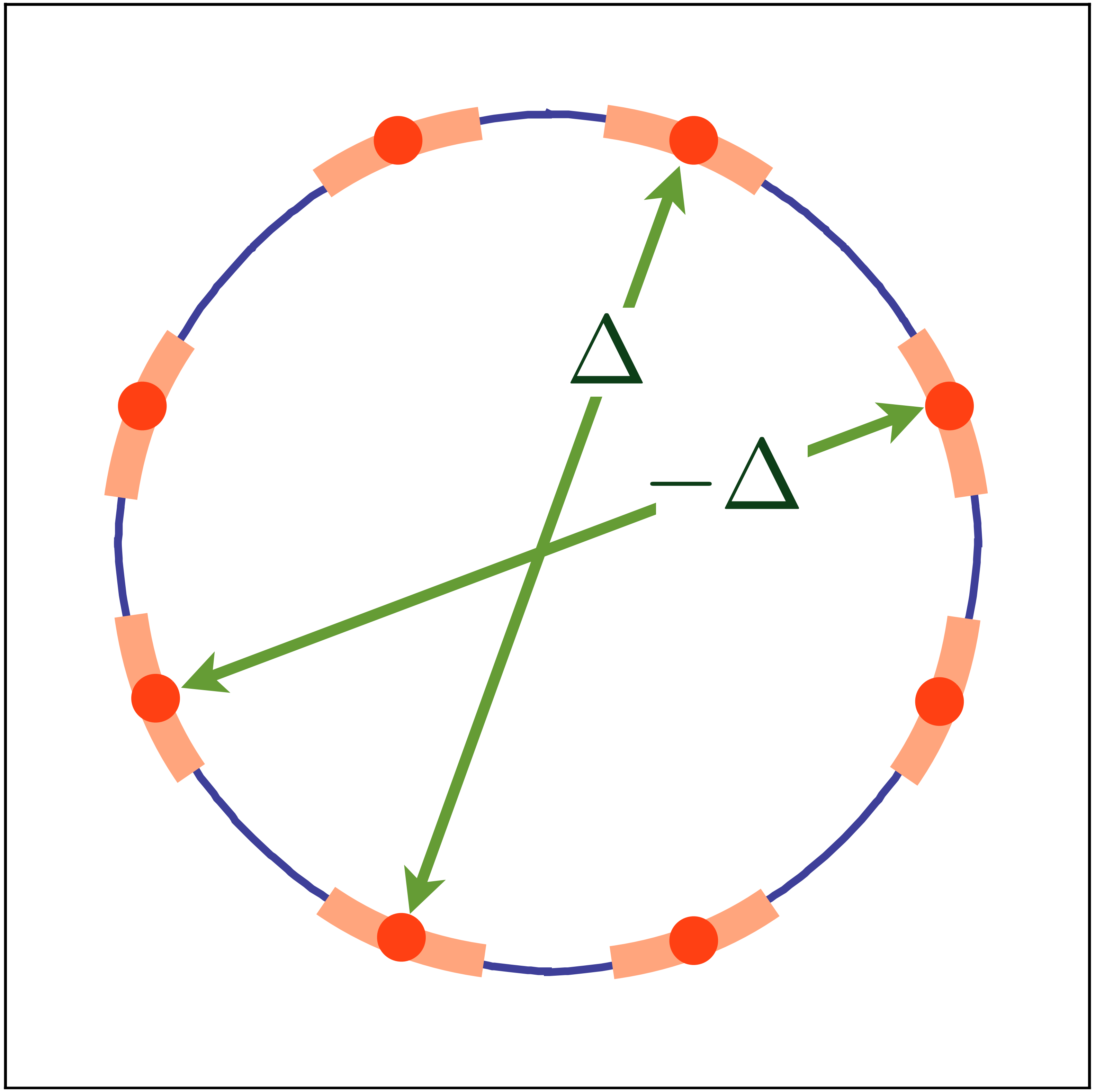
Non-zero solutions of this equation require that $\Delta_{\mathbf{k}}$ and $\Delta_{\mathbf{p}}$ have opposite signs when $\mathbf{p} - \mathbf{k} \approx \mathbf{K}$.

Pairing "glue" from antiferromagnetic fluctuations



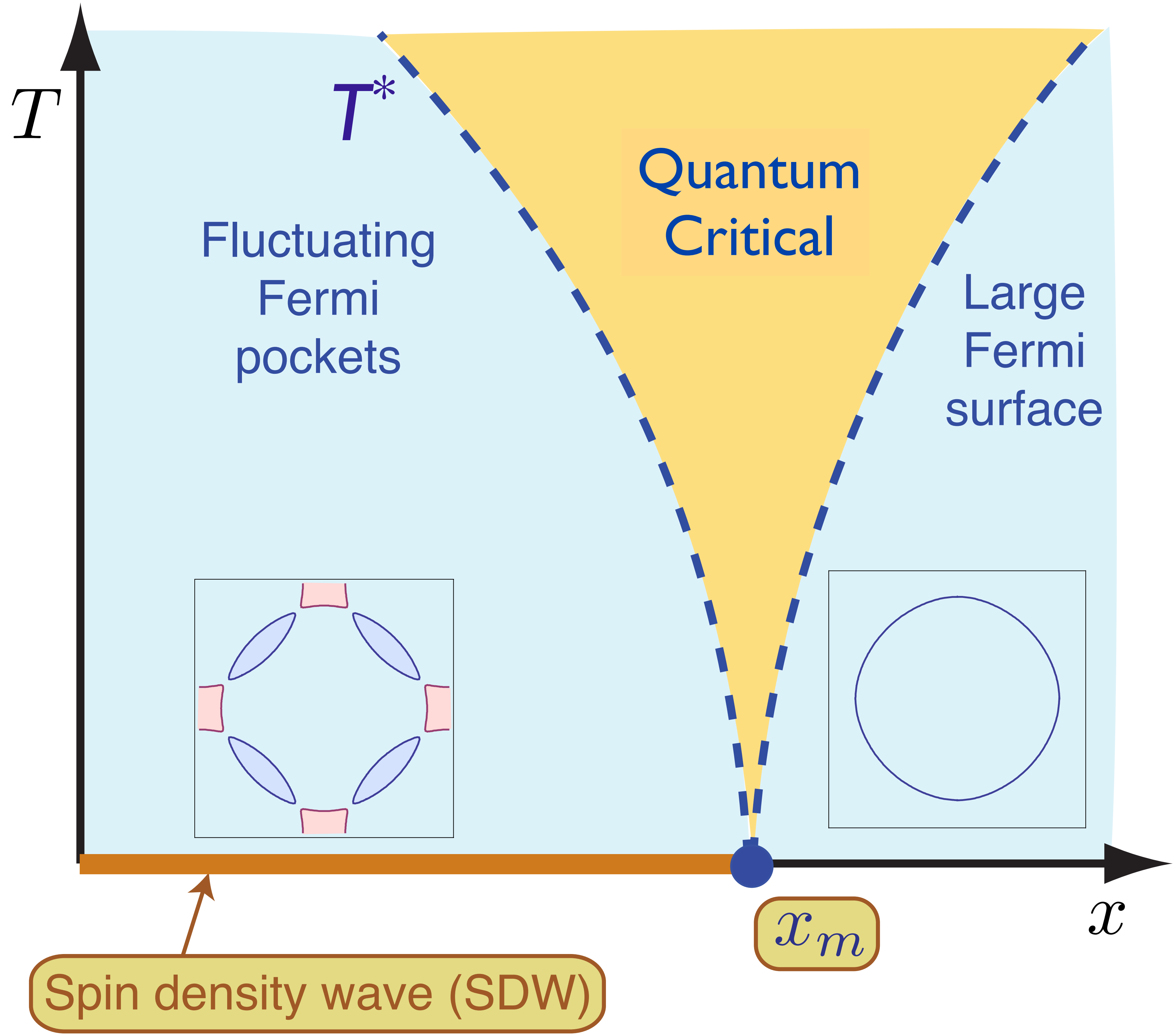
V. J. Emery, *J. Phys. (Paris) Colloq.* **44**, C3-977 (1983)
D.J. Scalapino, E. Loh, and J.E. Hirsch, *Phys. Rev. B* **34**, 8190 (1986)
K. Miyake, S. Schmitt-Rink, and C. M.Varma, *Phys. Rev. B* **34**, 6554 (1986)
S. Raghu, S.A. Kivelson, and D.J. Scalapino, *Phys. Rev. B* **81**, 224505 (2010)

$$\left\langle c^\dagger_{\mathbf{k}\alpha} c^\dagger_{-\mathbf{k}\beta} \right\rangle = \varepsilon_{\alpha\beta} \Delta (\cos k_x - \cos k_y)$$



Unconventional pairing at *<u>and near</u>* hot spots

Theory of quantum criticality in the cuprates



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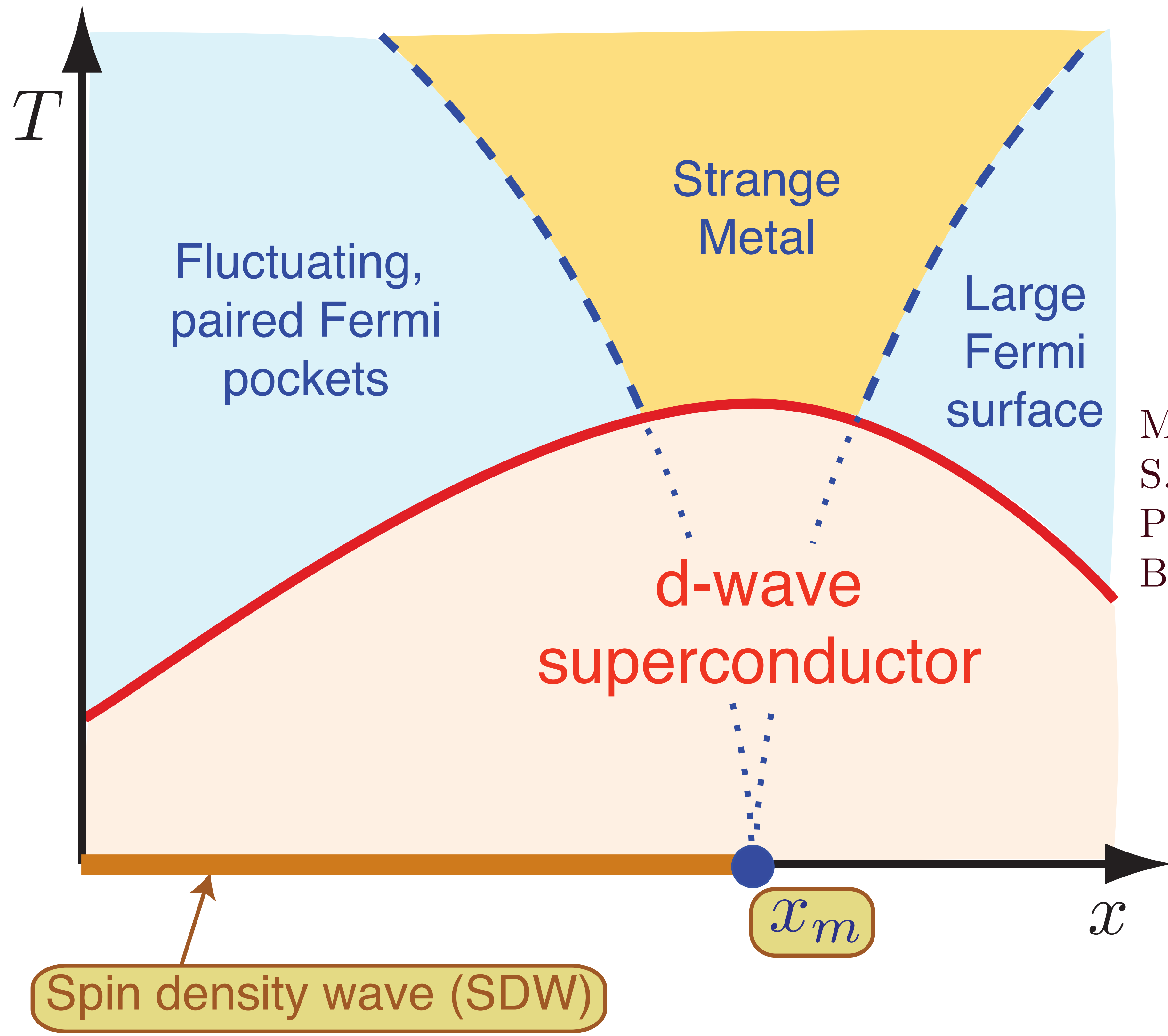

M. A. Metlitski and S. Sachdev, Physical Review B **82**, 075128 (2010)

SDW quantum critical point is unstable to d-wave superconductivity
This instability is stronger than that in the BCS theory

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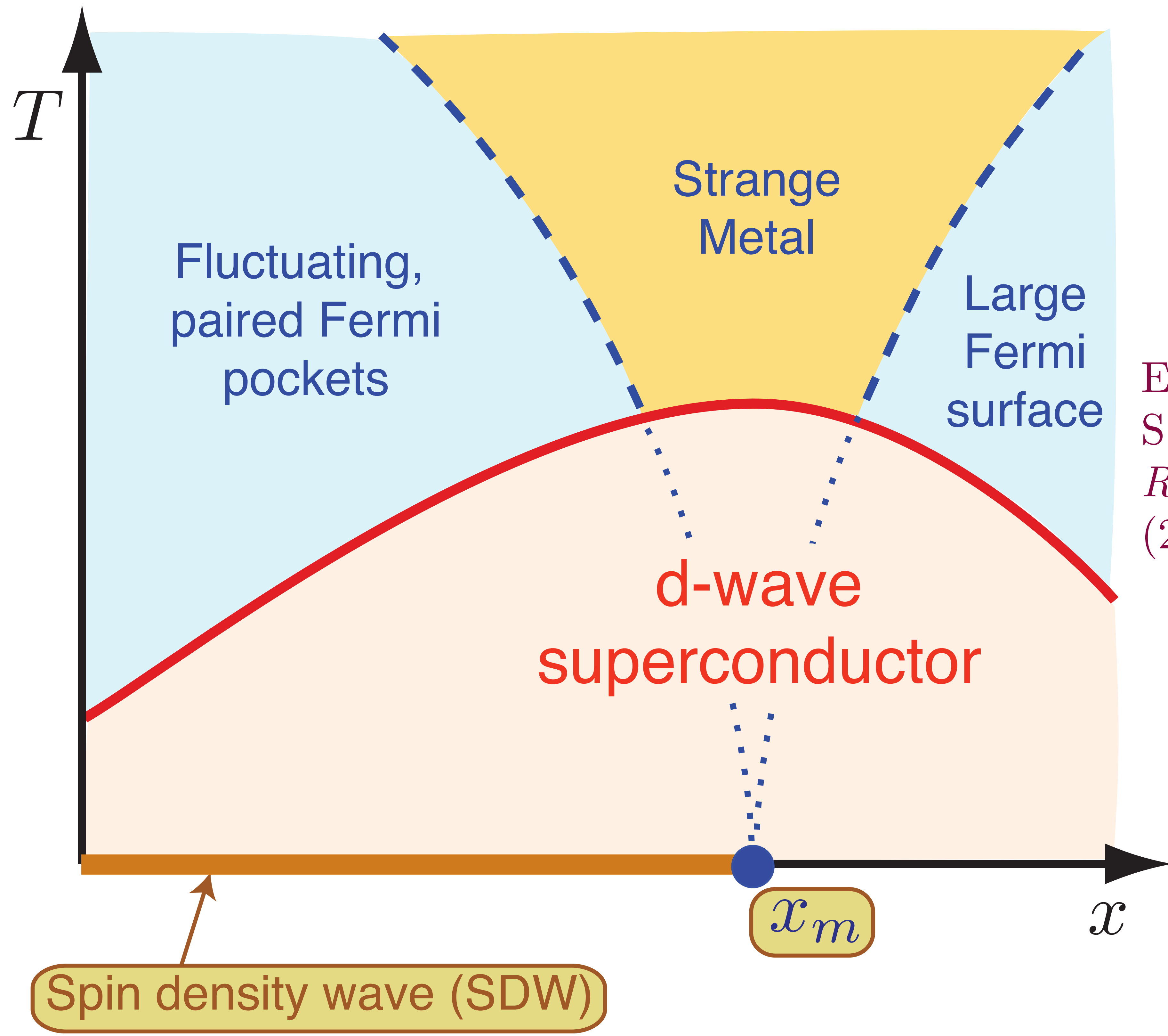

E. G. Moon and S. Sachdev, *Phy. Rev. B* **80**, 035117 (2009)

Competition between SDW order and superconductivity moves the actual quantum critical point to $x = x_s < x_m$.

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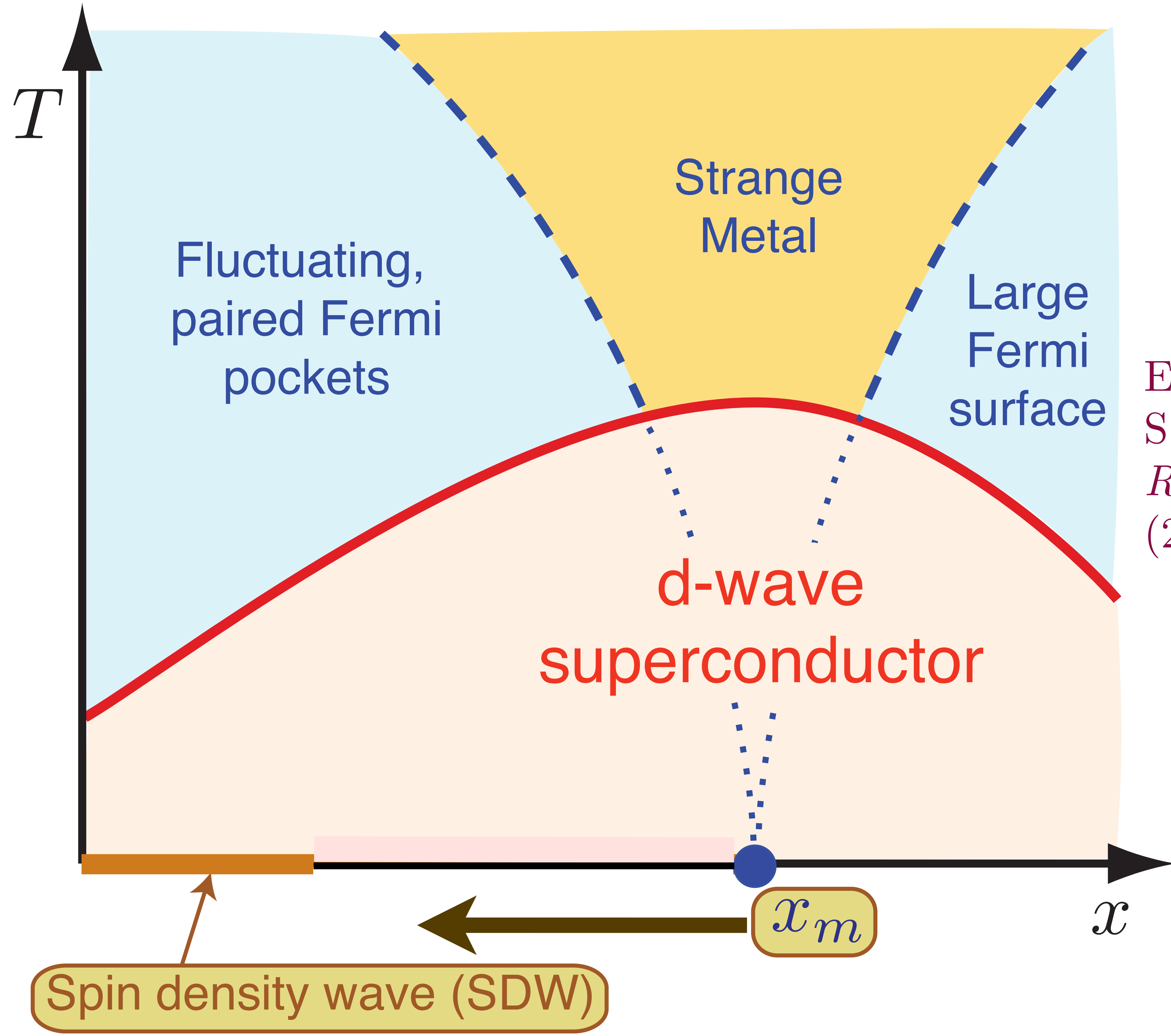

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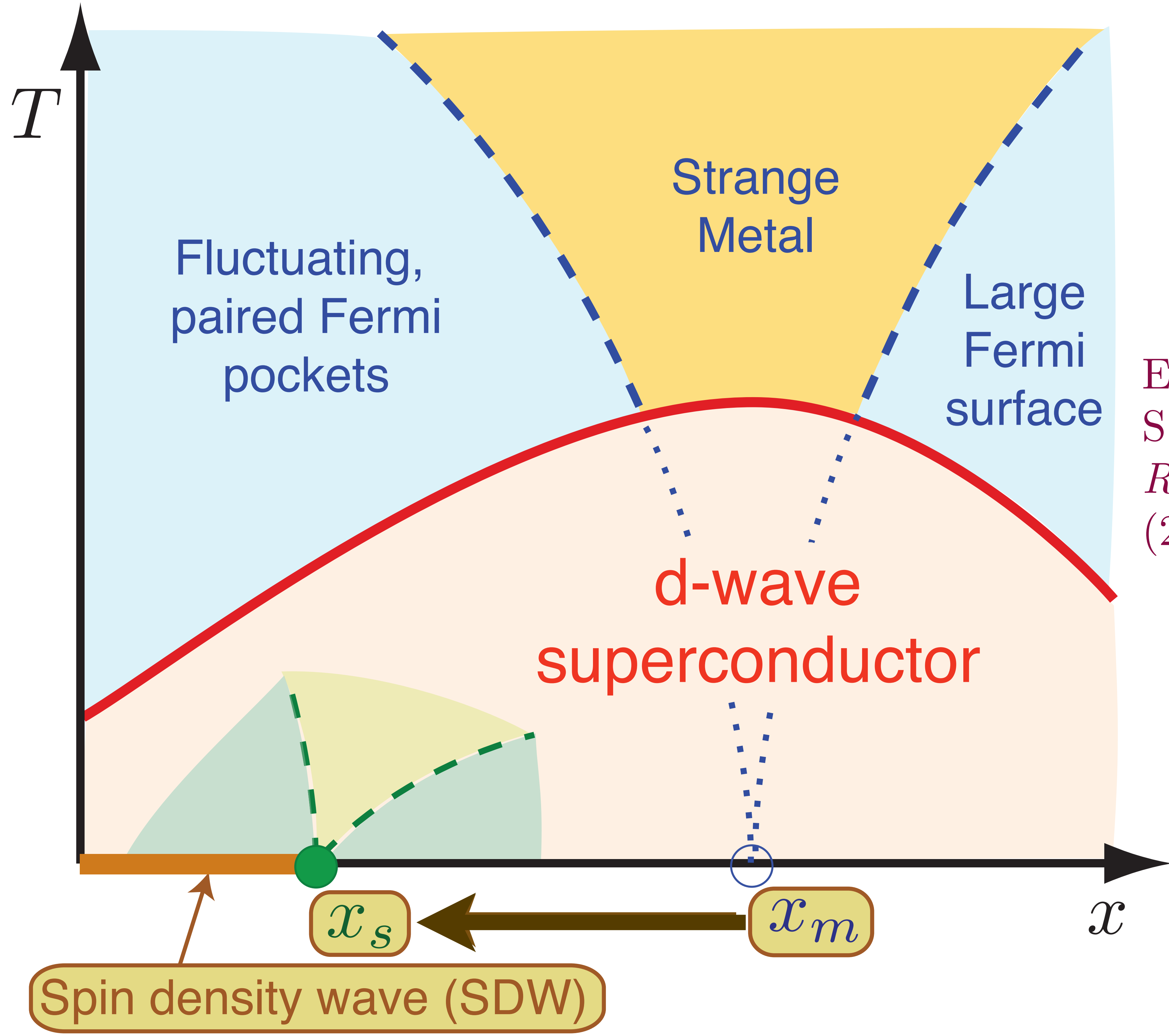

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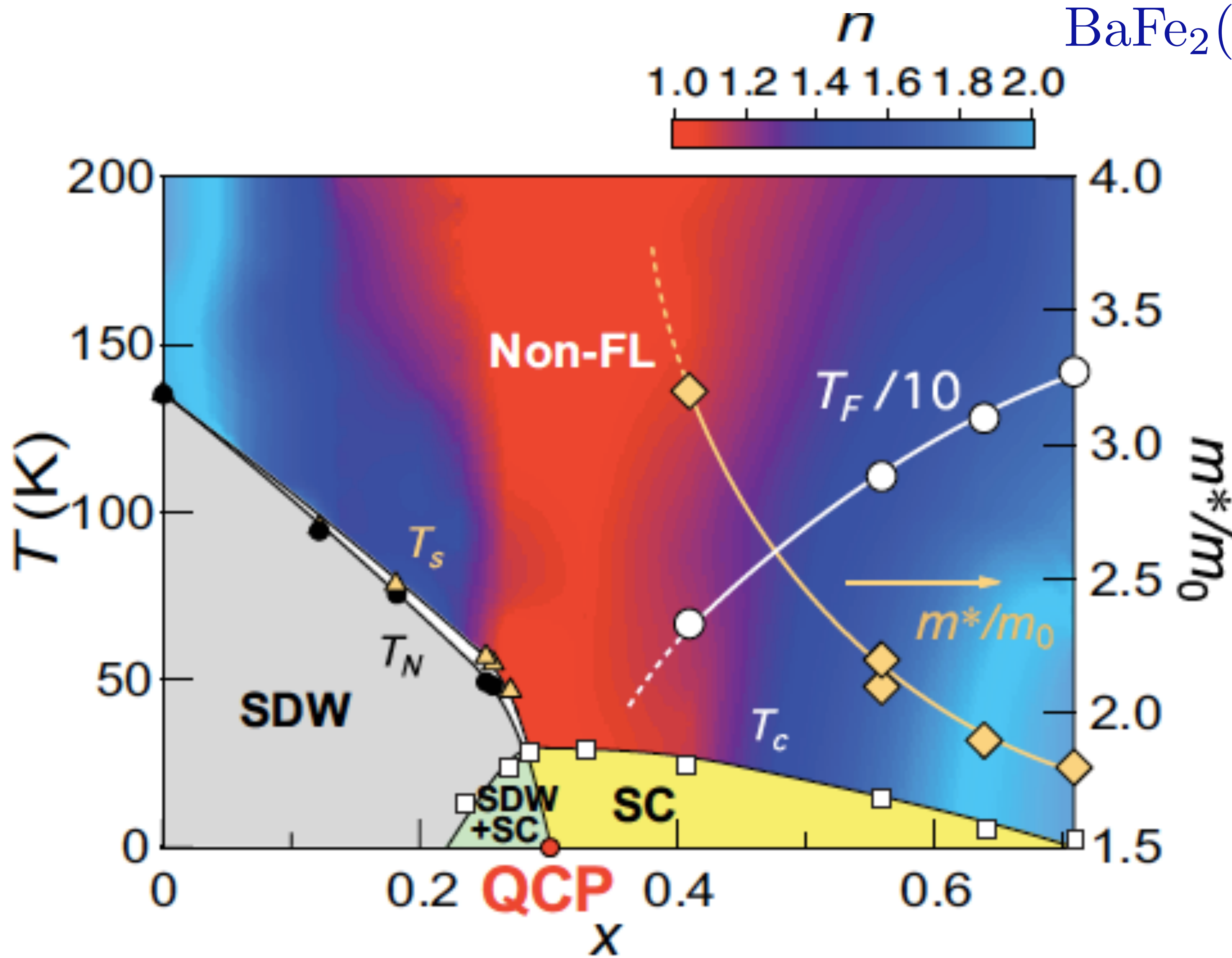

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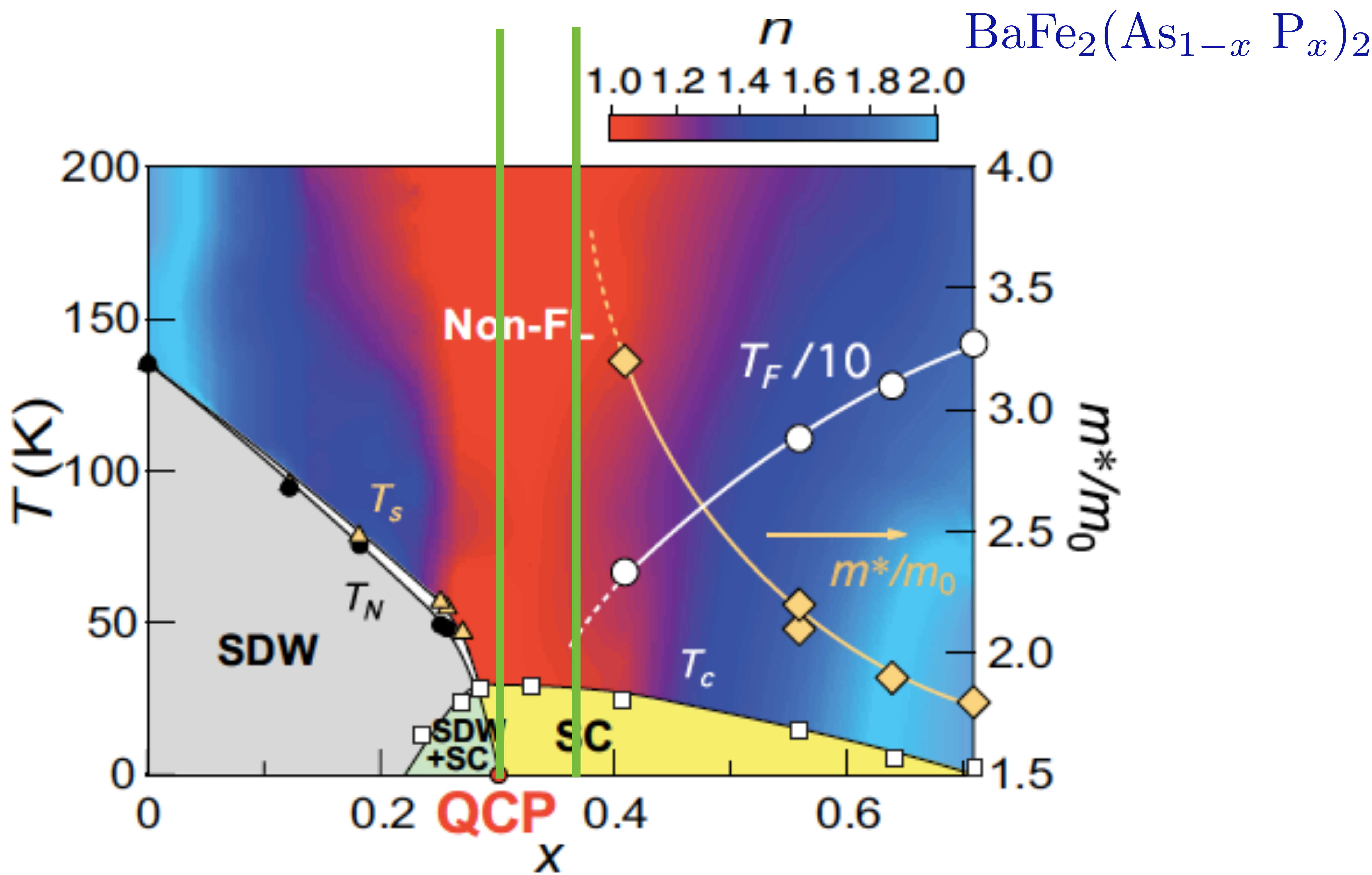

Notice shift between the position of the QCP in the superconductor, and the divergence in effective mass in the metal measured at high magnetic fields

At stronger coupling, different effects compete:

- Pairing glue becomes stronger.

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- Other instabilities can appear *e.g.* to charge density waves/stripe order.

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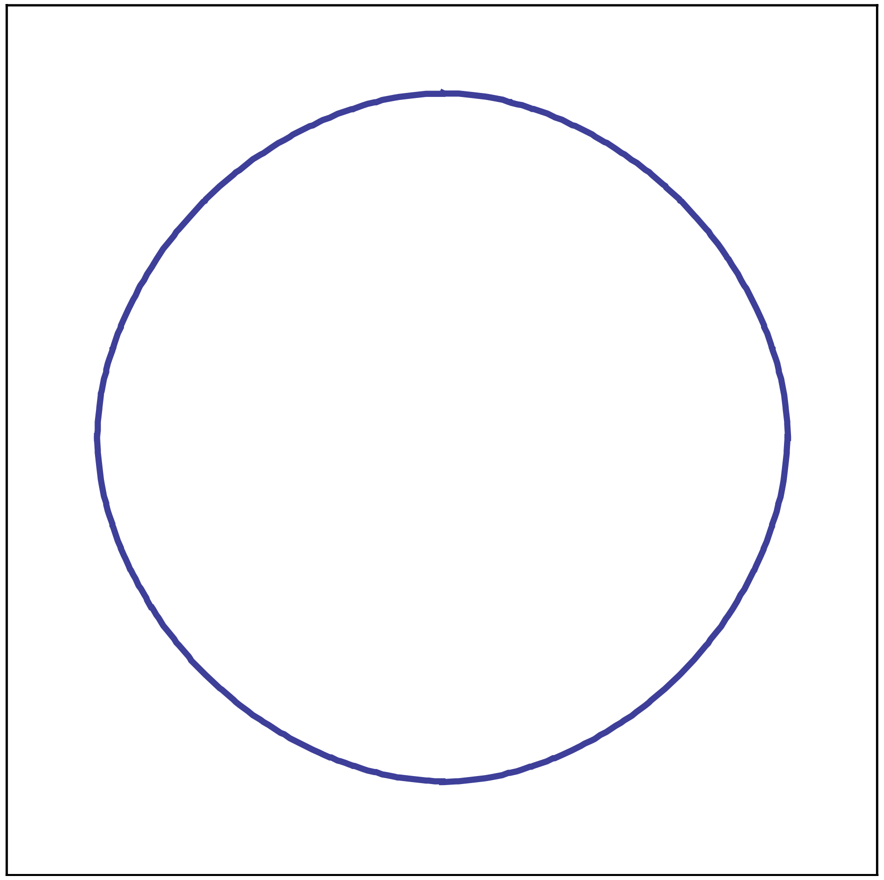

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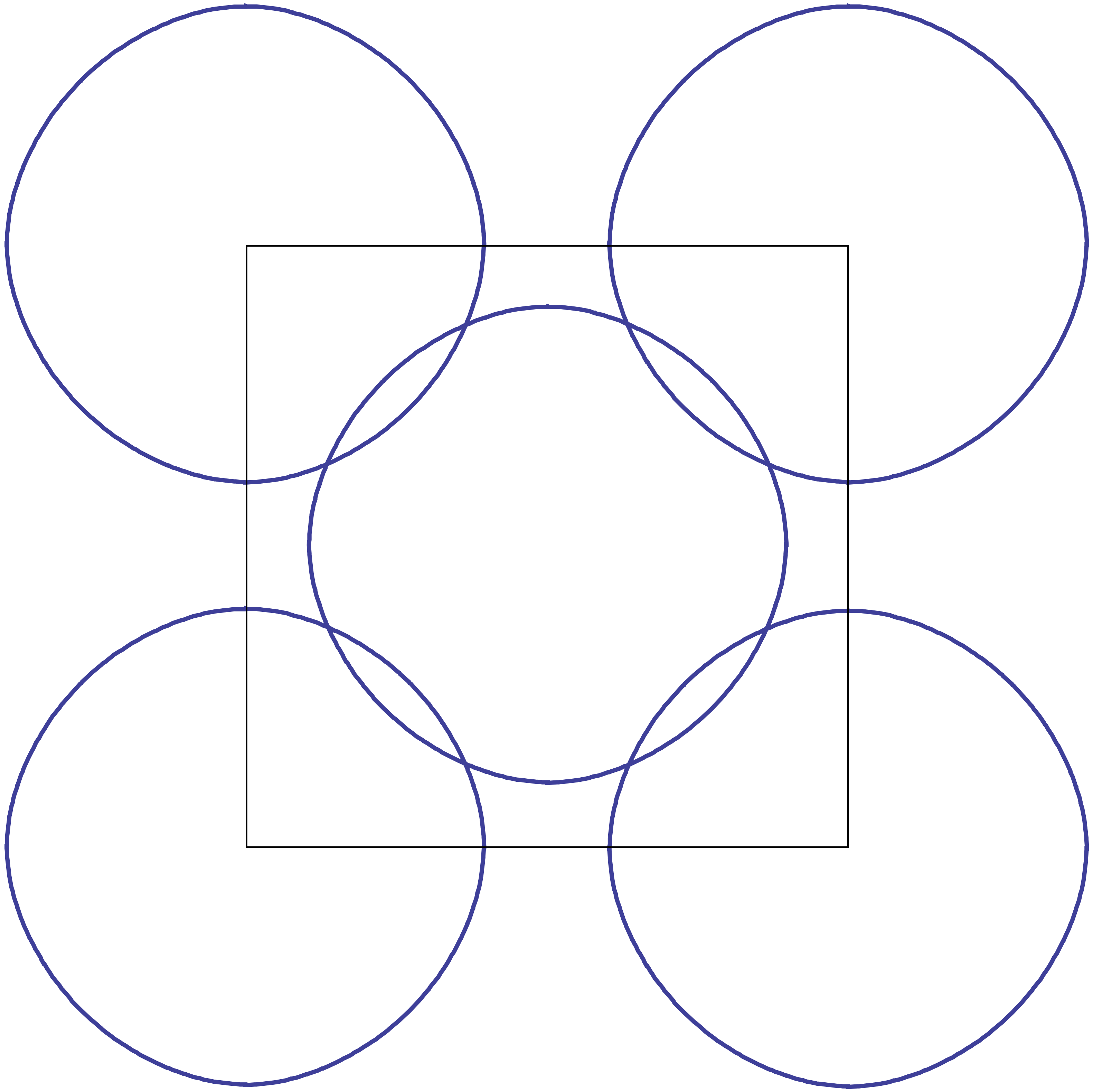
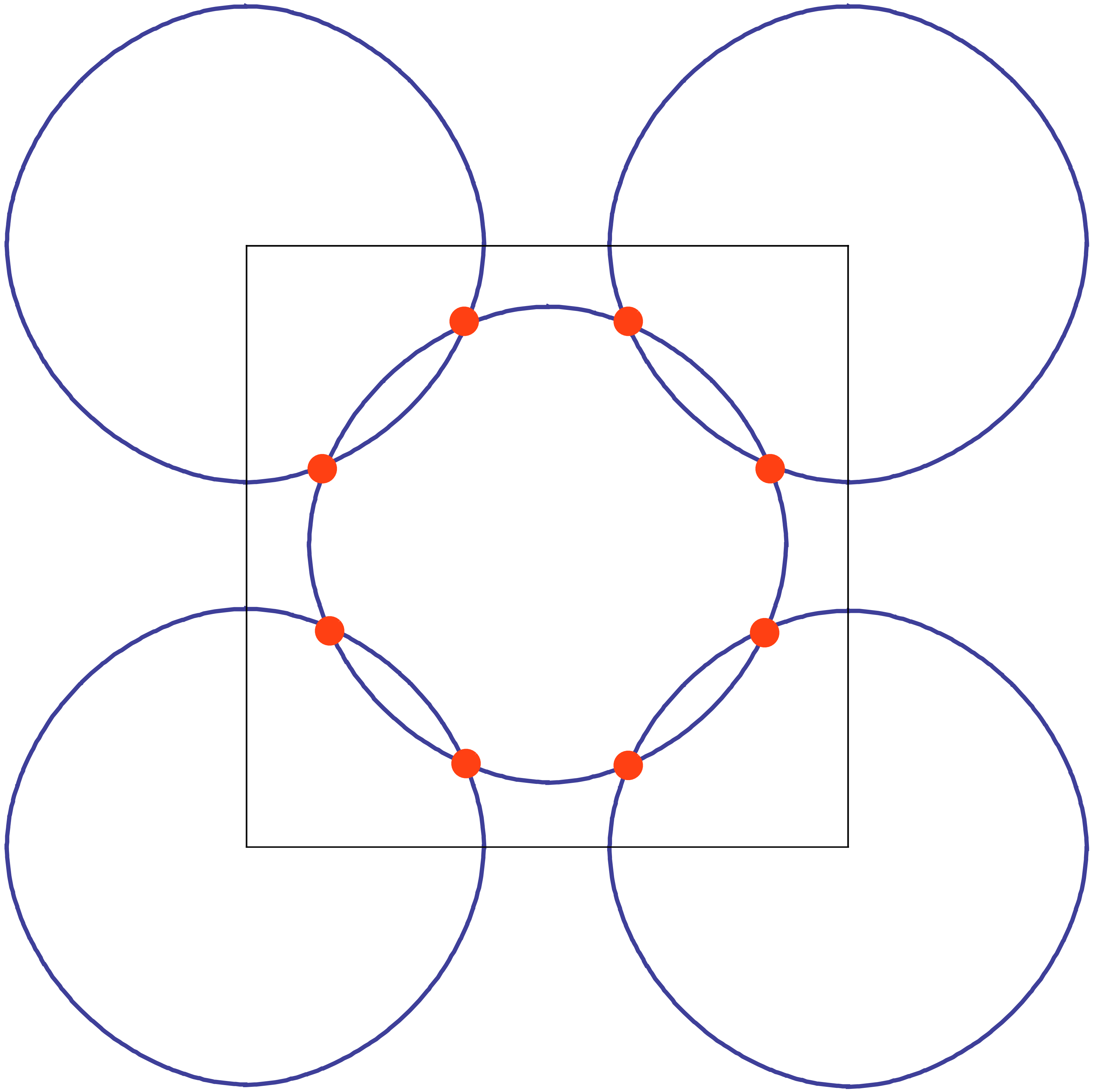


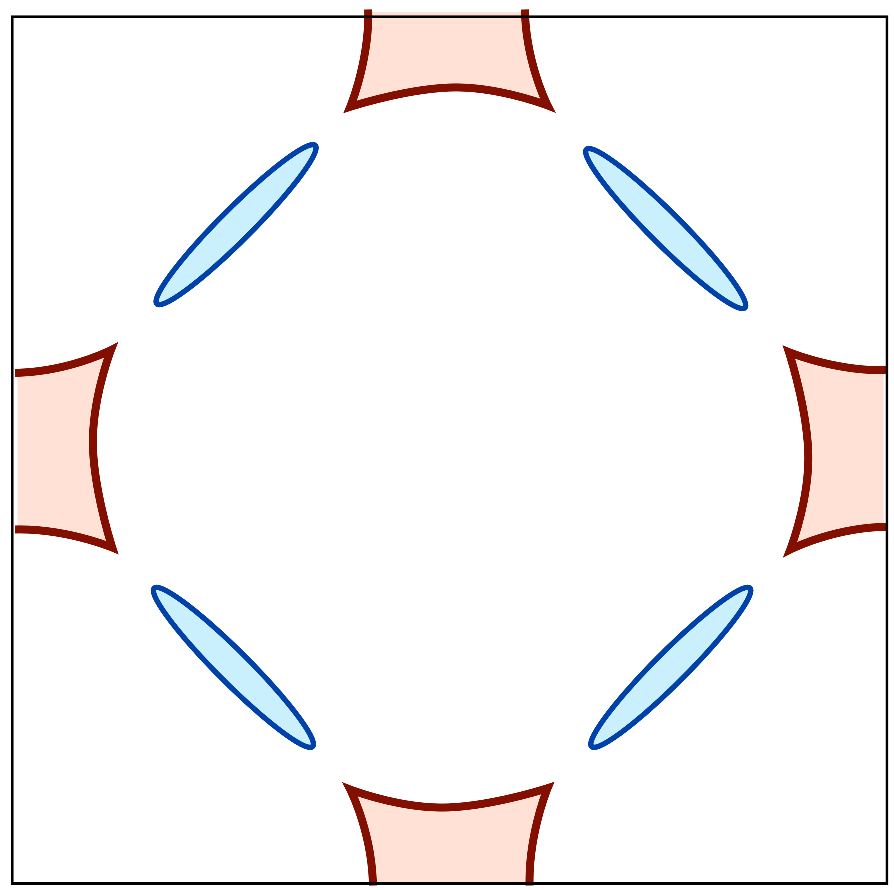
Fermi surfaces translated by $\mathbf{K} = (\pi, \pi)$.

Fermi surface+antiferromagnetism

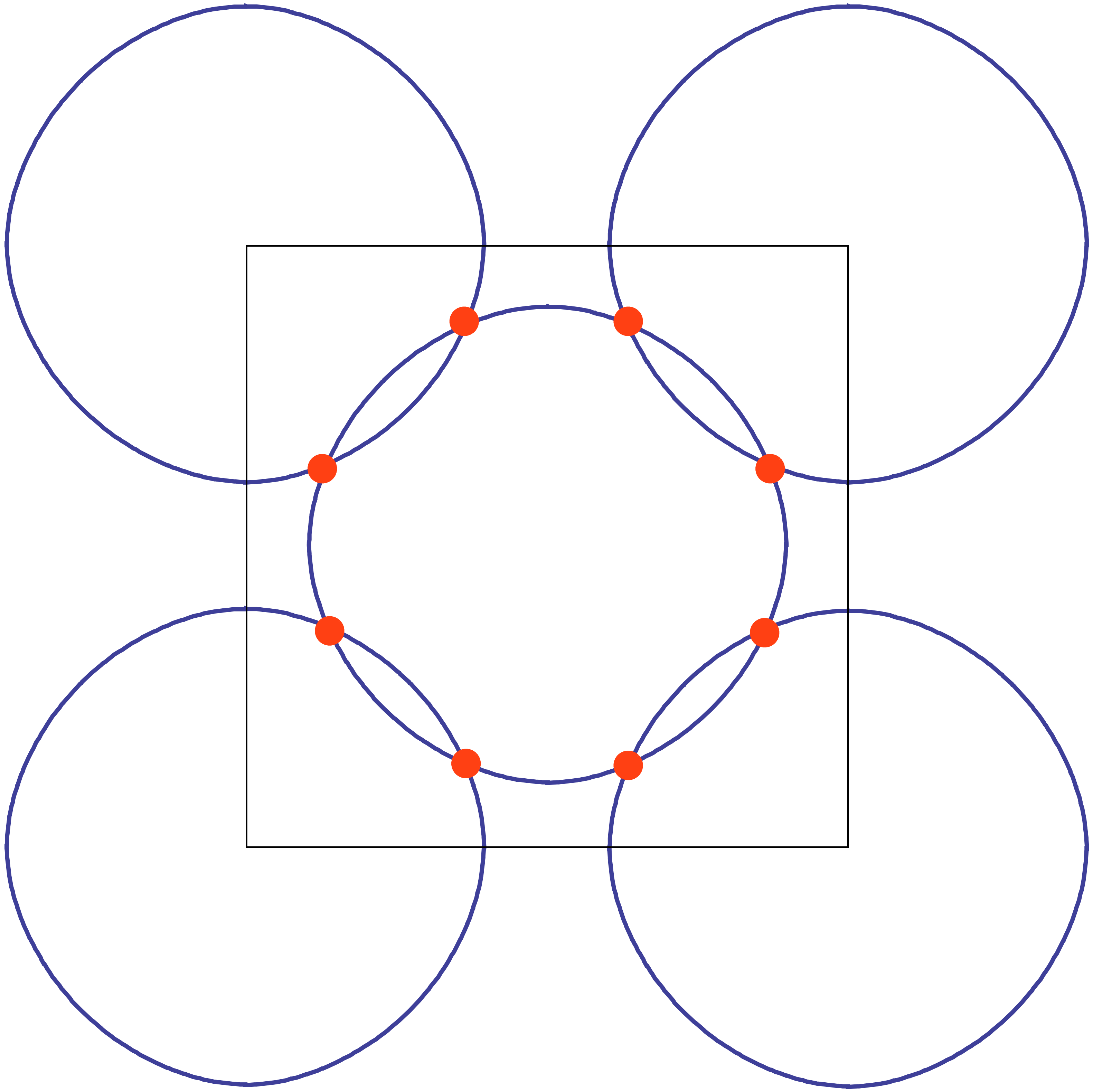


"Hot" spots

Fermi surface+antiferromagnetism



Electron and hole pockets in antiferromagnetic phase with $\langle \vec{\varphi} \rangle \neq 0$



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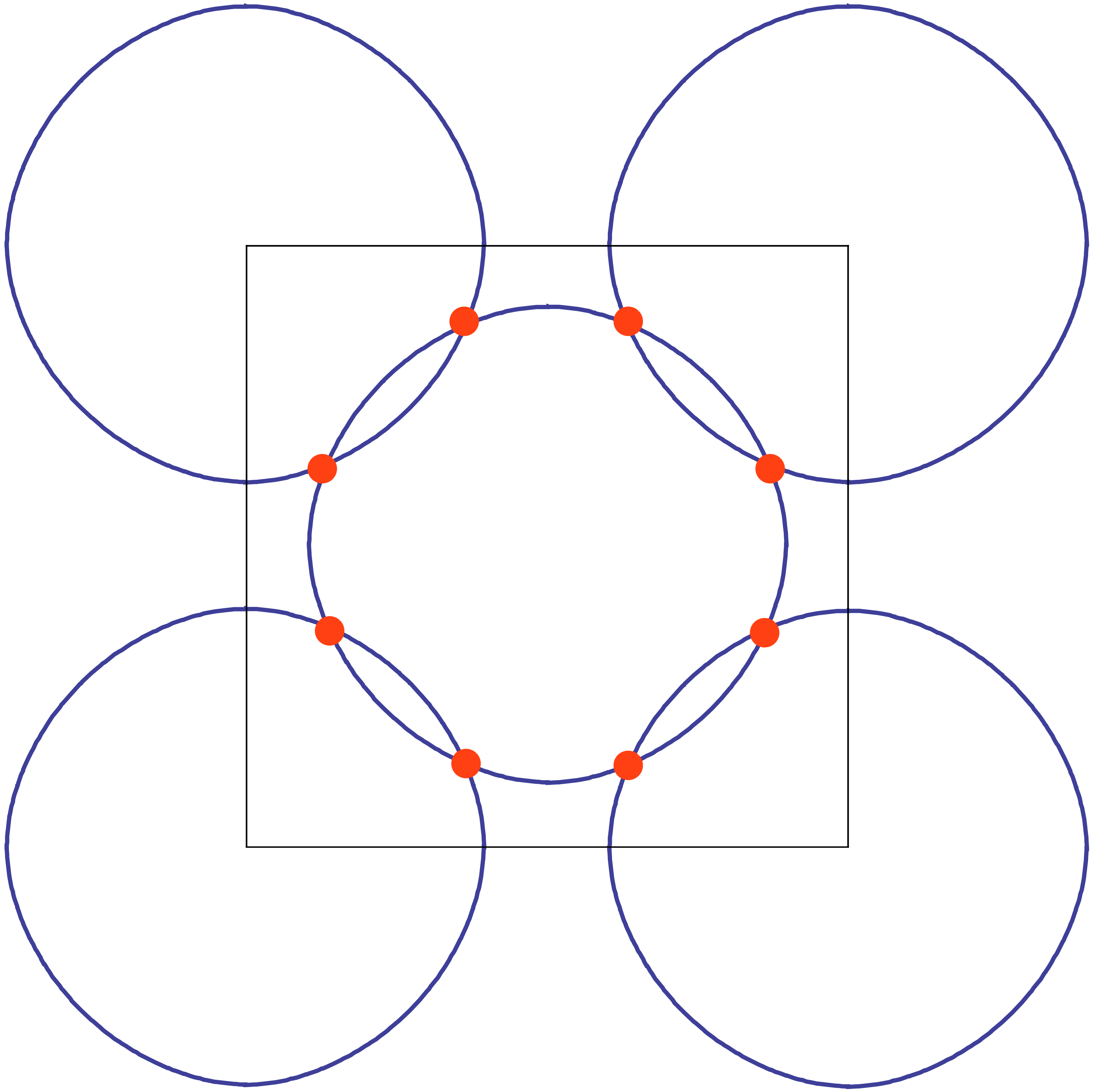
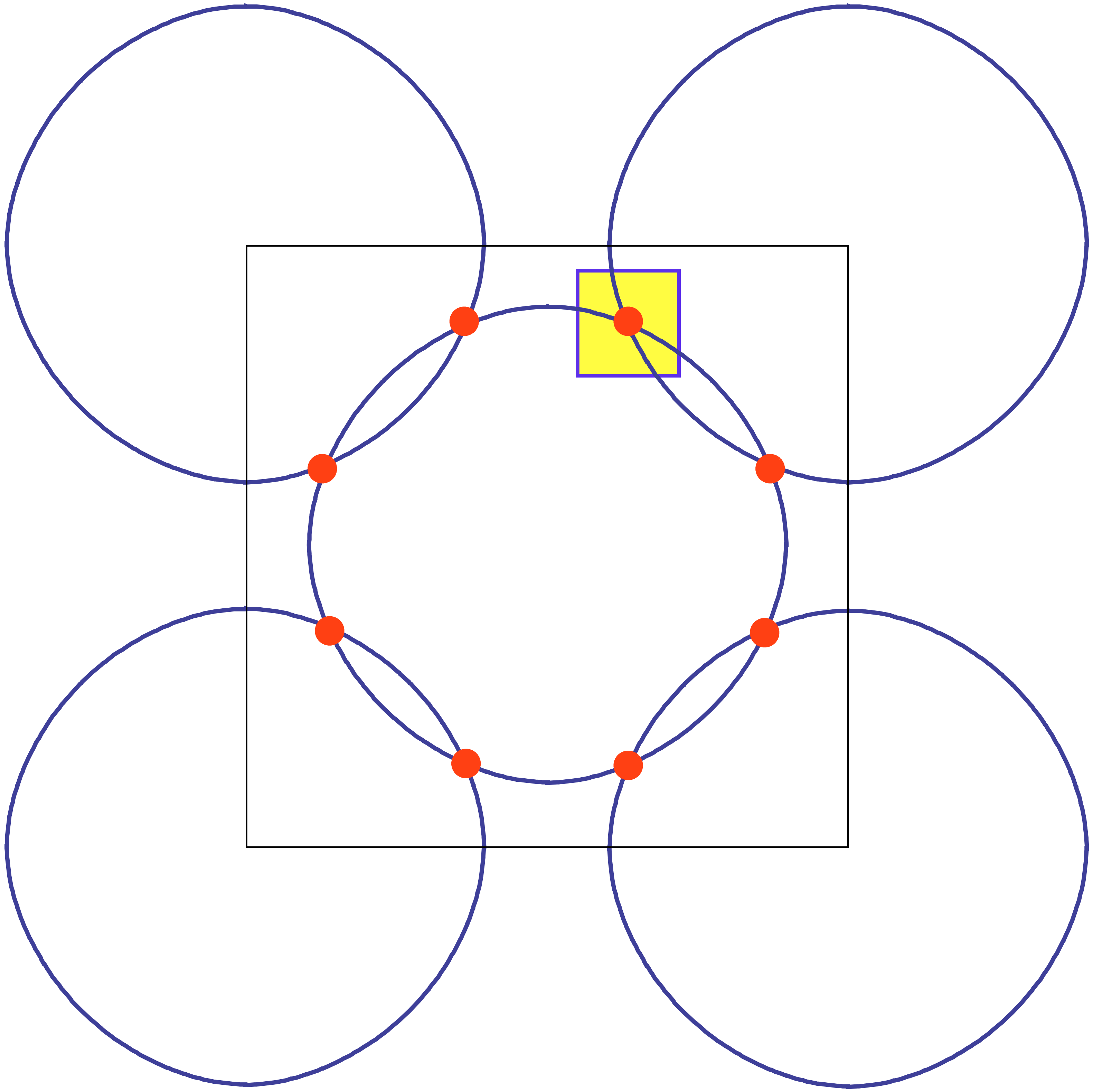
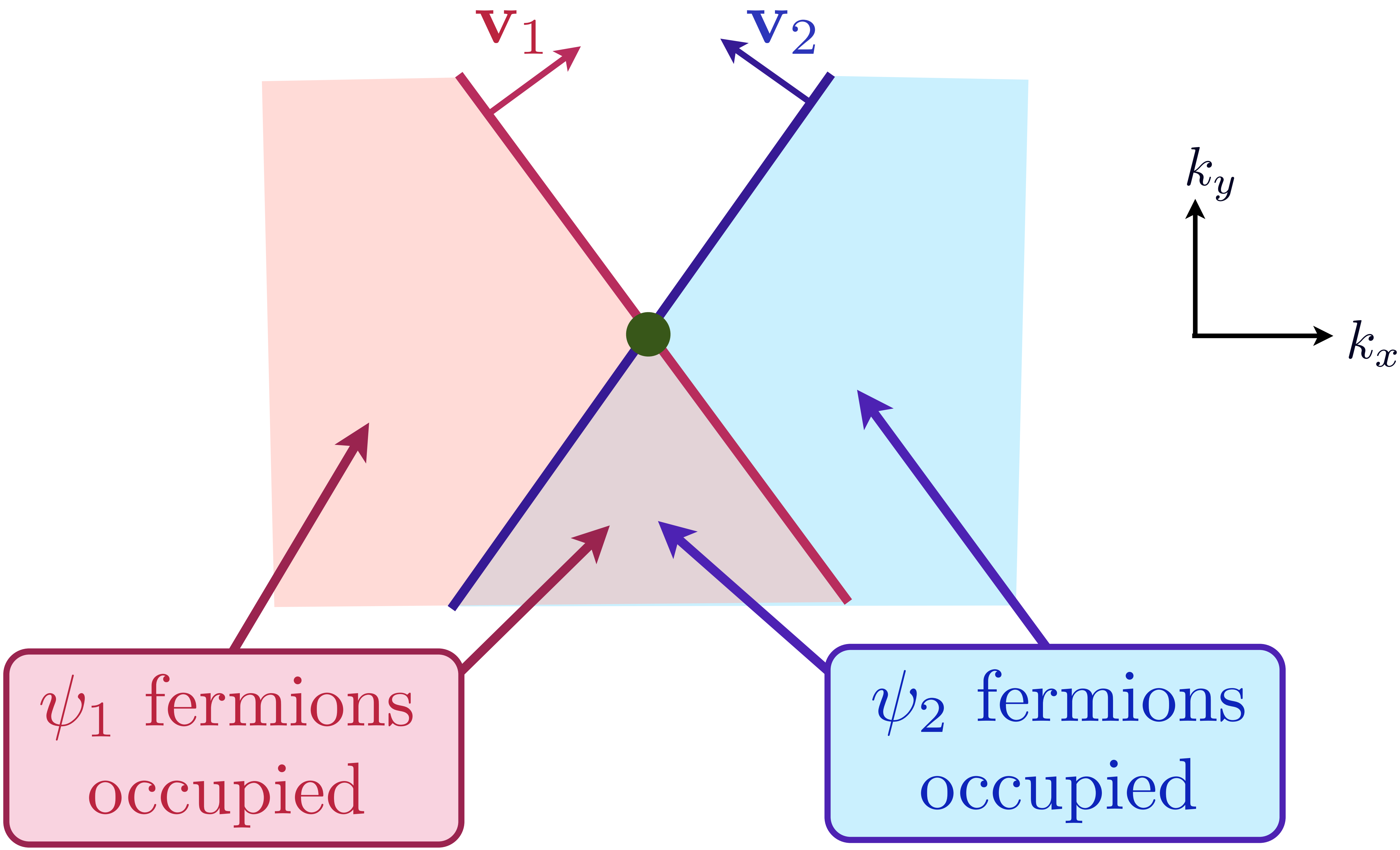


Low energy theory for critical point near hot spots

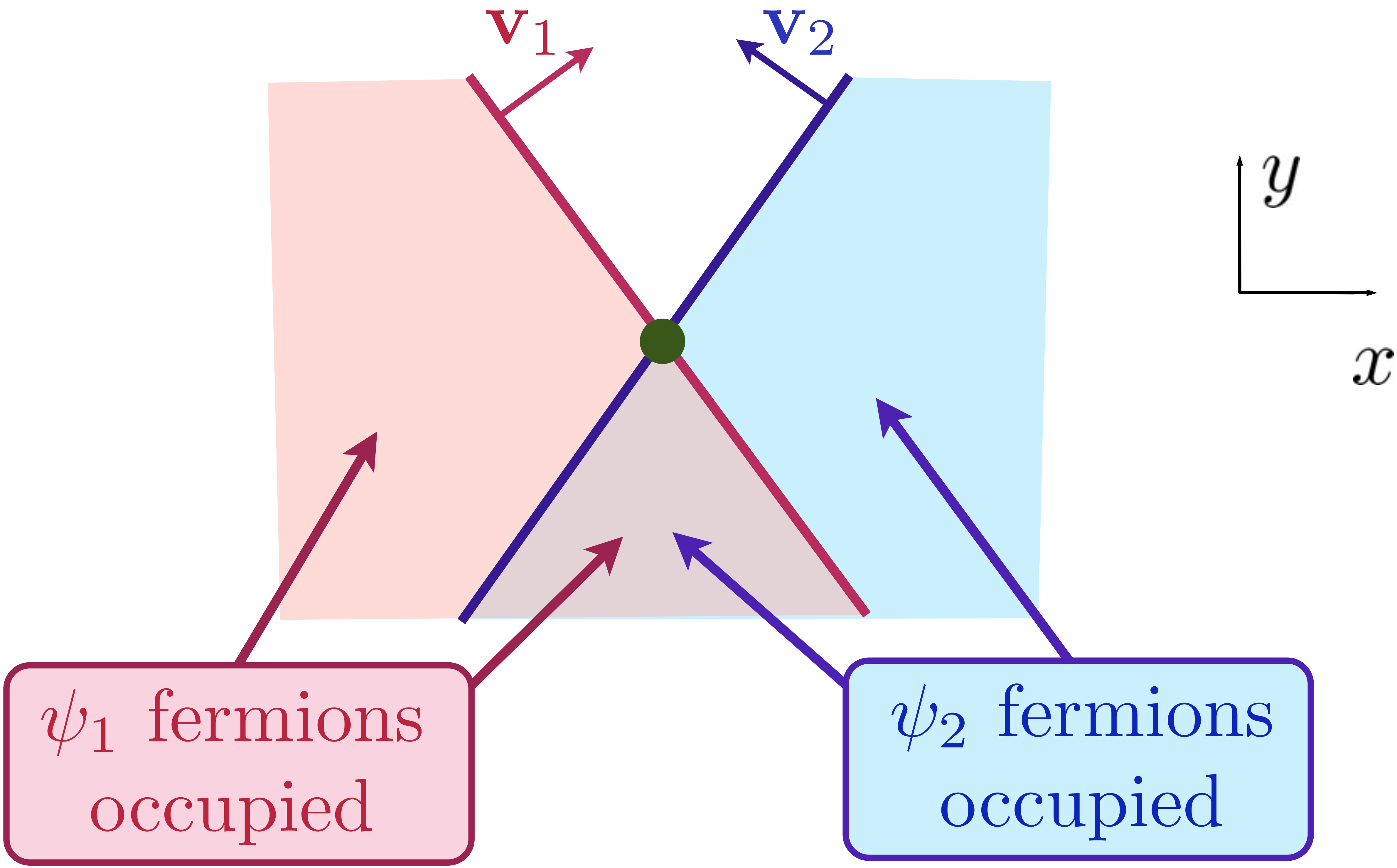


Low energy theory for critical point near hot spots

Theory has fermions $\psi_{1,2}$ (with Fermi velocities $\mathbf{v}_{1,2}$) and boson order parameter $\vec{\varphi}$, interacting with coupling λ



$$\mathcal{L}_f = \psi^\dagger_{1\alpha}\left(\zeta\partial_\tau - i\mathbf{v}_1\cdot\boldsymbol{\nabla}_r\right)\psi_{1\alpha} + \psi^\dagger_{2\alpha}\left(\zeta\partial_\tau - i\mathbf{v}_2\cdot\boldsymbol{\nabla}_r\right)\psi_{2\alpha}$$



Ar. Abanov and A.V. Chubukov, *Phys. Rev. Lett.* **93**, 255702 (2004).

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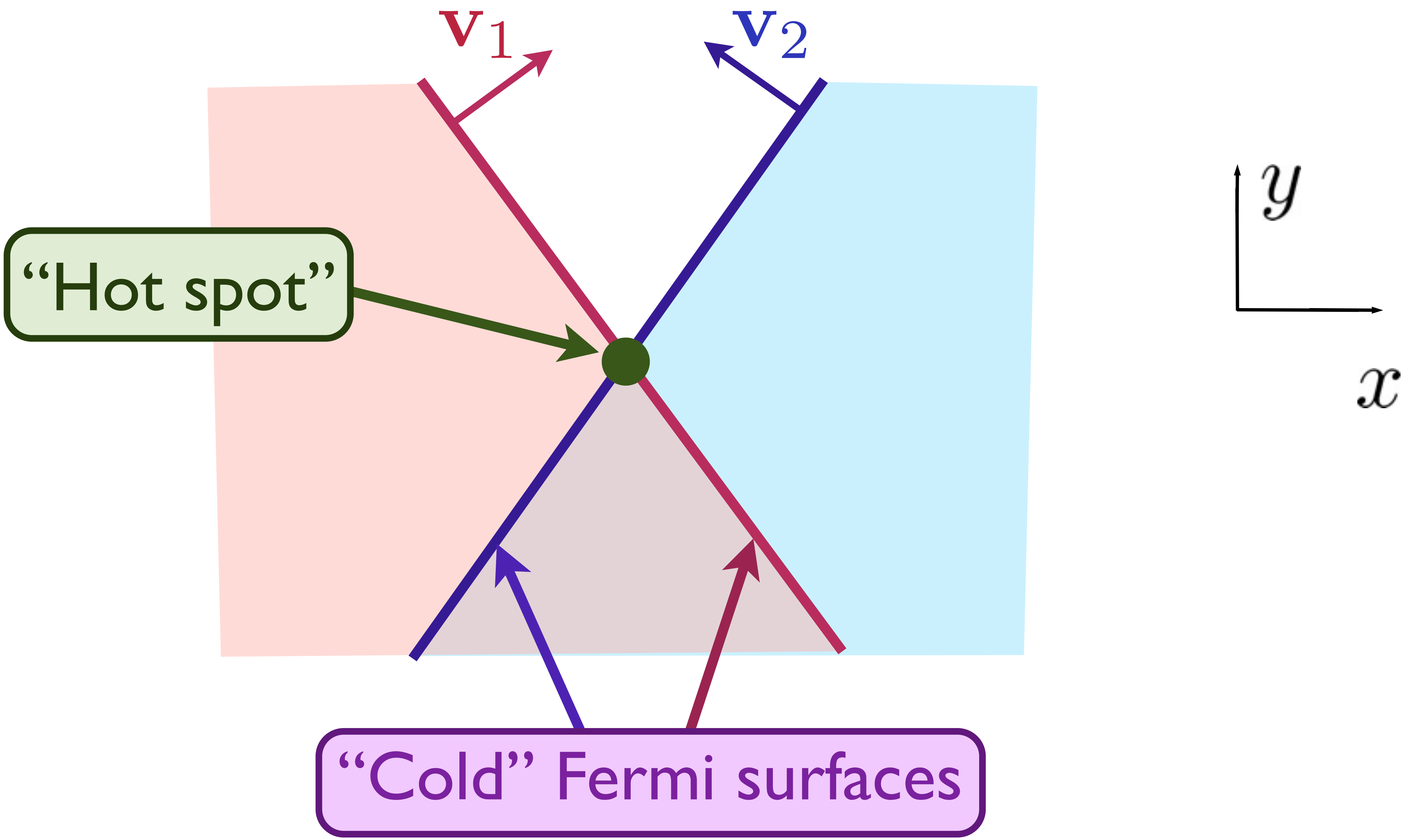

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Order parameter: $\mathcal{L}_\varphi = \frac{1}{2} \left(\boldsymbol{\nabla}_r \vec{\varphi} \right)^2 + \frac{\widetilde{\zeta}}{2} \left(\partial_\tau \vec{\varphi} \right)^2 + \frac{s}{2} \vec{\varphi}^2 + \frac{u}{4} \vec{\varphi}^4$

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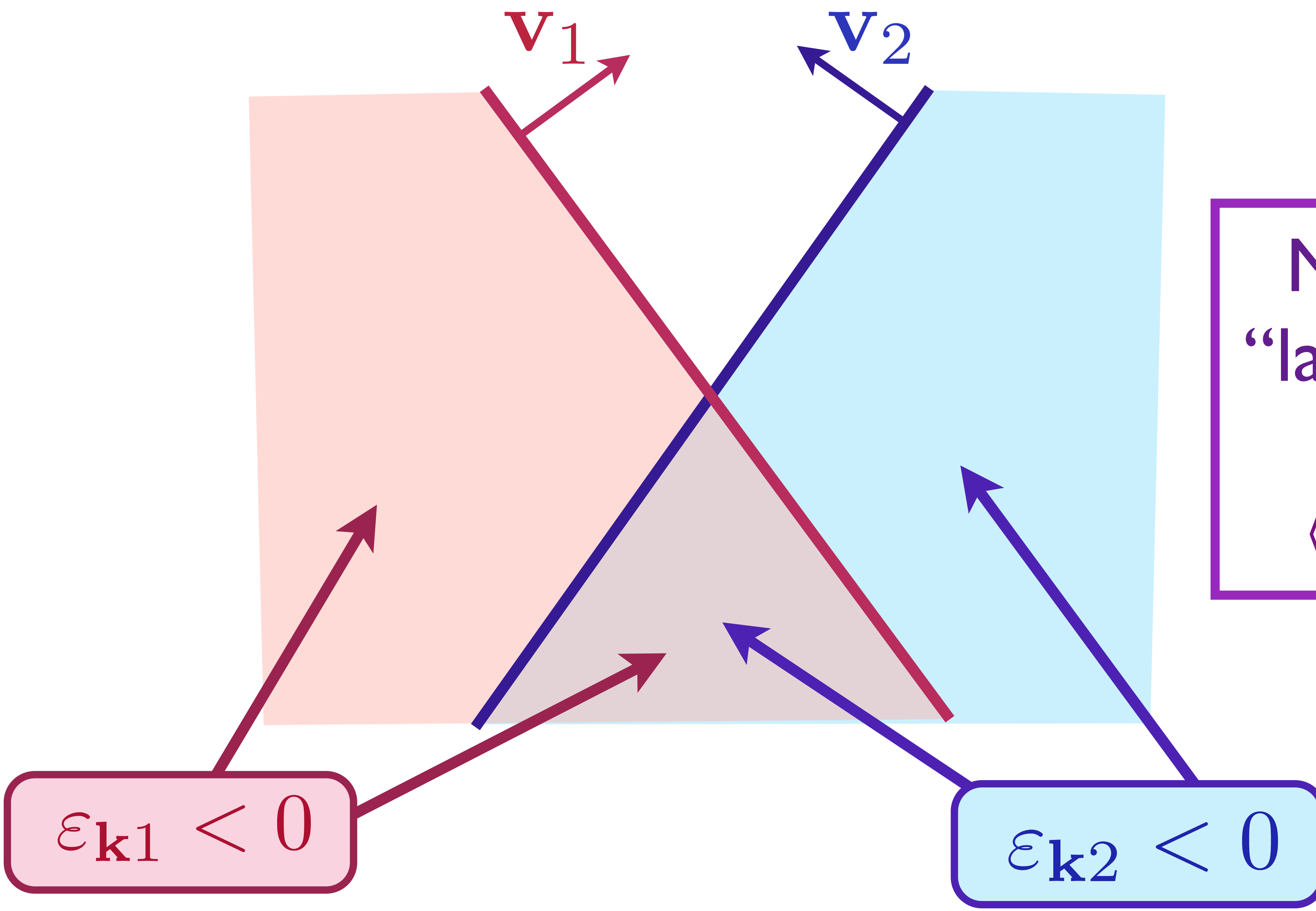
"Yukawa" coupling: $\mathcal{L}_c = -\lambda\vec{\varphi}\cdot\left(\psi^\dagger_{1\alpha}\vec{\sigma}_{\alpha\beta}\psi_{2\beta} + \psi^\dagger_{2\alpha}\vec{\sigma}_{\alpha\beta}\psi_{1\beta}\right)$

Ar. Abanov and A.V. Chubukov, *Phys. Rev. Lett.* **93**, 255702 (2004).

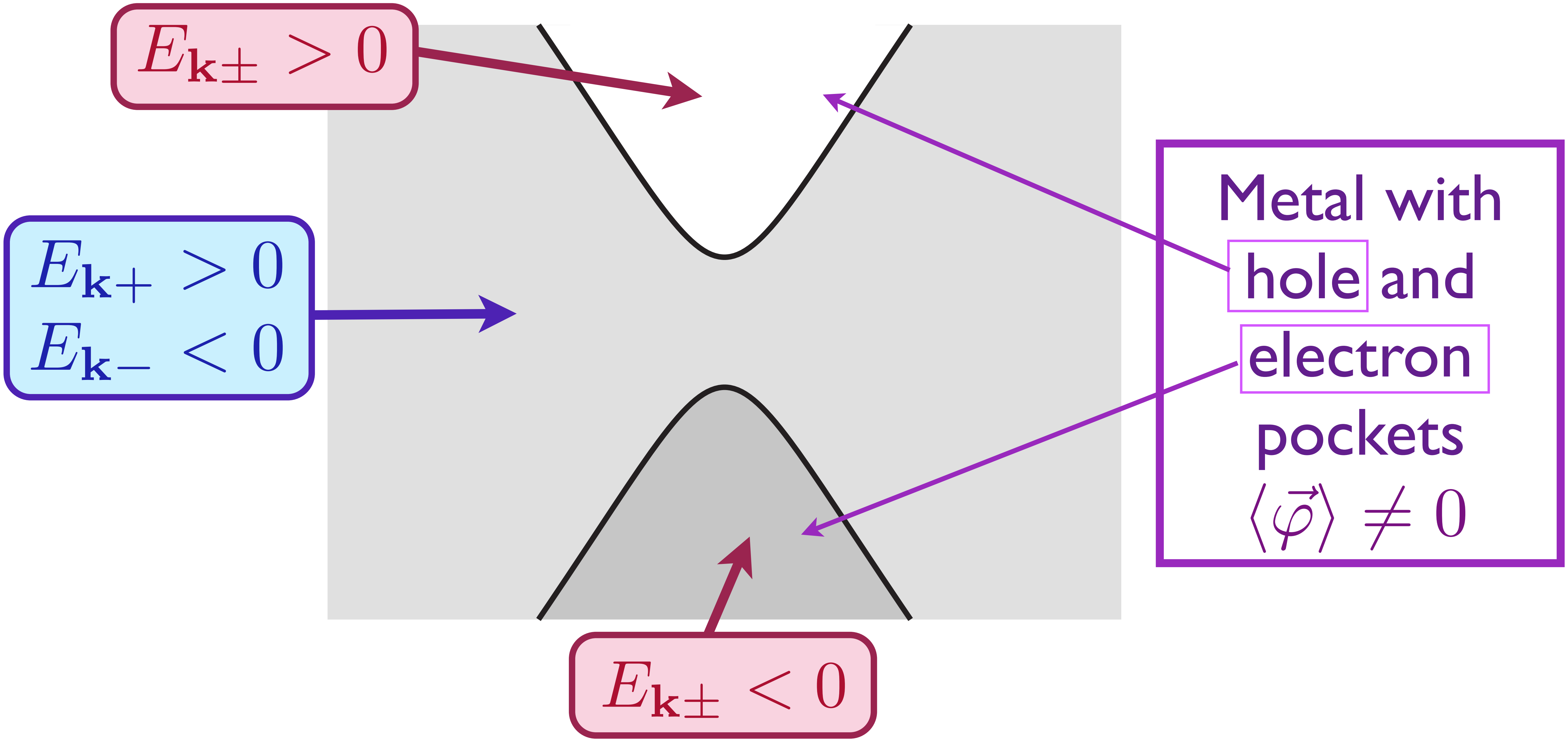
$$\mathcal{L}_f = \psi_{1\alpha}^\dagger \left(\zeta\partial_\tau - i\mathbf{v}_1 \cdot \boldsymbol{\nabla}_r\right) \psi_{1\alpha} + \psi_{2\alpha}^\dagger \left(\zeta\partial_\tau - i\mathbf{v}_2 \cdot \boldsymbol{\nabla}_r\right) \psi_{2\alpha}$$



Metal with "large" Fermi surface
$\langle \vec{\varphi} \rangle = 0$

Fermion dispersions: $\varepsilon_{\mathbf{k}1} = \mathbf{v}_1 \cdot \mathbf{k}$ and $\varepsilon_{\mathbf{k}2} = \mathbf{v}_2 \cdot \mathbf{k}$

$$\mathcal{L}_f = \psi^\dagger_{1\alpha}\left(\zeta\partial_\tau - i\mathbf{v}_1\cdot\boldsymbol{\nabla}_r\right)\psi_{1\alpha} + \psi^\dagger_{2\alpha}\left(\zeta\partial_\tau - i\mathbf{v}_2\cdot\boldsymbol{\nabla}_r\right)\psi_{2\alpha}$$
$$-\lambda\vec{\varphi}\cdot\left(\psi^\dagger_{1\alpha}\vec{\sigma}_{\alpha\beta}\psi_{2\beta} + \psi^\dagger_{2\alpha}\vec{\sigma}_{\alpha\beta}\psi_{1\beta}\right)$$

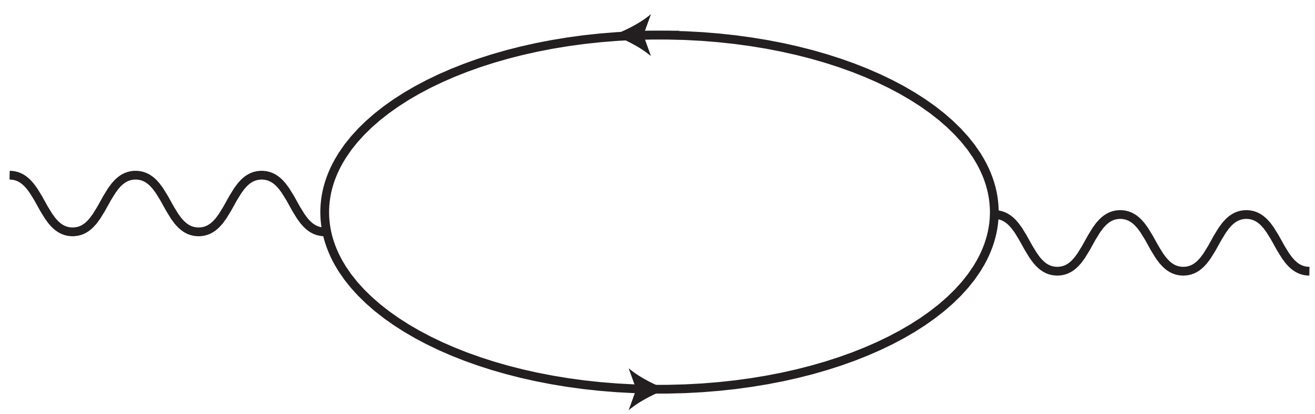


Fermion dispersions:

$$E_{\mathbf{k}\pm} = \frac{\varepsilon_{\mathbf{k}1}+\varepsilon_{\mathbf{k}2}}{2} \pm \sqrt{\left(\frac{\varepsilon_{\mathbf{k}1}-\varepsilon_{\mathbf{k}2}}{2}\right)^2 + \lambda^2|\vec{\varphi}|^2}$$

Hertz action.

Upon integrating the fermions out, the leading term in the $\vec{\varphi}$ effective action is $-\Pi(q,\omega_n)|\vec{\varphi}(q,\omega_n)|^2$, where $\Pi(q,\omega_n)$ is the fermion polarizability. This is given by a simple fermion loop diagram



$$\Pi(q,\omega_n) = \int \frac{d^d k}{(2\pi)^d} \int \frac{d\epsilon_n}{2\pi} \frac{1}{[-i\zeta(\epsilon_n+\omega_n)+\mathbf{v}_1\cdot(\mathbf{k}+\mathbf{q})][-i\zeta\epsilon_n+\mathbf{v}_2\cdot\mathbf{k}]} \tag{1}$$

We define oblique co-ordinates $p_1 = \mathbf{v}_1 \cdot \mathbf{k}$ and $p_2 = \mathbf{v}_2 \cdot \mathbf{k}$. It is then clear that the integrand in (1) is independent of the $(d-2)$ transverse momenta, whose integral yields an overall factor Λ^{d-2} (in $d=2$ this factor is precisely 1). Also, by shifting the integral over k_1 we note that the integral is independent of q. So we have

$$\Pi(q,\omega_n) = \frac{\Lambda^{d-2}}{|\mathbf{v}_1 \times \mathbf{v}_2|} \int \frac{dp_1 dp_2 d\epsilon_n}{8\pi^3} \frac{1}{[-i\zeta(\epsilon_n+\omega_n)+p_1][-i\zeta\epsilon_n+p_2]}. \tag{2}$$

Next, we evaluate the frequency integral to obtain

$$\begin{aligned} \Pi(q,\omega_n) &= \frac{\Lambda^{d-2}}{\zeta|\mathbf{v}_1 \times \mathbf{v}_2|} \int \frac{dp_1 dp_2}{4\pi^2} \frac{[\mathrm{sgn}(p_2)-\mathrm{sgn}(p_1)]}{-i\zeta\omega_n+p_1-p_2} \\ &= -\frac{|\omega_n|\Lambda^{d-2}}{4\pi|\mathbf{v}_1 \times \mathbf{v}_2|}. \end{aligned} \tag{3}$$

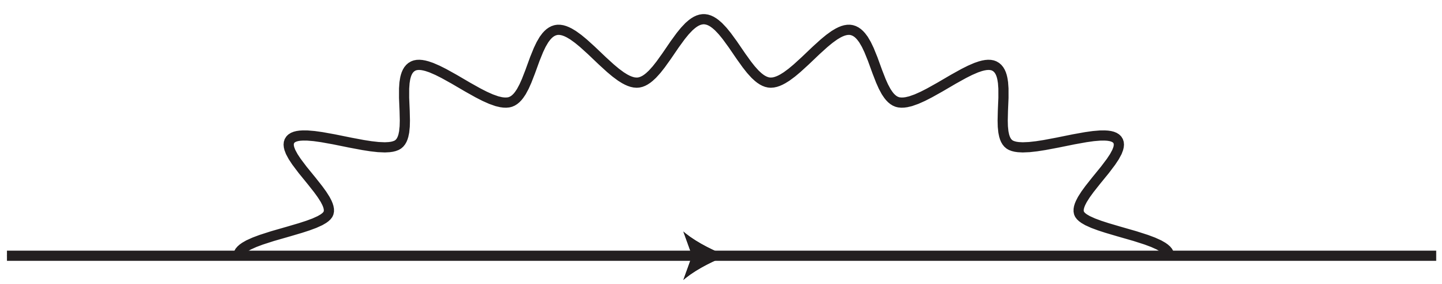
In the last step, we have dropped a frequency-independent, cutoff-dependent constant which can absorbed into a redefinition of r. Notice also that the factor of ζ has cancelled.
Inserting this fermion polarizability in the effective action for $\vec{\varphi}$, we obtain the Hertz action for the SDW transition:

$$\begin{aligned} \mathcal{S}_H = \int \frac{d^d k}{(2\pi)^d} T \sum_{\omega_n} \frac{1}{2} \left[k^2 + \gamma|\omega_n| + s\right] |\vec{\varphi}(k,\omega_n)|^2 \\ + \frac{u}{4} \int d^d x d\tau \left(\vec{\varphi}^2(x,\tau)\right)^2. \end{aligned} \tag{4}$$

Exercise: Perform a tree-level RG rescaling on $\mathcal{S}_H$. Now we rescale co-ordinates as $x' = xe^{-\ell}$ and $\tau' = \tau e^{-z\ell}$. Here z is the dynamic critical exponent. Show that the gradient and non-local terms become invariant for $z = 2$ (previous theories considered here had $z = 1$). Then show that the transformation of the quartic term is $u' = ue^{(2-d)\ell}$. This led Hertz to conclude that the SDW quantum critical point was described by a Gaussian theory for the SDW order parameter in $d \geq 2$.

Fate of the fermions.

Let us, for now, assume the validity of the Hertz Gaussian action, and compute the leading correction to the electronic Green's function. This is given by the following Feynman graph for the electron self energy, Σ. At zero momentum for the ψ_1 fermion we have



$$\Sigma_1(0,\omega_n) = \lambda^2 \int \frac{d^d q}{(2\pi)^d} \int \frac{d\epsilon_n}{2\pi} \frac{1}{\left[q^2 + \gamma|\epsilon_n|\right]\left[-i\zeta(\epsilon_n+\omega_n) + \mathbf{v}_2\cdot\mathbf{q}\right]}. \tag{5}$$

We first perform the integral over the $\mathbf{q}$ direction parallel to $\mathbf{v}_2$, while ignoring the subdominant dependence on this momentum in the boson propagator. The dependence on ζ immediately disappears, and we have

$$\Sigma_1(0,\omega_n) = i\,\frac{\lambda^2}{|v_2|}\int \frac{d^{d-1}q}{(2\pi)^{d-1}}\int \frac{d\epsilon_n}{2\pi}\,\frac{\mathrm{sgn}(\epsilon_n+\omega_n)}{|q|^2+\gamma|\epsilon_n|}$$
$$= i\,\frac{\lambda^2}{\pi|v_2|\gamma}\mathrm{sgn}(\omega_n)\int \frac{d^{d-1}q}{(2\pi)^{d-1}}\ln\left(\frac{|q|^2+\gamma|\omega_n|}{|q|^2}\right). \quad (6)$$

Evaluation of the q integral shows that

$$\Sigma_1(0,\omega_n) \sim |\omega_n|^{(d-1)/2} \quad (7)$$

The most important case is $d = 2$, where we have

$$\Sigma_1(0,\omega_n) = i\,\frac{\lambda^2}{\pi|v_2|\sqrt{\gamma}}\mathrm{sgn}(\omega_n)\sqrt{|\omega_n|} \quad , \quad d=2. \quad (8)$$

Strong coupling physics in $d = 2$

The theory so far has the boson propagator

$$\sim \frac{1}{q^2 + \gamma|\omega|}$$

which scales with dynamic exponent $z_b = 2$, and now a fermion propagator

$$\sim \frac{1}{-i\zeta\omega + c_1|\omega|^{(d-1)/2} + \mathbf{v}\cdot\mathbf{q}}.$$

First note that for $d < 3$, the bare $-i\zeta\omega$ term is less important than the contribution from the self energy at low frequencies. This indicates that ζ is *irrelevant* in the critical theory, and we can set $\zeta \to 0$. Fortunately, all the loop diagrams evaluated so far are independent of ζ.

Setting $\zeta = 0$, we see that the fermion propagator scales with dynamic exponent $z_f = 2/(d-1)$. For $d > 2$, $z_f < z_b$, and so at small momenta the boson fluctuations have lower energy than the fermion fluctuations. Thus it seems reasonable to assume that the fermion fluctuations are not as singular, and we can focus on an effective theory of the SDW order parameter $\vec{\varphi}$ alone. In other words, the Hertz assumptions appear valid for $d > 2$.

However, in $d = 2$, we have $z_f = z_b = 2$. Thus fermionic and bosonic fluctuations are equally important, and it is not appropriate to integrate the fermions out at an initial stage. We have to return to the original theory of coupled bosons and fermions. This turns out to be strongly coupled, and exhibits complex critical behavior. For more details, see

M. A. Metlitski and S. Sachdev, arXiv:1005.1288 (Physical Review B **82**, 075127 (2010)).

$$\mathcal{L}_f = \psi^\dagger_{1\alpha}\left(\zeta\partial_\tau - i\mathbf{v}_1\cdot\boldsymbol{\nabla}_r\right)\psi_{1\alpha} + \psi^\dagger_{2\alpha}\left(\zeta\partial_\tau - i\mathbf{v}_2\cdot\boldsymbol{\nabla}_r\right)\psi_{2\alpha}$$

Order parameter: $\mathcal{L}_\varphi = \frac{1}{2}\left(\boldsymbol{\nabla}_r\vec{\varphi}\right)^2 + \frac{\widetilde{\zeta}}{2}\left(\partial_\tau\vec{\varphi}\right)^2 + \frac{s}{2}\vec{\varphi}^2 + \frac{u}{4}\vec{\varphi}^4$

"Yukawa" coupling: $\mathcal{L}_c = -\lambda\vec{\varphi}\cdot\left(\psi^\dagger_{1\alpha}\vec{\sigma}_{\alpha\beta}\psi_{2\beta} + \psi^\dagger_{2\alpha}\vec{\sigma}_{\alpha\beta}\psi_{1\beta}\right)$

Perform RG on both fermions and $\vec{\varphi}$, using a *local* field theory.

$$\mathcal{L}_f = \psi_{1\alpha}^\dagger \left(\zeta \partial_\tau - i\mathbf{v}_1 \cdot \boldsymbol{\nabla}_r\right) \psi_{1\alpha} + \psi_{2\alpha}^\dagger \left(\zeta \partial_\tau - i\mathbf{v}_2 \cdot \boldsymbol{\nabla}_r\right) \psi_{2\alpha}$$

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Under the rescaling $x' = xe^{-\ell}$, $\tau' = \tau e^{-z\ell}$, the spatial gradients are fixed if the fields transform as

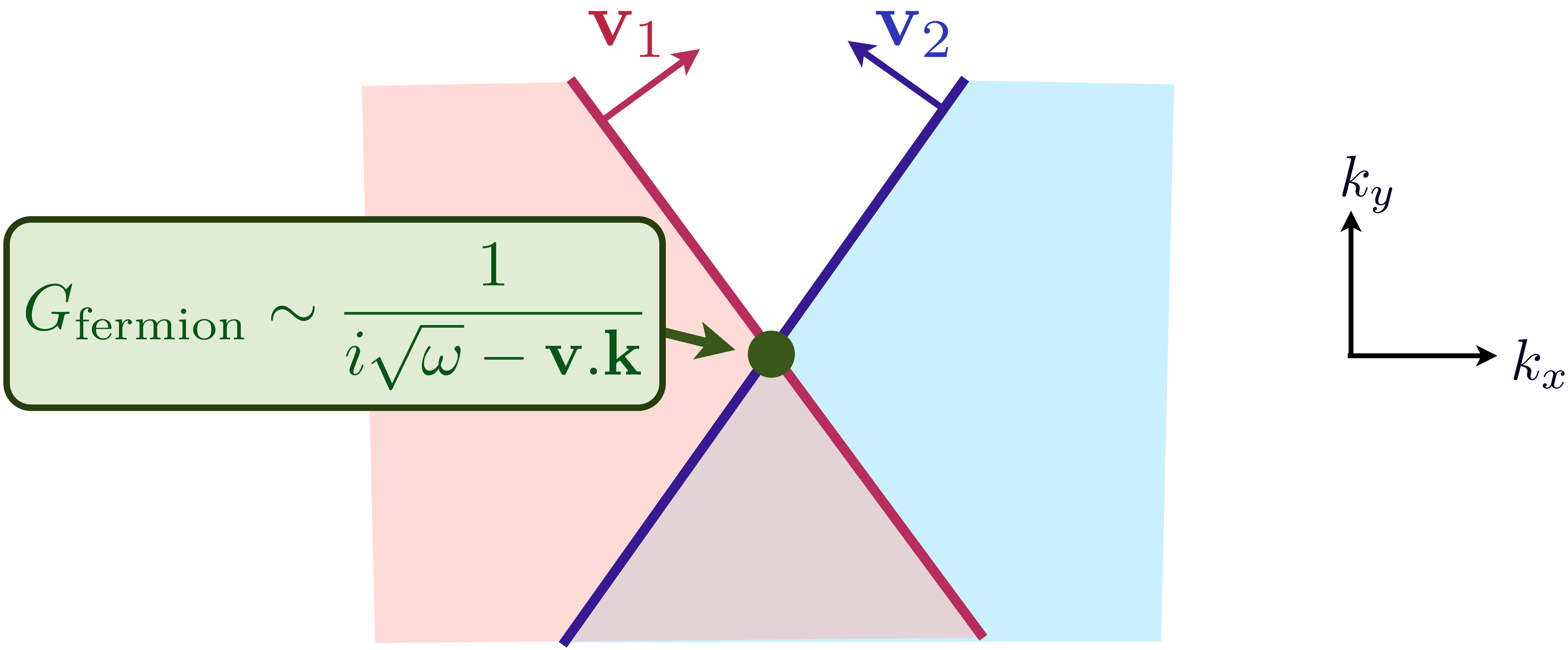
$$\vec{\varphi}' = e^{(d+z-2)\ell/2}\vec{\varphi} \quad ;\text{``} \quad \psi' = e^{(d+z-1)\ell/2}\psi.$$

Then the Yukawa coupling transforms as

$$\lambda' = e^{(4-d-z)\ell/2}\lambda$$

For $d = 2$, with $z = 2$ the bare time-derivative terms ζ, $\widetilde{\zeta}$ are irrelevant, but the Yukawa coupling is invariant. Thus we have to work at fixed $\lambda = 1$, and cannot expand in powers of λ: critical theory is *strongly coupled.*

Critical point theory is strongly coupled in $d = 2$
Results are *independent* of coupling λ



A. J. Millis, *Phys. Rev. B* **45**, 13047 (1992)
Ar. Abanov and A.V. Chubukov, *Phys. Rev. Lett.* **93**, 255702 (2004)

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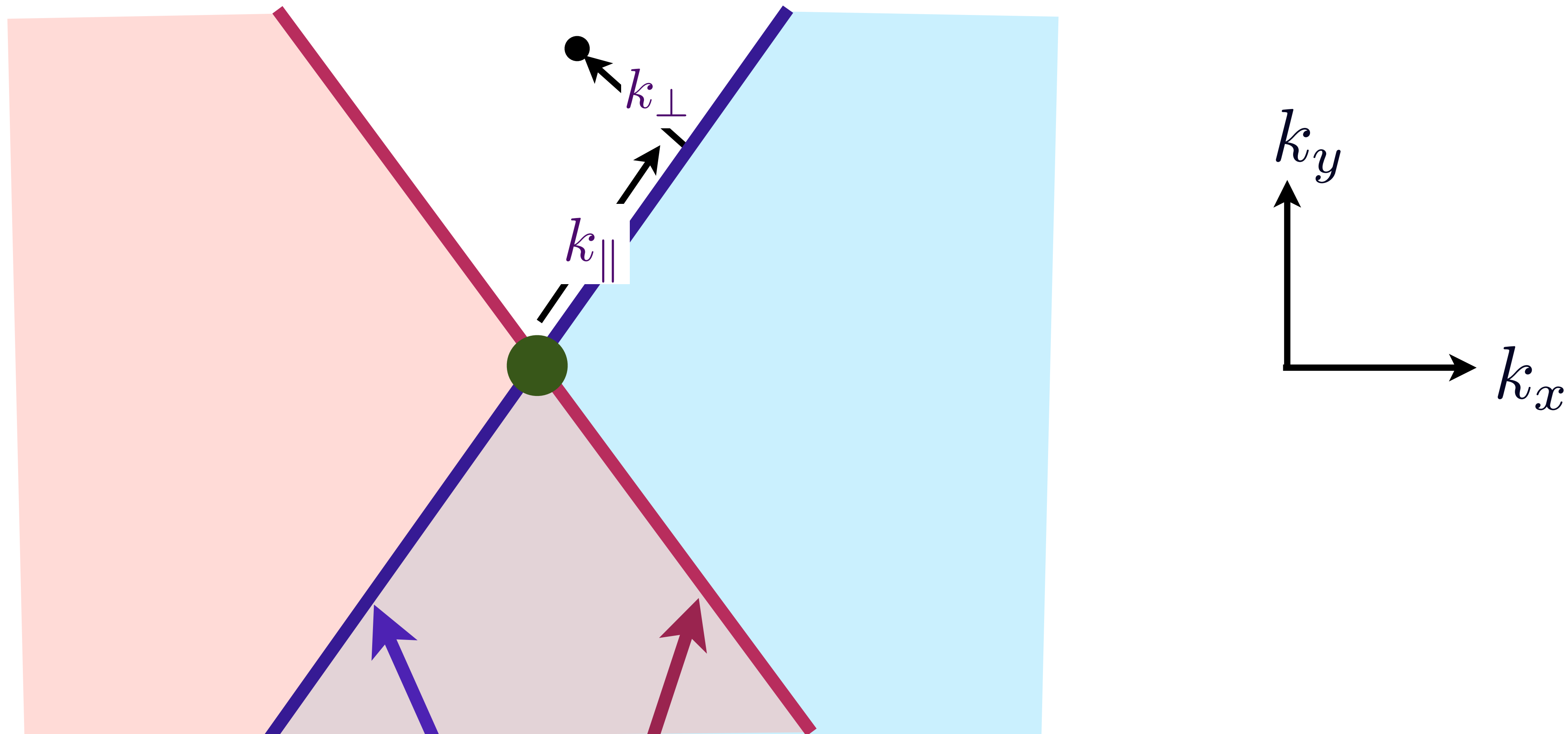

$$G_{\rm fermion} = \frac{Z(k_\parallel)}{i\omega - v_F(k_\parallel) k_\perp}, \quad Z(k_\parallel) \sim v_F(k_\parallel) \sim k_\parallel$$

M. A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)

Outline

1. Weak coupling theory of SDW ordering, and d-wave superconductivity

2. Universal critical theory of SDW ordering

3. Emergent pseudospin symmetry, and quadrupolar density wave

4. Quantum Monte Carlo without the sign problem

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Emergent $[SU(2)]^4$ pseudospin symmetry

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Introduce the spinors

$$\Psi_{1\alpha} = \begin{pmatrix} \psi_{1\alpha} \\ \epsilon_{\alpha\beta} \psi_{1\beta}^\dagger \end{pmatrix} \quad , \quad \Psi_{2\alpha} = \begin{pmatrix} \psi_{2\alpha} \\ \epsilon_{\alpha\beta} \psi_{2\beta}^\dagger \end{pmatrix}$$

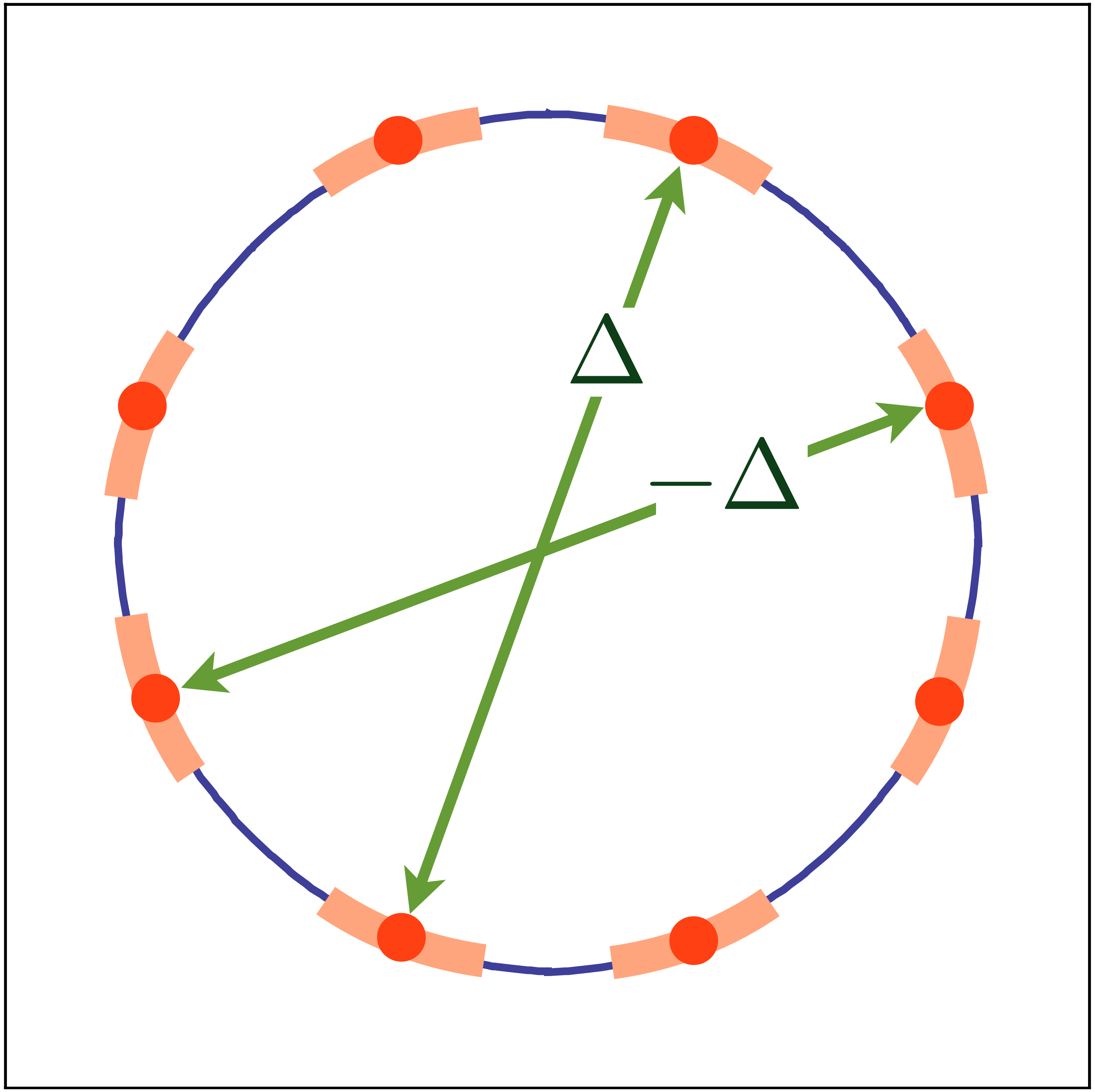
Then the Lagrangian is invariant under the SU(2) transformation U with

$$\Psi_1 \to U \Psi_1 \quad , \quad \Psi_2 \to U \Psi_2$$

Note that U can be chosen *independently* at the 4 pairs of hotspots.

This symmetry relies on the linearization of the fermion dispersion about the hot spots.

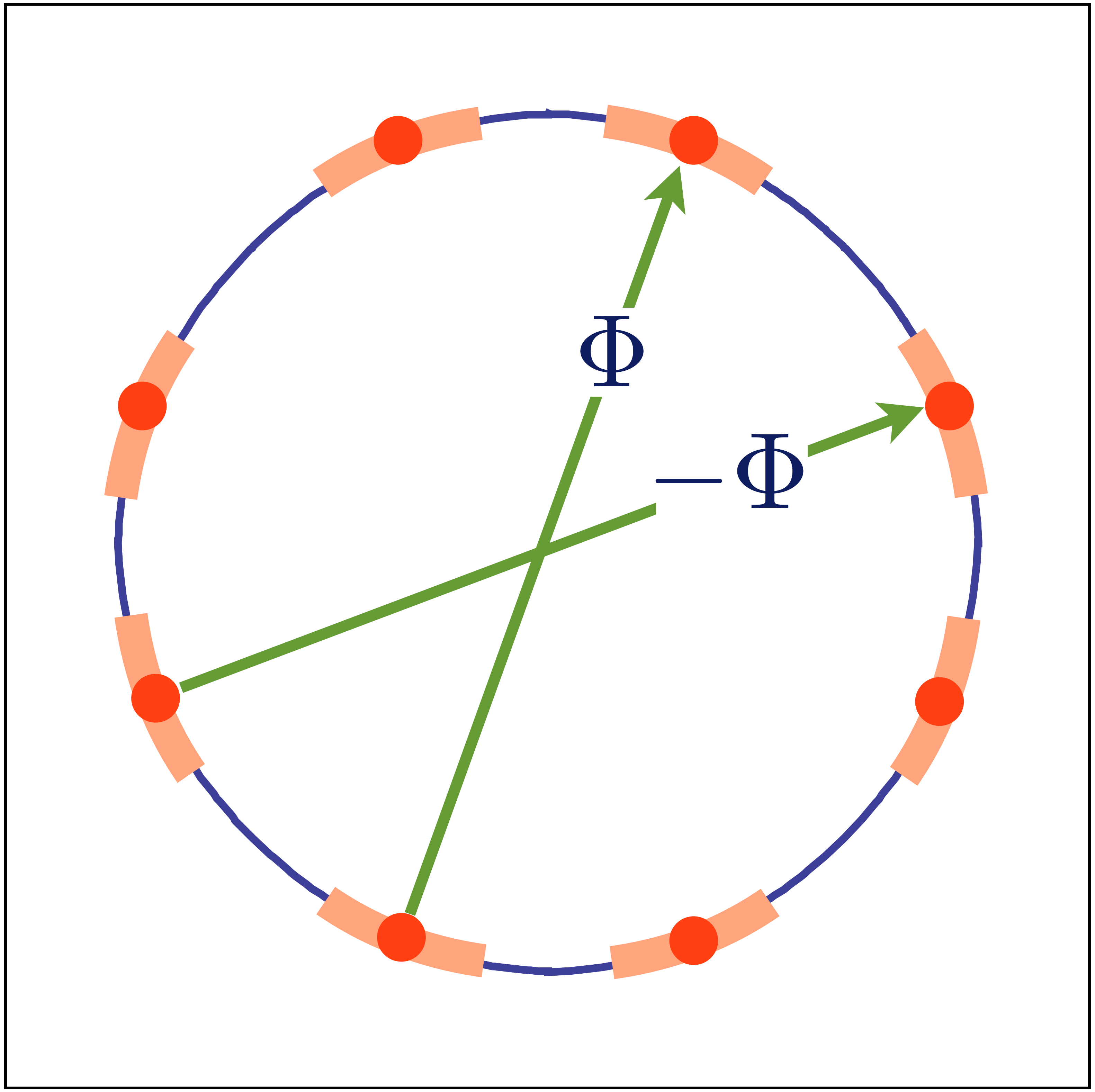
$$\left\langle c^{\dagger}_{\mathbf{k}\alpha} c^{\dagger}_{-\mathbf{k}\beta} \right\rangle = \varepsilon_{\alpha\beta} \Delta (\cos k_x - \cos k_y)$$



Unconventional pairing at *and near* hot spots

$$\left\langle c^{\dagger}_{\mathbf{k}-\mathbf{Q}/2,\alpha} c_{\mathbf{k}+\mathbf{Q}/2,\alpha} \right\rangle = \Phi(\cos k_x - \cos k_y)$$

After pseudospin rotation



$\mathbf{Q}$ is '$2k_F$' wavevector

M.A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)

K. B. Efetov, H. Meier, and C. Pepin, arXiv:1210.3276

Unconventional particle-hole pairing at *and near* hot spots

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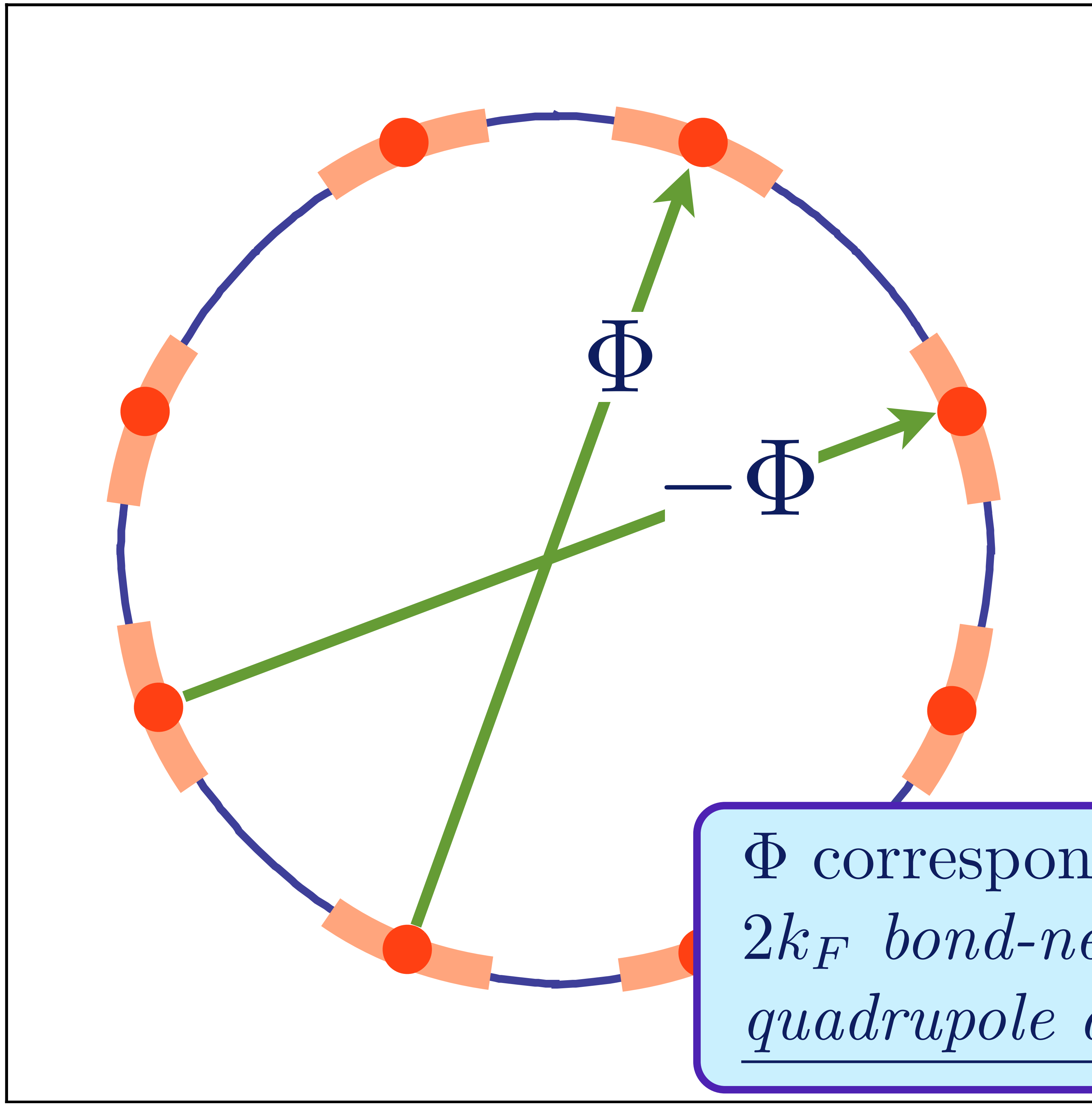

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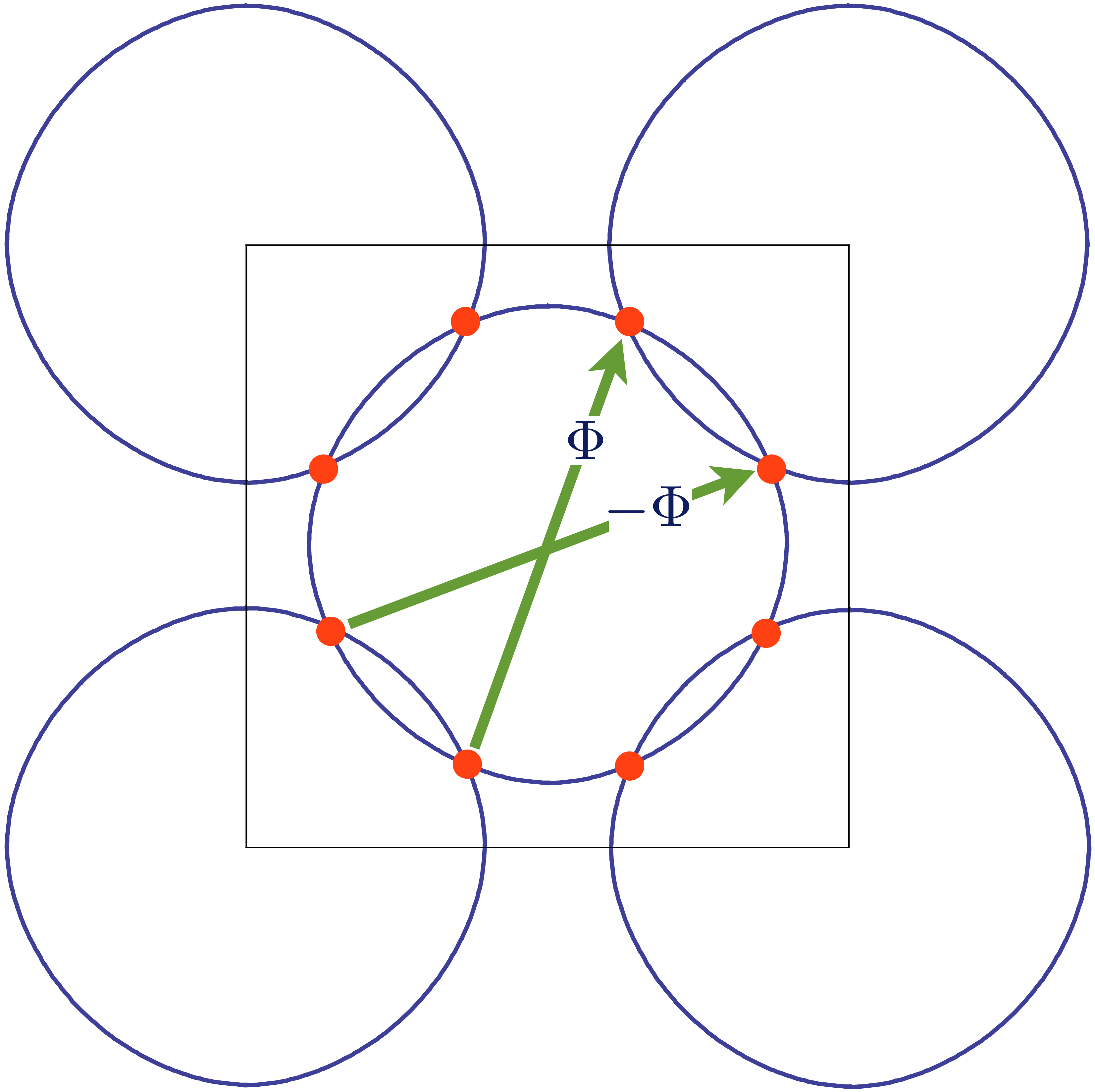
K. B. Efetov, H. Meier, and C. Pepin, arXiv:1210.3276

Φ corresponds to a $2k_F$ *bond-nematic* or a *quadrupole density wave*

Unconventional particle-hole pairing at *and near* hot spots

Quadrupole density wave



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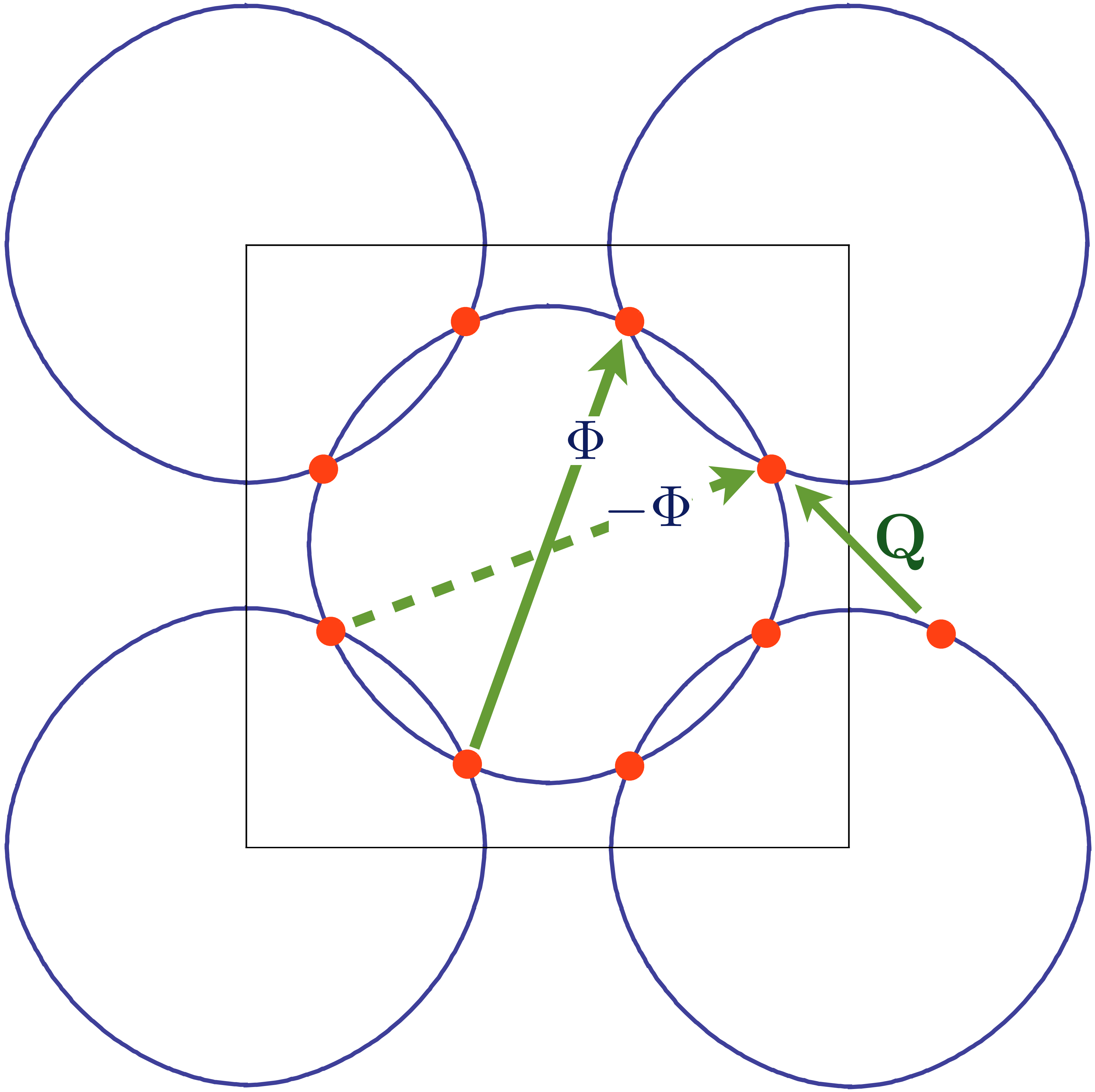

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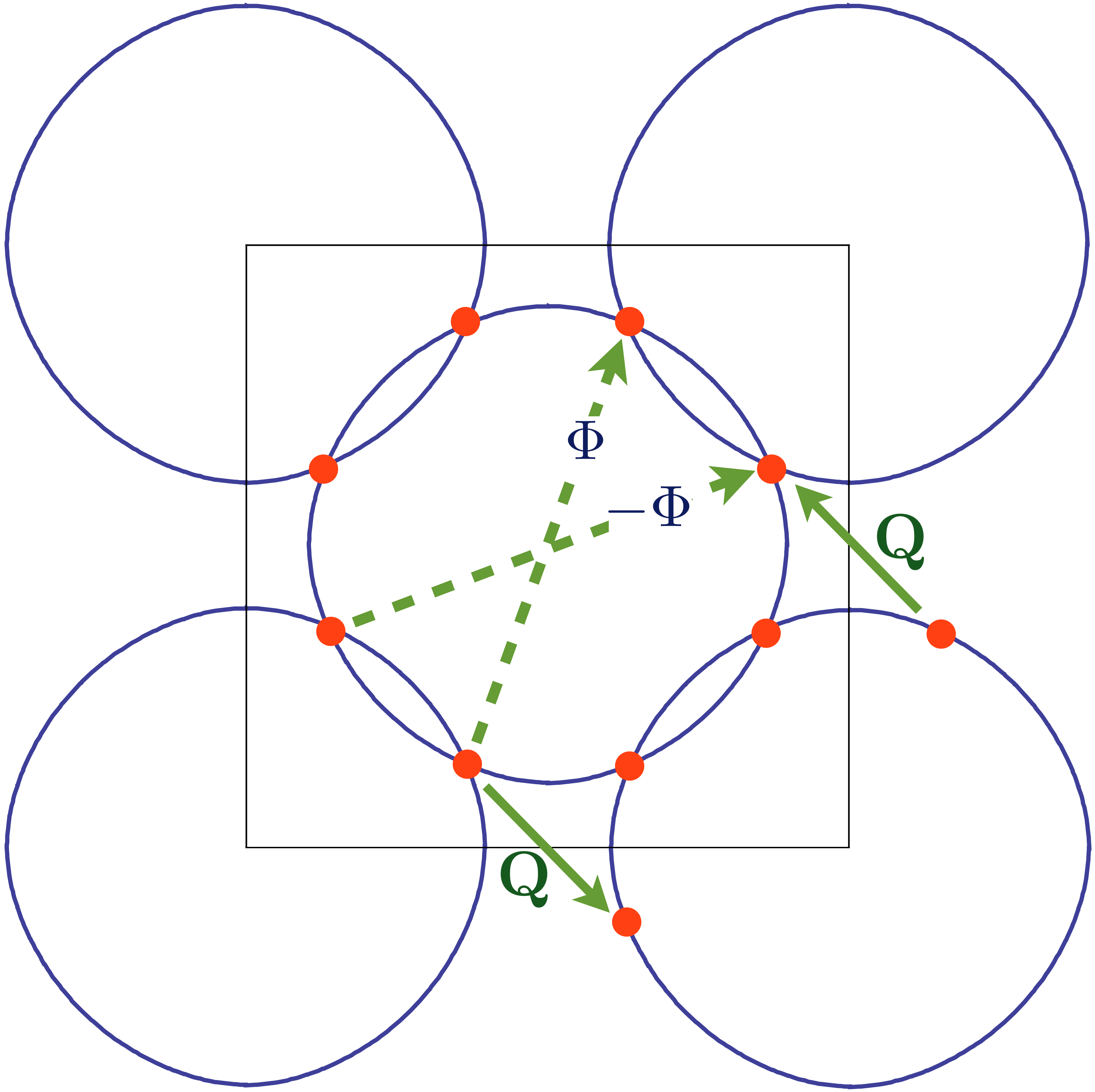

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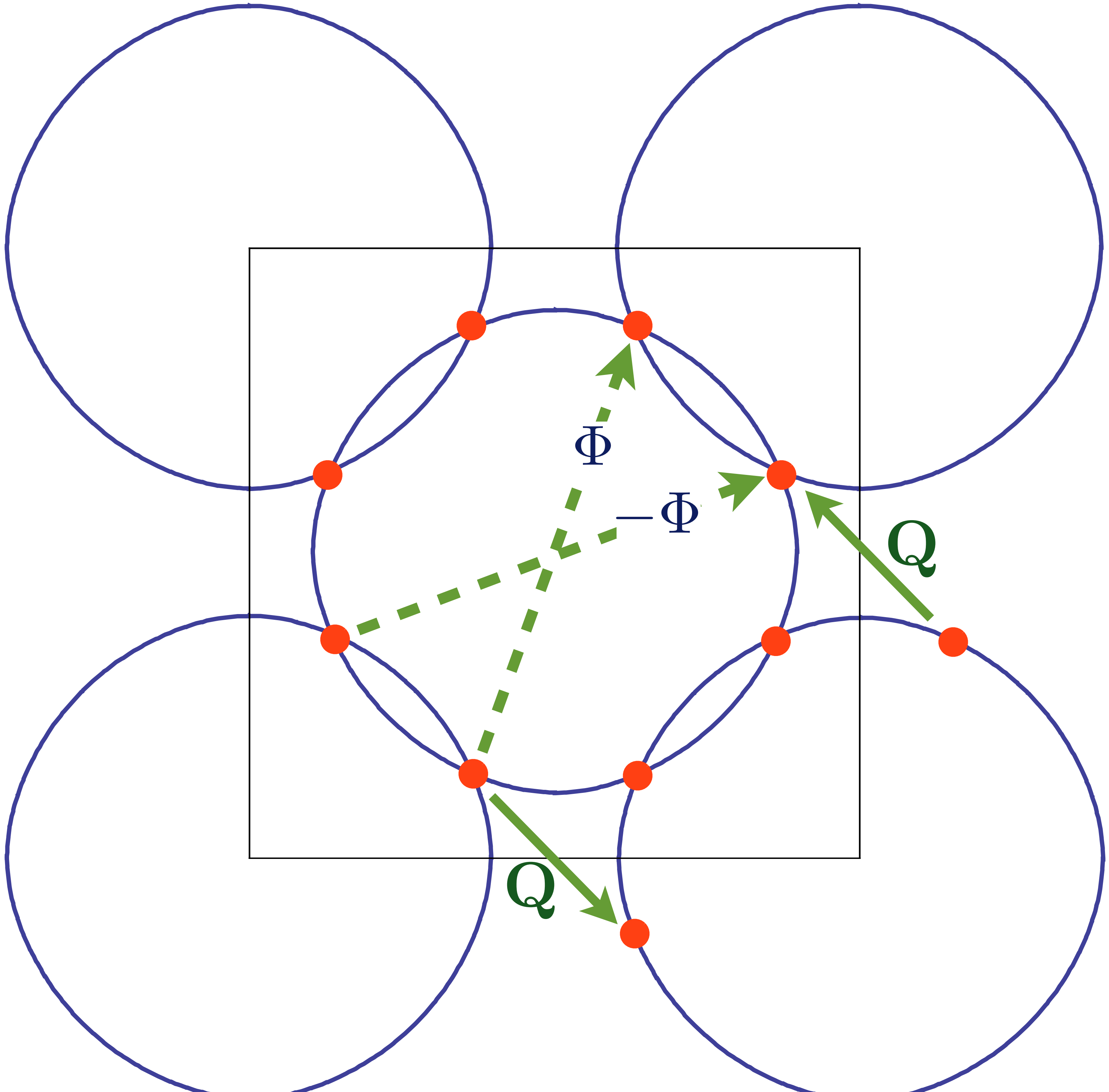

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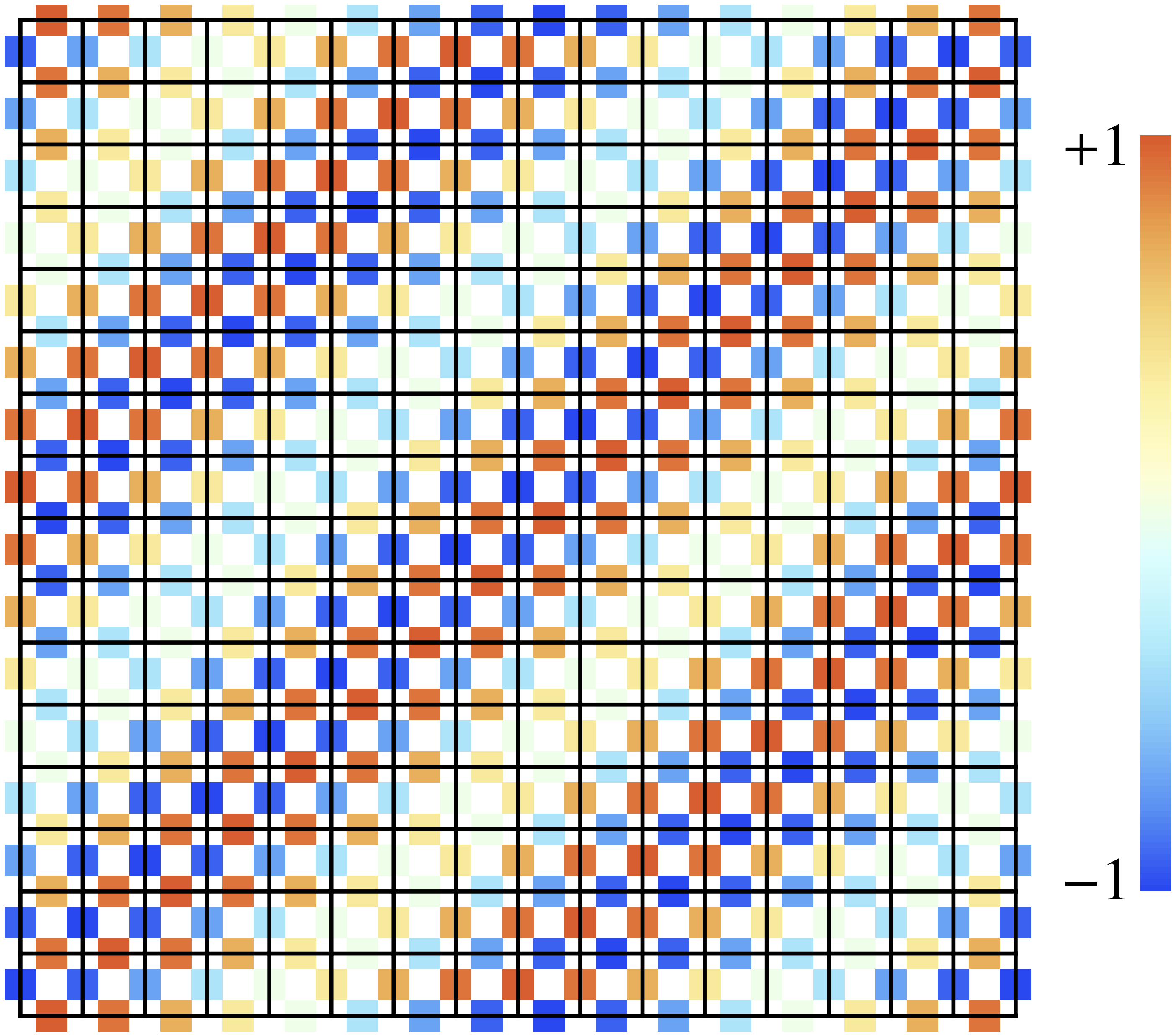
Quadrupole density wave



"Bond density" measures amplitude for electrons to be in spin-singlet valence bond.

No modulations on sites, $\langle c_{\mathbf{r}\alpha}^{\dagger} c_{\mathbf{s}\alpha} \rangle$ is modulated only for $\mathbf{r} \neq \mathbf{s}$.

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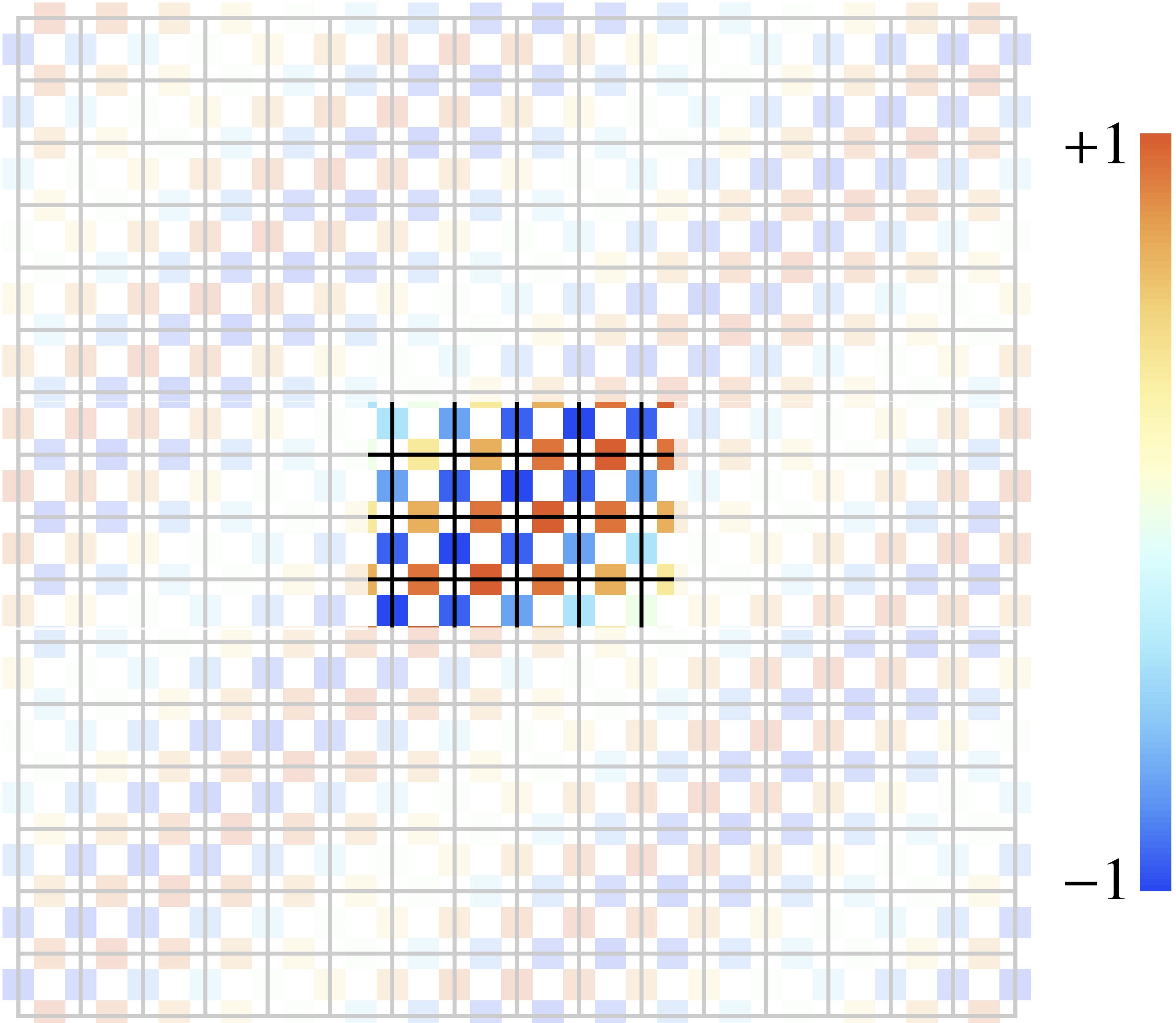

Local Ising nematic order with an envelope which oscillates

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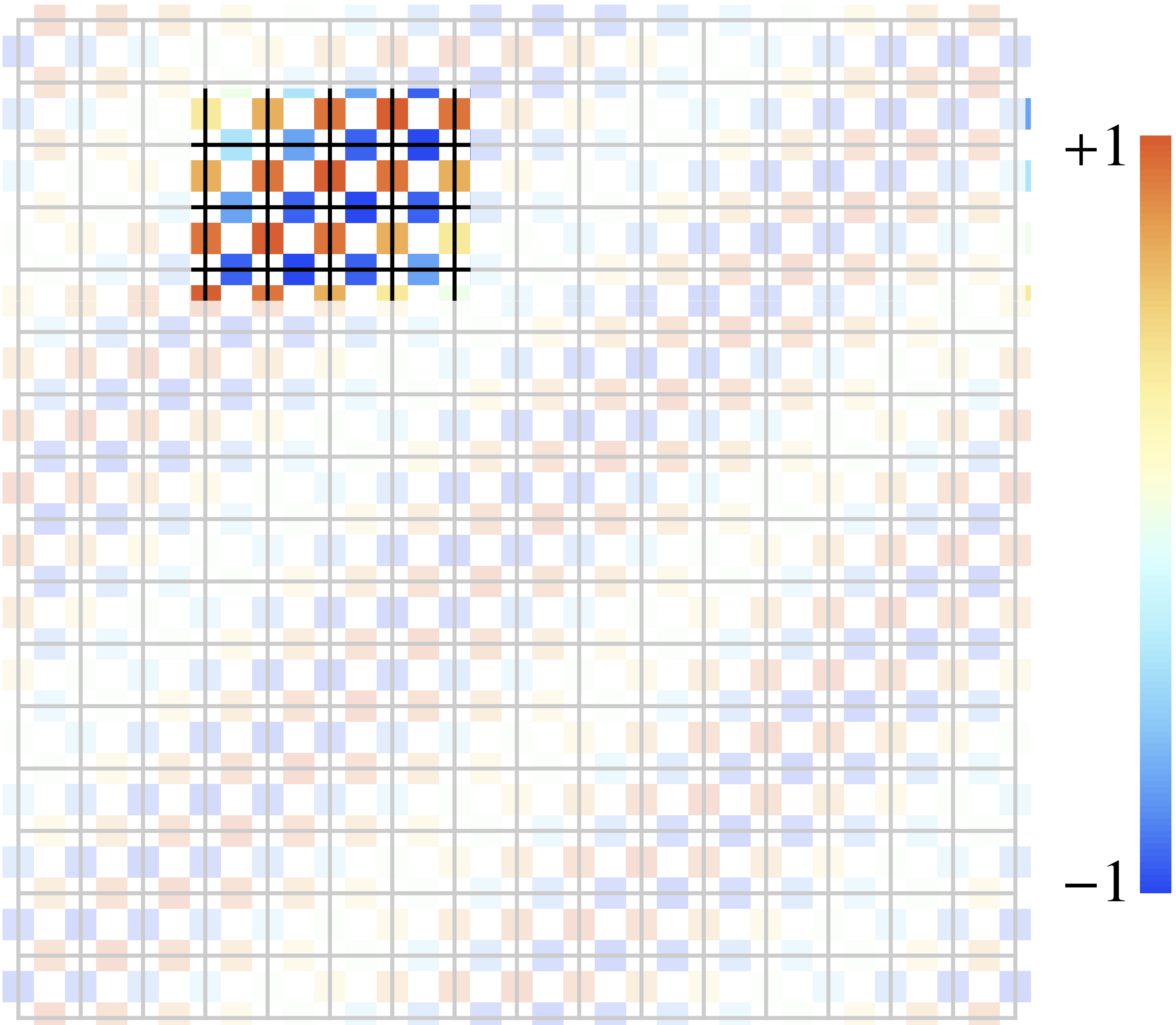

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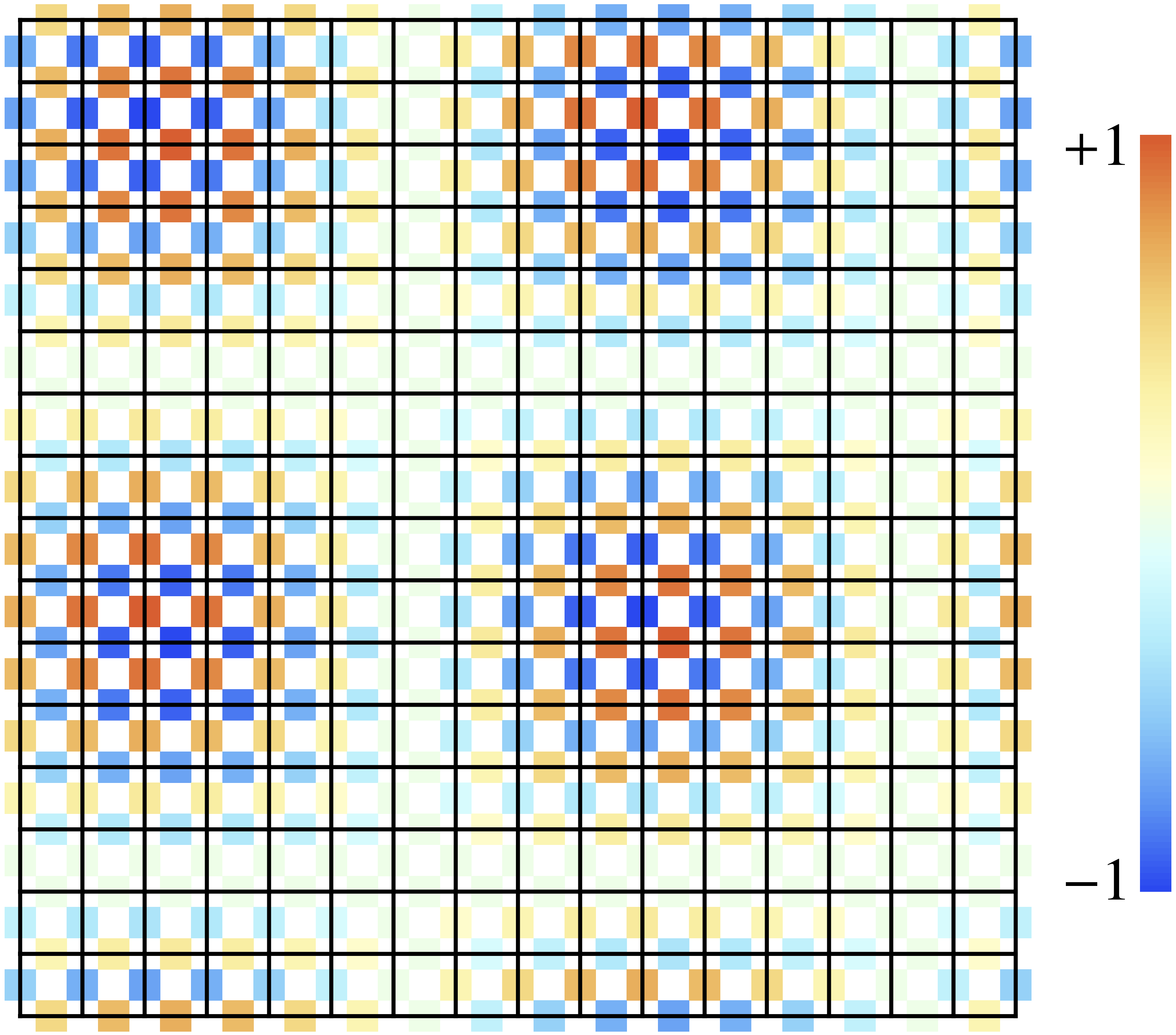

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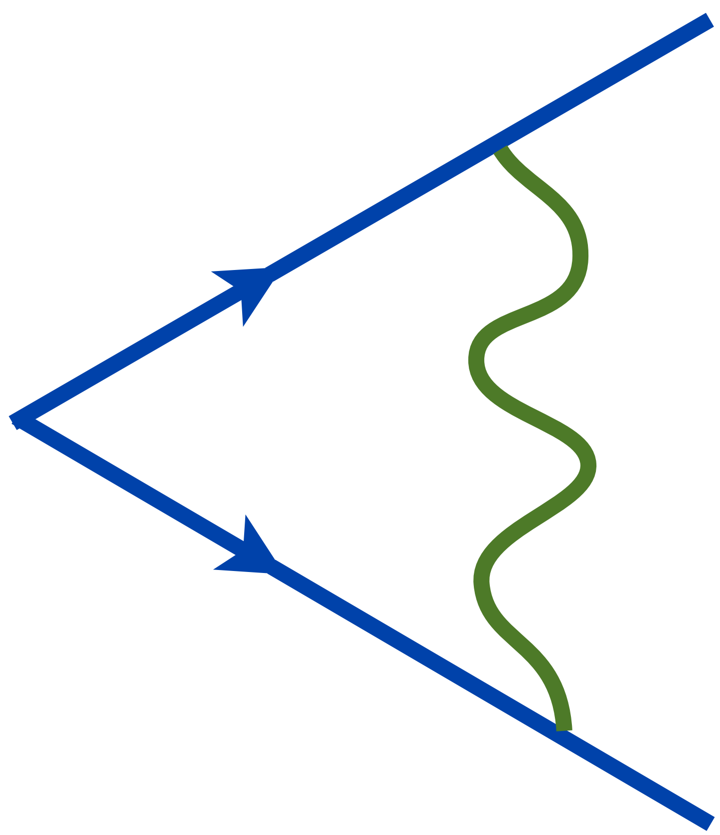
Strength of instability at quantum criticality

BCS theory

$$1 + \lambda_{\text{e-ph}} \log\left(\frac{\omega_D}{\omega}\right)$$

Cooper logarithm



Strength of instability at quantum criticality

BCS theory

$$1 + \lambda_{\text{e-ph}} \log\left(\frac{\omega_D}{\omega}\right)$$

Electron-phonon coupling

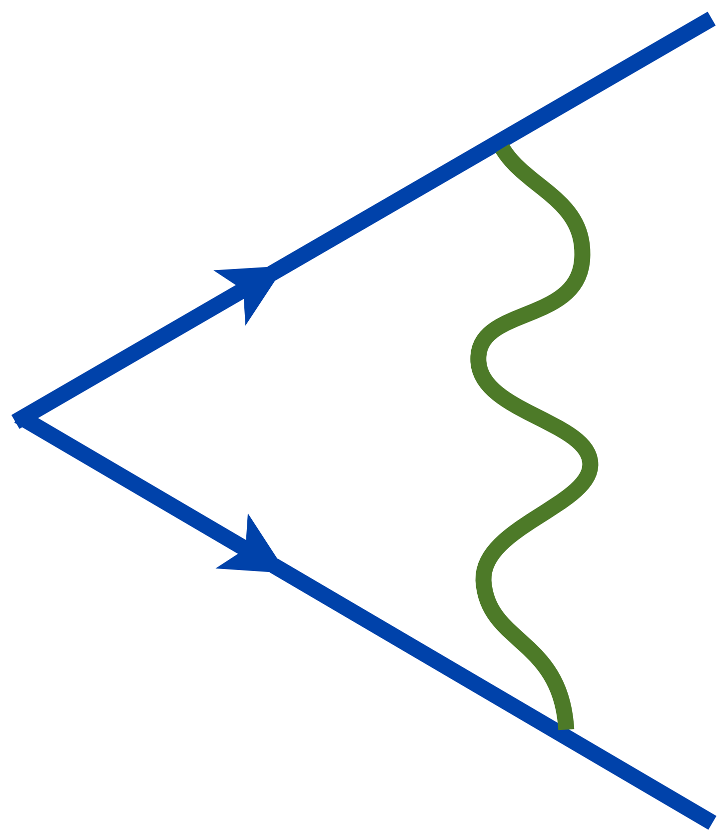
Debye frequency

Implies
$T_c \sim \omega_D \exp\left(-1/\lambda\right)$

Strength of instability at quantum criticality

Spin density wave quantum critical point

$$1 + \frac{\alpha}{\pi(1+\alpha^2)} \log^2 \left(\frac{E_F}{\omega} \right)$$



M.A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)
Y. Wang and A. Chubukov, arXiv:1210.2408

Strength of instability at quantum criticality

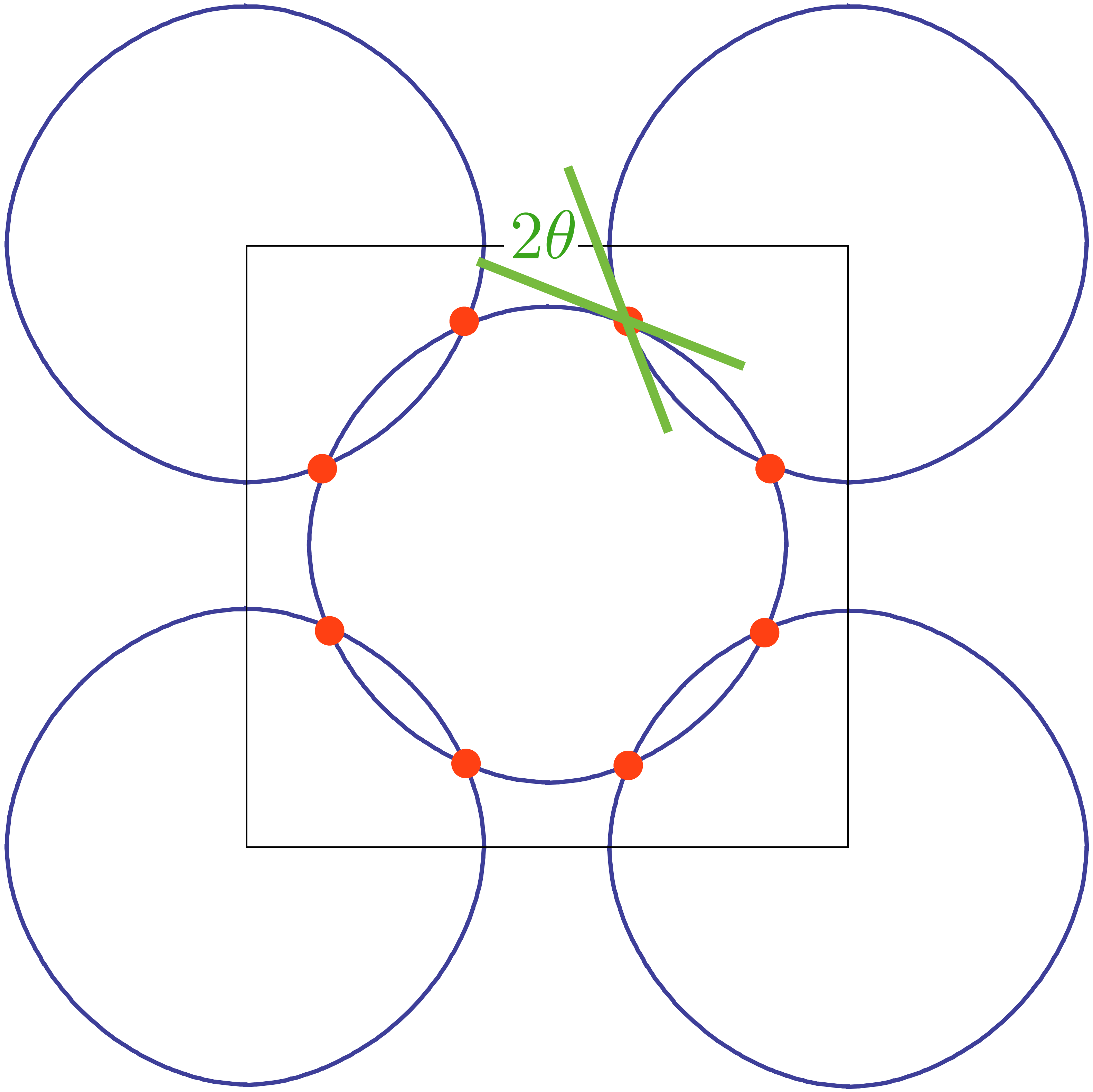
Spin density wave quantum critical point

$$1 + \frac{\alpha}{\pi(1+\alpha^2)} \log^2 \left(\frac{E_F}{\omega} \right)$$

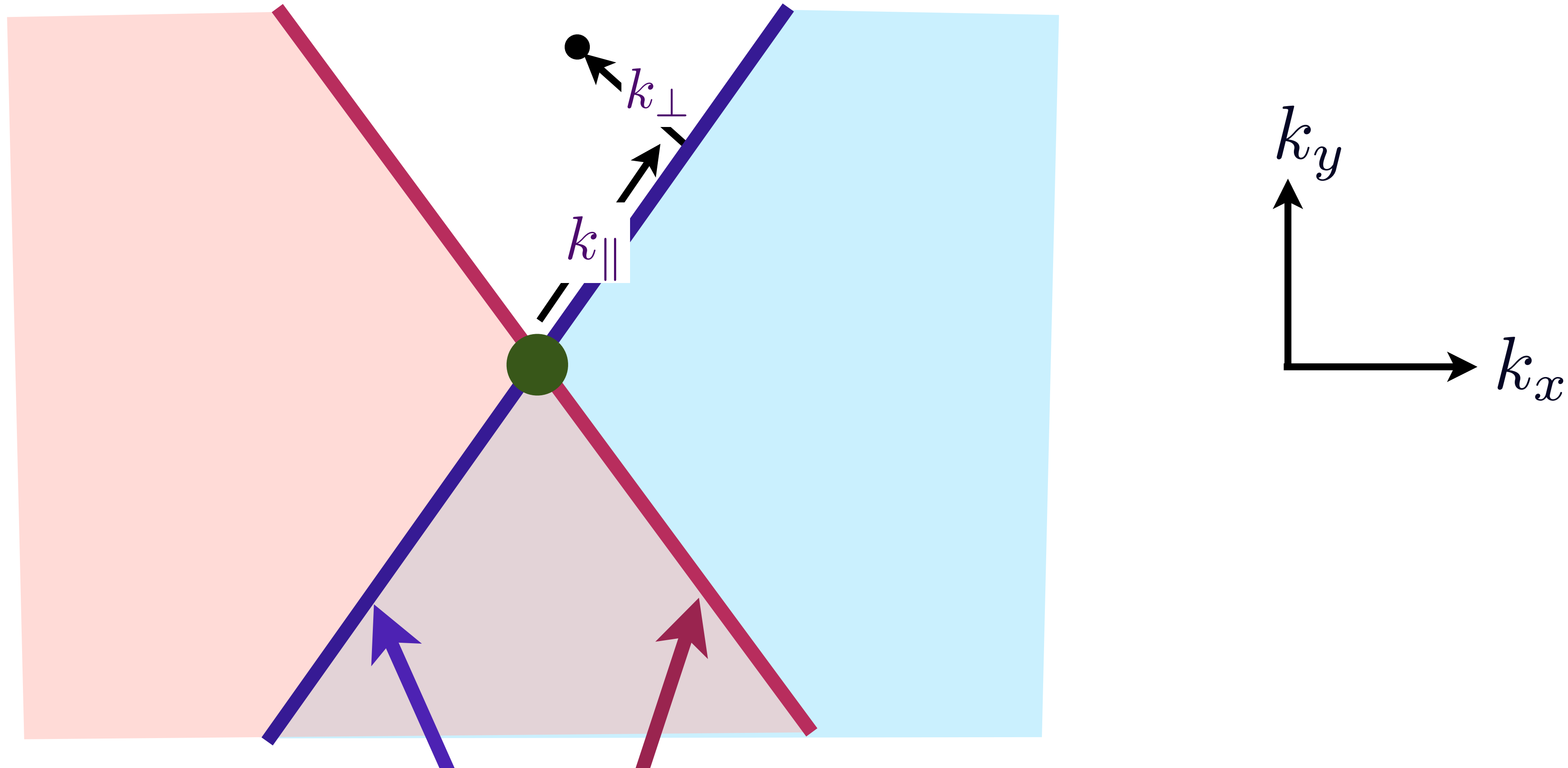
Fermi energy

$\alpha = \tan\theta$, where 2θ is the angle between Fermi lines.
Independent of interaction strength U in 2 dimensions.

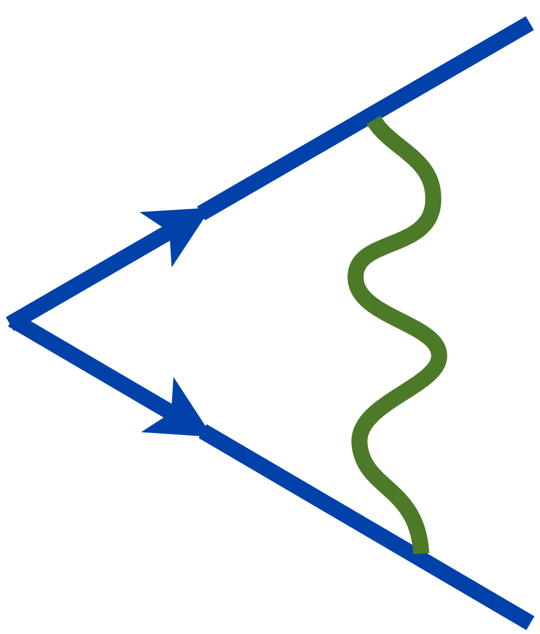
M. A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)
Y. Wang and A. Chubukov, arXiv:1210.2408


2θ

M. A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)

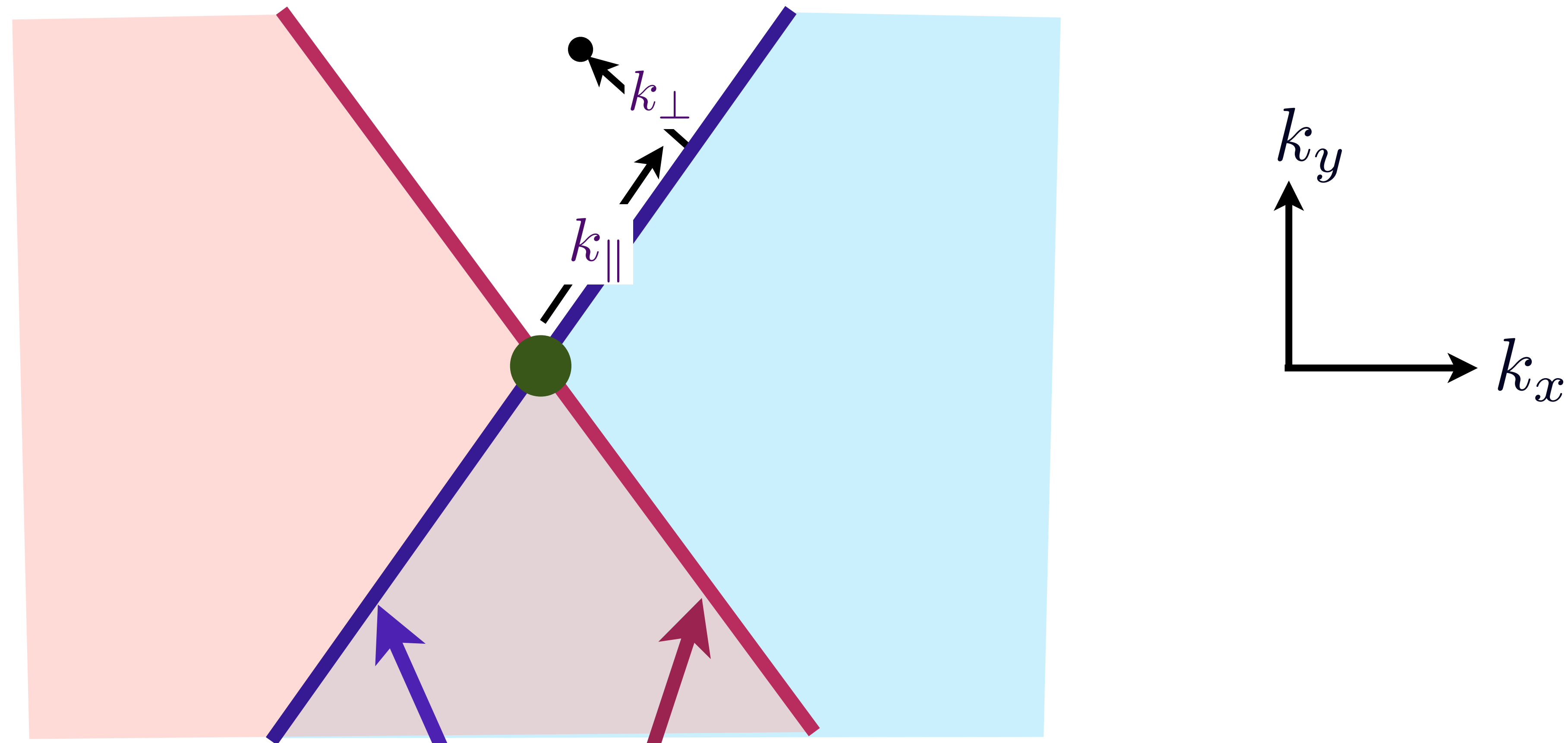


$$G_{\text{fermion}} = \frac{Z(k_\parallel)}{i\omega - v_F(k_\parallel) k_\perp}, \quad Z(k_\parallel) \sim v_F(k_\parallel) \sim k_\parallel$$

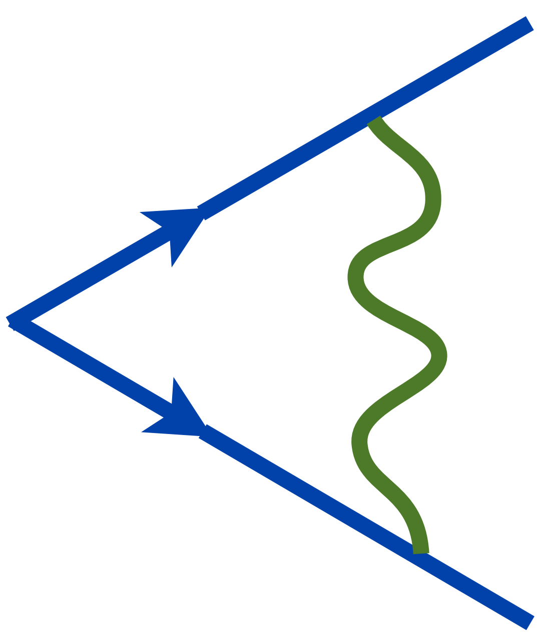


$$\int dk_\parallel \, \frac{1}{k_\parallel^2} \left(\frac{Z^2(k_\parallel)}{v_F(k_\parallel)} \right) \log \frac{k_\parallel^2}{\omega}$$

M. A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)



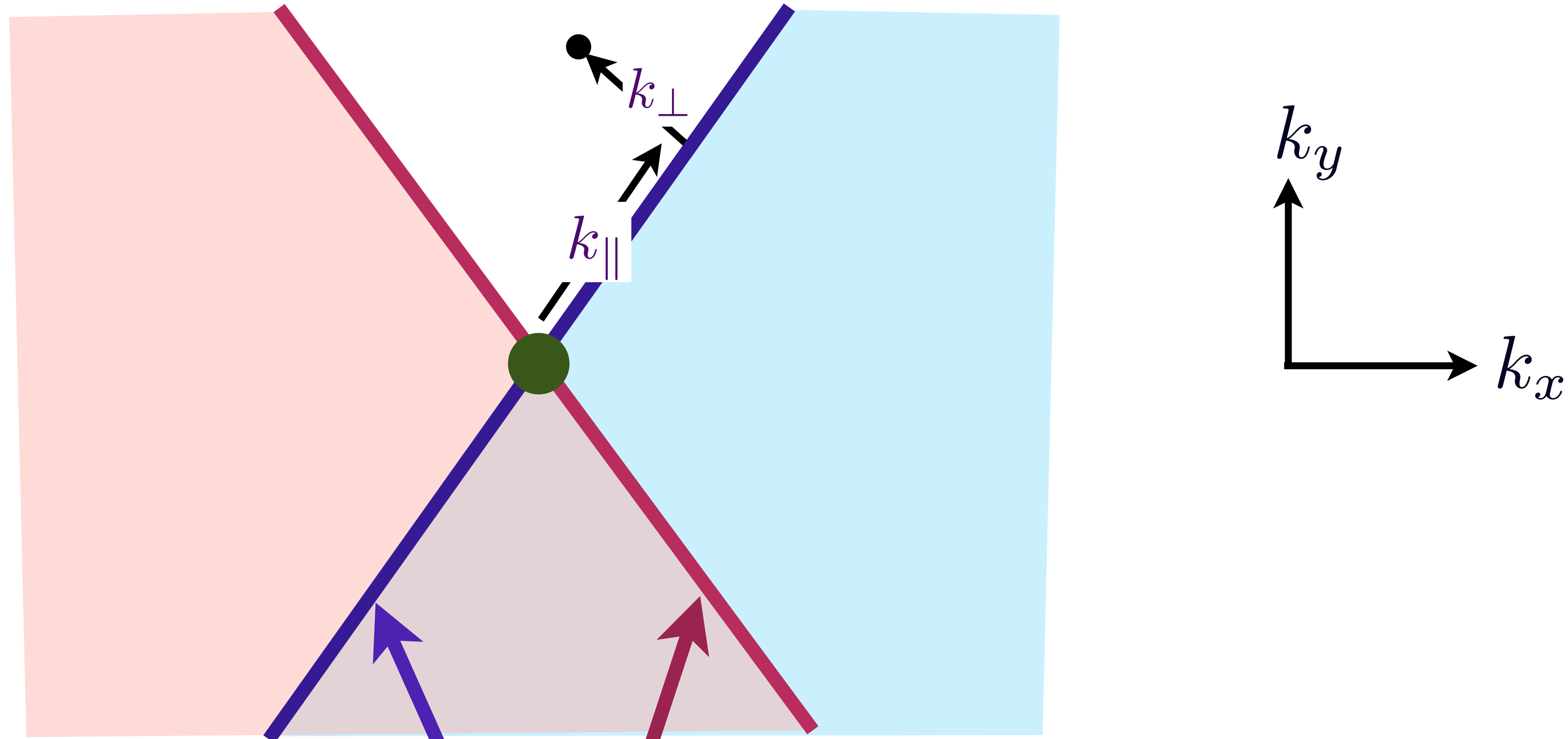
$$G_{\text{fermion}} = \frac{Z(k_\parallel)}{i\omega - v_F(k_\parallel)k_\perp}, \quad Z(k_\parallel) \sim v_F(k_\parallel) \sim k_\parallel$$



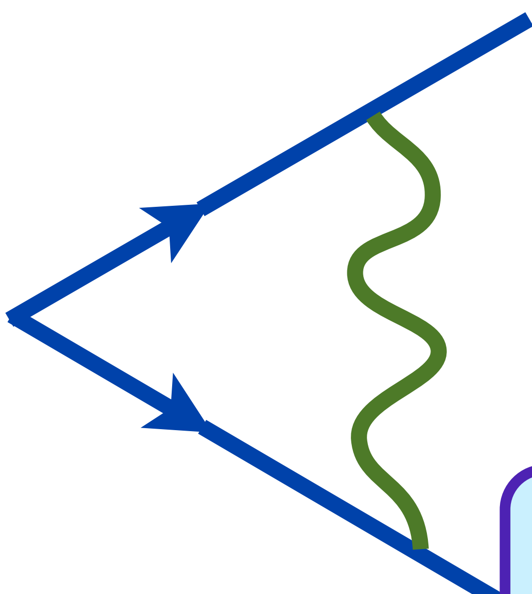
$$\int dk_\parallel \, \frac{1}{k_\parallel^2} \underbrace{\left(\frac{Z^2(k_\parallel)}{v_F(k_\parallel)} \right) \log \frac{k_\parallel^2}{\omega}}$$

Cooper logarithm

M. A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)



$$G_{\text{fermion}} = \frac{Z(k_\parallel)}{i\omega - v_F(k_\parallel)k_\perp}, \quad Z(k_\parallel) \sim v_F(k_\parallel) \sim k_\parallel$$



$$\int dk_\parallel \, \frac{1}{k_\parallel^2} \left(\frac{Z^2(k_\parallel)}{v_F(k_\parallel)} \right) \log \frac{k_\parallel^2}{\omega}$$

Spin fluctuation propagator

Cooper logarithm

Enhancement of pairing susceptibility by interactions

Spin density wave quantum critical point

$$1 + \frac{\alpha}{\pi(1+\alpha^2)} \log^2\left(\frac{E_F}{\omega}\right)$$

- $\log^2$ singularity arises from Fermi lines; singularity *at* hot spots is weaker.
- Interference between BCS and quantum-critical logs.
- Momentum dependence of self-energy is crucial.
- Not suppressed by $1/N$ factor in $1/N$ expansion.

Enhancement of Φ susceptibility by interactions

Spin density wave quantum critical point

$$1 + \frac{\alpha}{3\pi(1+\alpha^2)} \log^2 \left(\frac{E_F}{\omega} \right)$$

- Emergent pseudospin symmetry of low energy theory also induces $\log^2$ in a single "d-wave" particle-hole channel. Fermi-surface curvature reduces prefactor by 1/3.

- Φ corresponds to a $2k_F$ *bond-nematic* or a *quadrupole density wave*

M. A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)
K. B. Efetov, H. Meier, and C. Pepin, arXiv:1210.3276

Outline

1. Weak coupling theory of SDW ordering, and d-wave superconductivity

2. Universal critical theory of SDW ordering

3. Emergent pseudospin symmetry, and quadrupolar density wave

4. Quantum Monte Carlo without the sign problem

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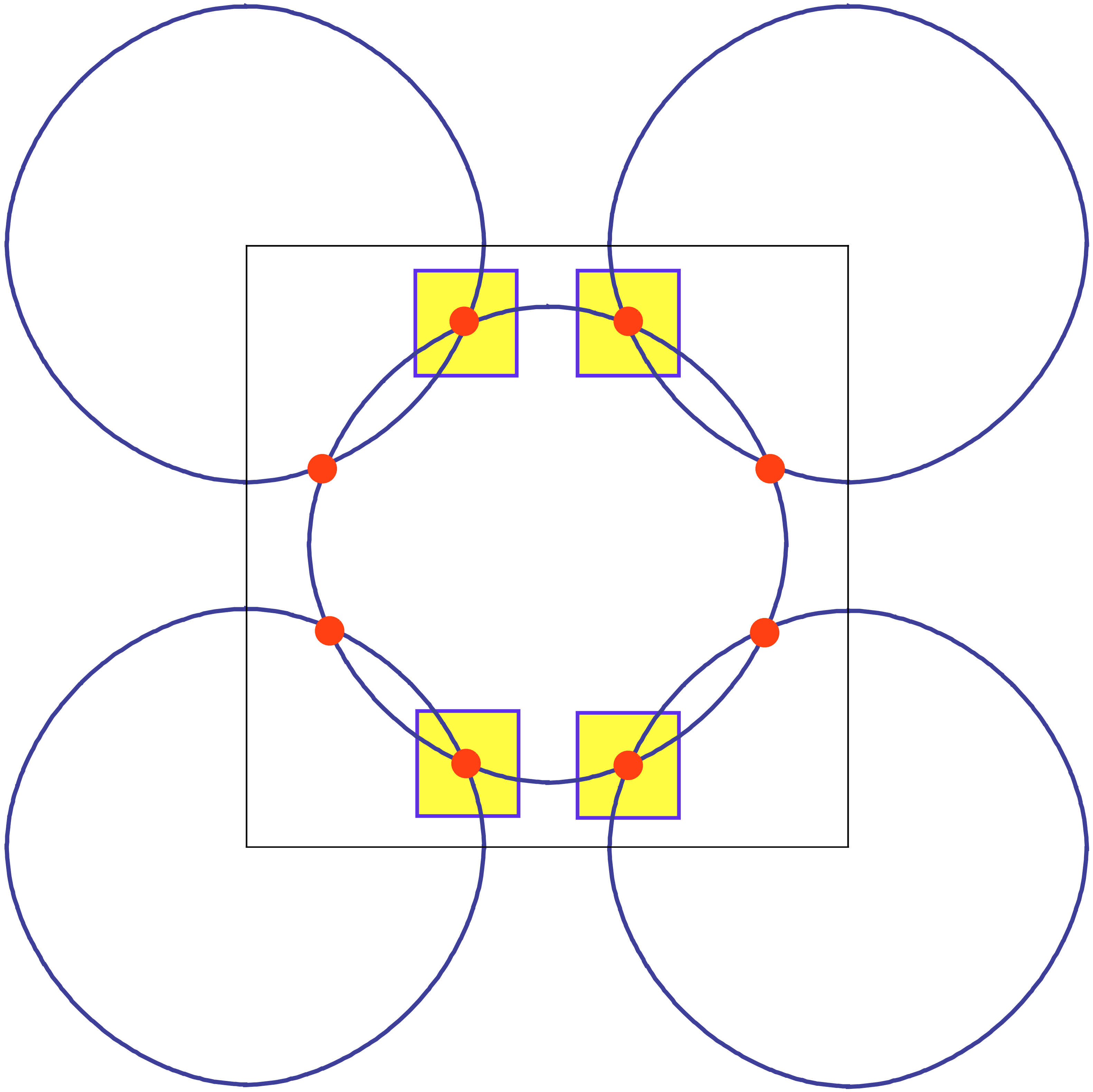
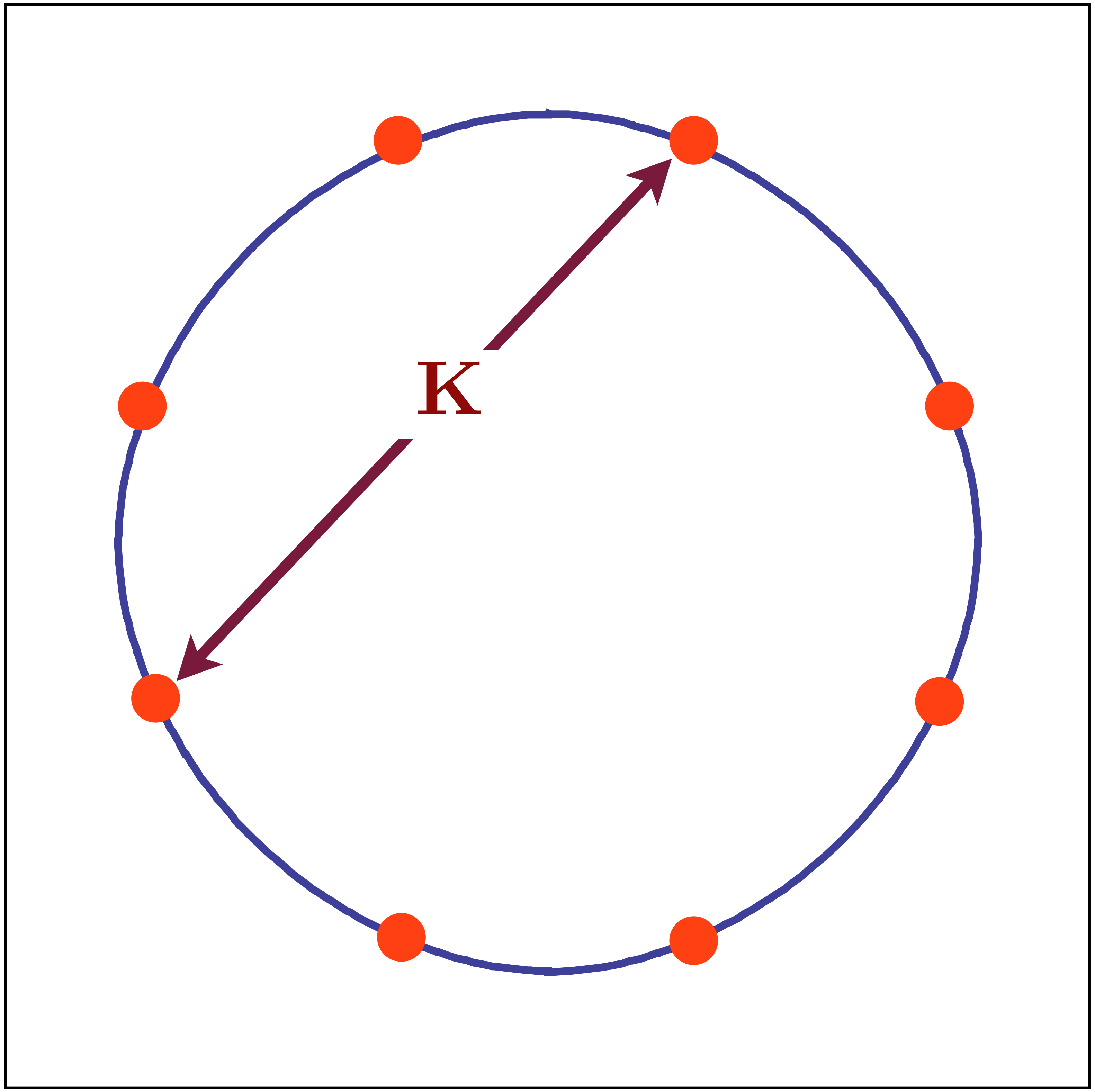


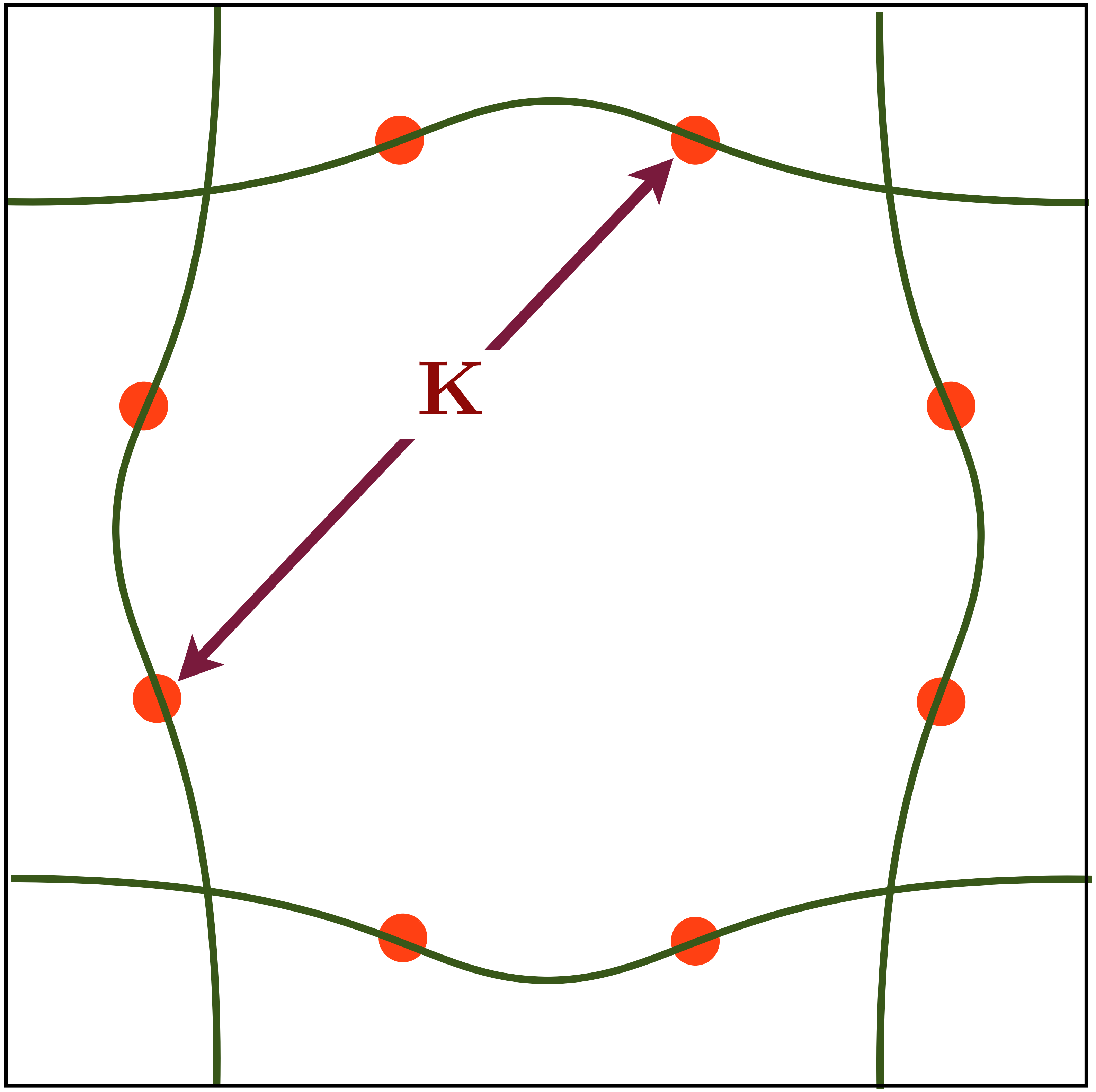
Low energy theory for critical point near hot spots

QMC for the onset of antiferromagnetism



Hot spots in a single band model

QMC for the onset of antiferromagnetism

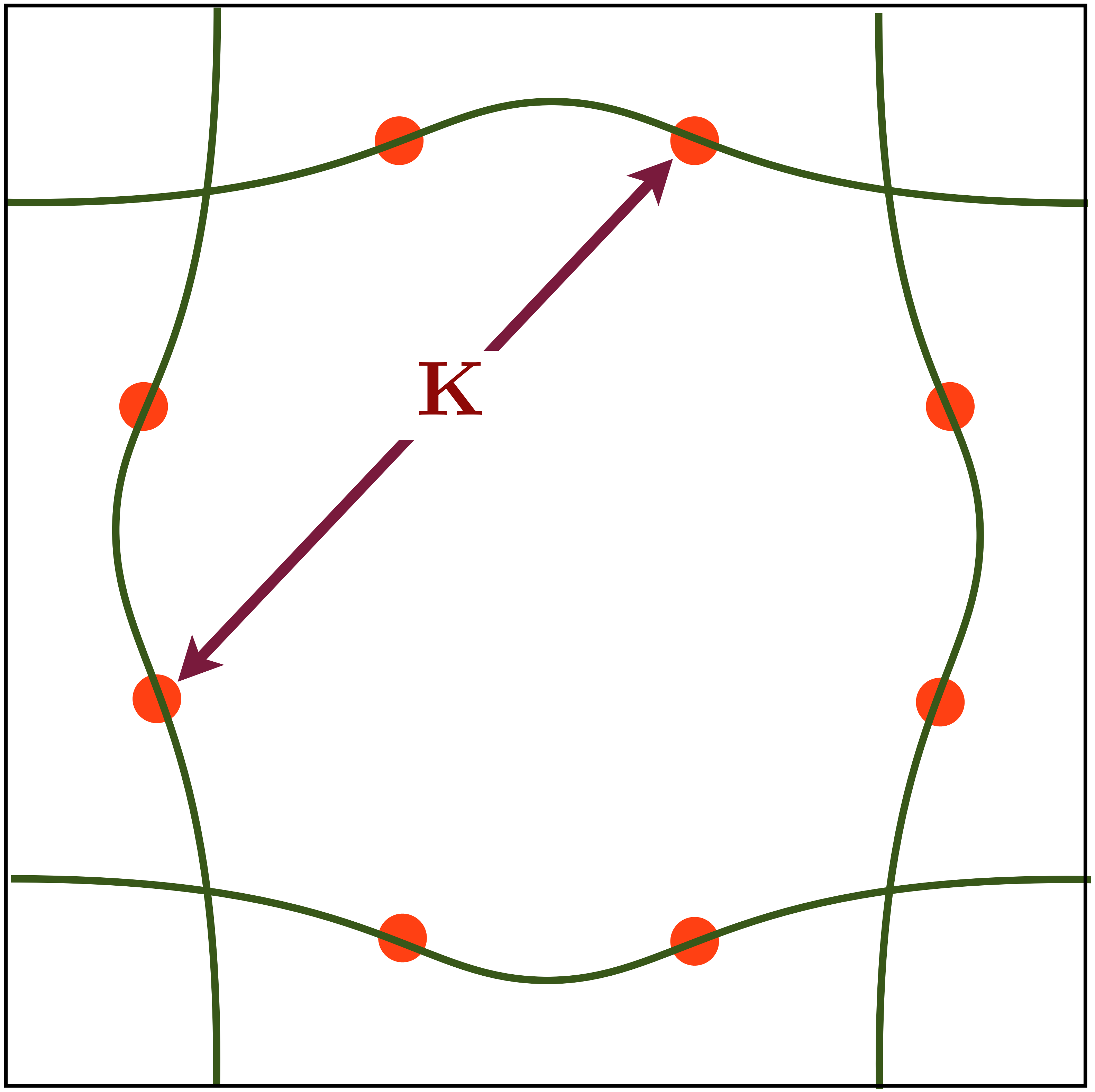


Hot spots in a two band model

E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

QMC for the onset of antiferromagnetism

Faithful realization of the *generic* universal low energy theory for the onset of antiferromagnetism.



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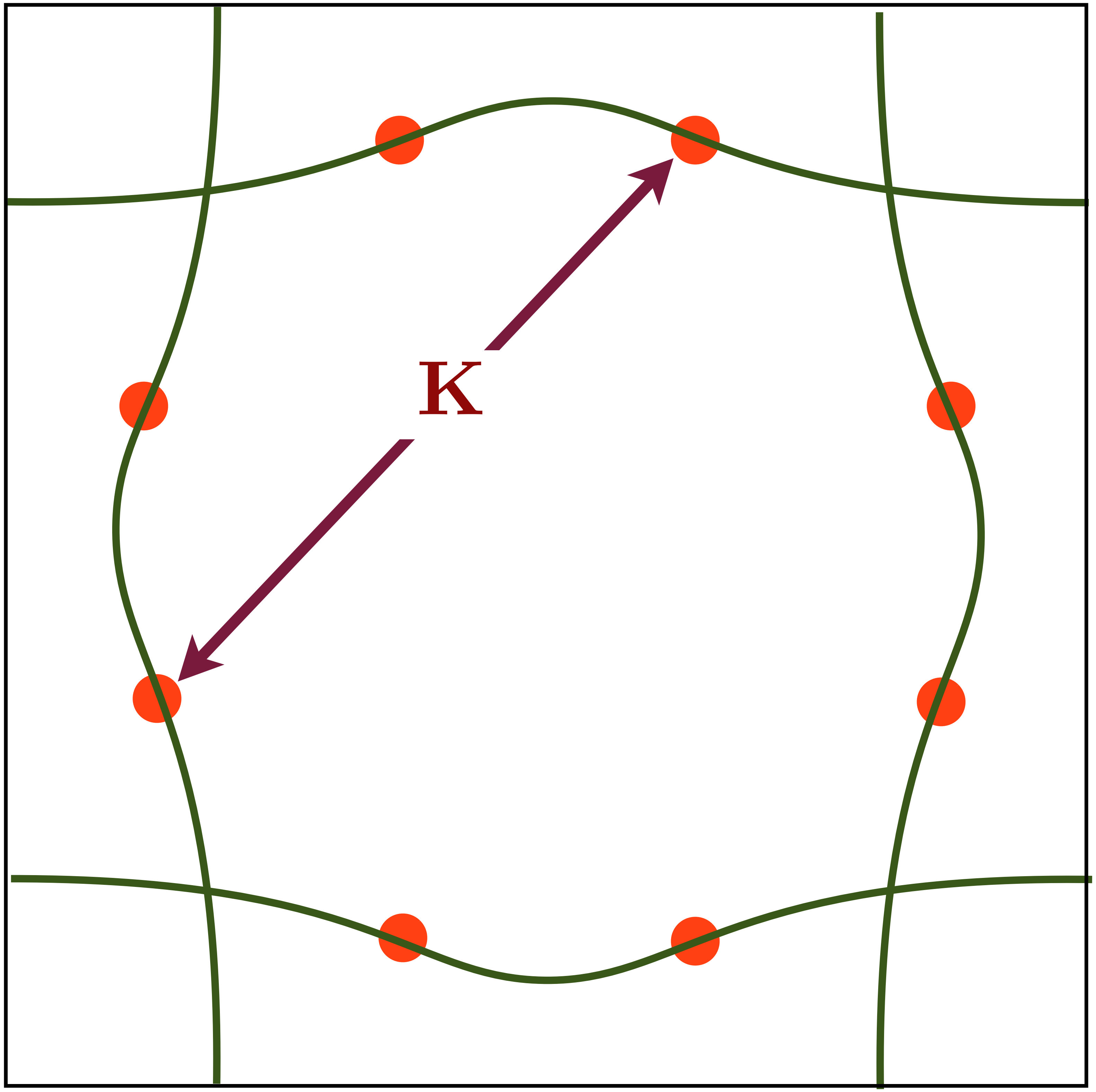

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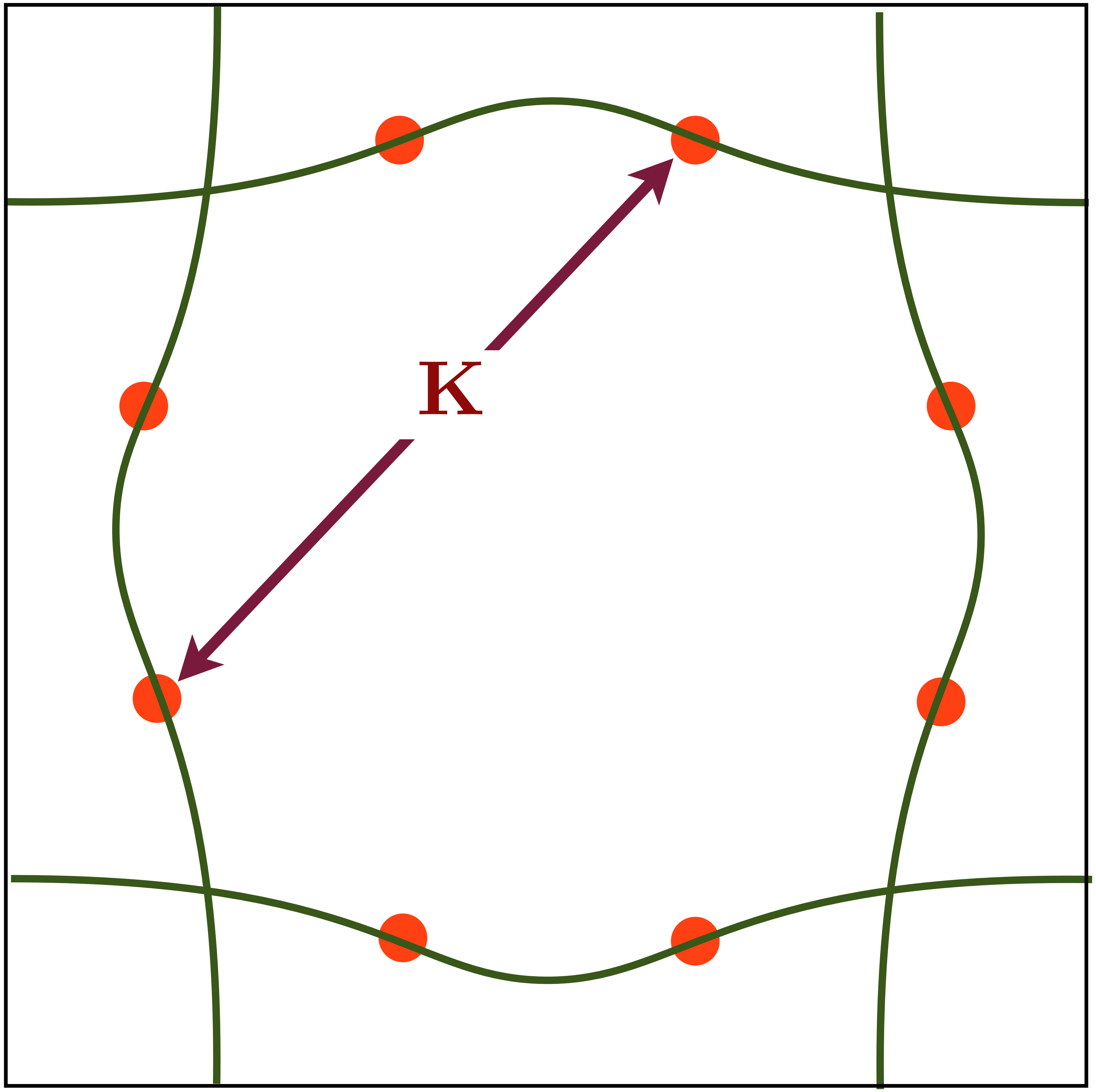
QMC for the onset of antiferromagnetism

Sign problem is absent as long as ***K*** connects hotspots in distinct bands



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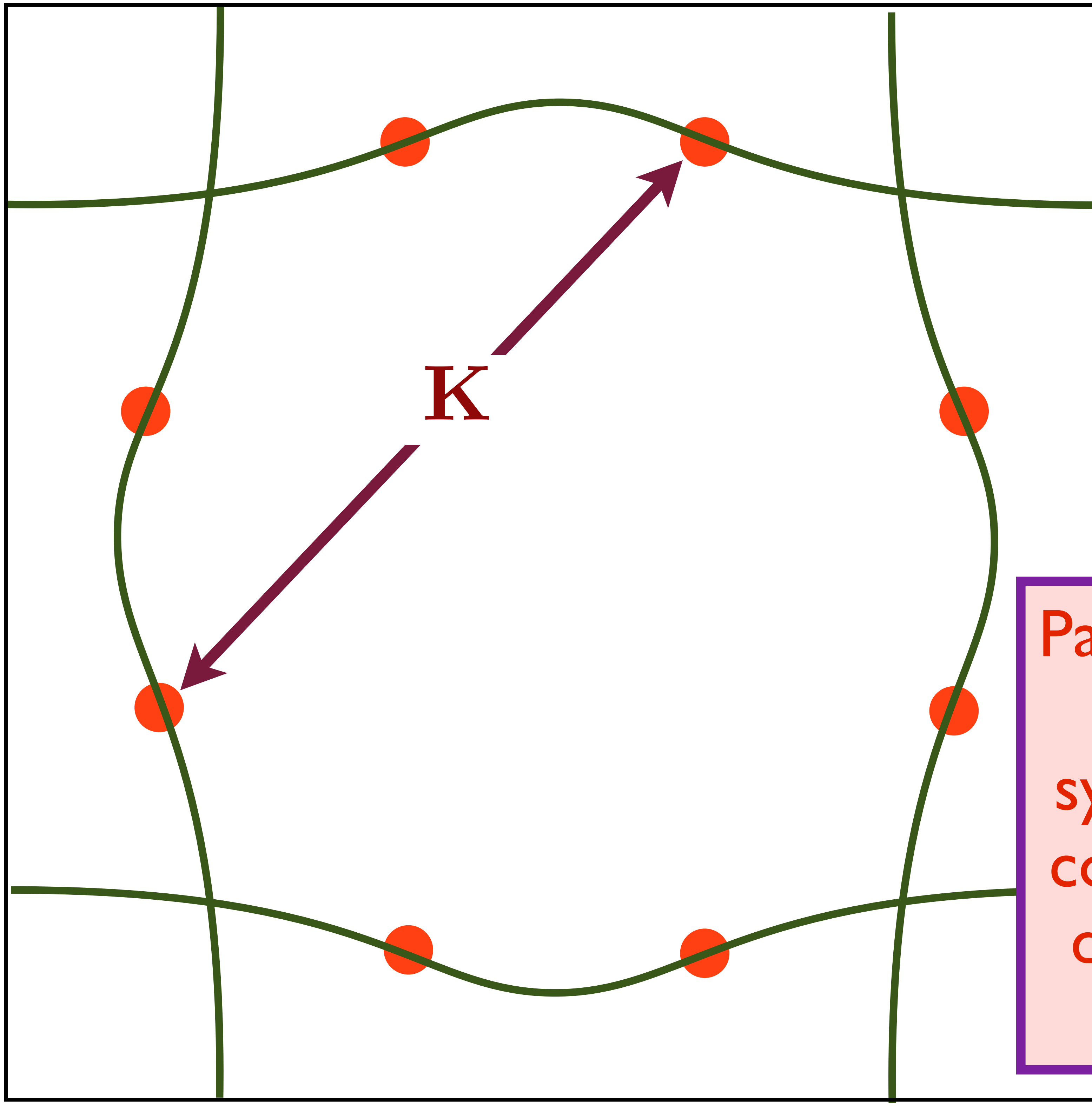

Hot spots in a two band model

E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

Particle-hole or point-group symmetries or commensurate densities ***not*** required !

QMC for the onset of antiferromagnetism

Electrons with dispersion $\varepsilon_{\mathbf{k}}$ interacting with fluctuations of the antiferromagnetic order parameter $\vec{\varphi}$.

$$\mathcal{Z} = \int \mathcal{D}c_\alpha \mathcal{D}\vec{\varphi} \exp\left(-\mathcal{S}\right)$$

$$\mathcal{S} = \int d\tau \sum_{\mathbf{k}} c^\dagger_{\mathbf{k}\alpha} \left(\frac{\partial}{\partial \tau} - \varepsilon_{\mathbf{k}} \right) c_{\mathbf{k}\alpha}$$

$$+ \int d\tau d^2 x \left[\frac{1}{2} \left(\boldsymbol{\nabla}_x \vec{\varphi} \right)^2 + \frac{r}{2} \vec{\varphi}^2 + \ldots \right]$$

$$- \lambda \int d\tau \sum_i \vec{\varphi}_i \cdot (-1)^{\mathbf{x}_i} c^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} c_{i\beta}$$

QMC for the onset of antiferromagnetism

Electrons with dispersions $\varepsilon_{\mathbf{k}}^{(x)}$ and $\varepsilon_{\mathbf{k}}^{(y)}$ interacting with fluctuations of the antiferromagnetic order parameter $\vec{\varphi}$.

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E. Berg,
M. Metlitski, and
S. Sachdev,
Science **338**, 1606
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Friday, January 11, 13

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E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

No sign problem !

QMC for the onset of antiferromagnetism

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E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

Applies without changes to the microscopic band structure in the iron-based superconductors

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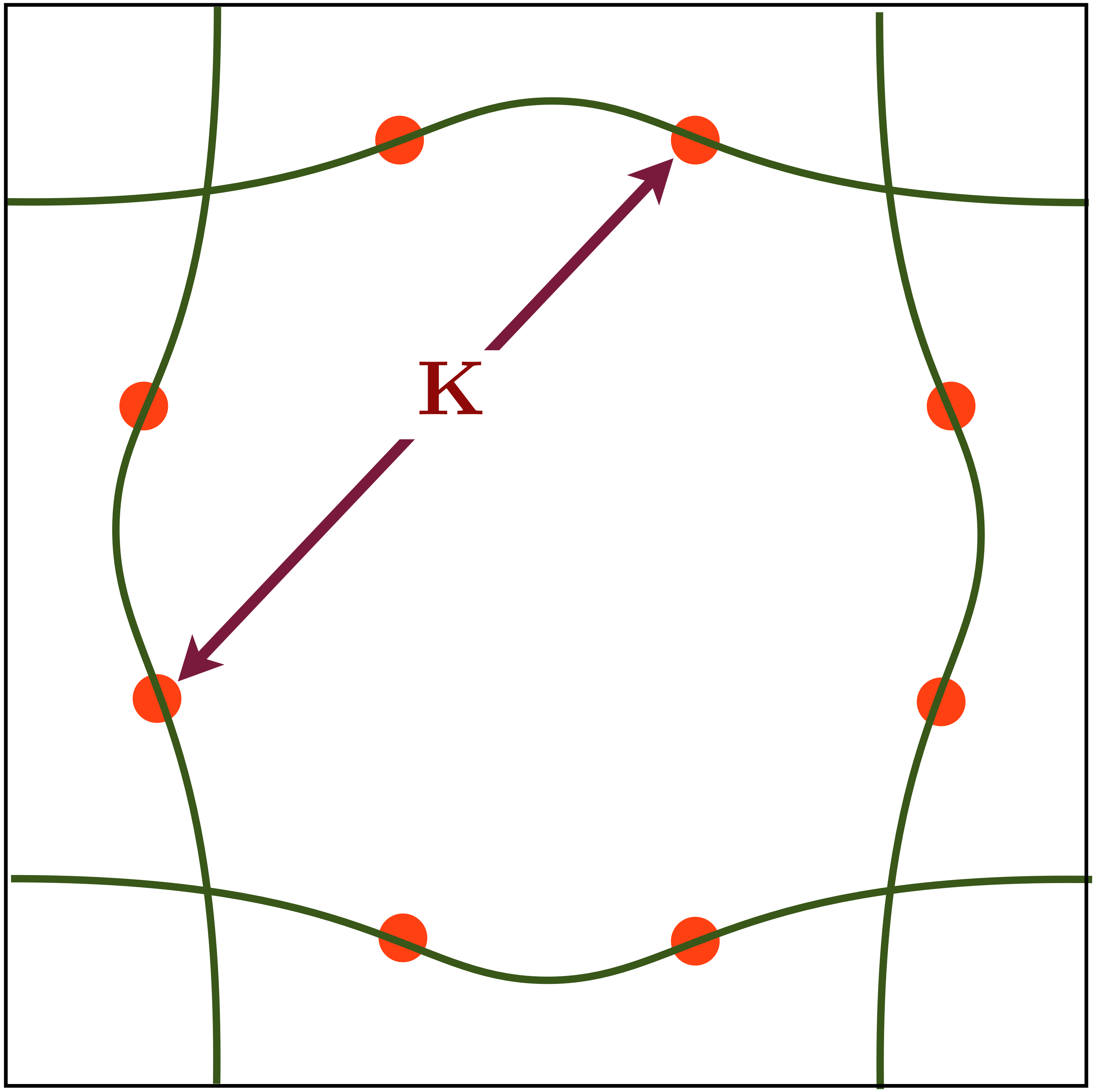
E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

Can integrate out $\vec{\varphi}$ to obtain an extended Hubbard model. The interactions in this model only couple electrons in separate bands.

QMC for the onset of antiferromagnetism



Hot spots in a two band model

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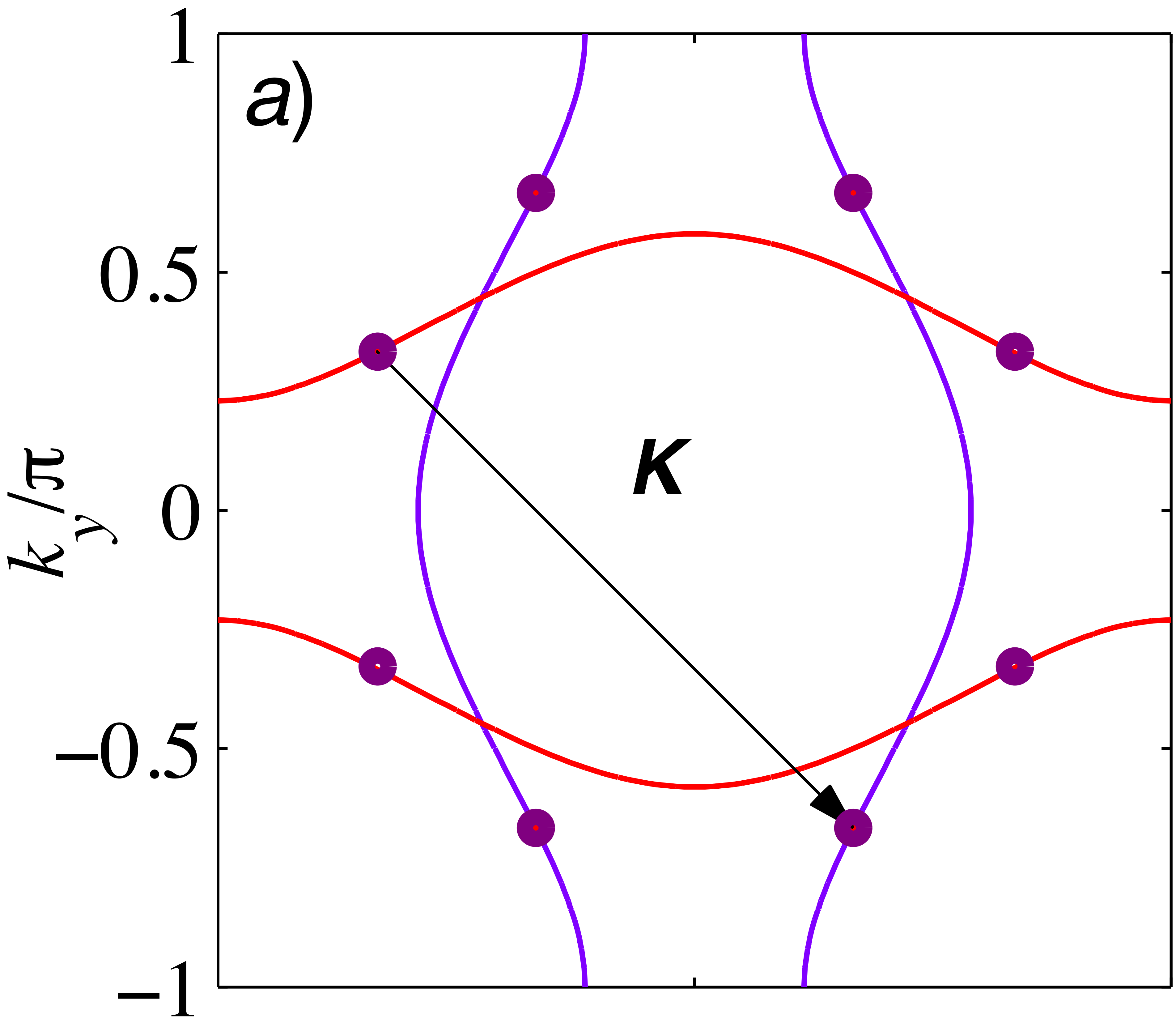
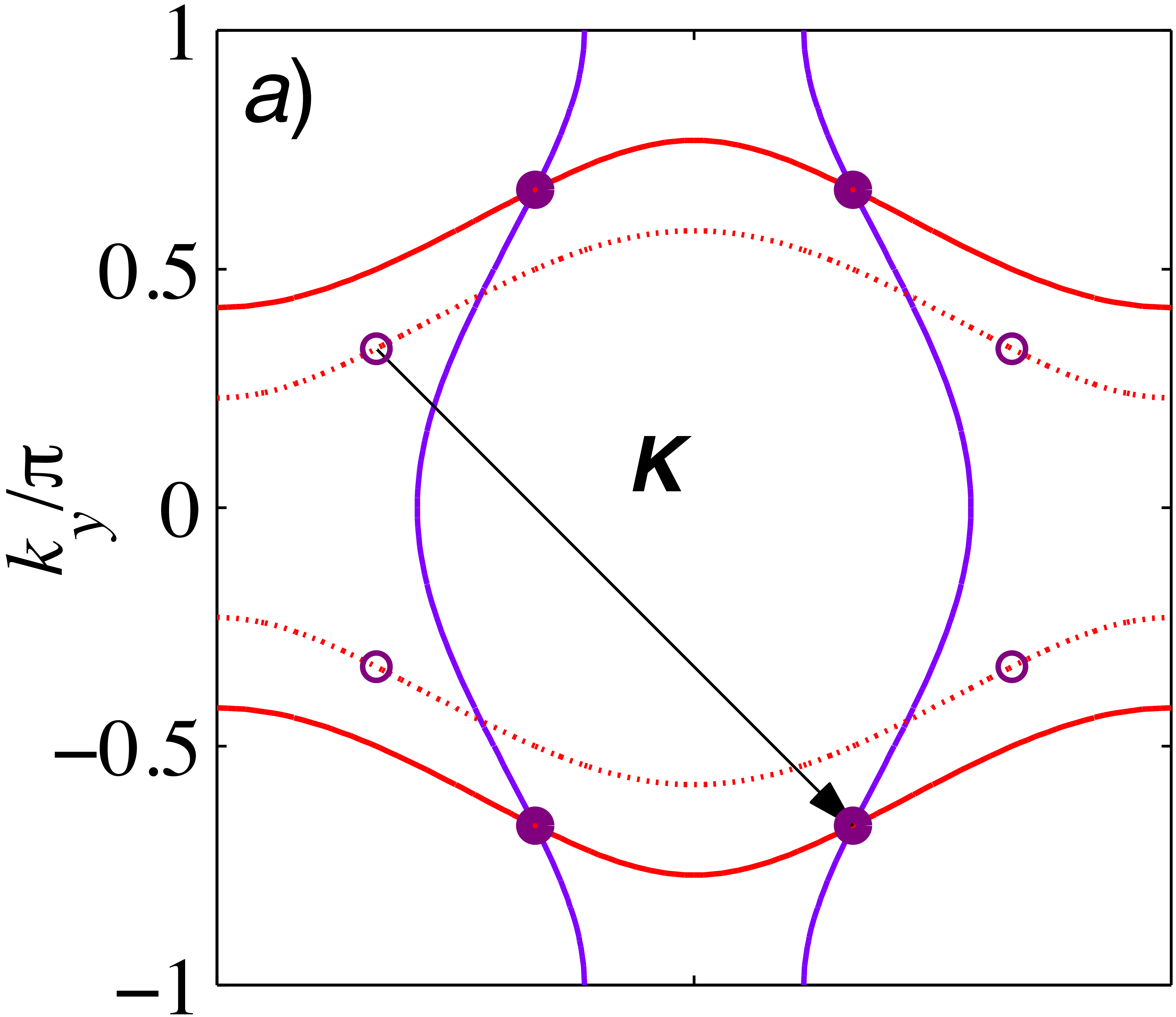


Center Brillouin zone at (π,π,)

E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

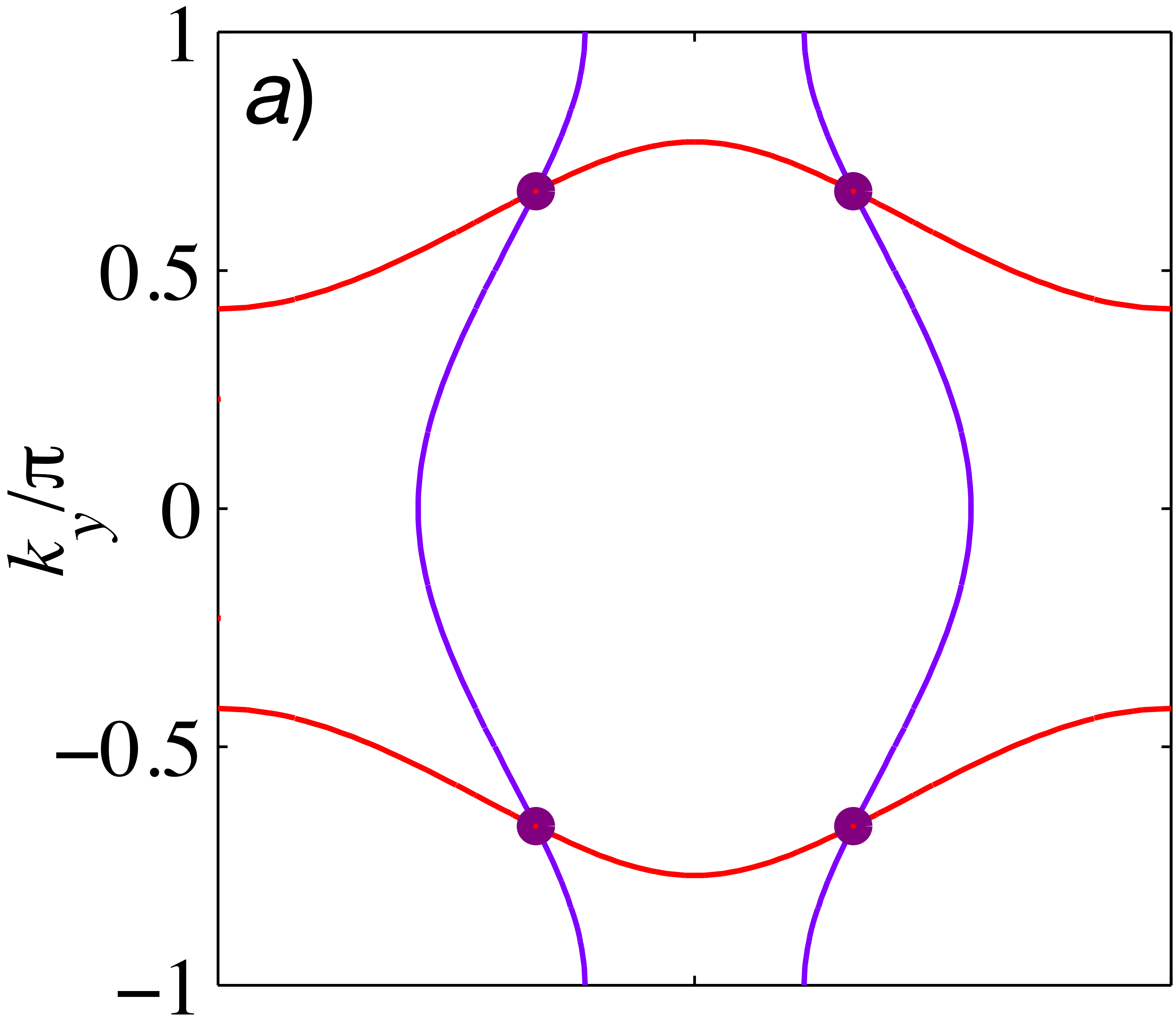
QMC for the onset of antiferromagnetism



E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

Move one of the Fermi surface by $(\pi,\pi,)$

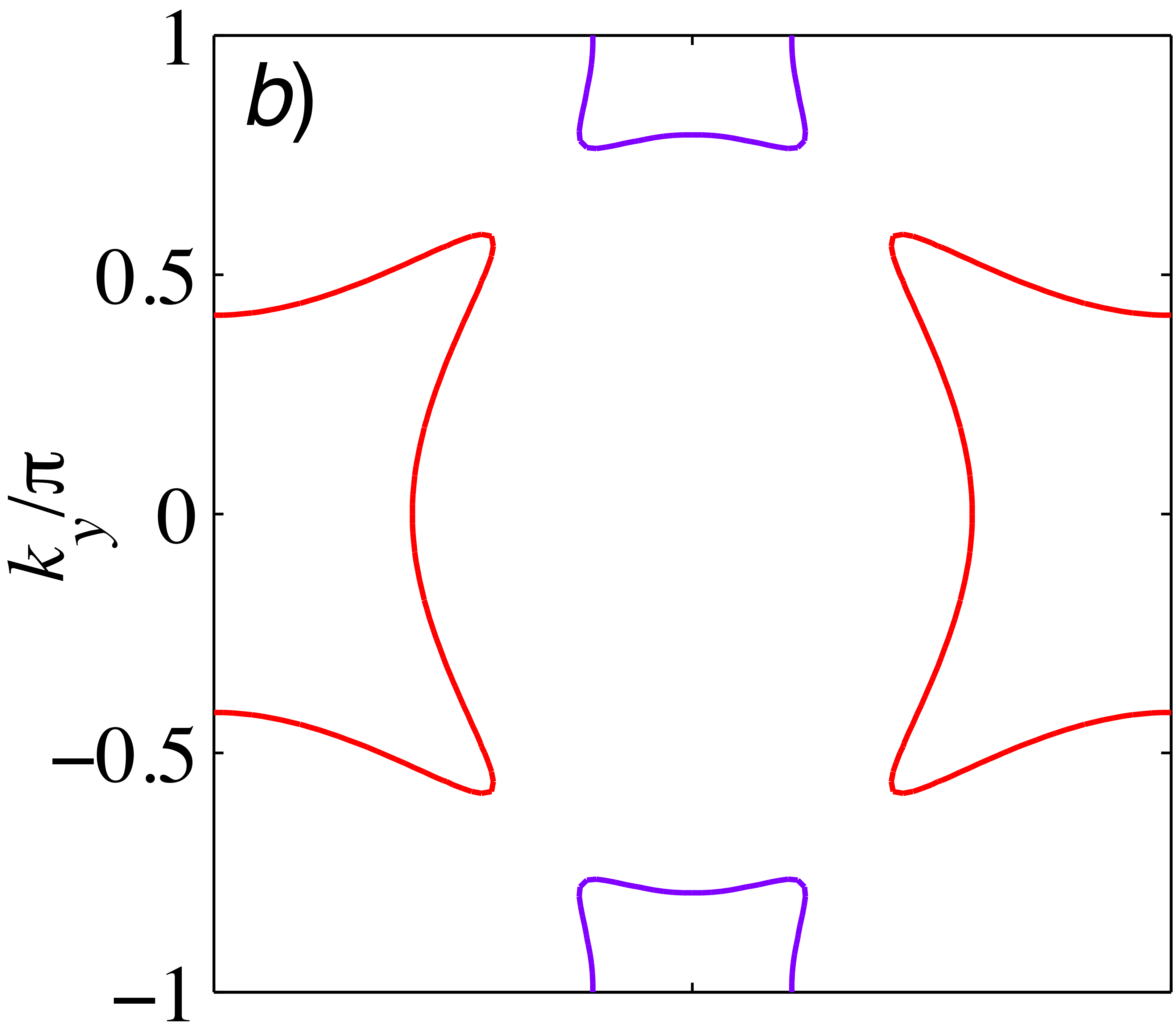
QMC for the onset of antiferromagnetism



E. Berg,
M. Metlitski, and
S. Sachdev,
Science **338**, 1606
(2012).

Now hot spots are at Fermi surface intersections

QMC for the onset of antiferromagnetism



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M. Metlitski, and
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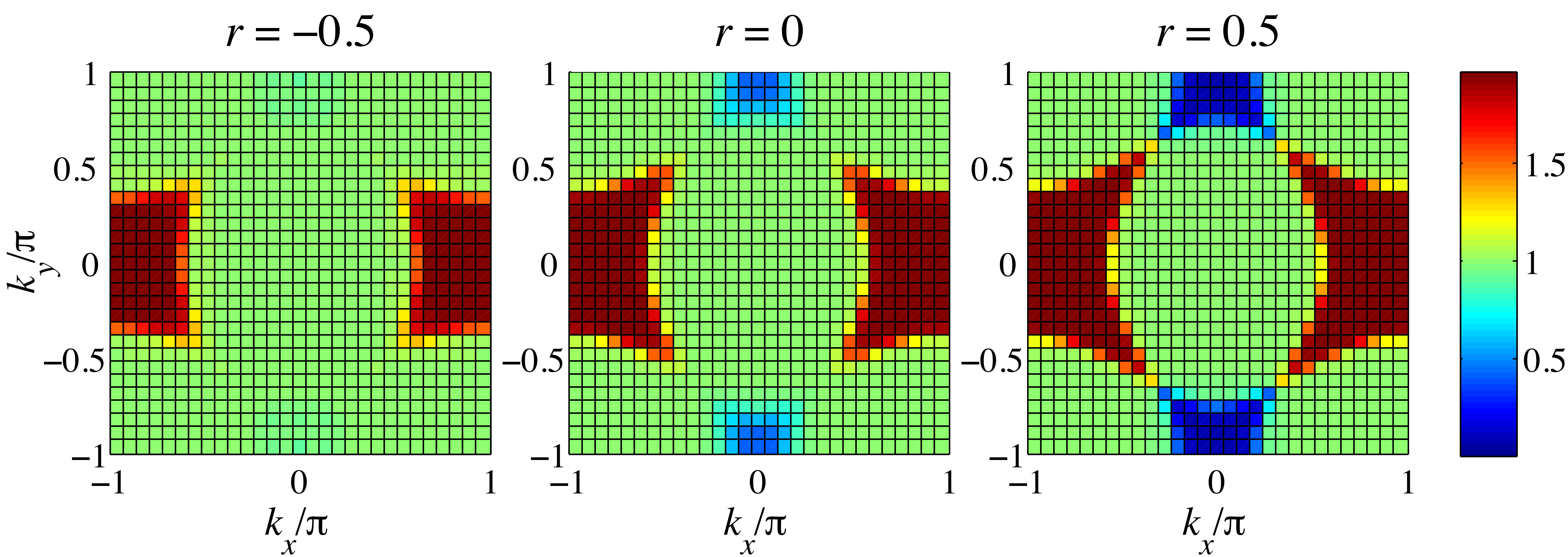
Science **338**, 1606
(2012).

Expected Fermi surfaces in the AFM ordered phase

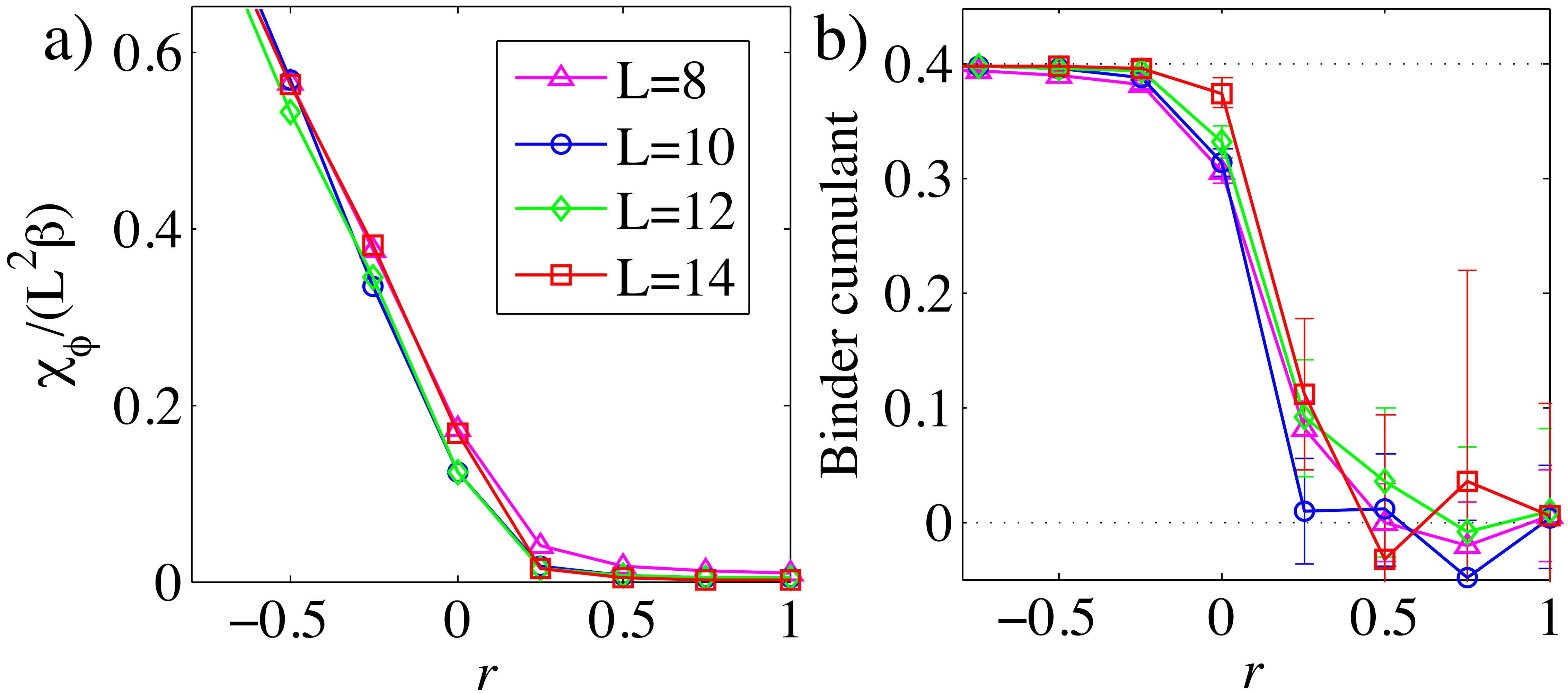
QMC for the onset of antiferromagnetism



Electron occupation number $n_{\mathbf{k}}$
as a function of the tuning parameter r

E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

QMC for the onset of antiferromagnetism



AF susceptibility, χ_φ, and Binder cumulant as a function of the tuning parameter r

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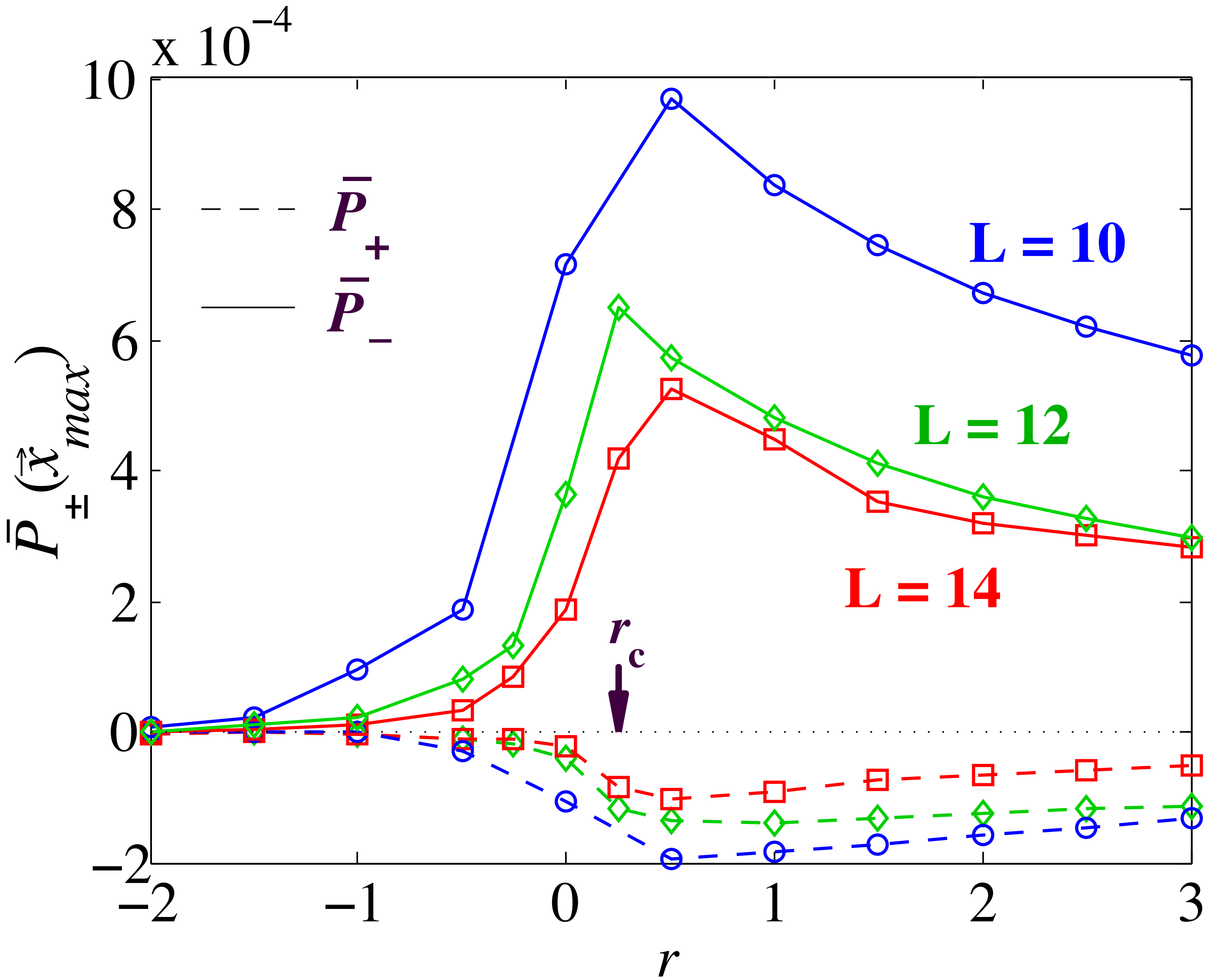
QMC for the onset of antiferromagnetism



s/d pairing amplitudes P_+/P_-
as a function of the tuning parameter r

E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012).

Conclusions

- Solved sign-problem for generic universal theory for the onset of antiferromagnetism in two-dimensional metals.

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- Good prospects for studying competing charge orders, and non-Fermi liquid physics at non-zero temperature.