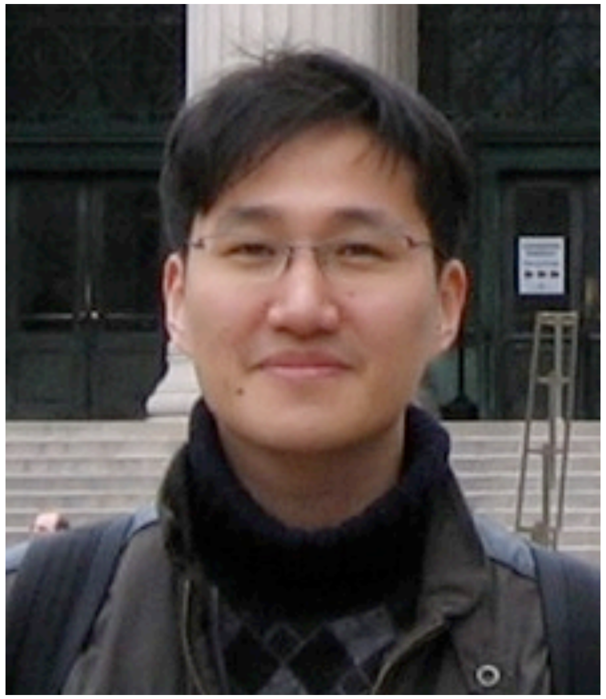
The phase diagrams of the high temperature superconductors

Talk online: sachdev.physics.harvard.edu

PHYSICS

VE RI TAS

HARVARD



Max Metlitski, Harvard

Eun Gook Moon, Harvard

PHYSICS

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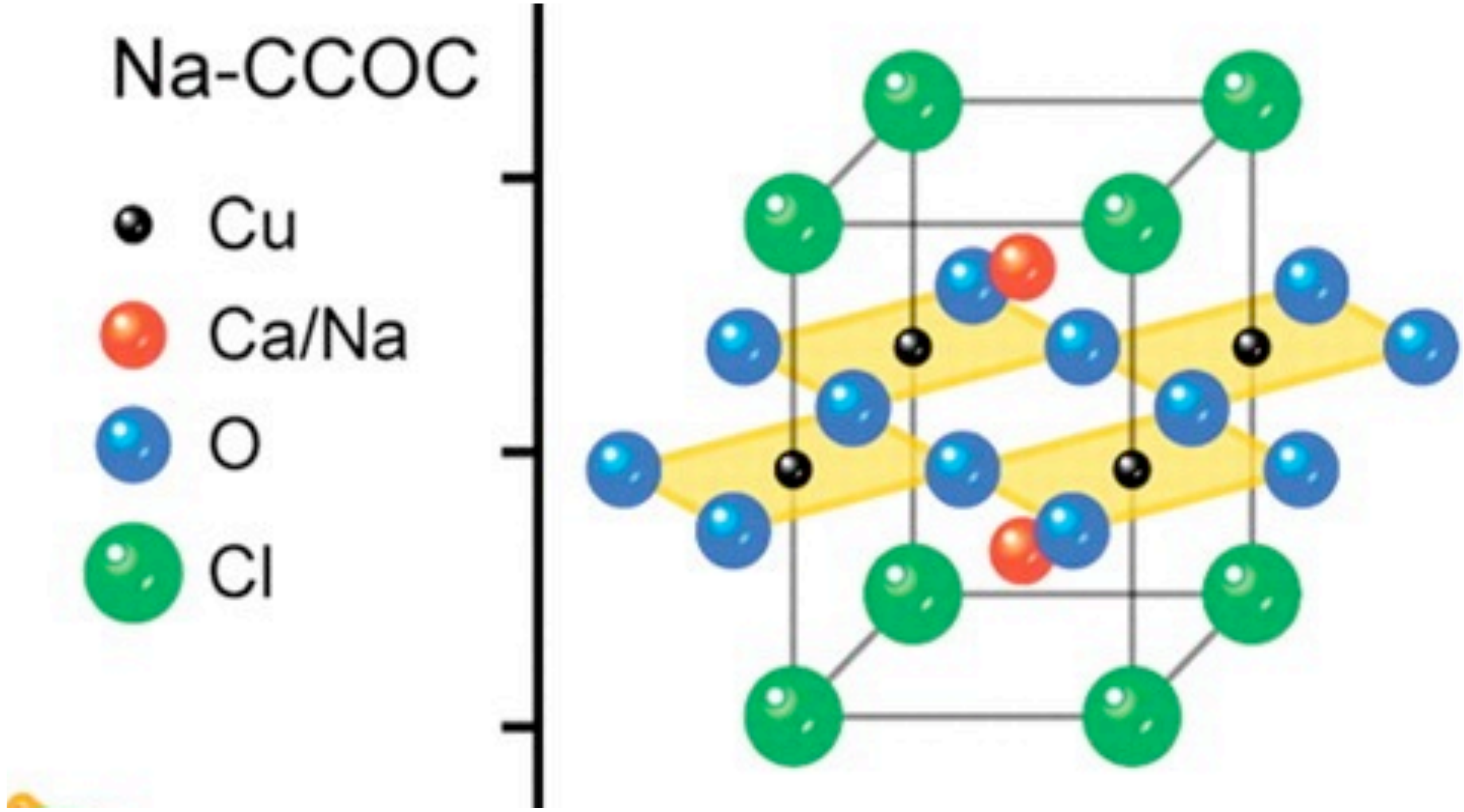
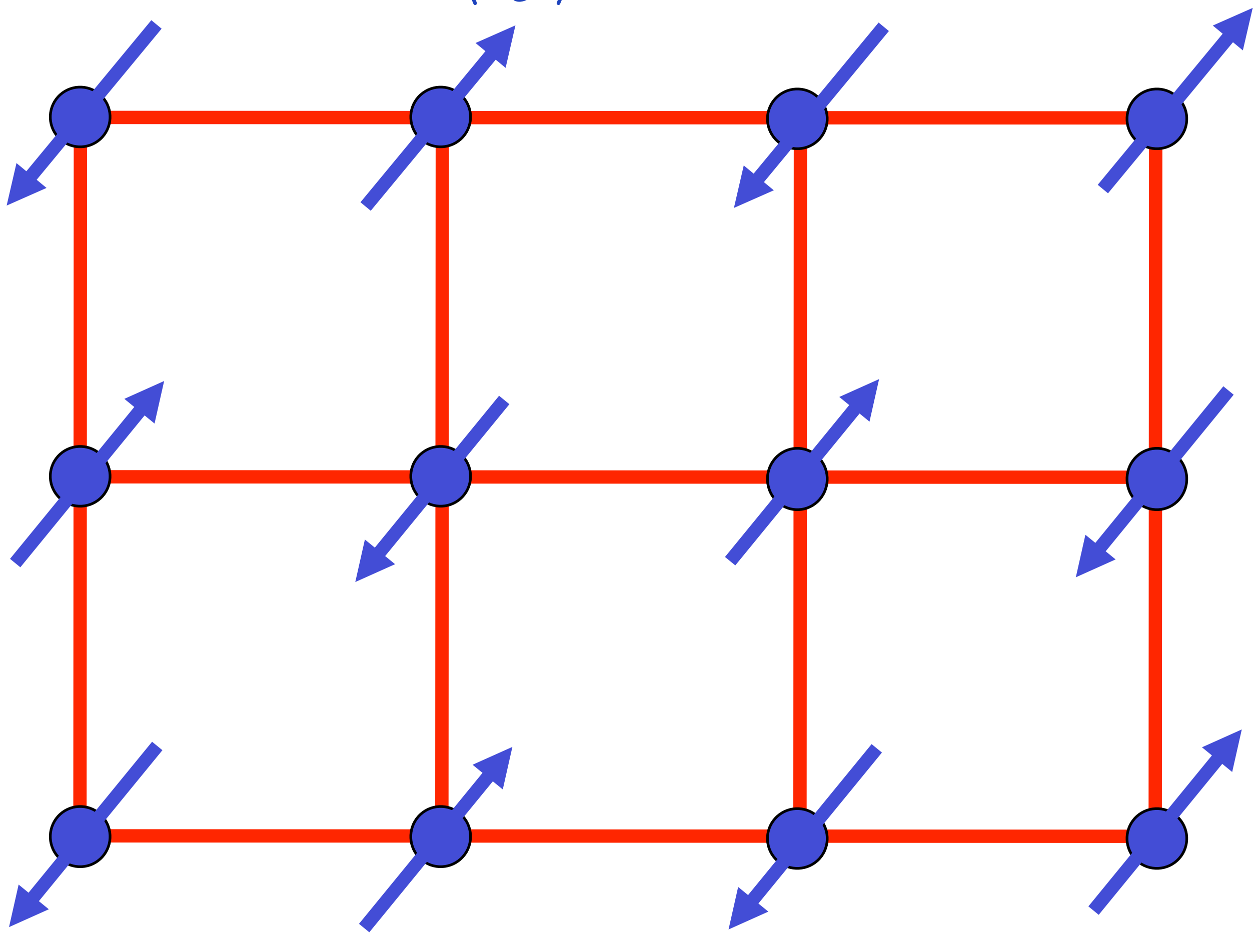
The cuprate superconductors



Square lattice antiferromagnet

$$H = \sum_{\langle ij \rangle} J_{ij} \vec{S}_i \cdot \vec{S}_j$$



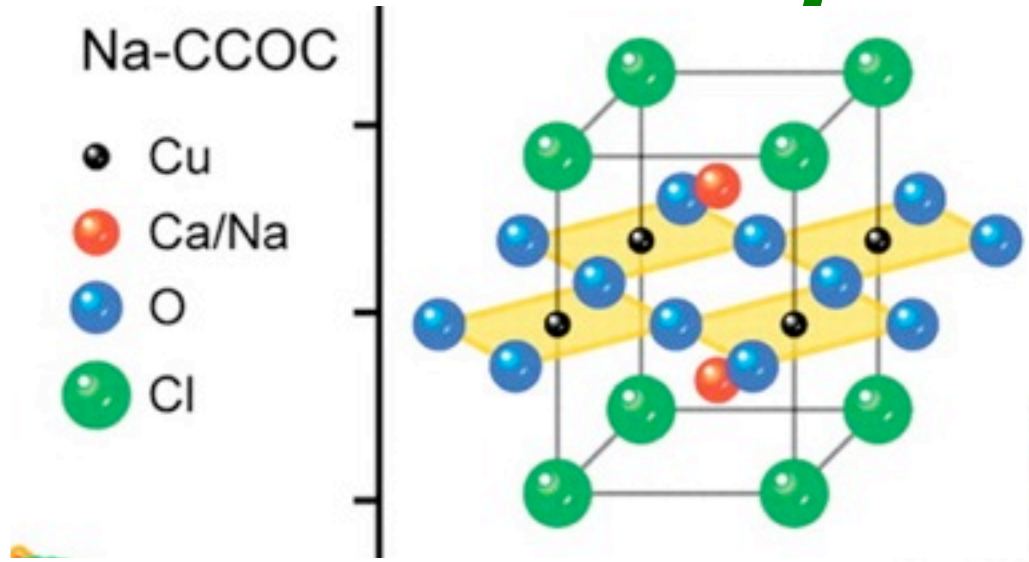
Ground state has long-range Néel order

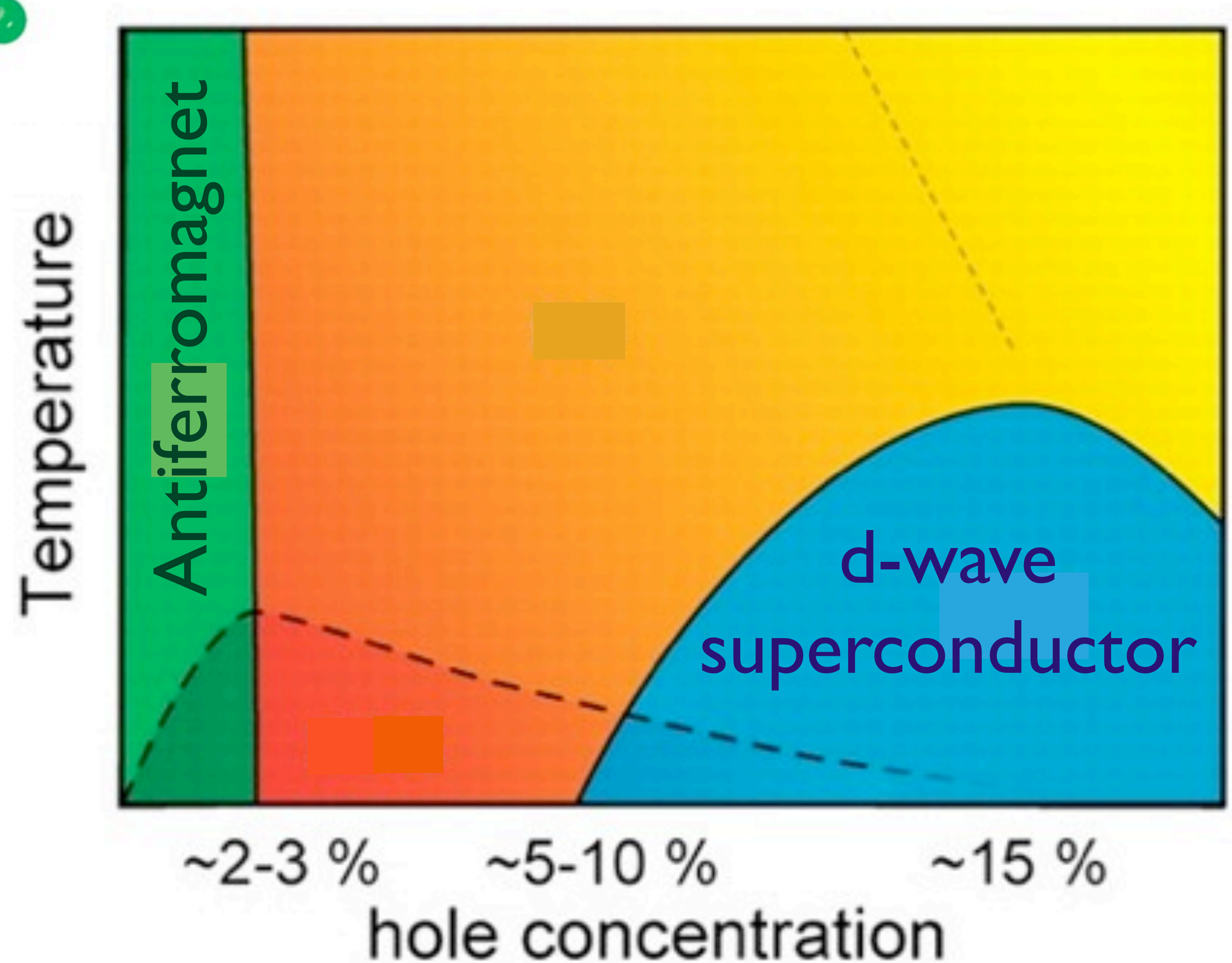
Order parameter is a single vector field $\vec{\varphi} = \eta_i \vec{S}_i$

$\eta_i = \pm 1$ on two sublattices

$\langle \vec{\varphi} \rangle \neq 0$ in Néel state.

The cuprate superconductors





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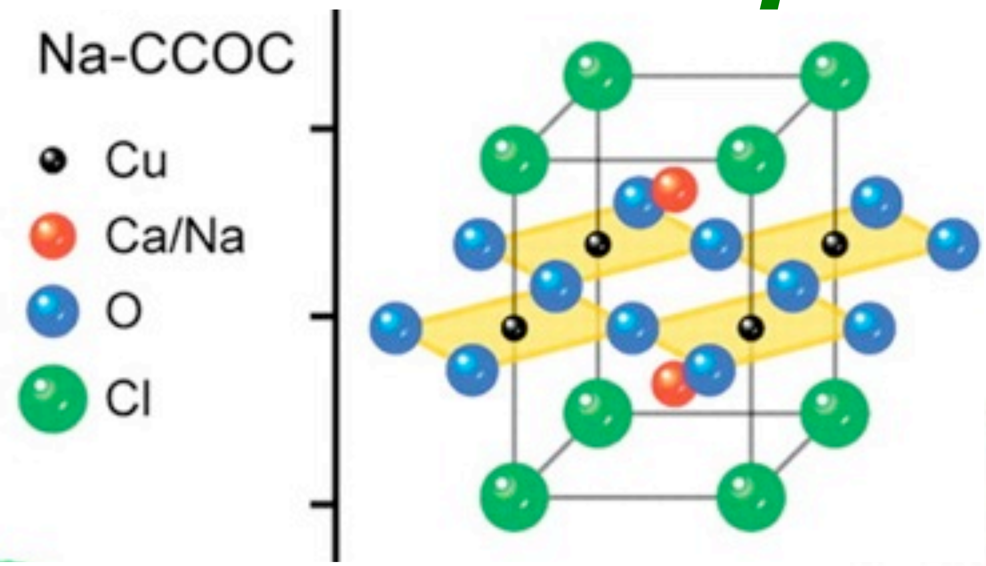
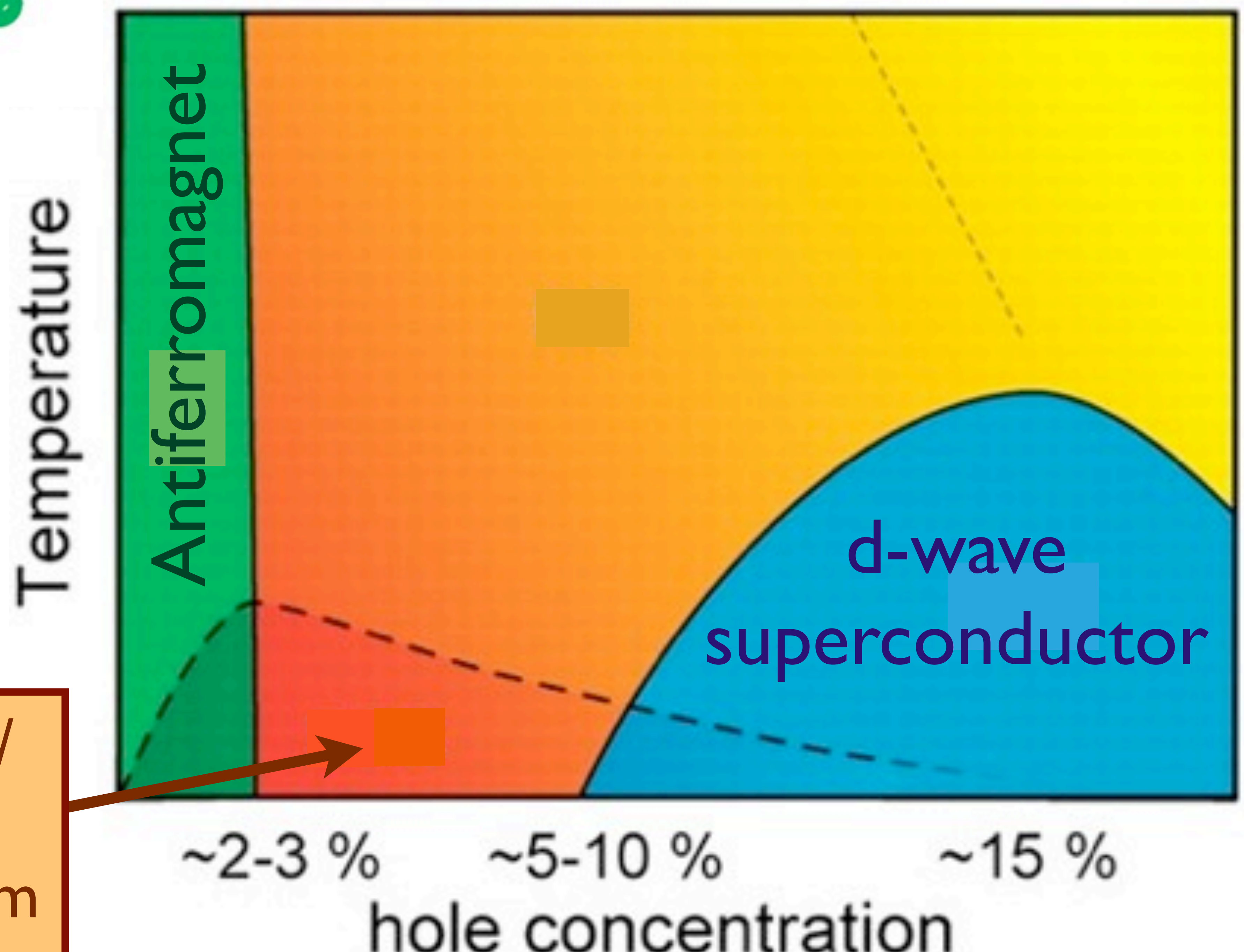
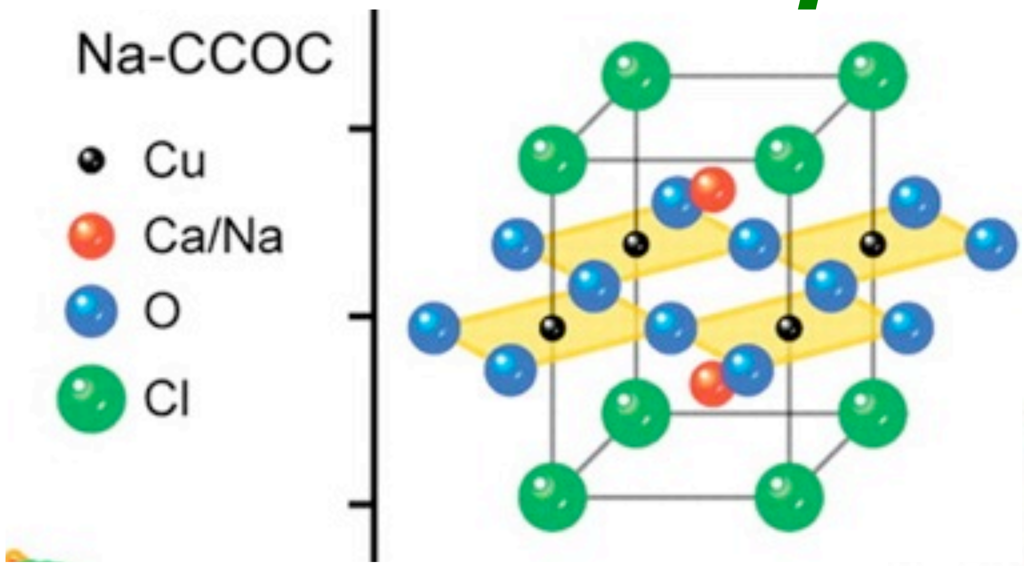
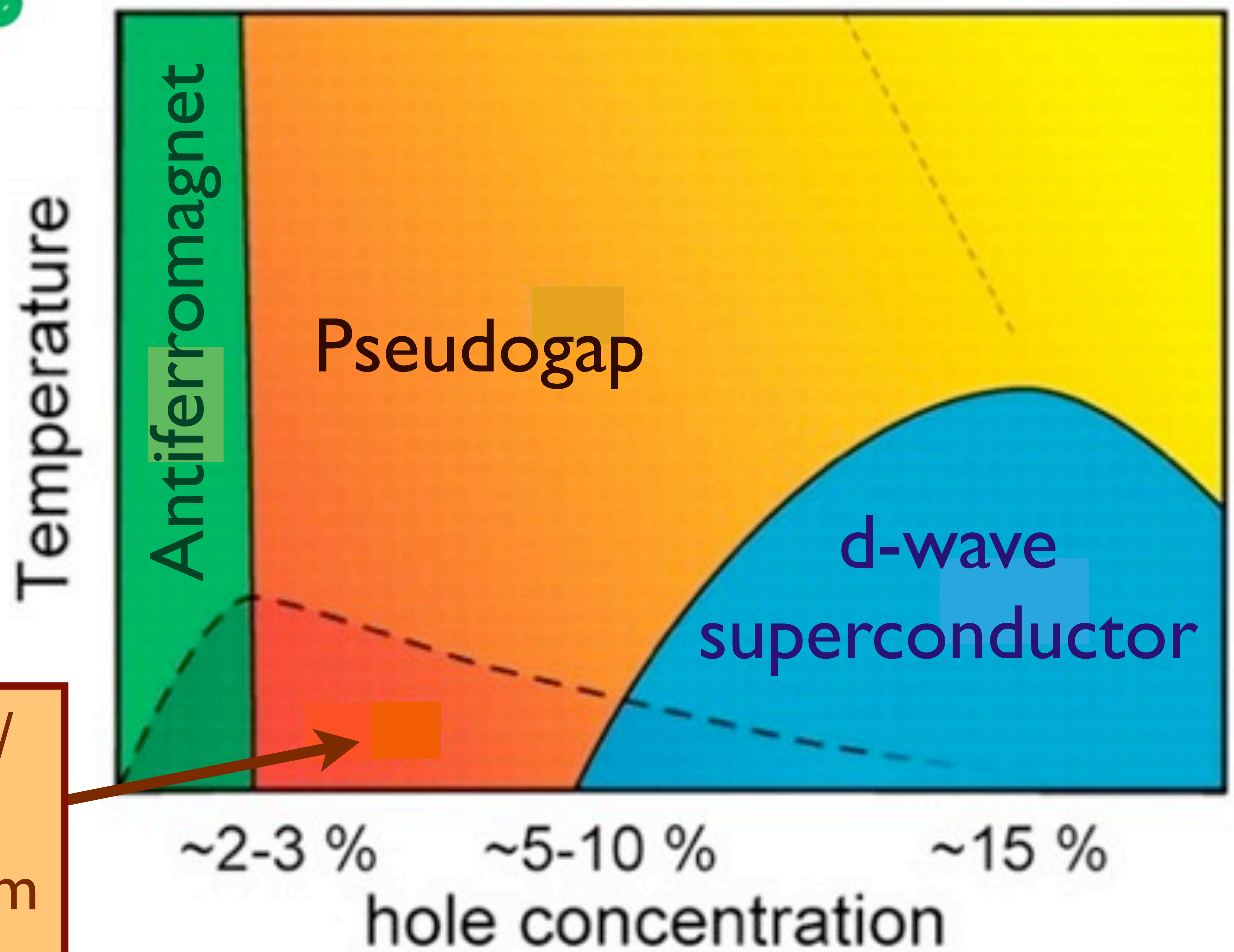




Incommensurate/ disordered antiferromagnetism and charge order

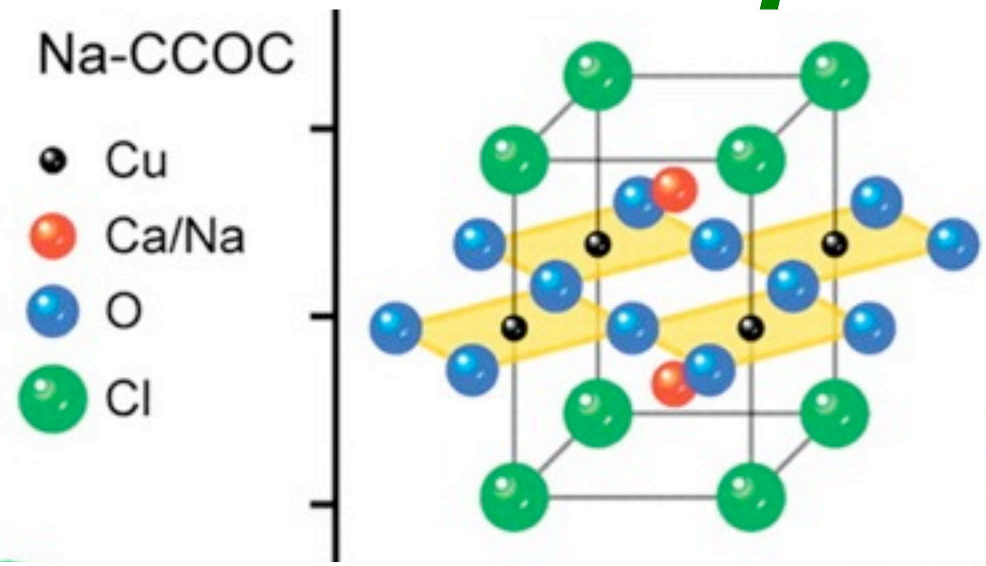
The cuprate superconductors

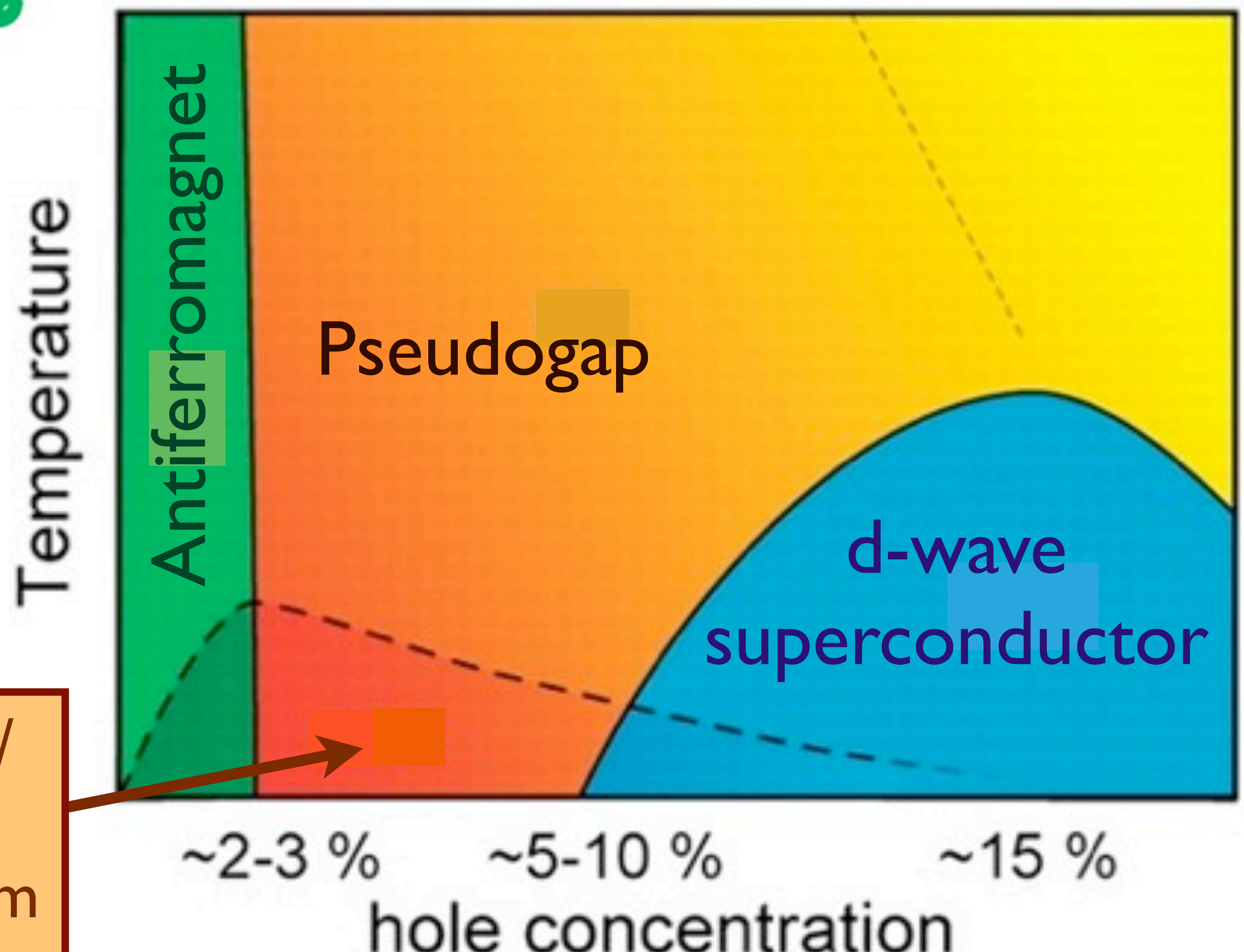




Incommensurate/
disordered
antiferromagnetism
and charge order

The cuprate superconductors





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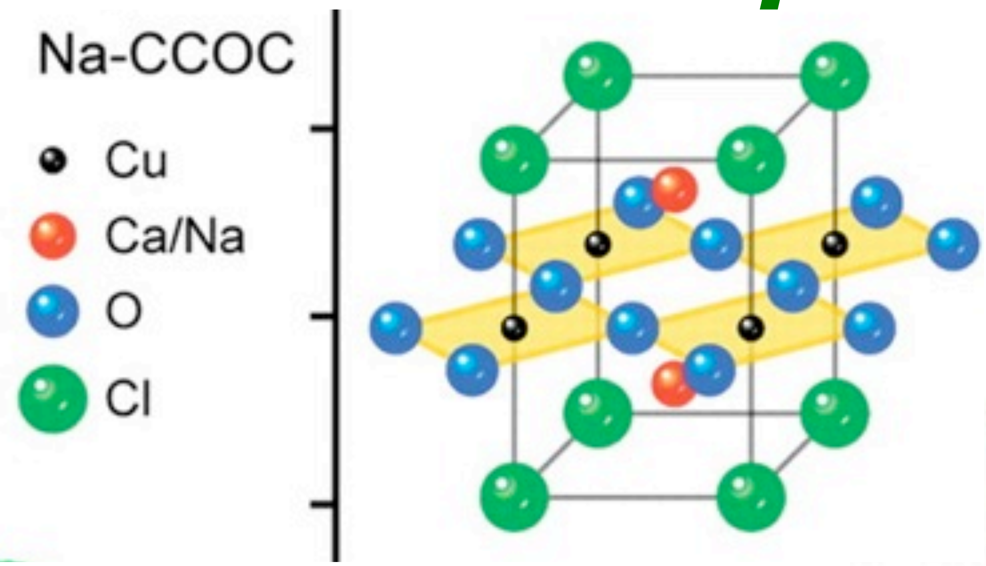
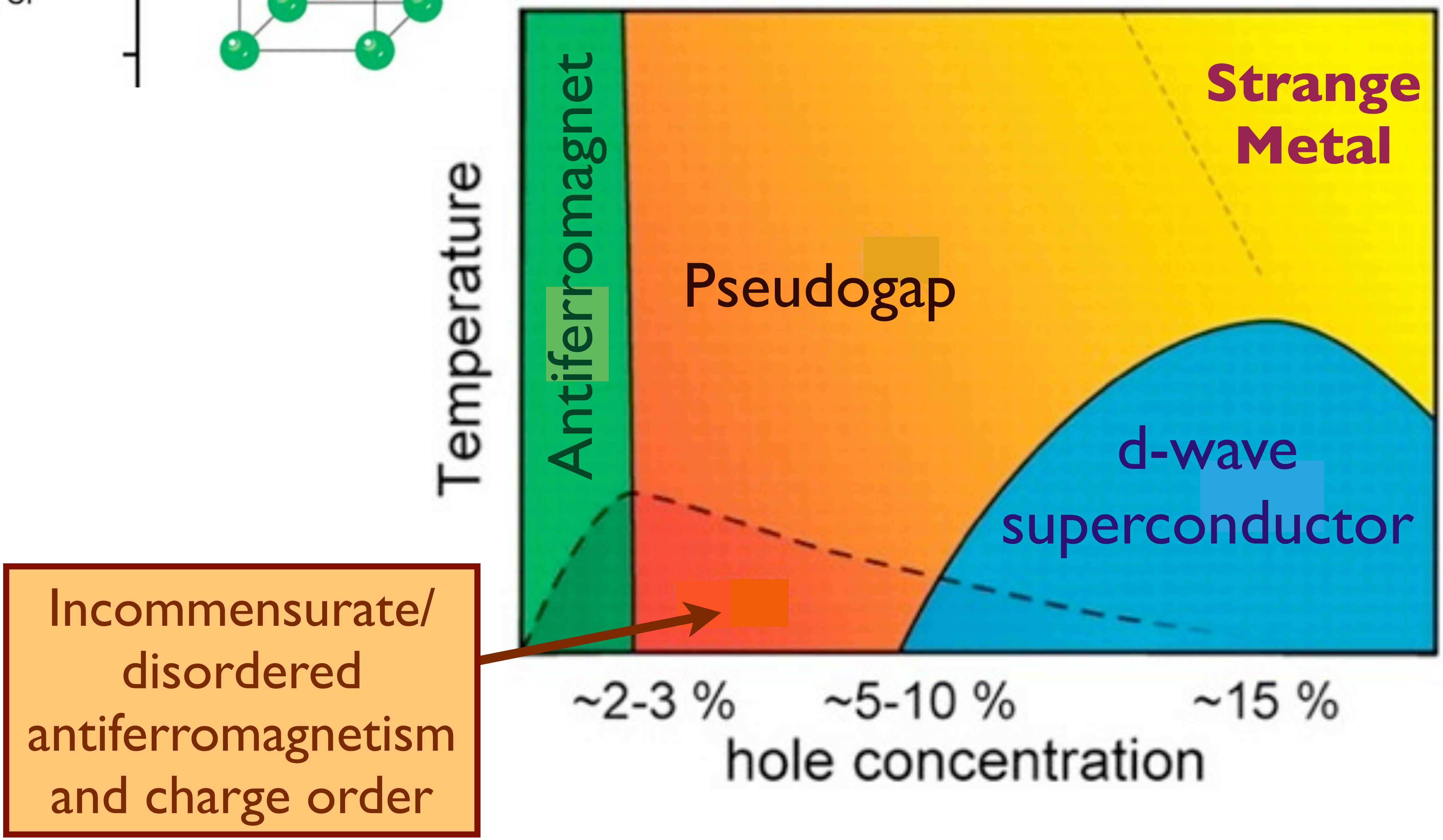
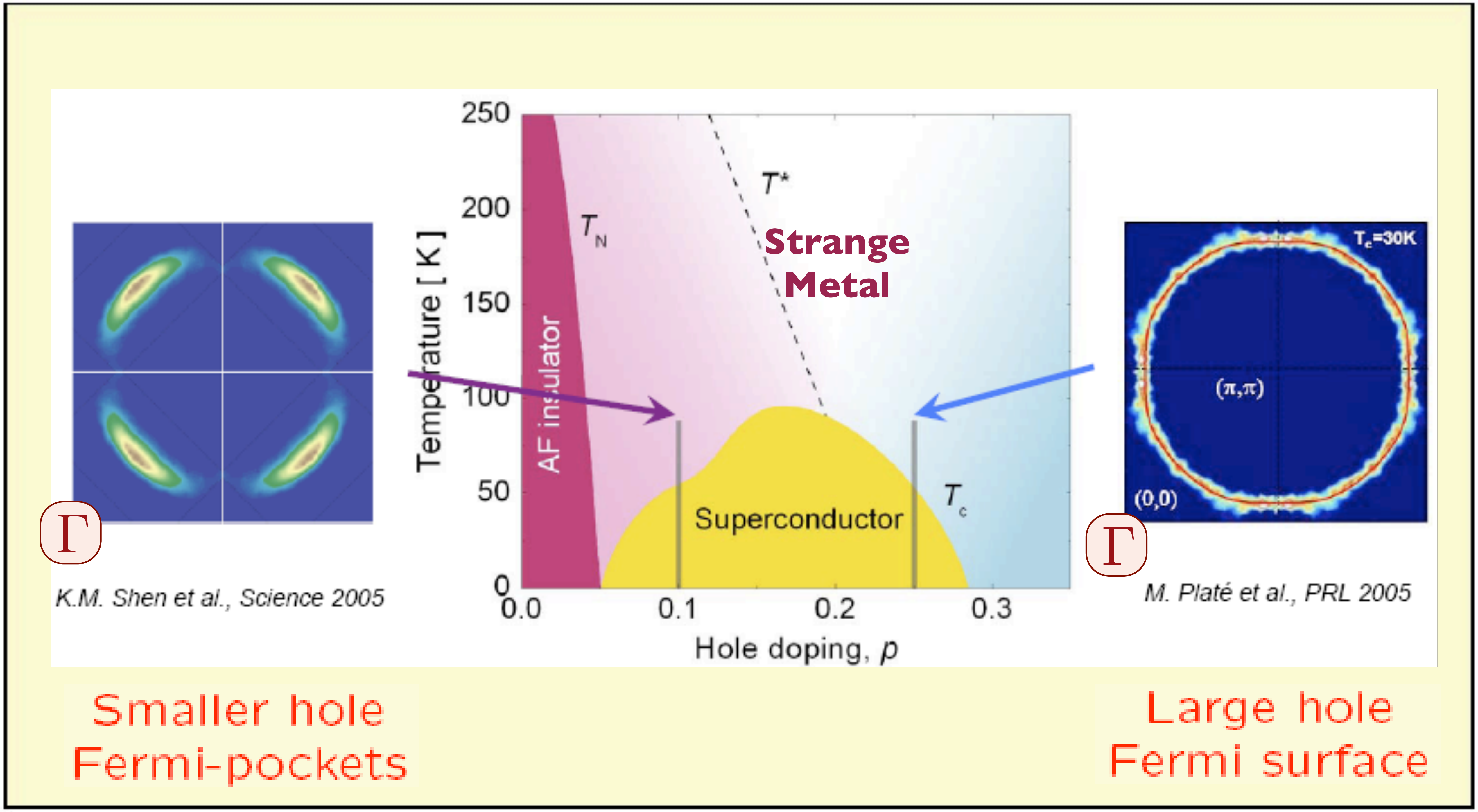


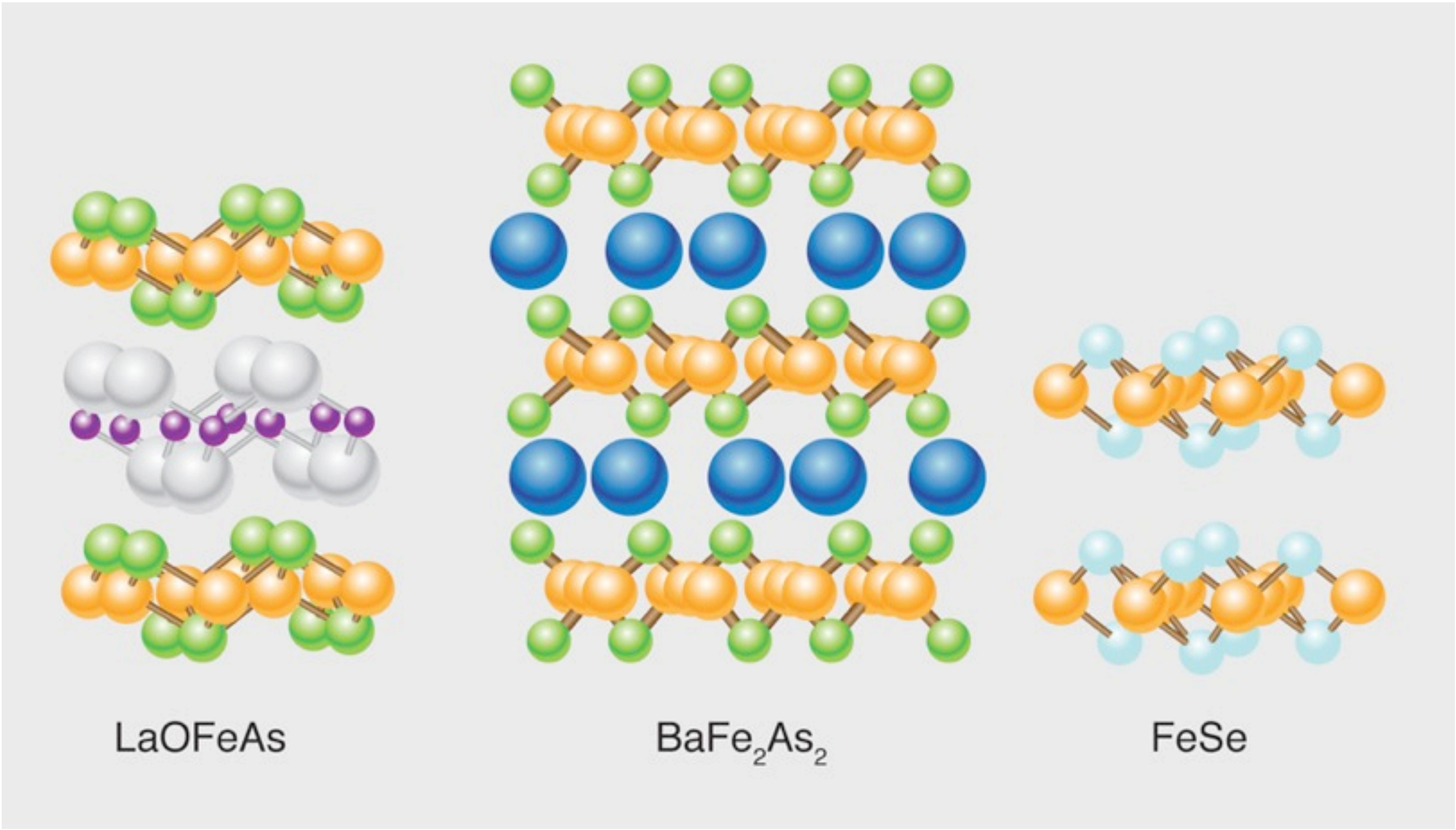


Central ingredients in cuprate phase diagram:
antiferromagnetism, superconductivity,
and change in Fermi surface



Iron pnictides:

a new class of high temperature superconductors



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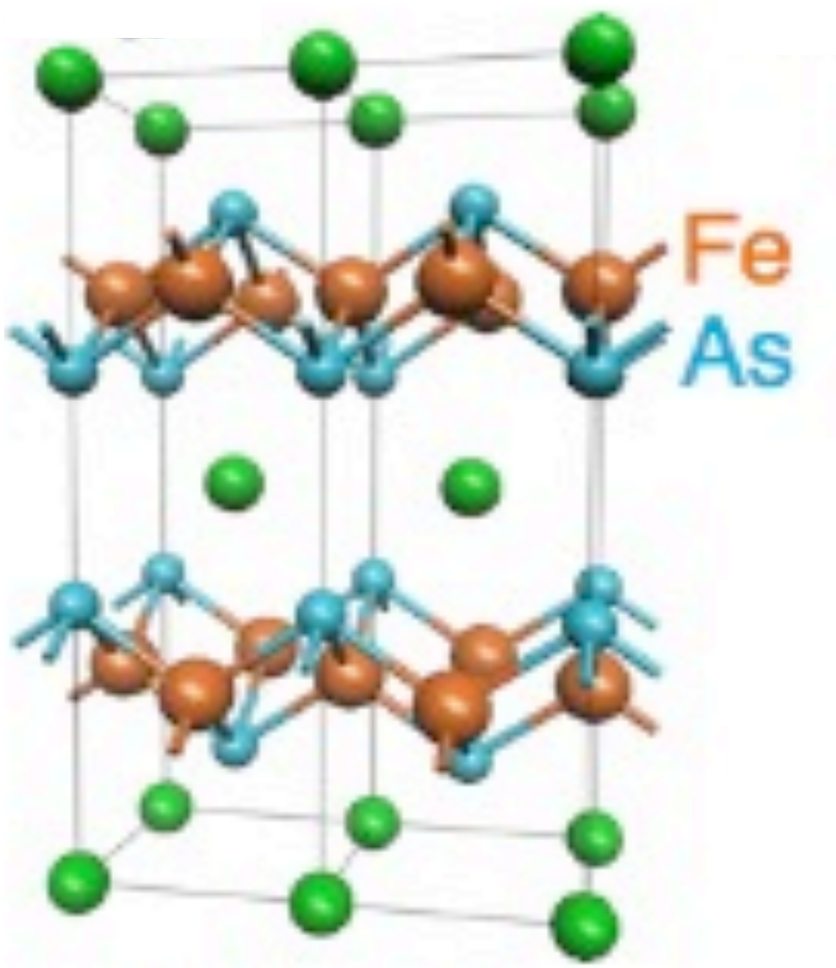
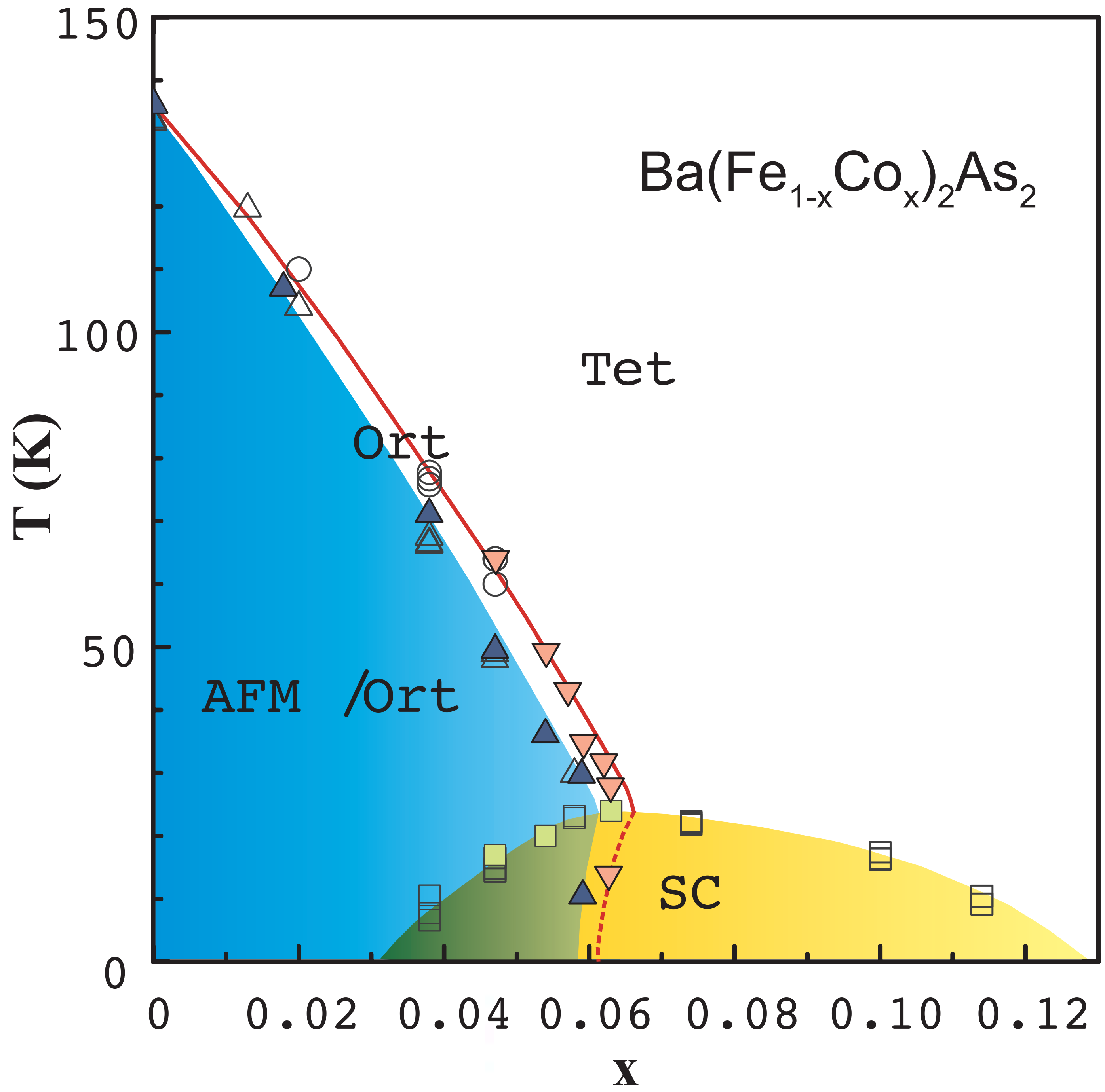
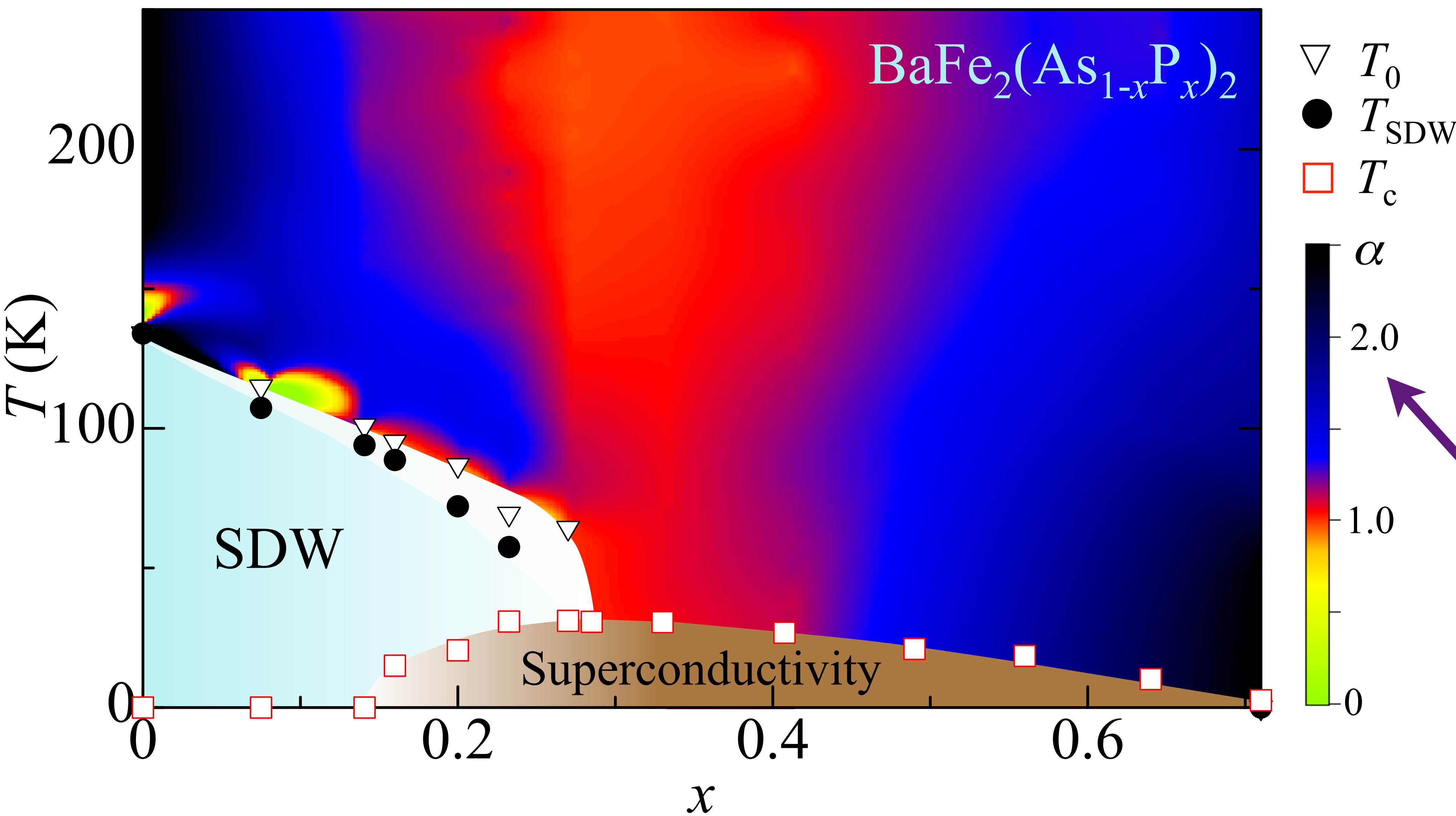


$BaFe_2As_2$
Unit cell



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).

Temperature-doping phase diagram of the iron pnictides:



Resistivity $\sim \rho_0 + AT^{\alpha}$

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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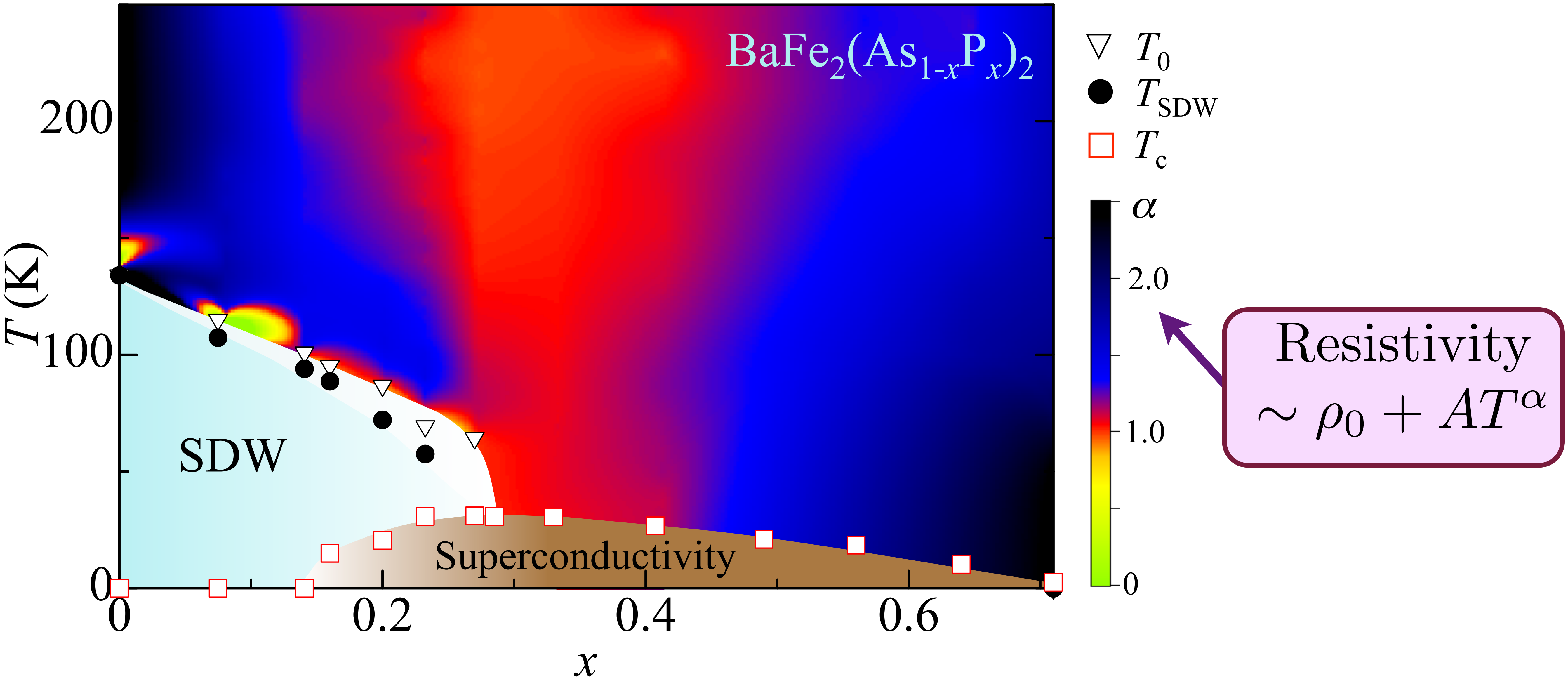

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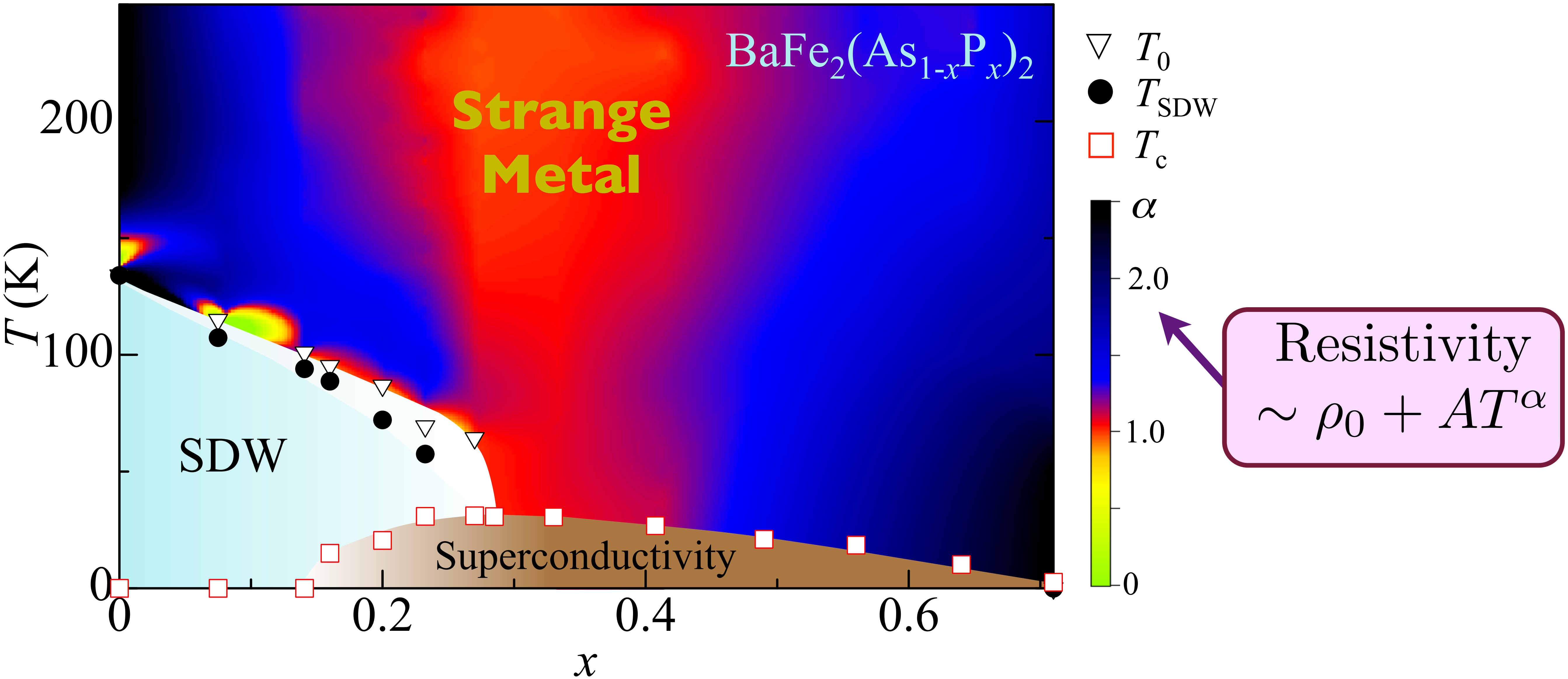

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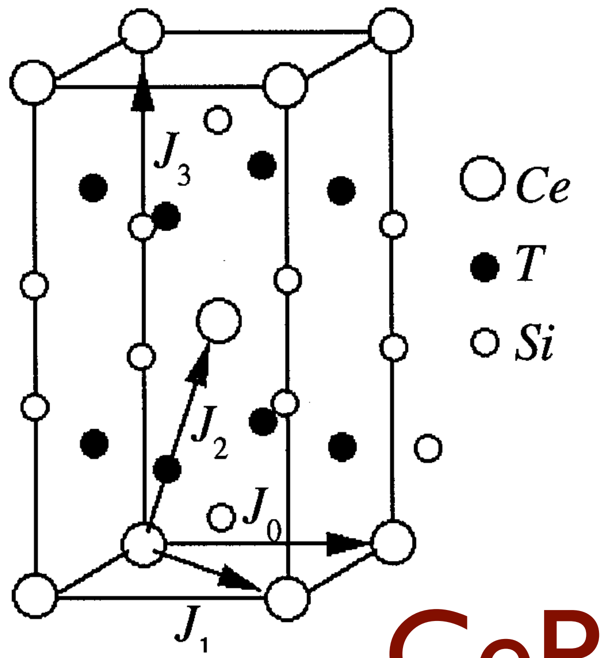
Lower T_c superconductivity in the heavy fermion compounds



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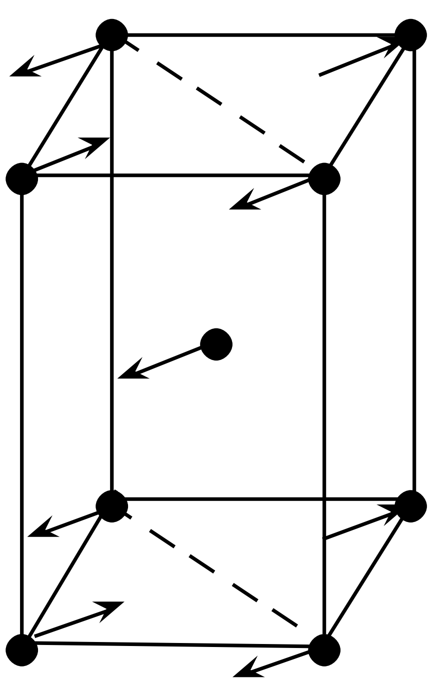
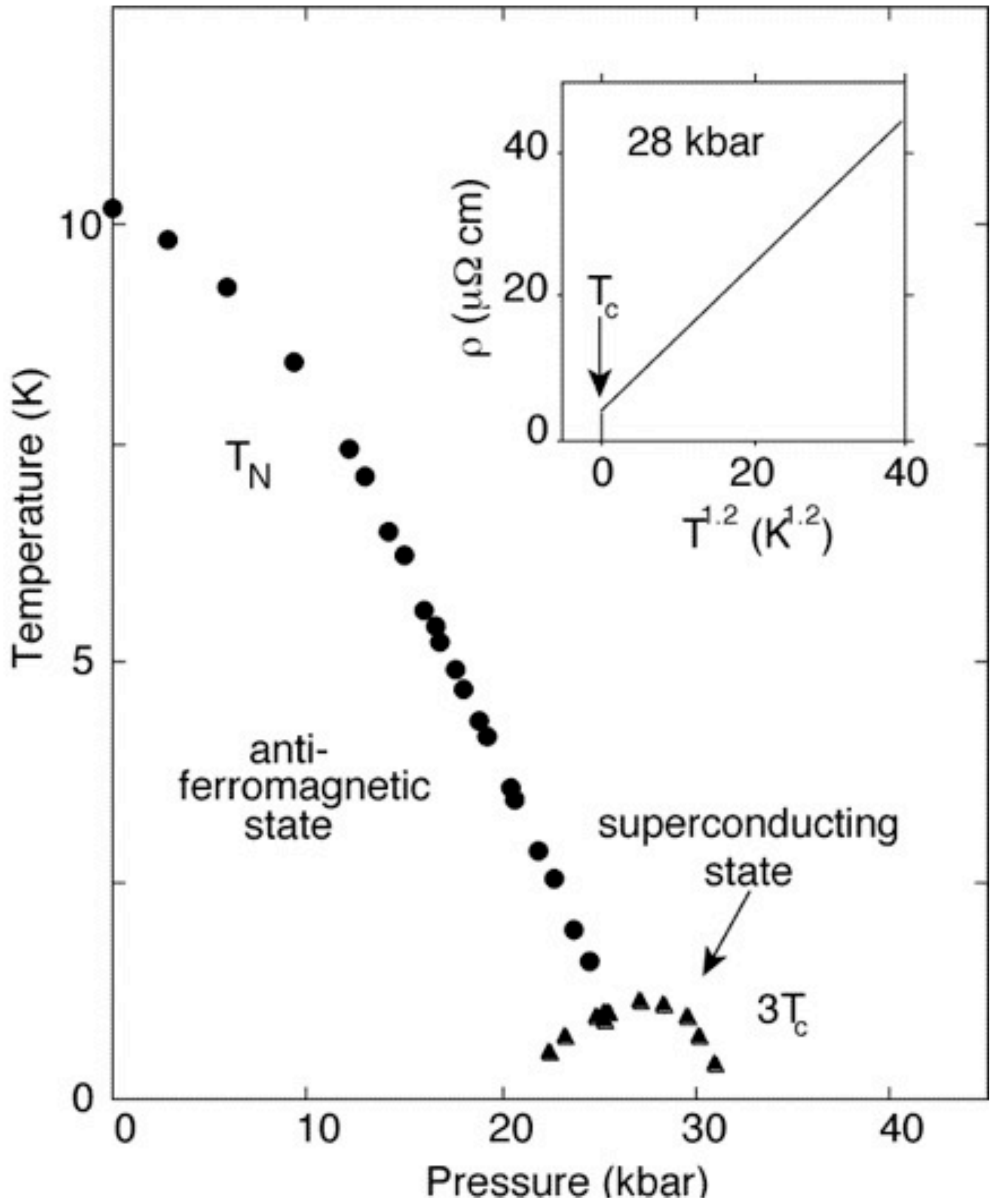


$CePd_2Si_2$



N. D. Mathur, F. M. Grosche, S. R. Julian, I. R. Walker, D. M. Freye, R. K. W. Haselwimmer, and G. G. Lonzarich, Nature **394**, 39 (1998)

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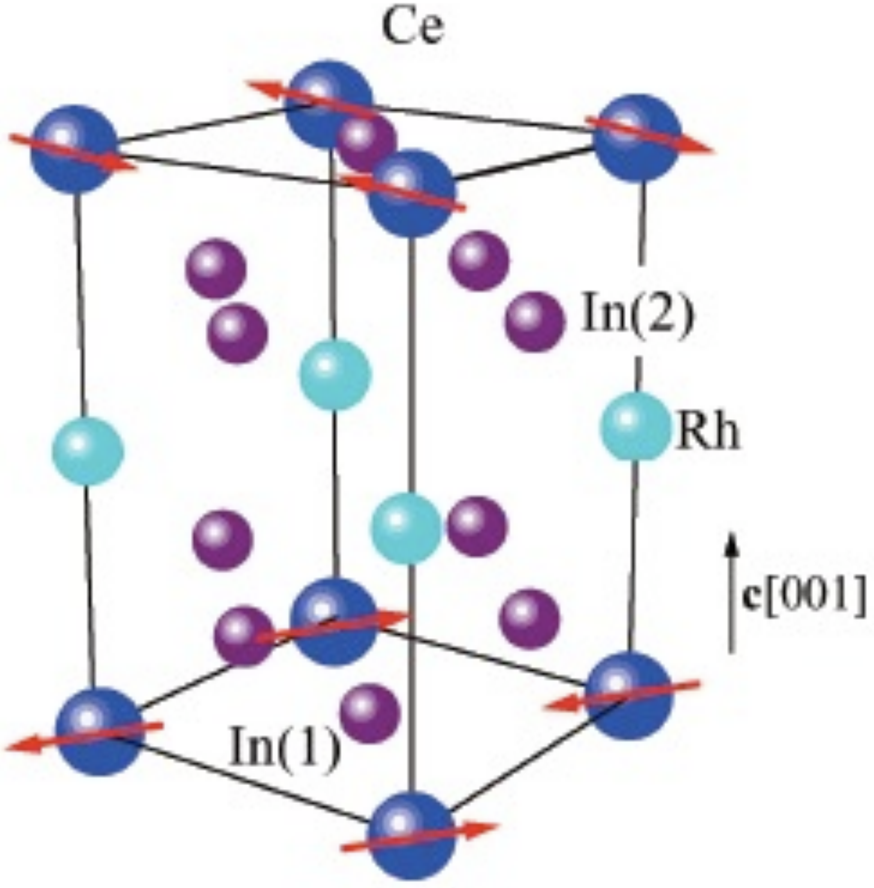

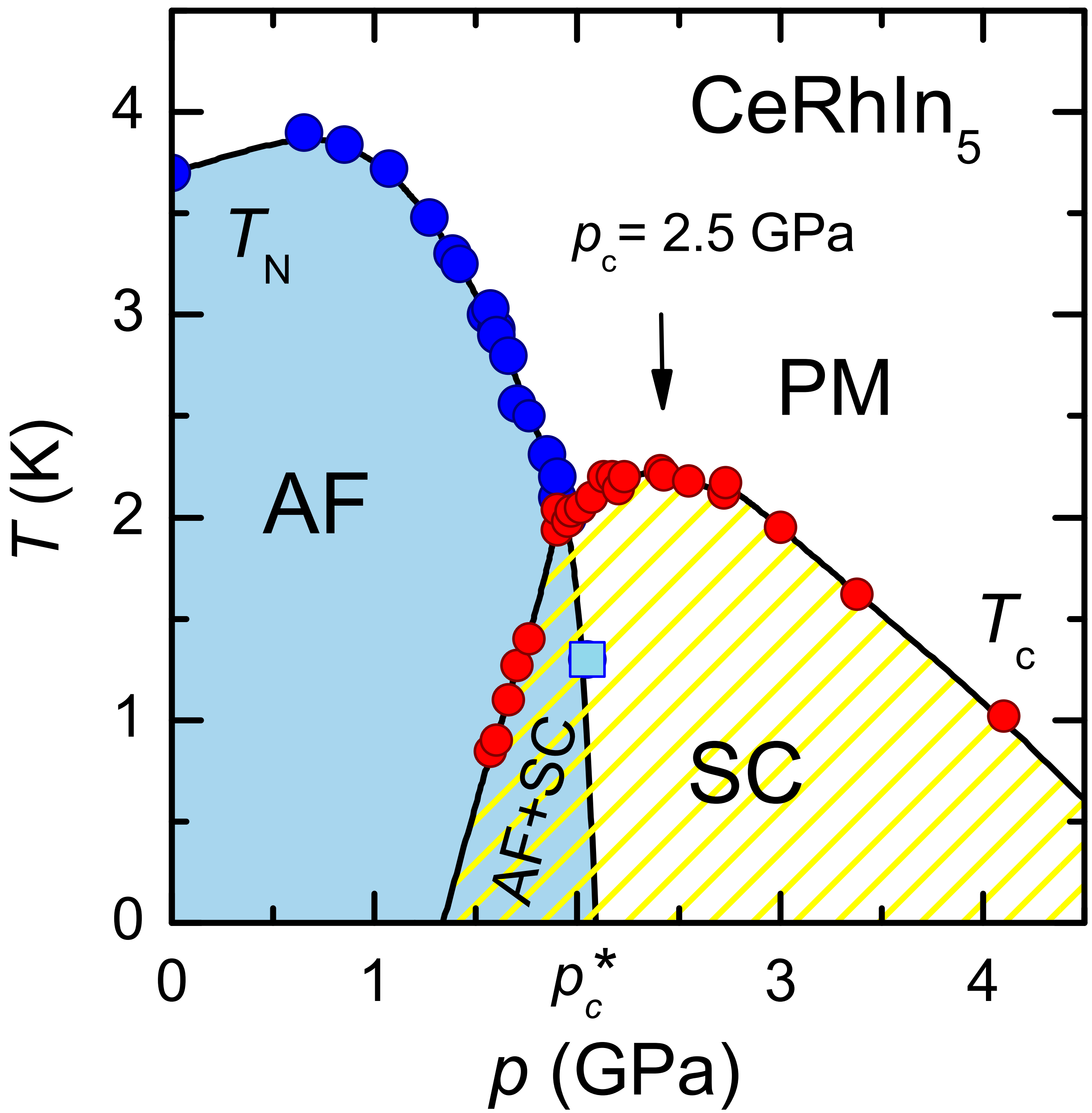

G. Knebel, D. Aoki, and J. Flouquet, arXiv:0911.5223

Questions

- *Can quantum fluctuations near the loss of antiferromagnetism induce higher temperature superconductivity ?*

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- *If so, why is there no antiferromagnetism in the cuprates near the point where the superconductivity is strongest ?*

- *What is the physics of the strange metal ?*

Outline

1. Loss of antiferromagnetism in an insulator
   Coupled-dimer antiferromagnets and quantum criticality

2. Onset of antiferromagnetism in a metal
   From large Fermi surfaces to Fermi pockets

3. Unconventional superconductivity
   Pairing from antiferromagnetic fluctuations

4. Competing orders
   Phase diagram in a magnetic field

5. Strongly-coupled quantum criticality in metals
   Fluctuating antiferromagnetism and Fermi surfaces

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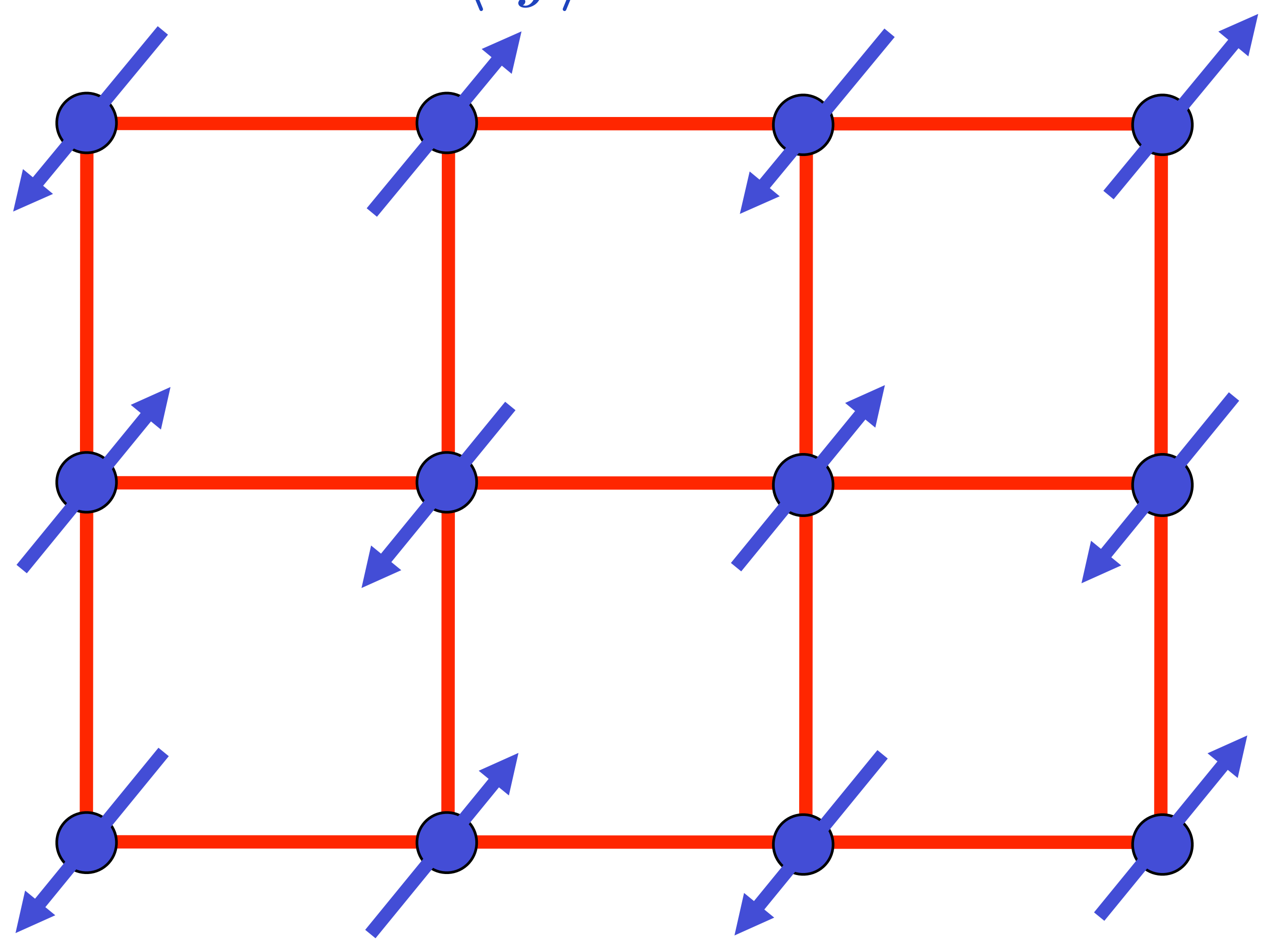

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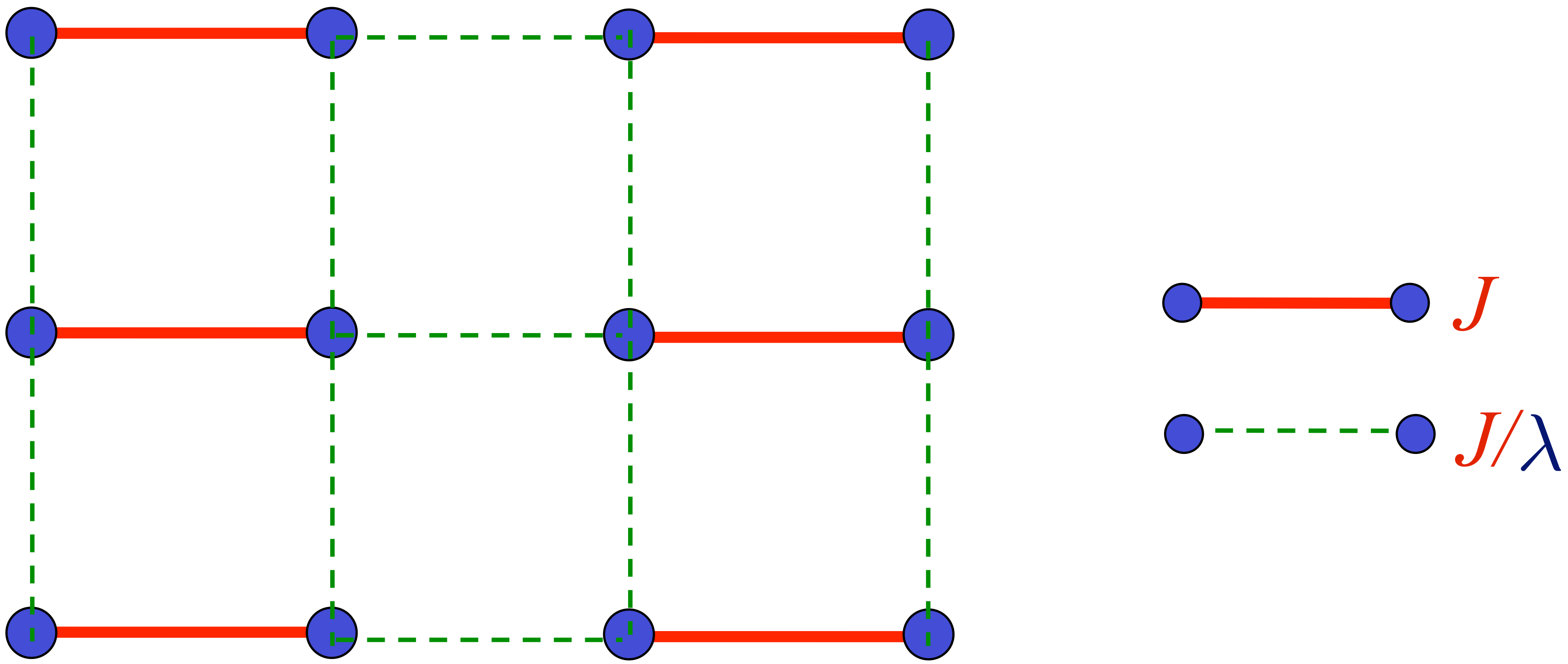

Weaken some bonds to induce spin entanglement in a new quantum phase

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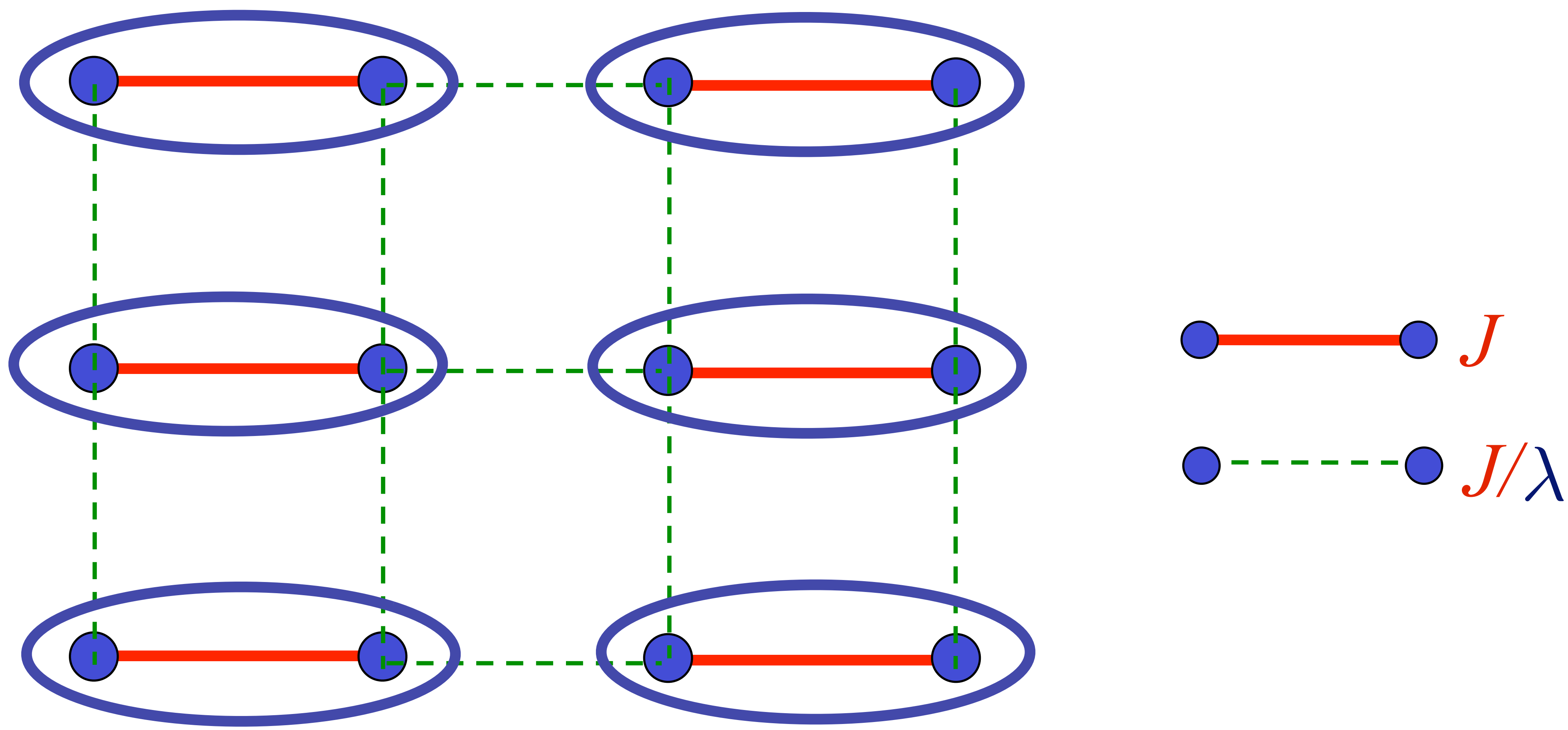
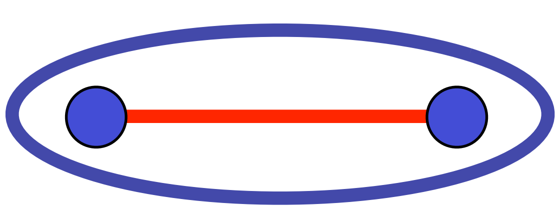
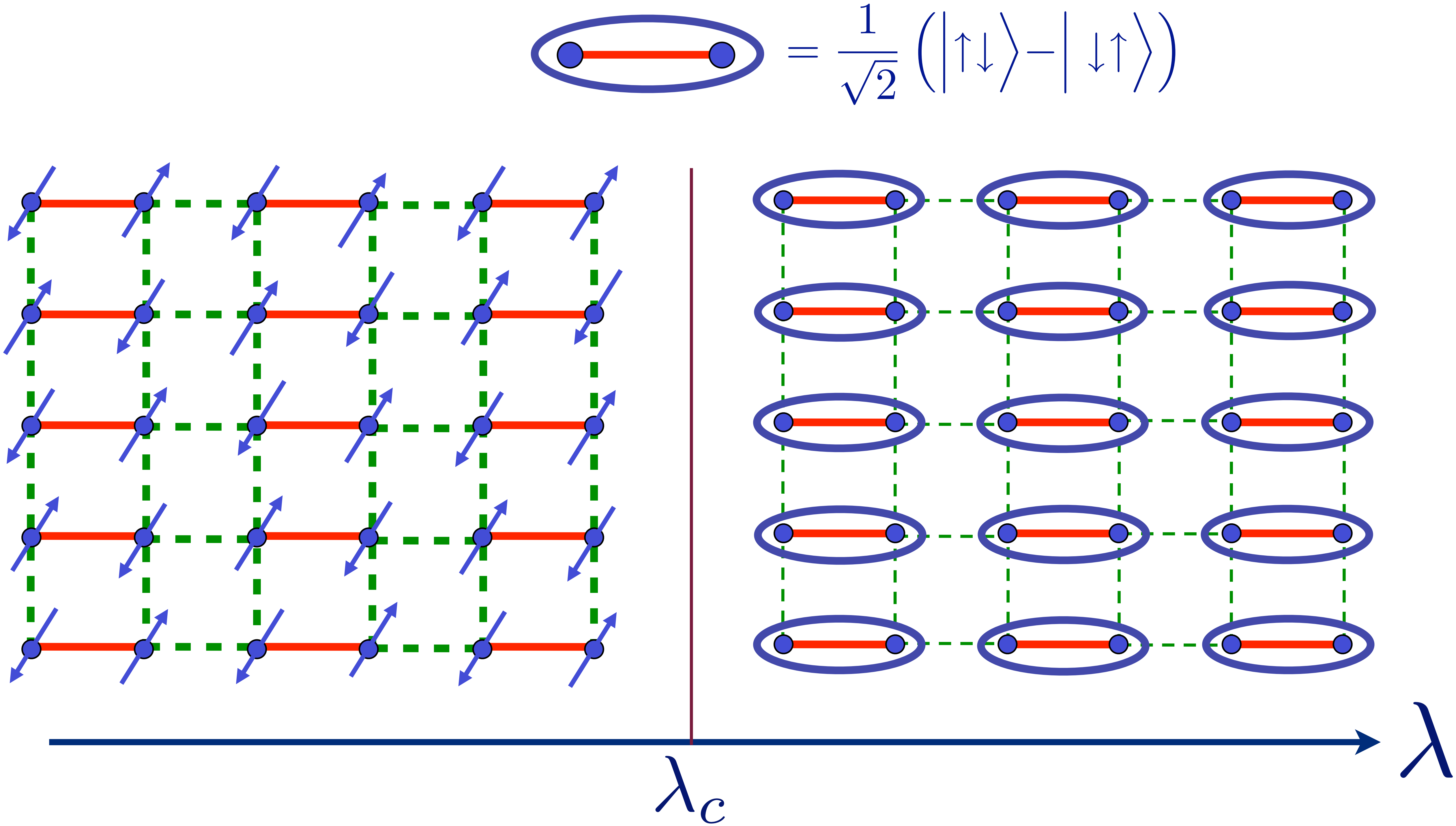


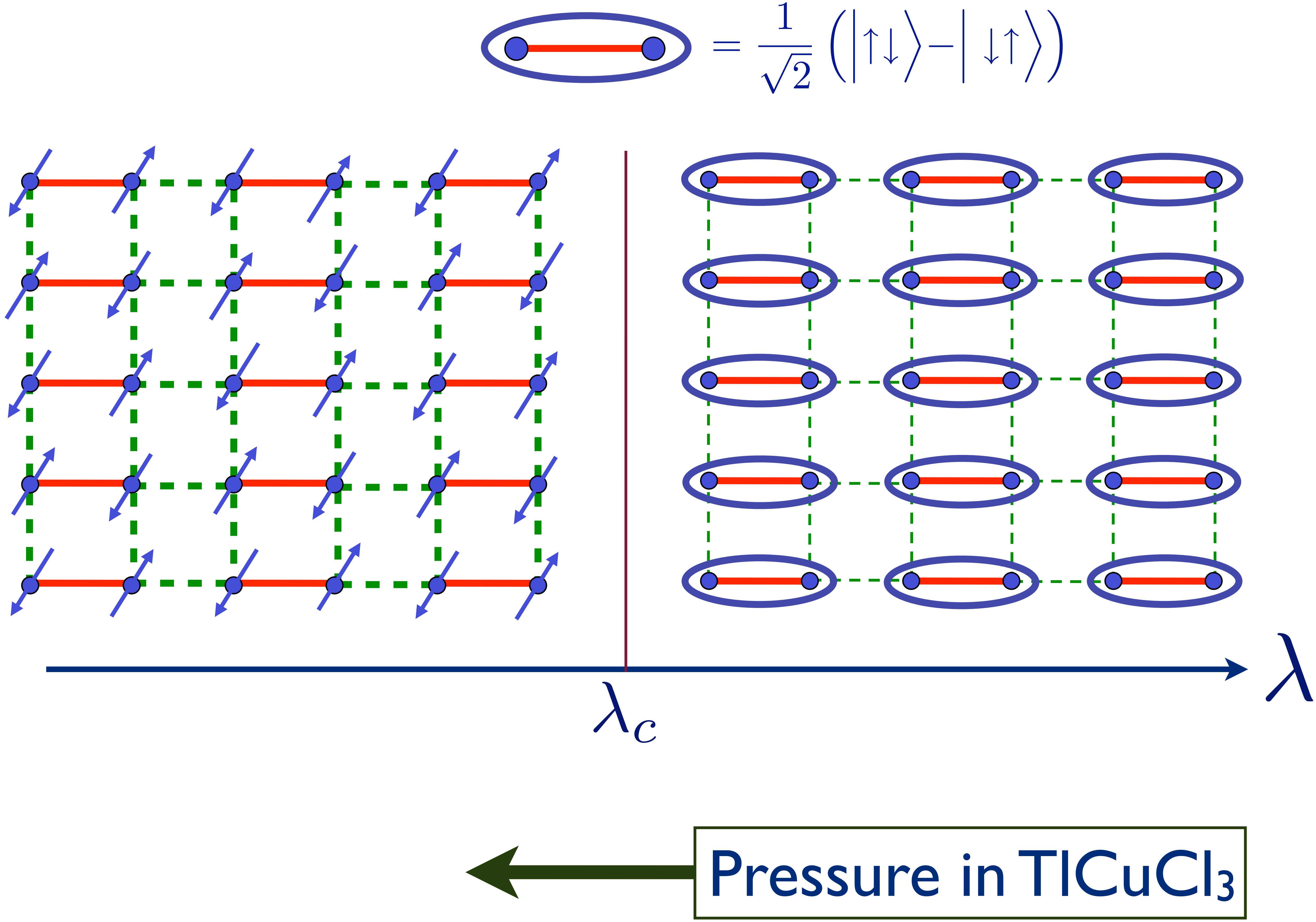
Ground state is a "quantum paramagnet" with spins locked in valence bond singlets



$$= \frac{1}{\sqrt{2}} \Big(\big|\uparrow\downarrow\big\rangle - \big|\downarrow\uparrow\big\rangle \Big)$$

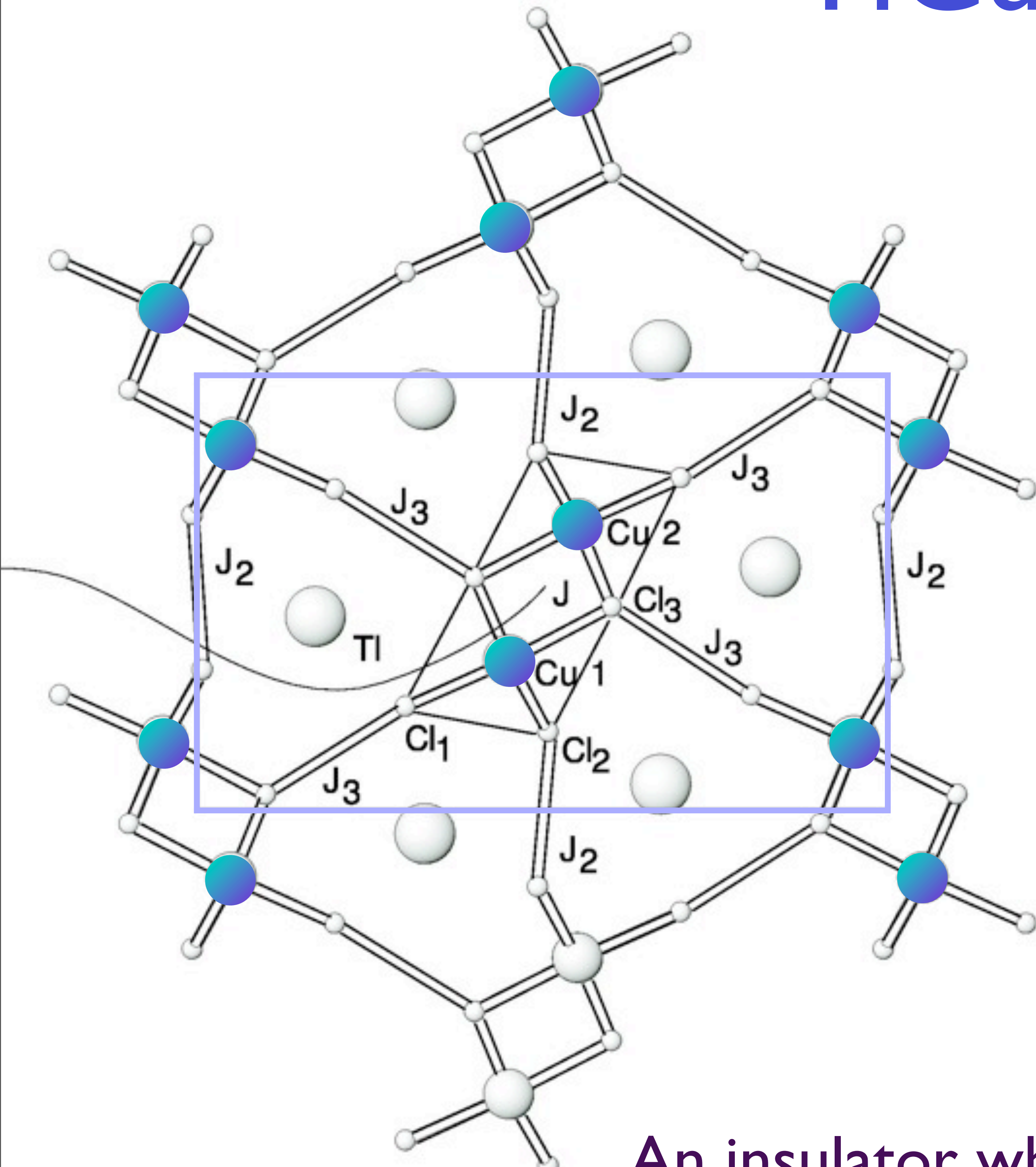


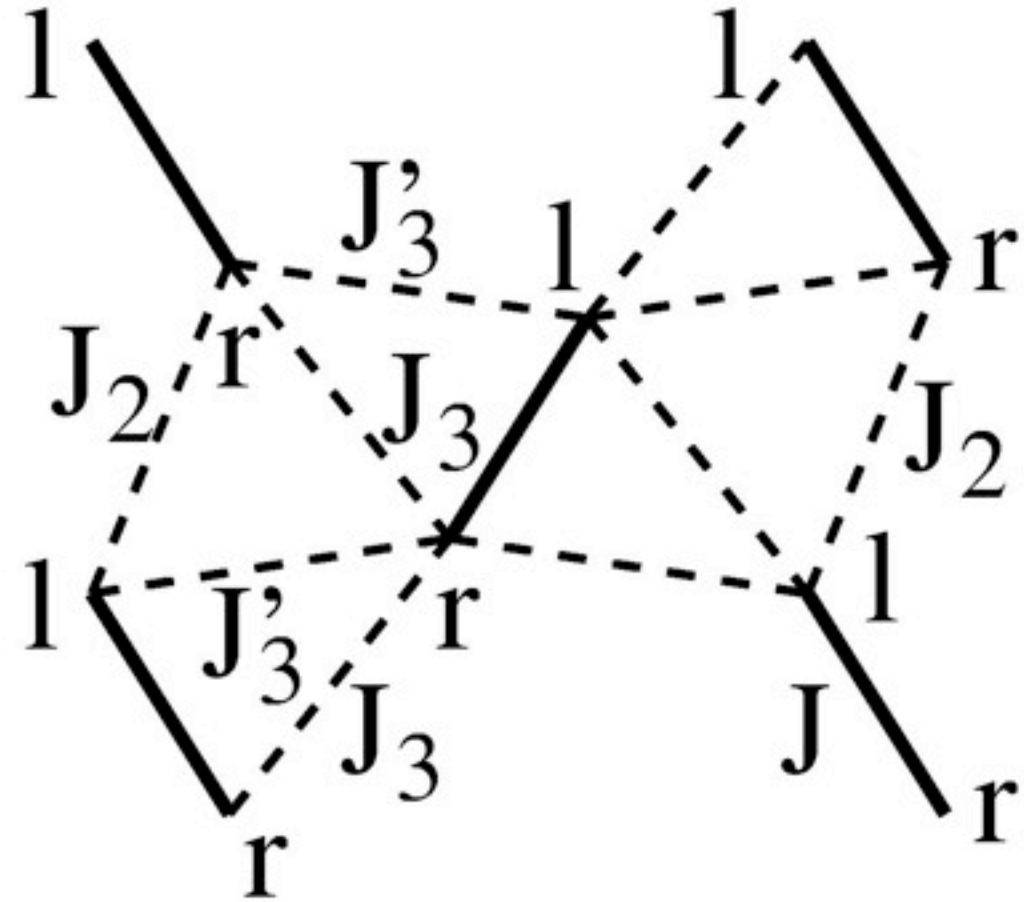
$= \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$
λ_c
λ



A. Oosawa, K. Kakurai, T. Osakabe, M. Nakamura, M. Takeda, and H. Tanaka, *Journal of the Physical Society of Japan*, **73**, 1446 (2004).

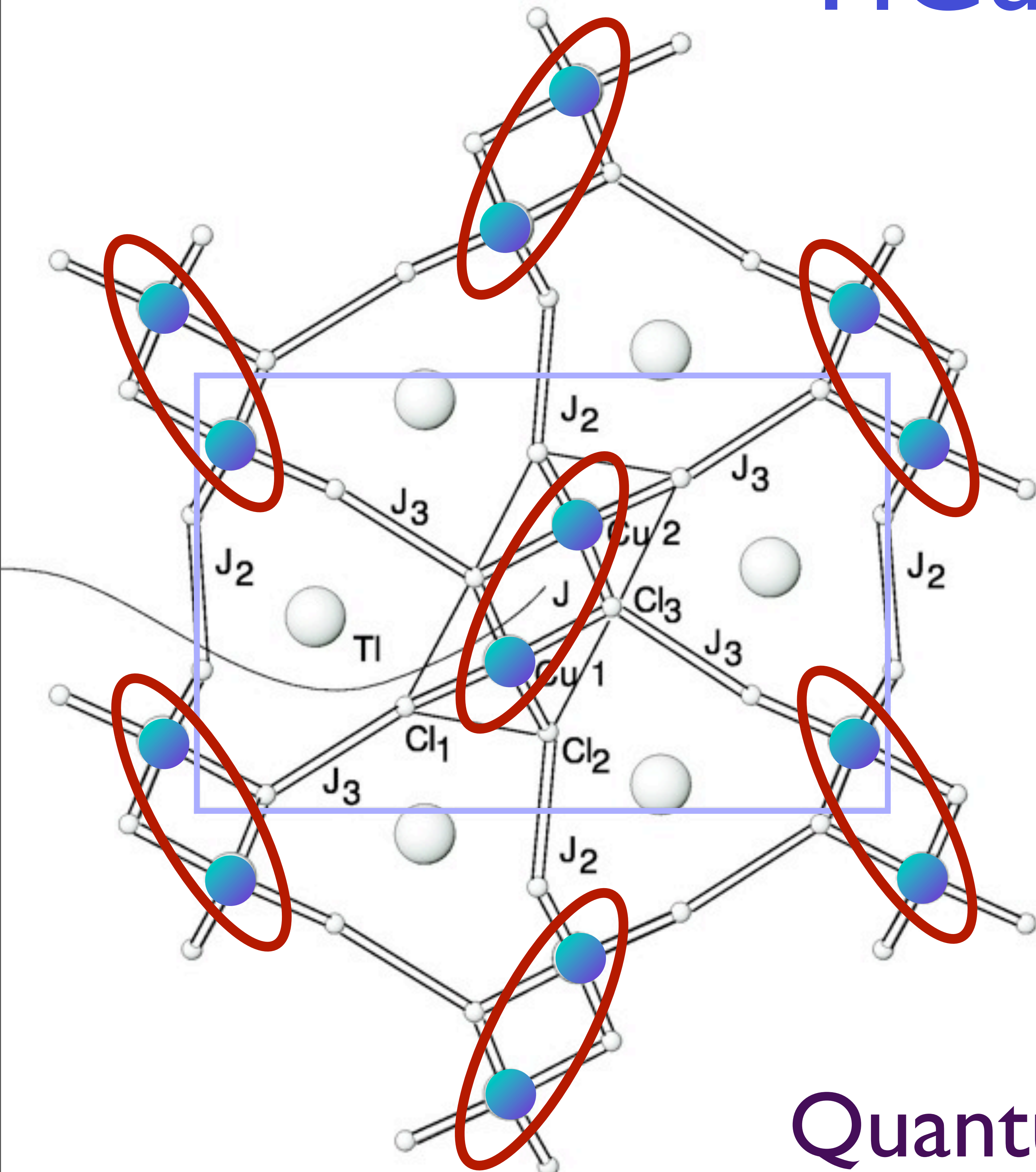
$TlCuCl_3$

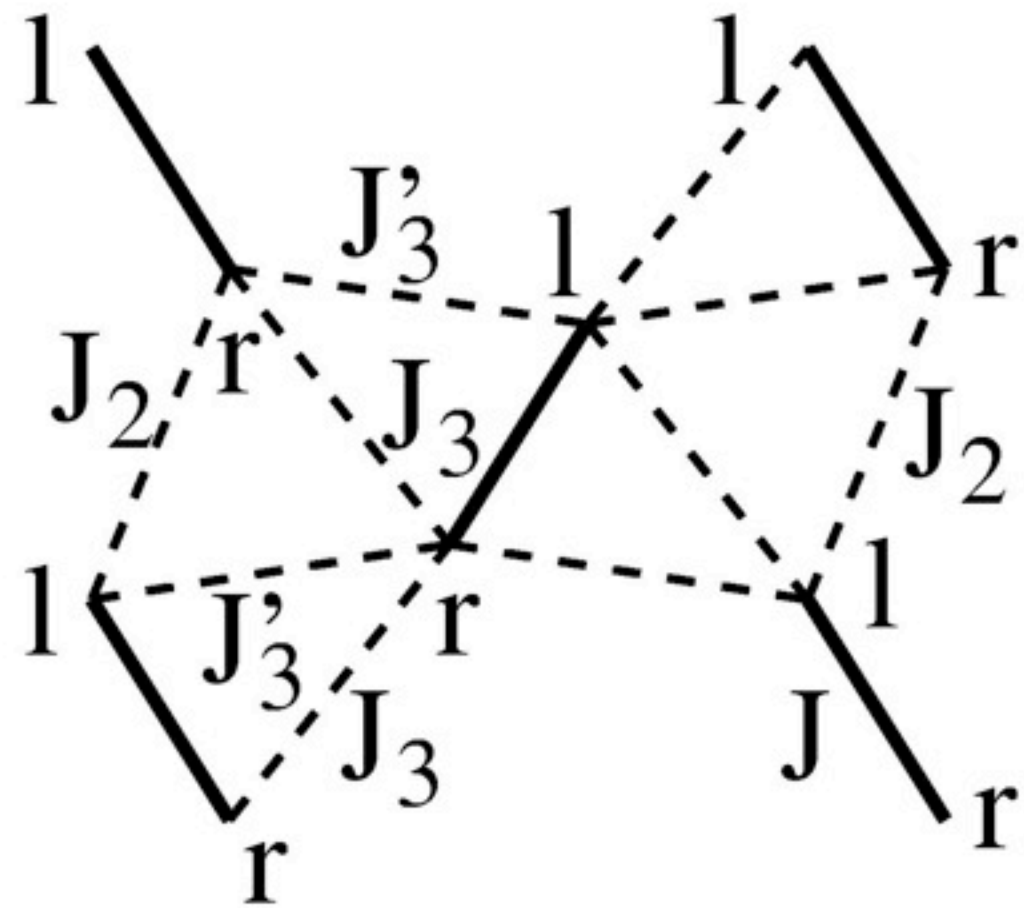




An insulator whose spin susceptibility vanishes exponentially as the temperature T tends to zero.

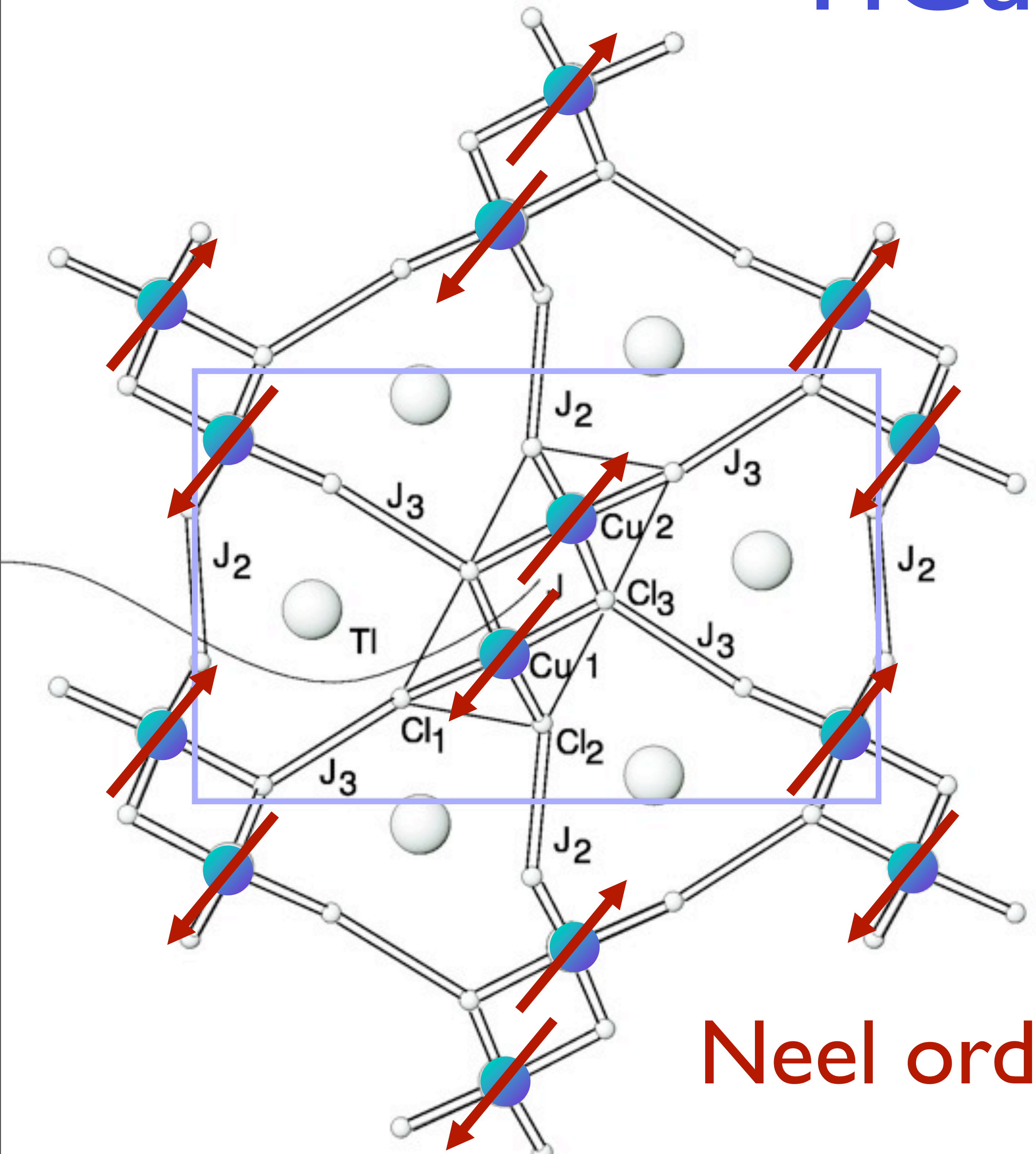
$TlCuCl_3$

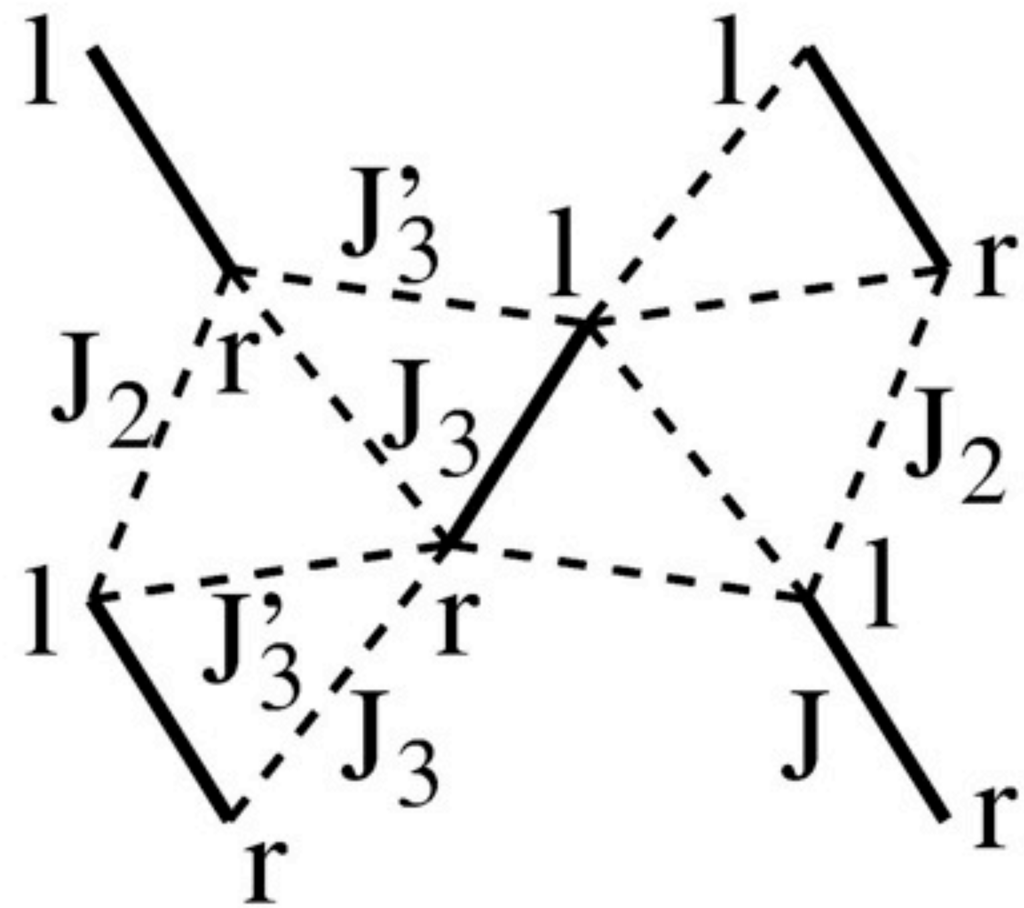




Quantum paramagnet at ambient pressure

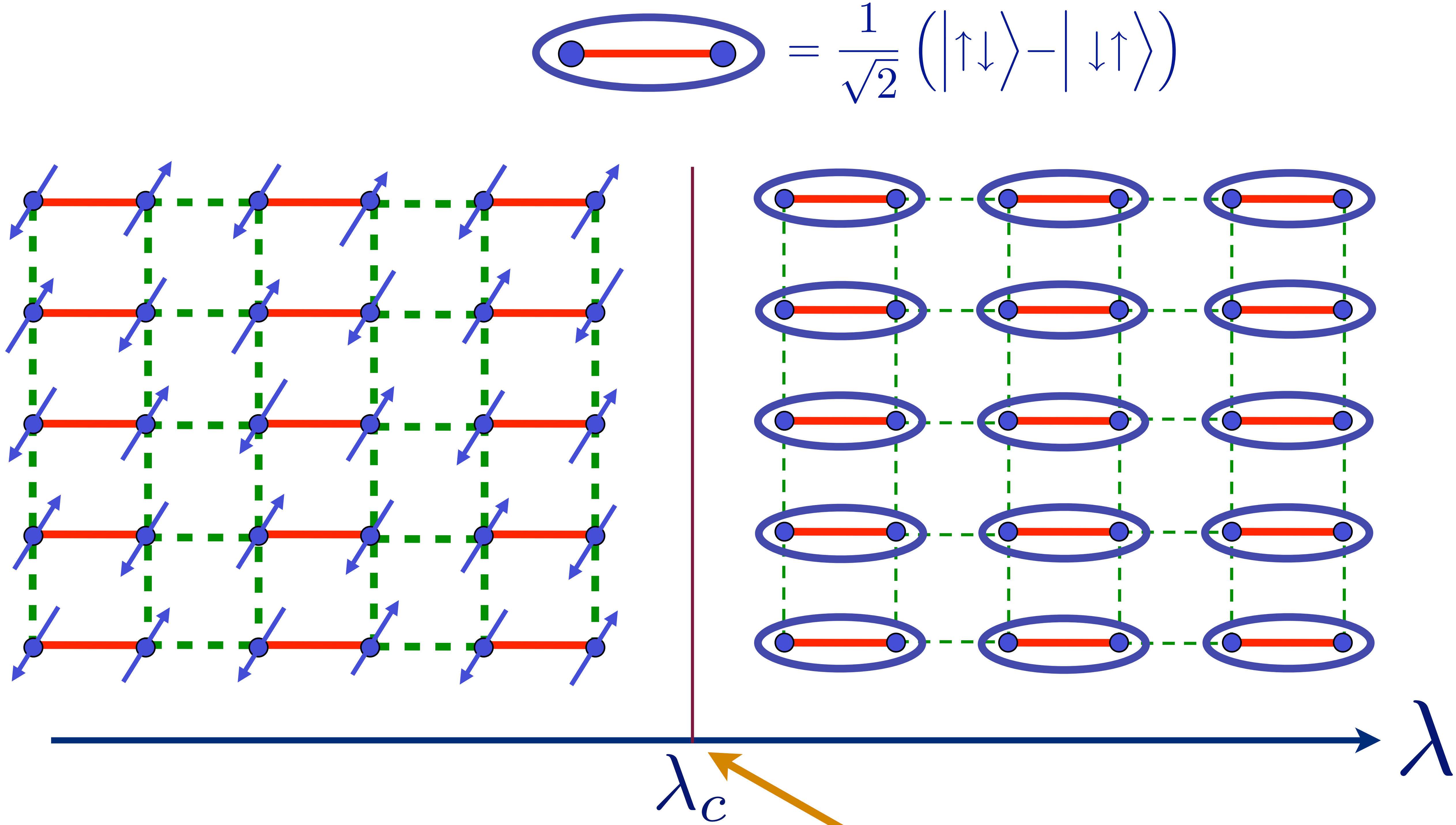
$TlCuCl_3$





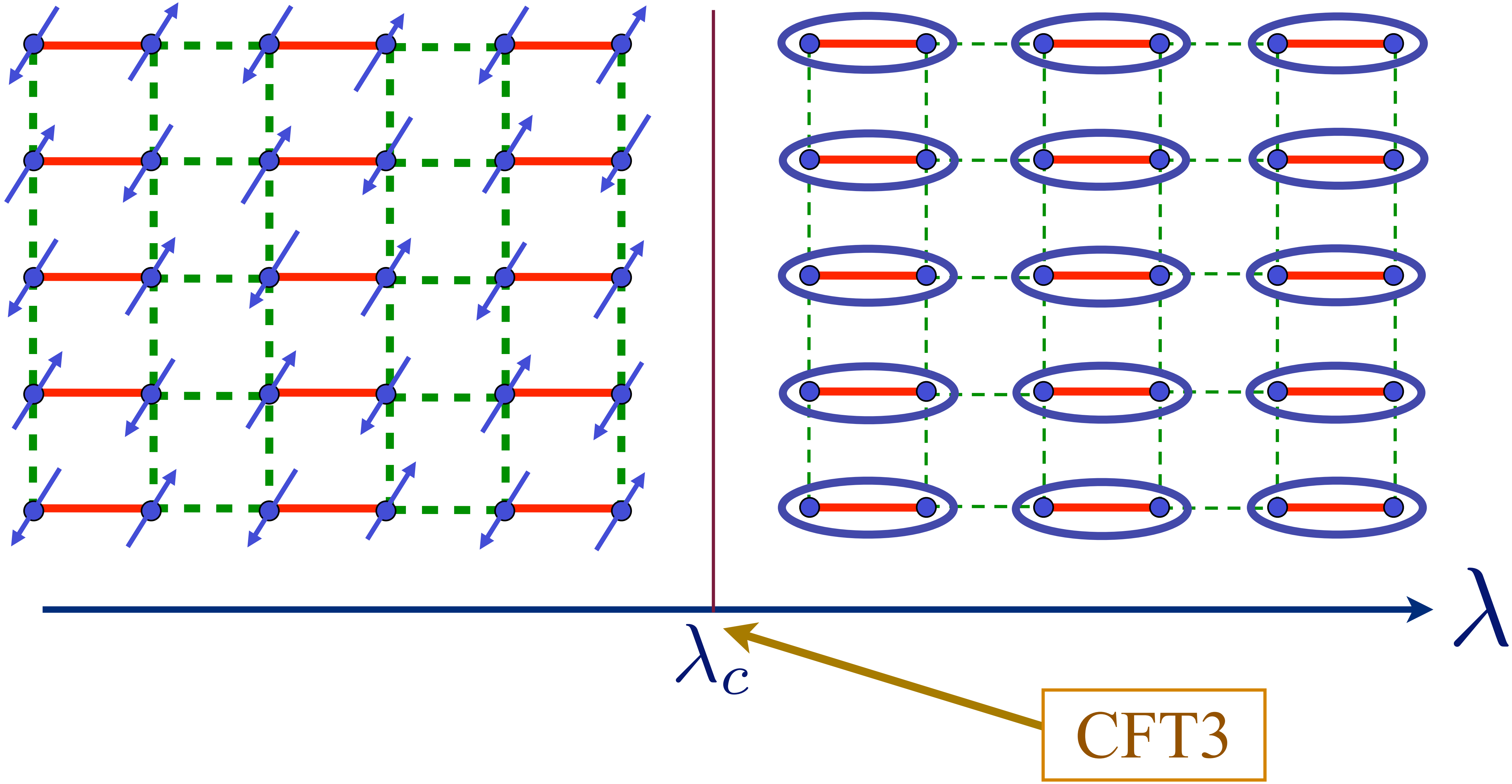
Neel order under pressure

A. Oosawa, K. Kakurai, T. Osakabe, M. Nakamura, M. Takeda, and H. Tanaka, *Journal of the Physical Society of Japan*, **73**, 1446 (2004).



Quantum critical point with non-local entanglement in spin wavefunction

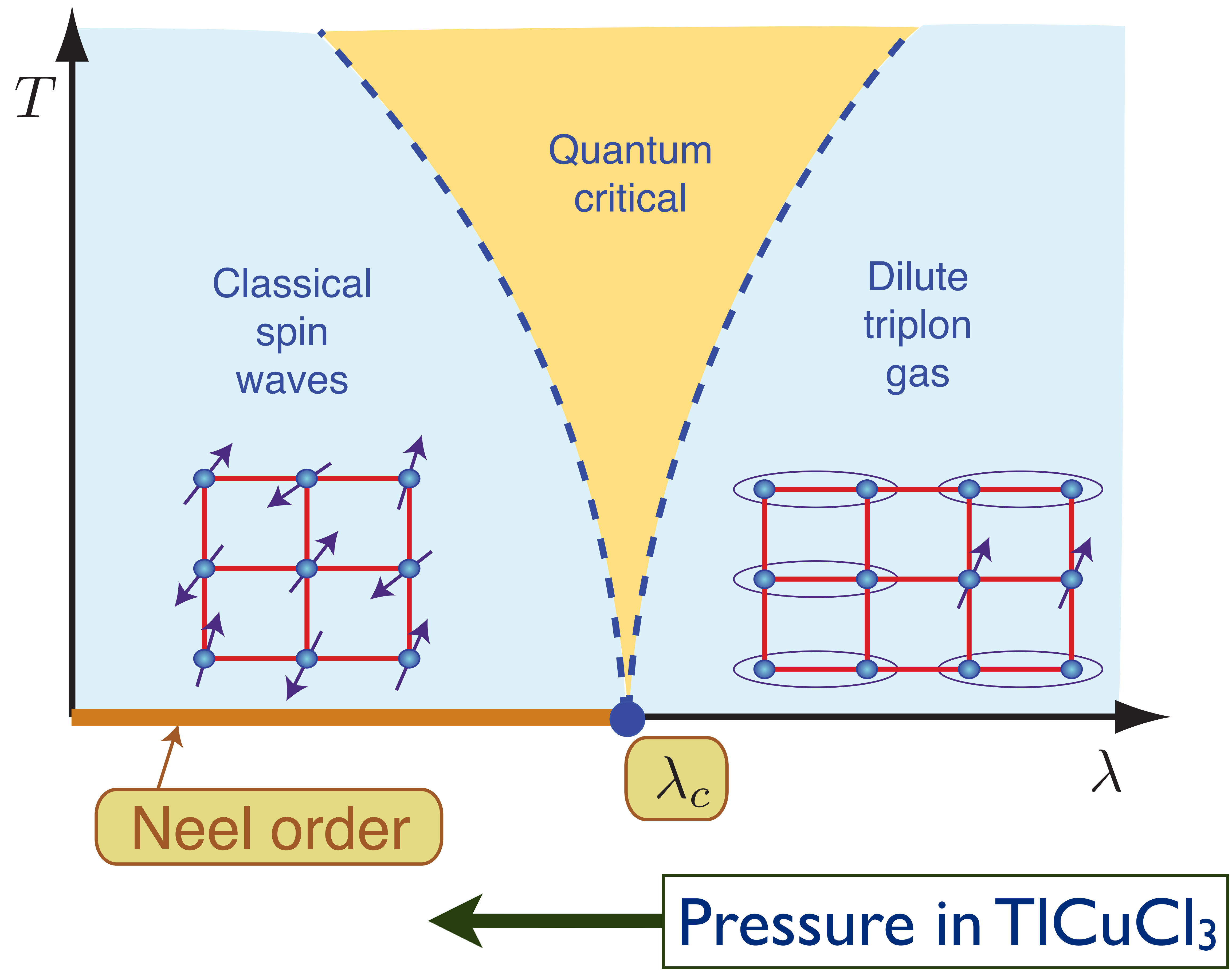
Description using Landau-Ginzburg field theory



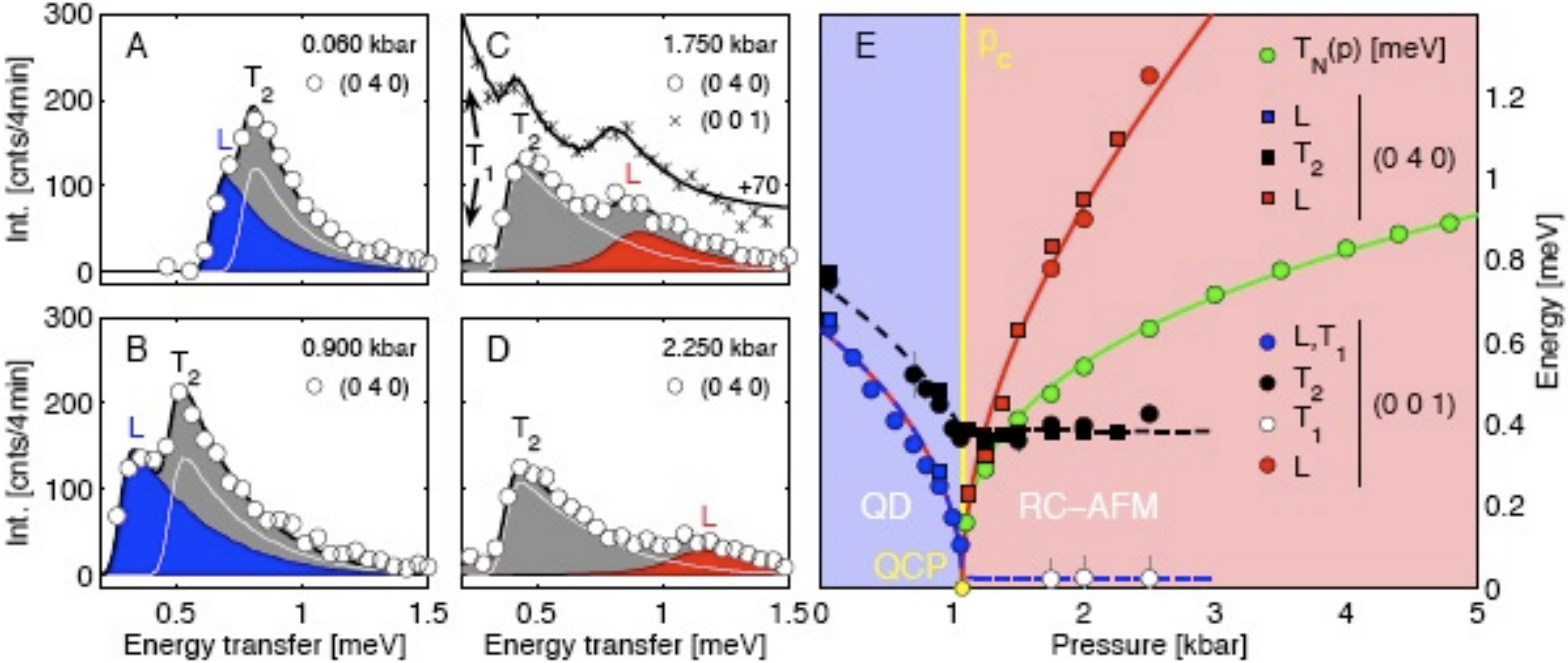
O(3) order parameter $\vec{\varphi}$

$$\mathcal{S} = \int d^2 r d\tau \left[(\partial_\tau \vec{\varphi})^2 + c^2 (\nabla_r \vec{\varphi})^2 + (\lambda - \lambda_c) \vec{\varphi}^2 + u \left(\vec{\varphi}^2 \right)^2 \right]$$

S. Sachdev and J. Ye, *Phys. Rev. Lett.* **69**, 2411 (1992).
A. V. Chubukov, S. Sachdev, and J. Ye, *Phys. Rev. B* **49**, 11919 (1994).



$TlCuCl_3$ with varying pressure



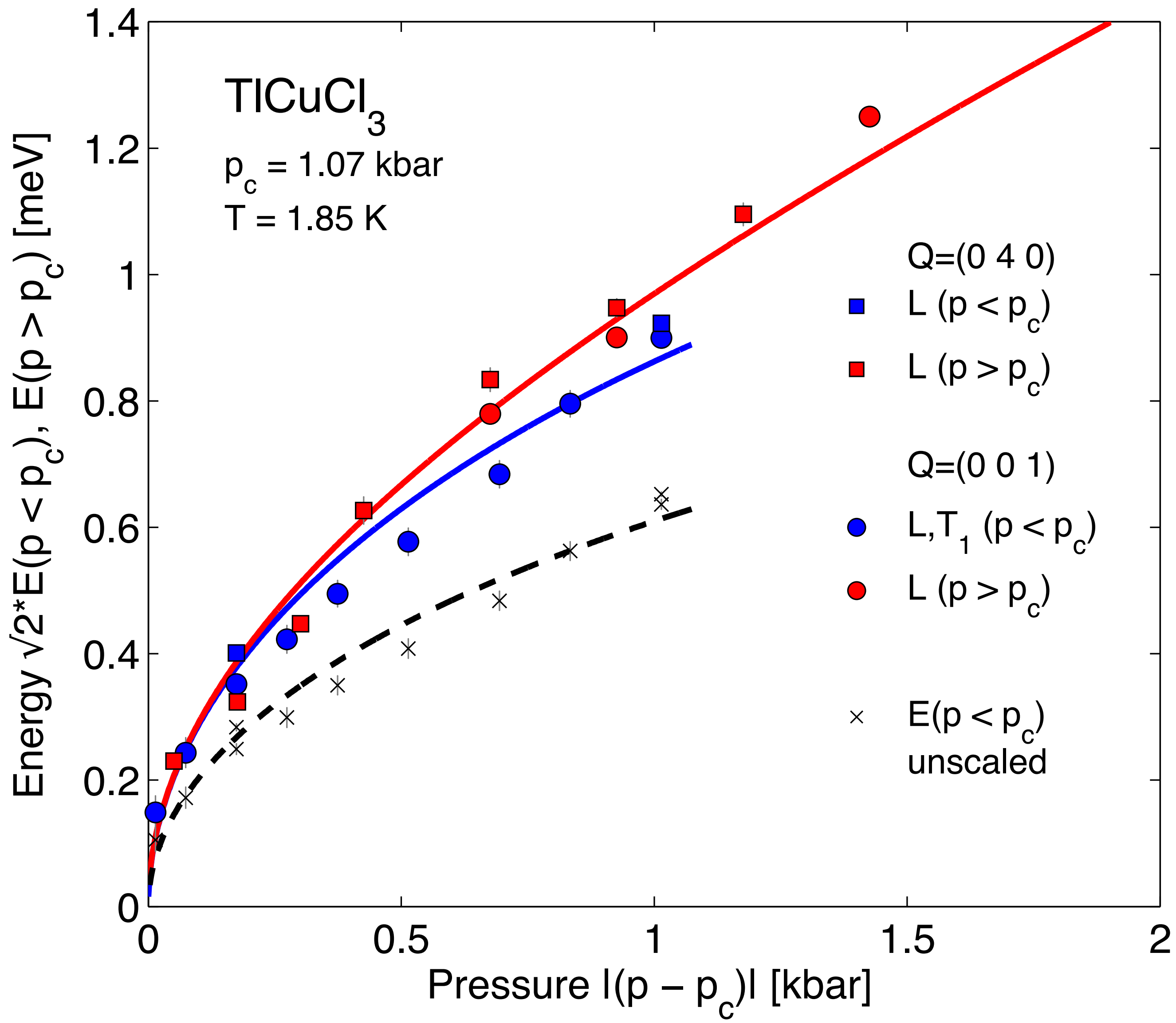
Observation of 3 → 2 low energy modes,
emergence of new Higgs particle in the Néel phase,
and vanishing of Néel temperature at the quantum critical point

Christian Ruegg, Bruce Normand, Masashige Matsumoto, Albert Furrer, Desmond McMorrow, Karl Kramer, Hans-Ulrich Gudel, Severian Gvasaliya, Hannu Mutka, and Martin Boehm, *Phys. Rev. Lett.* **100**, 205701 (2008)

Prediction of quantum field theory

$$\frac{\text{Energy of Higgs particle}}{\text{Energy of triplon}} = \sqrt{2}$$

$$V(\vec{\varphi}) = (\lambda - \lambda_c)\vec{\varphi}^2 + u\left(\vec{\varphi}^2\right)^2$$



S. Sachdev, arXiv:0901.4103

S. Sachdev and J. Ye, *Phys. Rev. Lett.* **69**, 2411 (1992).
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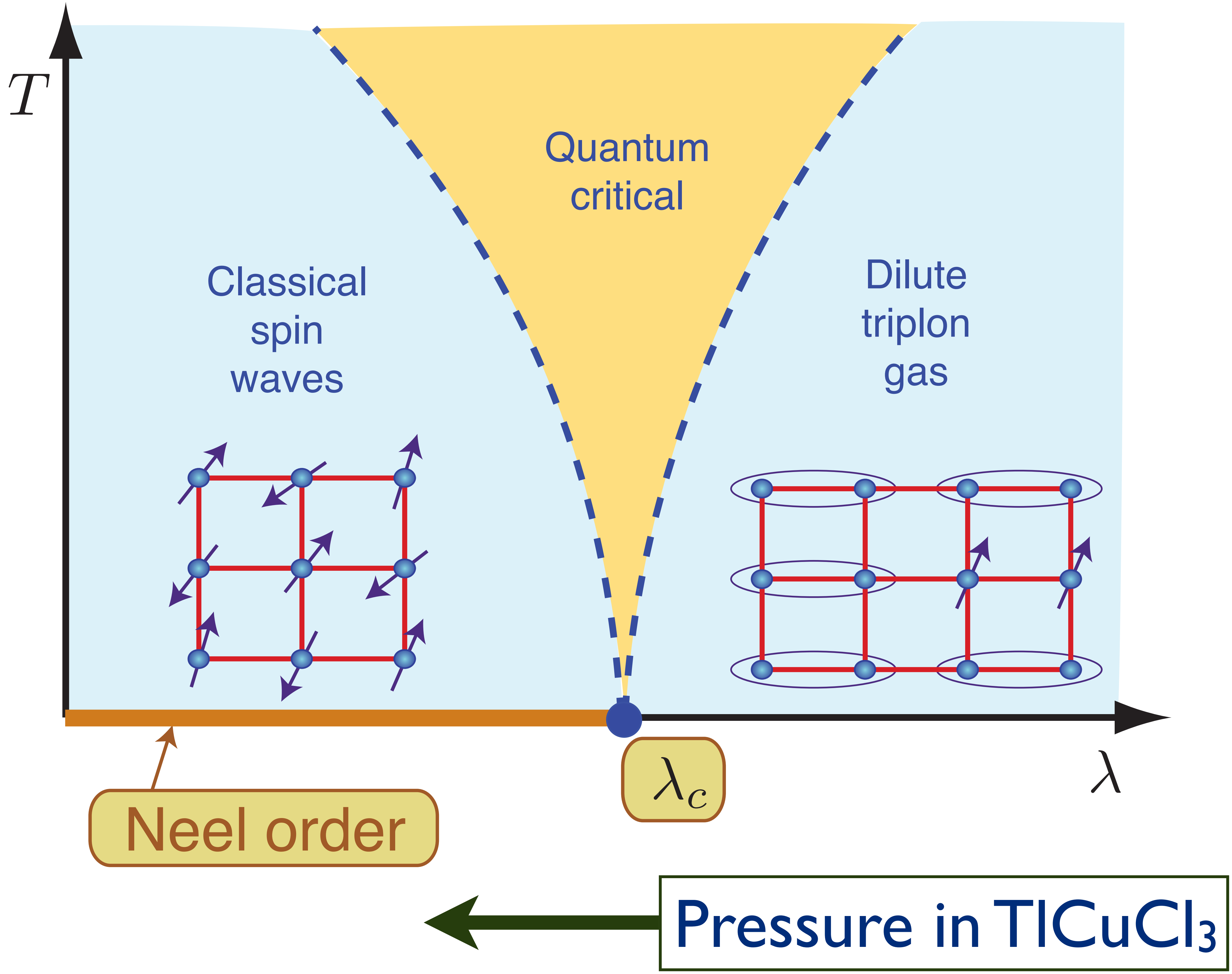

Lett. 69, 2411 (1992).
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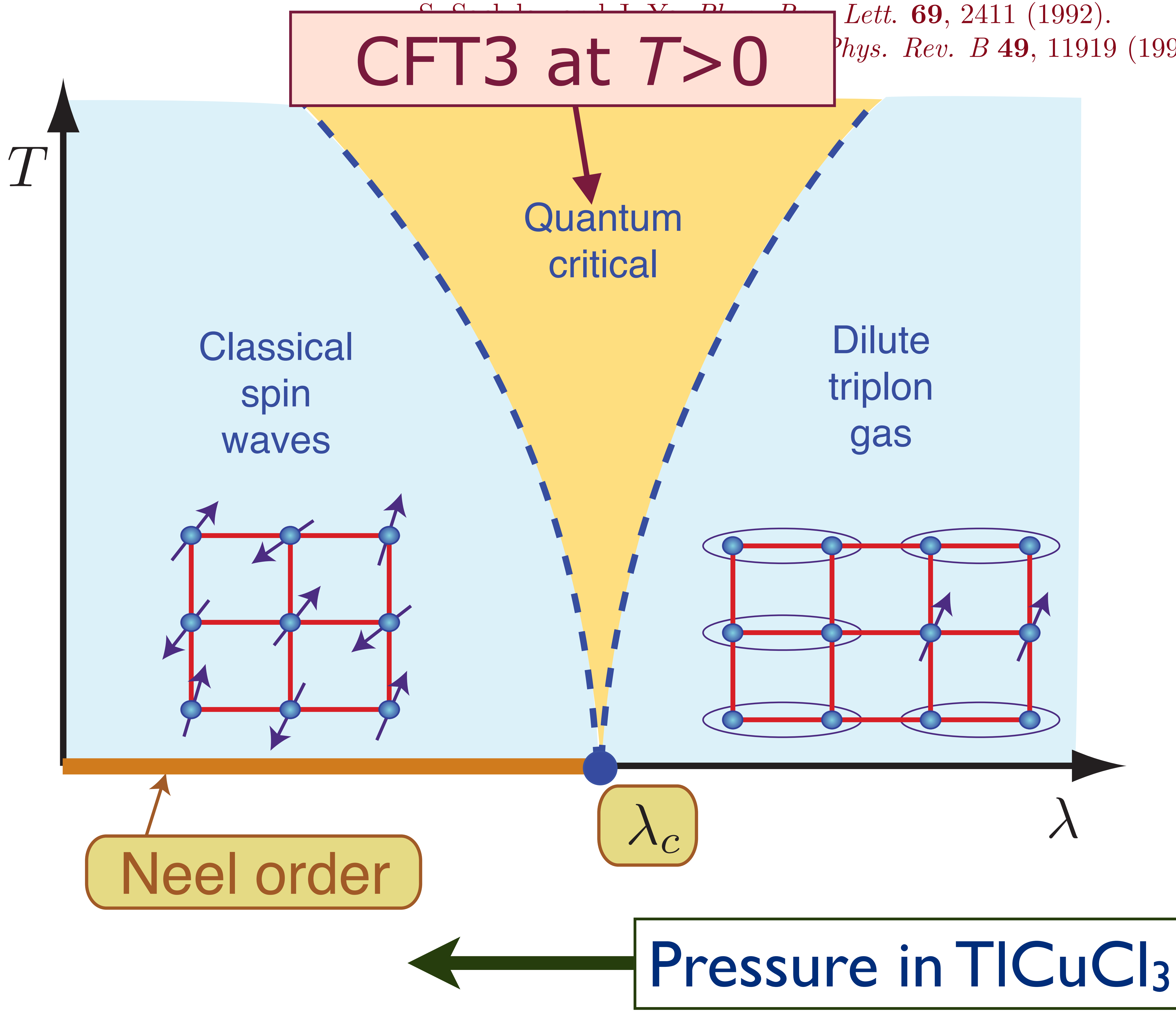

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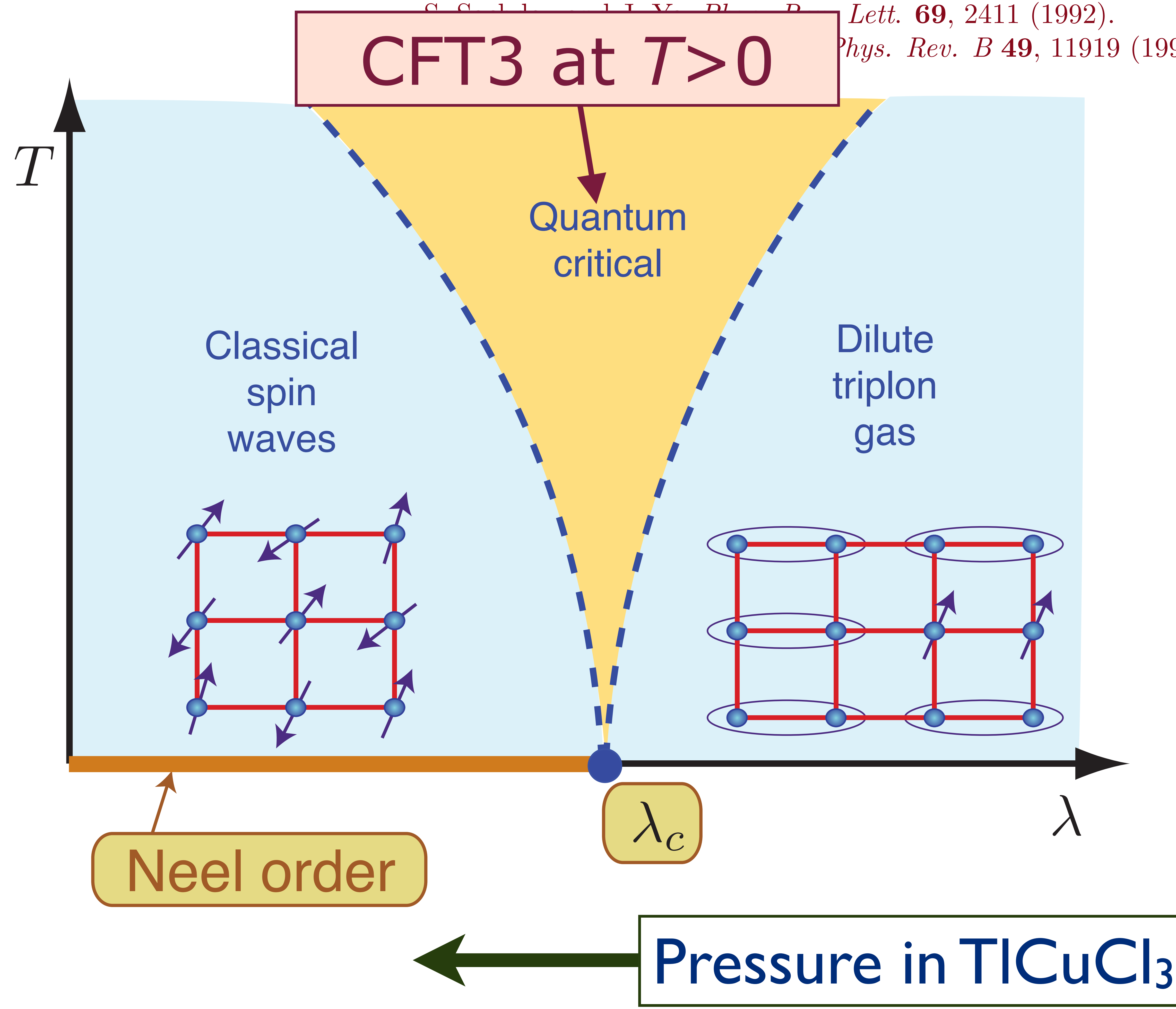

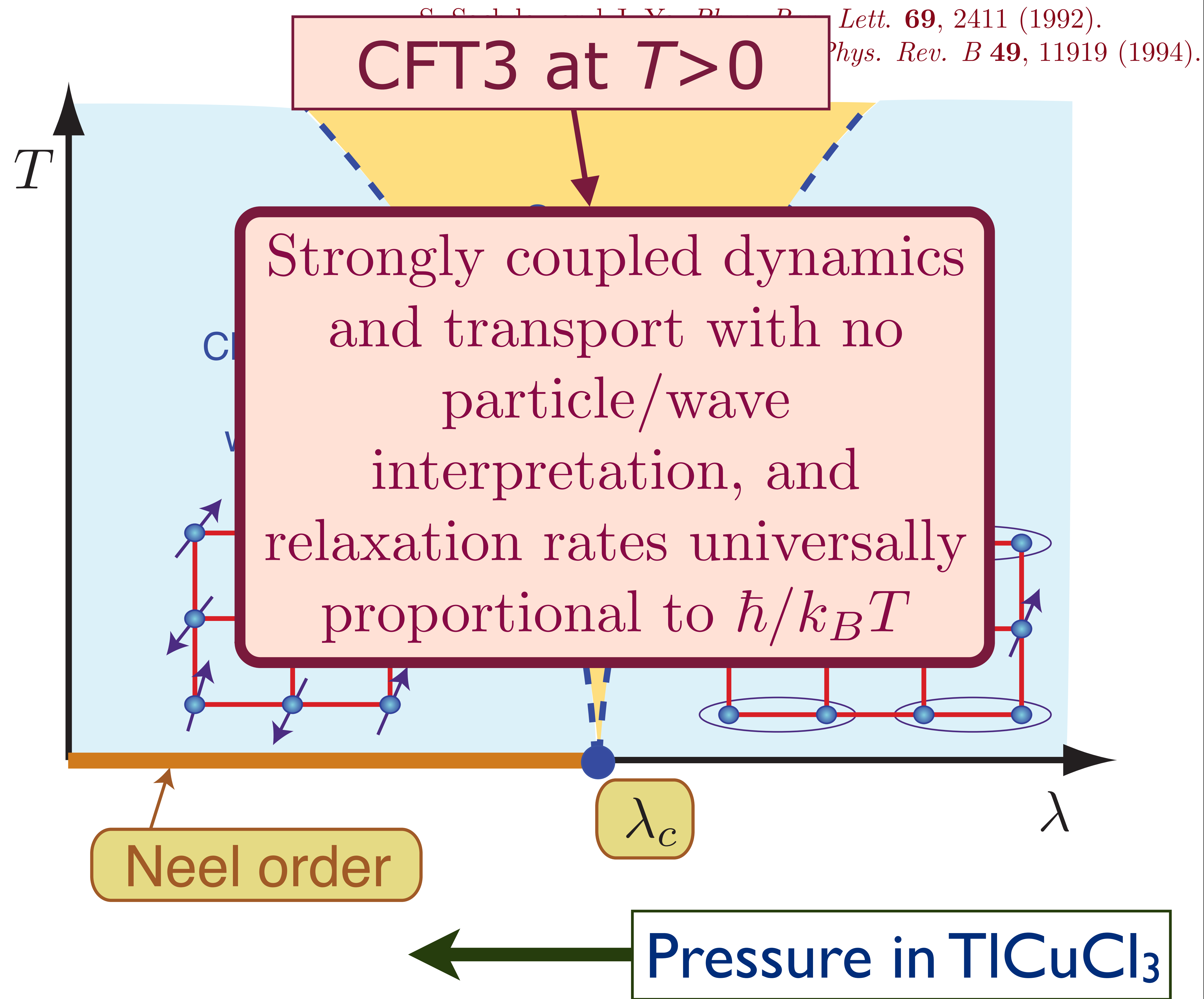

Lett. 69, 2411 (1992).
Phys. Rev. B 49, 11919 (1994).
CFT3 at $T>0$
T
Strongly coupled dynamics and transport with no particle/wave interpretation, and relaxation rates universally proportional to $\hbar/k_B T$
λ_c
λ
Neel order
Pressure in $TlCuCl_3$

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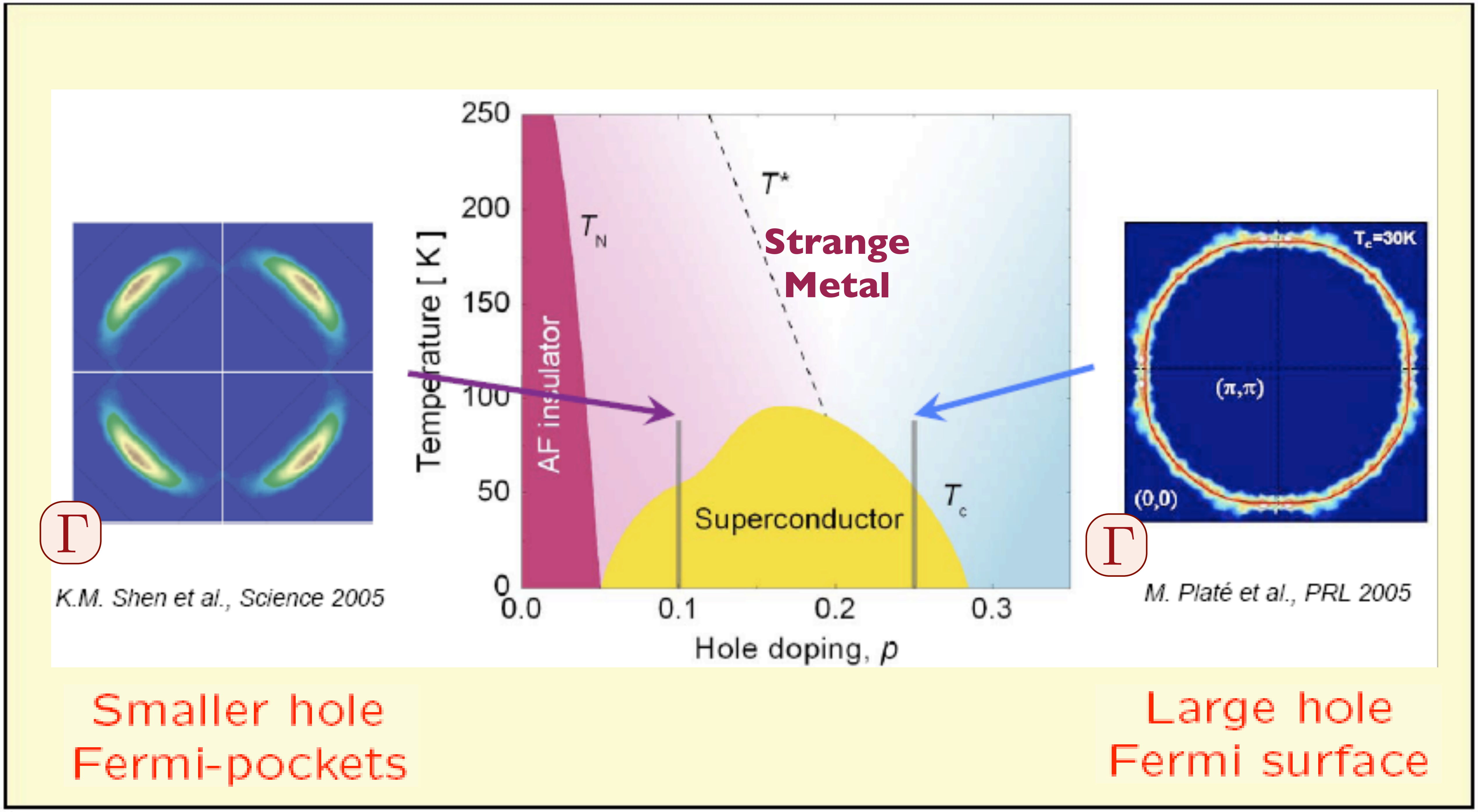
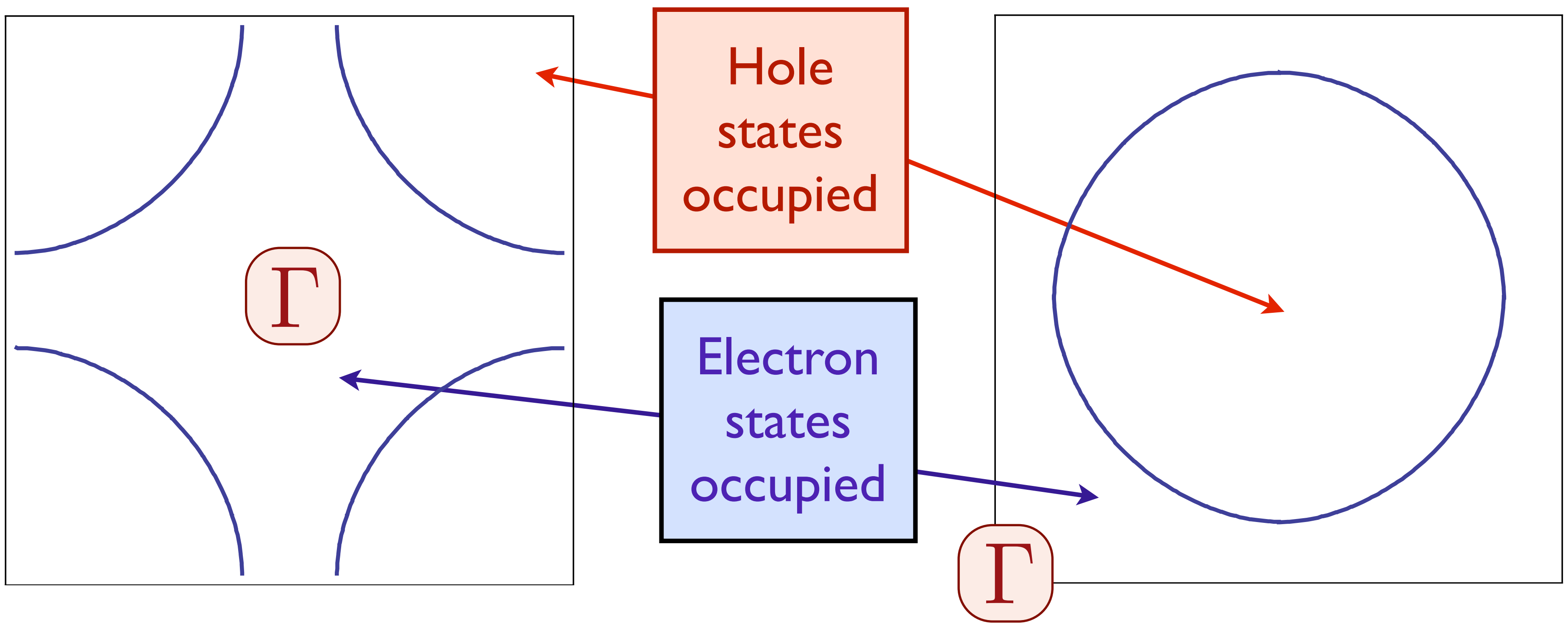
Central ingredients in cuprate phase diagram: antiferromagnetism, superconductivity, and change in Fermi surface



Fermi surface+antiferromagnetism

$$H_0 = -\sum_{i<j} t_{ij} c_{i\alpha}^{\dagger} c_{j\alpha}$$

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



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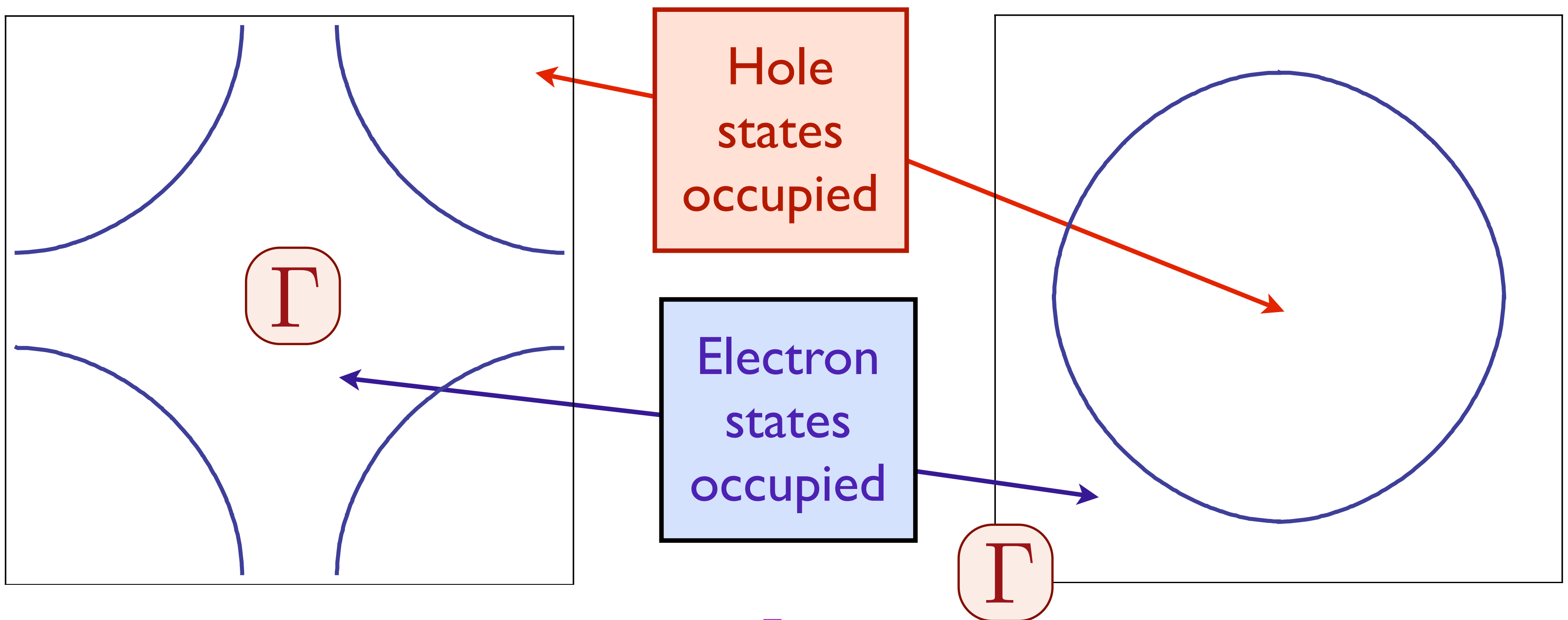

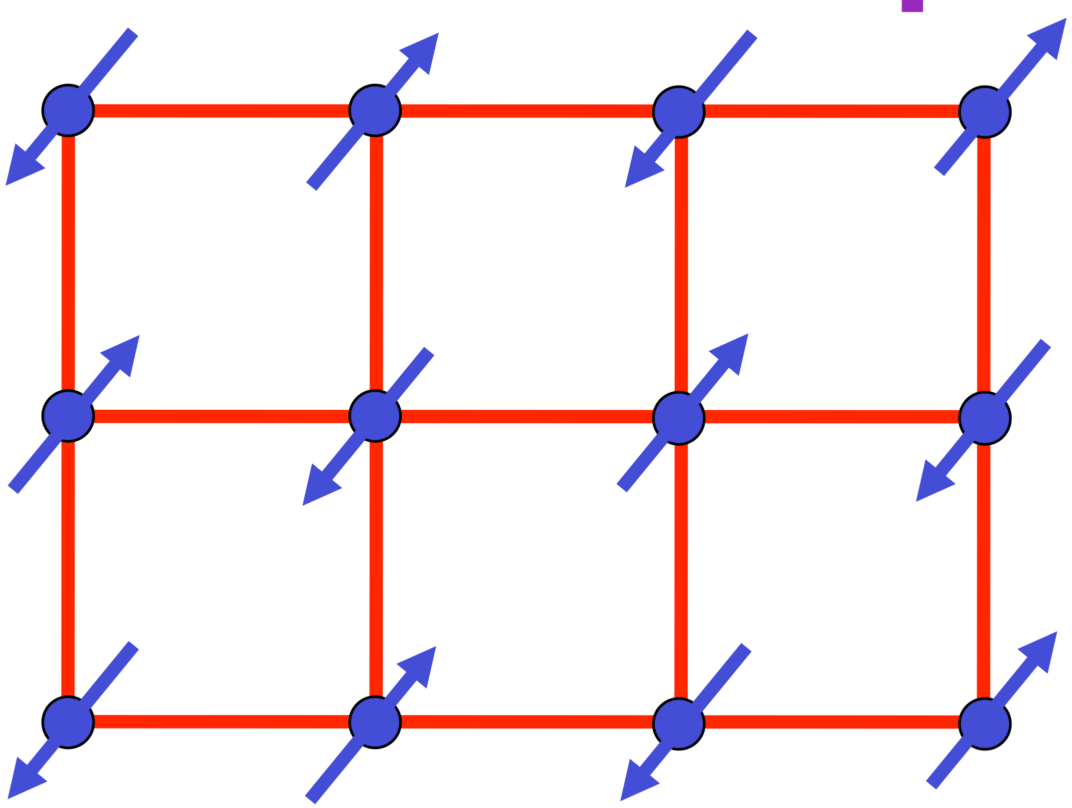

The electron spin polarization obeys

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

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

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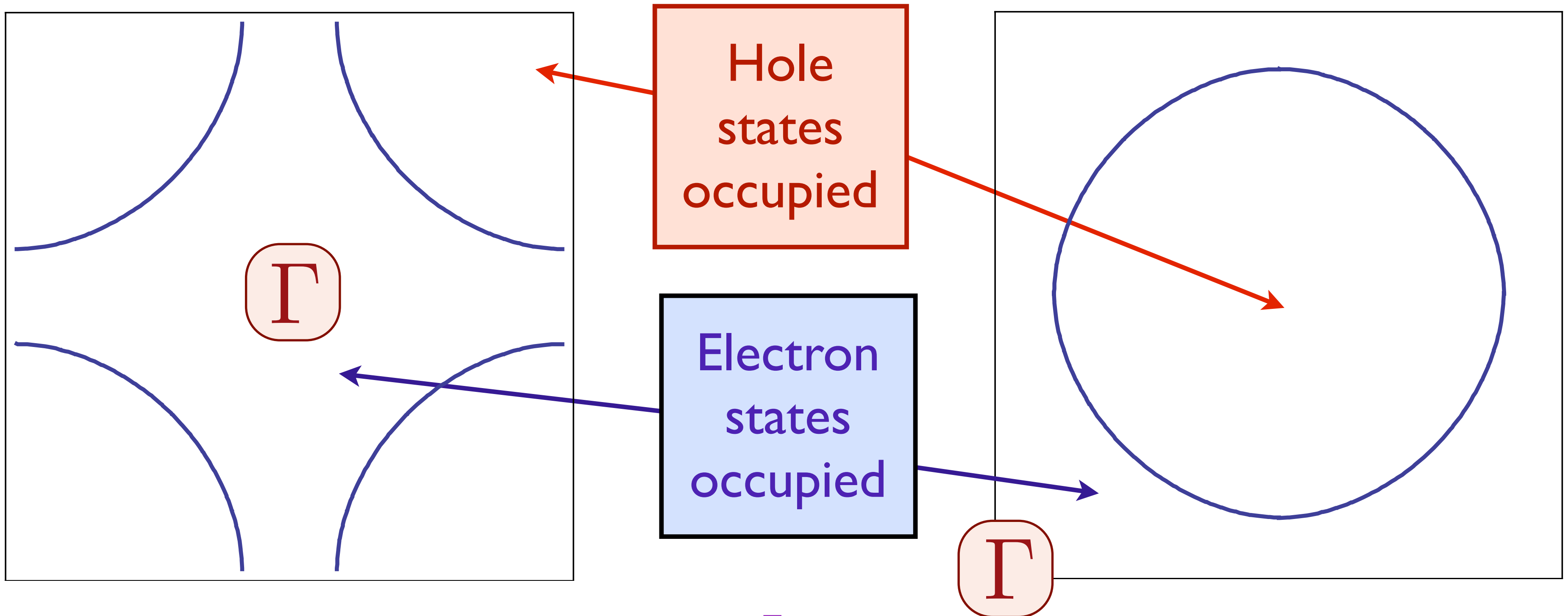
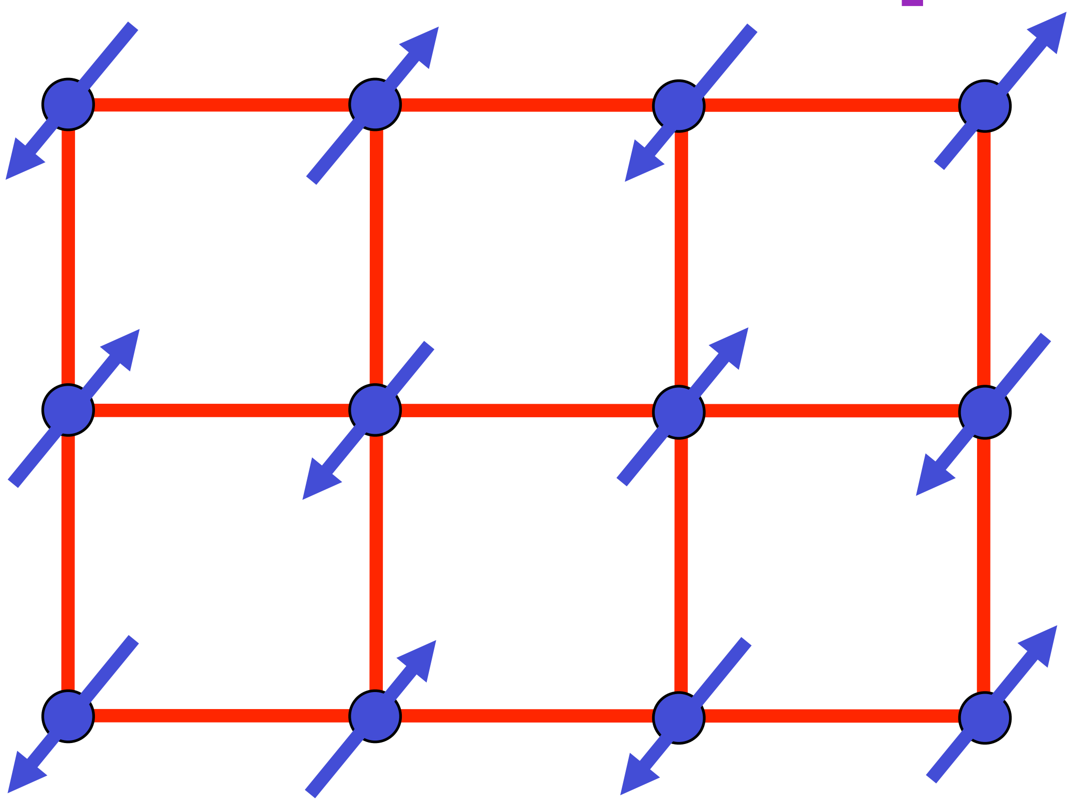
$$H_0 = -\sum_{i<j} t_{ij} c_{i\alpha}^\dagger c_{j\alpha}$$
$$\equiv \sum_{\mathbf{k}} \varepsilon_{\mathbf{k}} c_{\mathbf{k}\alpha}^\dagger c_{\mathbf{k}\alpha}$$



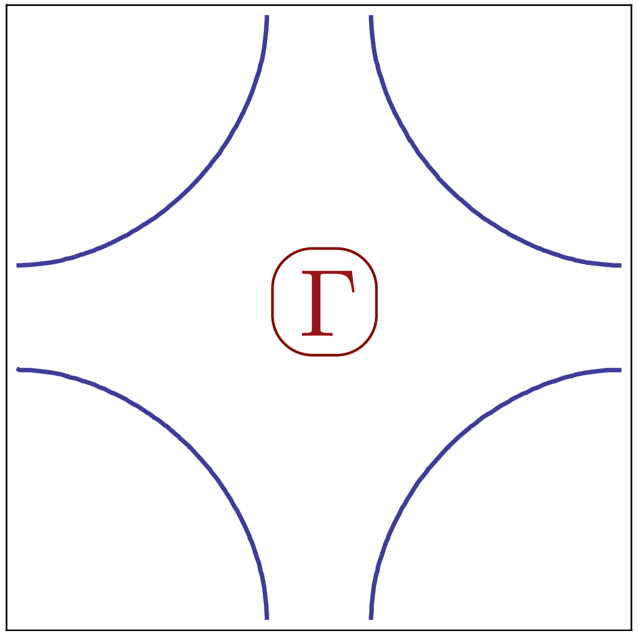
+



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

Hole-doped cuprates

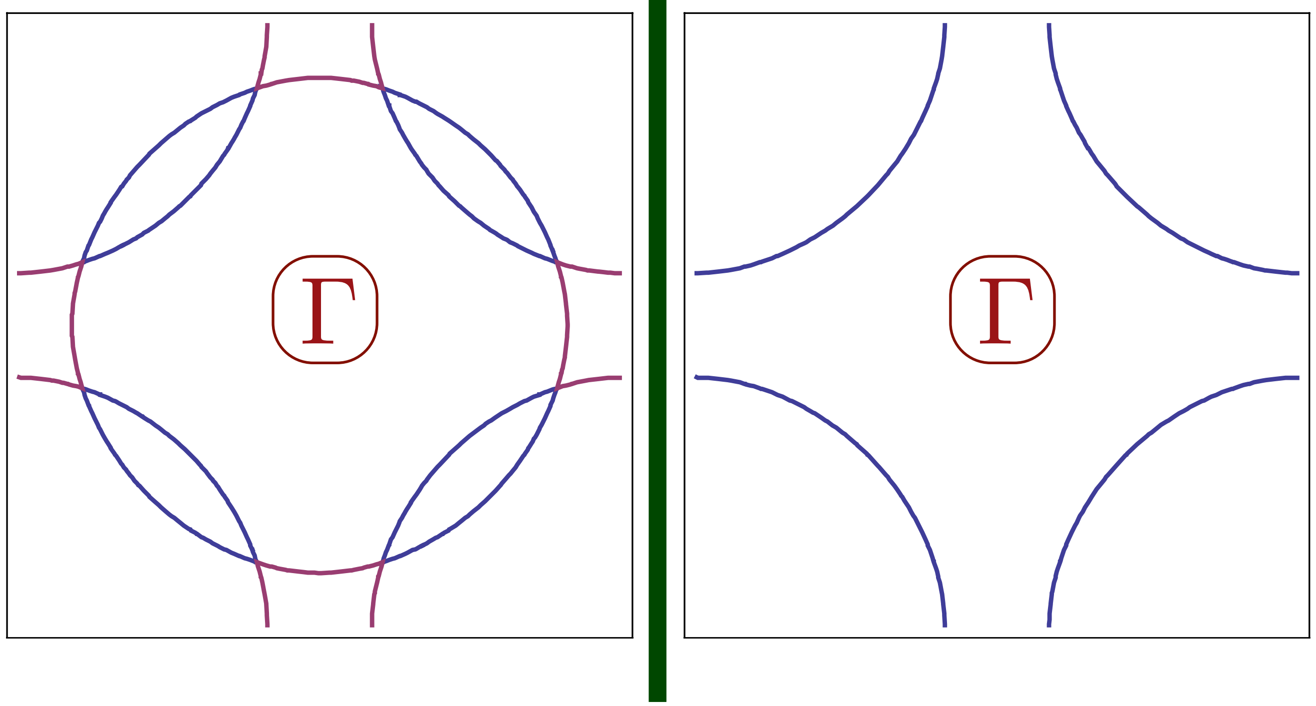
← Increasing SDW order



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).

Hole-doped cuprates

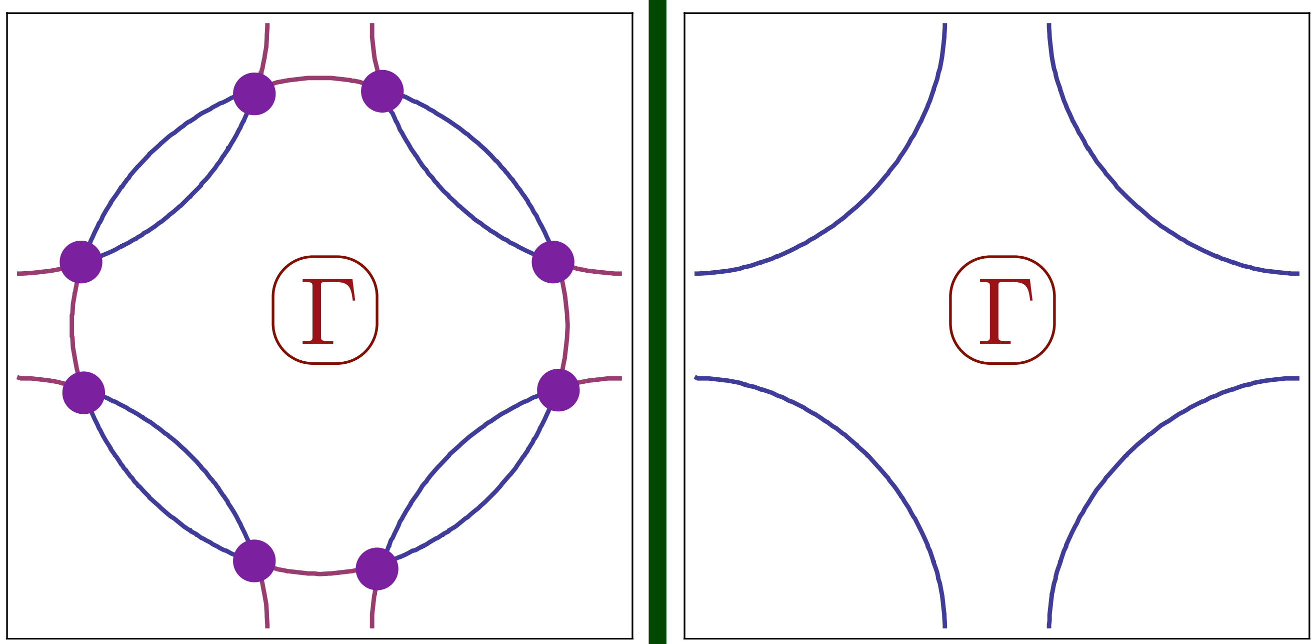
Increasing SDW order



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).

Hole-doped cuprates

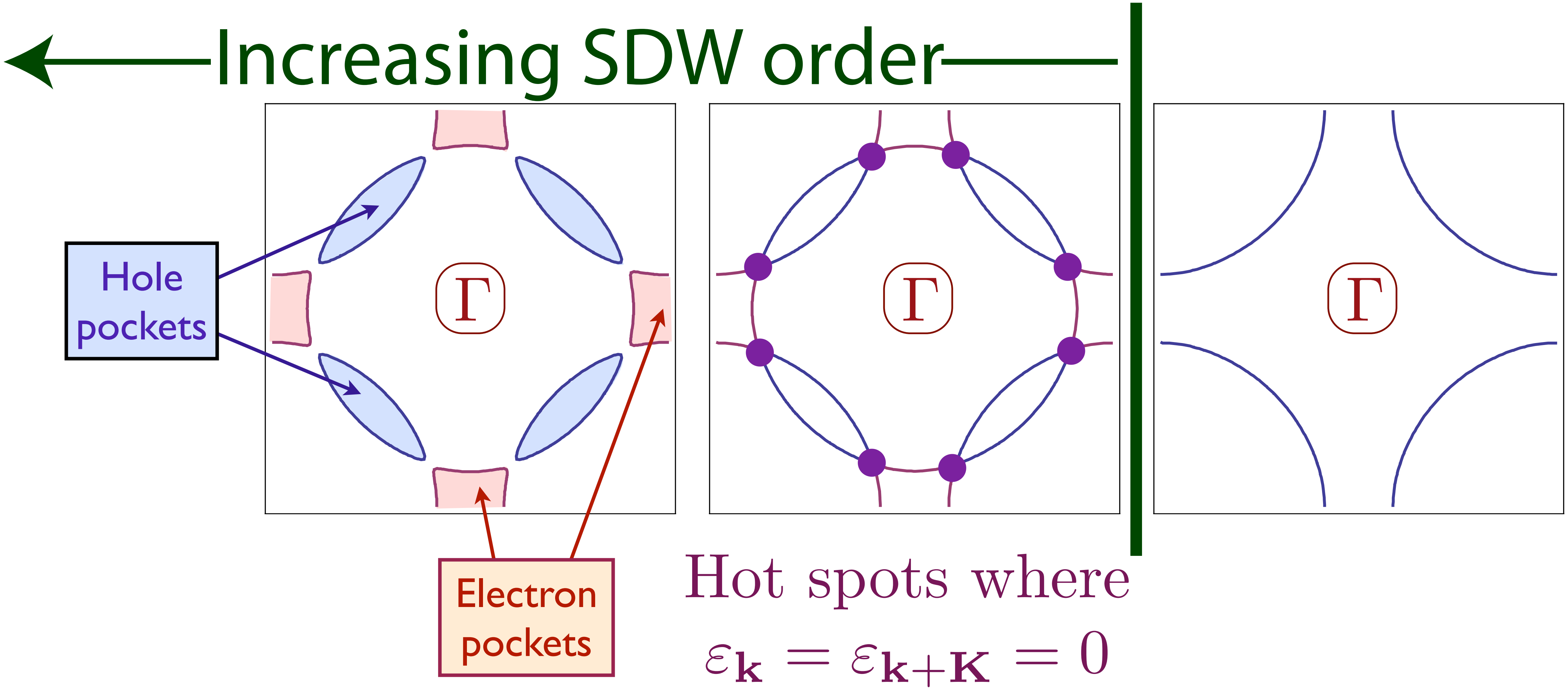
⟵ Increasing SDW order ——



Hot spots where
$\varepsilon_{\mathbf{k}} = \varepsilon_{\mathbf{k}+\mathbf{K}} = 0$

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).

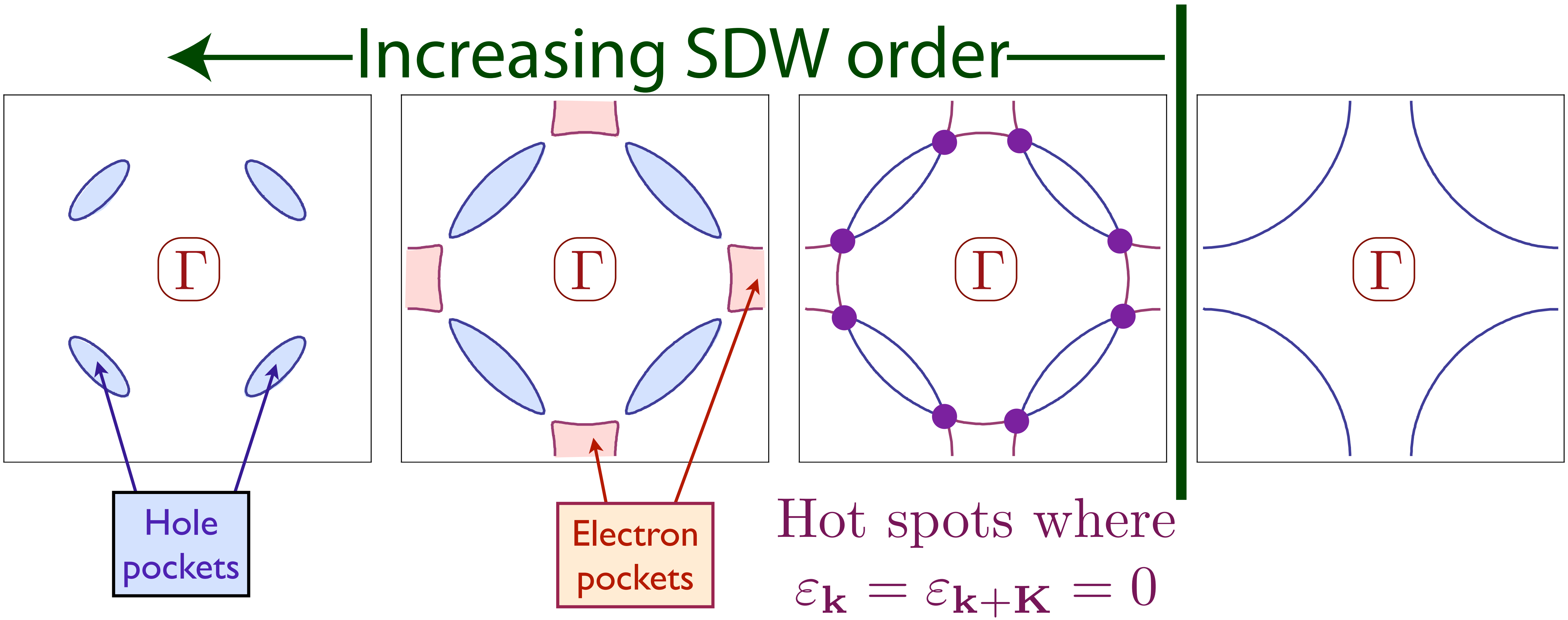
Hole-doped cuprates



Fermi surface breaks up at hot spots into electron and hole "pockets"

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).

Hole-doped cuprates



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A.V. Chubukov and D. K. Morr, *Physics Reports* **288**, 355 (1997).

Evidence for small Fermi pockets

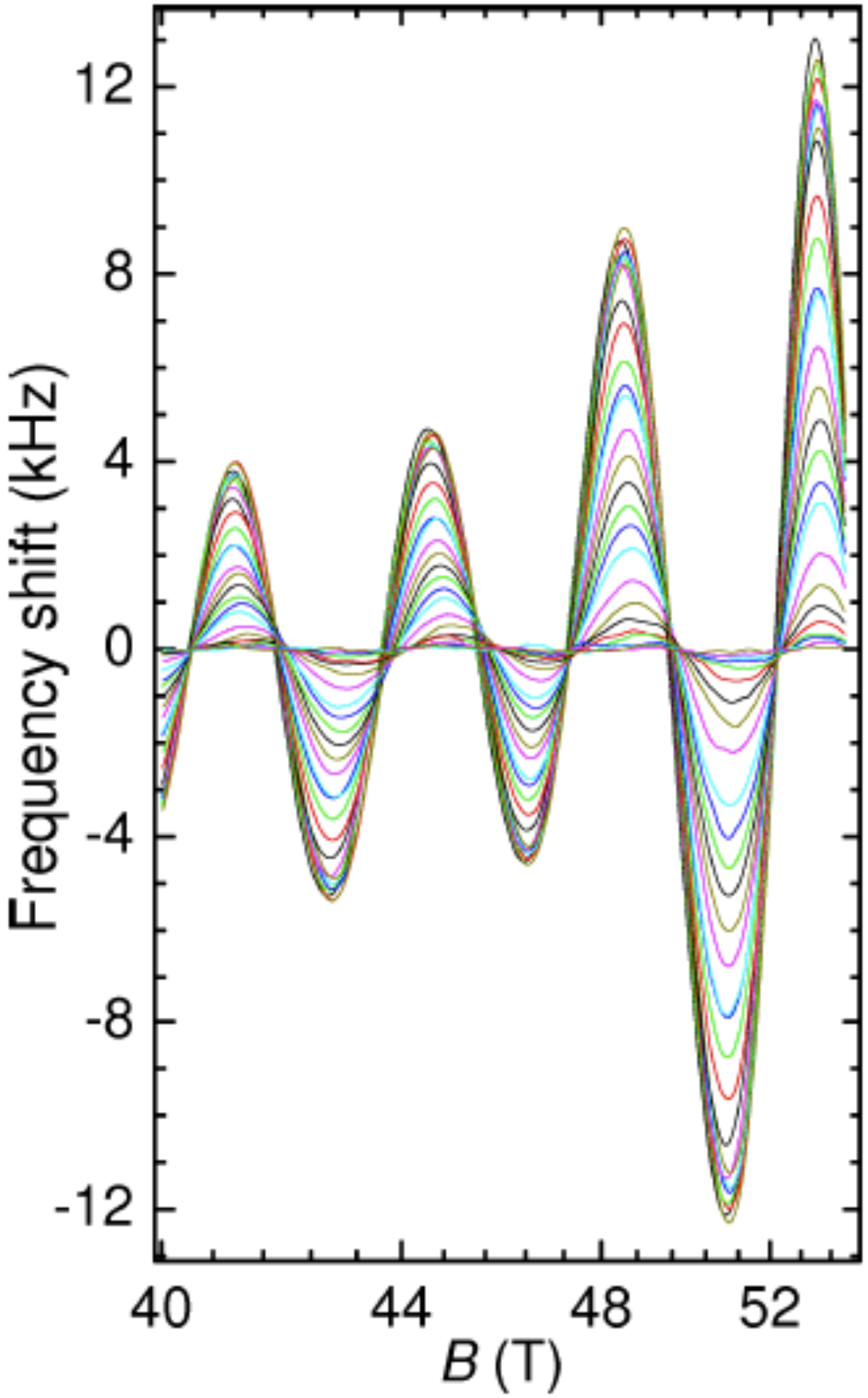
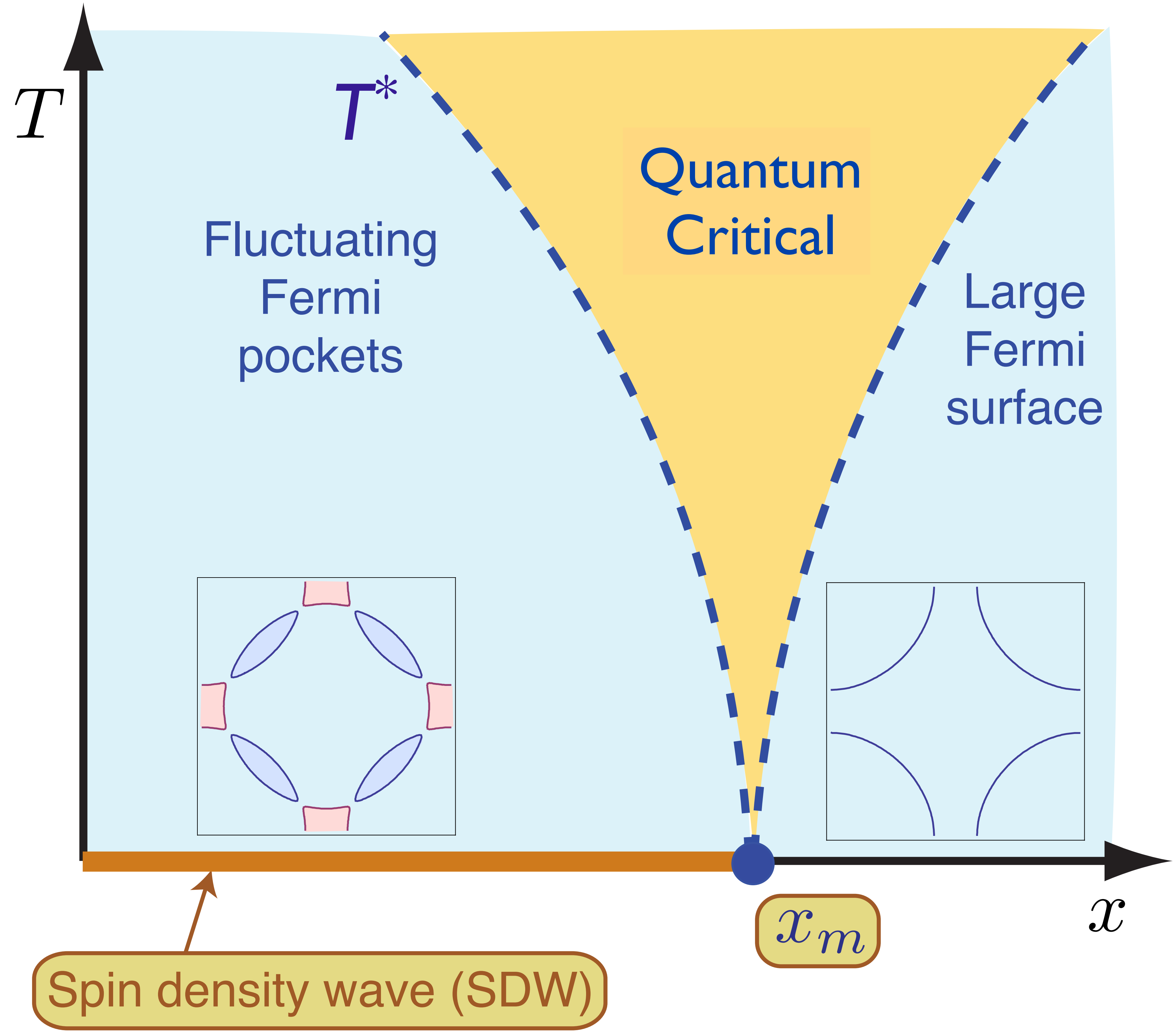


FIG. 2: Magnetic quantum oscillations measured in $YBa_2Cu_3O_{6+x}$ with $x \approx 0.56$ (after background polynomial subtraction). This restricted interval in $B = |\mathbf{B}|$ furnishes a dynamic range of $\sim$ 50 dB between T = 1 and 18 K. The actual T values are provided in Fig. 3.

Suchitra E. Sebastian, N. Harrison,
M. M. Altarawneh, Ruixing Liang, D. A. Bonn,
W. N. Hardy, and G. G. Lonzarich
Physical Review B **81**, 140505(R) (2010)

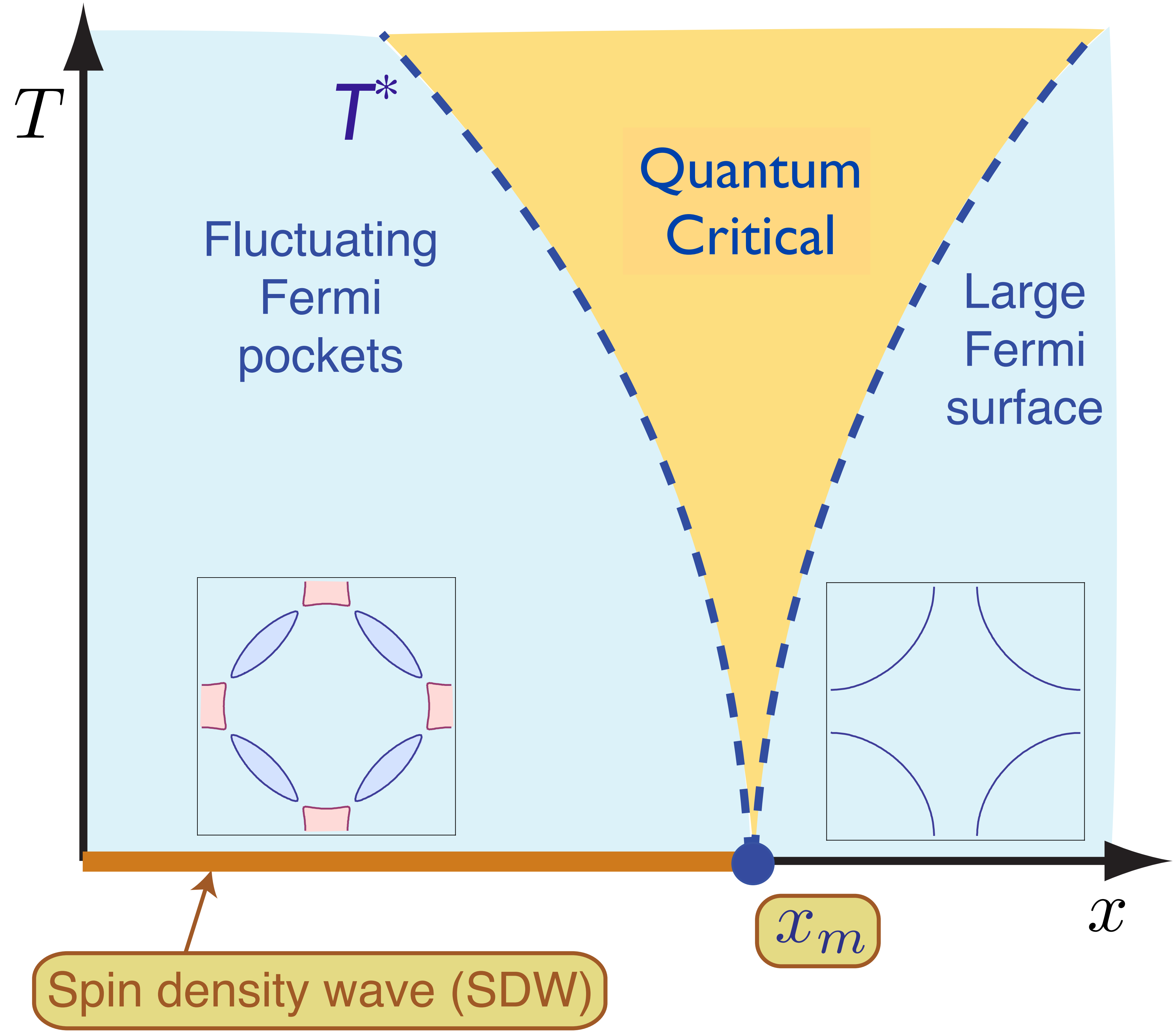
Original observation:
N. Doiron-Leyraud, C. Proust,
D. LeBoeuf, J. Levallois,
J.-B. Bonnemaison, R. Liang,
D. A. Bonn, W. N. Hardy,
and L. Taillefer,
Nature **447**, 565 (2007)

Theory of quantum criticality in the cuprates



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

Theory of quantum criticality in the cuprates



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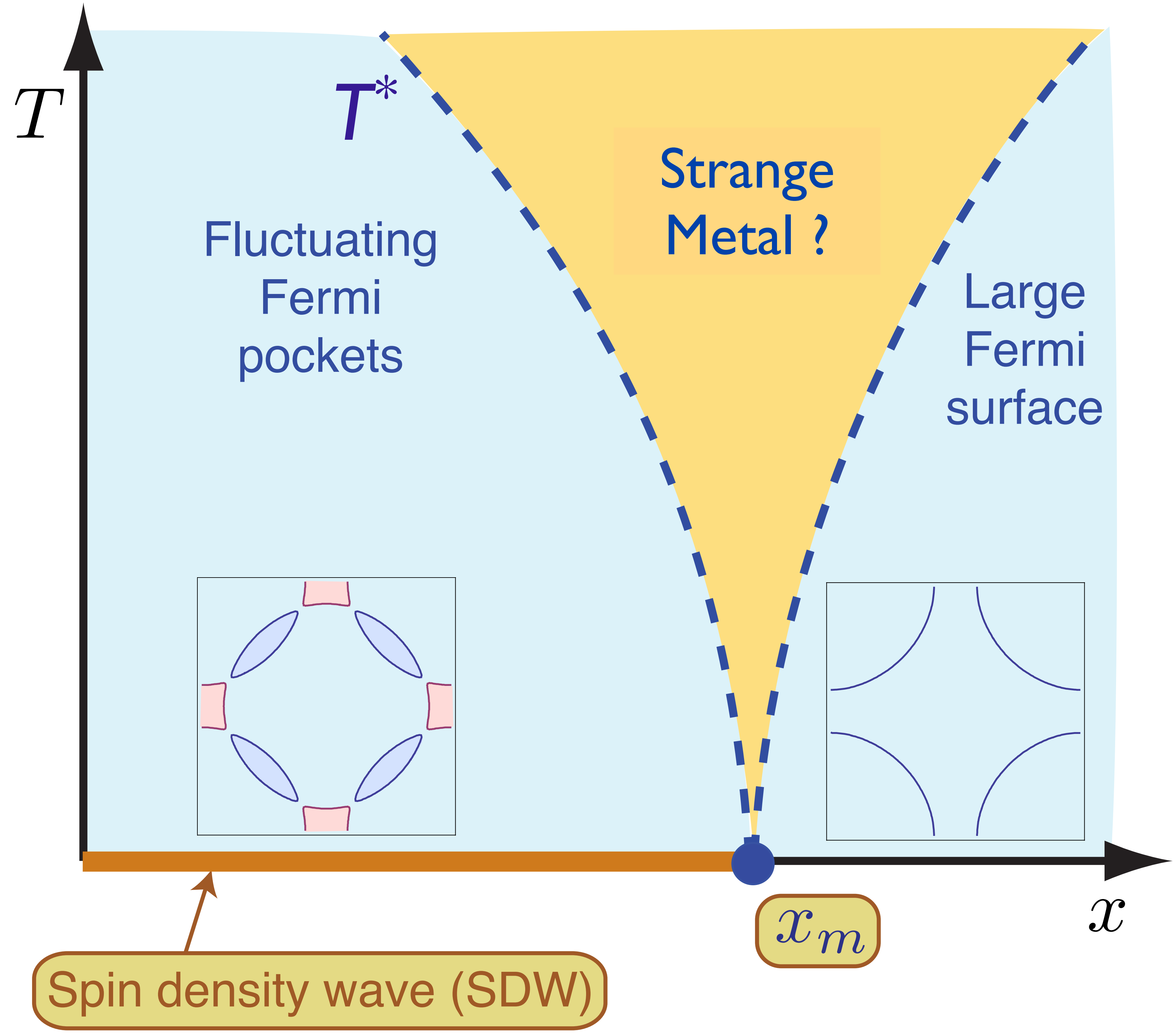

Underlying SDW ordering quantum critical point in **metal** at $x = x_m$

Outline

1. Loss of antiferromagnetism in an insulator
   Coupled-dimer antiferromagnets and quantum criticality

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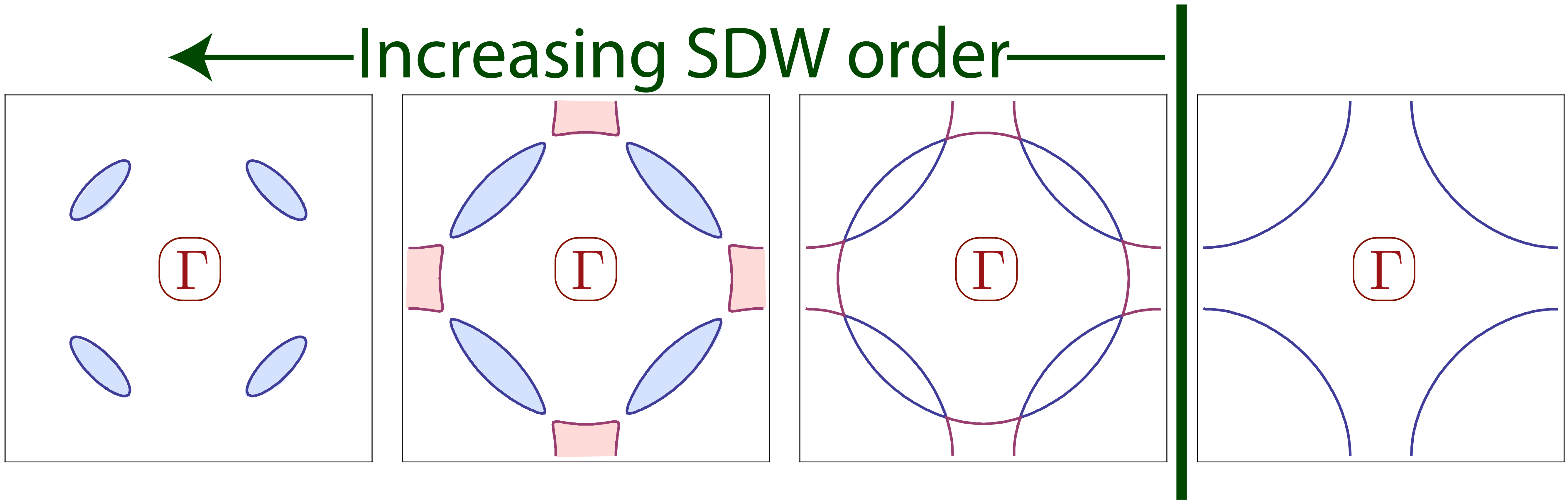
d-wave pairing near a spin-density-wave instability

D. J. Scalapino, E. Loh, Jr.,* and J. E. Hirsch†
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 23 June 1986)

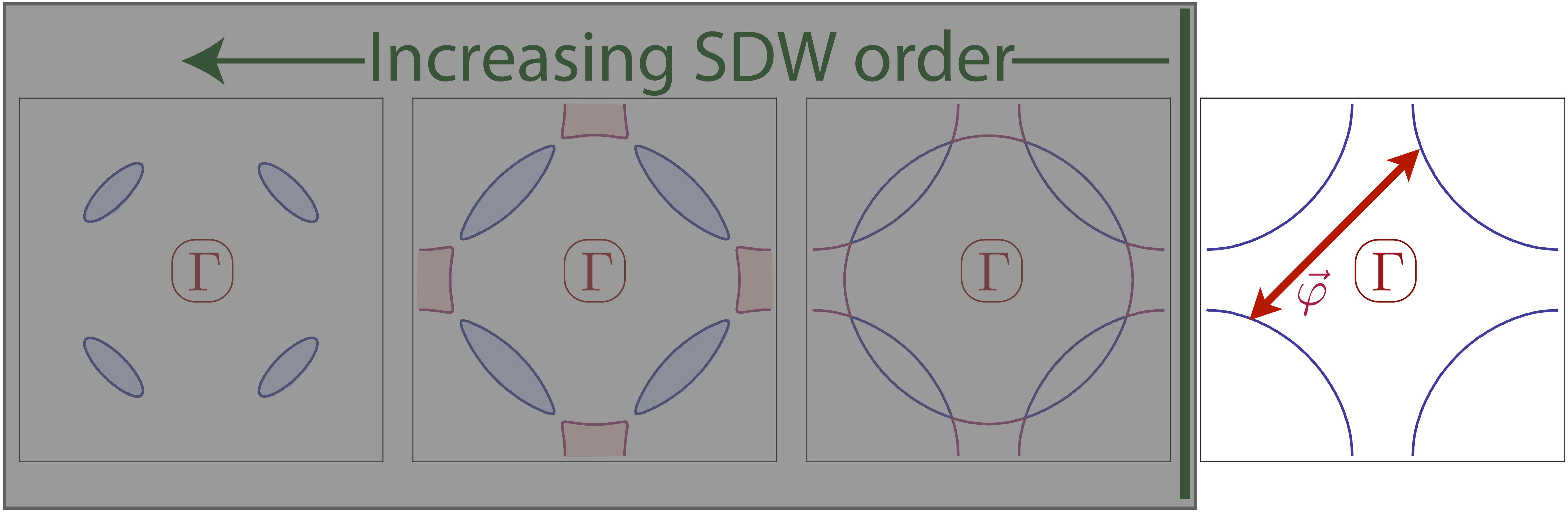
We investigate the three-dimensional Hubbard model and show that paramagnon exchange near a spin-density-wave instability gives rise to a strong singlet d-wave pairing interaction. For a cubic band the singlet ($d_{x^2-y^2}$ and $d_{3z^2-r^2}$) channels are enhanced while the singlet (d_{xy}, d_{xz}, d_{yz}) and triplet p-wave channels are suppressed. A unique feature of this pairing mechanism is its sensitivity to band structure and band filling.

Physical Review B **34**, 8190 (1986)

Spin density wave theory in hole-doped cuprates

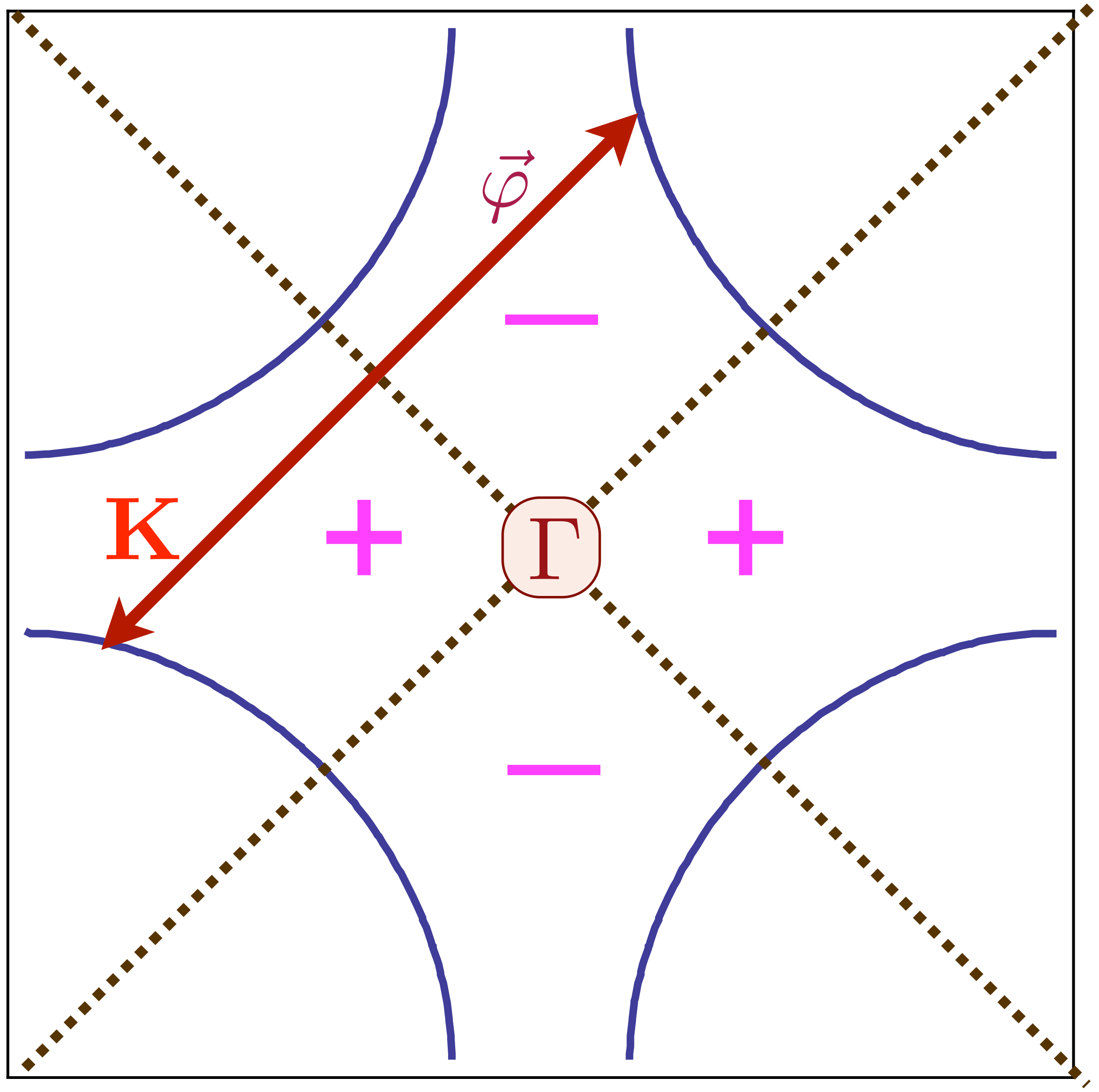


Spin-fluctuation exchange theory of d-wave superconductivity in the cuprates



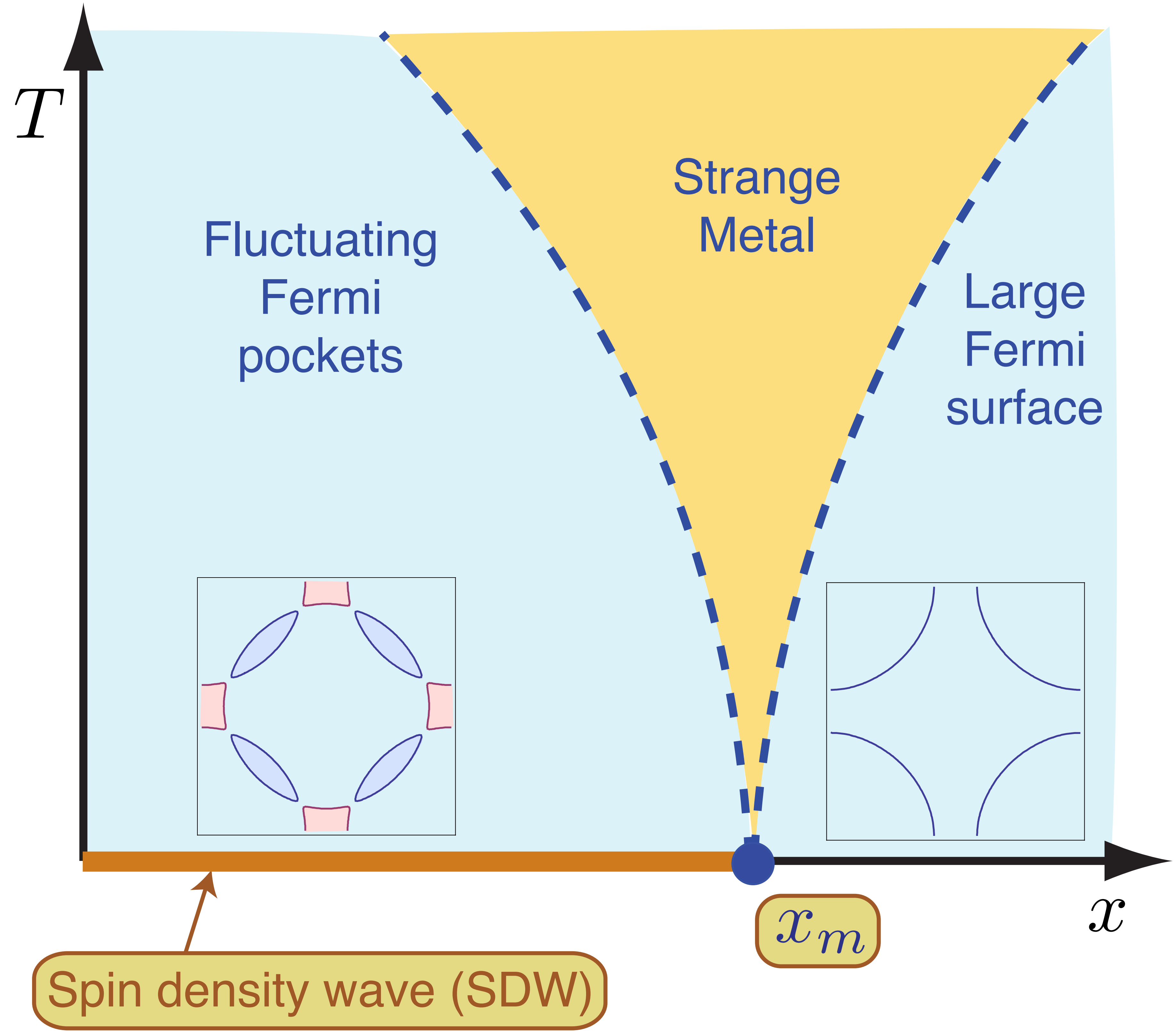
Fermions at the *large* Fermi surface exchange fluctuations of the SDW order parameter $\vec{\varphi}$.

d-wave pairing of the large Fermi surface



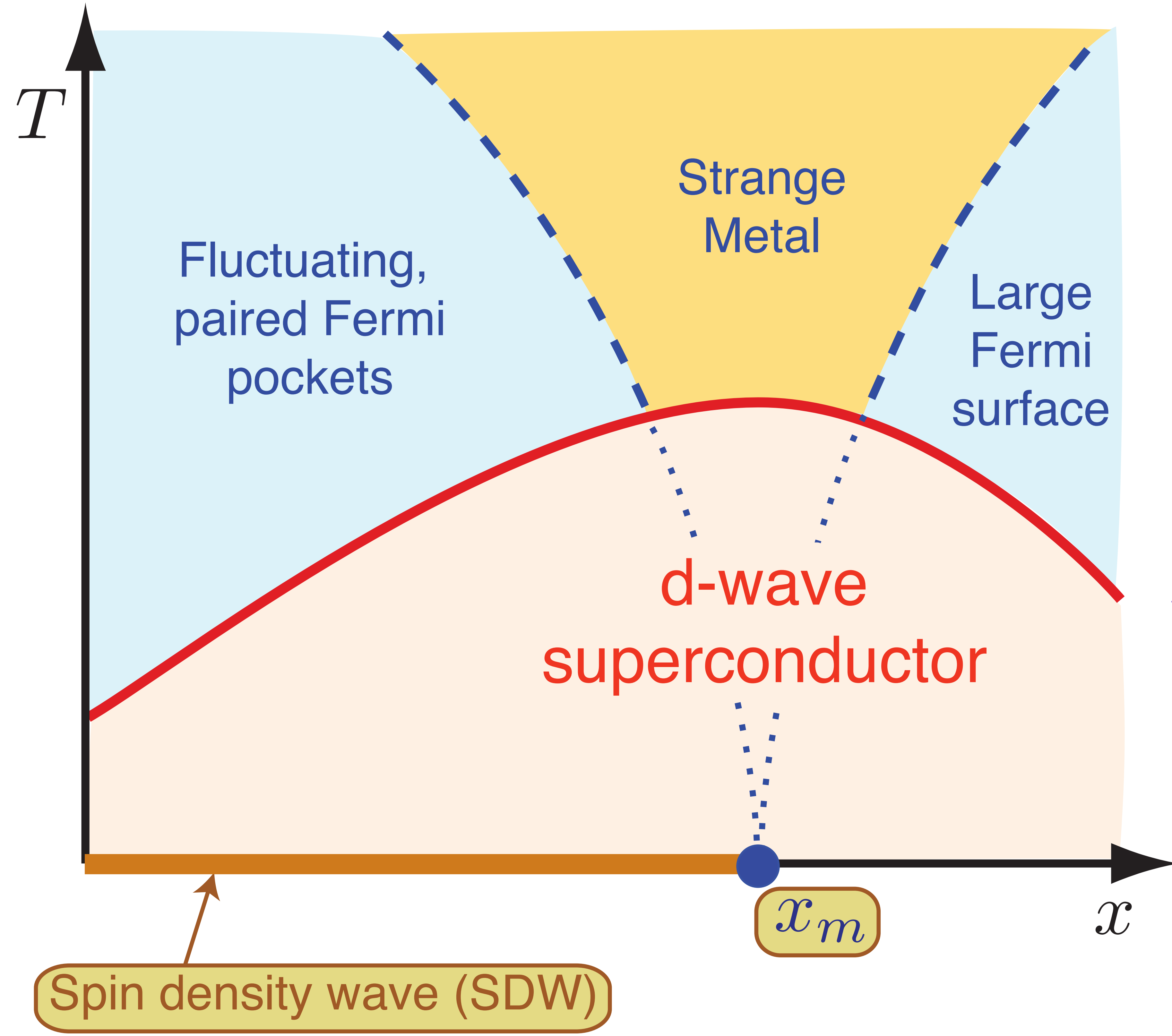
$$\langle c_{\mathbf{k}\uparrow} c_{-\mathbf{k}\downarrow} \rangle \propto \Delta_{\mathbf{k}} = \Delta_0 (\cos(k_x) - \cos(k_y))$$

Theory of quantum criticality in the cuprates



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

Theory of quantum criticality in the cuprates



Ar. Abanov, A.V. Chubukov, and J. Schmalian, *Advances in Physics* **52**, 119 (2003).

Onset of d-wave superconductivity hides the critical point $x = x_m$

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Phenomenological quantum theory of competing orders

Competition between superconductivity (SC) and spin-density wave (SDW) order

Begin with the Landau-Ginzburg field theory for quantum fluctuations of the antiferromagnetism ($\vec{\varphi}$).

$$\mathcal{S} = \int d^2r d\tau \left[\frac{1}{2}(\partial_\tau \vec{\varphi})^2 + \frac{c^2}{2}(\nabla_x \vec{\varphi})^2 + \frac{s}{2}\vec{\varphi}^2 + \frac{u}{4}\left(\vec{\varphi}^2\right)^2 \right.$$

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

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$$\left. + \int d^2r \left[|(\nabla_x - i(2e/\hbar c)\mathcal{A})\Delta|^2 - |\Delta|^2 + \frac{|\Delta|^4}{2} \right] \right.$$

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$$
\begin{aligned}
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& \left. \qquad + \kappa\, \vec{\varphi}^2 \left|\Delta\right|^2 \right] \\
& + \int d^2r \left[\left|(\nabla_x - i(2e/\hbar c)\mathcal{A})\Delta\right|^2 - \left|\Delta\right|^2 + \frac{\left|\Delta\right|^4}{2} \right]
\end{aligned}
$$

Include the simplest allowed coupling between the two orders, $\kappa > 0$, with a positive sign implying repulsion or competition between them.

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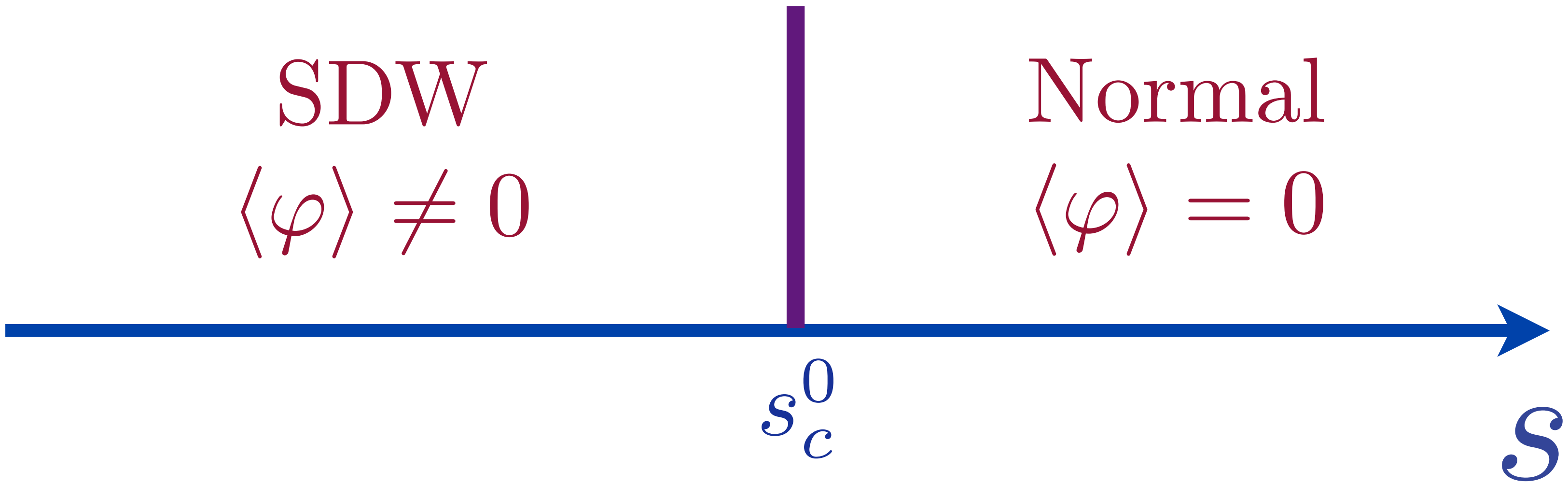

No SC

$\Delta = 0$

Phenomenological quantum theory of competing orders

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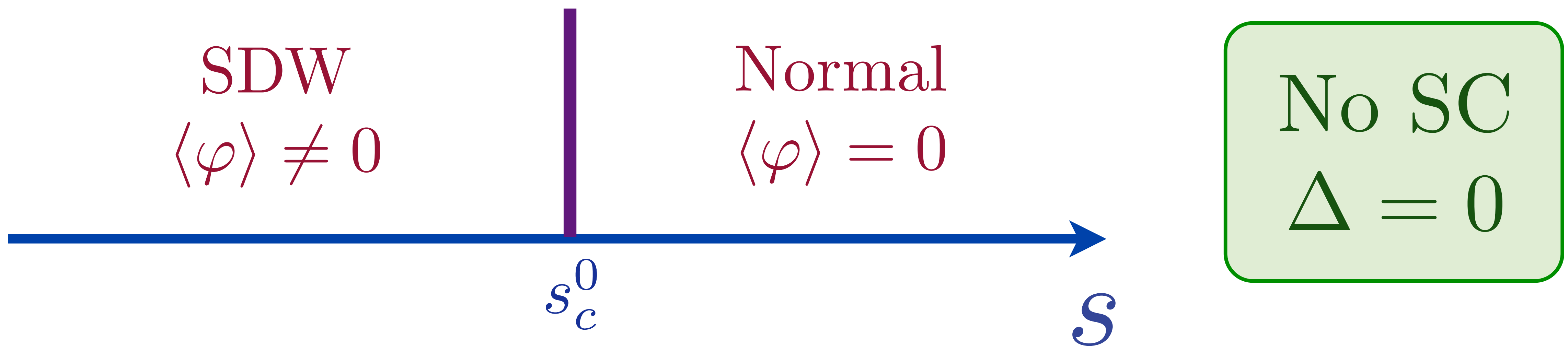
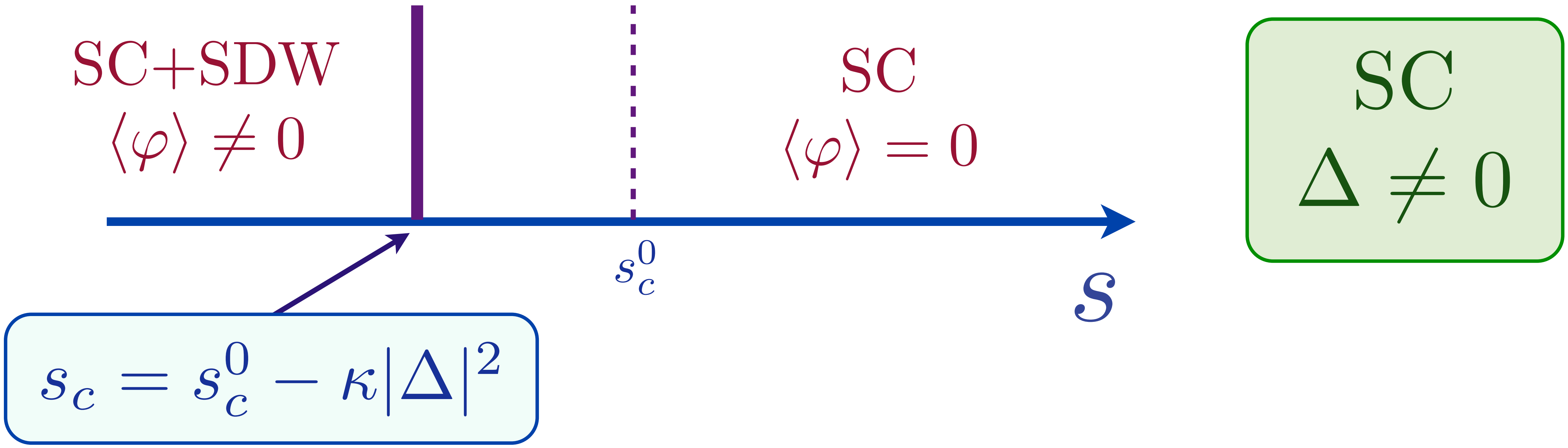
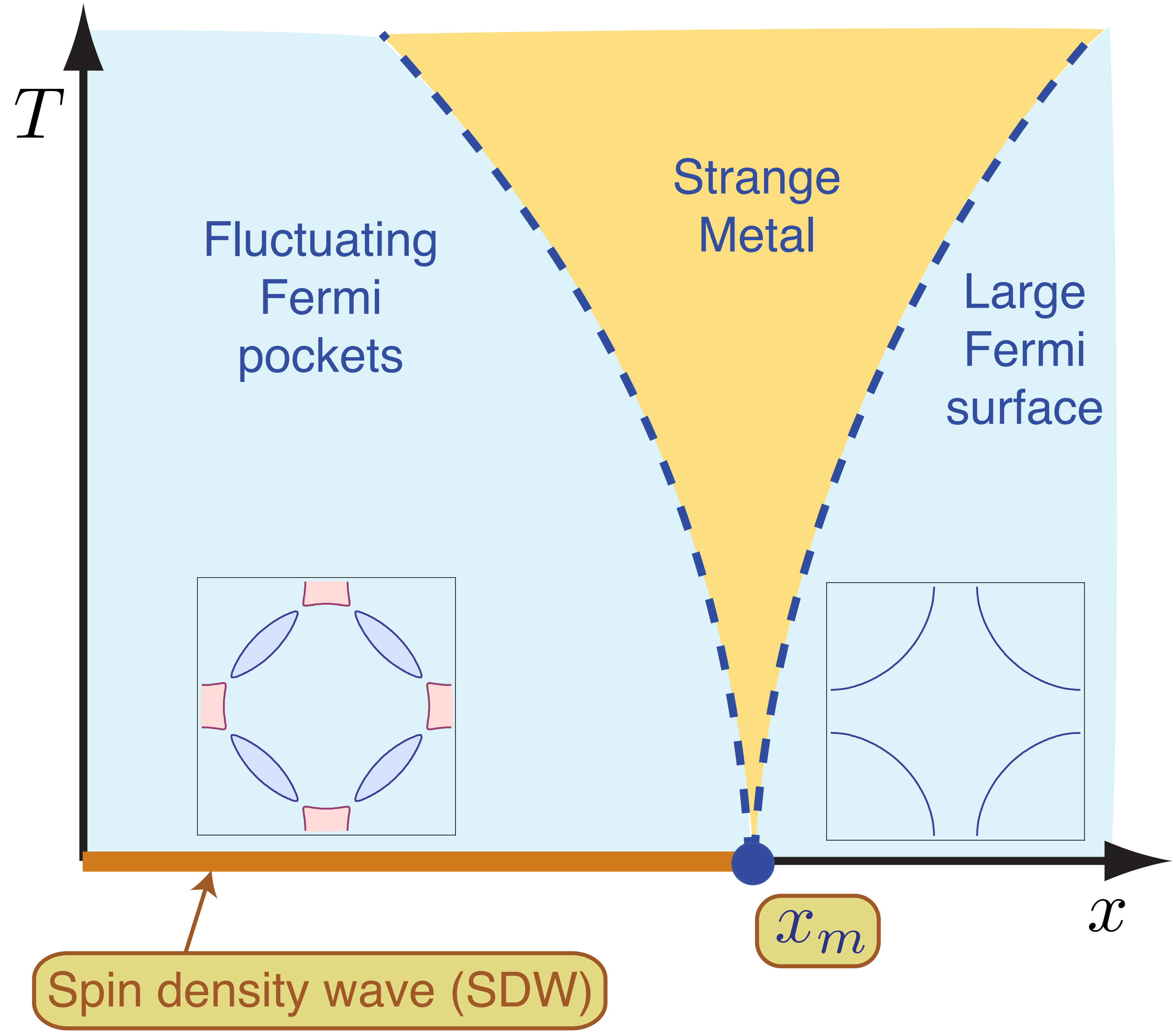




Theory of quantum criticality in the cuprates



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

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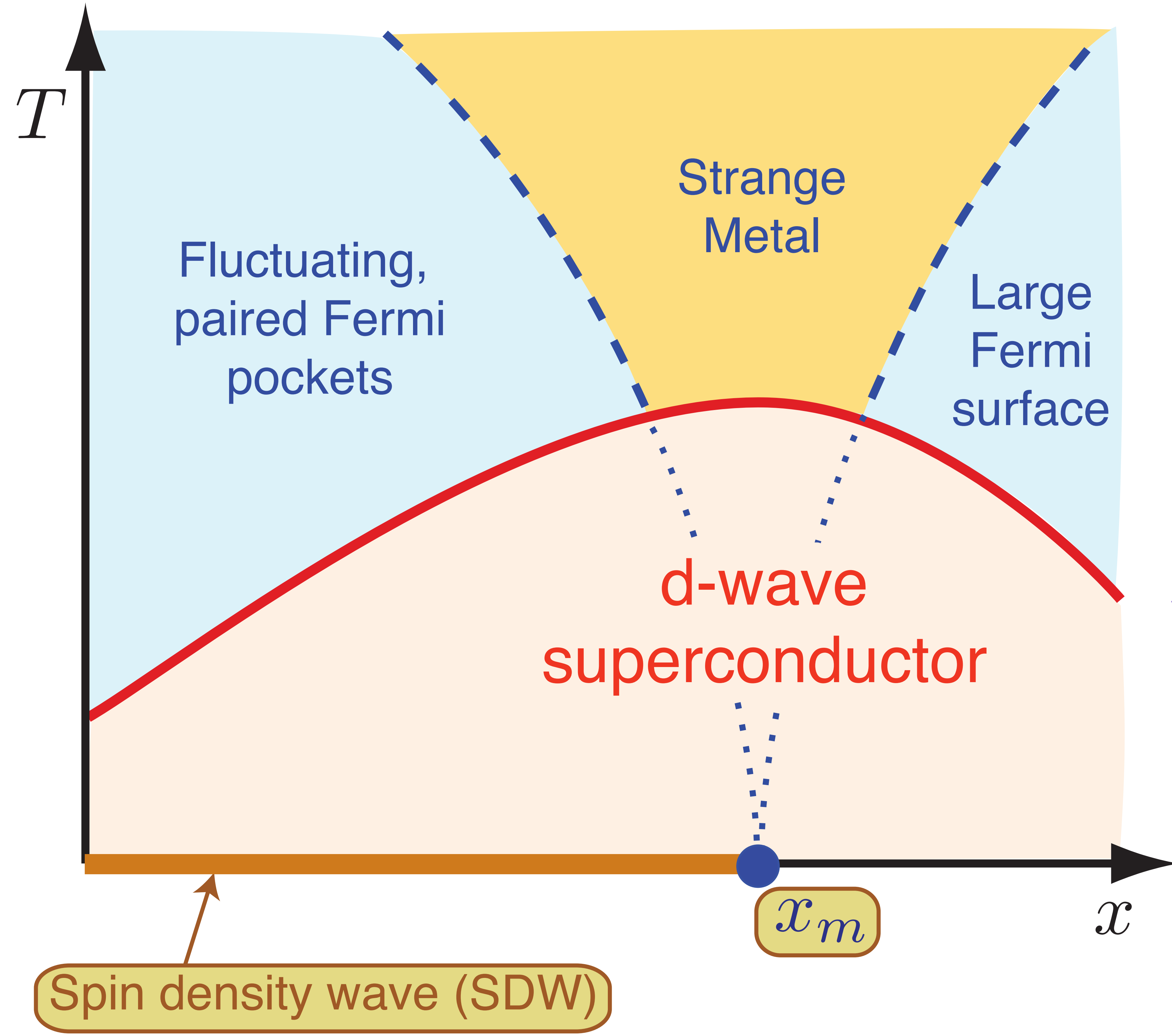

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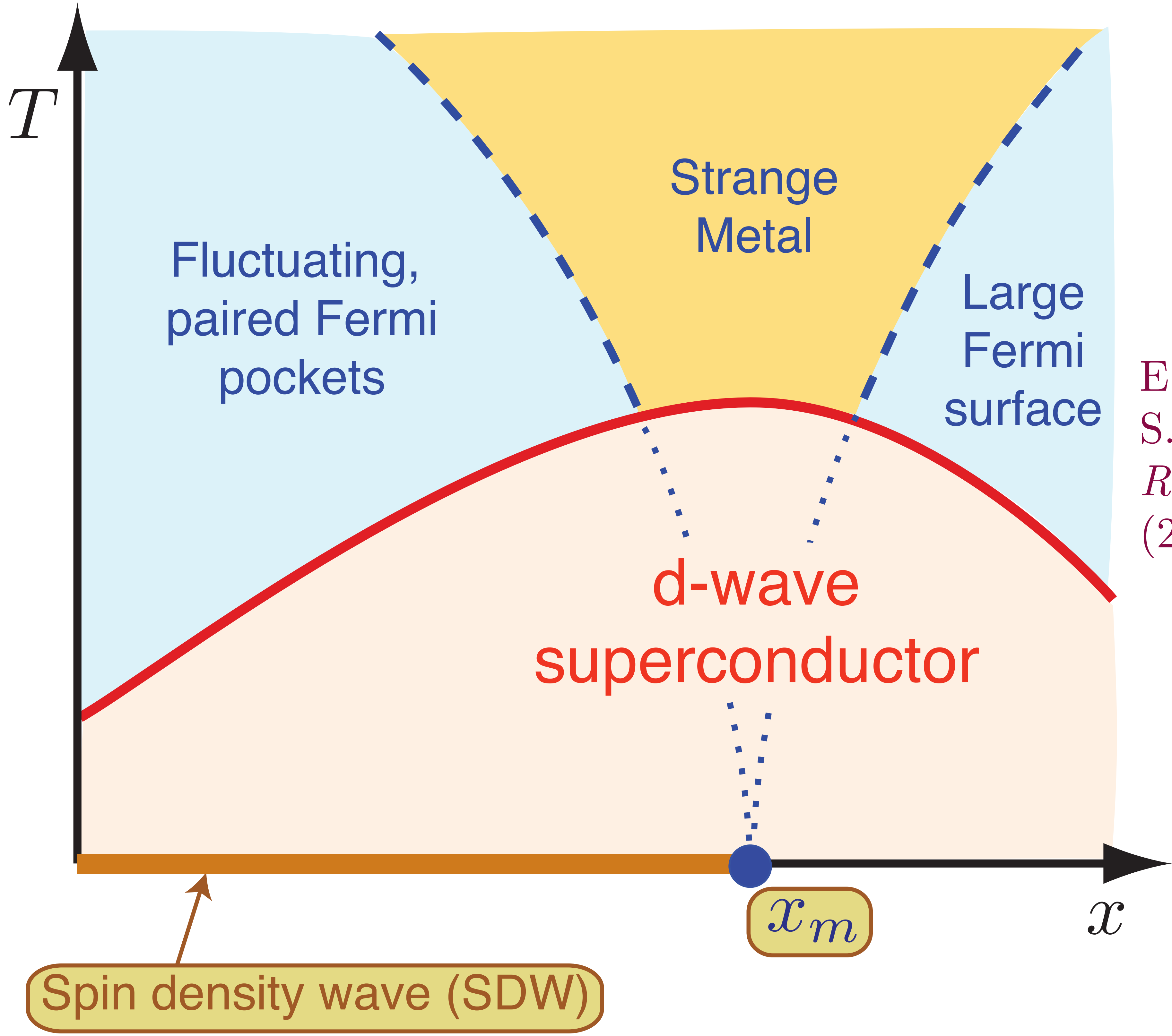
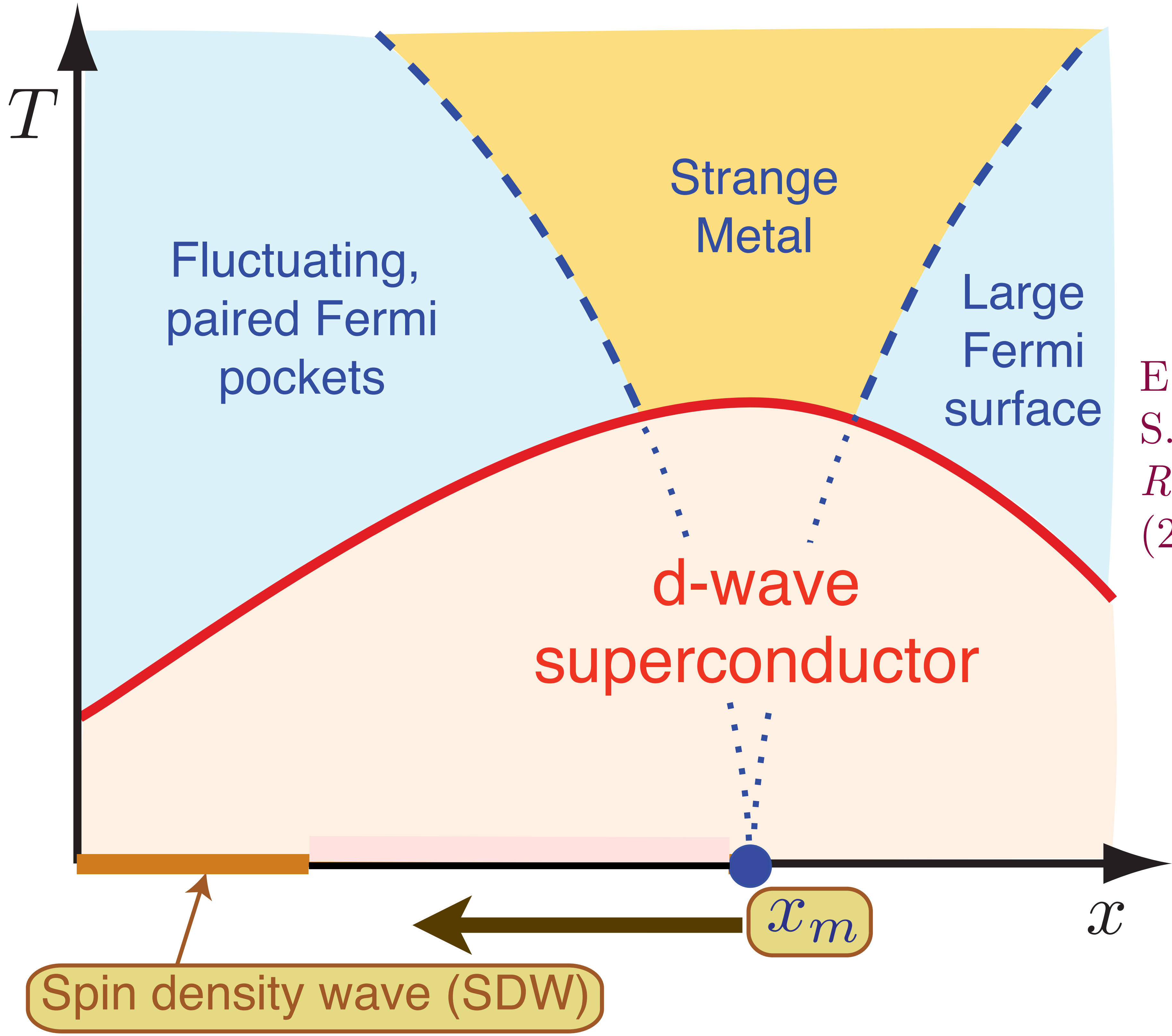


E. G. Moon and S. Sachdev, *Phy. Rev. B* **80**, 035117 (2009)

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

Theory of quantum criticality in the cuprates



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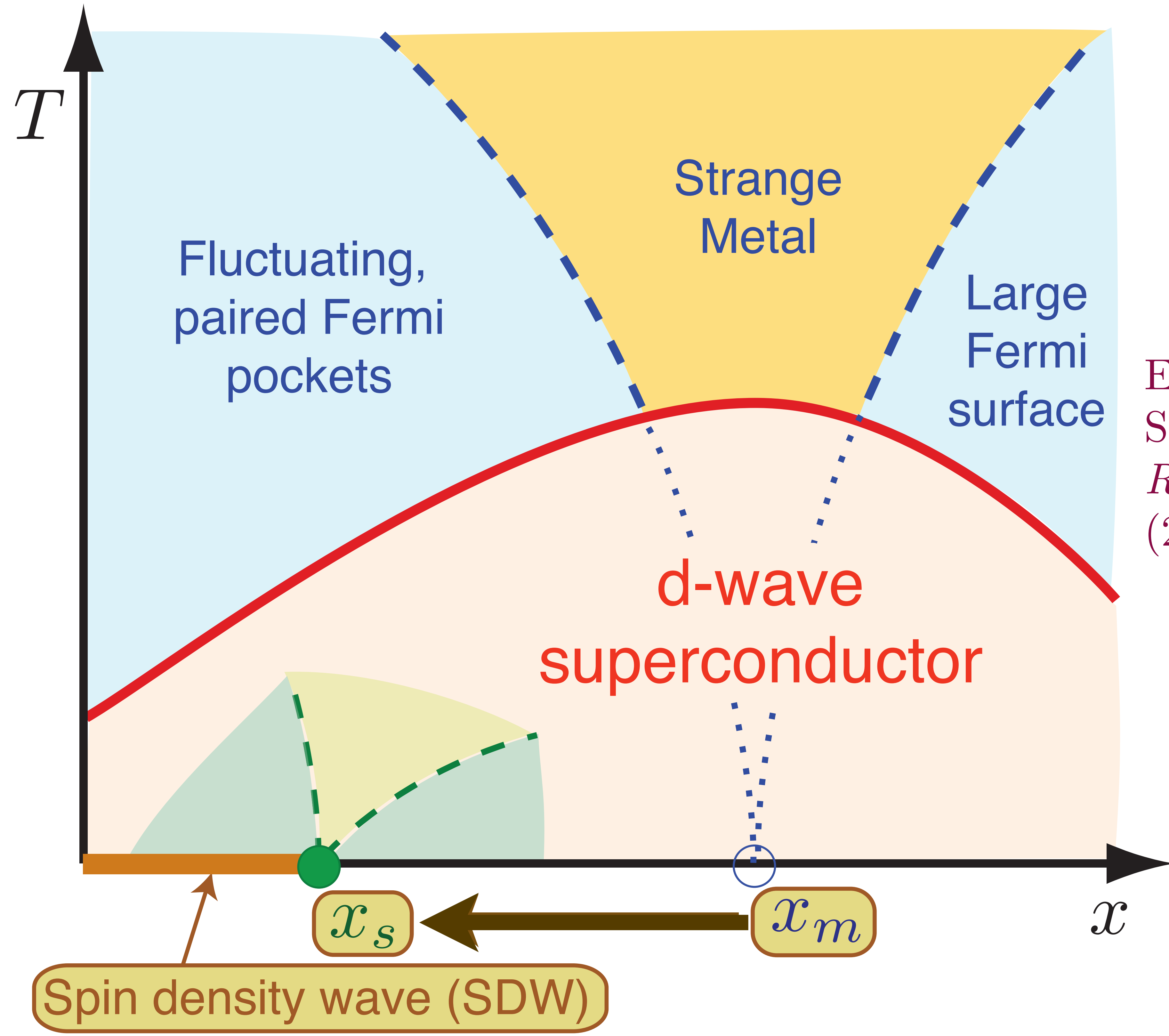

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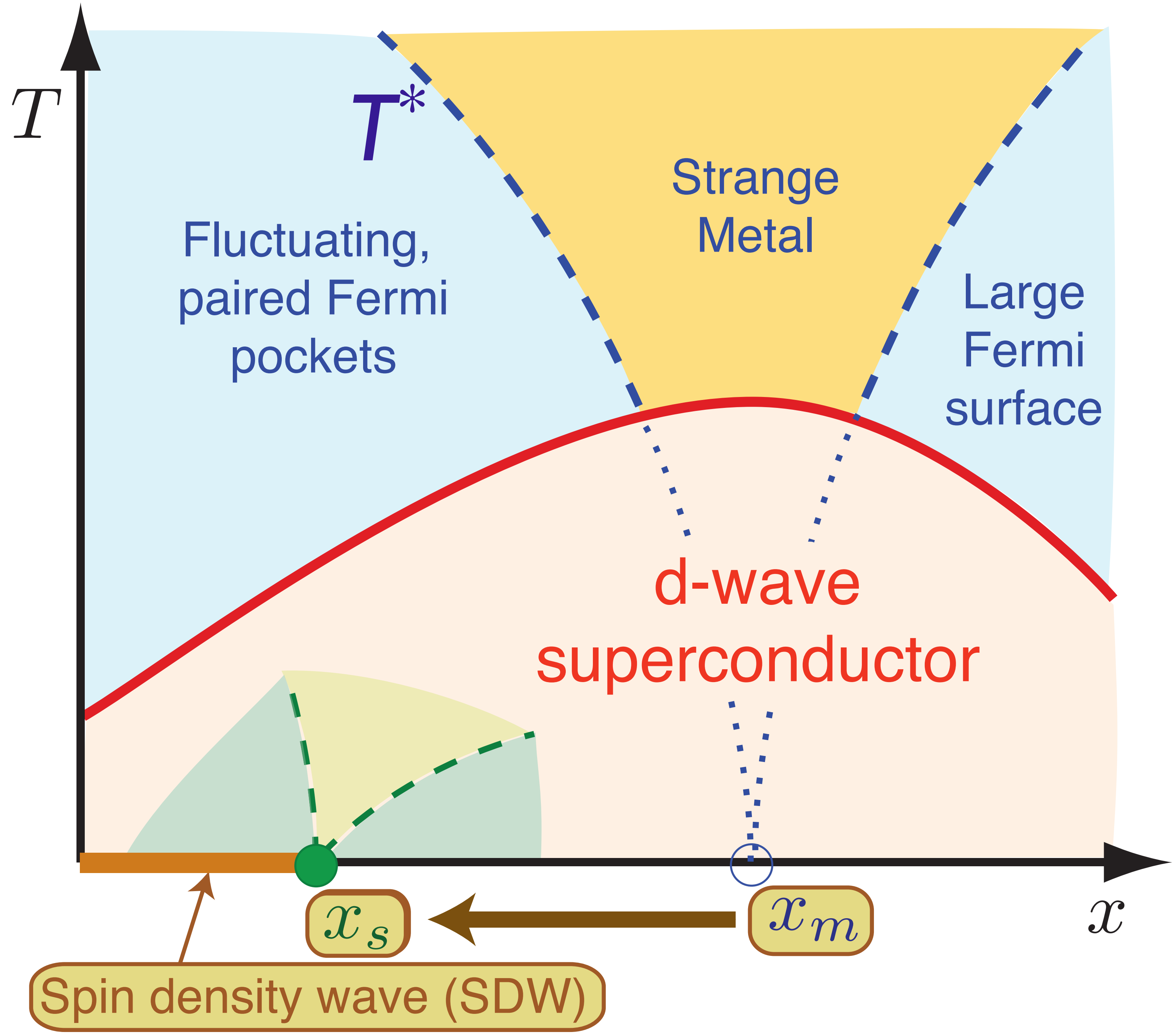
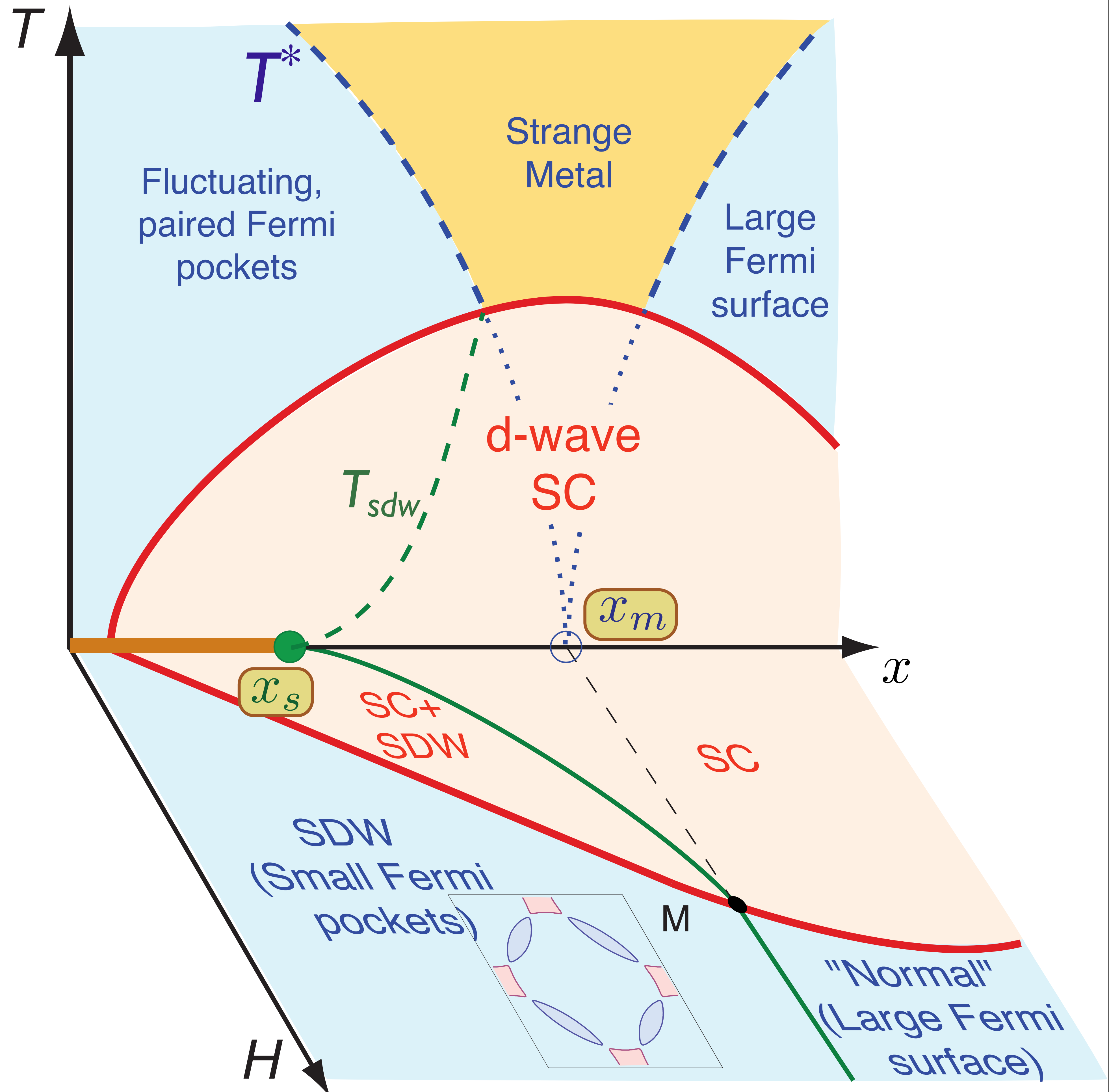


T
T^*
Fluctuating, paired Fermi pockets
Strange Metal
Large Fermi surface
d-wave superconductor
x_s
x_m
x
Spin density wave (SDW)

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



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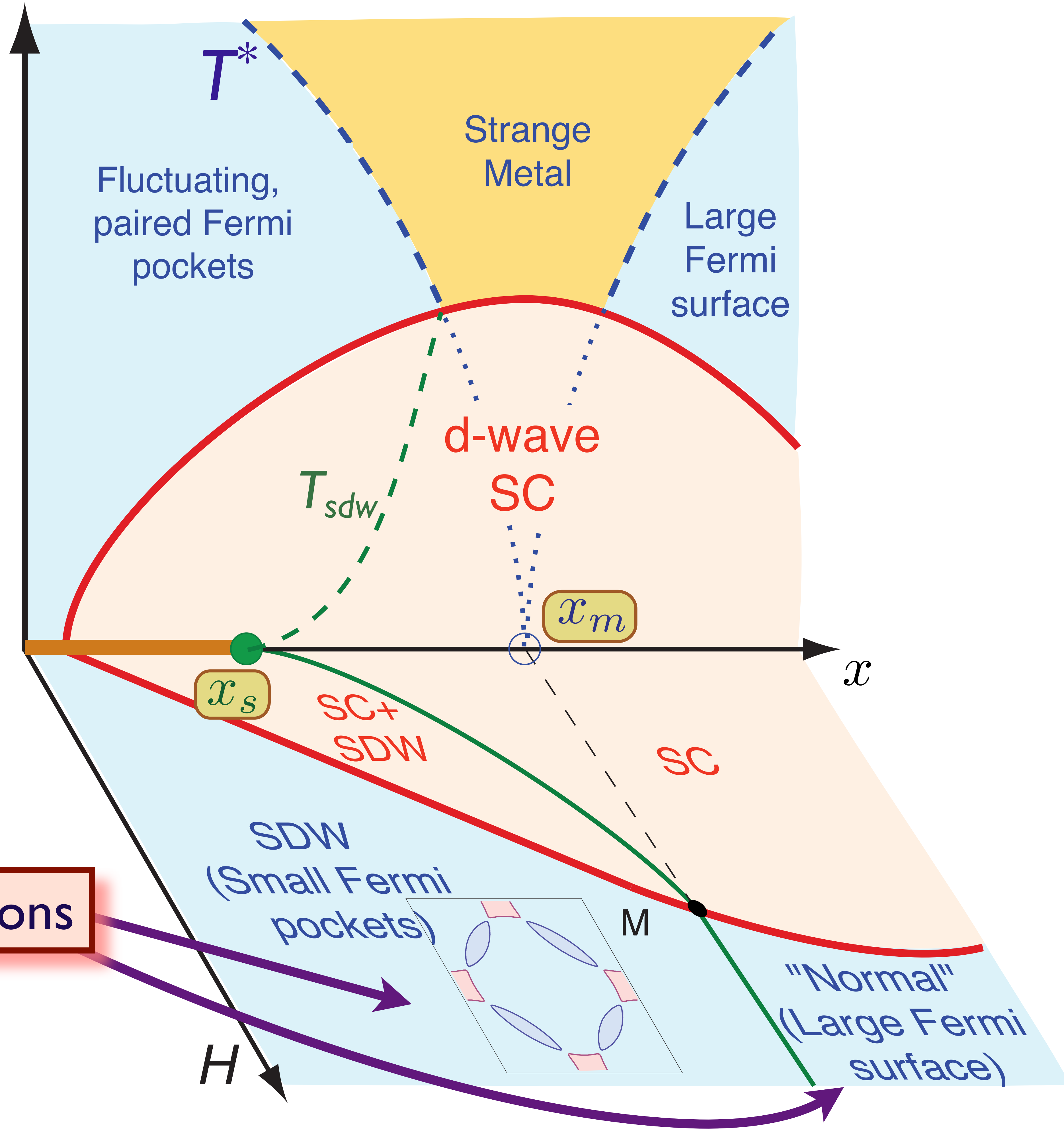
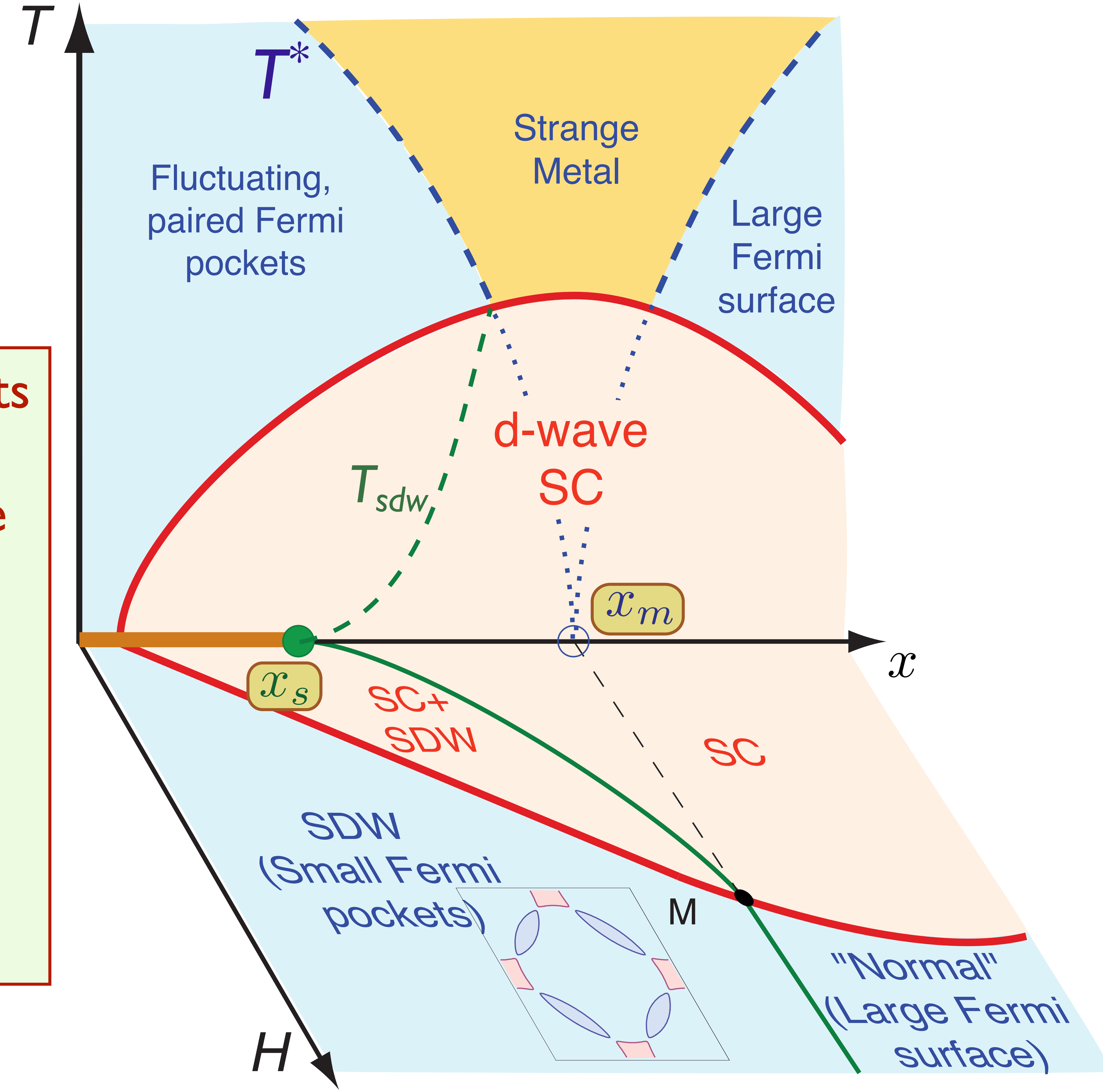
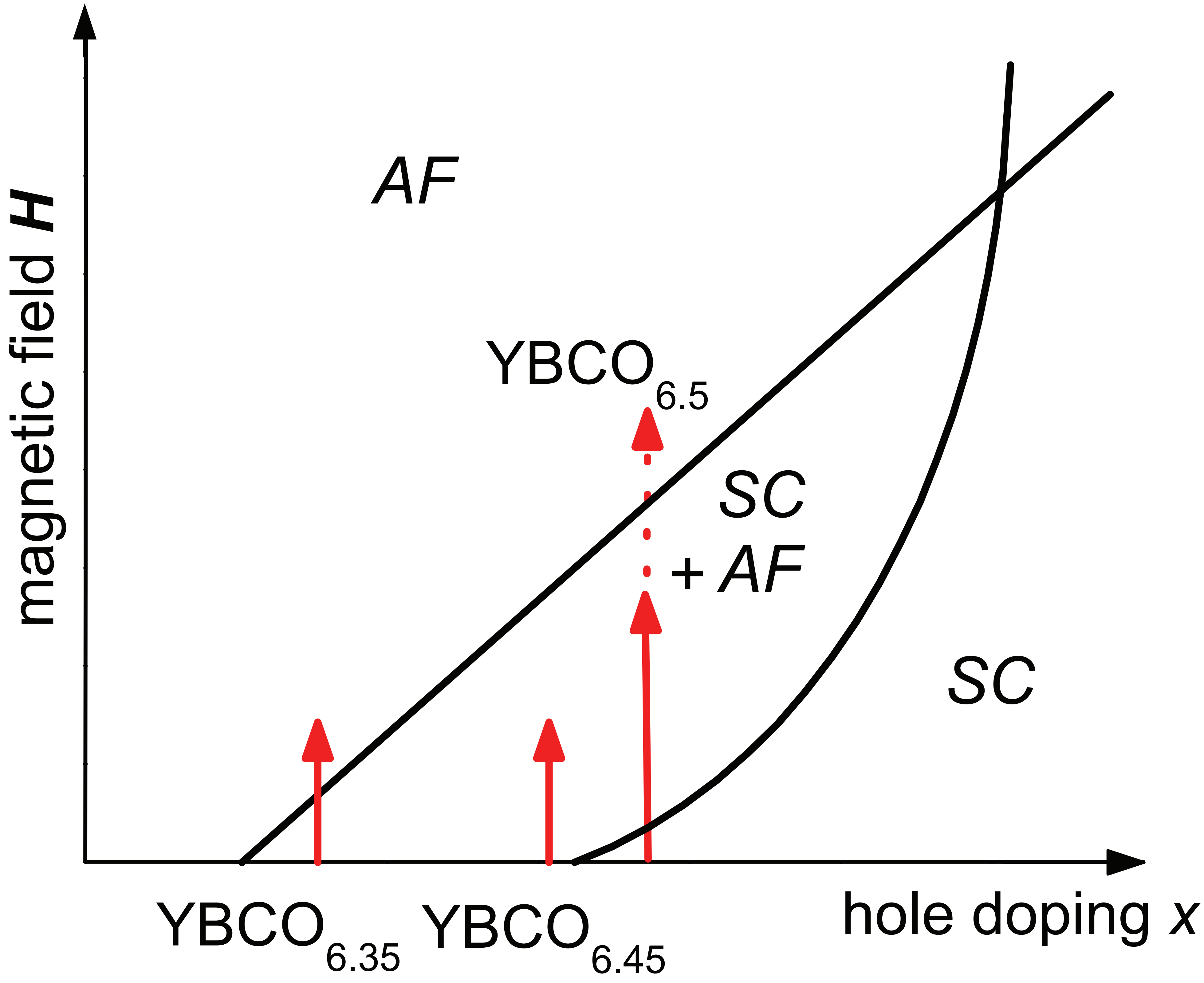


Quantum oscillations

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

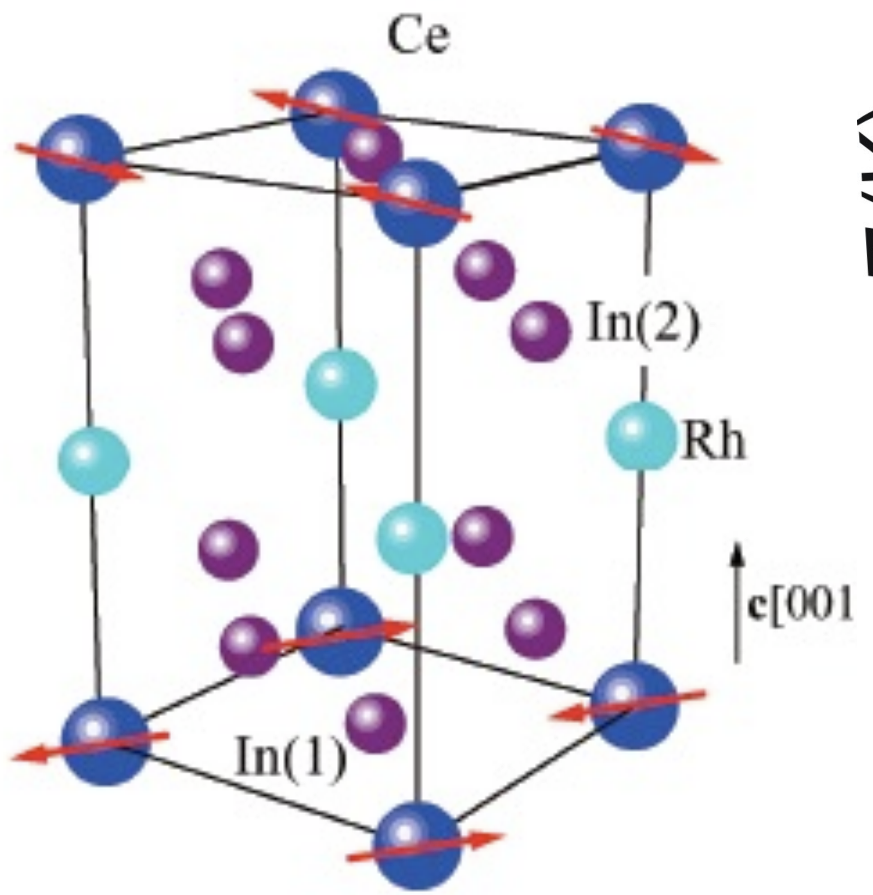
Many experiments have presented evidence for the predicted green quantum phase transition line from SC to SC +SDW in a magnetic field

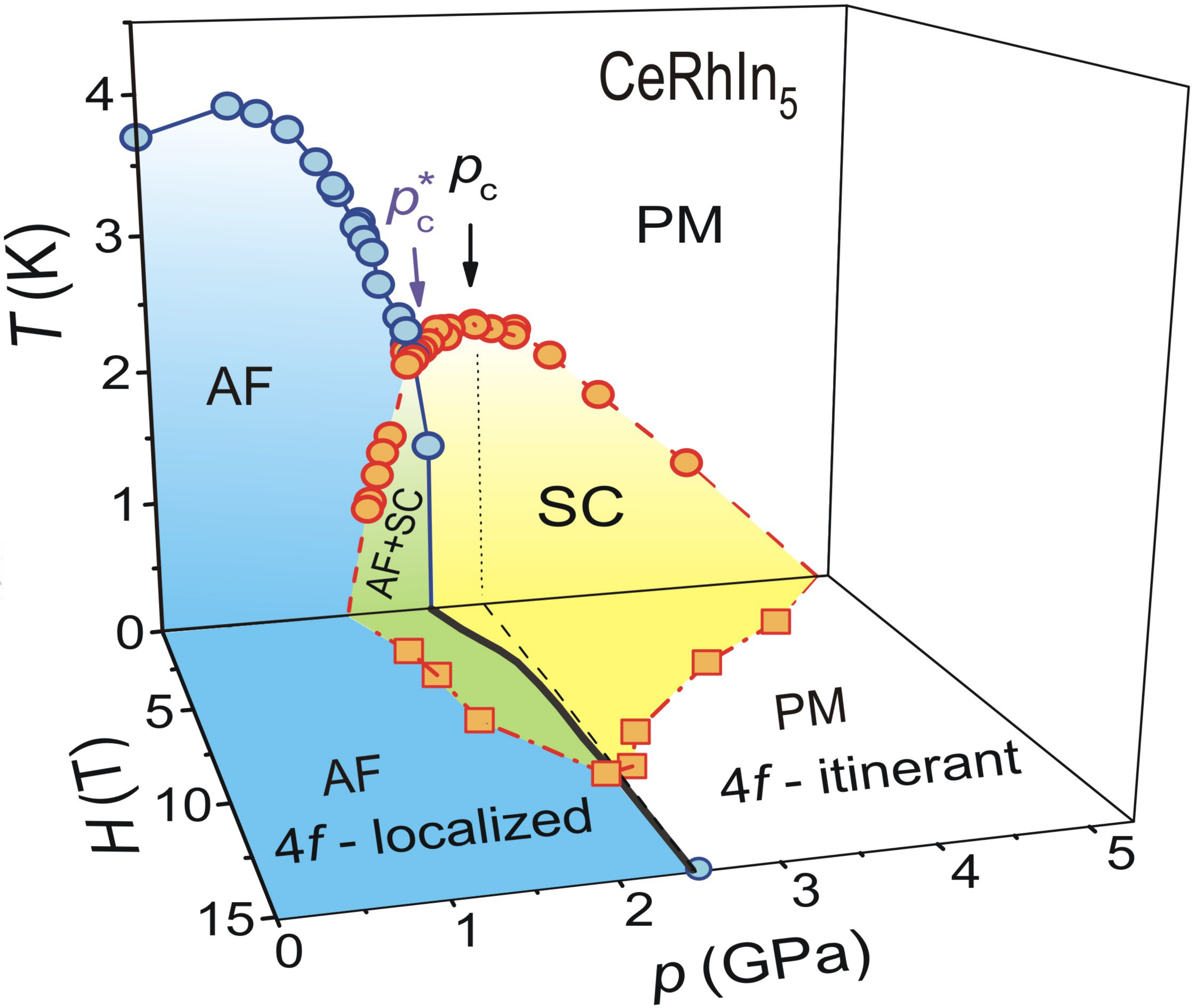




D. Haug, V. Hinkov, Y. Sidis, P. Bourges, N. B. Christensen, A. Ivanov, T. Keller, C. T. Lin, and B. Keimer, arXiv:1008.4298

Similar phase diagram for $CeRhIn_5$

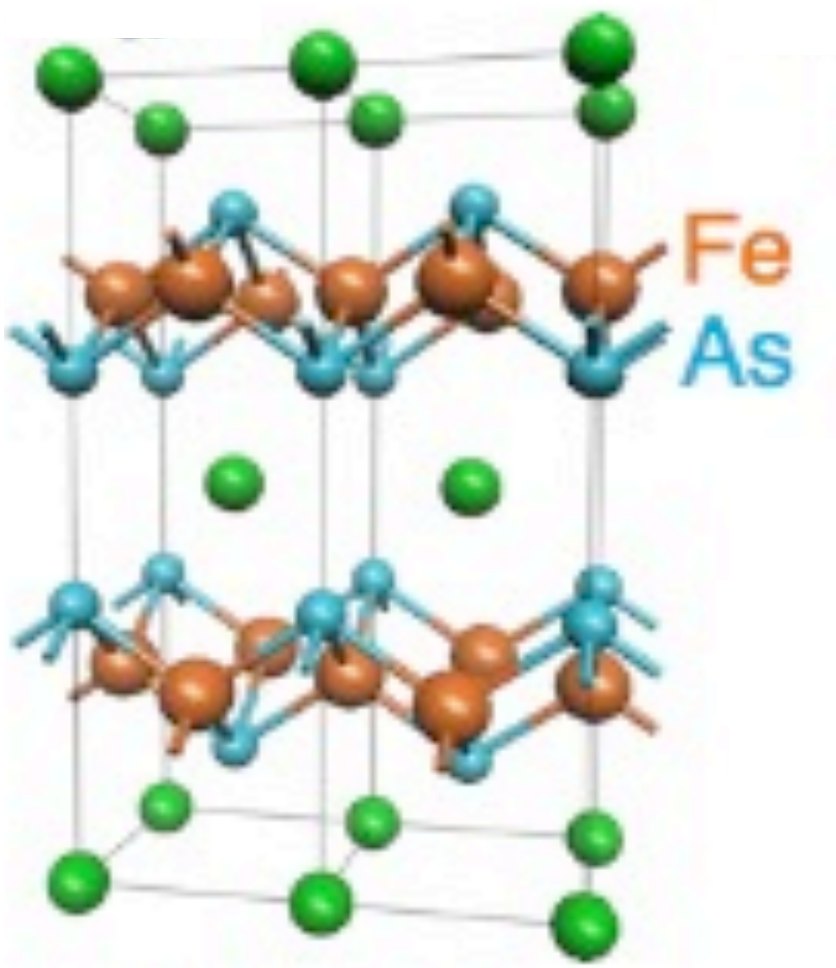


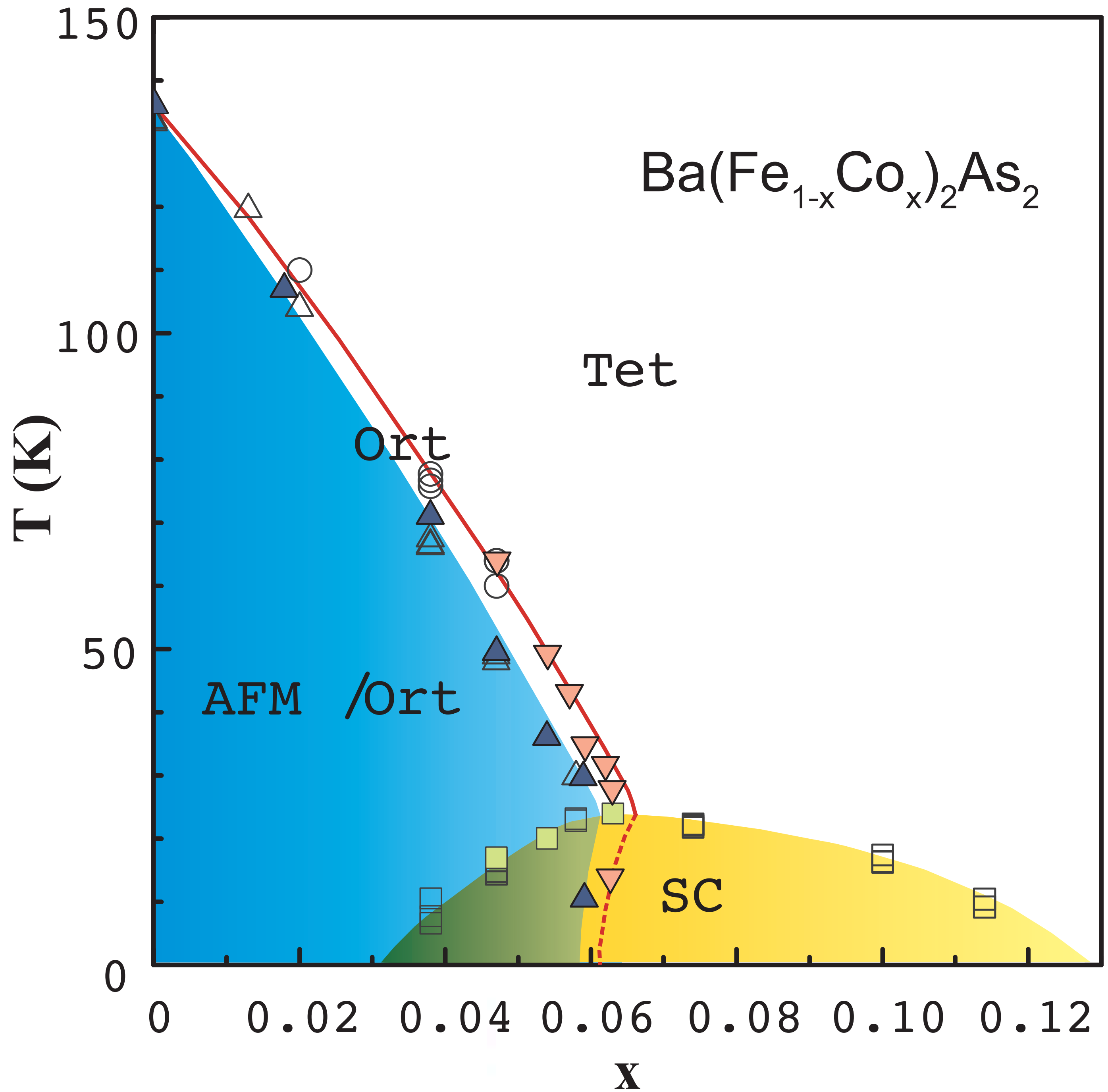


G. Knebel, D. Aoki, and J. Flouquet, arXiv:0911.5223

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).

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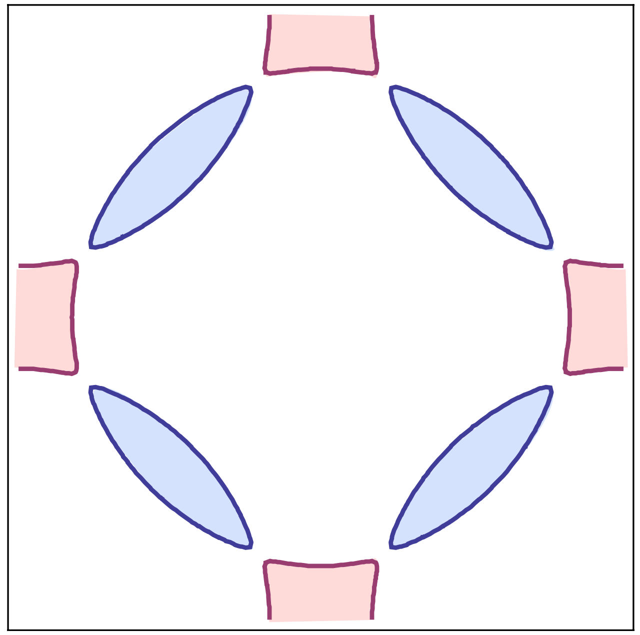
Quantum criticality of the onset of antiferromagnetism in a metal

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



Metal with electron and hole pockets

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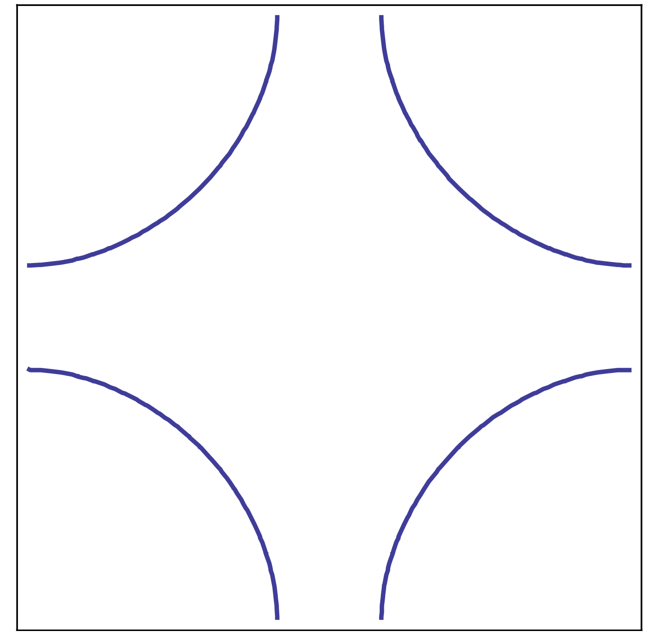

Metal with "large" Fermi surface

s

Quantum criticality of the onset of antiferromagnetism in a metal

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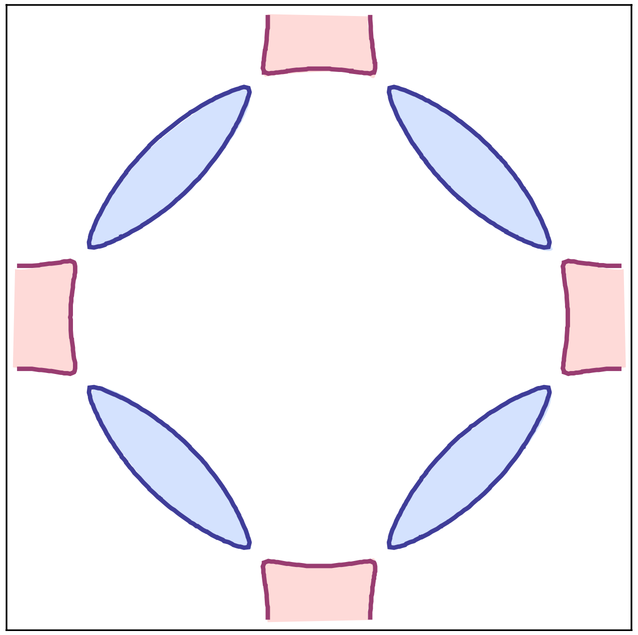

Metal with electron and hole pockets

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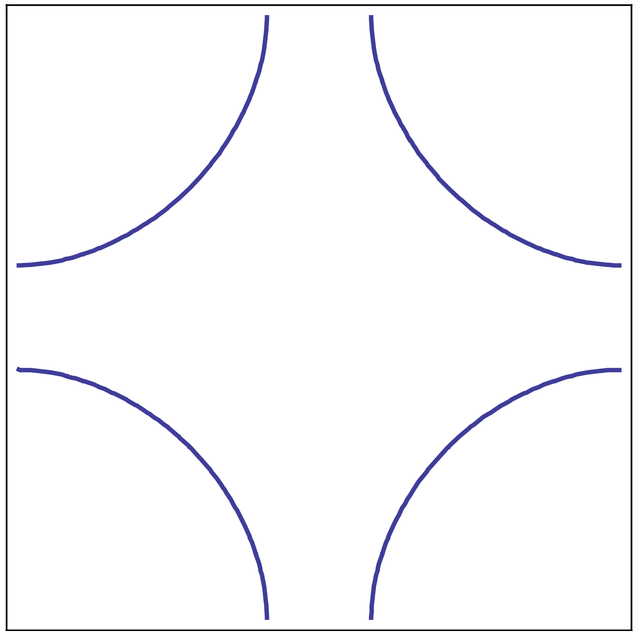

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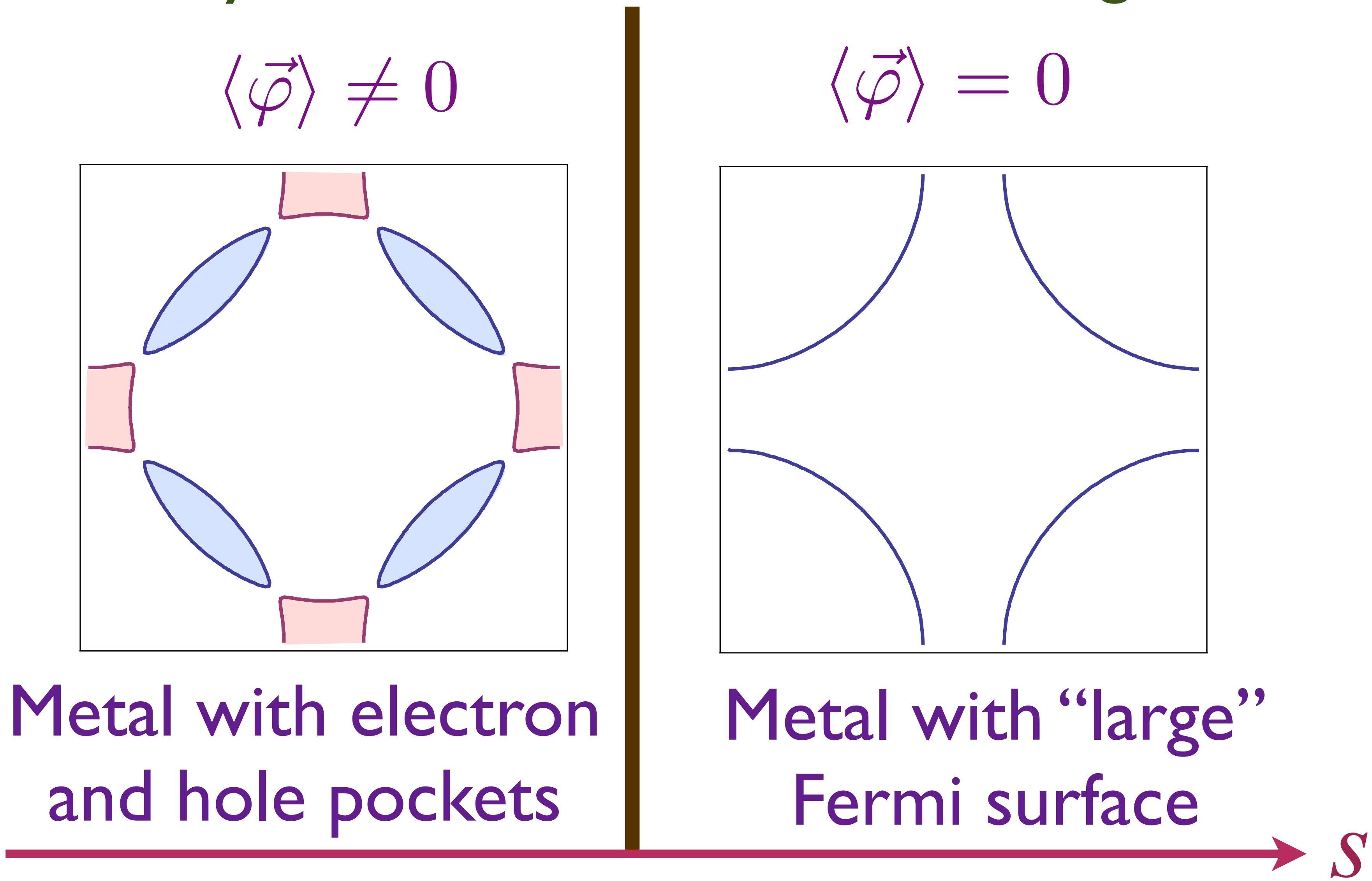
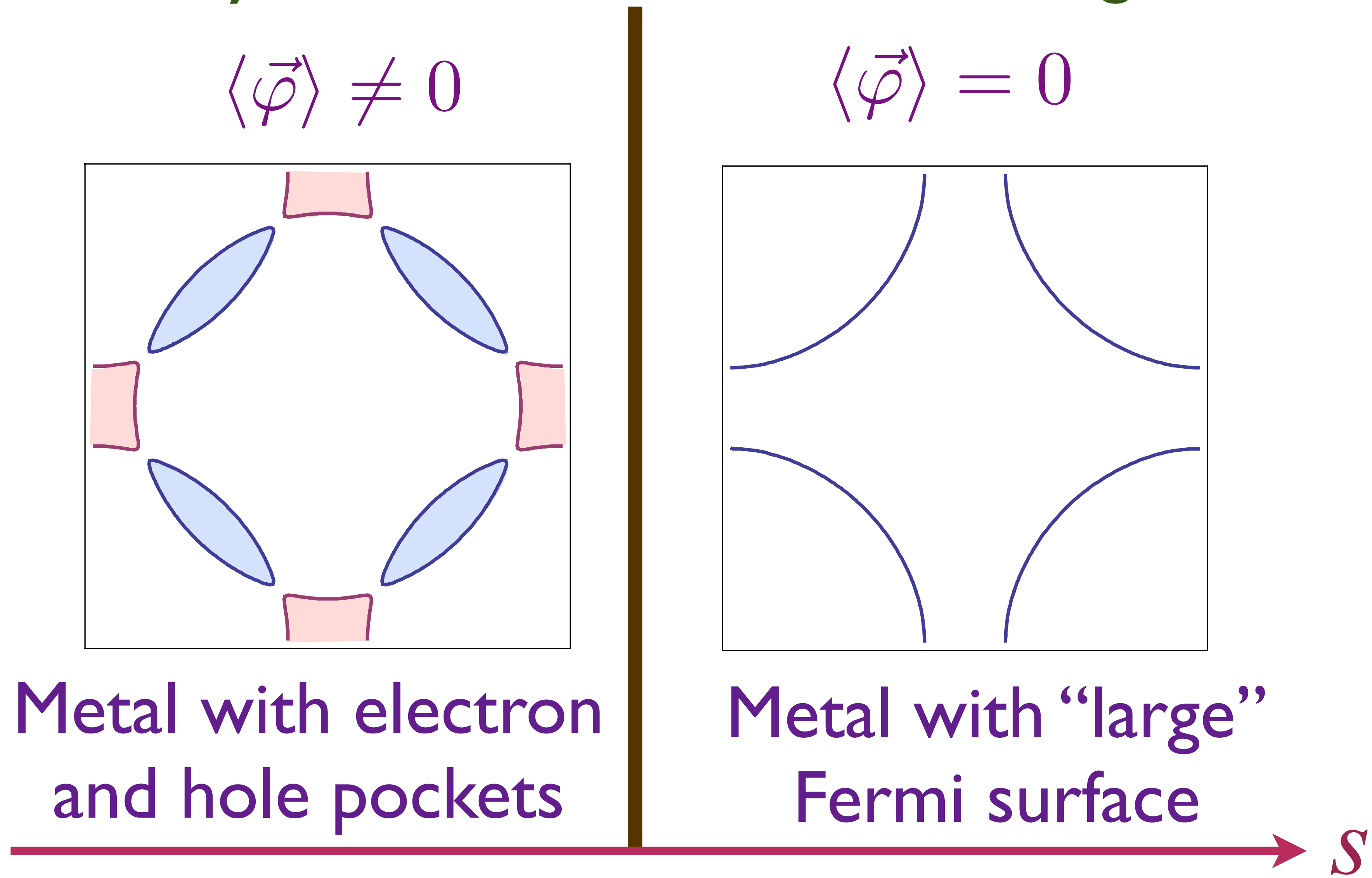


Quantum criticality of the onset of antiferromagnetism in a metal



- Quantum critical theory is ***strongly-coupled*** in two (but not higher) spatial dimensions (but not a CFT).

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

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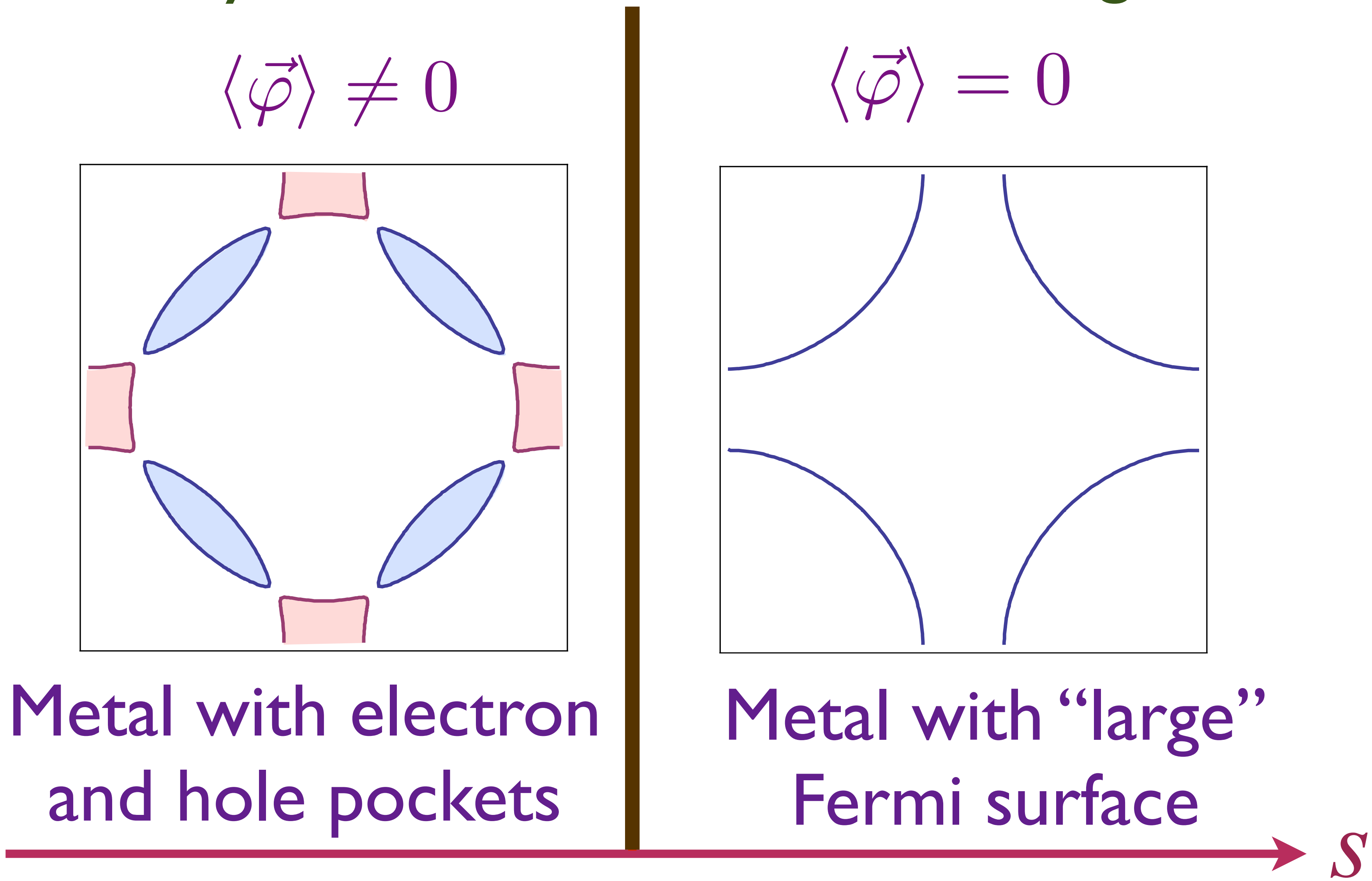

- Theory has strong (log-squared) instability already at the Fermi energy to superconductivity with sign-changing pairing amplitude near quantum criticality.

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

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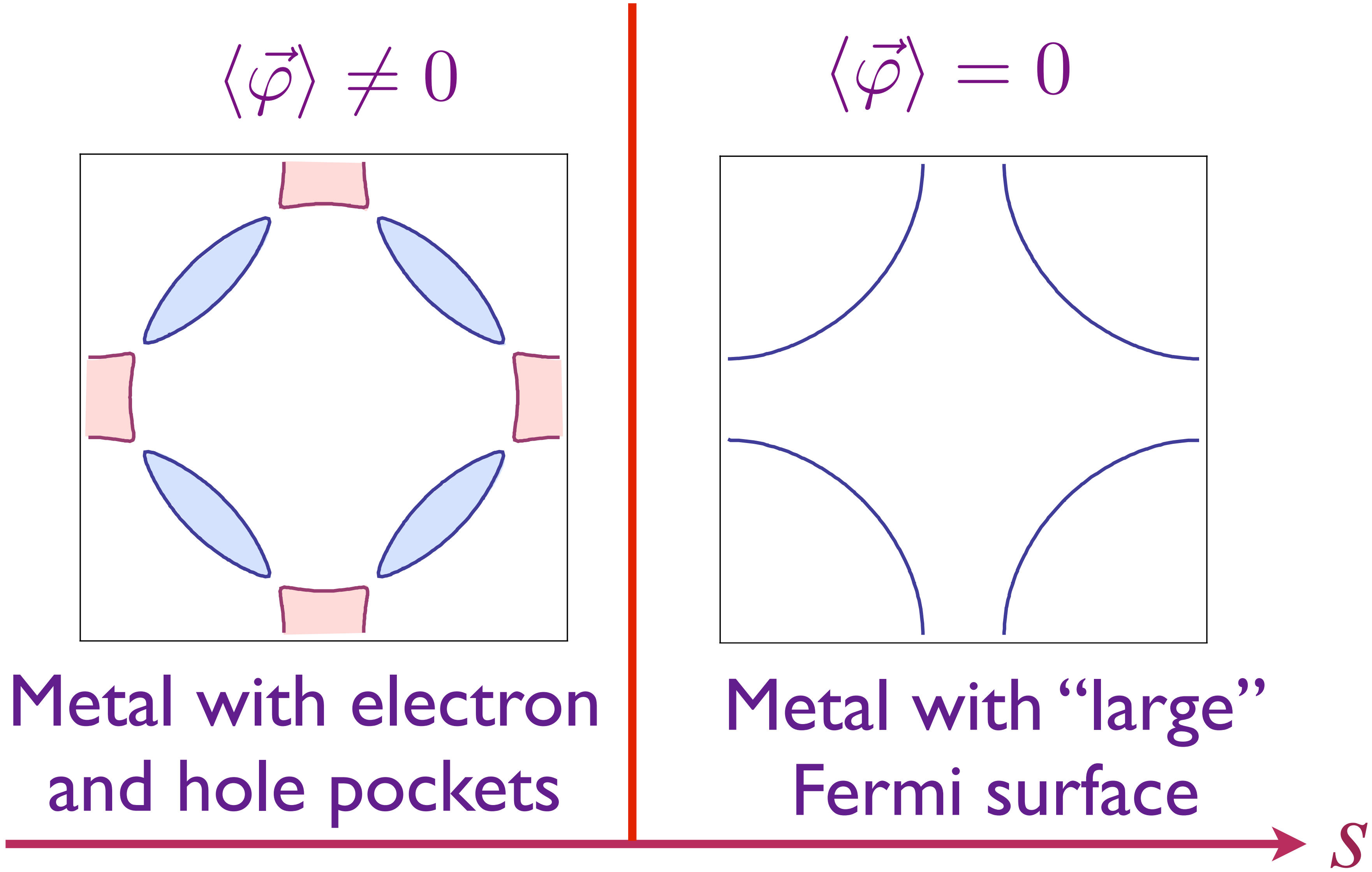

- There is non-Fermi liquid behavior at the QCP not only at hotspots, but on entire Fermi surface.

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

Questions

- *Can quantum fluctuations near the loss of antiferromagnetism induce higher temperature superconductivity ?*

- *If so, why is there no antiferromagnetism in the cuprates near the point where the superconductivity is strongest ?*

- *What is the physics of the strange metal ?*

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  Proposal: strongly-coupled quantum criticality of fluctuating antiferromagnetism in a metal