Paired electron pockets in the hole-doped cuprates

Talk online: sachdev.physics.harvard.edu

Paired electron pockets in the hole-doped cuprates

Hole dynamics in an antiferromagnet across a deconfined quantum critical point, R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, *Physical Review* B **75** , 235122 (2007).

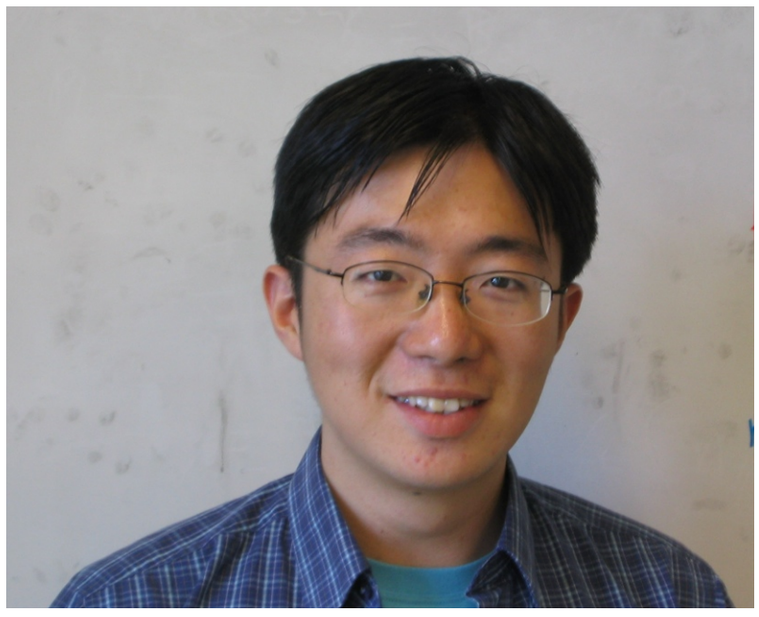
Algebraic charge liquids and the underdoped cuprates, R. K. Kaul, Y. B. Kim, S. Sachdev, and T. Senthil, *Nature Physics* **4**, 28 (2008).

Destruction of Neel order in the cuprates by electron doping, R. K. Kaul, M. Metlitksi, S. Sachdev, and C. Xu, *Physical Review B* **78**, 045110 (2008).

Paired electron pockets in the underdoped cuprates, V. Galitski and S. Sachdev, arXiv:0901.0005

Ribhu Kaul
UCSB

Victor Galitski
Maryland



Cenke Xu
Harvard

Outline

1. Nodal-anti-nodal dichotomy in the cuprates

   Survey of recent experiments

2. Spin density wave theory of normal metal

   From a "large" Fermi surface to electron and hole pockets

3. Algebraic charge liquids

   Pairing by gauge forces, d-wave superconductivity, and the nodal-anti-nodal dichotomy

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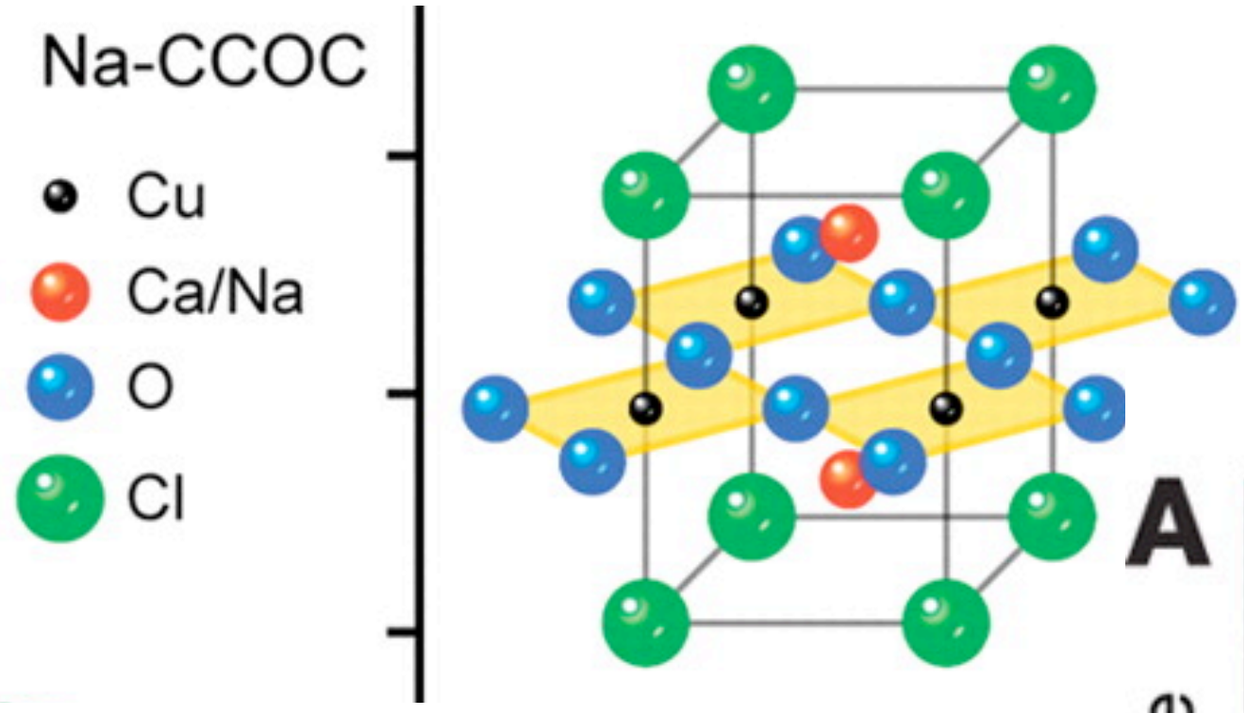
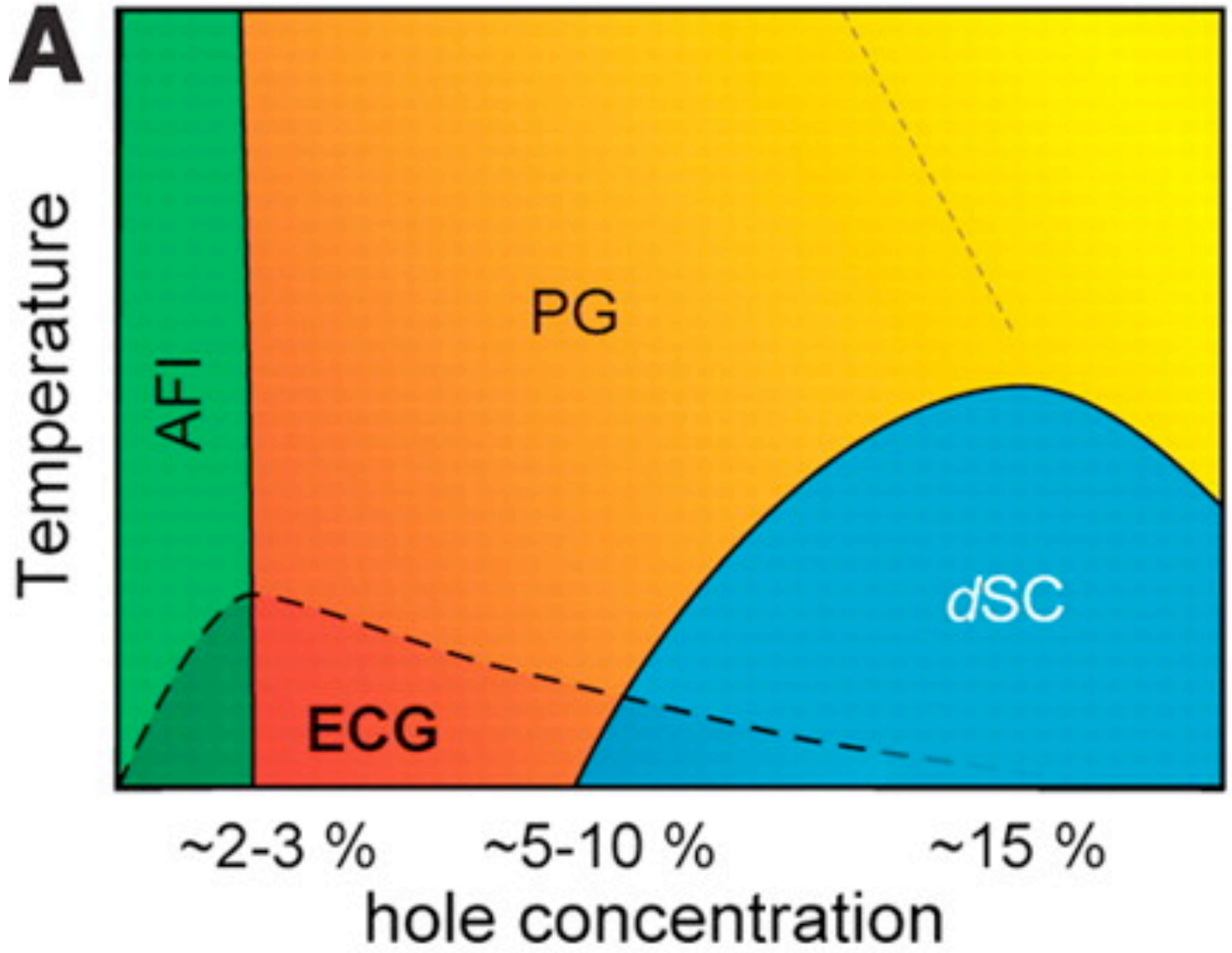
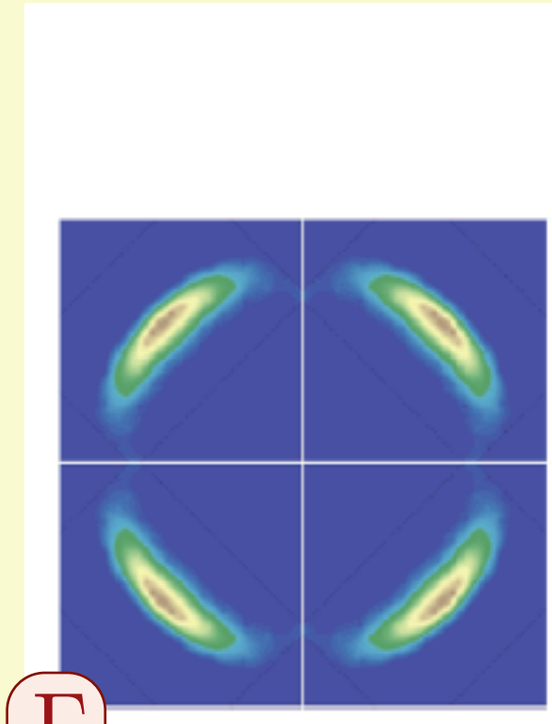
The cuprate superconductors





Evolution of the (ARPES) Fermi surface on the cuprate phase diagram



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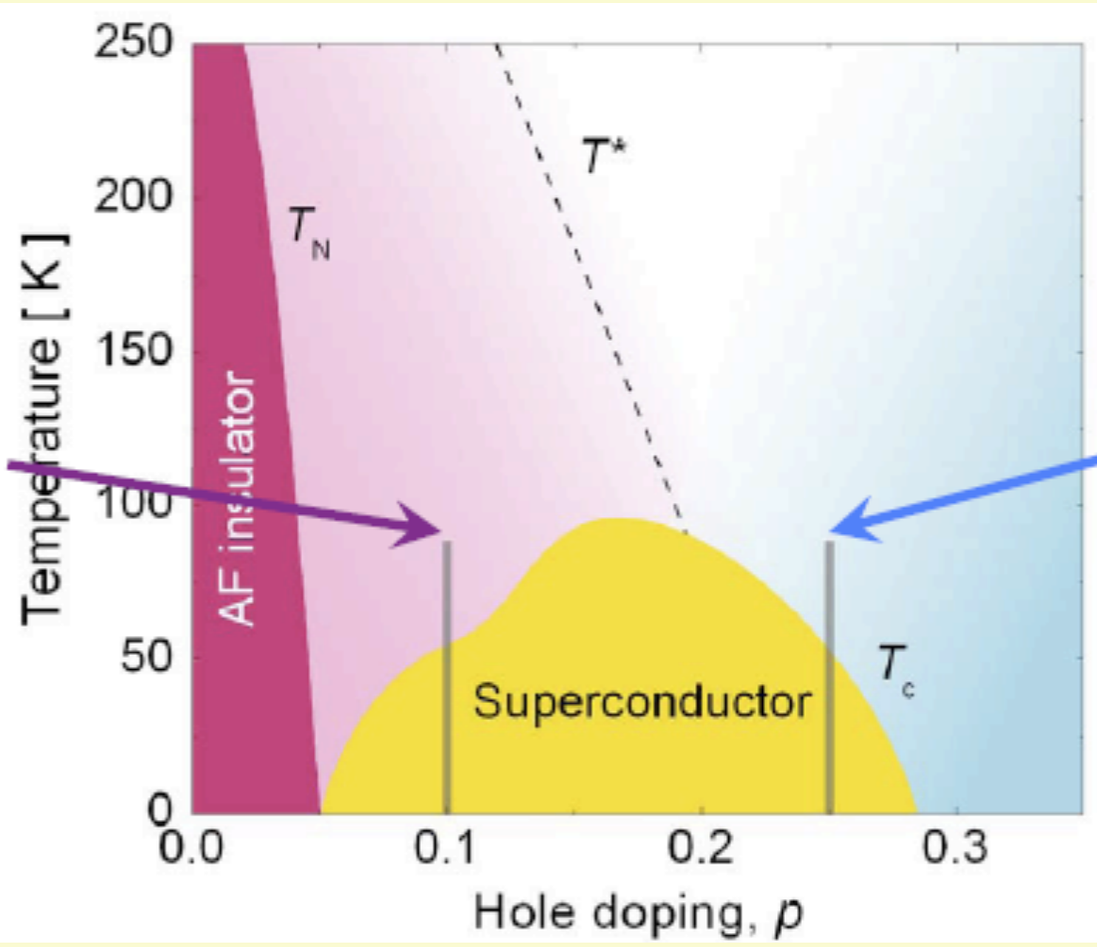
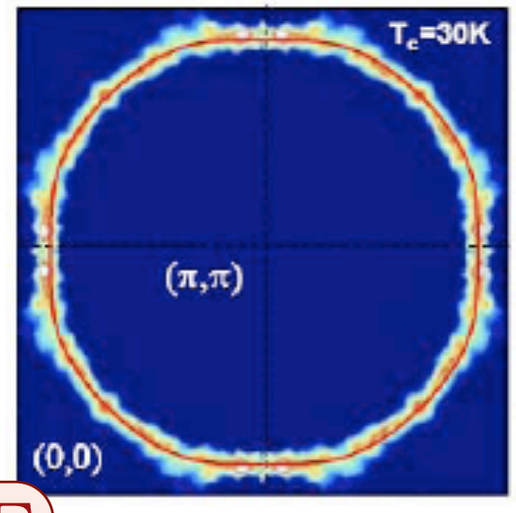
K.M. Shen et al., Science 2005





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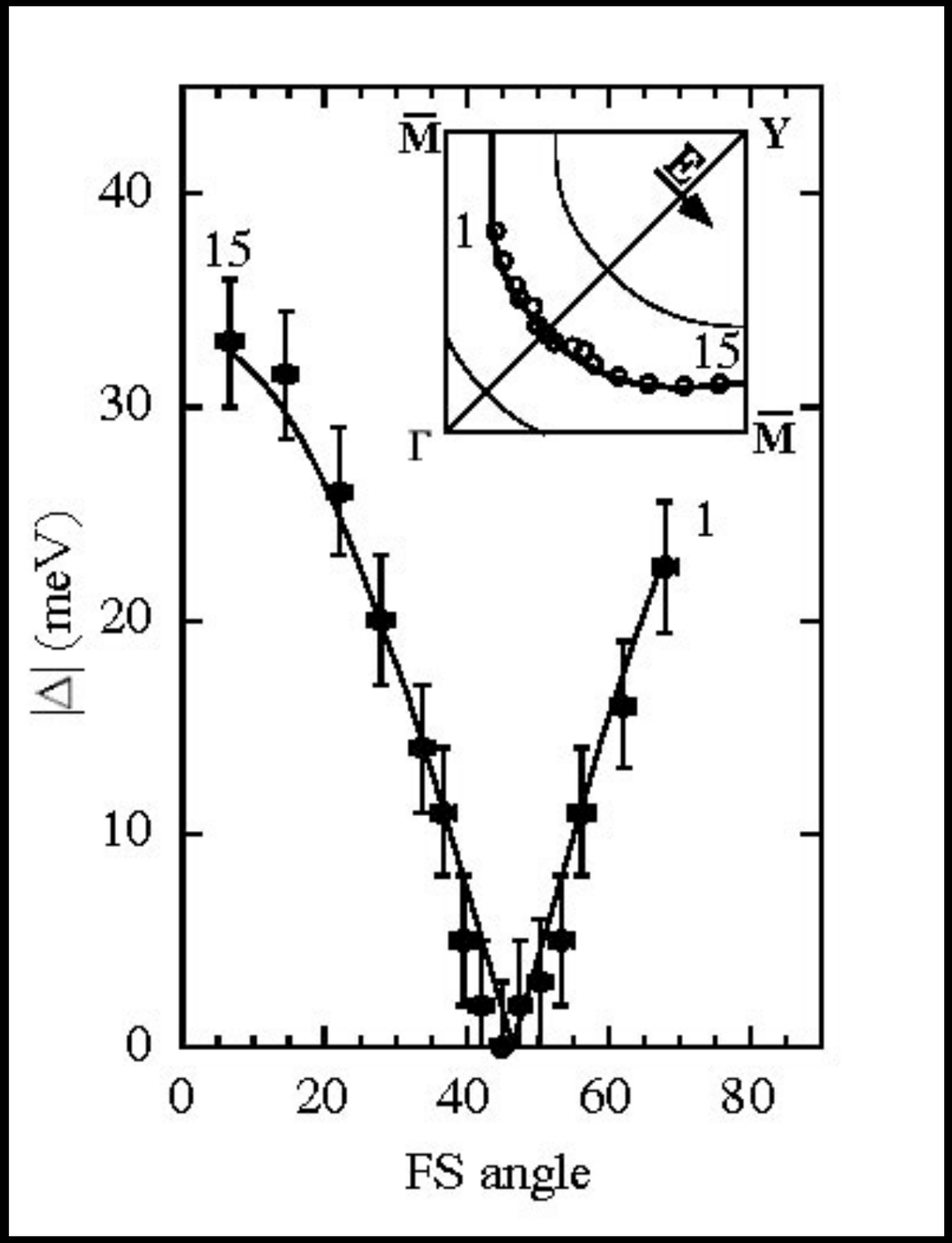
M. Platé et al., PRL 2005

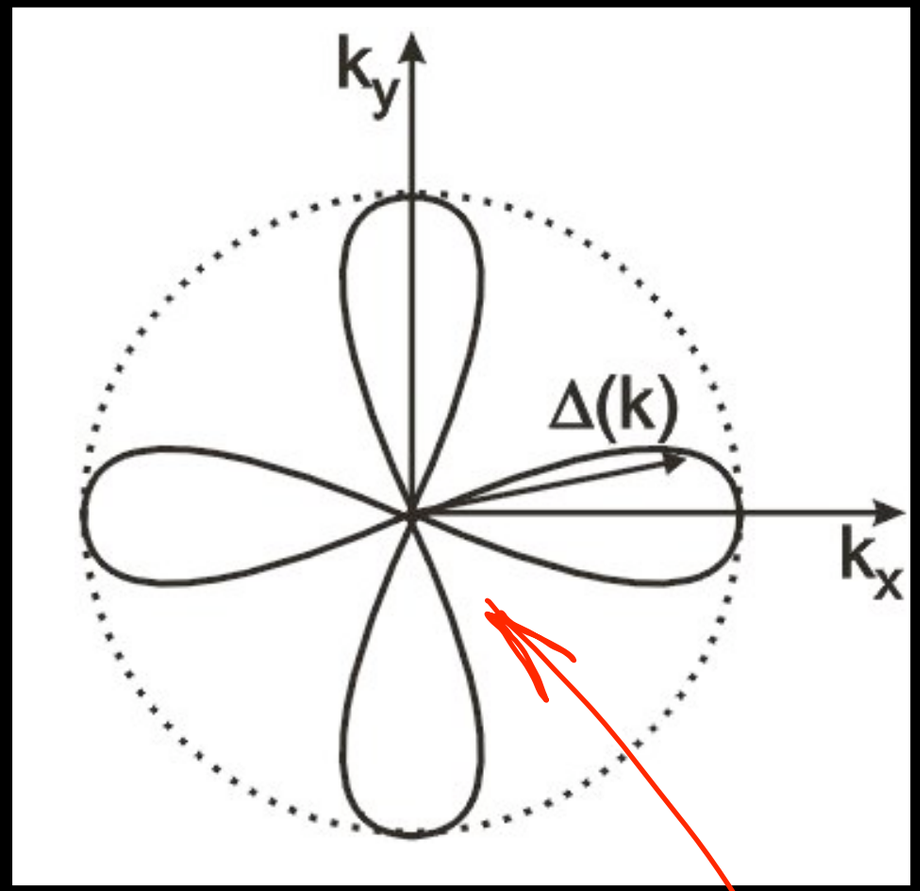
Smaller hole Fermi-pockets

Large hole Fermi surface

Overdoped SC State: Momentum-dependent Pair Energy Gap $\Delta(\vec{k})$

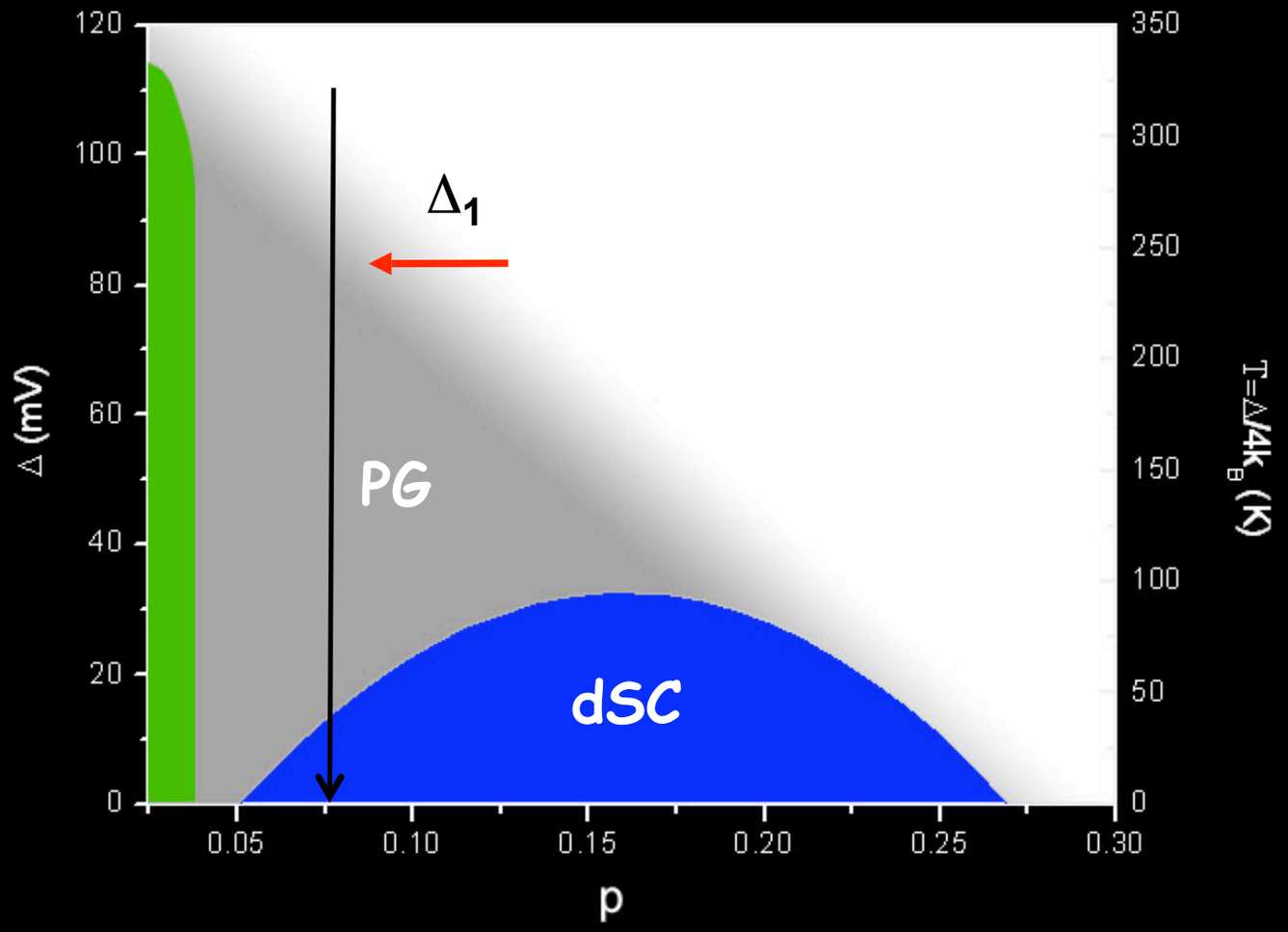


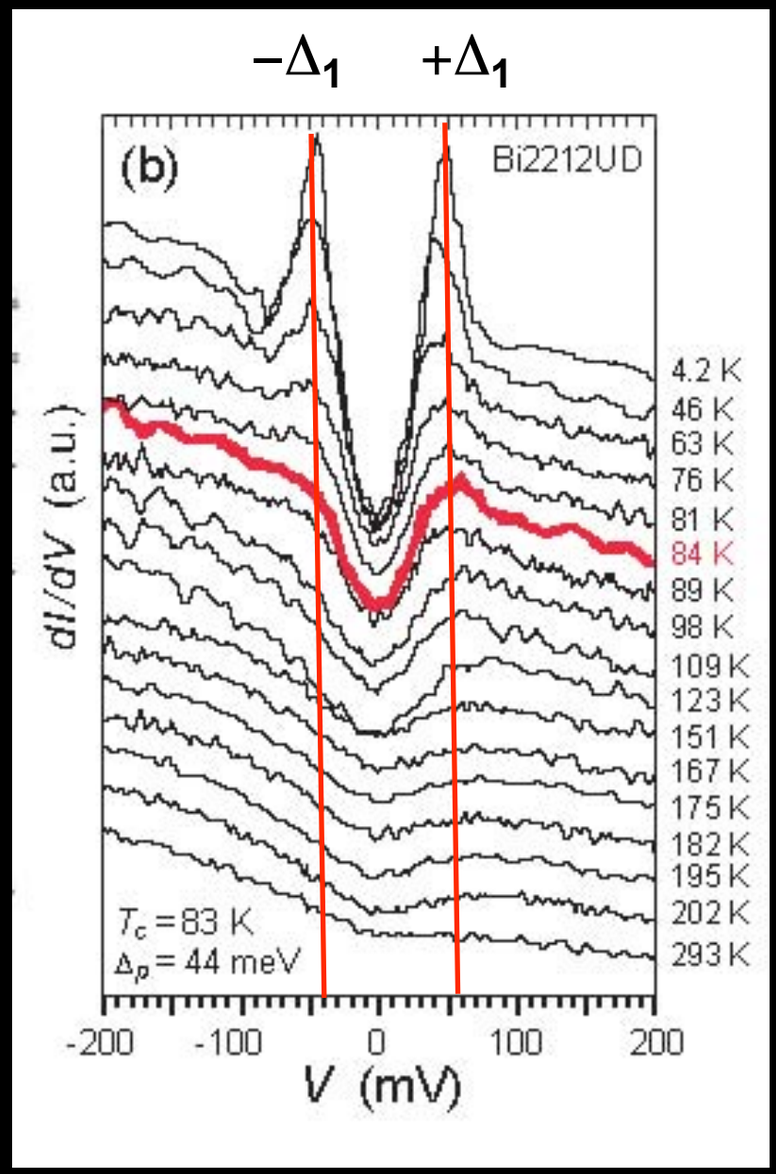
Shen et al PRL **70**, 3999 (1993)
Ding et al PRB **54** 9678 (1996)
Mesot et al PRL **83** 840 (1999)



The SC energy gap $\Delta(\vec{k})$ has four nodes.

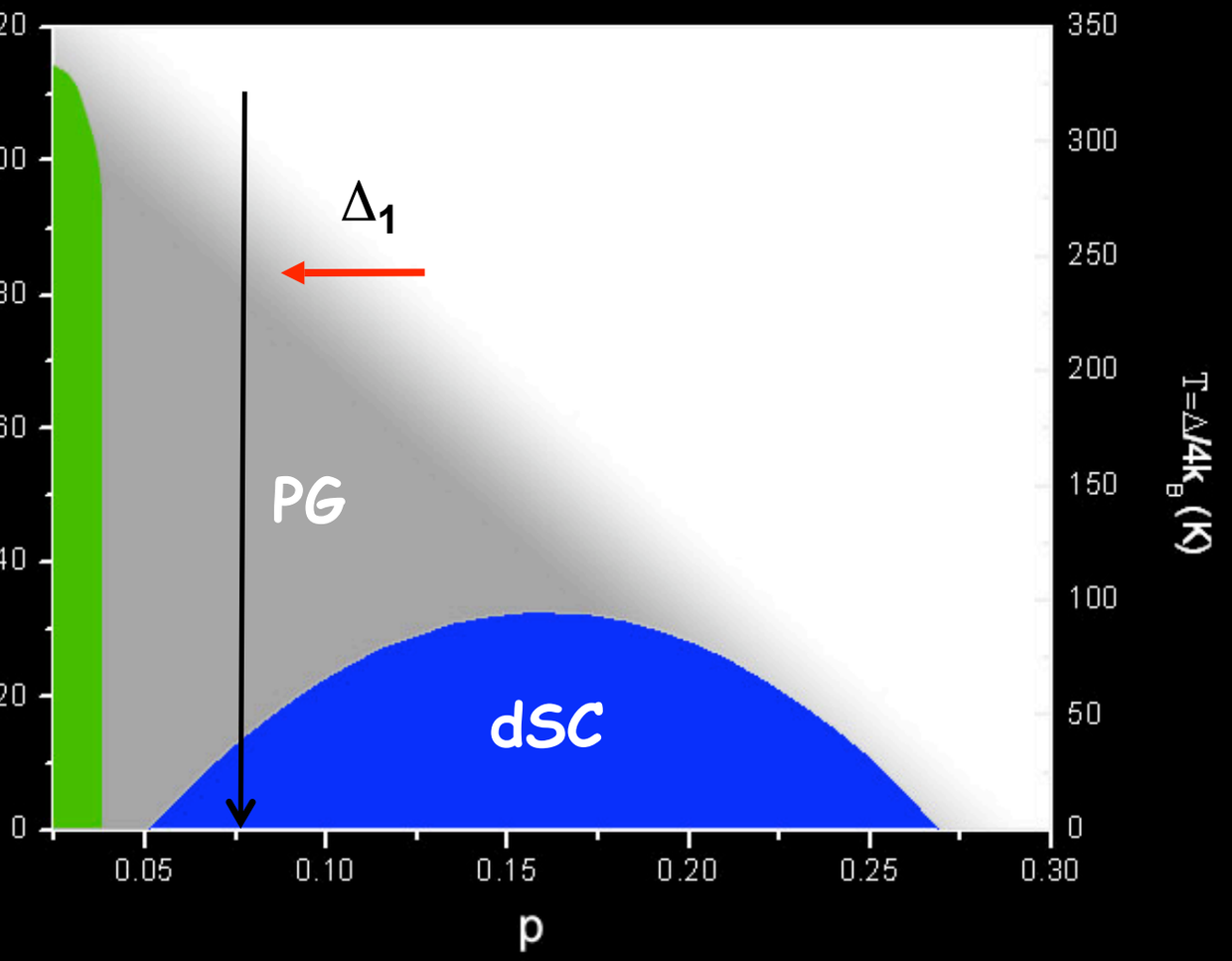
Pseudogap: Temperature-independent energy gap exists $T \gg T_c$

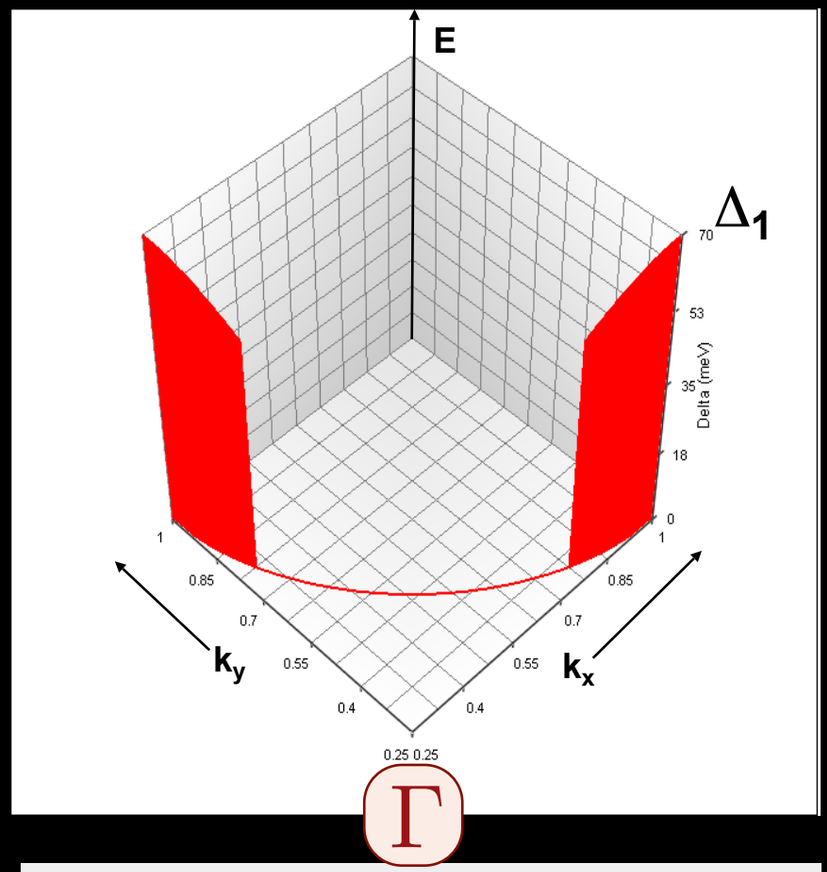


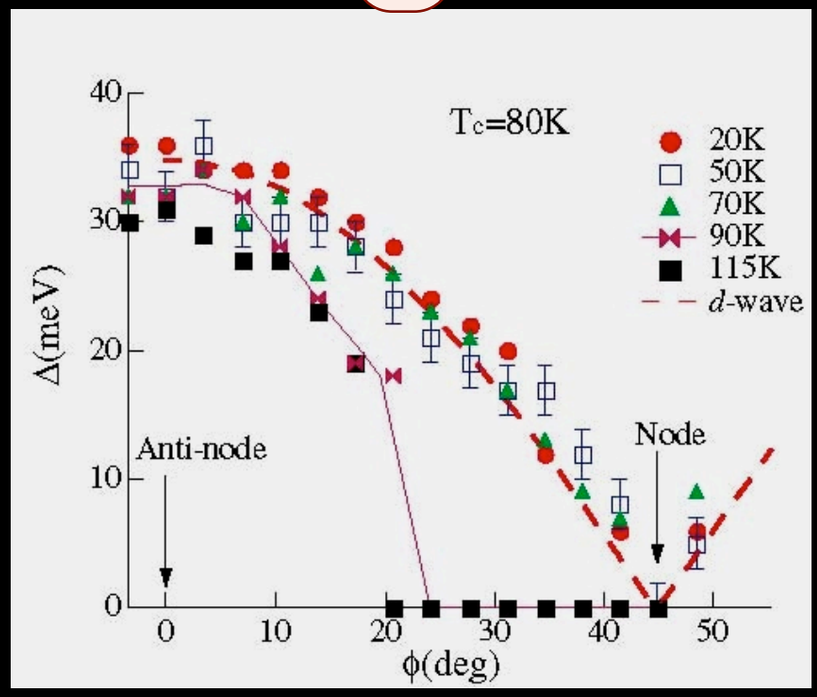


Ch. Renner et al, PRL 80, 149 (1998)
Ø. Fischer et al, RMP 79, 353 (2007)

Pseudogap: Temperature-independent energy gap near k~(π,0)

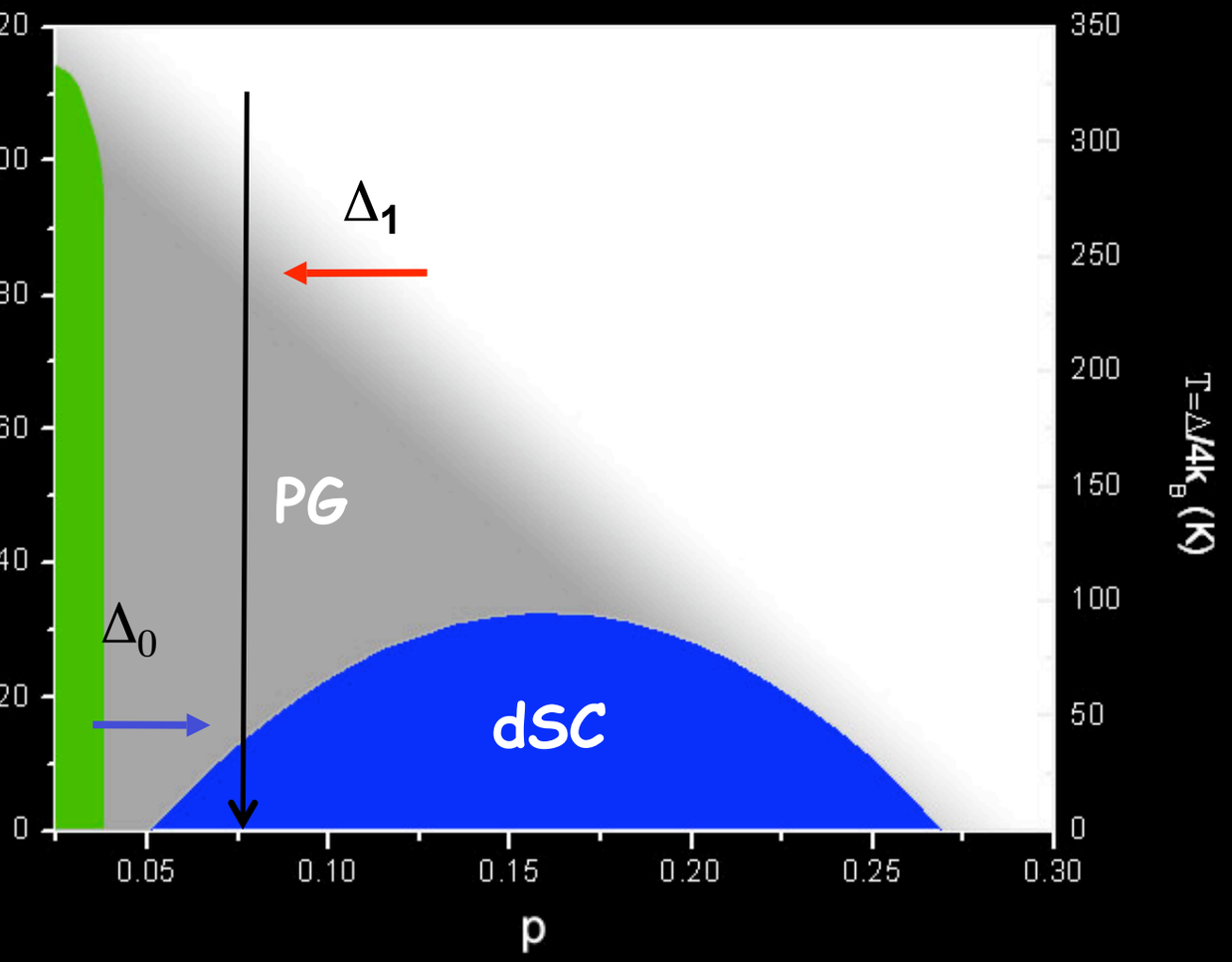


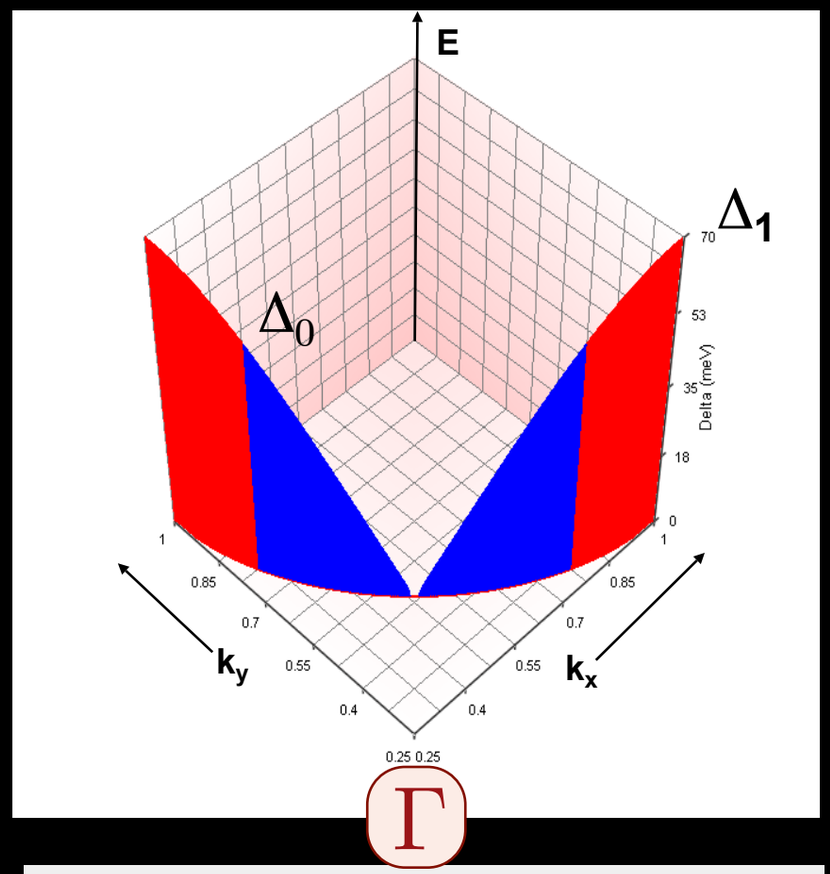


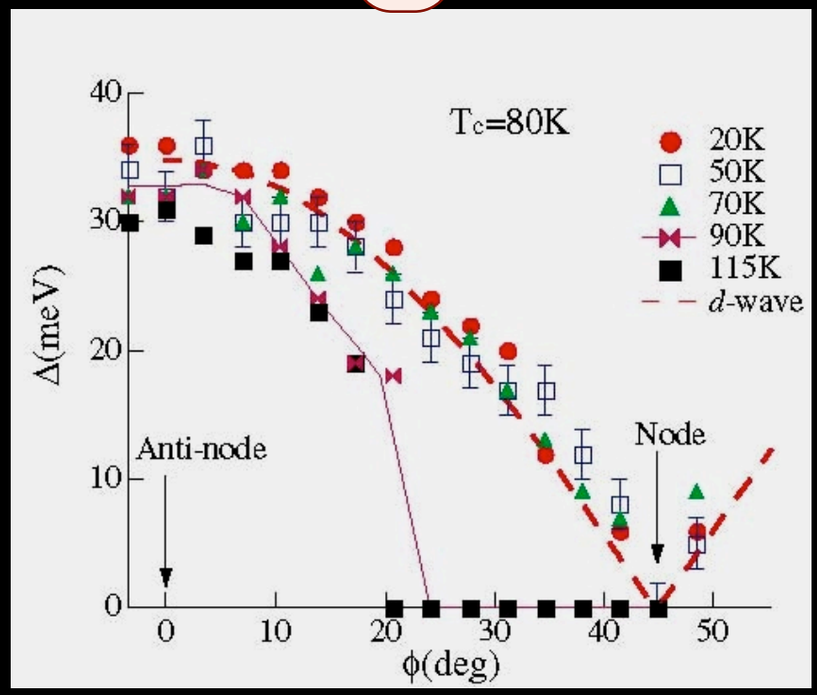


Loeser et al, Science 273 325 (1996)
Ding et al, Nature 382 51, (1996)
Norman et al, Nature 392 , 157 (1998)
Shen et al Science 307, 902 (2005)
Kanigel et al, Nature Physics 2,447 (2006)
Tanaka et al, Science 314, 1912 (2006)

Pseudogap: Temperature-dependent energy gap near node







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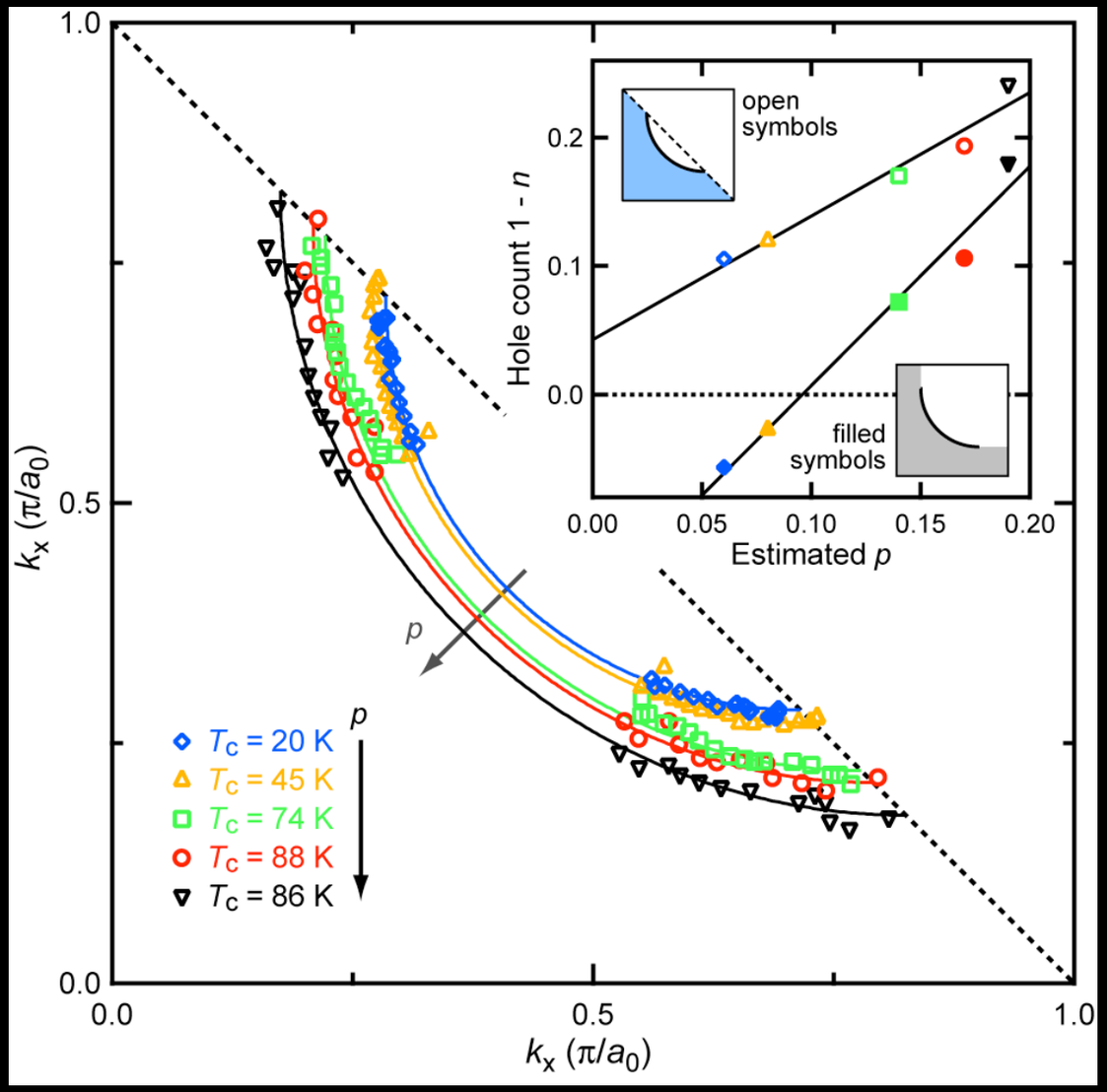
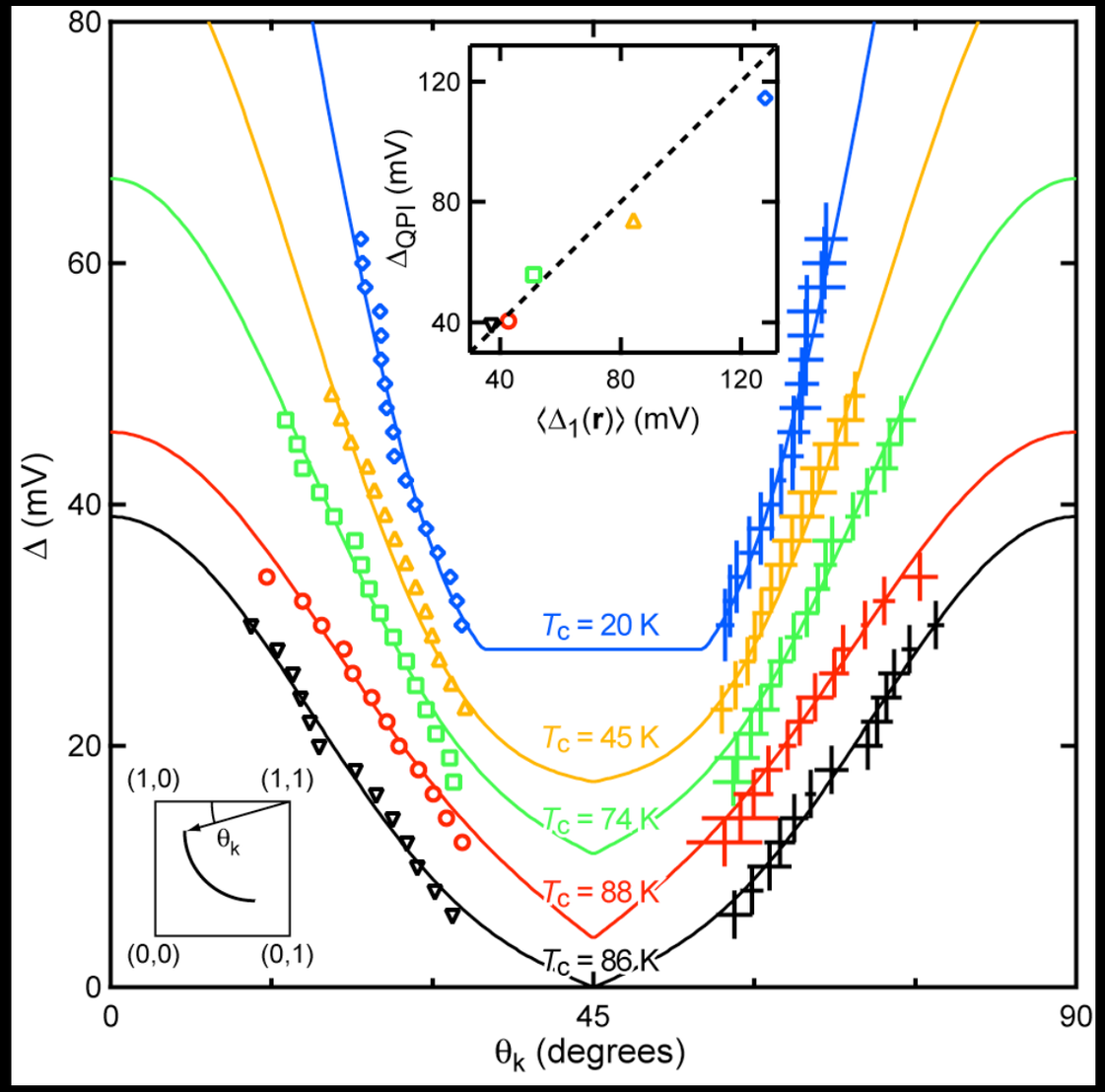
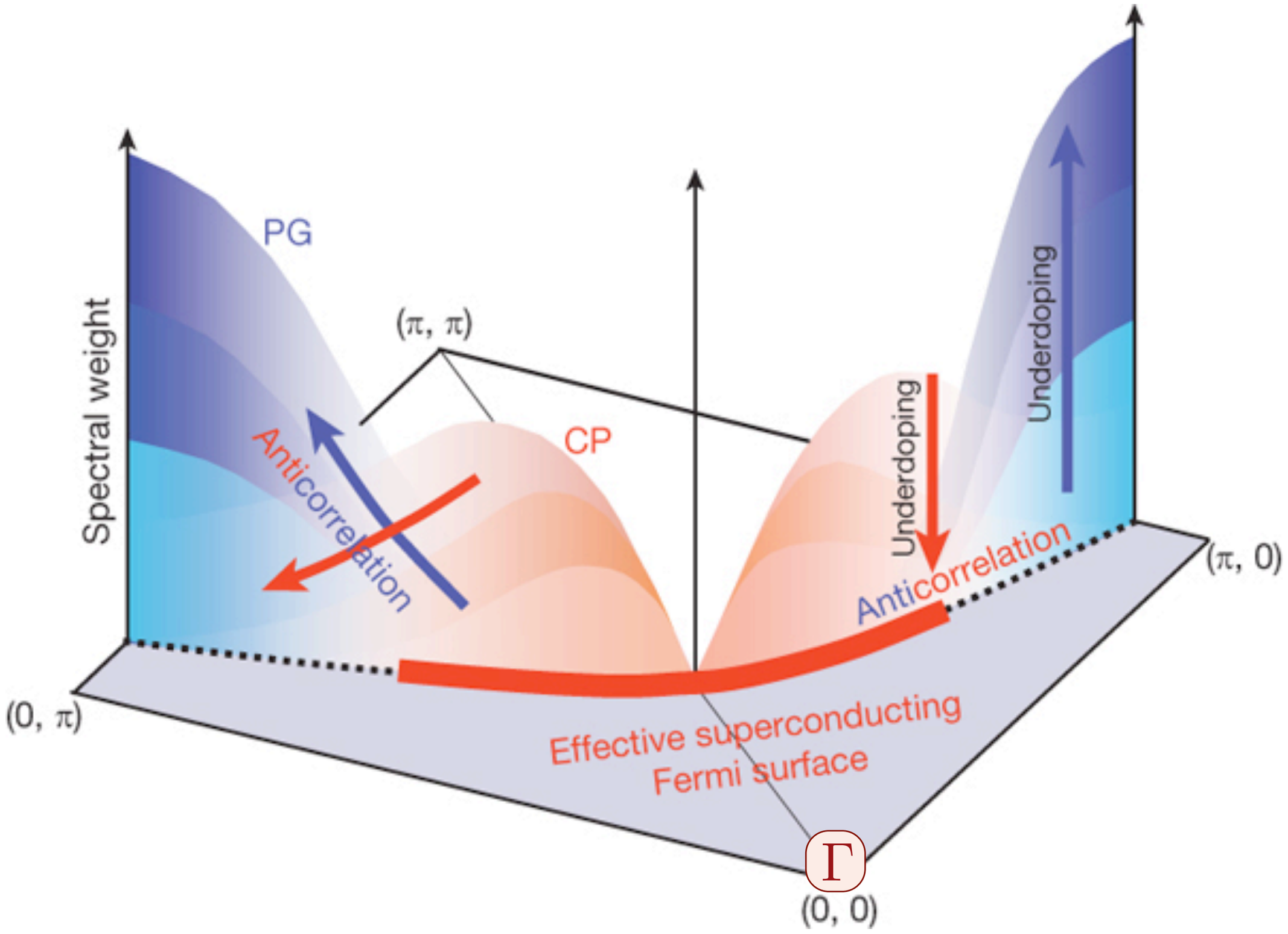
Tanaka et al, Science 314, 1912 (2006)

Development of Fermi arc with underdoping





Y. Kohsaka et al., Nature 454, 1072, (2008)



Competition between the pseudogap and superconductivity in the high-Tc copper oxides

T. Kondo, R. Khasanov, T. Takeuchi, J. Schmalian, A. Kaminski, *Nature* **457**, 296 (2009)

Nodal-anti-nodal dichotomy in the underdoped cuprates

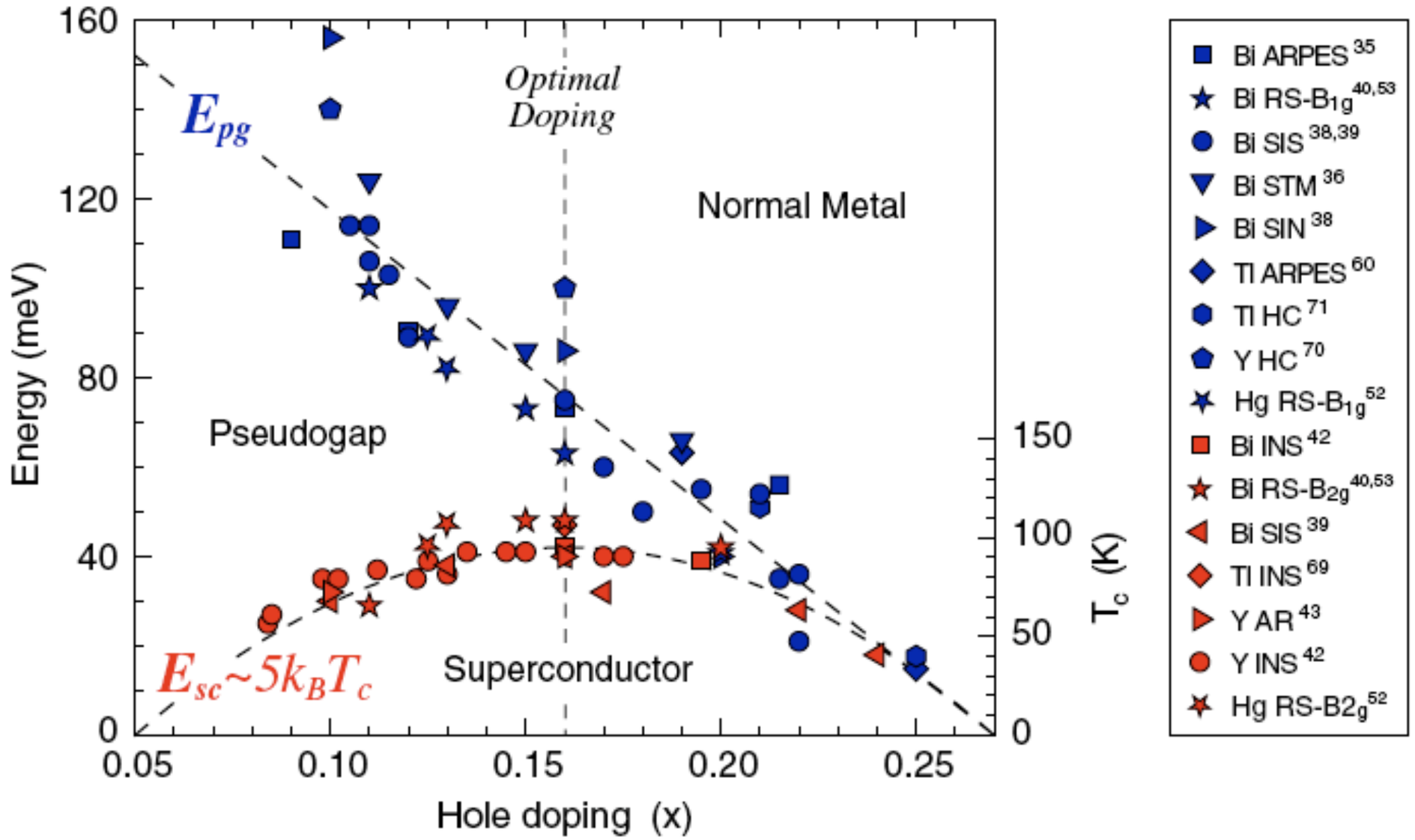


Figure 2. Pseudogap ($E_{pg} = 2\Delta_{pg}$) and superconducting ($E_{sc} \sim 5k_BT_c$) energy scales for a number of HTSCs with $T_c^{max} \sim 95$ K (Bi2212, Y123, Tl2201 and Hg1201). The datapoints were obtained, as a function of hole doping x, by angle-resolved photoemission spectroscopy (ARPES), tunneling (STM, SIN, SIS), Andreev reflection (AR), Raman scattering (RS) and heat conductivity (HC). On the same plot we are also including the energy Ω_r of the magnetic resonance mode measured by inelastic neutron scattering (INS), which we identify with E_{sc} because of the striking quantitative correspondence as a function of T_c. The data fall on two universal curves given by $E_{pg} = E_{pg}^{max}(0.27 - x)/0.22$ and $E_{sc} = E_{sc}^{max}[1 - 82.6(0.16 - x)^2]$, with $E_{pg}^{max} = E_{pg}(x = 0.05) = 152 \pm 8$ meV and $E_{sc}^{max} = E_{sc}(x = 0.16) = 42 \pm 2$ meV (the statistical errors refer to the fit of the selected datapoints; however, the spread of all available data would be more appropriately described by ± 20 and ± 10 meV, respectively).

S. Hufner, M.A. Hossain, A. Damascelli, and G.A. Sawatzky, *Rep. Prog. Phys.* **71**, 062501 (2008)

Superconductivity in a system with preformed pairs

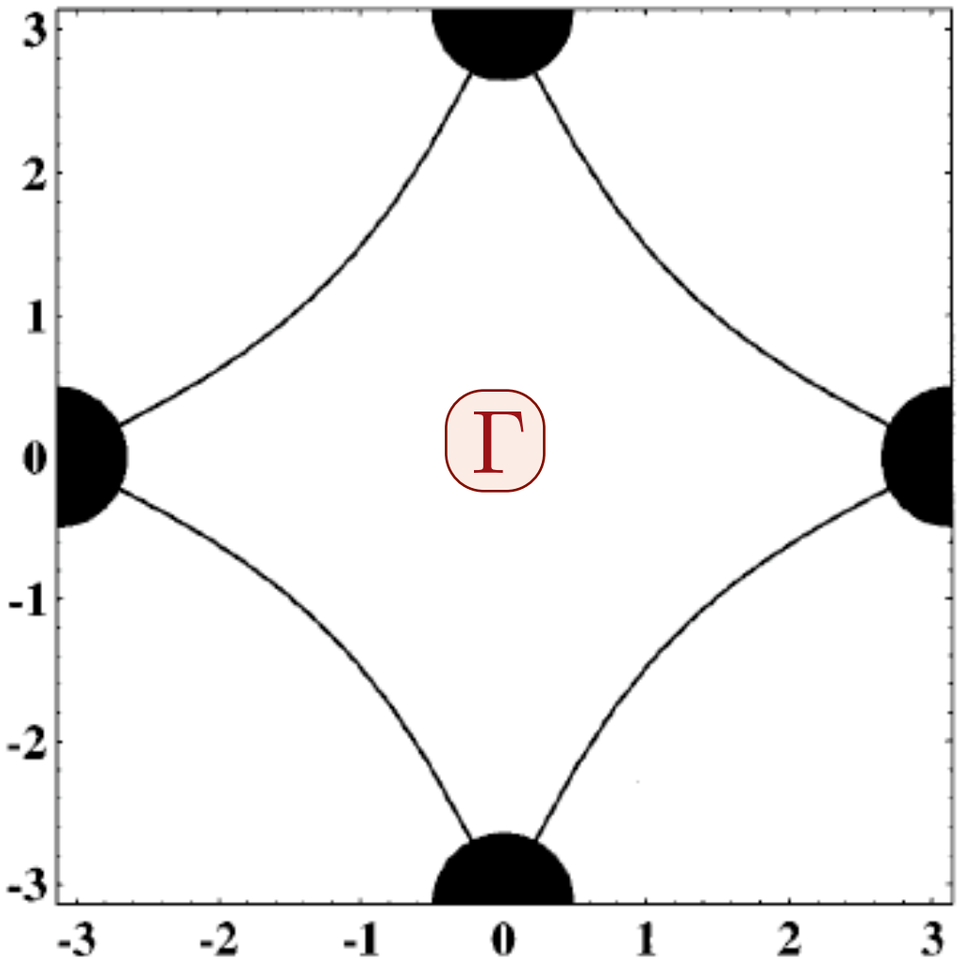


FIG. 1. Sketch of the Fermi line and region of the momentum space where pseudogap pairs is formed. The Fermi line shown here was obtained in the tight binding model with diagonal hopping $t' = -0.3t$; it is similar to the Fermi line observed in the underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Ref. 5). The shaded disks denote the part of the momentum space where a pseudogap was observed in the experiment. We shall assume that the fermions in these regions are paired into the bosons.

$$H = \sum_q \varepsilon b_q^\dagger b_q + \sum_{p,q}{}' V_{p,q}(b_q^\dagger c_{p\uparrow} c_{q-p\downarrow} + \text{H.c.})$$

$$+ \sum_p \xi_p c_{p,\sigma}^\dagger c_{p,\sigma};$$

$$V_{p,q} = Va^2(p_x^2 - p_y^2)$$

V. B. Geshkenbein, L. B. Ioffe, and A. I. Larkin, Phys. Rev. B **55**, 3173 (1997).

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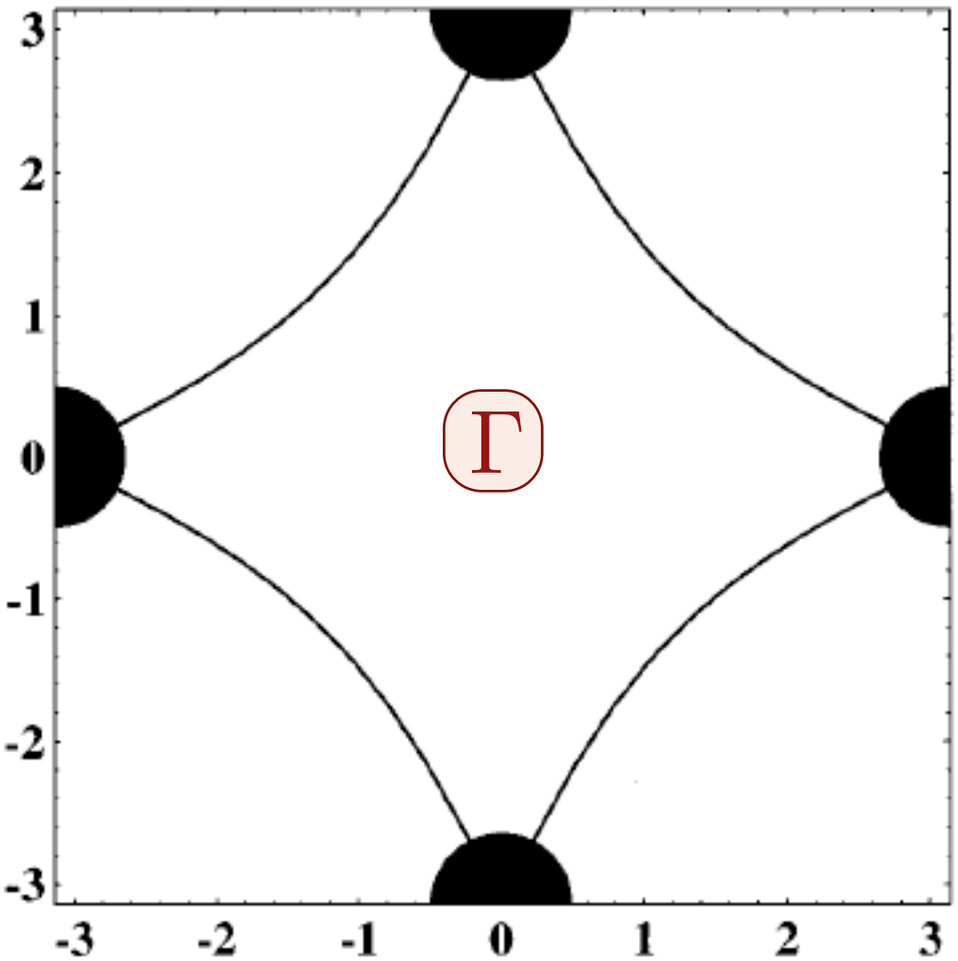

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Attractive phenomenological model, but theoretical and microscopic basis is unclear

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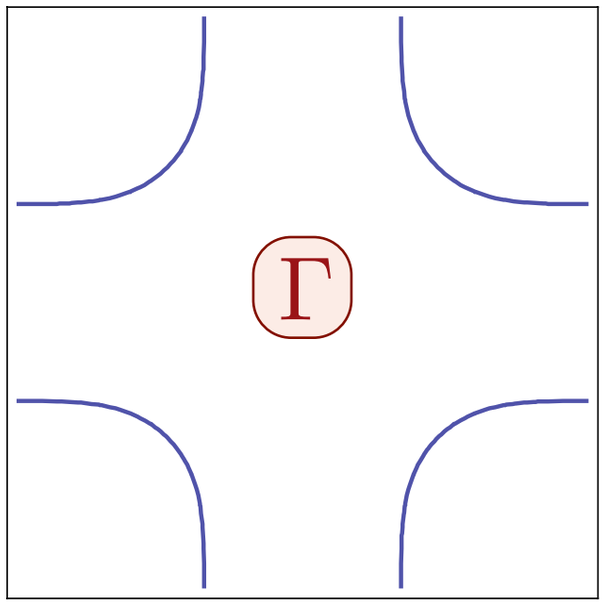
Spin density wave theory in electron-doped cuprates



S. Sachdev, A. V. Chubukov, and A. Sokol, *Phys. Rev. B* **51**, 14874 (1995).
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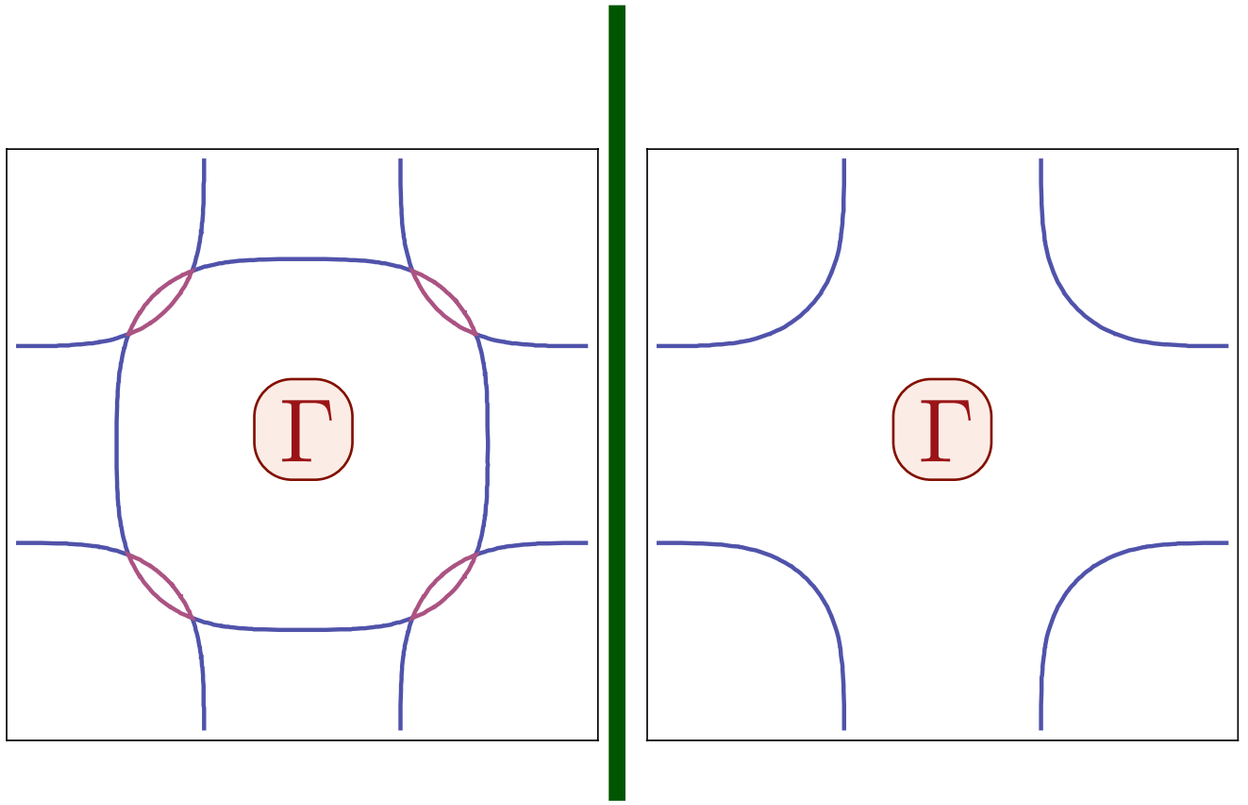

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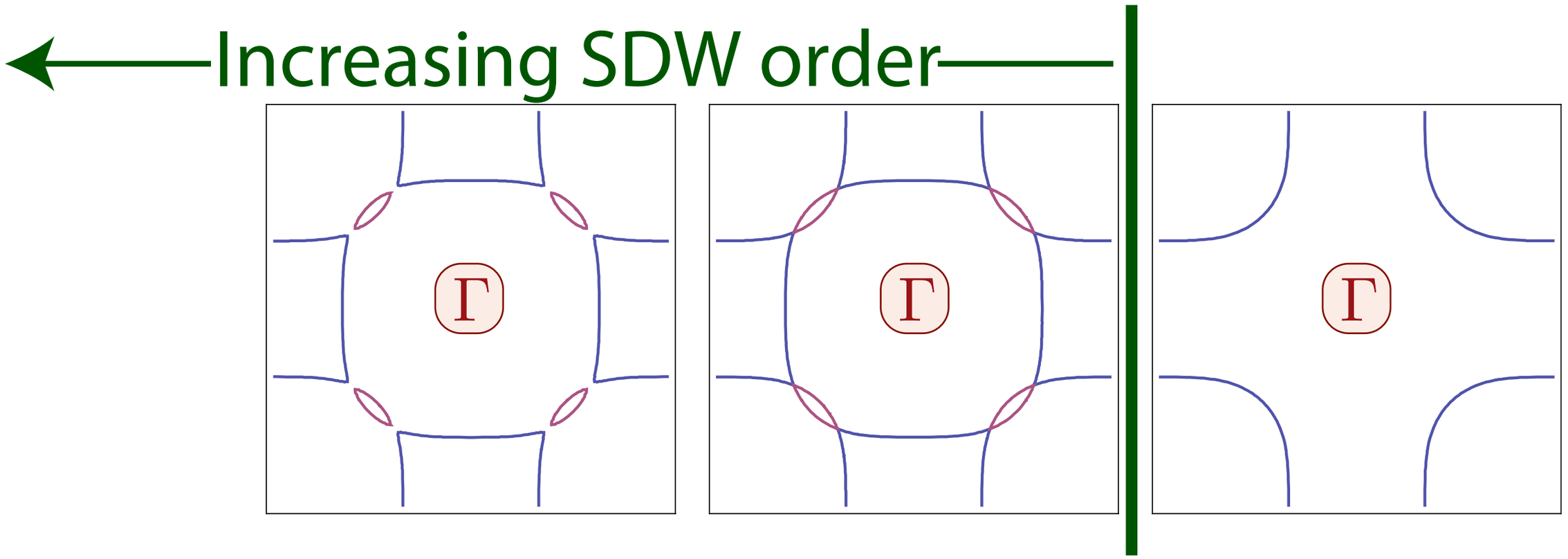

SDW order parameter is a vector, $\vec{\varphi}$,
whose amplitude vanishes at the transition
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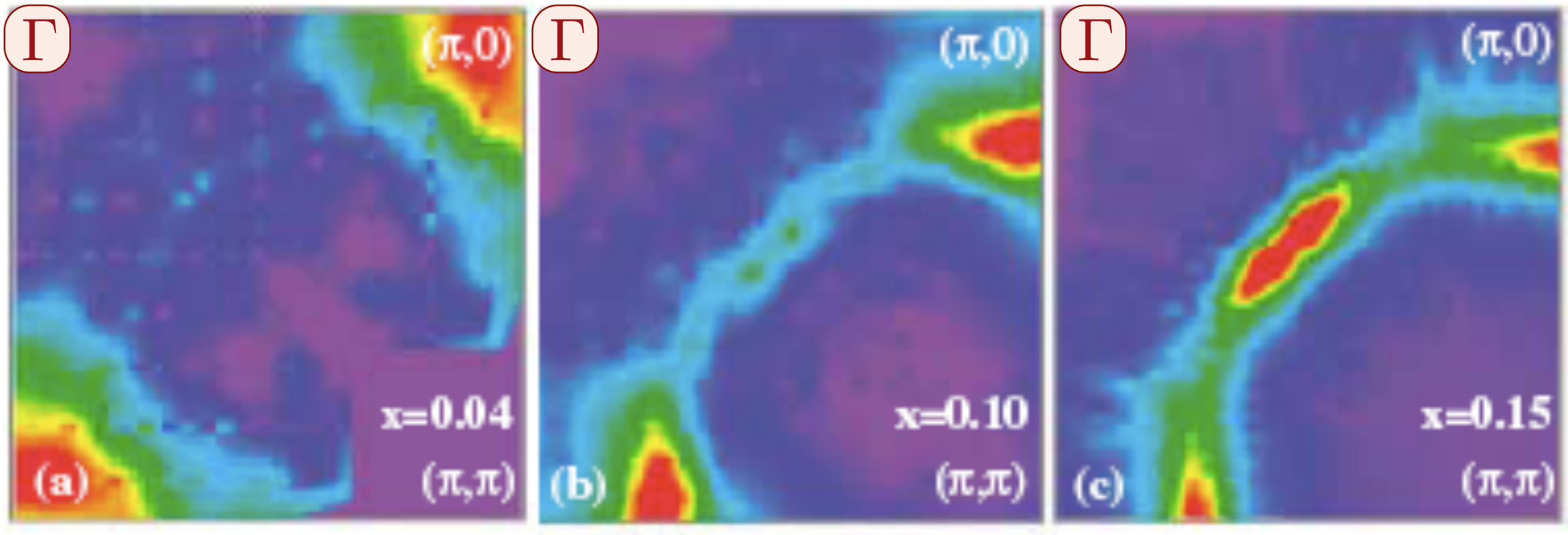
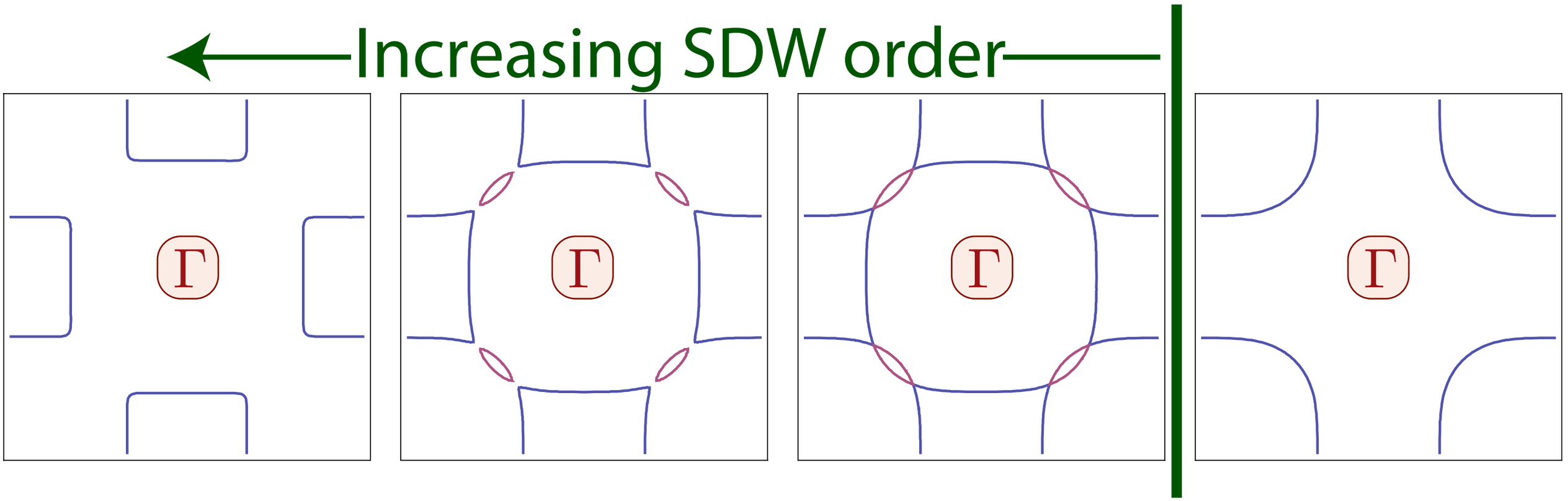
Photoemission in NCCO (electron-doped)



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

Spin density wave theory in electron-doped cuprates



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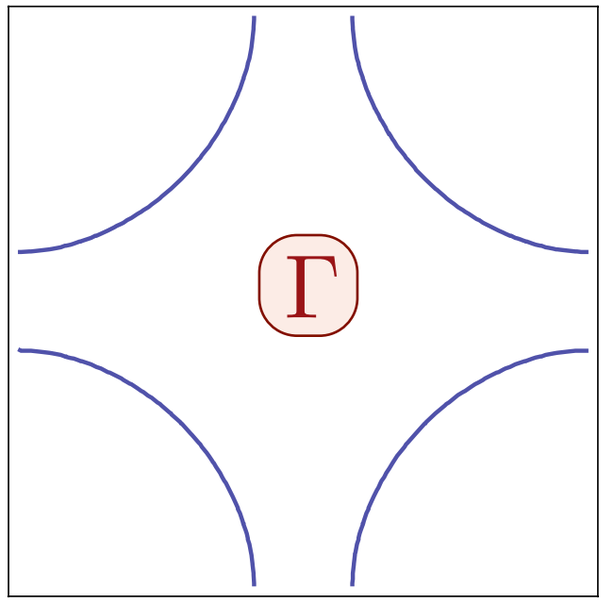

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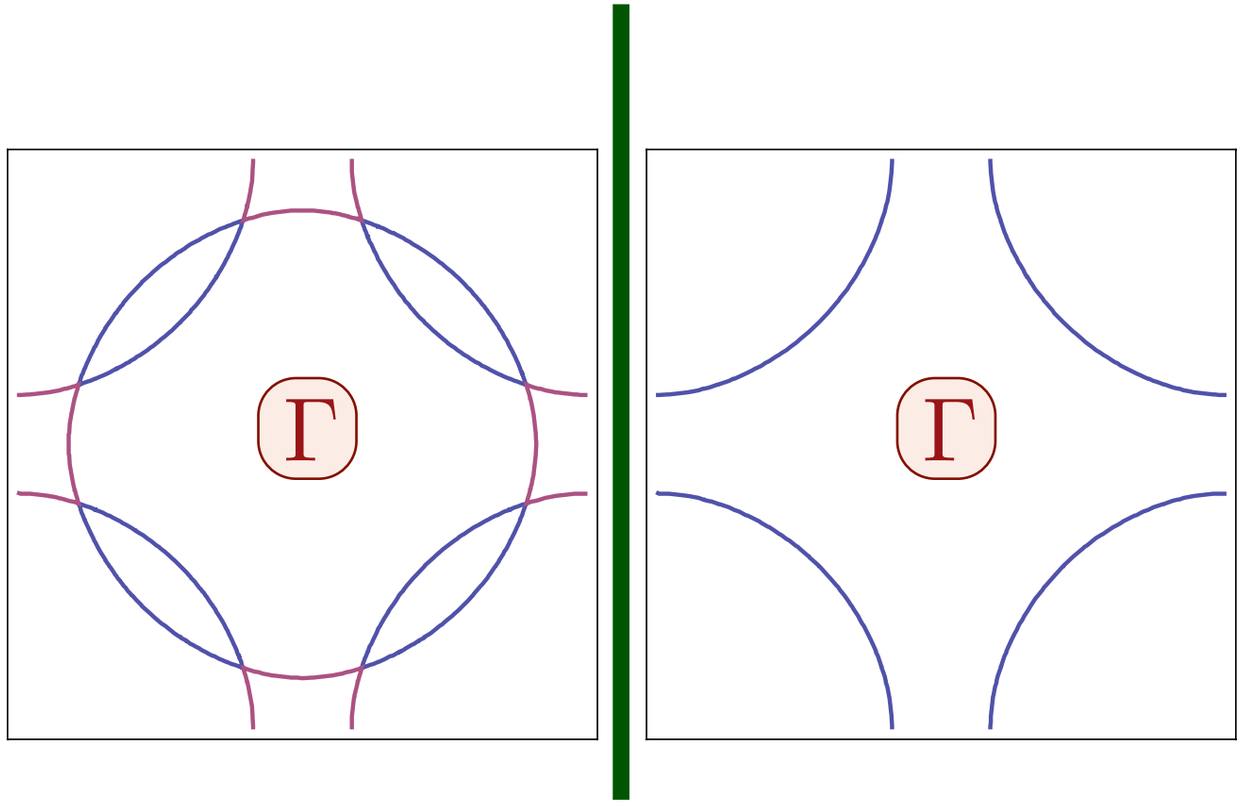

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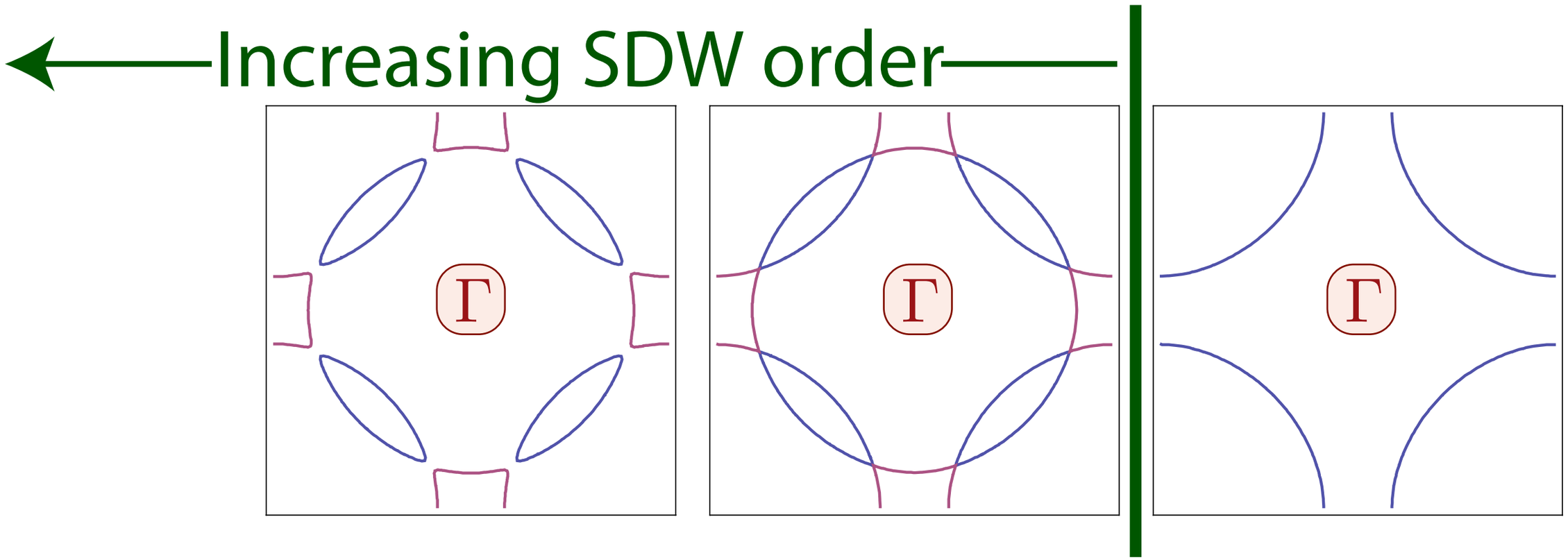

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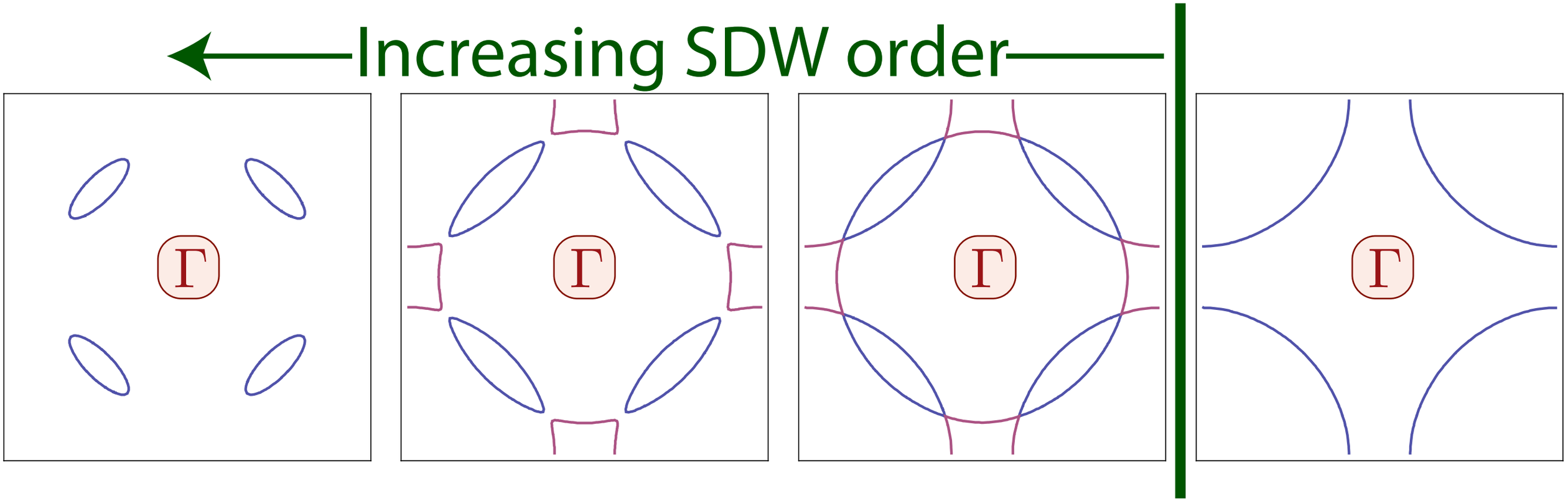

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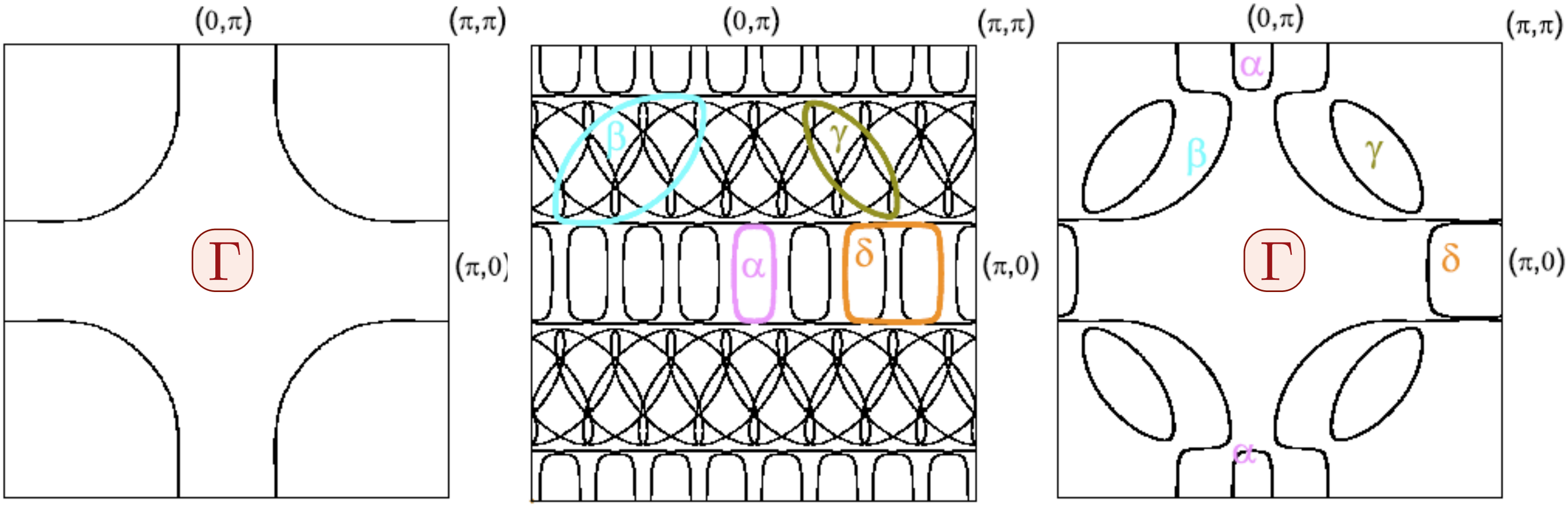
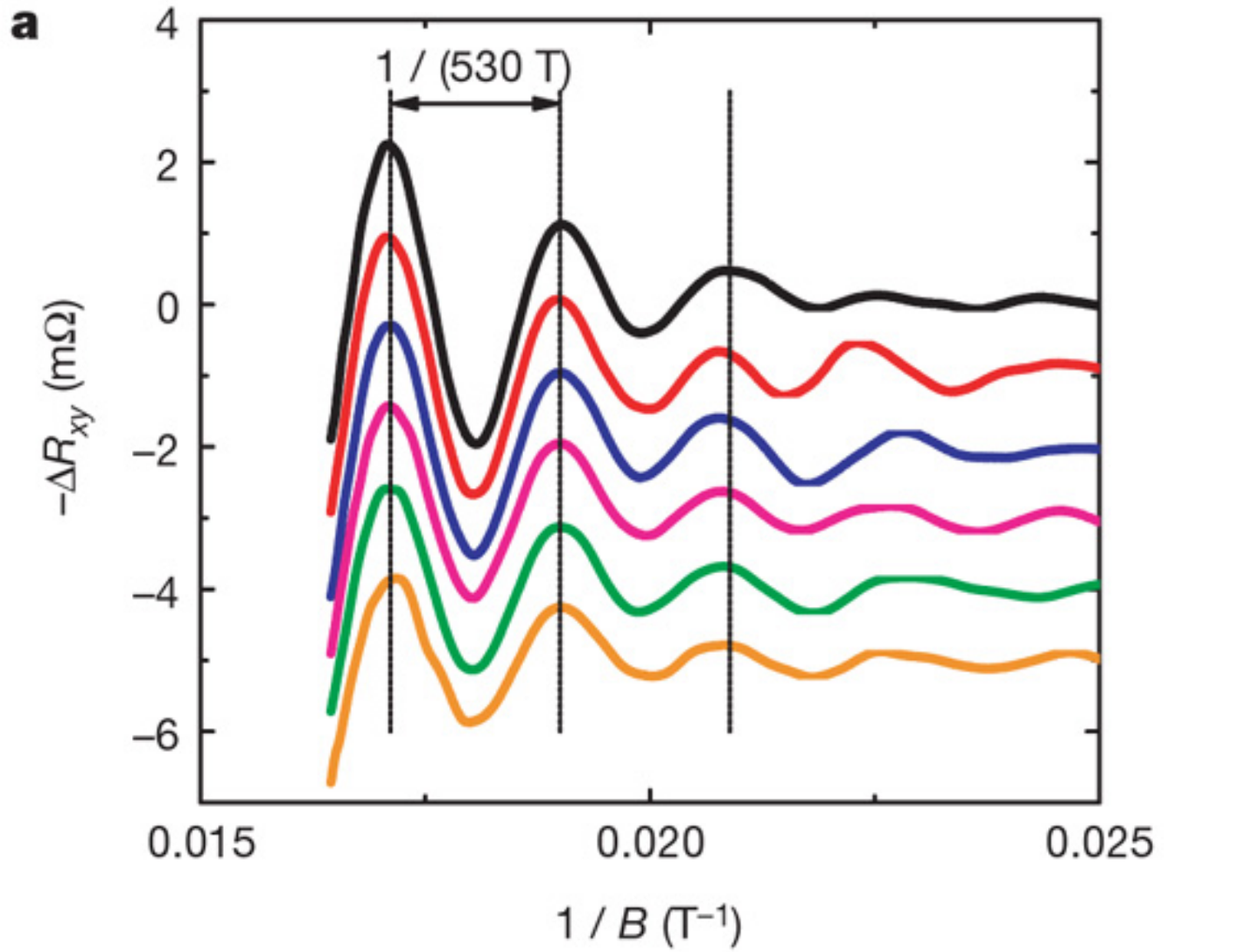
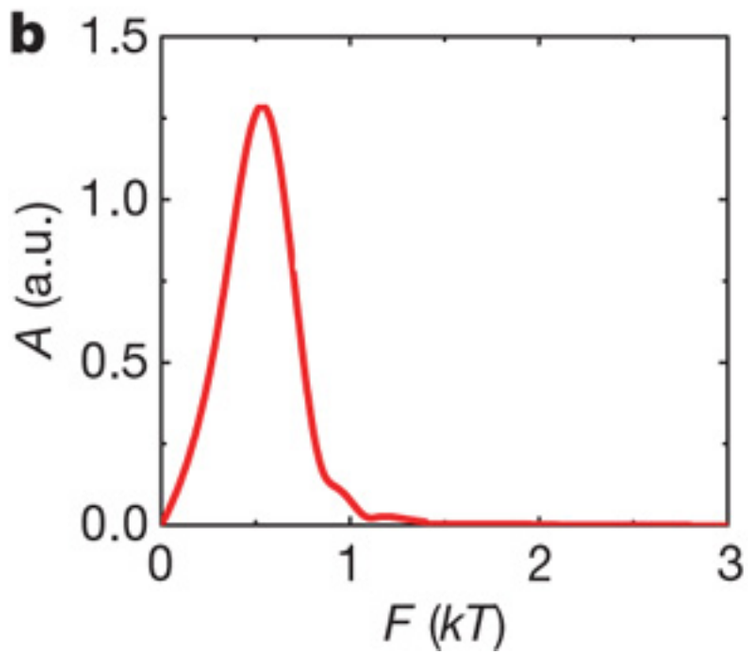


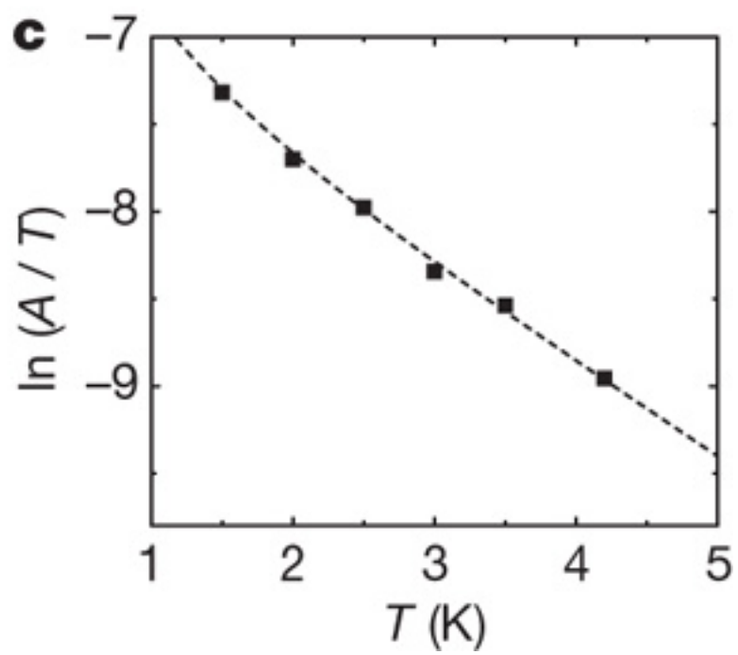
Incommensurate order in $YBa_2Cu_3O_{6+x}$

N. Harrison, arXiv:0902.2741.

Quantum oscillations and the Fermi surface in an underdoped high T_c superconductor (ortho-II ordered $YBa_2Cu_3O_{6.5}$). The period corresponds to a carrier density ≈ 0.076.





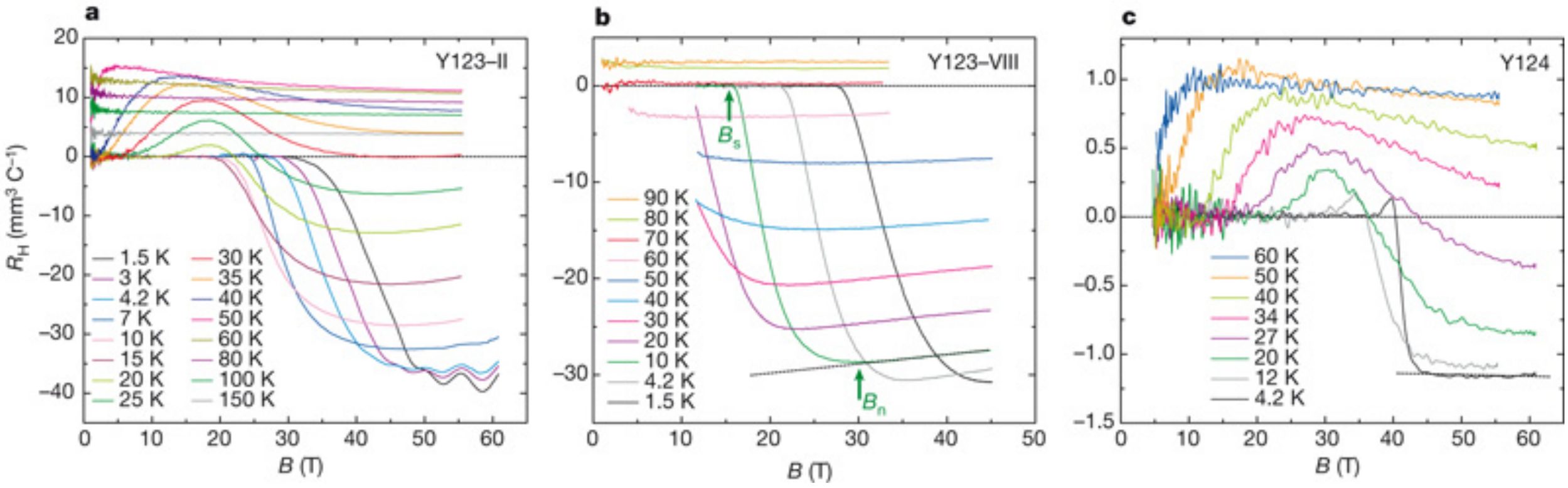


N. Doiron-Leyraud, C. Proust, D. LeBoeuf, J. Levallois, J.-B. Bonnemaison, R. Liang, D. A. Bonn, W. N. Hardy, and L. Taillefer, *Nature* **447**, 565 (2007)

Electron pockets in the Fermi surface of hole-doped high-T_c superconductors

David LeBoeuf[1], Nicolas Doiron-Leyraud[1], Julien Levallois[2], R. Daou[1], J.-B. Bonnemaison[1], N. E. Hussey[3], L. Balicas[4], B. J. Ramshaw[5], Ruixing Liang[5,6], D. A. Bonn[5,6], W. N. Hardy[5,6], S. Adachi[7], Cyril Proust[2] & Louis Taillefer[1,6]

Nature **450**, 533 (2007)



Outline

1. Nodal-anti-nodal dichotomy in the cuprates

   Survey of recent experiments

2. Spin density wave theory of normal metal

   From a "large" Fermi surface to electron and hole pockets

3. Algebraic charge liquids

   Pairing by gauge forces, d-wave superconductivity, and the nodal-anti-nodal dichotomy

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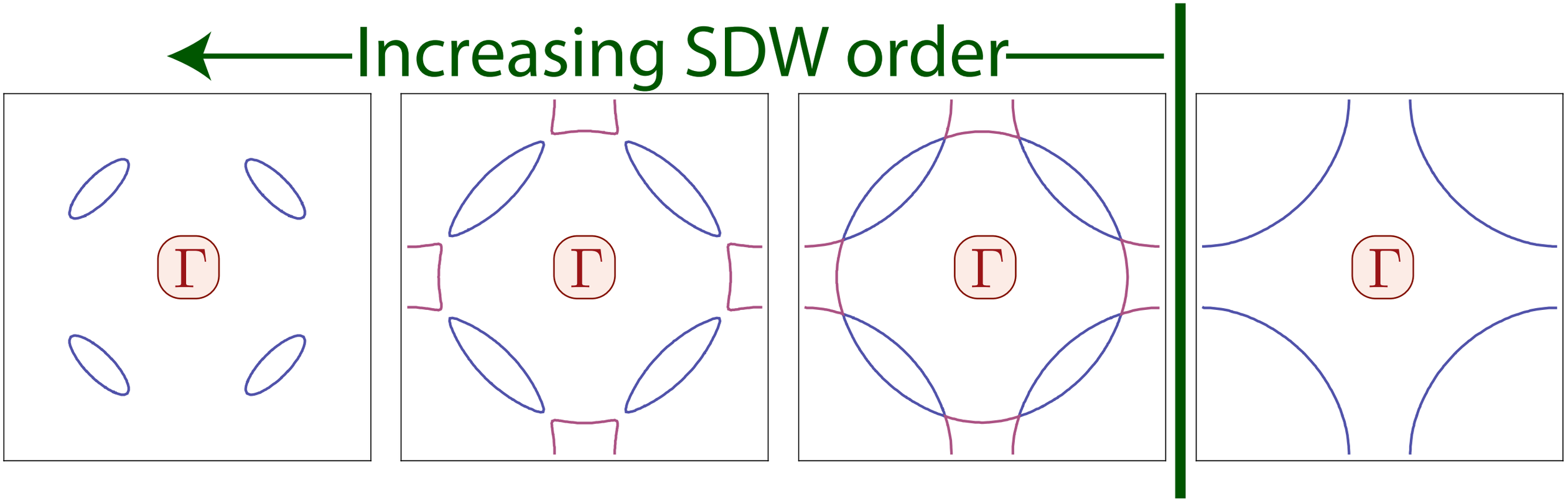
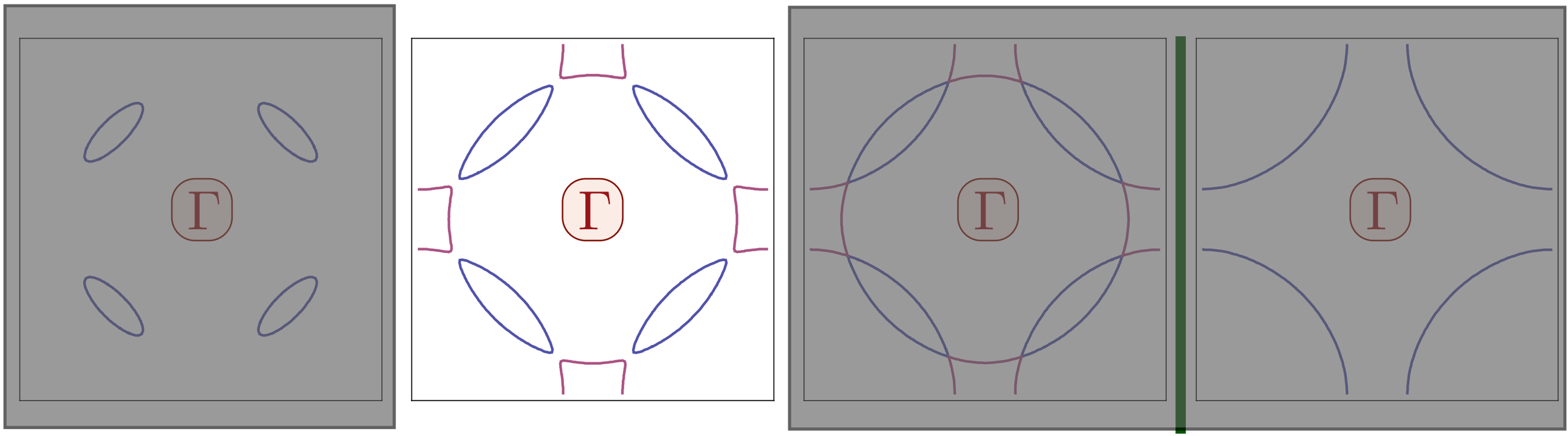
Spin density wave theory in hole-doped cuprates



SDW order parameter is a vector, $\vec{\varphi}$,
whose amplitude vanishes at the transition
to the Fermi liquid.

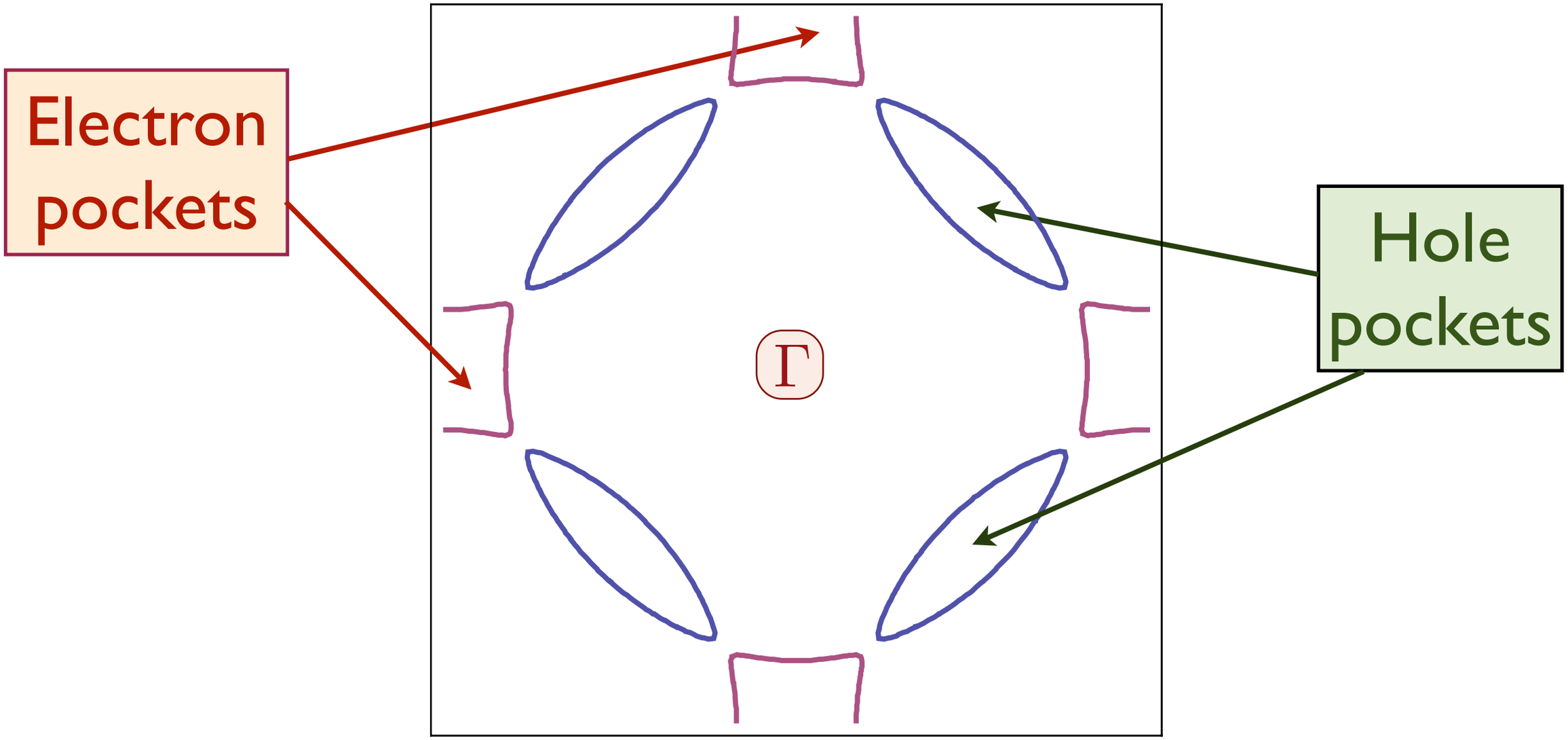
Fermi pockets in hole-doped cuprates



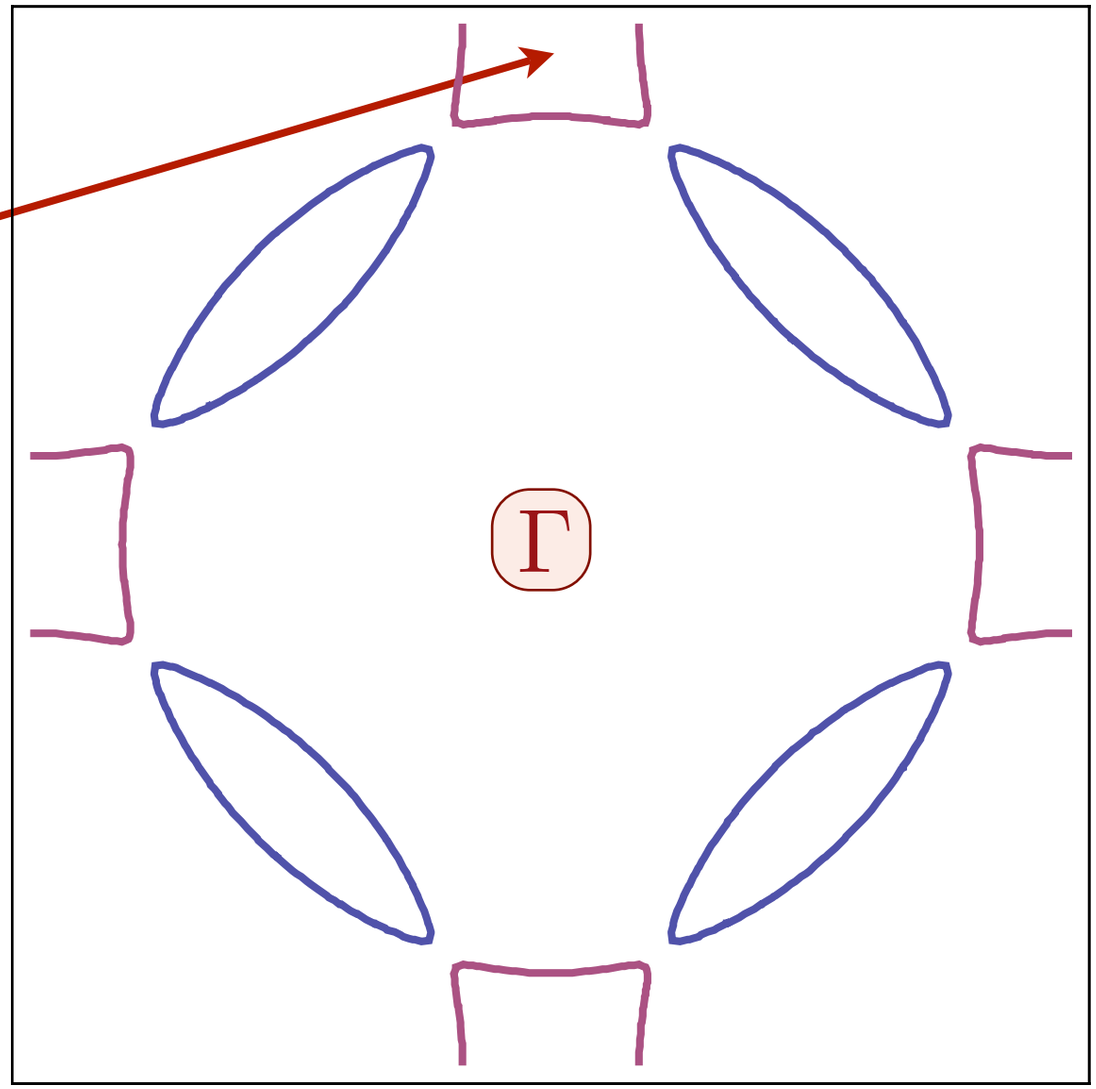
Begin with SDW ordered state, and focus on fluctuations in the *orientation* of $\vec{\varphi}$, by using a unit-length bosonic spinor z_α

$$\vec{\varphi} = z^*_\alpha \vec{\sigma}_{\alpha\beta} z_\beta$$

Charge carriers in the lightly-doped cuprates with Neel order

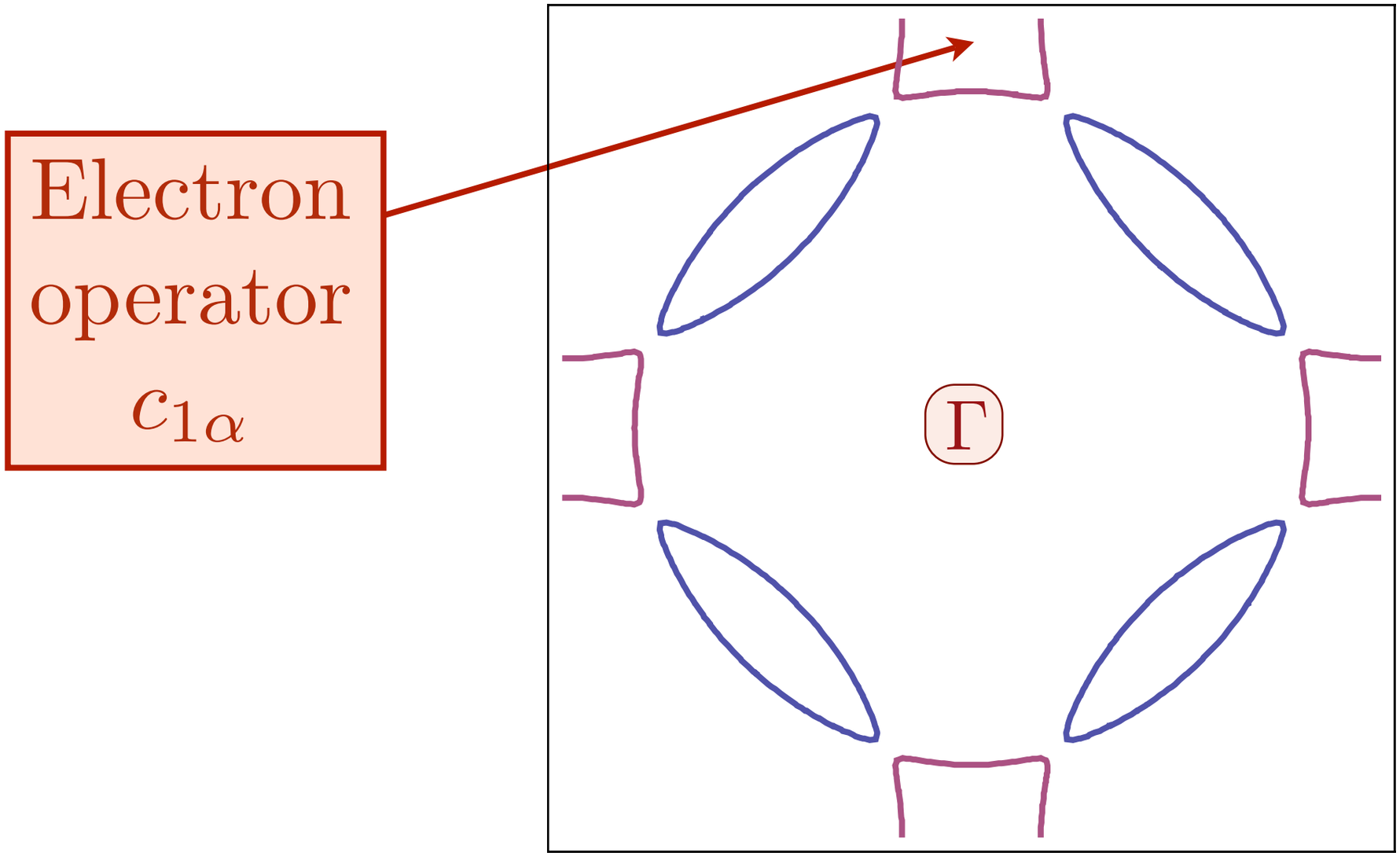


Electron operator $c_{1\alpha}$



For a uniform SDW order with $\vec{\varphi} \propto (0, 0, 1)$, write

$$\begin{pmatrix} c_{1\uparrow} \\ c_{1\downarrow} \end{pmatrix} = \quad \begin{pmatrix} g_+ \\ g_- \end{pmatrix}$$

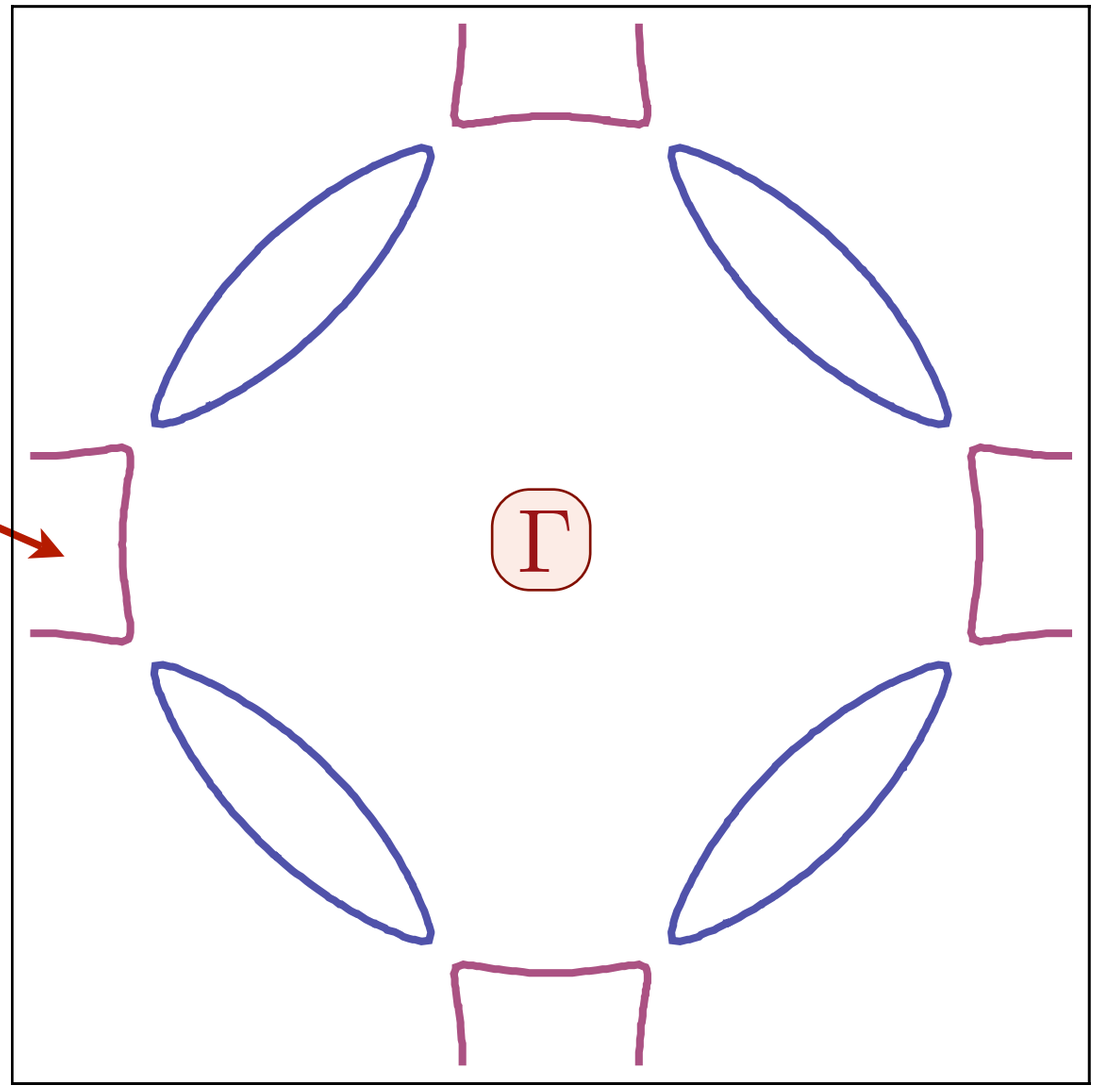


For a spacetime dependent SDW order, $\vec{\varphi} = z^*_\alpha \vec{\sigma}_{\alpha\beta} z_\beta$,

$$\begin{pmatrix} c_{1\uparrow} \\ c_{1\downarrow} \end{pmatrix} = \mathcal{R}_z \begin{pmatrix} g_+ \\ g_- \end{pmatrix} \quad ; \quad \mathcal{R}_z \equiv \begin{pmatrix} z_\uparrow & -z^*_\downarrow \\ z_\downarrow & z^*_\uparrow \end{pmatrix}.$$

So $g_\pm$ are the "up/down" electron operators
in a rotating reference frame defined by the local SDW order

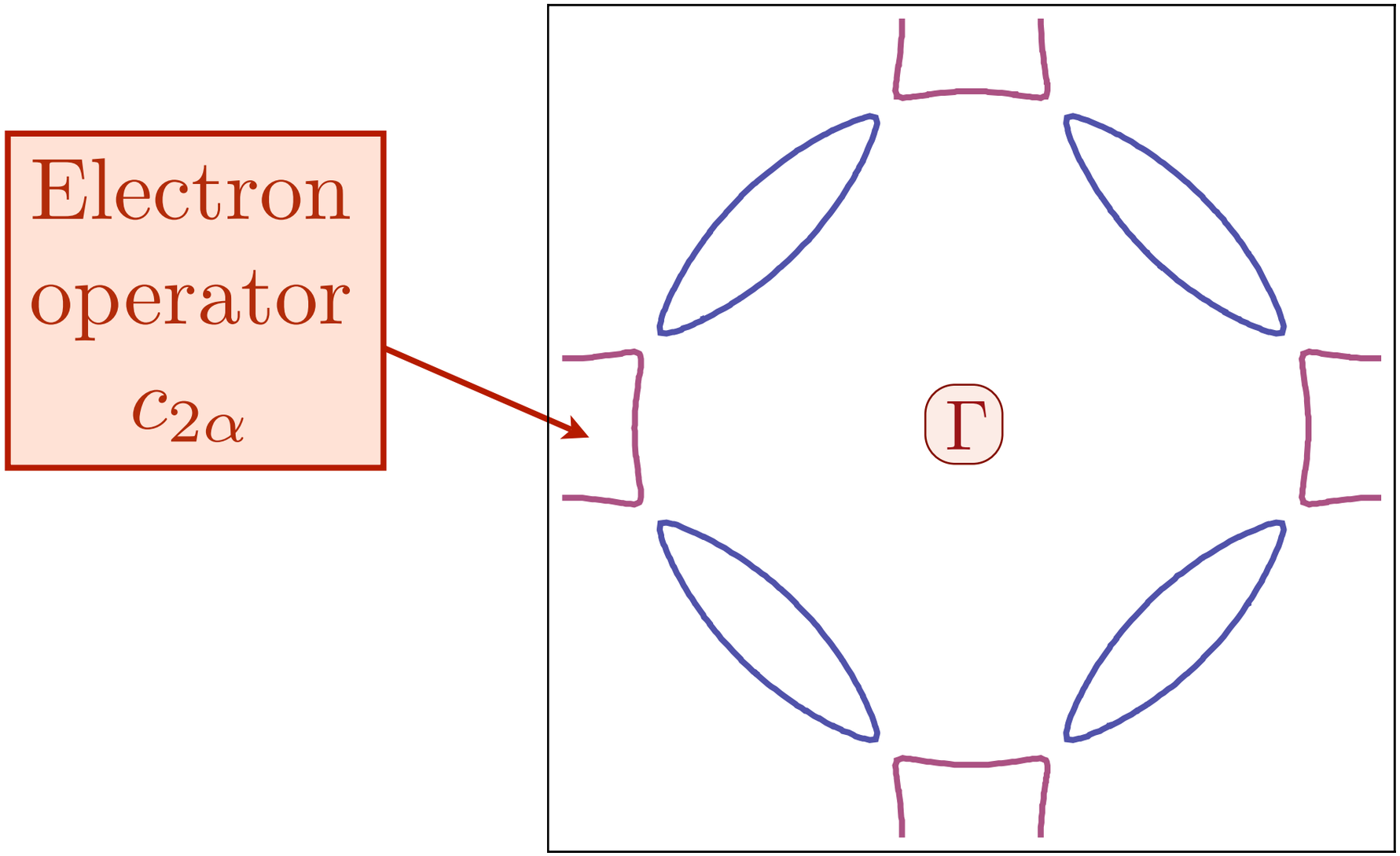
Electron operator $c_{2\alpha}$



SDW theory also specifies electrons at second pocket for $\vec{\varphi} \propto (0,0,1)$

$$\begin{pmatrix} c_{2\uparrow} \\ c_{2\downarrow} \end{pmatrix} = \begin{pmatrix} g_+ \\ -g_- \end{pmatrix}$$

,



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Same SU(2) matrix also rotates electrons in second pocket.

Low energy theory for spinless, charge $-e$ fermions $g_\pm$,
and spinful, charge 0 bosons z_α:

$$\begin{aligned}
\mathcal{L} &= \mathcal{L}_z + \mathcal{L}_g \\
\mathcal{L}_z &= \frac{1}{t}\Big[|(\partial_\tau - iA_\tau)z_\alpha|^2 + c^2|\nabla - i\mathbf{A})z_\alpha|^2\Big] \\
&+ \quad \text{Berry phases of monopoles in } A_\mu.
\end{aligned}$$

CP^1 field theory for z_α and an emergent U(1) gauge field A_μ.
Coupling t tunes the strength of SDW orientation fluctuations.

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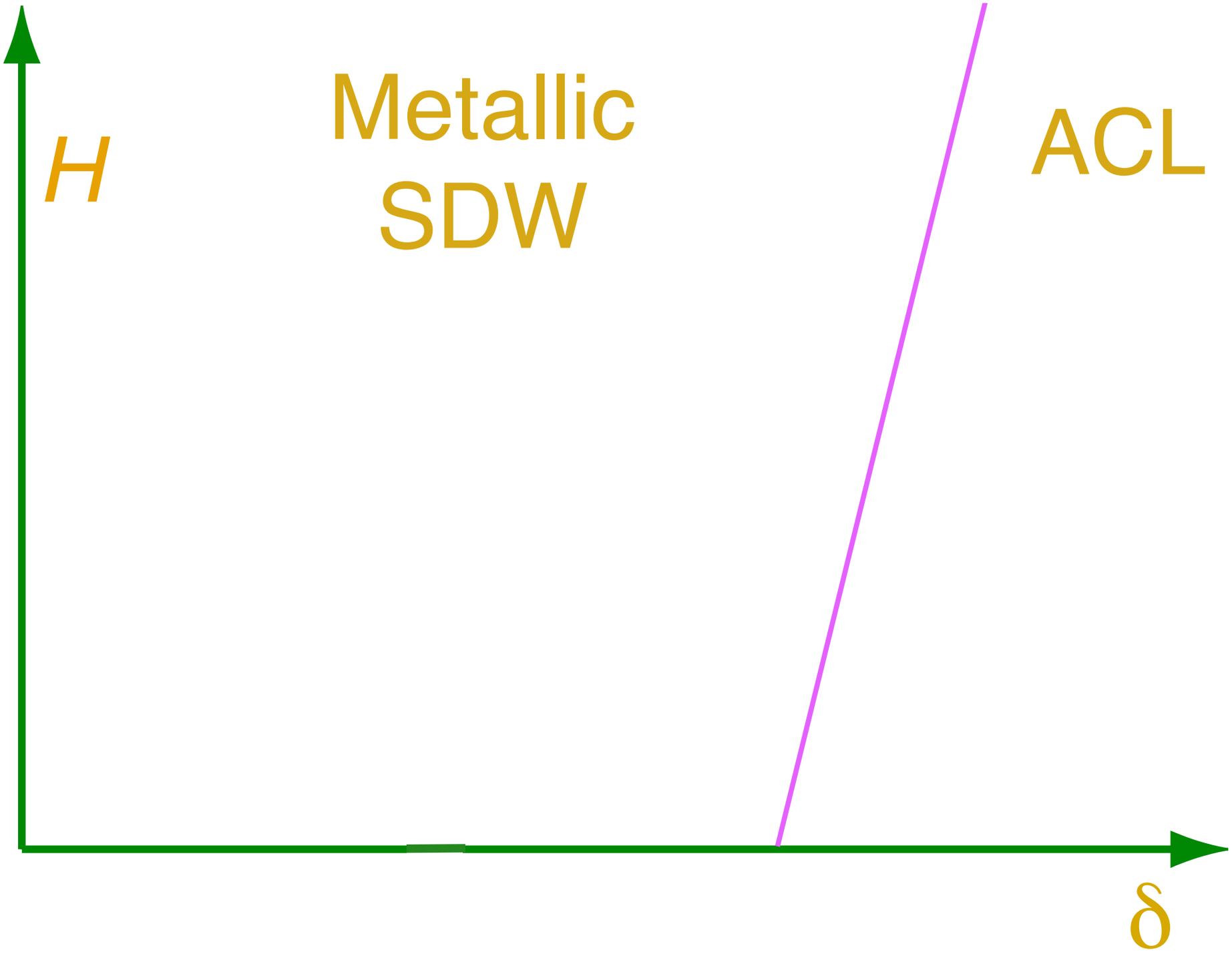
CP^1 field theory for z_α and an emergent U(1) gauge field A_μ.
Coupling t tunes the strength of SDW orientation fluctuations.

$$\begin{aligned}
\mathcal{L}_g &= g_+^\dagger \left[(\partial_\tau - iA_\tau) - \frac{1}{2m^*}(\nabla - i\mathbf{A})^2 - \mu\right] g_+ \\
&+ g_-^\dagger \left[(\partial_\tau + iA_\tau) - \frac{1}{2m^*}(\nabla + i\mathbf{A})^2 - \mu\right] g_-
\end{aligned}$$

Two Fermi surfaces coupled to the
emergent U(1) gauge field A_μ with opposite charges

Phase diagram

as a function of hole density $\delta \sim t$ and magnetic field H.



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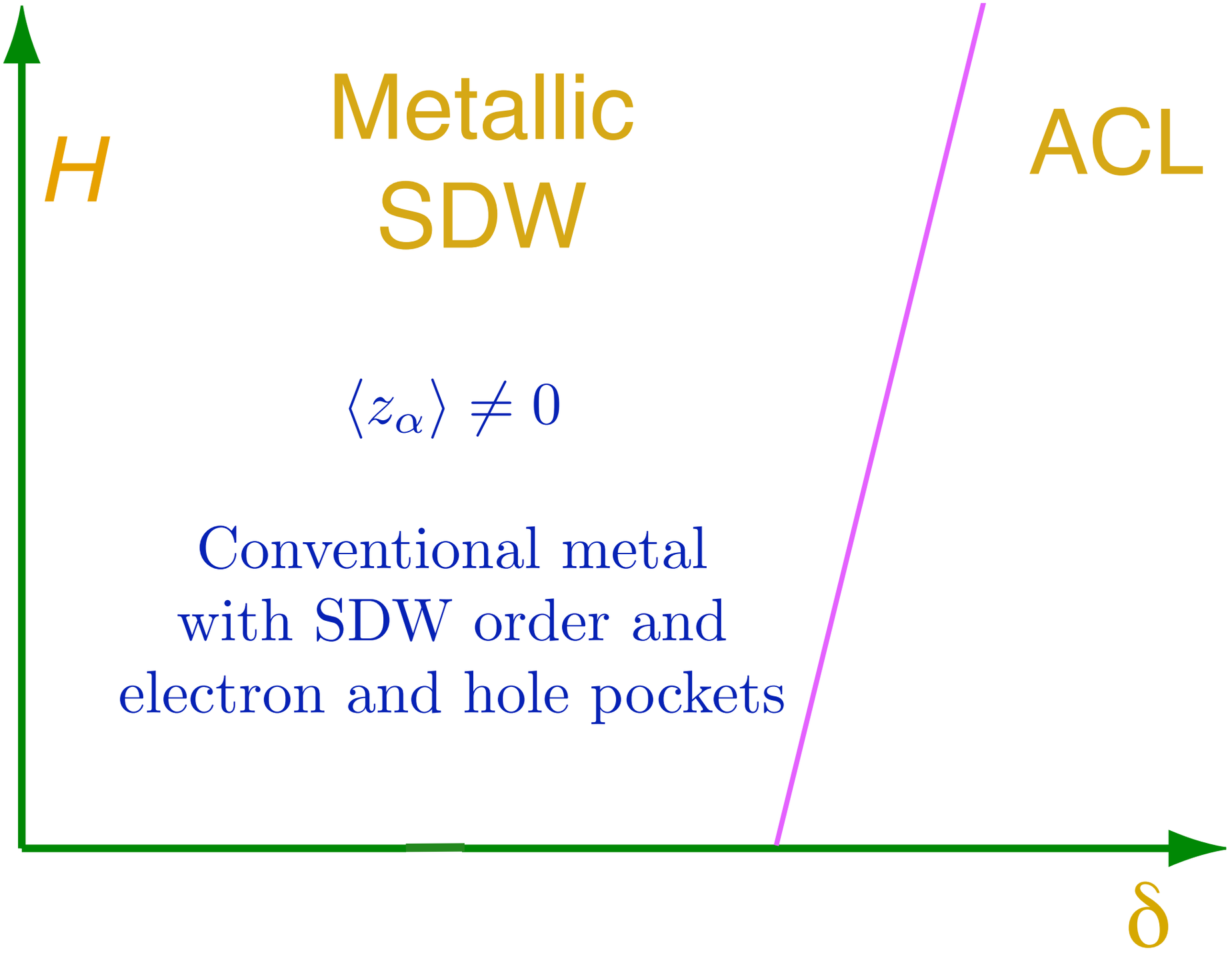

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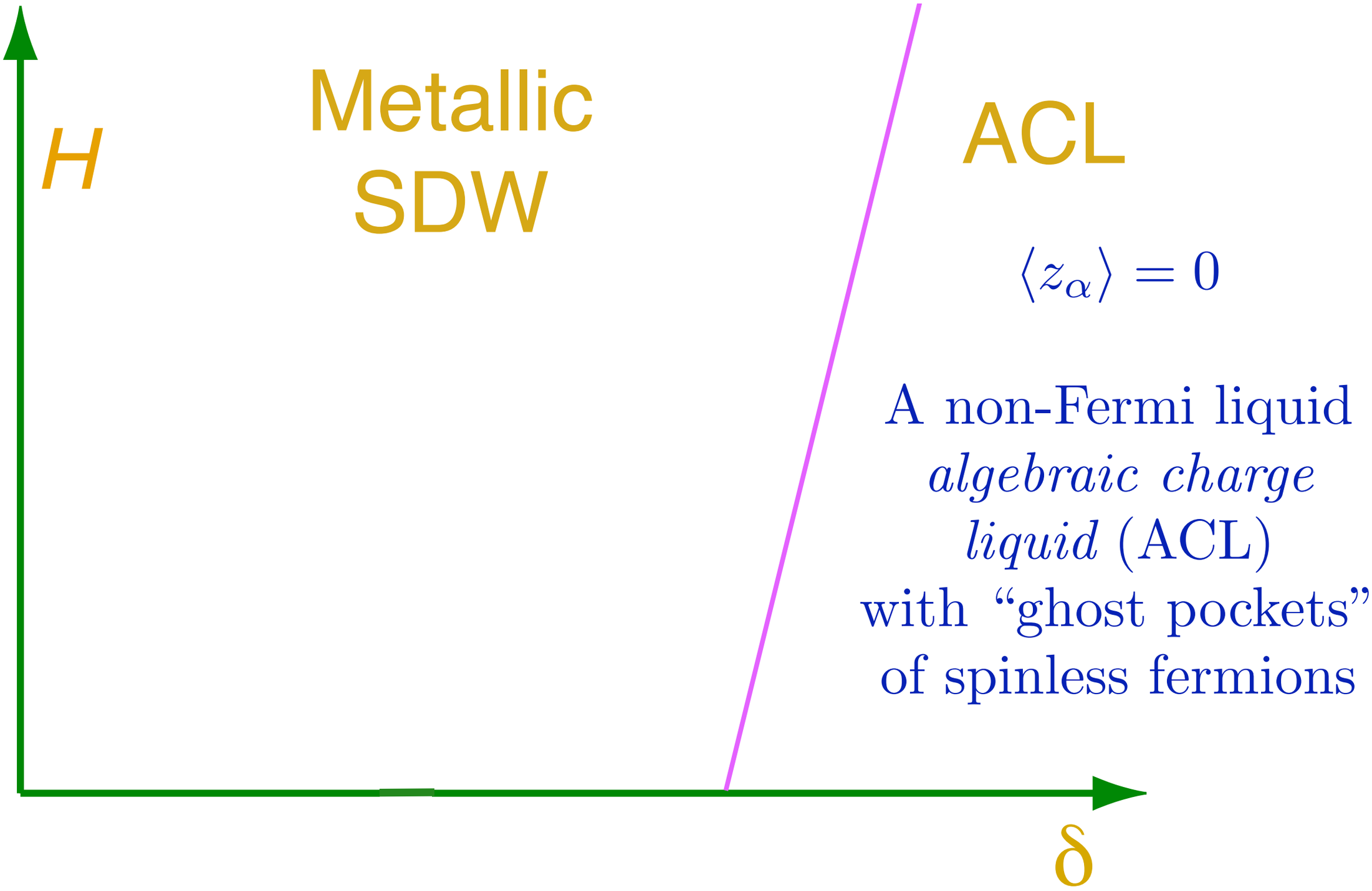

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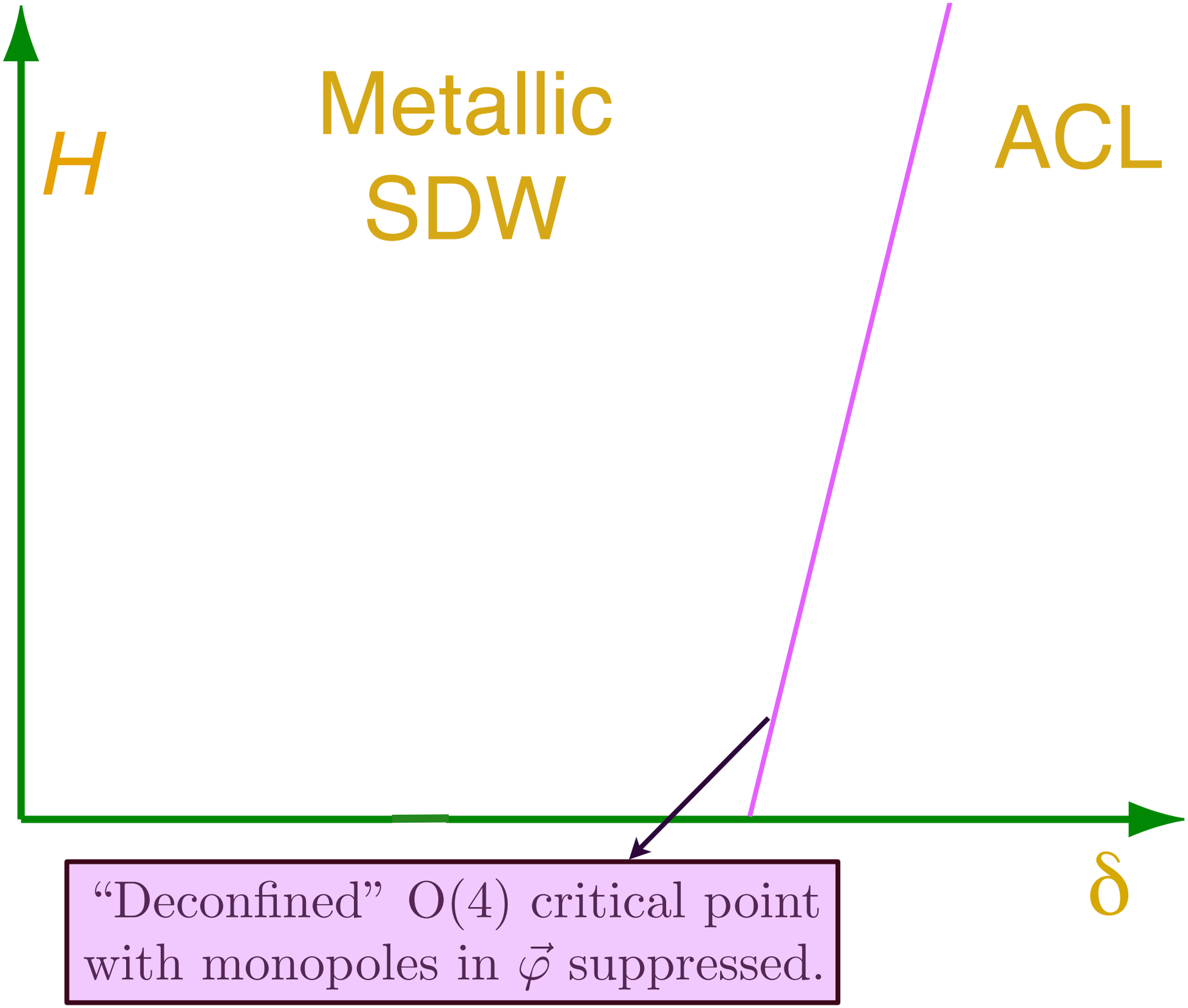

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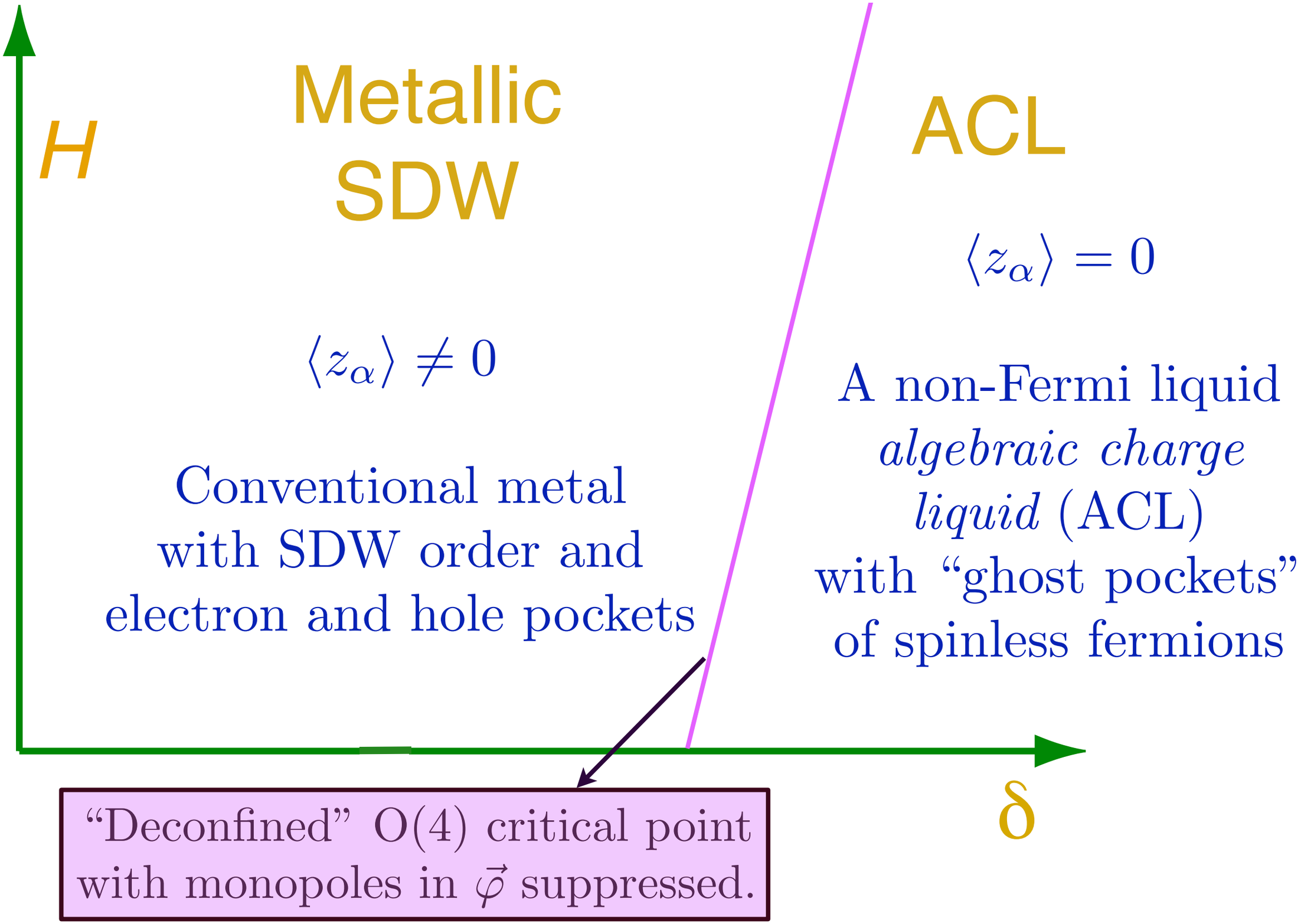

Strong pairing of the $g_\pm$ electron pockets

- Problem is similar to double layer quantum Hall systems at total filling fraction $\nu = 1$. At large layer spacing we have 2 composite fermion Fermi surfaces each at filling fraction $\nu = 1/2$. At small layer spacing, there is a paired state formed by attractive interaction mediated by antisymmetric gauge field.

N. E. Bonesteel, I. A. McDonald, and C. Nayak, *Phys. Rev. Lett.* **77**, 3009 (1996).
I. Ussishkin and A. Stern, *Phys. Rev. Lett.* **81**, 3932 (1998).

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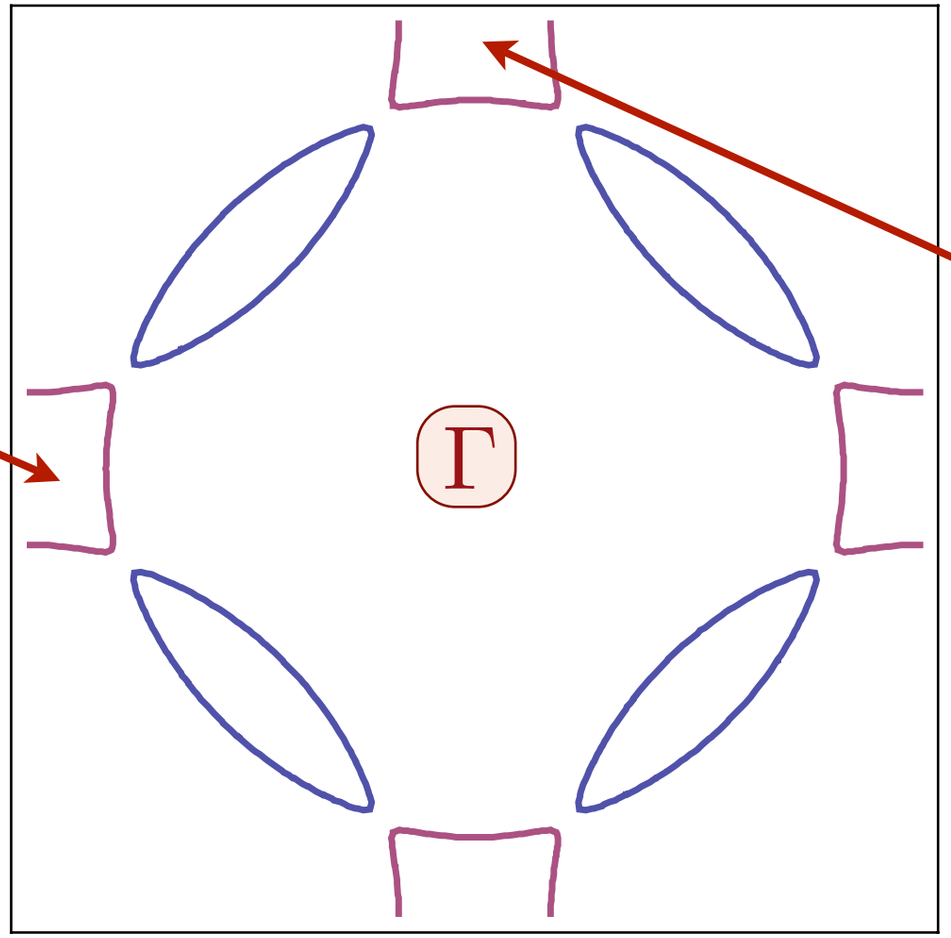
- Gauge forces lead to a s-wave paired state with a T_c of order the Fermi energy of the pockets. Inelastic scattering from low energy gauge modes lead to very singular $g_\pm$ self energy, but is *not* pair-breaking.

$$\langle g_+ g_- \rangle = \Delta$$

Strong pairing of the $g_\pm$ electron pockets

Electron operator $c_{2\alpha}$



Electron operator $c_{1\alpha}$

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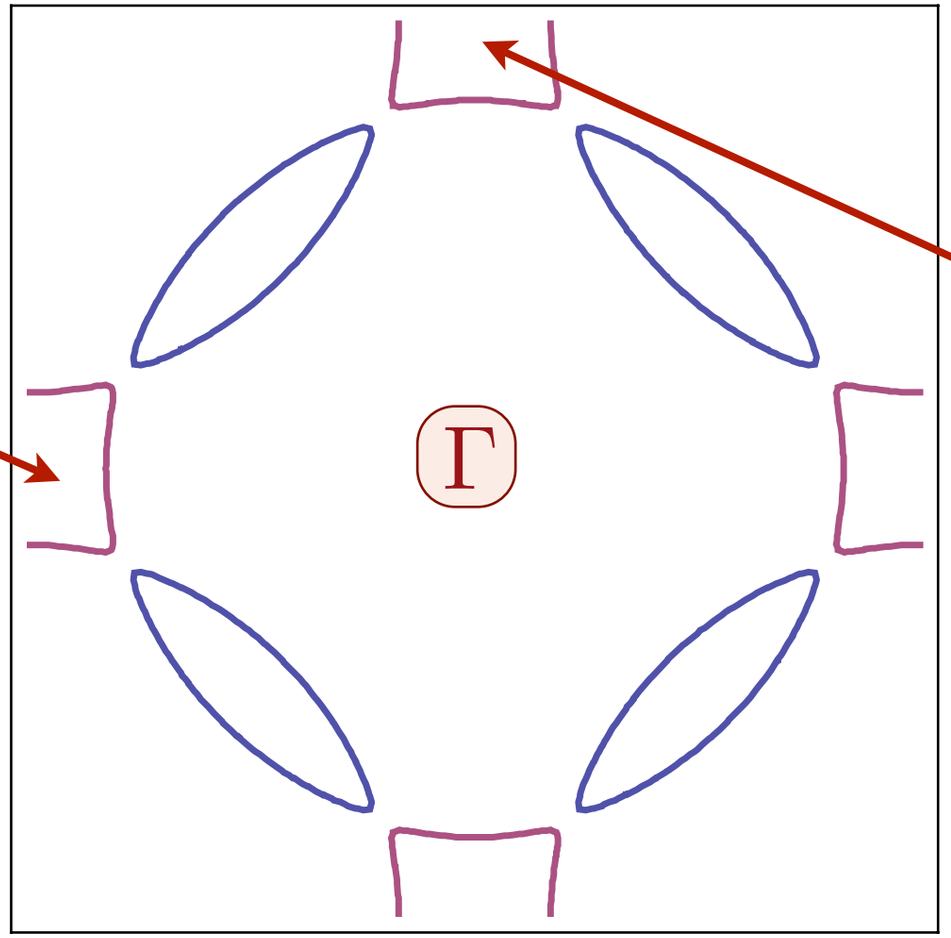

Electron operator $c_{1\alpha}$

- Transforming back to the physical fermions:

$$\begin{pmatrix} c_{1\uparrow} \\ c_{1\downarrow} \end{pmatrix} = \begin{pmatrix} z_\uparrow & -z_\downarrow^* \\ z_\downarrow & z_\uparrow^* \end{pmatrix} \begin{pmatrix} g_+ \\ g_- \end{pmatrix} \quad ; \quad \begin{pmatrix} c_{2\uparrow} \\ c_{2\downarrow} \end{pmatrix} = \begin{pmatrix} z_\uparrow & -z_\downarrow^* \\ z_\downarrow & z_\uparrow^* \end{pmatrix} \begin{pmatrix} g_+ \\ -g_- \end{pmatrix},$$

we find: $\langle c_{1\uparrow} c_{1\downarrow} \rangle = - \langle c_{2\uparrow} c_{2\downarrow} \rangle \sim \left\langle |z_\uparrow|^2 + |z_\downarrow|^2 \right\rangle \langle g_+ g_- \rangle \, ;$

Strong pairing of the $g_\pm$ electron pockets

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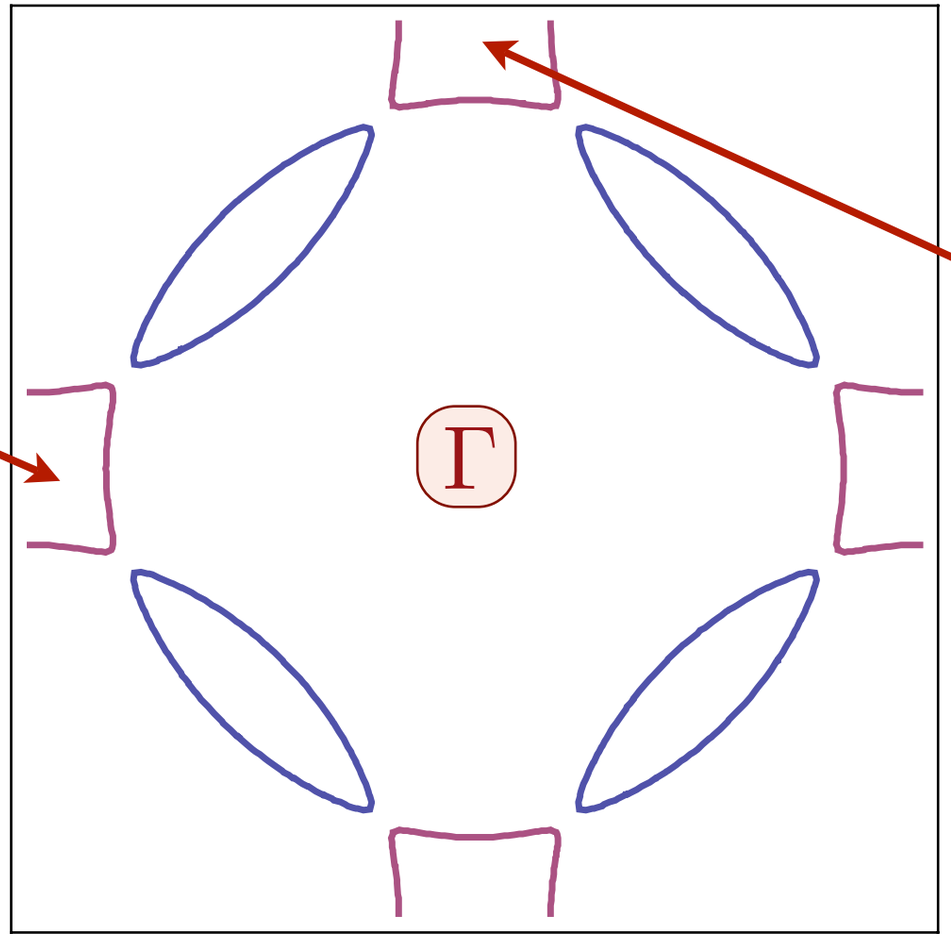

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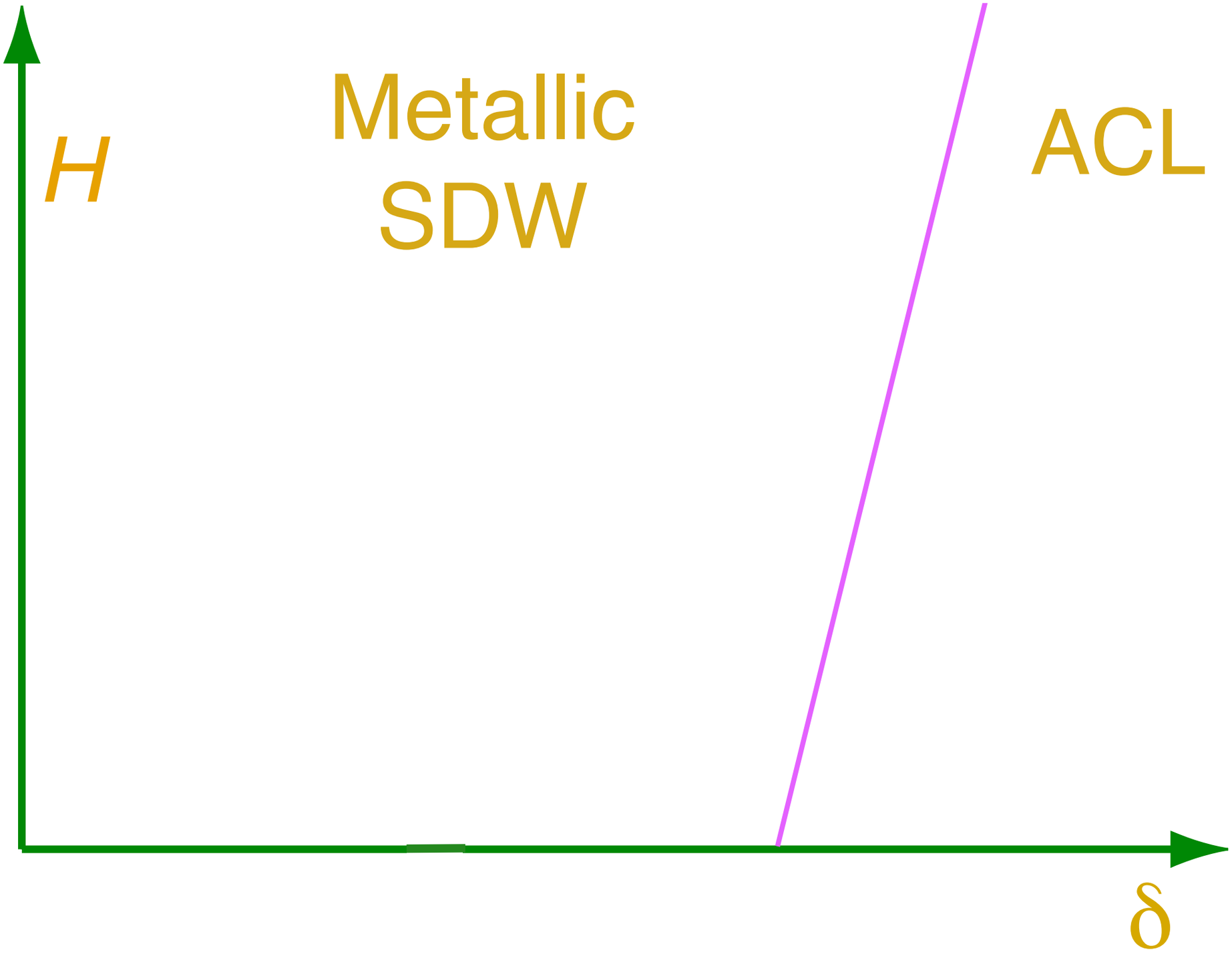
i.e. the pairing signature for the electrons is d-wave.

Phase diagram

as a function of hole density $\delta \sim t$ and magnetic field H.



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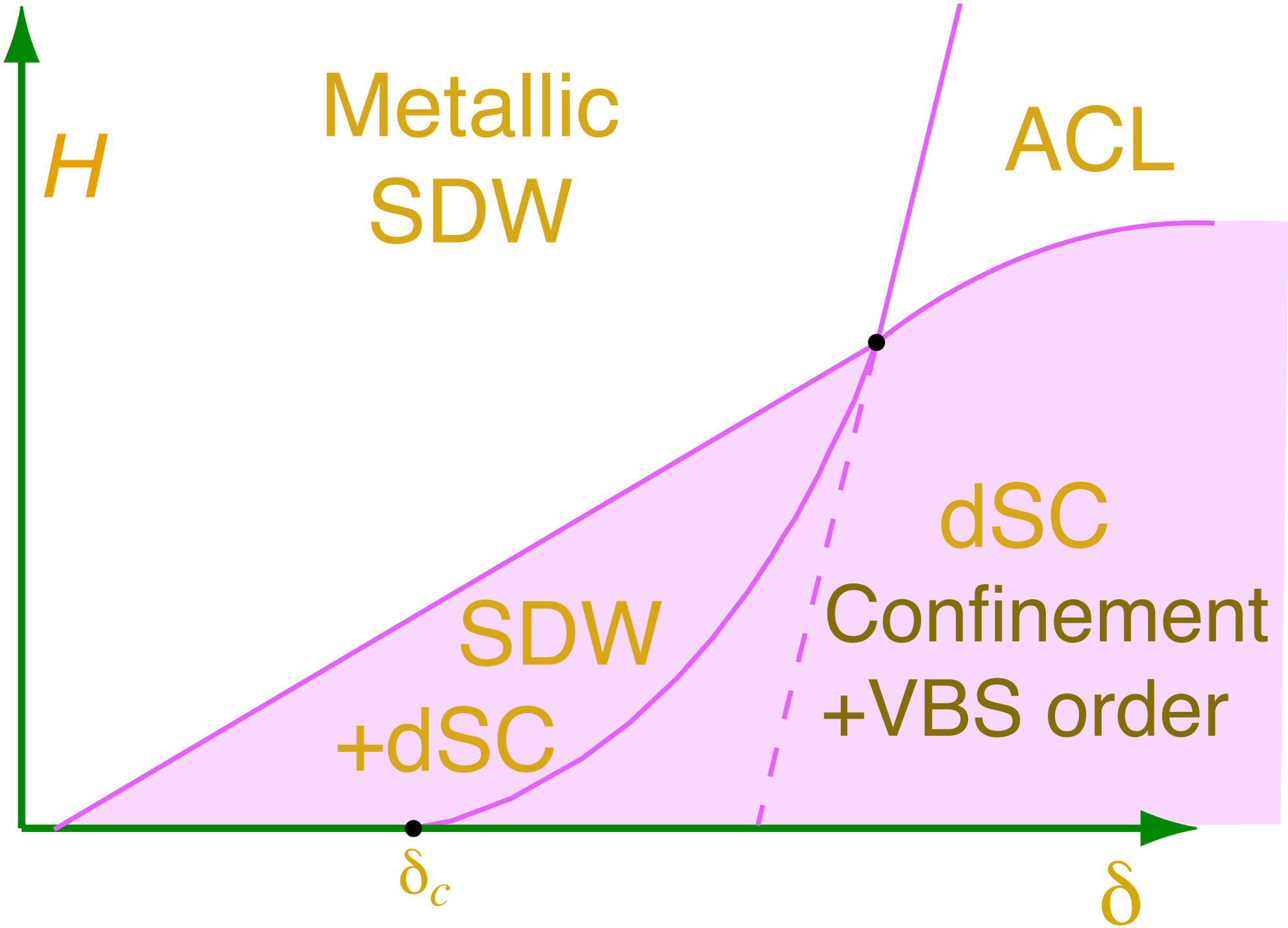

Interplay of dSC and SDW order is similar to theory of competing orders

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

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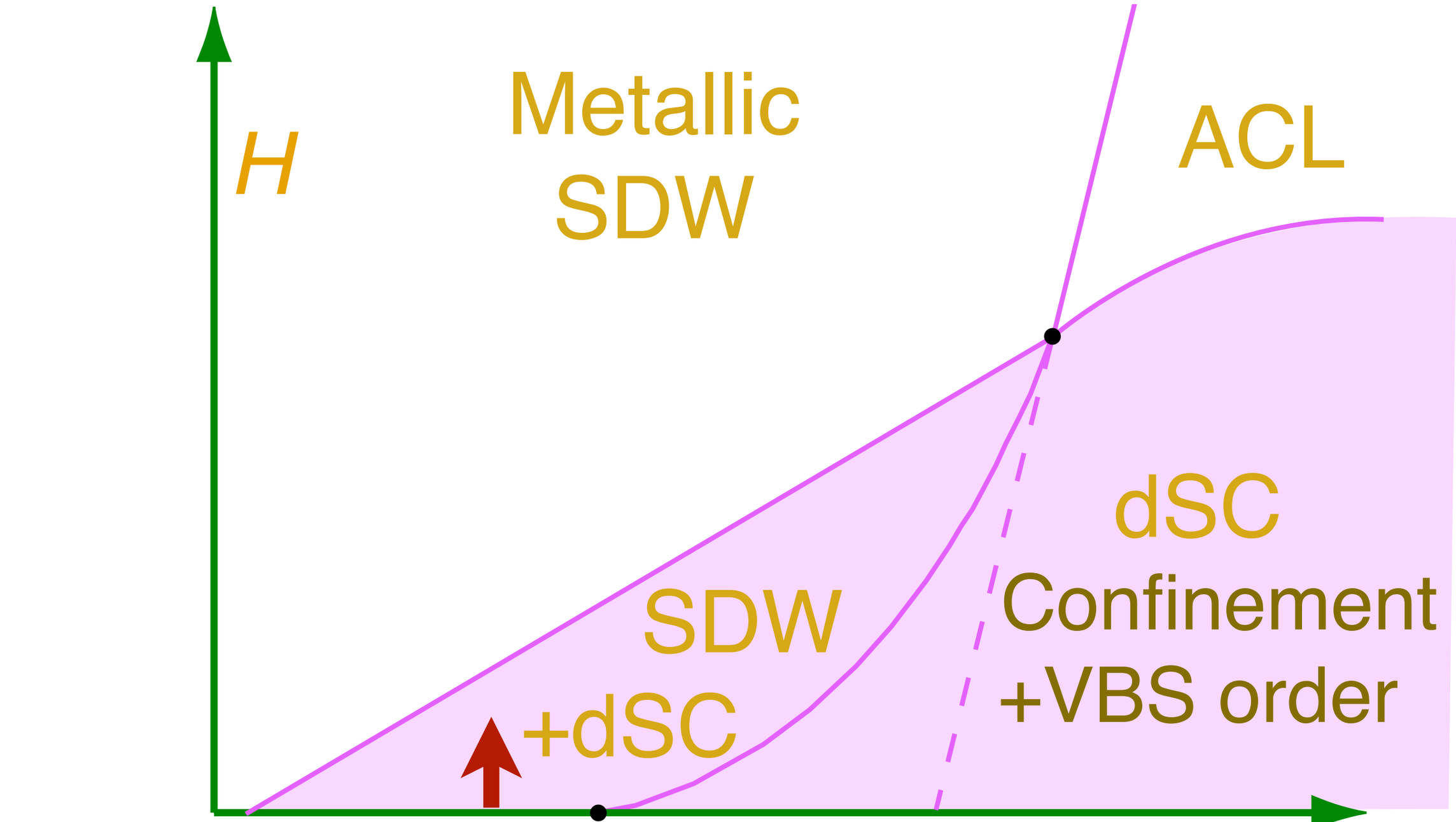

Neutron scattering on $La_{1.9}Sr_{0.1}CuO_4$

B. Lake *et al.*, *Nature* **415**, 299 (2002)

Phase diagram

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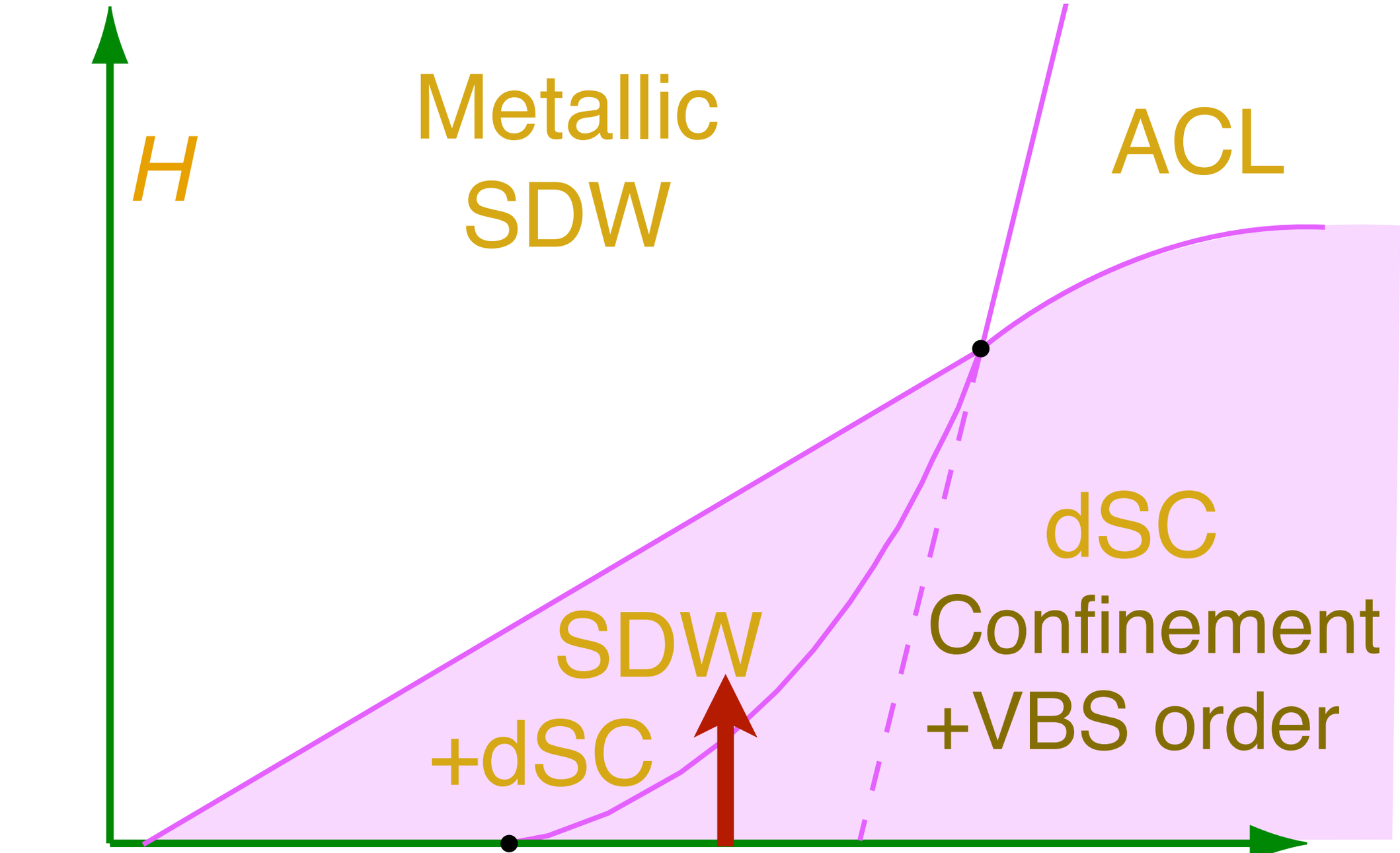

Neutron scattering on $La_{1.855}Sr_{0.145}CuO_4$
J. Chang *et al.*, arXiv:0902.1191

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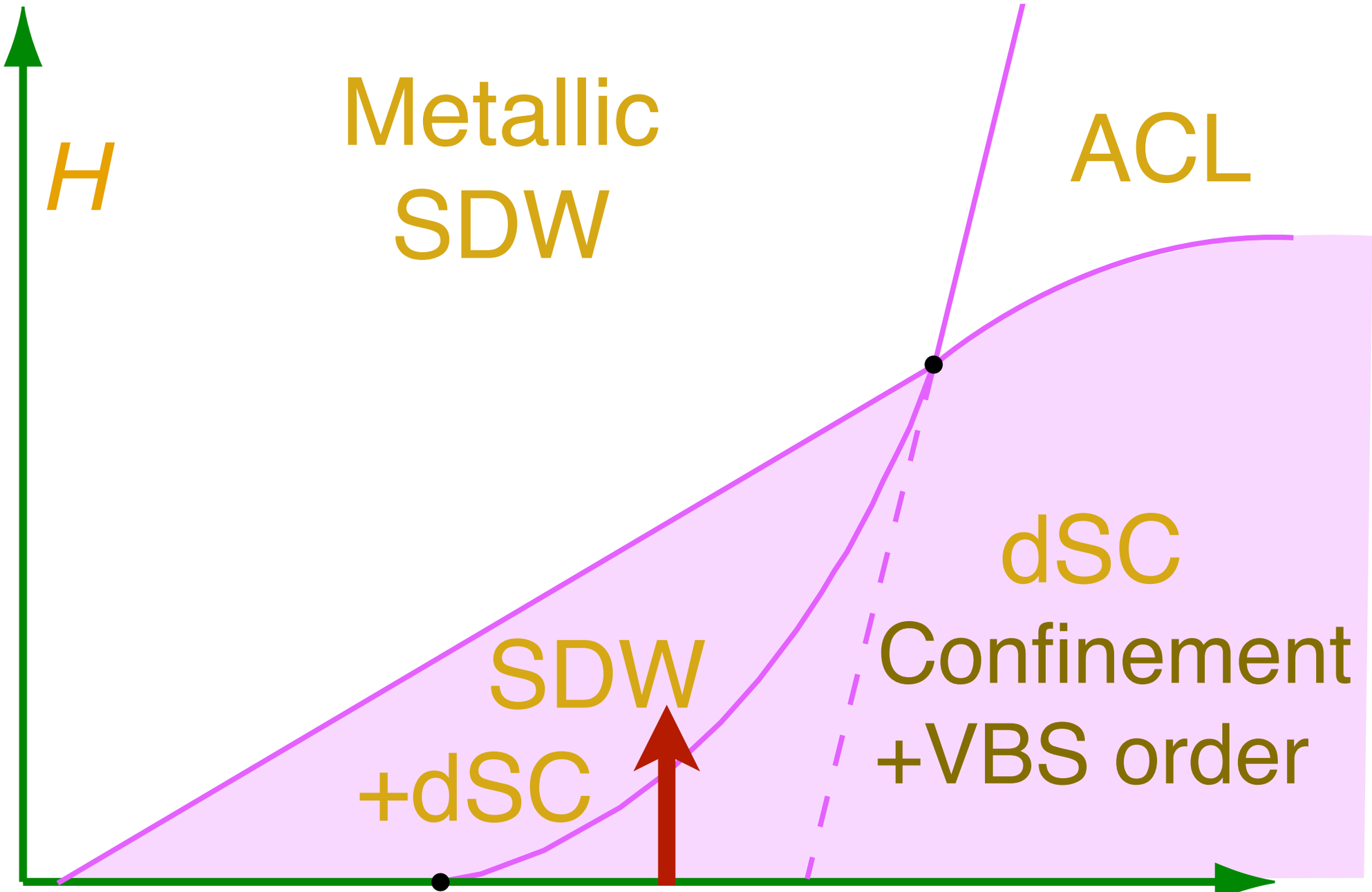

Neutron scattering on $YBa_2Cu_3O_{6.45}$

D. Haug *et al.*, arXiv:0902.3335

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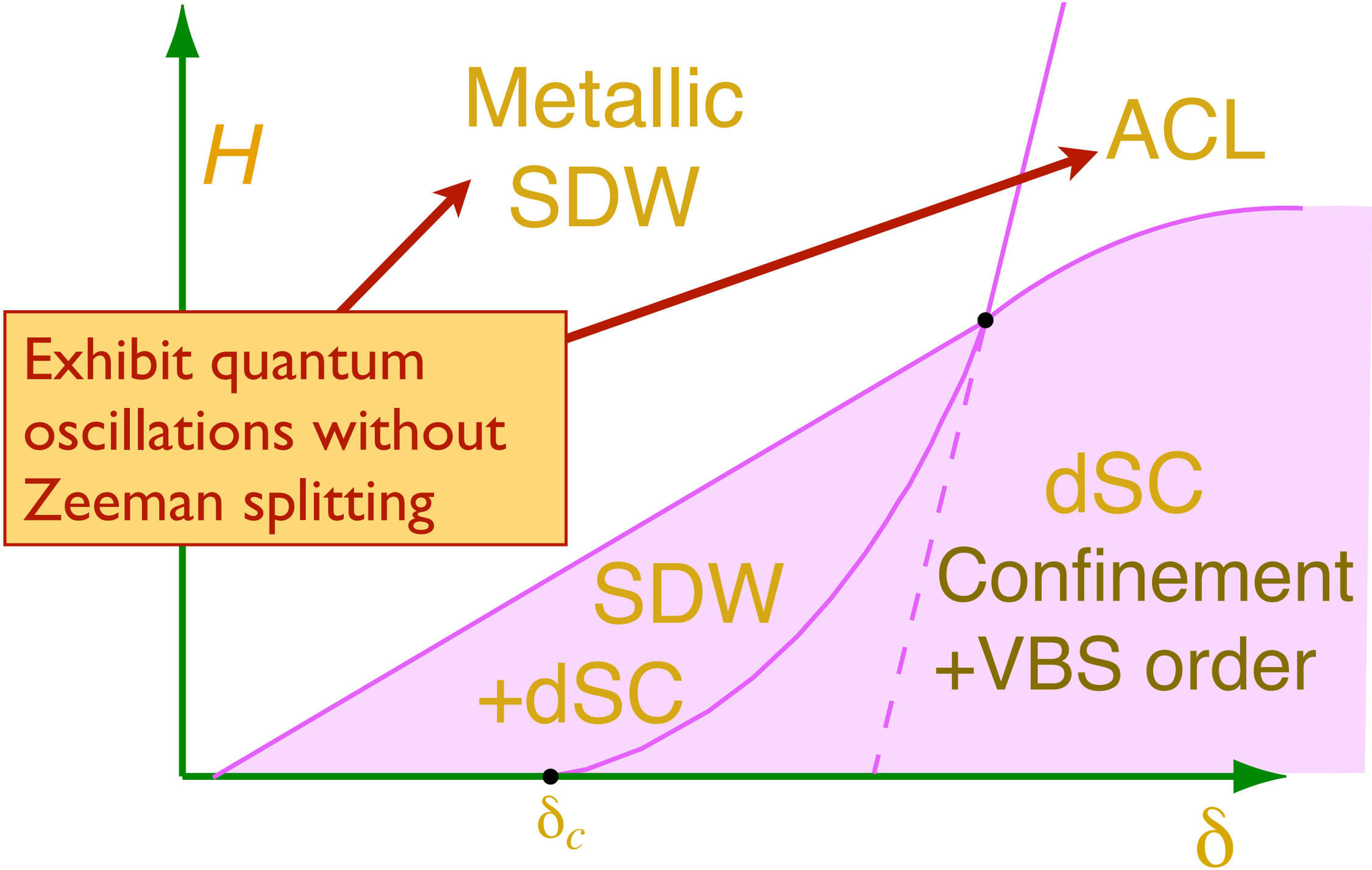

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Simple numerical estimates

- Oscillation experiments provide the following information:
  1. Effective mass: $m^* \sim (1\text{—}3) m_e$
  2. Area of the Fermi surface: $A_e \sim 3\% A_{BZ}$
  3. Fermi temperature: $T_F \sim (m_e/m^*)\, 700\,\mathrm{K}$
- The pairing critical field for the e-pocket:

$$H_{p2}(0) \sim H_{\text{onset of oscillations}} \sim 50\,\mathrm{T}$$

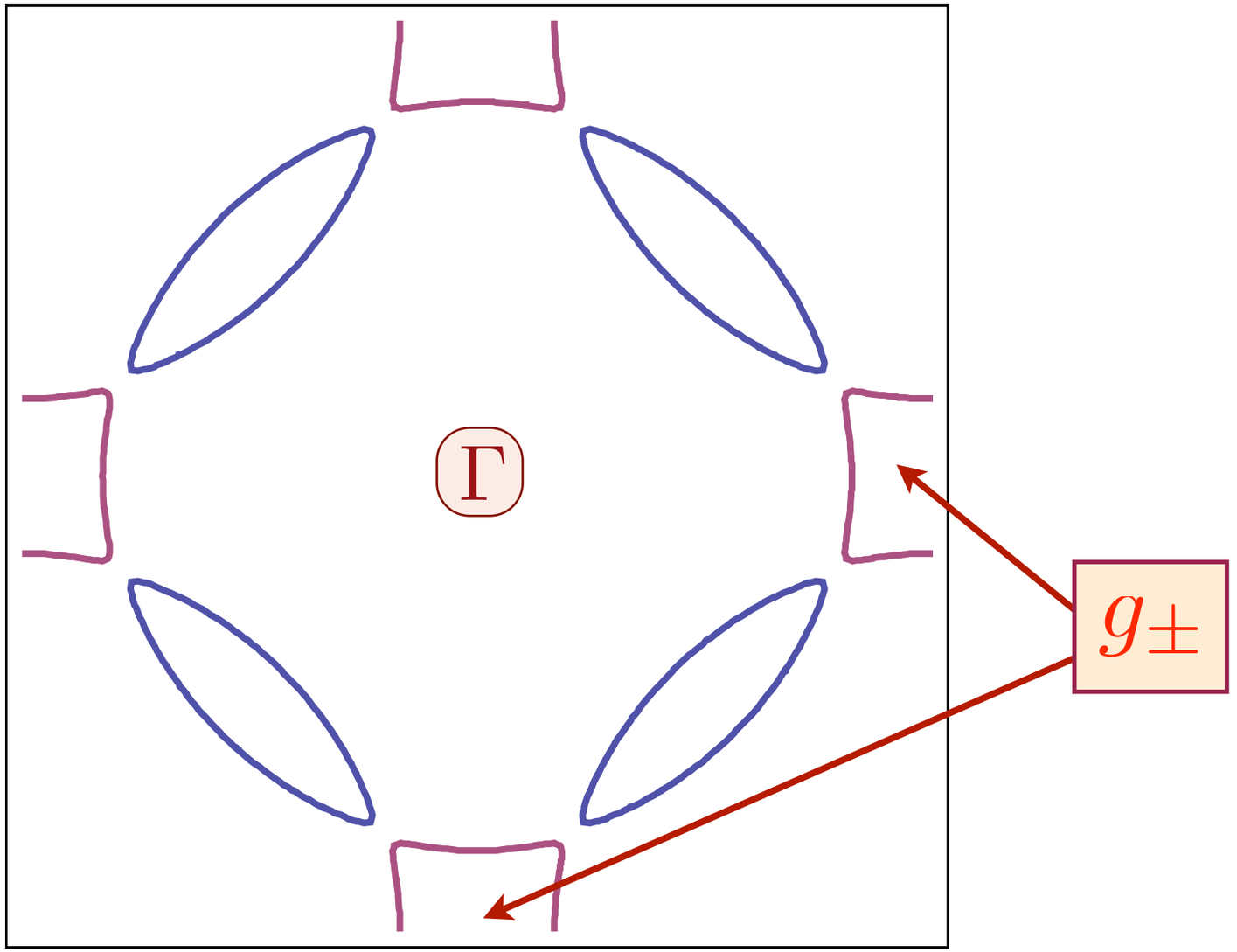
- For numerical estimates, we can use the BCS formula connecting $H_{p2}(0)$ and the pairing temperature:

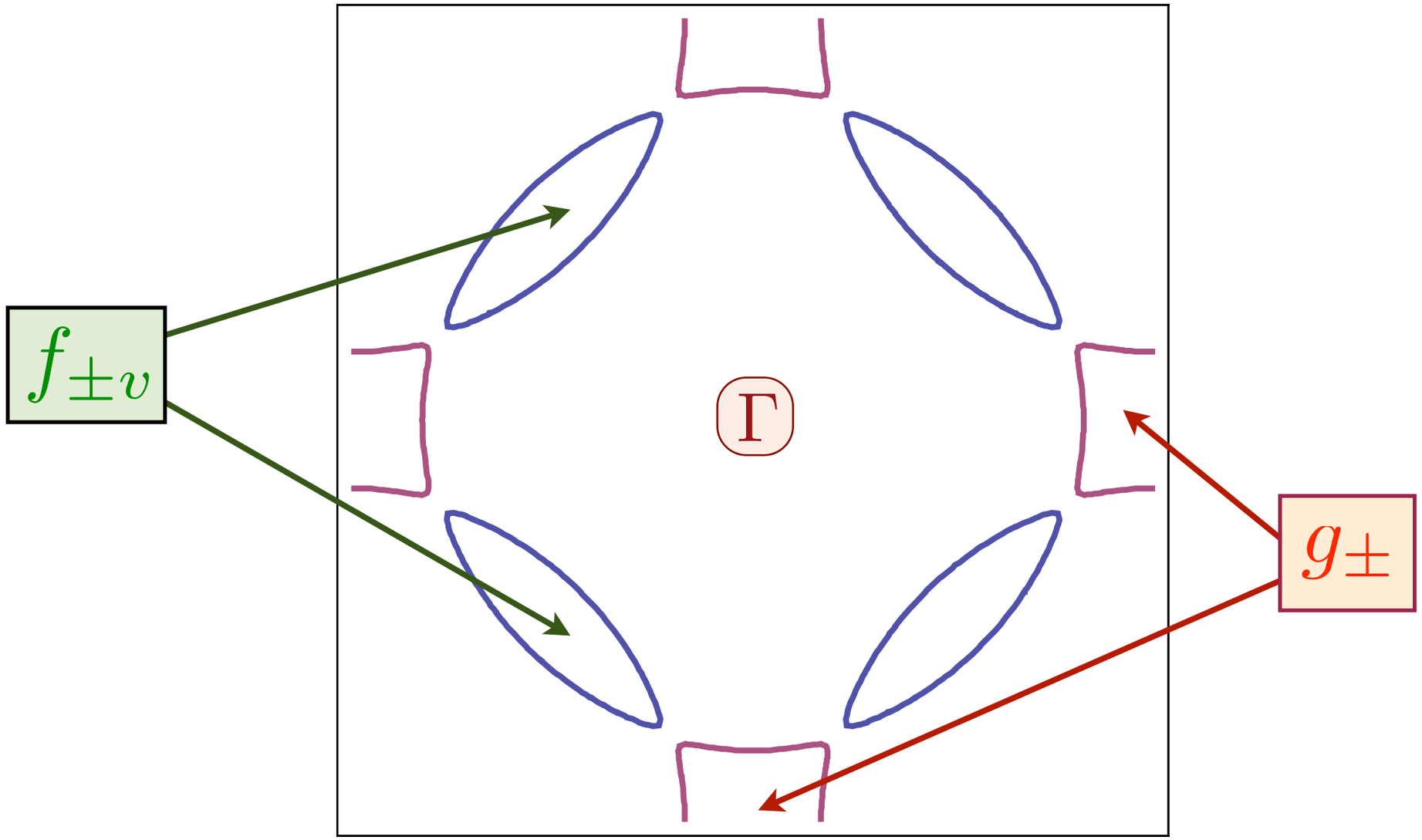
$$\frac{eH_{p2}(0)}{m^* c} = \frac{\pi^2}{\gamma_E} \frac{k_B}{\hbar} \frac{T_{p0}^2}{T_F}$$

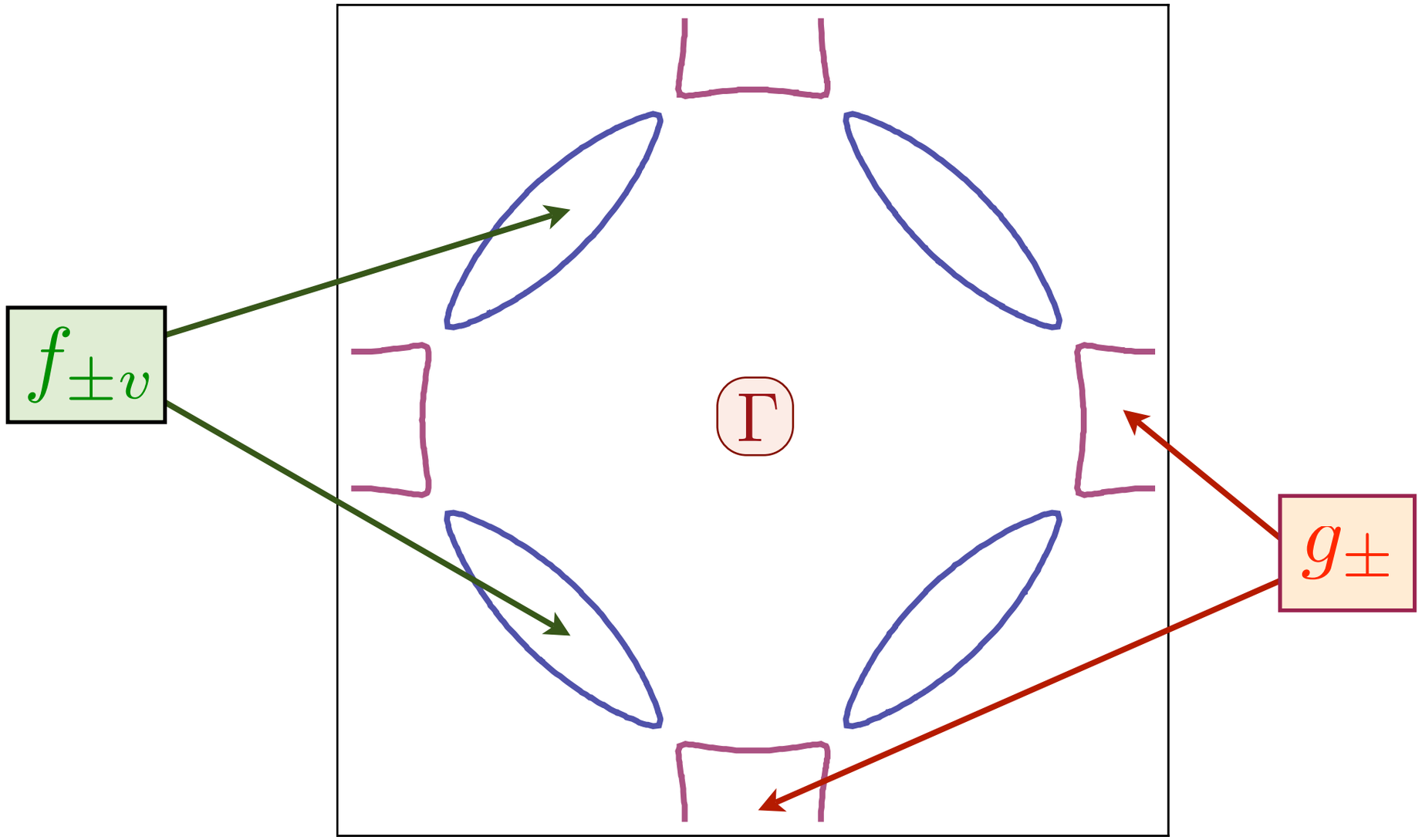
- This leads to the pairing temperature of order

$$T_{p0}\ \mathrm{K} \approx \sqrt{\frac{0.24 m_e}{m^*} [T_F\ \mathrm{K}][H_{p2}(0)\ \mathrm{T}]} \sim 100\,\mathrm{K} \text{ or } 2\Delta \sim 400\,\mathrm{K}$$

Strong e-pocket pairing removes Fermi surface signatures from *H=0* photoemission experiments


Γ
$g_\pm$


$f_{\pm v}$
Γ
$g_{\pm}$



Low energy theory for spinless, charge $+e$ fermions $f_{\pm v}$:

$$\mathcal{L}_f = \sum_{v=1,2} \Bigg\{ f^\dagger_{+v} \left[(\partial_\tau - iA_\tau) - \frac{1}{2m^*} (\nabla - i\mathbf{A})^2 - \mu \right] f_{+v} + f^\dagger_{-v} \left[(\partial_\tau + iA_\tau) - \frac{1}{2m^*} (\nabla + i\mathbf{A})^2 - \mu \right] f_{-v} \Bigg\}$$

Weak pairing of the $f_\pm$ hole pockets

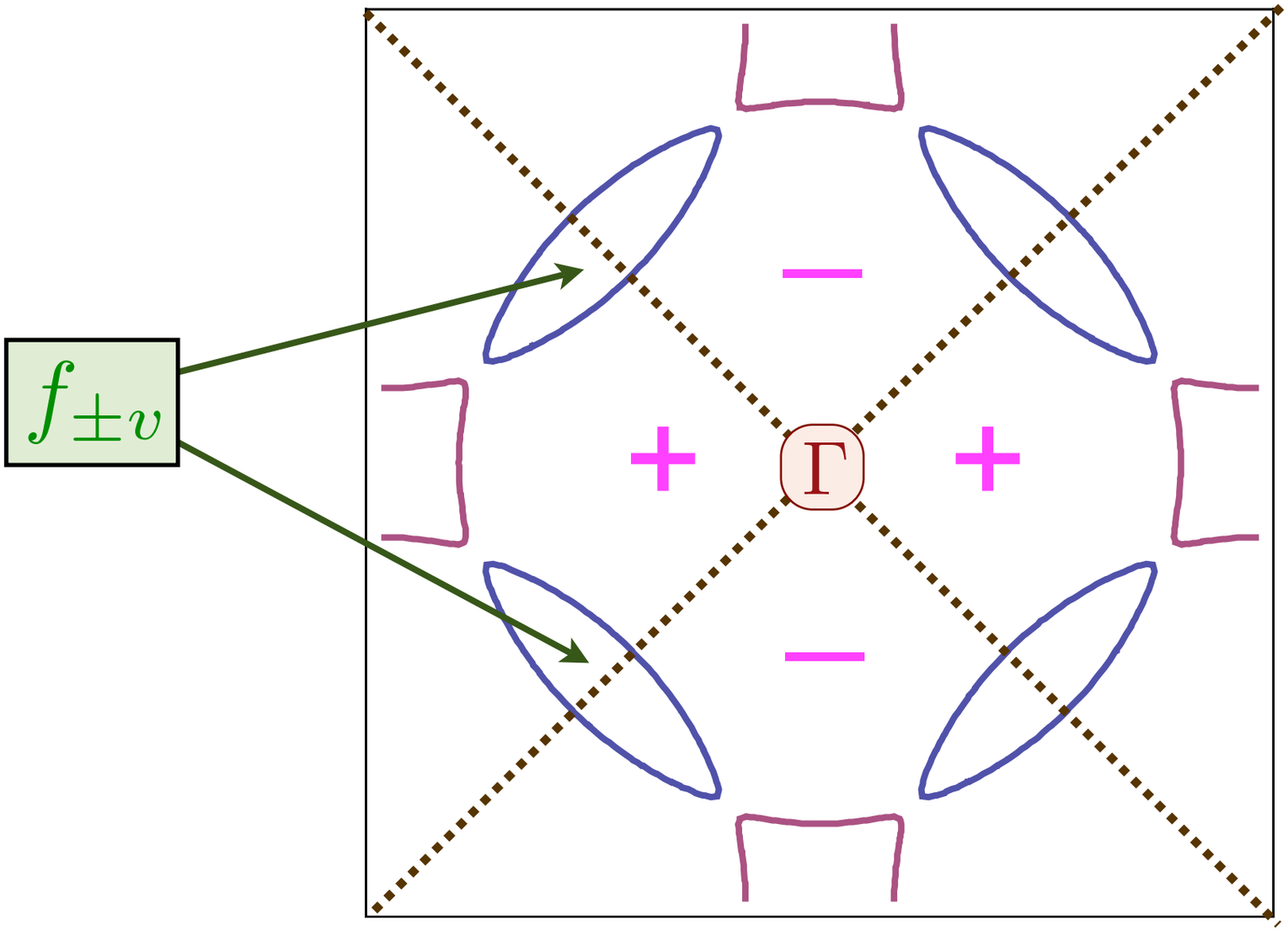
$$\mathcal{L}_{\rm Josephson} = iJ\Big[g_+ g_-\Big]\Big[f_{+1}\overleftrightarrow{\partial}_x f_{-1} - f_{+1}\overleftrightarrow{\partial}_y f_{-1} + f_{+2}\overleftrightarrow{\partial}_x f_{-2} + f_{+2}\overleftrightarrow{\partial}_y f_{-2}\Big] + \text{H.c.}$$

V. B. Geshkenbein, L. B. Ioffe, and A. I. Larkin, Phys. Rev. B **55**, 3173 (1997).

Proximity Josephson coupling J to $g_\pm$ fermions leads to p-wave pairing of the $f_{\pm v}$ fermions. The A_μ gauge forces are pair-breaking, and so the pairing is weak.

$$\begin{aligned}
\langle f_{+1}(\mathbf{k}) f_{-1}(-\mathbf{k})\rangle &\sim (k_x - k_y) J\langle g_+ g_-\rangle; \\
\langle f_{+2}(\mathbf{k}) f_{-2}(-\mathbf{k})\rangle &\sim (k_x + k_y) J\langle g_+ g_-\rangle; \\
\langle f_{+1}(\mathbf{k}) f_{-2}(-\mathbf{k})\rangle &= 0,
\end{aligned}$$

Weak pairing of the $f_\pm$ hole pockets



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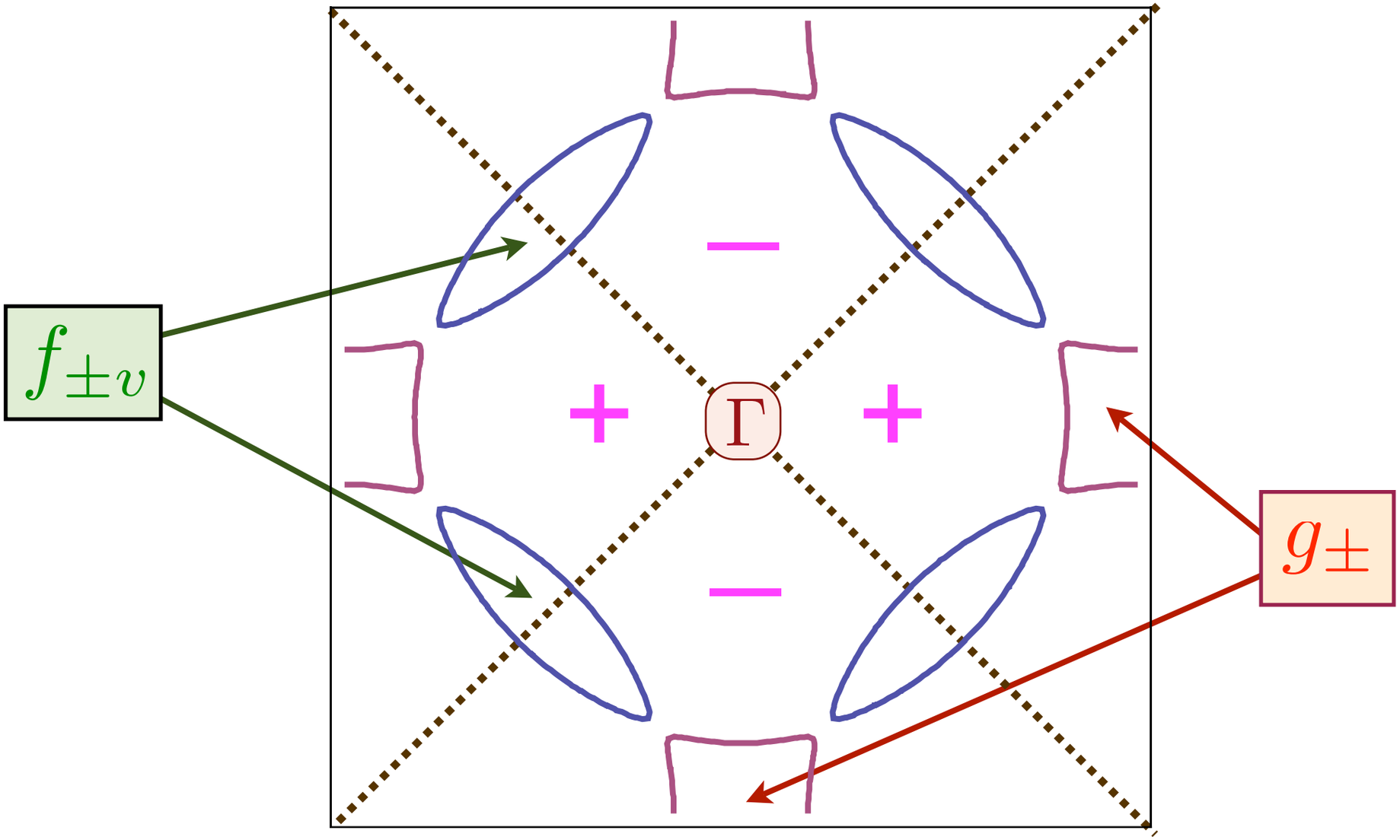

d-wave pairing of the electrons is associated with

- Strong s-wave pairing of $g_{\pm}$
- Weak p-wave pairing of $f_{\pm v}$.

Conclusions

- ★ Non-Landau-Ginzburg theory for loss of spin density wave order in a metal

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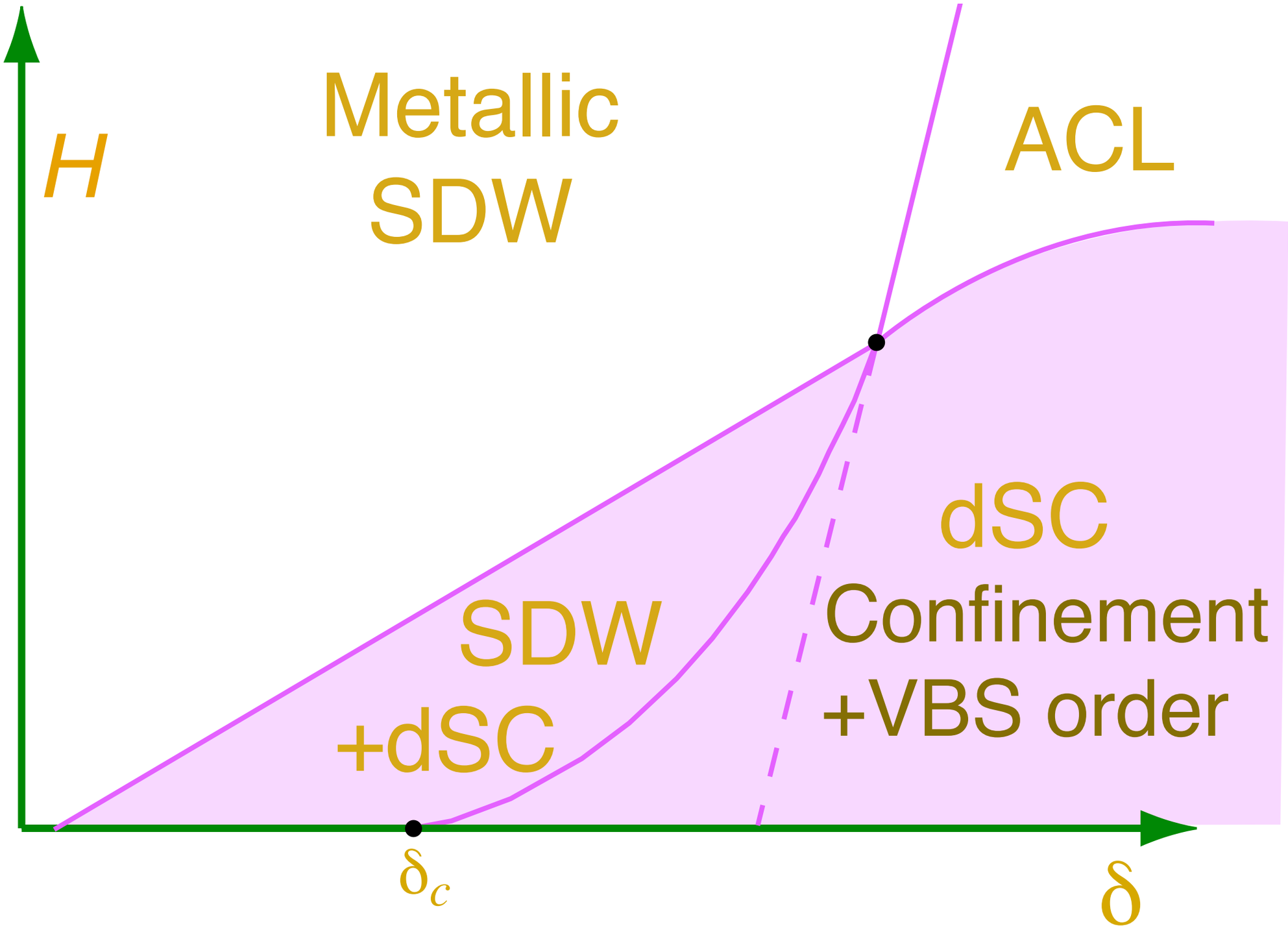
Conclusions

- ⋆ Non-Landau-Ginzburg theory for loss of spin density wave order in a metal
- ⋆ Natural route to *d*-wave pairing with strong pairing at the antinodes and weak pairing at the nodes
- ⋆ New metallic state, the ACL with "ghost" electron and hole pockets, is a useful starting point for building field-doping phase diagram

Phase diagram

as a function of hole density $\delta \sim t$ and magnetic field H.



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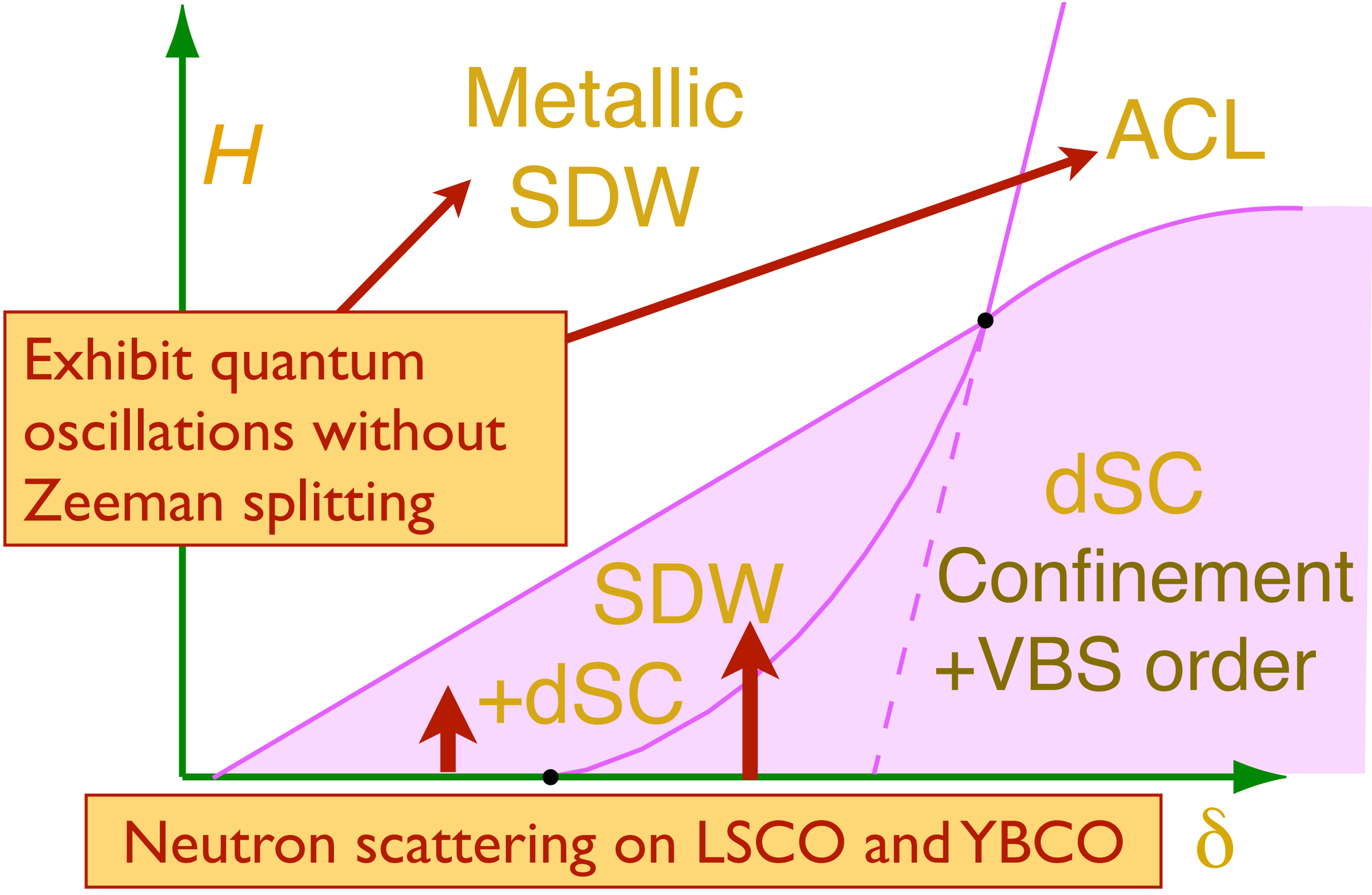
Phase diagram

as a function of hole density $\delta \sim t$ and magnetic field H.



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

Conclusions

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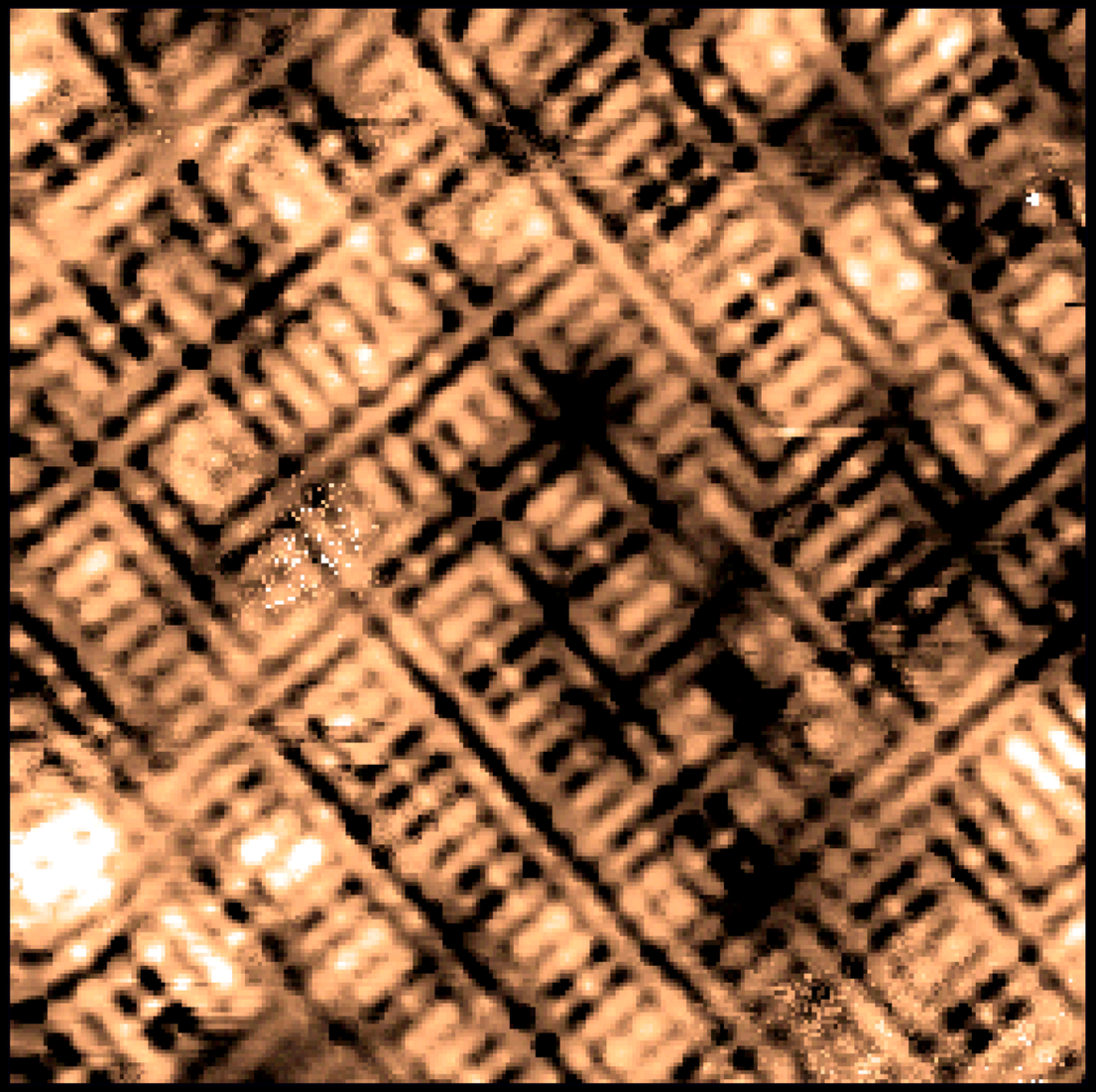
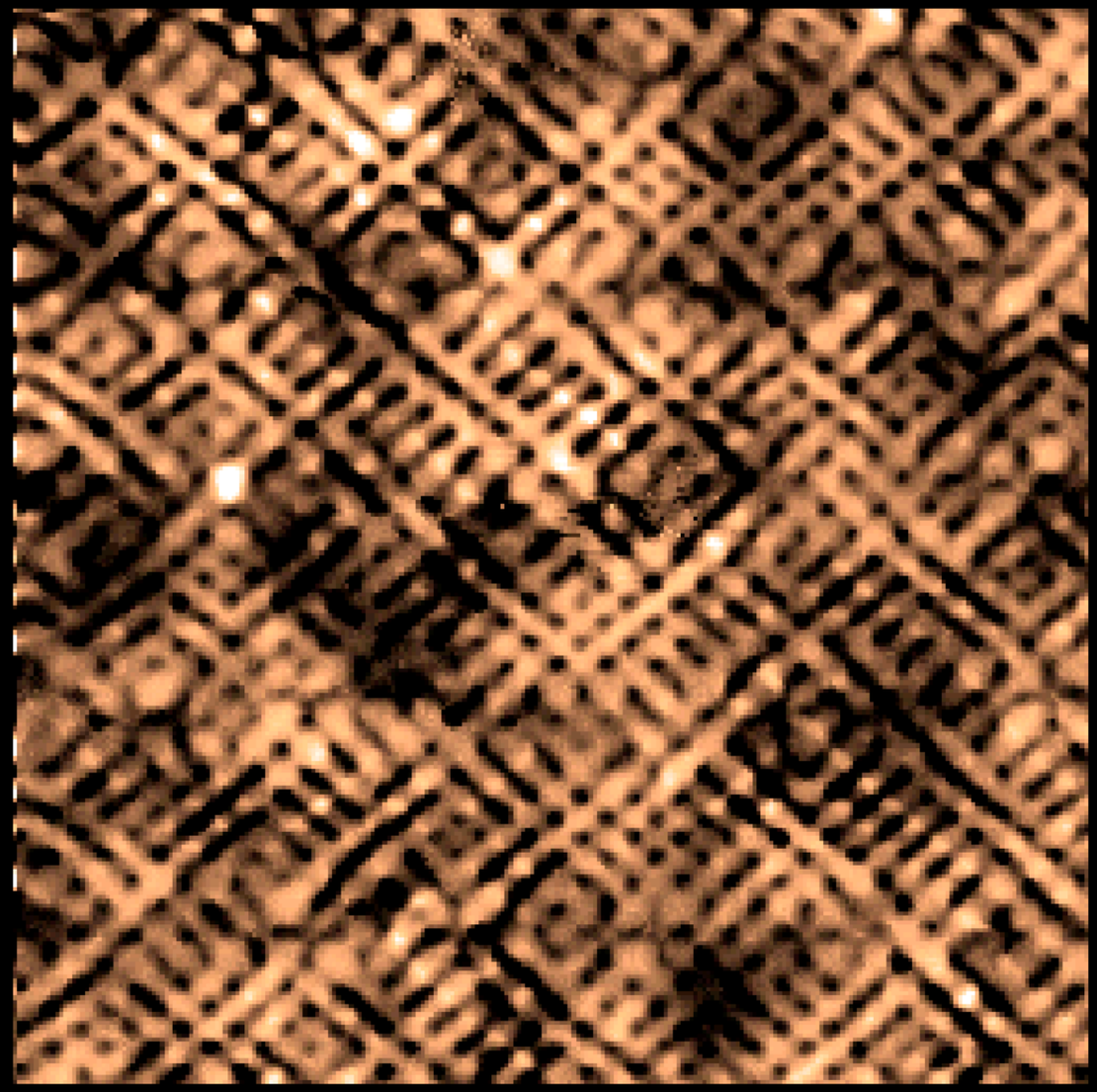
Tunneling Asymmetry (TA)-map at E=150meV

$Ca_{1.90}Na_{0.10}CuO_2Cl_2$



$Bi_{2.2}Sr_{1.8}Ca_{0.8}Dy_{0.2}Cu_2O_y$



12 nm

Indistinguishable bond-centered TA contrast

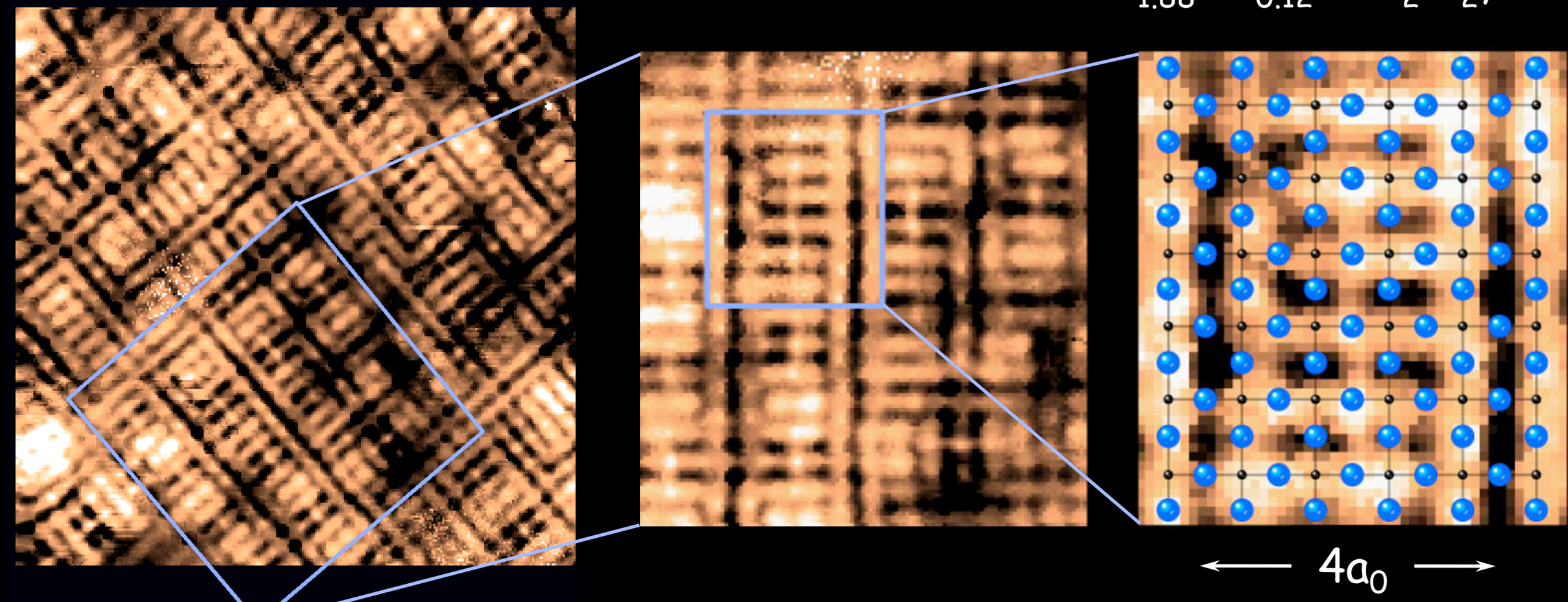
with disperse $4a_0$-wide nanodomains

Y. Kohsaka et al. Science 315, 1380 (2007)

TA Contrast is at oxygen site (Cu-O-Cu bond-centered)

R map (150 mV)

$Ca_{1.88}Na_{0.12}CuO_2Cl_2$, 4 K



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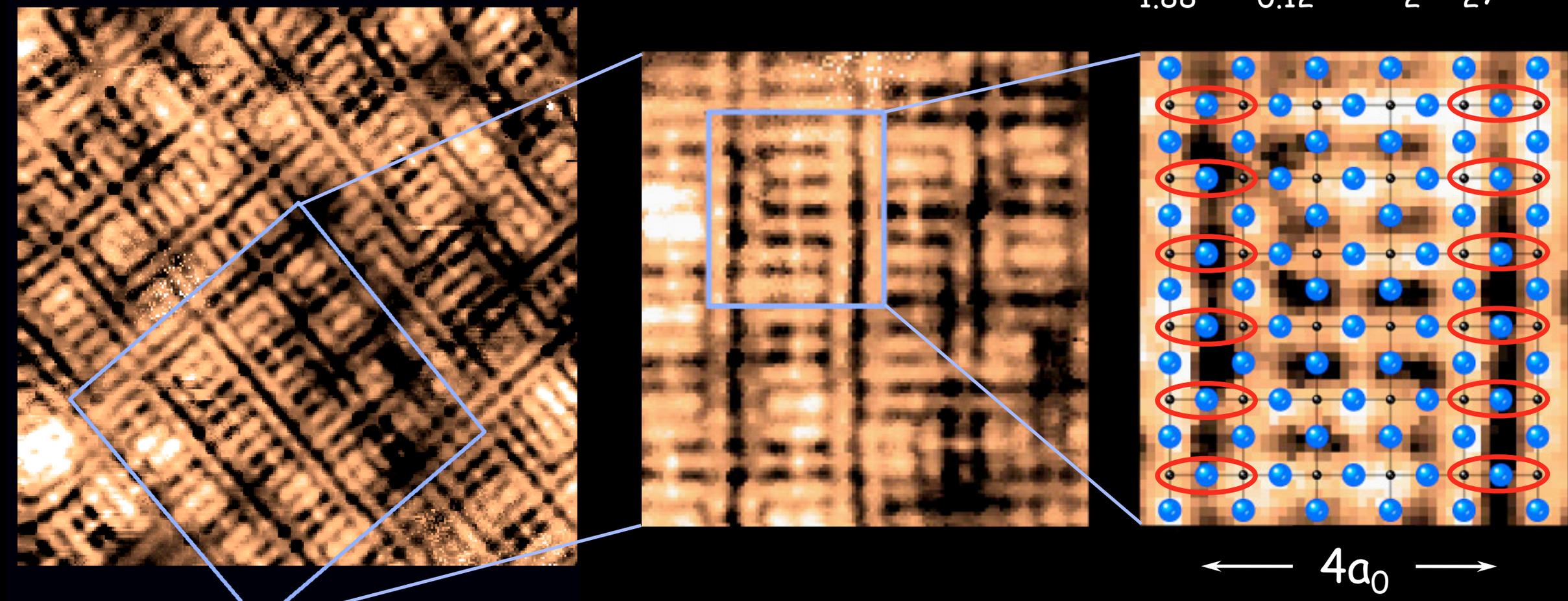

Evidence for a predicted valence bond supersolid

S. Sachdev and N. Read, *Int. J. Mod. Phys.* B **5**, 219 (1991).

M. Vojta and S. Sachdev, *Phys. Rev. Lett.* **83**, 3916 (1999).

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- ⋆ Needed: theory for transition to "large" Fermi surface at higher doping