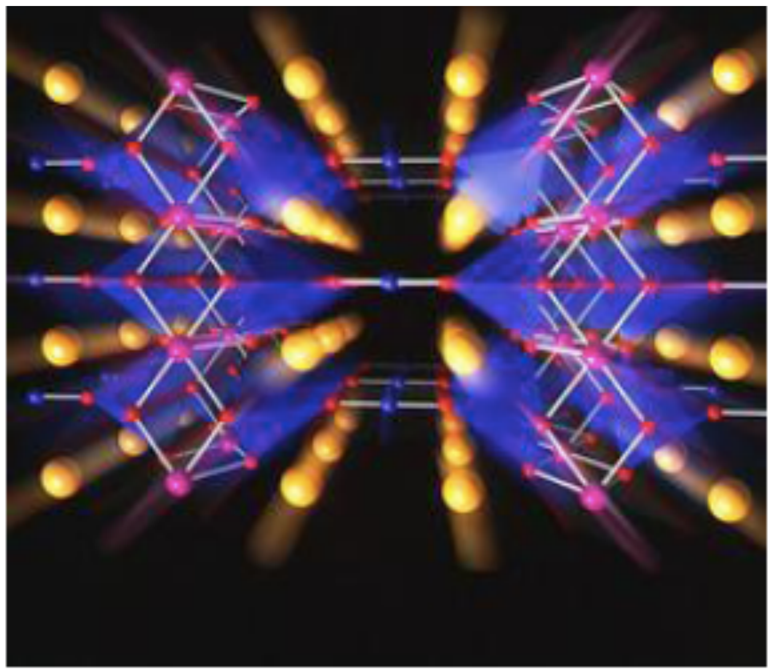
Published online 8 October 2010 | Nature | doi:10.1038/news.2010.527

News

Superconductors come of age

A South Korean company has placed by far the biggest commercial order for superconducting wires.

Superconducting wires could soon help to light up Seoul.



YBCO superconductors are likly to be used in more power grids in future.

LS Cable, a South Korean company based in Anyang-si near Seoul, has ordered three million metres of superconducting wire from US firm American Superconductor in Devens, Massachusetts. Jason Fredette, managing director of corporate communications at the company, says that LS Cable will use the wire to make about 20 circuit kilometres of cable as part of a programme to modernize the South Korean electricity network starting in the capital, Seoul.

The superconducting wire is made using the ceramic compound yttrium barium copper oxide (YBCO), part of a family of 'high-temperature' superconducting ceramics that were first discovered in 1986.

The onset of spin density wave order in metals

Talk online: sachdev.physics.harvard.edu

PHYSICS

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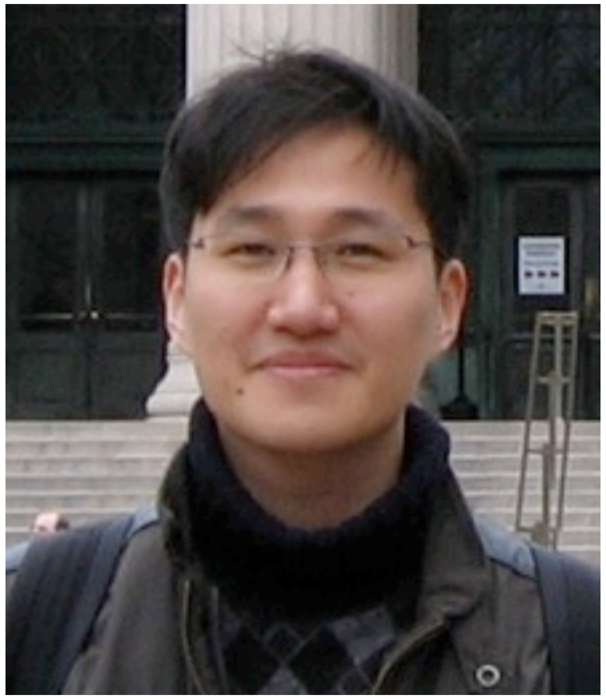
HARVARD

Max Metlitski, Harvard



Eun Gook Moon, Harvard

PHYSICS

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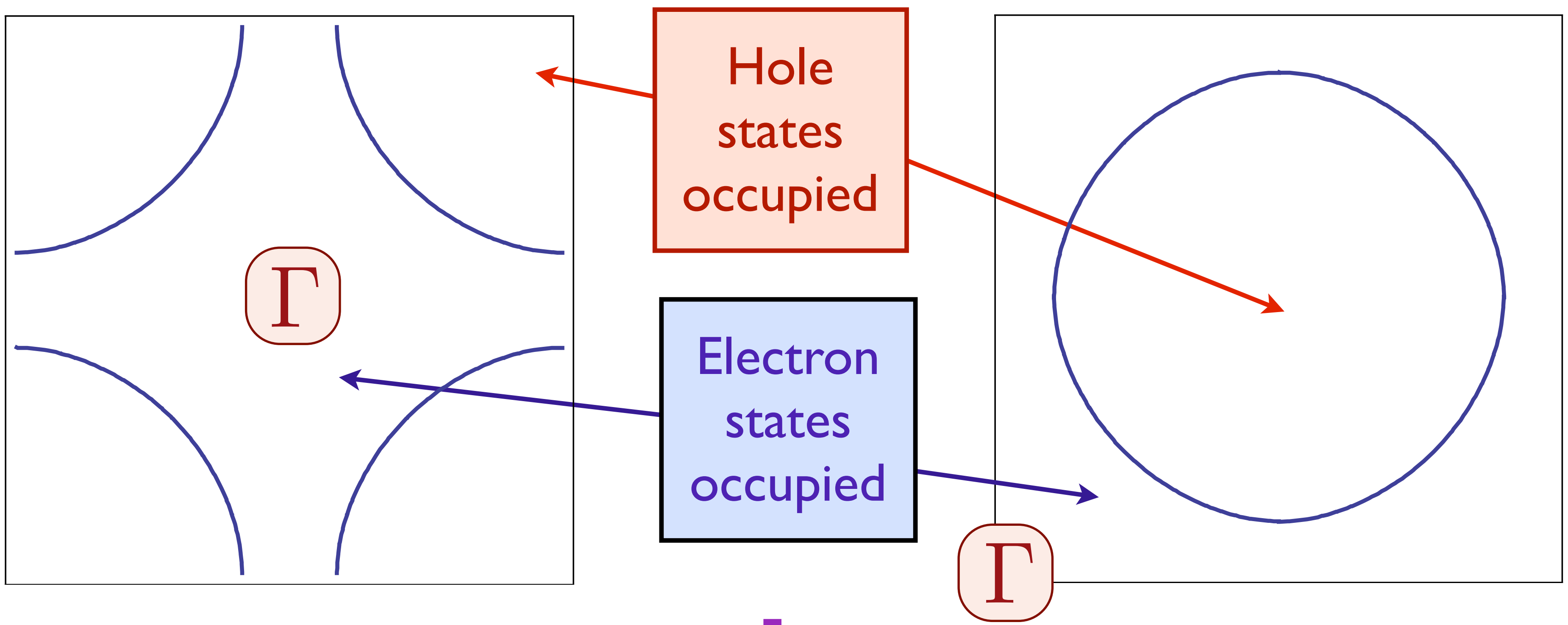
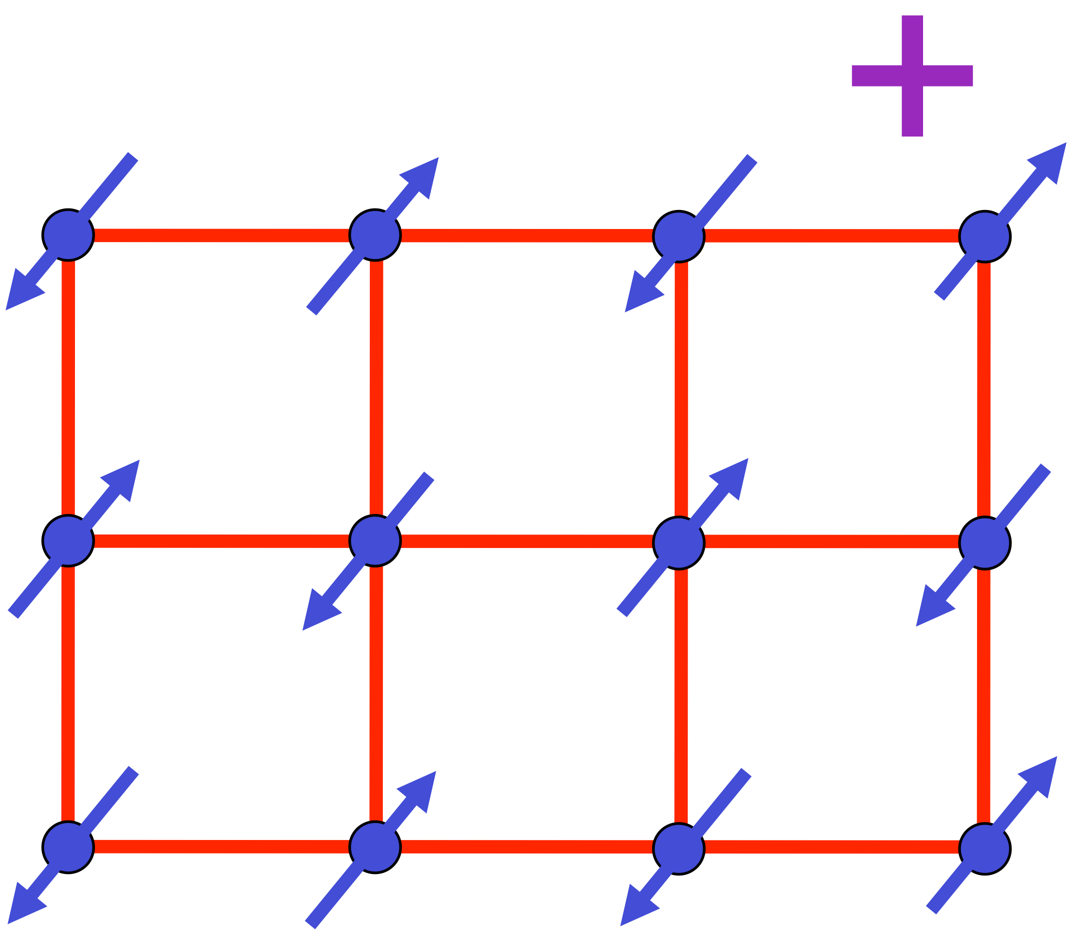
Fermi surface+antiferromagnetism

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



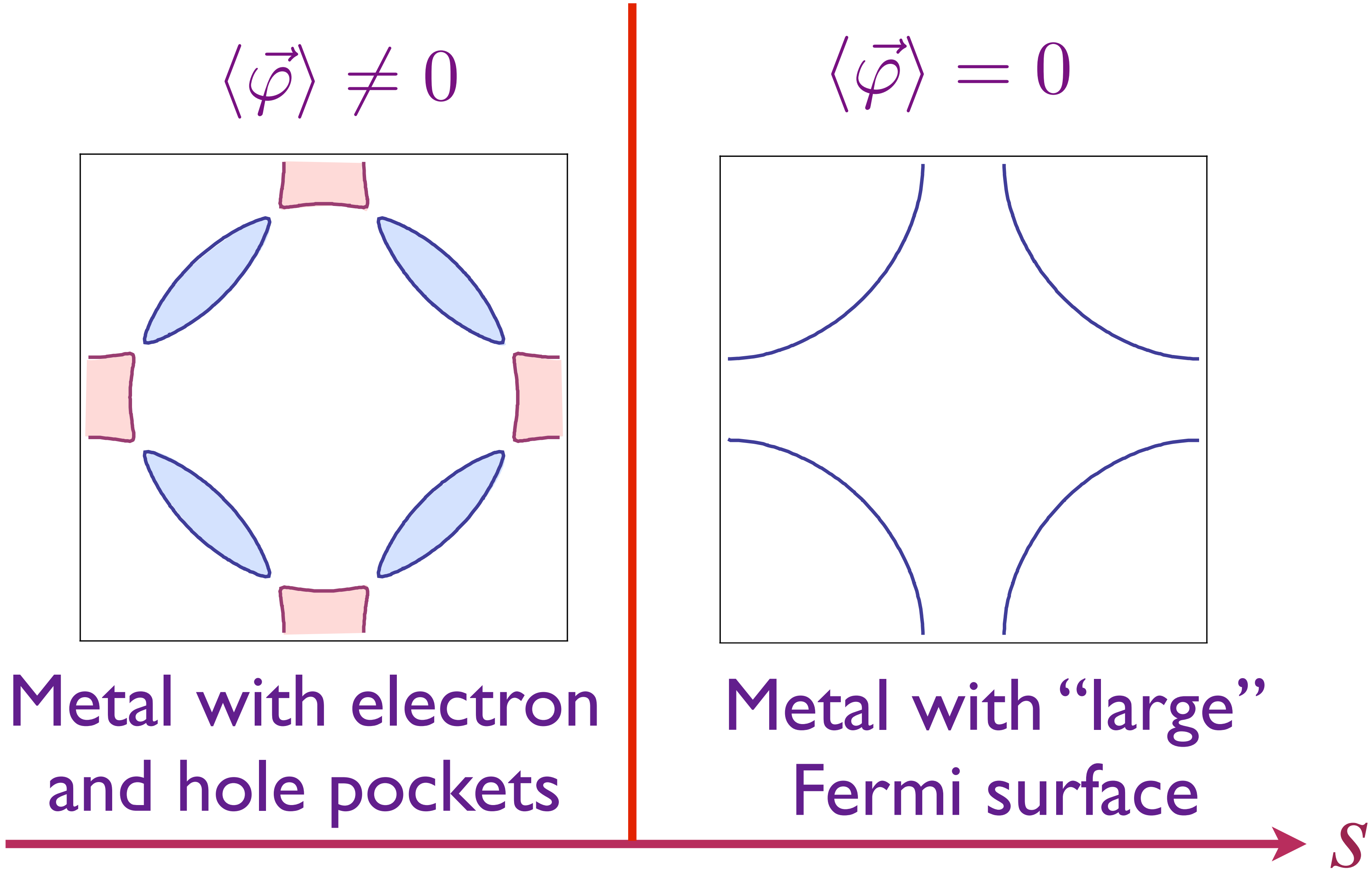


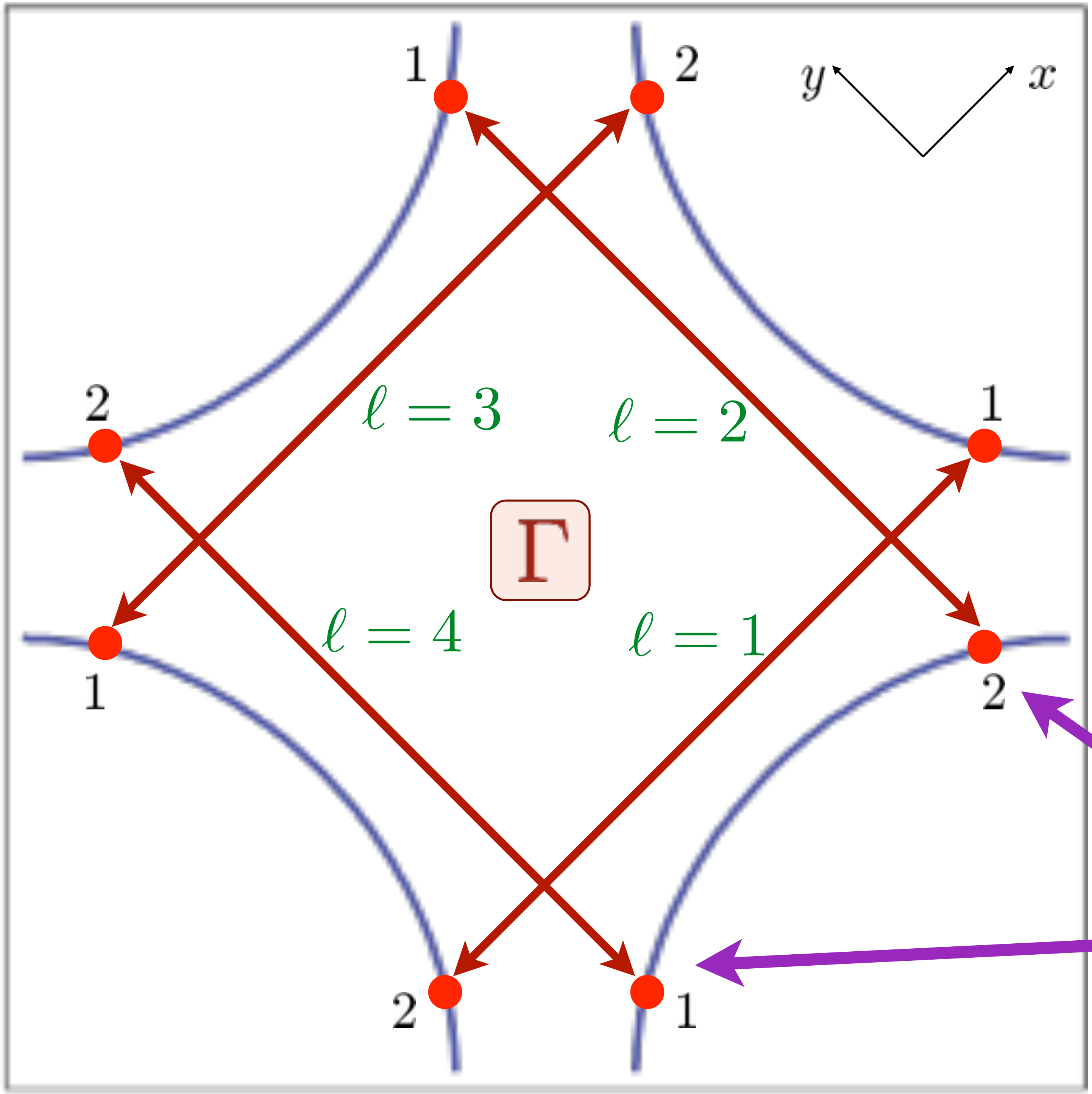
The electron spin polarization obeys

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

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

Quantum criticality of the onset of antiferromagnetism in a metal





Low energy fermions at hot spots $\mathbf{k} = \mathbf{k}_\ell$:

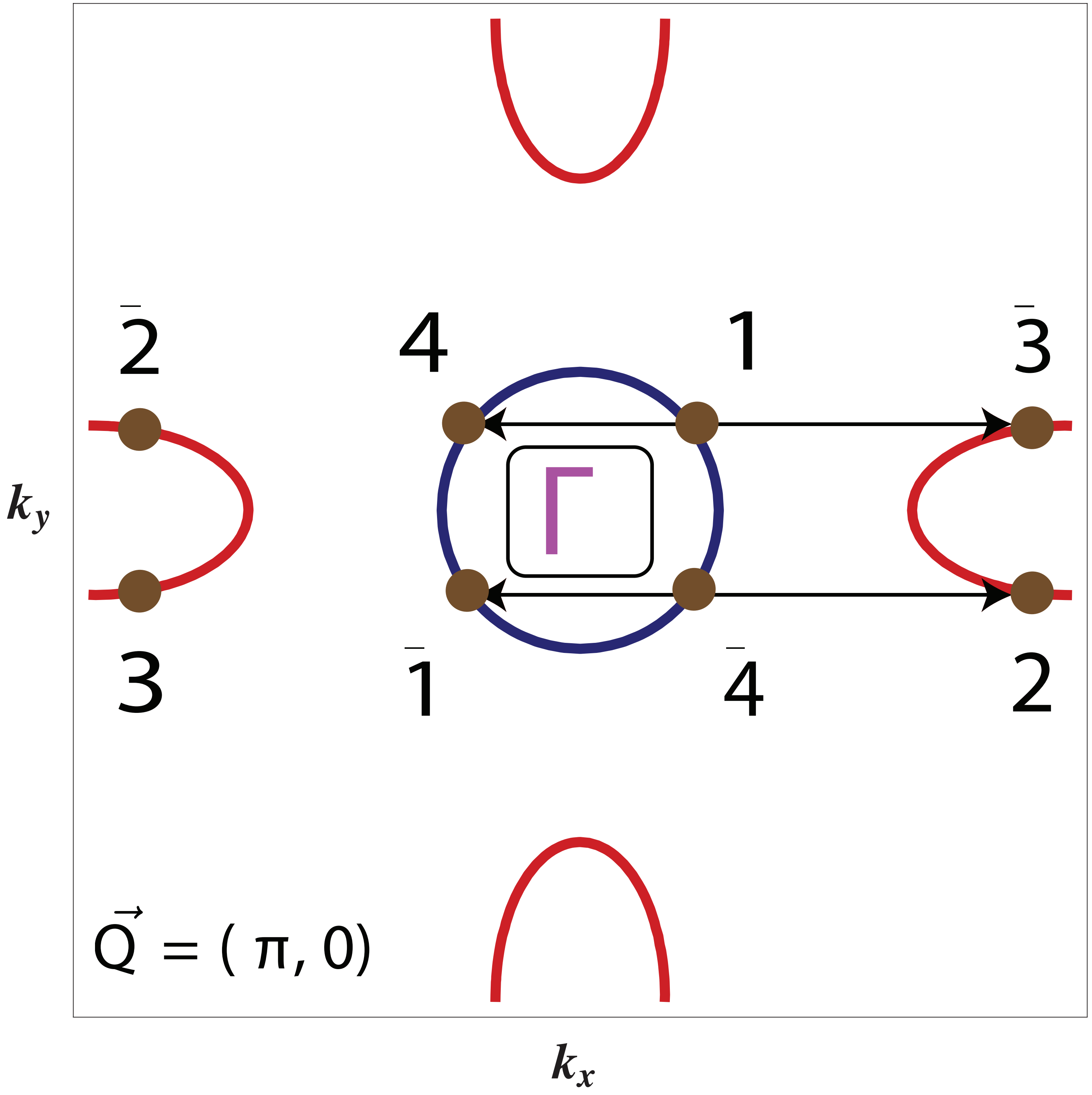
$\psi^\ell_{1\alpha}, \psi^\ell_{2\alpha}$

$\ell = 1, \ldots, 4.$

with $c_{\mathbf{k}+\mathbf{k}_\ell} = \psi^\ell(\mathbf{k})$

$$\mathcal{L}_f = \psi^{\ell\dagger}_{1\alpha}\left(\zeta\partial_\tau - i\mathbf{v}^\ell_1 \cdot \boldsymbol{\nabla}_r\right)\psi^\ell_{1\alpha} + \psi^{\ell\dagger}_{2\alpha}\left(\zeta\partial_\tau - i\mathbf{v}^\ell_2 \cdot \boldsymbol{\nabla}_r\right)\psi^\ell_{2\alpha}$$

$$\mathbf{v}^{\ell=1}_1 = (v_x, v_y),\ \mathbf{v}^{\ell=1}_2 = (-v_x, v_y)$$



Similar theory applies to the pnictides, and leads to $s_\pm$ pairing.

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

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: $\mathcal{L}_c = -\lambda\vec{\varphi}\cdot\left(\psi_{1\alpha}^{\ell\dagger}\vec{\sigma}_{\alpha\beta}\psi_{2\beta}^\ell + \psi_{2\alpha}^{\ell\dagger}\vec{\sigma}_{\alpha\beta}\psi_{1\beta}^\ell\right)$

Results of RG analysis at 2+ loops

- The Hertz-Millis-Moriya procedure is valid in $d = 3$, but breaks down strongly in $d = 2$. (*cf.* Abanov-Chubukov)

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

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M. A. Metlitski and S. Sachdev,
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- The $1/N$ expansion (N is the number of hot-spots) initially appears to be a genus expansion (*cf.* Sung-Sik Lee), but even this breaks down at 5 loops.

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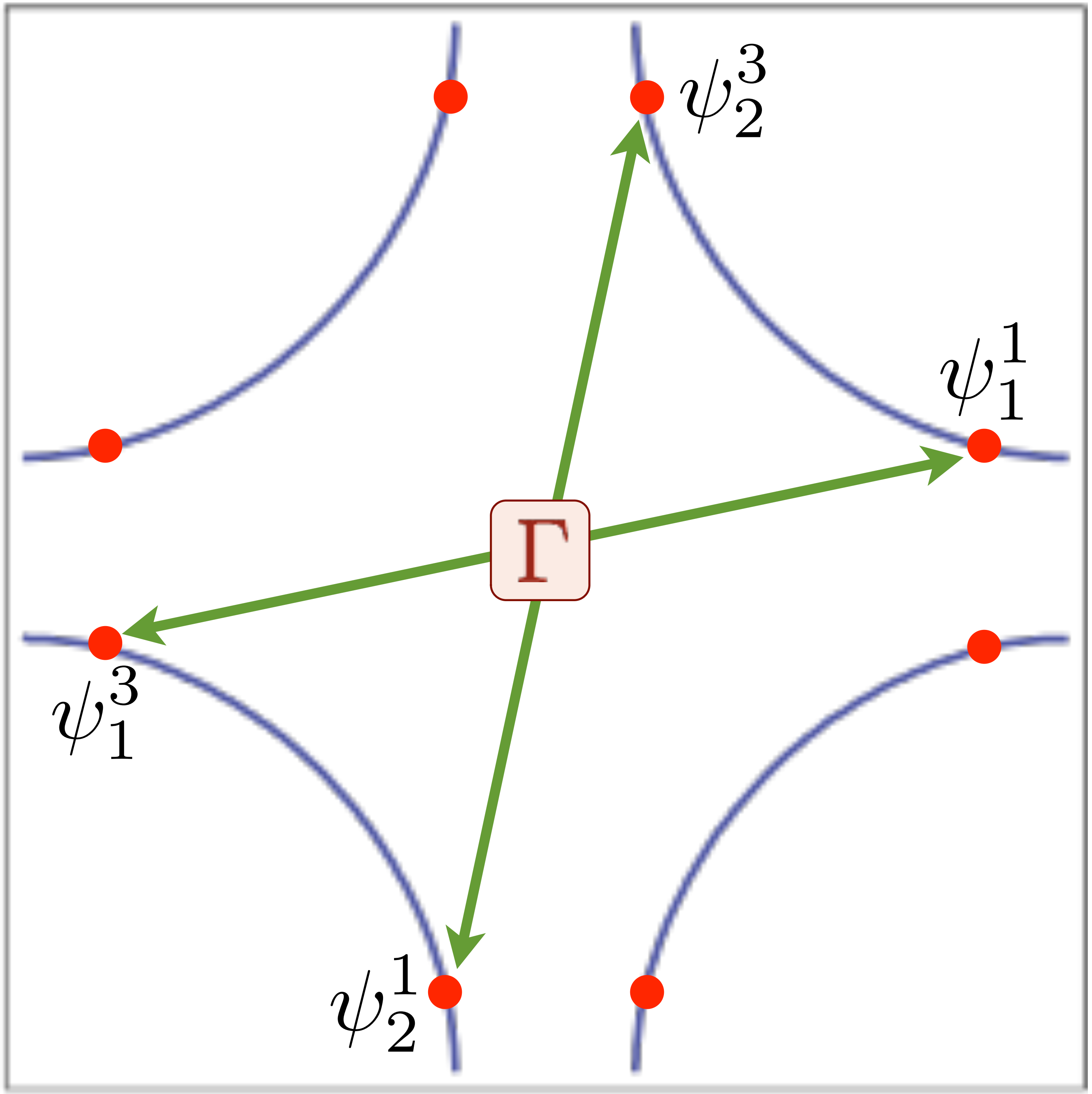
- The $1/N$ expansion (N is the number of hot-spots) initially appears to be a genus expansion (*cf.* Sung-Sik Lee), but even this breaks down at 5 loops.

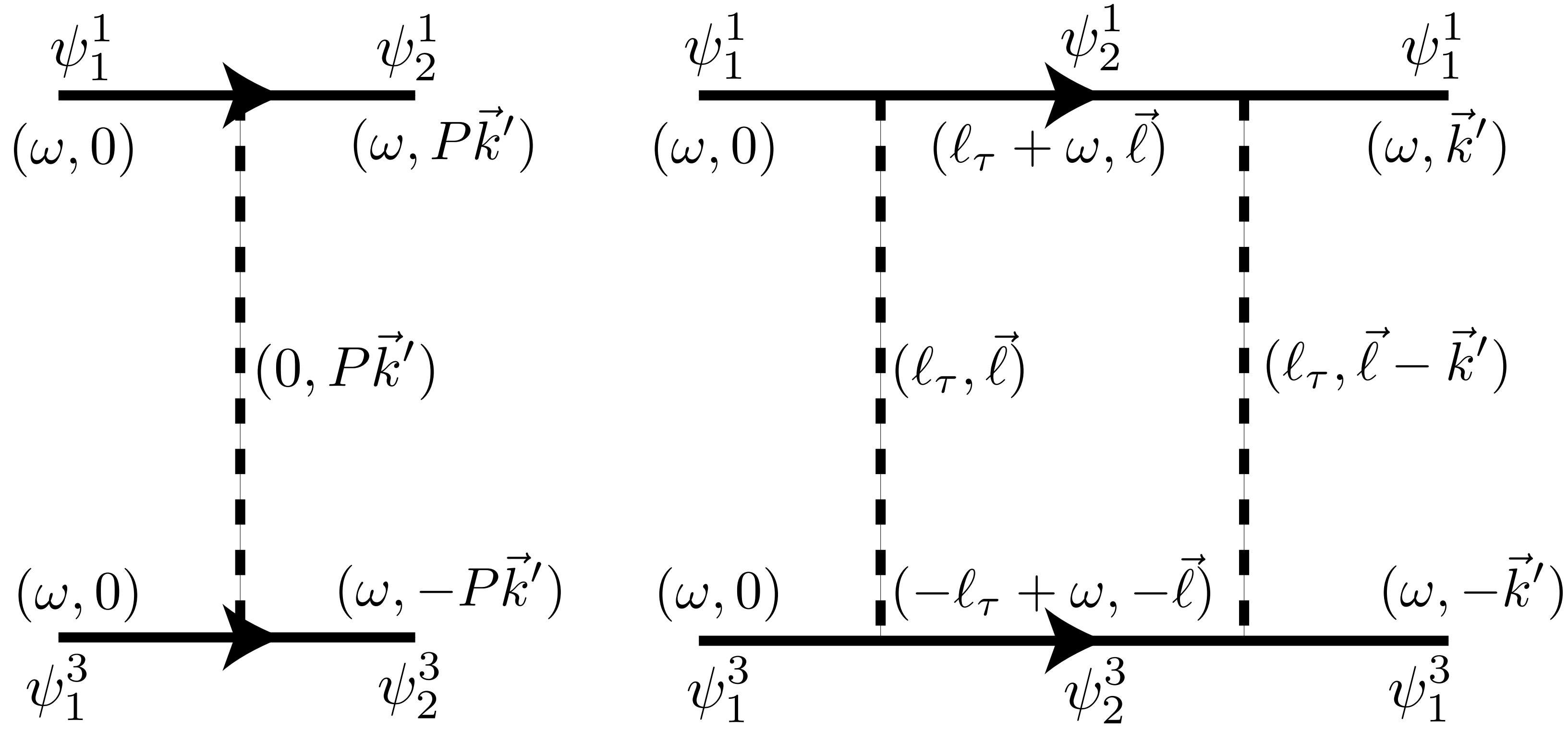
- There is a universal "log-squared" instability to unconventional (*i.e.* d-wave like) superconductivity with a coupling of order unity.

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

d-wave pairing



Pairing order parameter: $\varepsilon^{\alpha\beta}\left(\psi^3_{1\alpha}\psi^1_{1\beta} - \psi^3_{2\alpha}\psi^1_{2\beta}\right)$



Need fermion Green's functions on Fermi surface near hot spots:

$$G(\omega, \vec{p}) \sim \frac{\mathcal{Z}(p_\parallel)}{i\omega - v_F(p_\parallel) p_\perp}.$$

Near the hot spot we have $v_F \sim \mathcal{Z} \sim p_\parallel$. The pairing interaction is enhanced at one loop by the factor

$$\left[1 + \frac{\alpha}{\pi(\alpha^2 + 1)} \log^2 \frac{\vec{k}'^2}{\gamma |\omega|} \right]$$

where $\alpha = v_y / v_x$ is of order unity.

M. A. Metlitski and S. Sachdev,
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Results of RG analysis at 2+ loops

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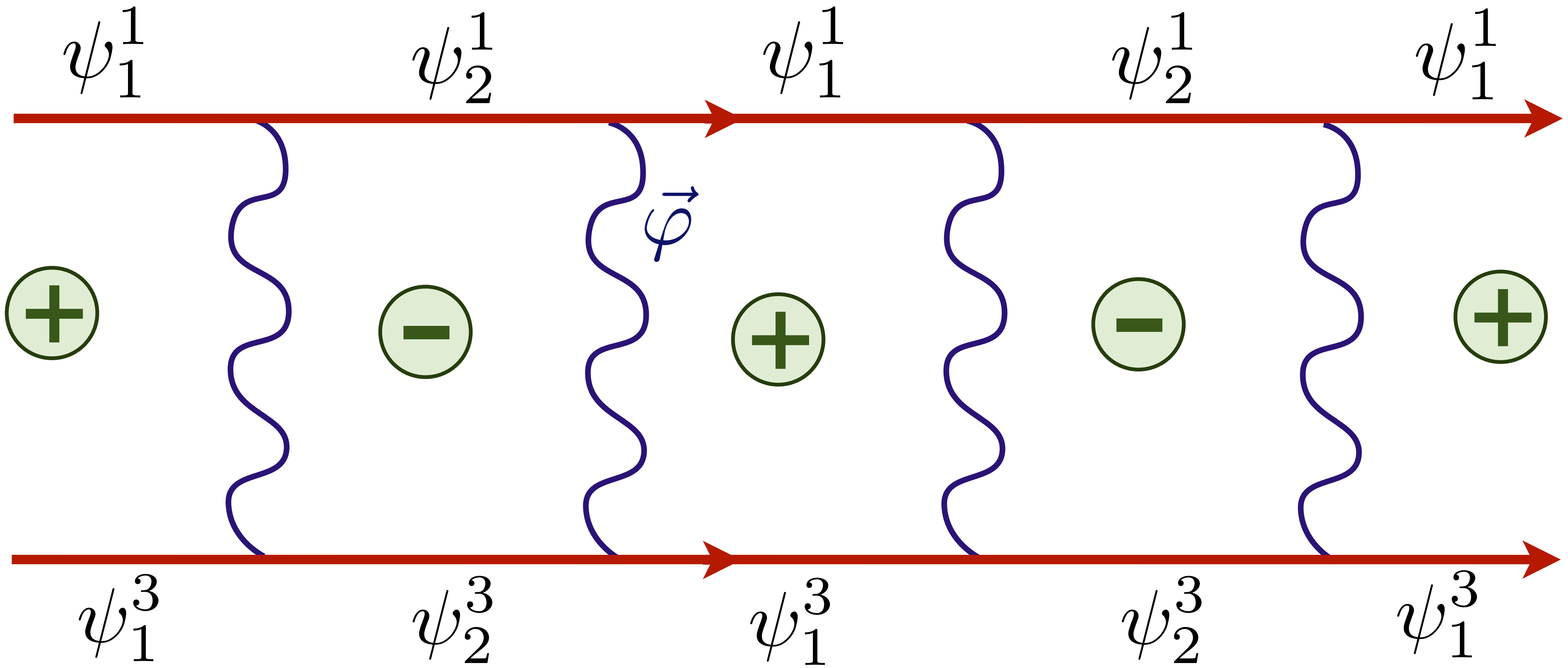
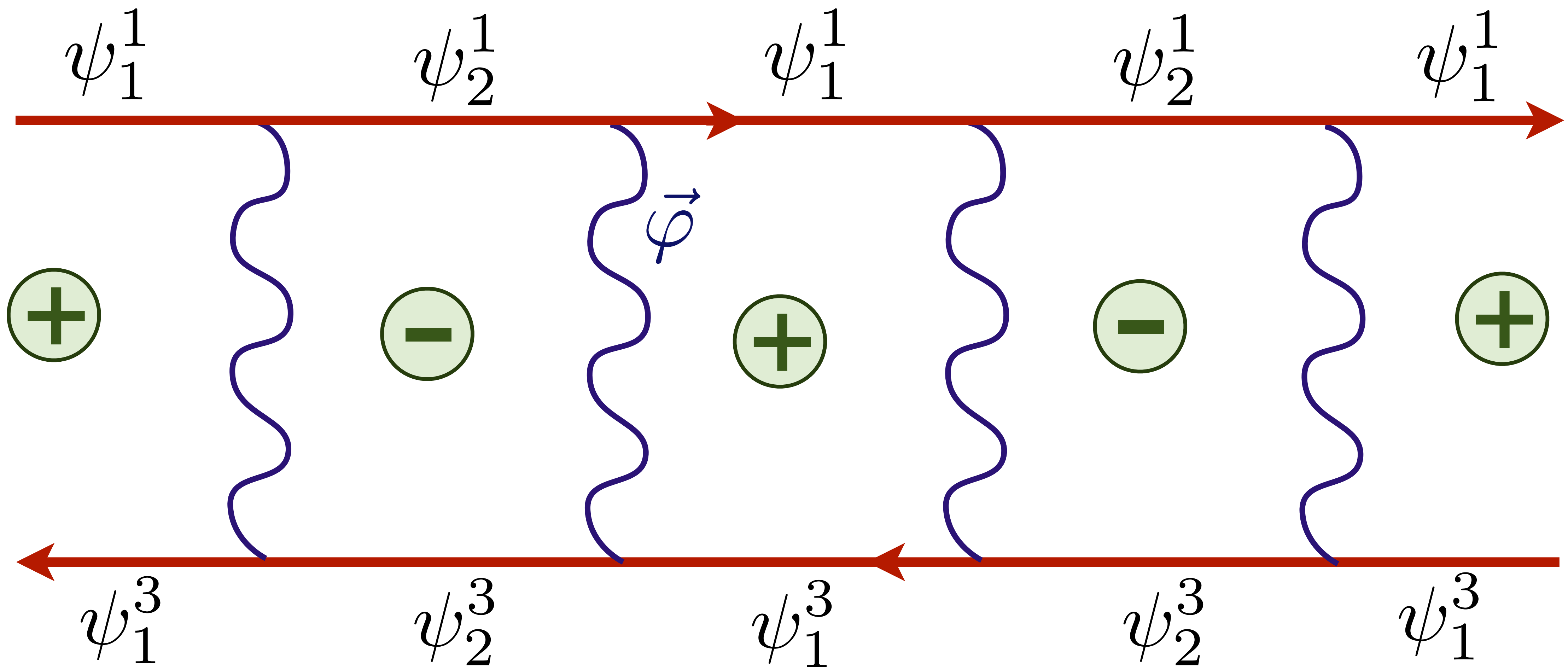
- There is a universal "log-squared" instability to unconventional (*i.e.* d-wave like) superconductivity with a coupling of order unity.

- There is a sub-dominant "log-squared" instability to a modulated bond order, which locally has a Ising-nematic character.

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

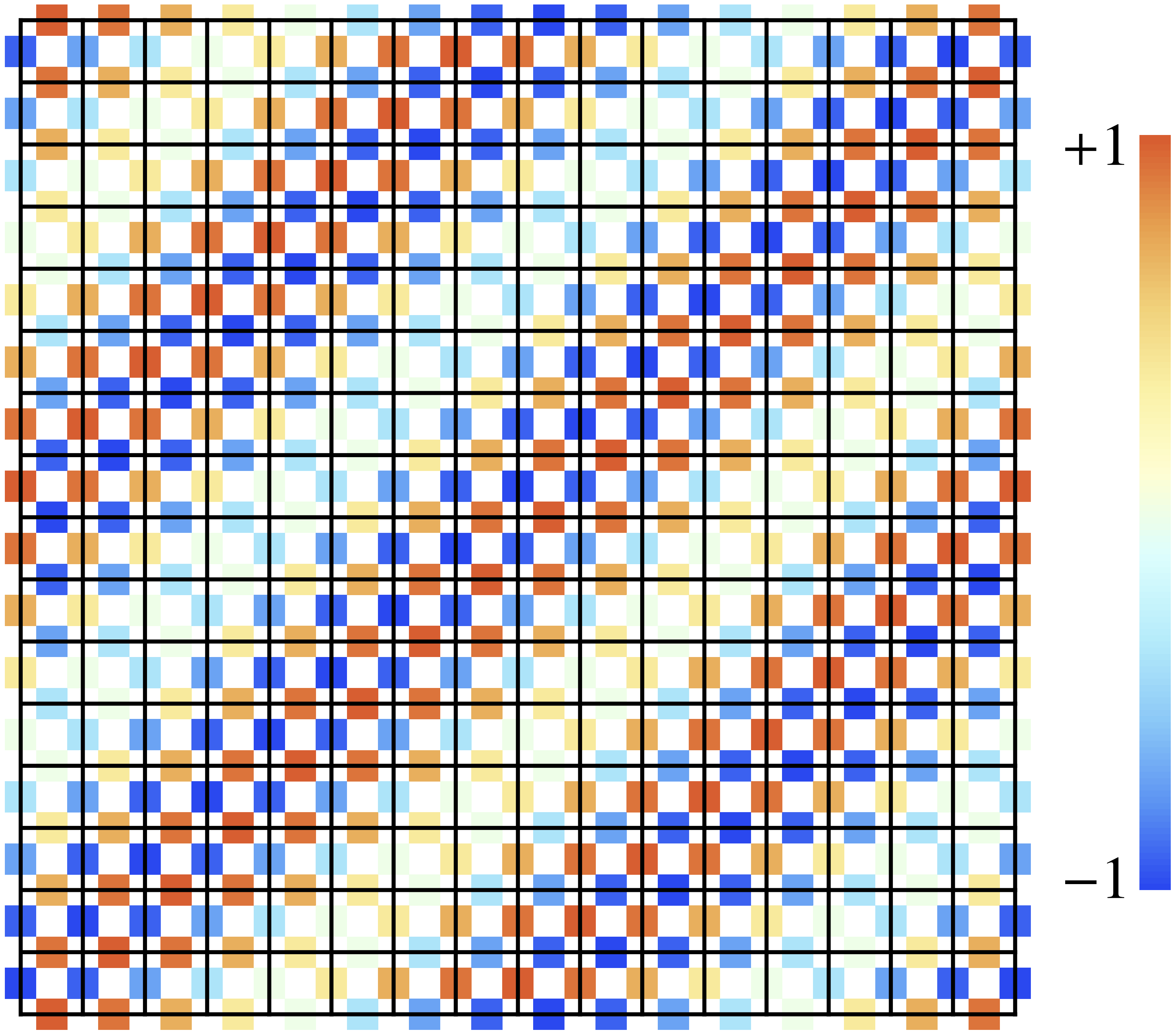


d-wave pairing instability in particle-particle channel



Bond density wave (with local Ising-nematic order) instability in particle-hole channel.

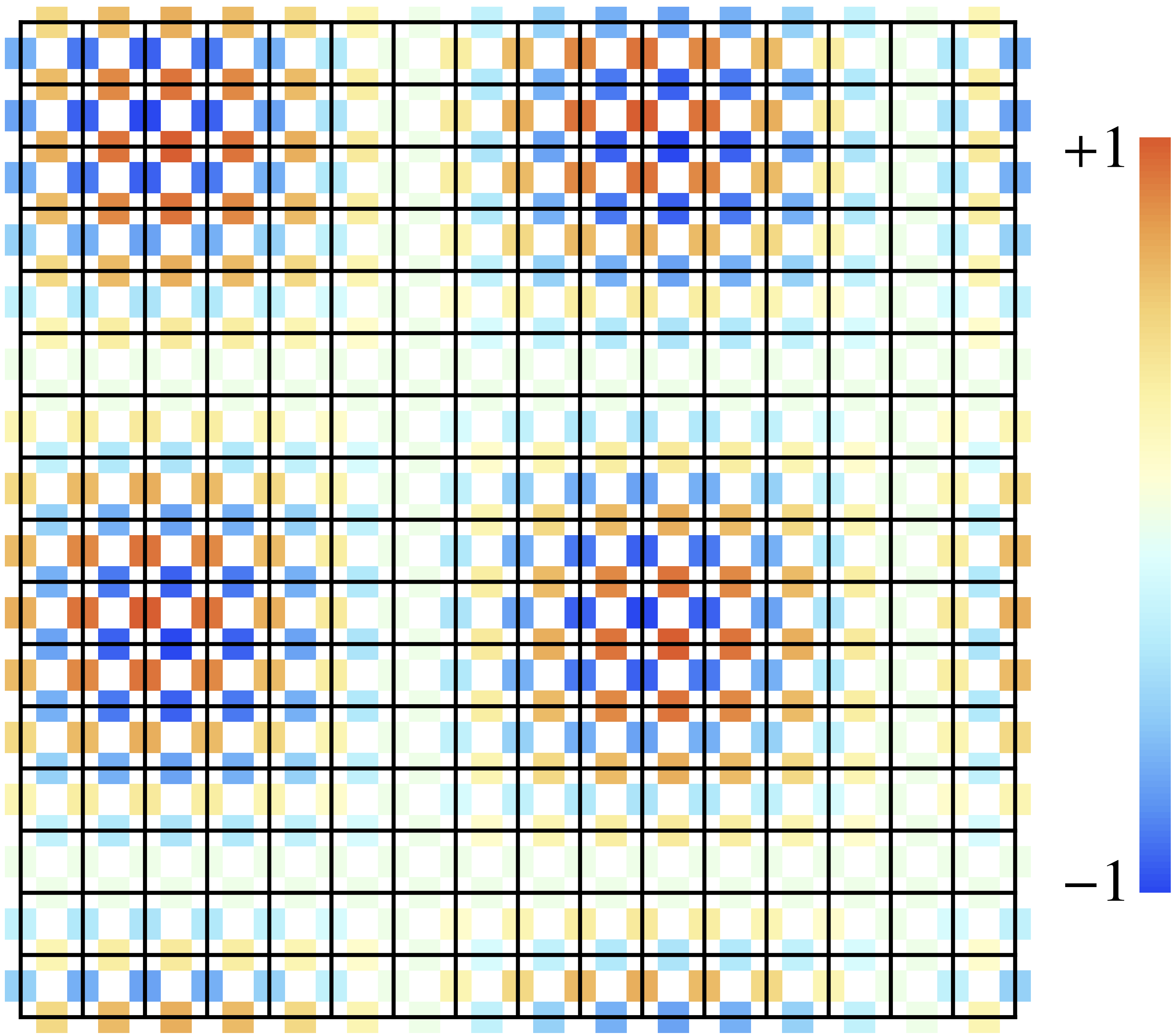
Nearly as strong as pairing instability because of a pseudospin symmetry of low energy theory



"Bond density" measures amplitude for electrons to be in spin-singlet valence bond: VBS order

No modulations on sites: $\langle c^\dagger_{\mathbf{r}\alpha} c_{\mathbf{s}\alpha} \rangle$ is non-zero only for $\mathbf{r} \neq \mathbf{s}$. Modulated bond-density wave with local Ising-nematic ordering:

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



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The co-existence of spin density wave order and d-wave superconductivity

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

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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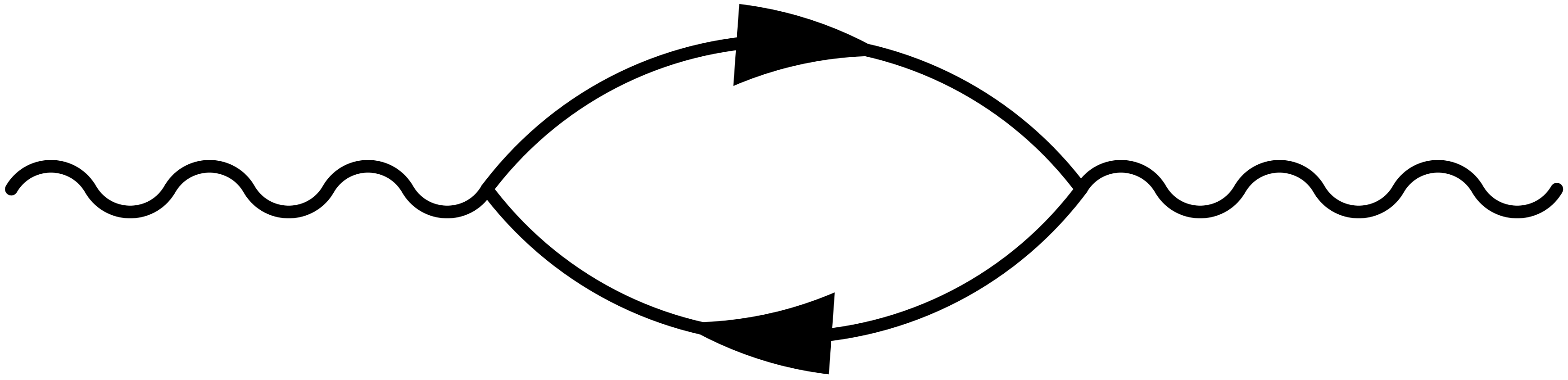
Pairing:
$$\mathcal{L}_\Delta = \Delta\varepsilon^{\alpha\beta}\left(\psi_{1\alpha}^3\psi_{1\beta}^1 - \psi_{2\alpha}^3\psi_{2\beta}^1 - \psi_{1\alpha}^4\psi_{1\beta}^2 - \psi_{2\alpha}^4\psi_{2\beta}^2\right) + \text{H.c.}$$

Include the possibility of pairing in the metal.
And then compute the shift in the critical value of the SDW transition, $s_c - s_c^0$ due to a non-zero Δ.



Compute the SDW susceptibility, χ, in the superconducting state. As $\Delta \to 0$, we find

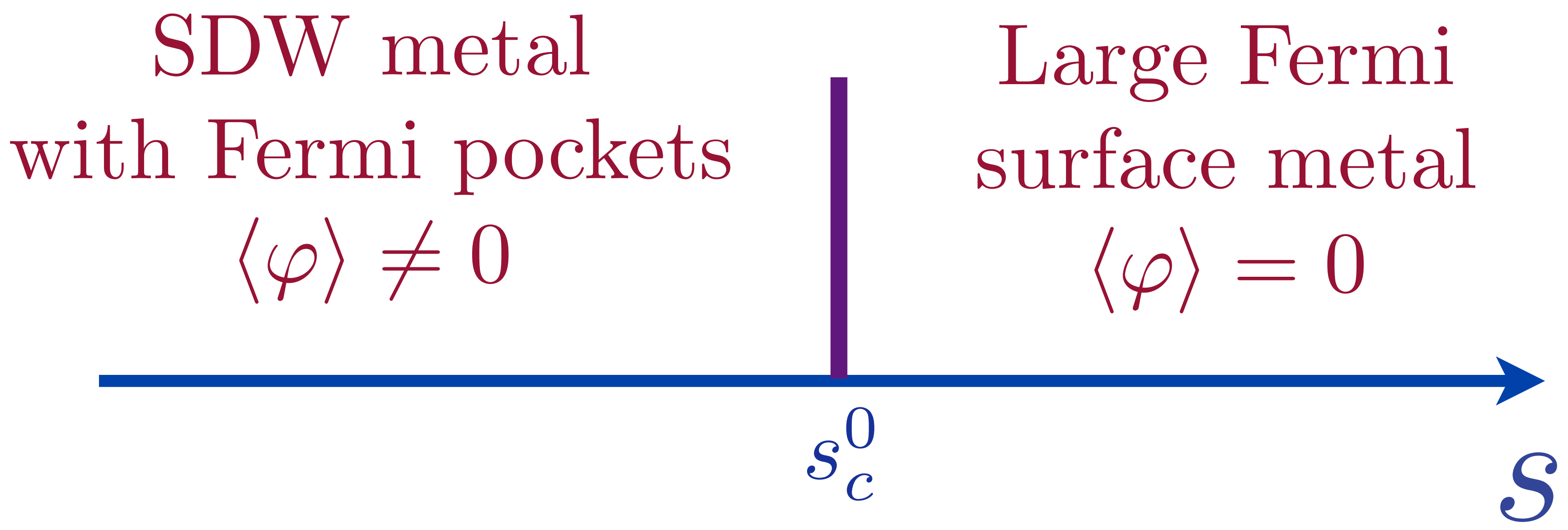
$$\chi(\Delta) = \chi(0) - C|\Delta|$$

where C is a universal constant dominated by the vicinity of the hot spots.

The weak-coupling theory with equivalent hotspots yields $C = 0$ - there is an exact cancellation of competition between SDW and SC at the hot spots, and attraction between SDW and SC away from the hot spot.

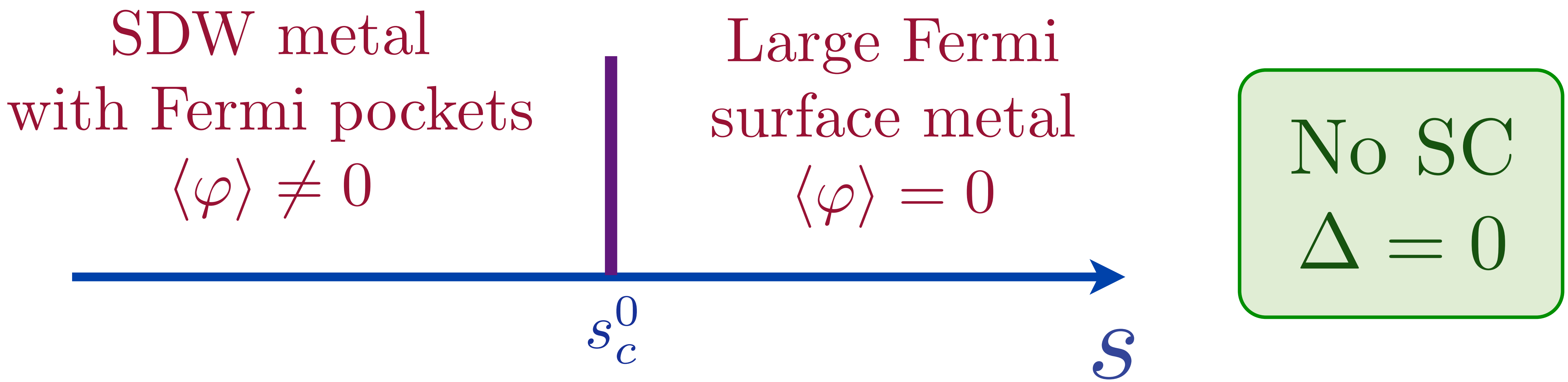
For inequivalent hot spots (as in pnictides, or with incommensurate order in the cuprates) in weak-coupling theory, or in a strong-coupling analysis, we generically find $C > 0$.

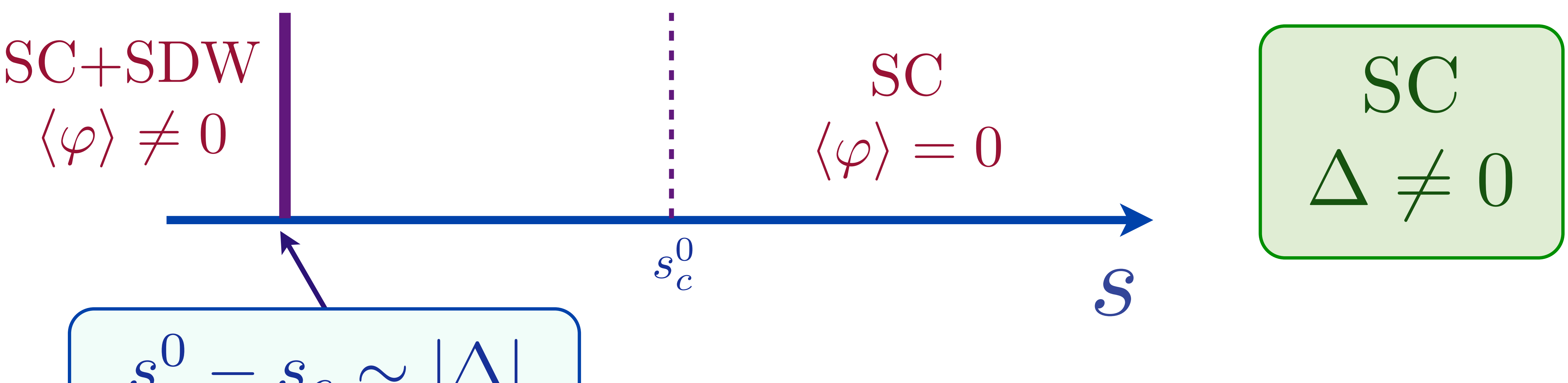
Fermi surface theory of competing orders



No SC
$\Delta = 0$

Fermi surface theory of competing orders

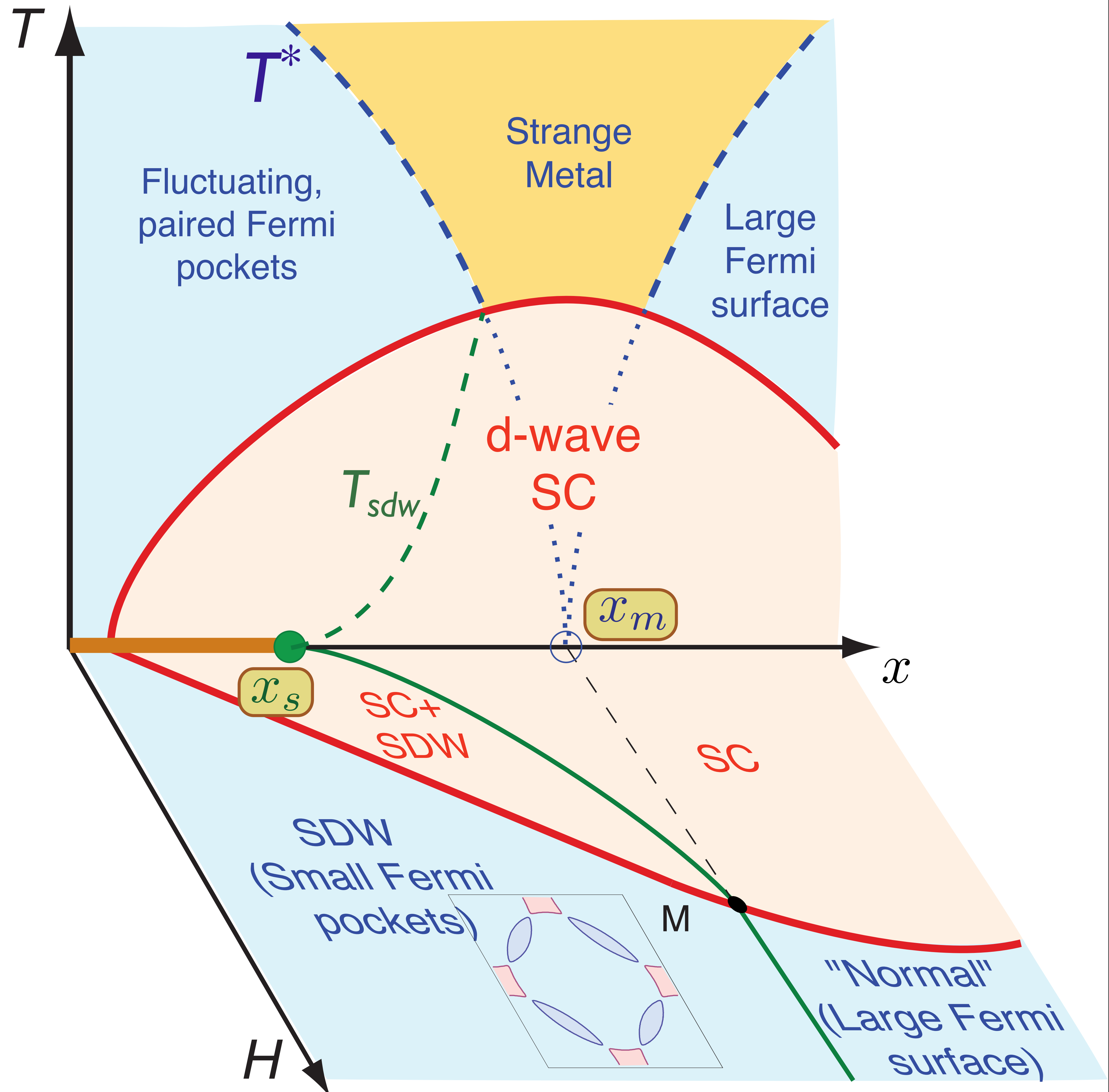


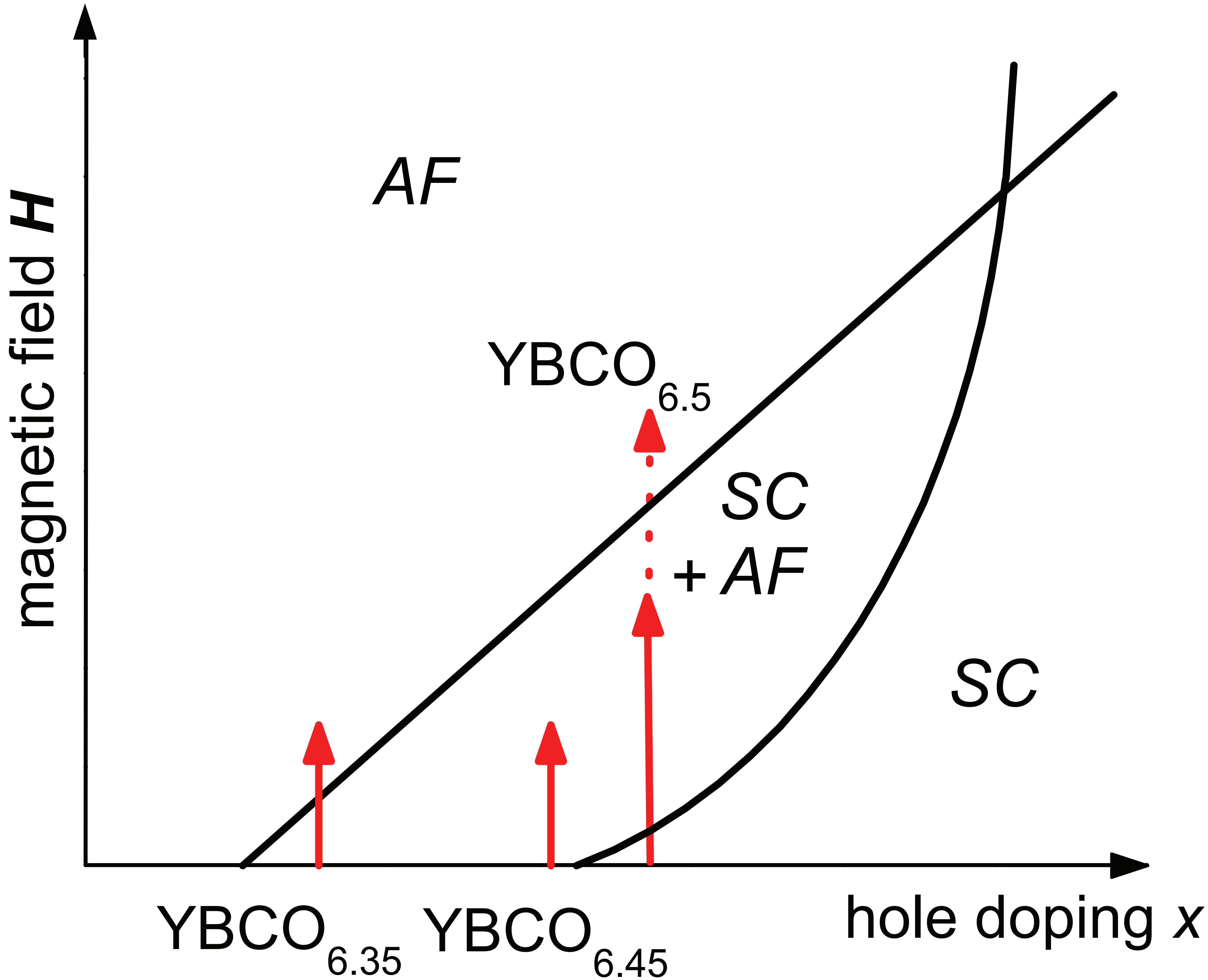


E. G. Moon and S. Sachdev, *Phy. Rev. B* **82**, 104516 (2010)

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

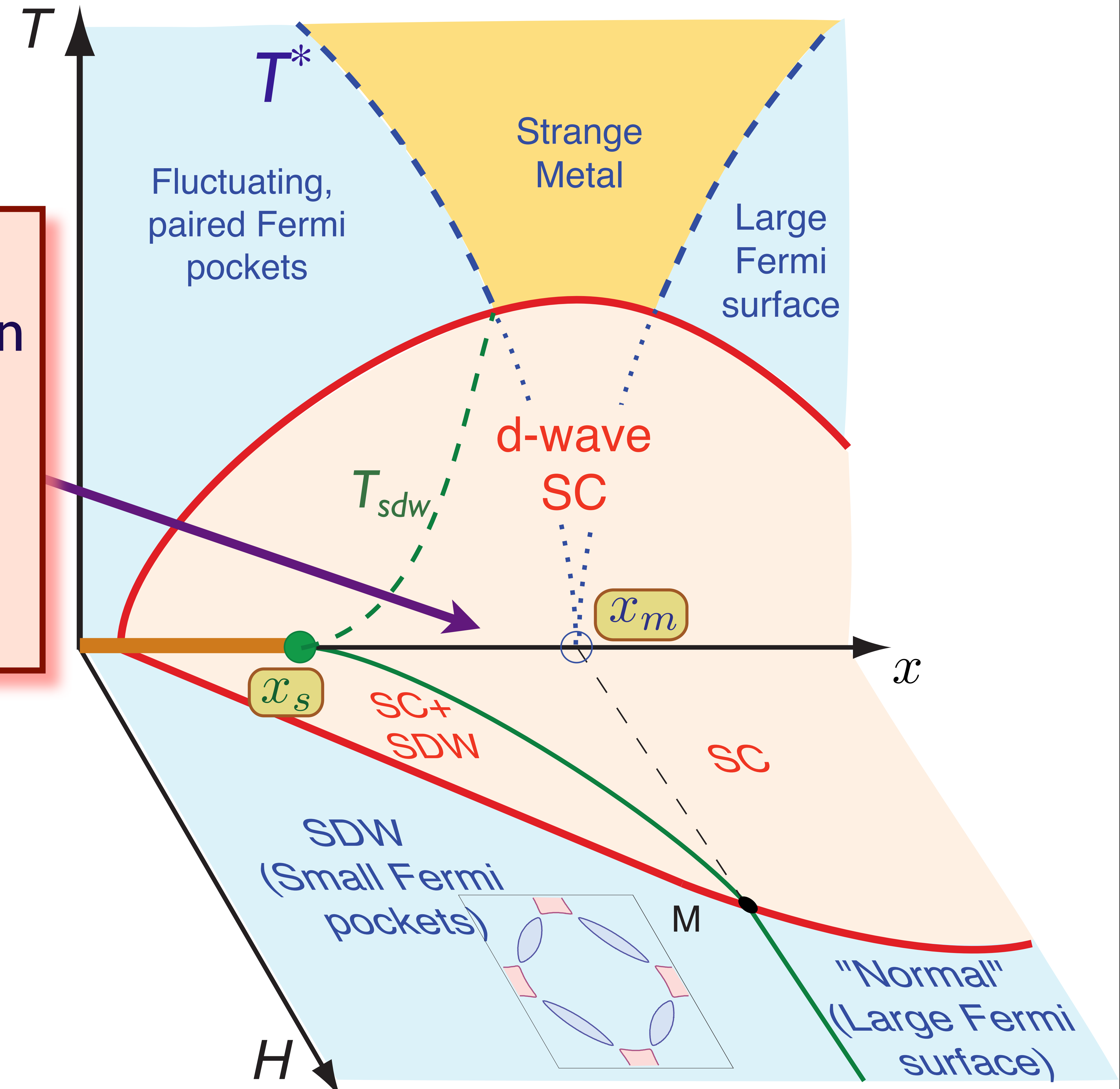
E. G. Moon and S. Sachdev, *Phy. Rev. B* **80**, 035117 (2009)

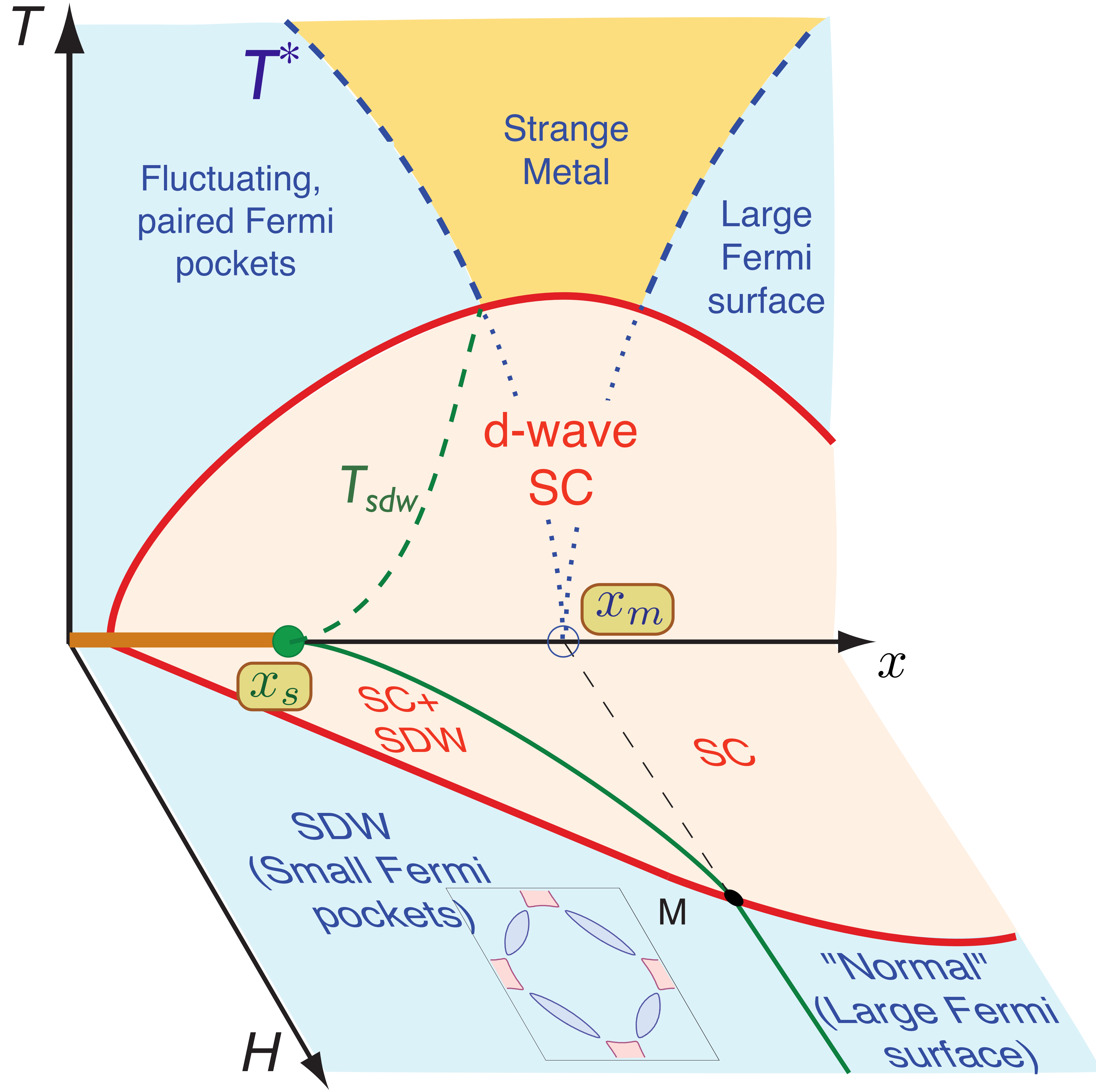




D. Haug, V. Hinkov, Y. Sidis, P. Bourges, N. B. Christensen, A. Ivanov, T. Keller, C. T. Lin, and B. Keimer, arXiv:1008.4298

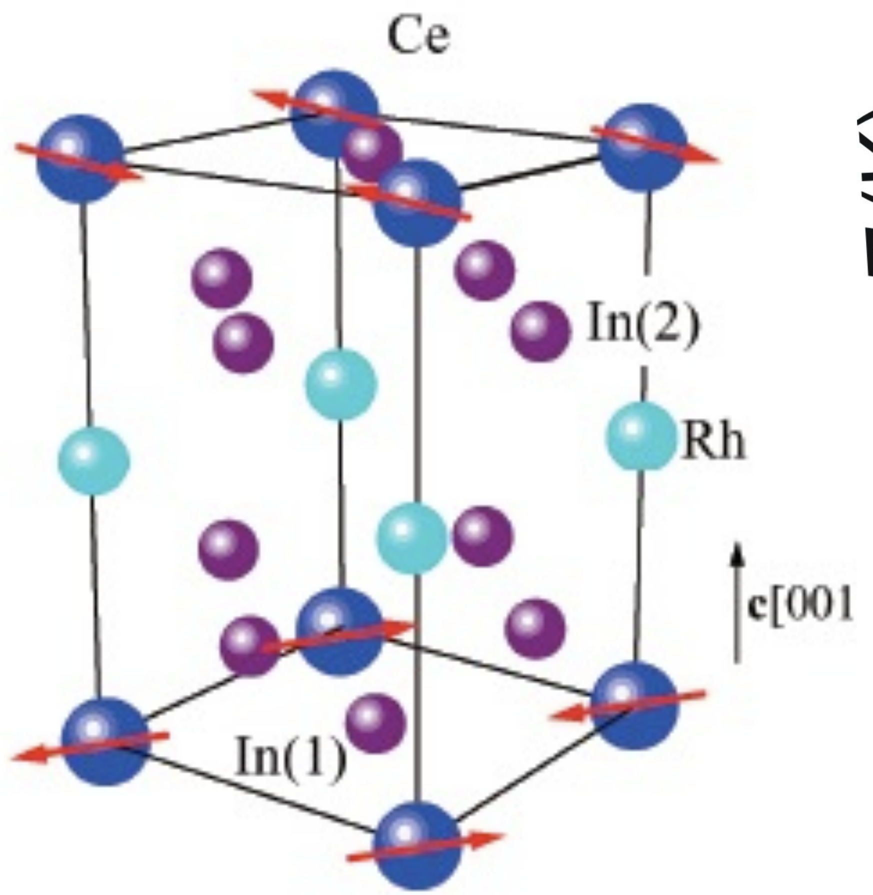
Other orders appear between x_s and x_m
e.g. nematic ordering, VBS, or even SC*

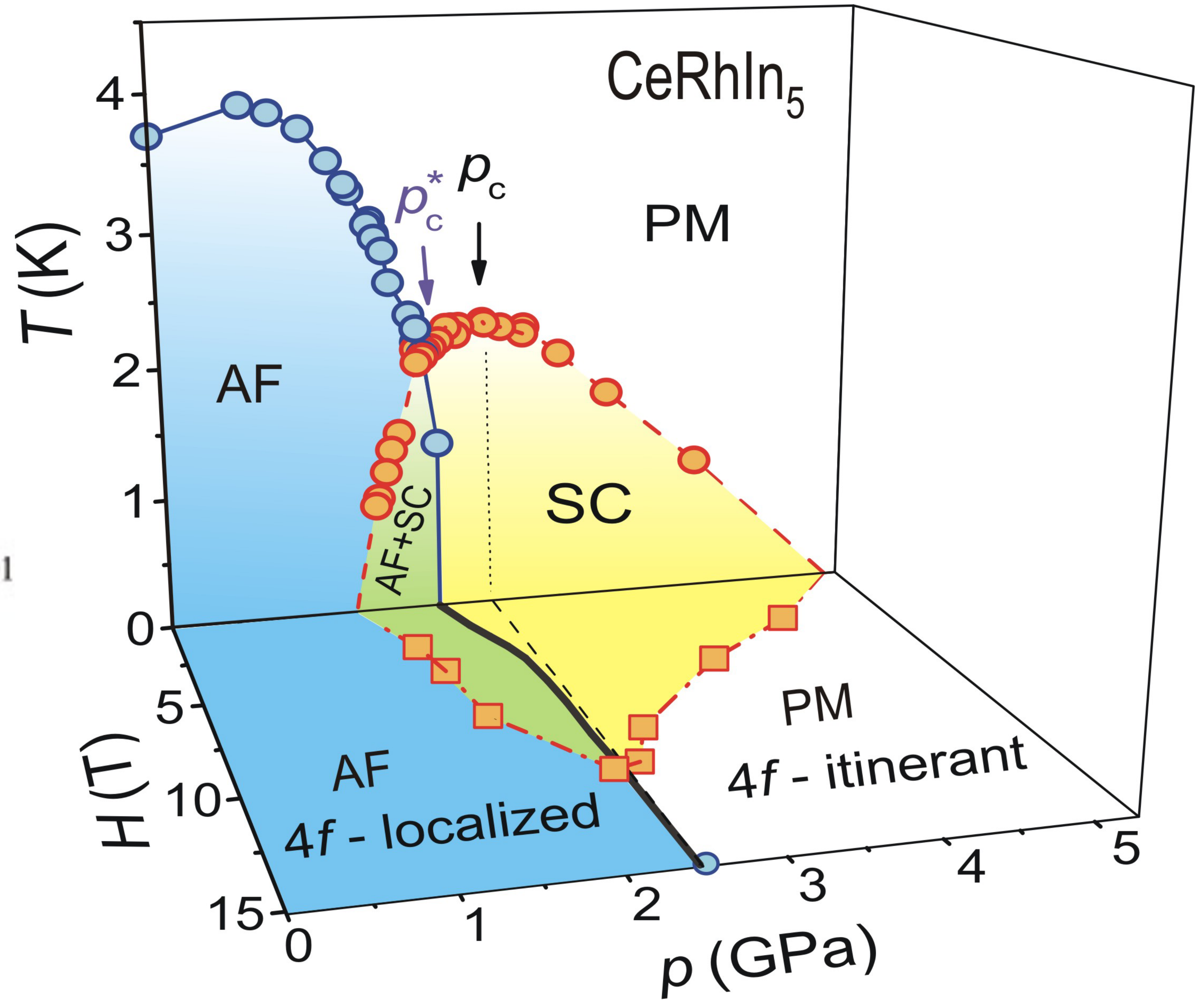




T
T^*
Fluctuating, paired Fermi pockets
Strange Metal
Large Fermi surface
d-wave SC
T_{sdw}
x_m
x
x_s
SC+ SDW
SC
SDW (Small Fermi pockets)
M
"Normal" (Large Fermi surface)
H

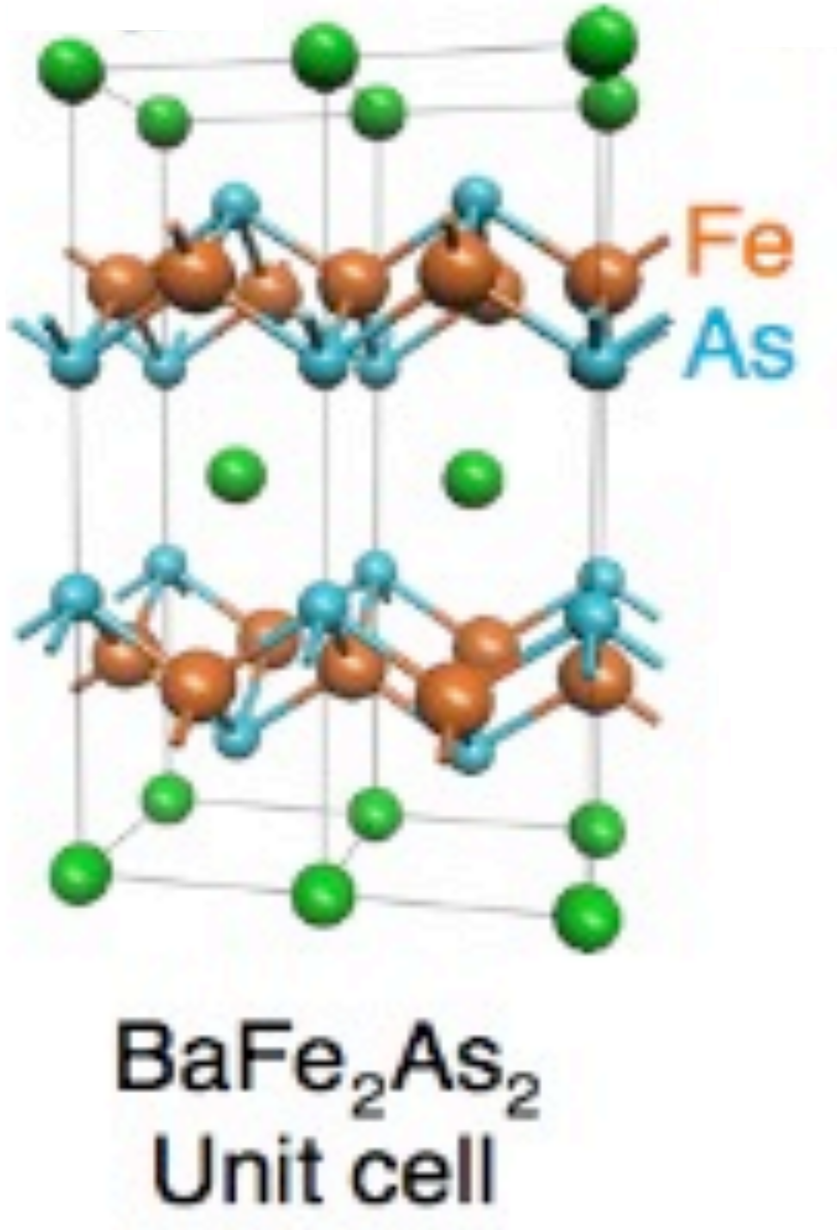
Similar phase diagram for $CeRhIn_5$

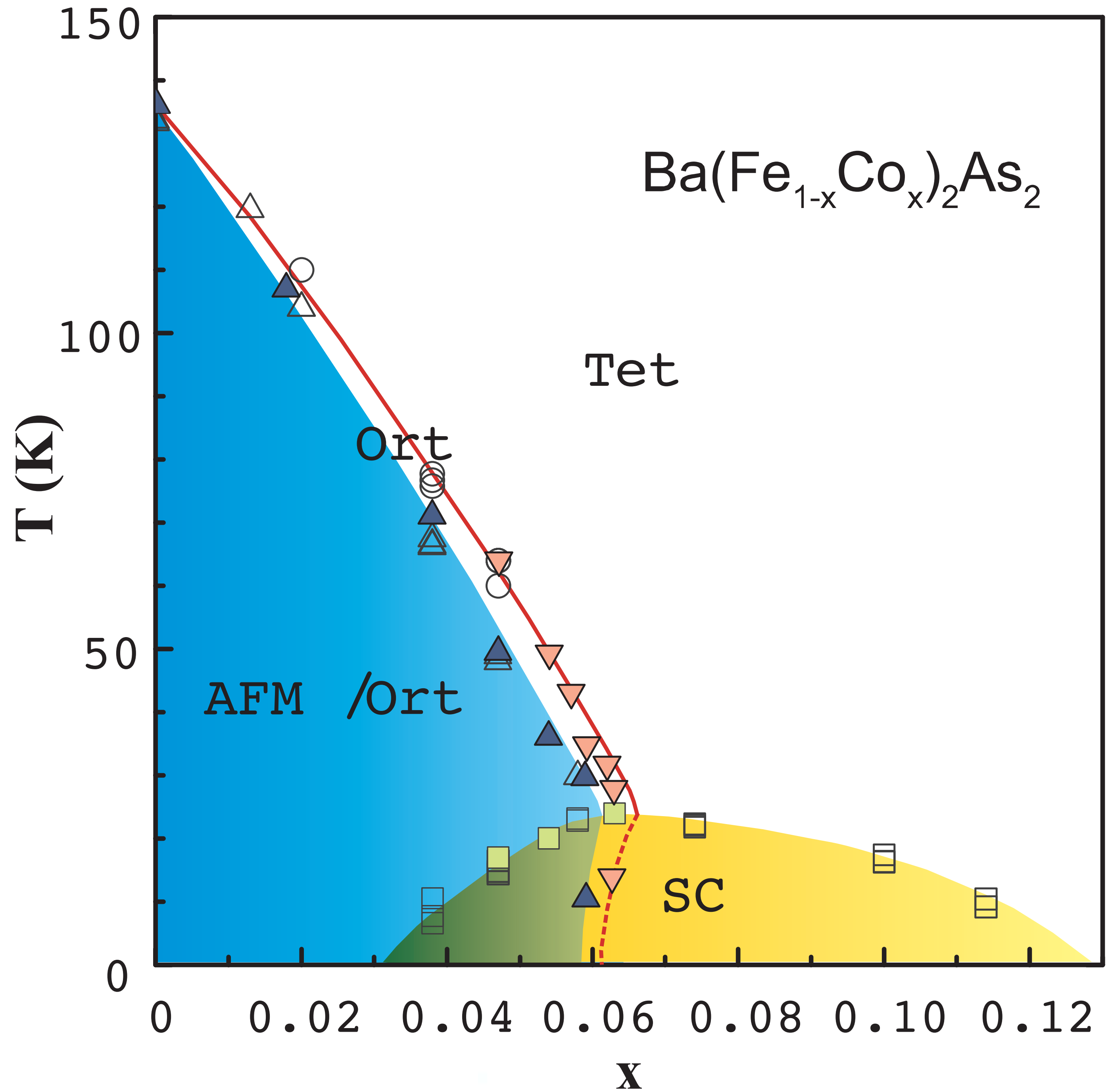




G. Knebel, D. Aoki, and J. Flouquet, arXiv:0911.5223

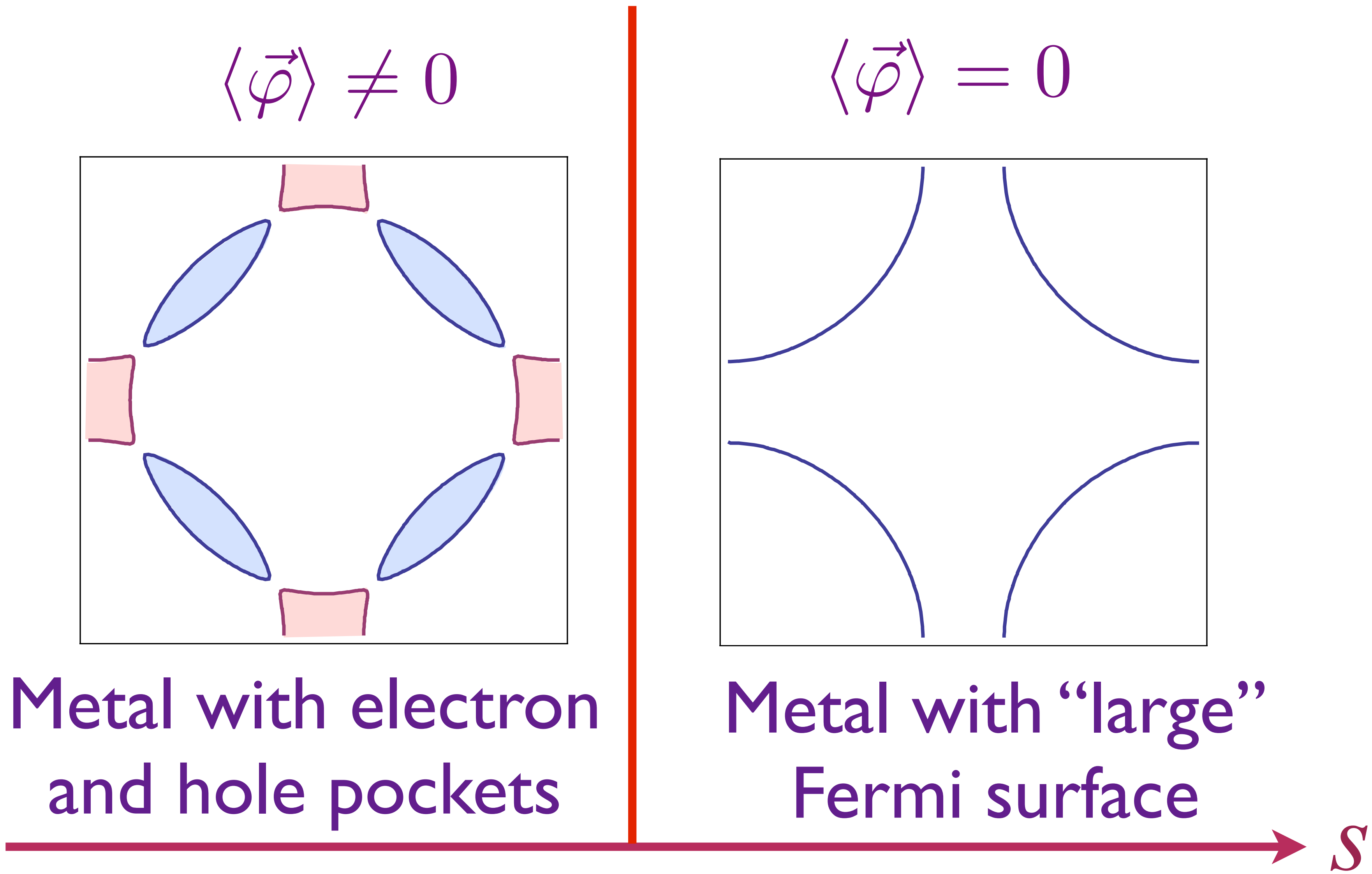
Similar phase diagram for the pnictides



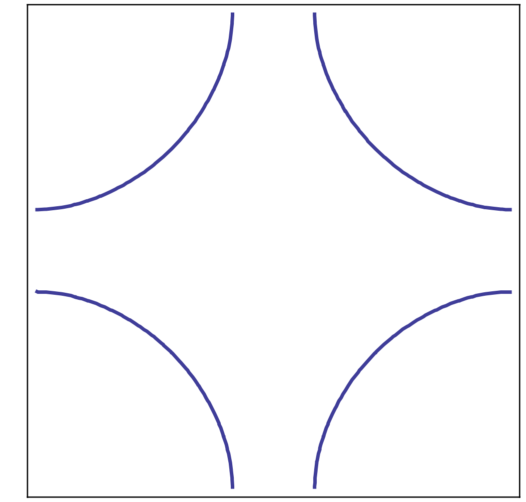


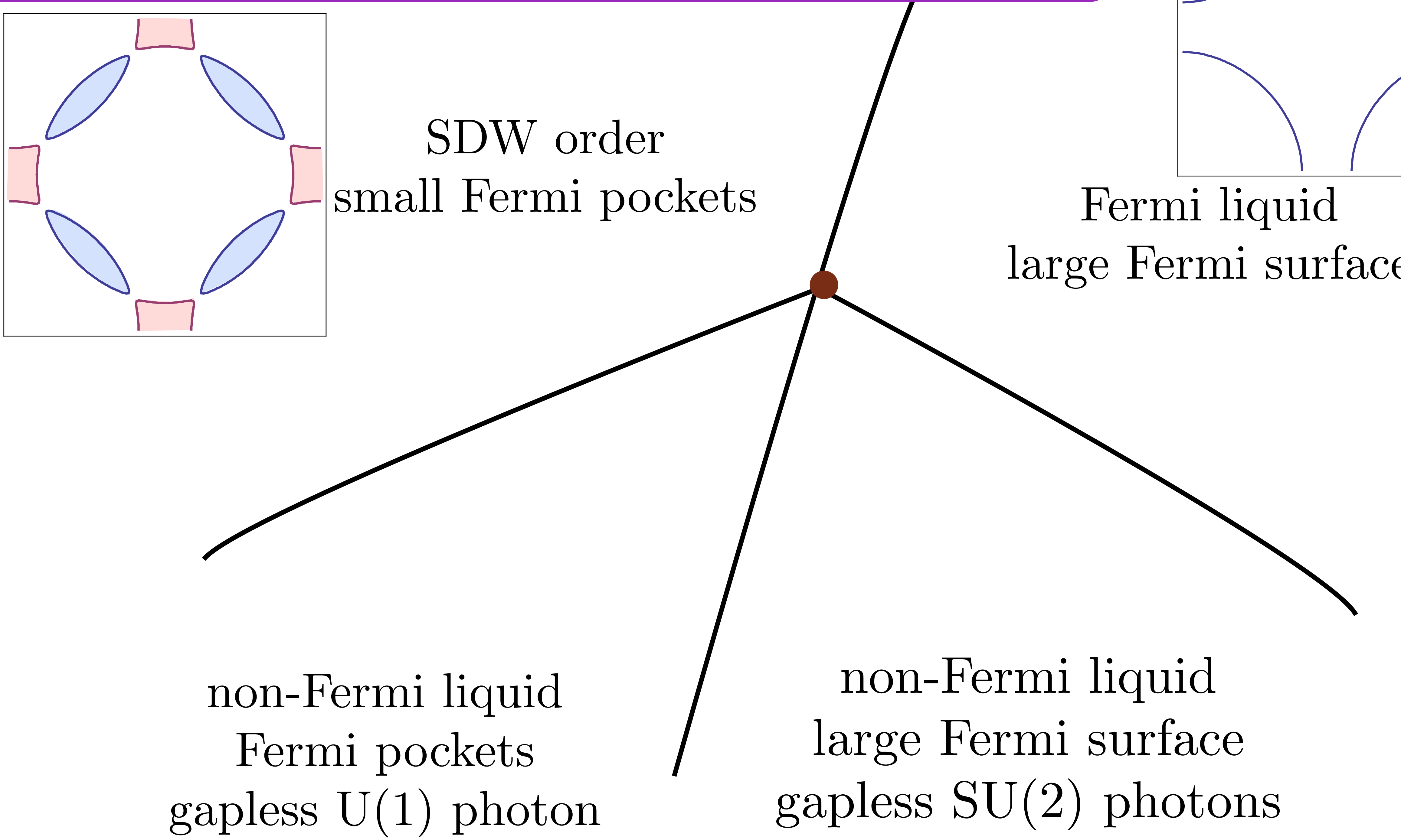
S. Nandi, M. G. Kim, A. Kreyssig, R. M. Fernandes, D. K. Pratt, A. Thaler, N. Ni, S. L. Bud'ko, P. C. Canfield, J. Schmalian, R. J. McQueeney, and A. I. Goldman, *Physical Review Letters* **104**, 057006 (2010)

Quantum criticality of the onset of antiferromagnetism in a metal



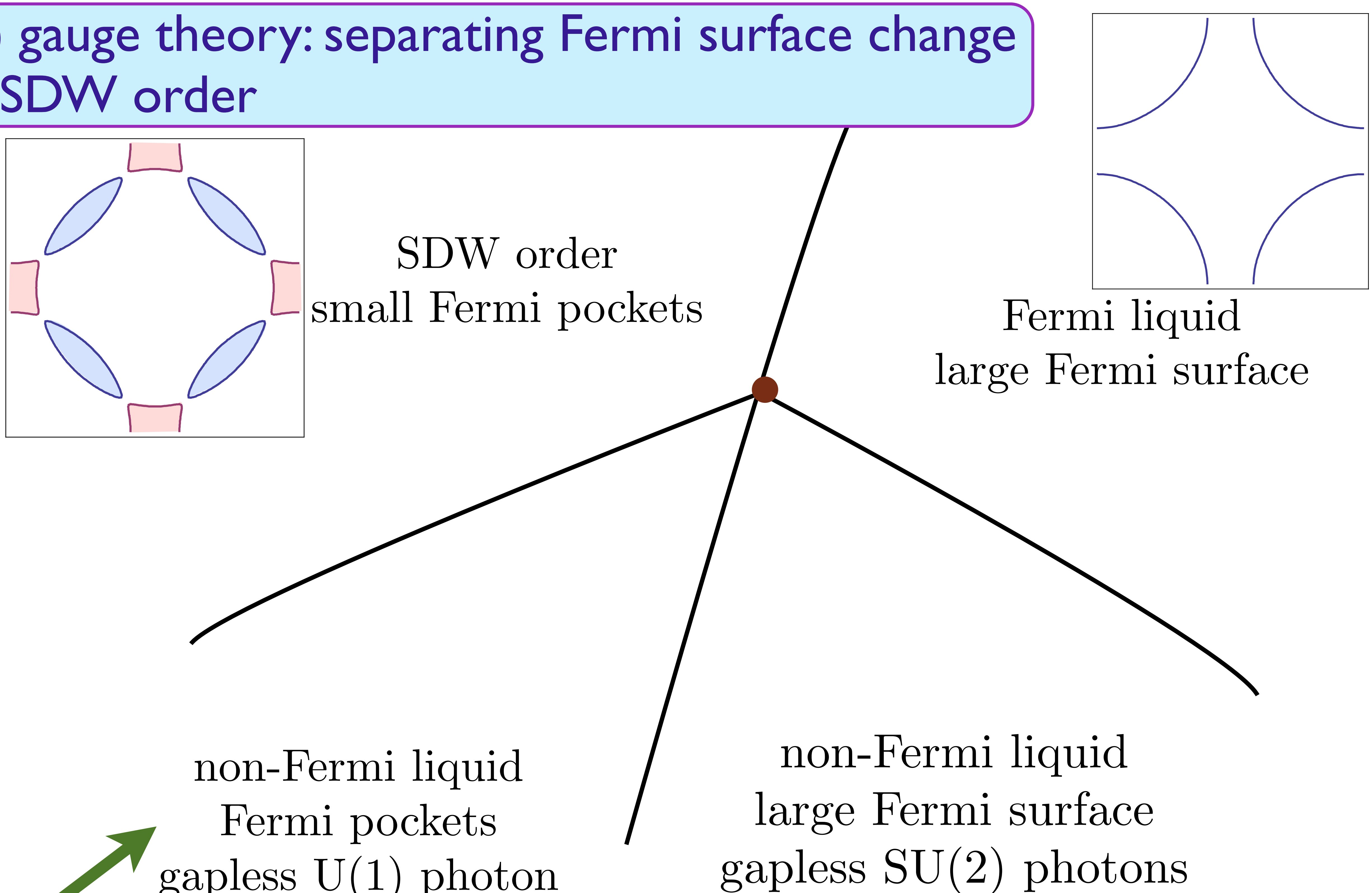
SU(2) gauge theory: separating Fermi surface change from SDW order





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

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



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

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