Quantum phase transitions
and
Fermi surface reconstruction

Talk online: sachdev.physics.harvard.edu

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Max Metlitski

Matthias Punk

Erez Berg

PHYSICS

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1. Fate of the Fermi surface: reconstruction or not ? Experimental motivations from cuprates and pnictides

2. Conventional theory and its breakdown in two spatial dimensions

3. Fermi surface reconstruction: onset of unconventional superconductivity

4. Fermi surface reconstruction *without* symmetry breaking: metals with “topological” order

5. The nematic transition: field theory of antipodal Fermi surface points

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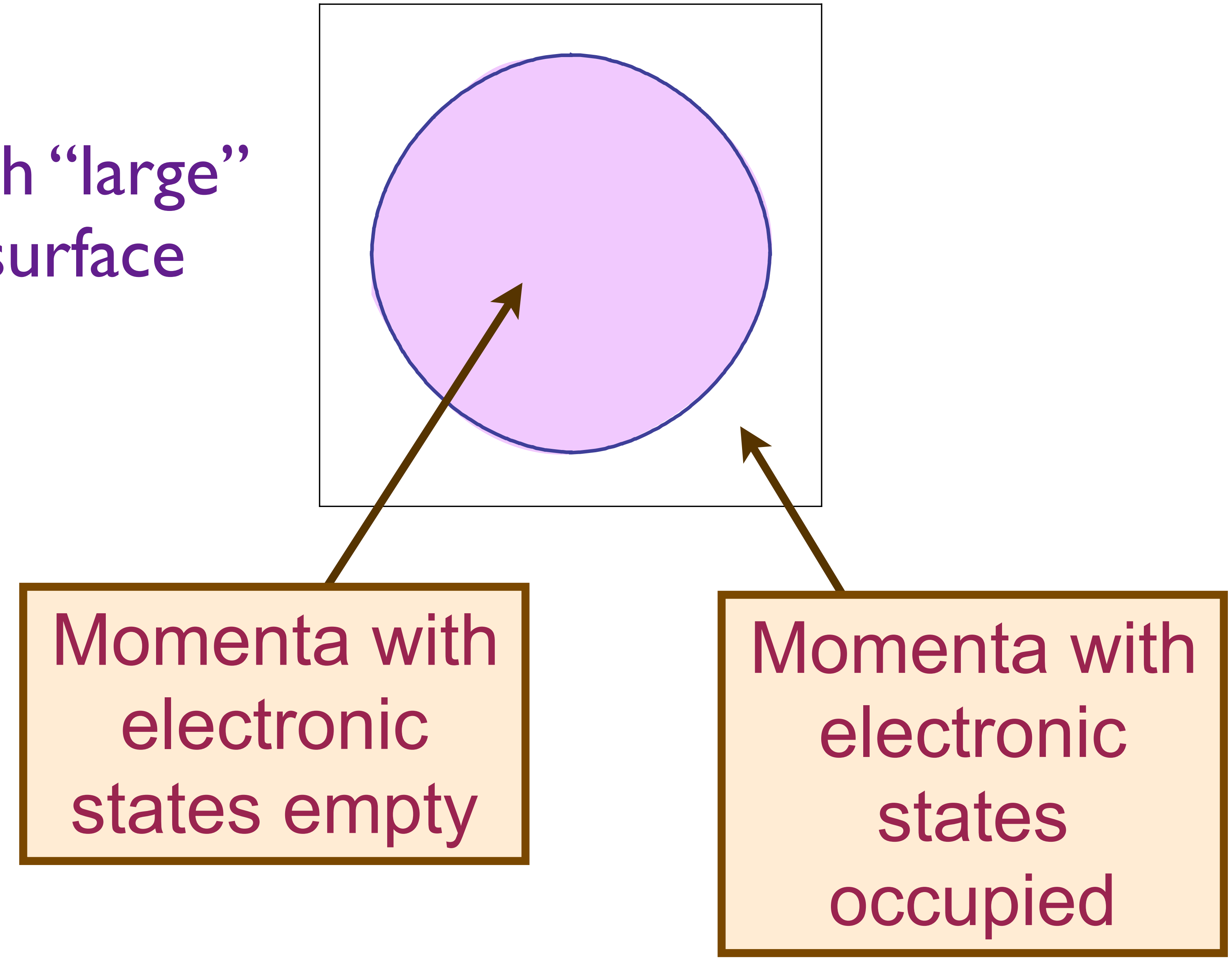
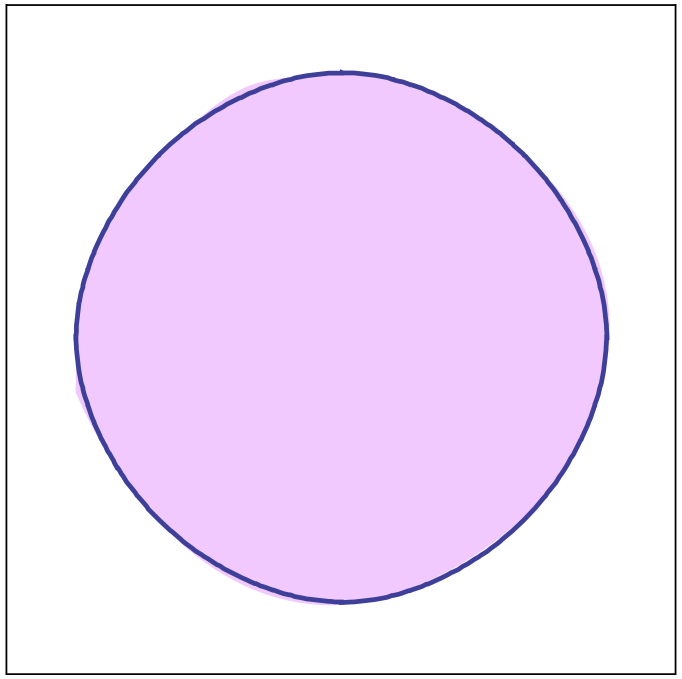
Fermi surface

Metal with “large” Fermi surface



Fermi surface+antiferromagnetism

Metal with "large"
Fermi surface



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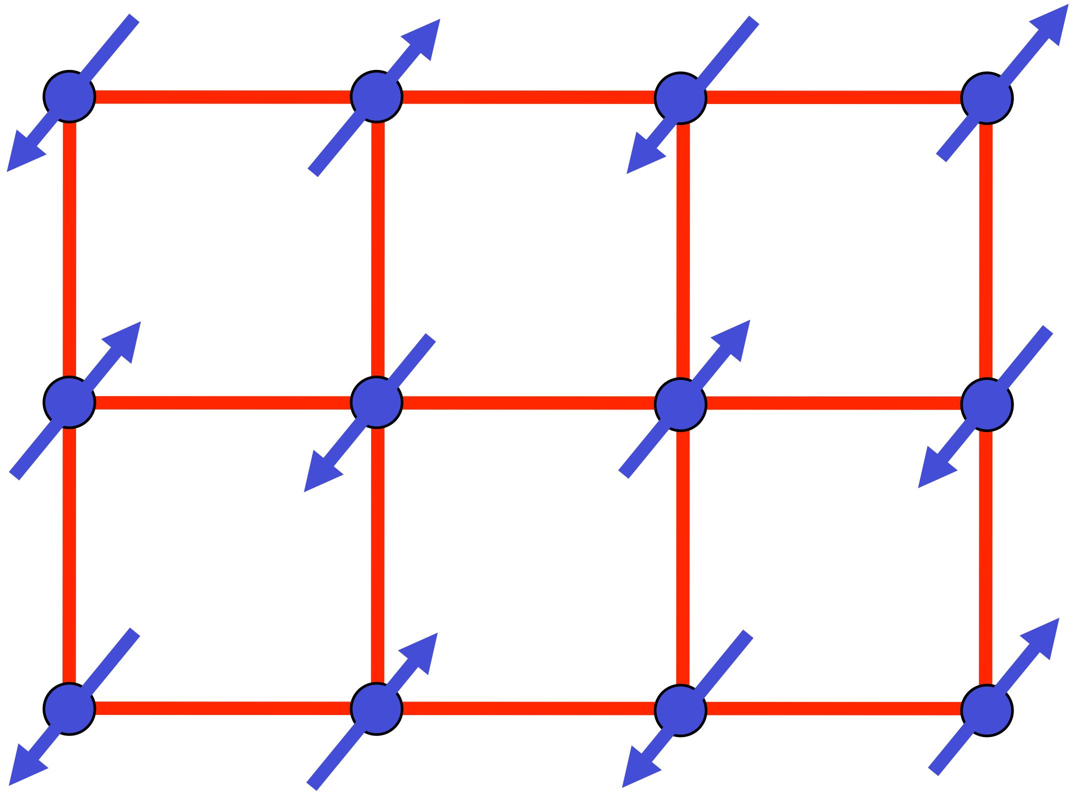
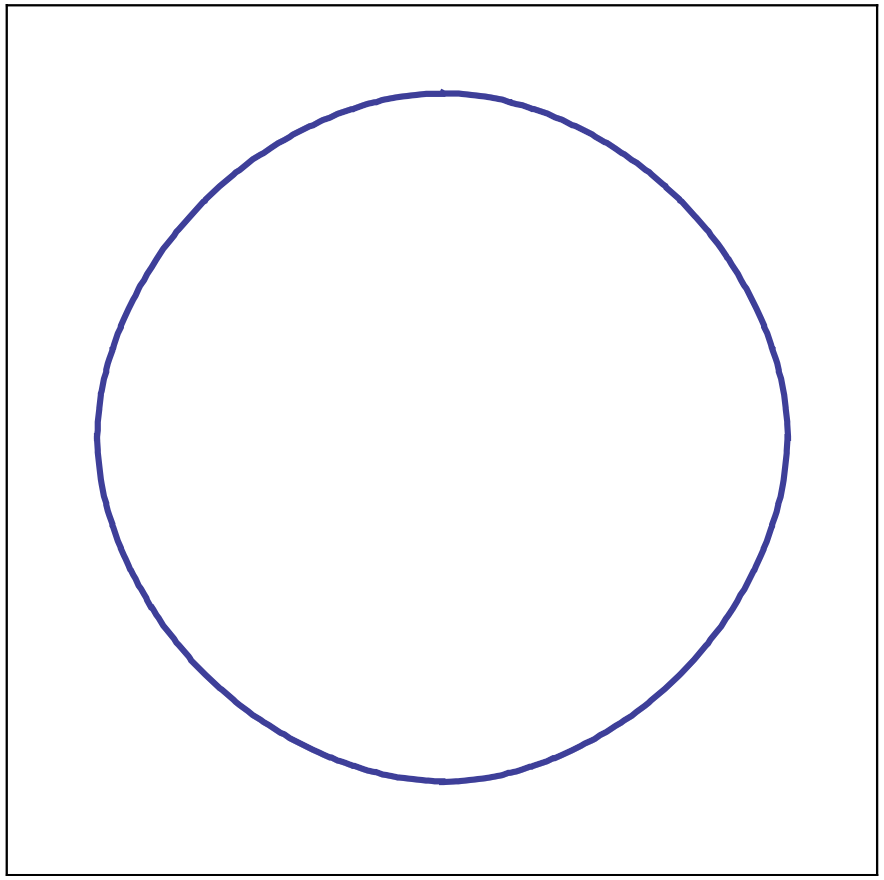


The electron spin polarization obeys

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

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



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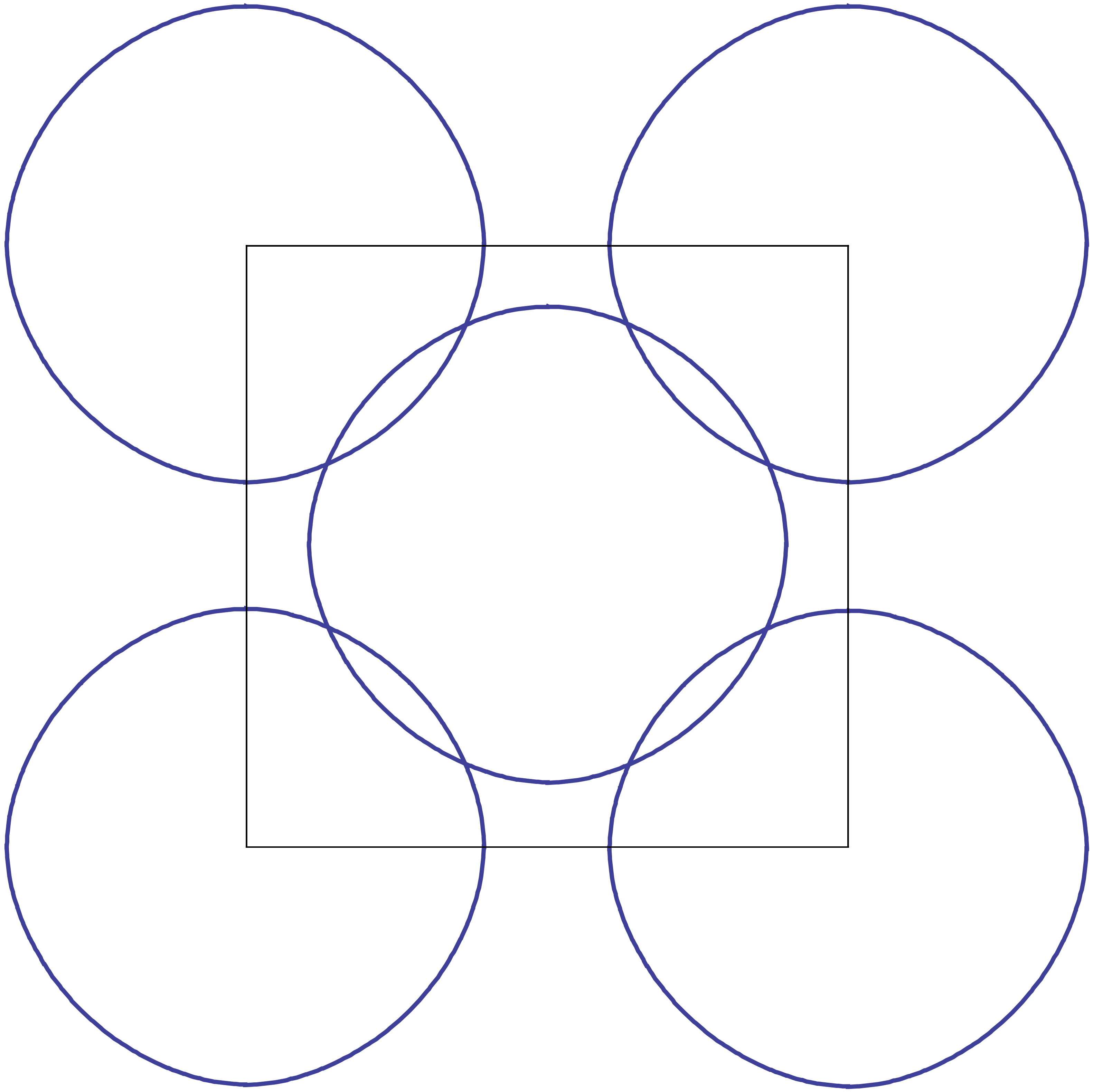
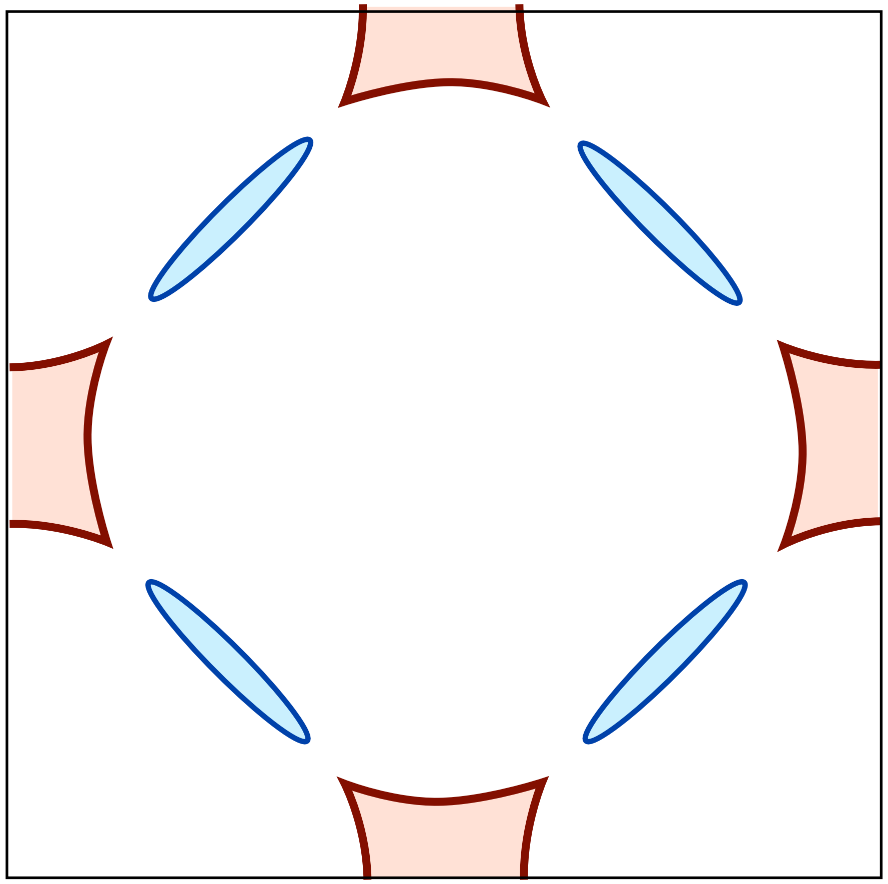
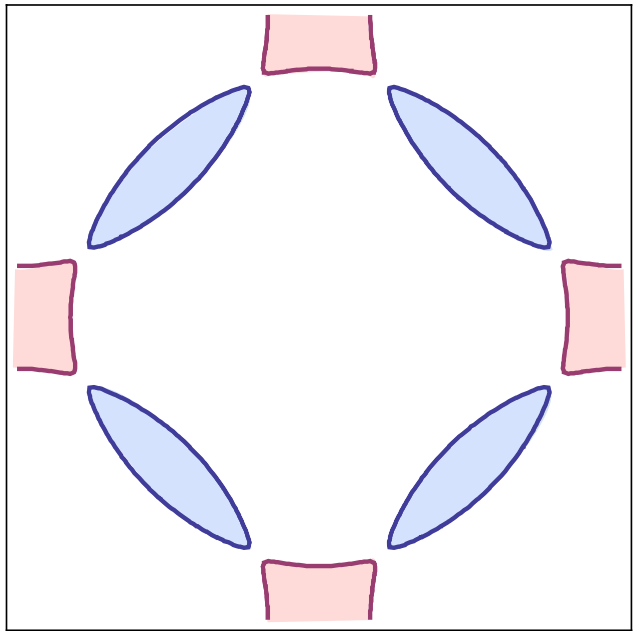


Fermi surfaces translated by $\mathbf{K} = (\pi, \pi)$.



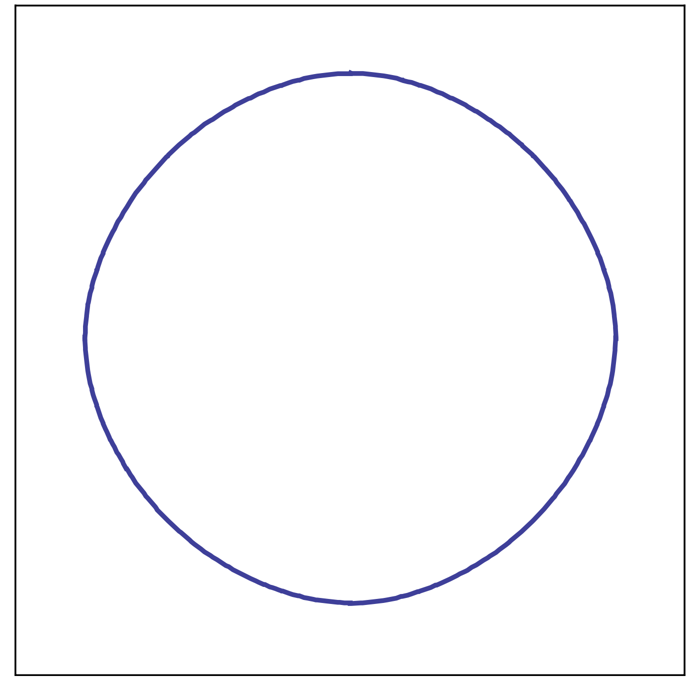
Fermi surface reconstruction into electron and hole pockets in antiferromagnetic phase with $\langle \vec{\varphi} \rangle \neq 0$

Quantum phase transition with Fermi surface reconstruction



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

Metal with electron and hole pockets



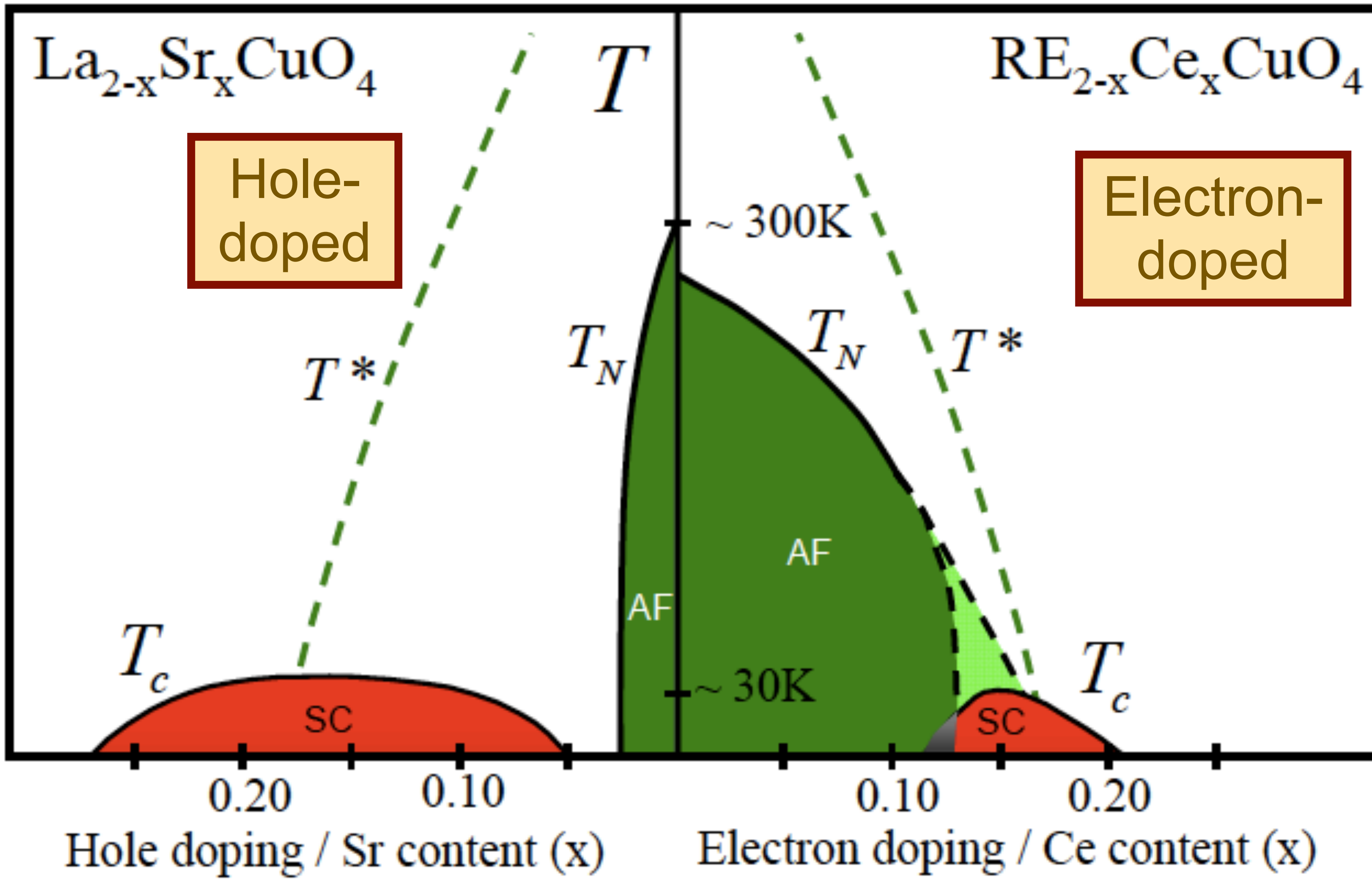
$\langle \vec{\varphi} \rangle = 0$

Metal with "large" Fermi surface

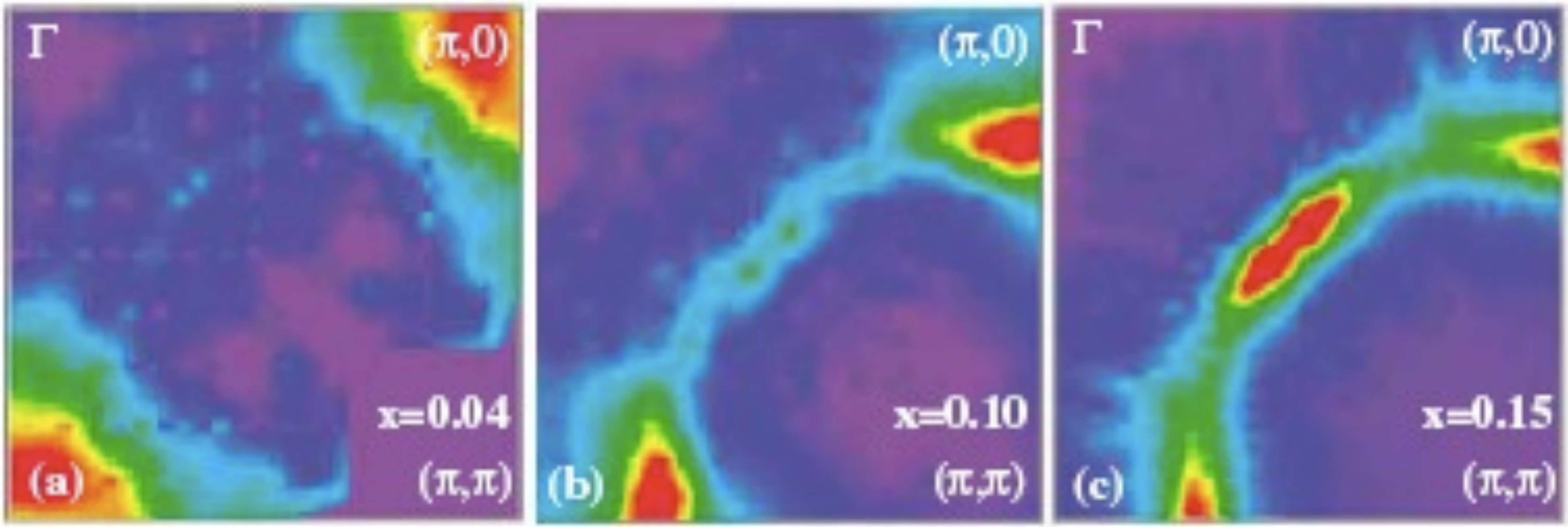
Increasing interaction

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).

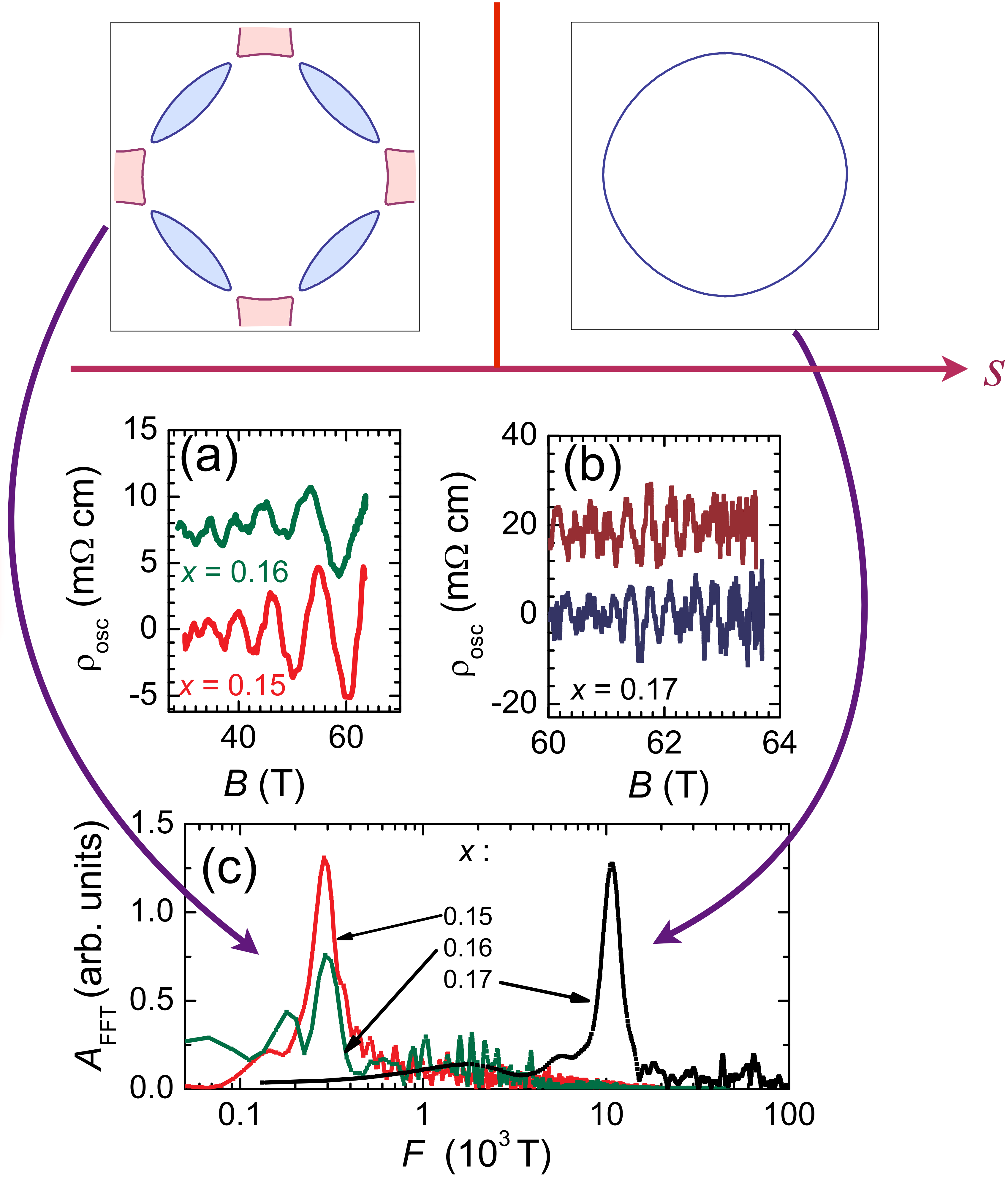
Electron-doped cuprate superconductors



Photoemission in $Nd_{2-x}Ce_xCuO_4$



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

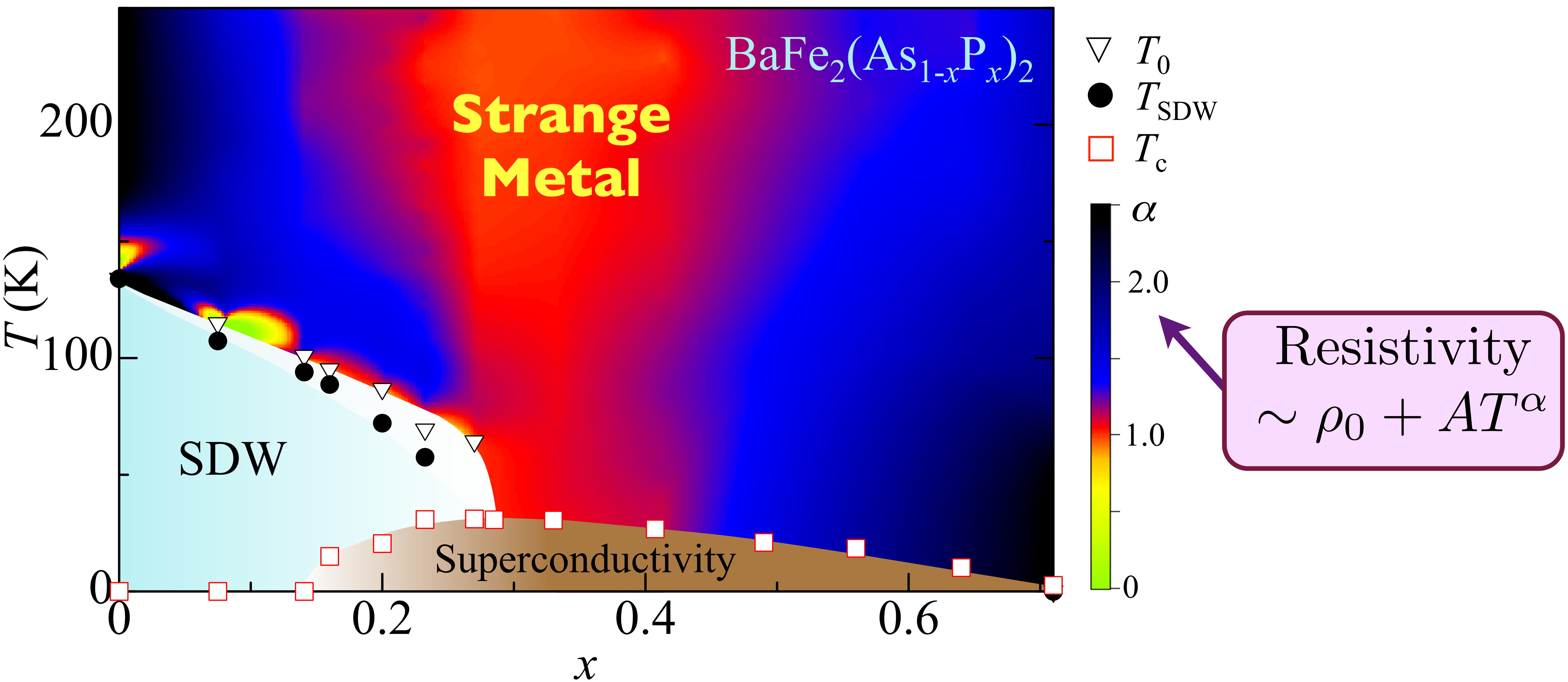


Quantum oscillations

$Nd_{2-x}Ce_xCuO_4$

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

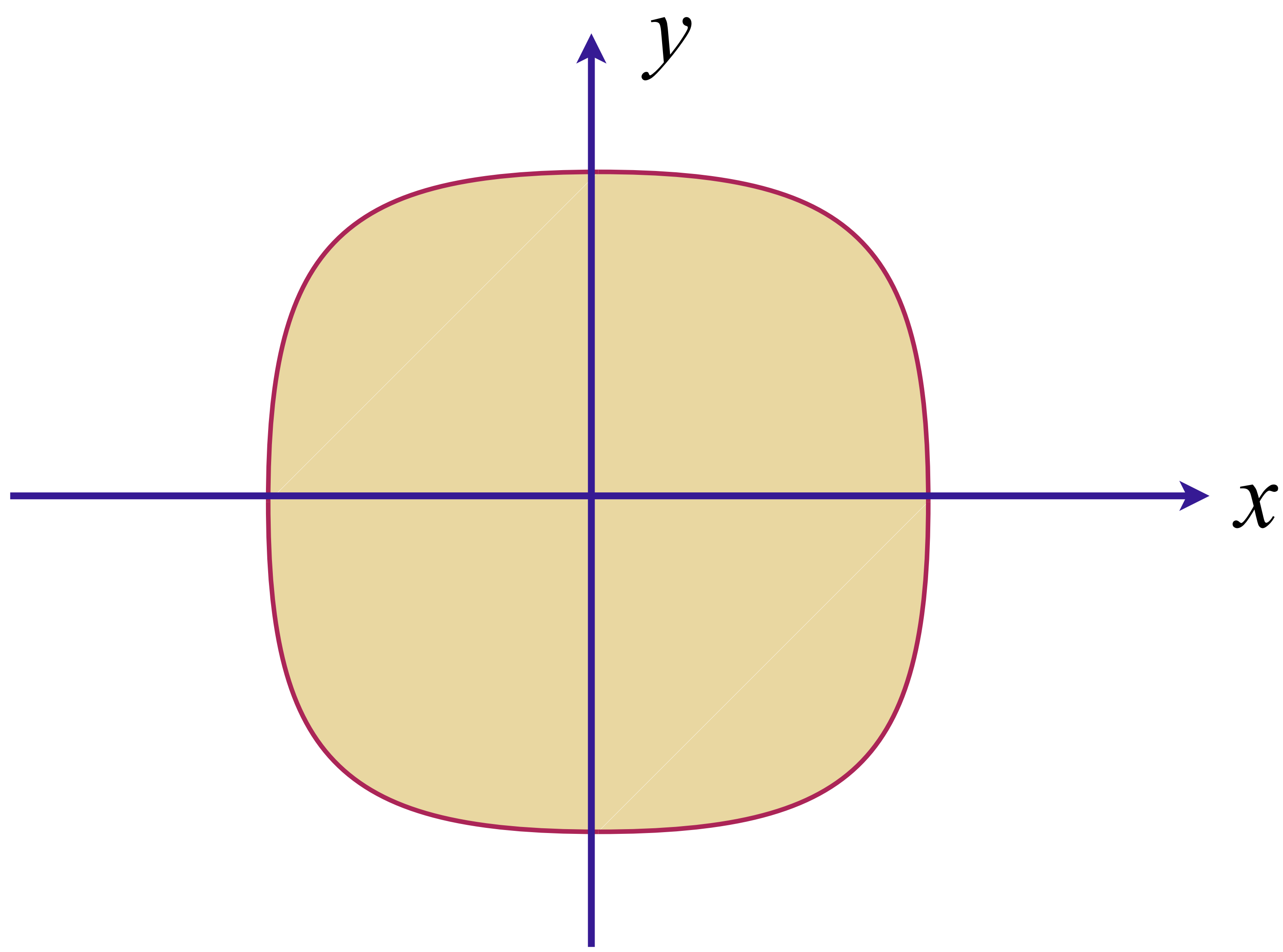
Temperature-doping phase diagram of the iron pnictides:



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

Quantum phase transition with Ising-nematic order

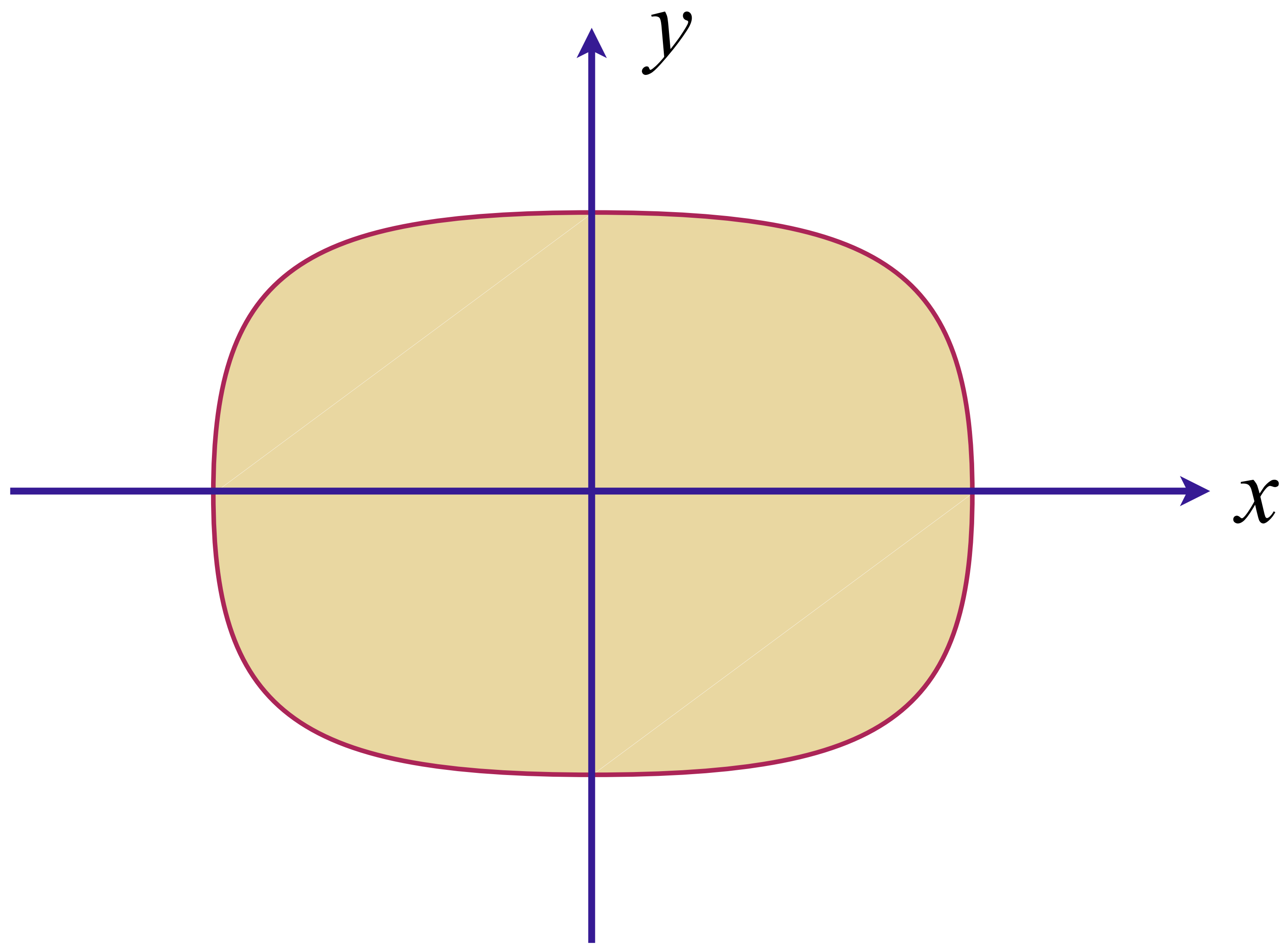
No Fermi surface reconstruction



Fermi surface with full square lattice symmetry

Quantum phase transition with Ising-nematic order

No Fermi surface reconstruction



Spontaneous elongation along x direction:

Quantum phase transition with Ising-nematic order

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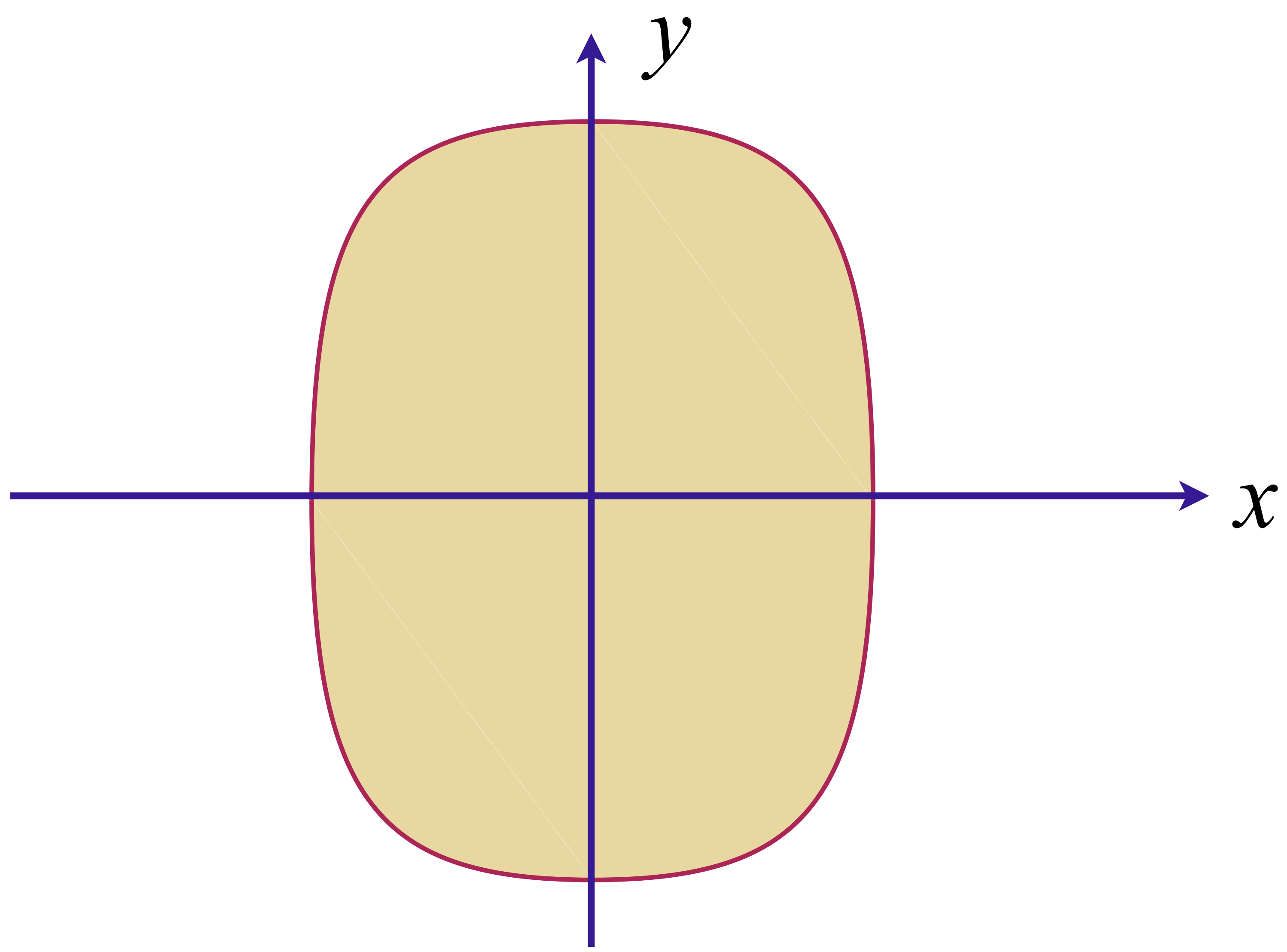


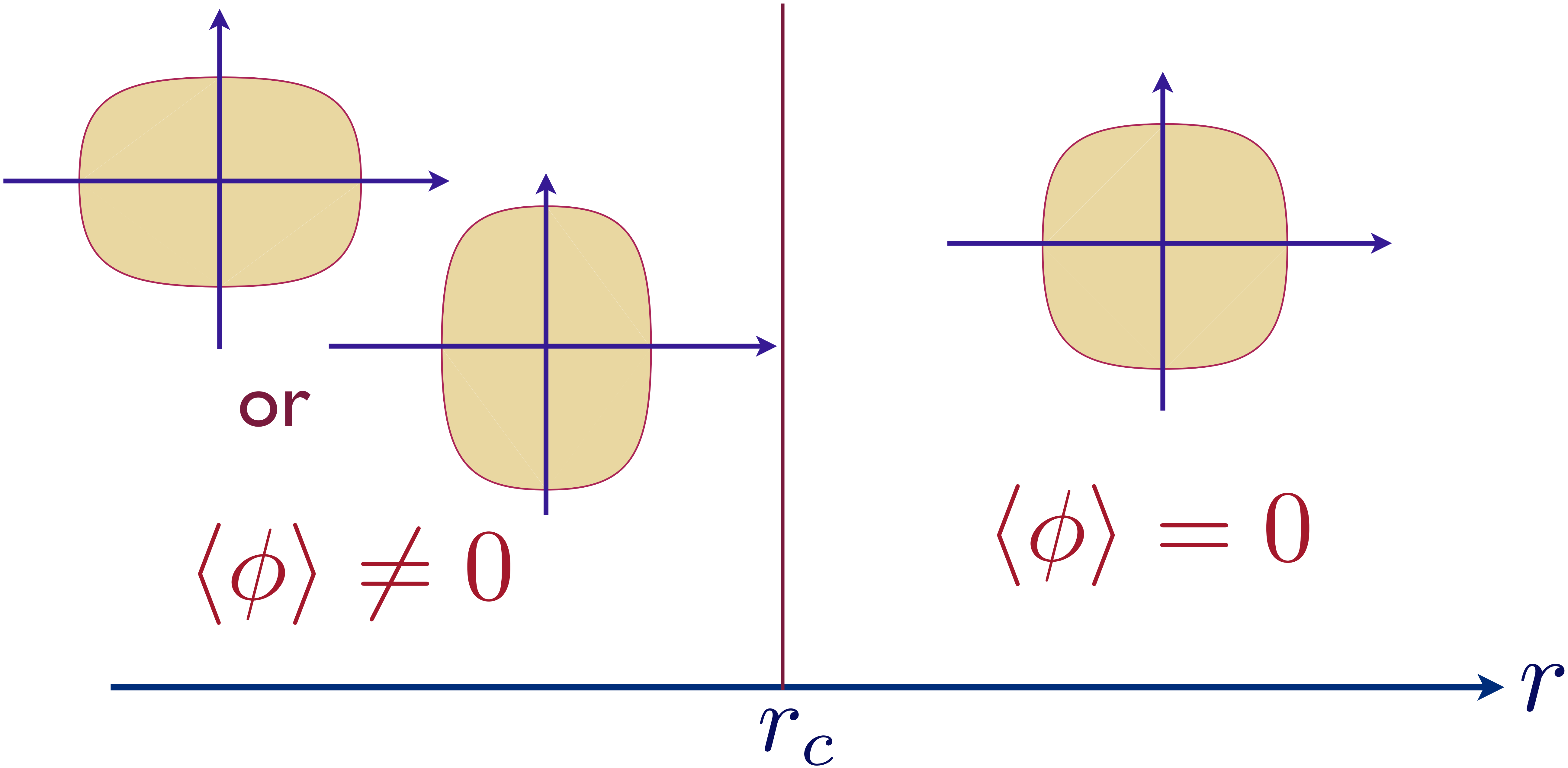
Spontaneous elongation along y direction:

Ising-nematic order parameter

$$\phi \sim \int d^2k \, (\cos k_x - \cos k_y) \, c^\dagger_{\mathbf{k}\sigma} c_{\mathbf{k}\sigma}$$

Measures spontaneous breaking of square lattice point-group symmetry of underlying Hamiltonian

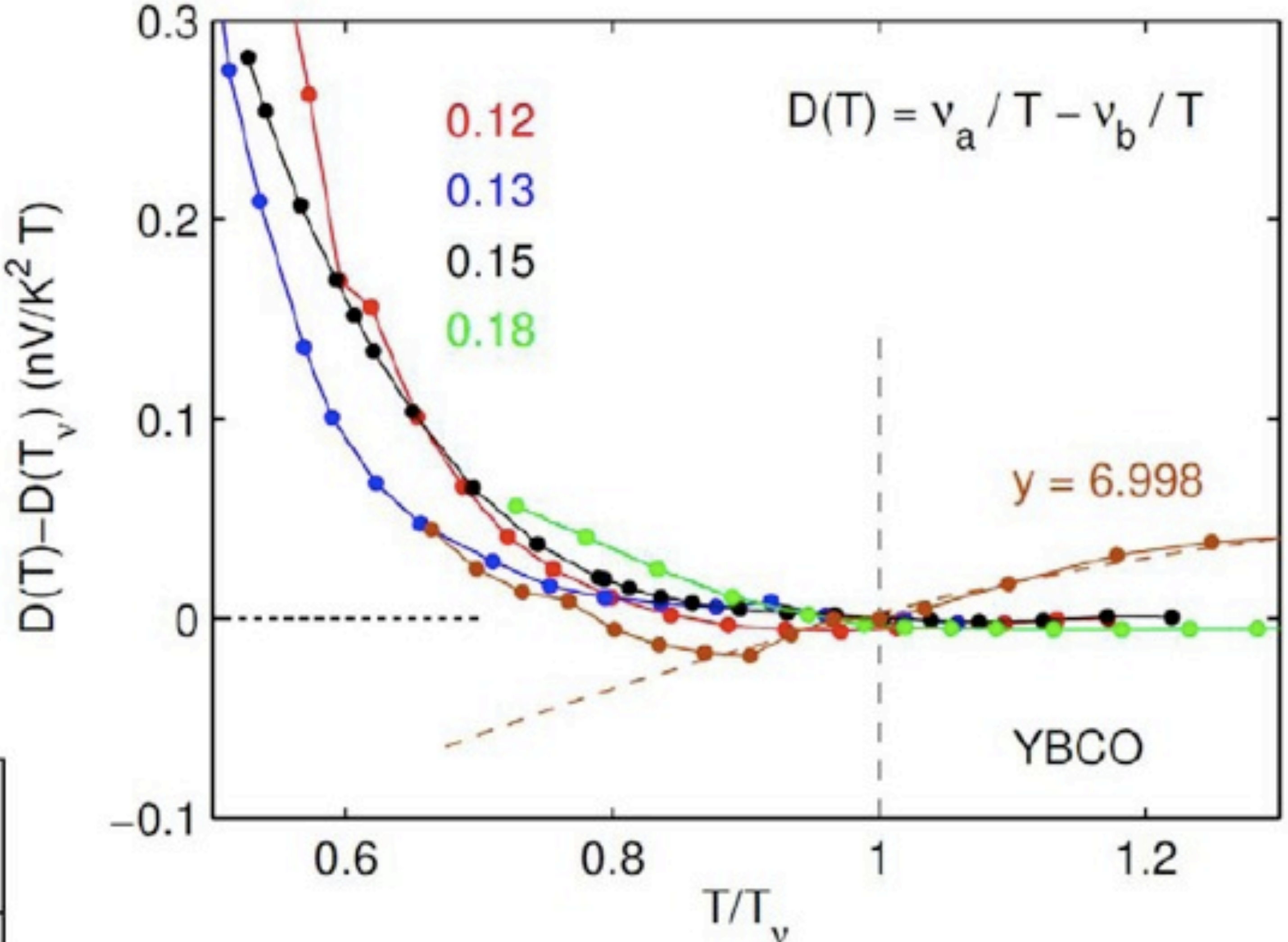
Quantum criticality of Ising-nematic ordering

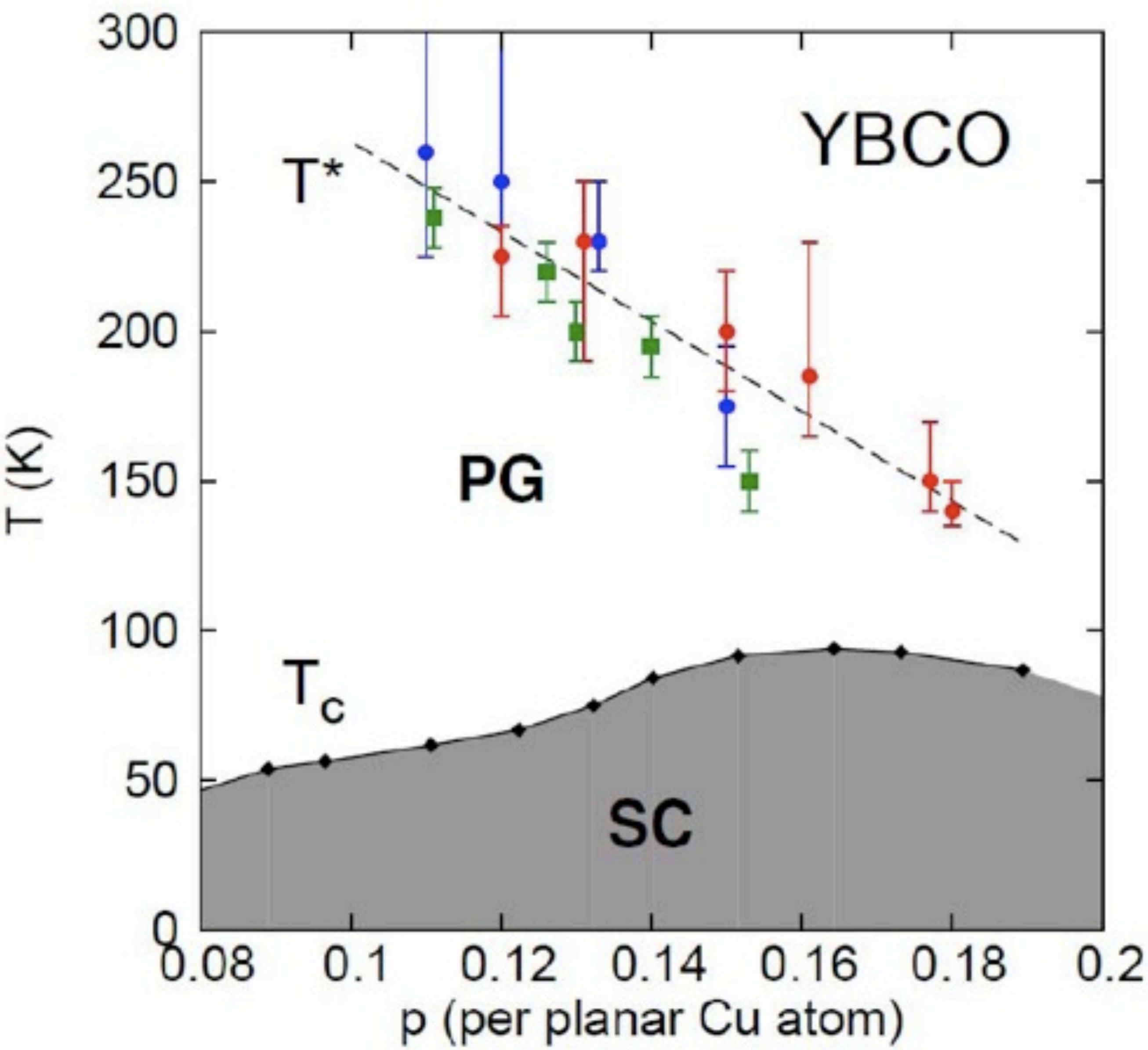


Pomeranchuk instability as a function of coupling r

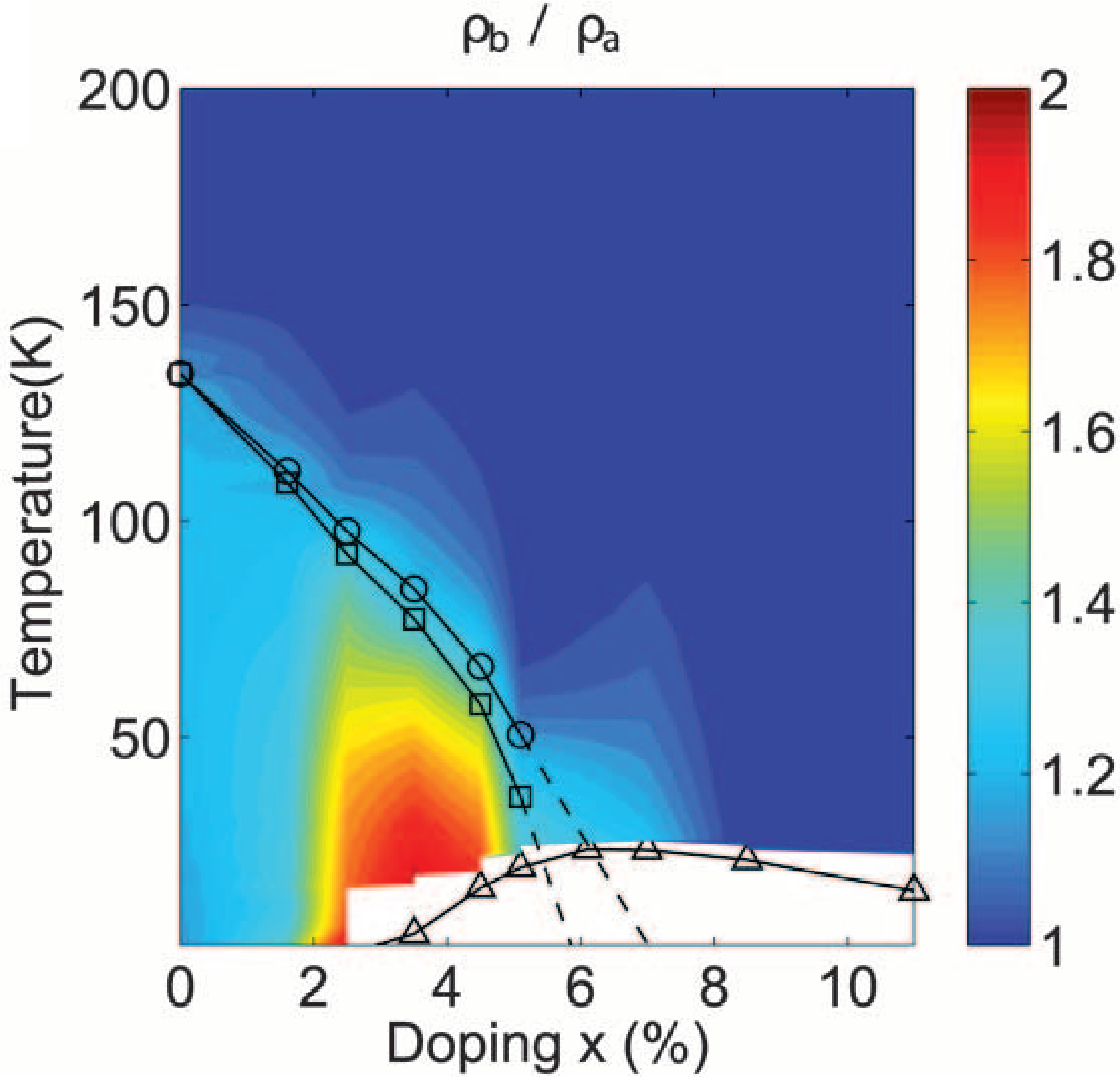
Broken rotational symmetry in the pseudogap phase of a high-Tc superconductor

R. Daou, J. Chang, David LeBoeuf, Olivier Cyr-Choiniere, Francis Laliberte, Nicolas Doiron-Leyraud, B. J. Ramshaw, Ruixing Liang, D.A. Bonn, W. N. Hardy, and Louis Taillefer
Nature, **463**, 519 (2010).





In-plane resistivity anisotropy in $Ba(Fe_{1-x}Co_x)_2As_2$



Jiun-Haw Chu, J. G. Analytis, K. De Greve, P. L. McMahon, Z. Islam, Y. Yamamoto, and I. R. Fisher, *Science* **329**, 824 (2010)

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Hertz-Moriya-Millis theory

- Integrate out Fermi surface quasiparticles and obtain an effective theory for the order parameter $\vec{\varphi}$ alone.

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- This is dangerous, and will lead to non-local in the $\vec{\varphi}$ theory. Hertz focused on only the simplest such non-local term.

Hertz-Moriya-Millis theory

- Integrate out Fermi surface quasiparticles and obtain an effective theory for the order parameter $\vec{\varphi}$ alone.

- This is dangerous, and will lead to non-local in the $\vec{\varphi}$ theory. 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 two spatial dimensions.

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

- In $d = 2$, we *must* work in local theores which keeps both the order parameter and the Fermi surface quasiparticles "alive".

Sung-Sik Lee, *Phys. Rev. B* **80**, 165102 (2009)
M. A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)
M. A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075128 (2010)

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- The theories can be organized in a $1/N$ expansion, where N is the number of fermion "flavors".

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- In $d = 2$, we *must* work in local theores which keeps both the order parameter and the Fermi surface quasiparticles "alive".
- The theories can be organized in a $1/N$ expansion, where N is the number of fermion "flavors".
- At subleading order, resummation of all "planar" graphics is required (at least): this theory is even more complicated than QCD.

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M.A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)
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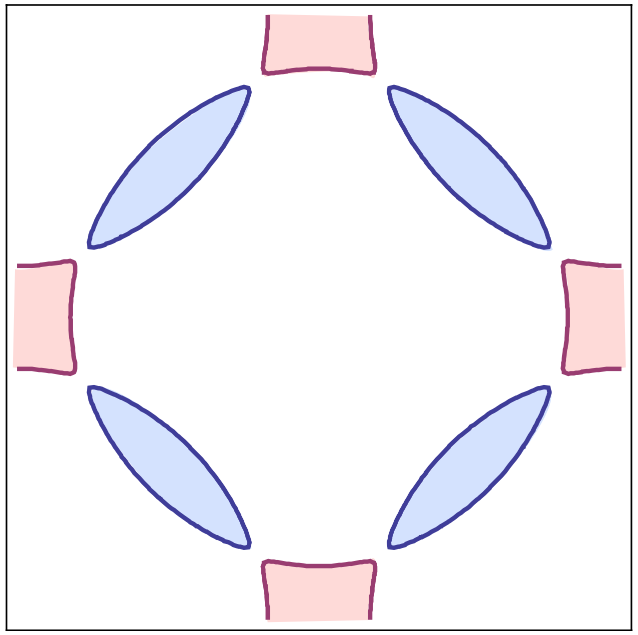
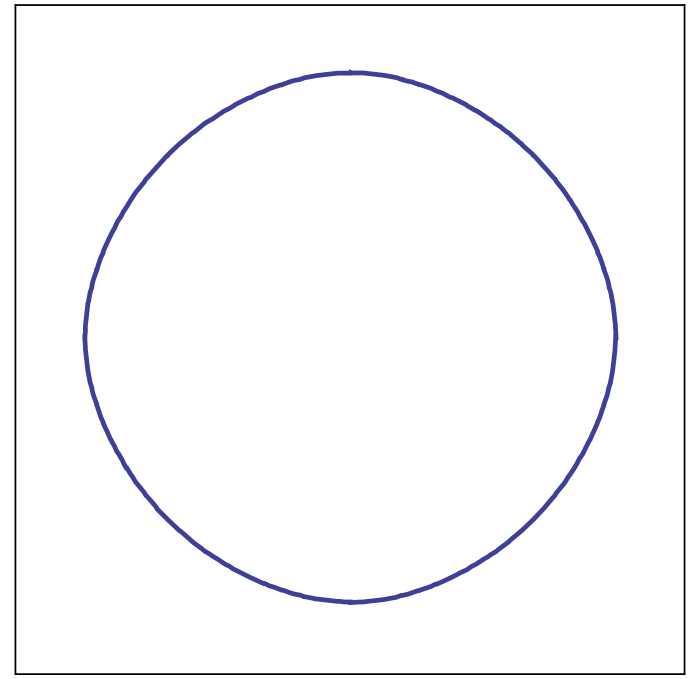
Quantum phase transition with Fermi surface reconstruction





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

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Metal with electron and hole pockets

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).

- Steglich: Evidence for two types of quantum critical points between the SDW metal and the heavy fermion metal (both Fermi liquid phases) in $d = 3$: one described by SDW theory, and the other by Kondo breakdown in Kondo lattice model (Q Si, P. Coleman)

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- Our theory: Because the phases on either side are qualitatively identical, there is only one theory, whether one uses the SDW or Kondo lattice models. In $d = 2$, this theory is strongly coupled. In $d = 3$, we can show that the weak coupling (as in Hertz-Millis-Moriya) theory is stable; however there may also be another fixed point at strong coupling.

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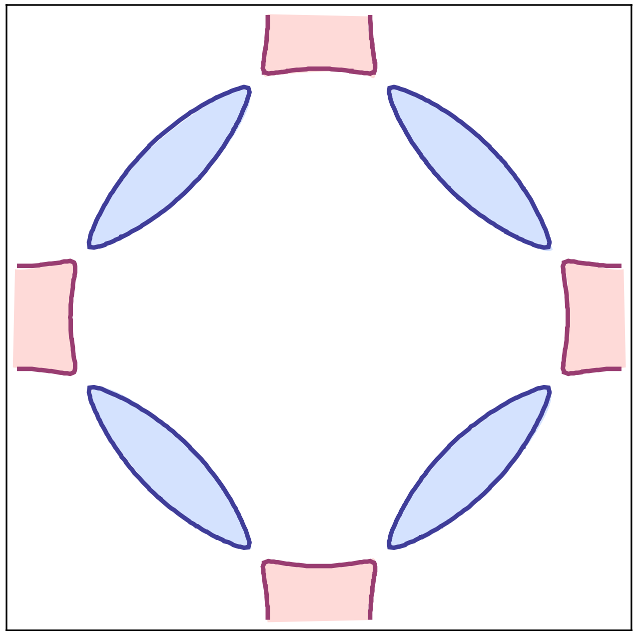

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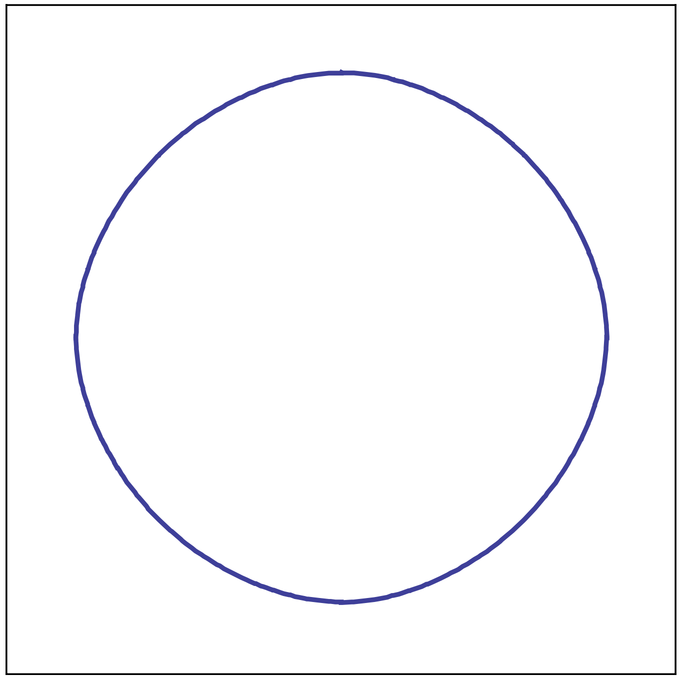

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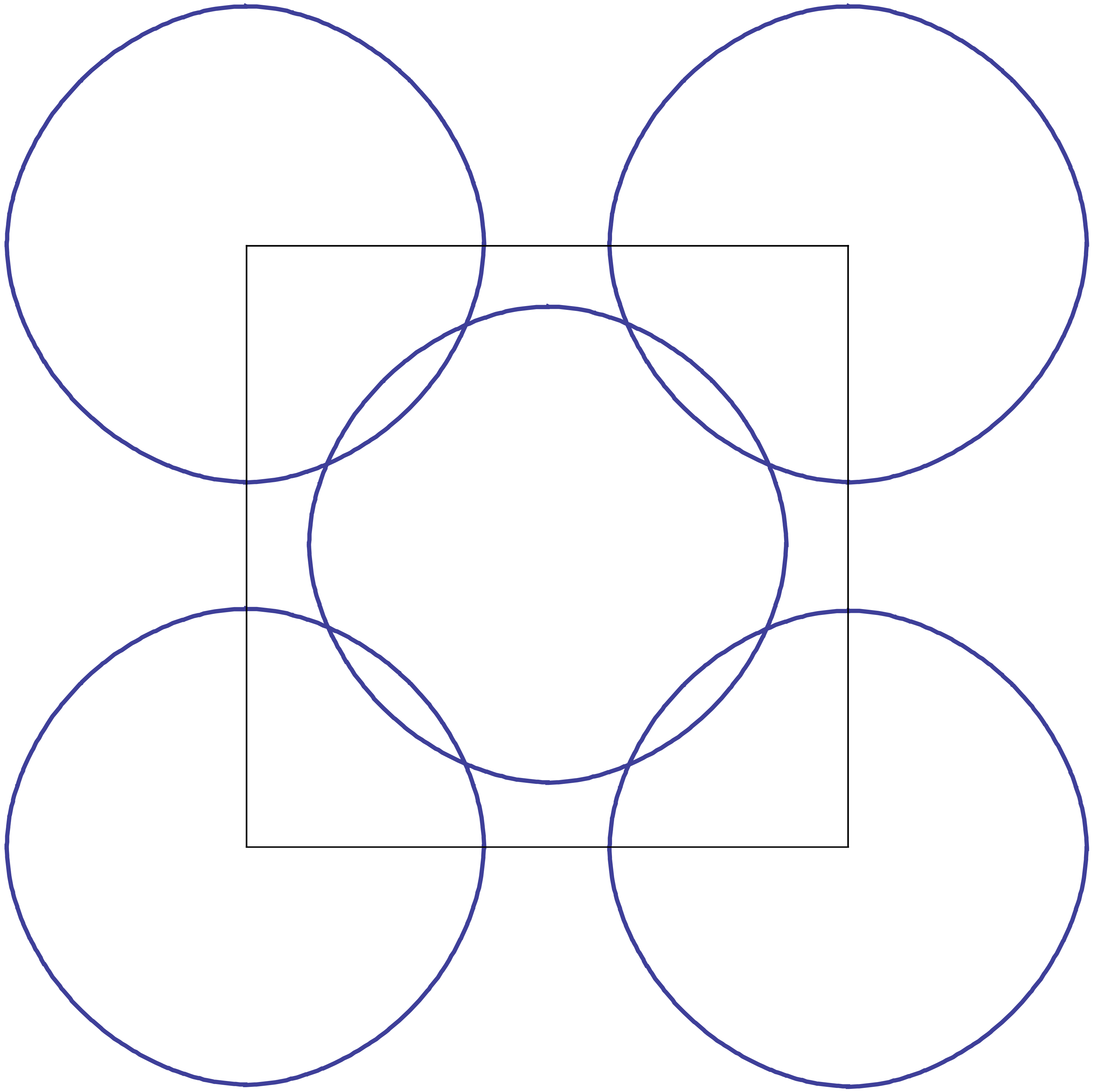
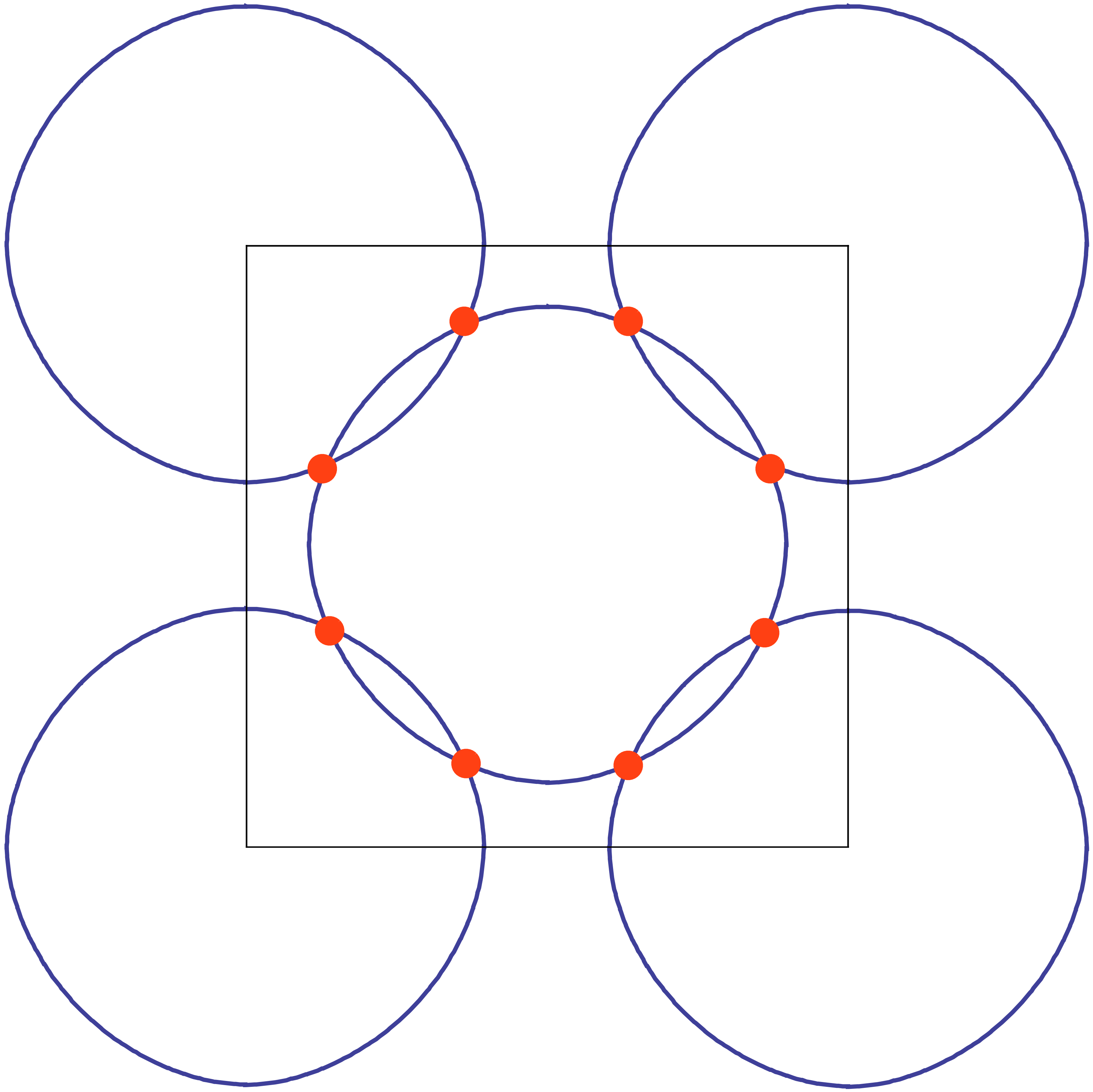
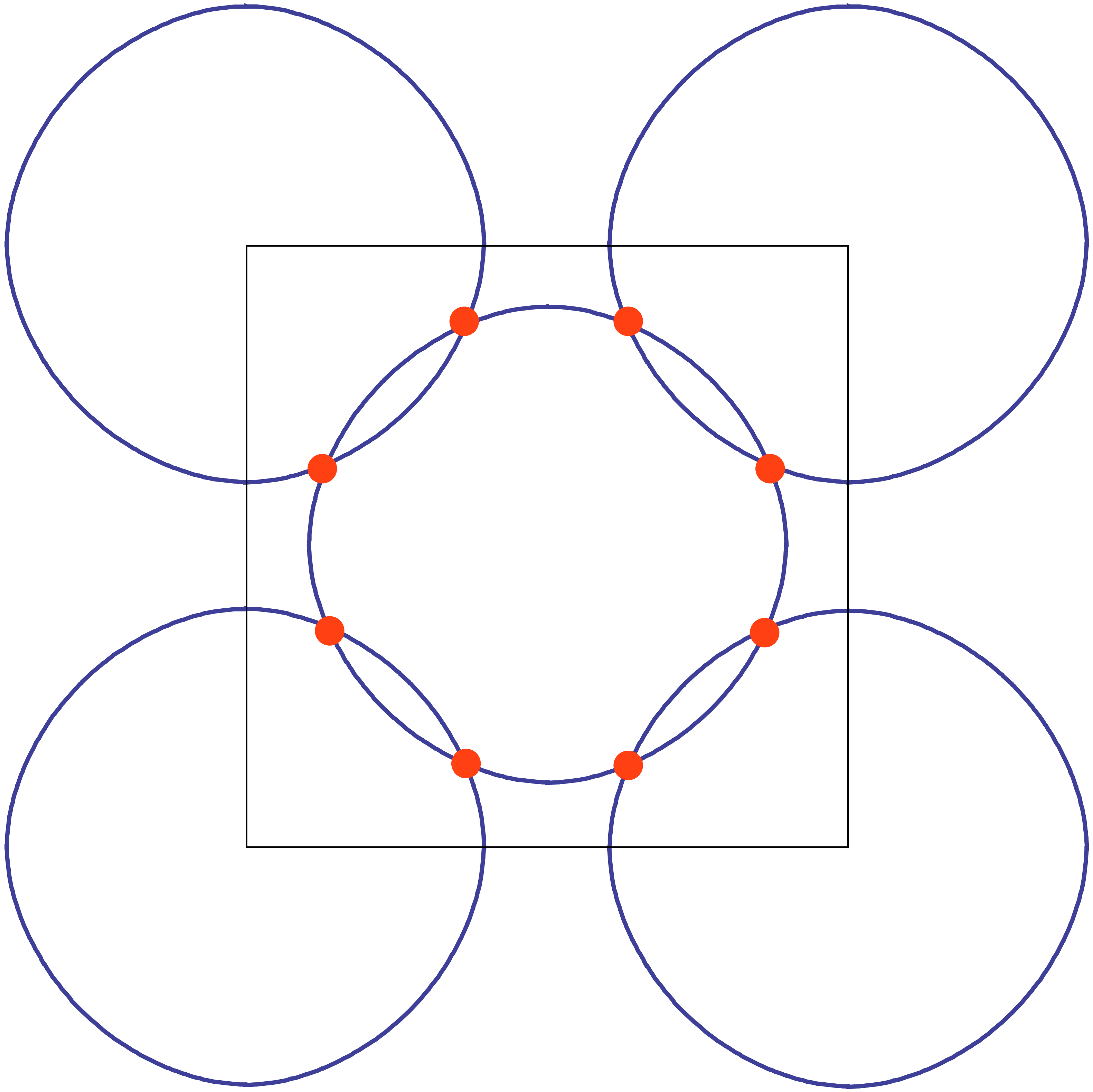


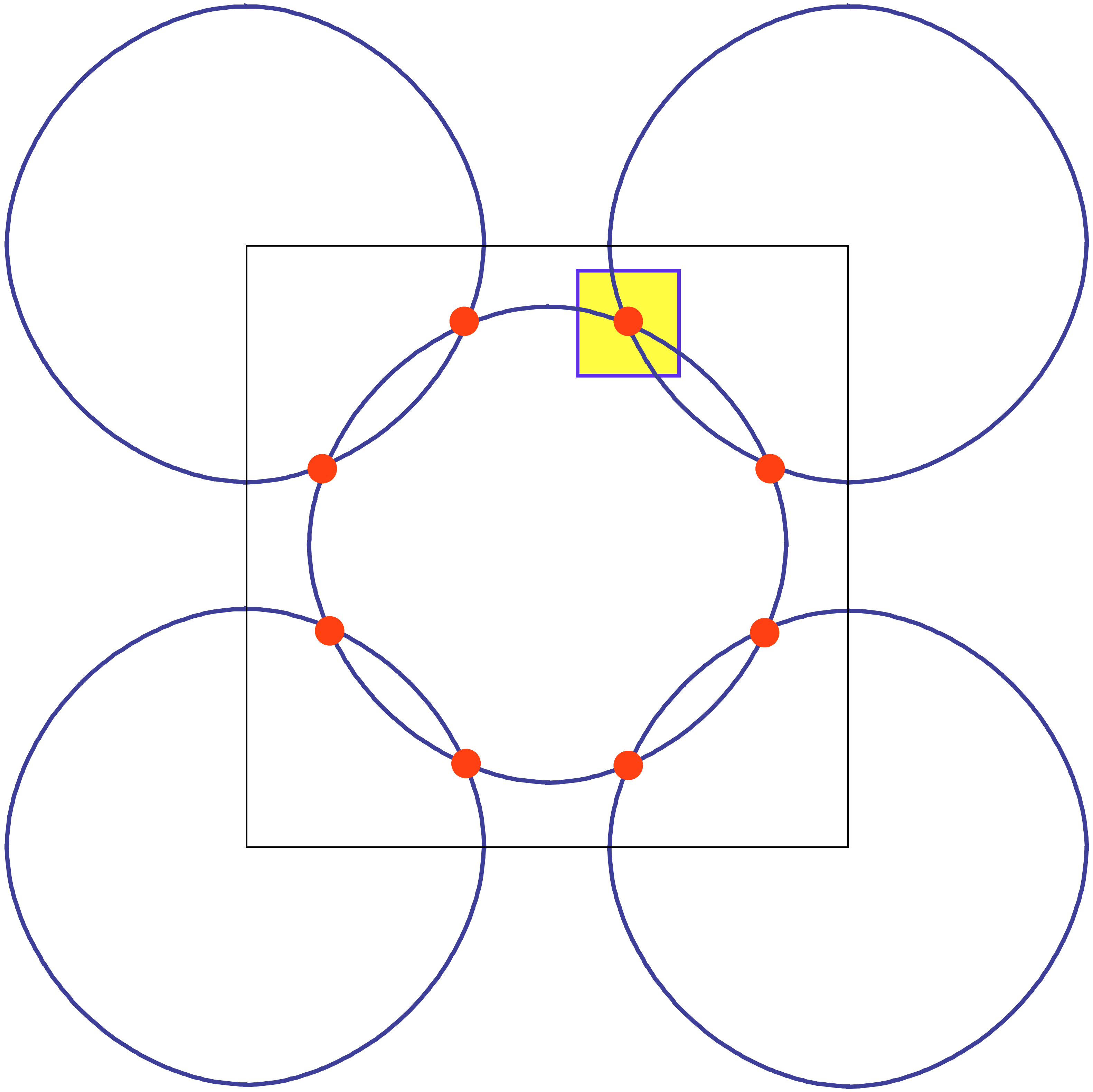
Fermi surfaces translated by $\mathbf{K} = (\pi, \pi)$.



“Hot” spots

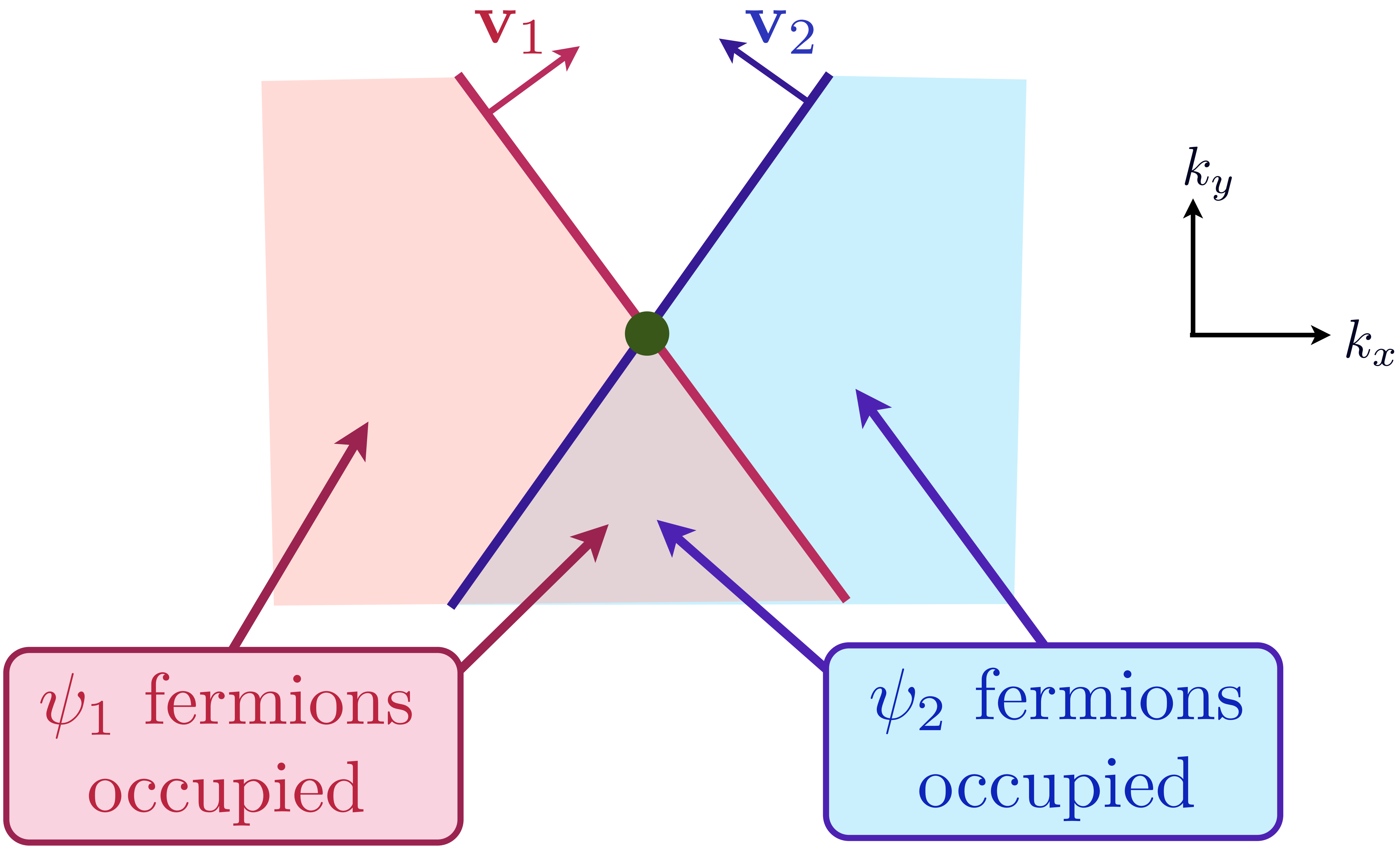


Low energy theory for critical point near hot spots

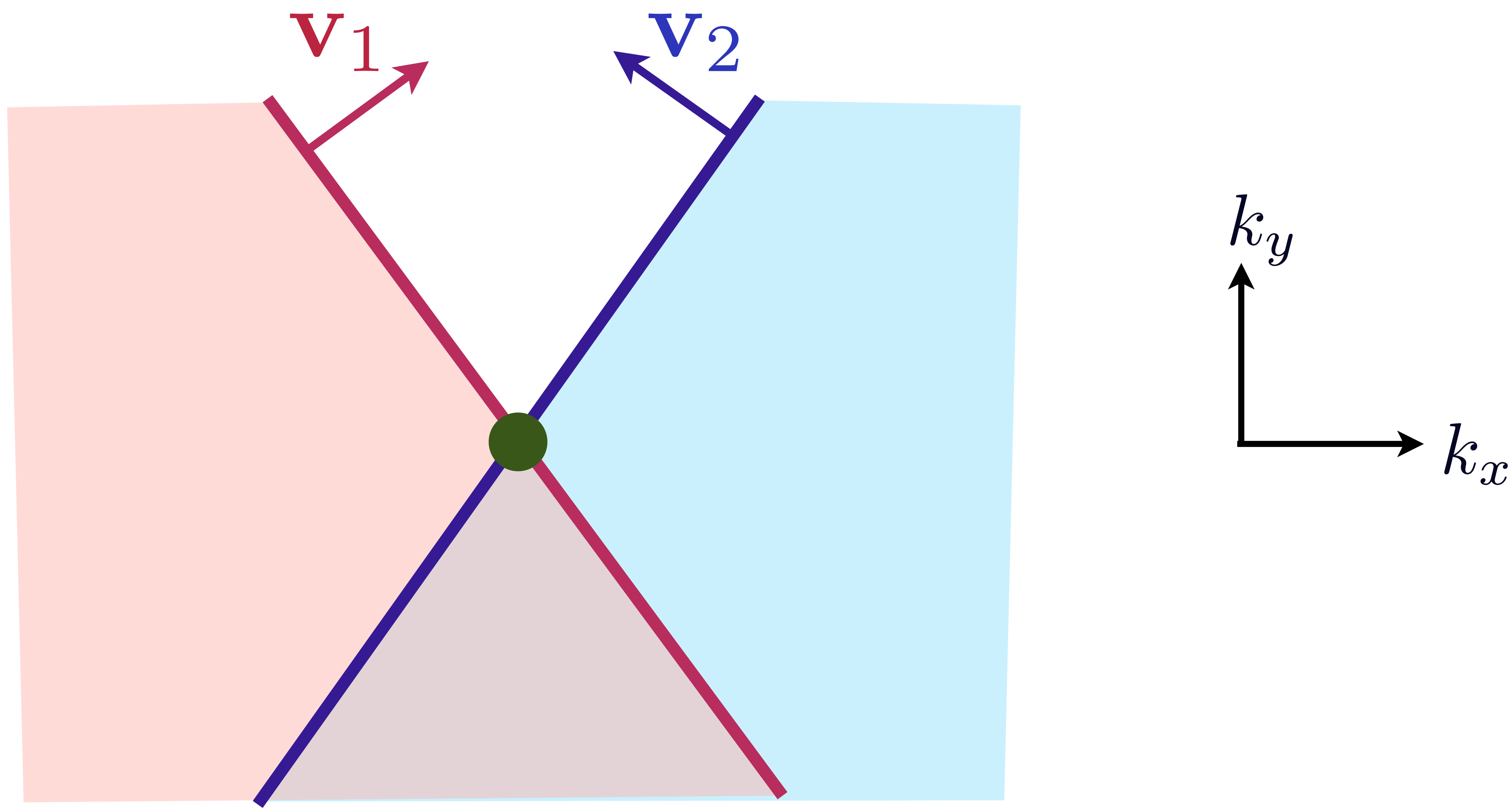


Low energy theory for critical point near hot spots

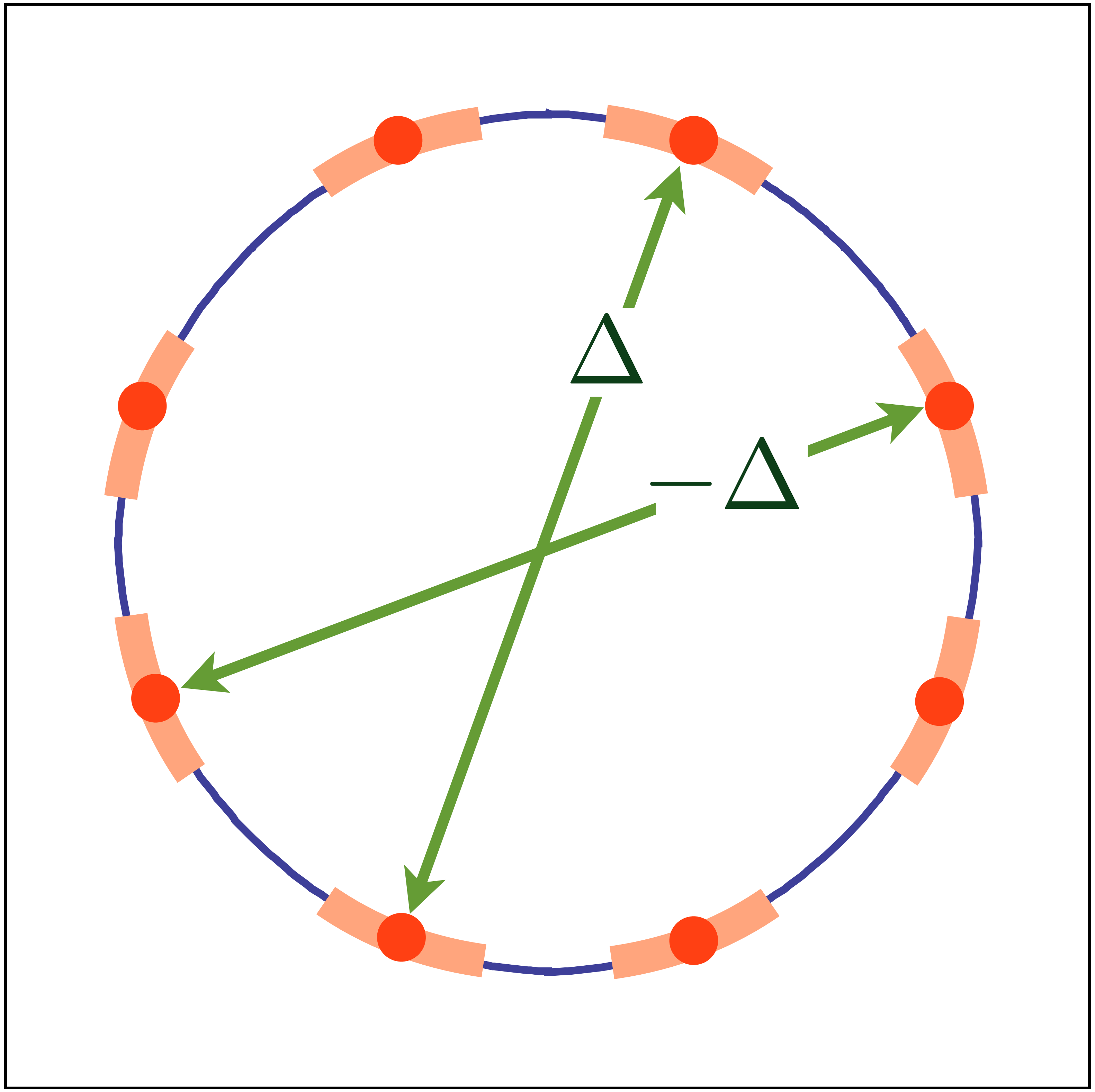
Theory has fermions $\psi_{1,2}$ (with Fermi velocities $\mathbf{v}_{1,2}$) and boson order parameter $\vec{\varphi}$, interacting with coupling λ



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

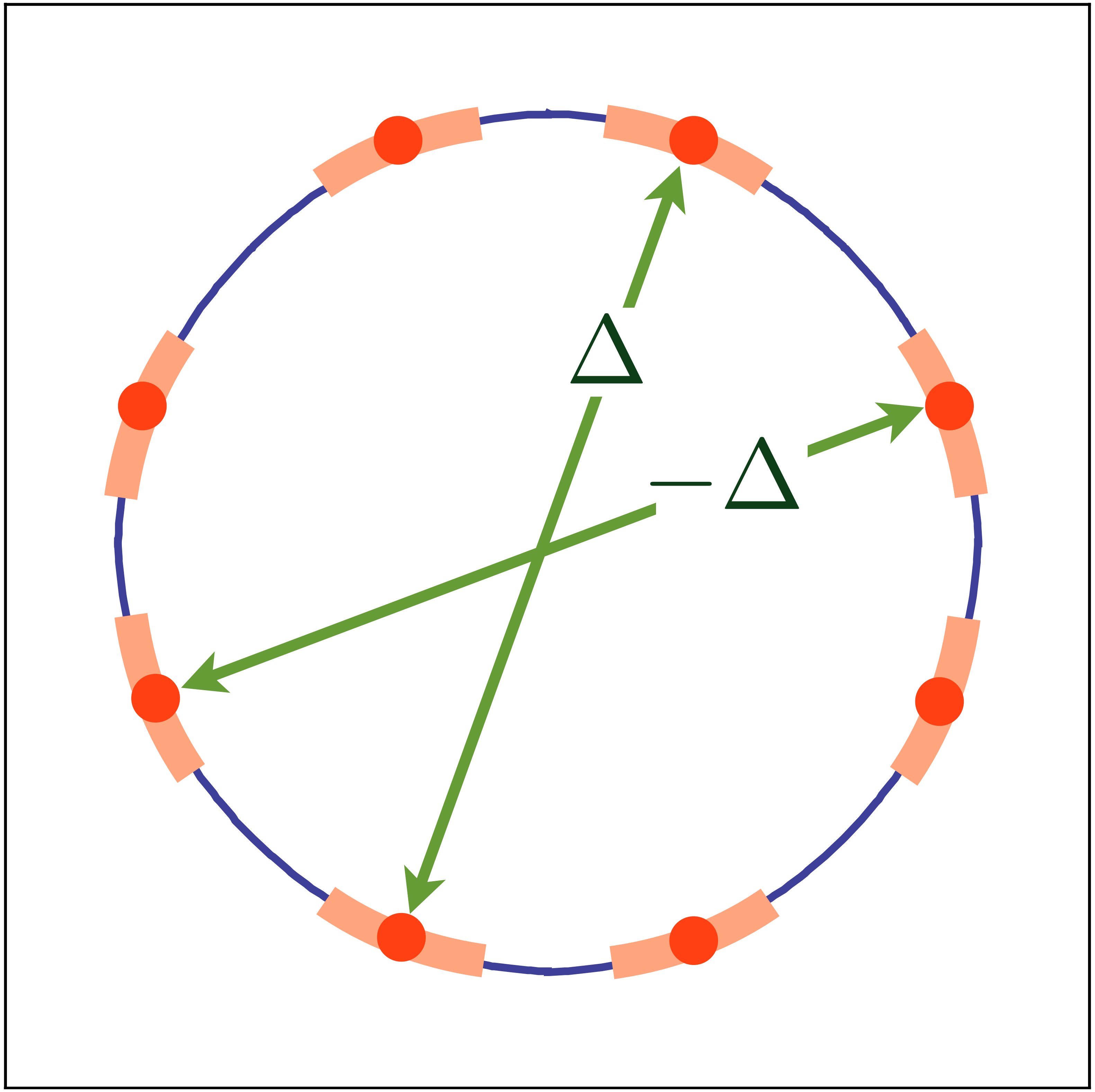


M.A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)



Unconventional pairing at ***and near*** hot spots

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

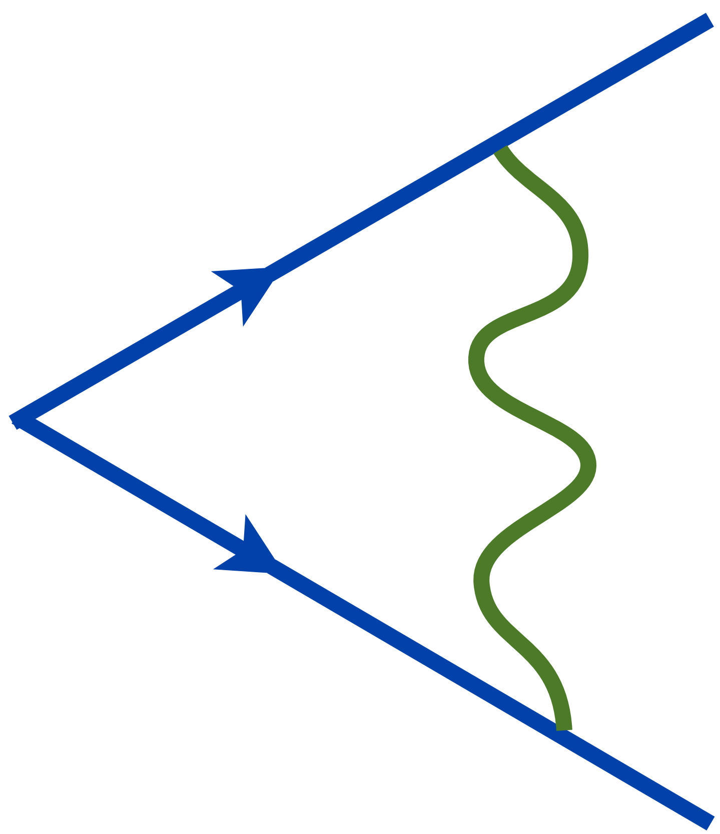


Unconventional pairing at *and near* hot spots

BCS theory

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

Cooper logarithm



Wednesday, August 31, 2011

BCS theory

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

Electron-phonon coupling

Debye frequency

Implies

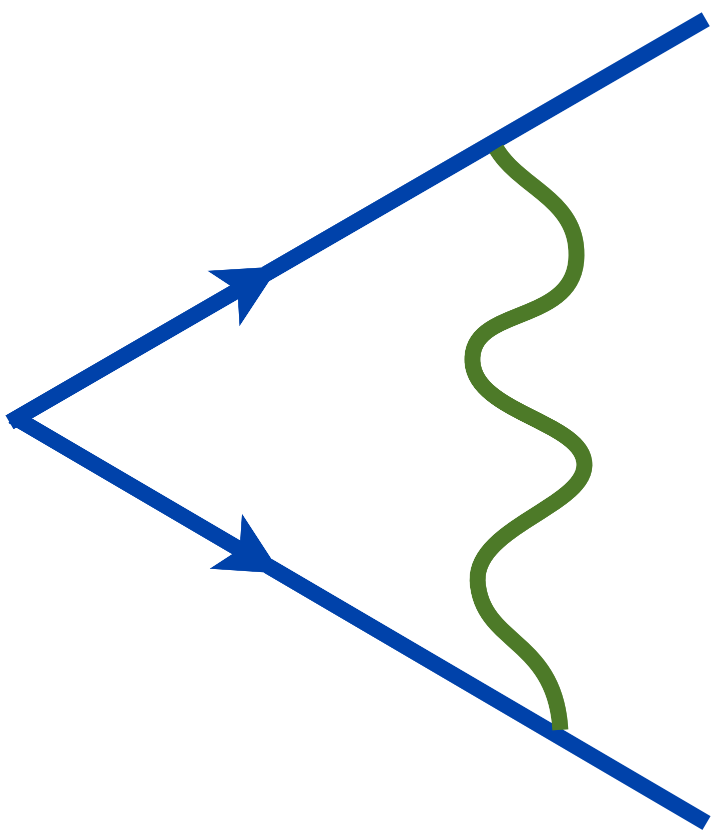
$$T_c \sim \omega_D \exp\left(-1/\lambda\right)$$

Enhancement of pairing susceptibility by interactions

Antiferromagnetic fluctuations: weak-coupling

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

Cooper logarithm



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

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)
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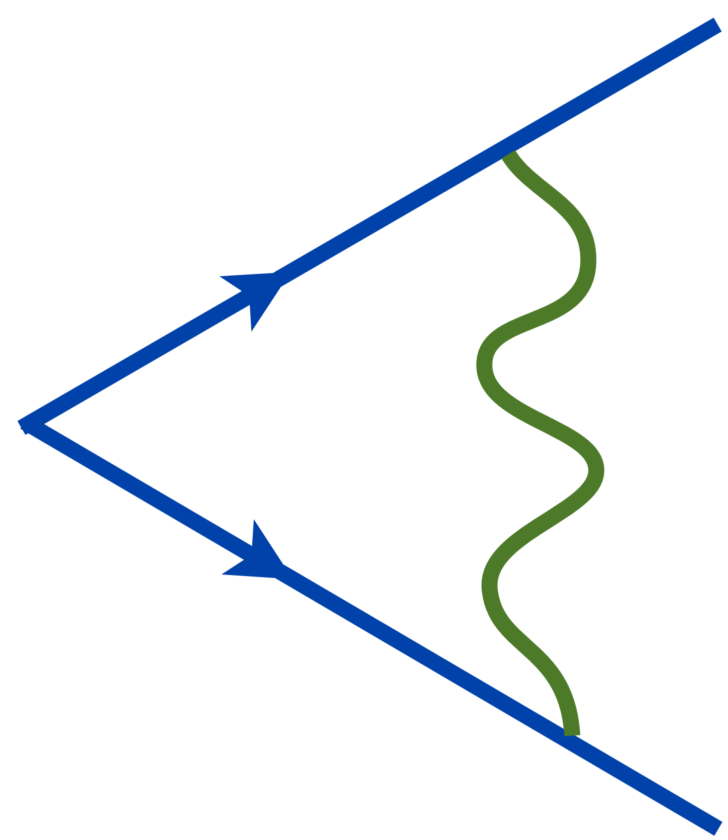
Enhancement of pairing susceptibility by interactions

Spin density wave quantum critical point

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



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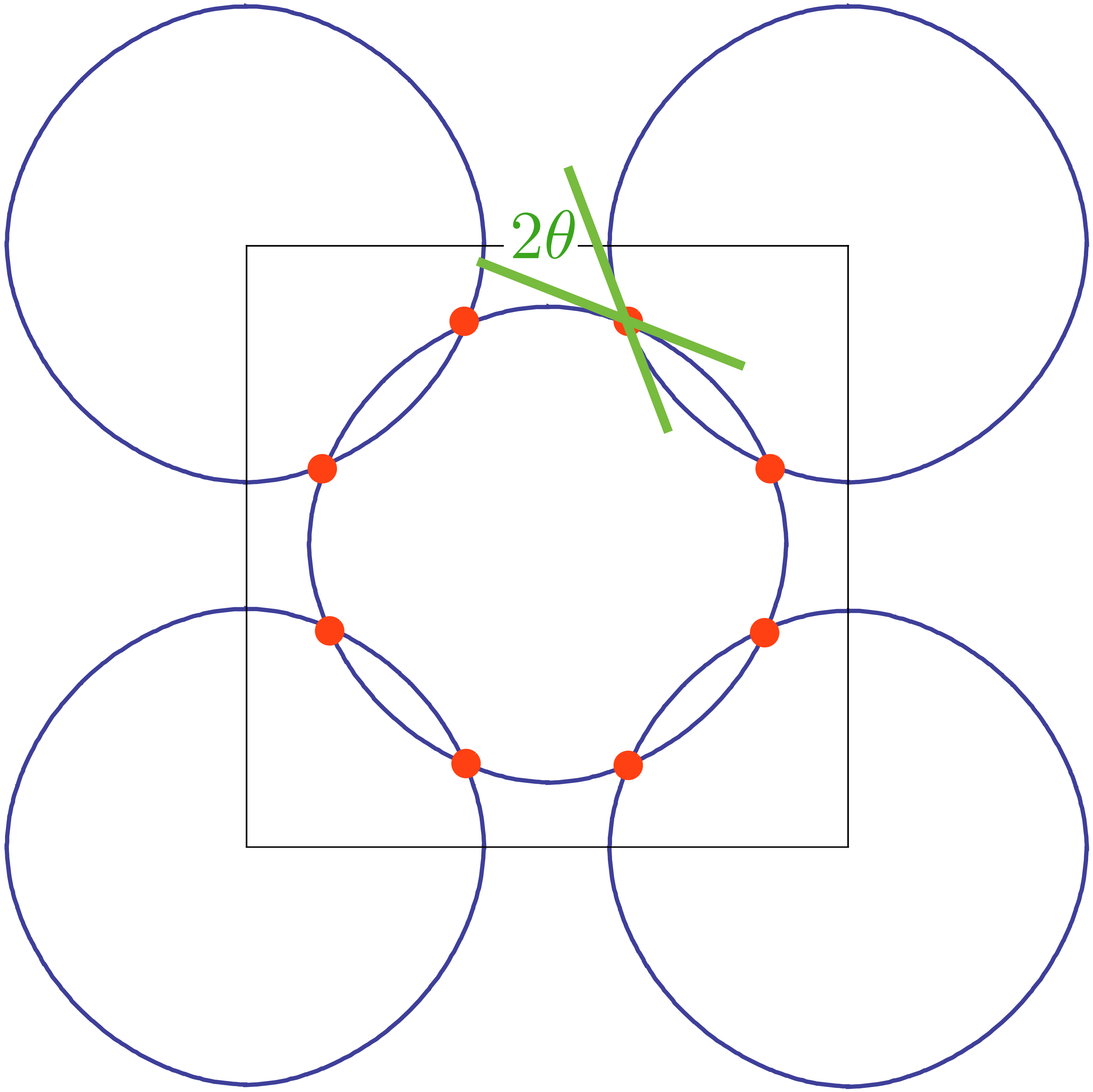
Fermi energy

$\alpha = \tan\theta$, 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

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.

Ar. Abanov, A.V. Chubukov, and A. M. Finkel'stein, *Europhys. Lett.* **54**, 488 (2001)
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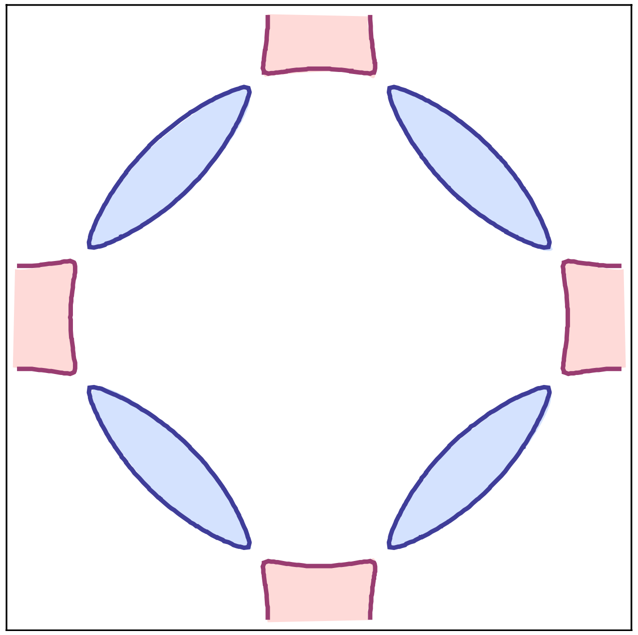
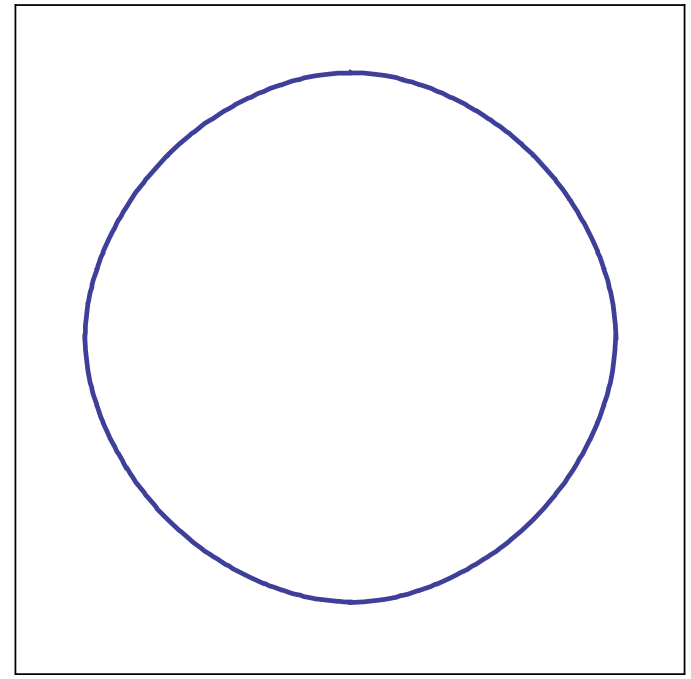
Quantum phase transition with Fermi surface reconstruction



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

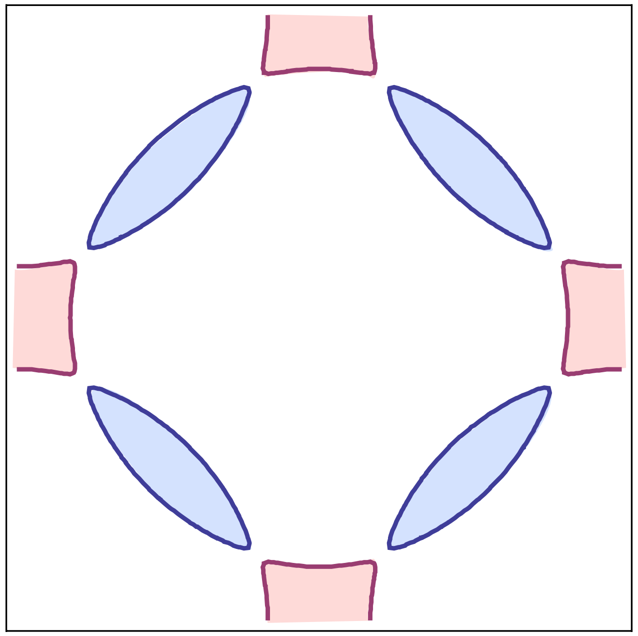
Metal with electron and hole pockets



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

Metal with "large" Fermi surface

Separating onset of SDW order and Fermi surface reconstruction



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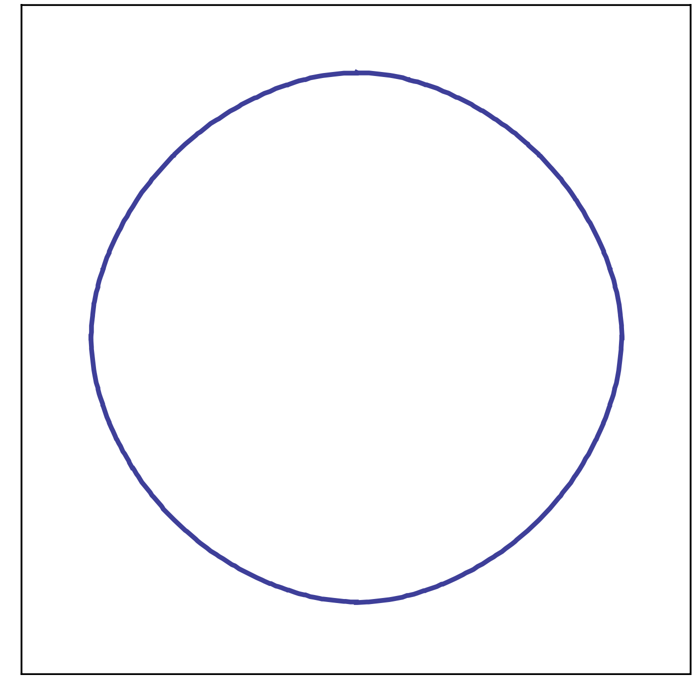

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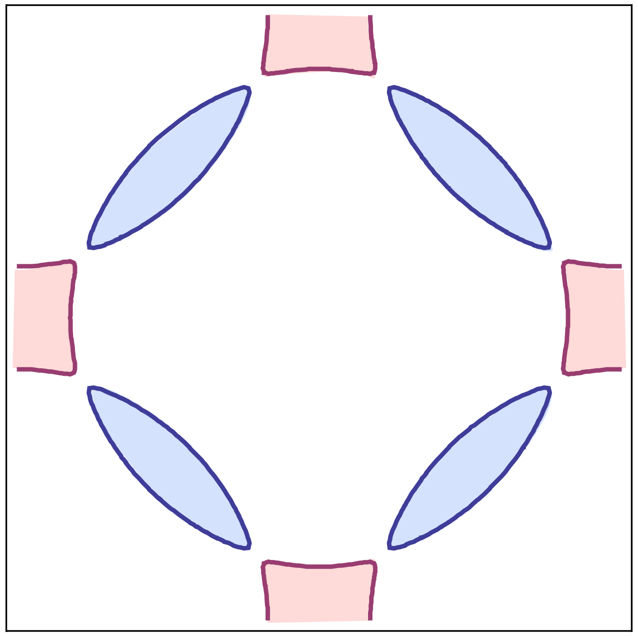

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Metal with electron and hole pockets

Electron and/or hole Fermi pockets form in "local" SDW order, but quantum fluctuations destroy long-range SDW order

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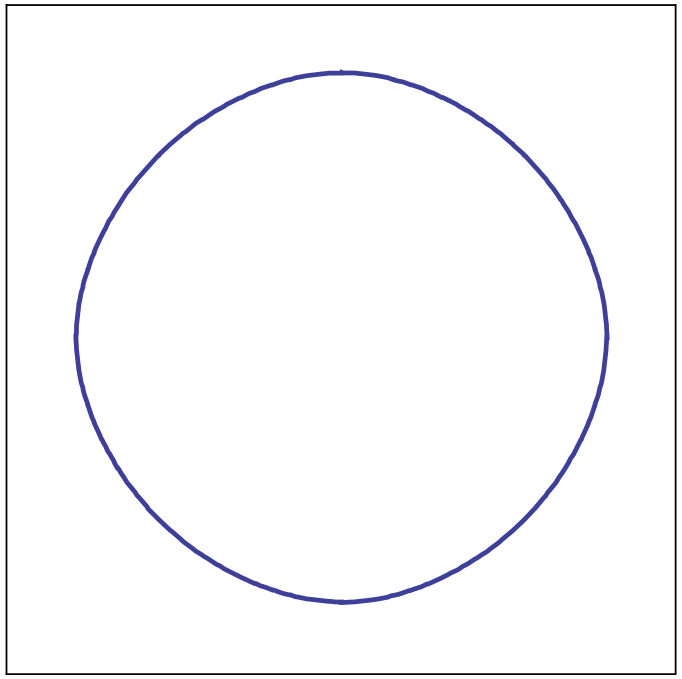

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T. Senthil, S. Sachdev, and M. Vojta, *Phys. Rev. Lett.* **90**, 216403 (2003)

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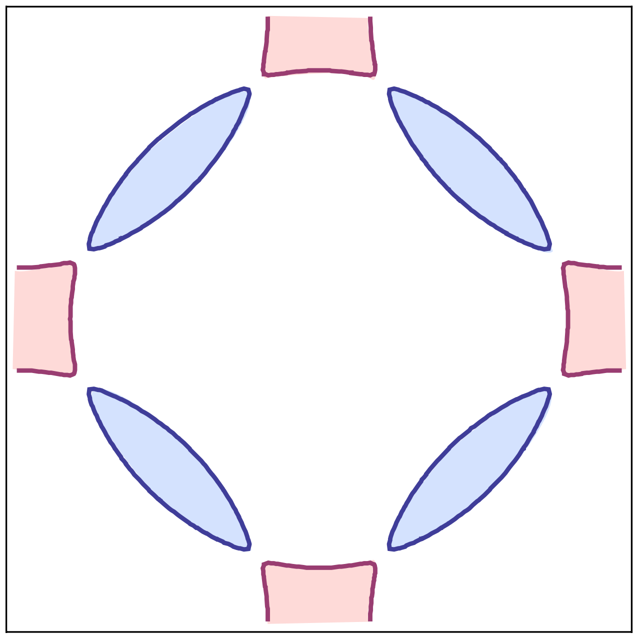

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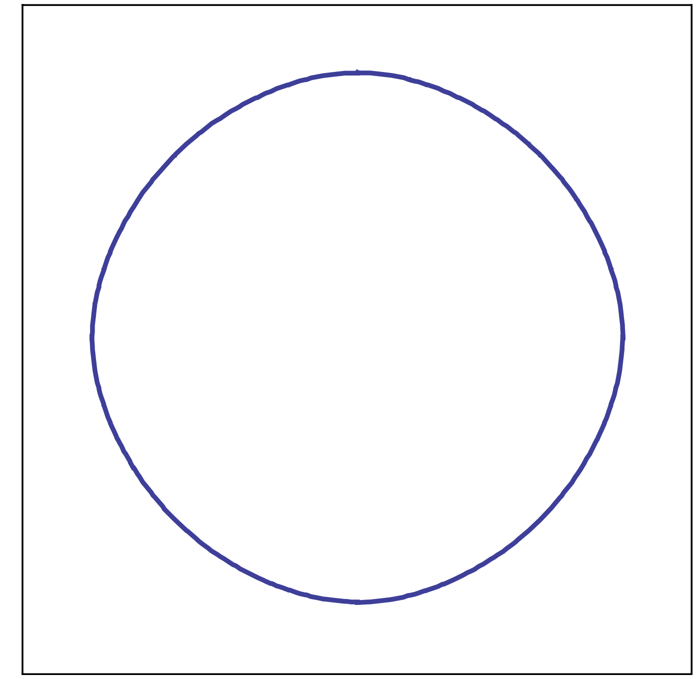

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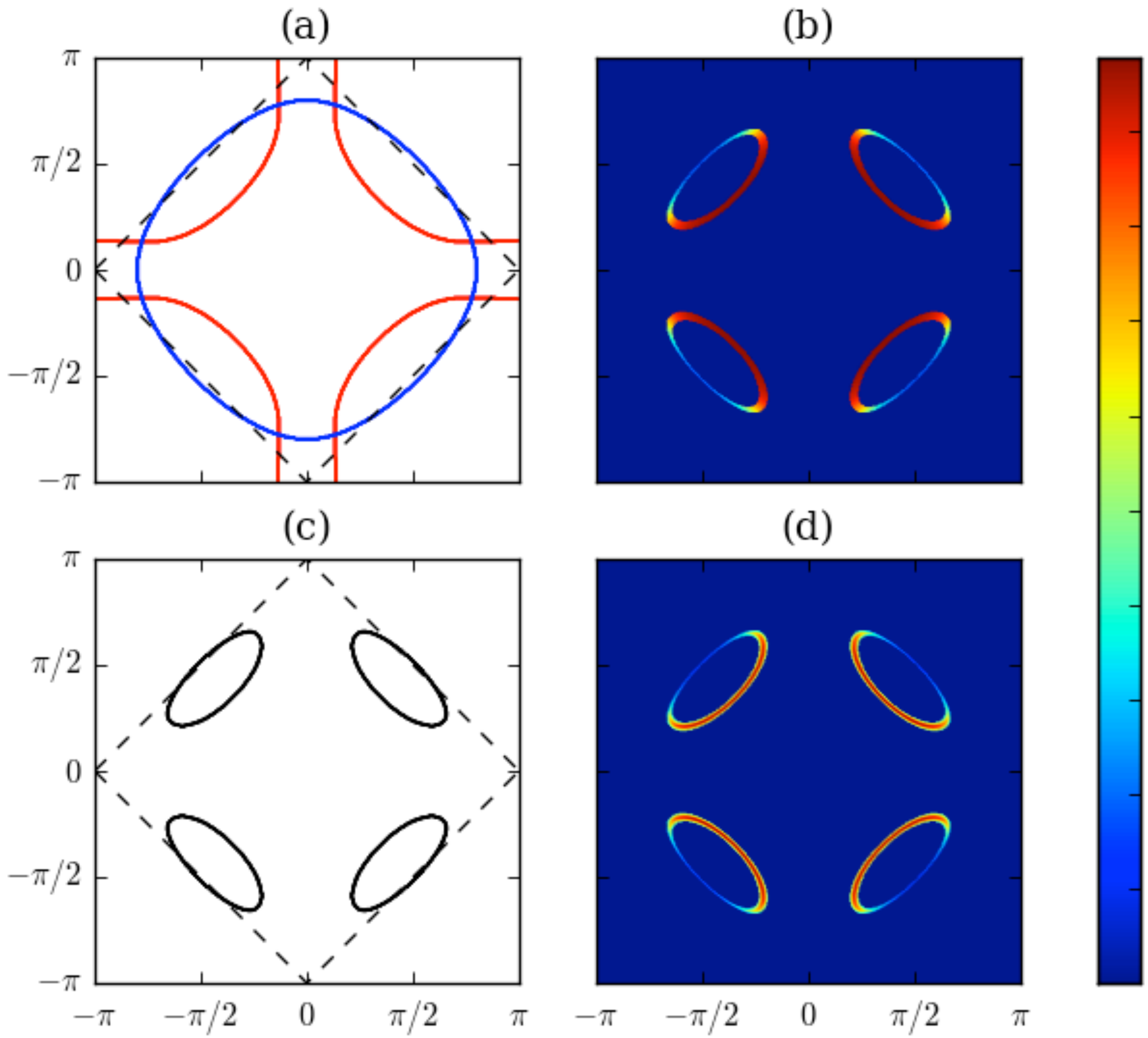
Metal with electron and hole pockets

Fractionalized Fermi liquid (FL*) phase with no symmetry breaking and "small" Fermi surface

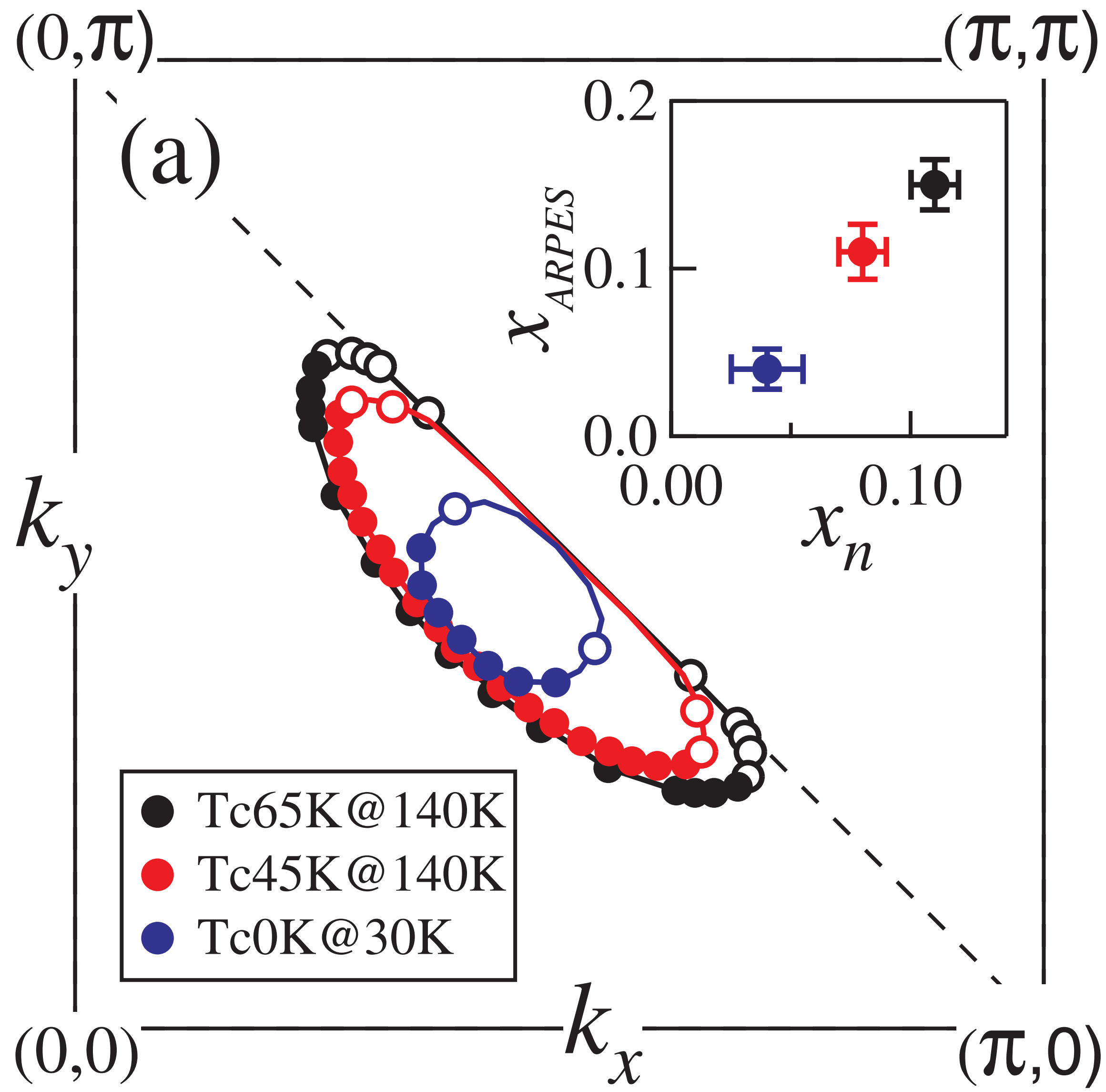
Metal with "large" Fermi surface

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

FL* phase has Fermi pockets without long-range antiferromagnetism, along with emergent gauge excitations



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

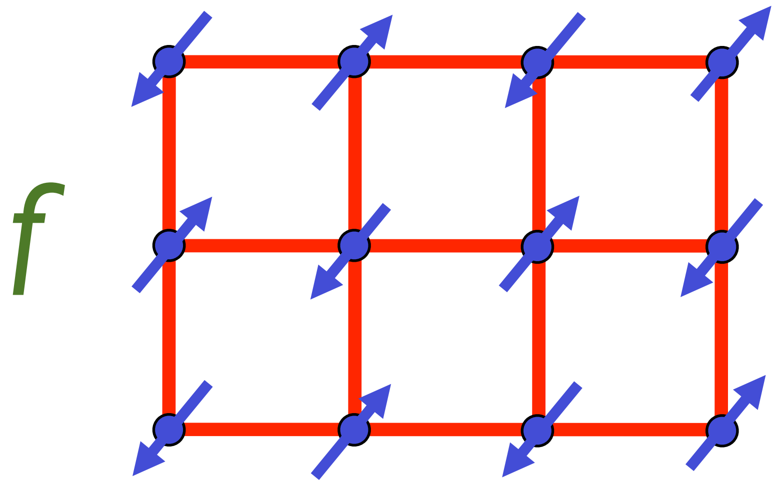


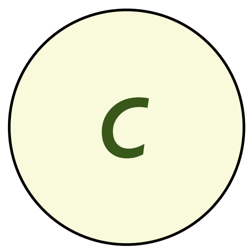
PRL **107,** 047003 (2011) PHYSICAL REVIEW LETTERS week ending 22 JULY 2011

Reconstructed Fermi Surface of Underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ Cuprate Superconductors

H.-B. Yang,[1] J. D. Rameau,[1] Z.-H. Pan,[1] G. D. Gu,[1] P. D. Johnson,[1] H. Claus,[2] D. G. Hinks,[2] and T. E. Kidd[3]

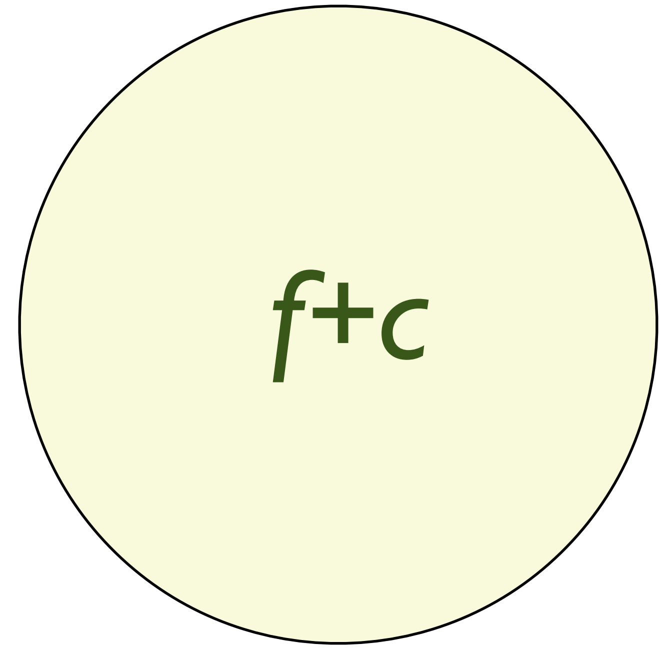
Magnetic order and the heavy Fermi liquid in the Kondo lattice





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

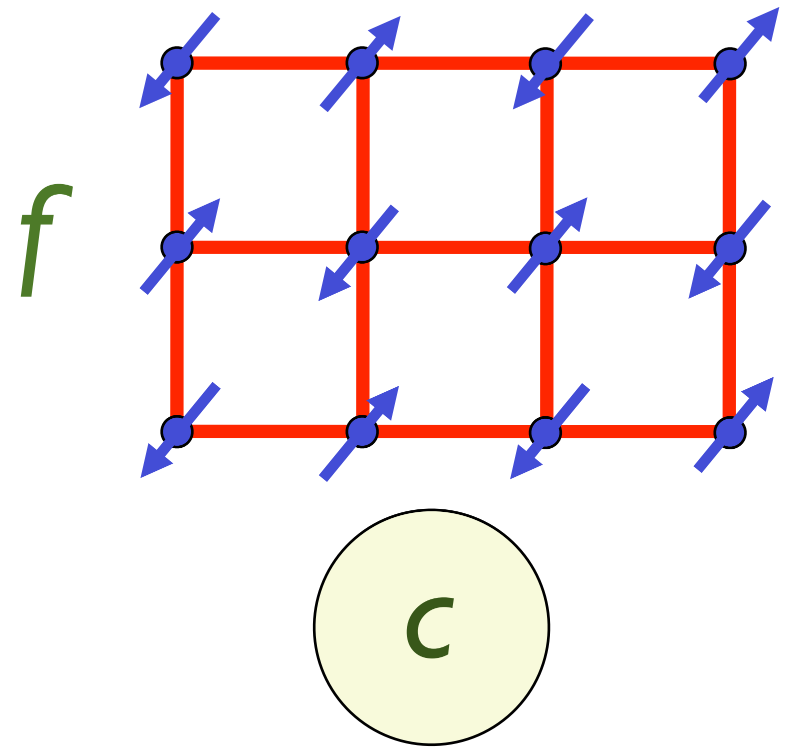
Magnetic Metal:
f-electron moments
and
c-conduction electron
Fermi surface



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

Heavy Fermi liquid
with “large” Fermi
surface of
hydridized *f* and
c-conduction
electrons

Separating onset of SDW order and the heavy Fermi liquid in the Kondo lattice



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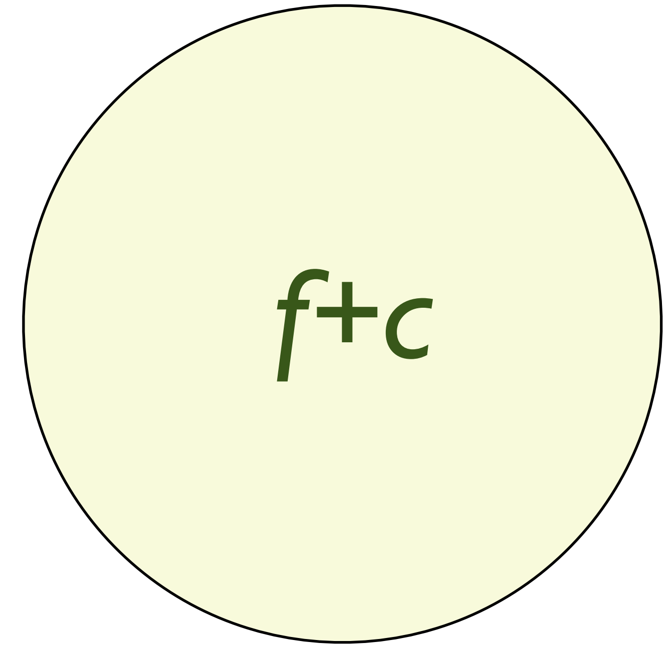

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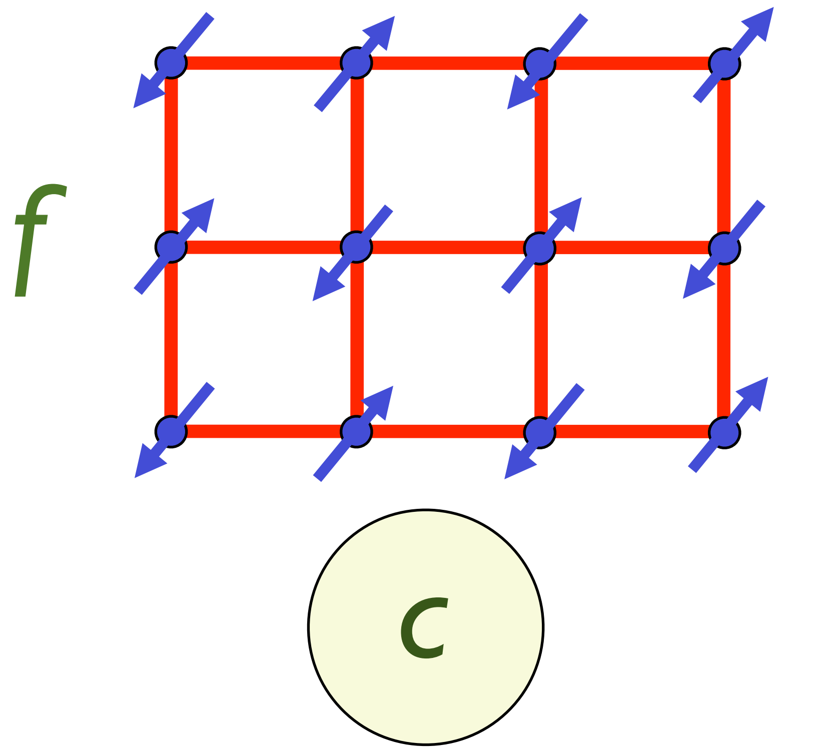

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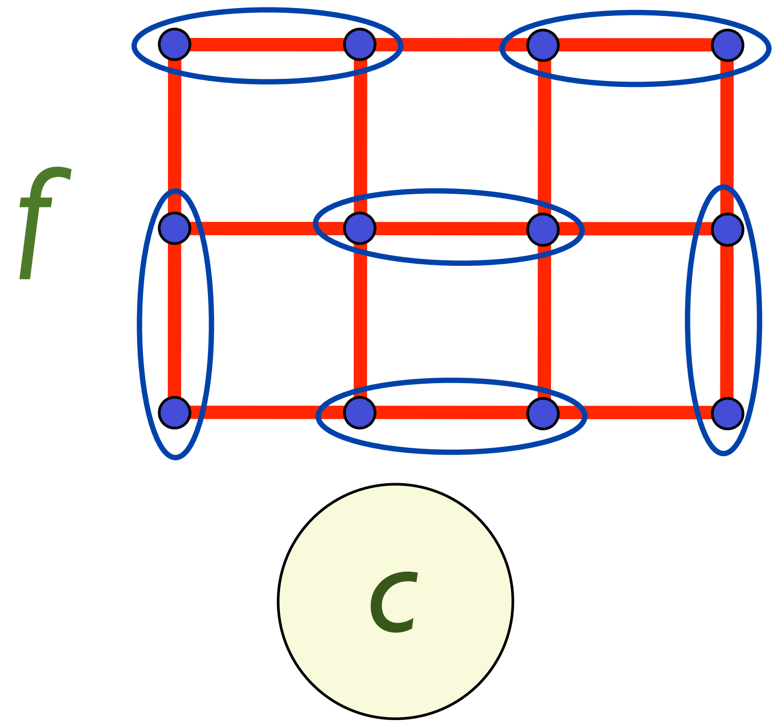

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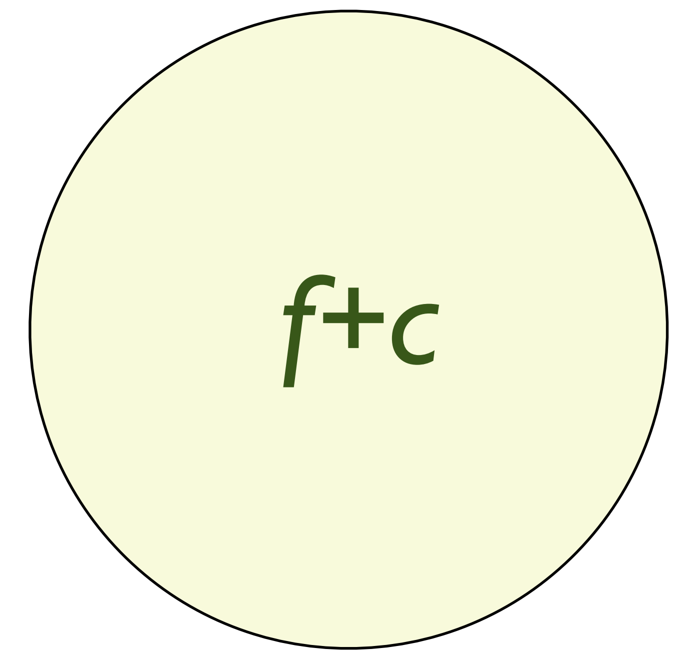
Conduction electron
Fermi surface
and
spin-liquid of
f-electrons



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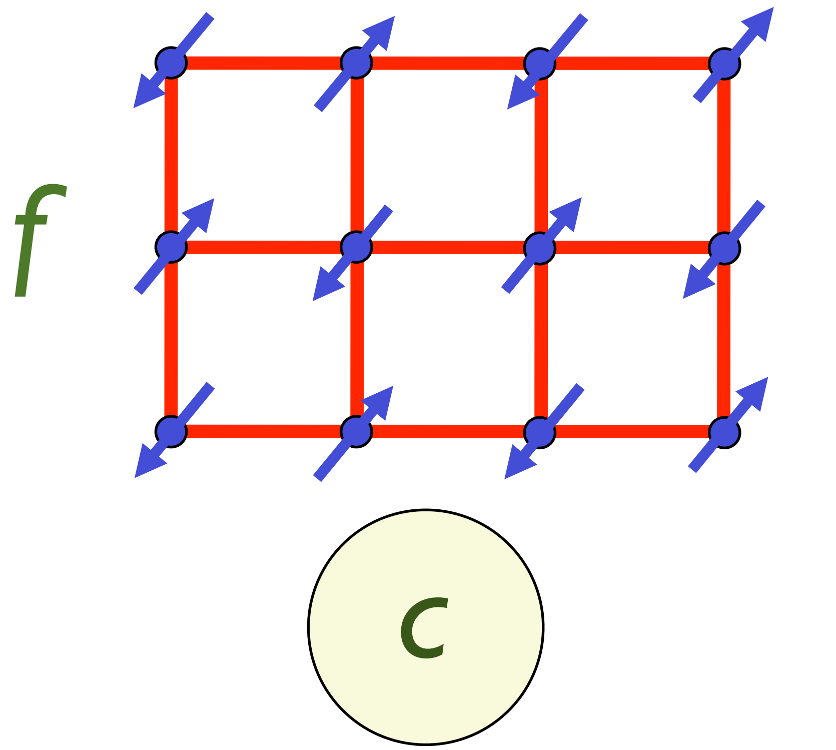

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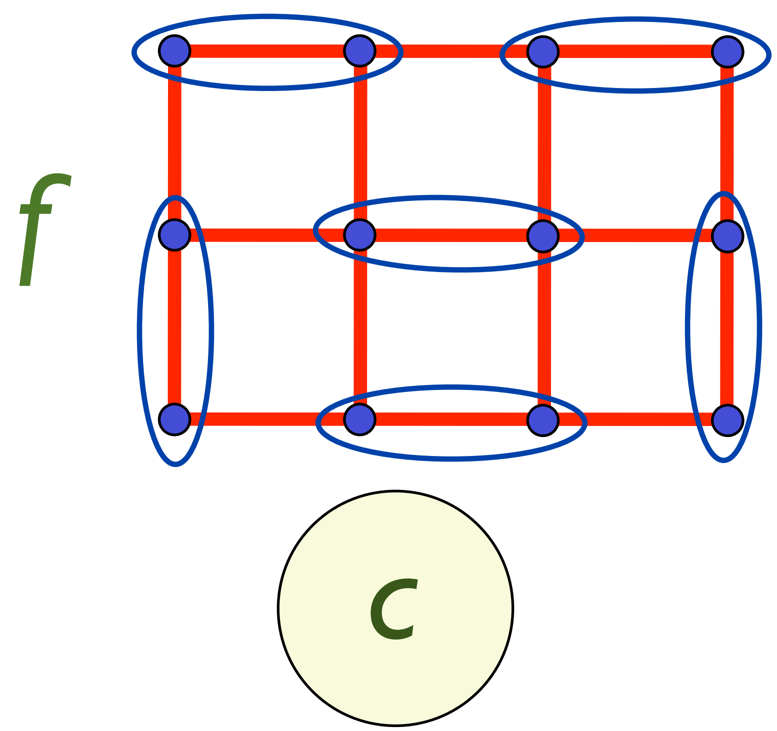

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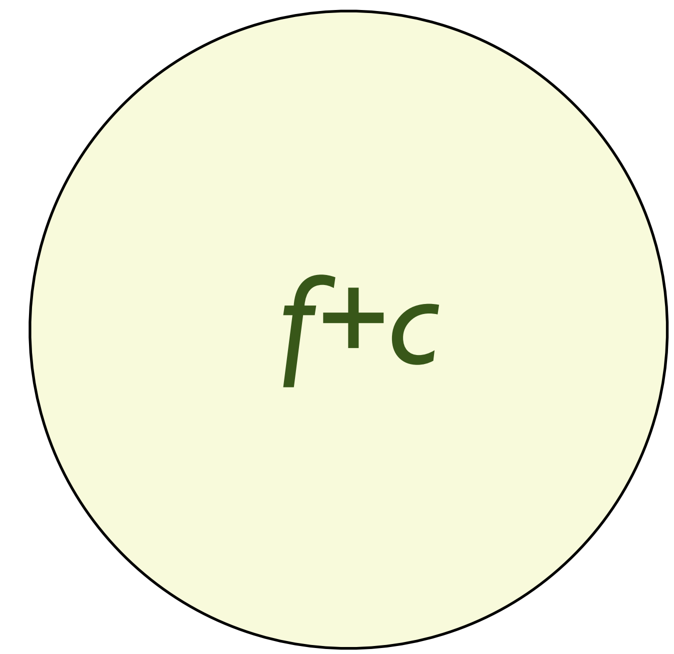

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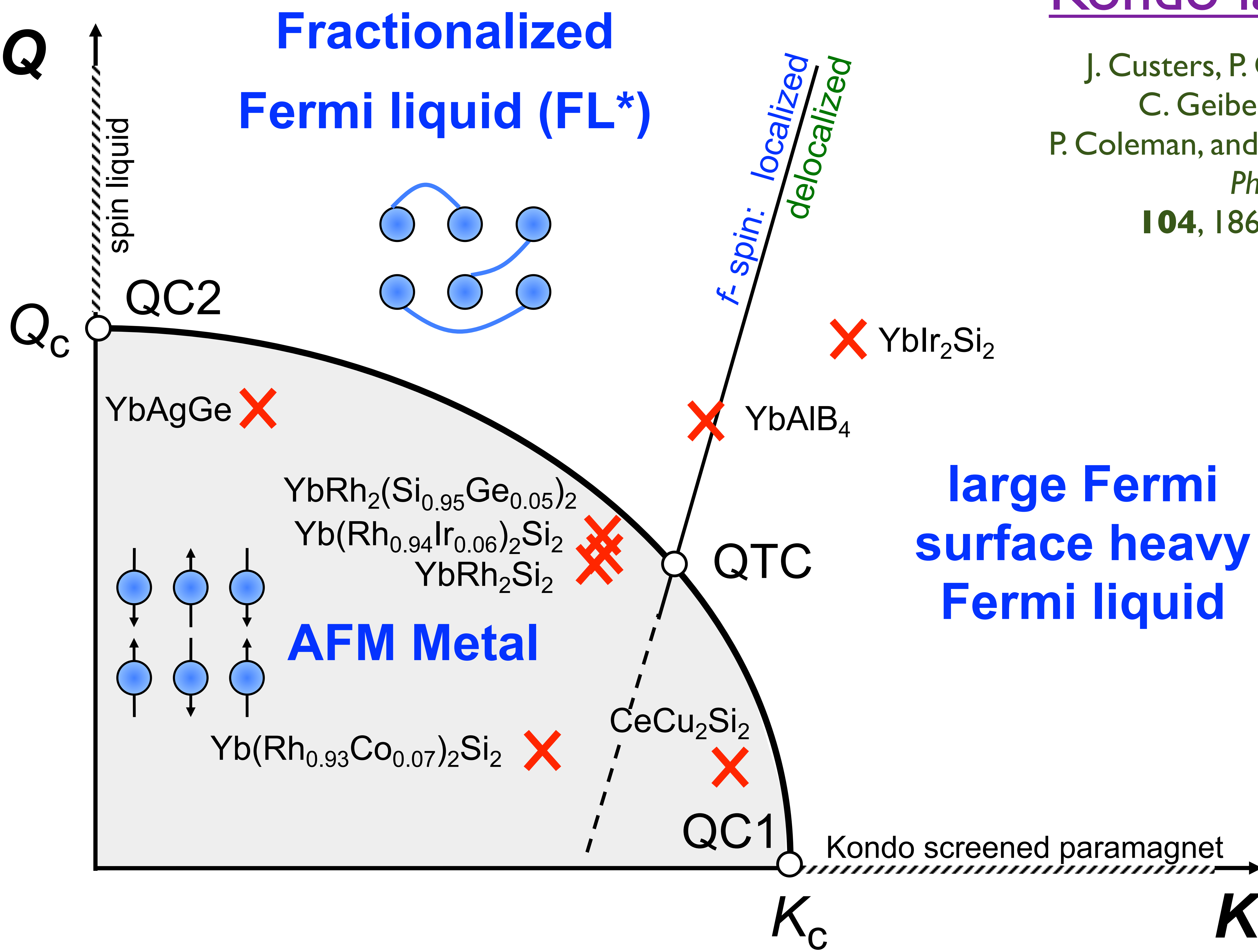
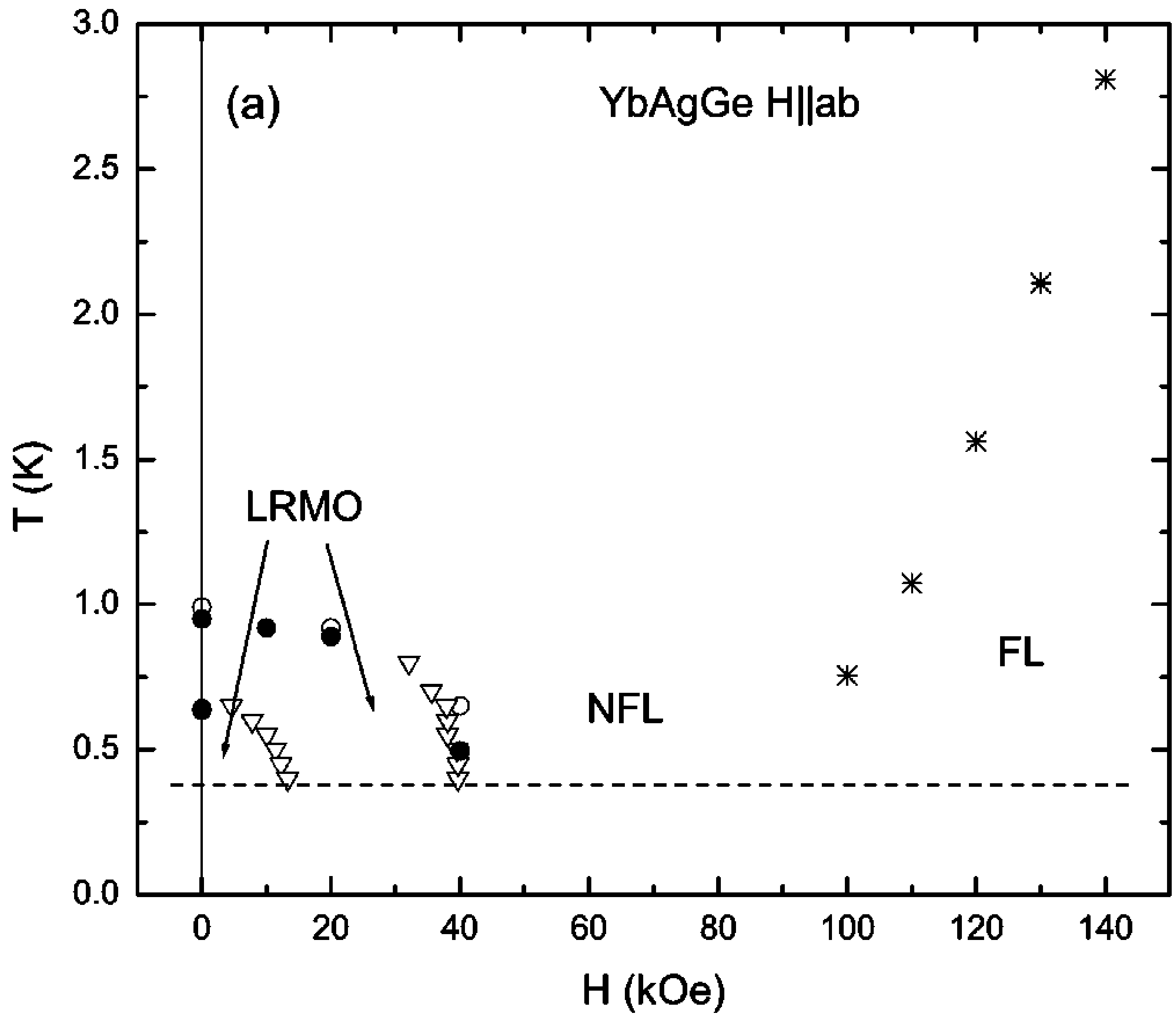
Experimental perpective on same phase diagrams of Kondo lattice

J. Custers, P. Gegenwart, C. Geibel, F. Steglich, P. Coleman, and S. Paschen, *Phys. Rev. Lett.* **104**, 186402 (2010)

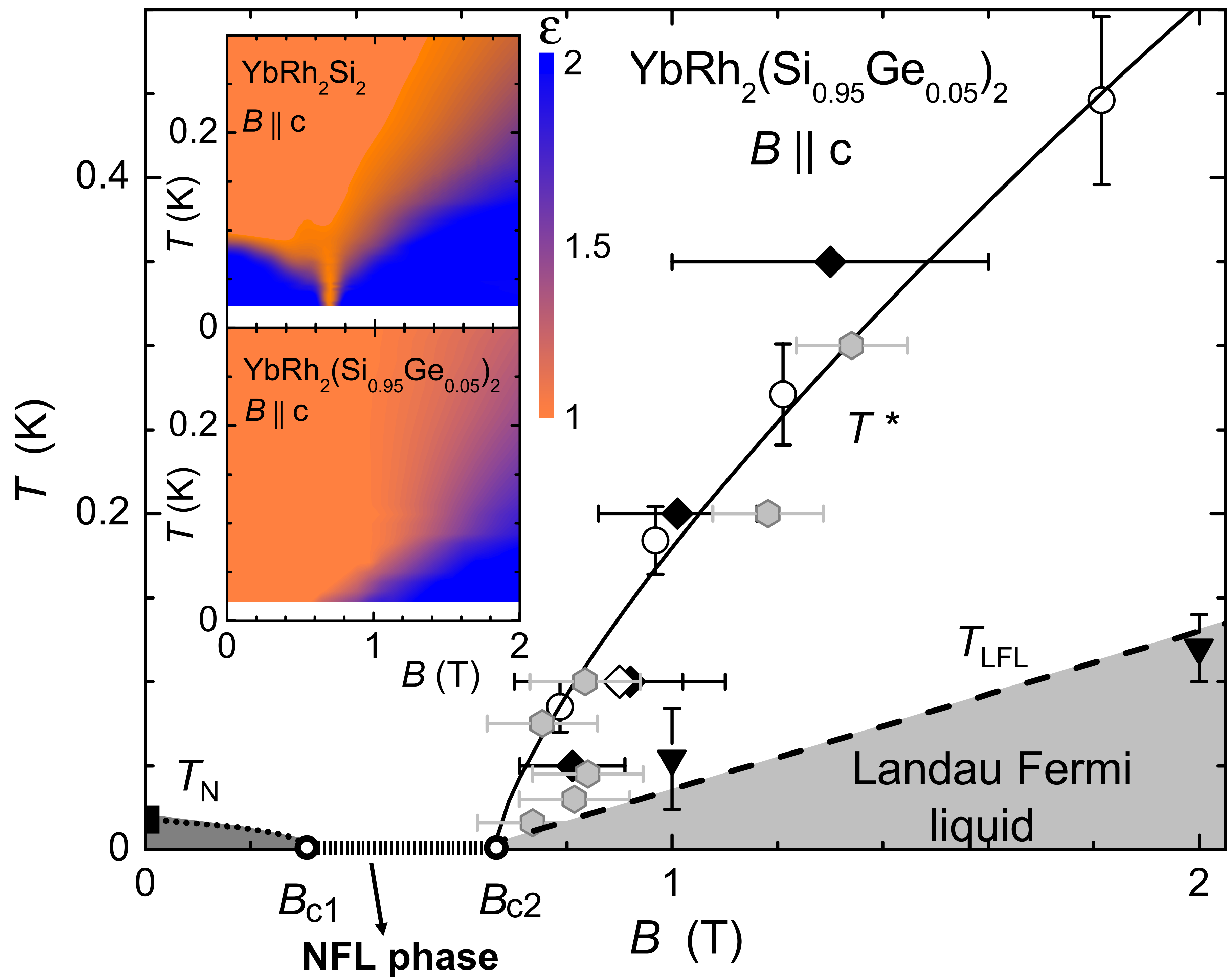




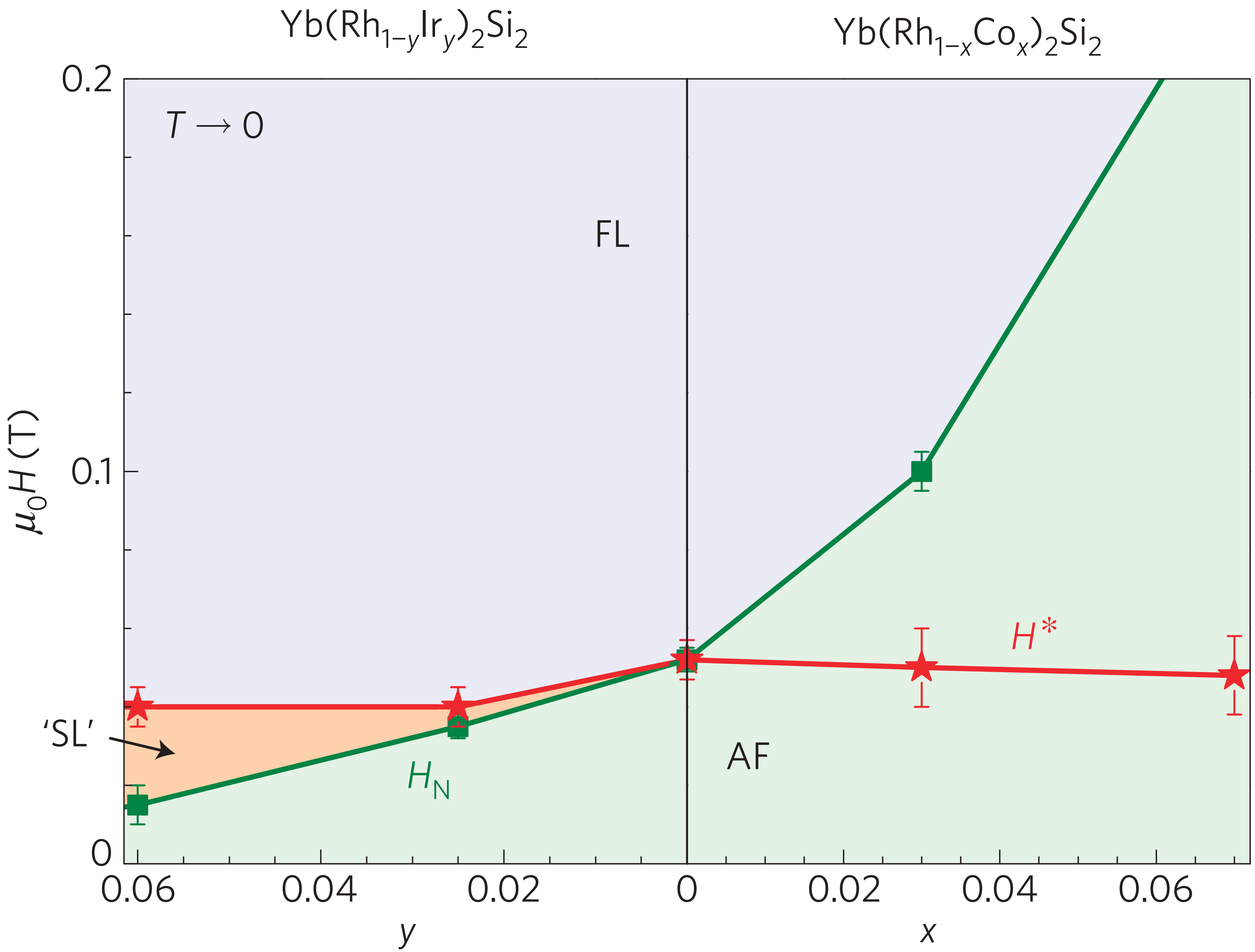
PHYSICAL REVIEW B **69**, 014415 (2004)

Magnetic field induced non-Fermi-liquid behavior in YbAgGe single crystals

S. L. Bud'ko,[1] E. Morosan,[1,2] and P. C. Canfield[1,2]



J. Custers, P. Gegenwart, C. Geibel, F. Steglich, P. Coleman, and S. Paschen, *Phys. Rev. Lett.* **104**, 186402 (2010)



Detaching the antiferromagnetic quantum critical point from the Fermi-surface reconstruction in $YbRh_2Si_2$

Nature Physics 5, 465 (2009)

S. Friedemann[1★], T. Westerkamp[1], M. Brando[1], N. Oeschler[1], S. Wirth[1], P. Gegenwart[1,2], C. Krellner[1], C. Geibel[1] and F. Steglich[1★]

Characteristics of FL* phase

- Fermi surface volume does not count all electrons.

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

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- Such a phase *must* have neutral $S = 1/2$ excitations (”spinons”), and collective spinless gauge excitations (“topological” order).

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

Characteristics of FL* phase

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- Such a phase *must* have neutral $S = 1/2$ excitations (”spinons”), and collective spinless gauge excitations (“topological” order).

- These topological excitations are needed to account for the deficit in the Fermi surface volume, in M. Oshikawa’s proof of the Luttinger theorem.

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

1. Fate of the Fermi surface: reconstruction or not ? Experimental motivations from cuprates and pnictides

2. Conventional theory and its breakdown in two spatial dimensions

3. Fermi surface reconstruction: onset of unconventional superconductivity

4. Fermi surface reconstruction *without* symmetry breaking: metals with "topological" order

5. The nematic transition: field theory of antipodal Fermi surface points

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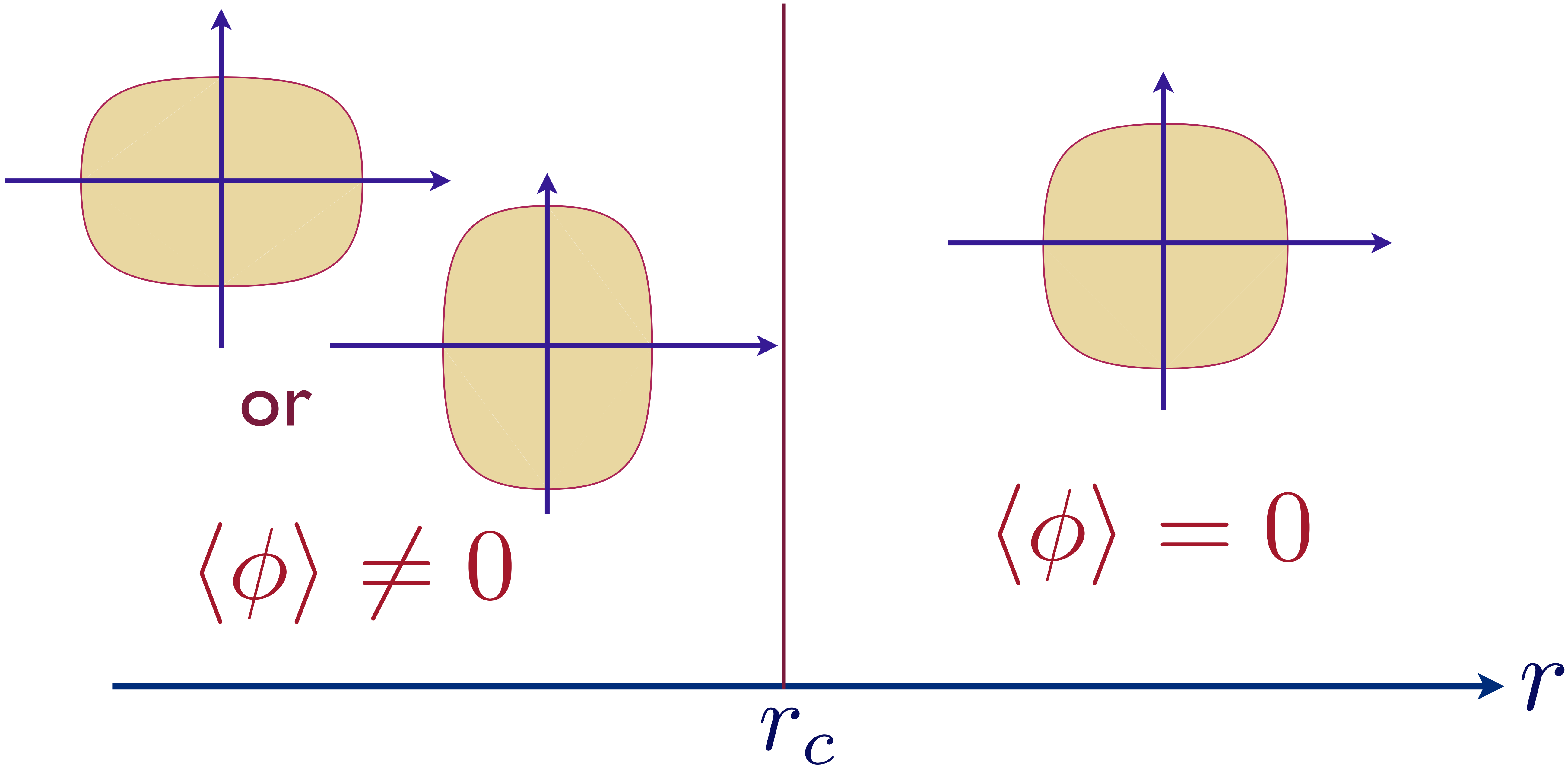
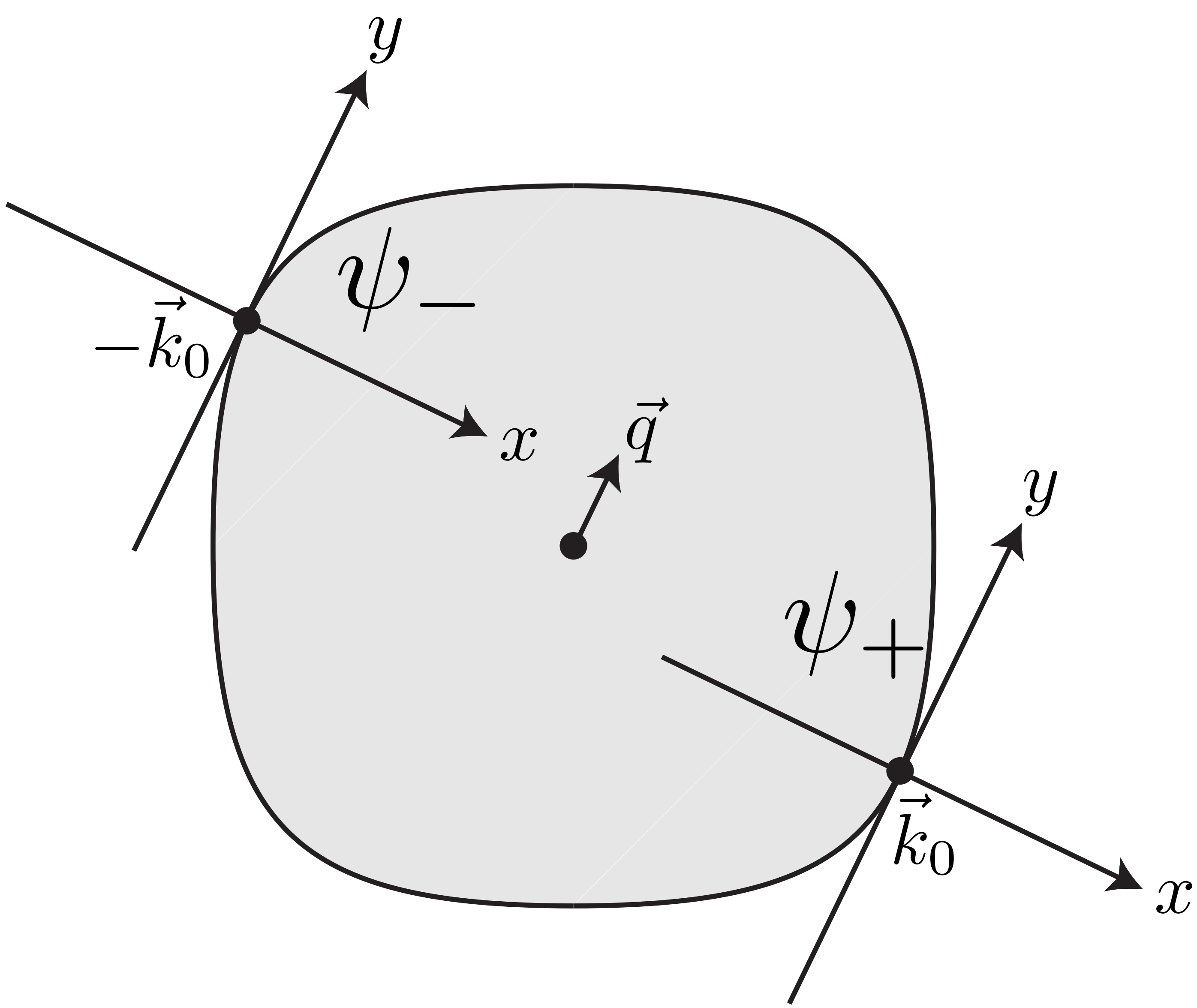
Quantum criticality of Ising-nematic ordering



Pomeranchuk instability as a function of coupling r

Quantum criticality of Ising-nematic ordering



- Critical point is described by an *infinite* set of 2+1 dimensional field theories, one for each direction $\hat{q}$. Each theory has a finite Fermi surface curvature, with quasiparticle dispersion $= v_F q_x + q_y^2/(2m^*)$.

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

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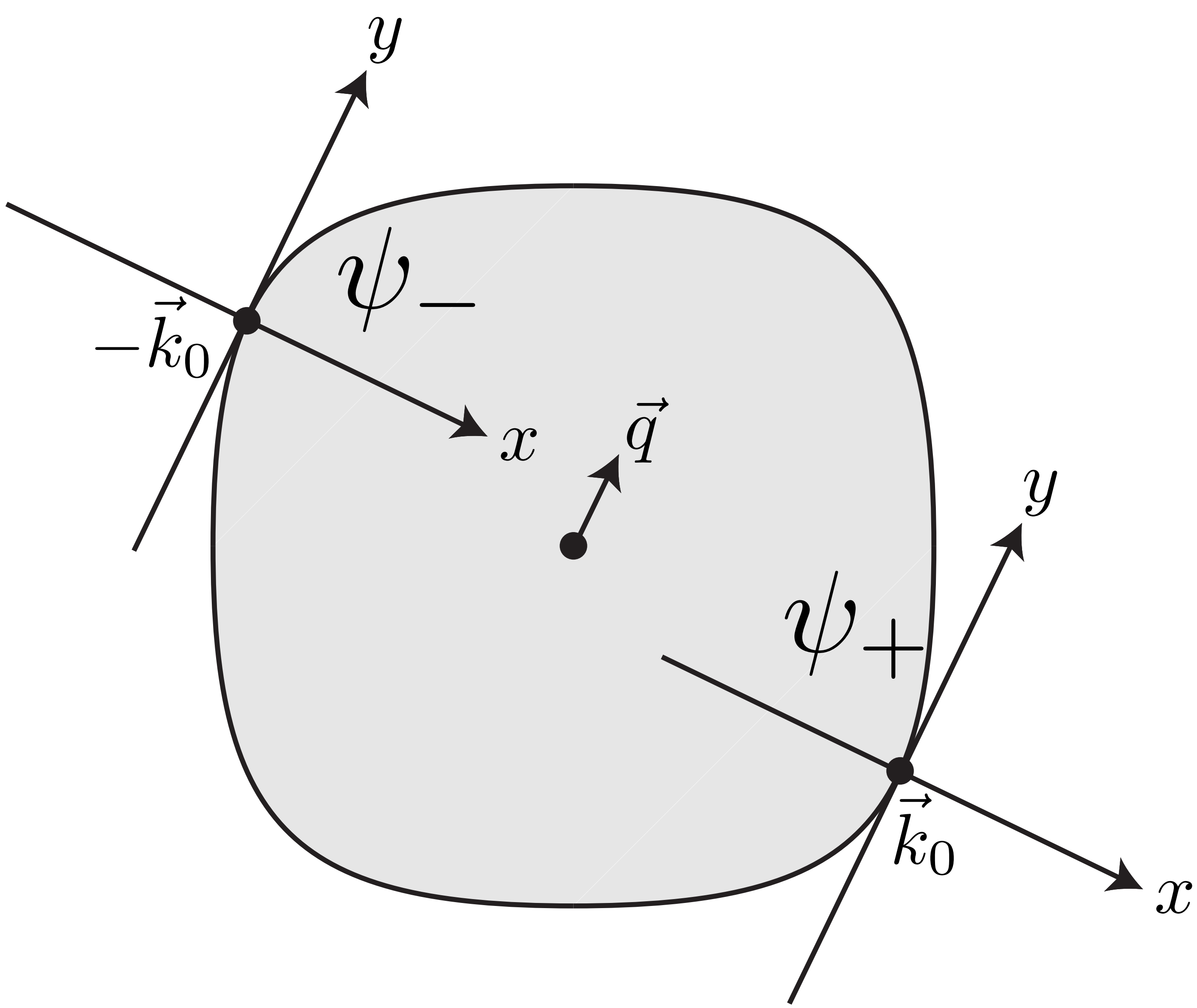

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M.A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)

Quantum criticality of Ising-nematic ordering

Strong coupling problem: Infinite number of 2+1 dimensional field theories at Ising-nematic quantum critical point

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

Conclusions

All quantum phase transitions of metals
in two spatial dimensions
involving symmetry breaking
are strongly-coupled
and
and very different from the
"Stoner" mean field theory

Conclusions

There is an instability of
universal strength to
unconventional superconductivity
near the onset of antiferromagnetism
in a two-dimensional metal

Conclusions

The strong-coupling physics may also apply in three spatial dimensions, but the "Stoner" mean field theory is locally stable.

Conclusions

There can be an intermediate
non-Fermi liquid phase
between the two Fermi liquids:
the antiferromagnetic metal
with “small” Fermi surfaces
and
the metal with “large” Fermi surfaces

Conclusions

This *non-Fermi liquid phase*
has neutral S=1/2 excitations,
and "topological" gauge excitations,
which account for
deficits in the Luttinger count of the volume
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