Fermi surface reconstruction in two-dimensional metals

Ringberg Symposium on
High Temperature Superconductivity,

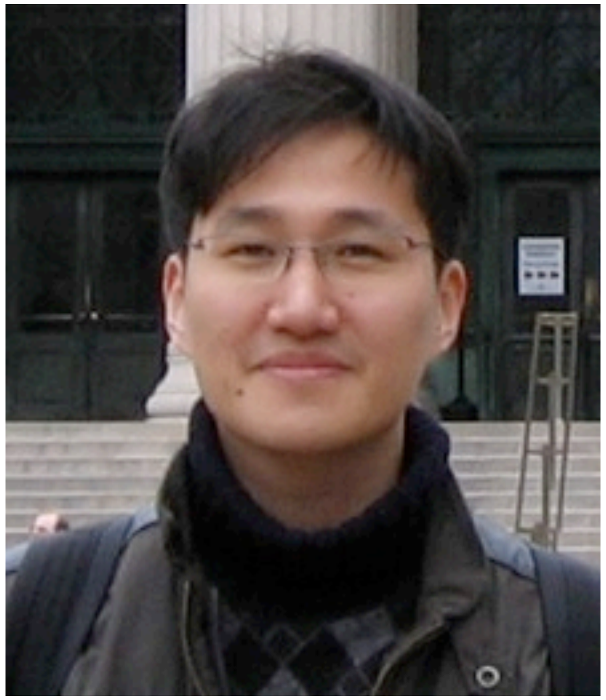
May 15, 2011

Talk online: sachdev.physics.harvard.edu

PHYSICS

HARVARD

Max Metlitski



Eun Gook Moon

Sean Hartnoll

Diego Hofman

PHYSICS

VE RI TAS

HARVARD

1. Low energy theory of spin density wave quantum critical point

A. Instabilities near the quantum critical point: unconventional superconductivity and $2k_F$ bond-nematic ordering

B. Scattering off composite operators

2. Phenomenology of the phase diagram in a magnetic field

3. Possible intermediate non-Fermi liquid phases

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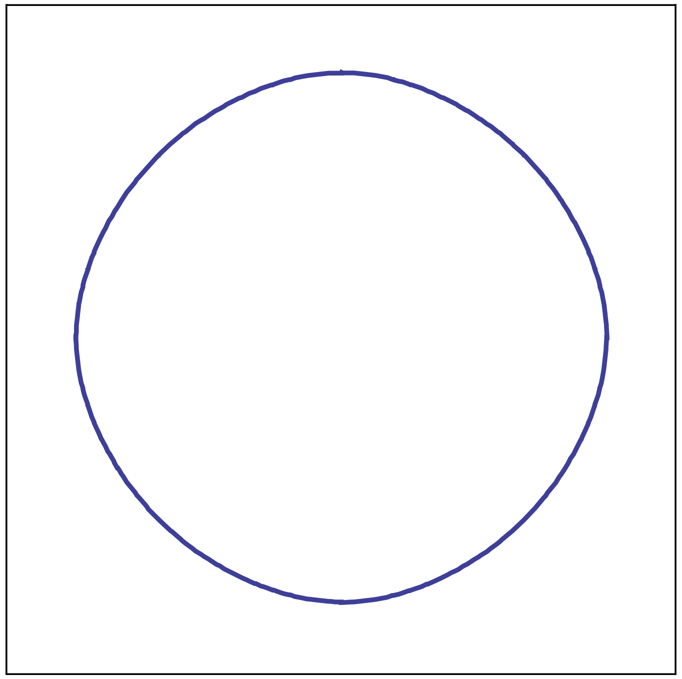
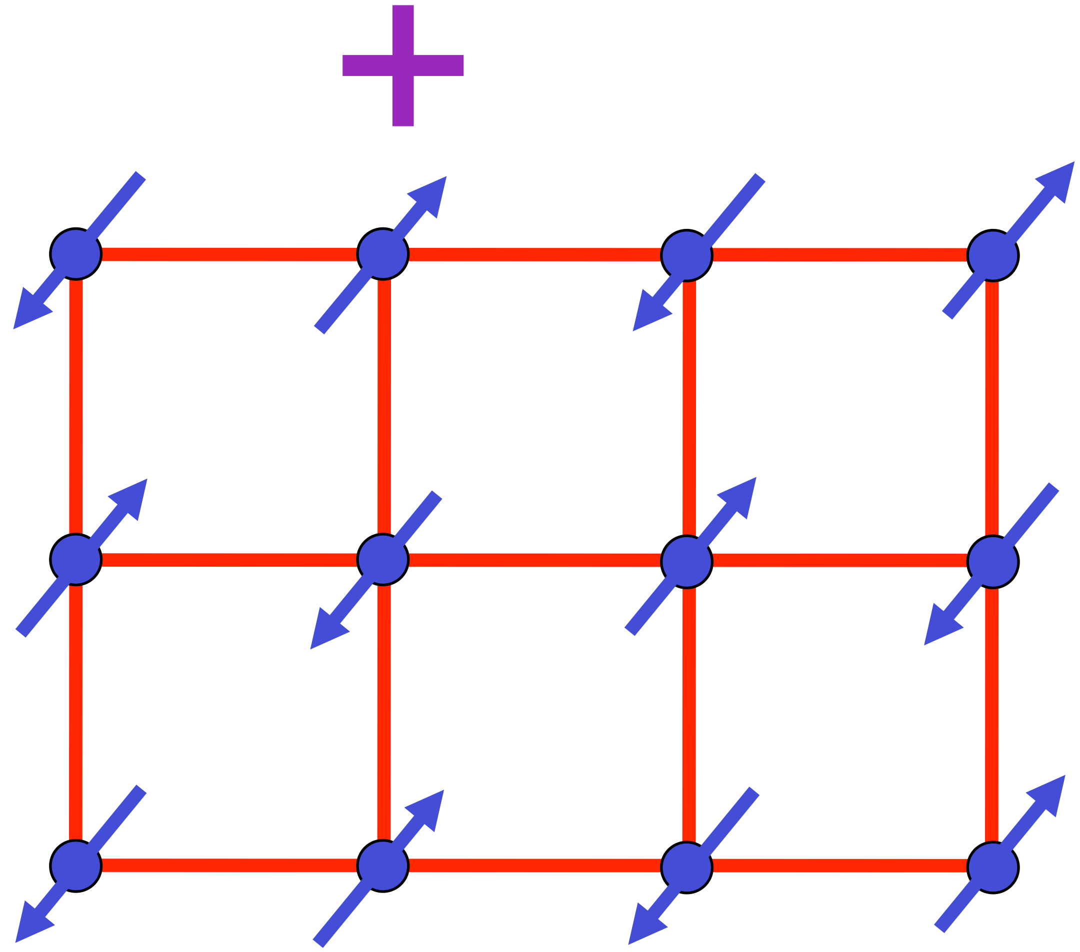
Fermi surface+antiferromagnetism

Metal with "large"
Fermi surface



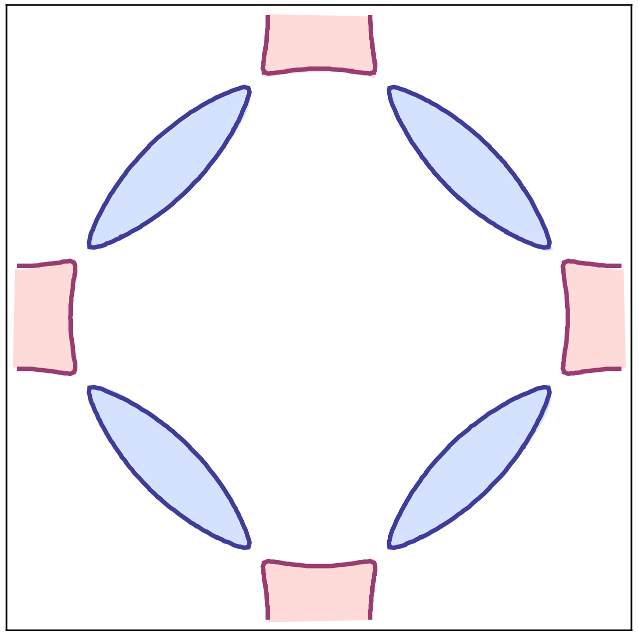


The electron spin polarization obeys

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

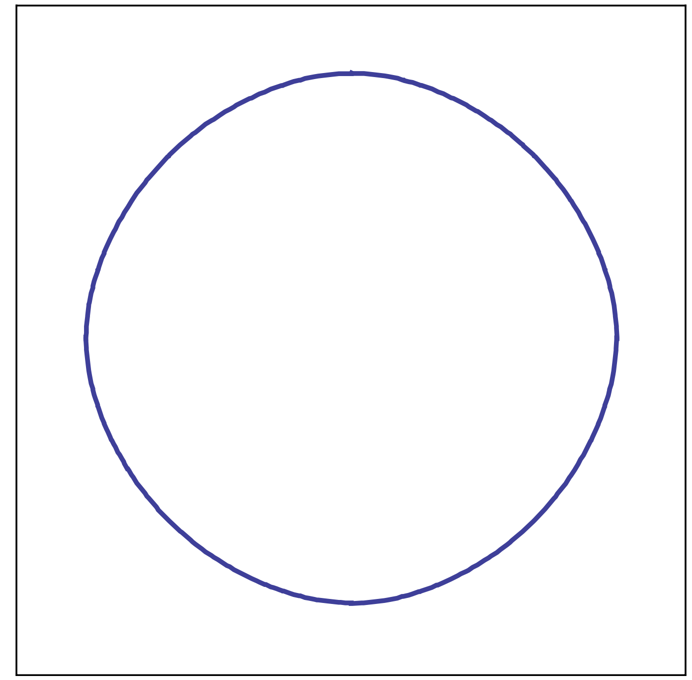
where $\mathbf{K}$ is the ordering wavevector.

Fermi surface+antiferromagnetism



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

Metal with electron and hole pockets



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

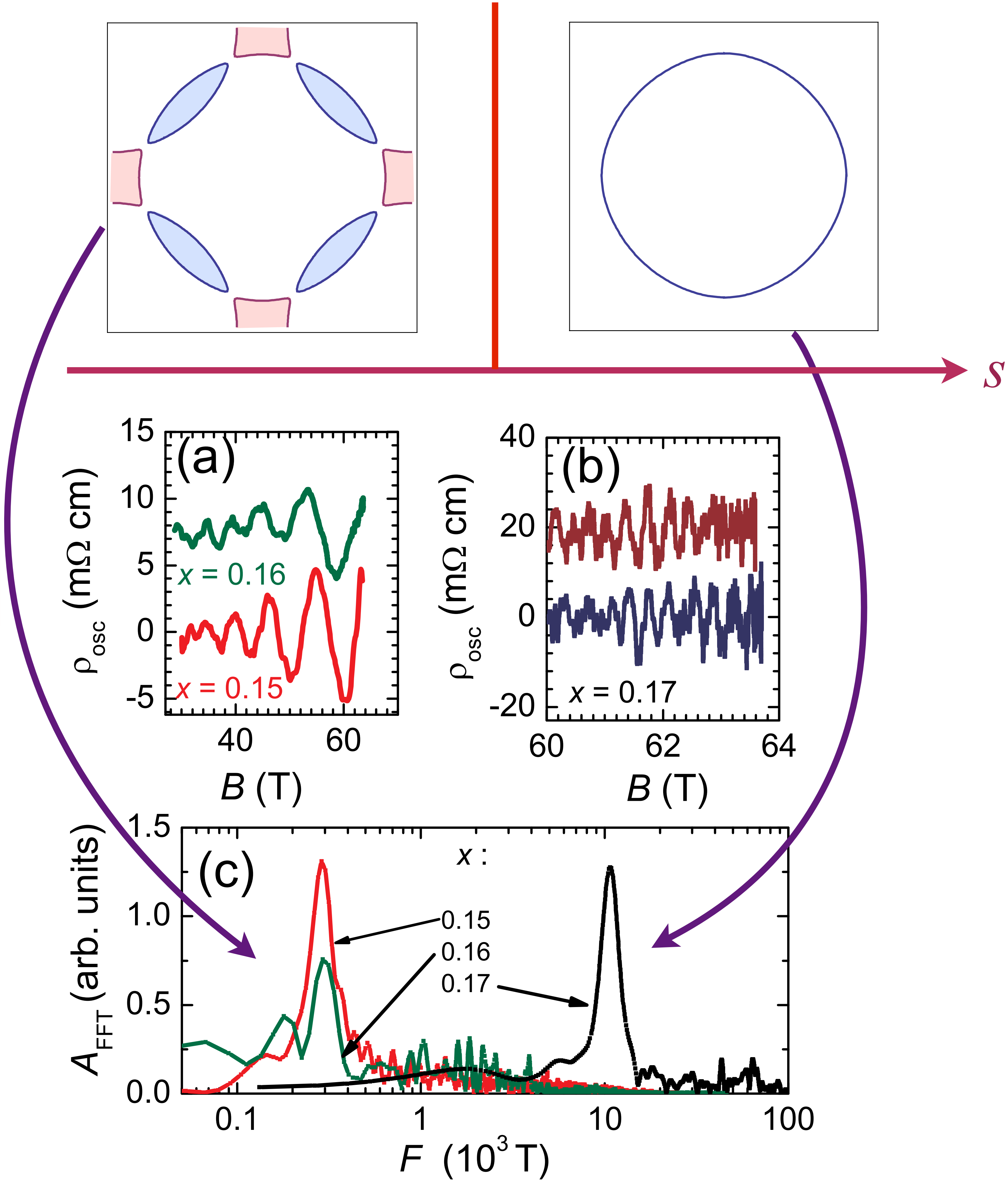
Metal with "large" Fermi surface

Increasing interaction

S. Sachdev, A.V. Chubukov, and A. Sokol, *Phys. Rev. B* **51**, 14874 (1995).
A.V. Chubukov and D. K. Morr, *Physics Reports* **288**, 355 (1997).

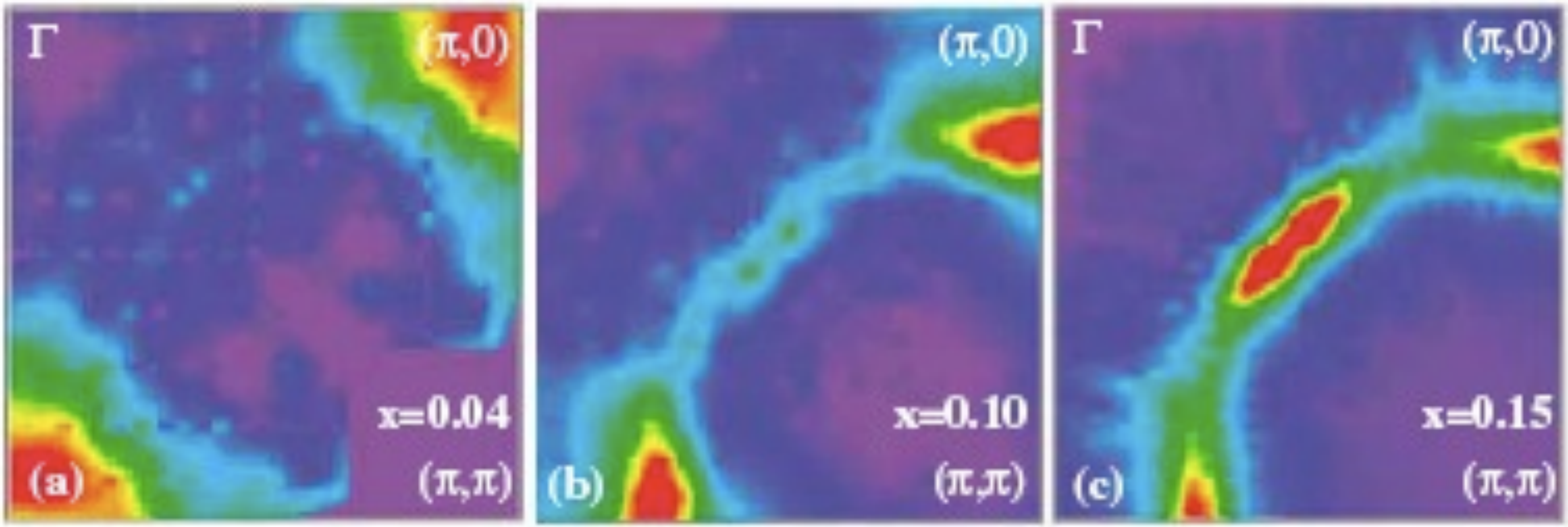
Quantum oscillations

$Nd_{2-x}Ce_xCuO_4$



T. Helm, M.V. Kartsovnik, M. Bartkowiak, N. Bittner, M. Lambacher, A. Erb, J. Wosnitza, and R. Gross, *Phys. Rev. Lett.* **103**, 157002 (2009).

Photoemission in $Nd_{2-x}Ce_xCuO_4$



N. P. Armitage *et al.*, Phys. Rev. Lett. **88**, 257001 (2002).

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

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

$$\mathcal{S} = \int d\tau \sum_{\mathbf{k}} c^\dagger_{\mathbf{k}\alpha} \left(\frac{\partial}{\partial \tau} - \varepsilon_{\mathbf{k}} \right) c_{\mathbf{k}\alpha}$$
$$+ \int d\tau d^2 r \left[\frac{1}{2} \left(\boldsymbol{\nabla}_r \vec{\varphi} \right)^2 + \frac{s}{2} \vec{\varphi}^2 + \ldots \right]$$
$$- \lambda \int d\tau \sum_i \vec{\varphi}_i \cdot (-1)^{\mathbf{r}_i} c^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} c_{i\beta}$$

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

A technical aside......

Hertz-Moriya-Millis theory

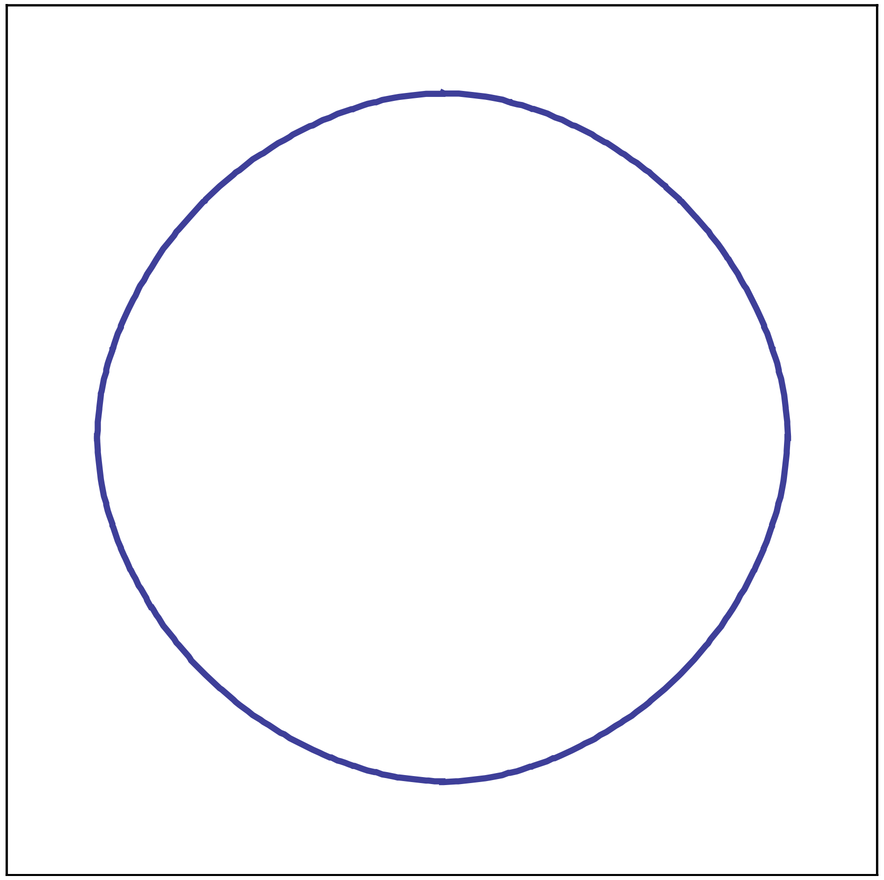
Integrate out fermions and obtain an effective action for the boson field $\vec{\varphi}$ alone. Because the fermions are gapless, this is potentially dangerous, and will lead to non-local terms in the $\vec{\varphi}$ effective action. Hertz focused on only the simplest such non-local term. However, there are an infinite number of non-local terms at higher order, and these lead to a breakdown of the Hertz theory in $d = 2$.

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

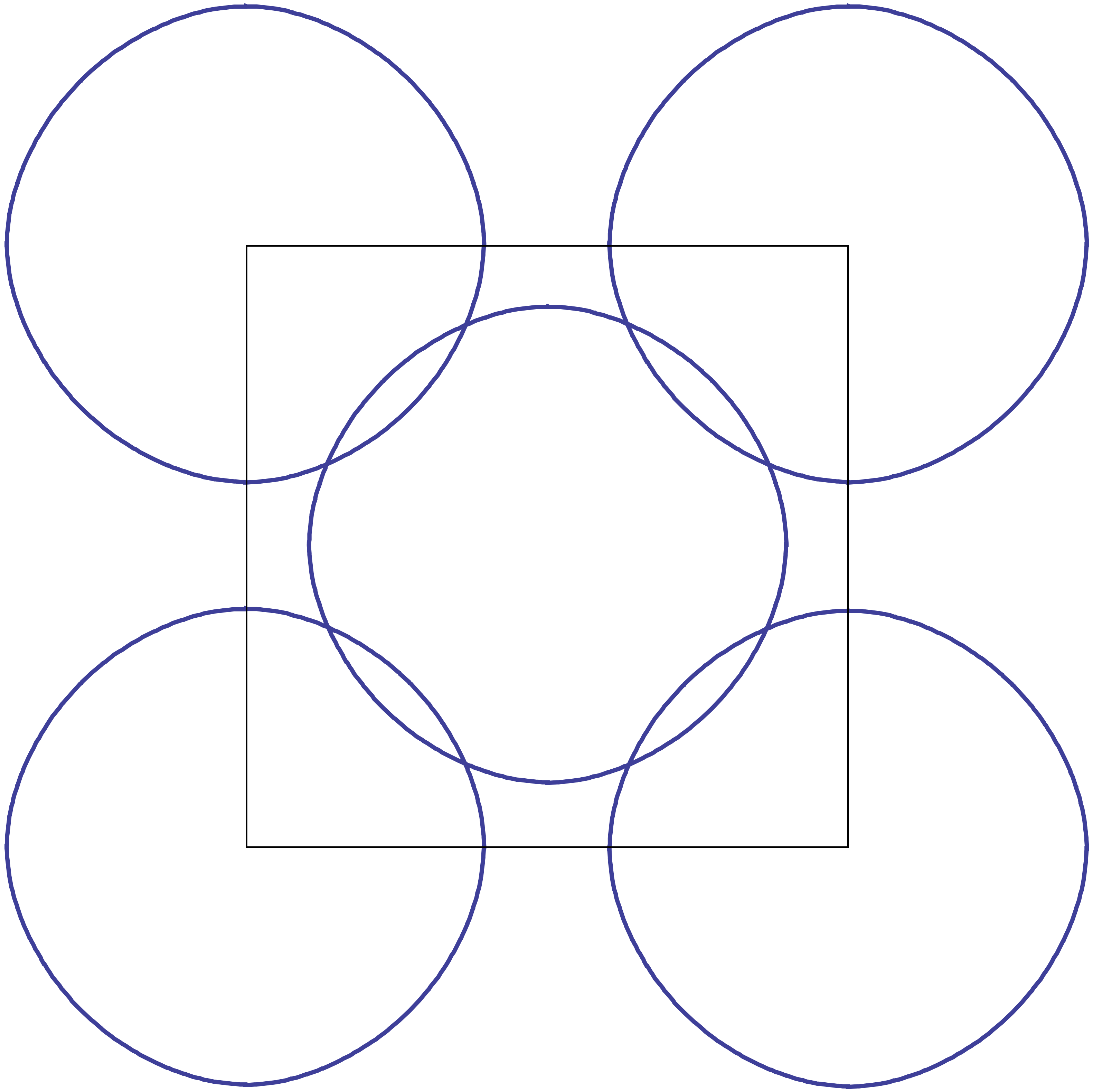
A technical aside......

We need to perform an RG analysis on a local theory of both the fermions and the $\vec{\varphi}$. It appears that such a theory can be analyzed using a $1/N$ expansion, where N is the number of fermion flavors. At two-loop order, the $1/N$ expansion is well-behaved, and we can determine consistent RG flow equations. However, at higher loops we find corrections to the renormalizations which require summation of all planar graphs even at the leading order in $1/N$, and the $1/N$ expansion appears to be organized as a genus expansion of random surfaces. But even this genus expansion breaks down in the renormalization of a quartic coupling of $\vec{\varphi}$. In the following, I will describe some of the two loop results.

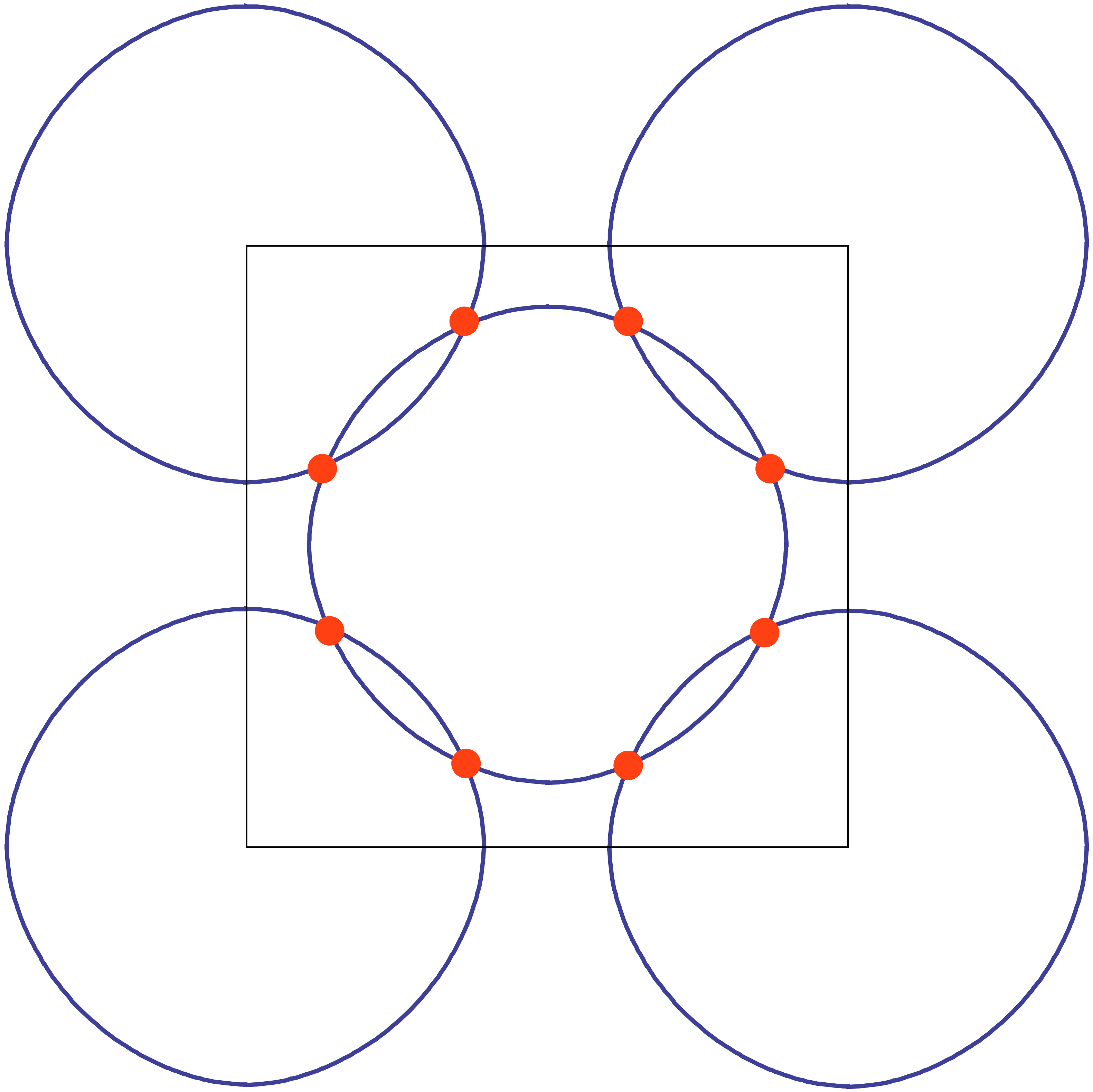
M. A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)



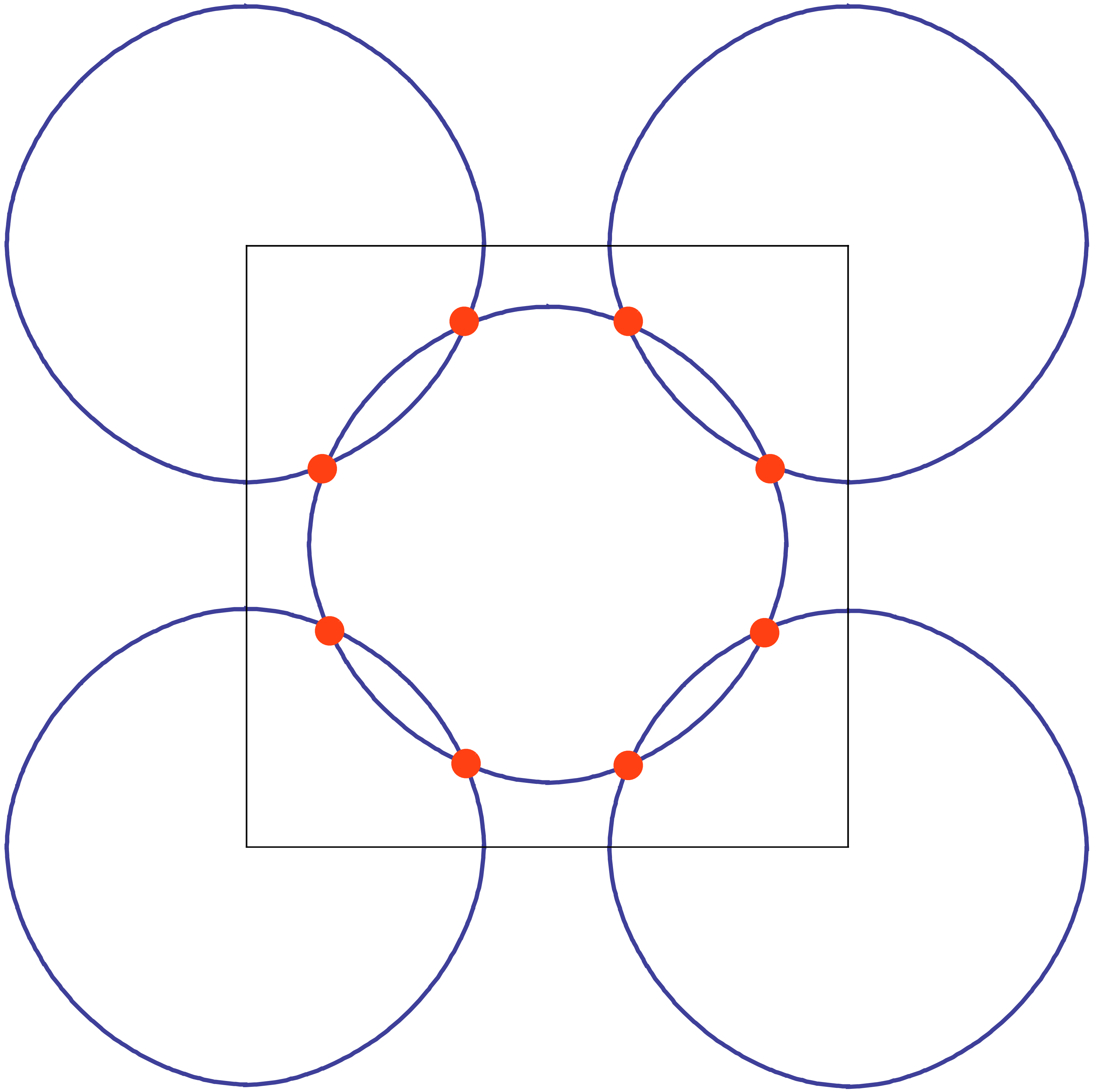
Metal with “large” Fermi surface



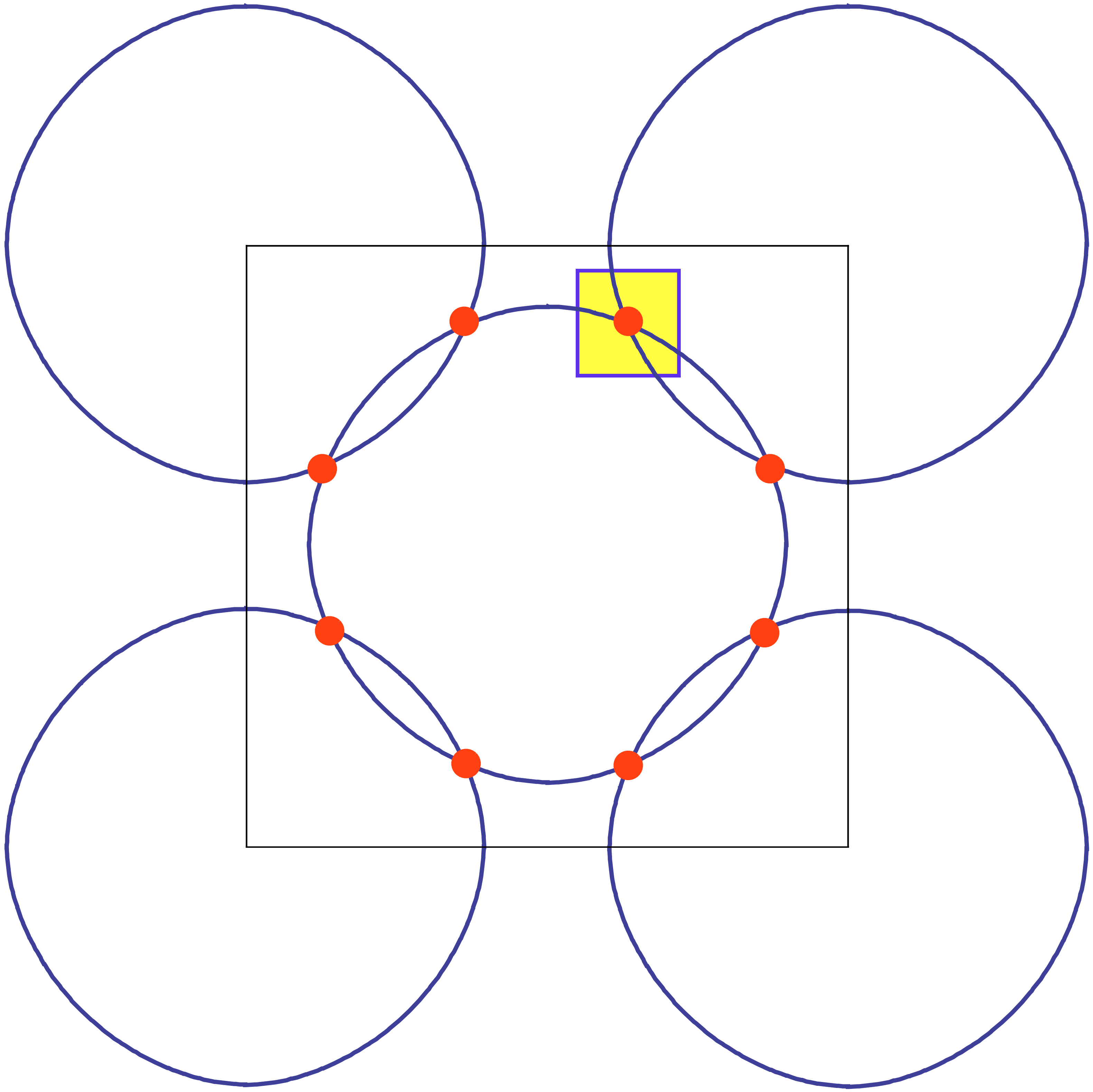
Fermi surfaces translated by $\mathbf{K} = (\pi, \pi)$.



"Hot" spots

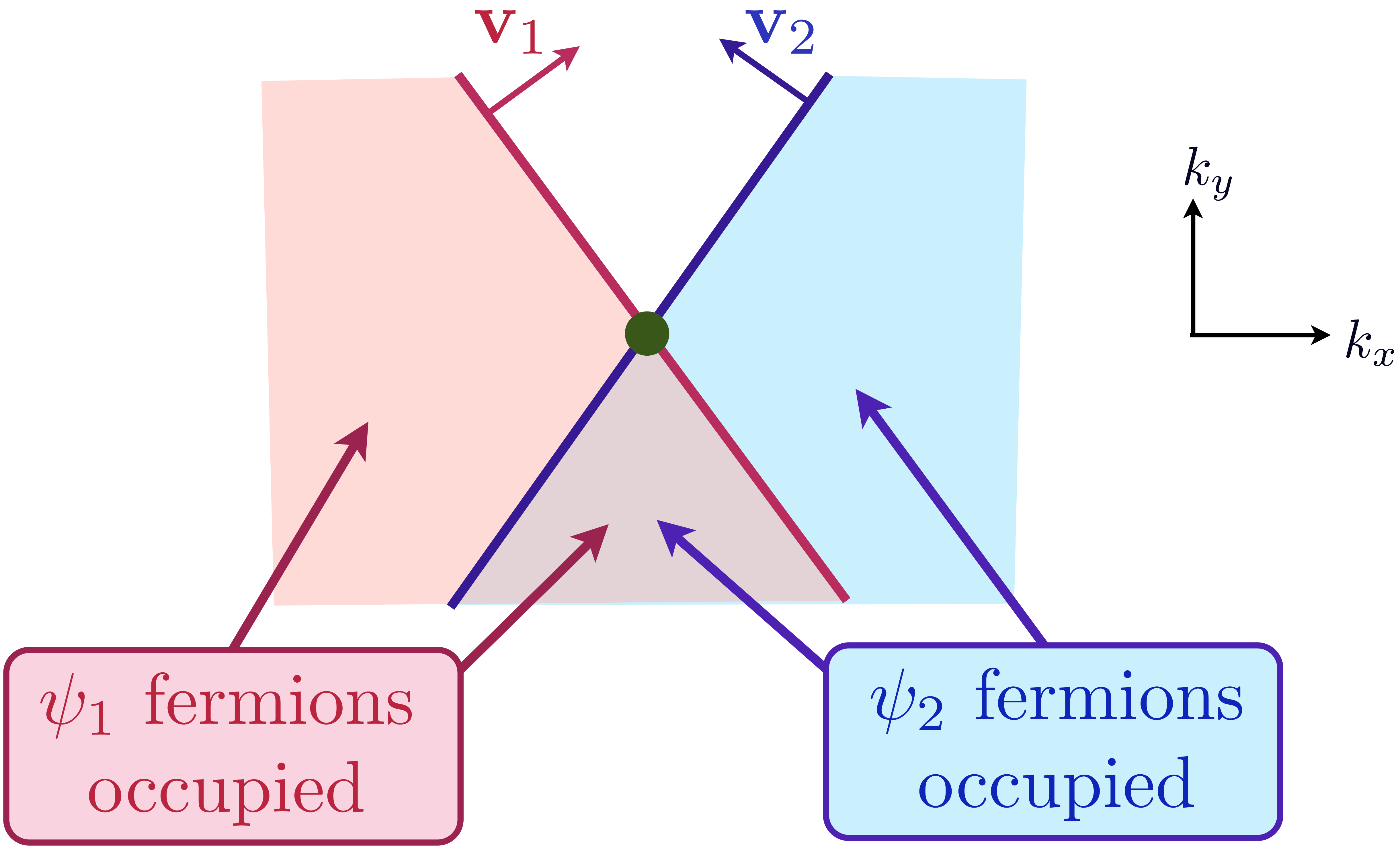


Low energy theory for critical point near hot spots



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



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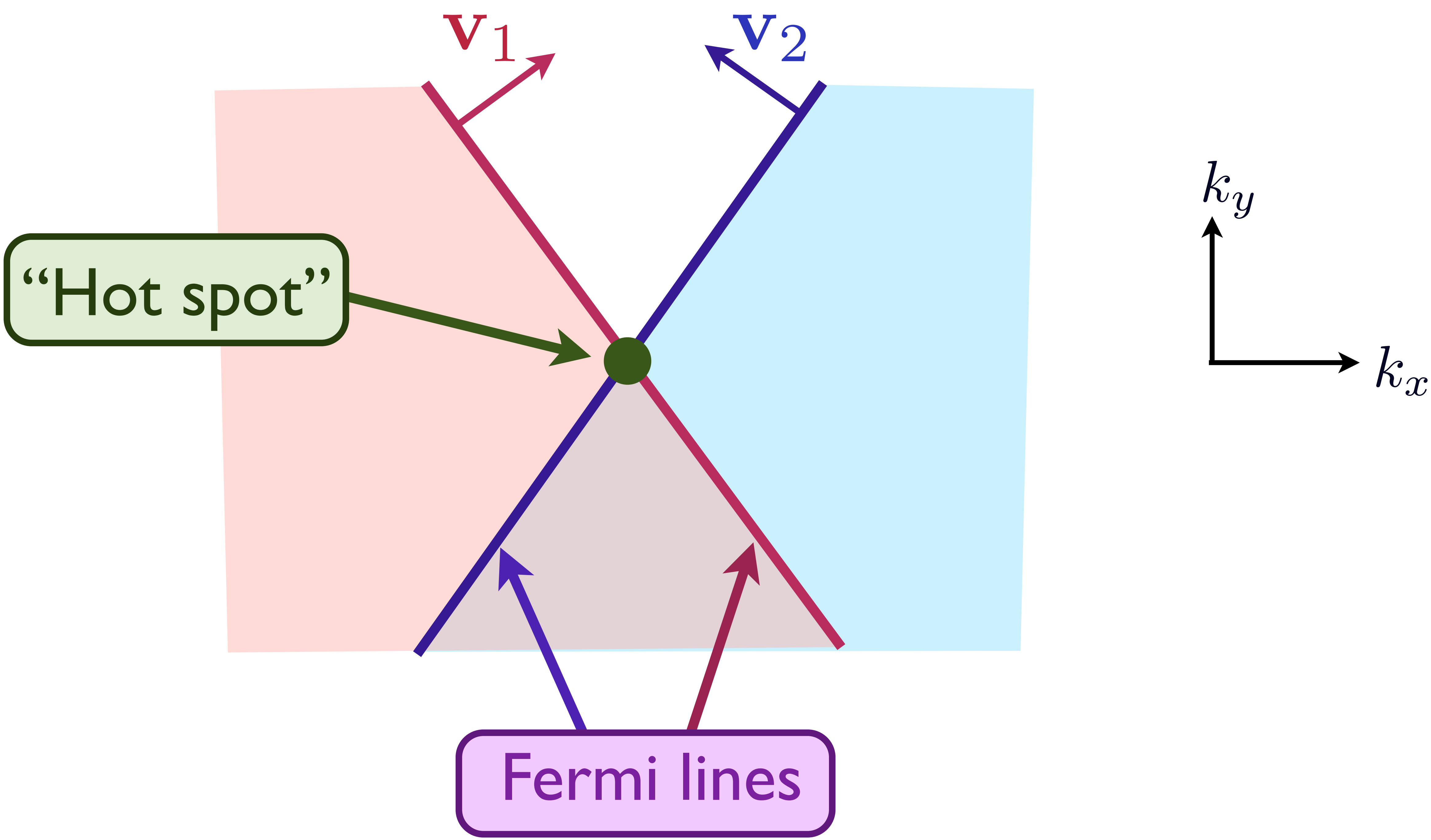
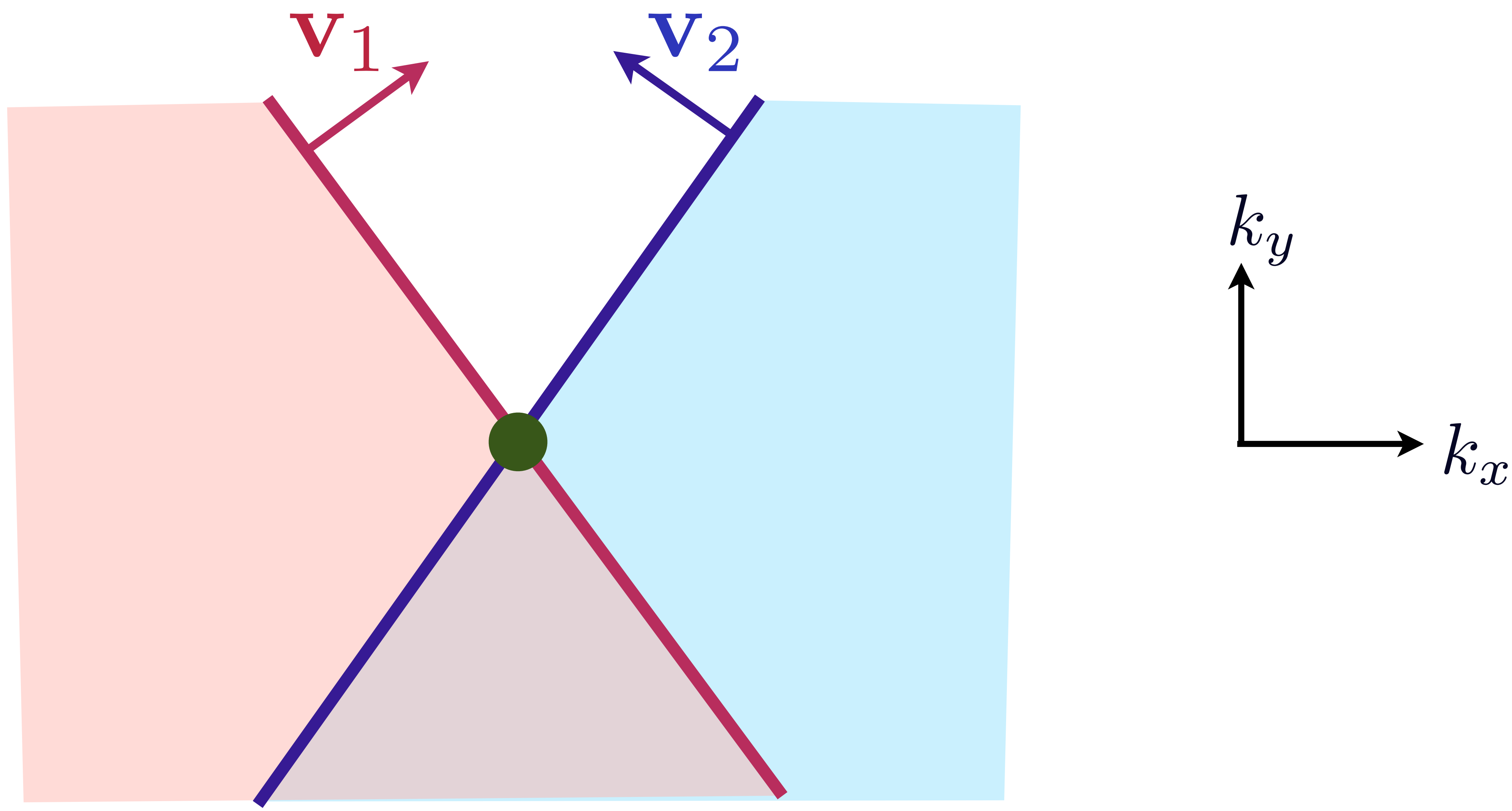


Critical point theory is strongly coupled in $d = 2$
Results are *independent* of coupling λ



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

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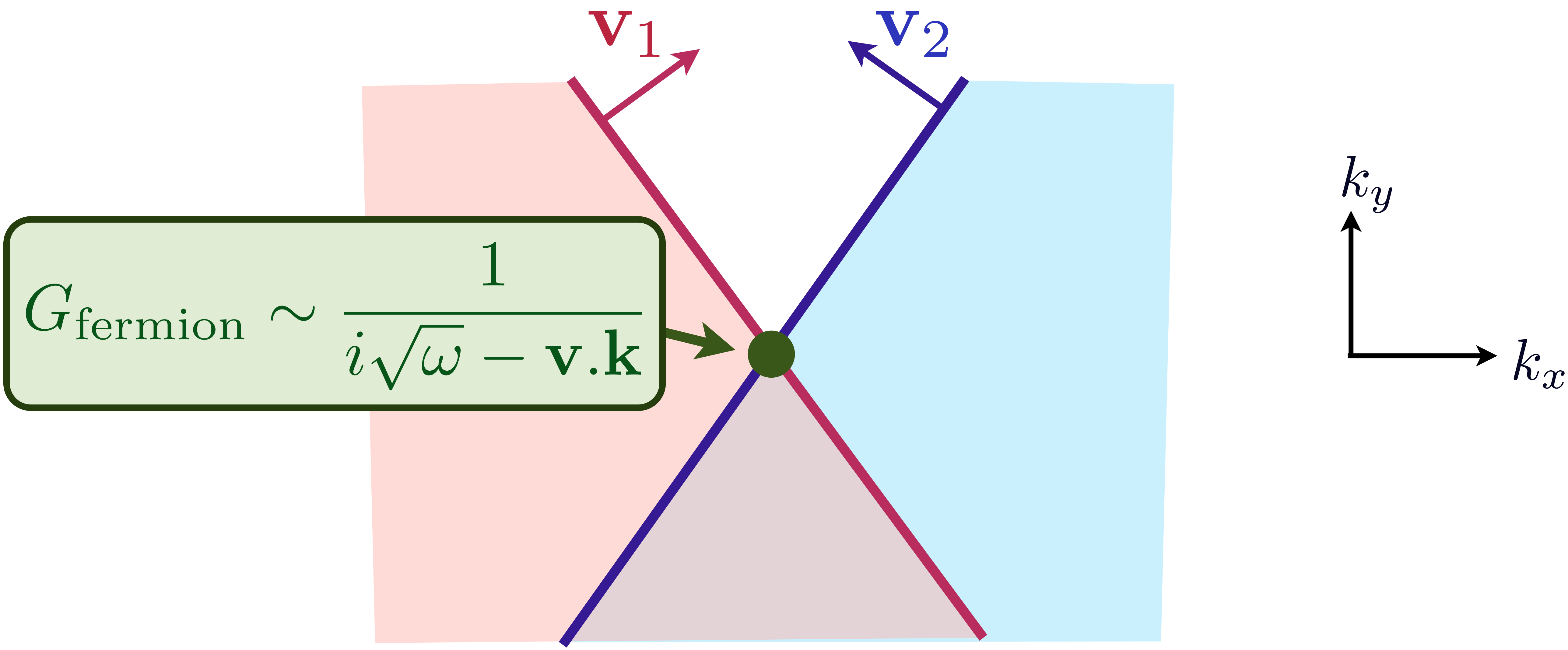

A. J. Millis, *Phys. Rev. B* **45**, 13047 (1992)
Ar. Abanov and A.V. Chubukov, *Phys. Rev. Lett.* **93**, 255702 (2004)

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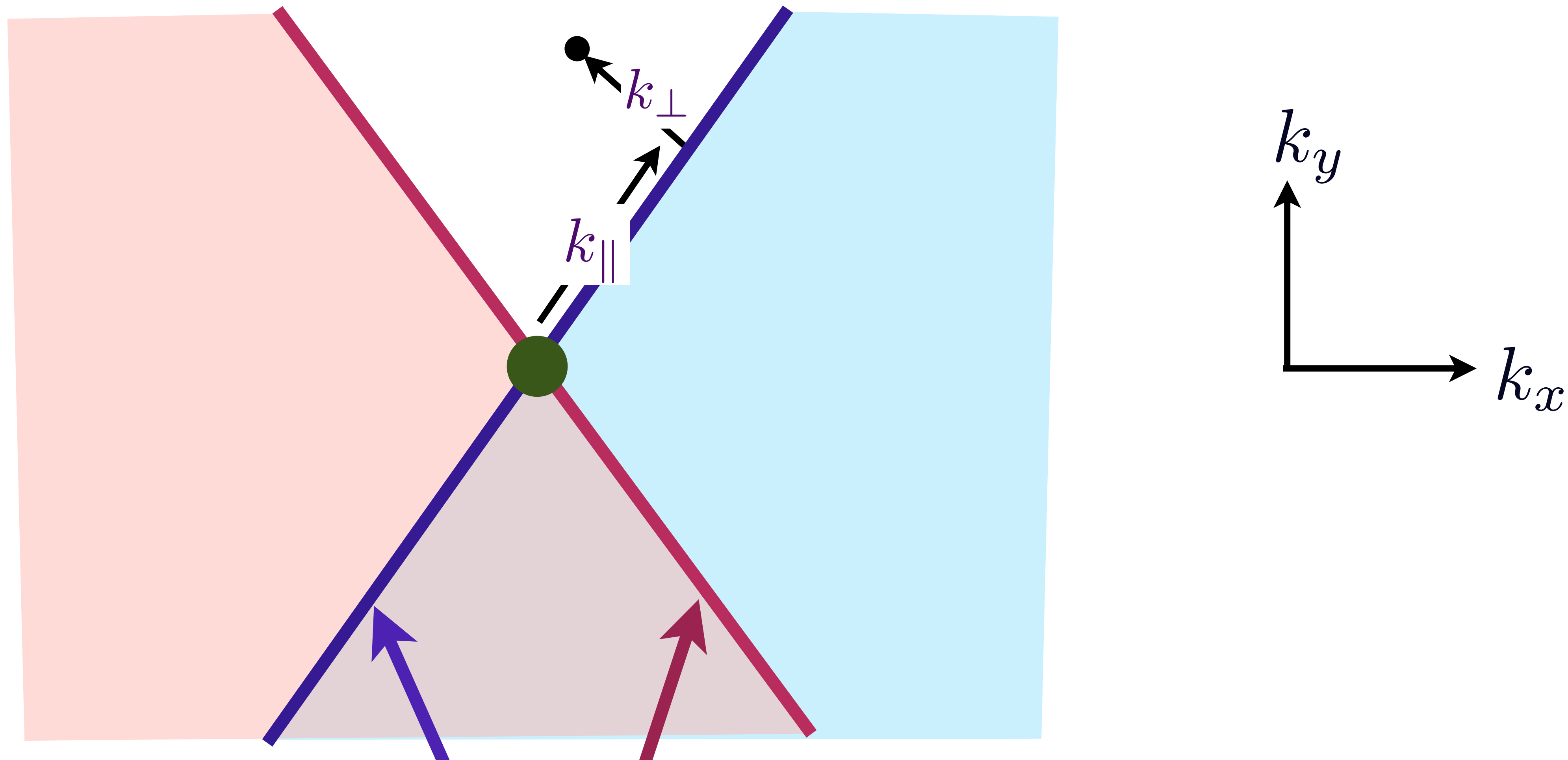

$$G_{\text{fermion}} = \frac{Z(k_\parallel)}{i\omega - v_F(k_\parallel)k_\perp}, \quad Z(k_\parallel) \sim v_F(k_\parallel) \sim k_\parallel$$

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

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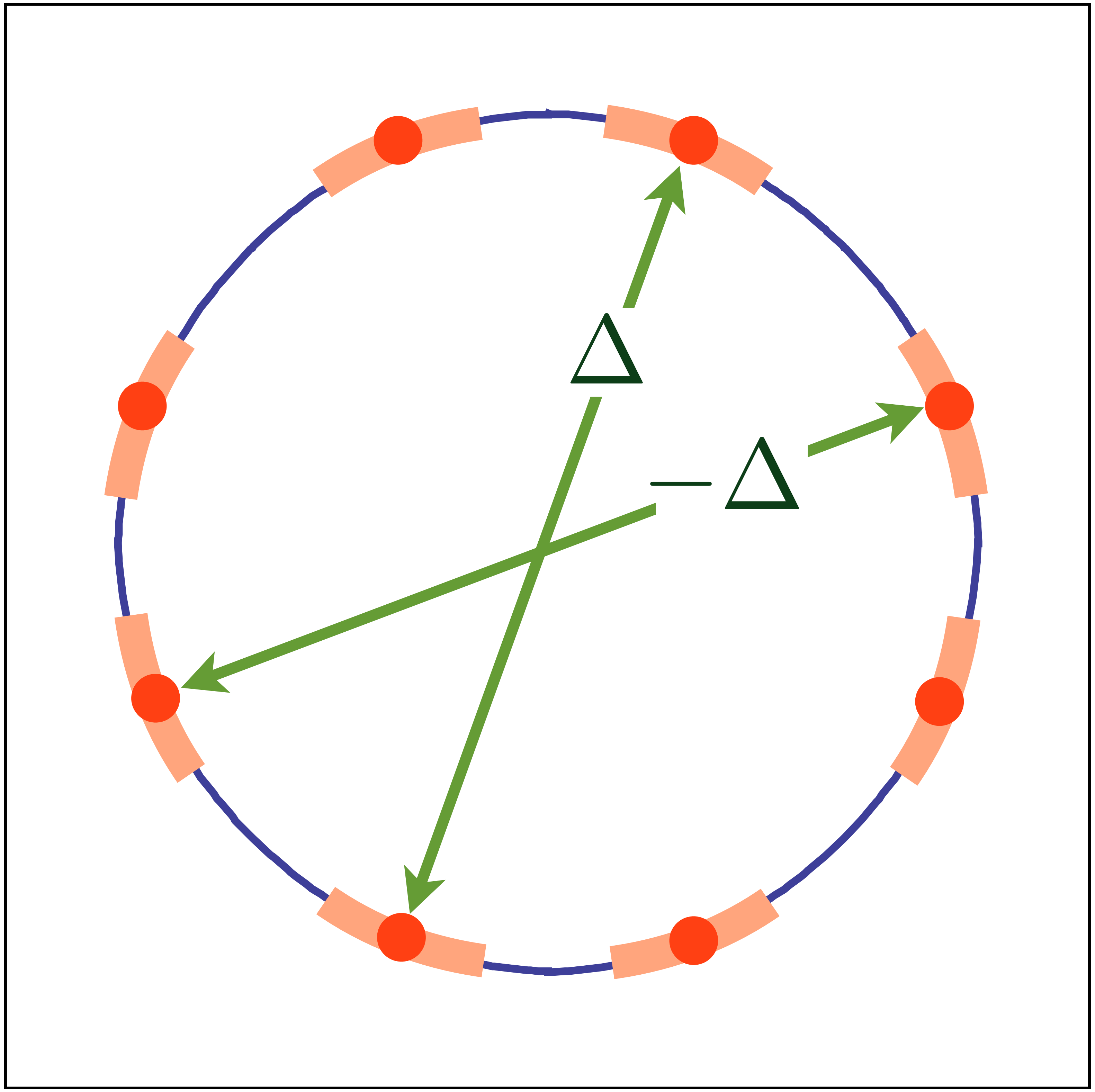
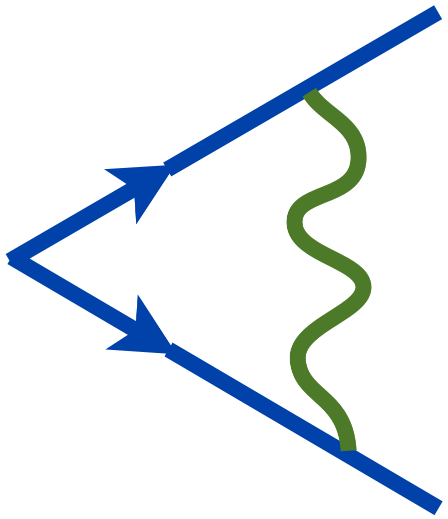


Unconventional pairing at *and near* hot spots

BCS theory



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

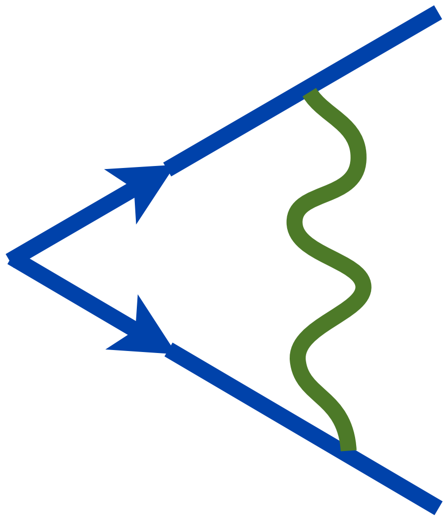
Electron-phonon coupling

Debye frequency

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

Enhancement of pairing susceptibility by interactions

Antiferromagnetic fluctuations: weak-coupling



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

Applies in a Fermi liquid as repulsive interaction $U \to 0$.

Fermi energy

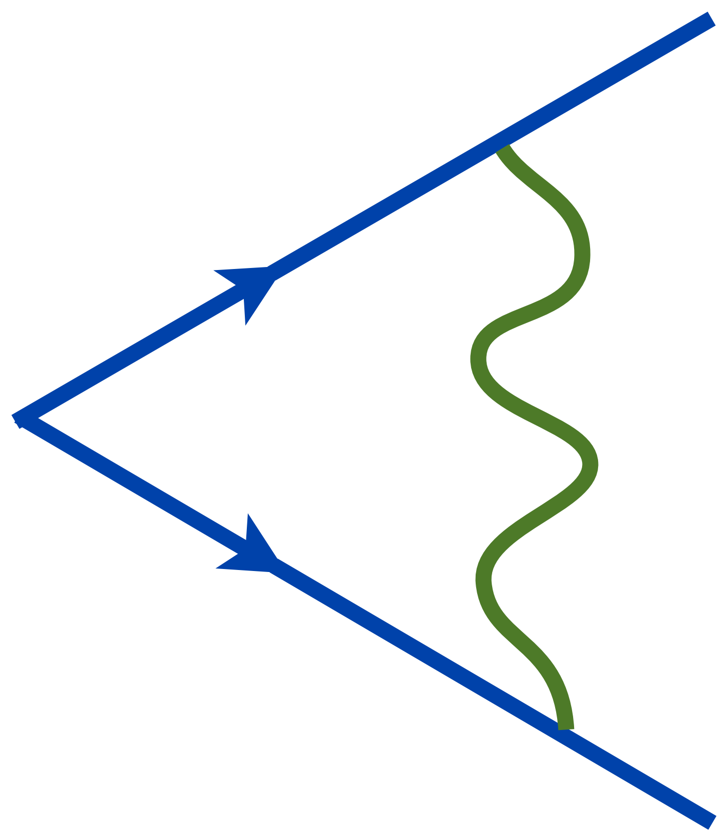
Implies $T_c \sim E_F \exp\left(-(t/U)^2\right)$

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)

Enhancement of pairing susceptibility by interactions

Spin density wave quantum critical point

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



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

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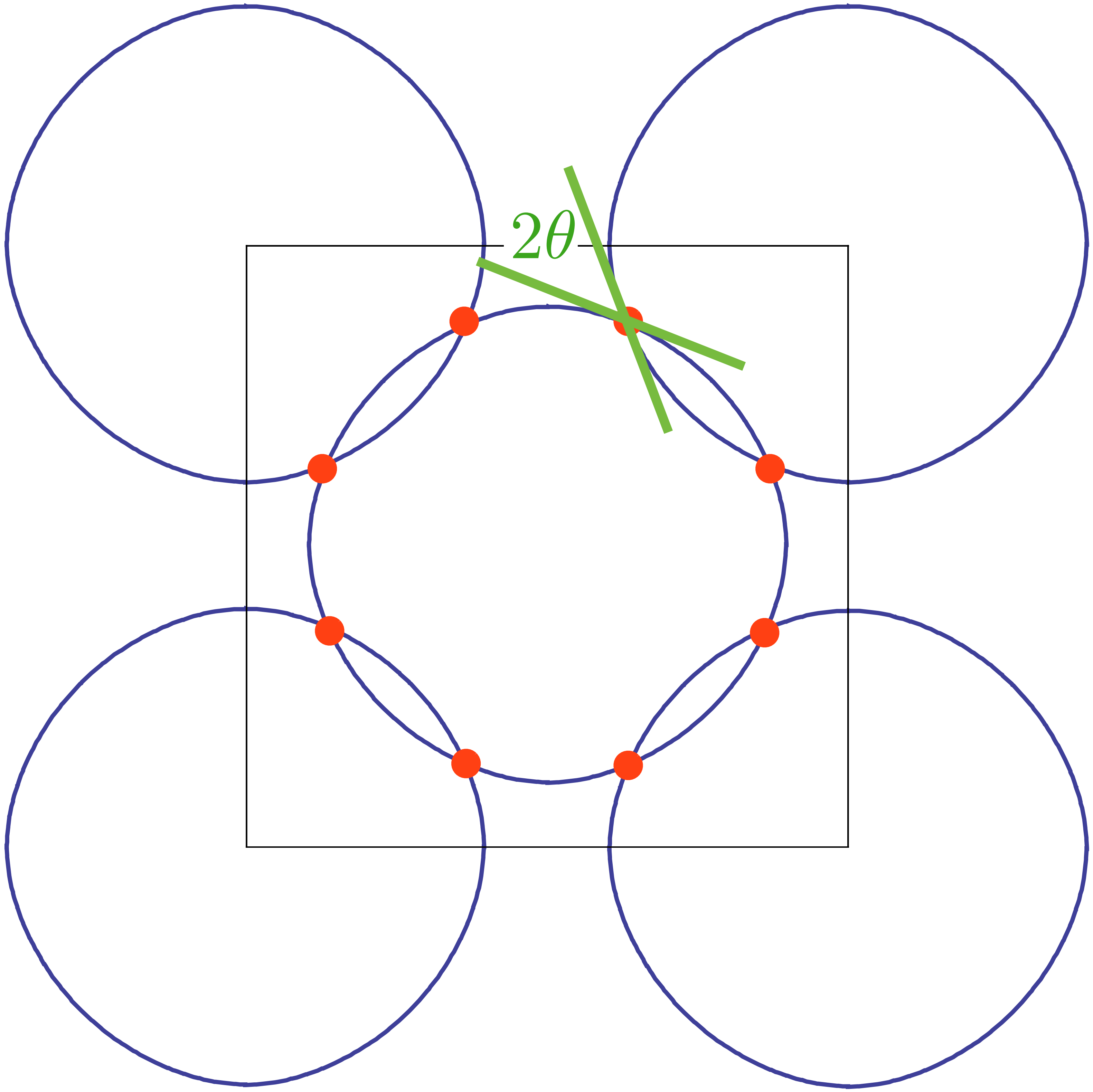
Spin density wave quantum critical point

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

Fermi energy

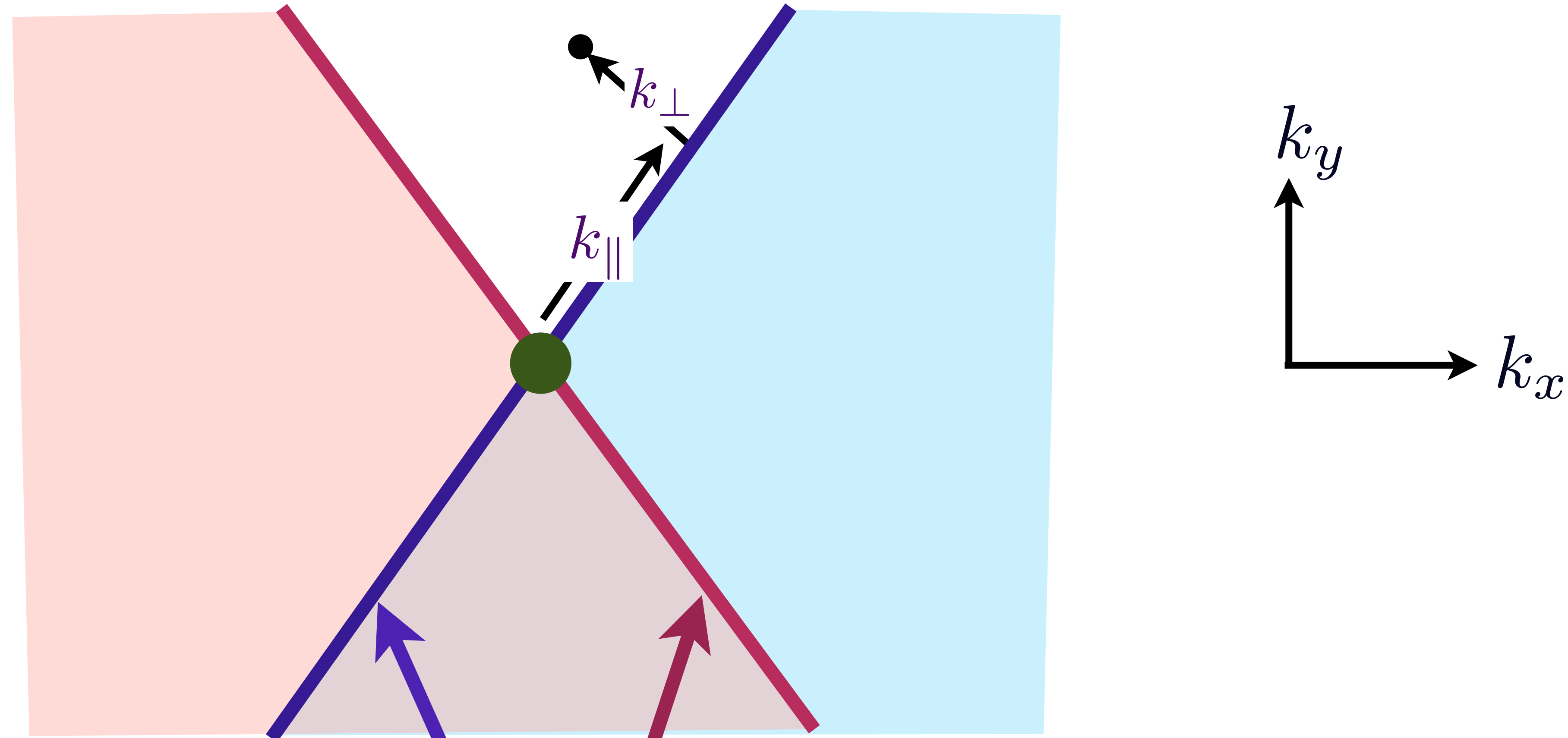
$\alpha = \tan\theta$, where 2θ is the angle between Fermi lines.
Independent of interaction strength U in 2 dimensions.

(see also Ar. Abanov, A.V. Chubukov, and A. M. Finkel'stein, *Europhys. Lett.* **54**, 488 (2001))
M.A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)



2θ

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



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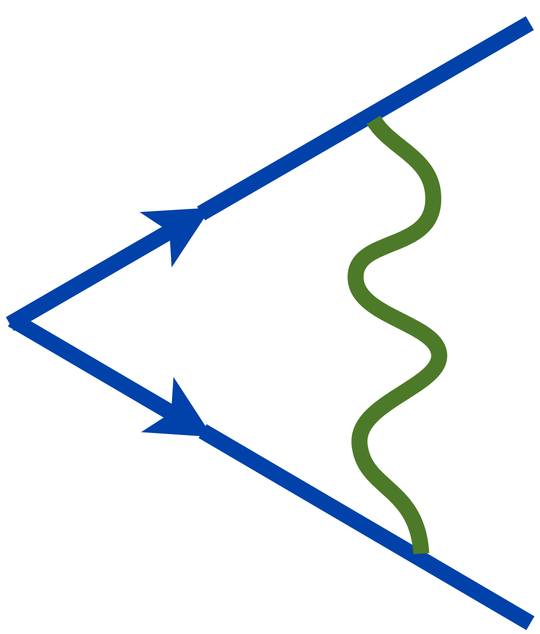
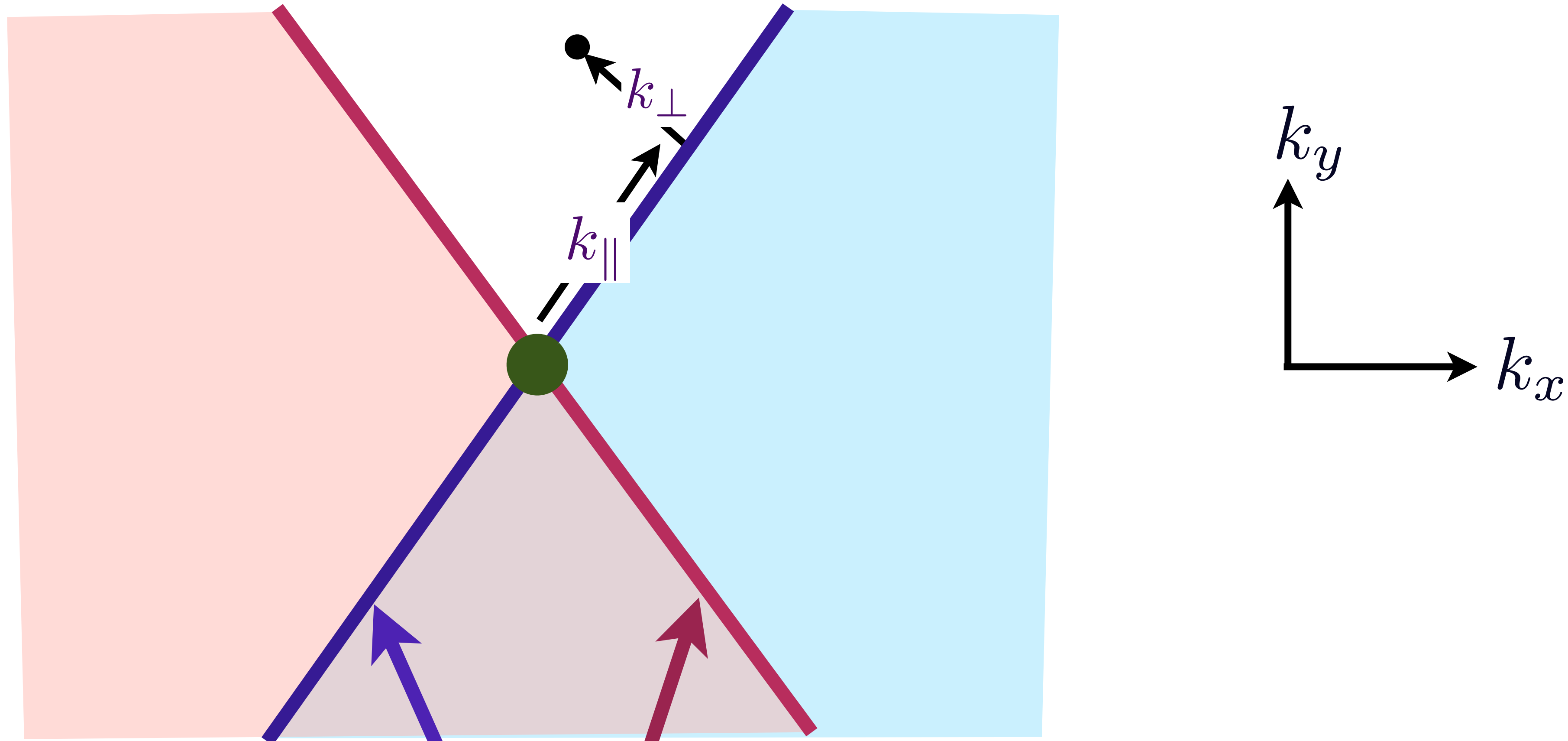


$$\int dk_\parallel \, \frac{1}{k_\parallel^2} \left(\frac{Z^2(k_\parallel)}{v_F(k_\parallel)} \right) \log \frac{k_\parallel^2}{\omega}$$

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



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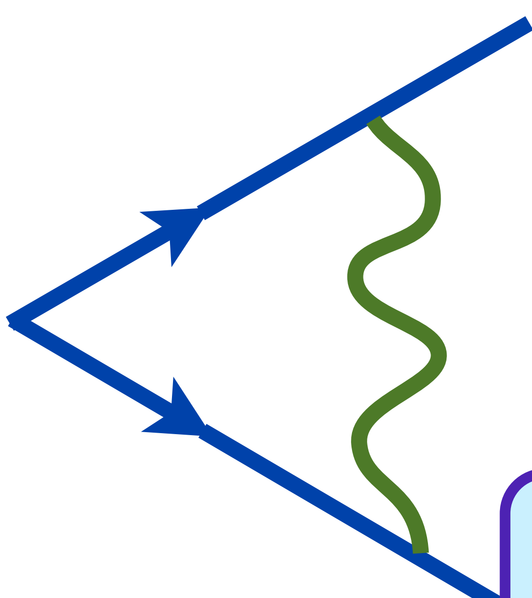


$$\int dk_\parallel \, \frac{1}{k_\parallel^2} \left(\frac{Z^2(k_\parallel)}{v_F(k_\parallel)} \right) \log \frac{k_\parallel^2}{\omega}$$

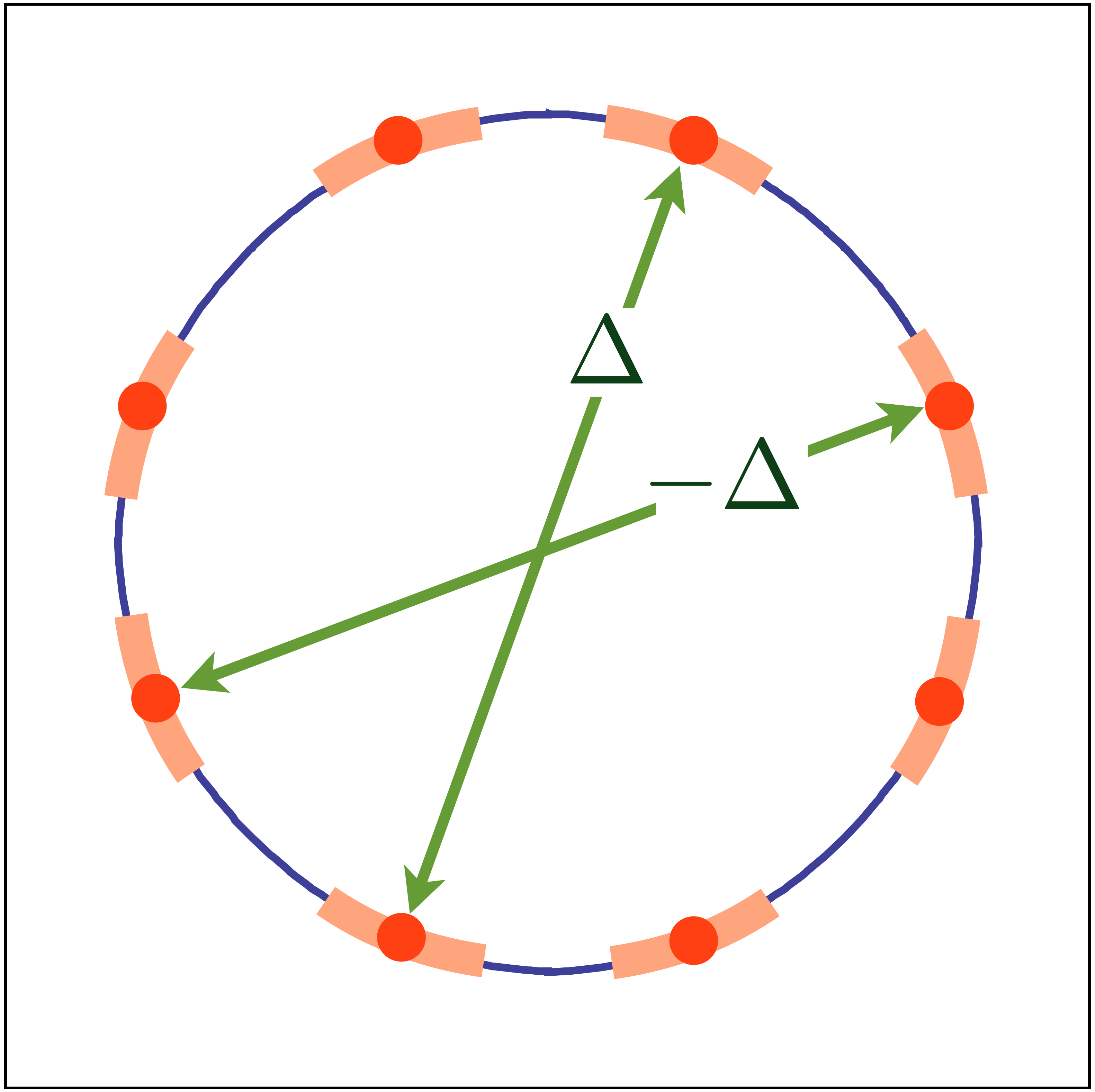
Spin fluctuation propagator

Cooper logarithm

Is there a *log*^{2} for any other susceptibility ?

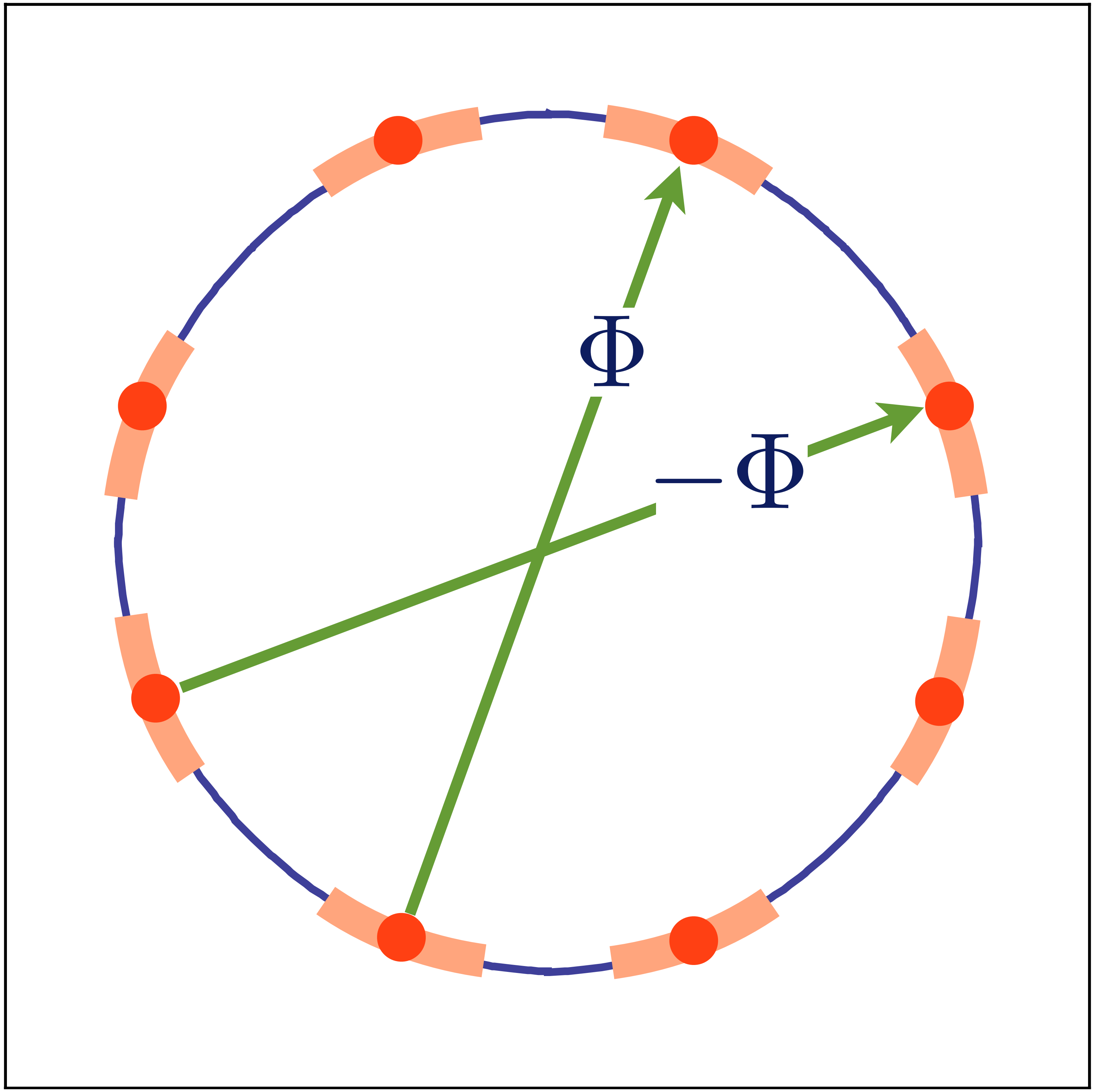
Only one other

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



Unconventional pairing at *and near* hot spots

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



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

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

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 order*

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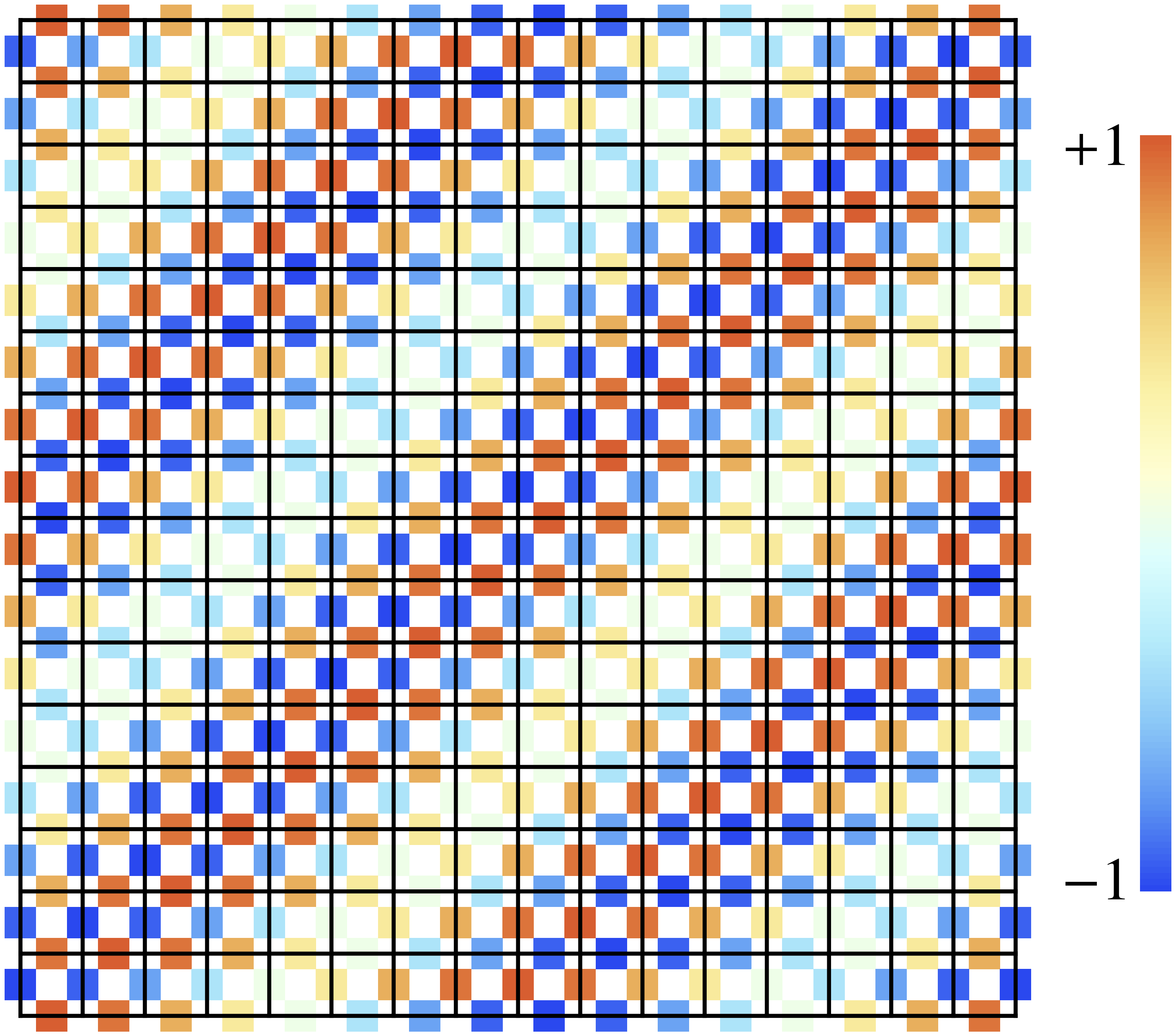
$2k_F$ bond-nematic order



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

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

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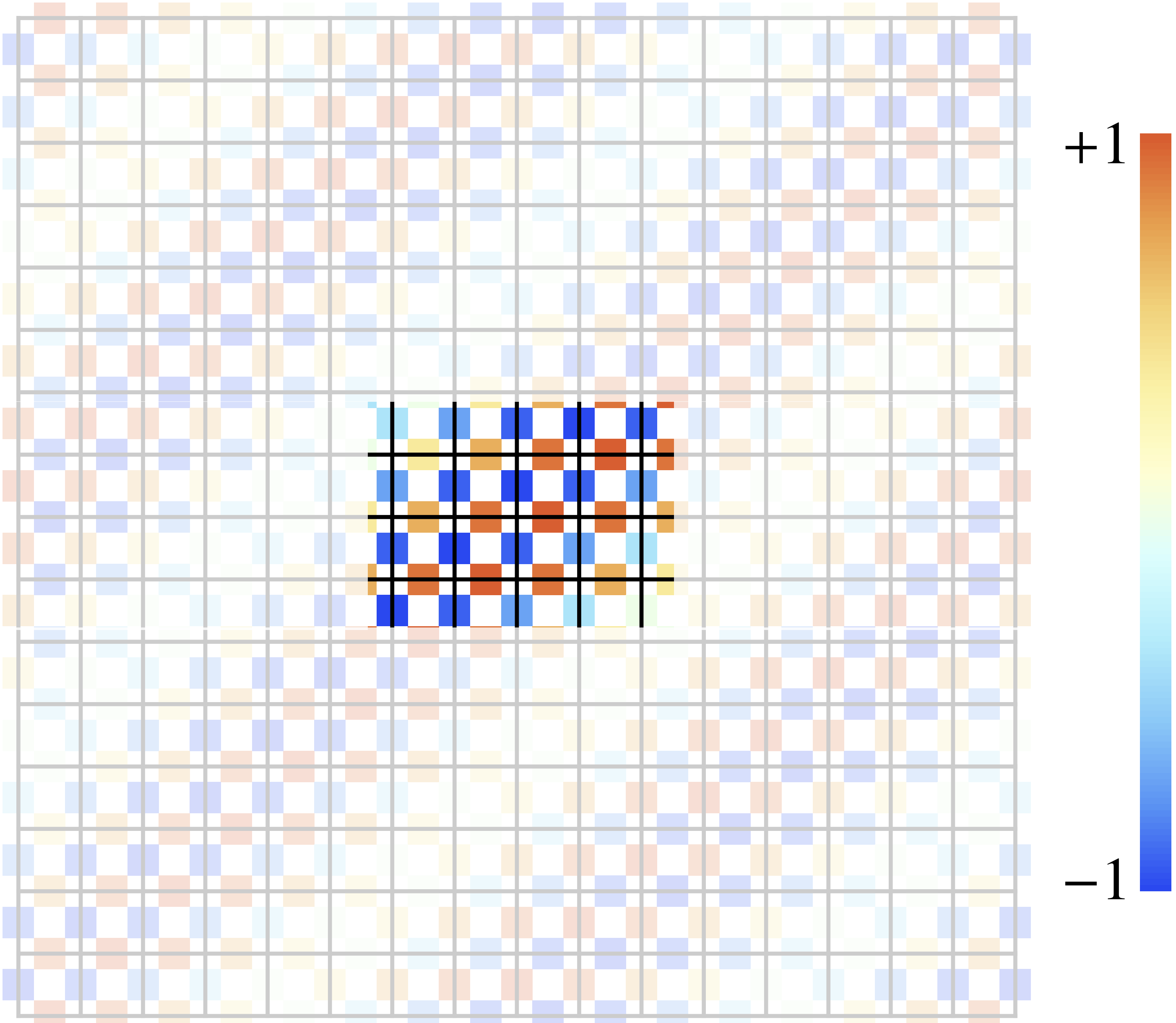
$2k_F$ bond-nematic order



Local Ising nematic order with an envelope which oscillates

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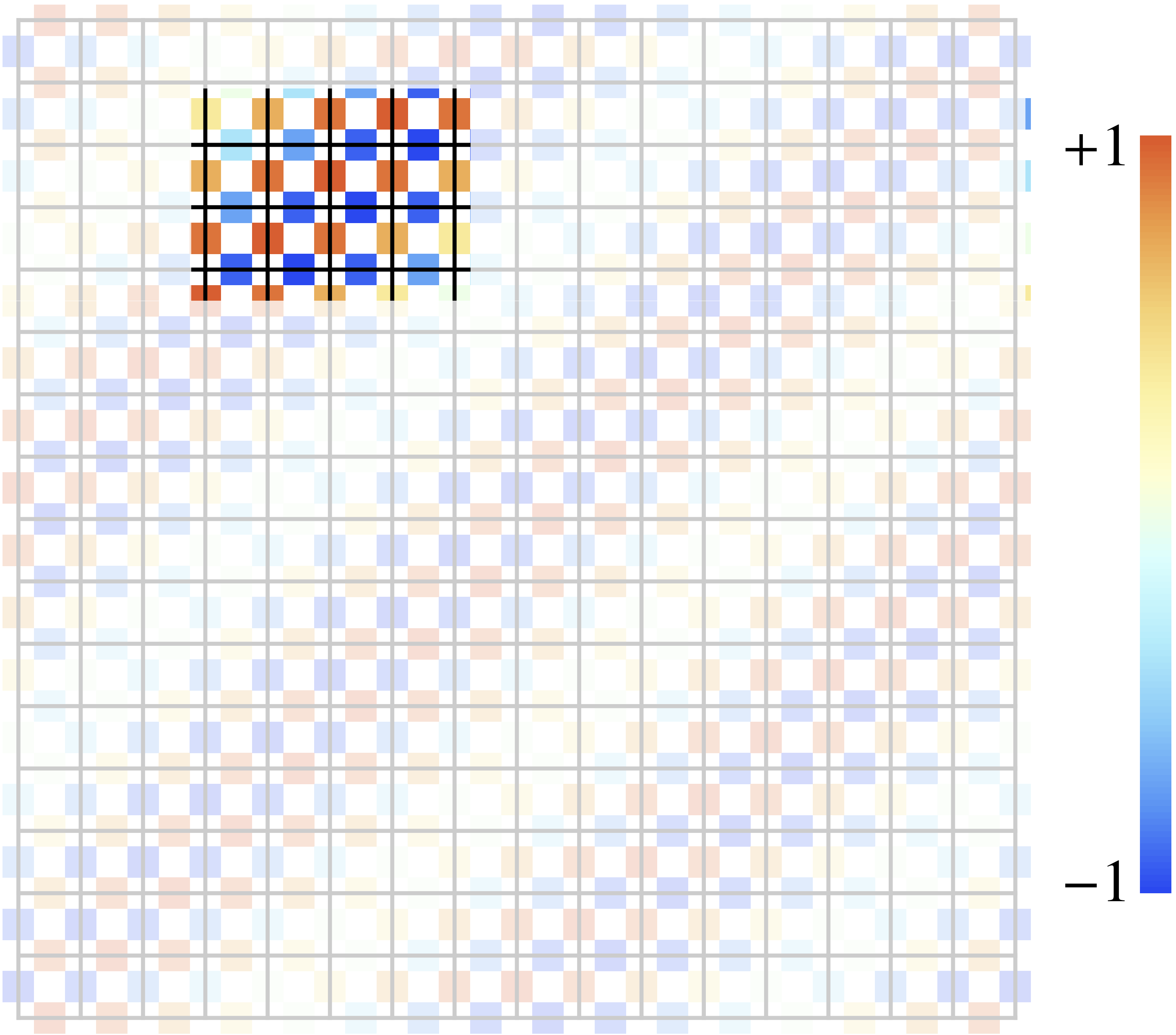

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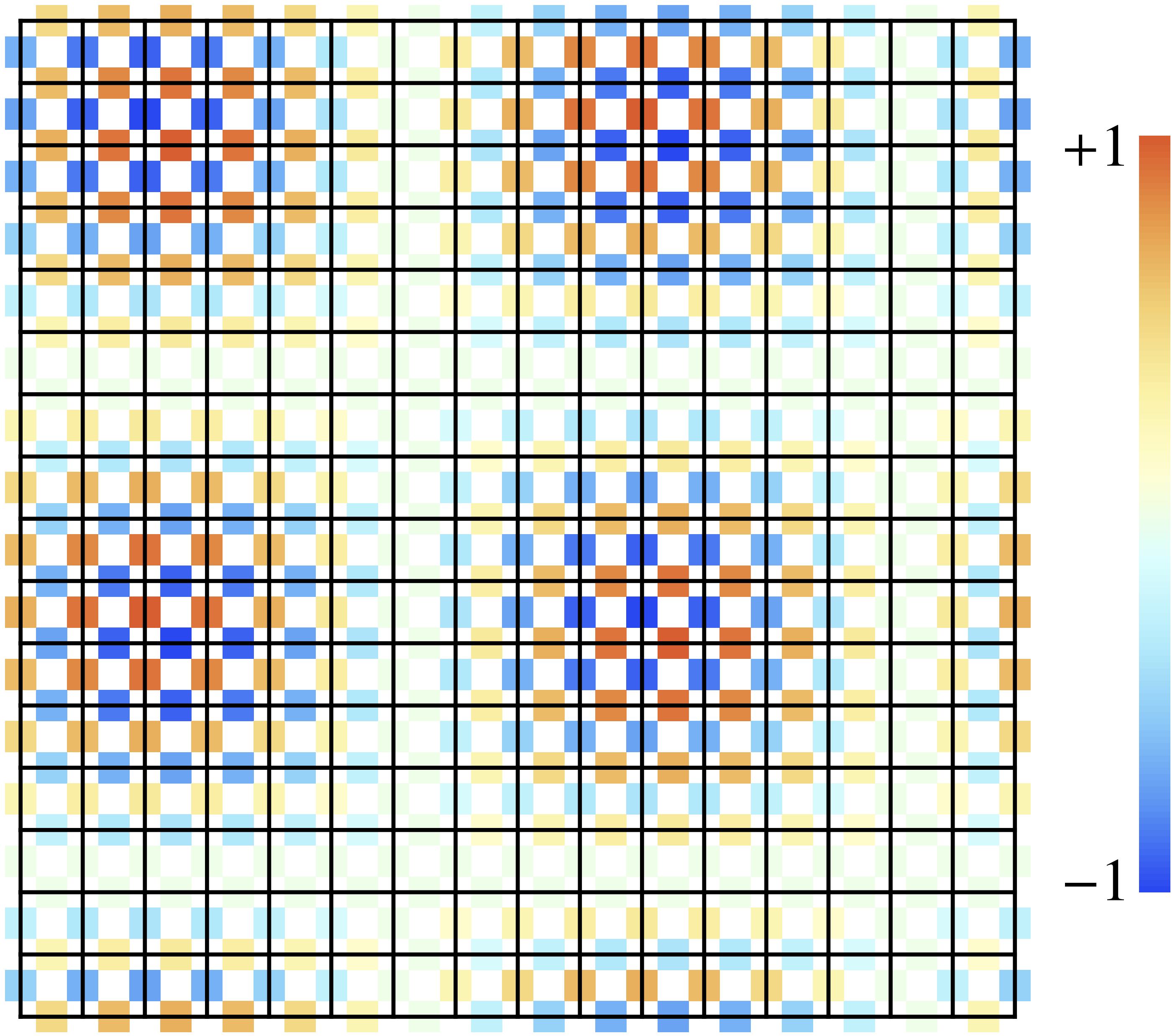

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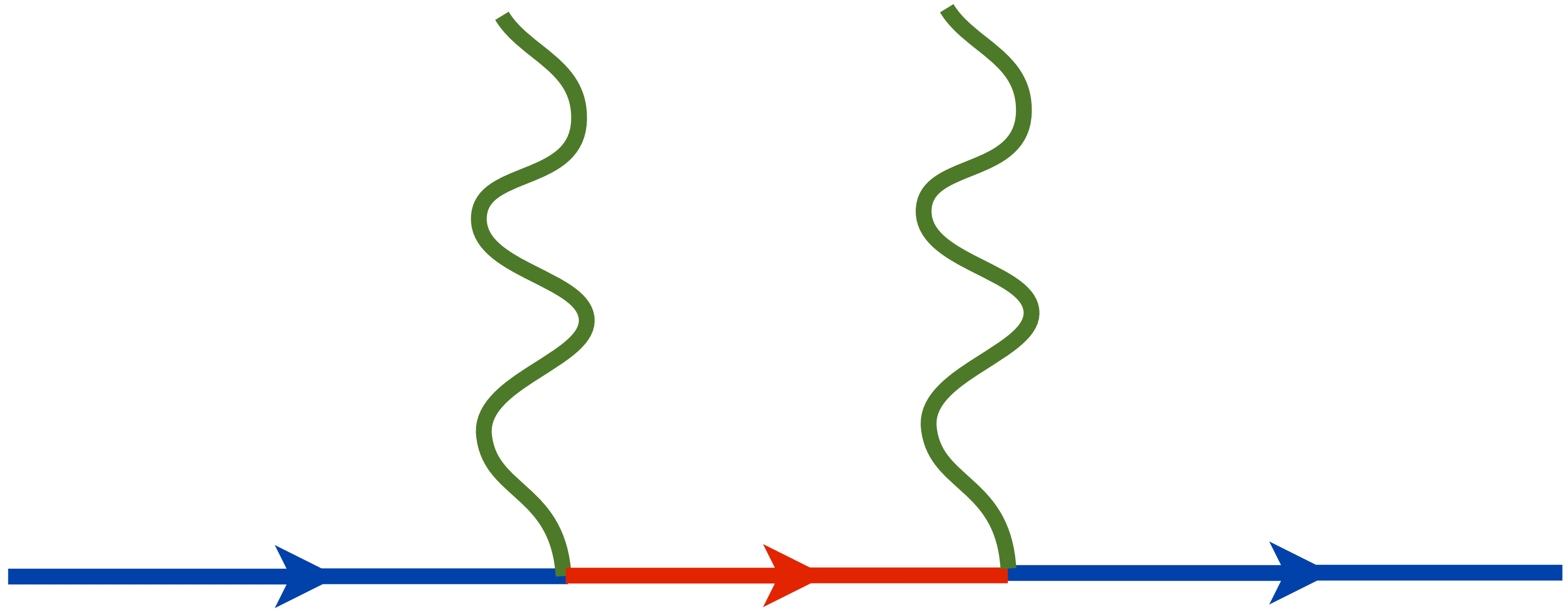
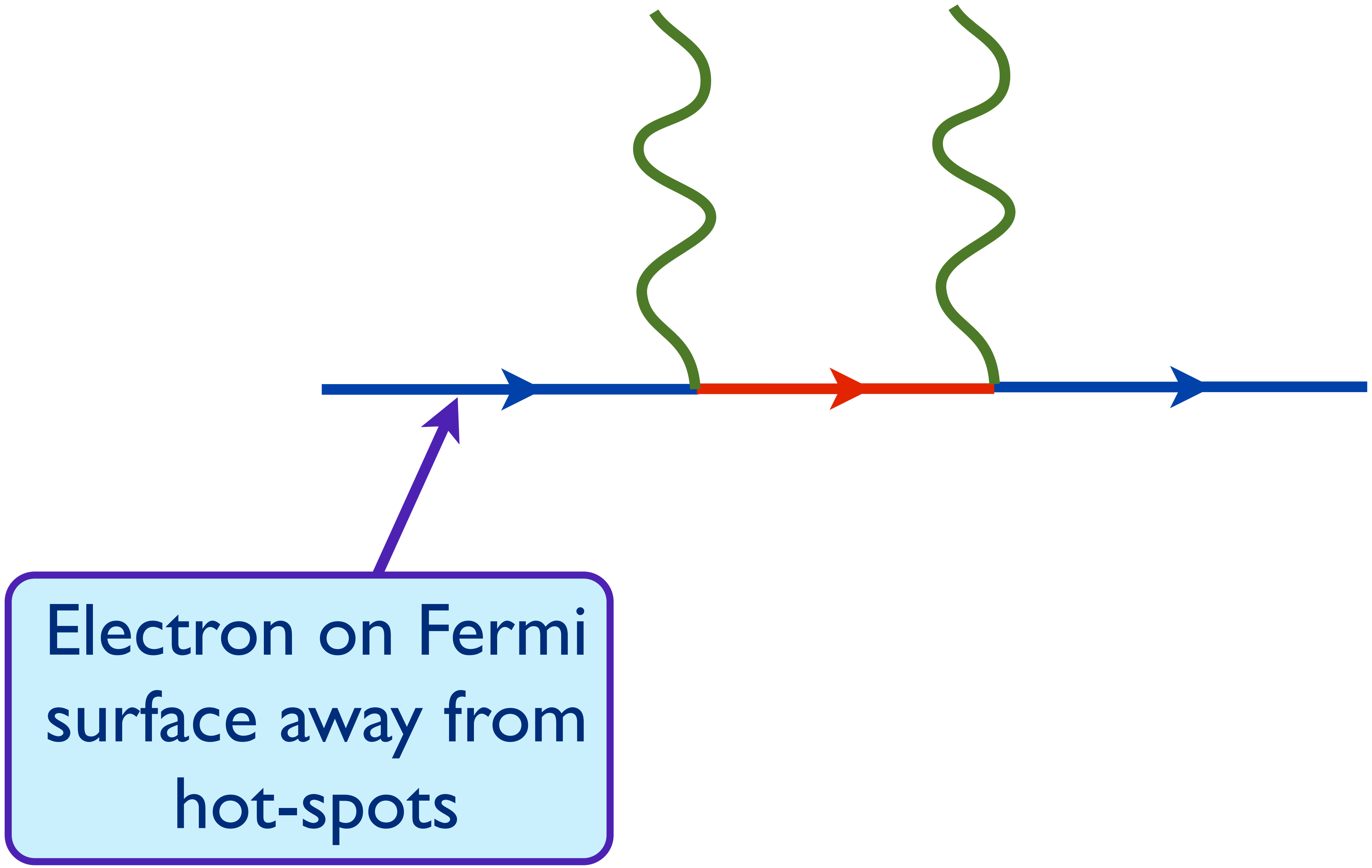
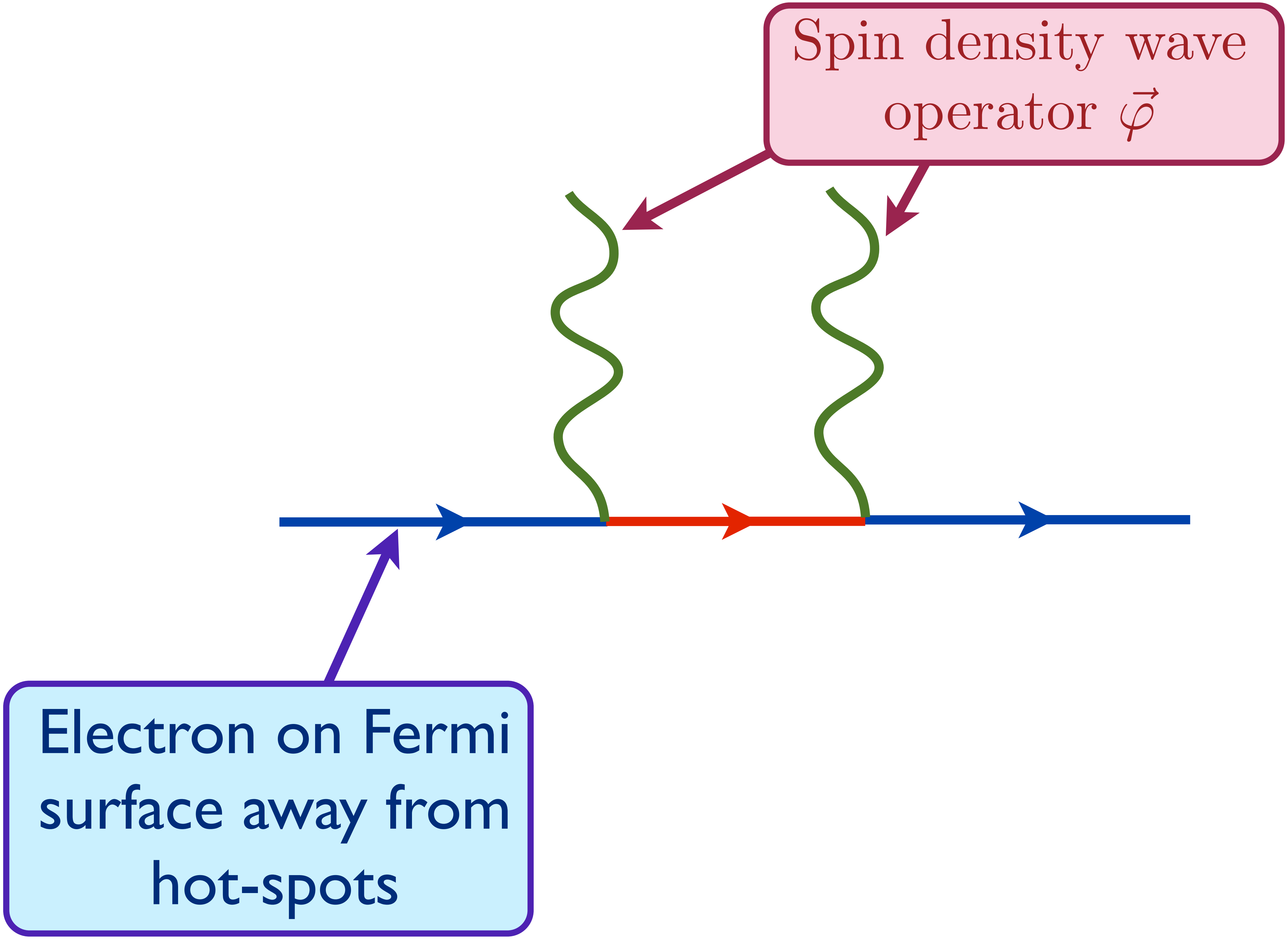
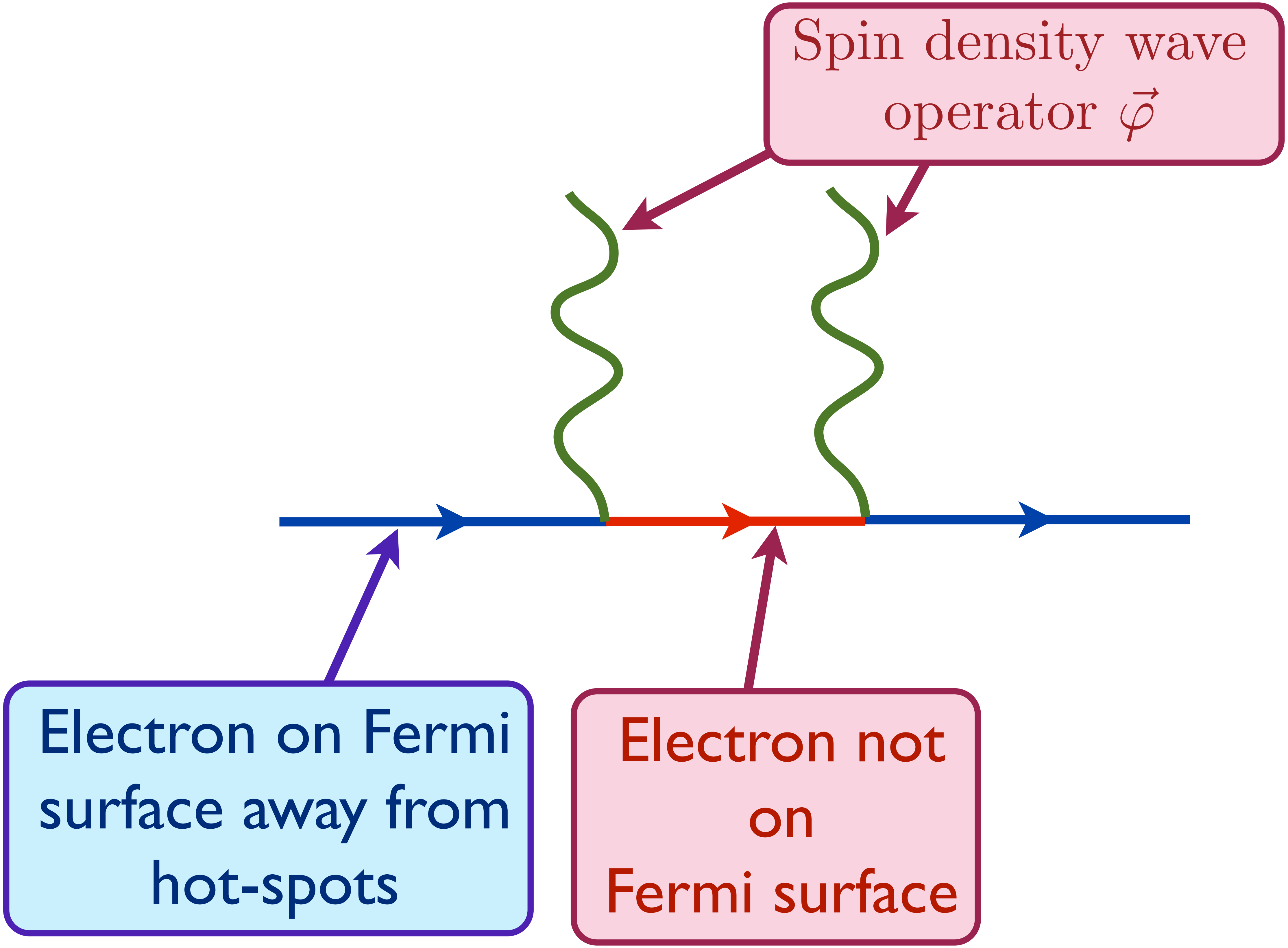
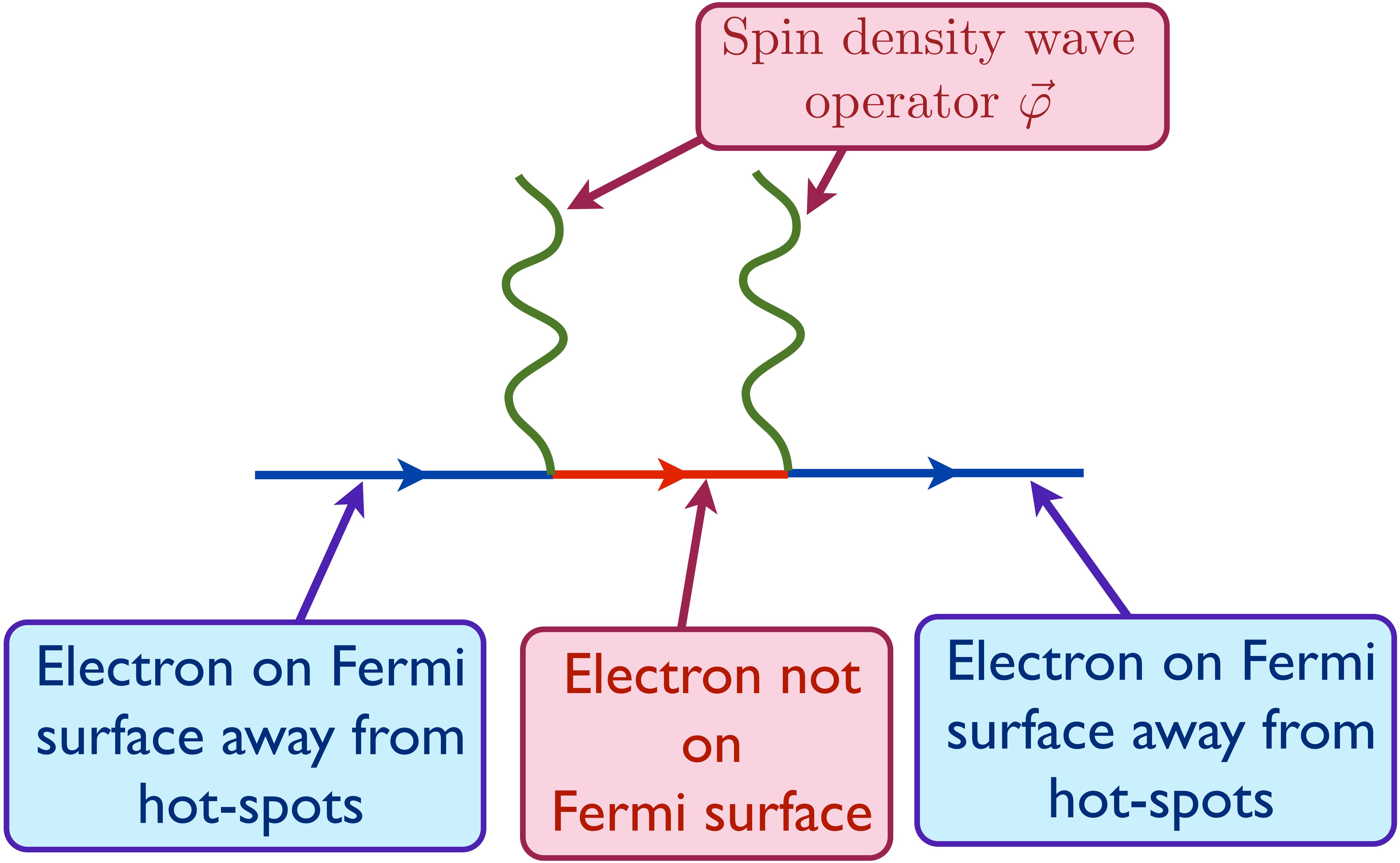



Electron on Fermi
surface away from
hot-spots

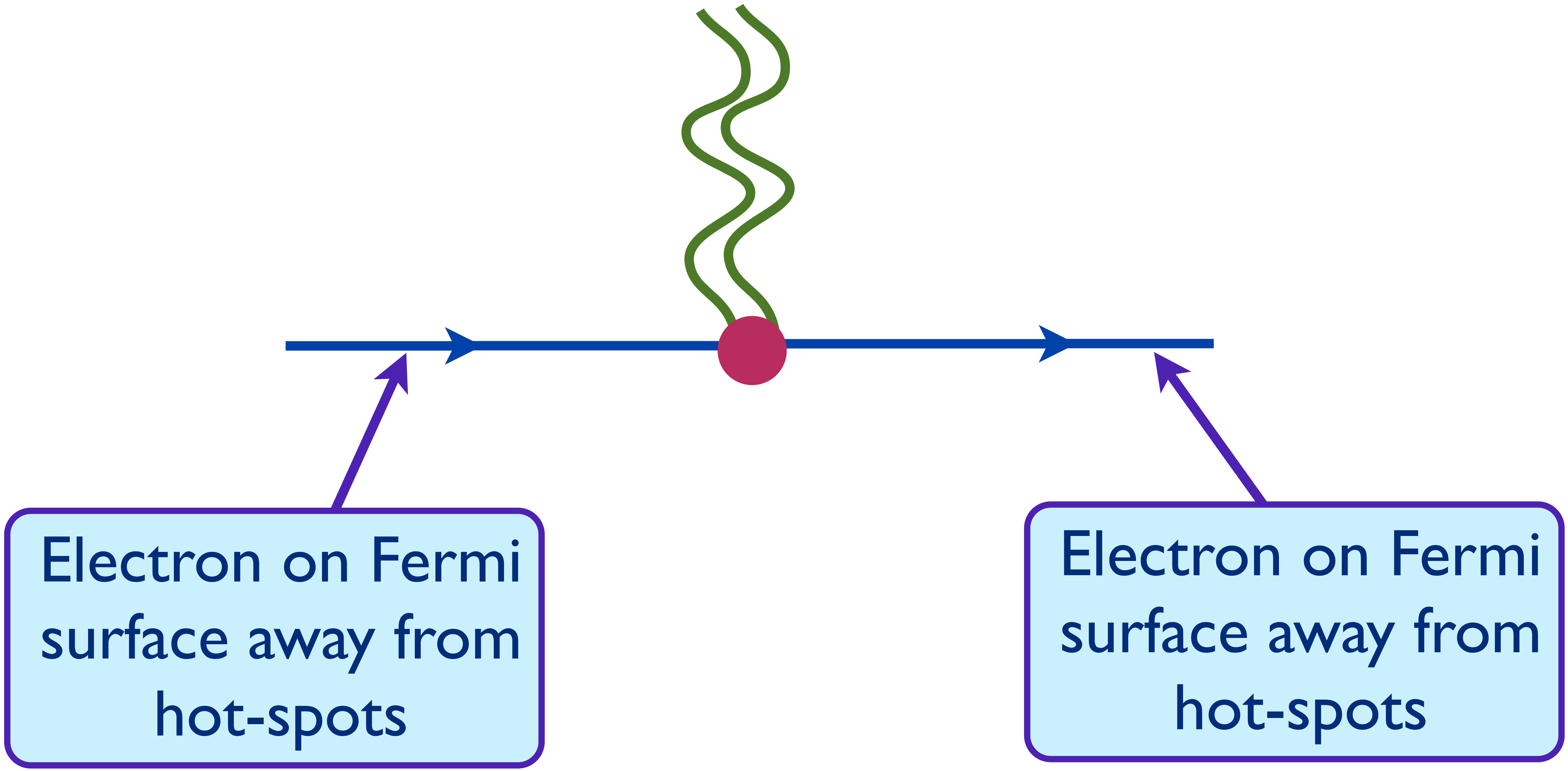

Spin density wave operator $\vec{\varphi}$
Electron on Fermi surface away from hot-spots



Spin density wave operator $\vec{\varphi}$
Electron on Fermi surface away from hot-spots
Electron not on Fermi surface



Spin density wave operator $\vec{\varphi}$
Electron on Fermi surface away from hot-spots
Electron not on Fermi surface
Electron on Fermi surface away from hot-spots


Electron on Fermi surface away from hot-spots
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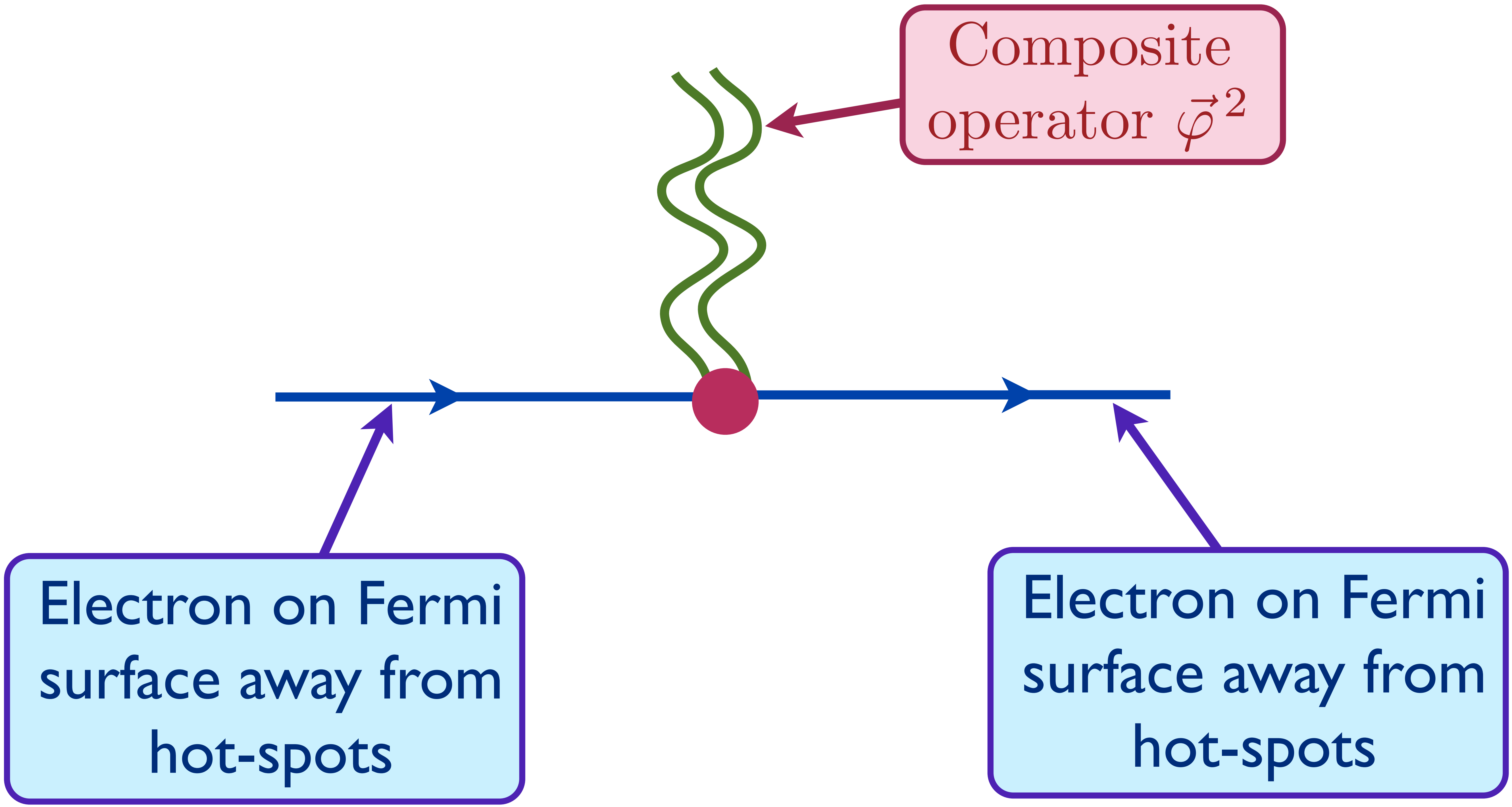
Composite operator $\vec{\varphi}^2$
Electron on Fermi surface away from hot-spots
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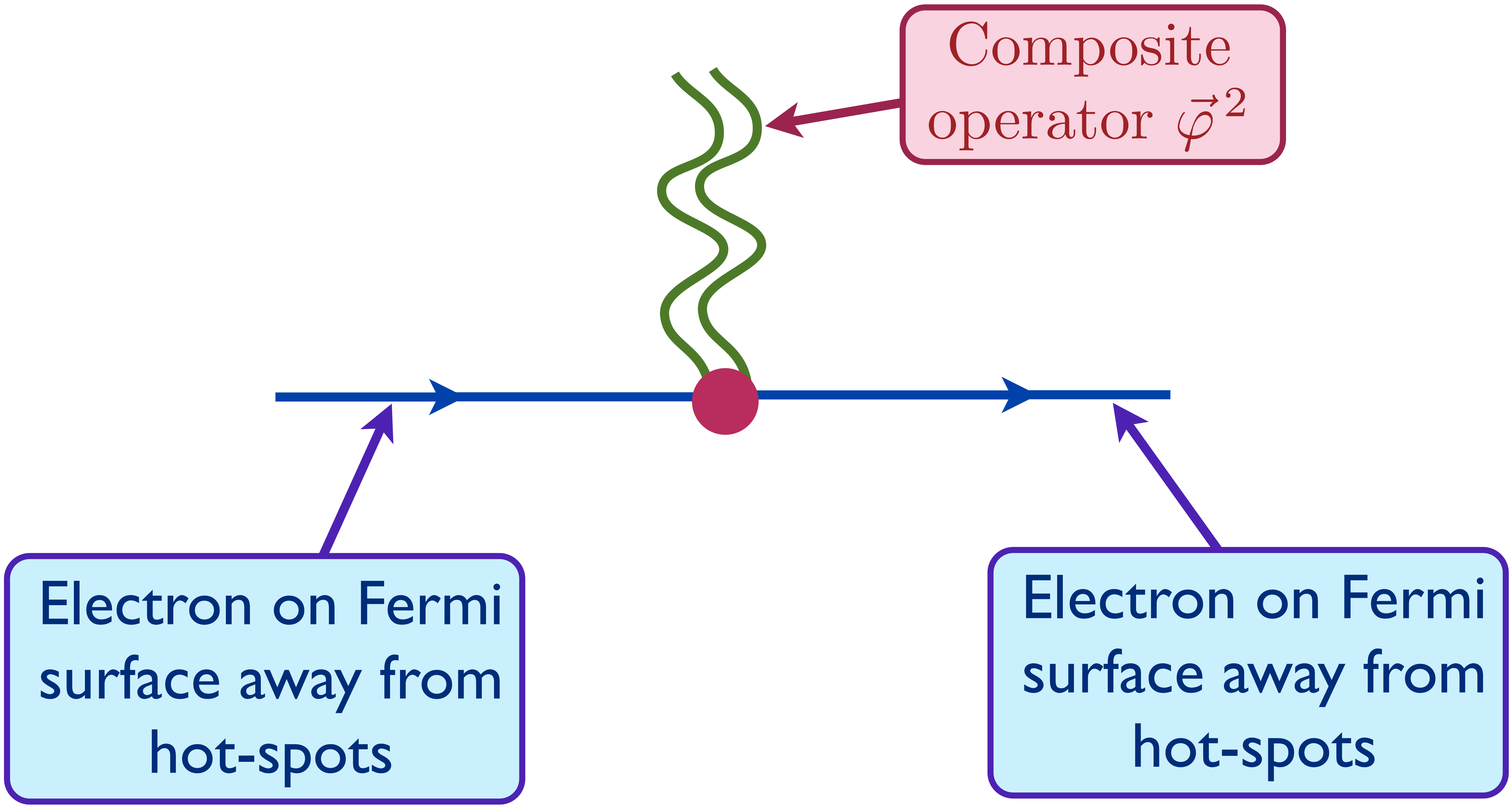
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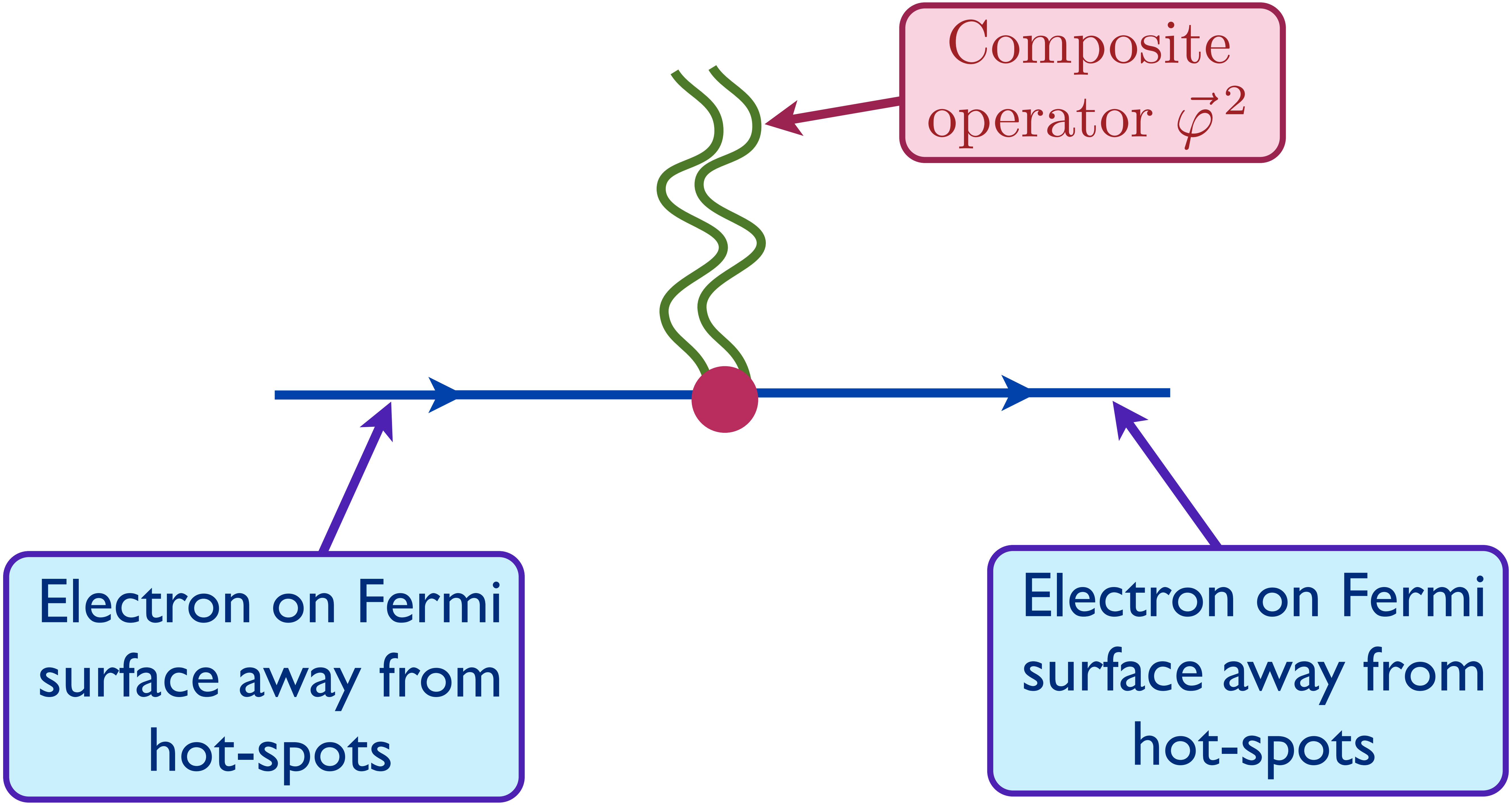
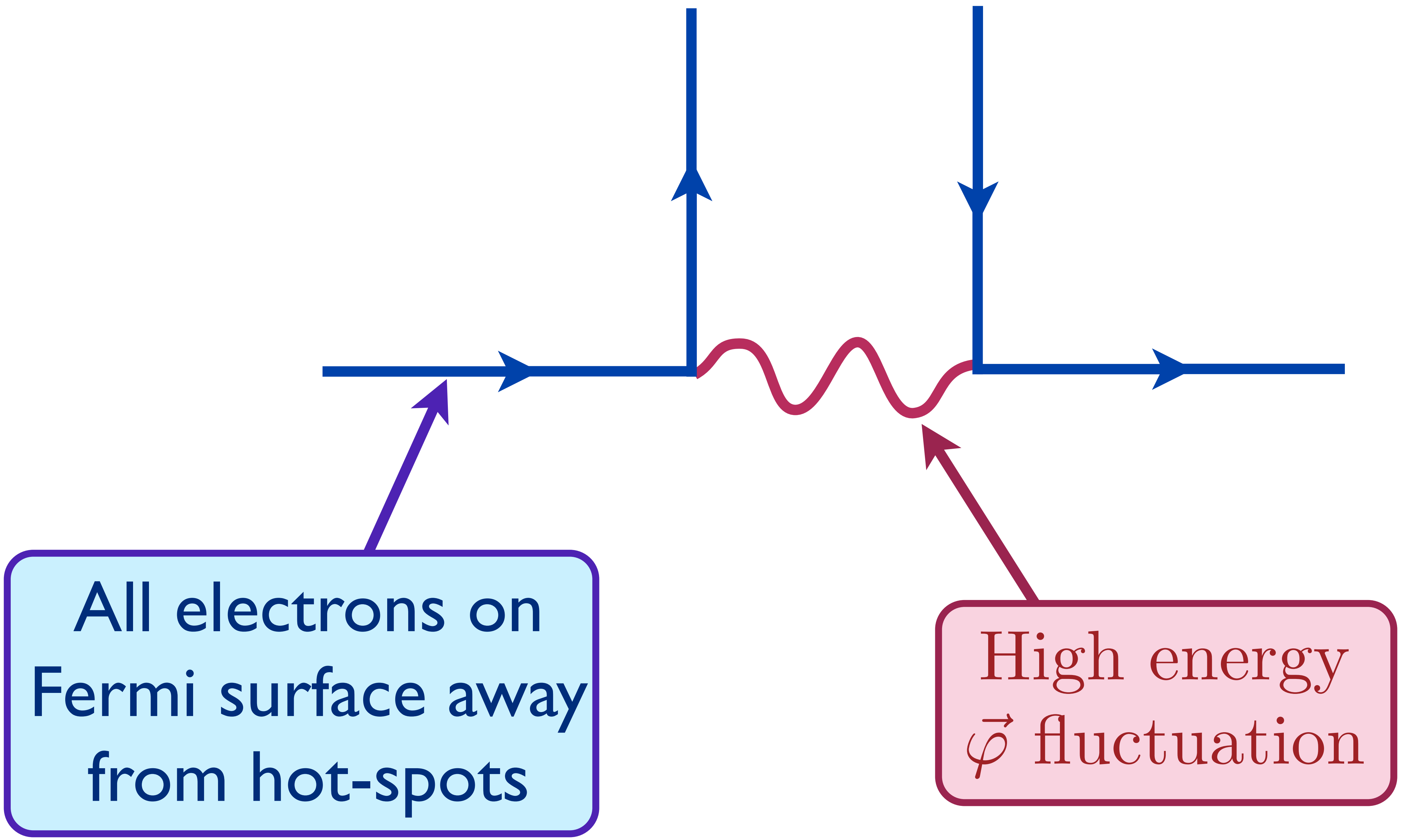
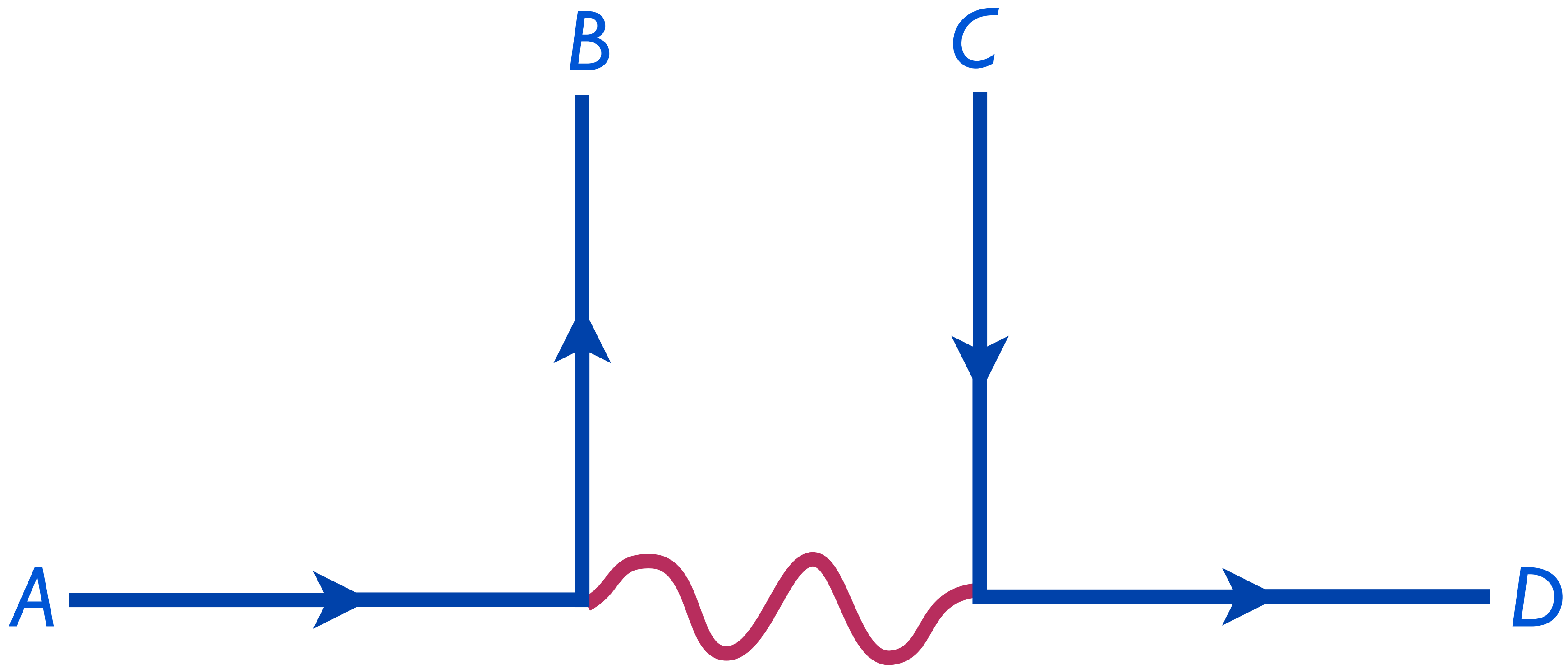
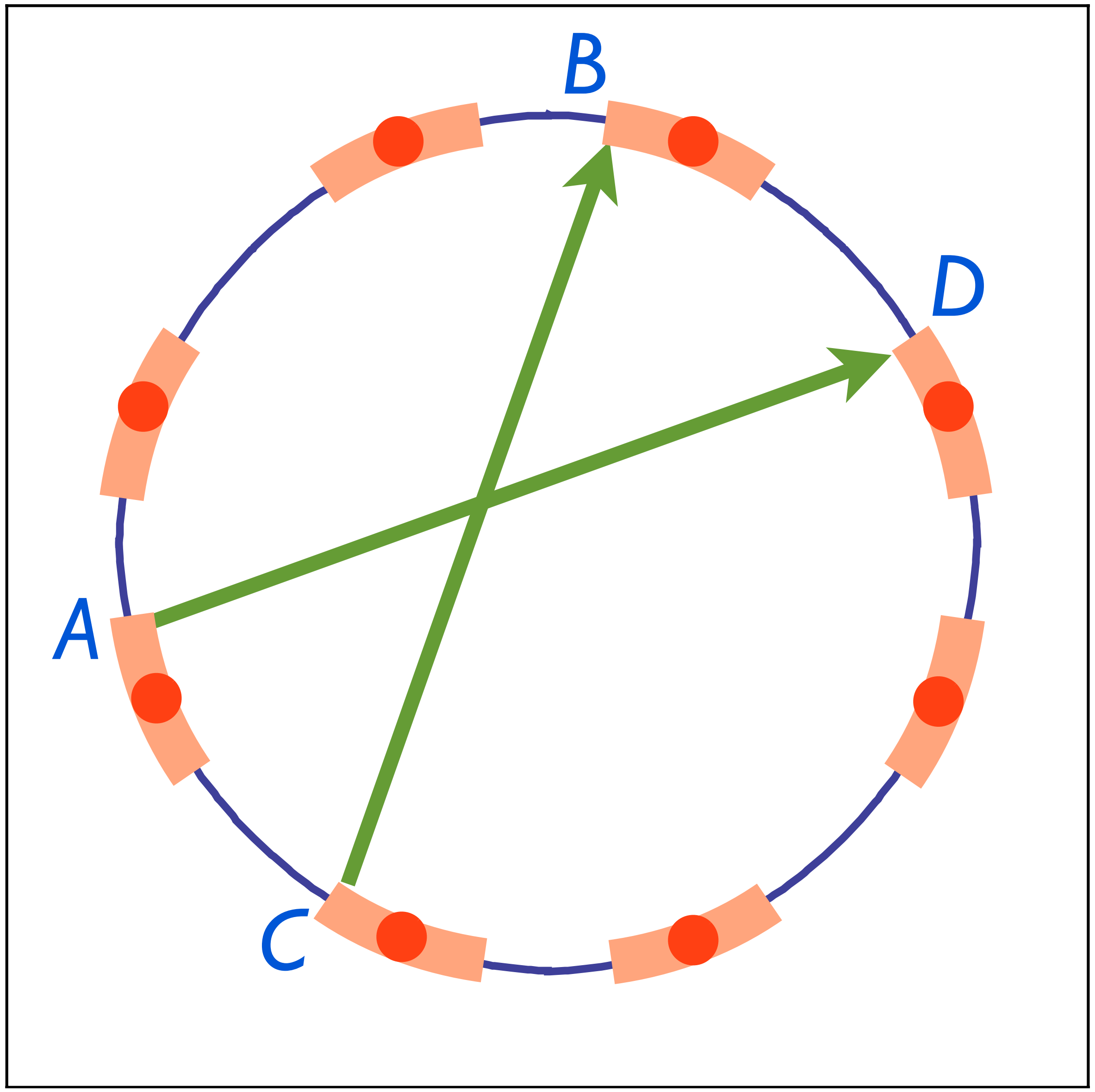
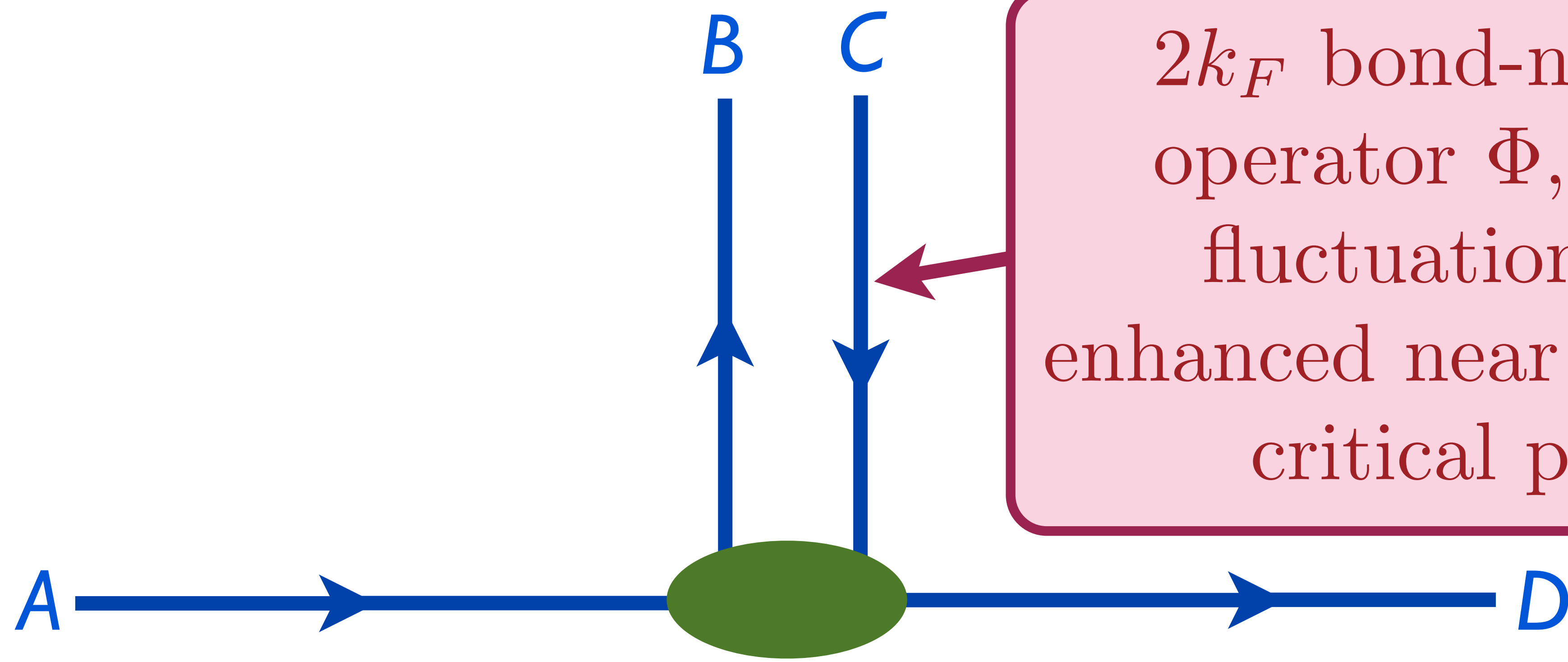


All excitations are low energy

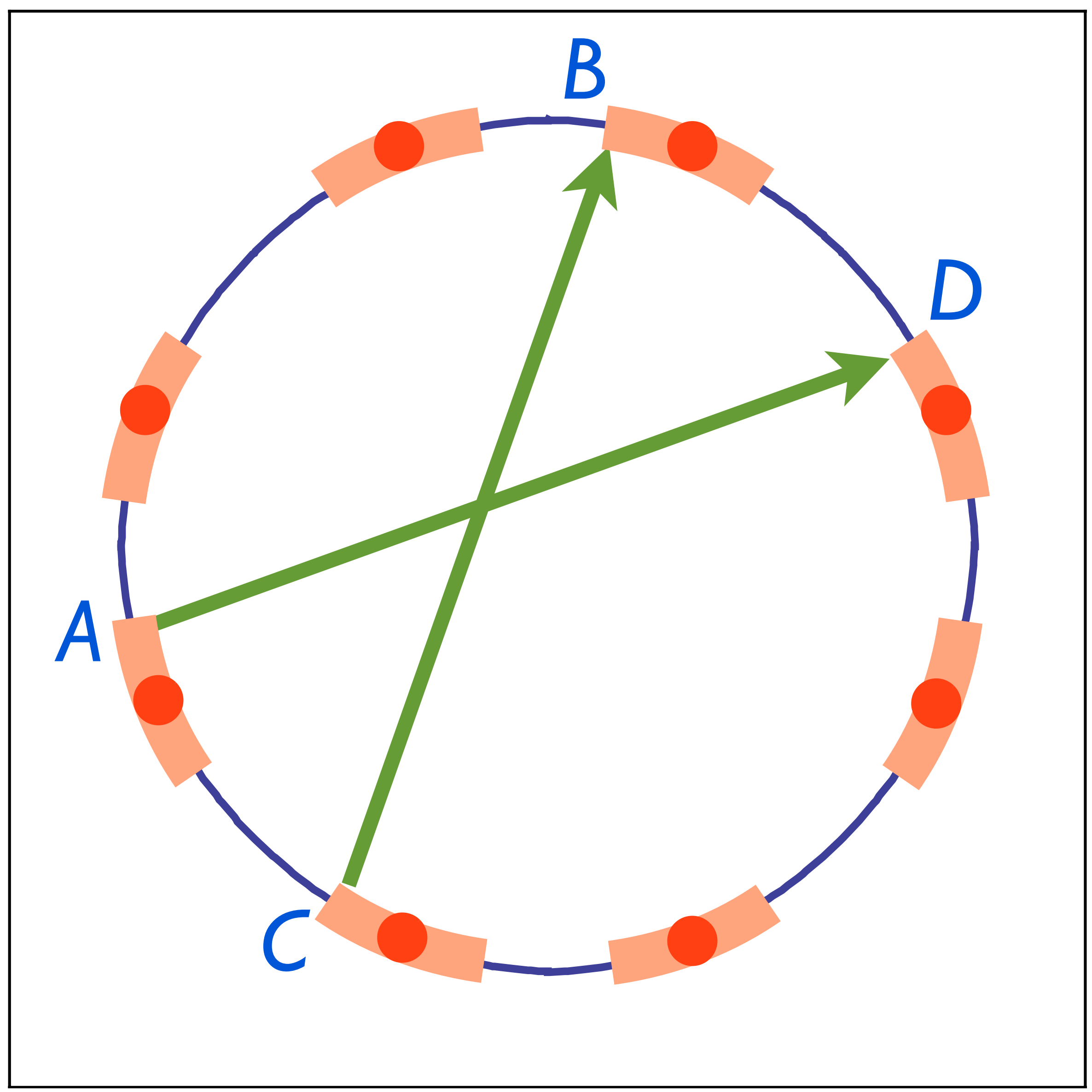

All electrons on Fermi surface away from hot-spots
High energy $\vec{\varphi}$ fluctuation

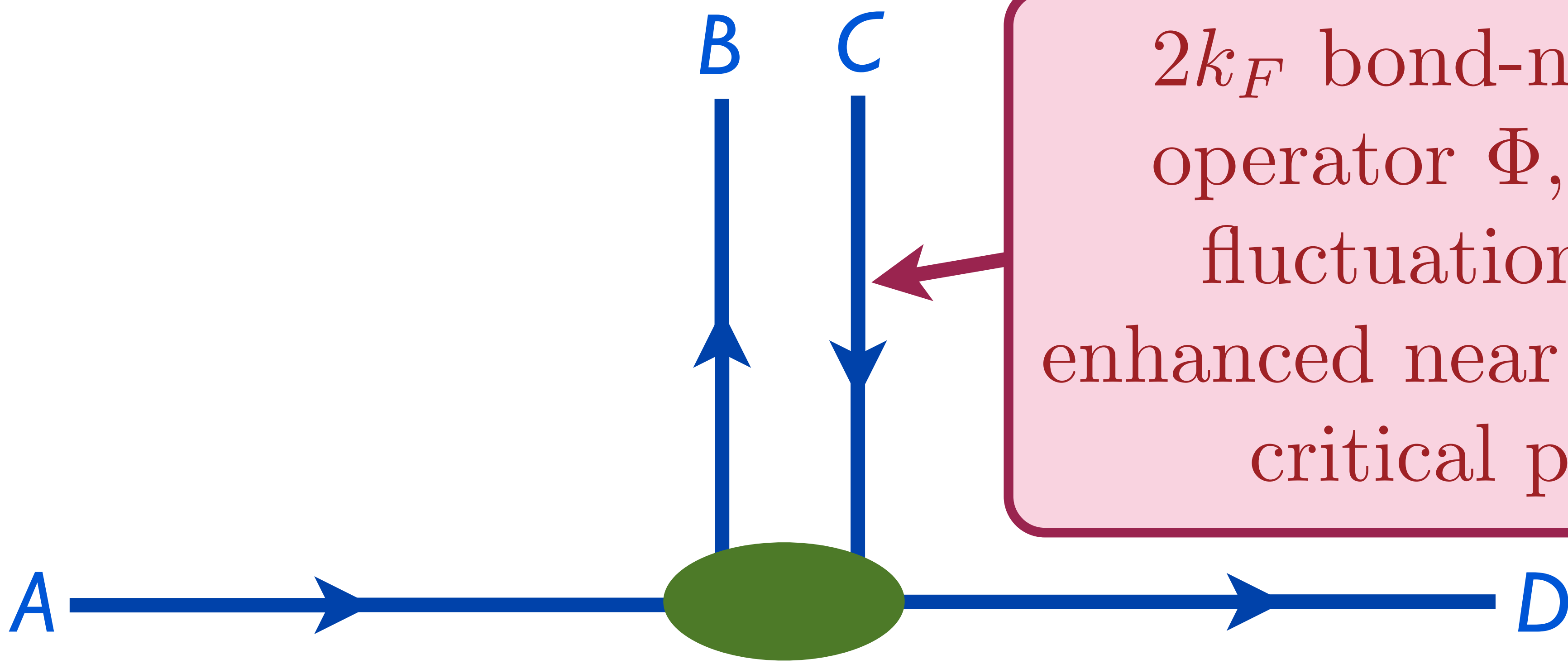

B
C
A
D


B
D
A
C

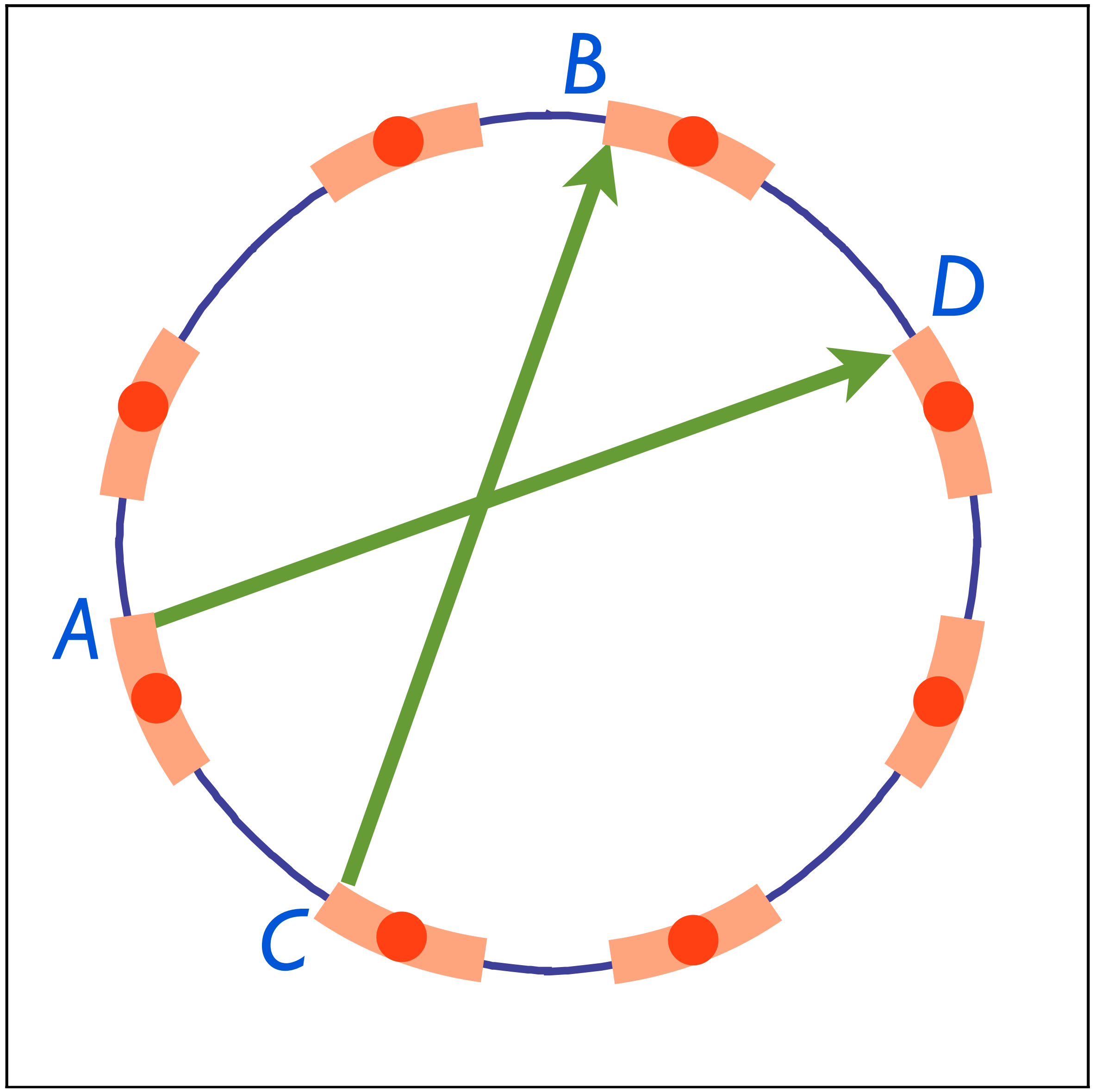


$2k_F$ bond-nematic operator Φ, whose fluctuations are enhanced near the SDW critical point





$2k_F$ bond-nematic operator Φ, whose fluctuations are enhanced near the SDW critical point



All low energy excitations in an umklapp process: this is important for transport properties

Consequences of composite operators

- Non-Fermi liquid spectral functions around *entire* Fermi surface.

- Scattering off $\vec{\varphi}$ and $\vec{\varphi}^2$ fluctuations leads to strong scattering of electronic excitations, but contribution to optical conductivity is suppressed by vertex corrections. Quasiparticles break down at the hot spots, but survive elsewhere (at leading order).

- Strong contribution to optical conductivity, $\sigma(\omega)$, arises from $2k_F$ umklapp scattering.

1. Low energy theory of spin density wave quantum critical point

A. Instabilities near the quantum critical point: unconventional superconductivity and $2k_F$ bond-nematic ordering

B. Scattering off composite operators

2. Phenomenology of the phase diagram in a magnetic field

3. Possible intermediate non-Fermi liquid phases

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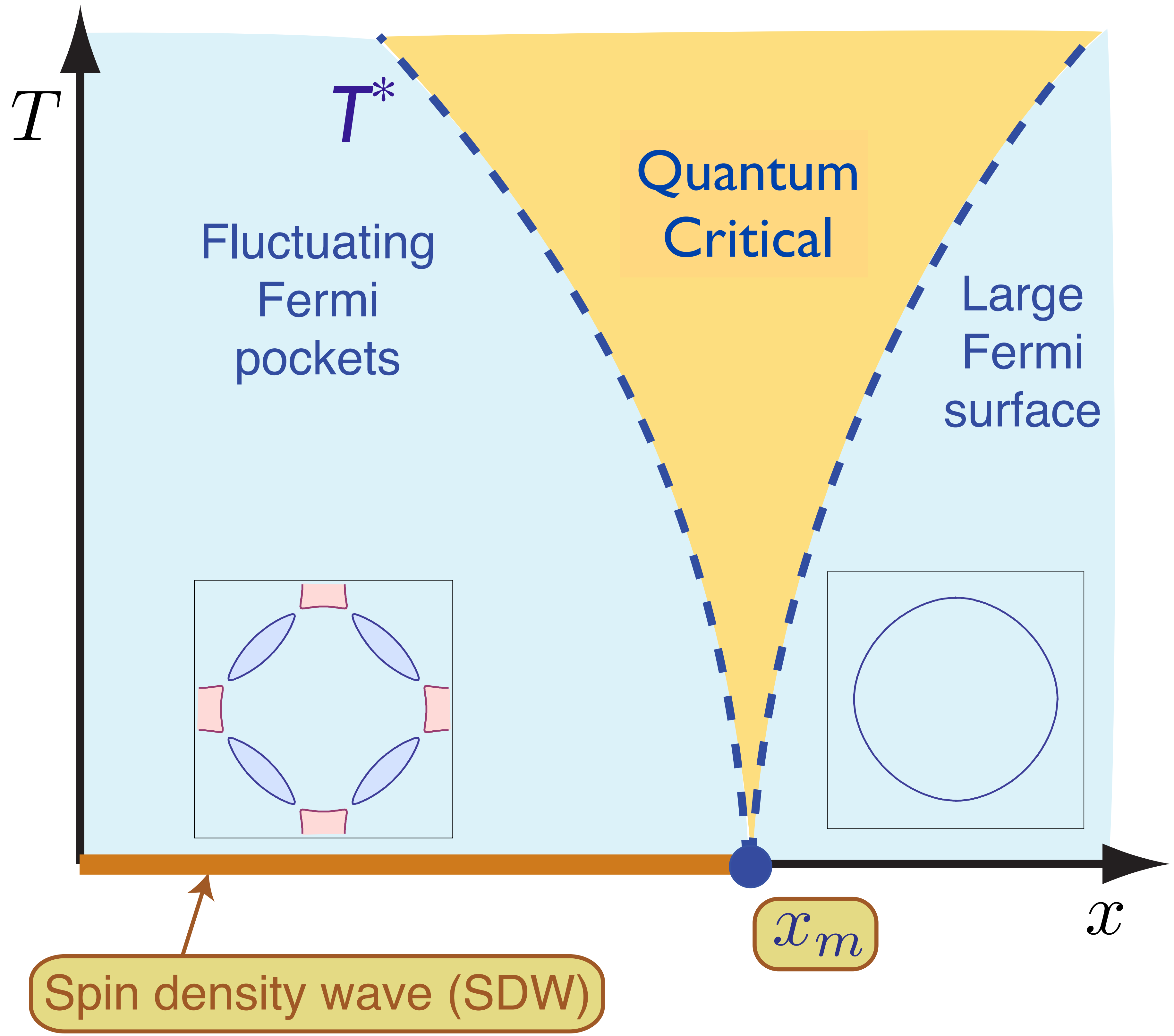
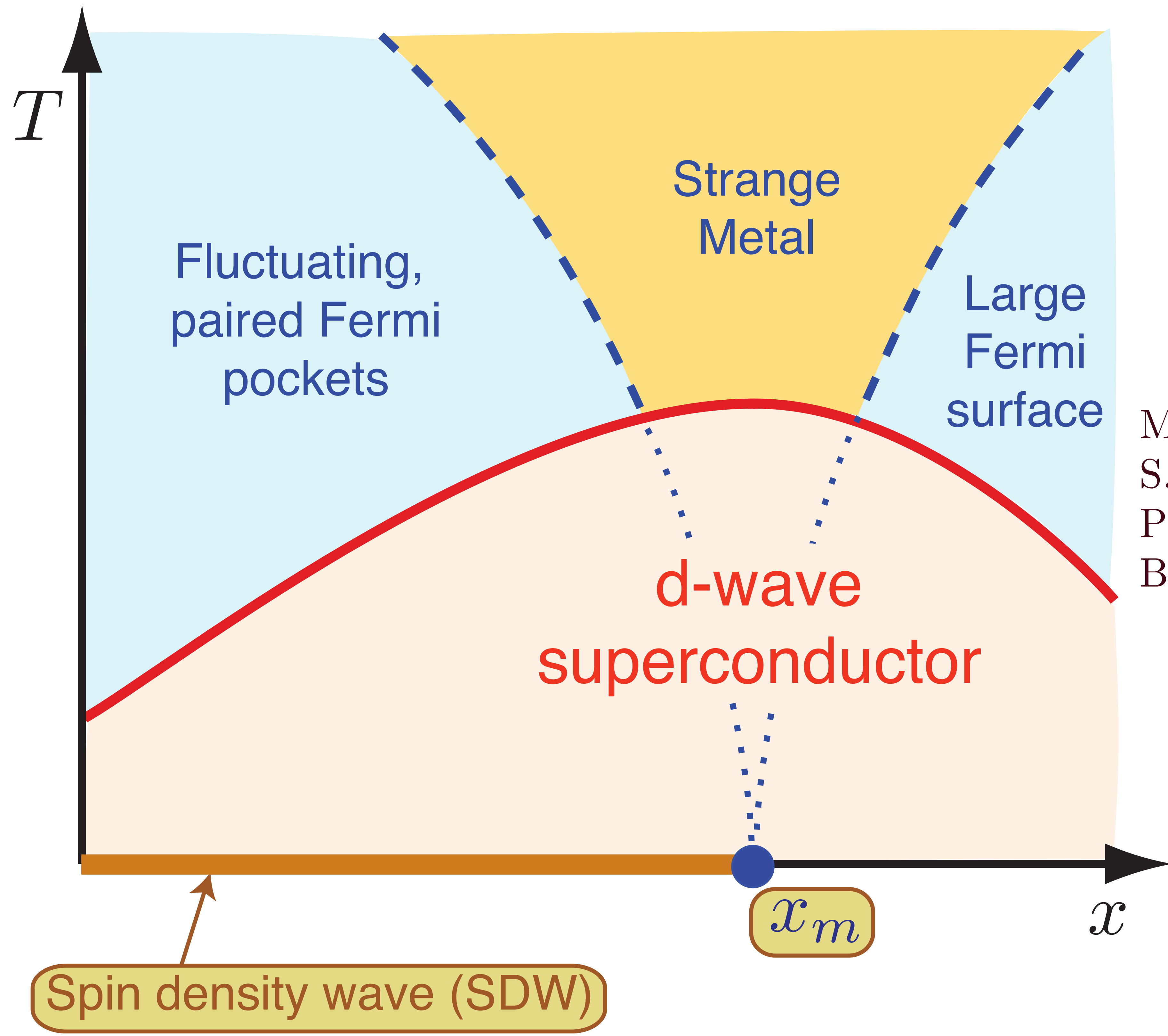


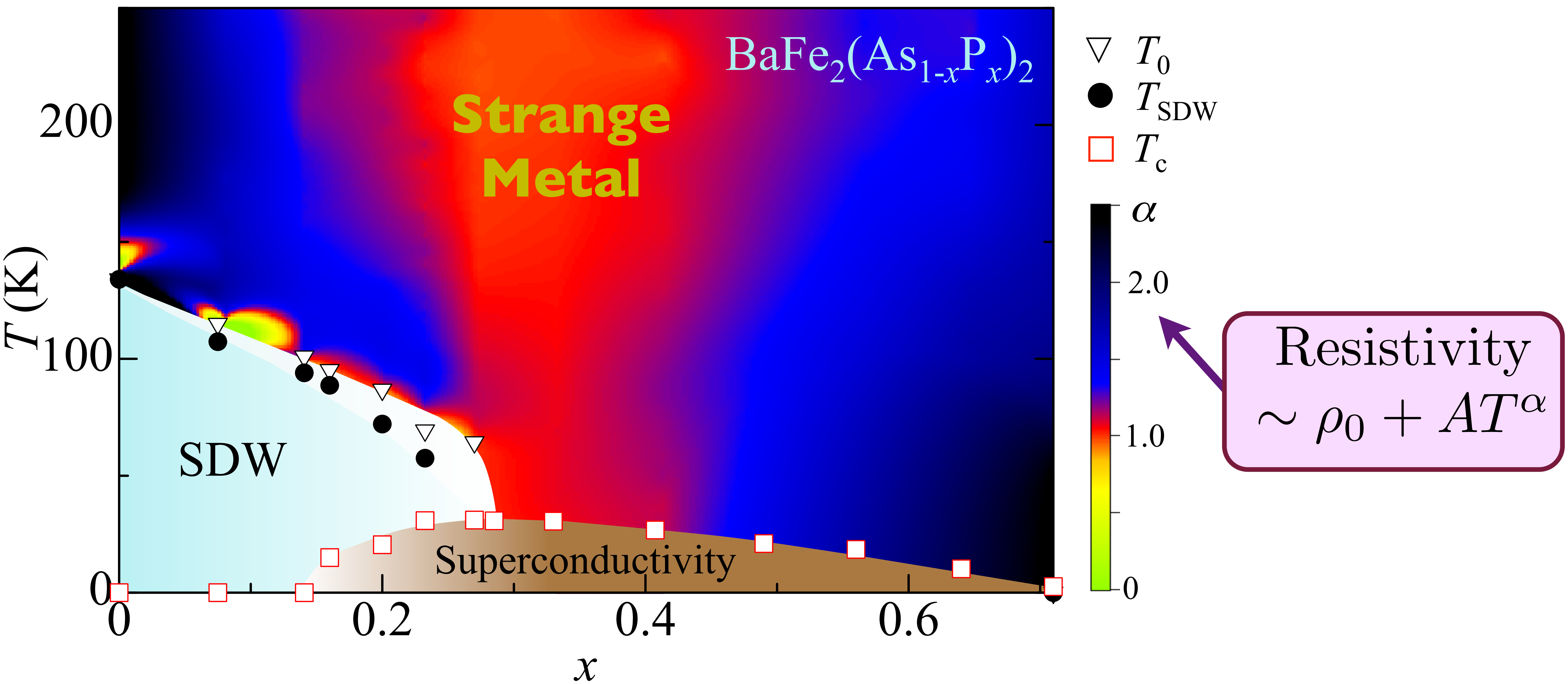
Underlying SDW ordering quantum critical point in **metal** at $x = x_m$



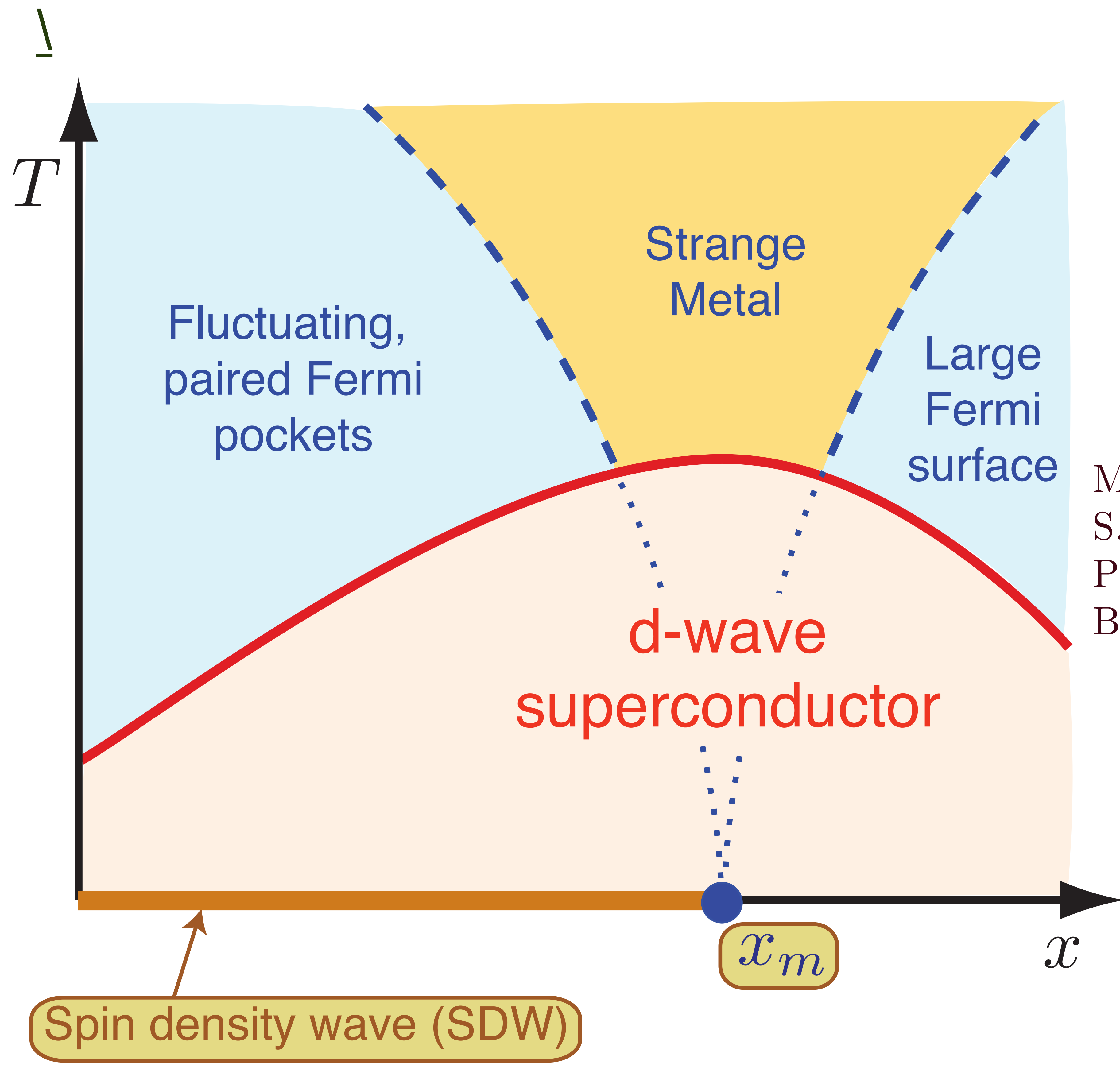
M. A. Metlitski and S. Sachdev, Physical Review B **82**, 075128 (2010)

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

Temperature-doping phase diagram of the iron pnictides:



S. Kasahara, T. Shibauchi, K. Hashimoto, K. Ikada, S. Tonegawa, R. Okazaki, H. Shishido, H. Ikeda, H. Takeya, K. Hirata, T. Terashima, and Y. Matsuda, *Physical Review B* **81**, 184519 (2010)



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SDW quantum critical point is unstable to d-wave superconductivity
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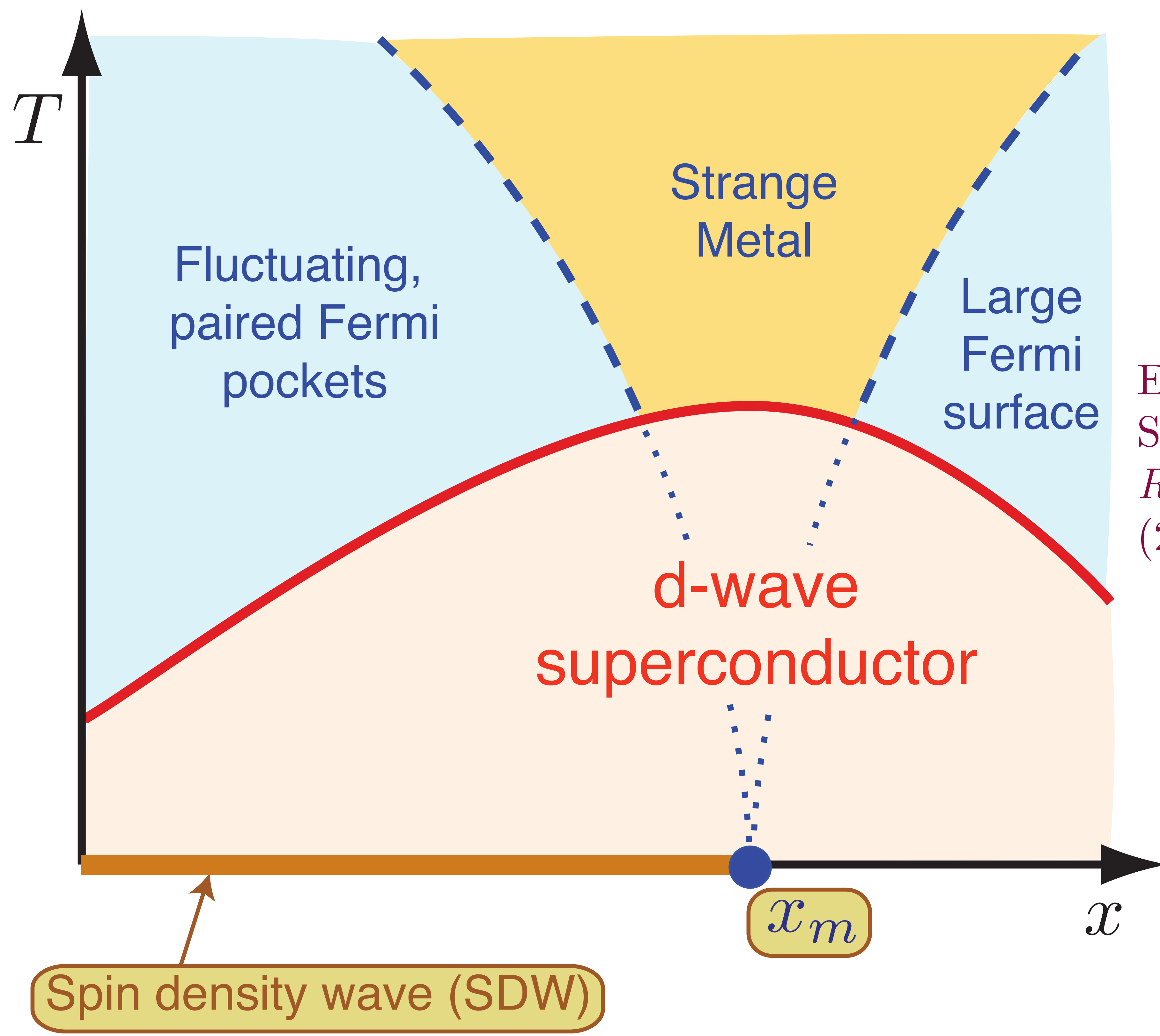
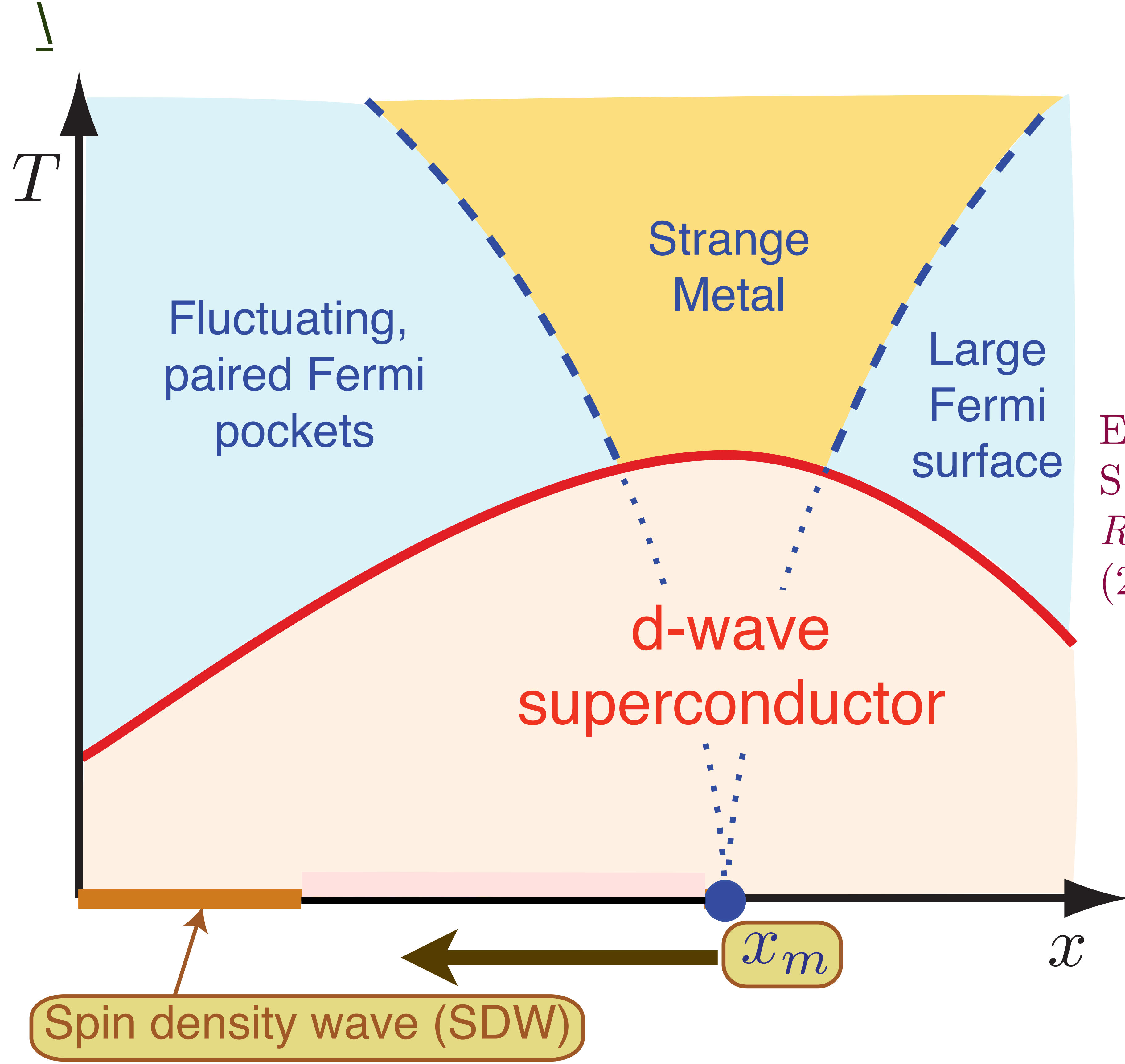


E. G. Moon and S. Sachdev, *Phy. Rev. B* **80**, 035117 (2009)

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



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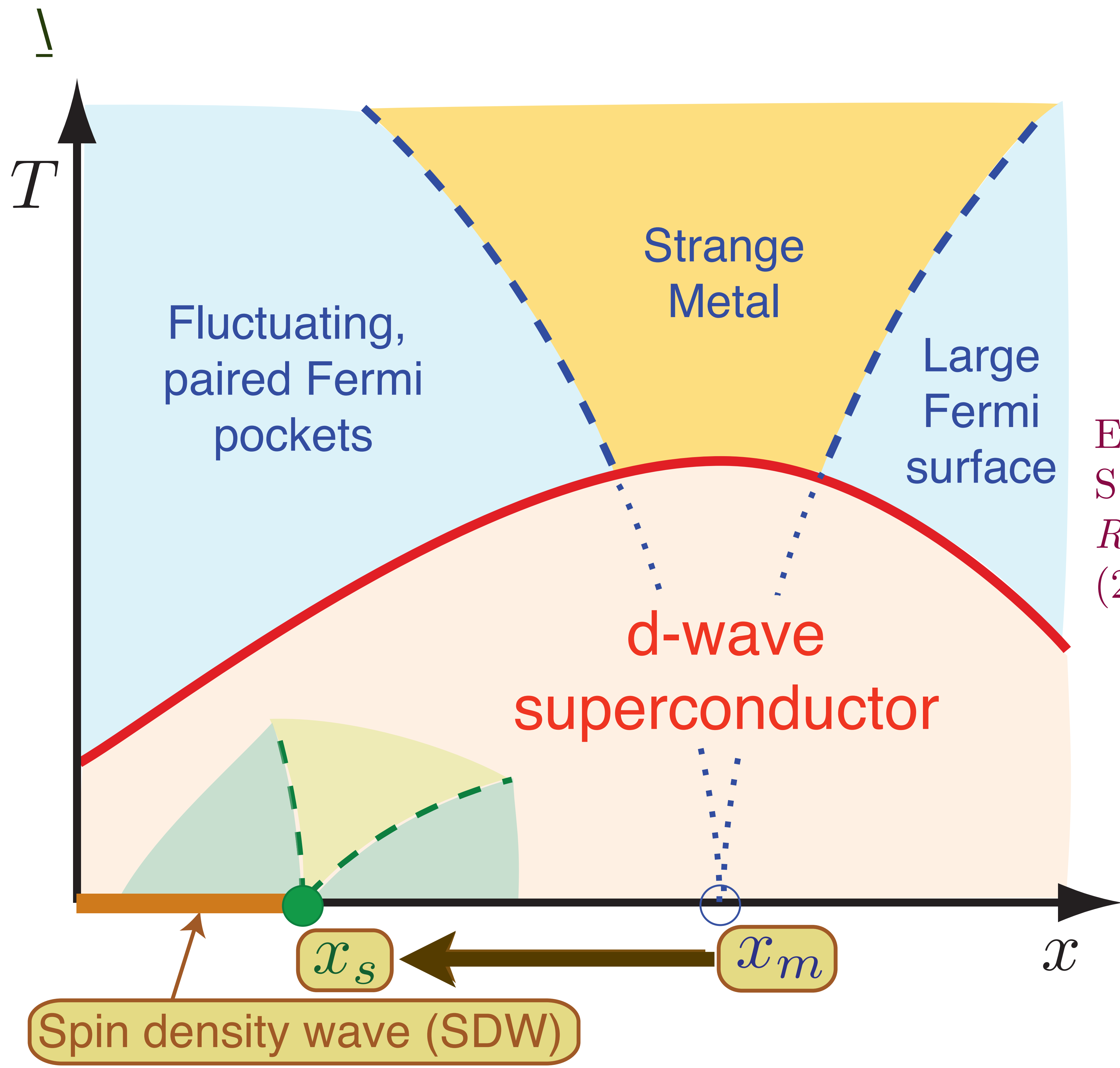

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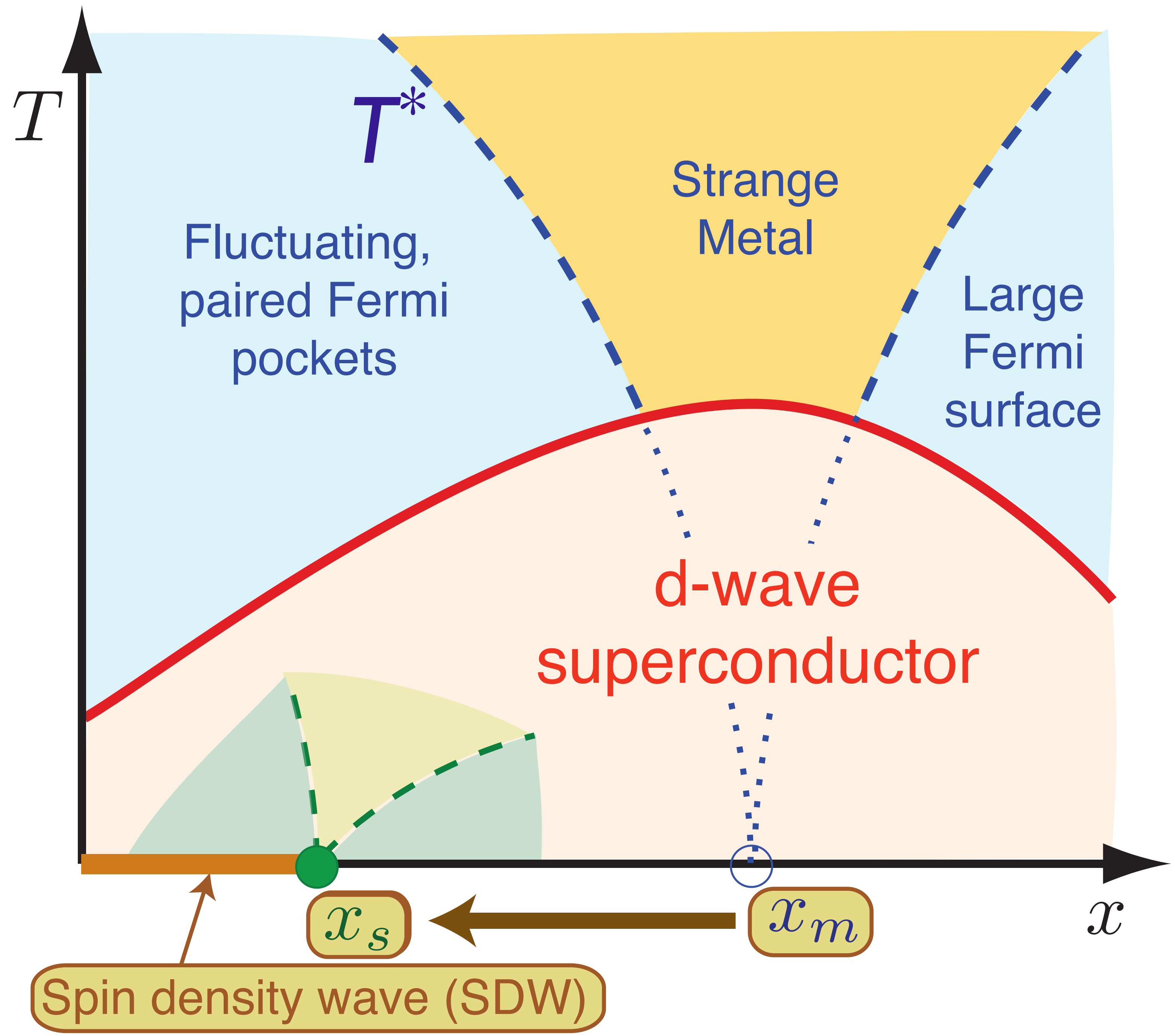
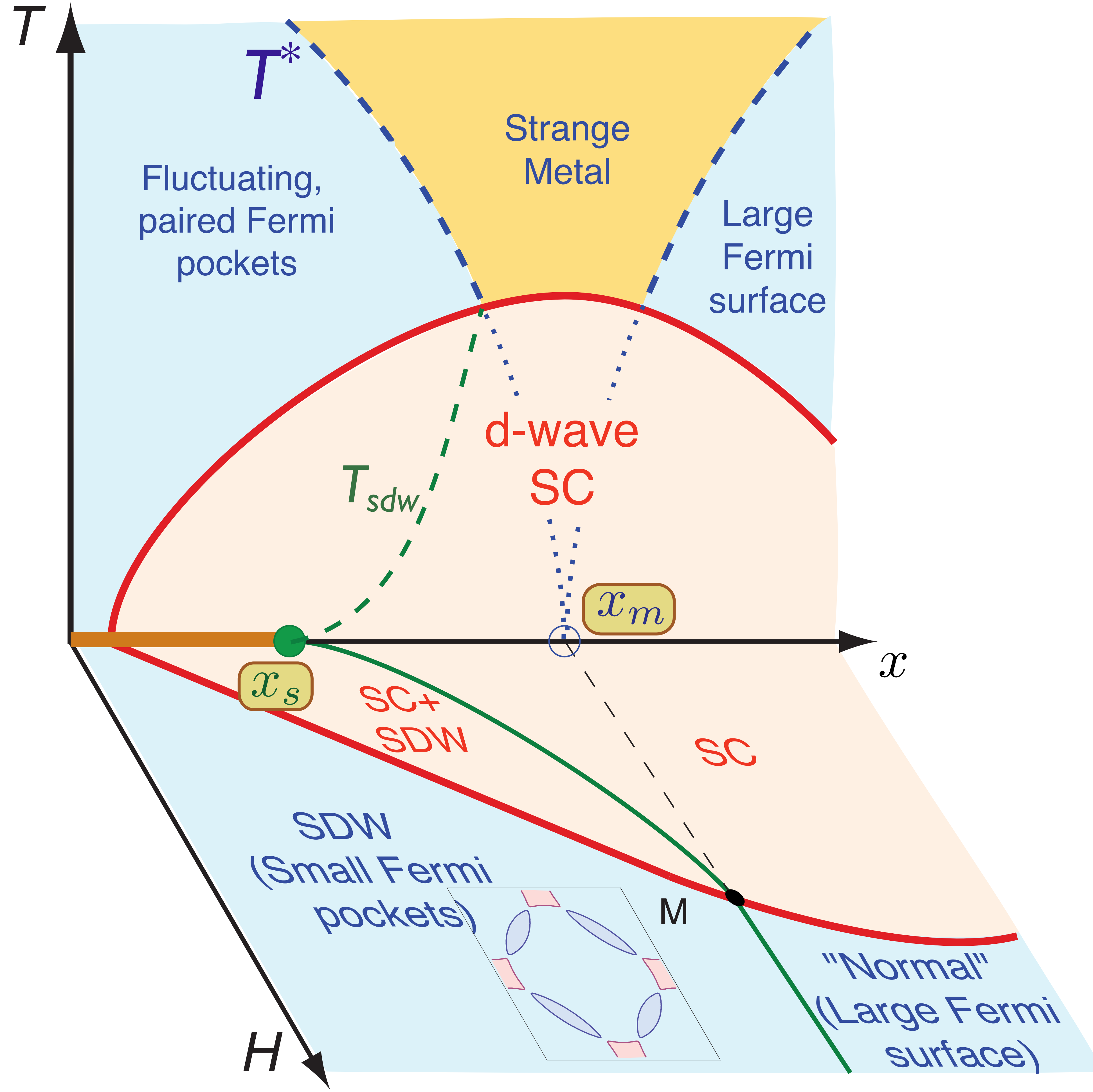


T
T^*
Strange Metal
Fluctuating, paired Fermi pockets
Large Fermi surface
d-wave superconductor
x_s
x_m
x
Spin density wave (SDW)

E. Demler, S. Sachdev and Y. Zhang, *Phys. Rev. Lett.* **87**, 067202 (2001).



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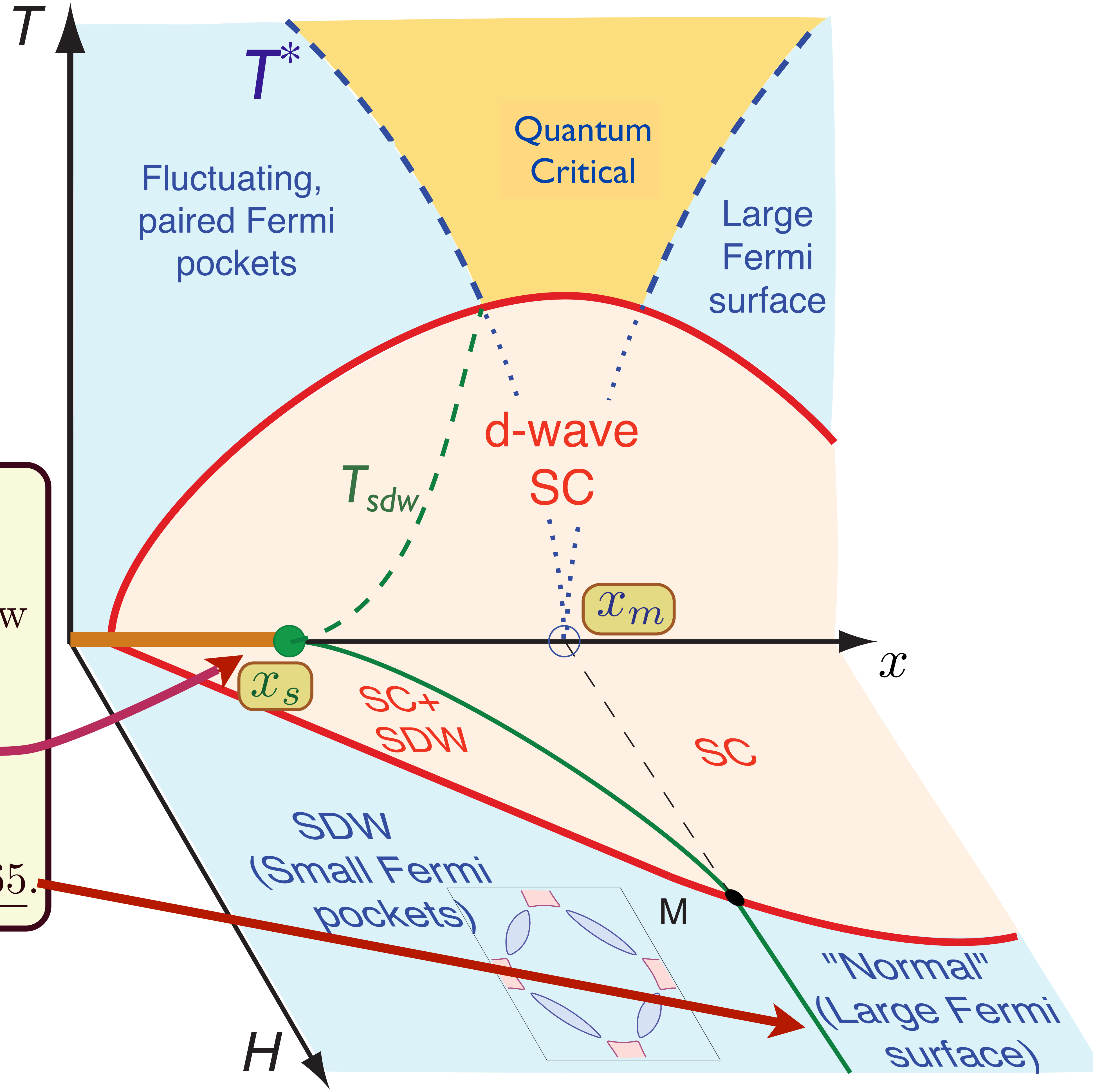
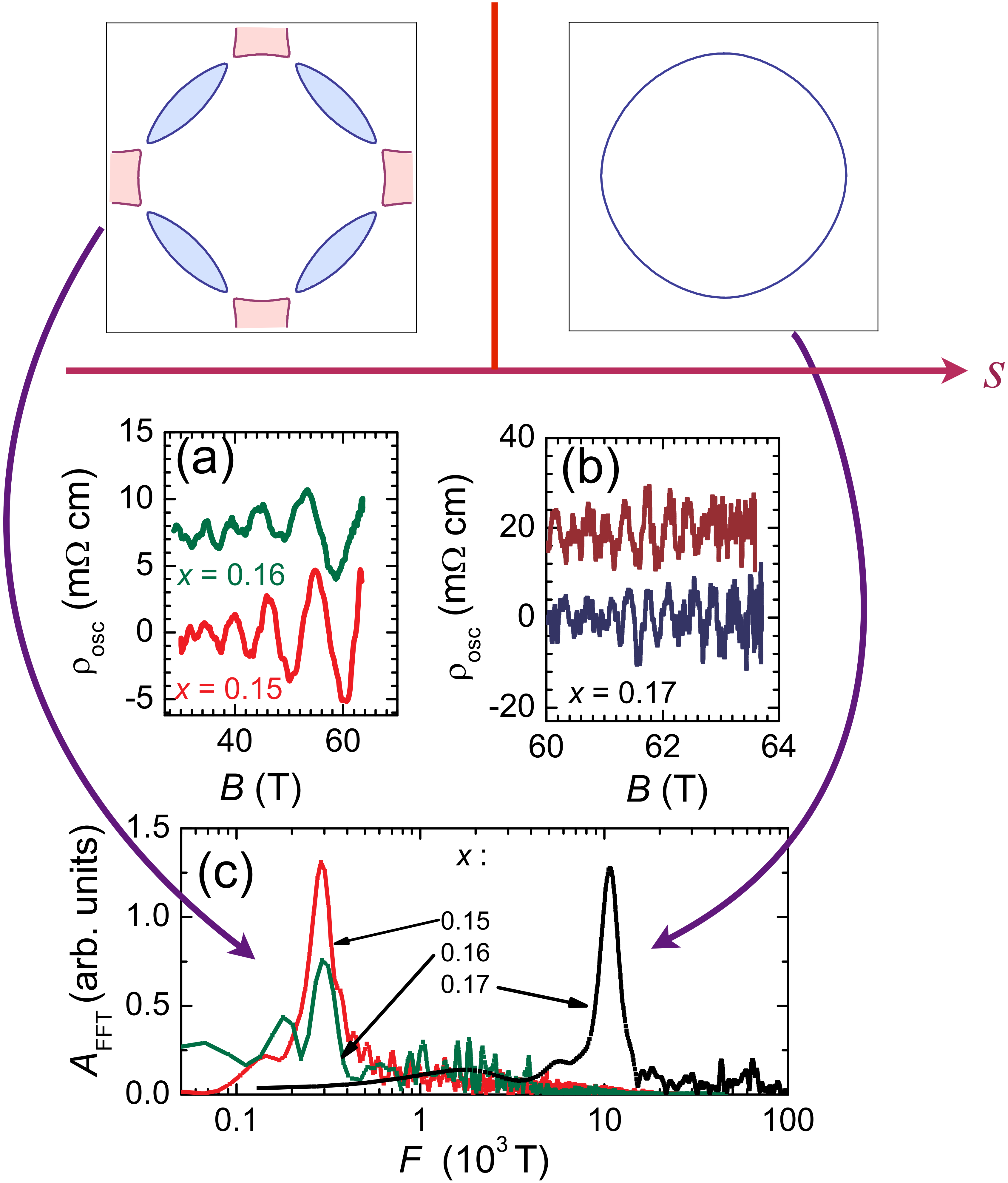


Neutron scattering experiments on $Nd_{2-x}Ce_xCuO_4$ show that at low fields $x_s = 0.14$, while quantum oscillations at high fields show that $x_m = 0.165$.

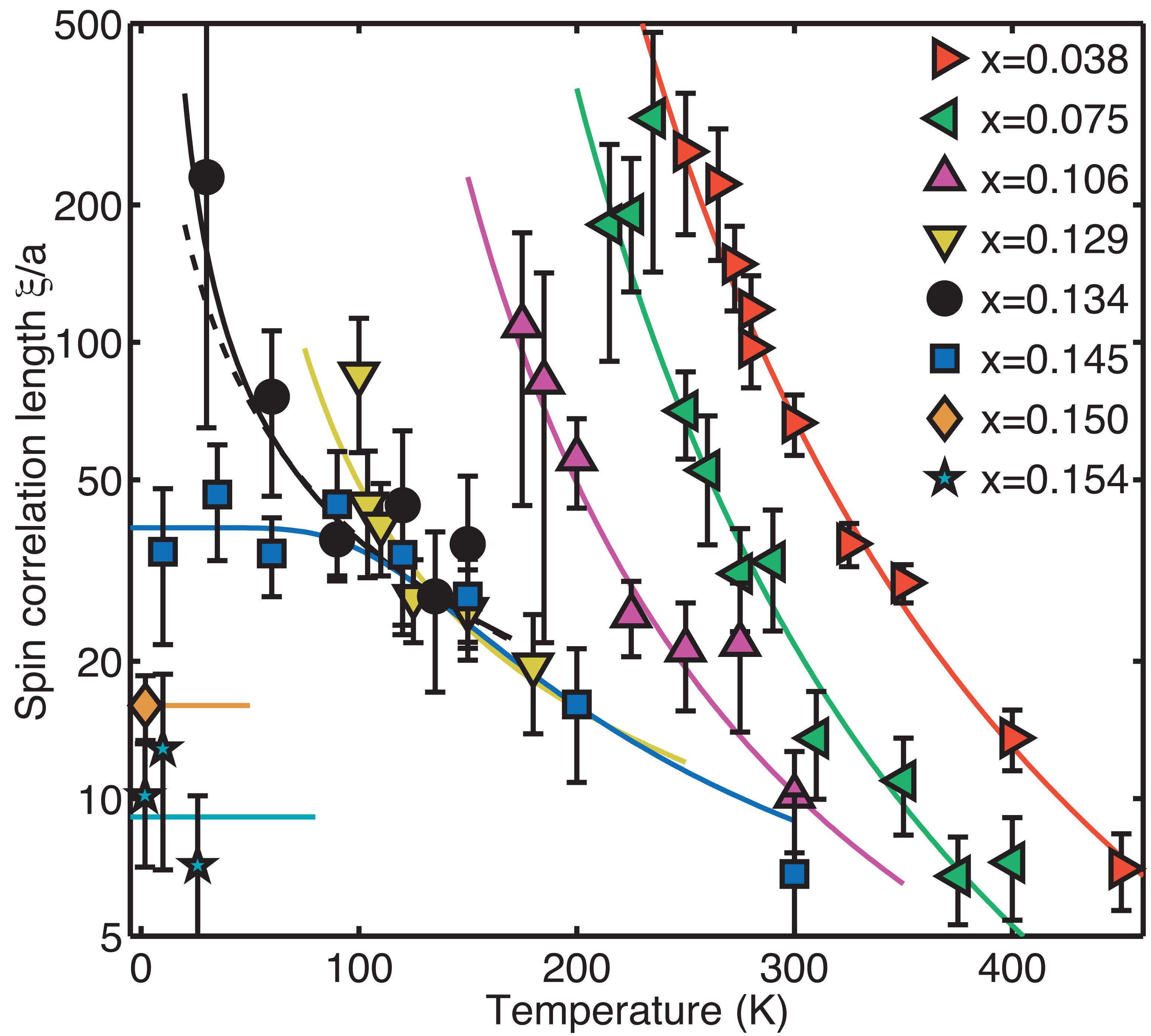
Quantum oscillations



$Nd_{2-x}Ce_xCuO_4$

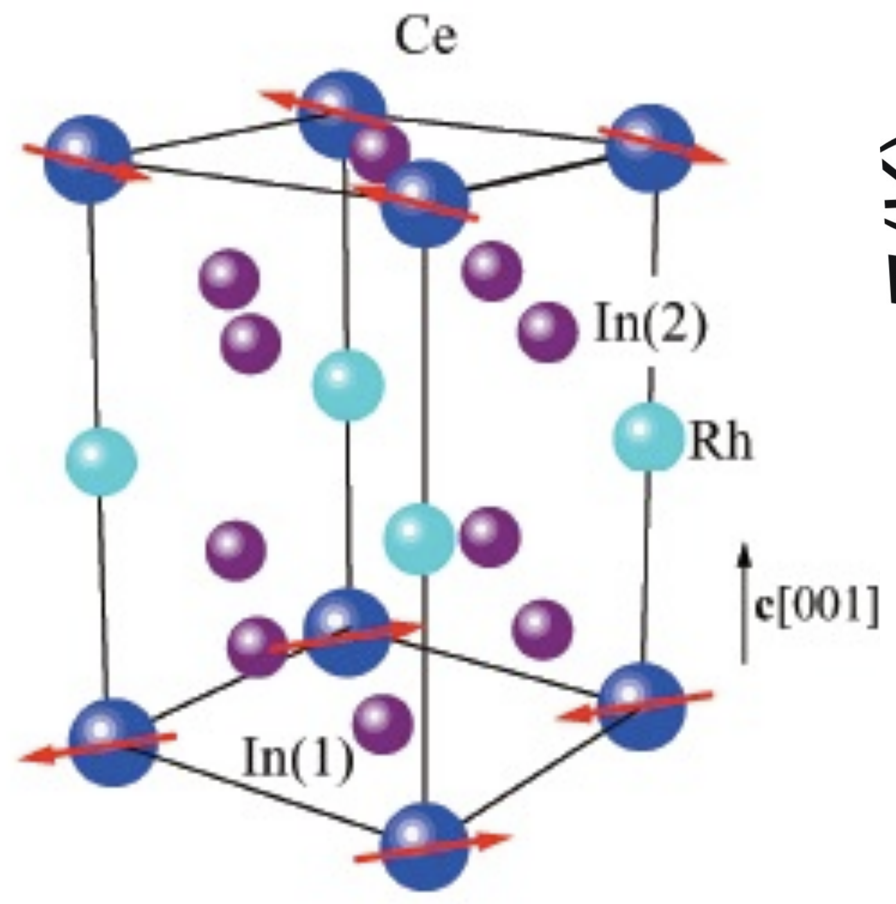
T. Helm, M.V. Kartsovnik, M. Bartkowiak, N. Bittner, M. Lambacher, A. Erb, J. Wosnitza, and R. Gross, *Phys. Rev. Lett.* **103**, 157002 (2009).

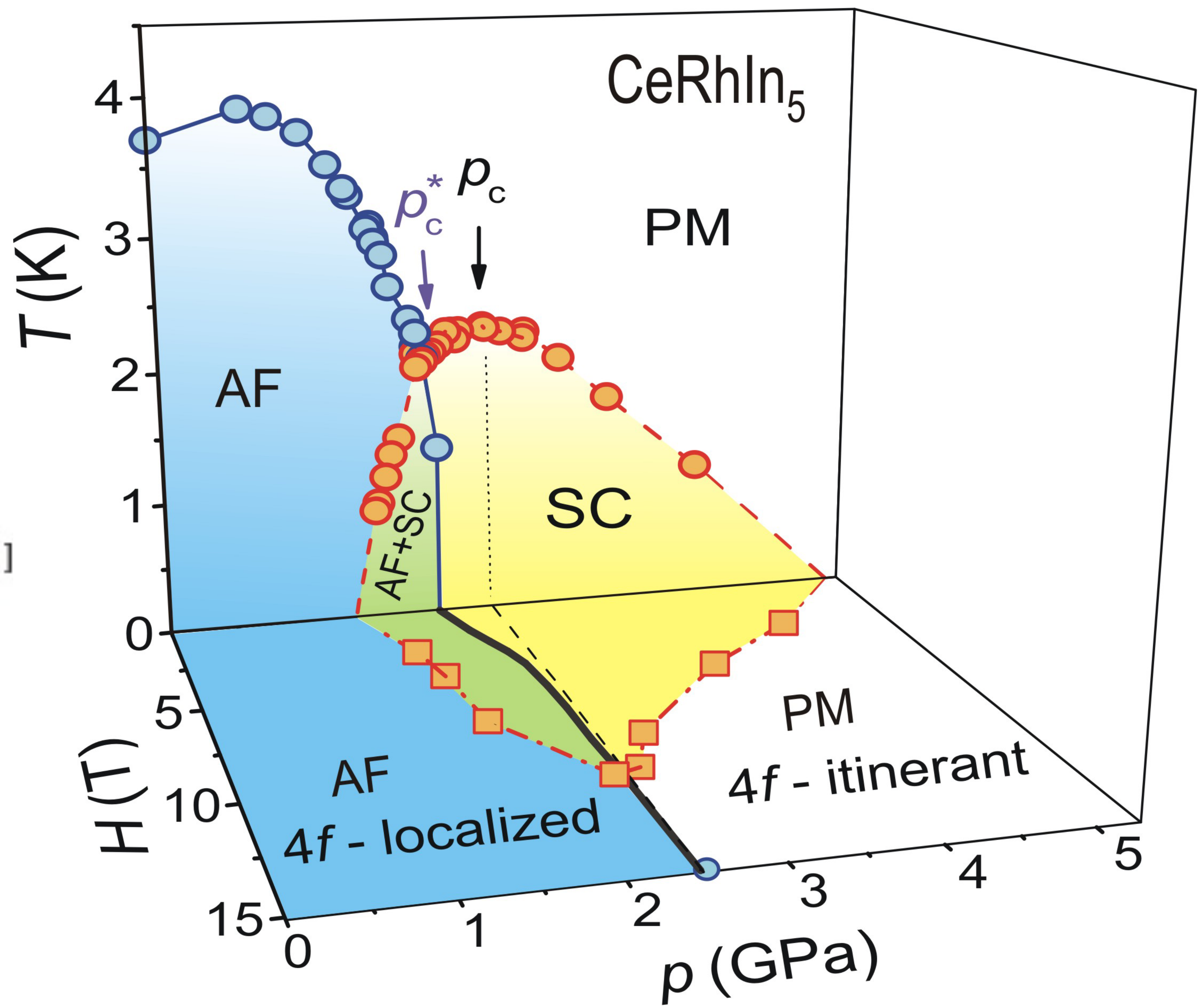
$Nd_{2-x}Ce_xCuO_4$



E. M. Motoyama, G. Yu, I. M. Vishik, O. P. Vajk, P. K. Mang, and M. Greven, *Nature* **445**, 186 (2007).

Similar phase diagram for $CeRhIn_5$

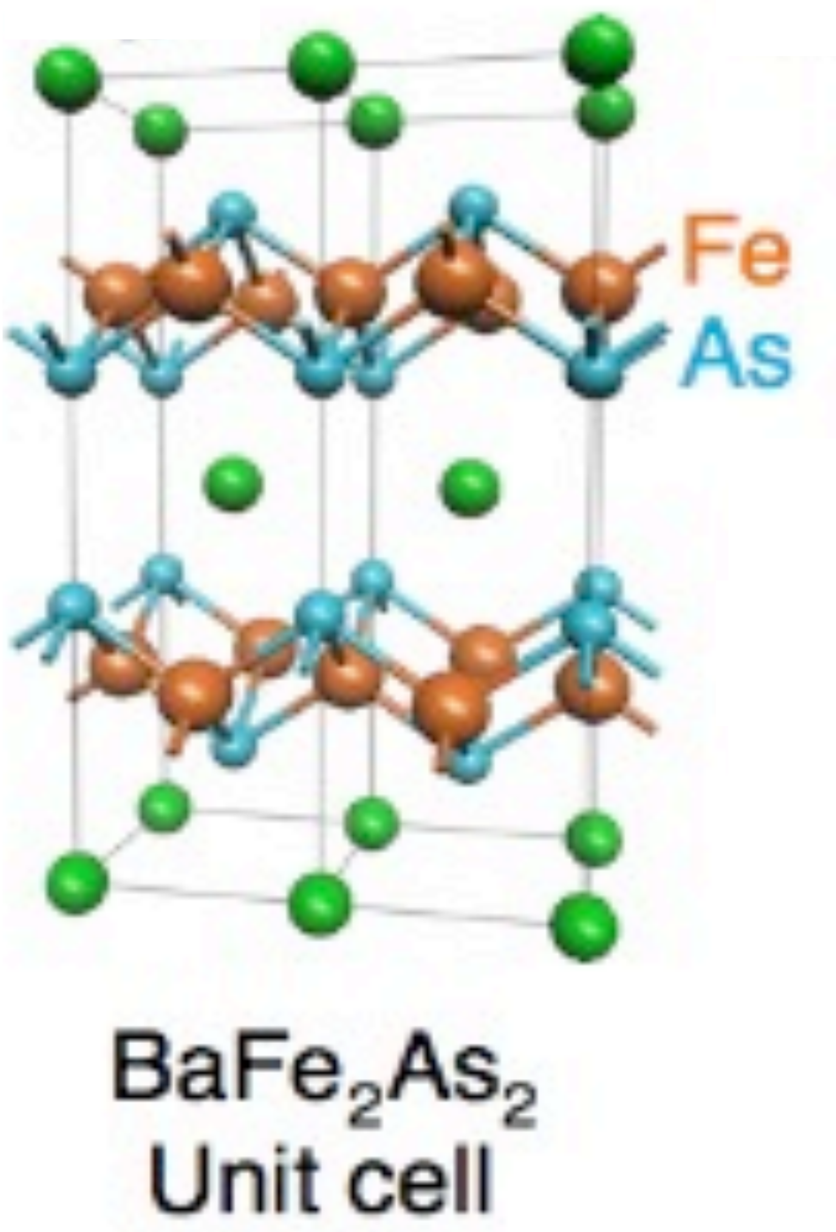


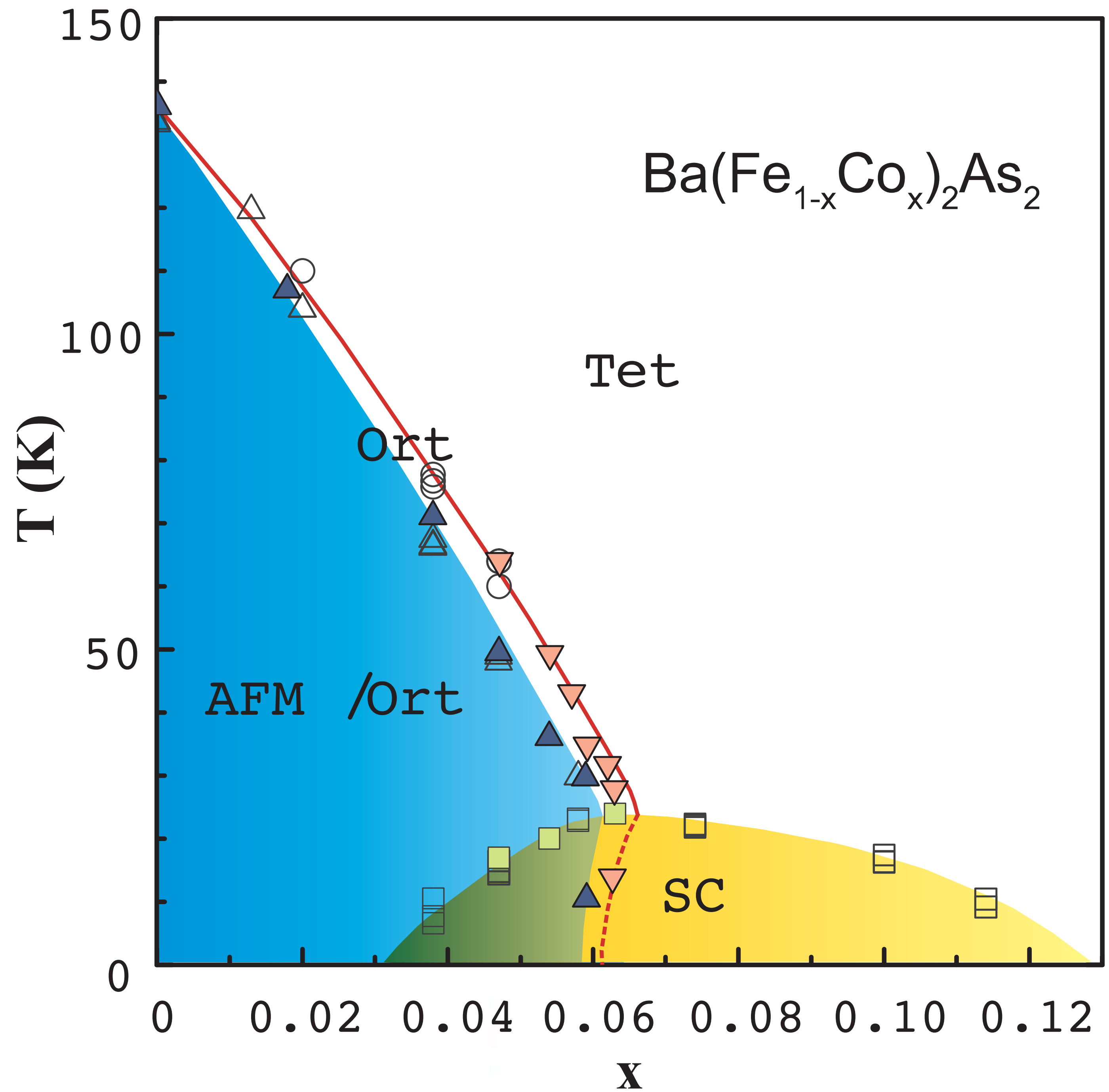


G. Knebel, D. Aoki, and J. Flouquet, arXiv:0911.5223.
Tuson Park, F. Ronning, H. Q. Yuan, M. B. Salamon, R. Movshovich, J. L. Sarrao, and J. D. Thompson, *Nature* **440**, 65 (2006)

Iron pnictides:

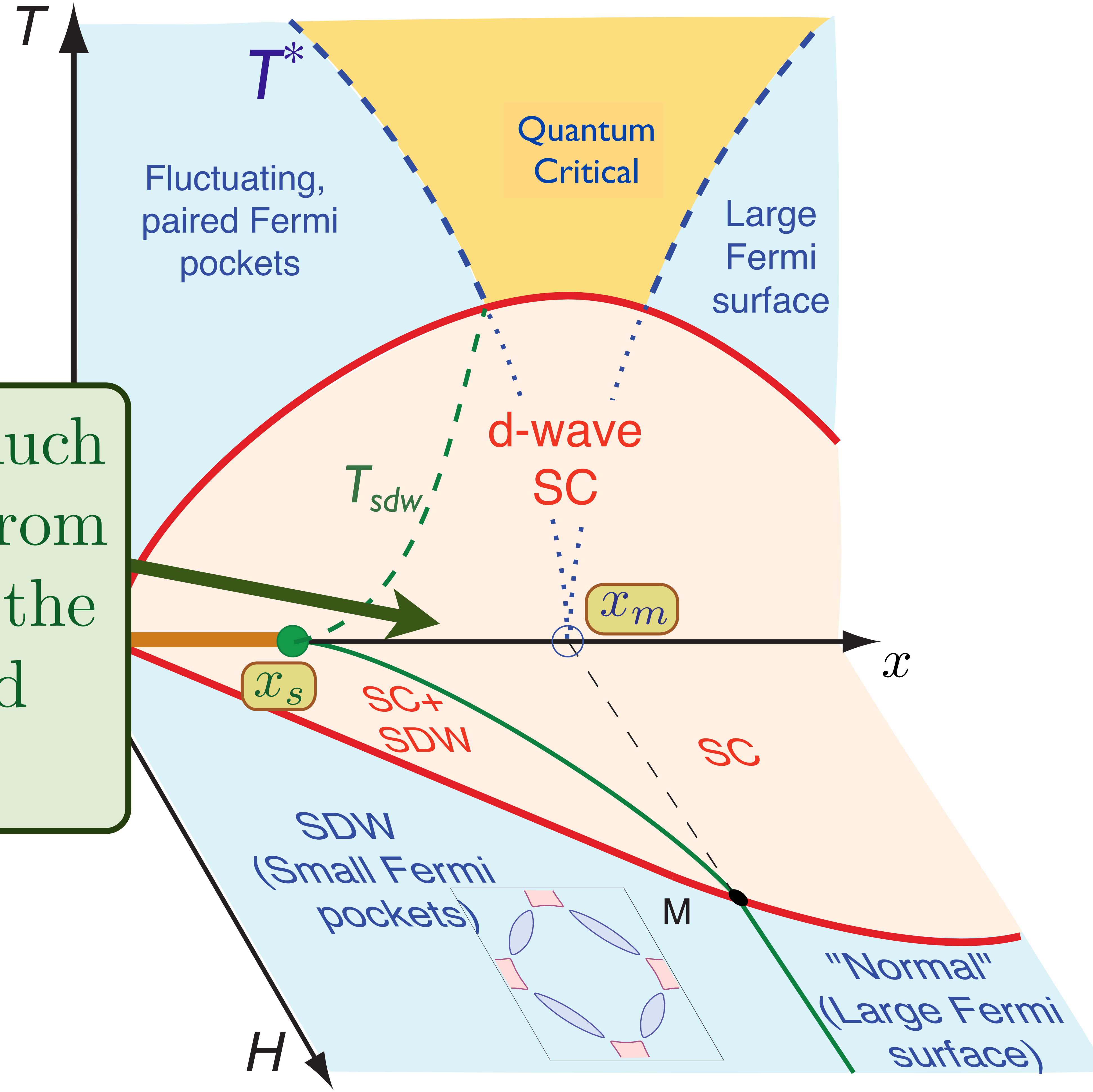
a new class of high temperature superconductors





S. Nandi, M. G. Kim, A. Kreyssig, R. M. Fernandes, D. K. Pratt, A. Thaler, N. Ni, S. L. Bud'ko, P. C. Canfield, J. Schmalian, R. J. McQueeney, A. I. Goldman, *Physical Review Letters* **104**, 057006 (2010).

There is a much larger shift from x_m to x_s in the hole-doped cuprates.



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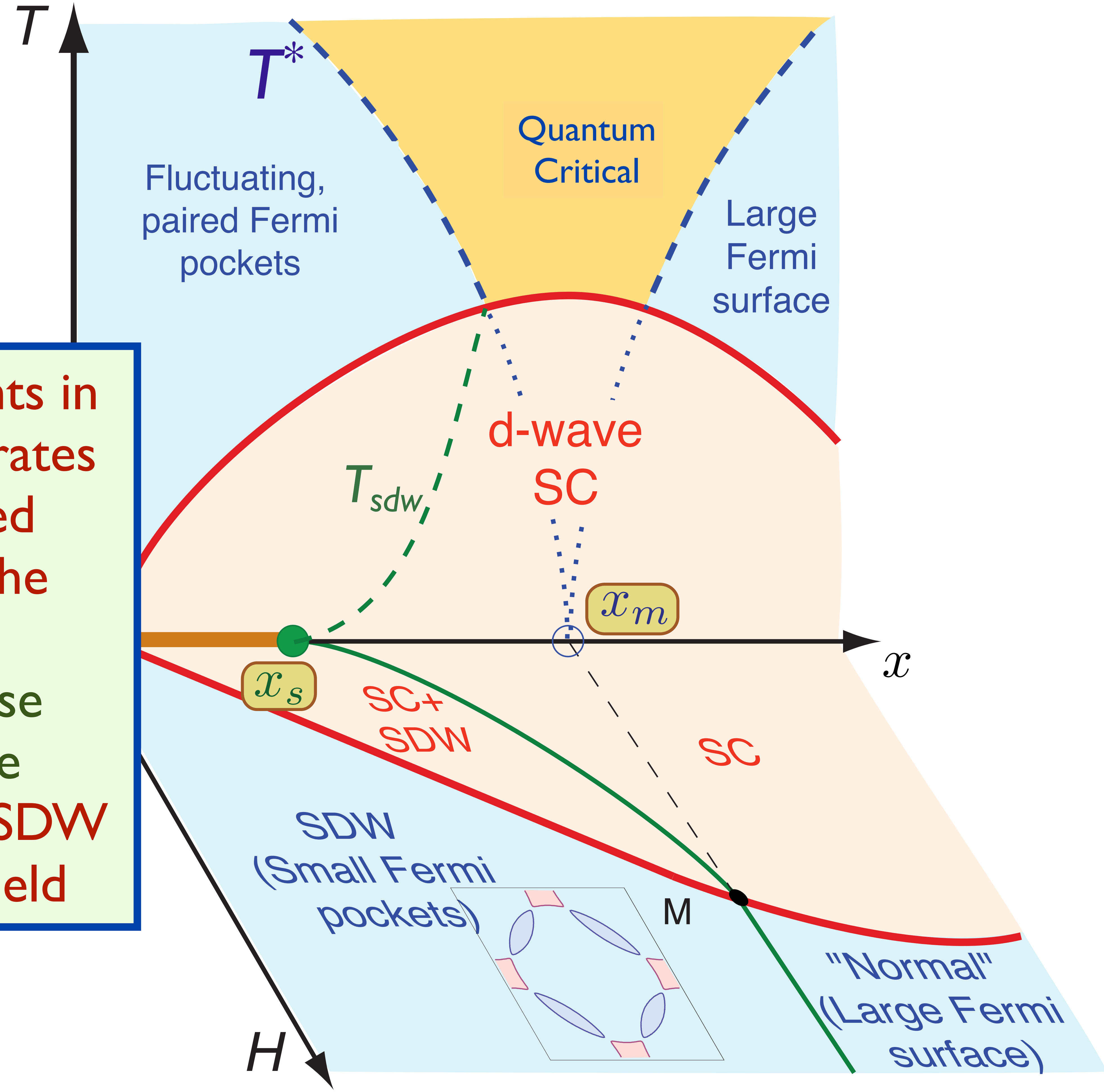
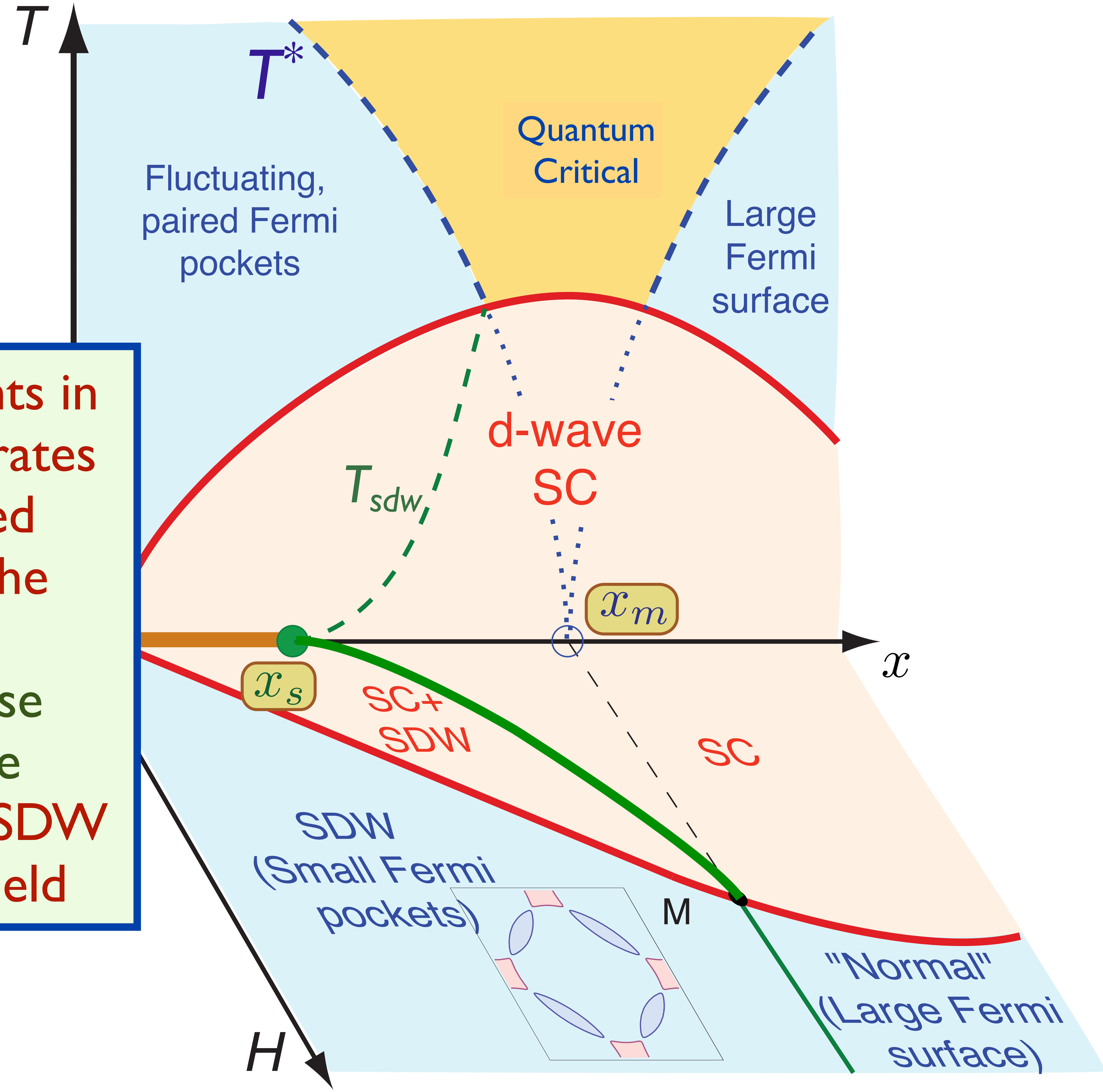


Many experiments in hole-doped cuprates have presented evidence for the predicted quantum phase transition line from SC to SC+SDW in a magnetic field

E. Demler, S. Sachdev and Y. Zhang, *Phys. Rev. Lett.* **87**, 067202 (2001).



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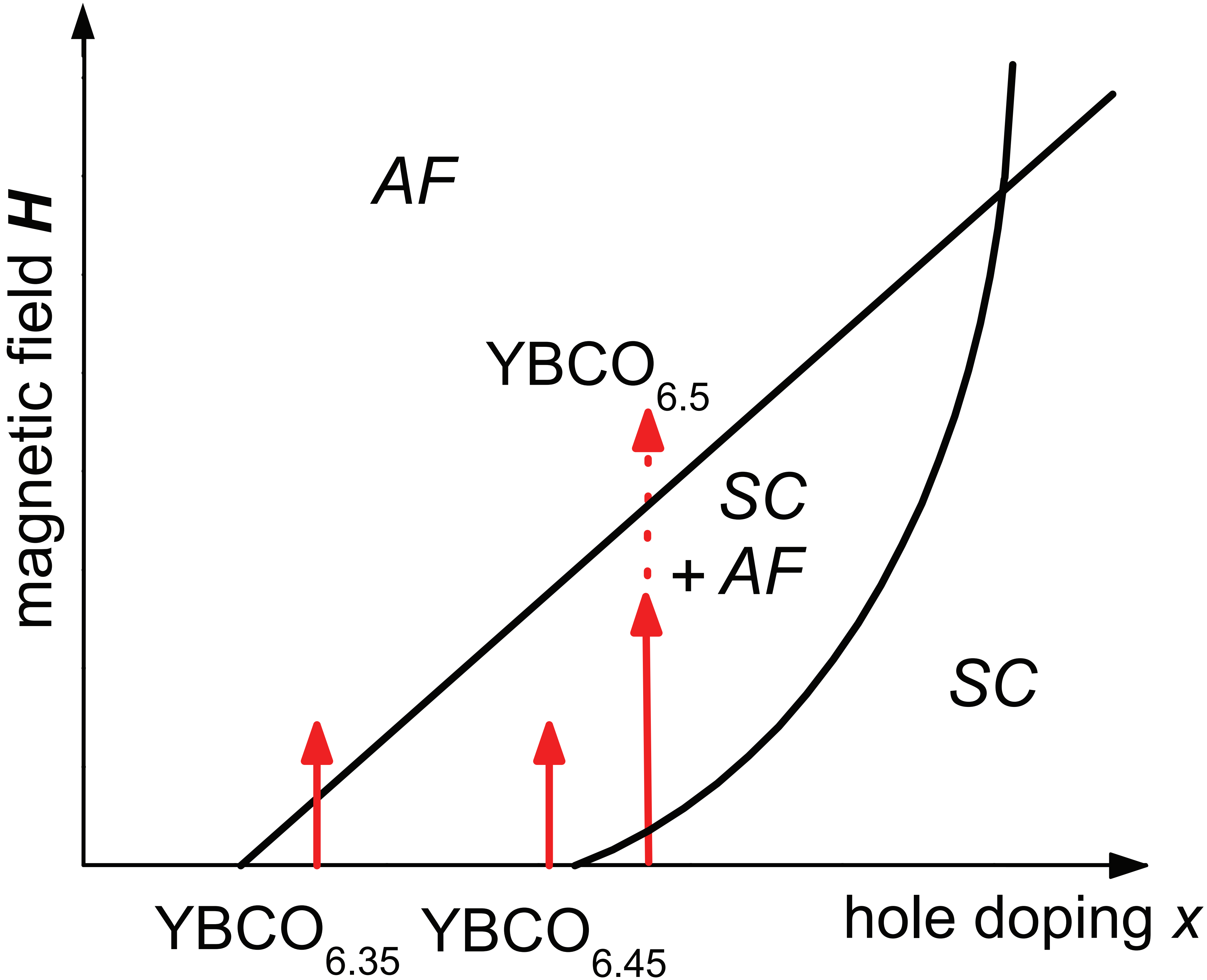
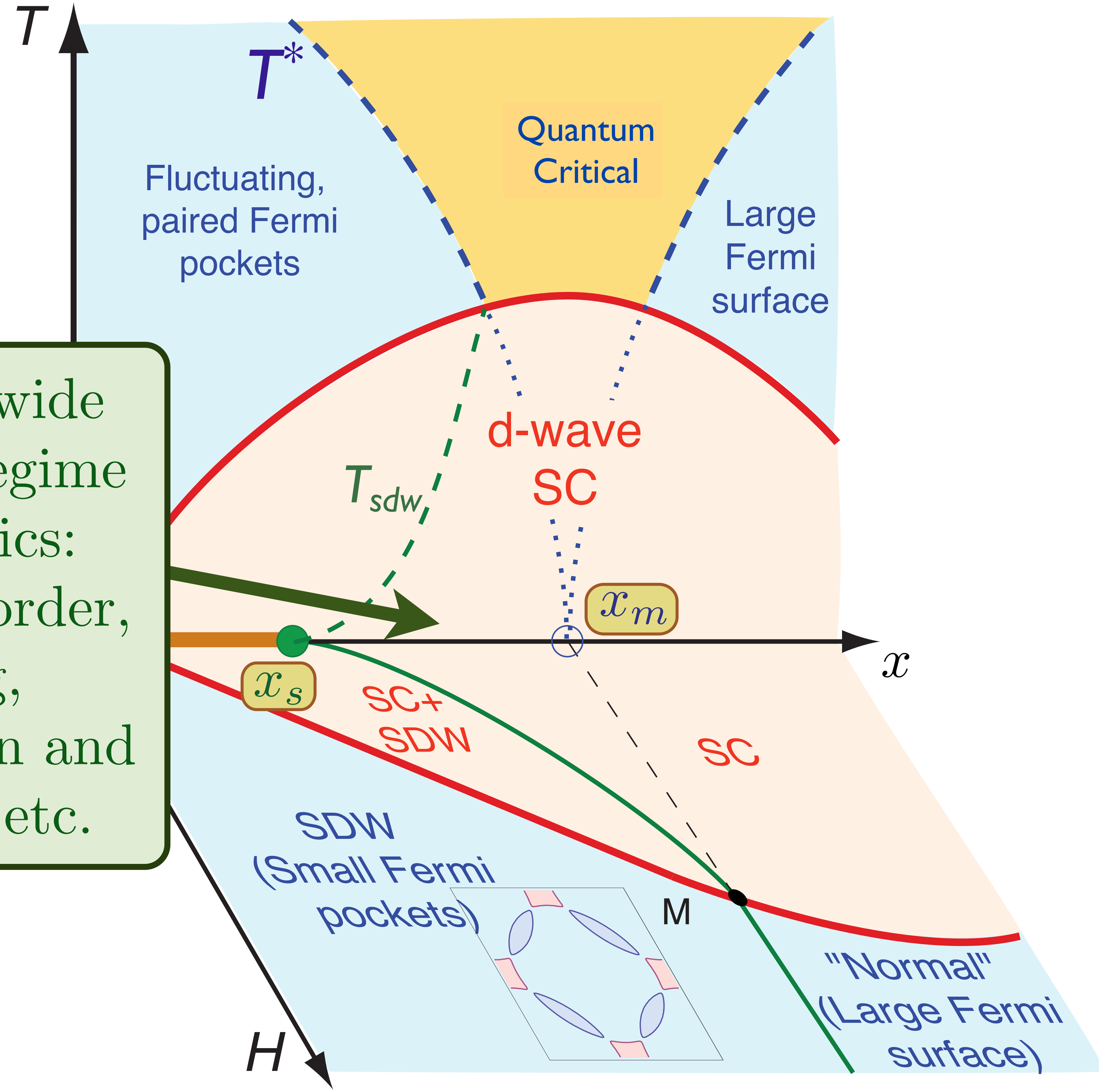


D. Haug, V. Hinkov, Y. Sidis, P. Bourges, N. B. Christensen, A. Ivanov, T. Keller, C. T. Lin, and B. Keimer, *New J. Phys.* **12**, 105006 (2010)

This opens a wide intermediate regime for new physics: bond-nematic order, T-breaking, fractionalization and Mott physics etc.



1. Low energy theory of spin density wave quantum critical point

A. Instabilities near the quantum critical point: unconventional superconductivity and $2k_F$ bond-nematic ordering

B. Scattering off composite operators

2. Phenomenology of the phase diagram in a magnetic field

3. Possible intermediate non-Fermi liquid phases

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Possible exotic intermediate phases

Fermi pockets without spin density wave order

Transform electrons to a
"rotating reference frame",
quantizing spins in the direction of the
local antiferromagnetic order

Possible exotic intermediate phases

Fermi pockets without spin density wave order

Transform electrons to a "rotating reference frame", quantizing spins in the direction of the local antiferromagnetic order

This is facilitated by writing the vector antiferromagnetic order parameter $\vec{\varphi}$ in terms of a bosonic spinor z_α, with $\alpha = \uparrow, \downarrow$ and

$$\vec{\varphi} = z_\alpha^* \vec{\sigma}_{\alpha\beta} z_\beta.$$

Possible exotic intermediate phases

Fermi pockets without spin density wave order

$$\left(\begin{array}{c} c_\uparrow \\ c_\downarrow \end{array} \right) = \left(\begin{array}{cc} z_\uparrow & -z_\downarrow^* \\ z_\downarrow & z_\uparrow^* \end{array} \right) \left(\begin{array}{c} \psi_+ \\ \psi_- \end{array} \right)$$

Possible exotic intermediate phases

Fermi pockets without spin density wave order

$$\begin{pmatrix} c_\uparrow \\ c_\downarrow \end{pmatrix} = \begin{pmatrix} z_\uparrow & -z_\downarrow^* \\ z_\downarrow & z_\uparrow^* \end{pmatrix} \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix}$$

Spinless fermions

Possible exotic intermediate phases

Fermi pockets without spin density wave order

$$\begin{pmatrix} c_\uparrow \\ c_\downarrow \end{pmatrix} = \bullet \begin{pmatrix} z_\uparrow & -z_\downarrow^* \\ z_\downarrow & z_\uparrow^* \end{pmatrix} \quad \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix}$$

$\mathrm{SU(2)_{spin}}$

Possible exotic intermediate phases

Fermi pockets without spin density wave order

$$\begin{pmatrix} c_\uparrow \\ c_\downarrow \end{pmatrix} = \begin{pmatrix} z_\uparrow & -z_\downarrow^* \\ z_\downarrow & z_\uparrow^* \end{pmatrix} \bullet \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix}$$

$\mathrm{U}(1)_{\mathrm{charge}}$

Possible exotic intermediate phases

Fermi pockets without spin density wave order

$$\begin{pmatrix} c_\uparrow \\ c_\downarrow \end{pmatrix} = \begin{pmatrix} z_\uparrow & -z_\downarrow^* \\ z_\downarrow & z_\uparrow^* \end{pmatrix} \bullet \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix}$$

$U \times U^{-1}$

$\mathrm{SU(2)}_{\mathrm{s;gauge}}$

Possible exotic intermediate phases

Fermi pockets without spin density wave order

$$\left(\begin{array}{c} c_\uparrow \\ c_\downarrow \end{array} \right) = \left(\begin{array}{cc} z_\uparrow & -z_\downarrow^* \\ z_\downarrow & z_\uparrow^* \end{array} \right) \left(\begin{array}{c} \psi_+ \\ \psi_- \end{array} \right)$$

The Hubbard model can be written as a lattice gauge theory with a

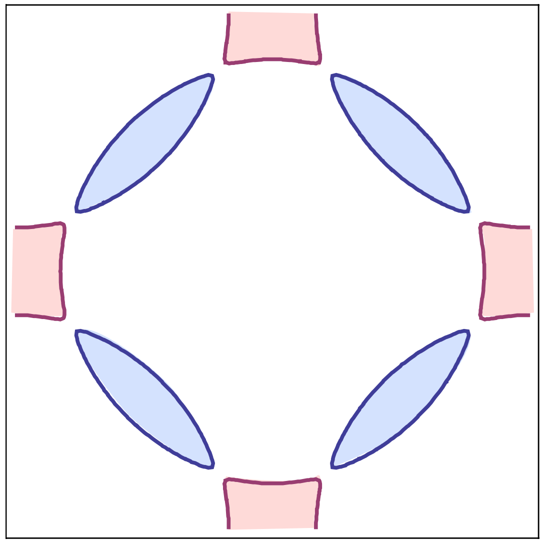
$$\mathrm{SU}(2)_{s;g} \times \mathrm{SU}(2)_{\mathrm{spin}} \times \mathrm{U}(1)_{\mathrm{charge}}$$

invariance.

The $\mathrm{SU}(2)_{s;g}$ is a gauge invariance, while $\mathrm{SU}(2)_{\mathrm{spin}} \times \mathrm{U}(1)_{\mathrm{charge}}$ is a global symmetry

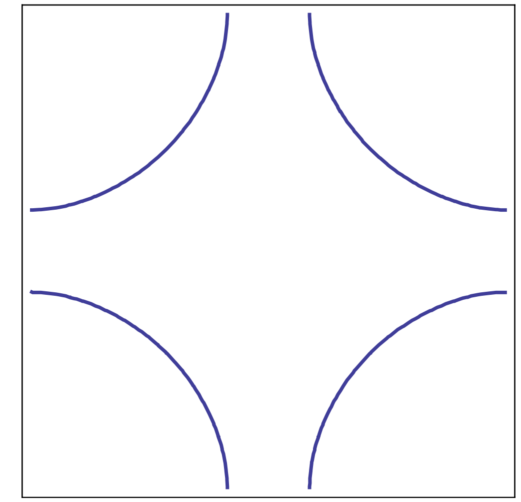
S. Sachdev, M.A. Metlitski, Y. Qi, and C. Xu, *Physical Review B* **80**, 155129 (2009)

Phases of SU(2) gauge theory



SDW order
small Fermi pockets

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



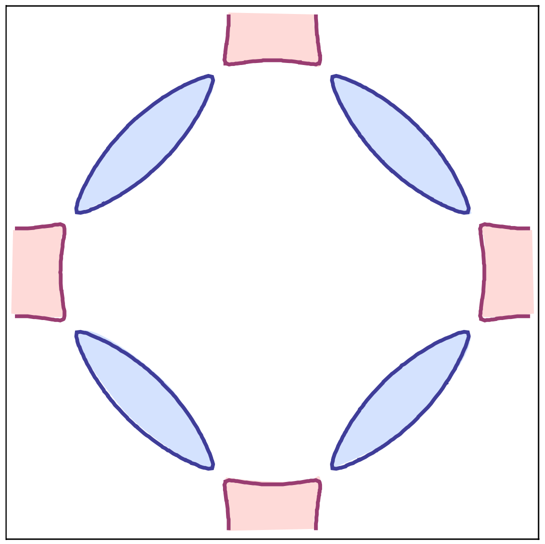
Fermi liquid
large Fermi surface

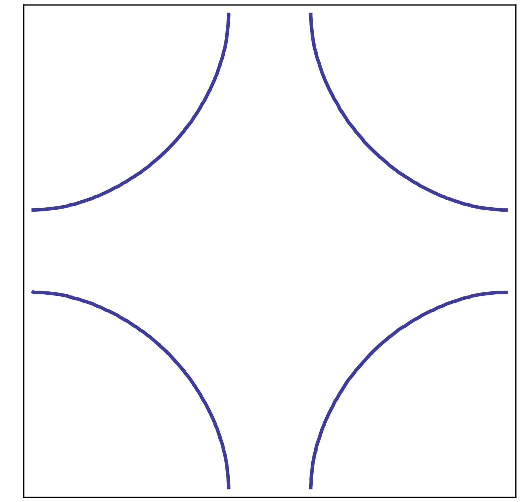
$\langle \vec{\varphi} \rangle = 0$

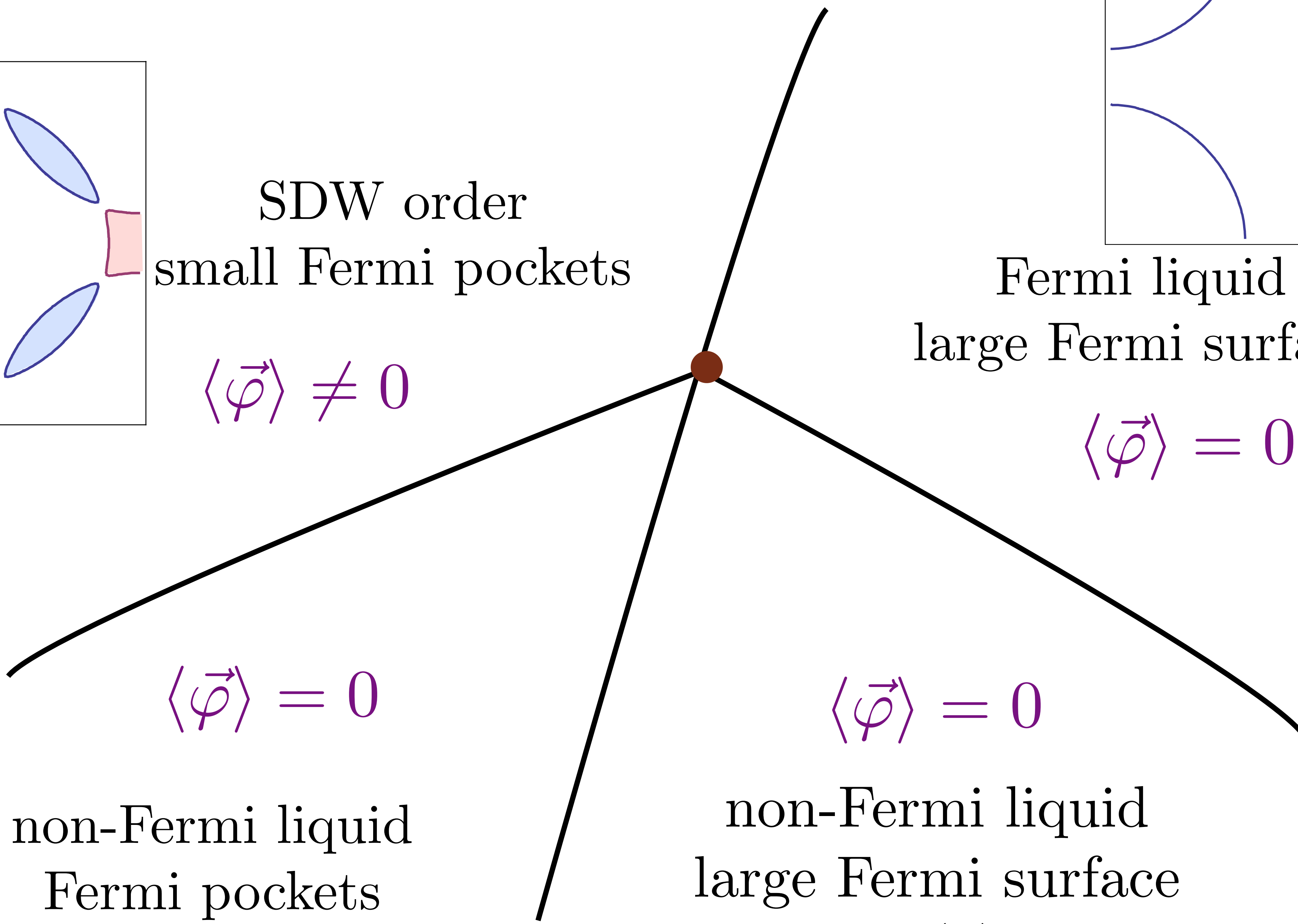
Fermi liquid phases considered so far

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

Phases of SU(2) gauge theory







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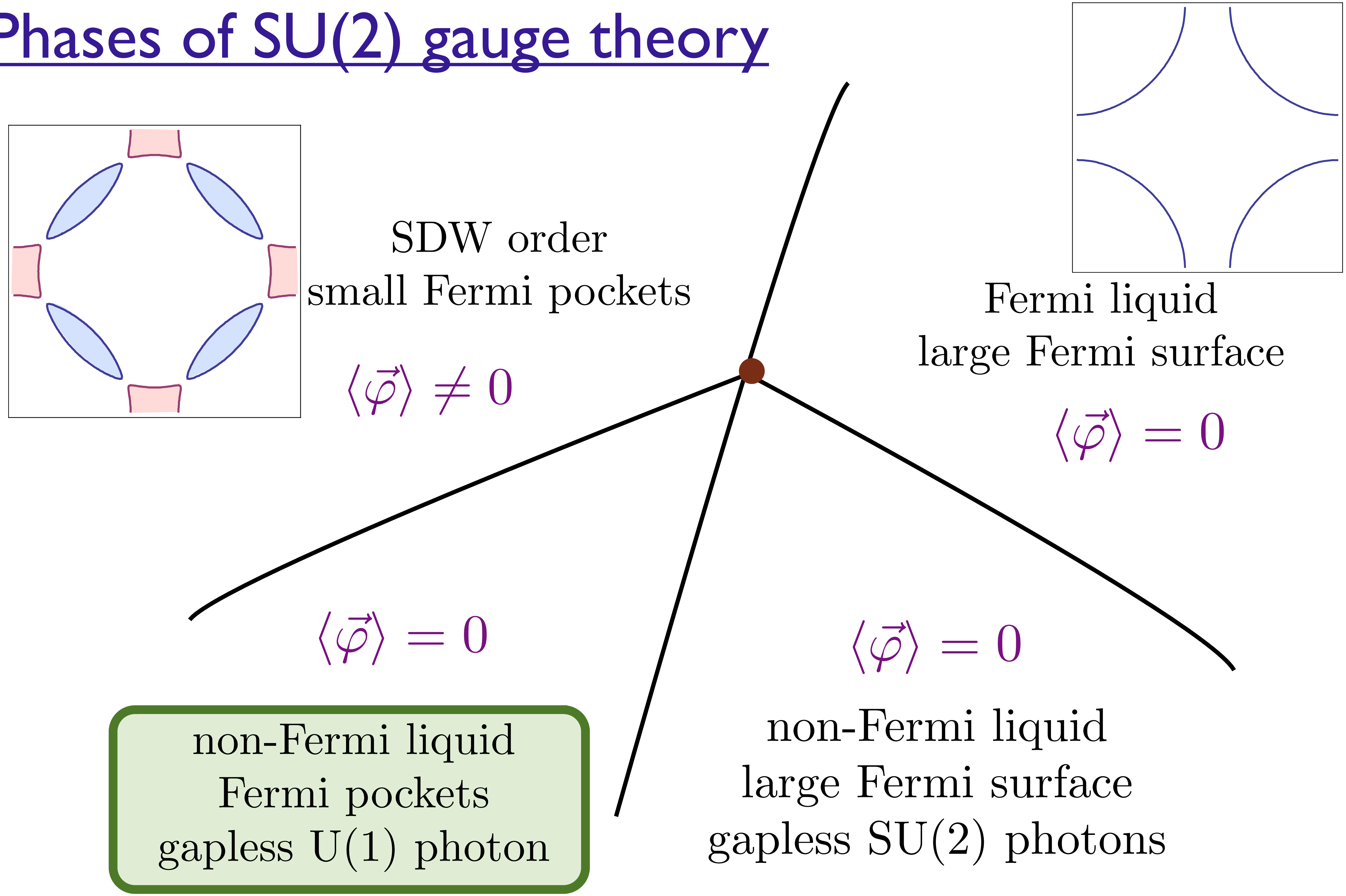
Tuesday, May 17, 2011

Phases of SU(2) gauge theory



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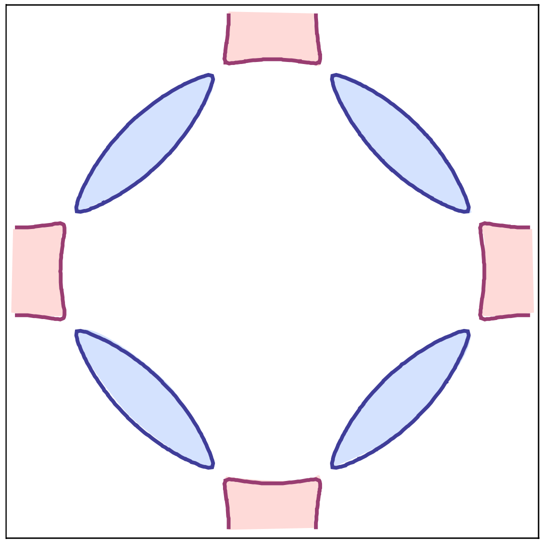
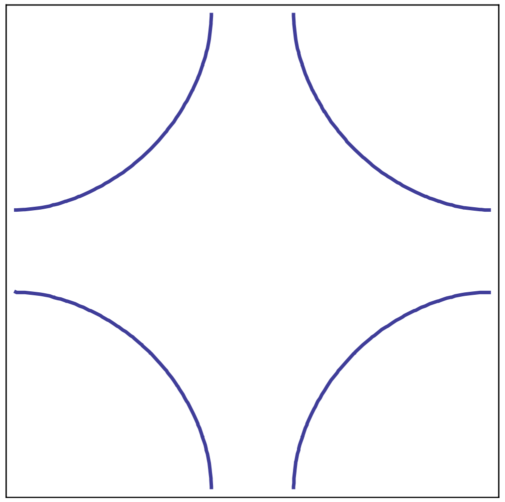


Electron doped

SDW order
small Fermi pockets

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



Fermi liquid
large Fermi surface

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

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

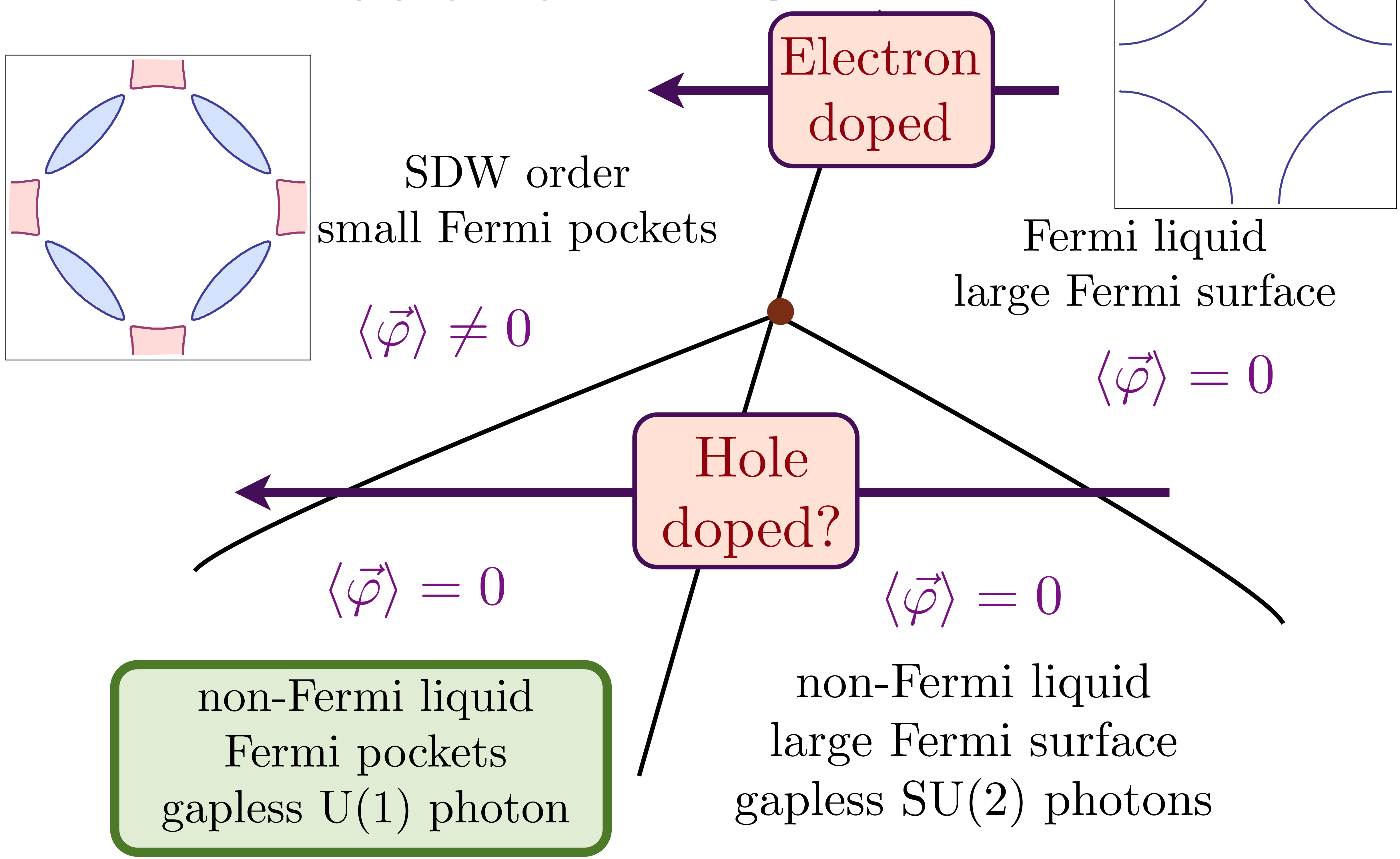
non-Fermi liquid
Fermi pockets
gapless U(1) photon

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

non-Fermi liquid
large Fermi surface
gapless SU(2) photons

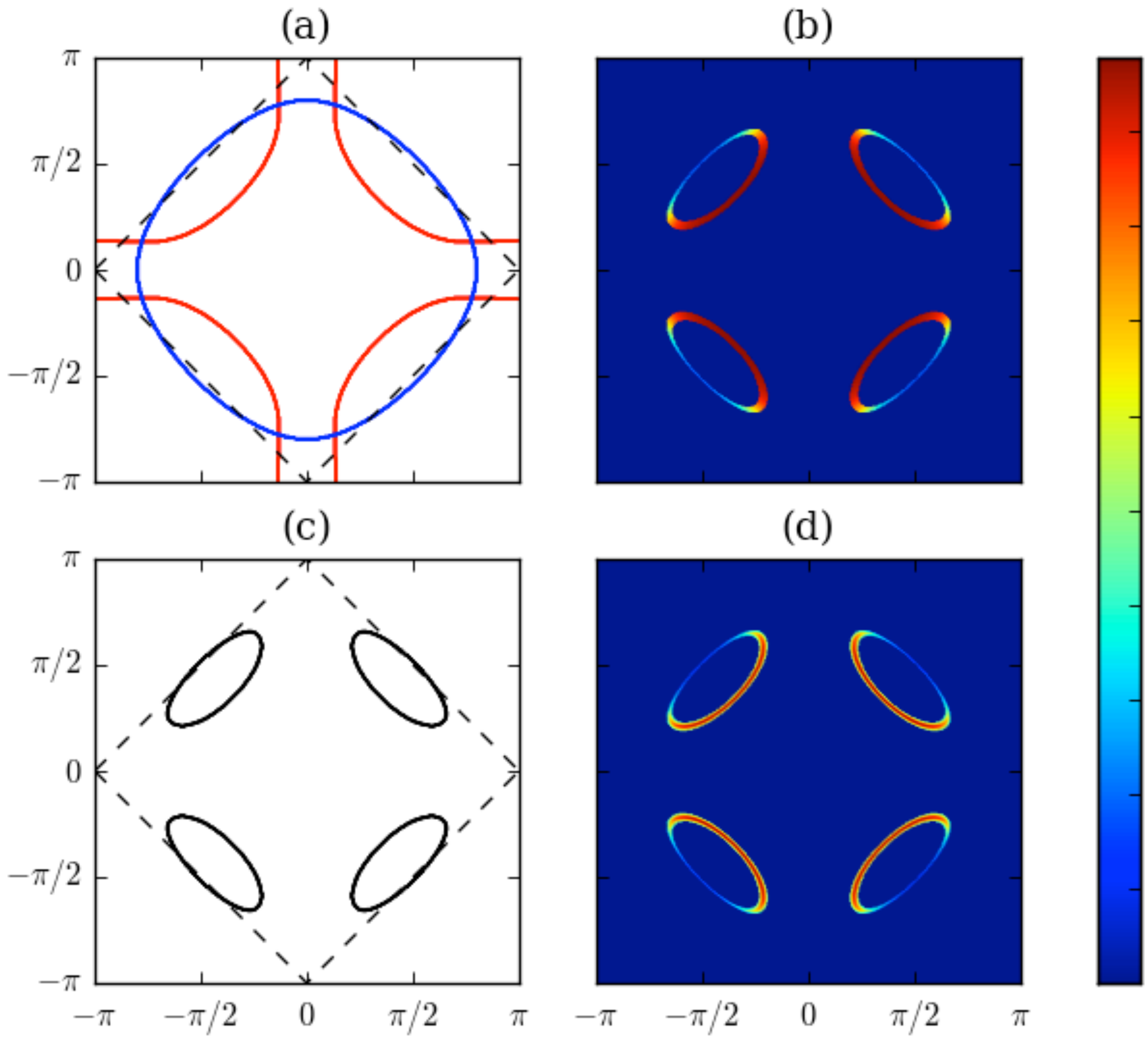
S. Sachdev, M.A. Metlitski, Y. Qi, and C. Xu, *Physical Review B* **80**, 155129 (2009)

Phases of SU(2) gauge theory



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

Exotic non-Fermi liquid has Fermi pockets without long-range antiferromagnetism, along with emergent gauge excitations



Y. Qi and S. Sachdev, *Physical Review B* **81**, 115129 (2010)

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)

Conclusions

The quantum critical point describing the onset of spin-density-wave order in metals is strongly coupled in two spatial dimensions, and displays universal non-Fermi liquid physics which is independent of electron interaction strength.

Conclusions

The quantum critical point has
an instability to
unconventional "*d*-wave" pairing, with a
universal *log-squared* enhancement
of the pairing susceptibility,
which is independent of
electron interaction strength.

Conclusions

Composite operators lead to
non-Fermi liquid behavior
around entire Fermi surface

Conclusions

Phenomenological phase diagram
in a magnetic field provides
a unified description of many
higher temperature superconductors