

Higgs Criticality in a two-dimensional metal



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Debanjan Chowdhury and Subir Sachdev



PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS



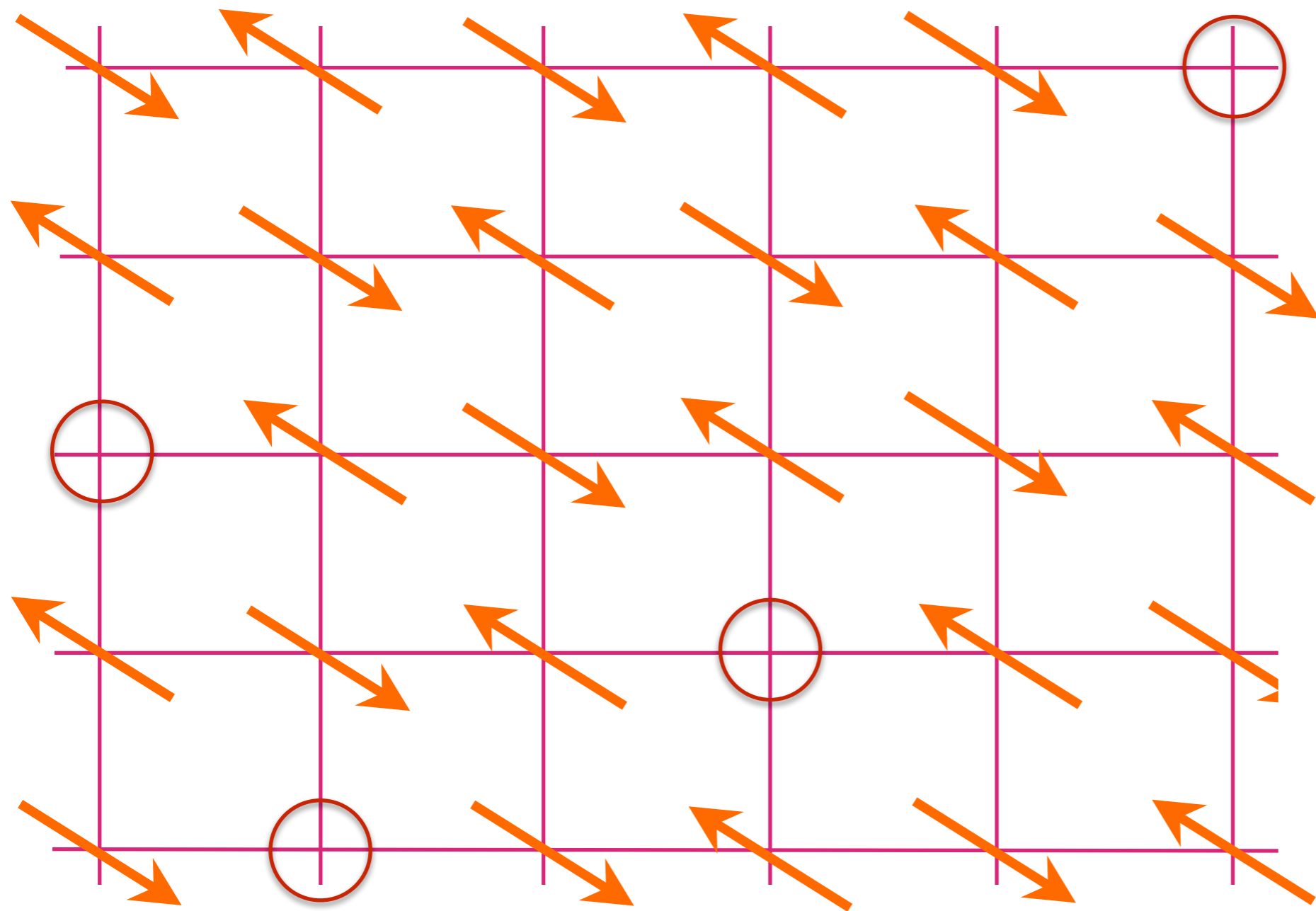
JOHN TEMPLETON
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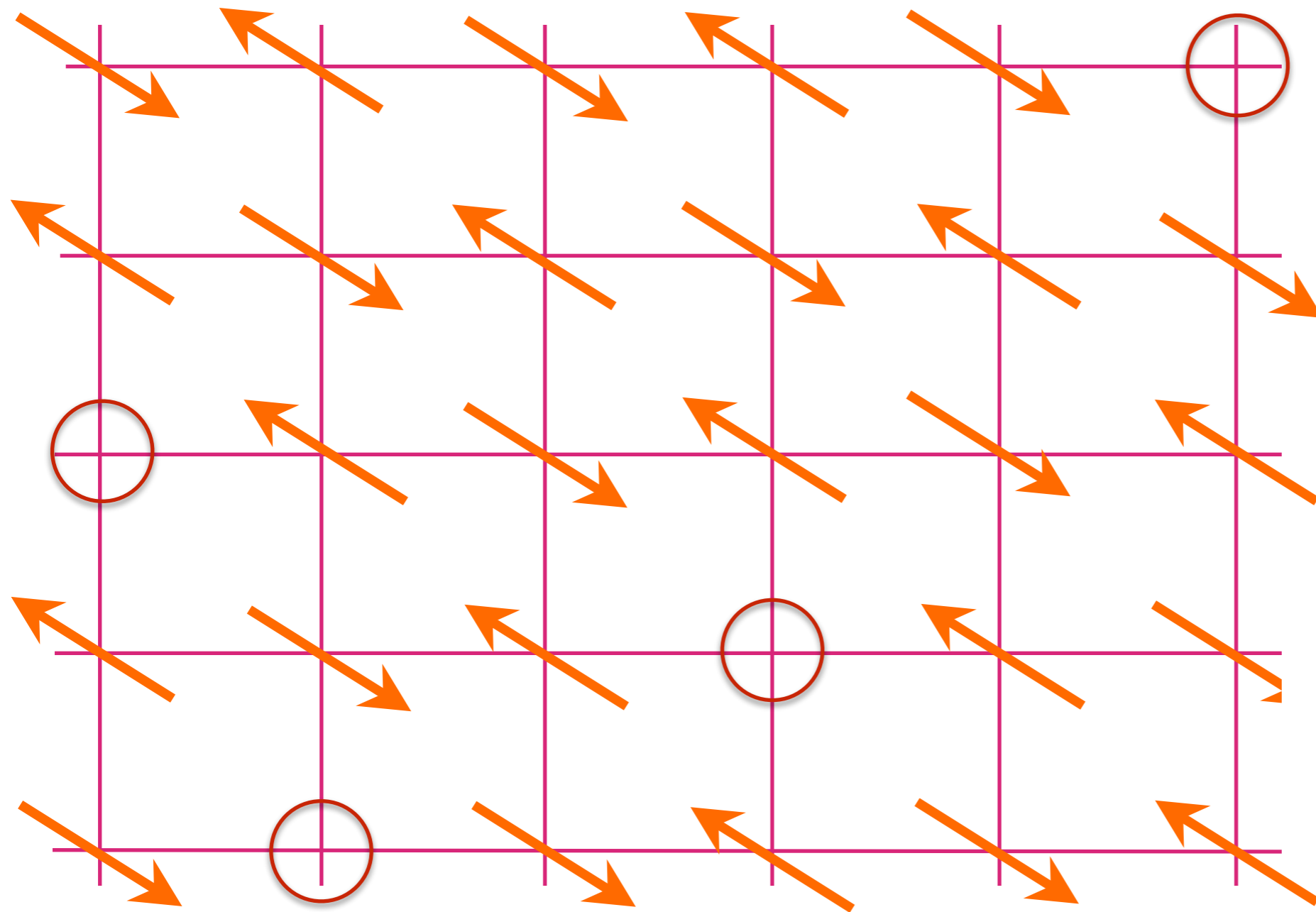


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Talk online: sachdev.physics.harvard.edu

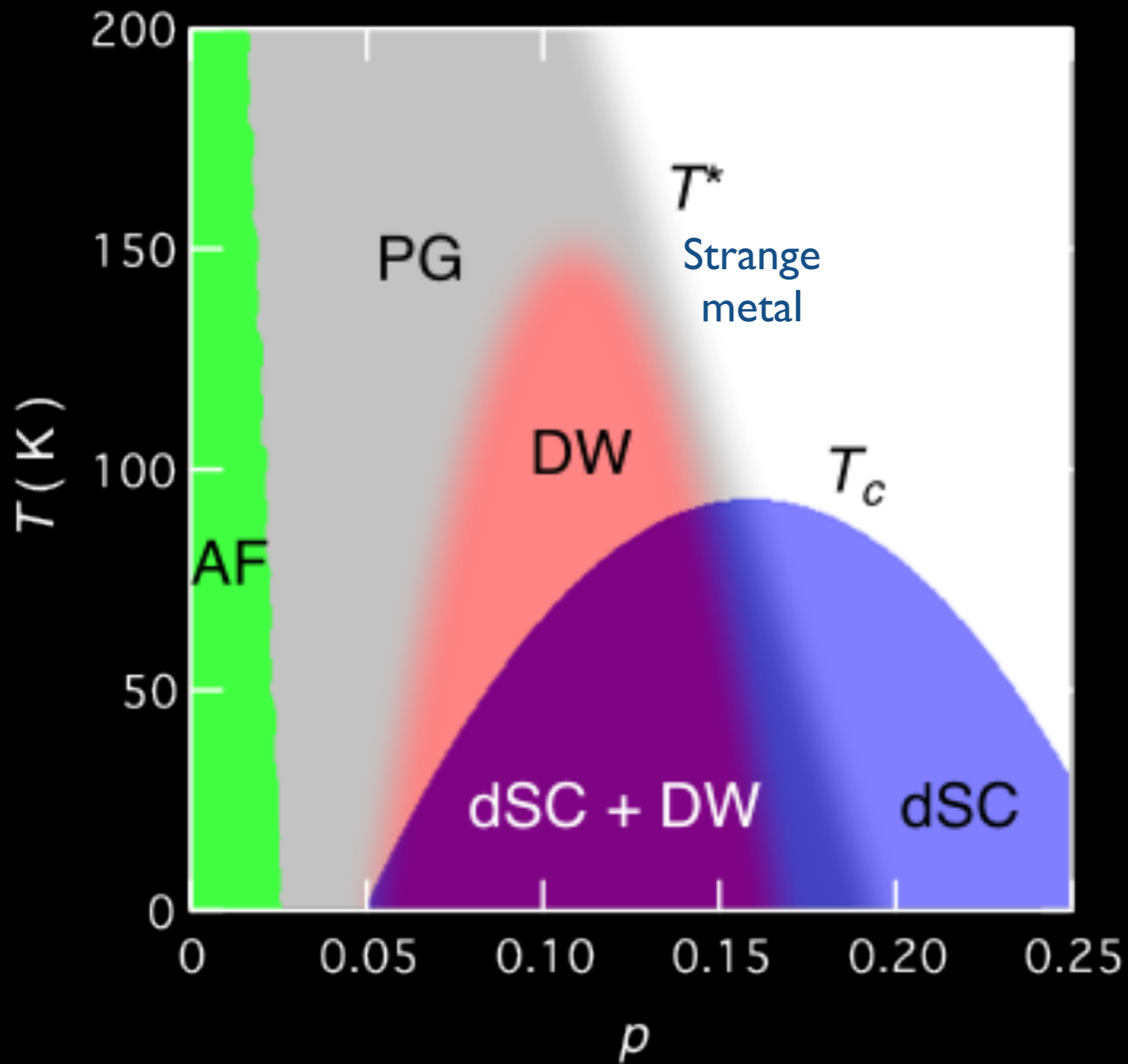


Anti-ferromagnet
with p holes
per square

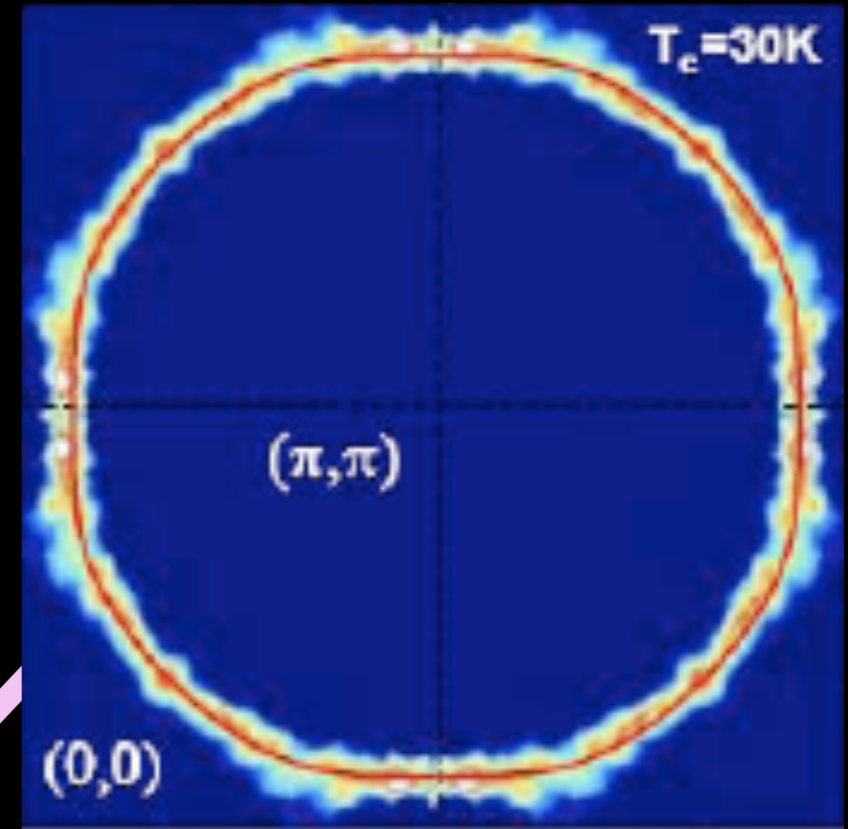
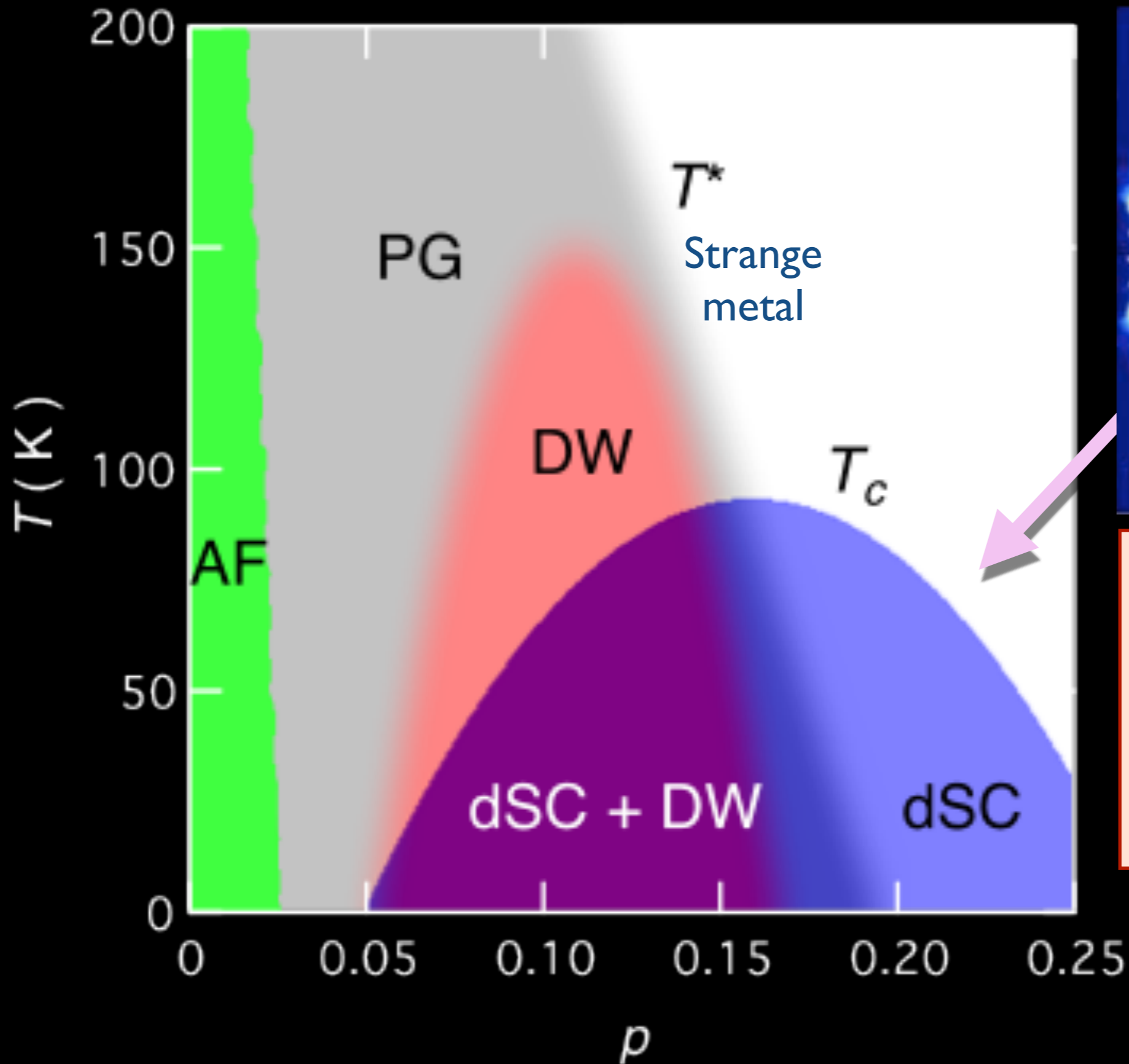


Anti-ferromagnet
with p holes
per square

But relative
to the band
insulator,
there are
 $1 + p$ holes
per square

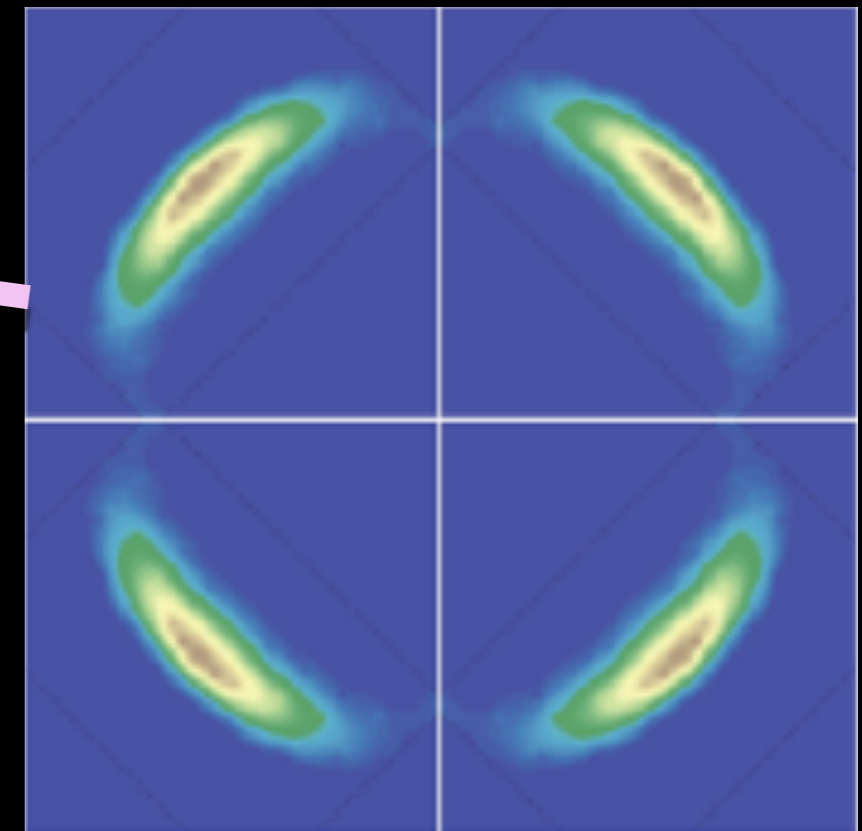
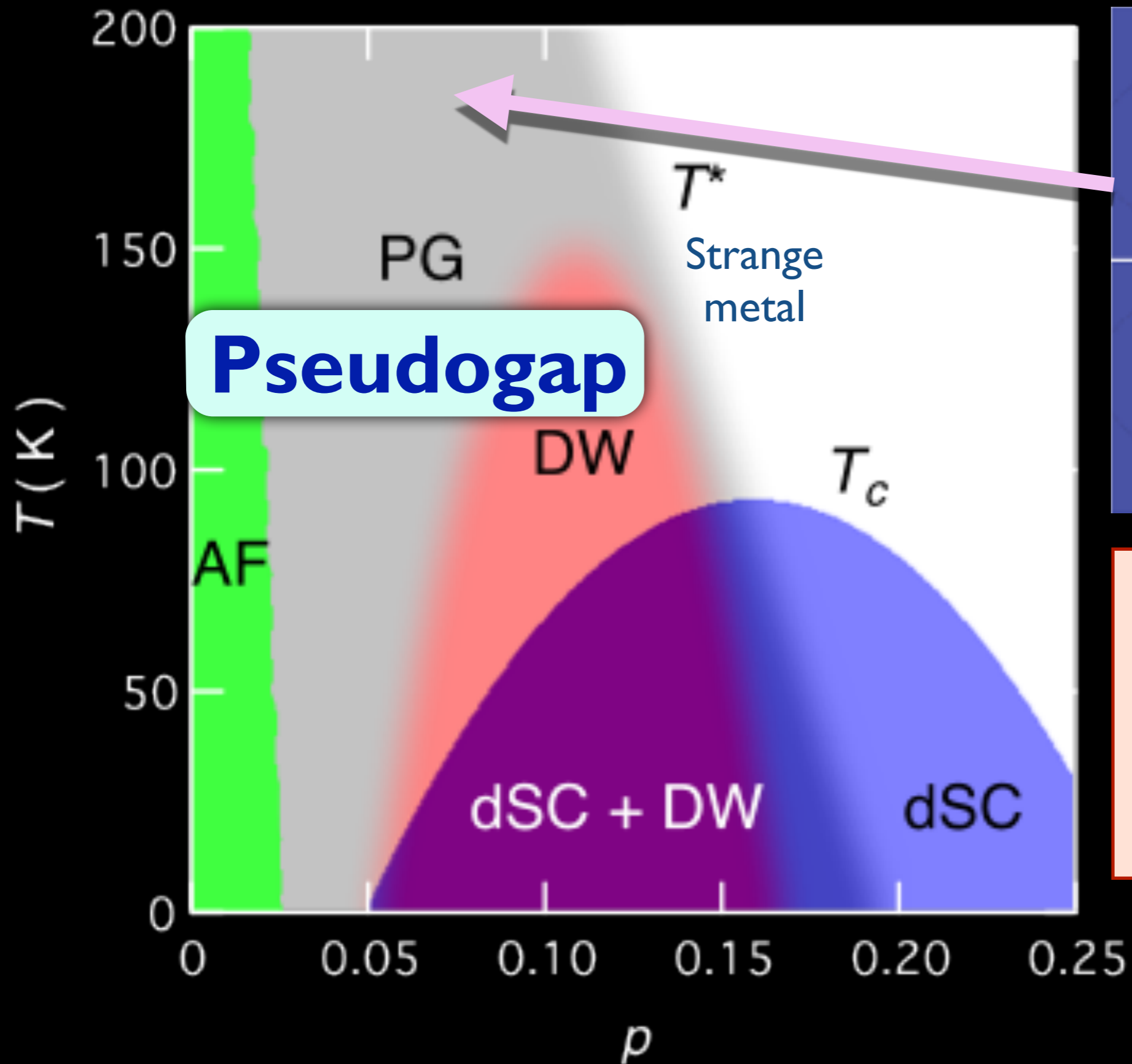


M. Platié, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)



Fermi liquid:
Area enclosed
by Fermi surface
 $= | + p$

Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, *Science* **307**, 901 (2005)



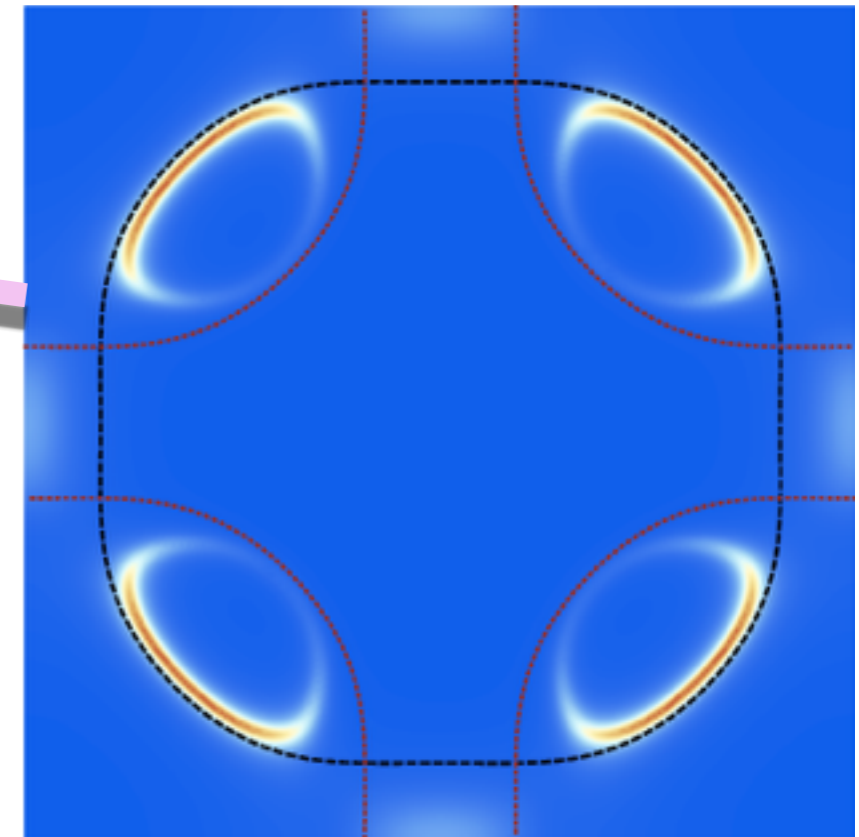
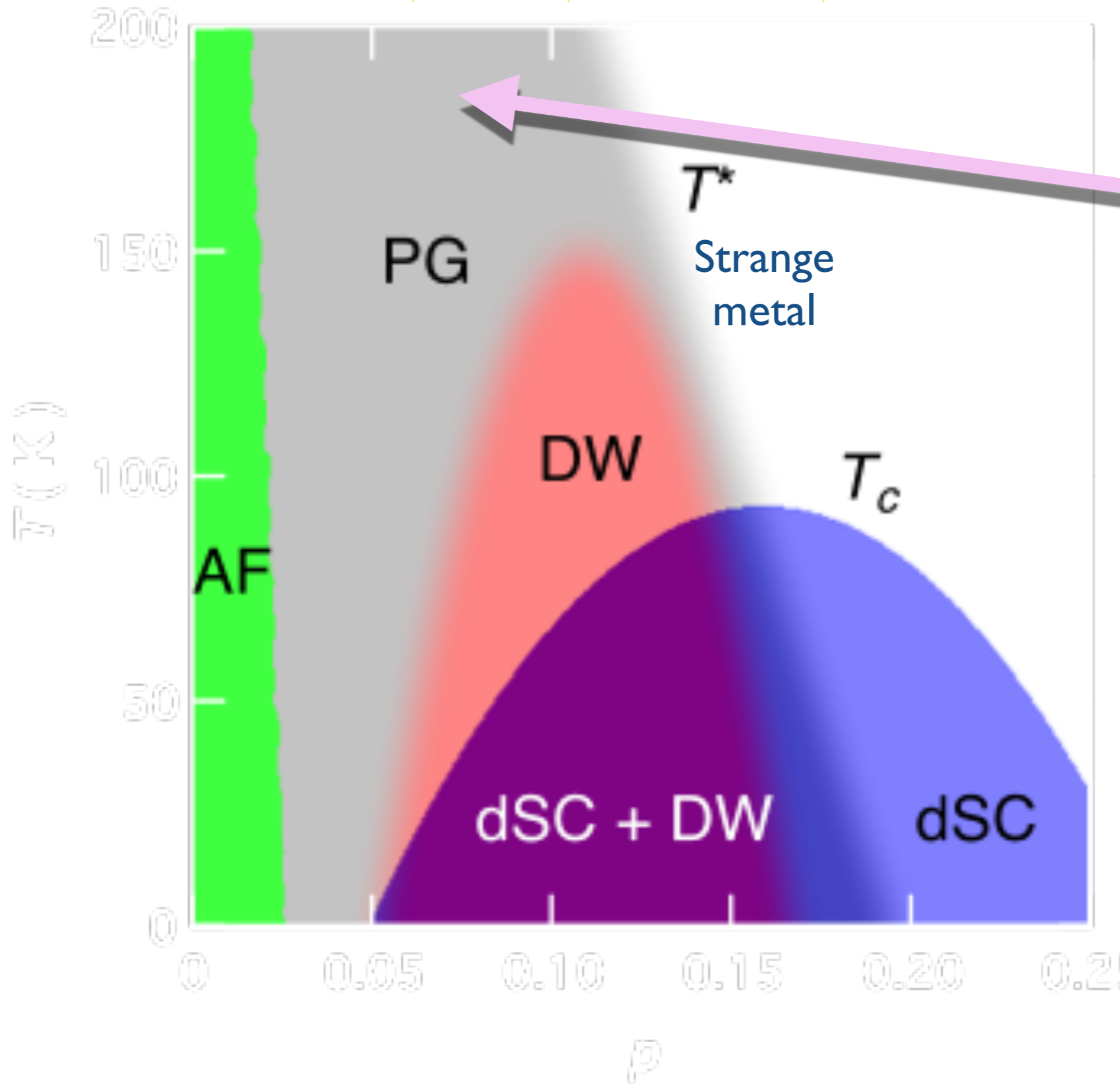
“Fermi arcs”
at
low p

R. K. Kaul, A. Kolezhuk, M. Levin, S. S., and T. Senthil, Phys. Rev. B **75**, 235122 (2007)

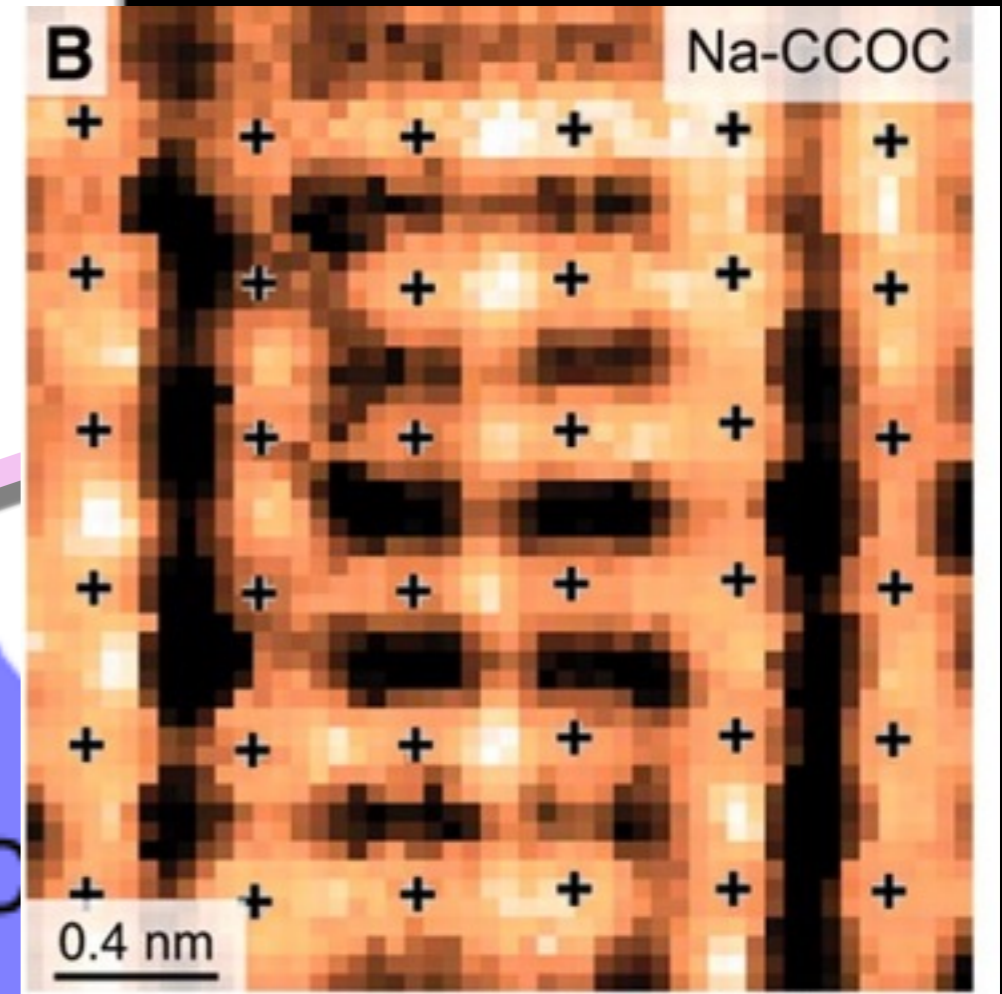
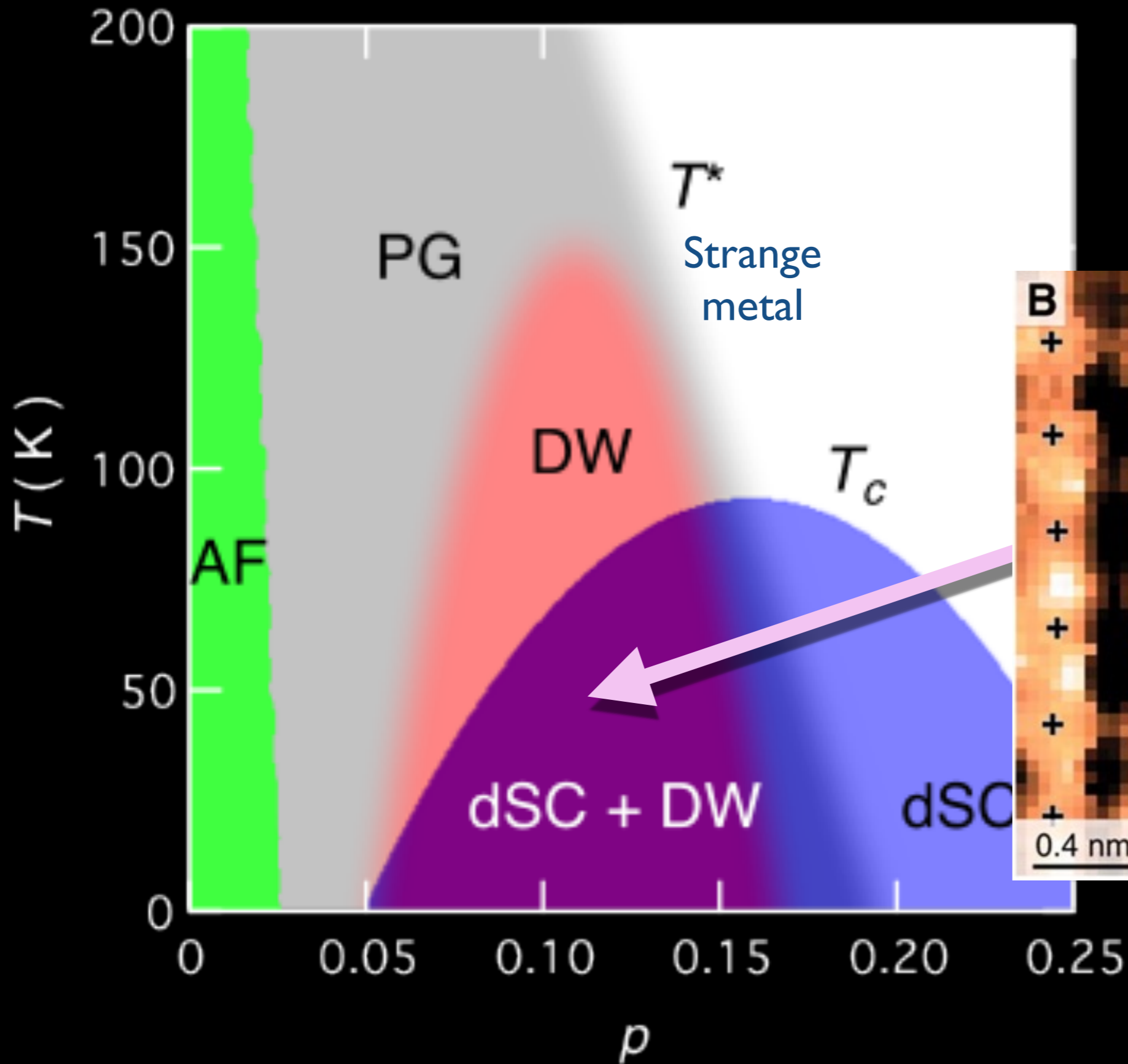
Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)

D. Chowdhury and S. Sachdev, Phys. Rev. B **90**, 245136 (2014).

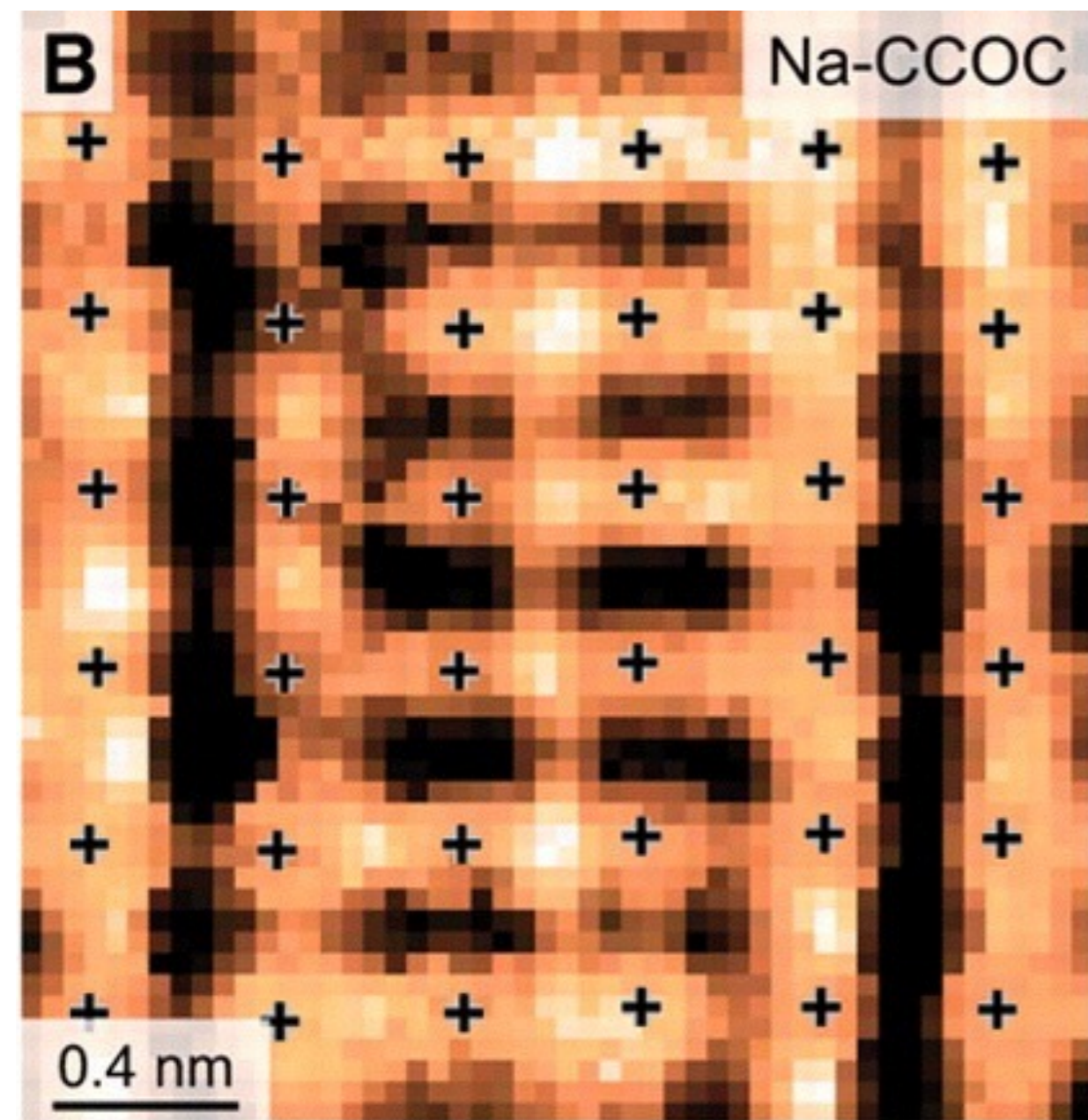
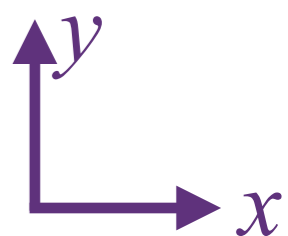
M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978



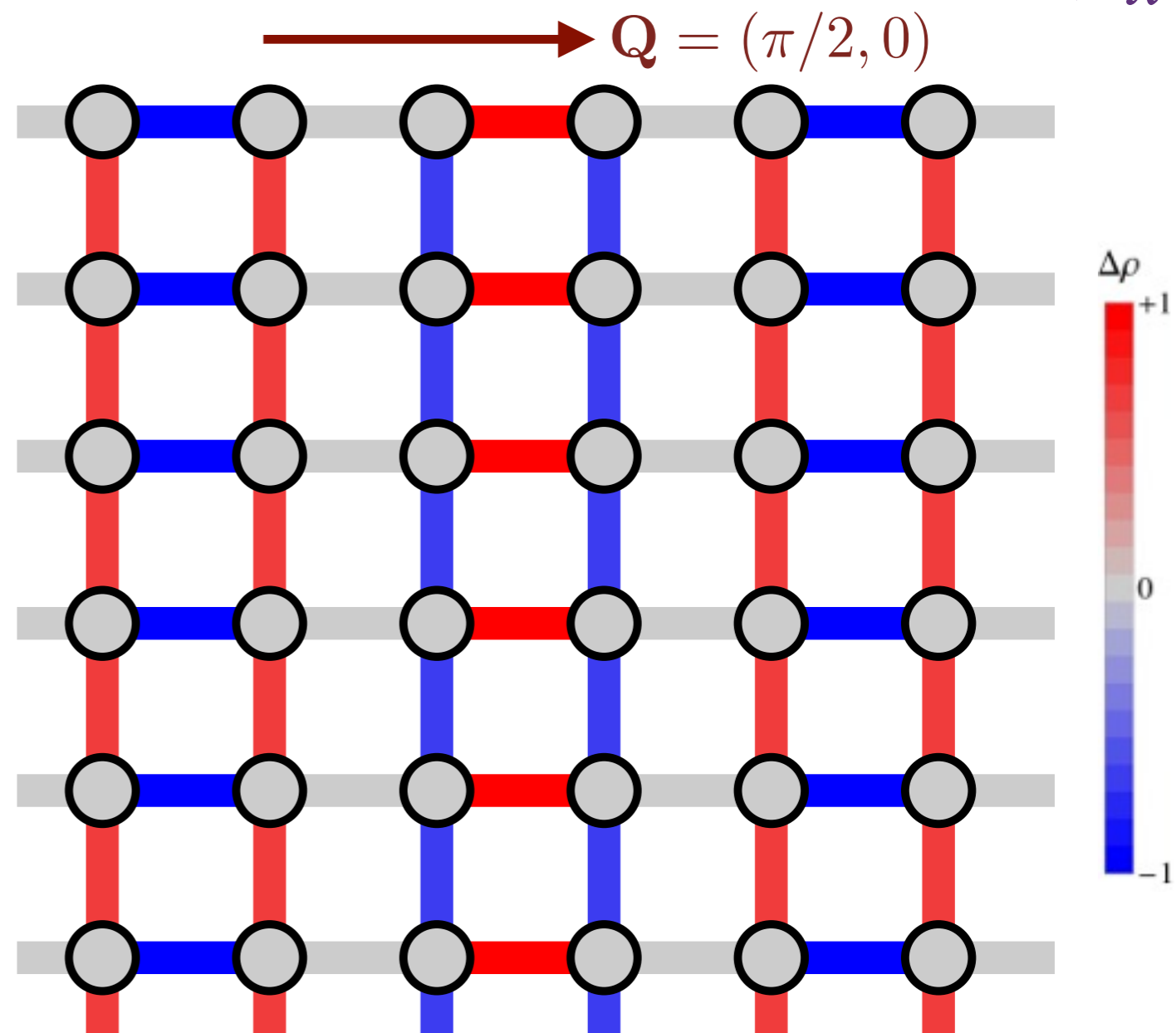
A “Fractionalized Fermi liquid” (FL*) of holes of density p : has fermions of spin $S=1/2$ and charge $+e$ along with topological order in a background spin liquid



M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075128 (2010).
 S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).



Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)

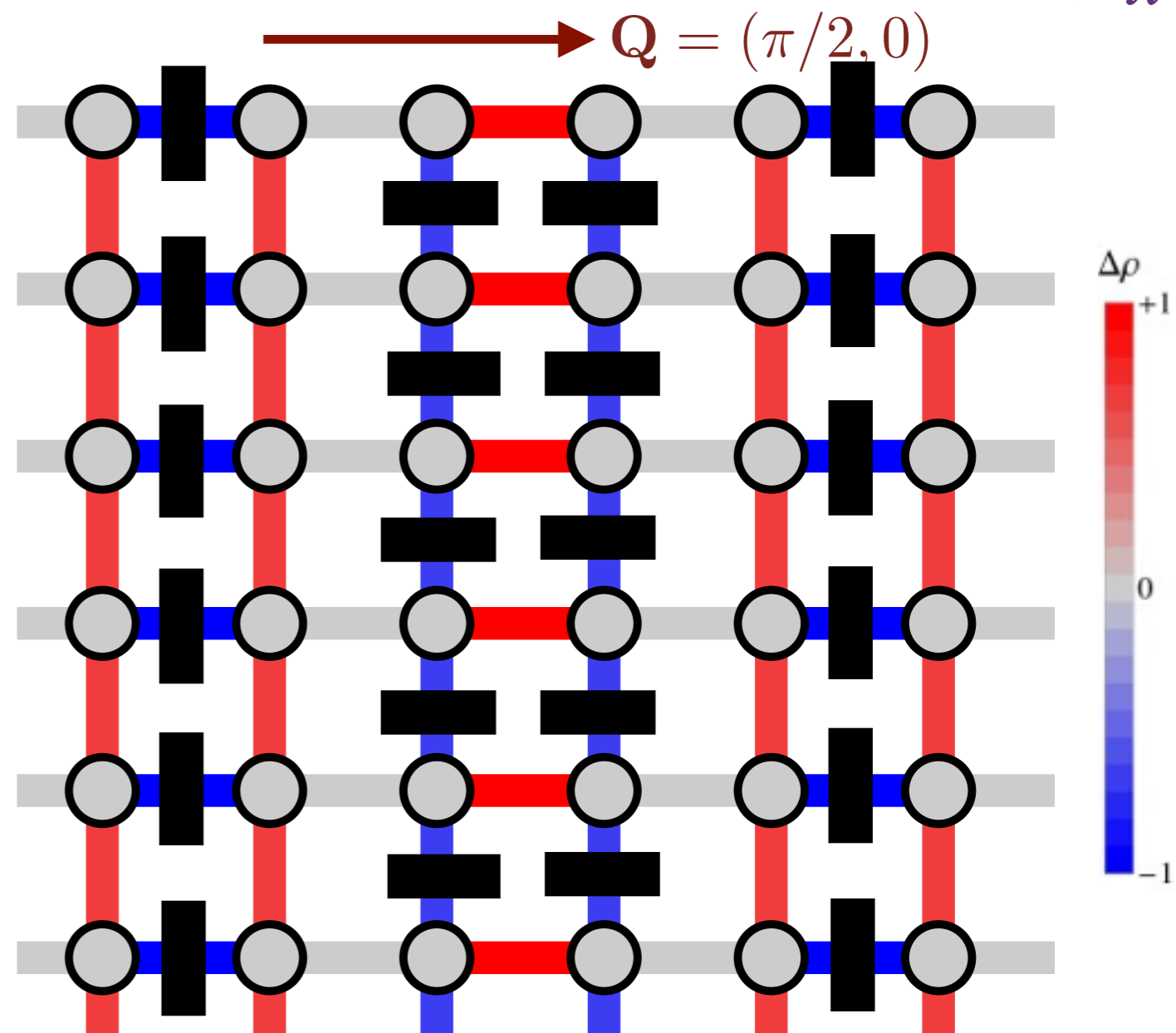
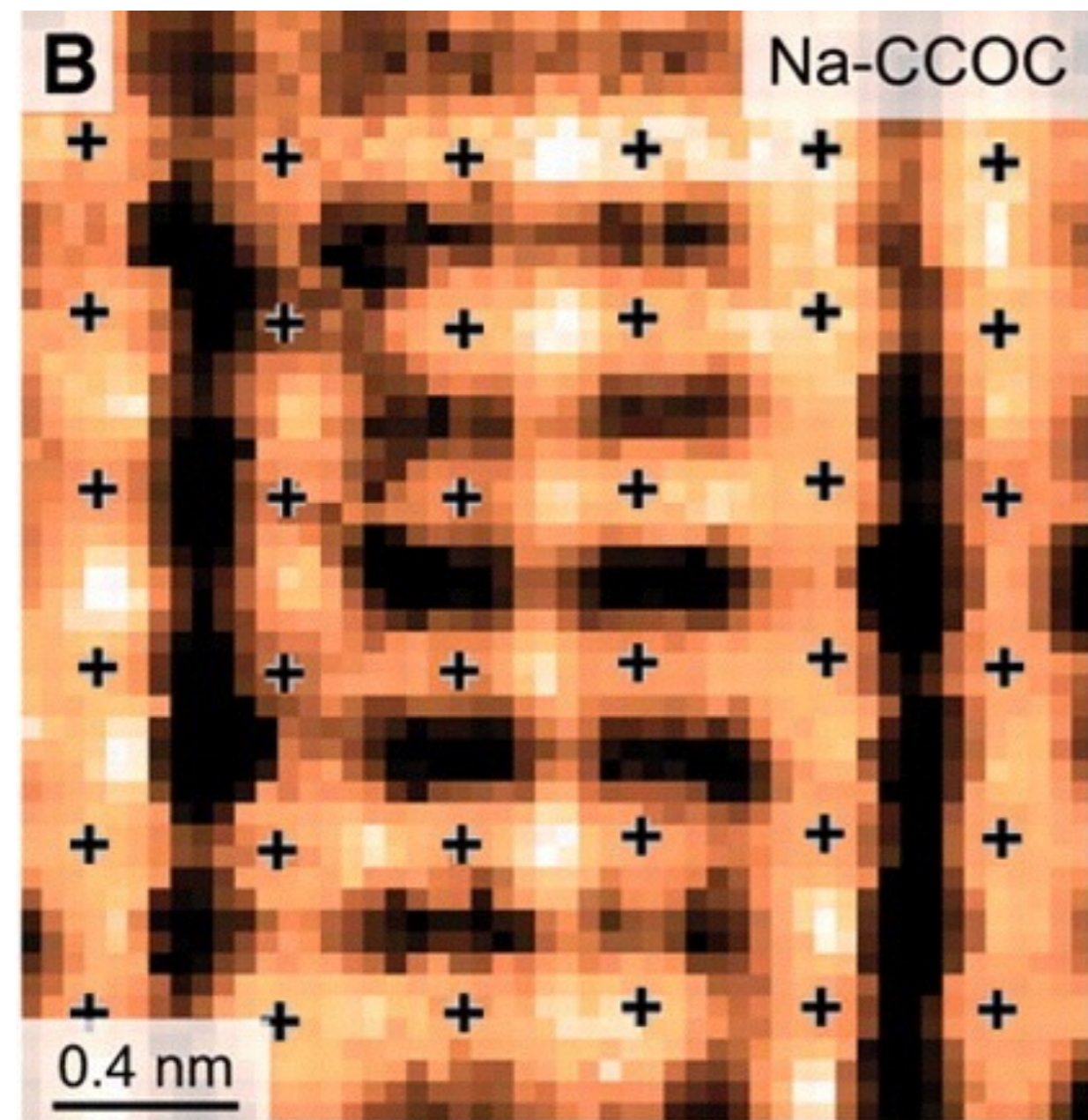
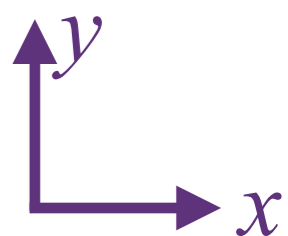


d-form factor density wave order

Predicted *d* form factor observed
 in STM measurements on BSCCO, Na-CCOC

K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075128 (2010).
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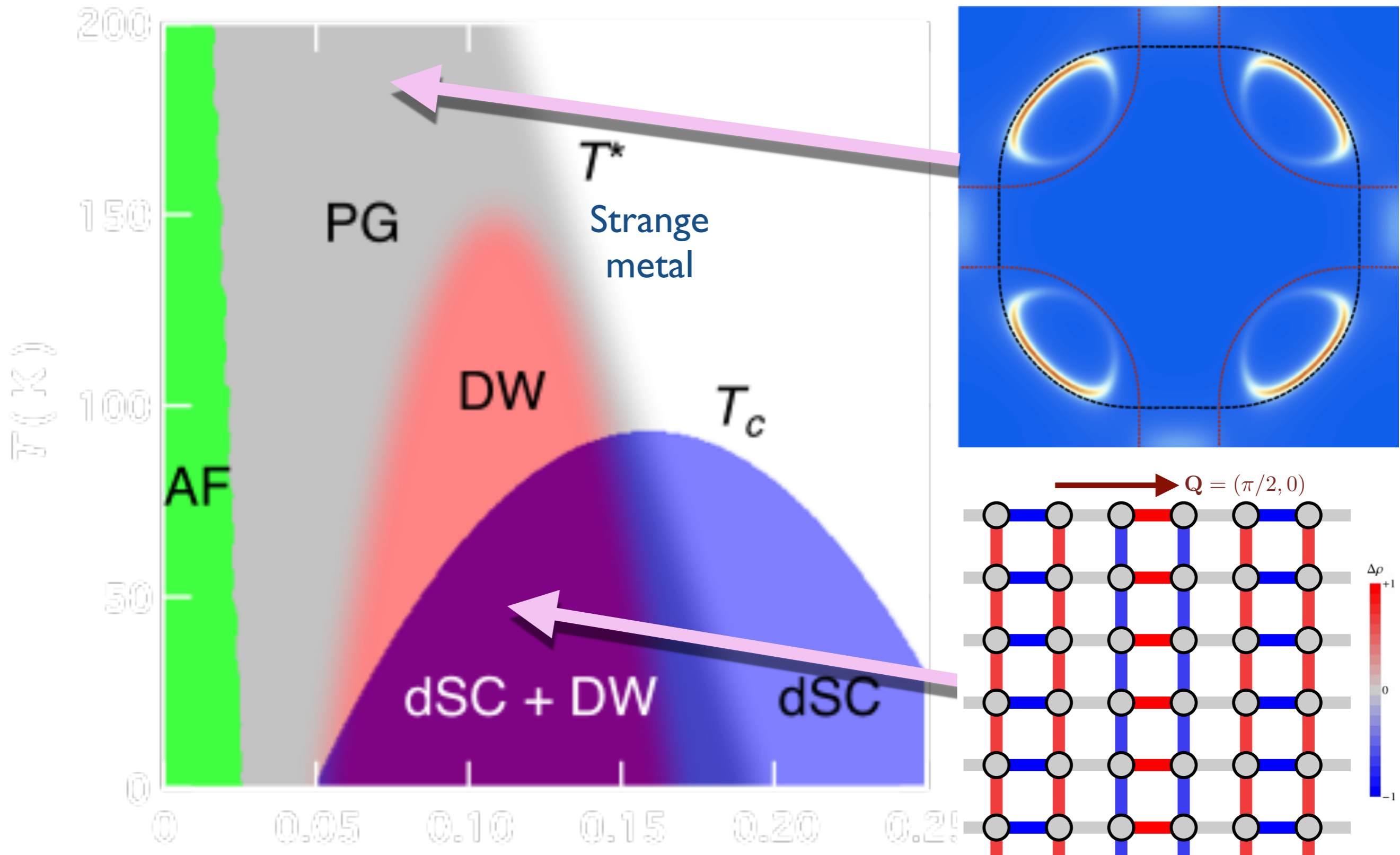
Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)

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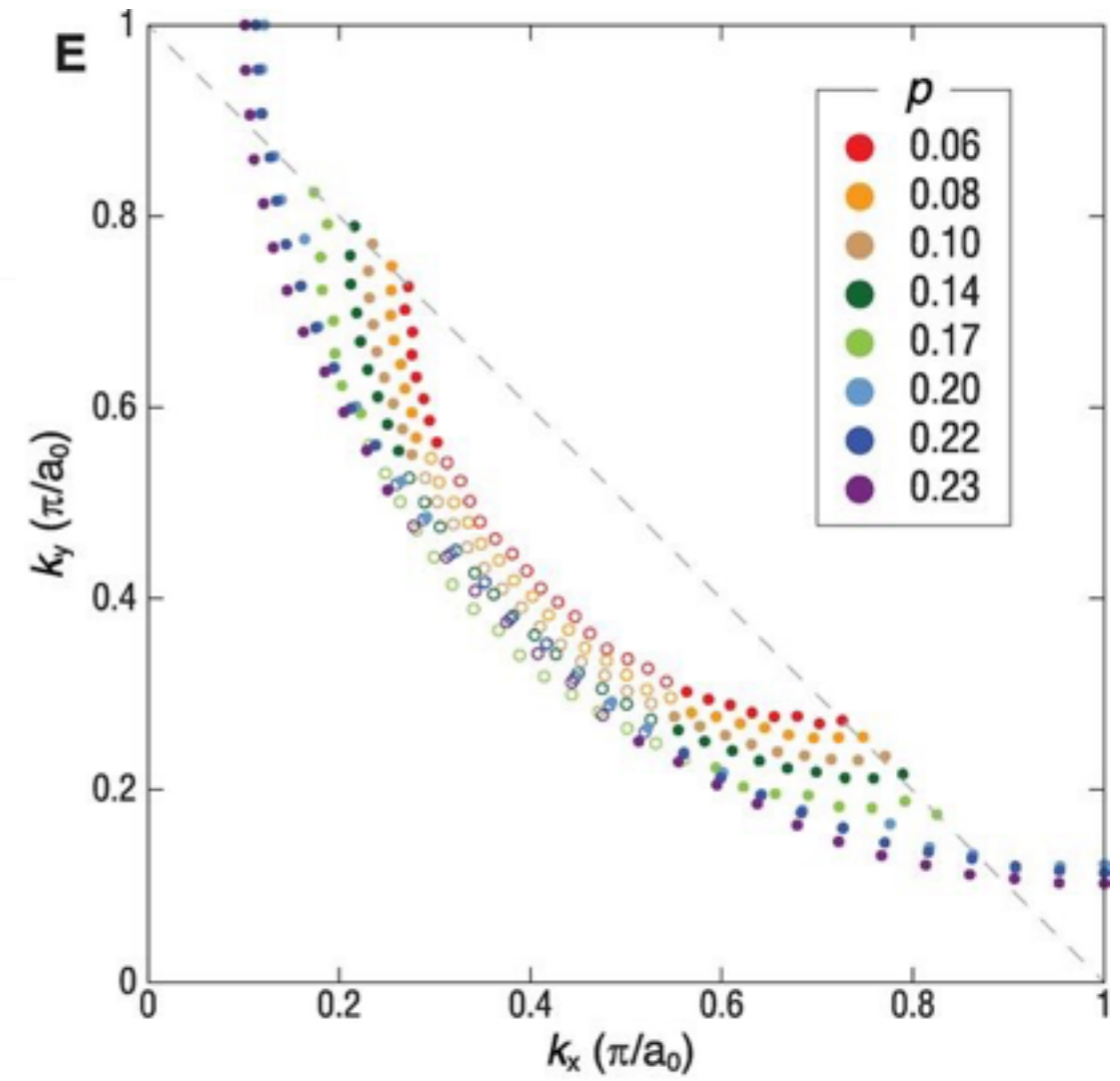
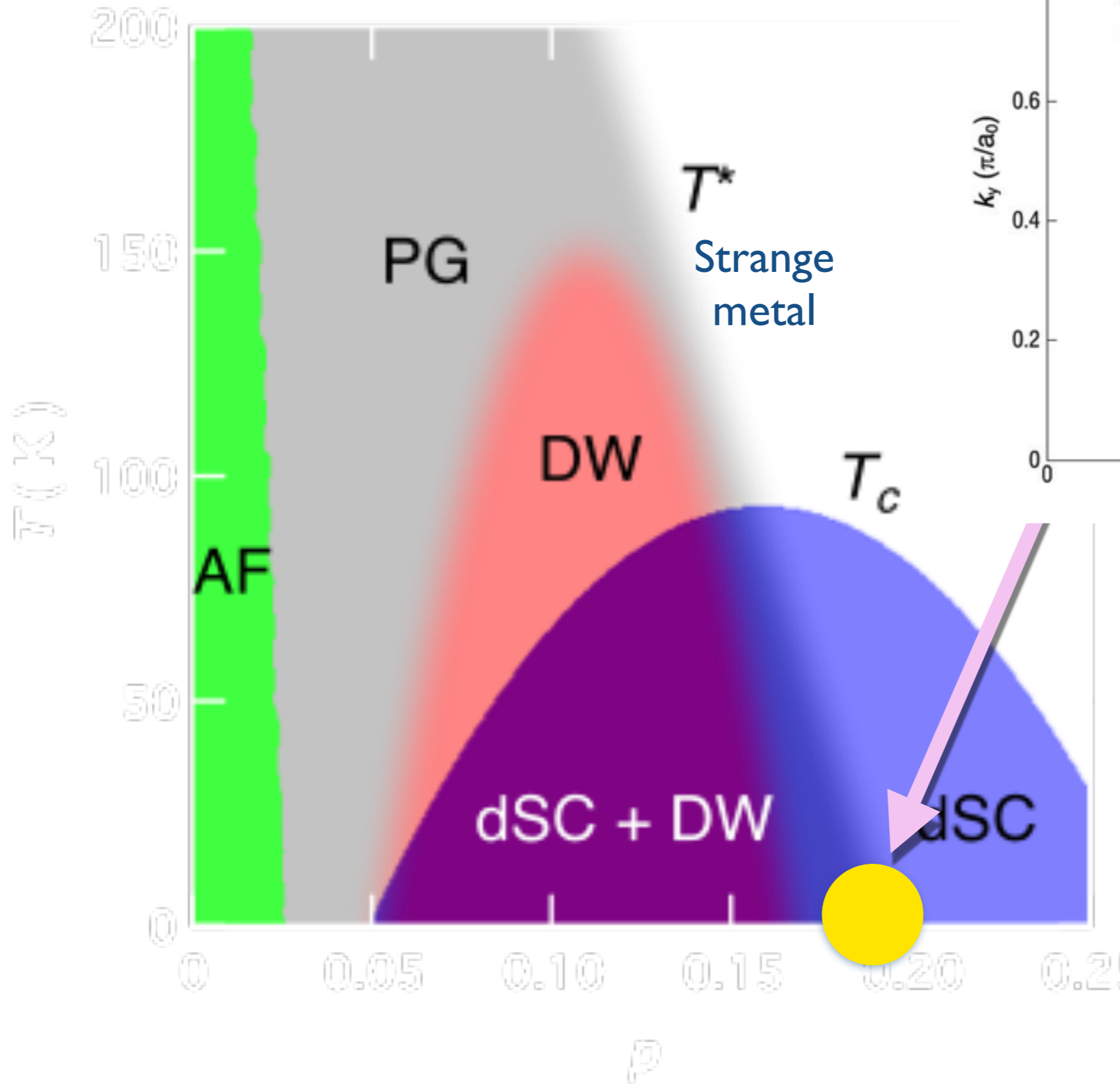
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

d -form factor density wave arises an instability of FL*



D. Chowdhury and S. Sachdev,
Phys. Rev. B **90**, 245136 (2014). ρ

Y. He *et al.*, Science **344**, 608-611 (2014)
K. Fujita *et al.*, Science **344**, 612-616 (2014)

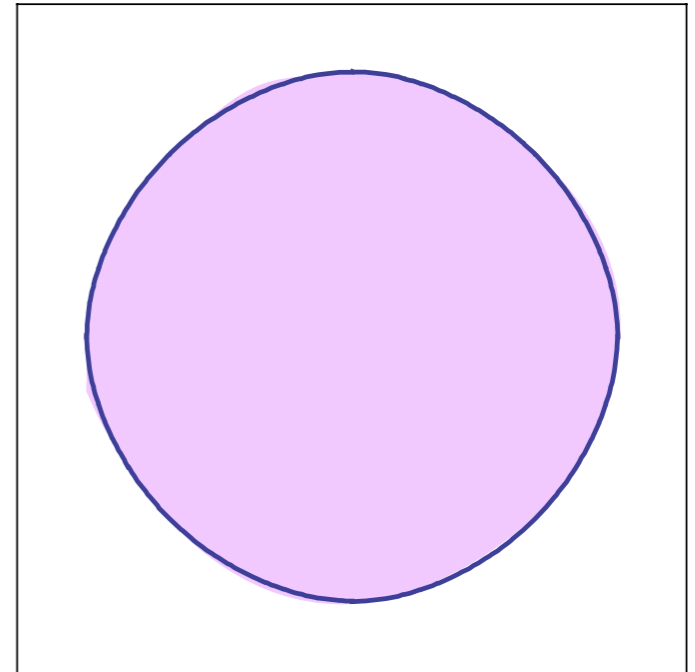


Sudden change in Fermi surface, as observed by STM, at optimal doping.

Apparent transition from p fermionic quasiparticles to $1+p$ quasiparticles

Fermi surface+antiferromagnetism

Metal with “large”
Fermi surface

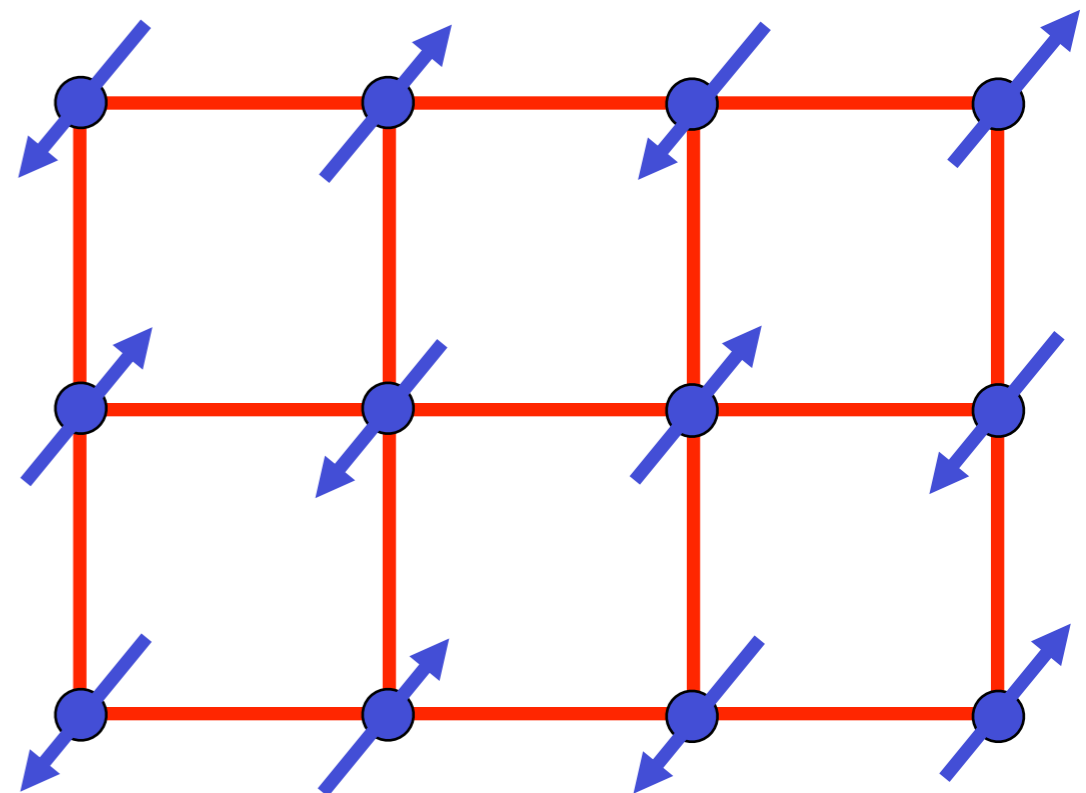


+

The electron spin polarization obeys

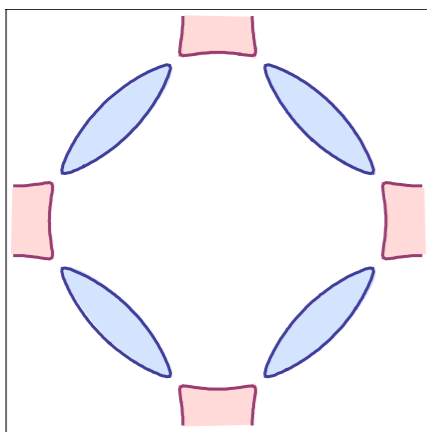
$$\langle \vec{S}(\mathbf{r}, \tau) \rangle = \vec{\varphi}(\mathbf{r}, \tau) e^{i\mathbf{K} \cdot \mathbf{r}}$$

where $\mathbf{K} = (\pi, \pi)$ is the ordering
wavevector.

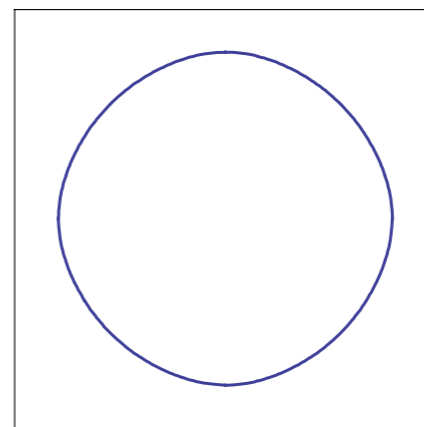


Conventional
Fermi liquids

(A) AFM order with
small Fermi pockets
of electrons



(B) Fermi liquid with
large Fermi surface
of electrons



$1/g$

s

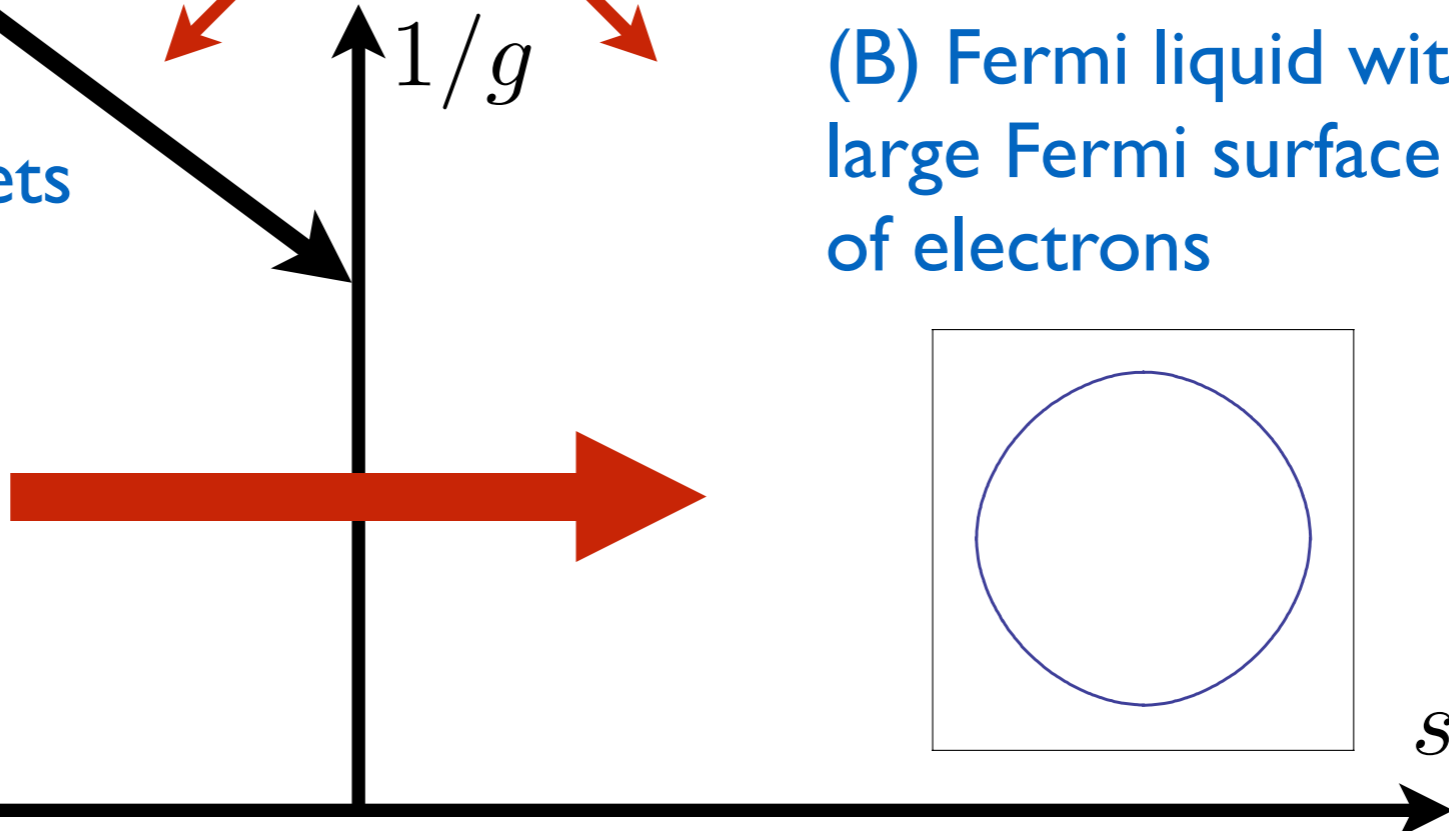
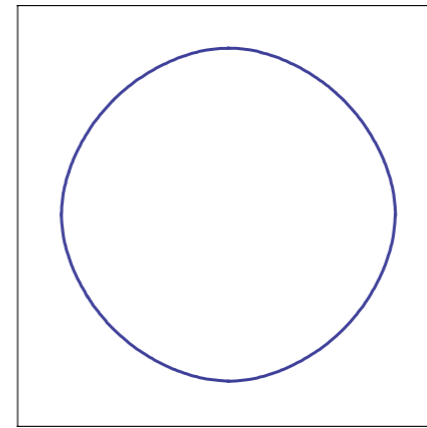
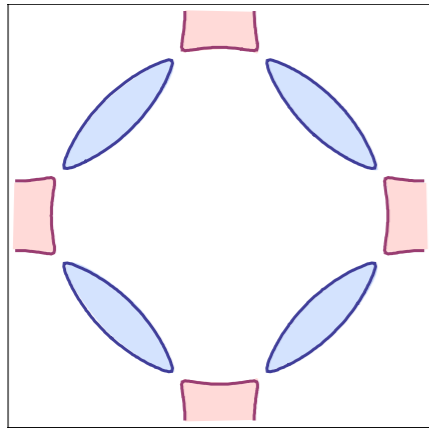


Hertz-Millis
criticality
of AFM order

Conventional
Fermi liquids

(A) AFM order with
small Fermi pockets
of electrons

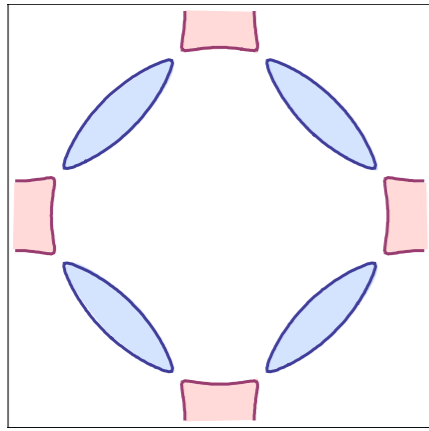
(B) Fermi liquid with
large Fermi surface
of electrons



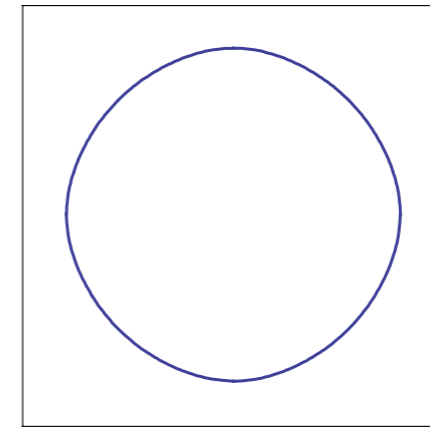
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Conventional
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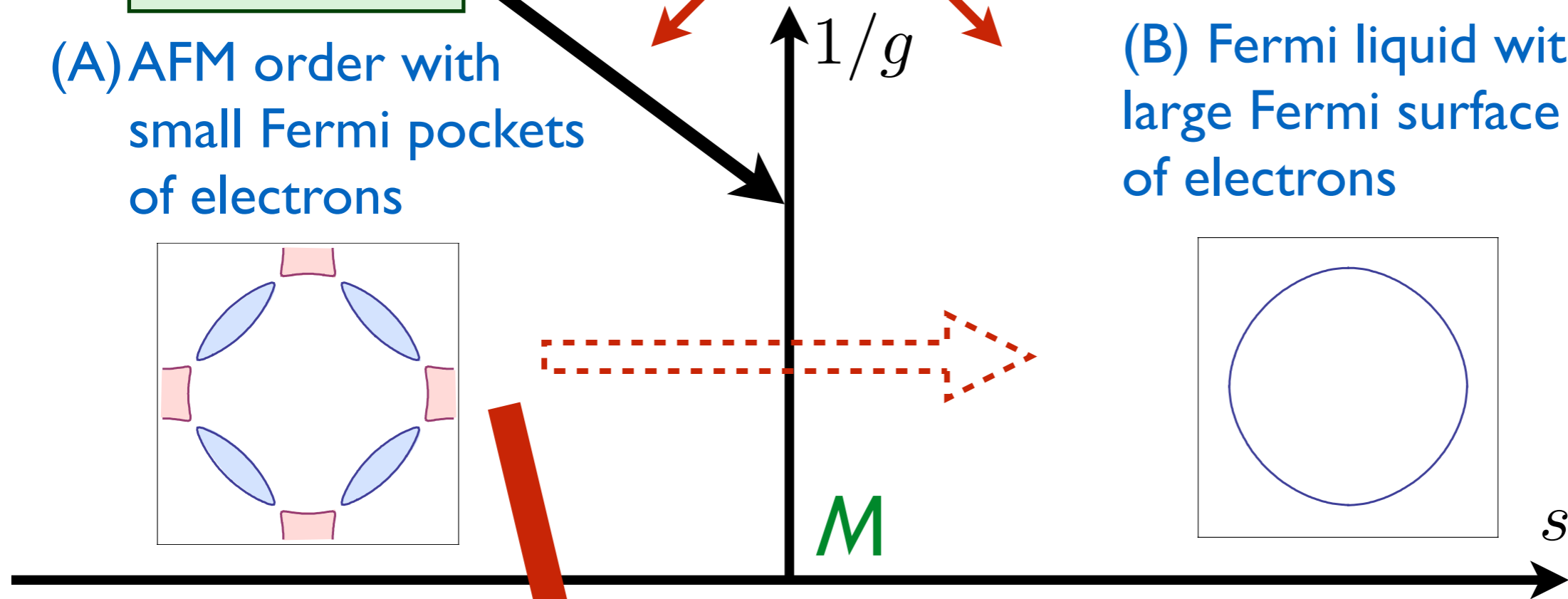
(B) Fermi liquid with
large Fermi surface
of electrons



(C) U(1) ACL with
small holon pockets

Non-Fermi
liquid

R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev,
and T. Senthil, Phys. Rev. B **75**, 235122 (2007).
Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010).

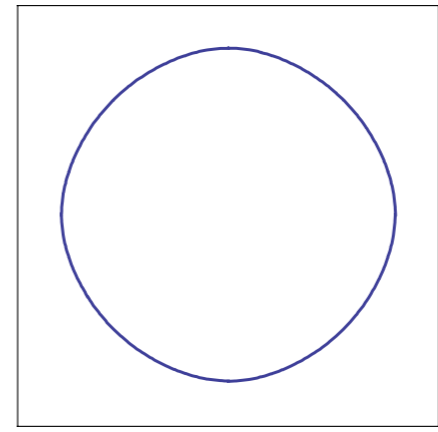
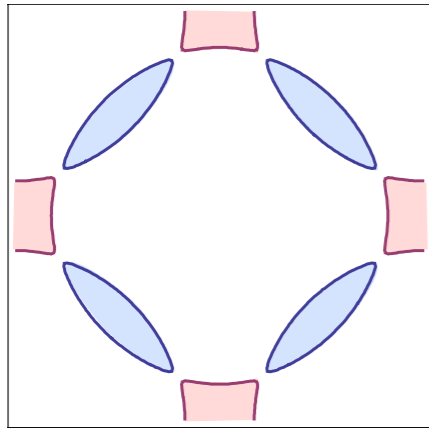


Hertz-Millis
criticality
of AFM order

Conventional
Fermi liquids

(A) AFM order with
small Fermi pockets
of electrons

(B) Fermi liquid with
large Fermi surface
of electrons

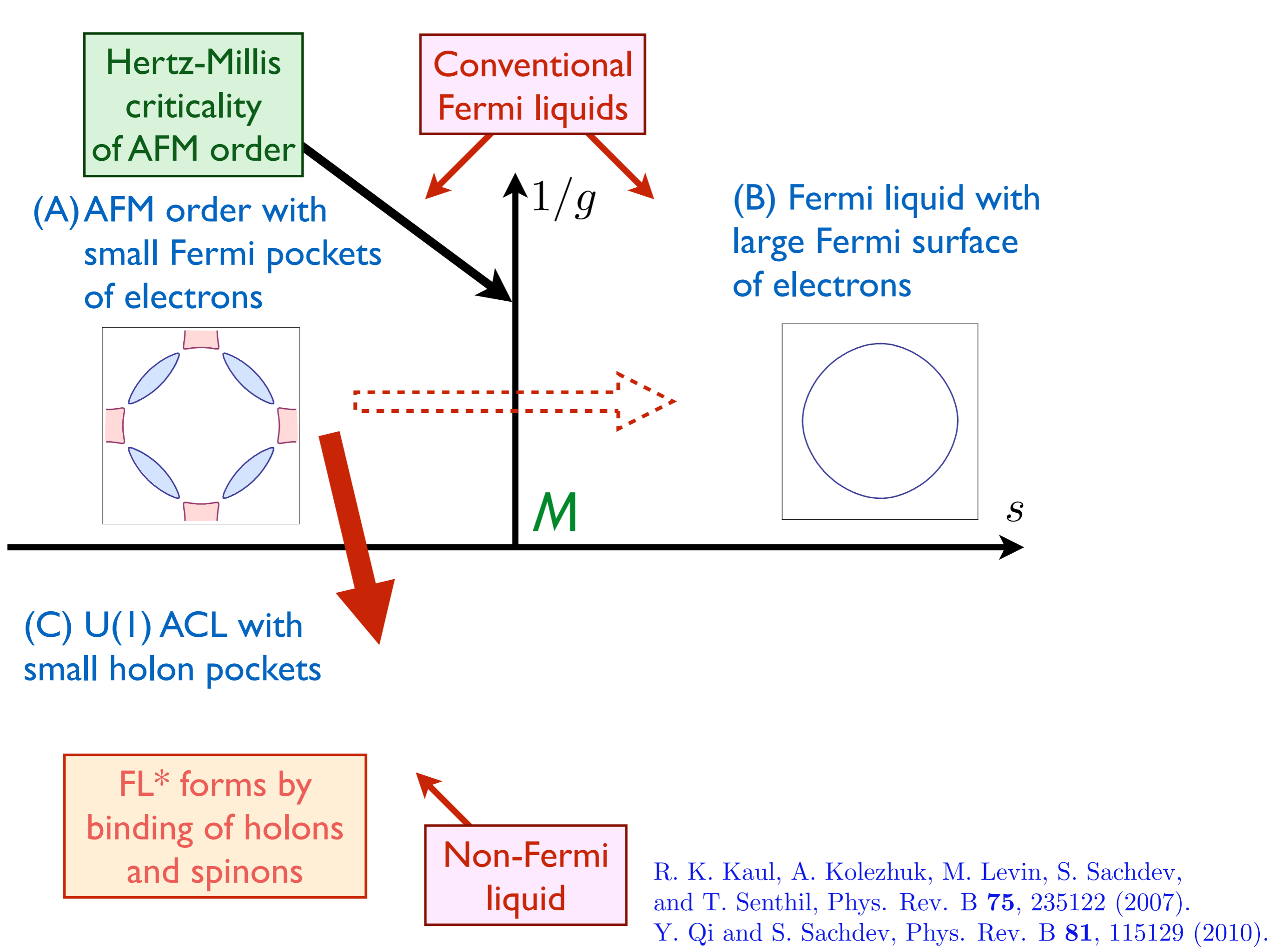


(C) U(1) ACL with
small holon pockets

FL* forms by
binding of holons
and spinons

Non-Fermi
liquid

R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev,
and T. Senthil, Phys. Rev. B **75**, 235122 (2007).
Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010).

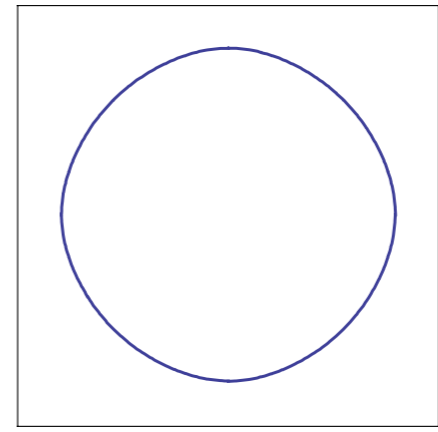
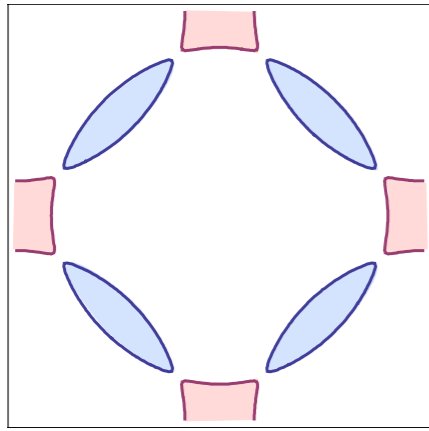


Hertz-Millis
criticality
of AFM order

Conventional
Fermi liquids

(A) AFM order with
small Fermi pockets
of electrons

(B) Fermi liquid with
large Fermi surface
of electrons



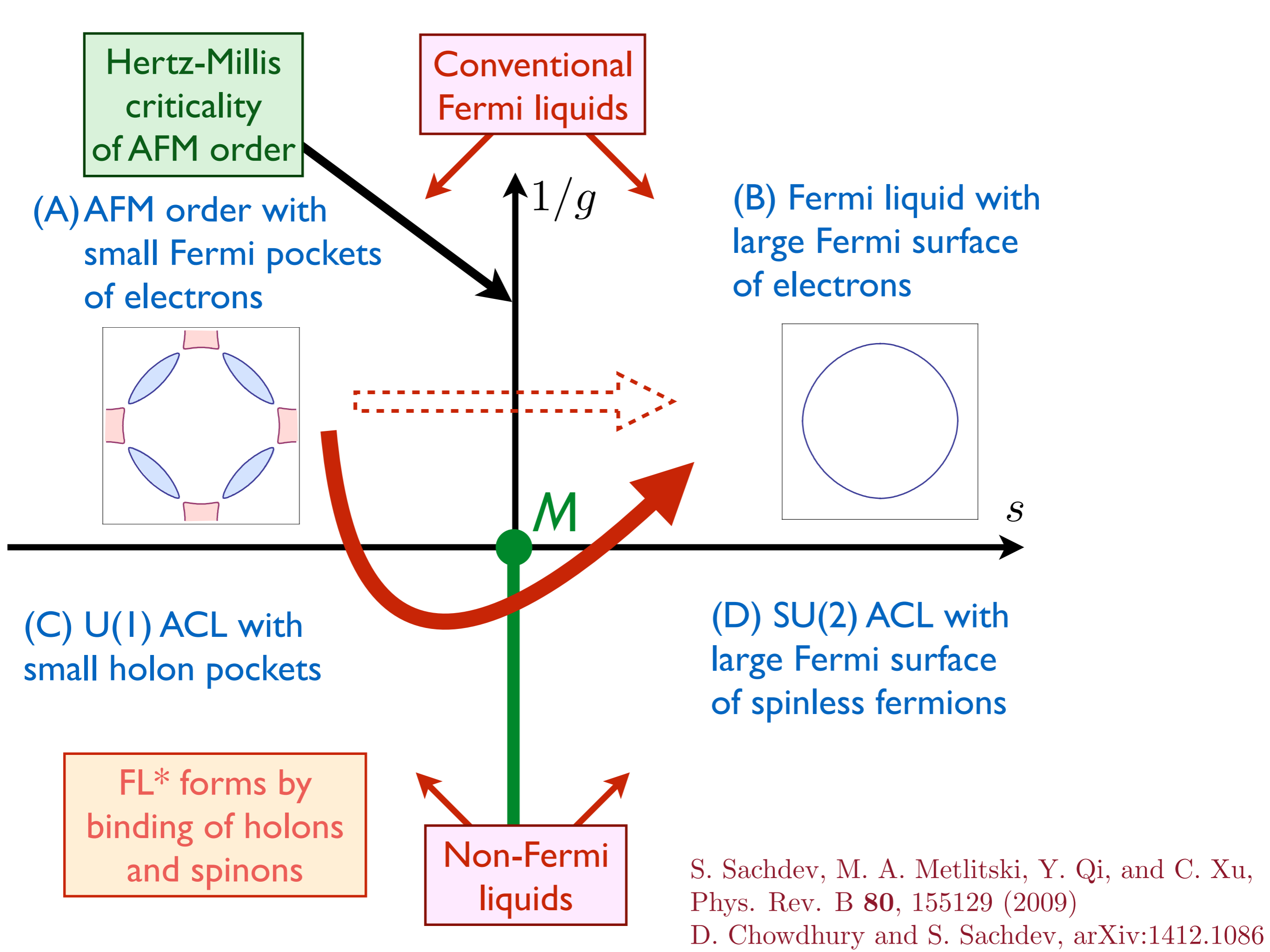
(C) U(1) ACL with
small holon pockets

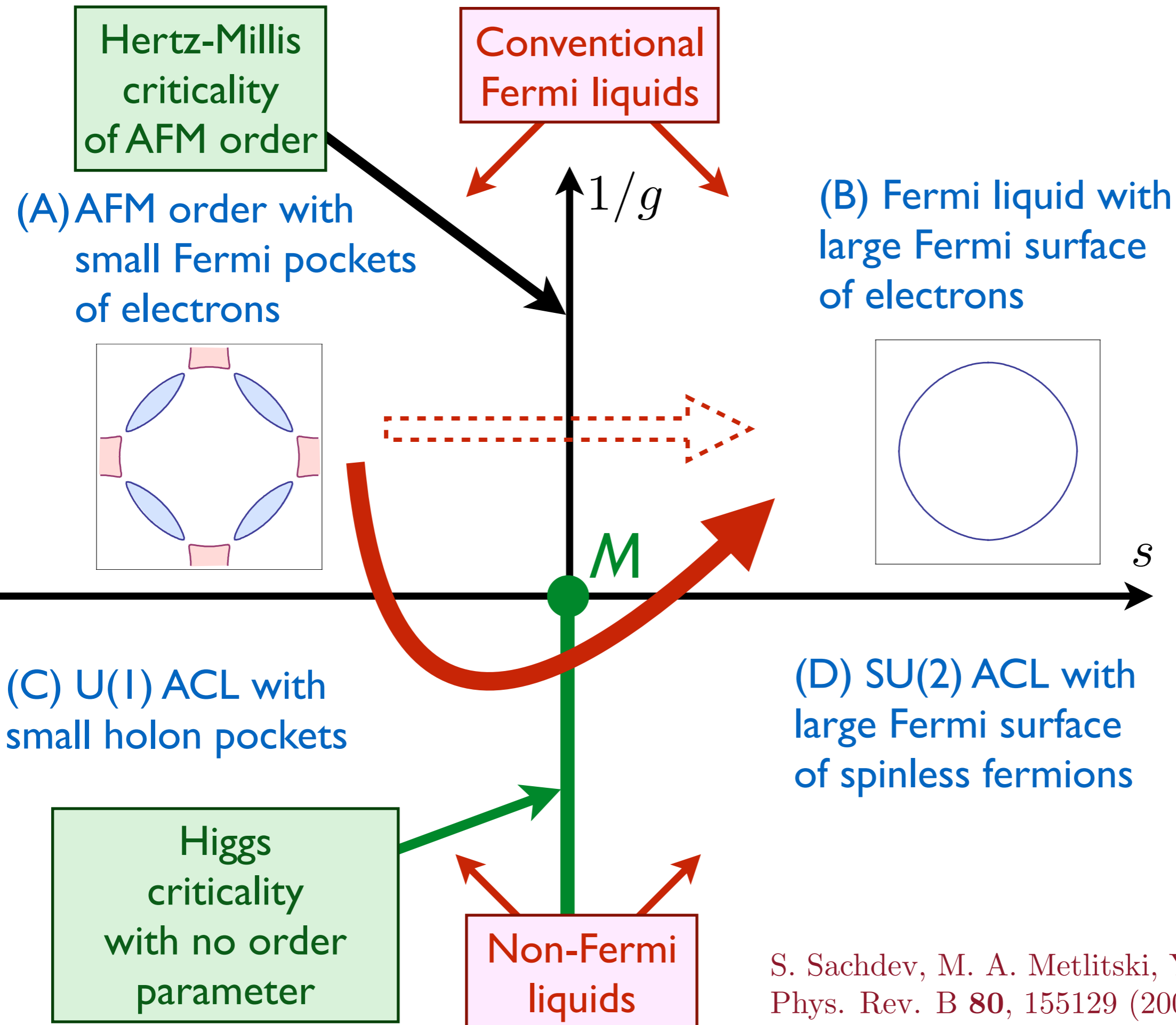
(D) SU(2) ACL with
large Fermi surface
of spinless fermions

FL* forms by
binding of holons
and spinons

Non-Fermi
liquids

S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu,
Phys. Rev. B **80**, 155129 (2009)
D. Chowdhury and S. Sachdev, arXiv:1412.1086





S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, Phys. Rev. B **80**, 155129 (2009)
 D. Chowdhury and S. Sachdev, arXiv:1412.1086

SU(2) gauge theory

Write the electron operator c_α ($\alpha = \uparrow, \downarrow$ are spin indices) as

$$\begin{pmatrix} c_\uparrow \\ c_\downarrow \end{pmatrix} = R \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix}$$

where R is a SU(2) matrix which determines the orientation of the local antiferromagnetic order, and ψ_\pm are spinless fermions which carry the global electron U(1) charge.

This parameterization is invariant under a SU(2) *gauge* transformation

$$\begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix} \rightarrow U \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix} ; \quad R \rightarrow RU^\dagger$$

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

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SU(2) gauge theory

Assume field R is non-critical.

- Fermion ψ , transforming as a gauge SU(2) fundamental, with dispersion $\varepsilon_{\mathbf{k}}$ from the band structure, at a non-zero chemical potential: has a “large” Fermi surface.
- A SU(2) gauge boson.

SU(2) gauge theory

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The electrons, c_{α} move in the presence of local antiferromagnetic order \vec{n} . In the rotating reference frame, this is equivalent to a Yukawa coupling between the ψ fermions and a spin-singlet, gauge-SU(2) adjoint *Higgs field* H^a given by

$$H^a = \frac{1}{2} \text{Tr} [\sigma^{\ell} R \sigma^a R^{\dagger}] n_{\ell}$$

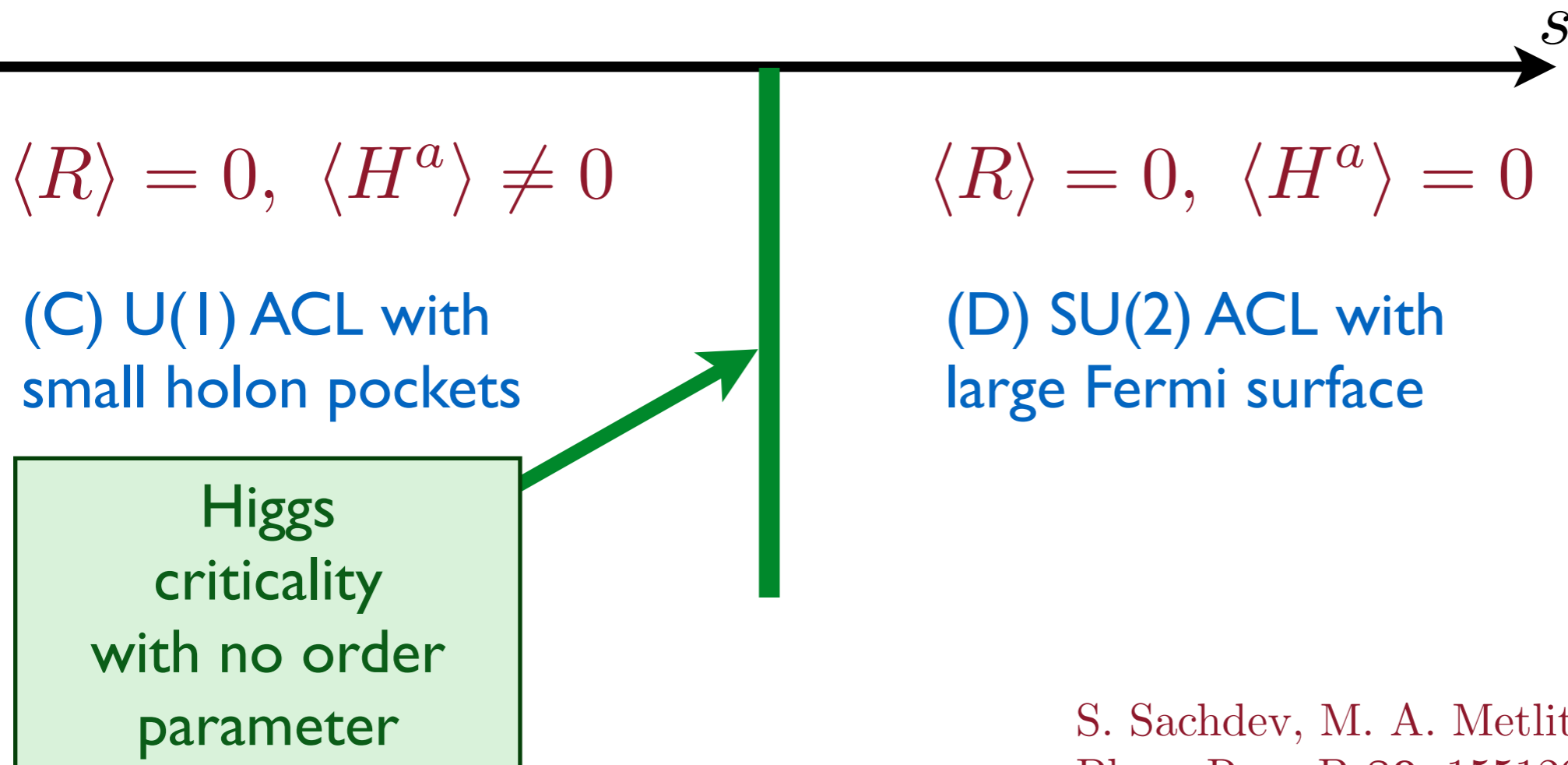
SU(2) gauge theory

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- A SU(2) gauge boson.
- A real Higgs field, H , transforming as a gauge SU(2) adjoint, carrying lattice momentum (π, π) . Condensation of the Higgs breaks $SU(2) \rightarrow U(1)$, and transforms the large Fermi surface to a small Fermi surface.

SU(2) gauge theory for underlying quantum critical point

- The quantum critical theory is the Higgs transition where the gauge “symmetry” breaks from SU(2) down to U(1), in the presence of a Fermi surface of fermions carrying fundamental SU(2) charges.



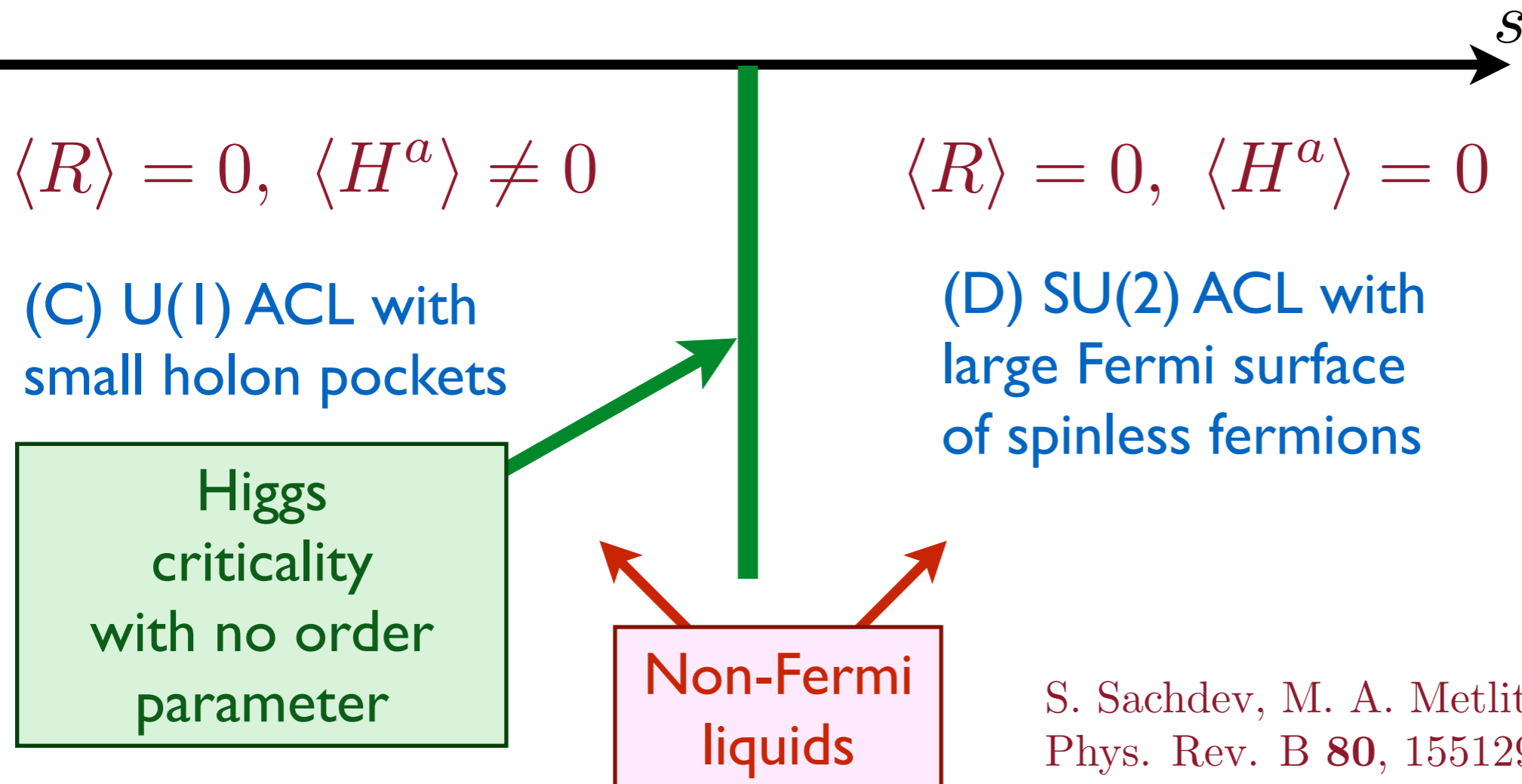
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- The Higgs condensation does not give the fermions a “mass”; instead it reconstructs the Fermi surface from *large* to *small*.

SU(2) gauge theory for underlying quantum critical point

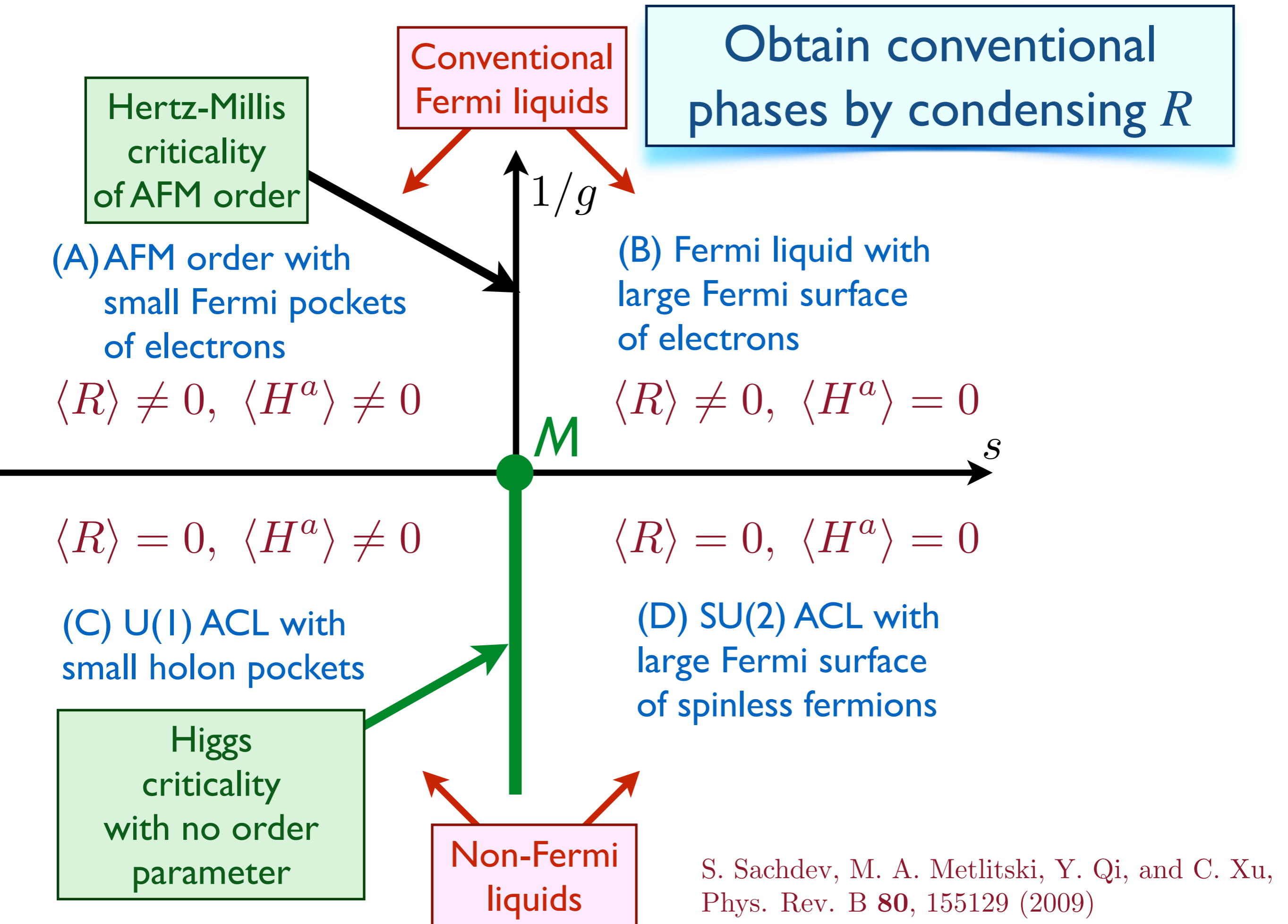
- The quantum critical theory is the Higgs transition where the gauge “symmetry” breaks from SU(2) down to U(1), in the presence of a Fermi surface of fermions carrying fundamental SU(2) charges.
- The Higgs condensation does not give the fermions a “mass”; instead it reconstructs the Fermi surface from *large* to *small*.
- The quantum phase transition has no gauge-invariant “order parameter”, and it does not break any global symmetries.

Higgs transition between non-Fermi liquid metals with large and small Fermi surfaces



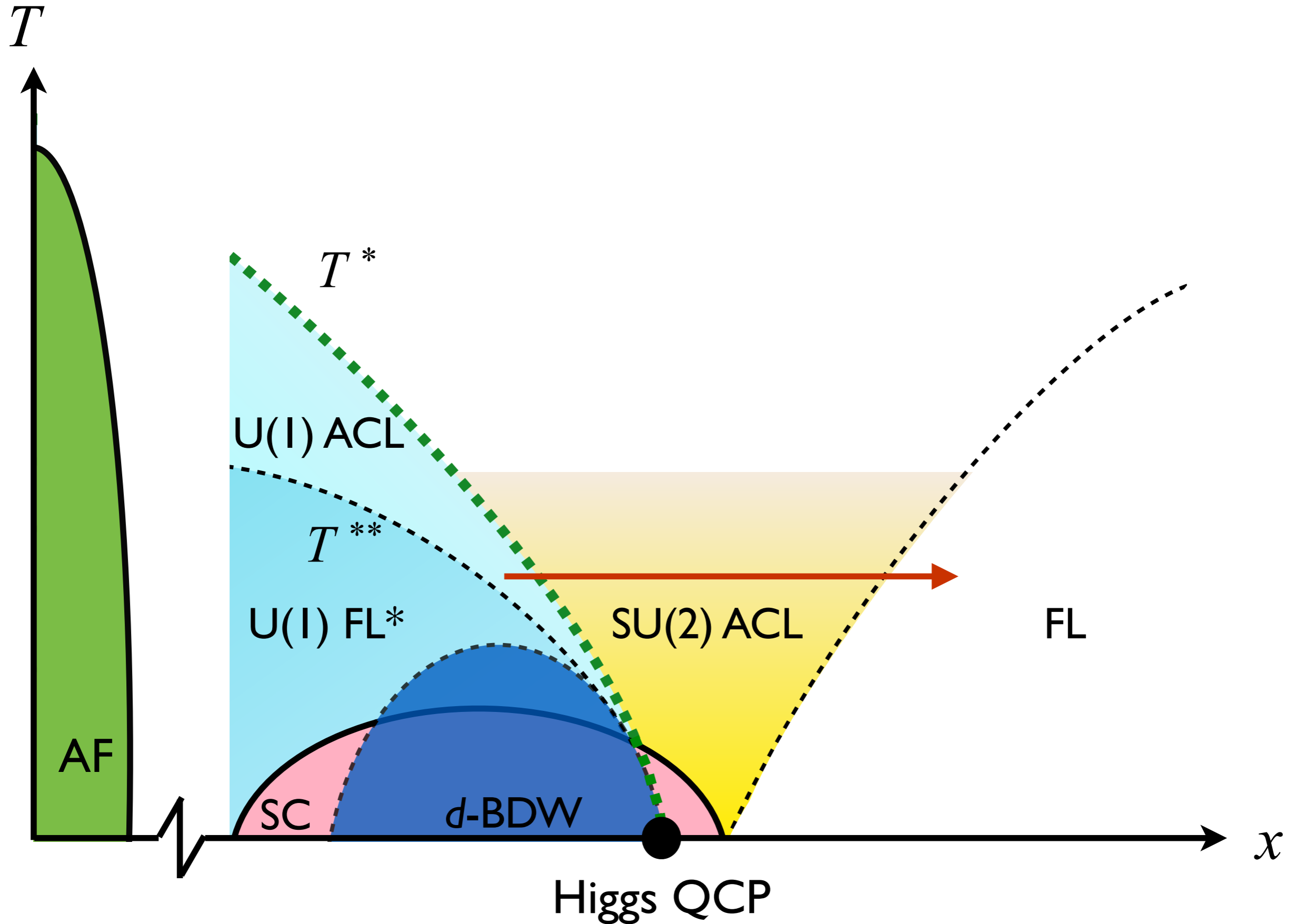
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 D. Chowdhury and S. Sachdev, arXiv:1412.1086

SU(2) gauge theory for underlying quantum critical point



Transport in QC regime:

All points on the Fermi surface have a rapid relaxation to local thermal equilibrium by processes which conserve a suitably defined momentum.

Relaxation of the momentum occurs at a slower rate.

SU(2) gauge theory for underlying quantum critical point

The resistivity of this strange metal is *not* determined by the scattering rate of charged excitations near the Fermi surface, but by the dominant rate of momentum loss by *any* excitation, whether neutral or charged, or fermionic or bosonic.

There is a dominant contribution $\rho(T) \sim T$ by the coupling of long-wavelength disorder to the gauge-invariant operator $\mathcal{O} \sim H^2$.

Conclusions

1. Predicted d -form factor density wave order observed in the non-La hole-doped cuprate superconductors.
2. Sudden change in Fermi surface, as observed by STM, at optimal doping: apparent transition from p fermionic quasiparticles to $|+p$ quasiparticles
3. Proposed a Higgs transition at optimal doping: involves change in Fermi surface and topological order, but has no order parameter.