The onset of antiferromagnetism in metals: from the cuprates to the heavy fermion compounds

Twelfth Arnold Sommerfeld Lecture Series
January 31 - February 3, 2012

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1. 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 and the heavy fermion compounds

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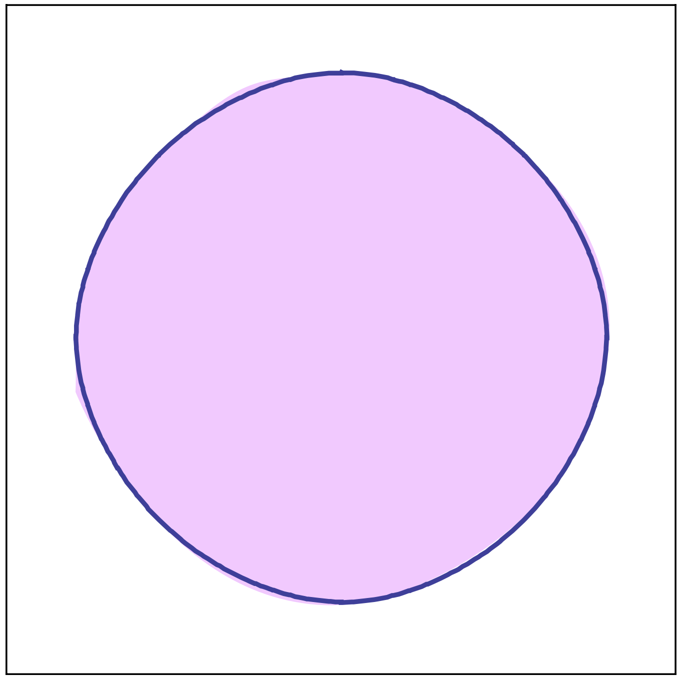
Fermi surface+antiferromagnetism

Metal with "large" Fermi surface



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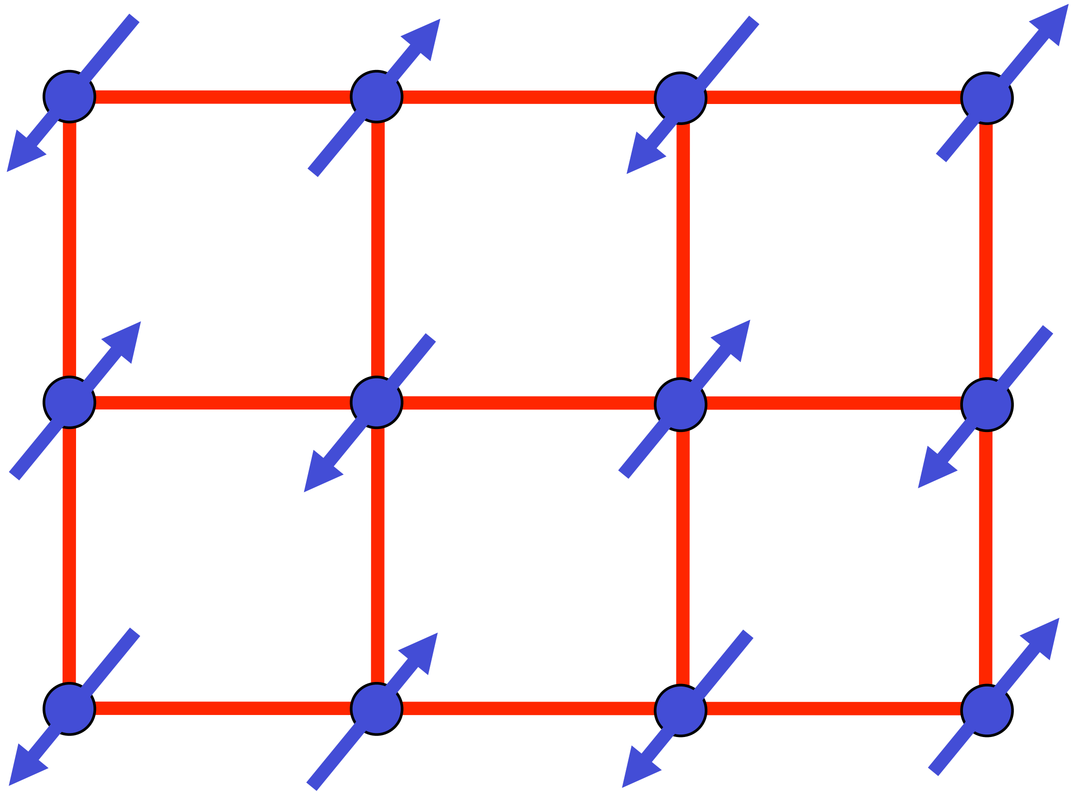
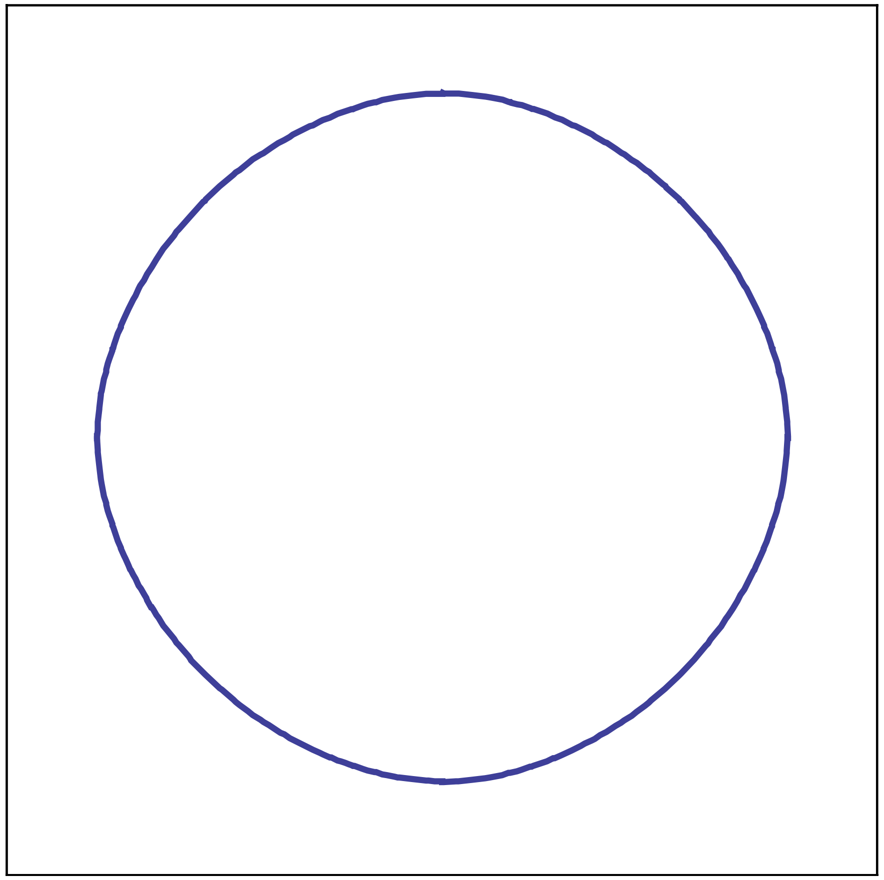


The electron spin polarization obeys

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

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



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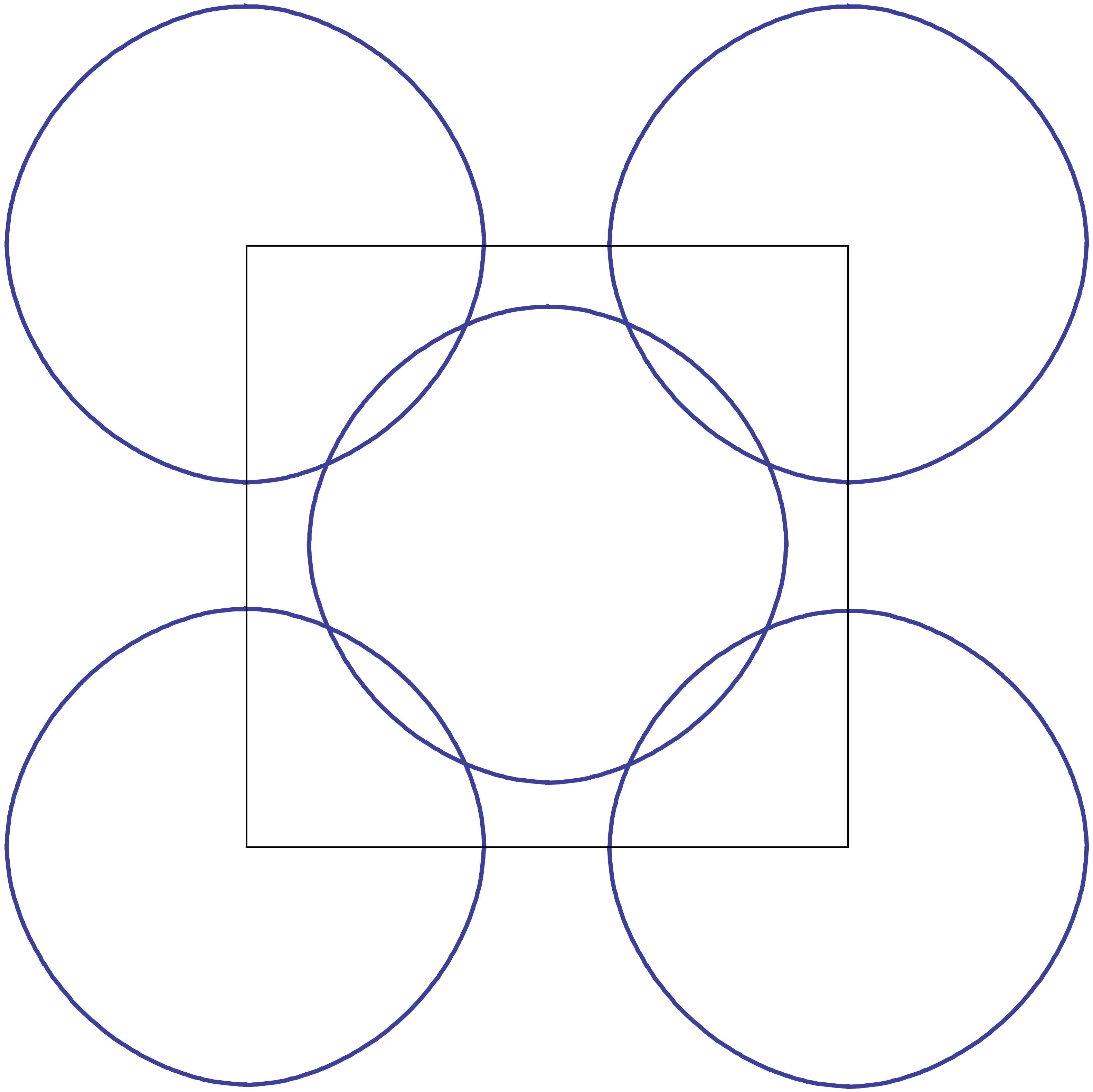
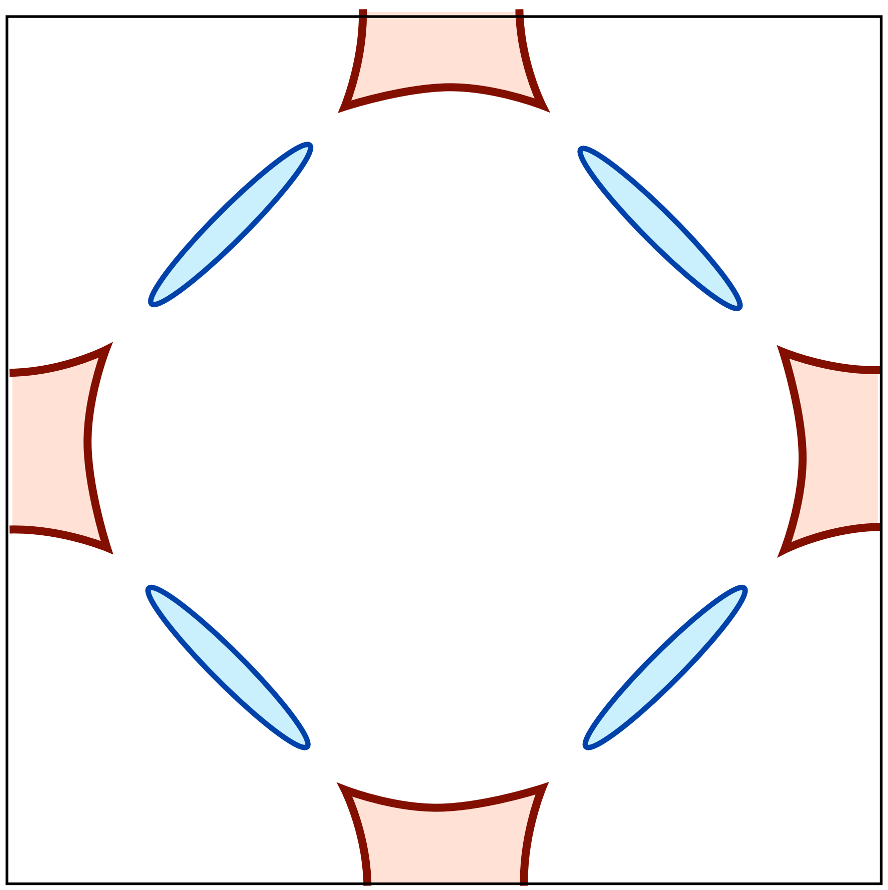
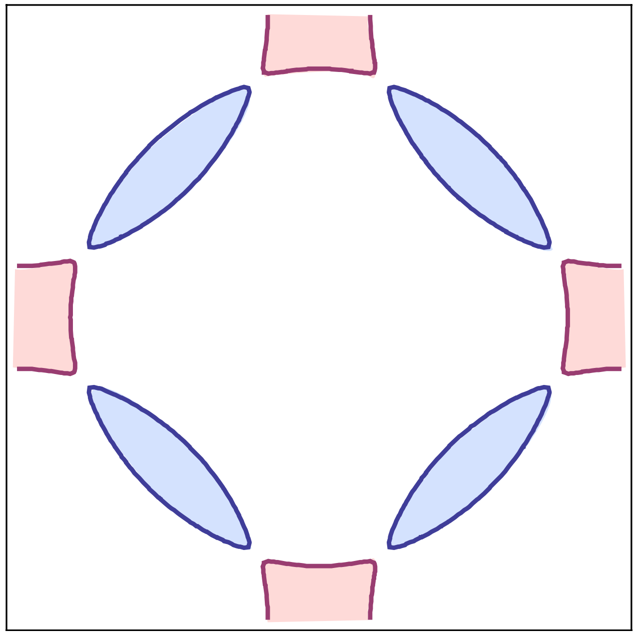


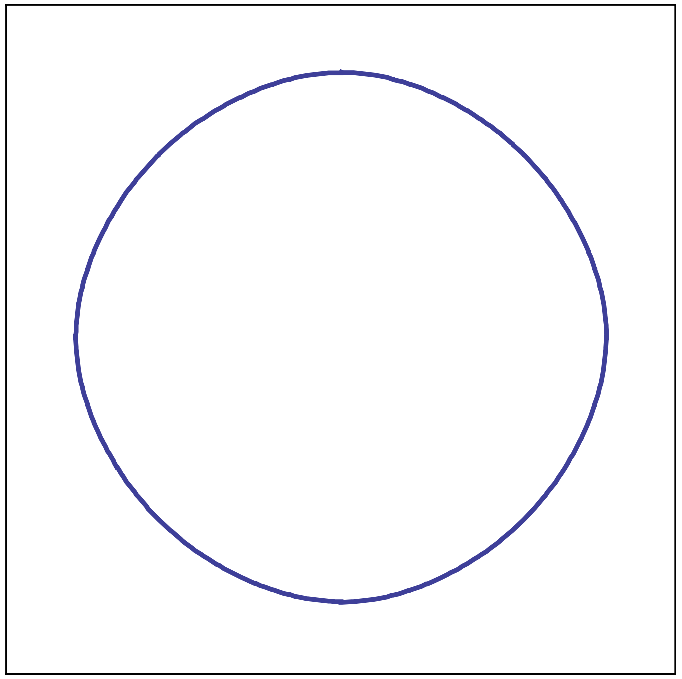
Fermi surfaces translated by $\mathbf{K} = (\pi, \pi)$.



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





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Increasing interaction

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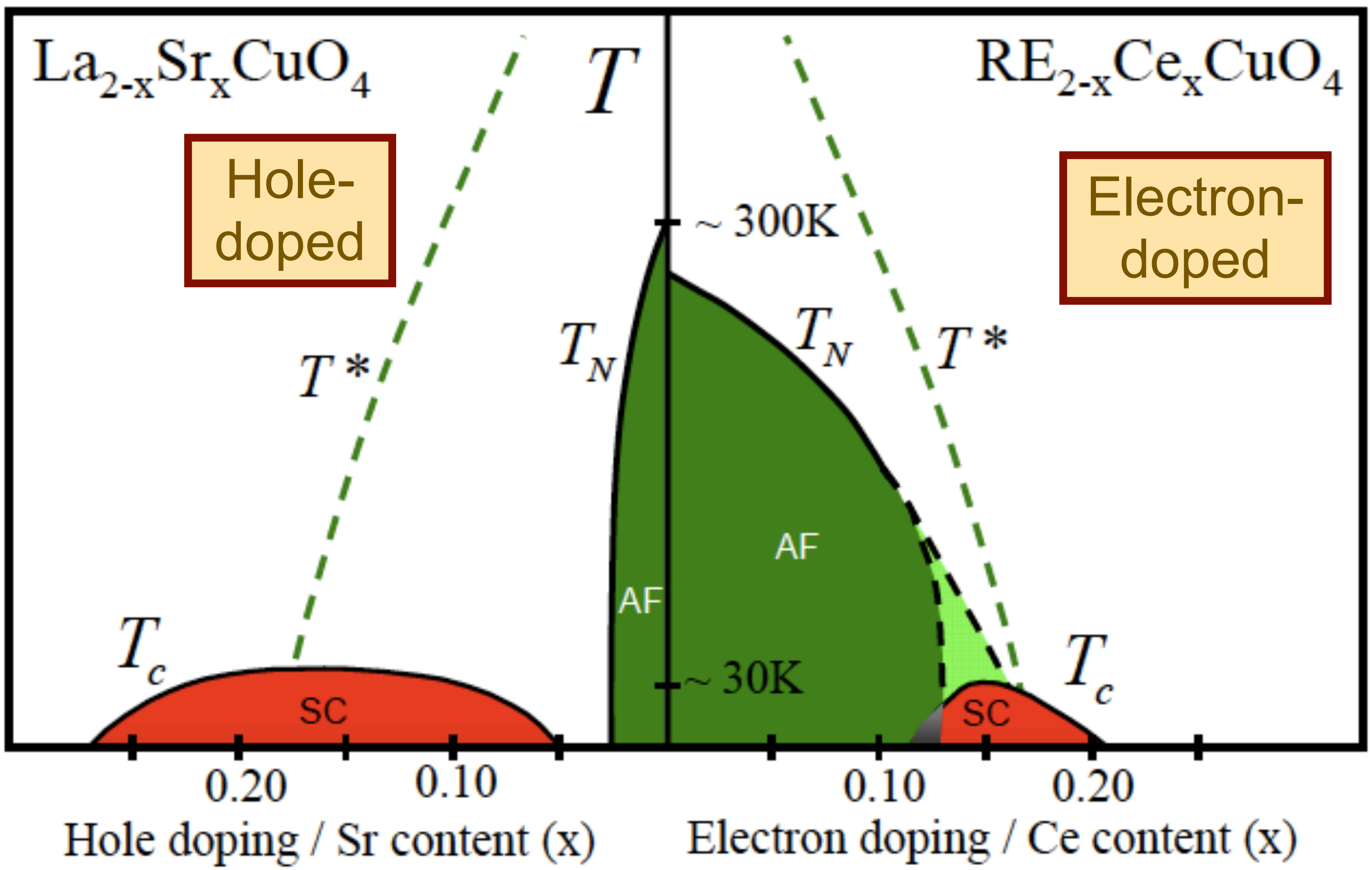
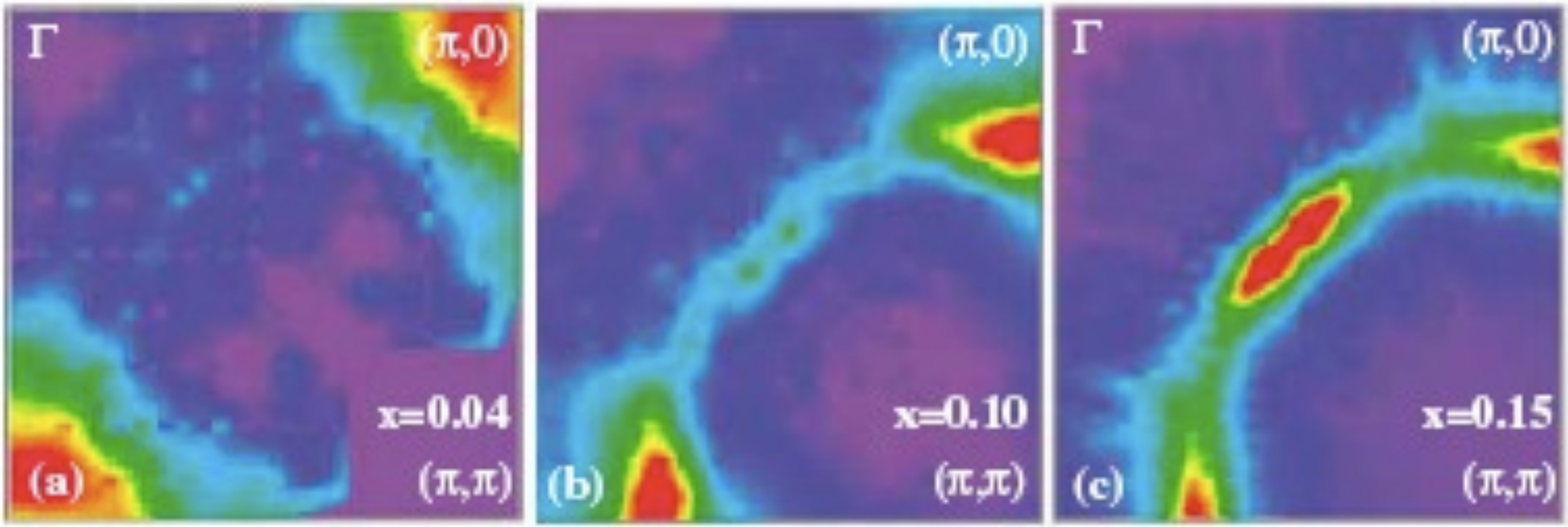
A.V. Chubukov and D. K. Morr, *Physics Reports* **288**, 355 (1997).

Hole and electron-doped cuprate superconductors

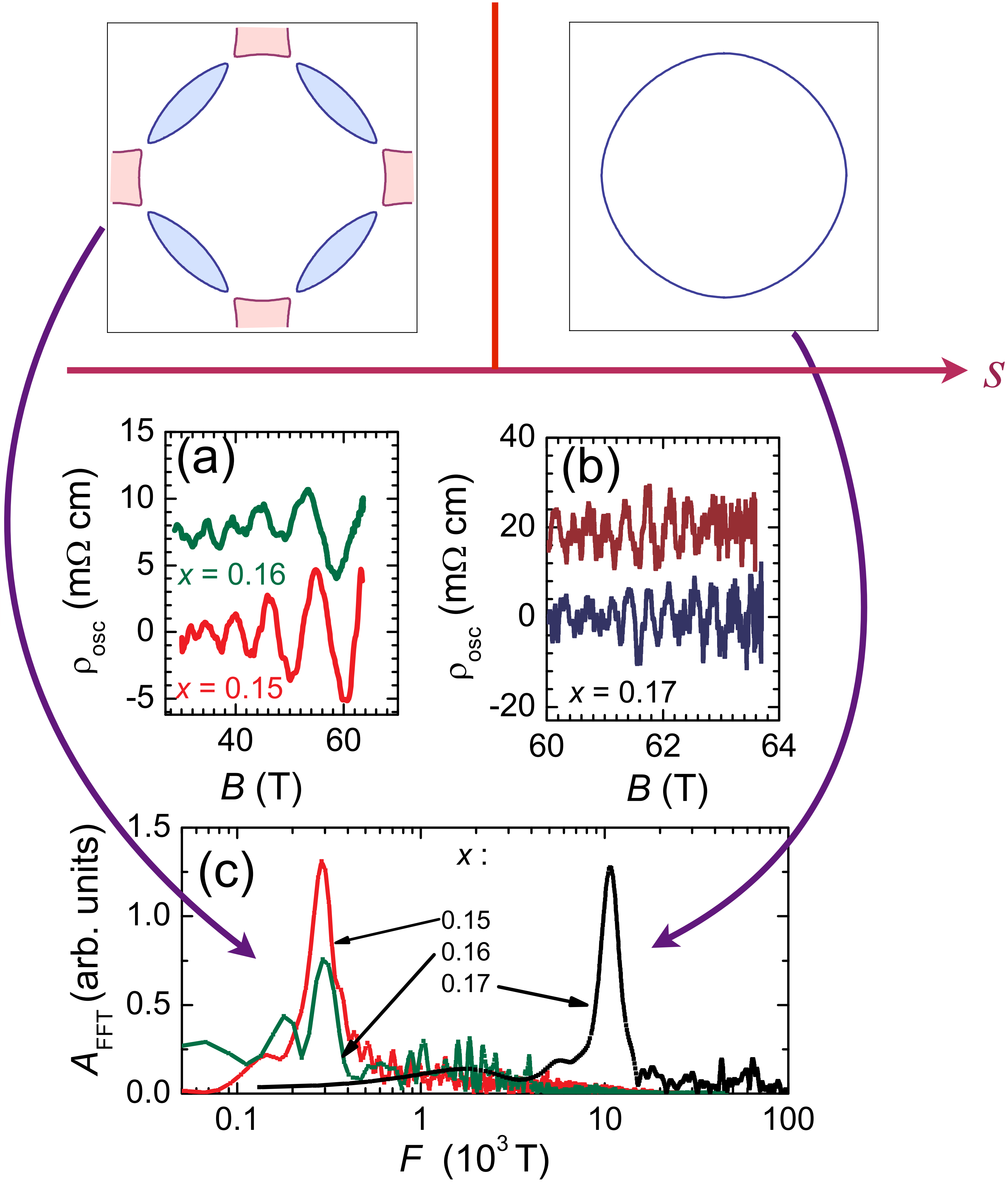


Photoemission in $Nd_{2-x}Ce_xCuO_4$



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

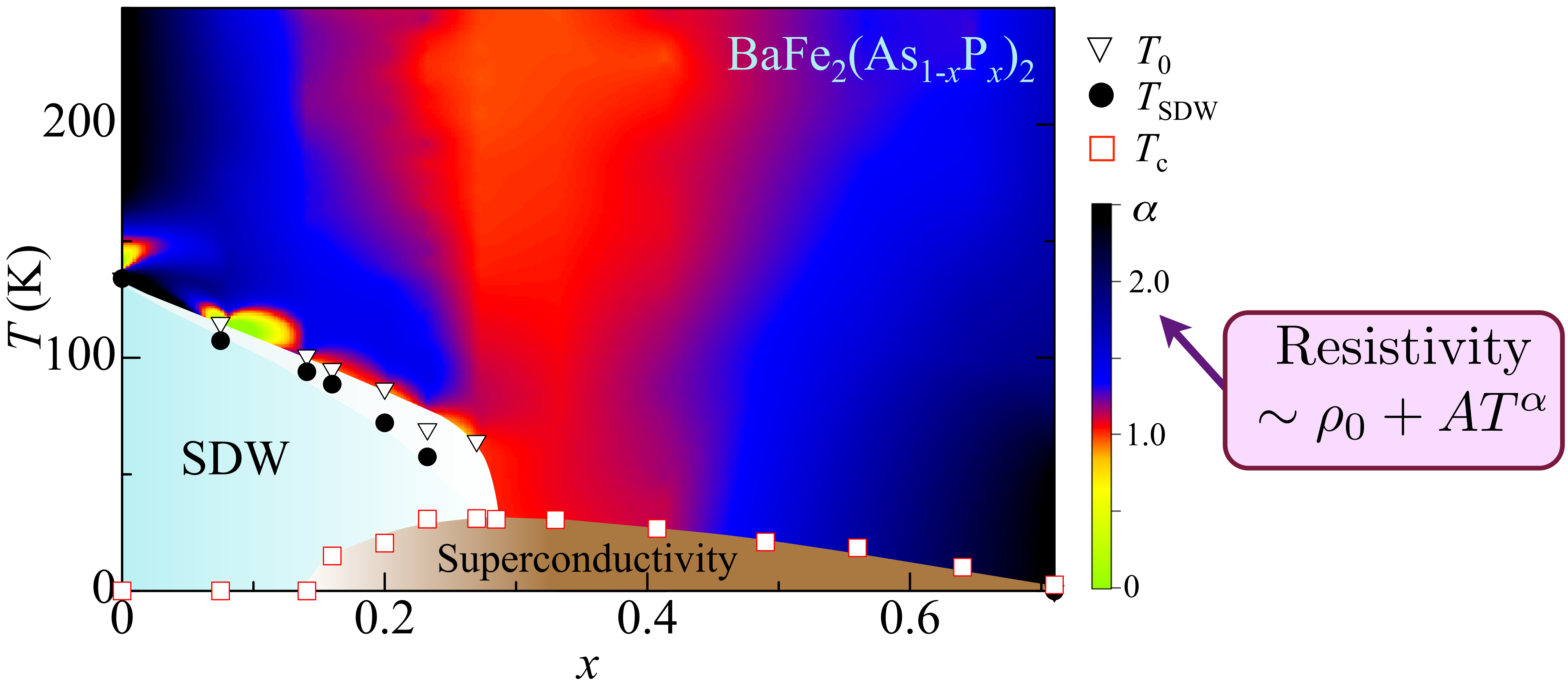
Quantum oscillations



$Nd_{2-x}Ce_xCuO_4$

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

Tuesday, January 31, 2012

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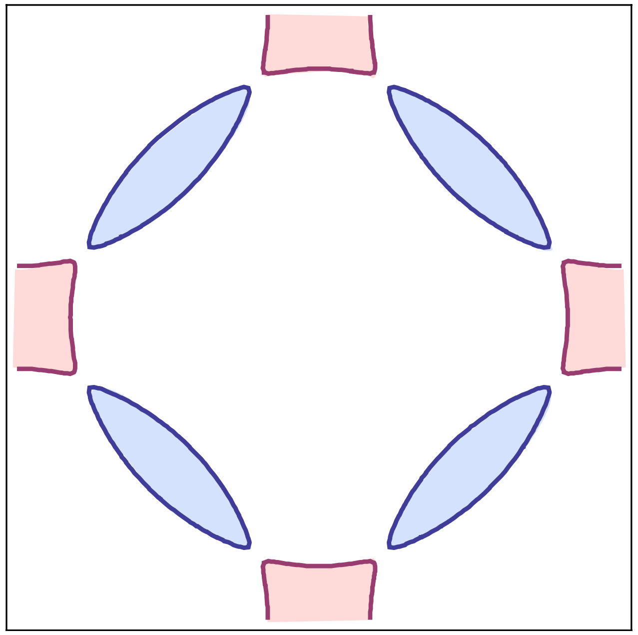

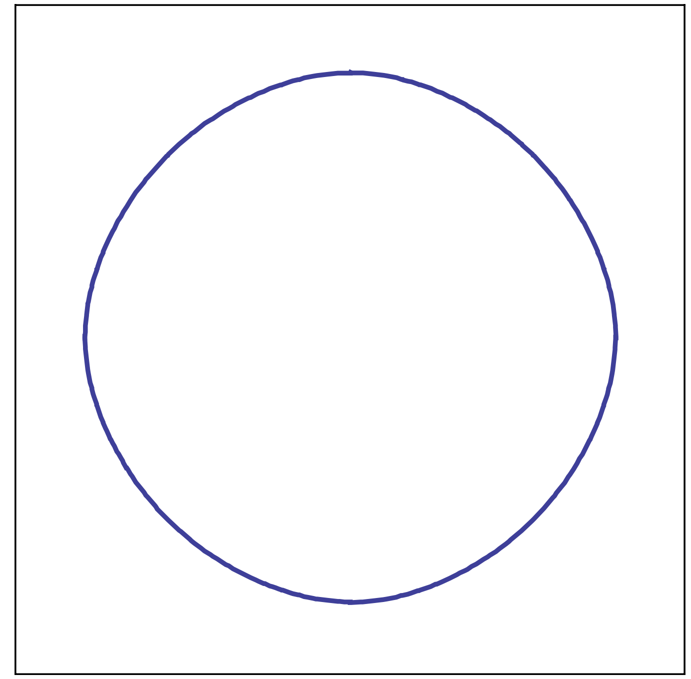

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Metal with electron and hole pockets

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Boson-fermion theory for both phases

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

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

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

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

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

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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- 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)
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- 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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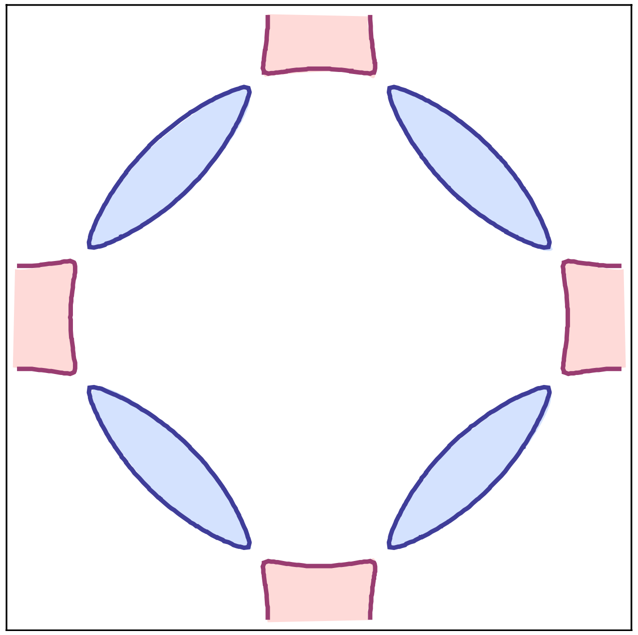

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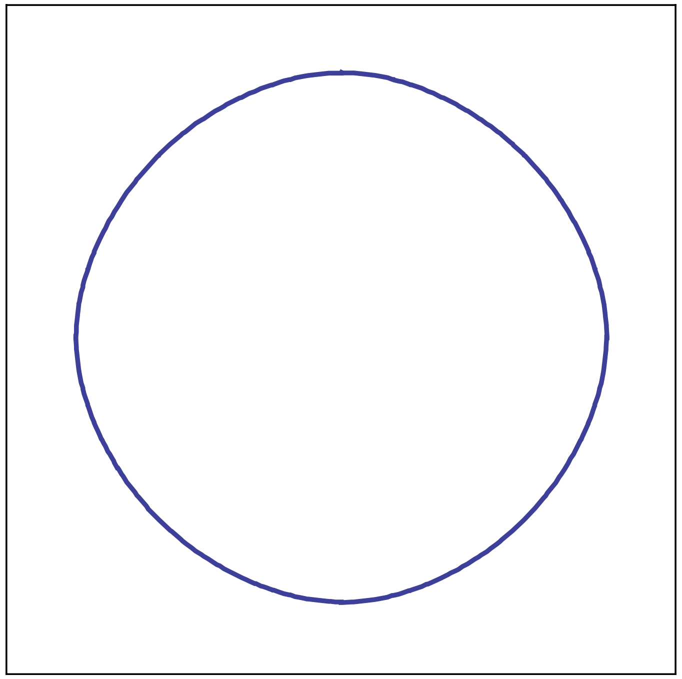
Metal with electron and hole pockets



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Can antiferromagnetic fluctuations, represented by the boson φ_α, provide the pairing glue which leads to high temperature superconductivity ?

There is an instability in weak-coupling, but T_c is low where the theory is reliable:

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)

At stronger coupling, different effects compete:

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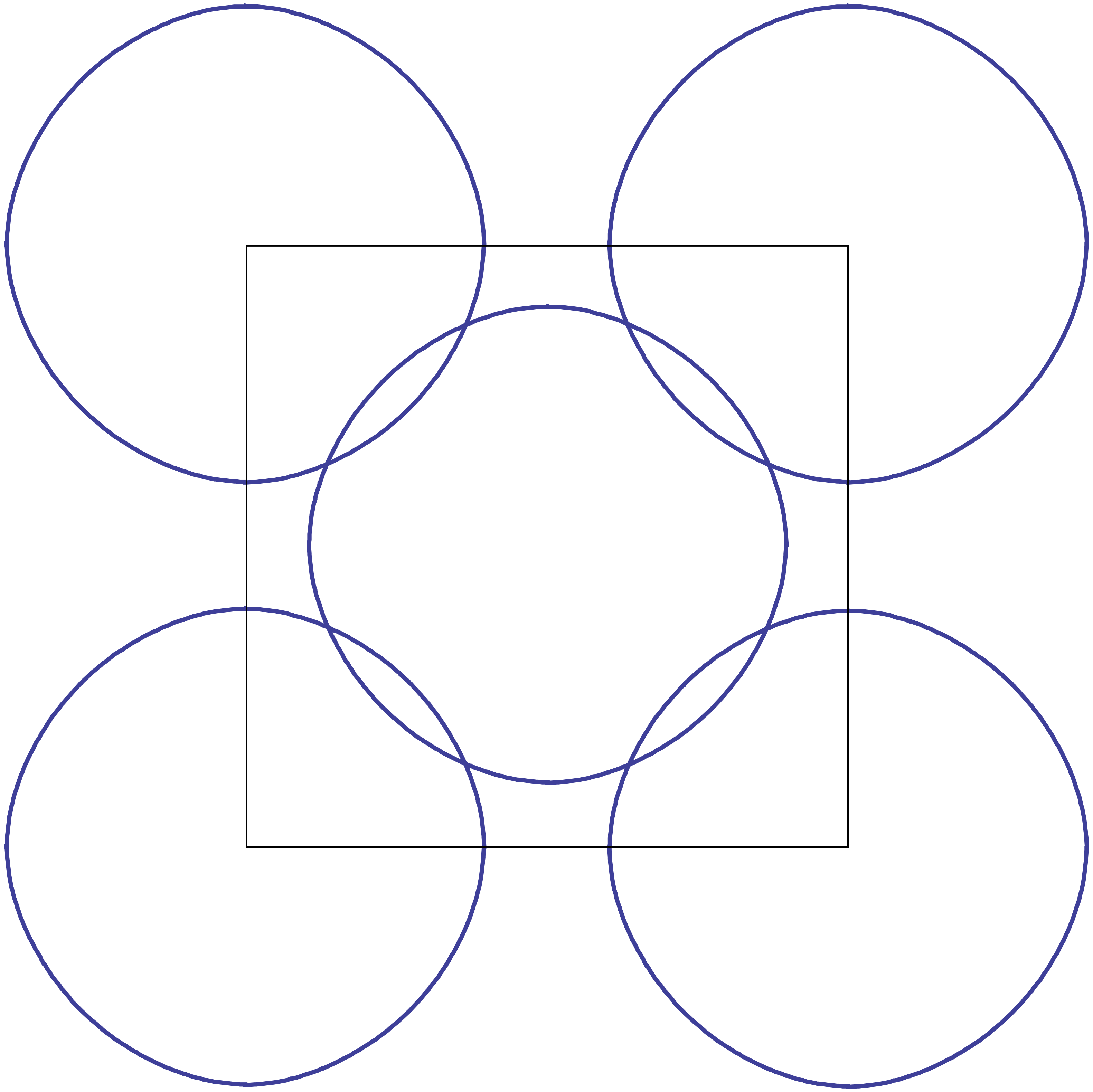
- Other instabilities can appear *e.g.* to charge density waves/stripe order.



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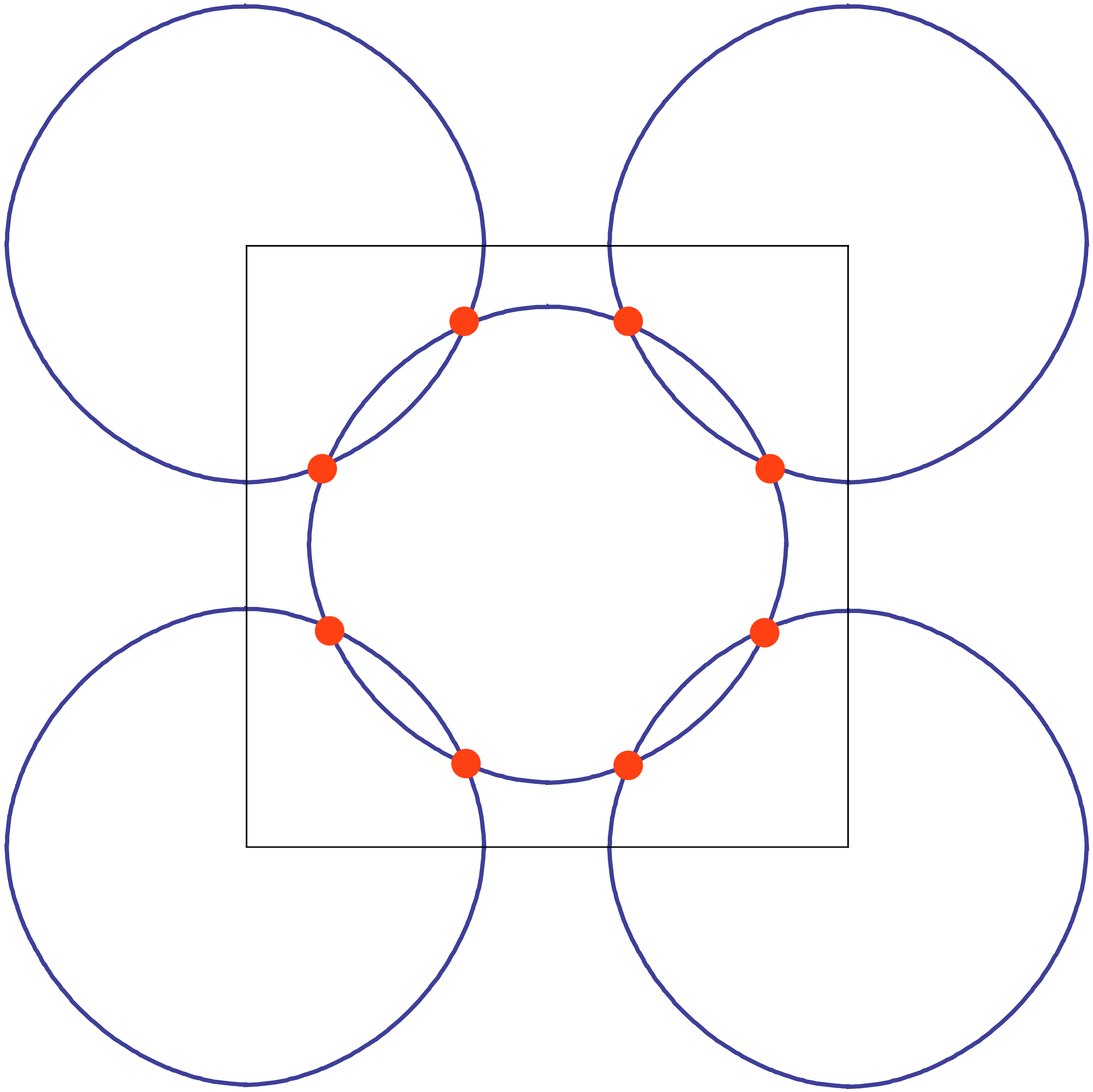
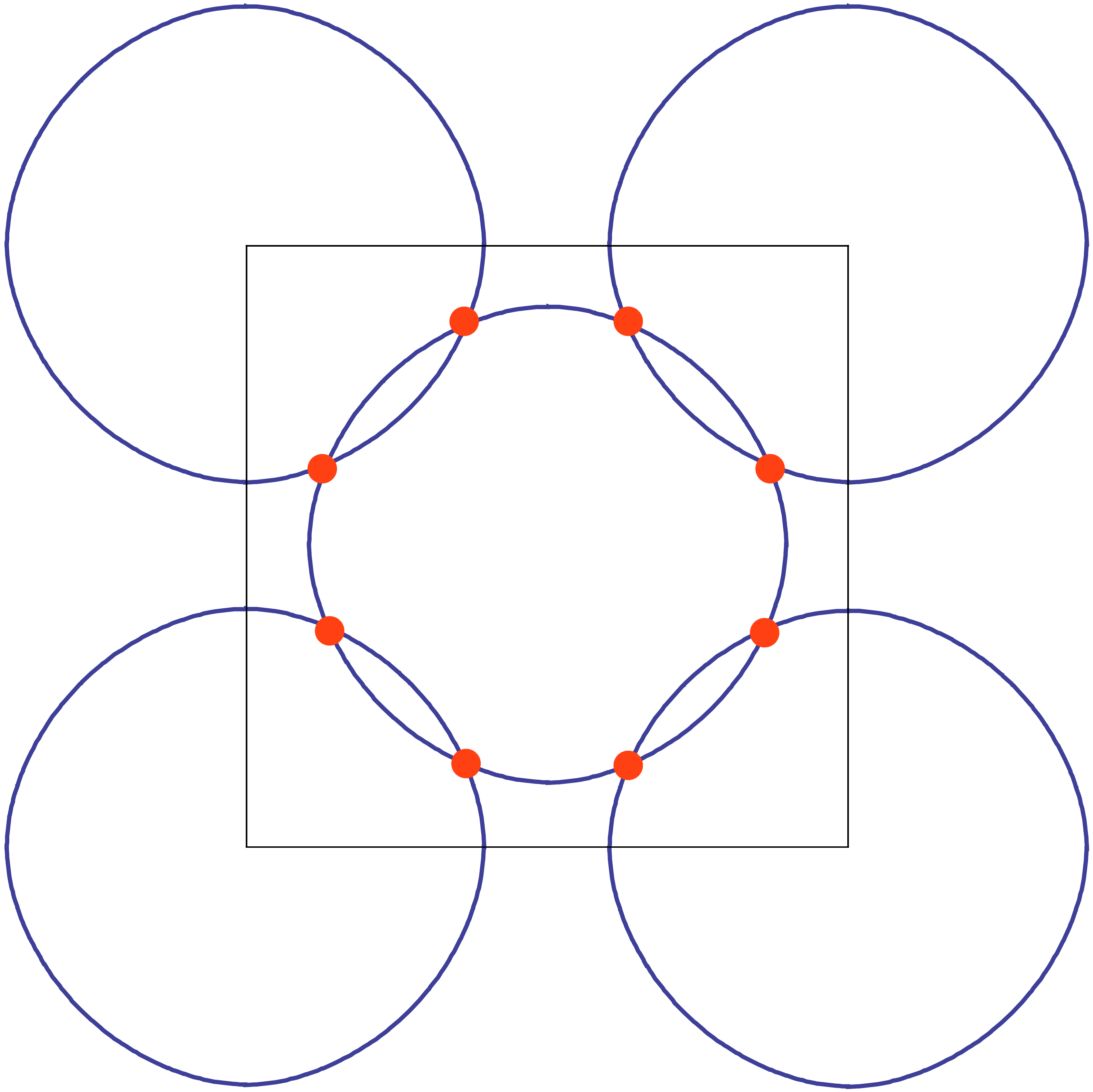
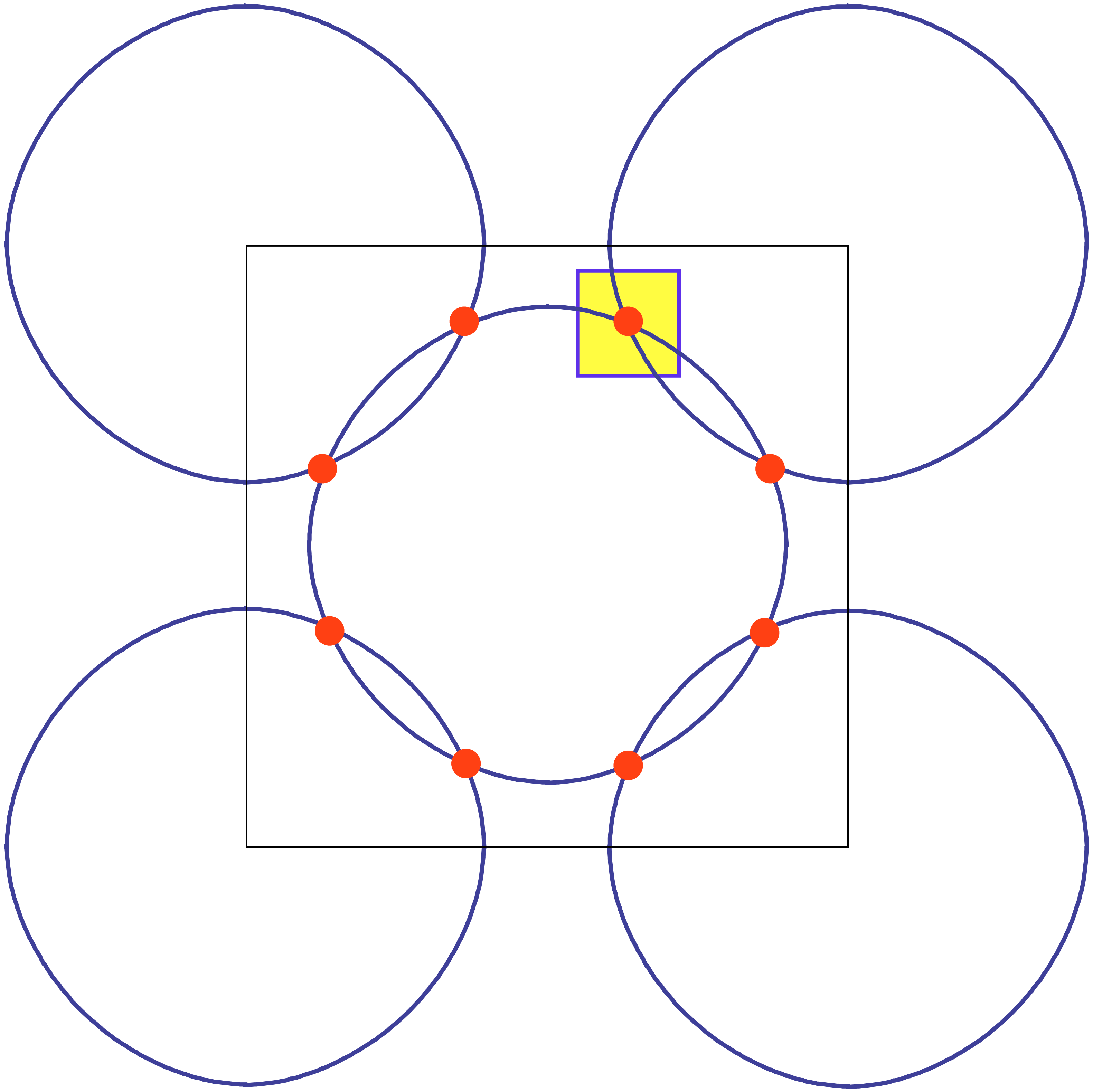


“Hot” spots

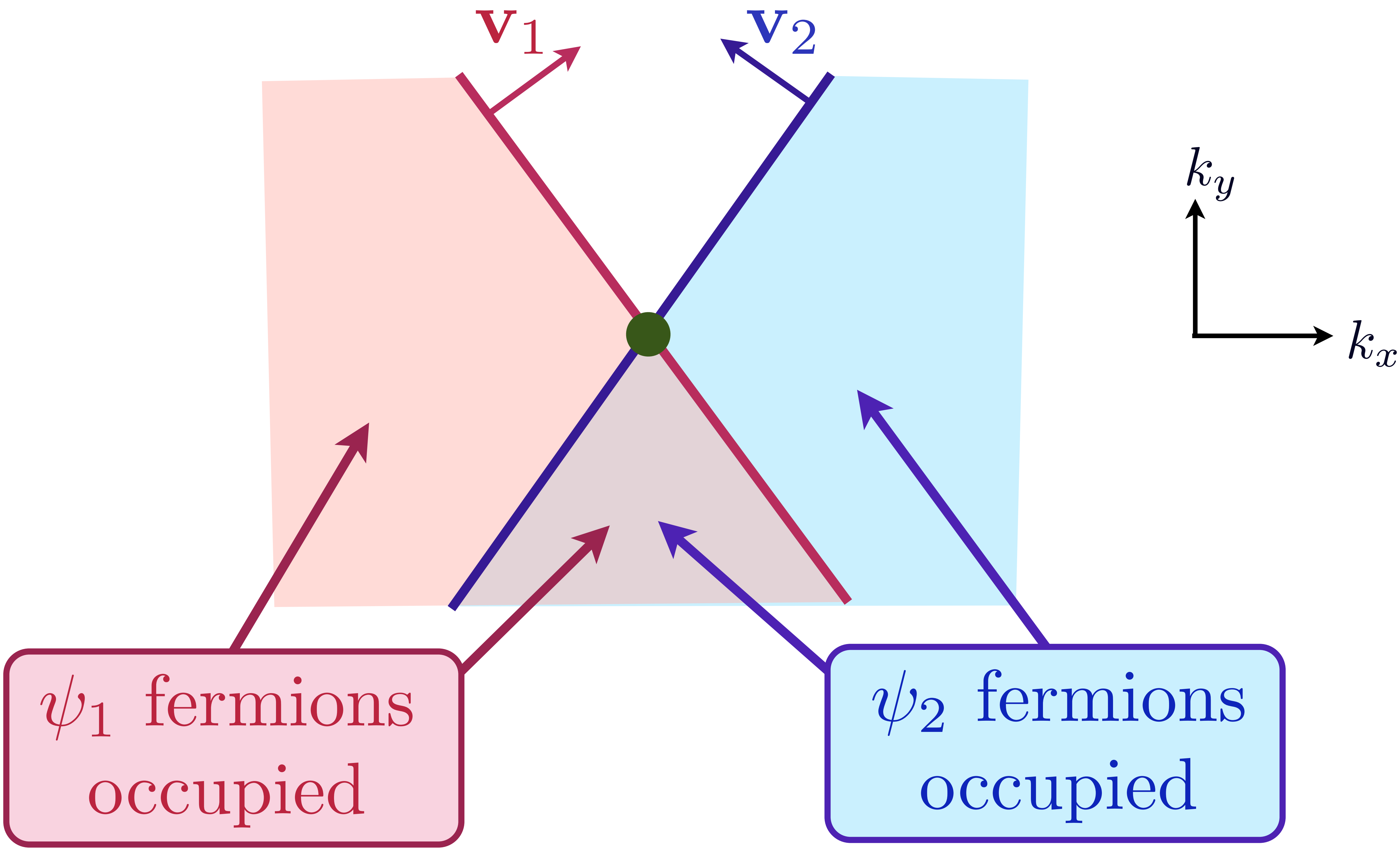


Low energy theory for critical point near hot spots



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



Low energy theory for critical point near hot spots

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

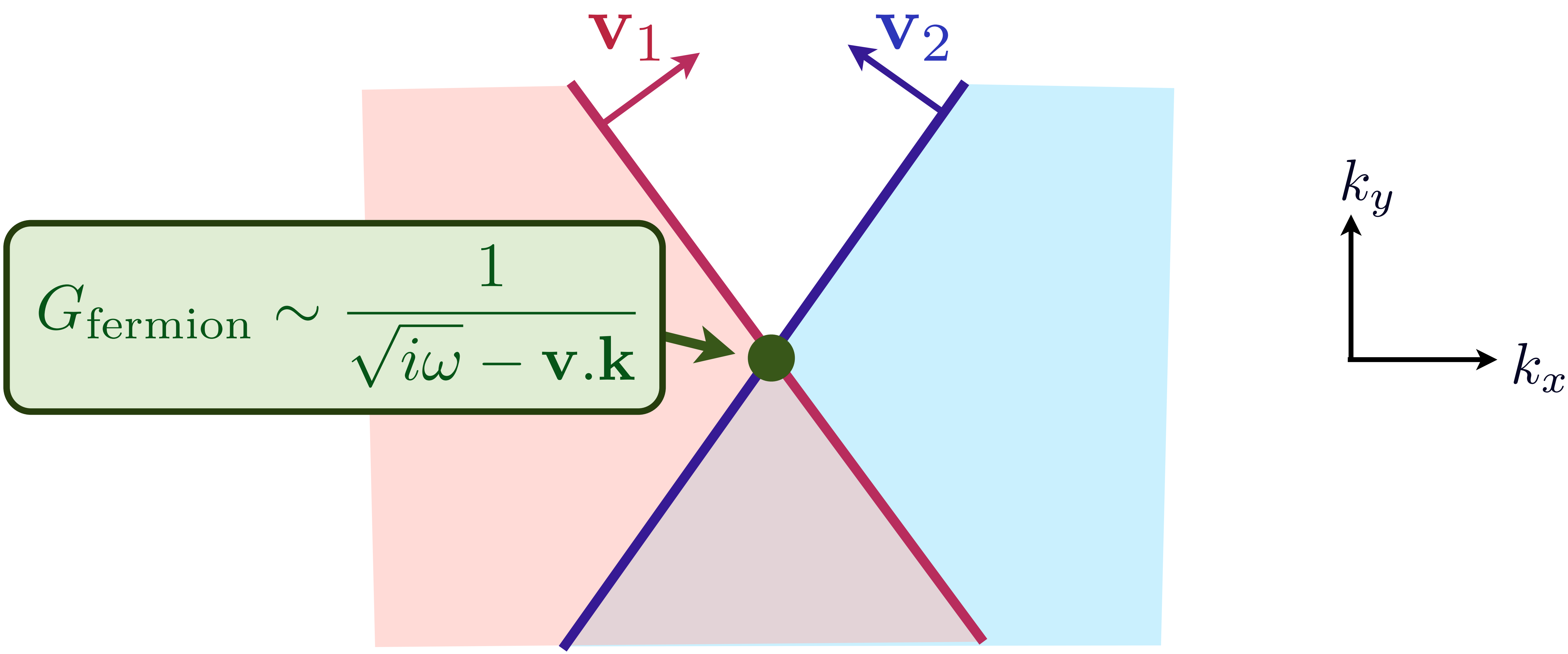
$$\mathcal{L}_\psi = \psi_{1a}^\dagger \left(\frac{\partial}{\partial\tau} - i\mathbf{v}_1 \cdot \boldsymbol{\nabla} \right) \psi_{1a} + \psi_{2a}^\dagger \left(\frac{\partial}{\partial\tau} - i\mathbf{v}_2 \cdot \boldsymbol{\nabla} \right) \psi_{2a}$$

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

$$\mathcal{L}_{\psi\varphi} = \lambda\varphi_\alpha\sigma_{ab}^\alpha \left(\psi_{1a}^\dagger \psi_{2b} + \psi_{2a}^\dagger \psi_{1b} \right).$$

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

Critical point theory is strongly coupled in $d = 2$



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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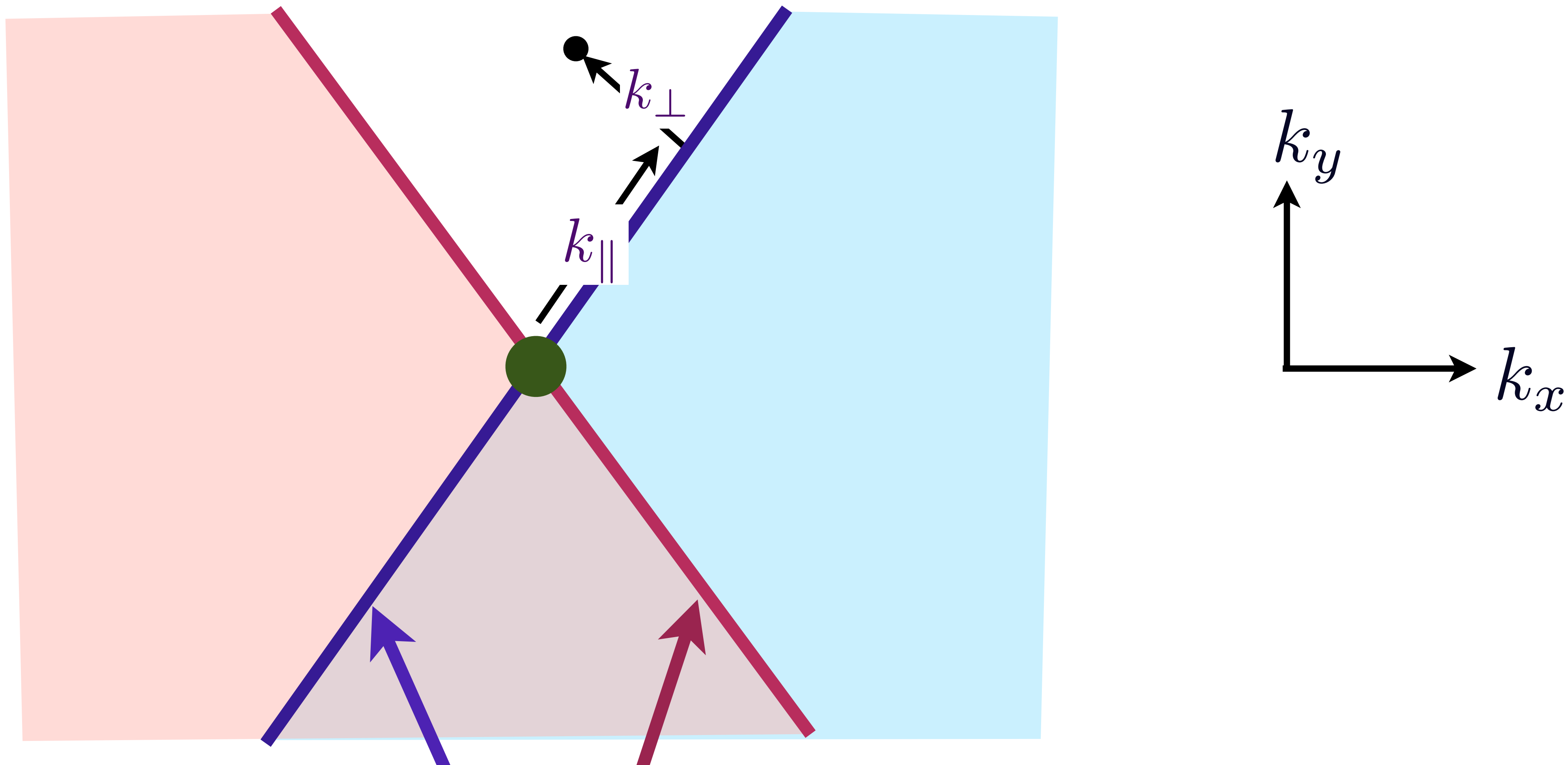

$$G_{\text{fermion}} = \frac{Z(k_\parallel)}{\omega - v_F(k_\parallel)k_\perp}, \quad Z(k_\parallel) \sim v_F(k_\parallel) \sim k_\parallel$$

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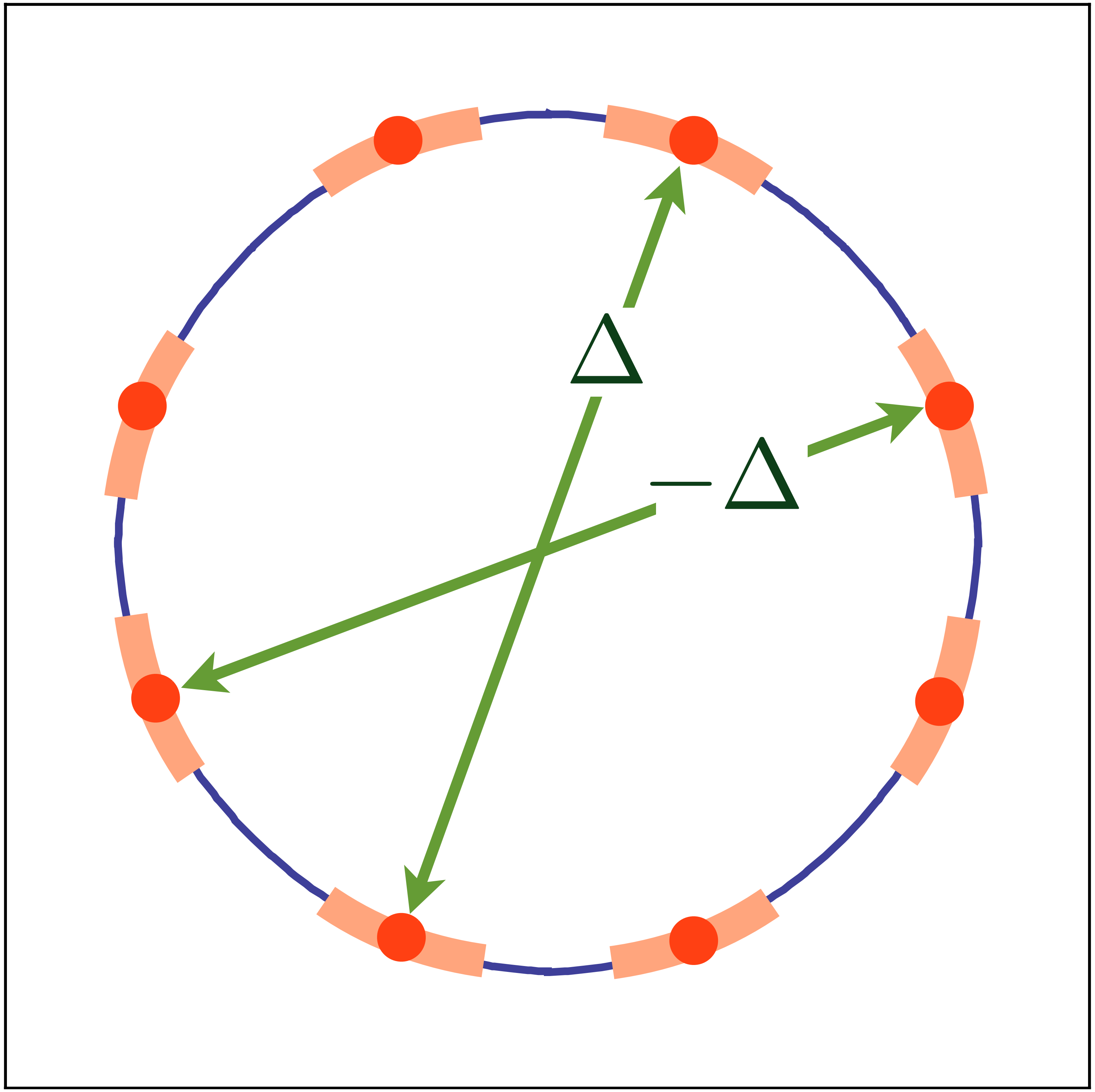
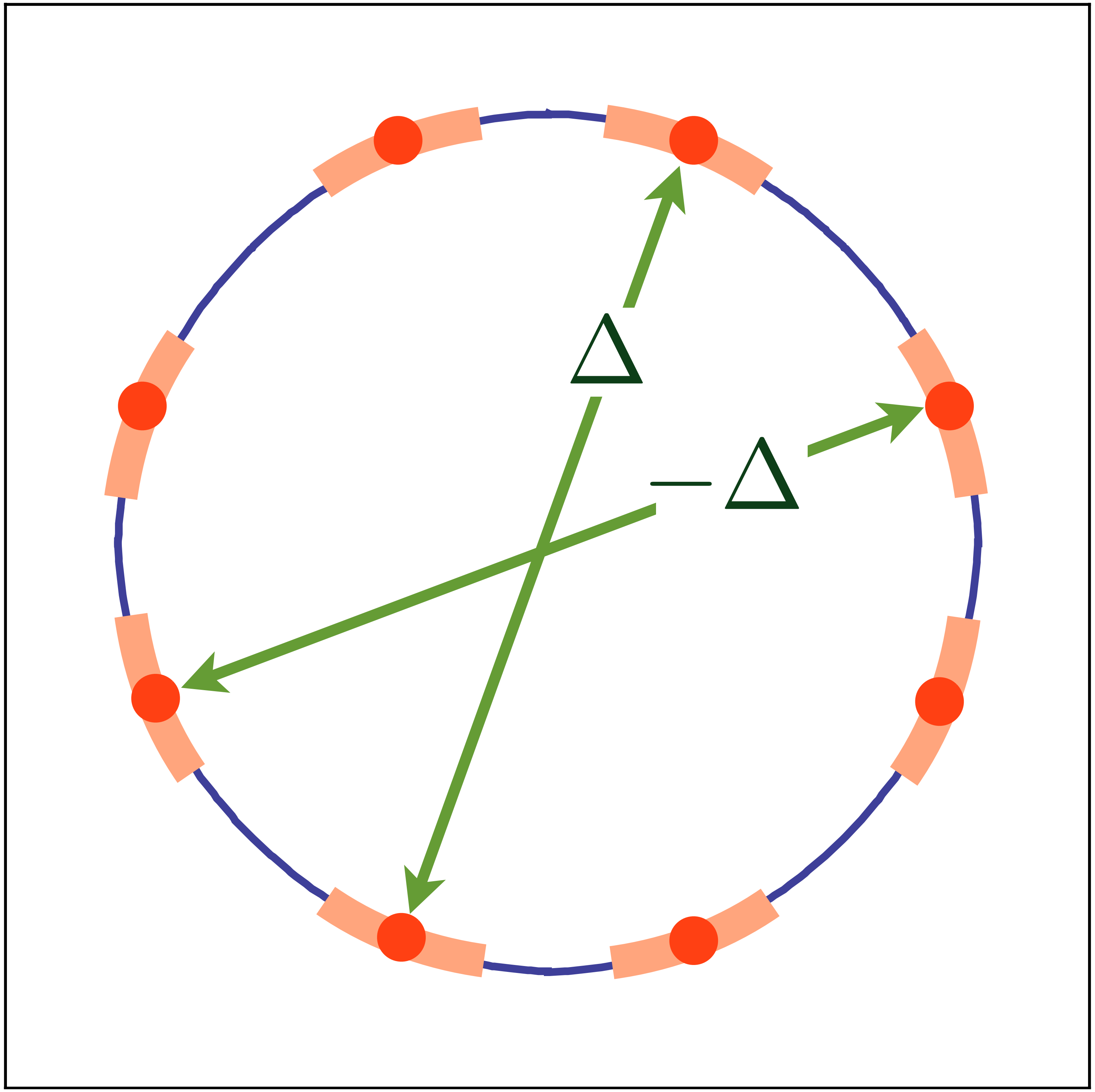


Unconventional pairing at *and near* hot spots

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

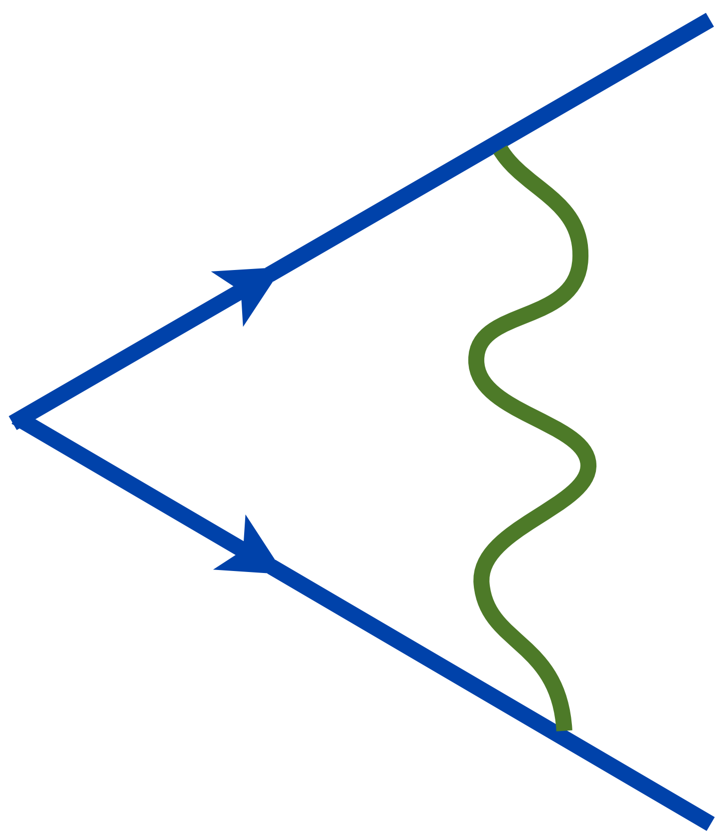


Unconventional pairing at *and near* hot spots

BCS theory

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

Cooper logarithm



BCS theory

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

Electron-phonon coupling

Debye frequency

Implies

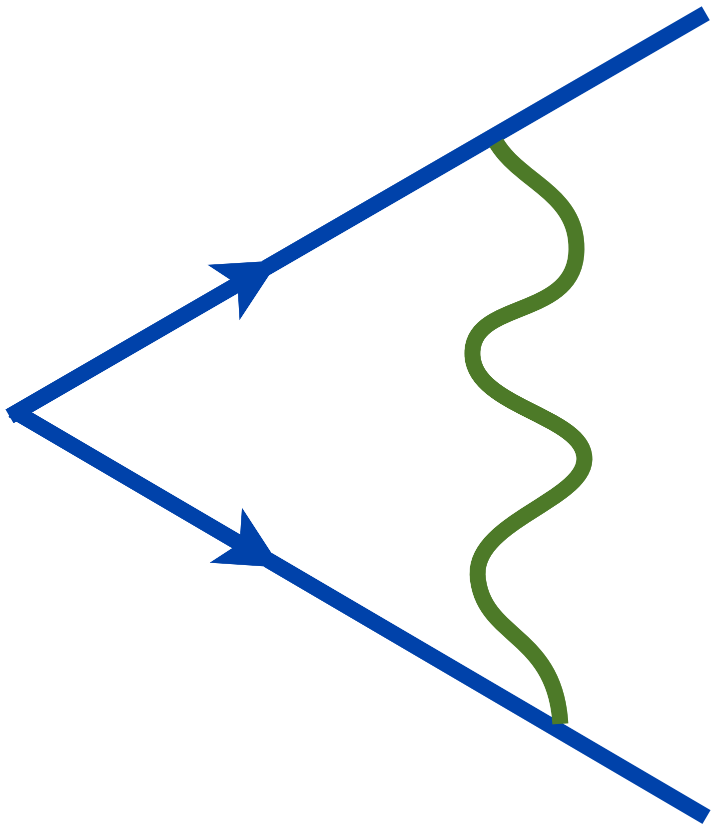
$$T_c \sim \omega_D \exp\left(-1/\lambda\right)$$

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



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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

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

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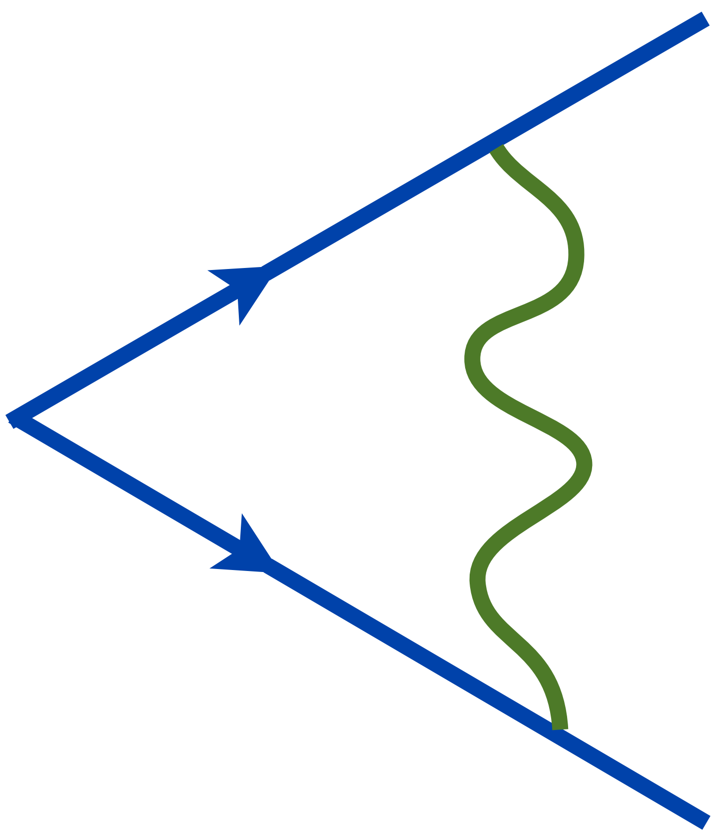
$$1 + \frac{\sin\theta}{2\pi} \log^2\left(\frac{E_F}{\omega}\right)$$



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Fermi energy

θ 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))
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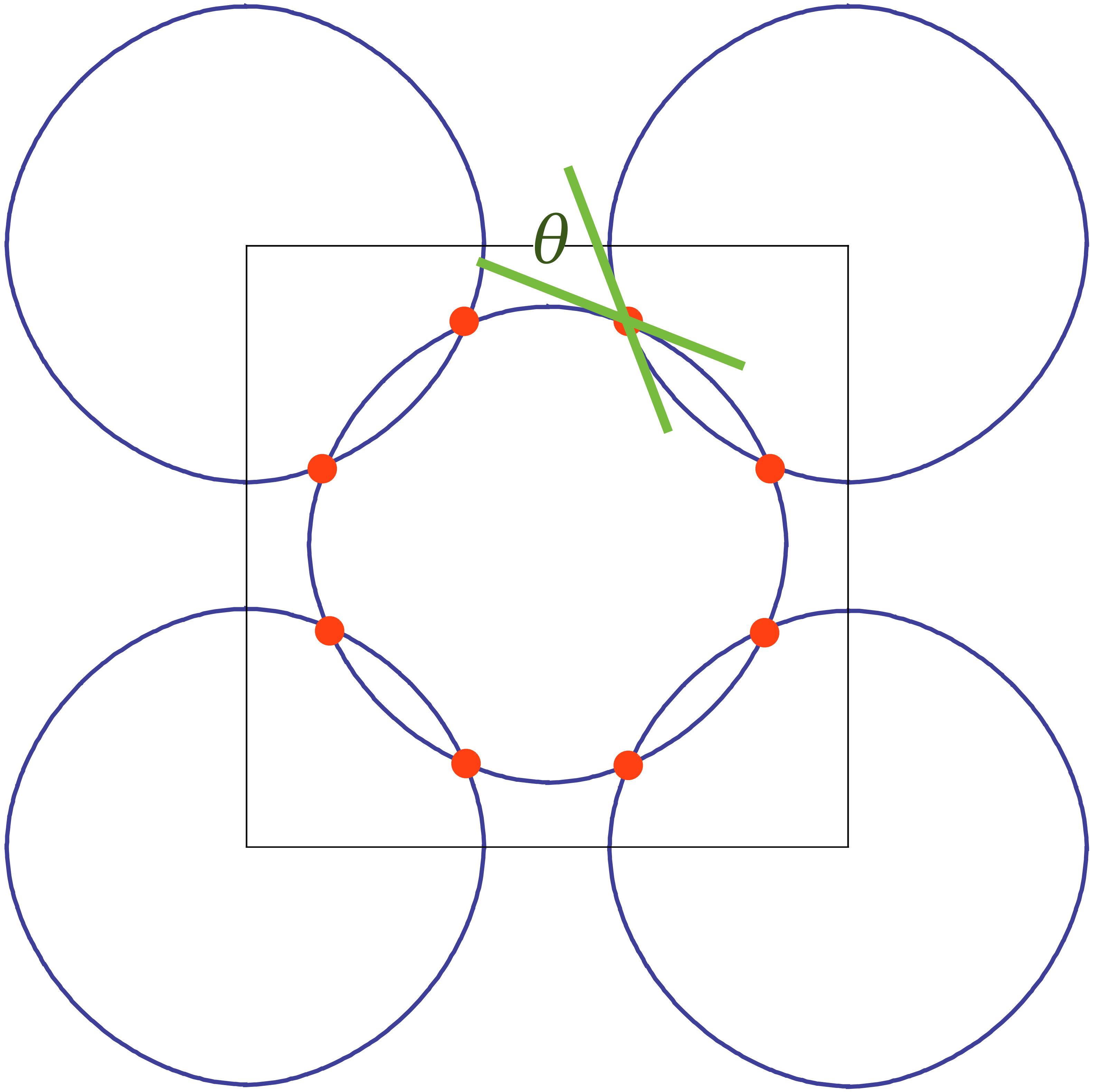
θ

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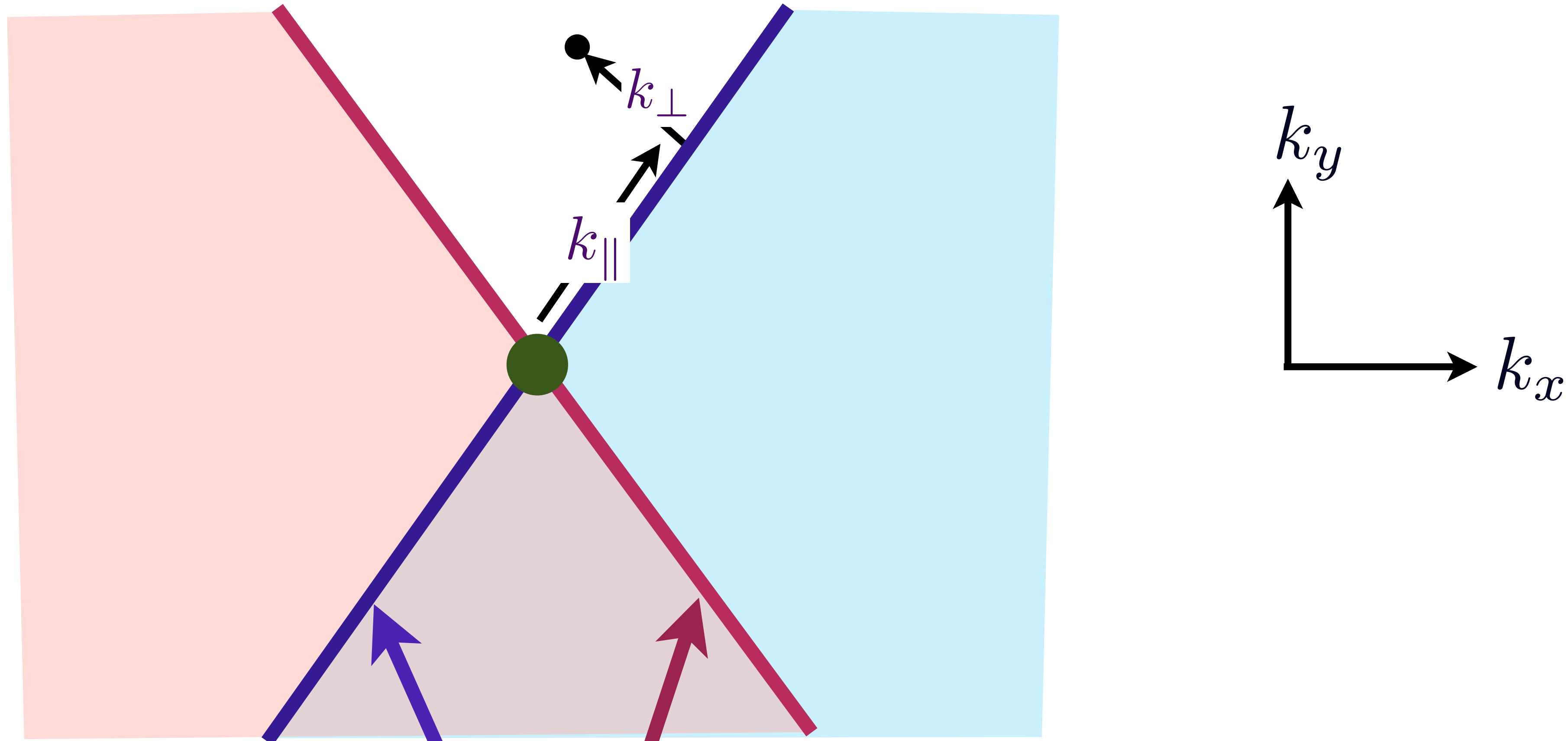

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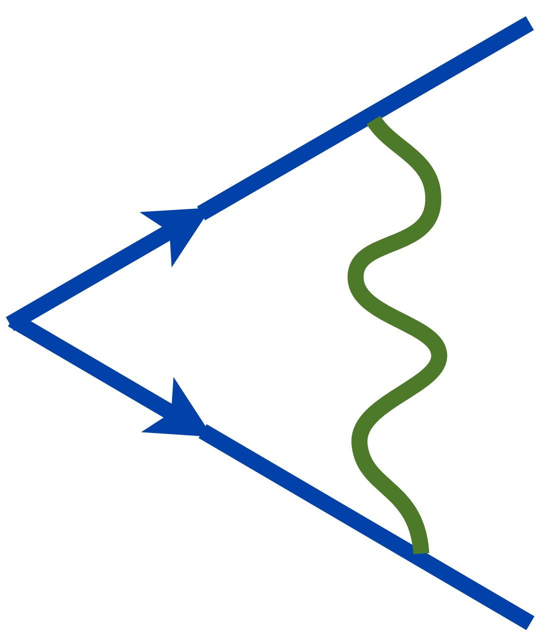

$$\int dk_\parallel \, \frac{1}{k_\parallel^2} \left(\frac{Z^2(k_\parallel)}{v_F(k_\parallel)} \right) \log \frac{k_\parallel^2}{\omega}$$

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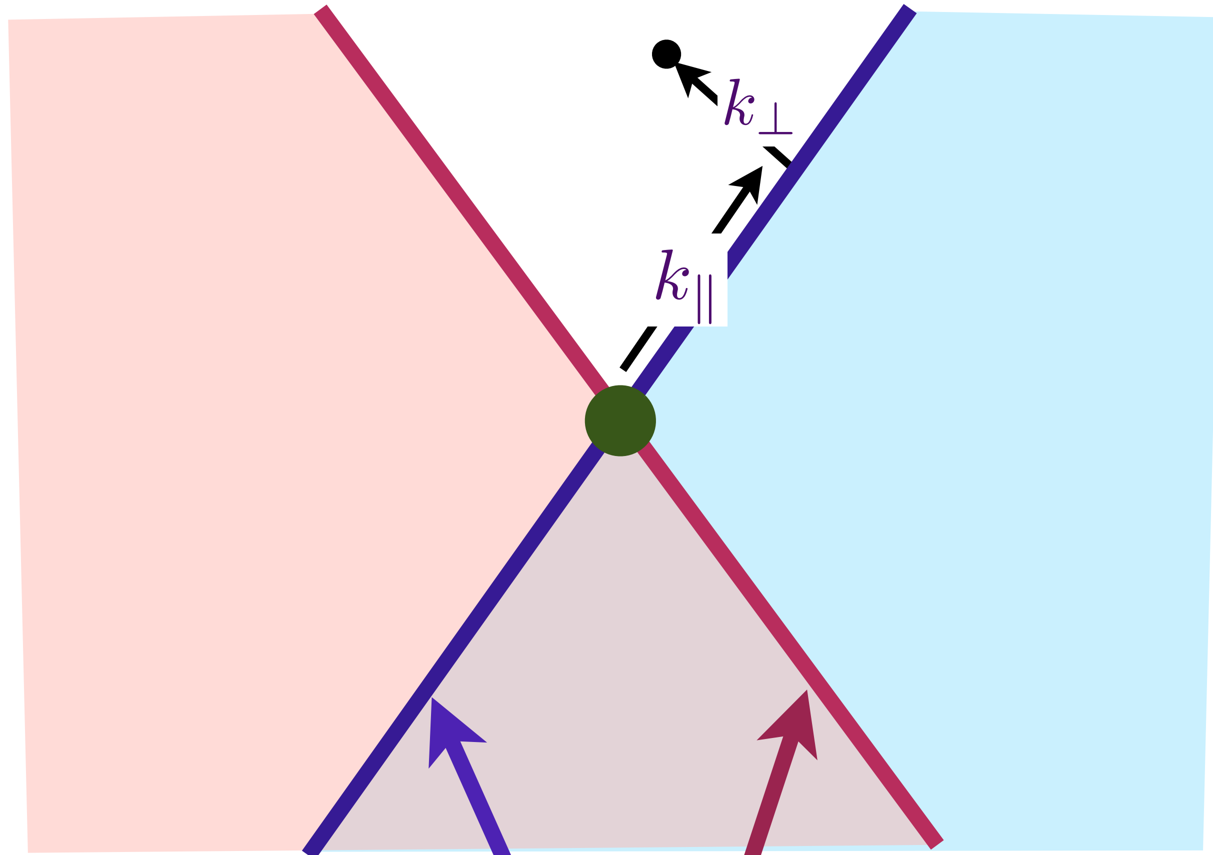

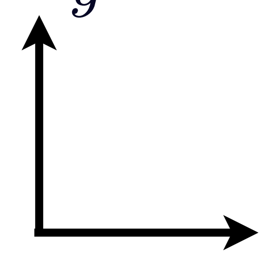

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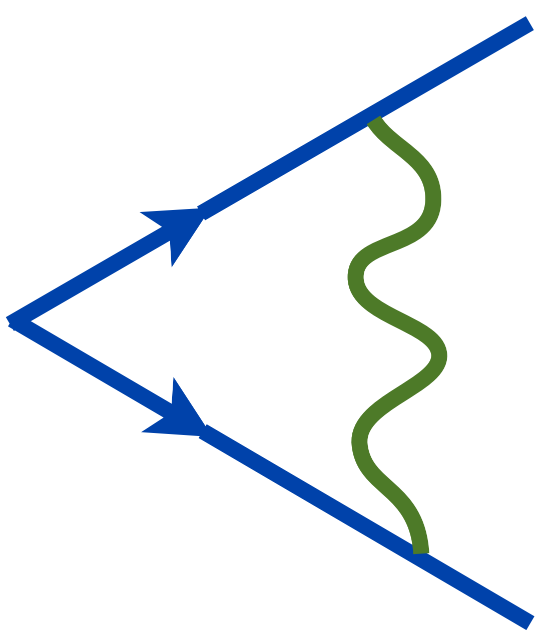
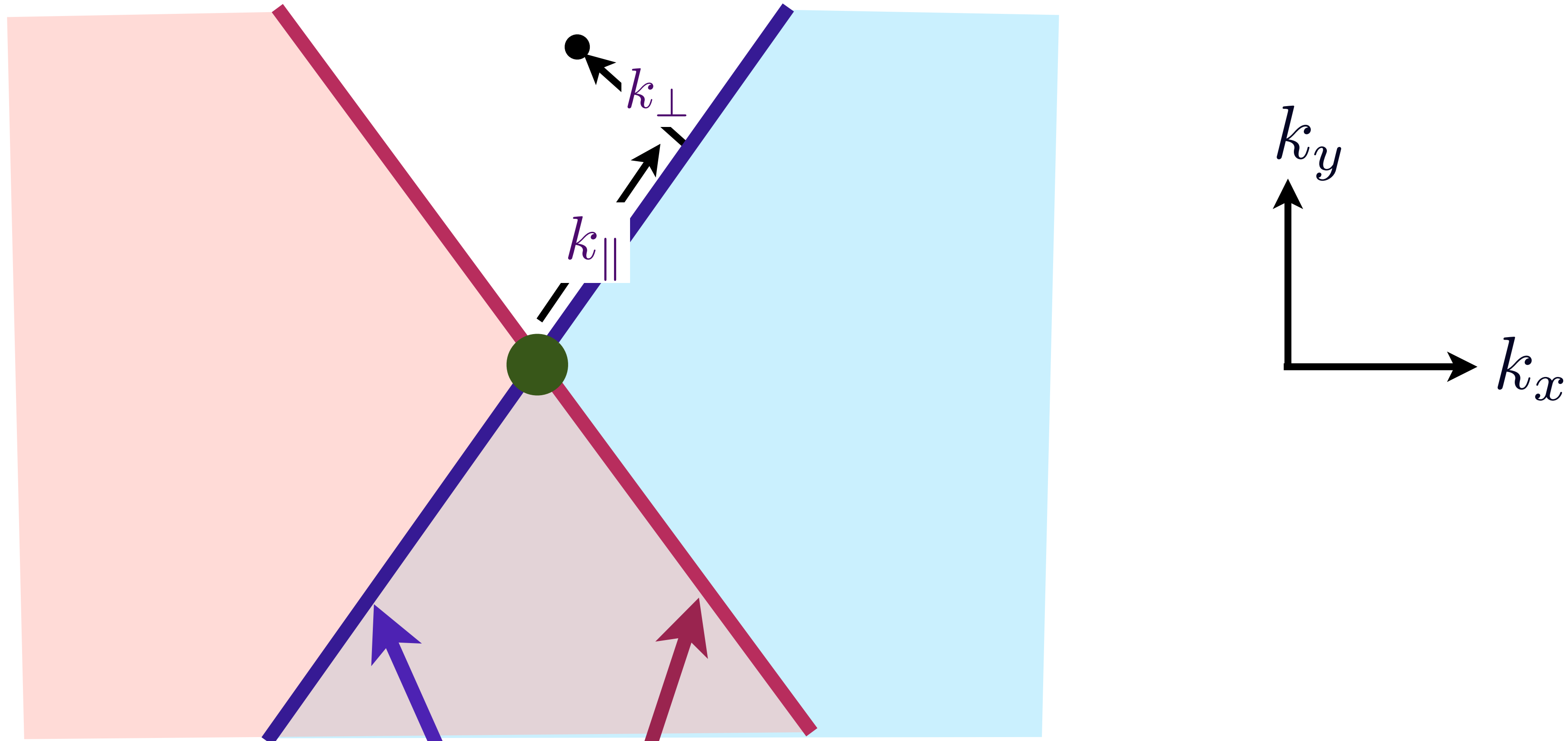


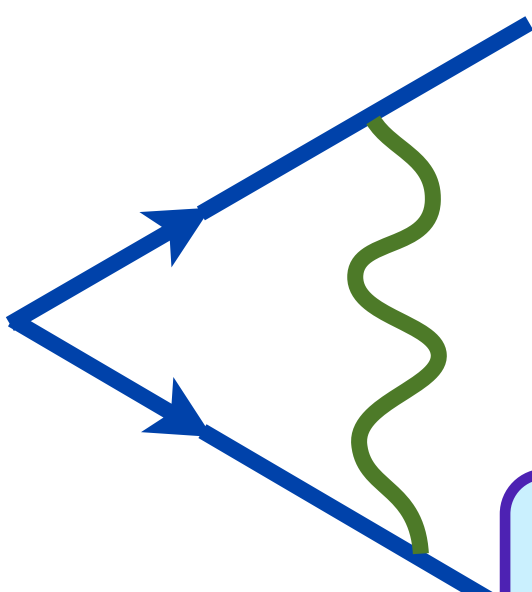
$$\int dk_\parallel \frac{1}{k_\parallel^2} \underbrace{\left(\frac{Z^2(k_\parallel)}{v_F(k_\parallel)}\right) \log \frac{k_\parallel^2}{\omega}}$$

Cooper logarithm

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



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



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

Spin fluctuation propagator

Cooper logarithm

Enhancement of pairing susceptibility by interactions

Antiferromagnetic critical point

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

- $\log^2$ 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.

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

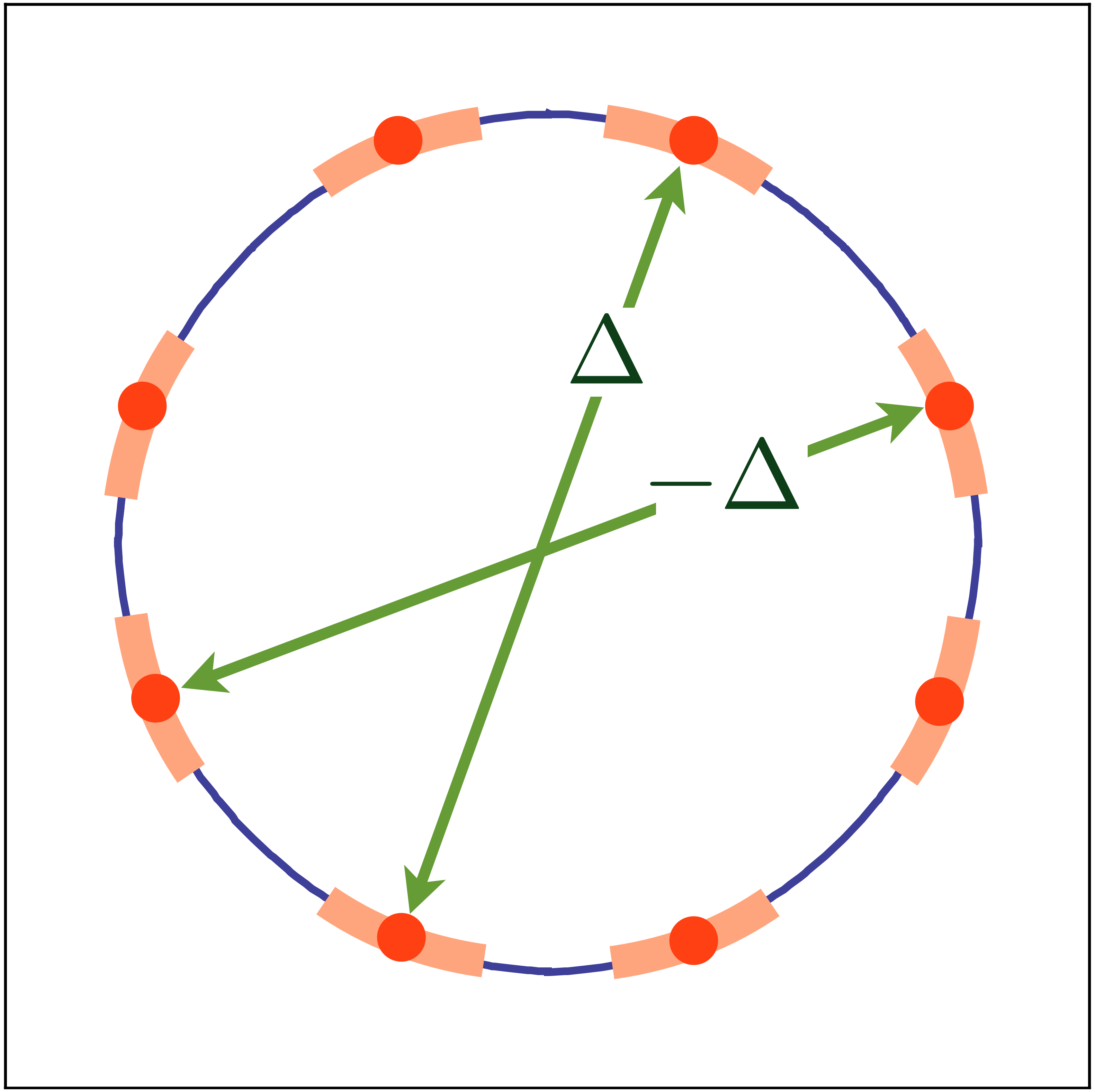
Is there a log^2 towards any other instability ?

Is there a *log*^{2} towards any other instability ?

Only one other: to a $2k_F$ bond-nematic order, which is smaller by a factor of 3.

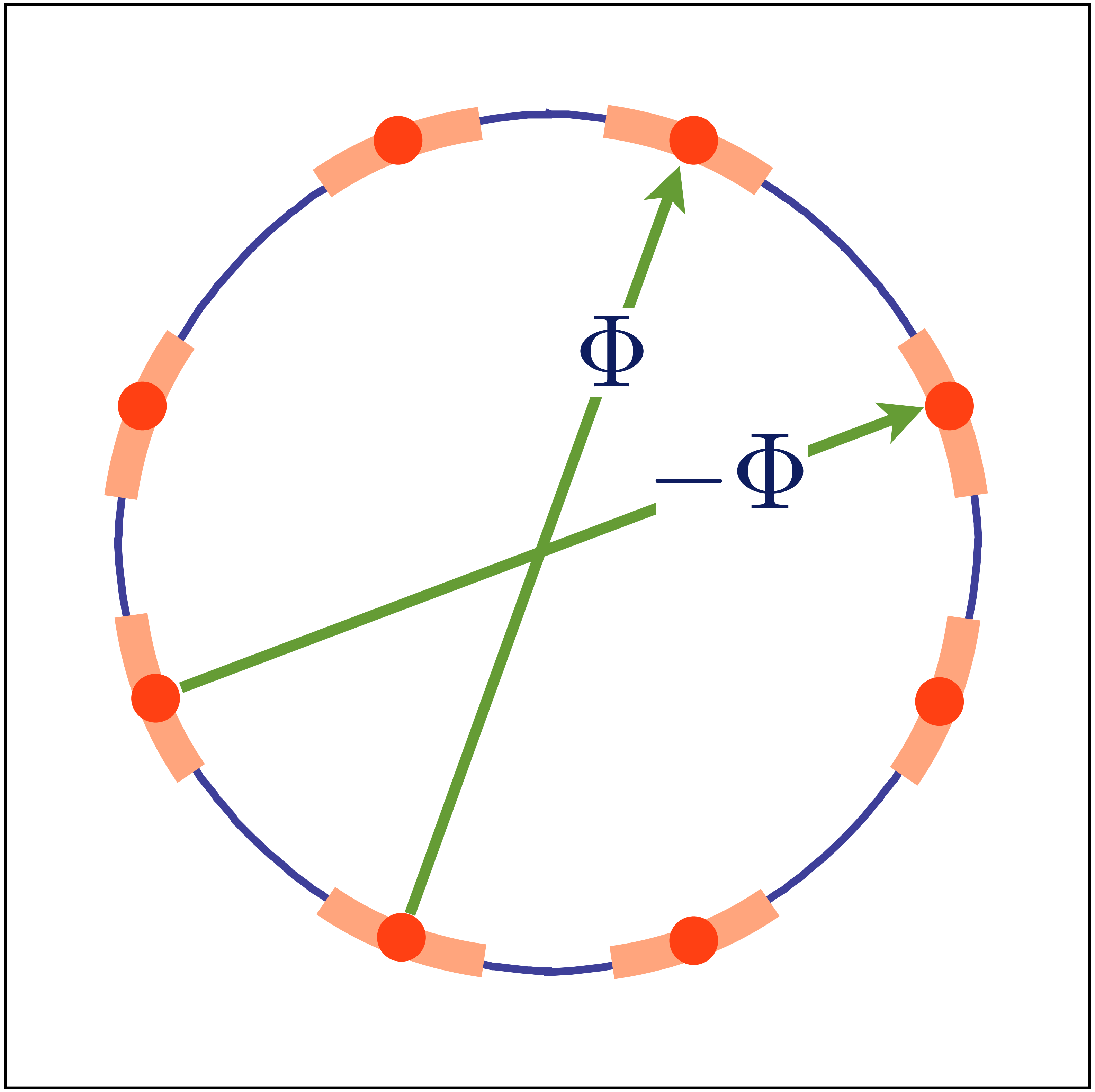
$$1 + \frac{\sin\theta}{6\pi} \log^2 \left(\frac{E_F}{\omega} \right)$$

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



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 *and near* hot spots

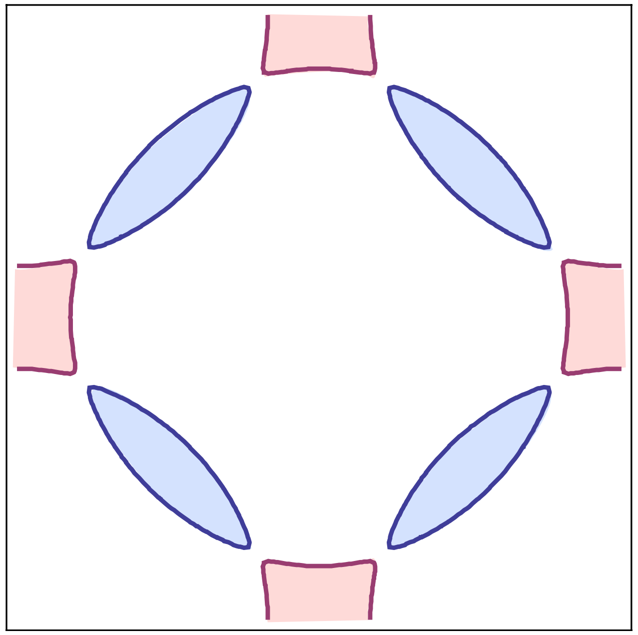
1. Experimental motivations from cuprates and pnictides

2. Conventional theory and its breakdown in two spatial dimensions

3. Fermi surface reconstruction: onset of unconventional superconductivity

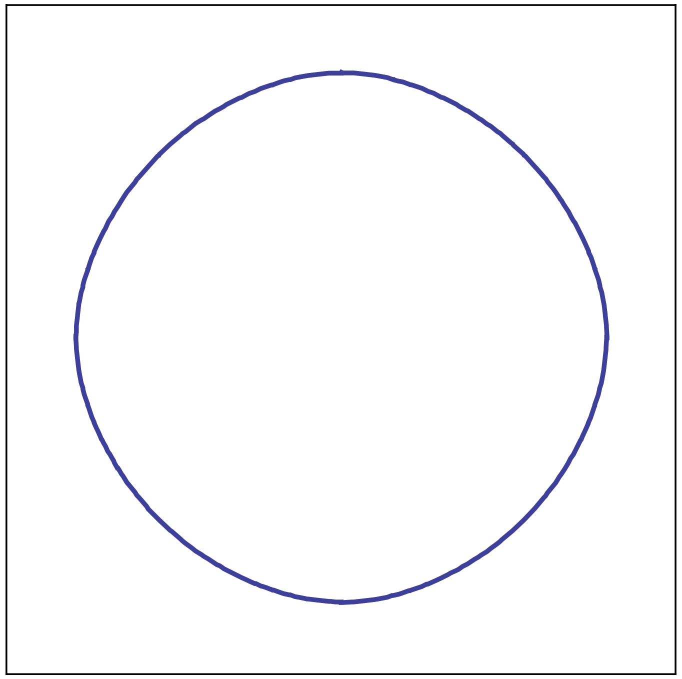
4. Fermi surface reconstruction *without* symmetry breaking: metals with "topological" order and the heavy fermion compounds

Quantum phase transition with Fermi surface reconstruction



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

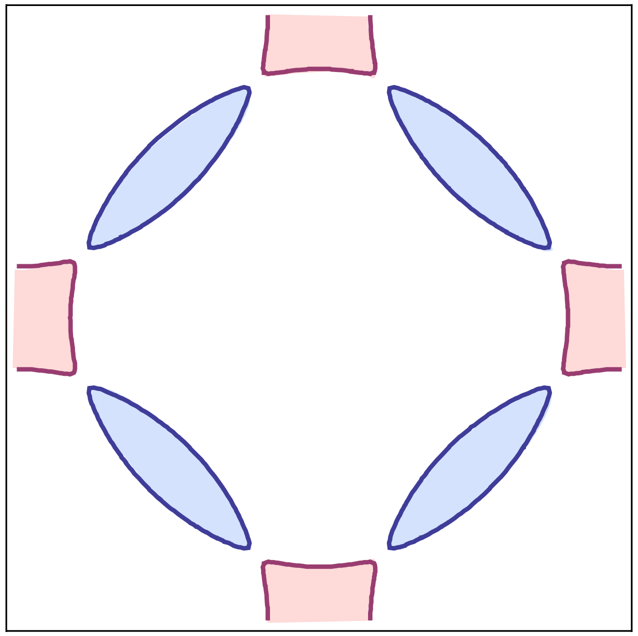
Metal with electron and hole pockets



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

Metal with "large" Fermi surface

Separating onset of SDW order and Fermi surface reconstruction



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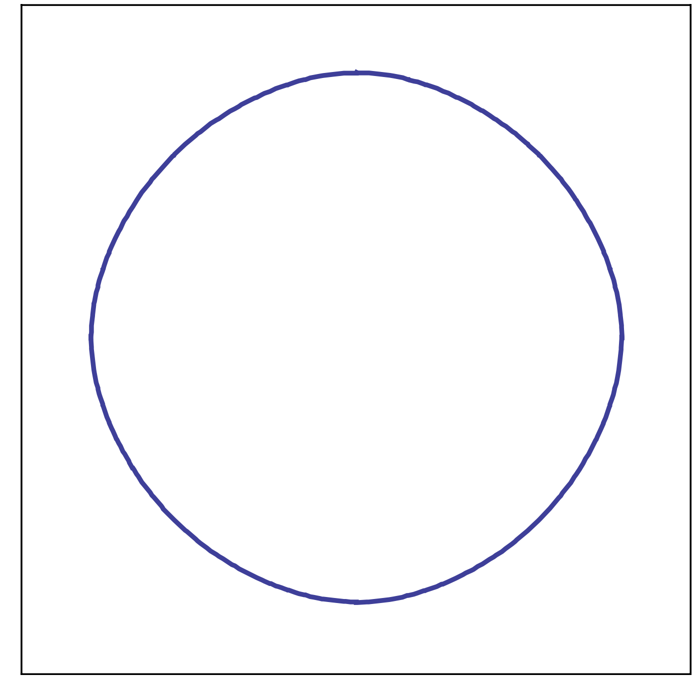

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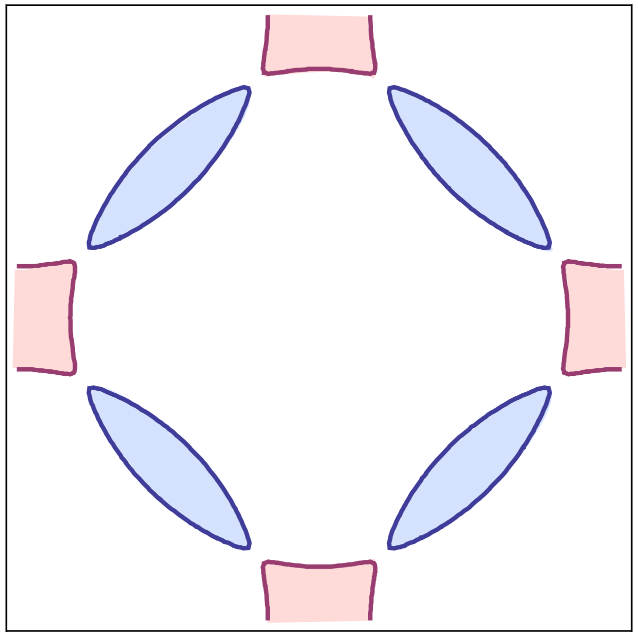

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Metal with electron and hole pockets

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

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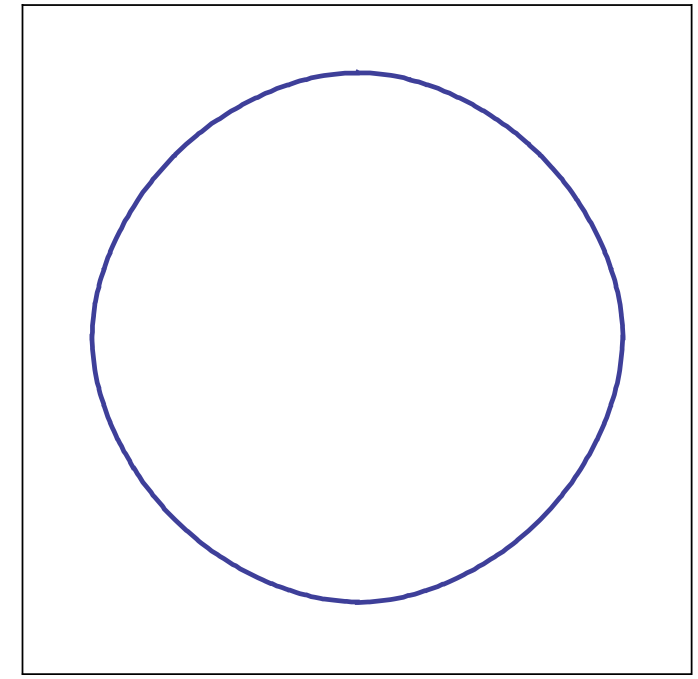

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T. Senthil, S. Sachdev, and M. Vojta, *Phys. Rev. Lett.* **90**, 216403 (2003)

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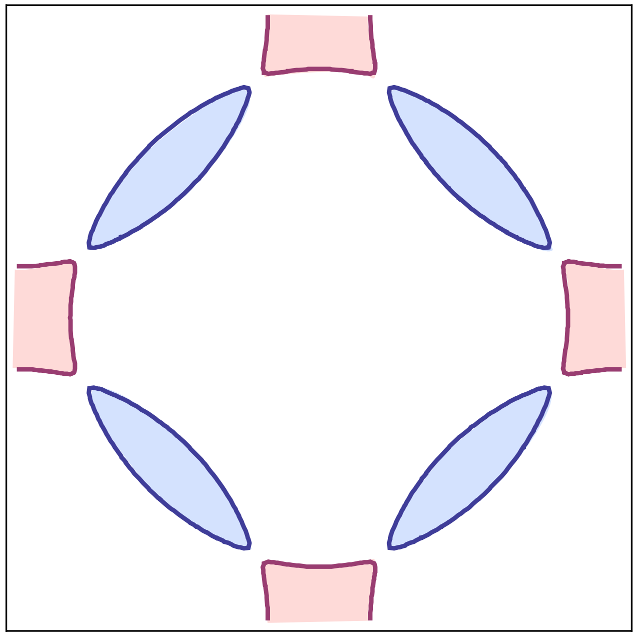

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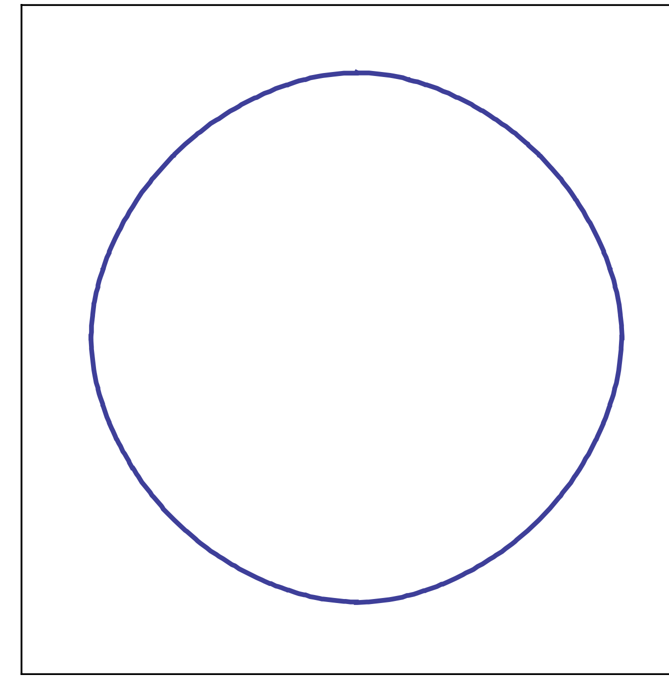
Fractionalized Fermi liquid (FL*) phase with no symmetry breaking and "small" Fermi surface



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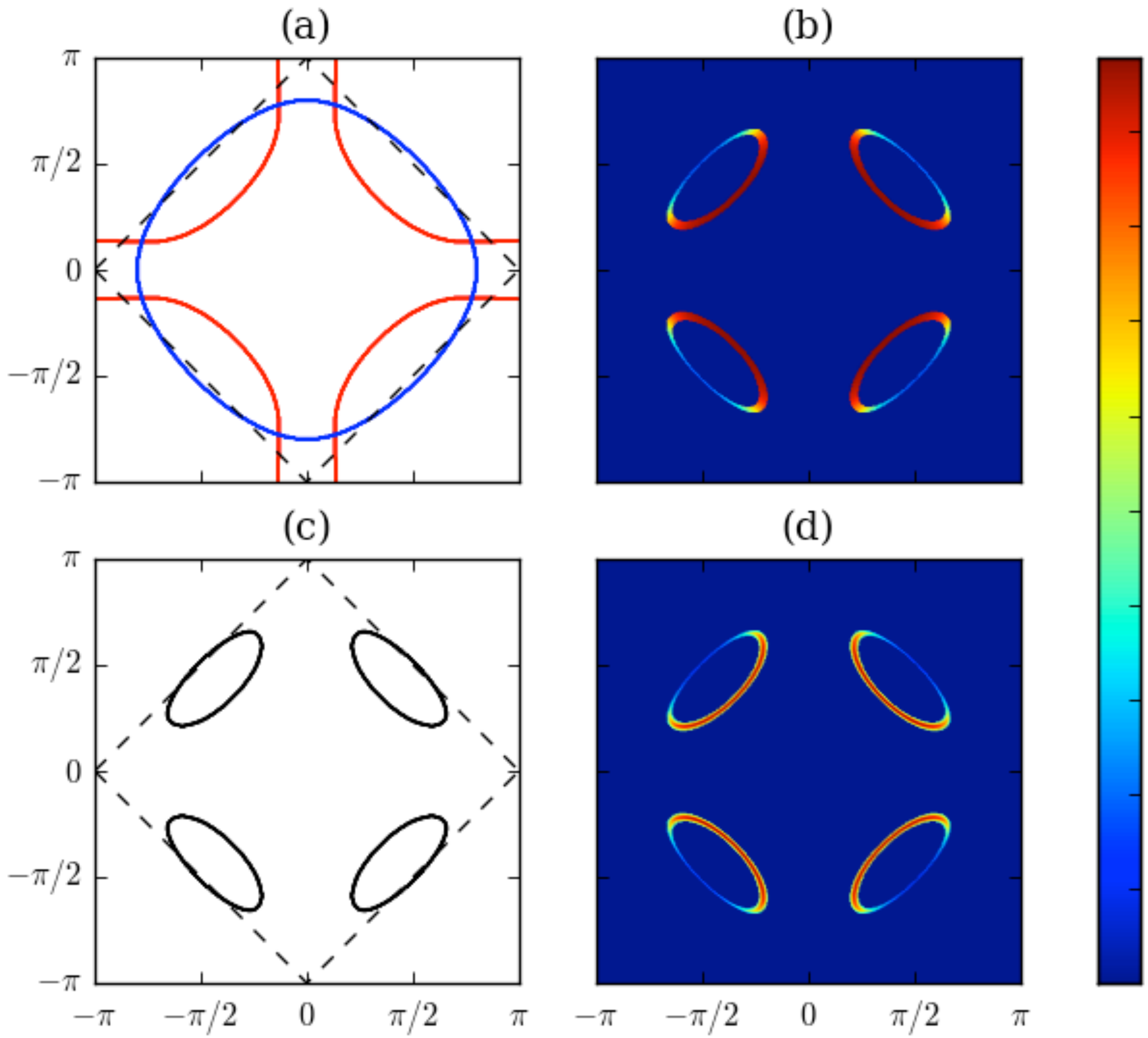
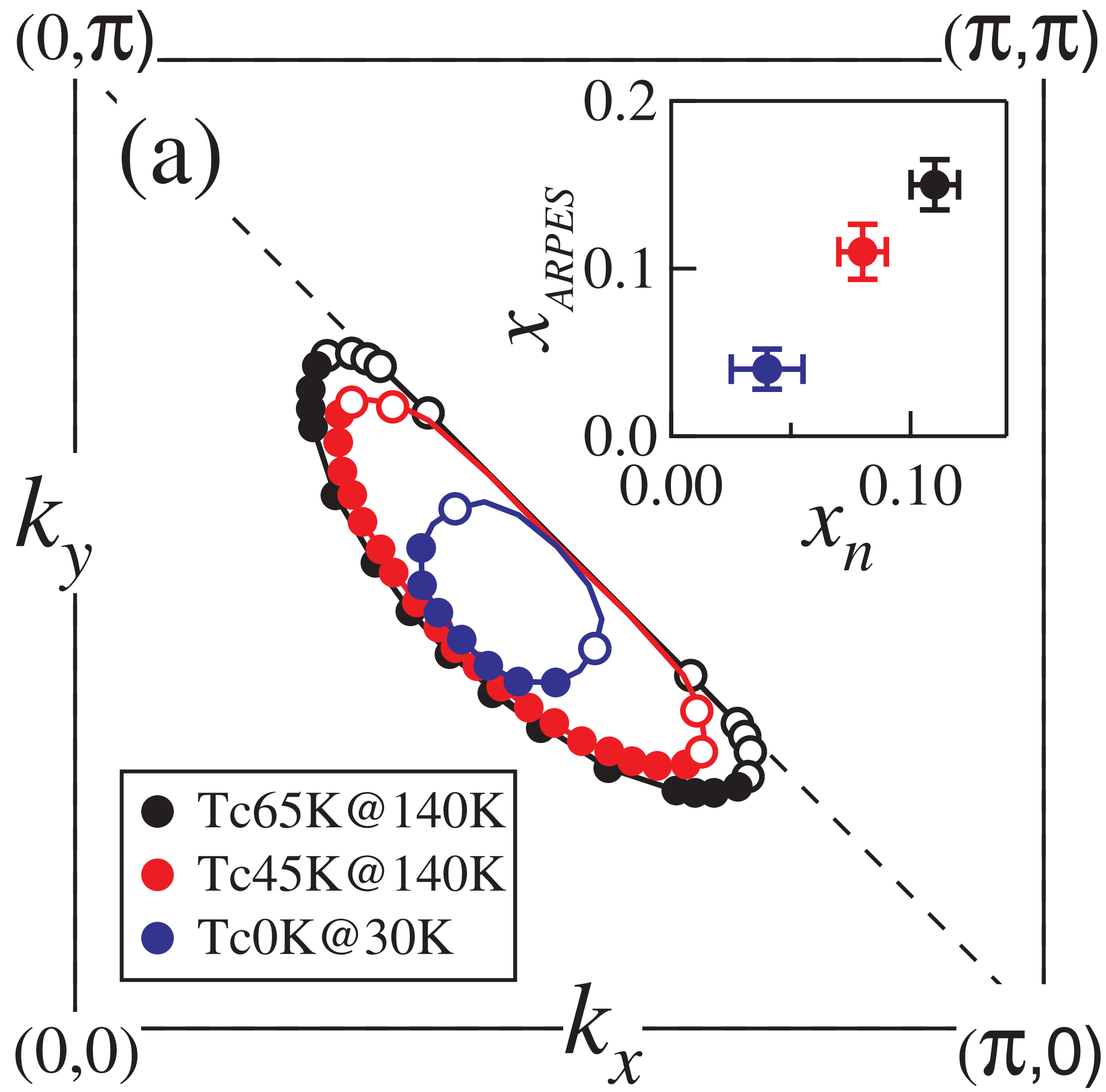
Metal with "large" Fermi surface

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)



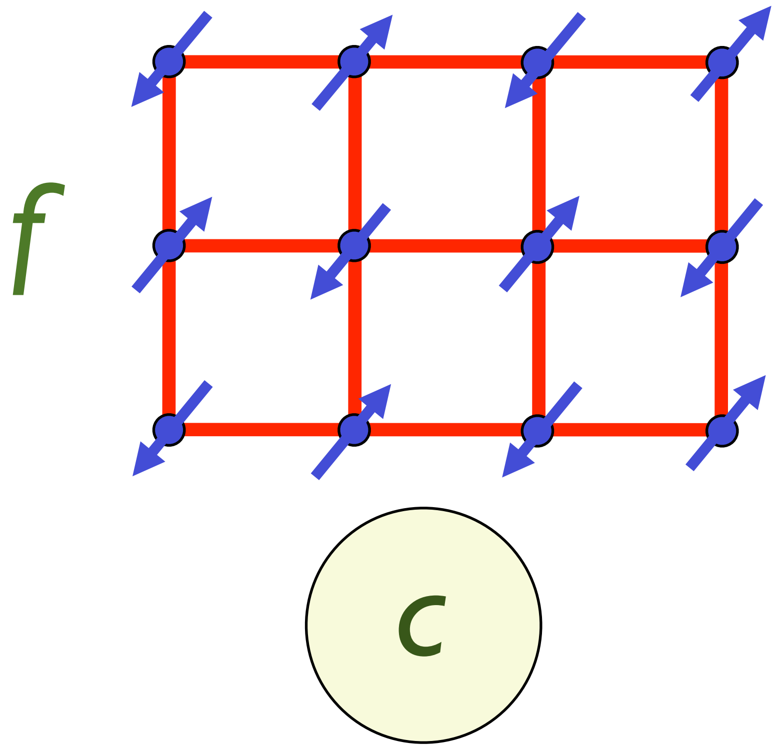
PRL **107,** 047003 (2011) PHYSICAL REVIEW LETTERS week ending 22 JULY 2011

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]

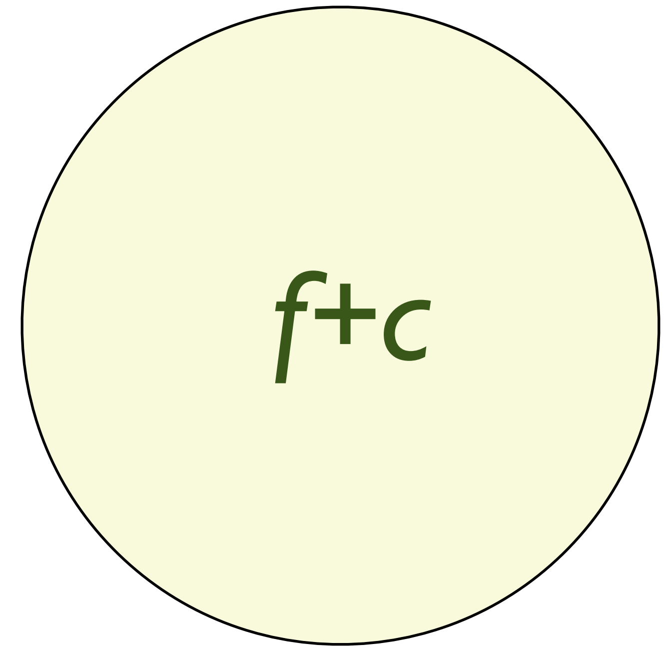
Tuesday, January 31, 2012

Magnetic order and the heavy Fermi liquid in the Kondo lattice



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

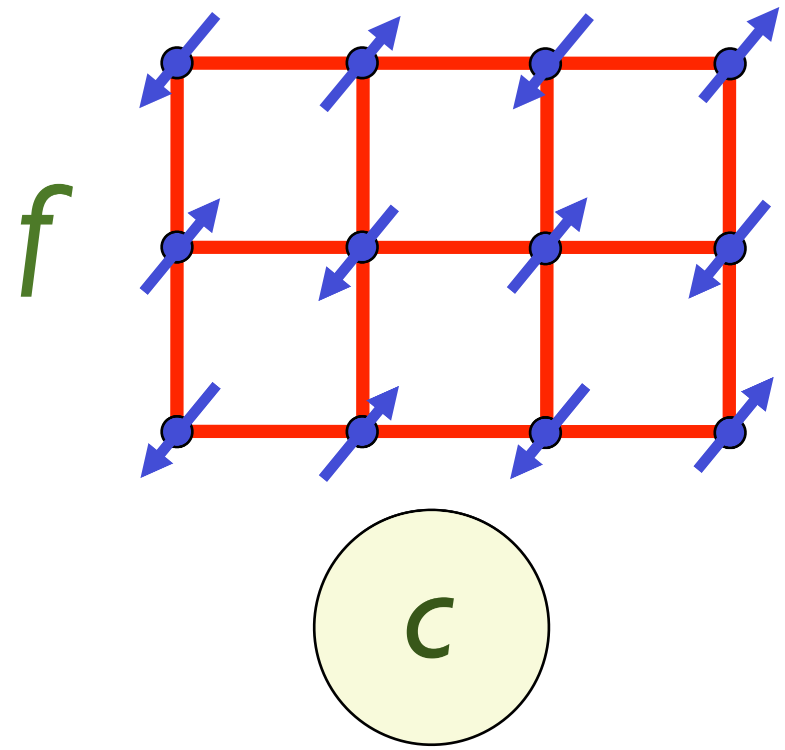
Magnetic Metal:
f-electron moments
and
c-conduction electron
Fermi surface



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

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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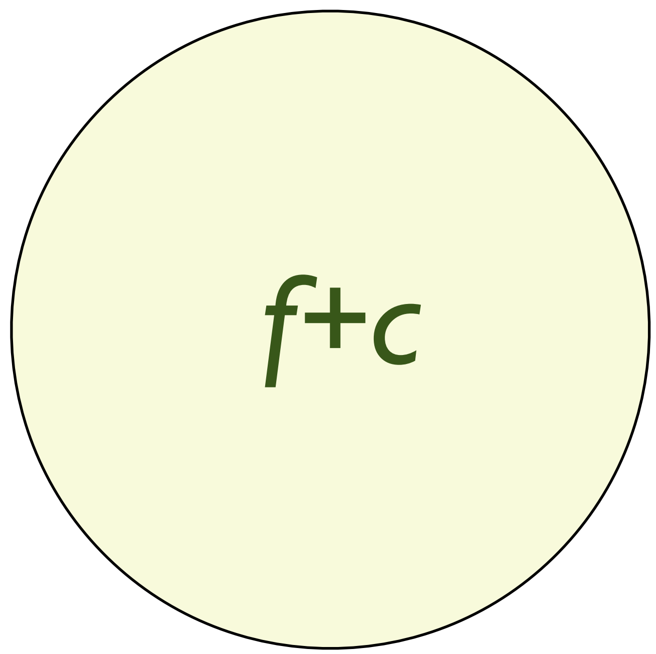

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T. Senthil, S. Sachdev, and M. Vojta, *Phys. Rev. Lett.* **90**, 216403 (2003)

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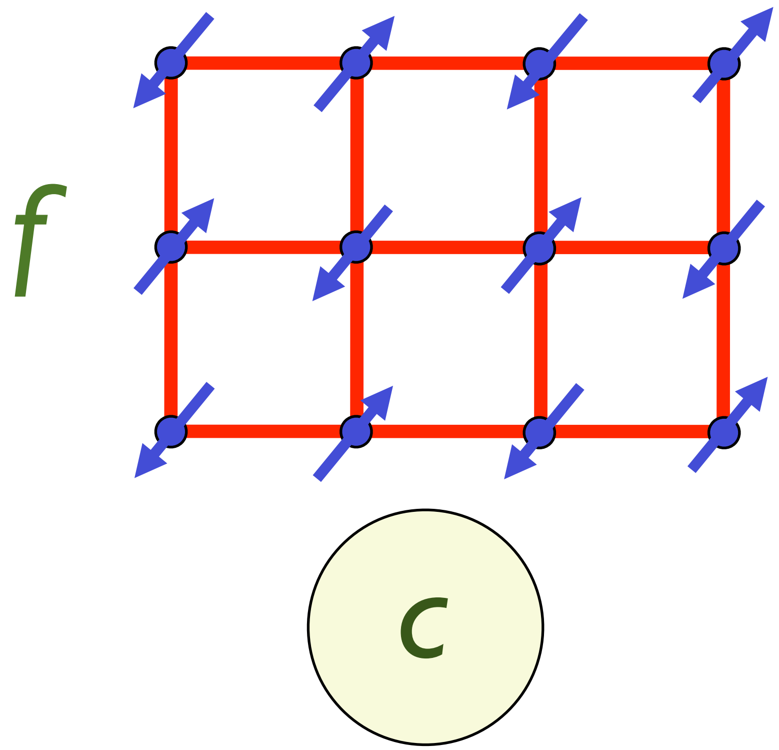

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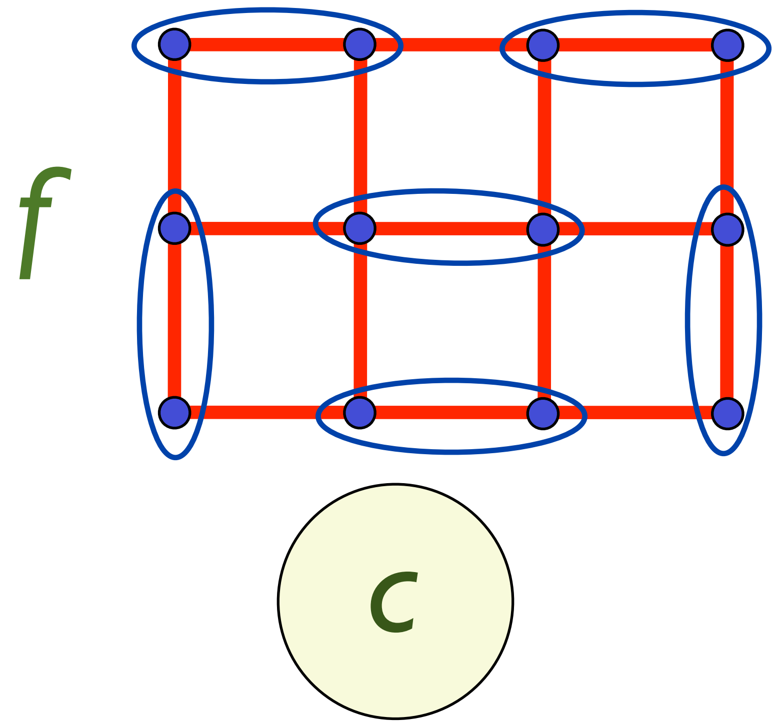
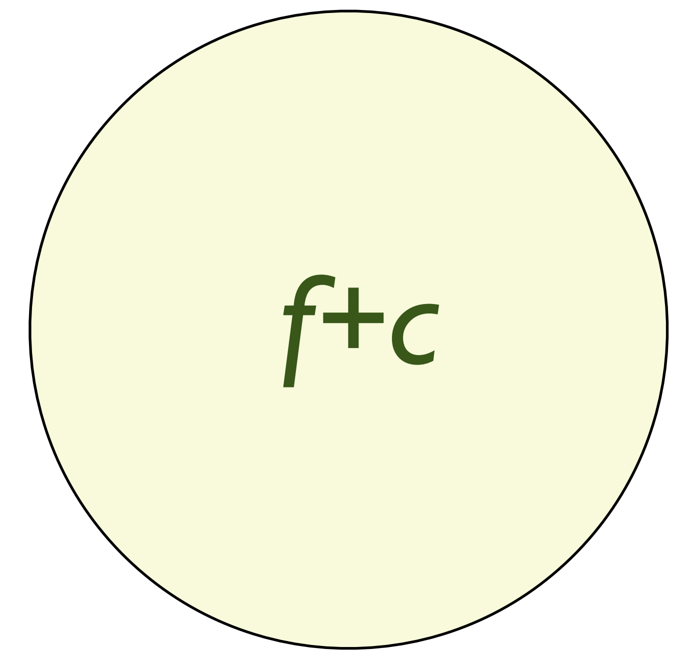


$\langle \vec{\varphi} \rangle = 0$

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



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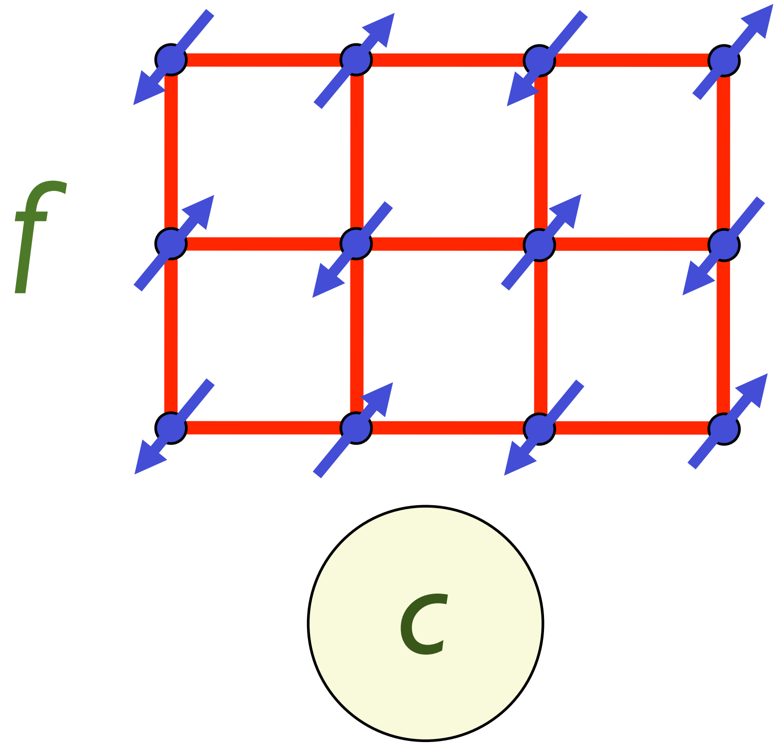

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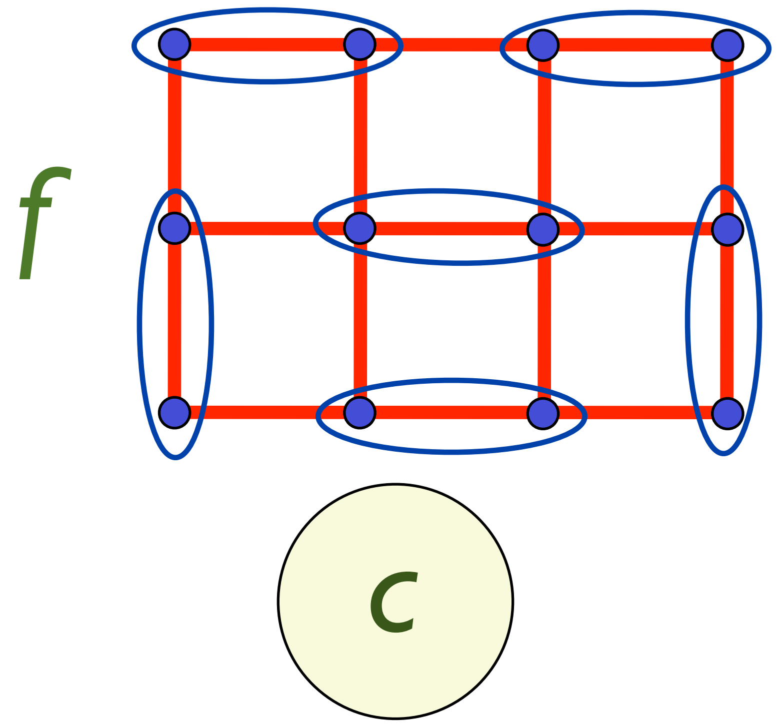

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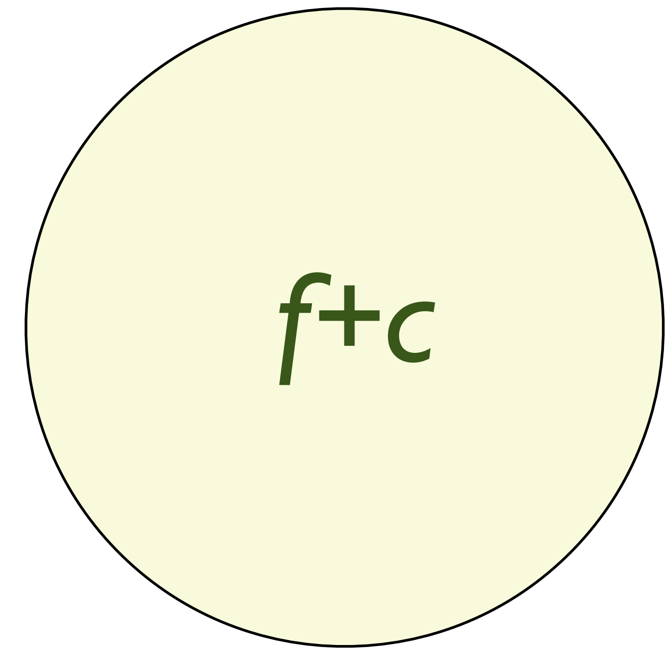
Fractionalized Fermi liquid (FL*) phase with no symmetry breaking and "small" Fermi surface



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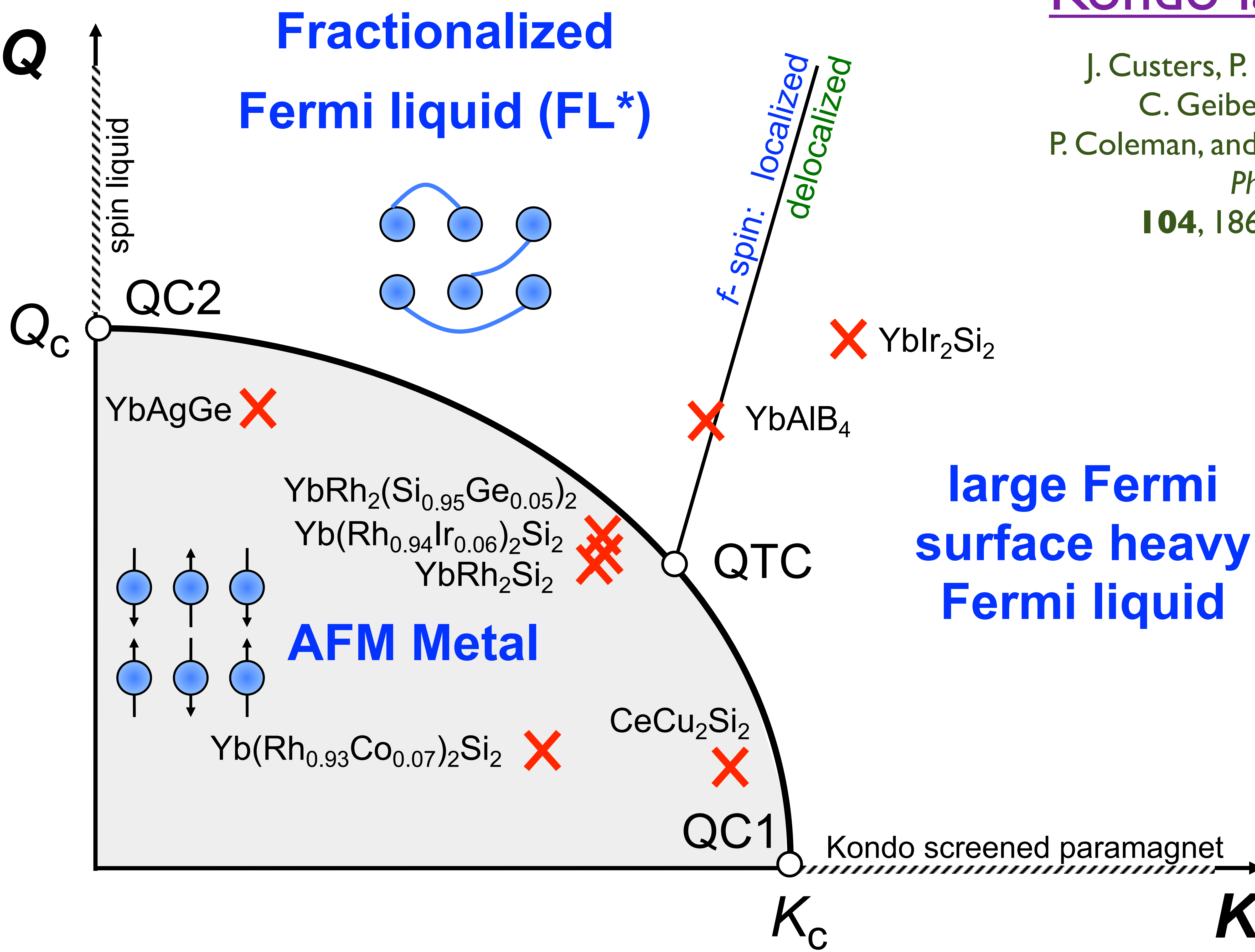
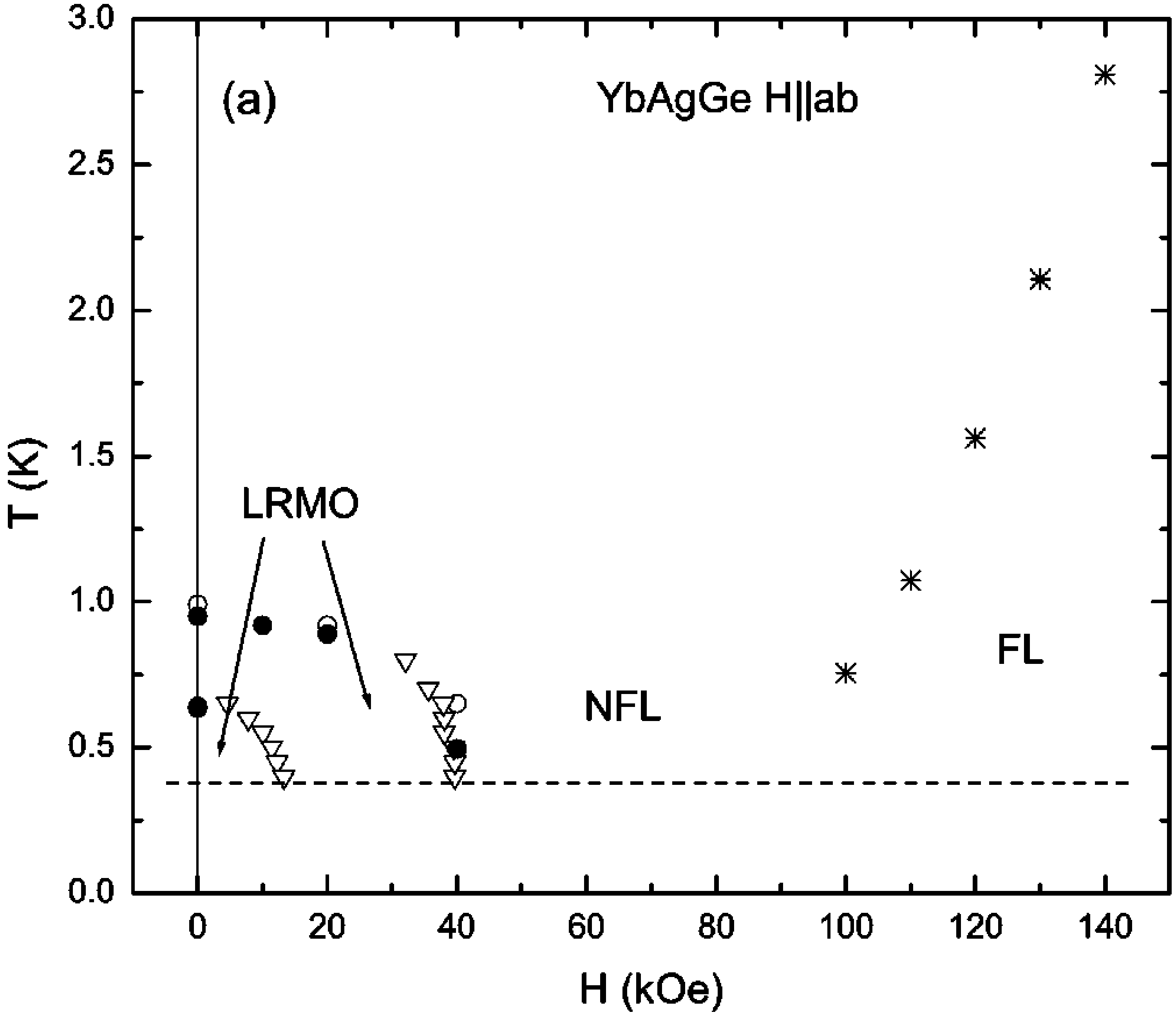
T. Senthil, S. Sachdev, and M. Vojta, *Phys. Rev. Lett.* **90**, 216403 (2003)

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)

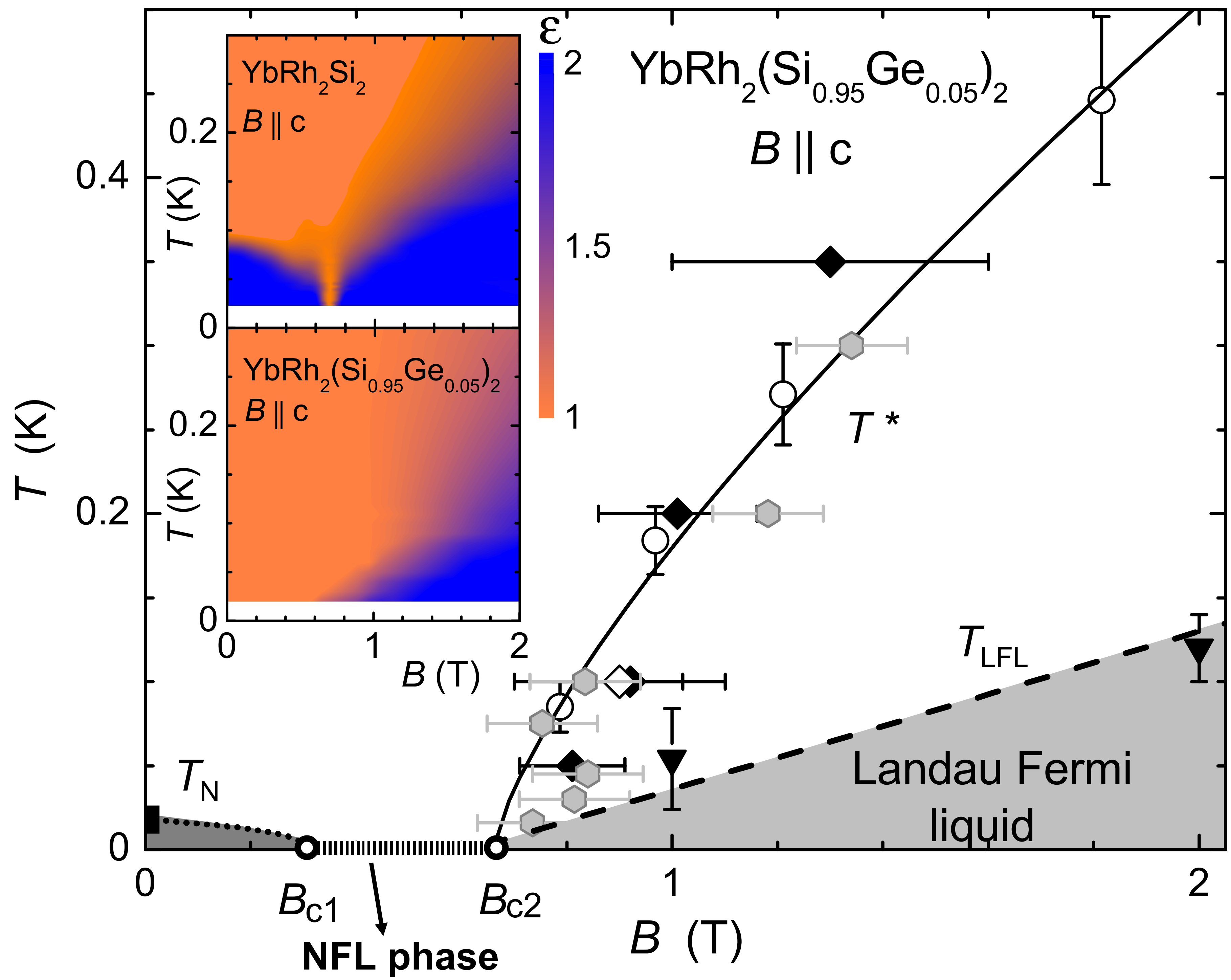




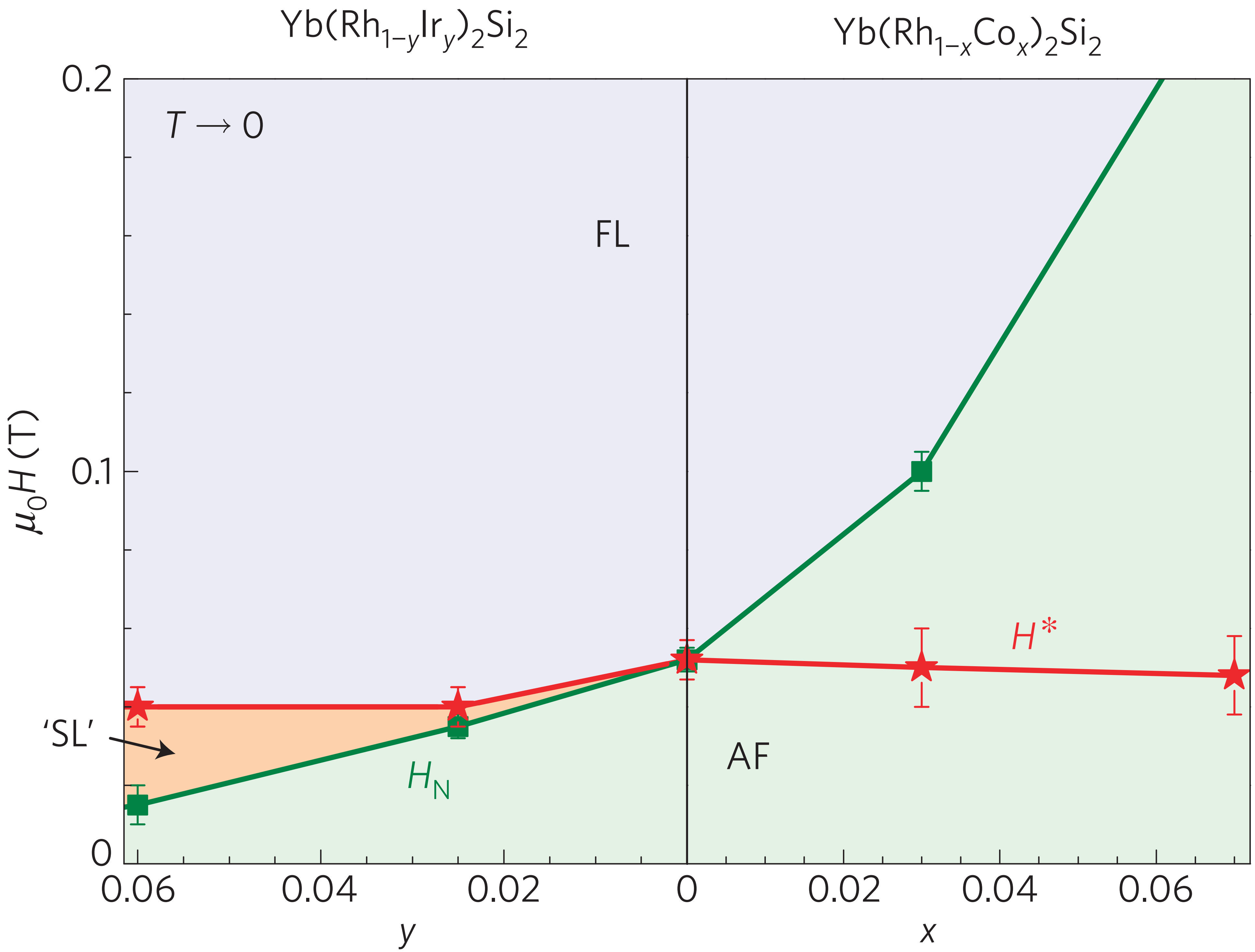
PHYSICAL REVIEW B **69**, 014415 (2004)

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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- Fermi surface volume does not count all electrons.

- 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

- Fermi surface volume does not count all electrons.

- 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)

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

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
enclosed by the Fermi surfaces