Unveiling the order of the high temperature superconductors

University of Virginia
April 11, 2014

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Talk online: sachdev.physics.harvard.edu

PHYSICS
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Theorists at Harvard

Max Metlitski

Rolando
La Placa

Andrea Allais

Johannes
Bauer

Debanjan
Chowdhury

Jay Deep
Sau

Experimentalists at Harvard


Yang He


Yi Yin


Martin Zech


Anjan Soumyanarayanan


Ilija Zelkovic


Michael Yee


Jennifer Hoffman

Experimentalists at Cornell

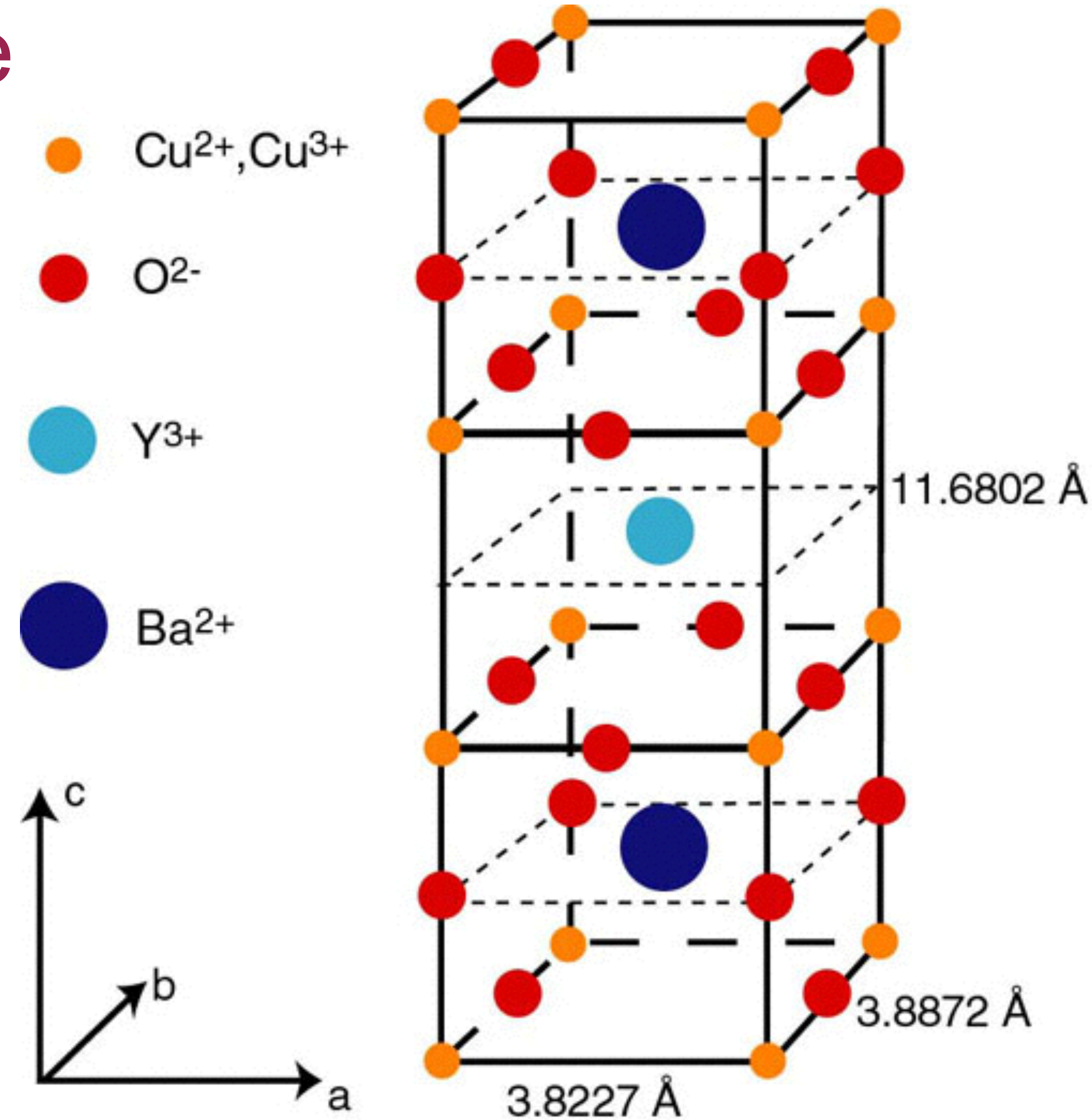
Kazuhiro Fujita
Cornell/ BNL

Mohammad Hamidian
Cornell / BNL

Stephen Edkins
Cornell / St Andrews

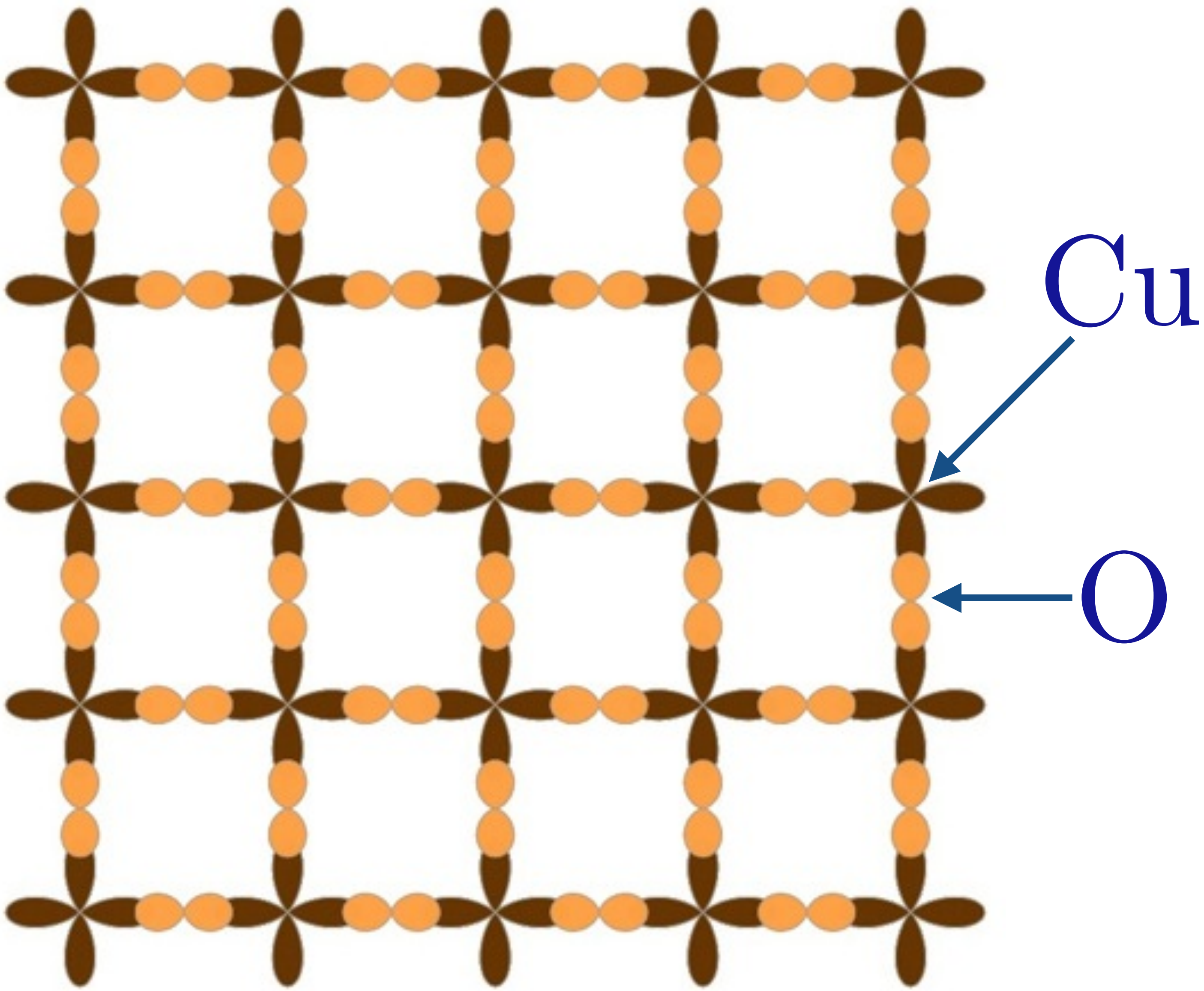
J. C. Seamus Davis

High temperature superconductors

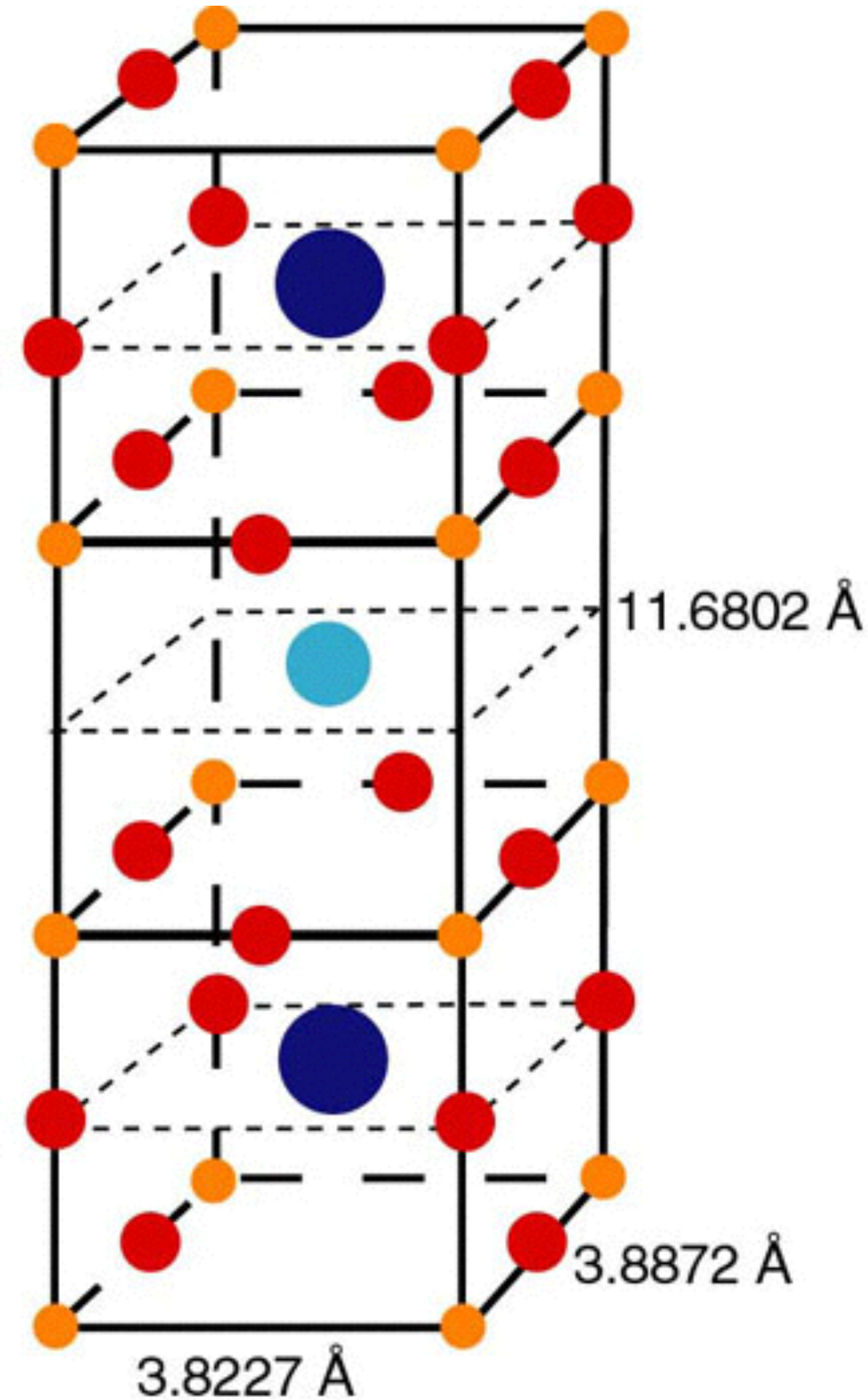


$$YBa_2Cu_3O_{6+x}$$

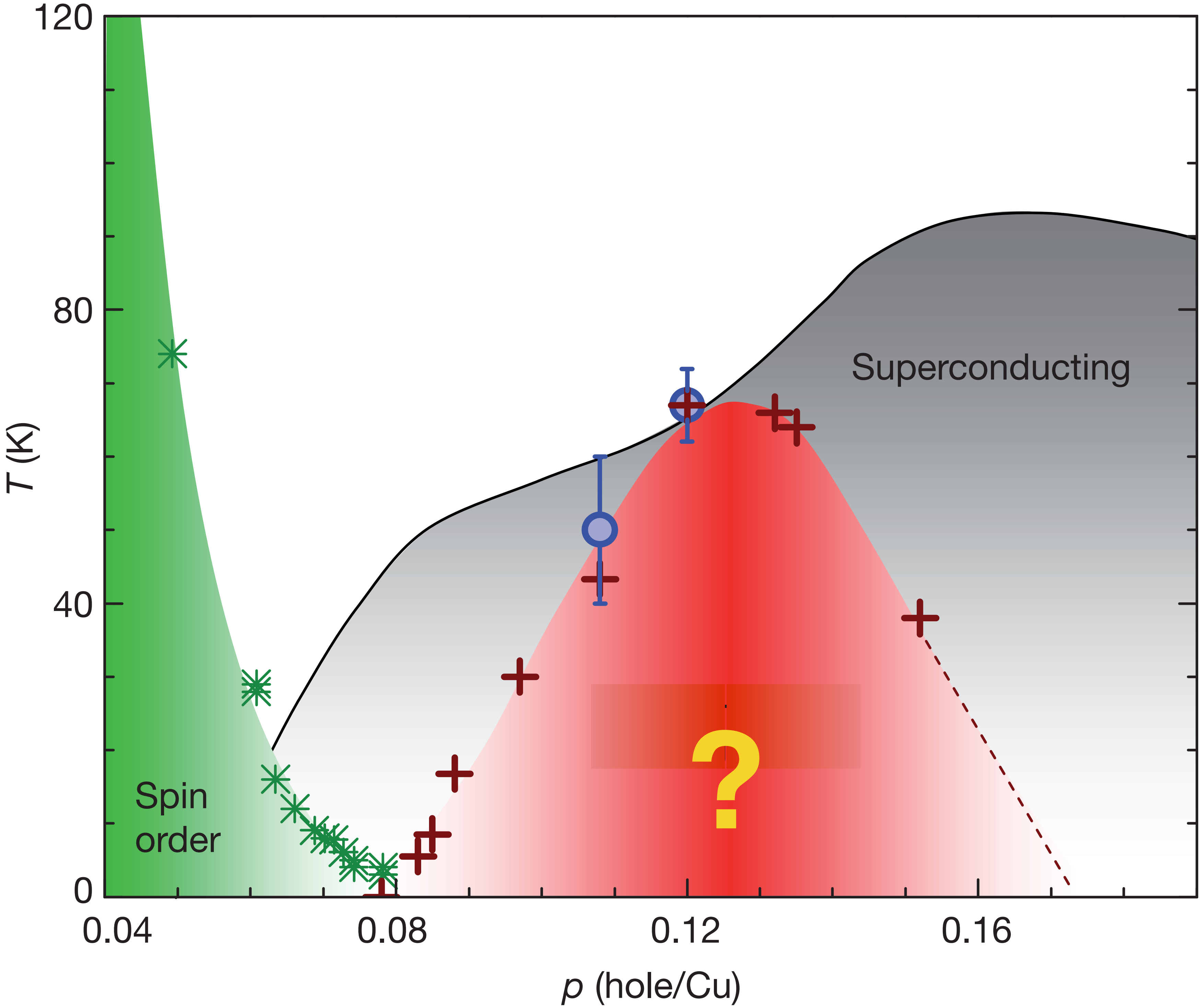
High temperature superconductors

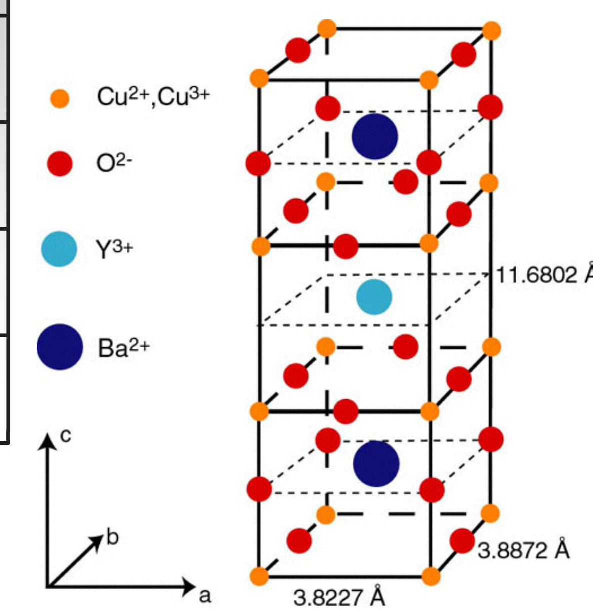


CuO_2 plane

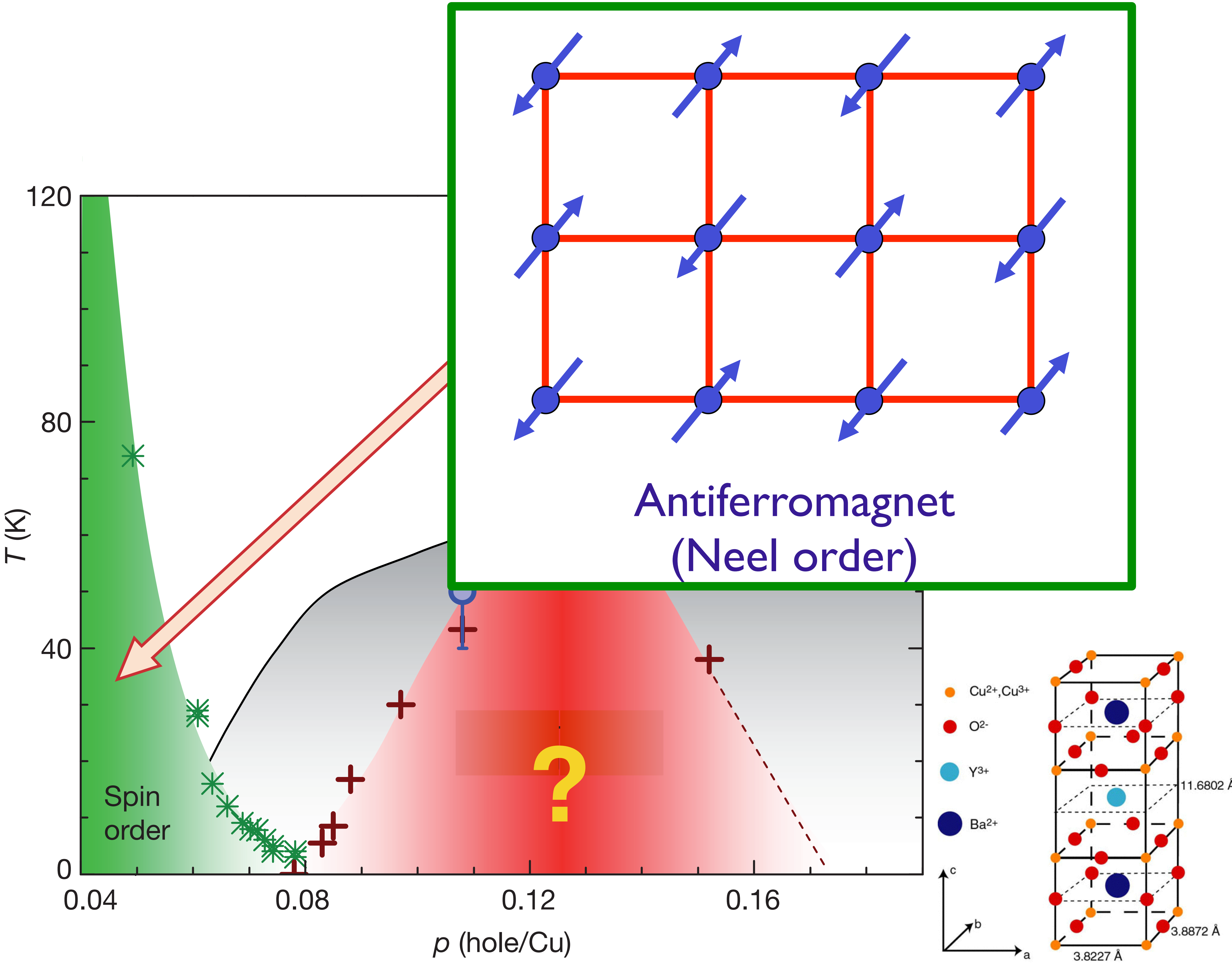


$YBa_2Cu_3O_{6+x}$





T. Wu, H. Mayaffre, S. Kramer, M. Horvatic, C. Berthier, W.N. Hardy, R. Liang, D.A. Bonn, and M.-H. Julien, Nature **477**, 191 (2011).



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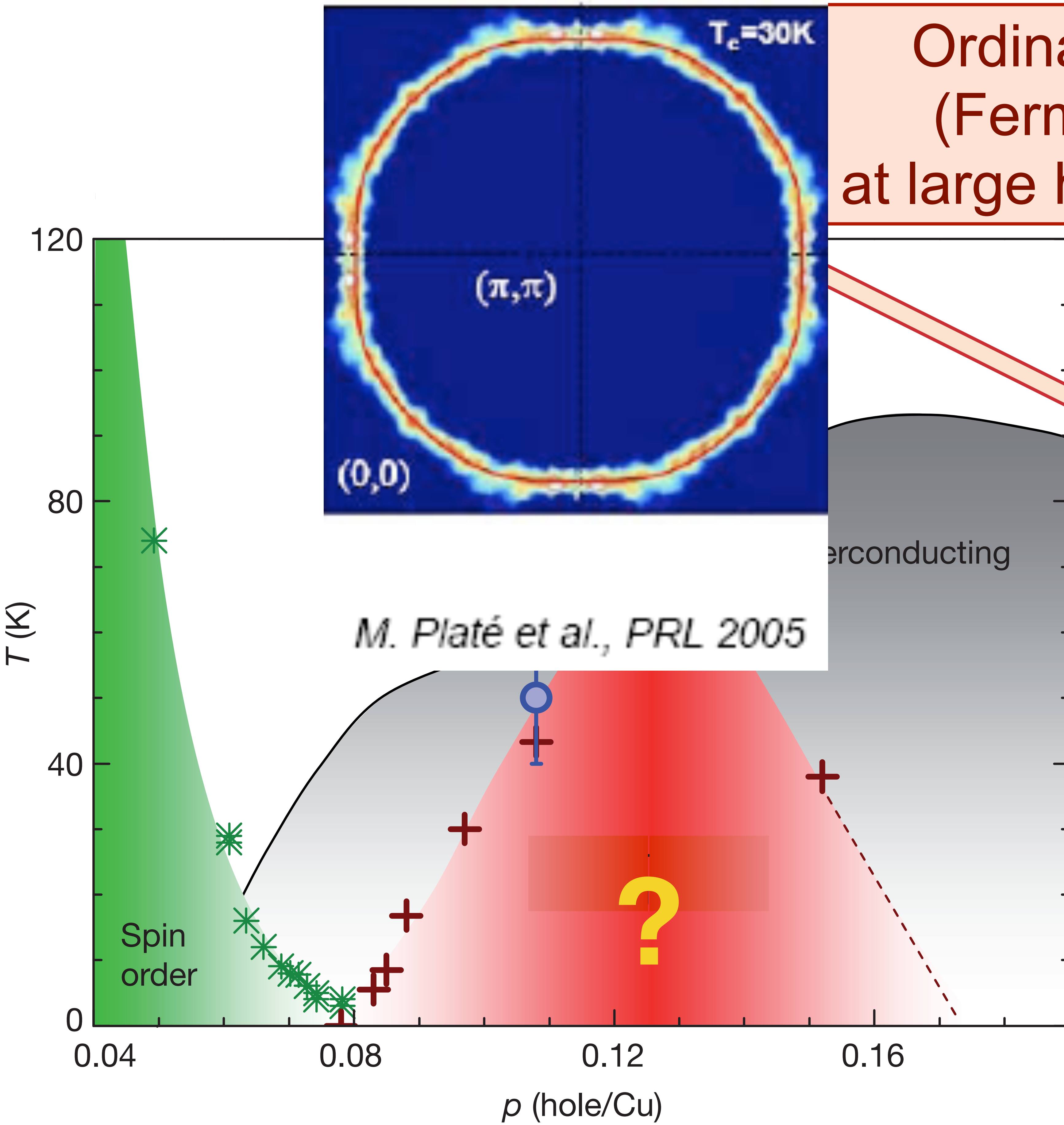
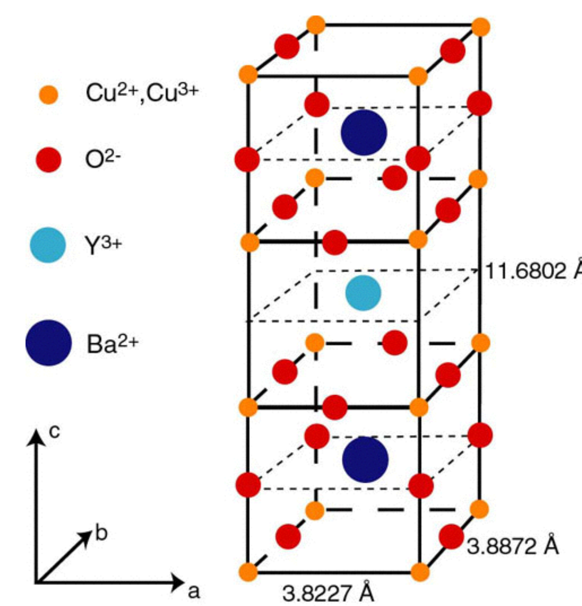
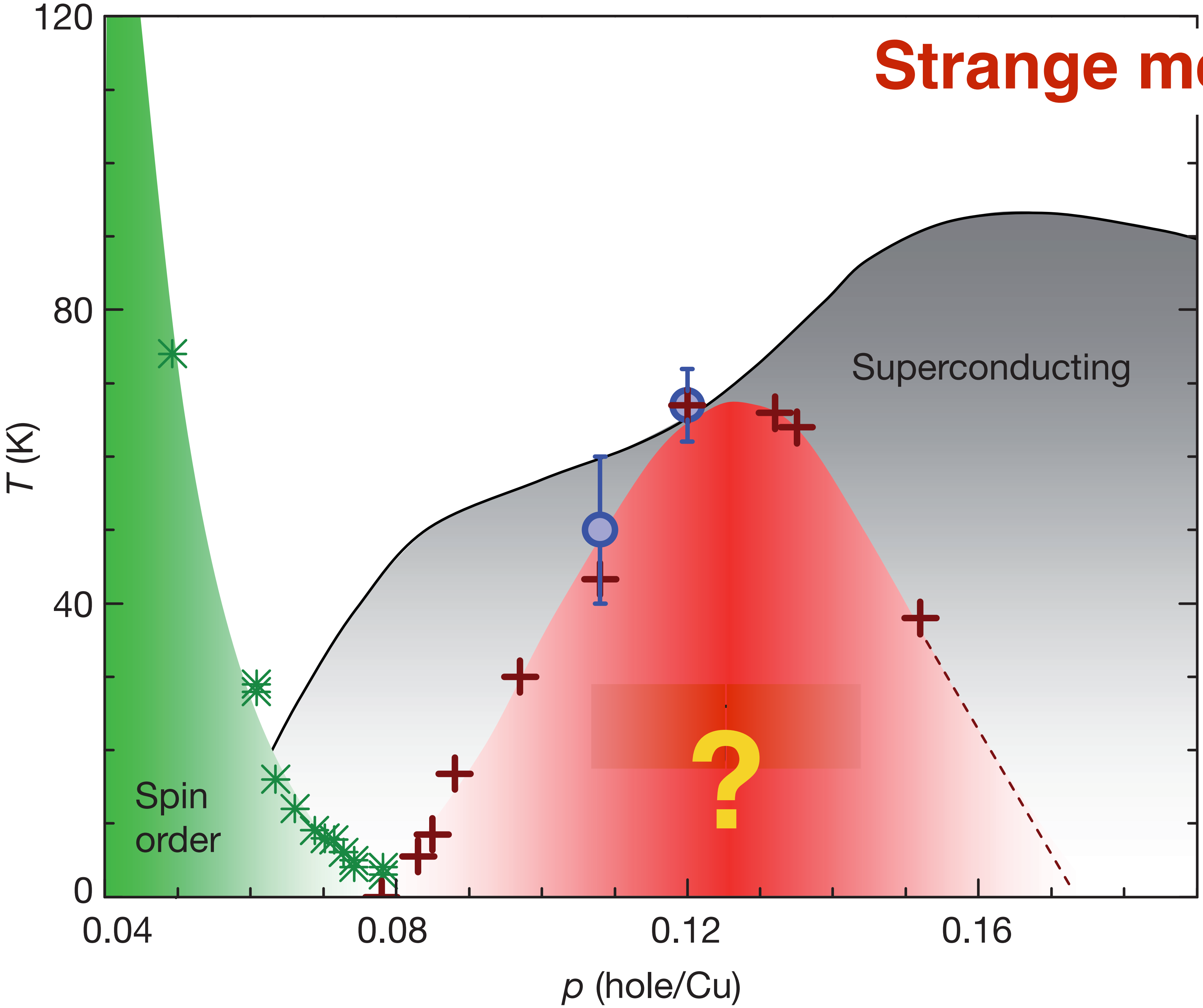
Ordinary metal
(Fermi liquid)
at large hole density

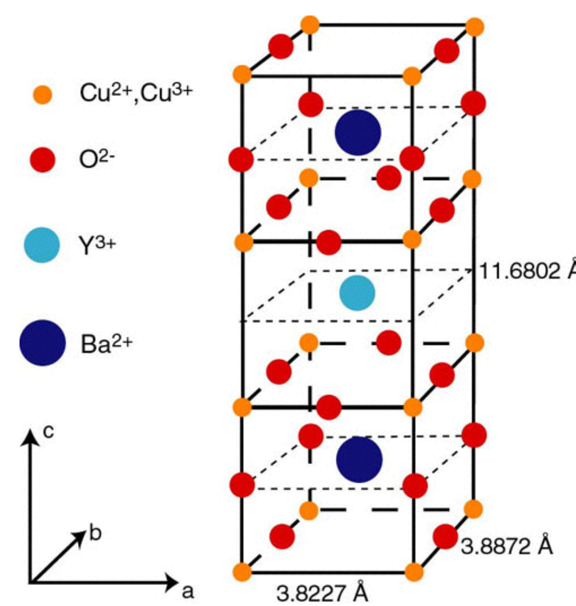




T. Wu, H. Mayaffre, S. Kramer, M. Horvatic, C. Berthier, W.N. Hardy, R. Liang, D.A. Bonn, and M.-H. Julien, Nature **477**, 191 (2011).

Strange metal





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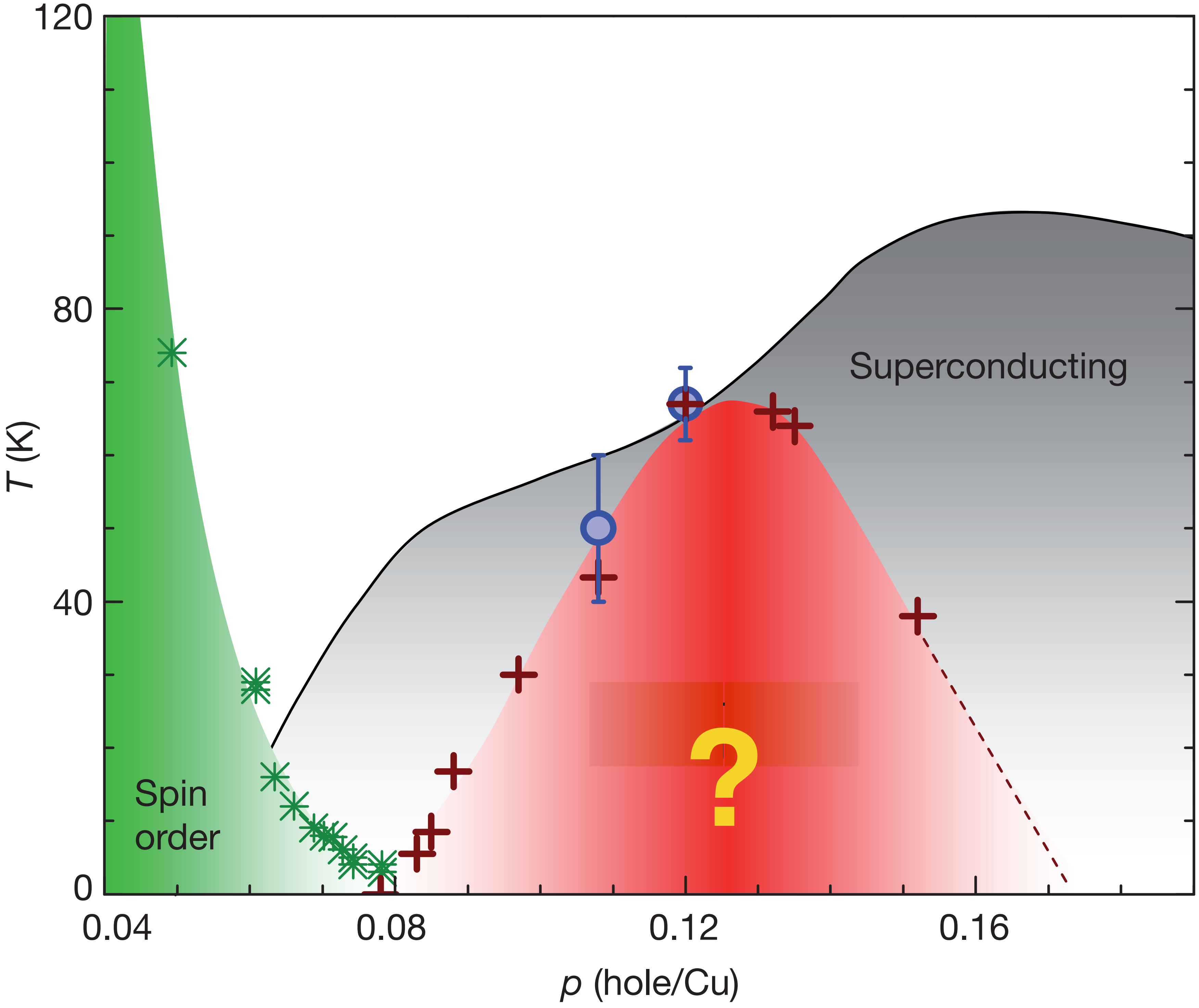
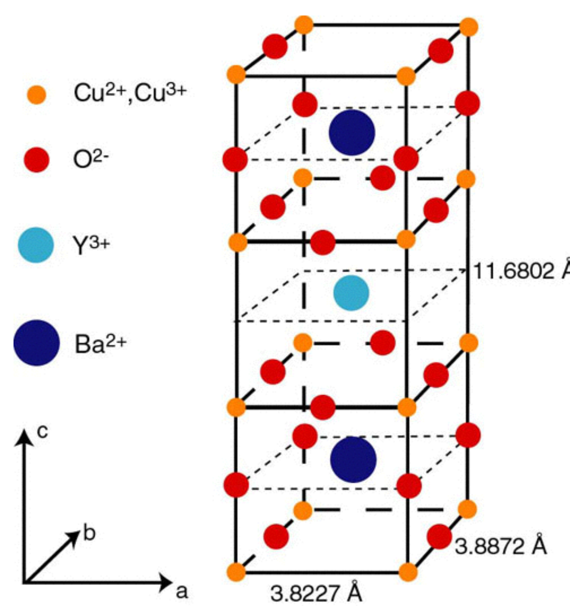
In the La-based superconductors, the region with magnetic order overlaps with the red region - I will not discuss these materials: see S. A. Kivelson, I.P. Bindloss, E. Fradkin, V. Oganesyan, J. M. Tranquada, A. Kapitulnik, and C. Howald, *Rev. Mod. Phys.* **75**, 1201(2003)





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Outline

1. *d*-wave superconductivity

2. Low hole density state:
   d-wave bond order

3. Theoretical background

4. Evolution of Fermi surface

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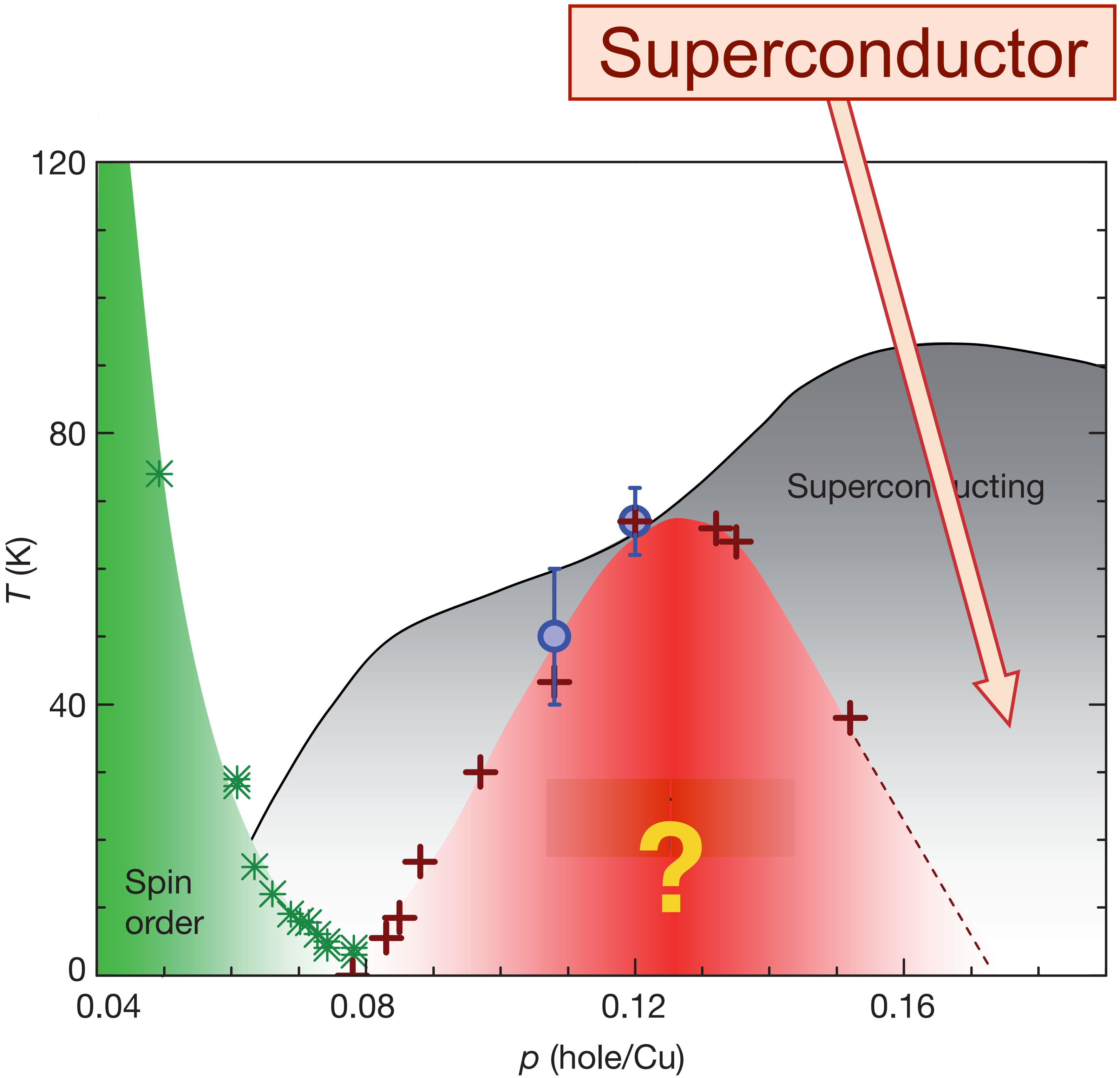

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Superconductivity:
Bose condensation of Cooper pairs of electrons

$$\varepsilon^{\alpha\beta} \left\langle c_\alpha^\dagger(\mathbf{r}_1) c_\beta^\dagger(\mathbf{r}_2) \right\rangle = \left[P(\mathbf{r}_1 - \mathbf{r}_2) \right] \times \Psi_{SC} \left(\frac{\mathbf{r}_1 + \mathbf{r}_2}{2} \right)$$

$$\alpha, \beta = \uparrow, \downarrow \quad ; \quad \varepsilon^{\uparrow\downarrow} = -\varepsilon^{\downarrow\uparrow} = 1 \, ; \, \varepsilon^{\uparrow\uparrow} = \varepsilon^{\downarrow\downarrow} = 0$$

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Nearly constant condensate wavefunction
(superconducting order parameter)

$$\alpha,\beta = \uparrow,\downarrow \quad ; \quad \varepsilon^{\uparrow\downarrow} = -\varepsilon^{\downarrow\uparrow} = 1\,;\, \varepsilon^{\uparrow\uparrow} = \varepsilon^{\downarrow\downarrow} = 0$$

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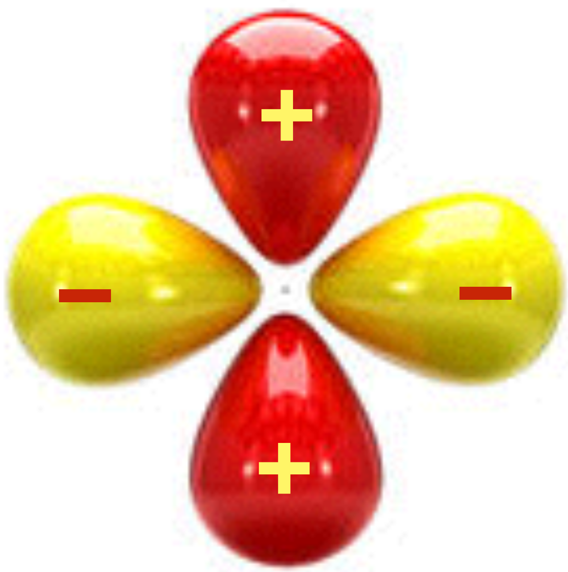
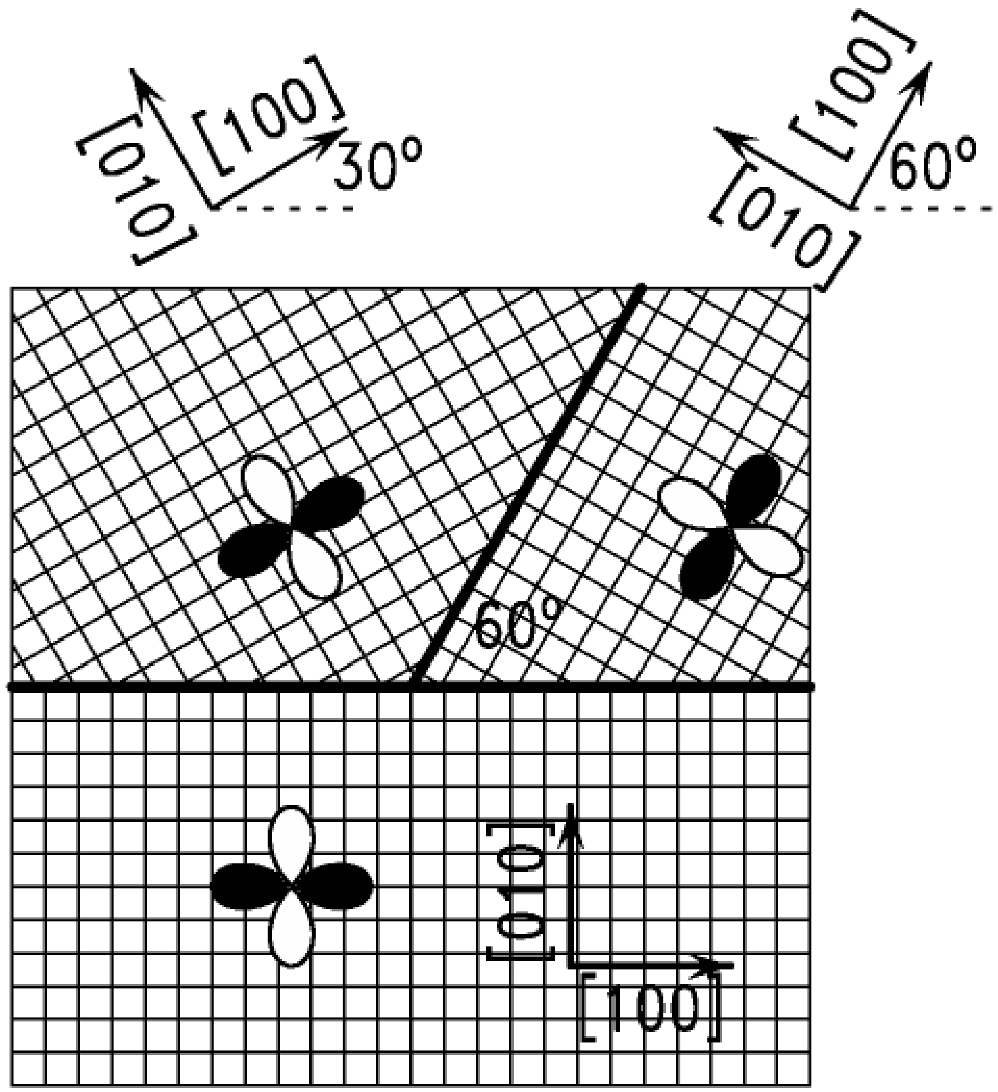


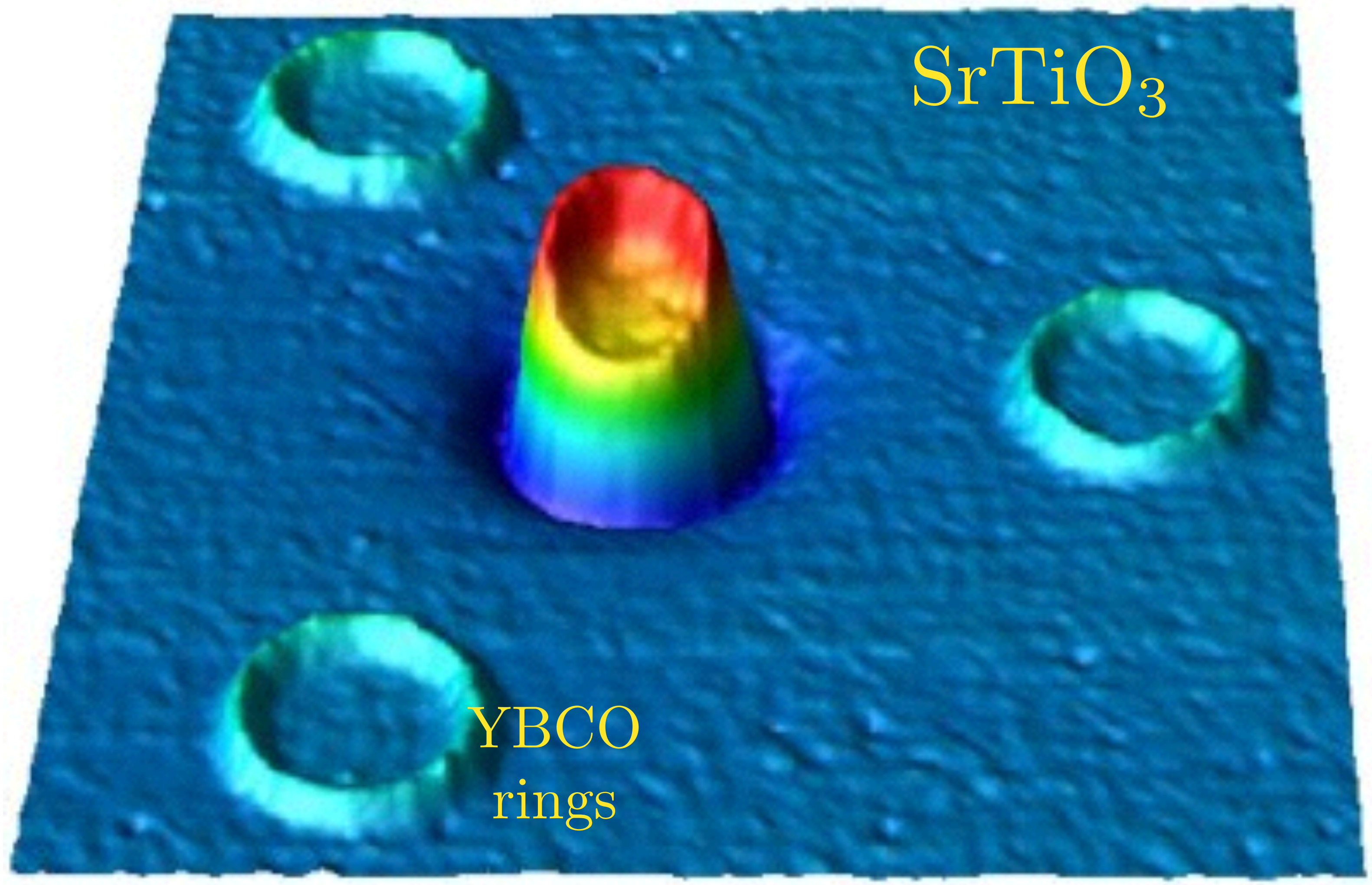
Internal Cooper-pair wavefunction.
Has *d*-wave form in cuprates

$$\alpha, \beta = \uparrow, \downarrow \quad ; \quad \varepsilon^{\uparrow\downarrow} = -\varepsilon^{\downarrow\uparrow} = 1 \, ; \, \varepsilon^{\uparrow\uparrow} = \varepsilon^{\downarrow\downarrow} = 0$$

Phase-sensitive measurement of the *d*-wave symmetry of Cooper pairs



$SrTiO_3$



$\leftarrow 50\mu m \rightarrow$

Pairing Symmetry and Flux Quantization in a Tricrystal Superconducting Ring of $YBa_2Cu_3O_{7-\delta}$

C. C. Tsuei, J. R. Kirtley, C. C. Chi,* Lock See Yu-Jahnes, A. Gupta, T. Shaw, J. Z. Sun, and M. B. Ketchen
IBM Thomas J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598

Phys. Rev. Lett. **73**, 593 (1994)

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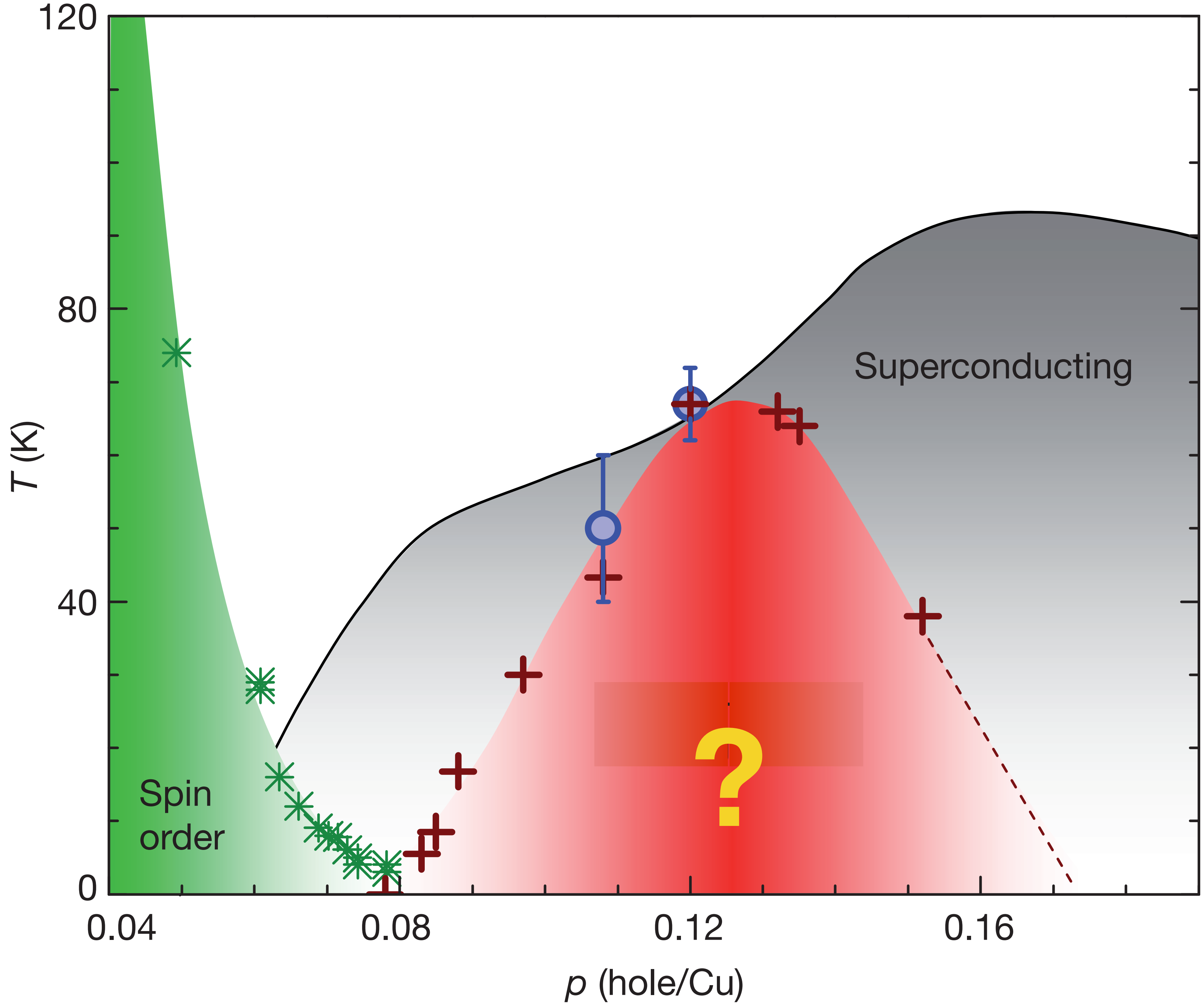

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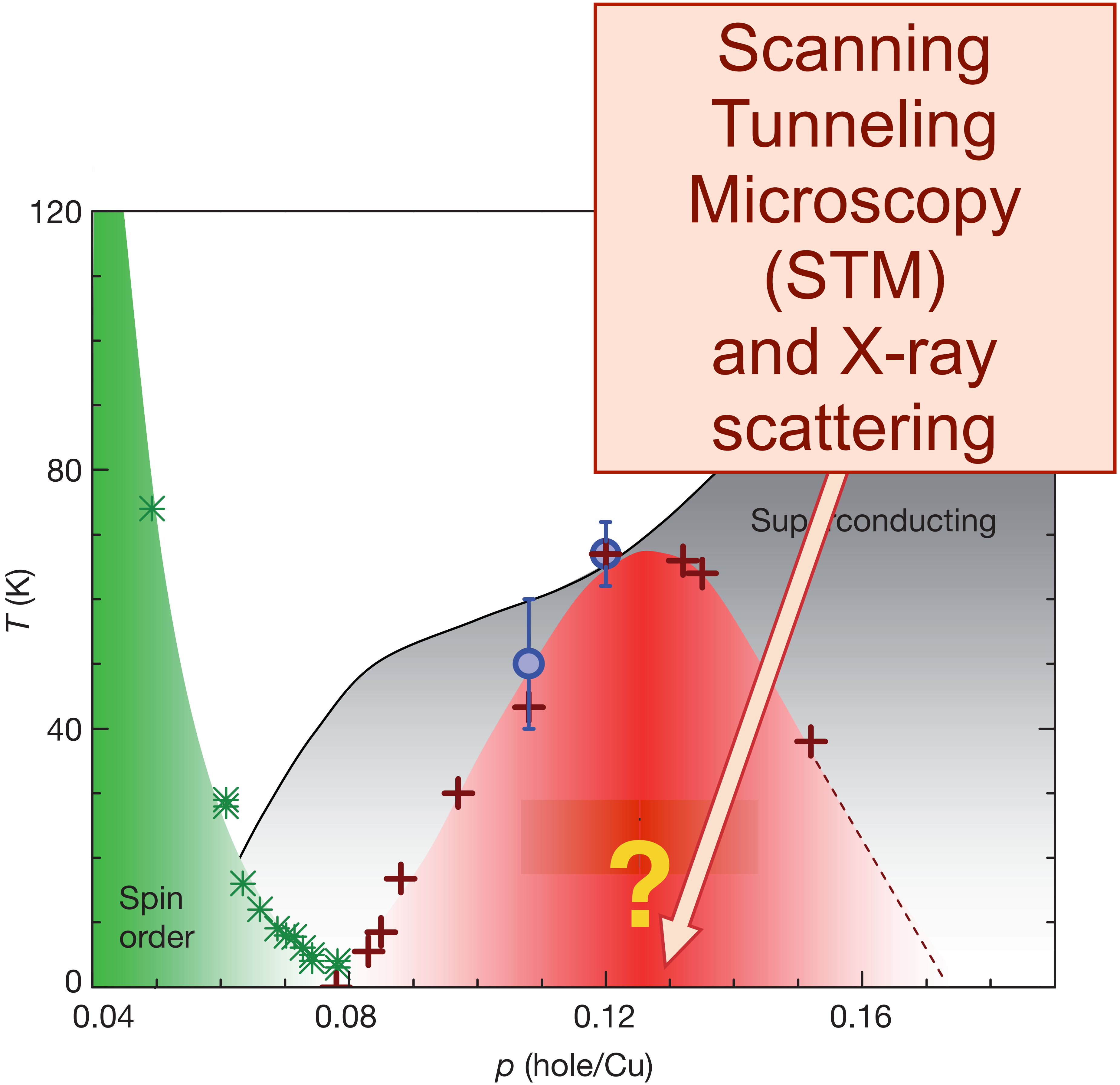

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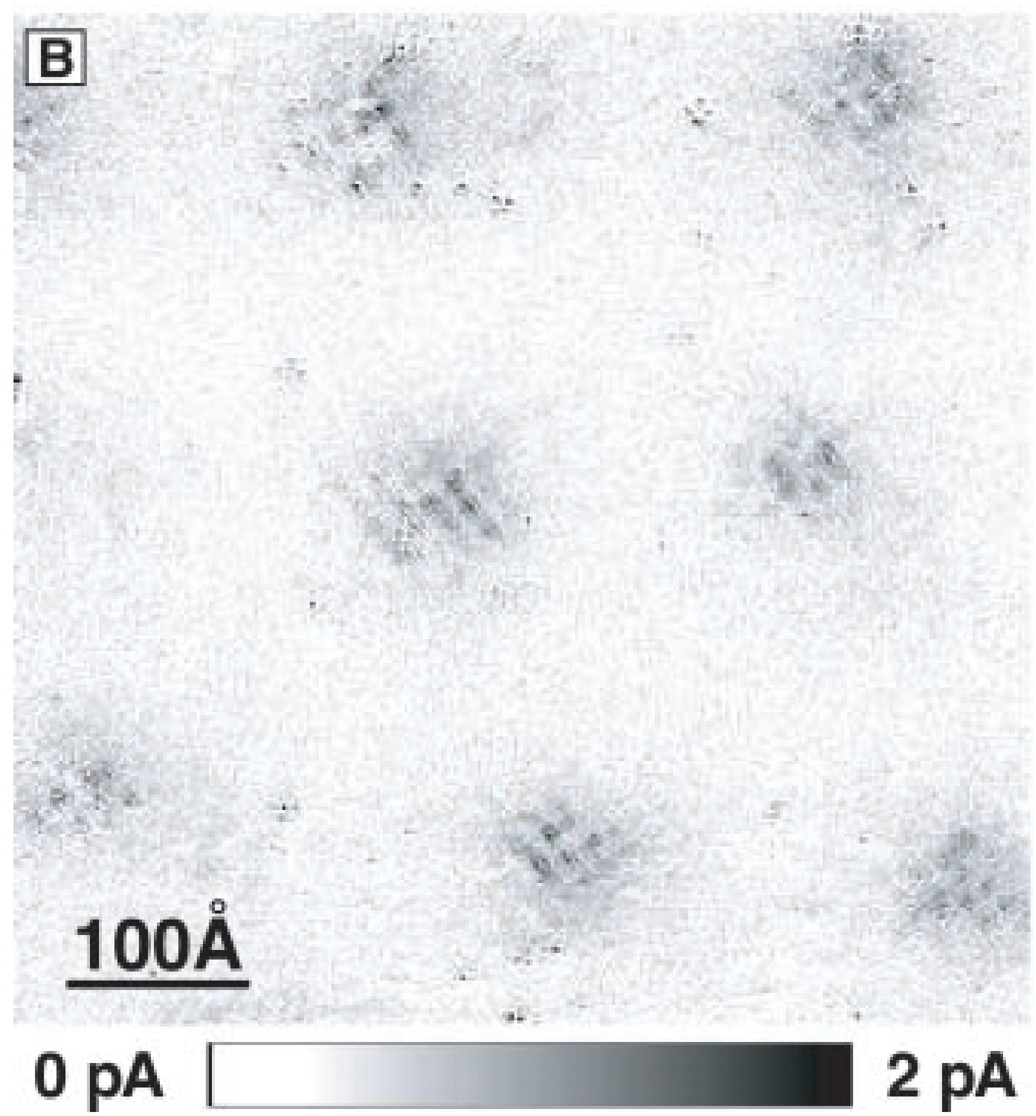
A Four Unit Cell Periodic Pattern of Quasi-Particle States Surrounding Vortex Cores in $Bi_2Sr_2CaCu_2O_{8+\delta}$

J. E. Hoffman, E. W. Hudson, K. M. Lang, V. Madhavan, H. Eisaki, S. Uchida, and J. C. Davis, Science **295**, 466 (2002).



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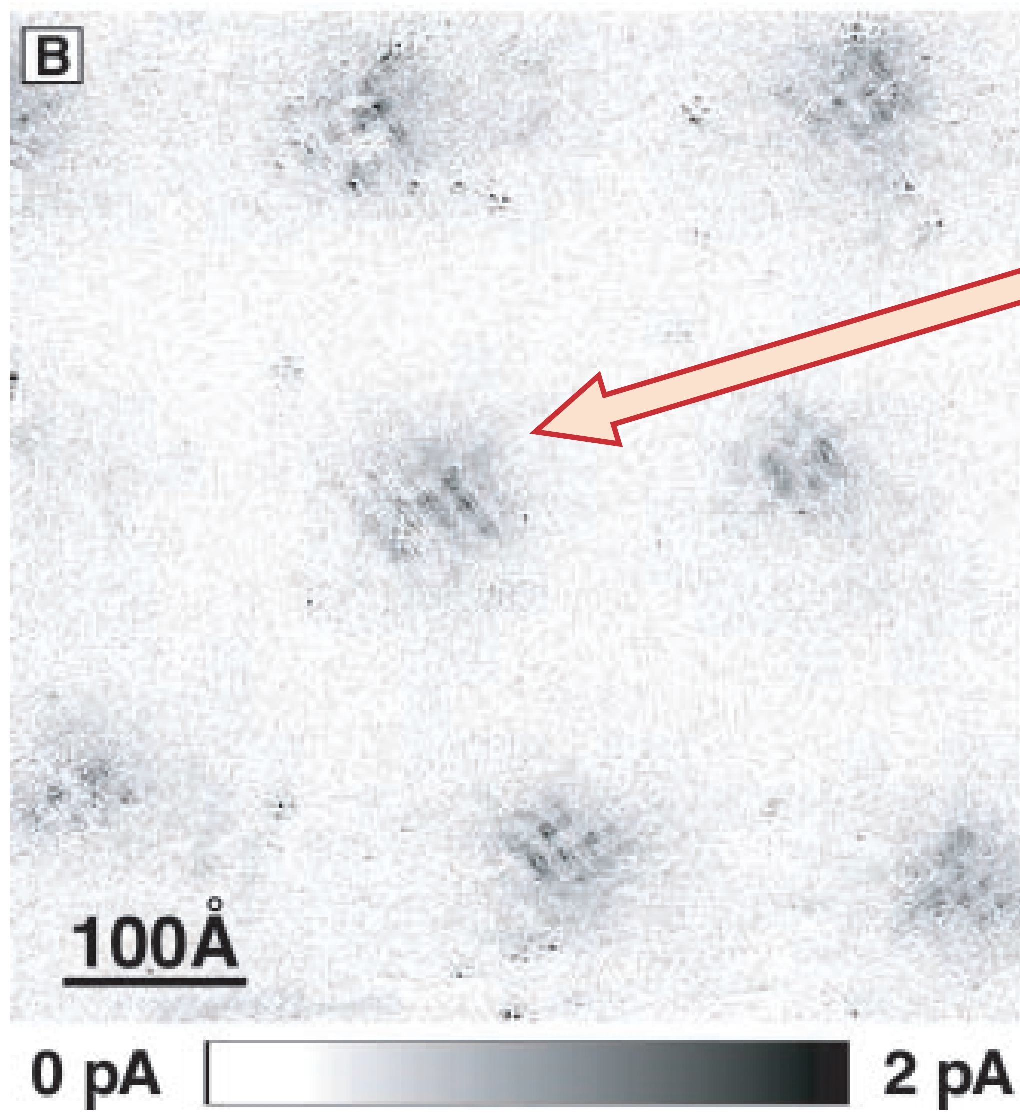
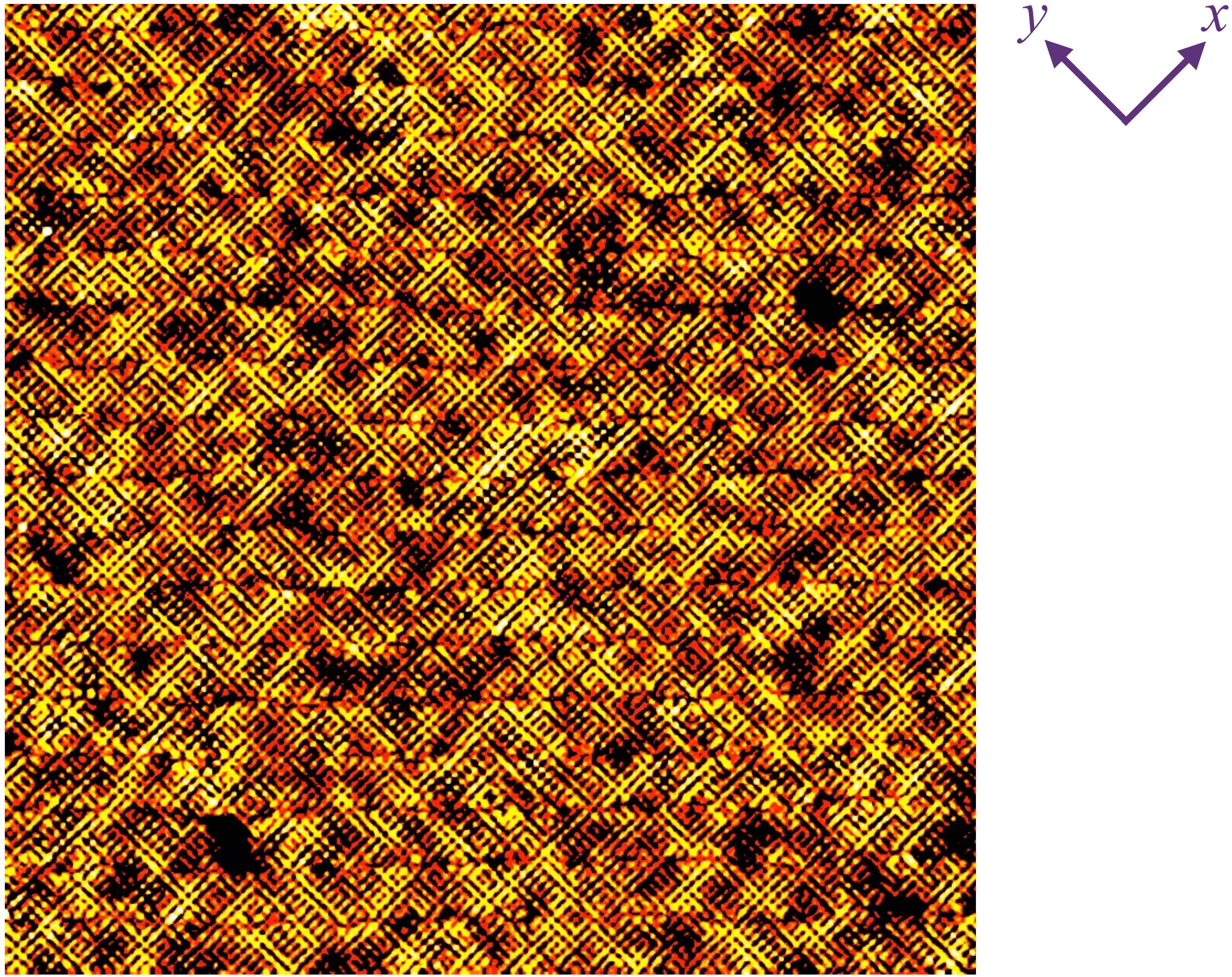
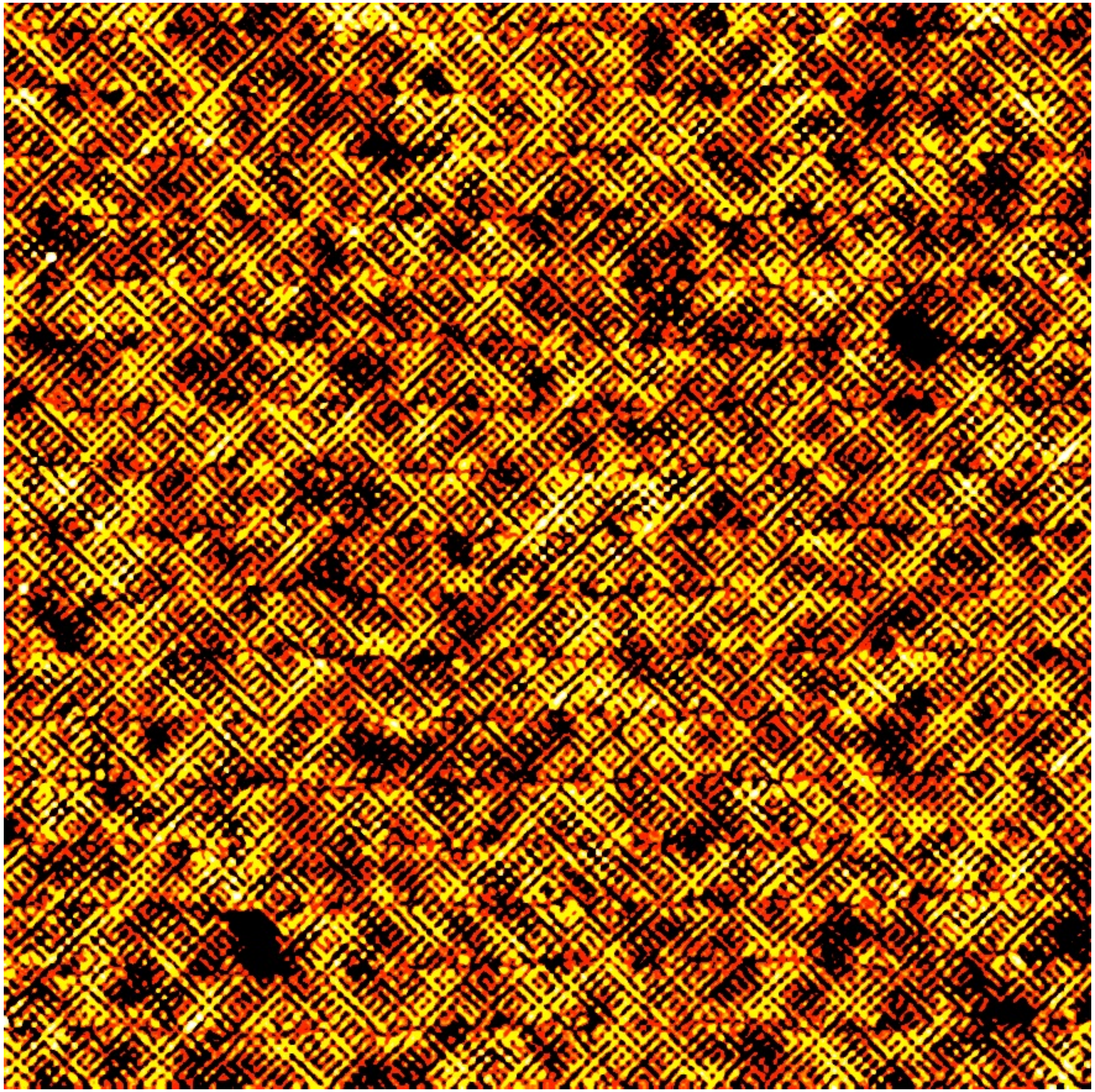
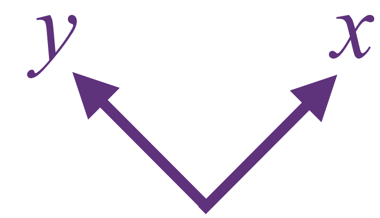


A charge density wave
(CDW with wavelength = 4 lattice spacings)
around vortex cores ?



“R-map” of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007).





"Cosmic background" map of a superconductor

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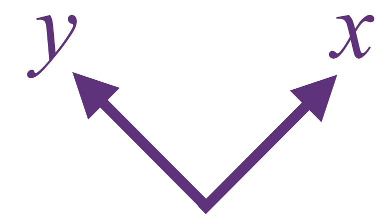
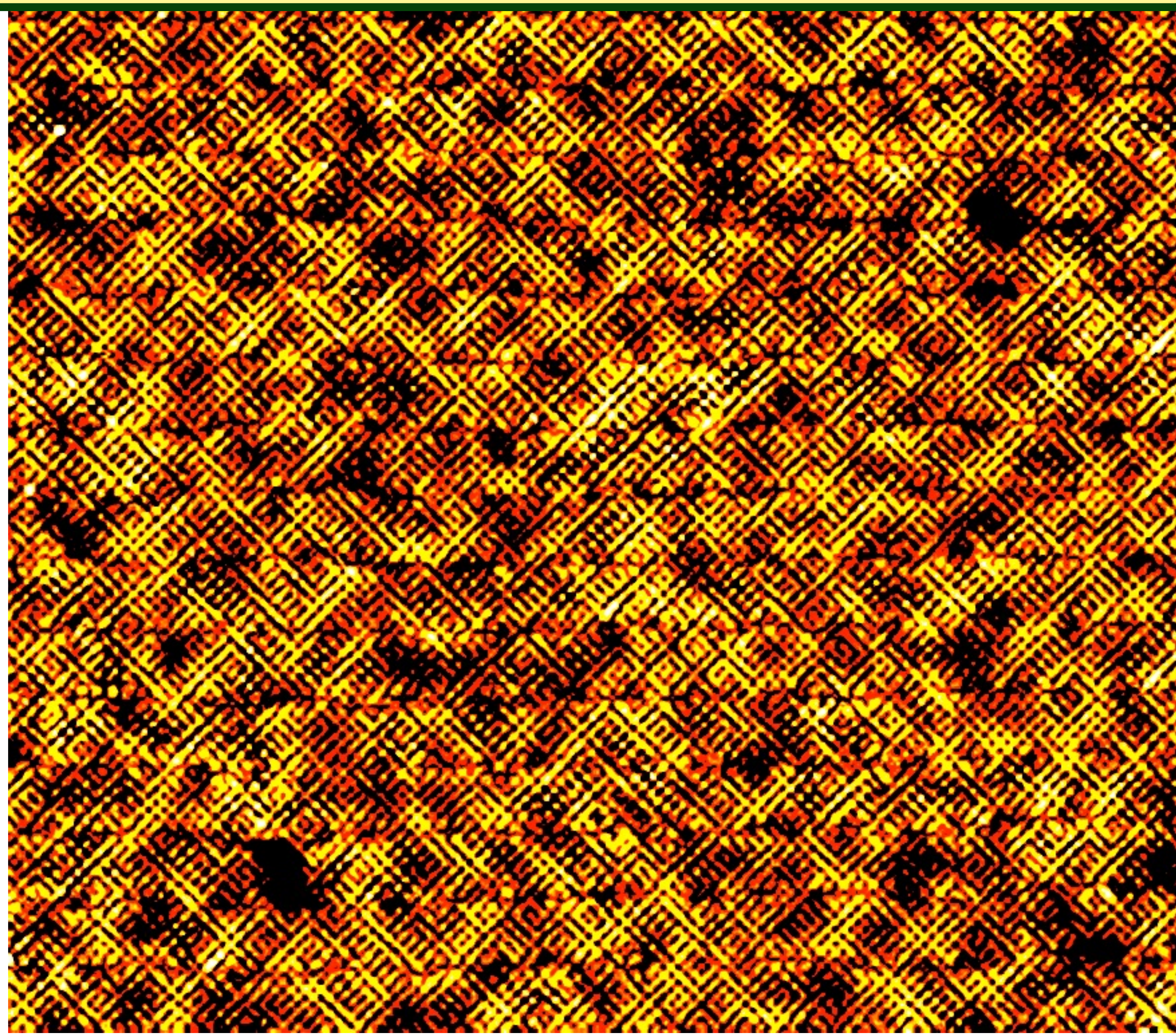
Fourier transform yields non-dispersing peaks at $\mathbf{Q} \approx 2\pi(\pm 1/4, 0)$ and $\approx 2\pi(0, \pm 1/4)$





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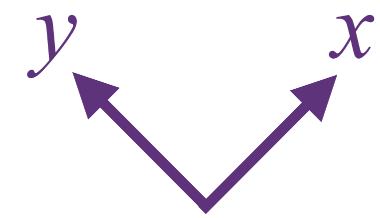
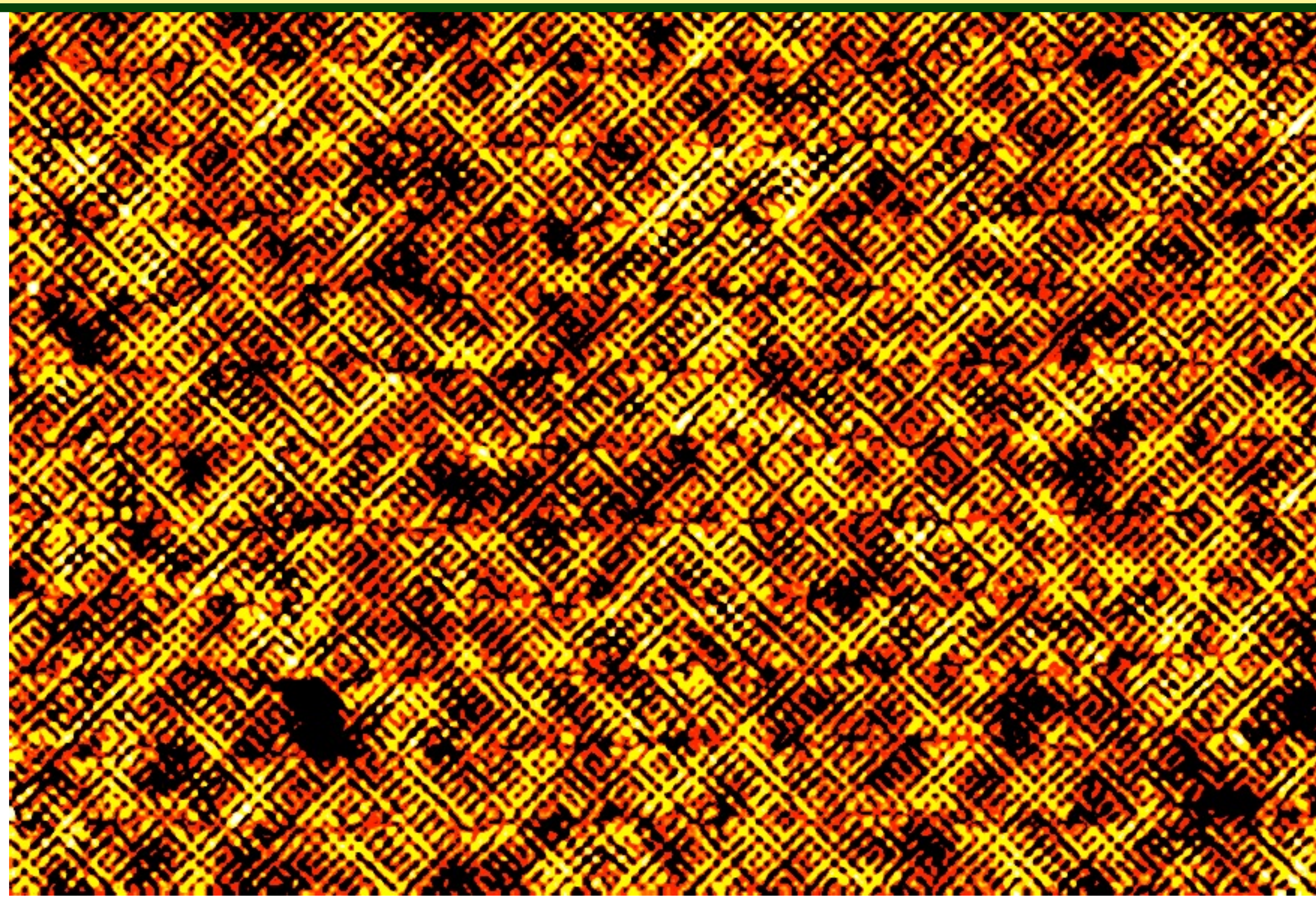
But there seems to be much more structure in the map ...





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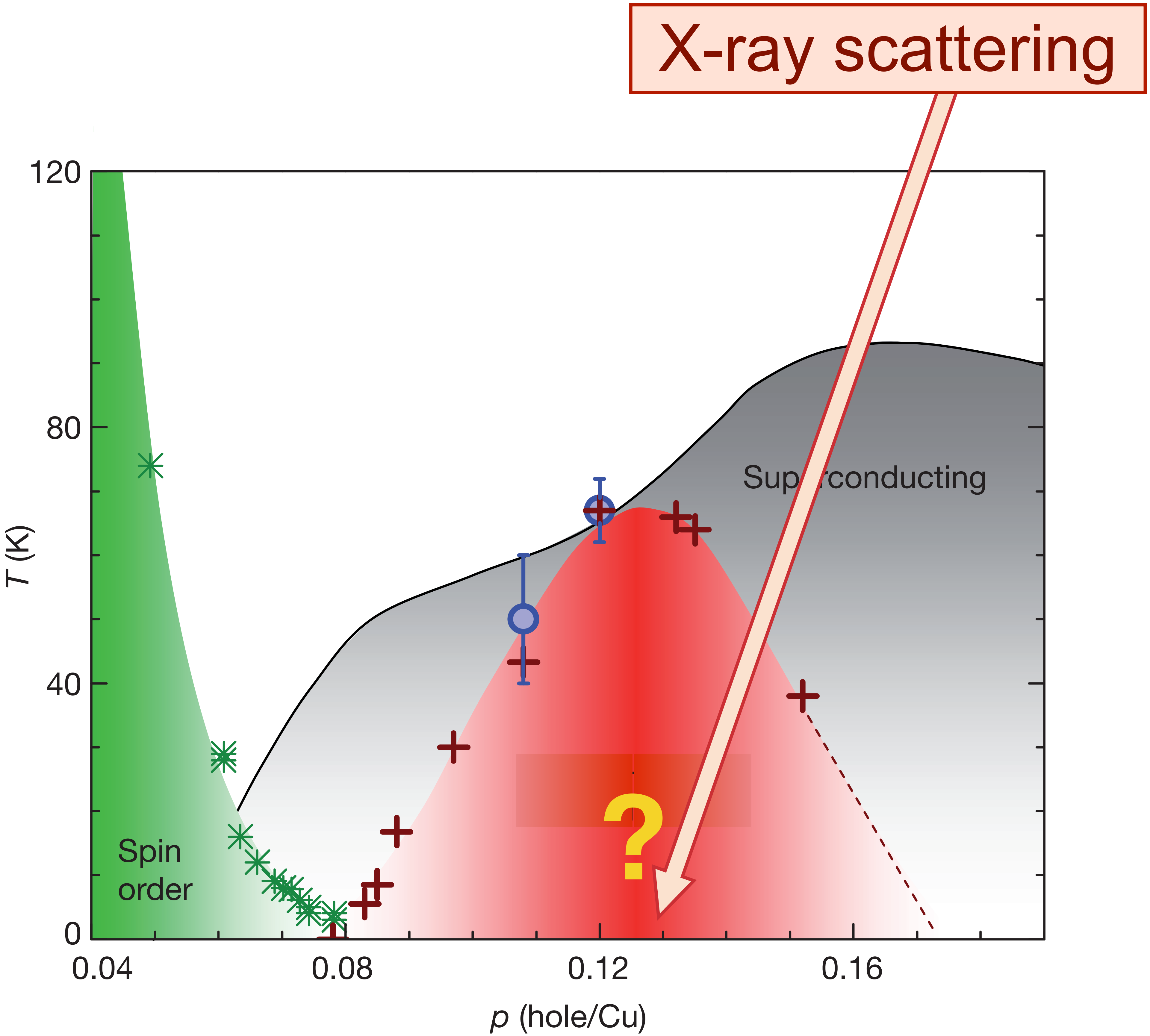

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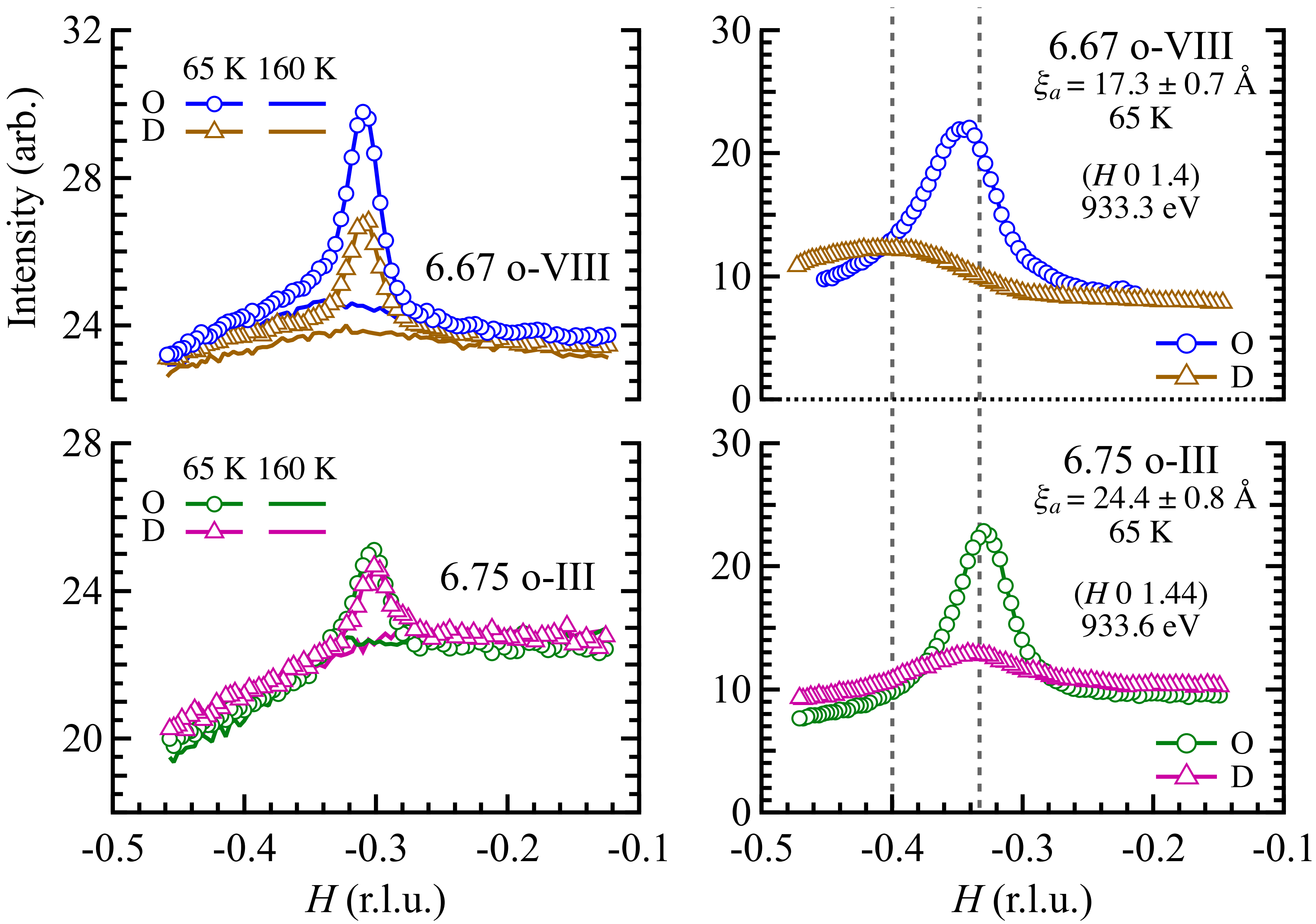

A. J. Achkar, X. Mao, Christopher McMahon, R. Sutarto, F. He, Ruixing Liang, D. A. Bonn, W. N. Hardy, and D. G. Hawthorn, arXiv:1312.6630

Many groups have observed CDW peaks in X-ray scattering over the past 2 years.

The X-ray wavevector is found to agree with the wavevector obtained from STM.
R. Comin, A. Frano, M. M. Yee, Y. Yoshida, H. Eisaki, E. Schierle, E. Weschke, R. Sutarto, F. He, A. Soumyanarayanan, Yang He, M. Le Tacon, I.S. Elfimov, J. E. Hoffman, G.A. Sawatzky, B. Keimer, A. Damascelli, Science **343**, 390 (2014).

Charge density wave (CDW) order

$$\left\langle c_\alpha^\dagger(\mathbf{r}) c_\alpha(\mathbf{r}) \right\rangle = \Psi_{CDW}\left(\mathbf{r}\right) e^{i\mathbf{Q}\cdot\mathbf{r}} + \text{c.c.}$$

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CDW wavevector $\mathbf{Q}$

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Nearly constant CDW order parameter

Generalized charge density wave (CDW) :
Bose condensation of particle-hole pairs

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$$= \left[\mathcal{P}(\mathbf{r}_1 - \mathbf{r}_2)\right] \times \Psi_{CDW}\left(\frac{\mathbf{r}_1 + \mathbf{r}_2}{2}\right) e^{i\mathbf{Q}\cdot(\mathbf{r}_1+\mathbf{r}_2)/2} + \text{c.c.}$$

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Internal particle-hole pair wavefunction $\mathcal{P}(\mathbf{r}) = \int \frac{d^2k}{4\pi^2} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{r}}$

Time-reversal symmetry requires $\mathcal{P}(\mathbf{k}) = \mathcal{P}(-\mathbf{k})$.
We expand
$\mathcal{P}(\mathbf{k}) = \mathcal{P}_s + \mathcal{P}_{s'}(\cos k_x + \cos k_y) + \mathcal{P}_d(\cos k_x - \cos k_y) \ldots$

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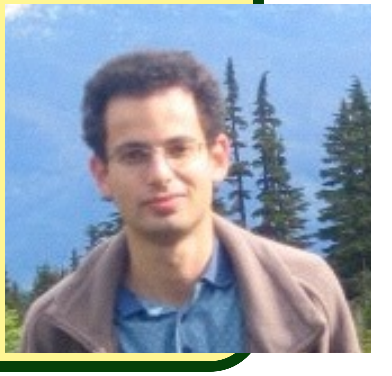

A CDW with $\mathcal{P}_d \neq 0$ is nearly degenerate with SC near the quantum-critical point for antiferromagnetism in a metal.

M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075128 (2010)

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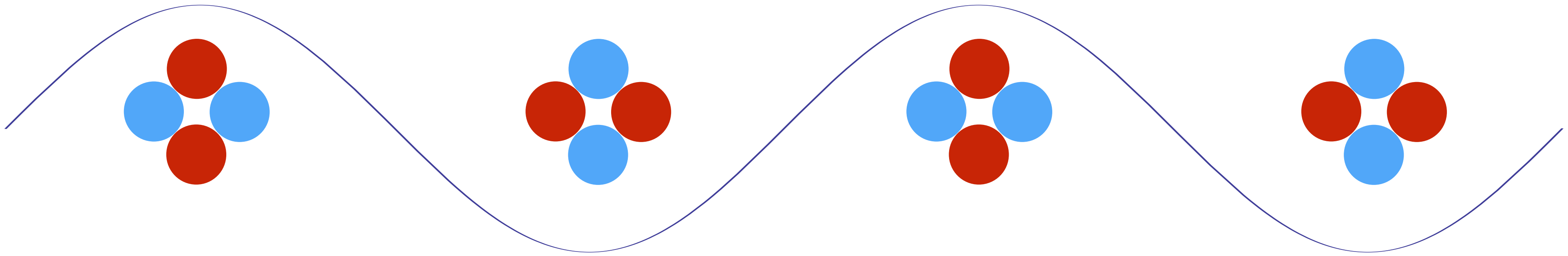

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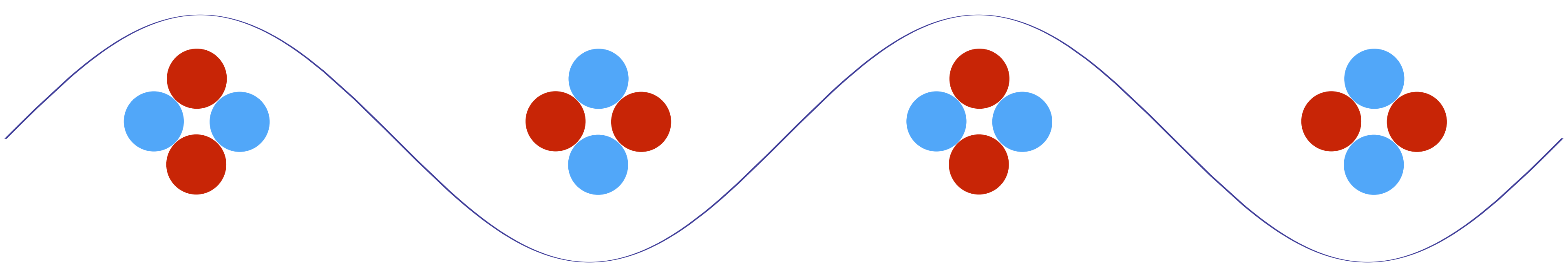

(Adapted from a picture of a gravity wave)

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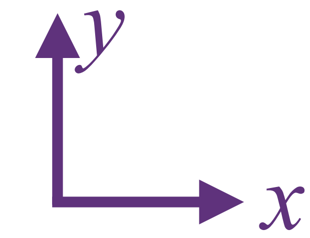
M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075128 (2010)

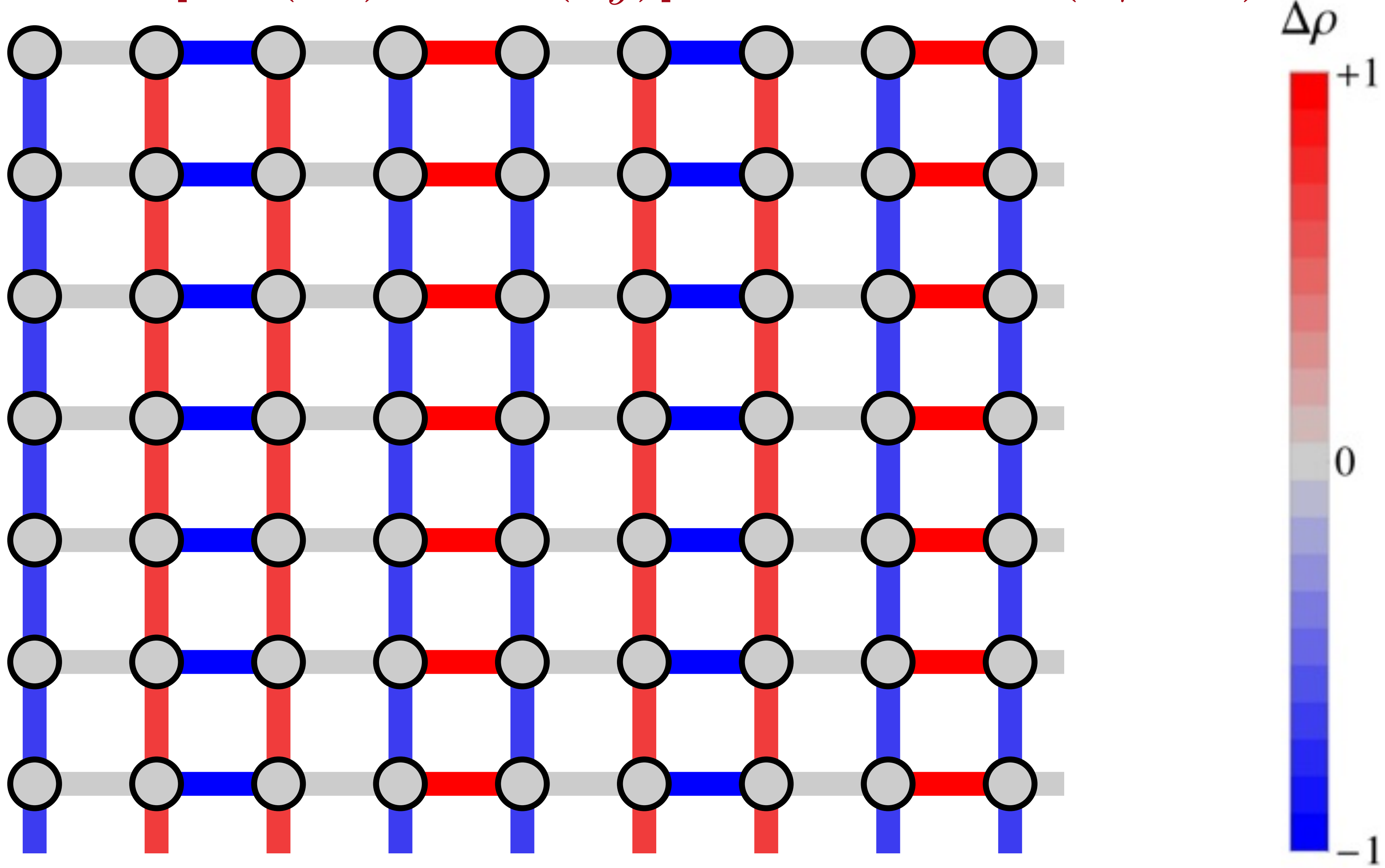
d-wave bond order.



Plot of $P_{ij} = \left\langle c_{i\alpha}^\dagger c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

$$P_{ij} = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2} + \text{c.c.}$$

$$\mathcal{P}(\mathbf{k}) = e^{i\phi} [\cos(k_x) - \cos(k_y)] \quad \text{and} \quad \mathbf{Q} = (\pi/2, 0)$$



This d-wave bond order was first discussed in
S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).

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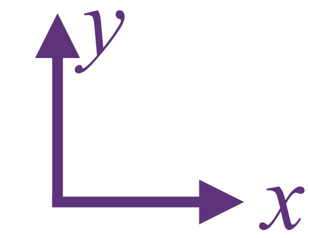

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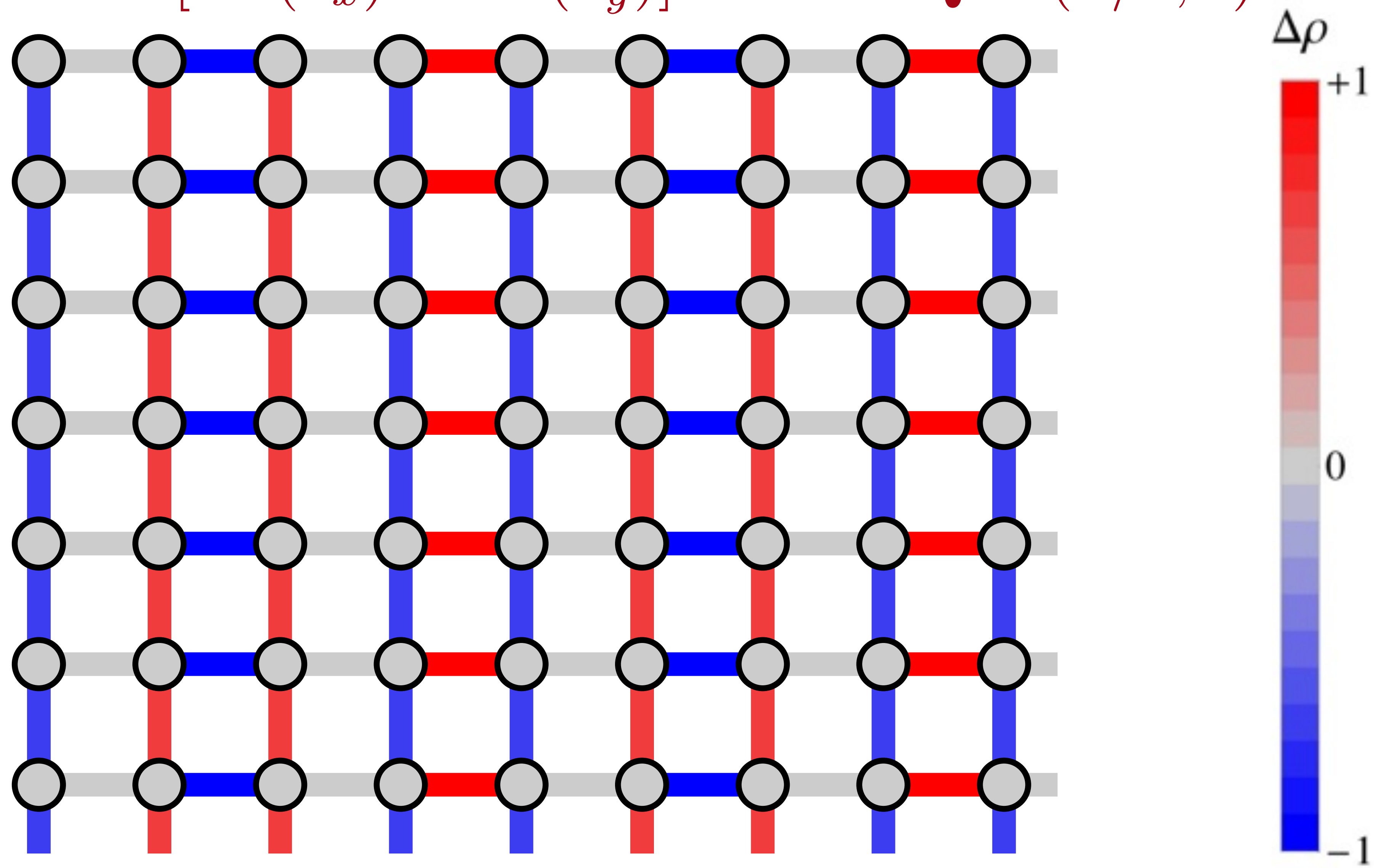
$$P_{ij} = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2} + \text{c.c.}$$

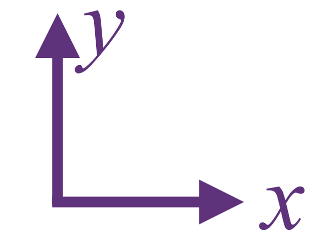
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) - \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = (\pi/2, 0)$$

Density wave on horizontal bonds has a phase-shift of π relative to the wave on vertical bonds



This d-wave bond order was first discussed in S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).

Time-reversal symmetry breaking state



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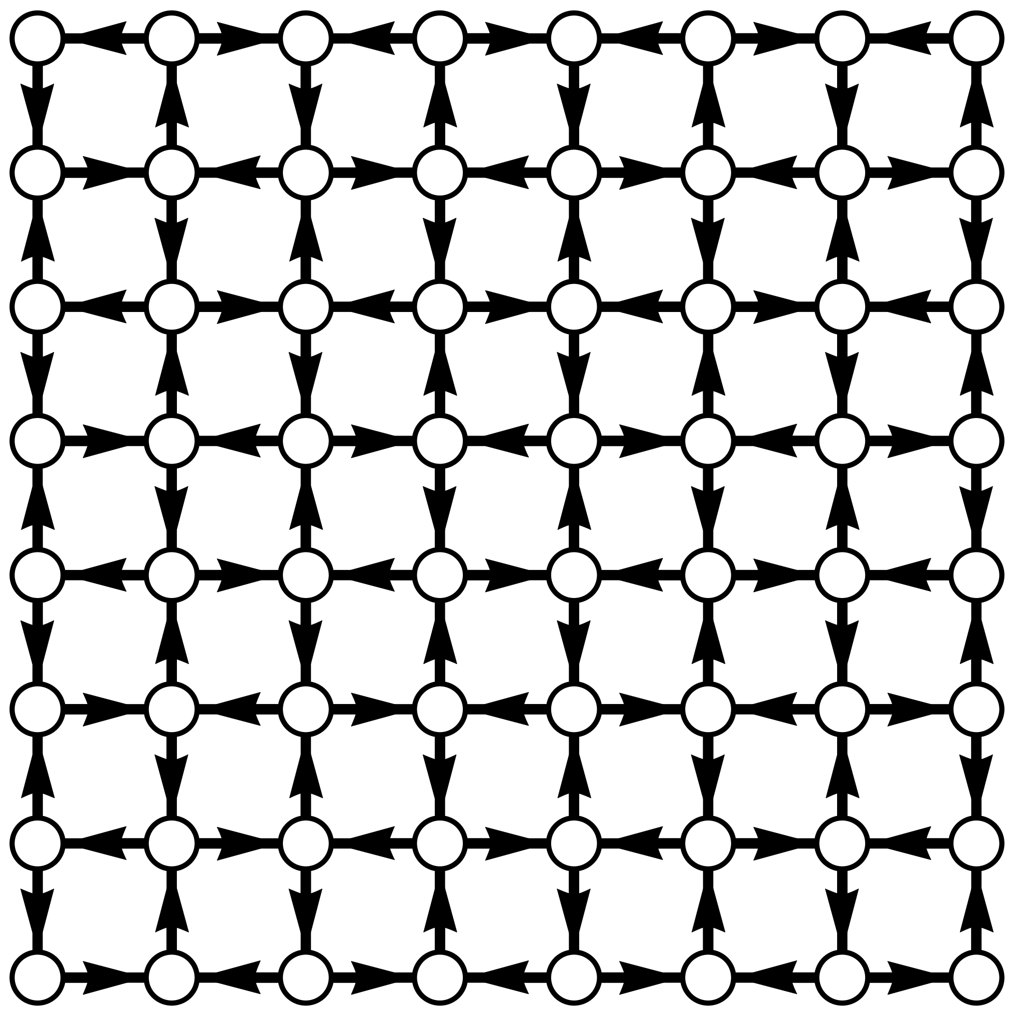
$$\mathcal{P}(\mathbf{k}) = \sin(k_x) - \sin(k_y) \quad \text{and} \quad \mathbf{Q} = (\pi, \pi)$$

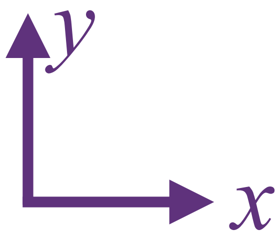


p-wave current order

This state breaks time-reversal and is also known as "*d*-density wave" (*unfortunately*), and "staggered-flux (SF)".

S. Chakravarty, R. B. Laughlin, D. K. Morr, and C. Nayak, Phys. Rev. B **63**, 094503 (2001).
P. A. Lee, N. Nagaosa, and X.-G. Wen, Rev. Mod. Phys. **78**, 17 (2006).
R. B. Laughlin, Phys. Rev. B **89**, 035134 (2014).

d-wave bond order.



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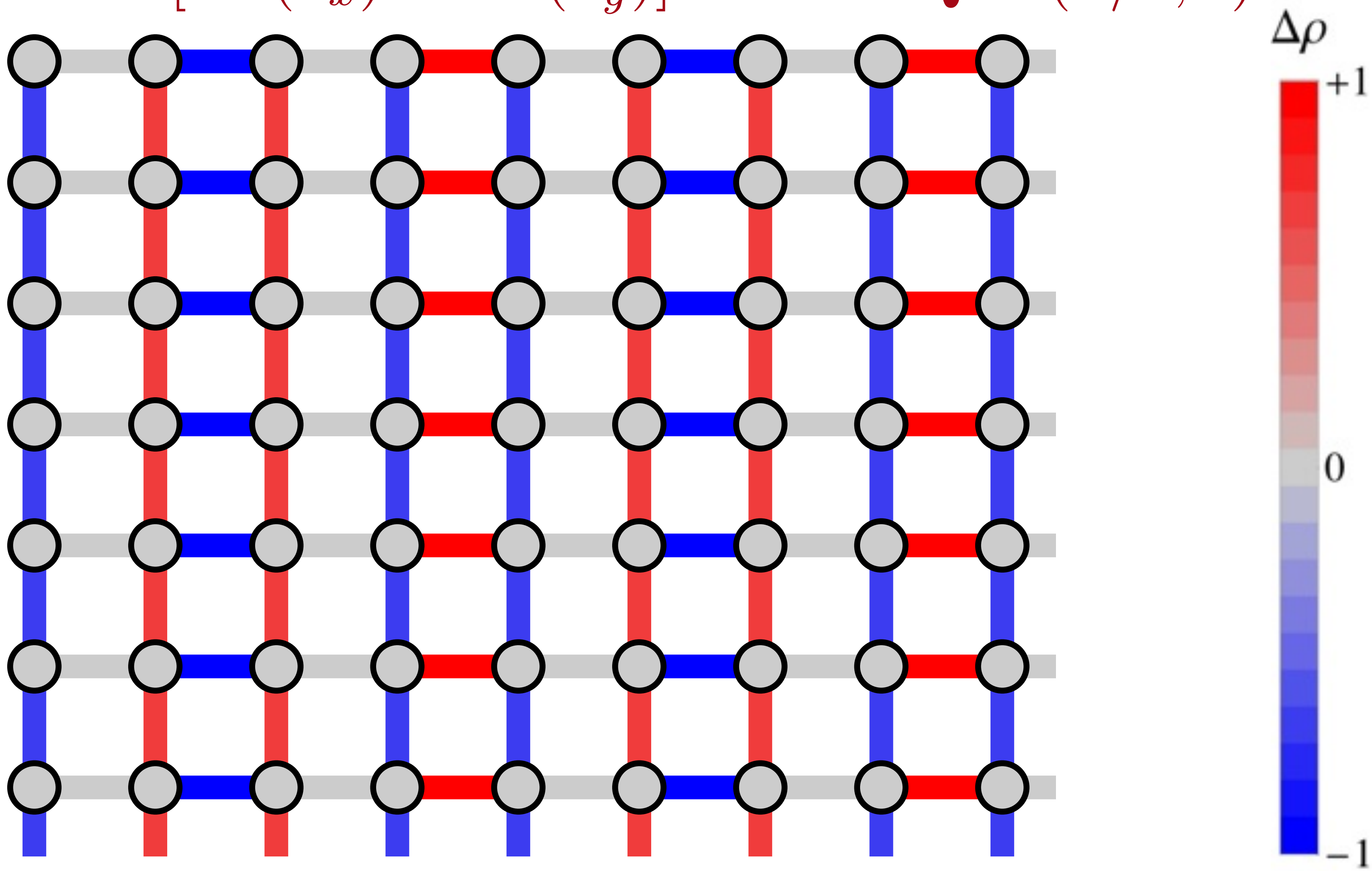

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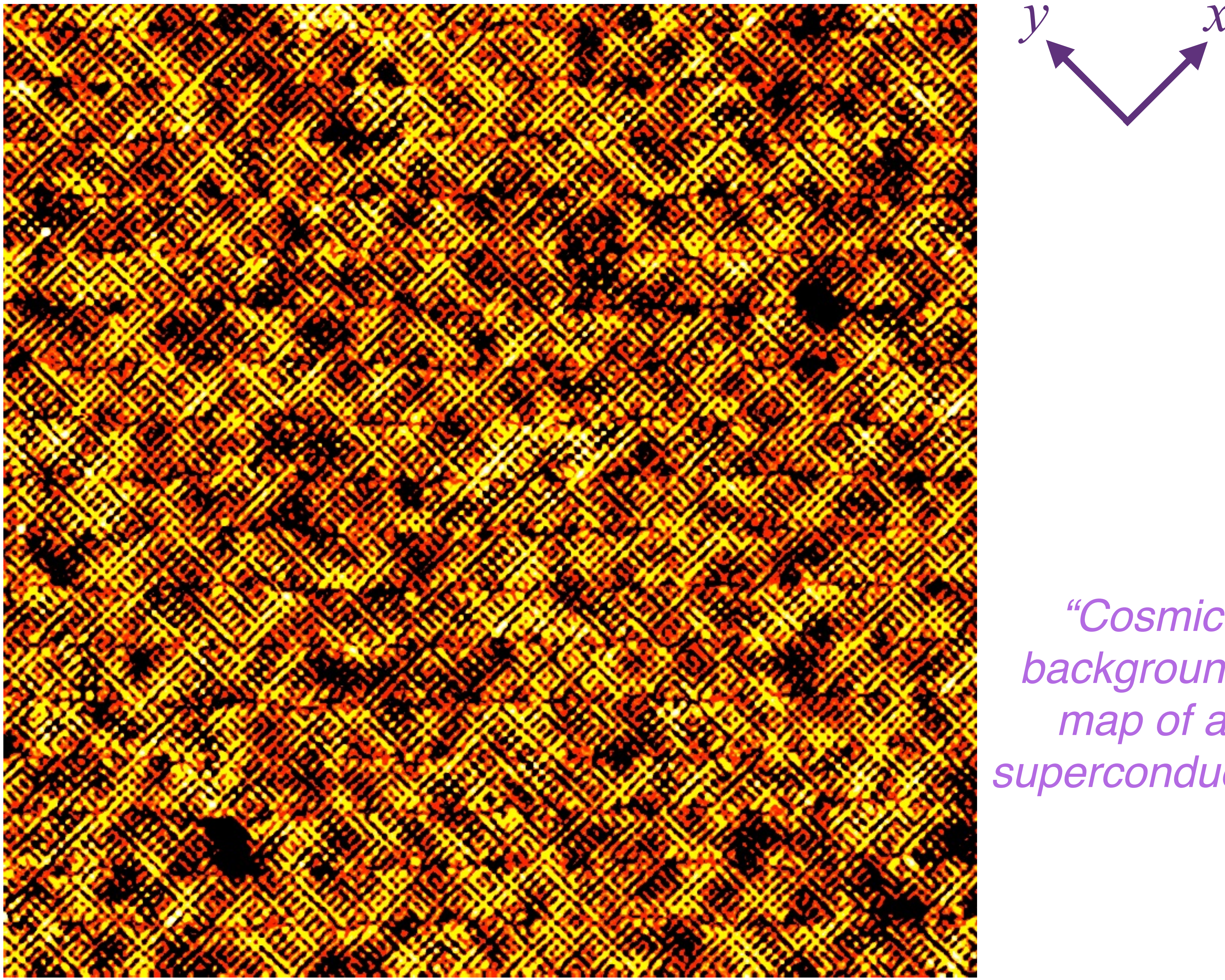

“Cosmic background” map of a superconductor

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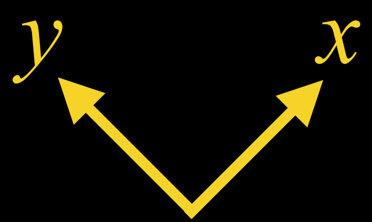
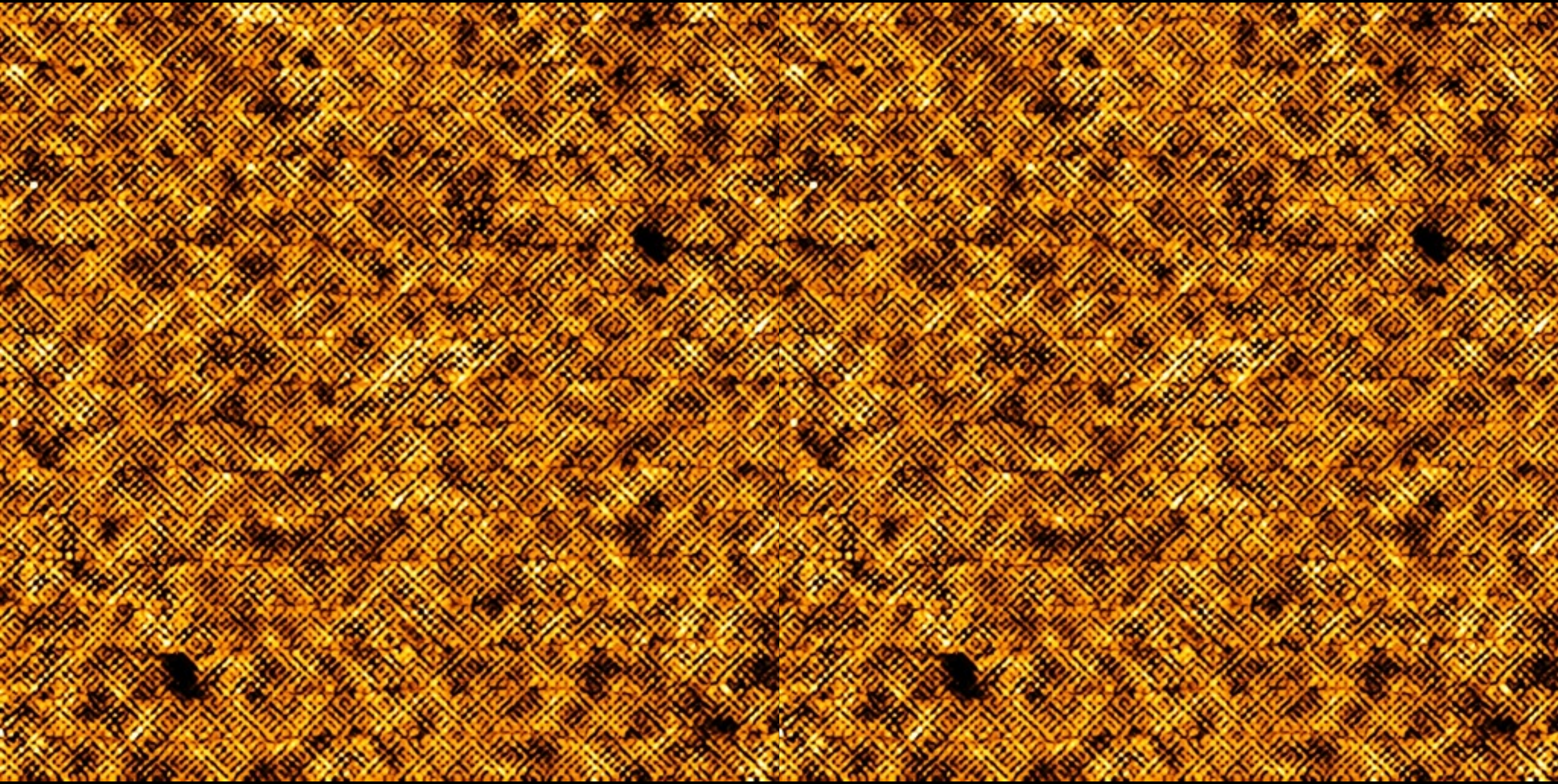
UD45K
BSCCO

R(r,150mV)

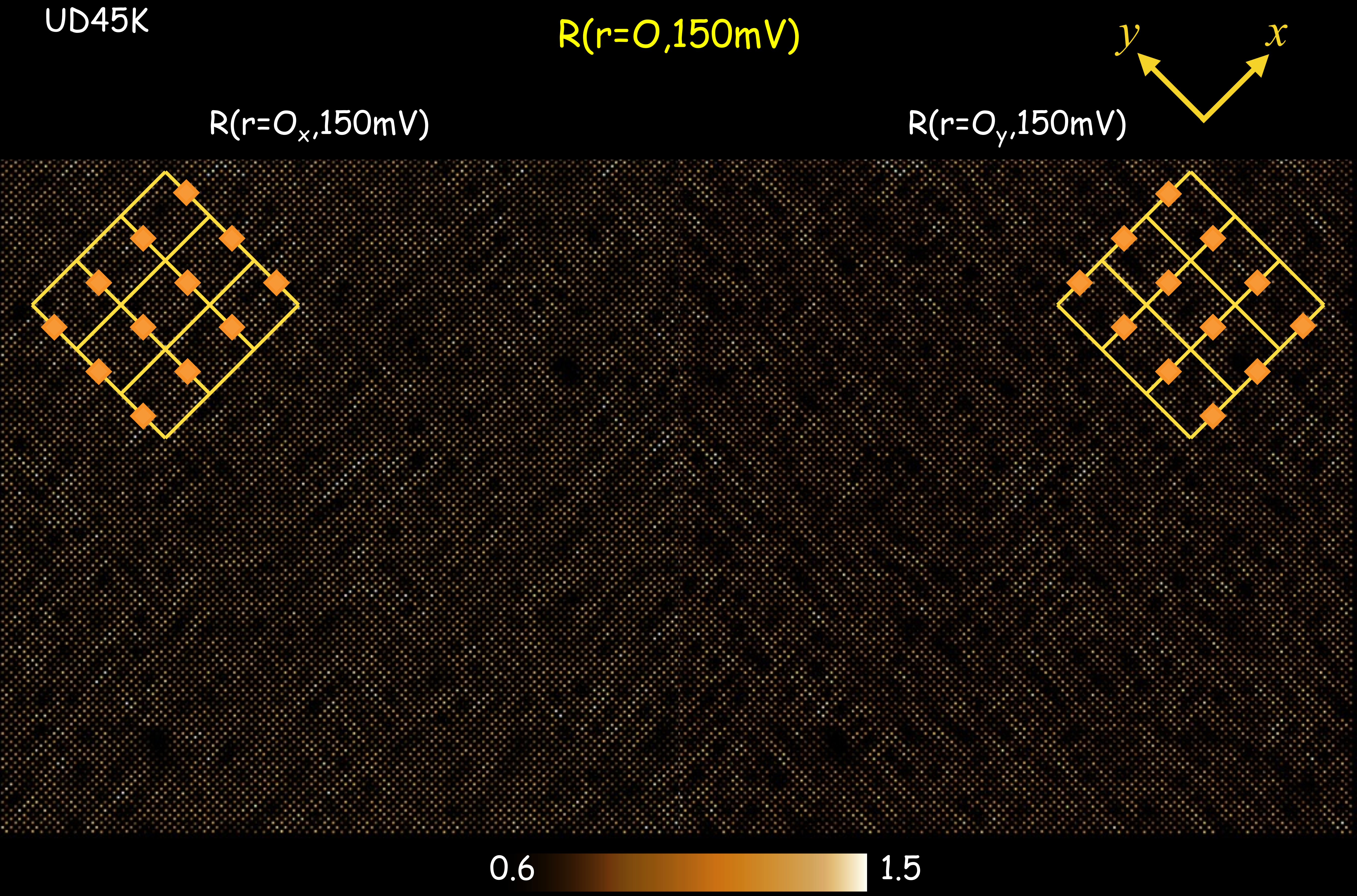


R(r,150mV) R(r,150mV)



Note that these are identical images.

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, arXiv:1404.0362



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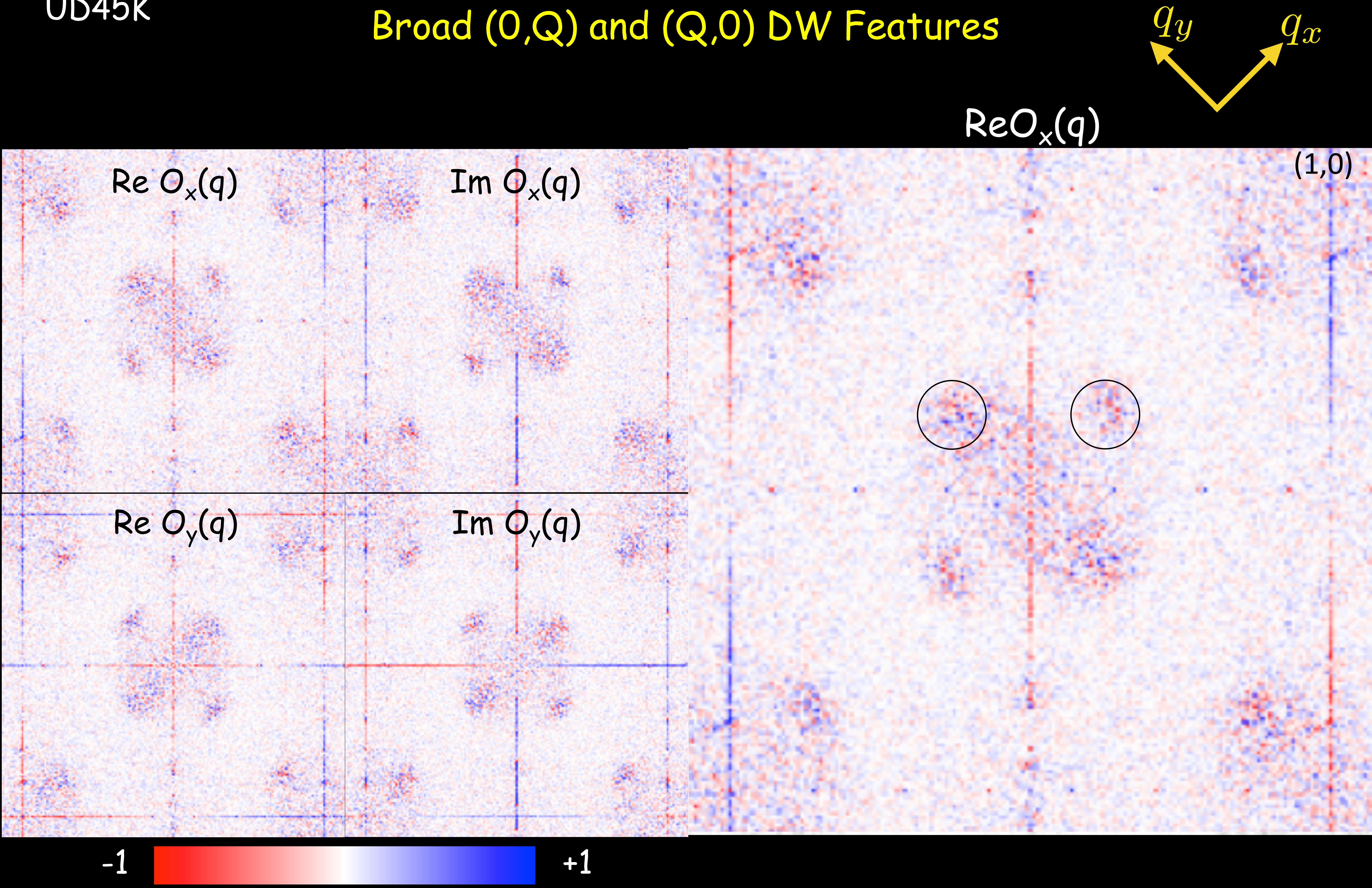
UD45K

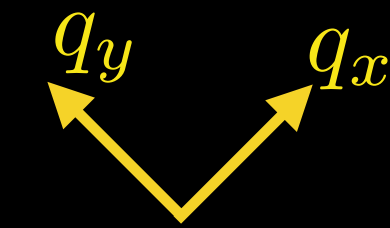
Broad (0,Q) and (Q,0) DW Features

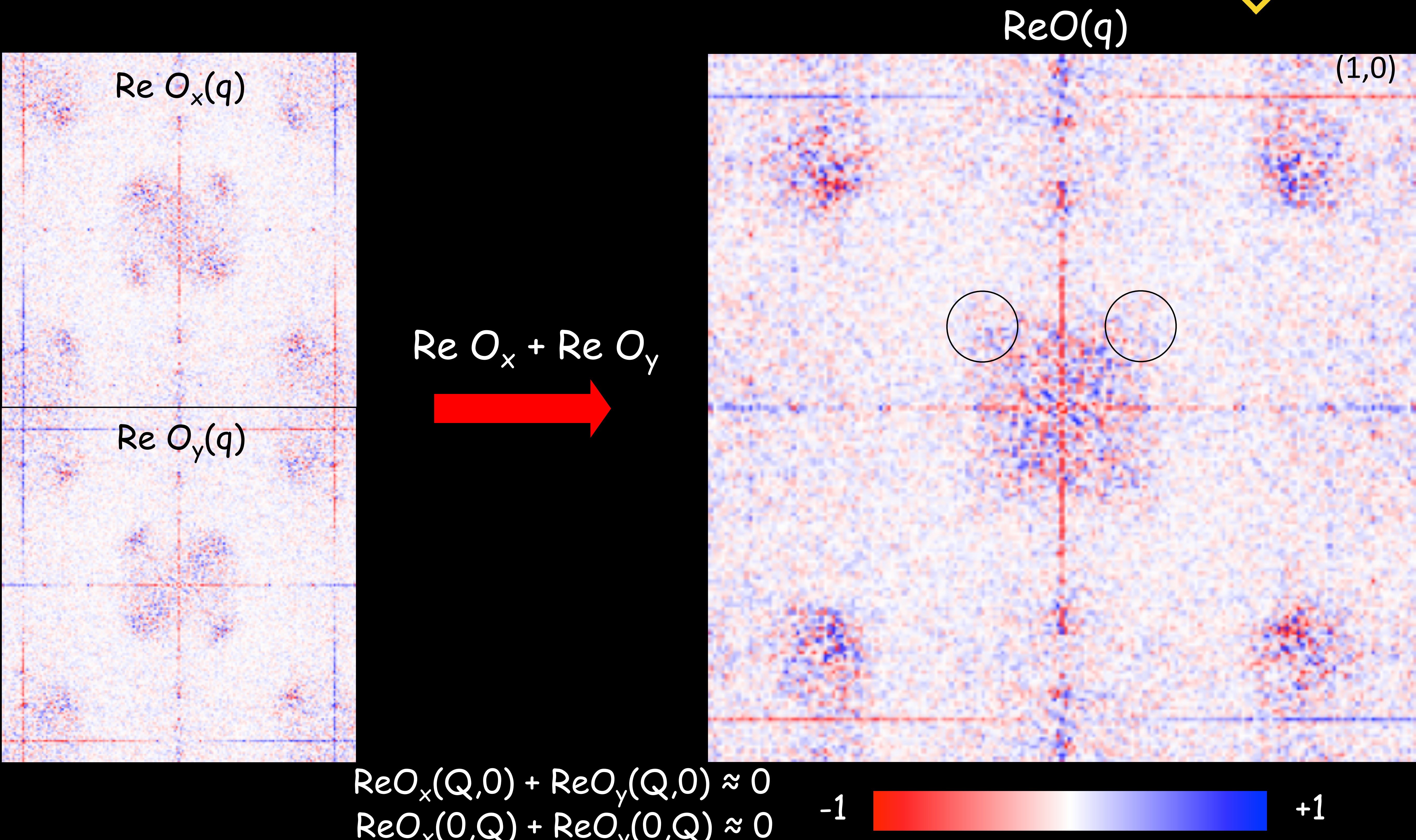


K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, arXiv:1404.0362

UD45K

$ReQ_x(0,Q)$ Vs $ReO_y(0,Q)$

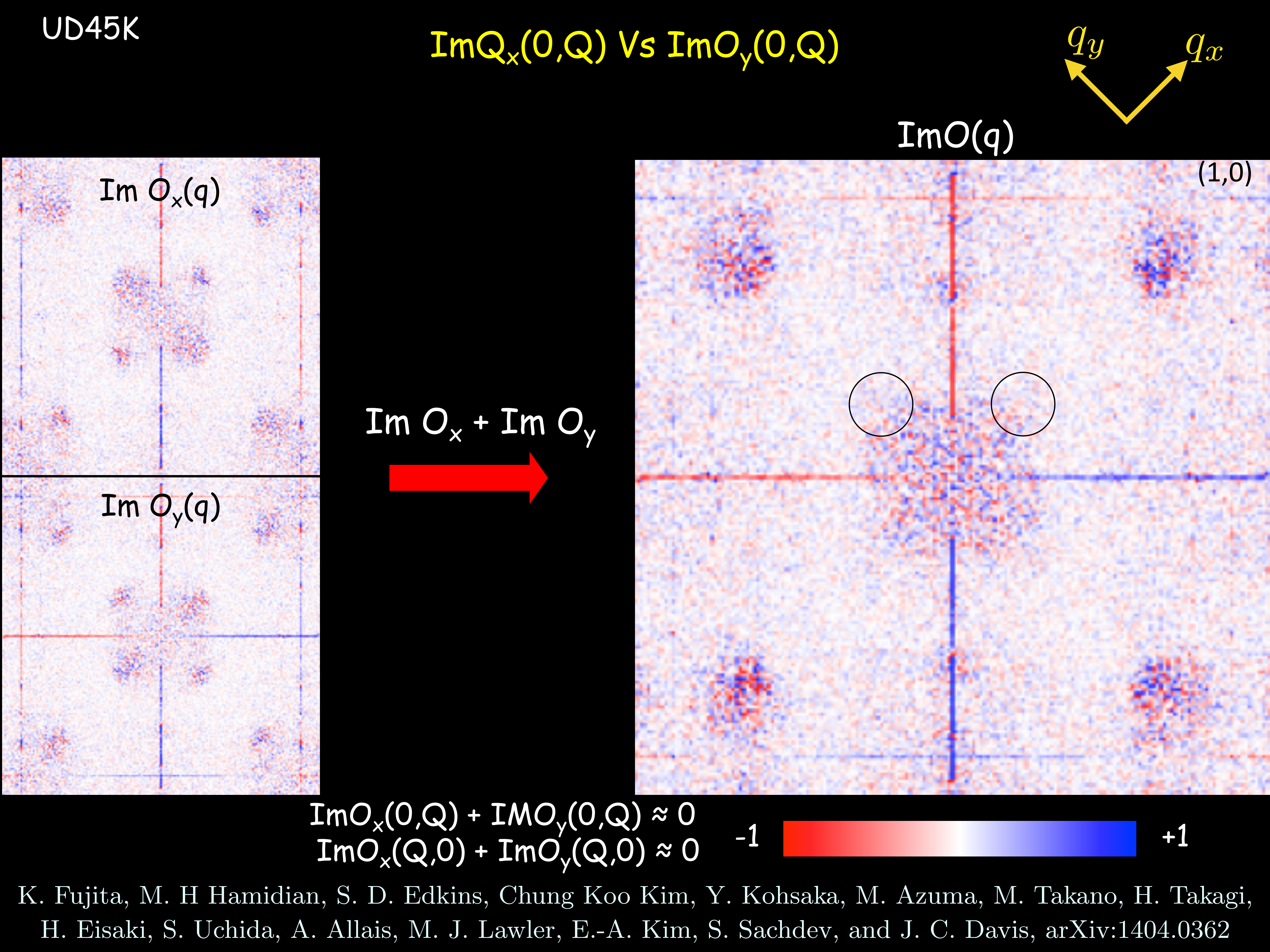


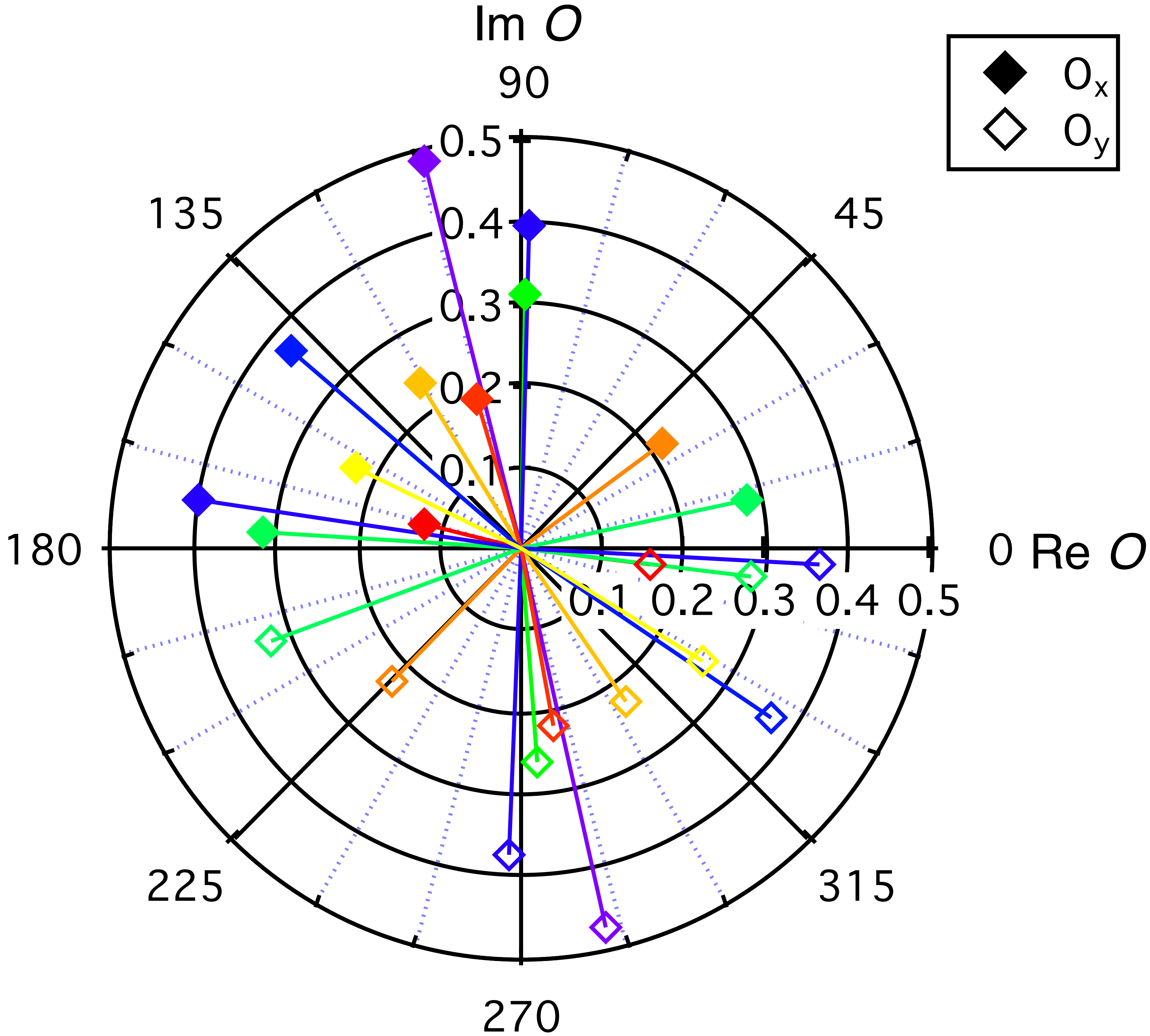


$ReO_x(Q,0) + ReO_y(Q,0) \approx 0$

$ReO_x(0,Q) + ReO_y(0,Q) \approx 0$

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, arXiv:1404.0362


UD45K
ImQ$_x$(0,Q) Vs ImO$_y$(0,Q)
q_y
q_x
ImO(q)
Im O$_x$(q)
Im O$_y$(q)
Im O$_x$ + Im O$_y$
(1,0)
ImO$_x$(0,Q) + IMO$_y$(0,Q) ≈ 0
ImO$_x$(Q,0) + ImO$_y$(Q,0) ≈ 0
-1
+1
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, arXiv:1404.0362



Phase-sensitive measurement of the *d* symmetry of charge density wave order

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, arXiv:1404.0362

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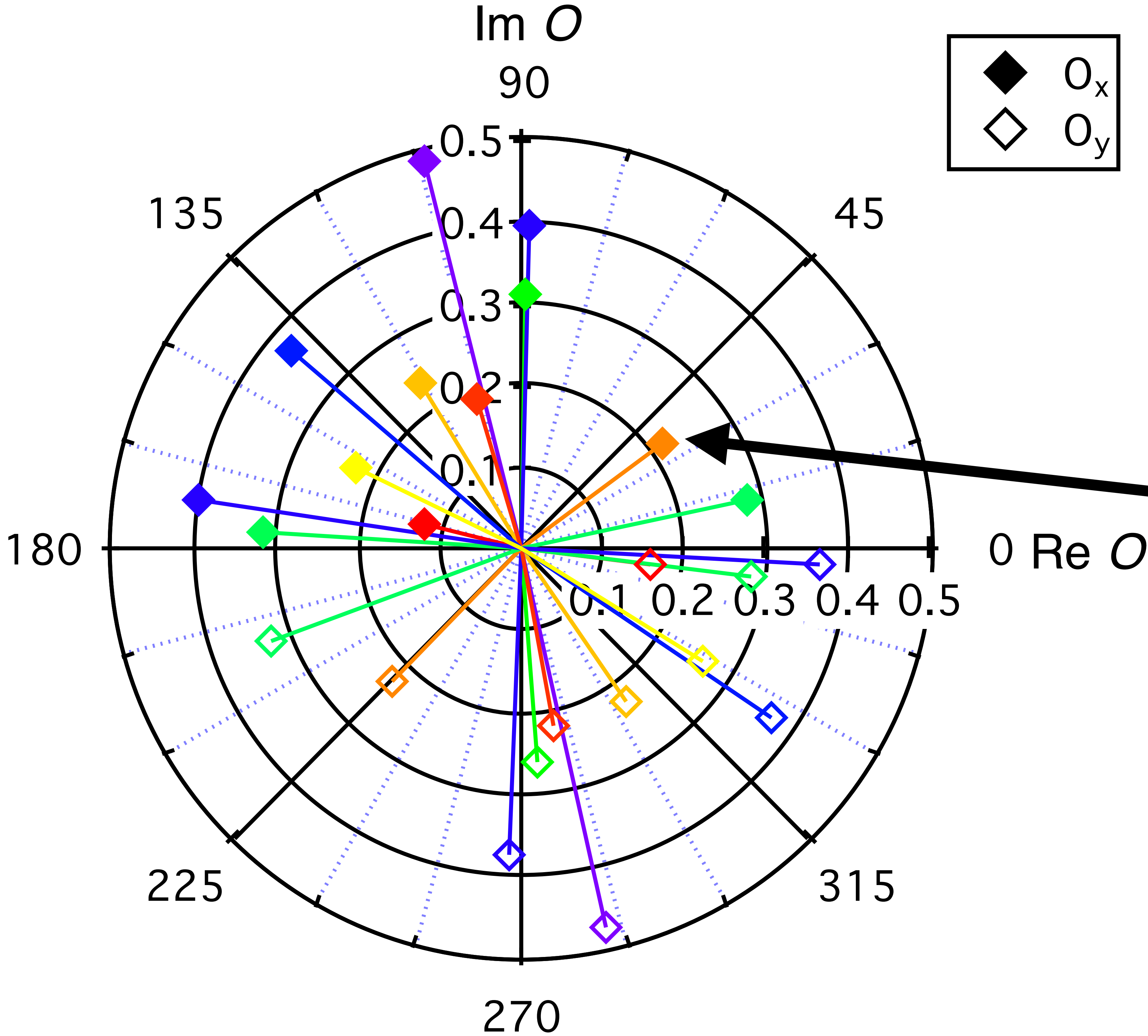

Complex value of O_x at a pixel

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, arXiv:1404.0362

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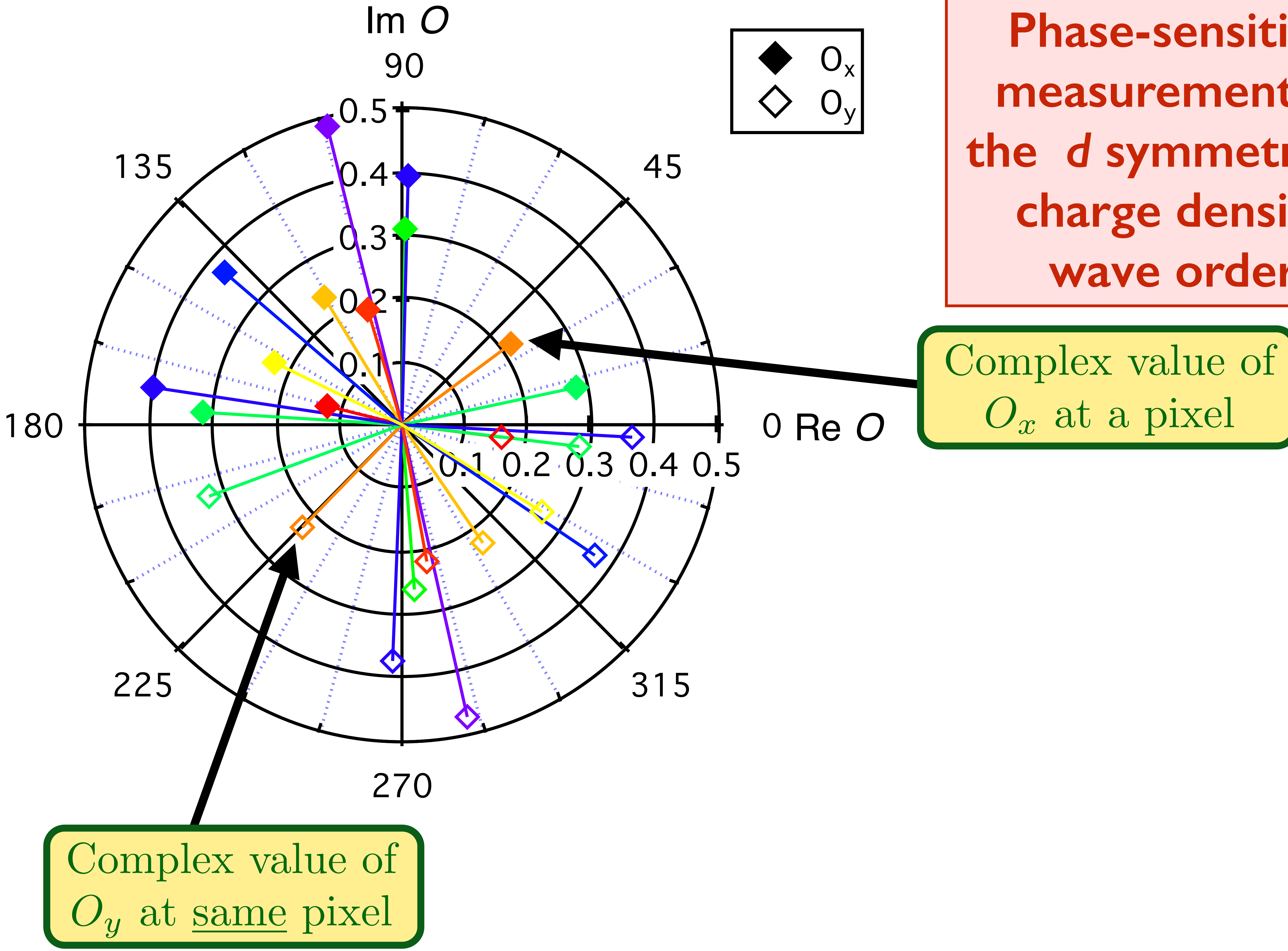

K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, arXiv:1404.0362

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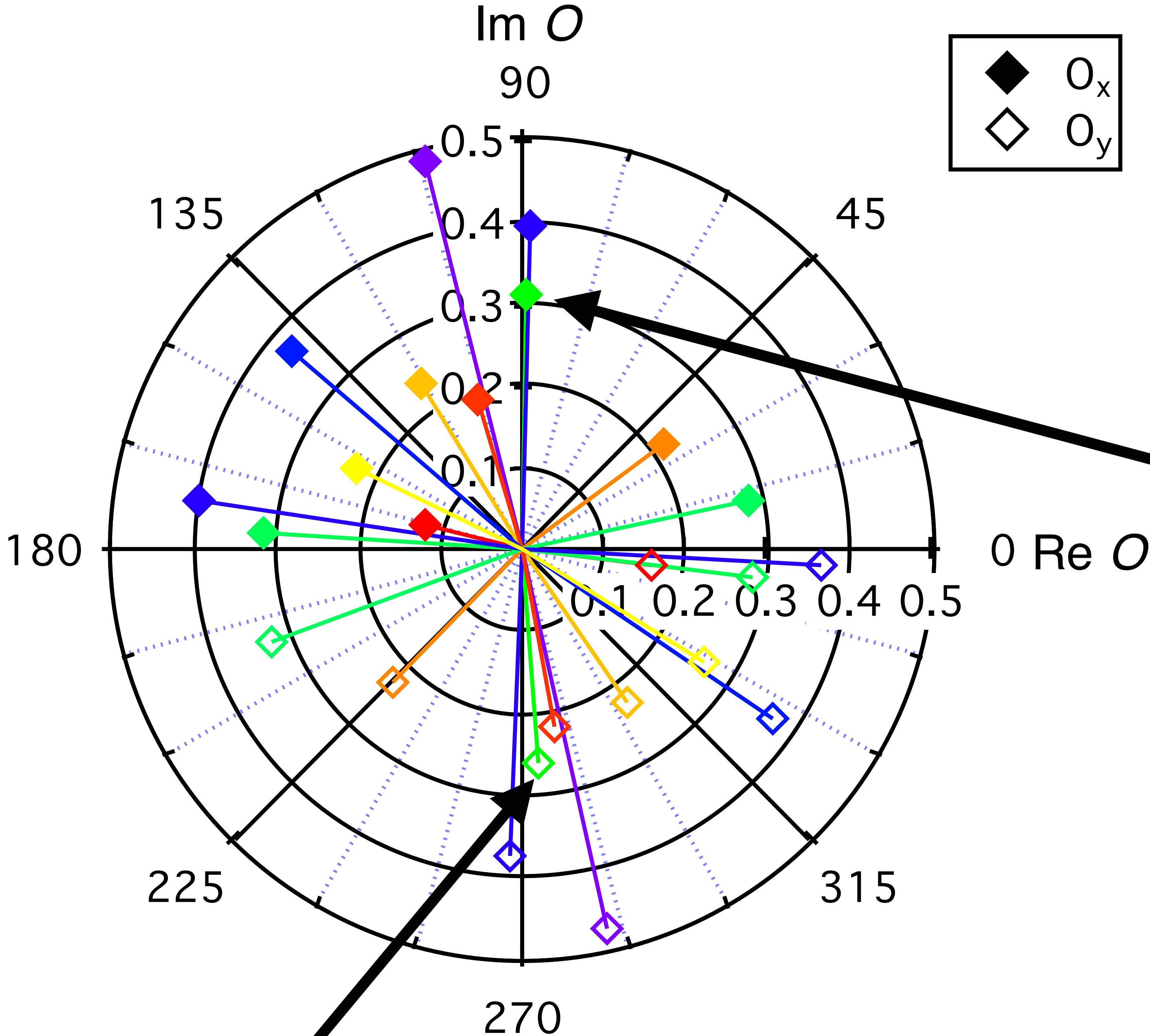

Complex value of O_x at a pixel

Complex value of O_y at same pixel

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, arXiv:1404.0362

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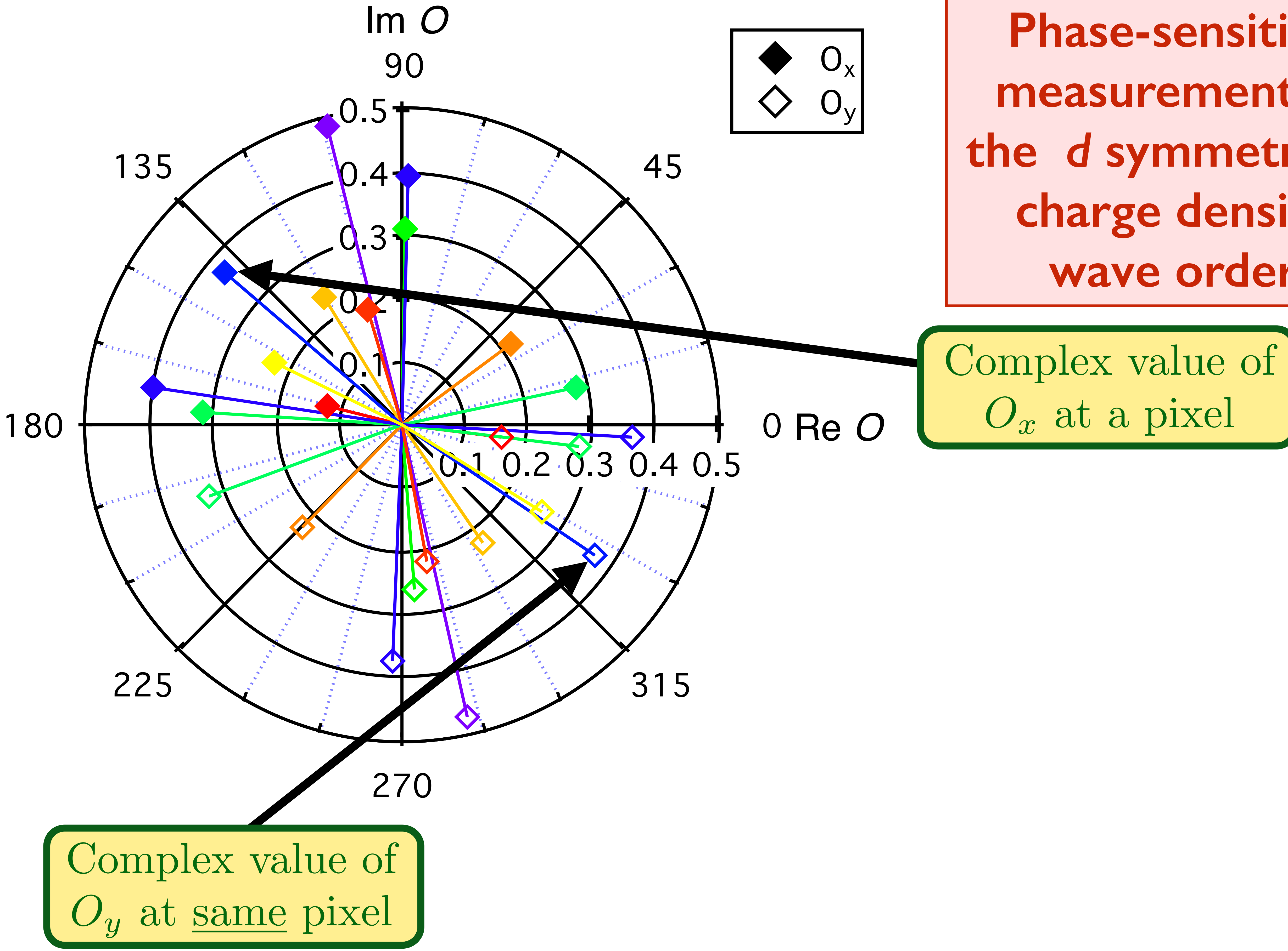

K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, arXiv:1404.0362

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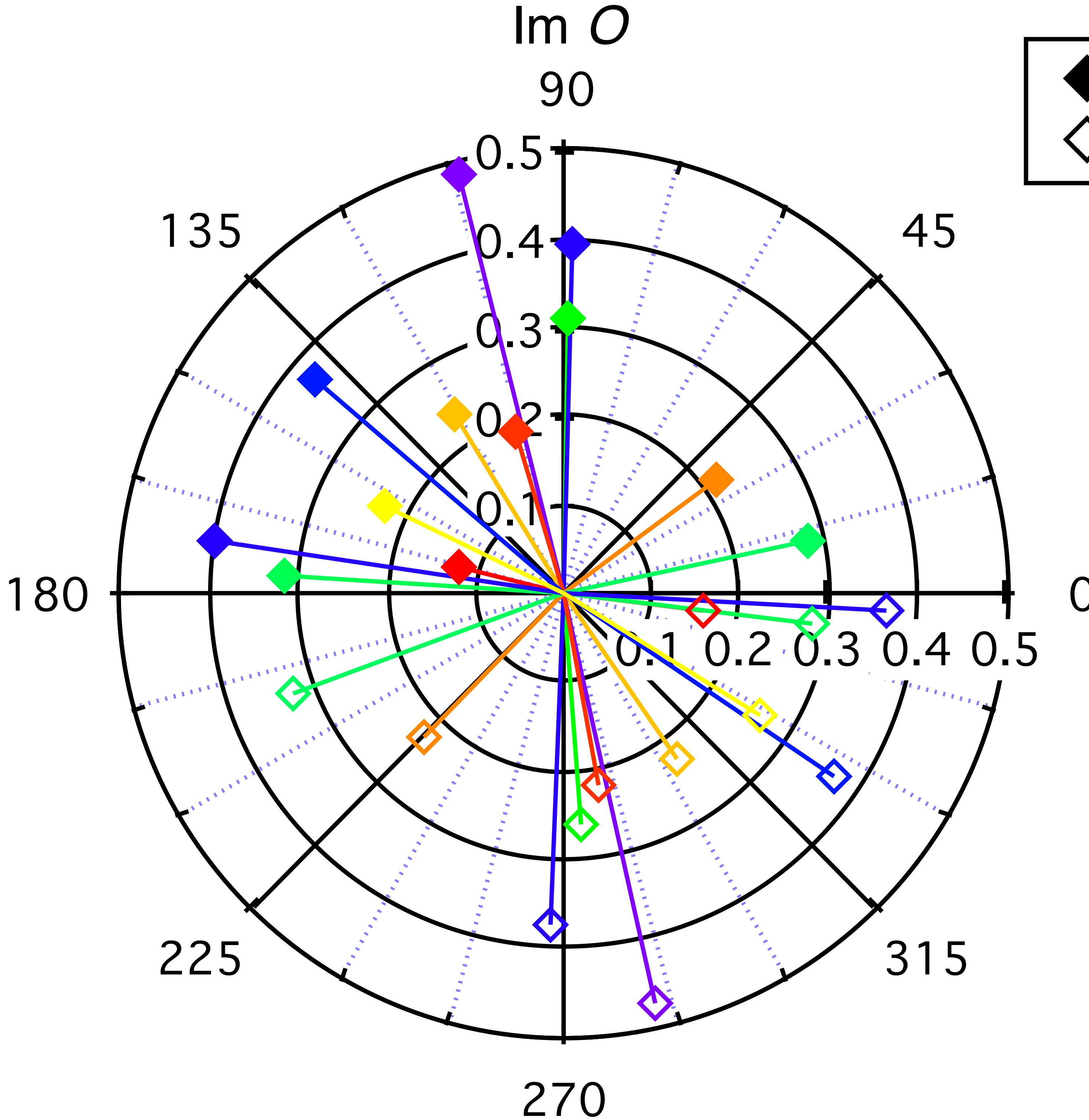

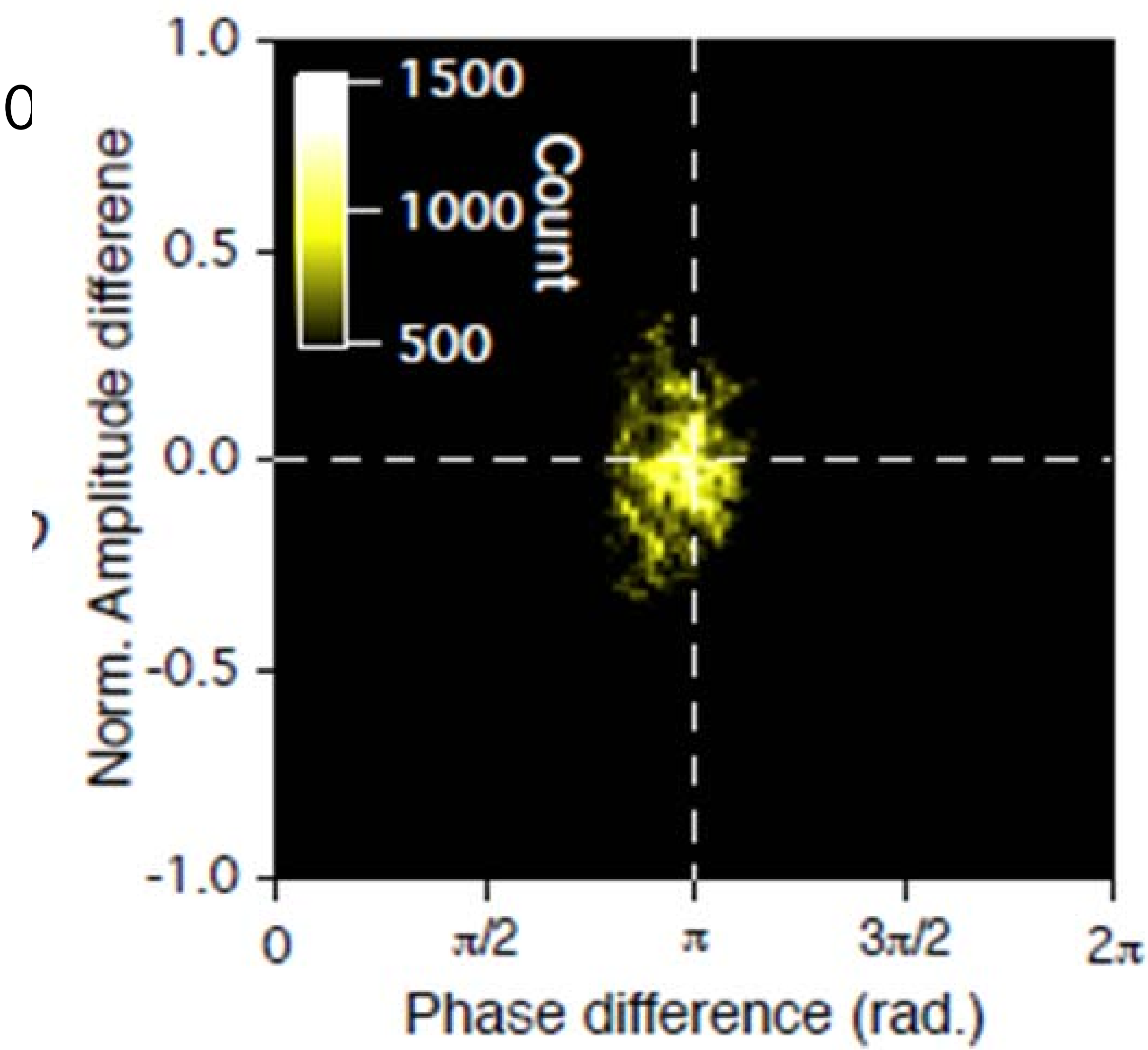

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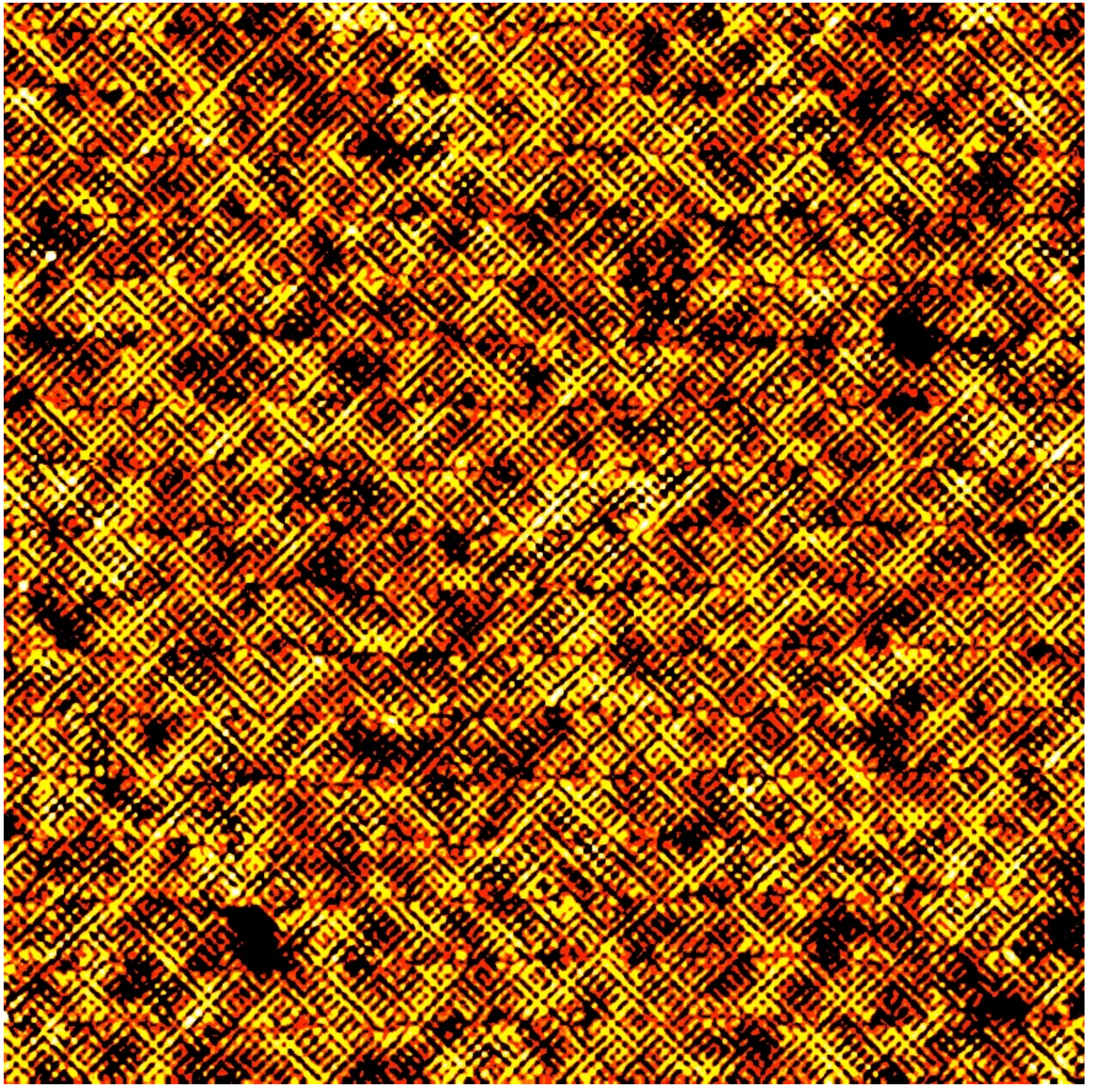

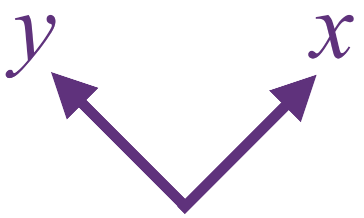

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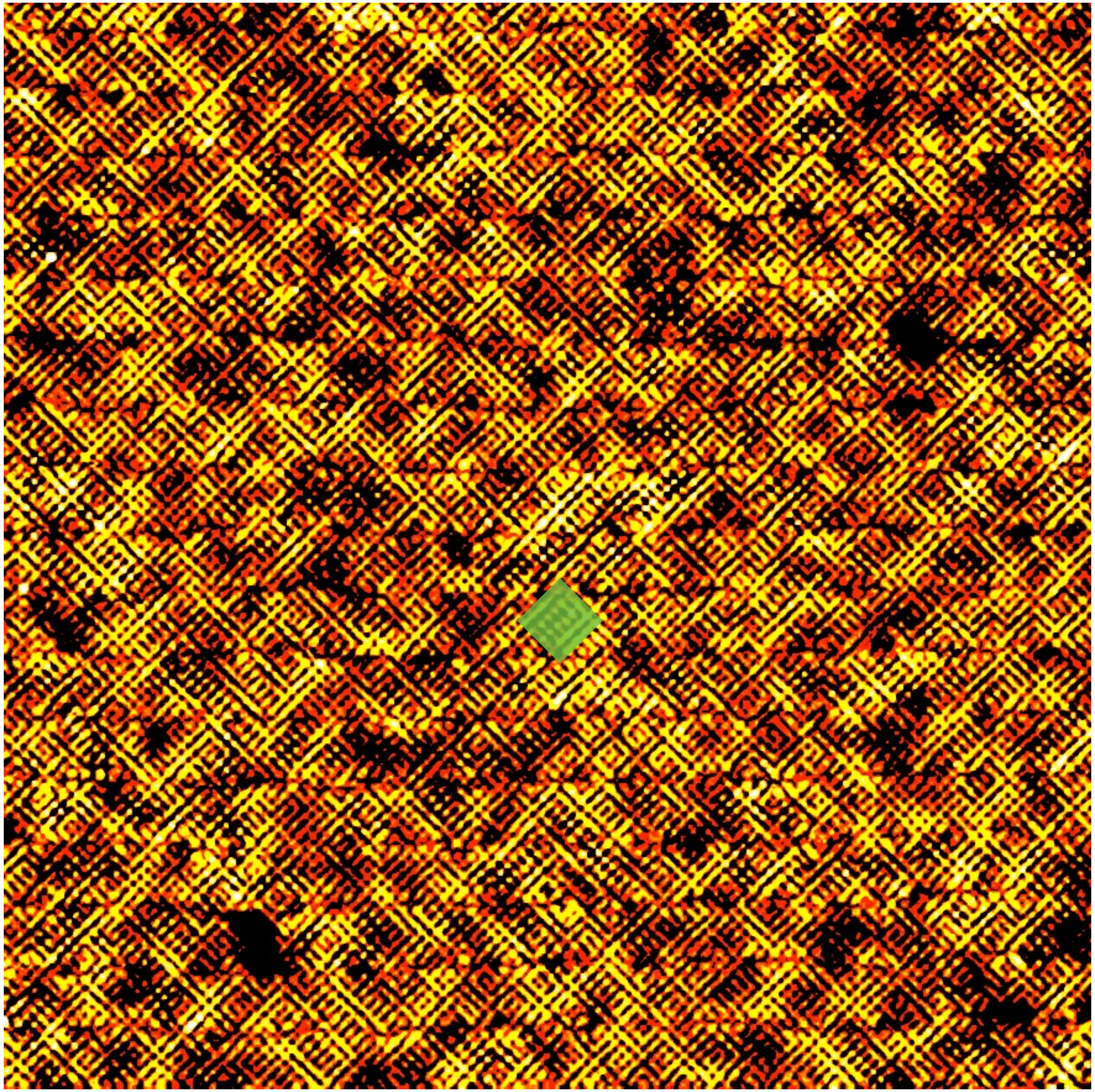
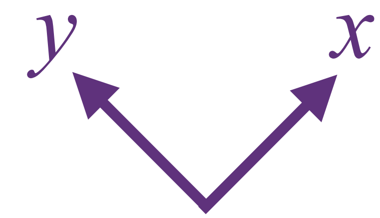
“R-map” of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007).





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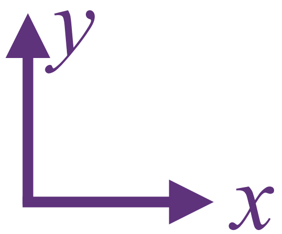
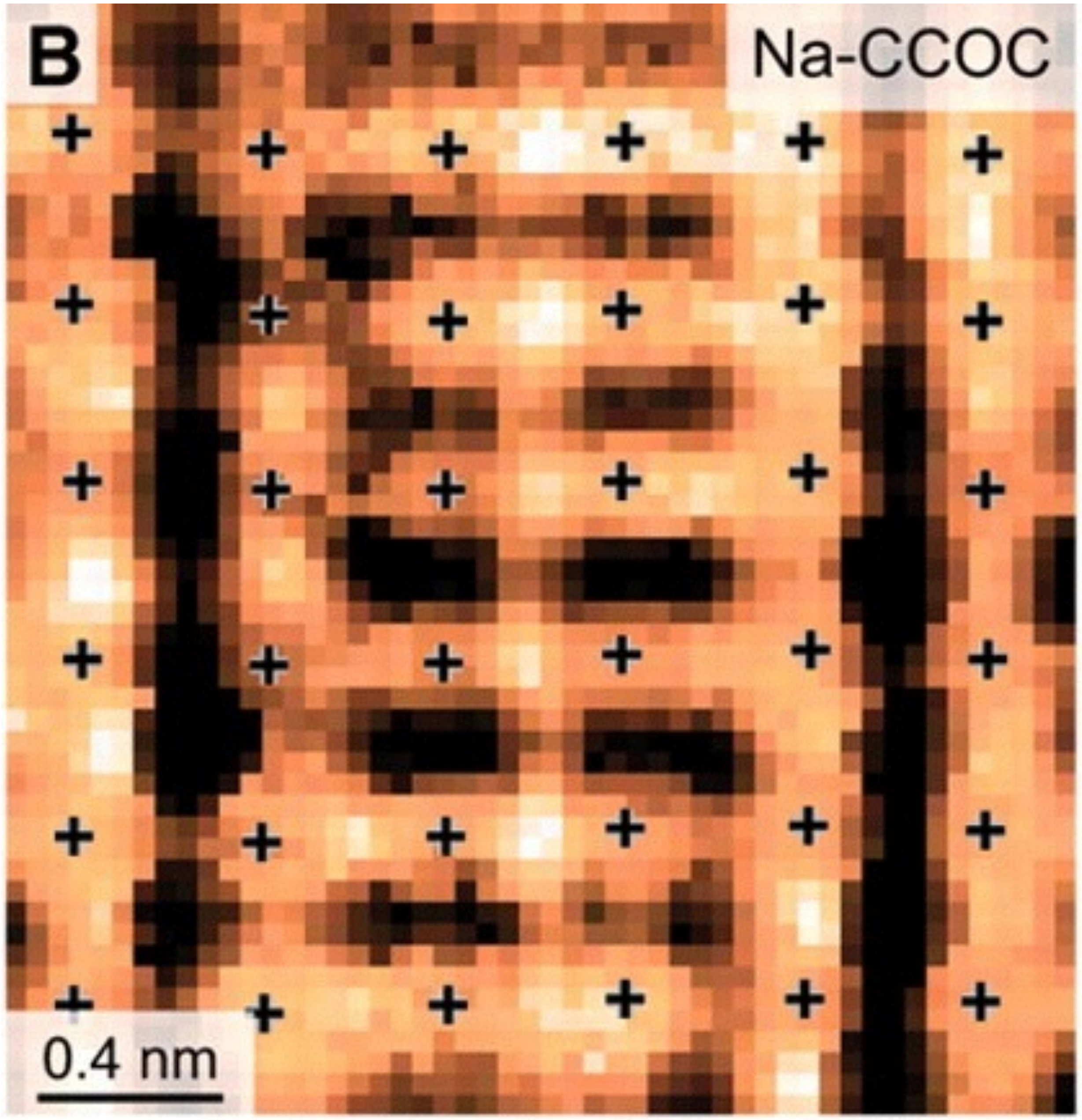
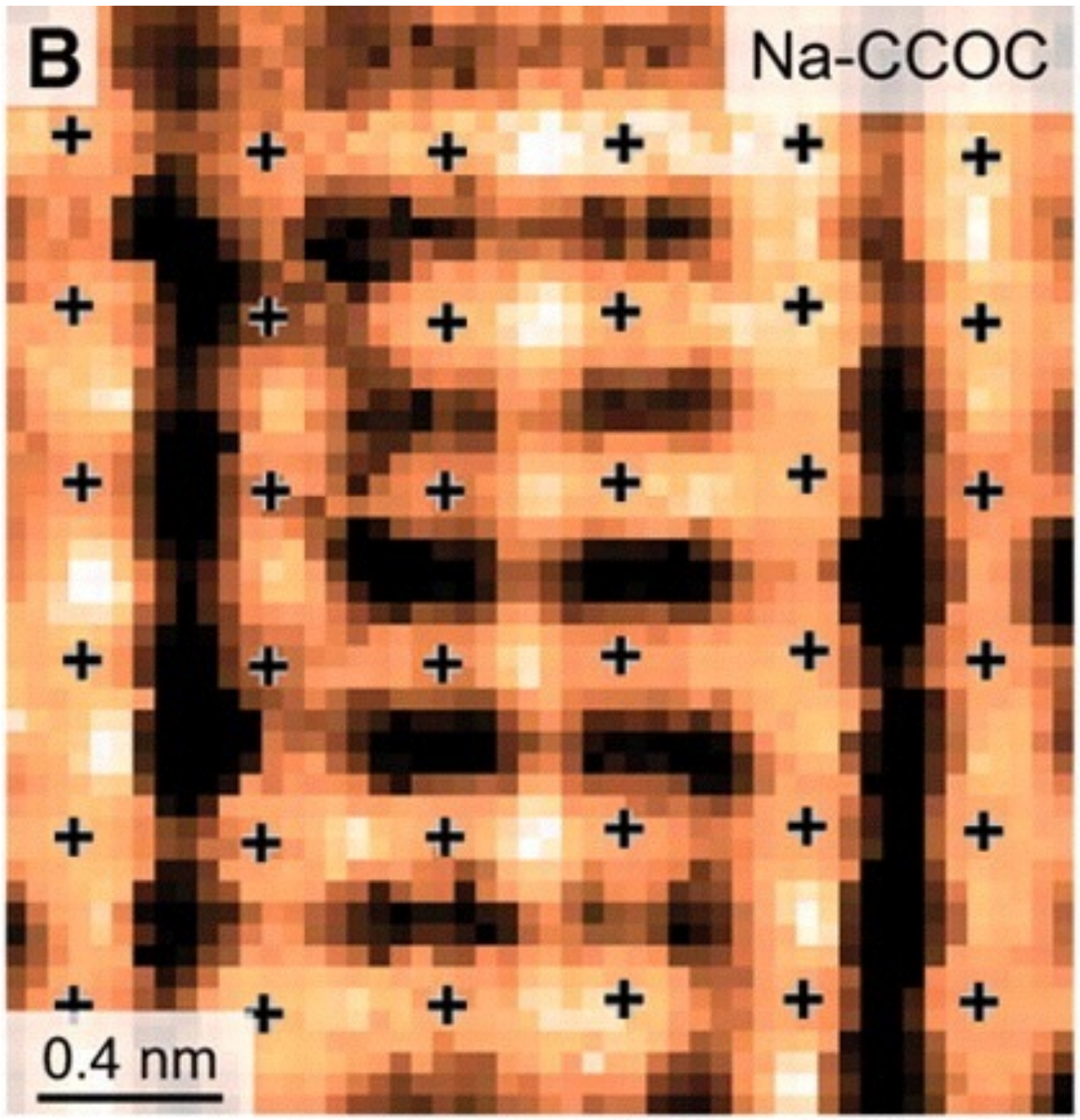




Y. Kohsaka *et al.*, Science **315**, 1380 (2007)



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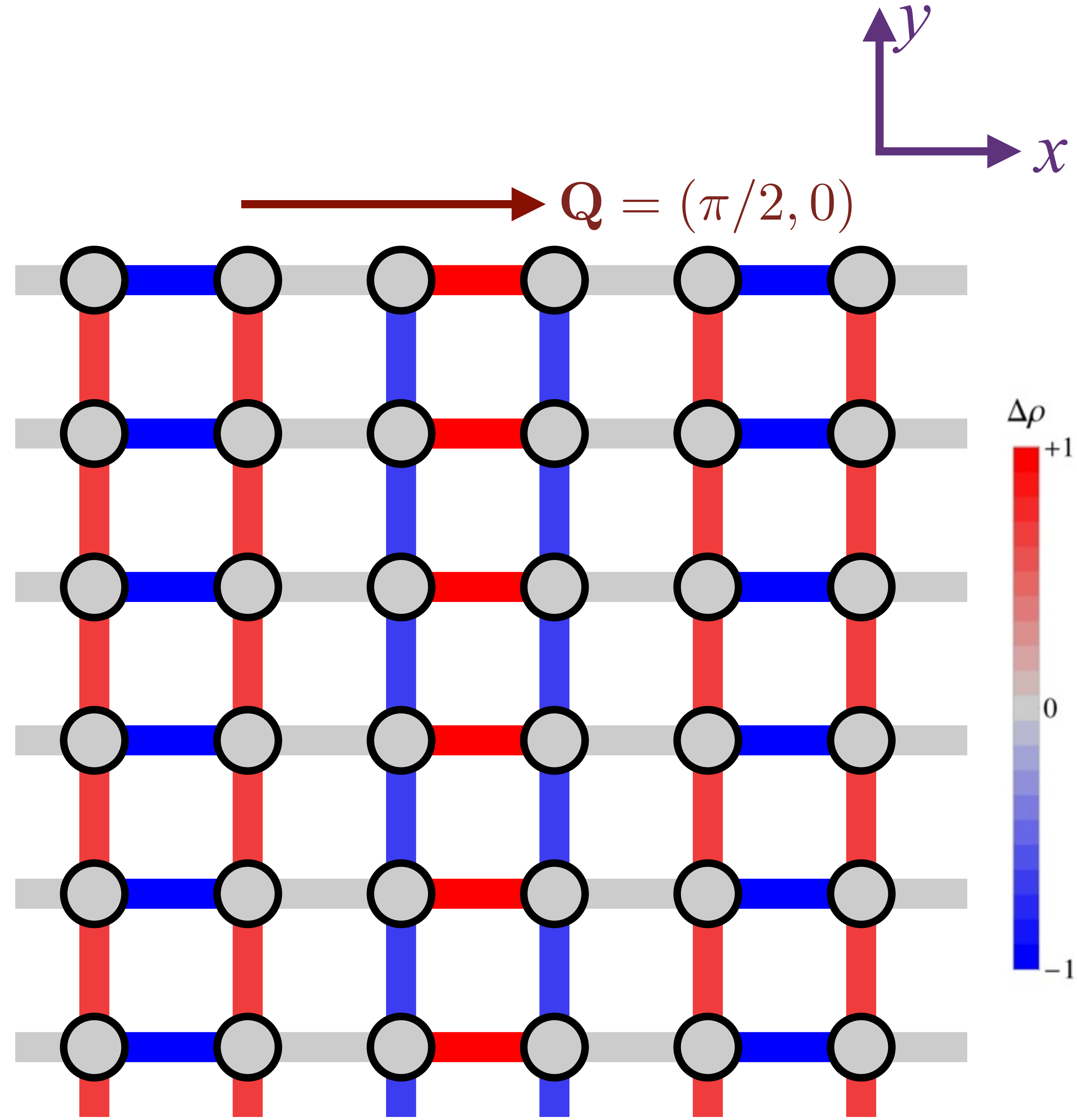

d-wave bond order

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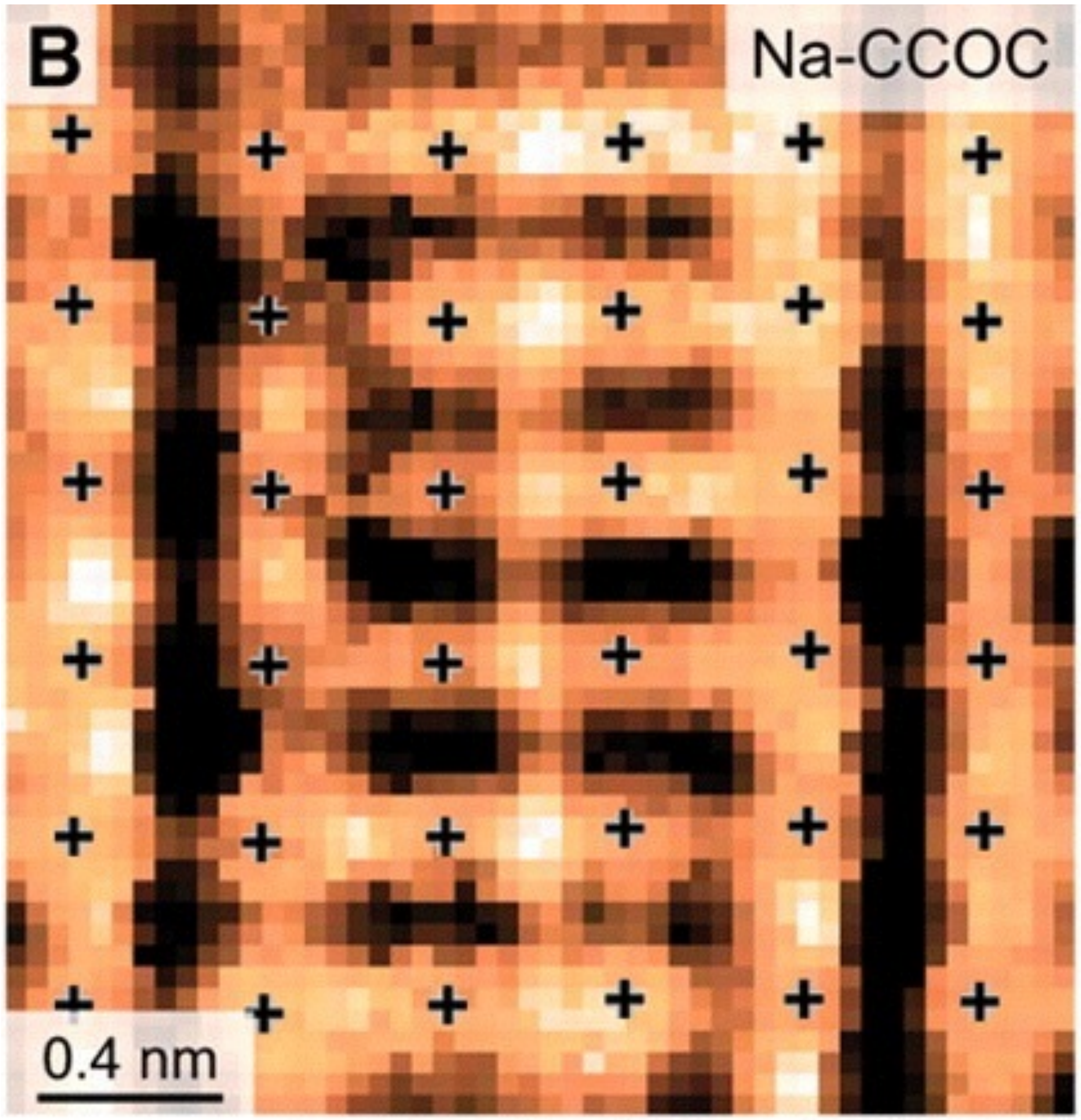
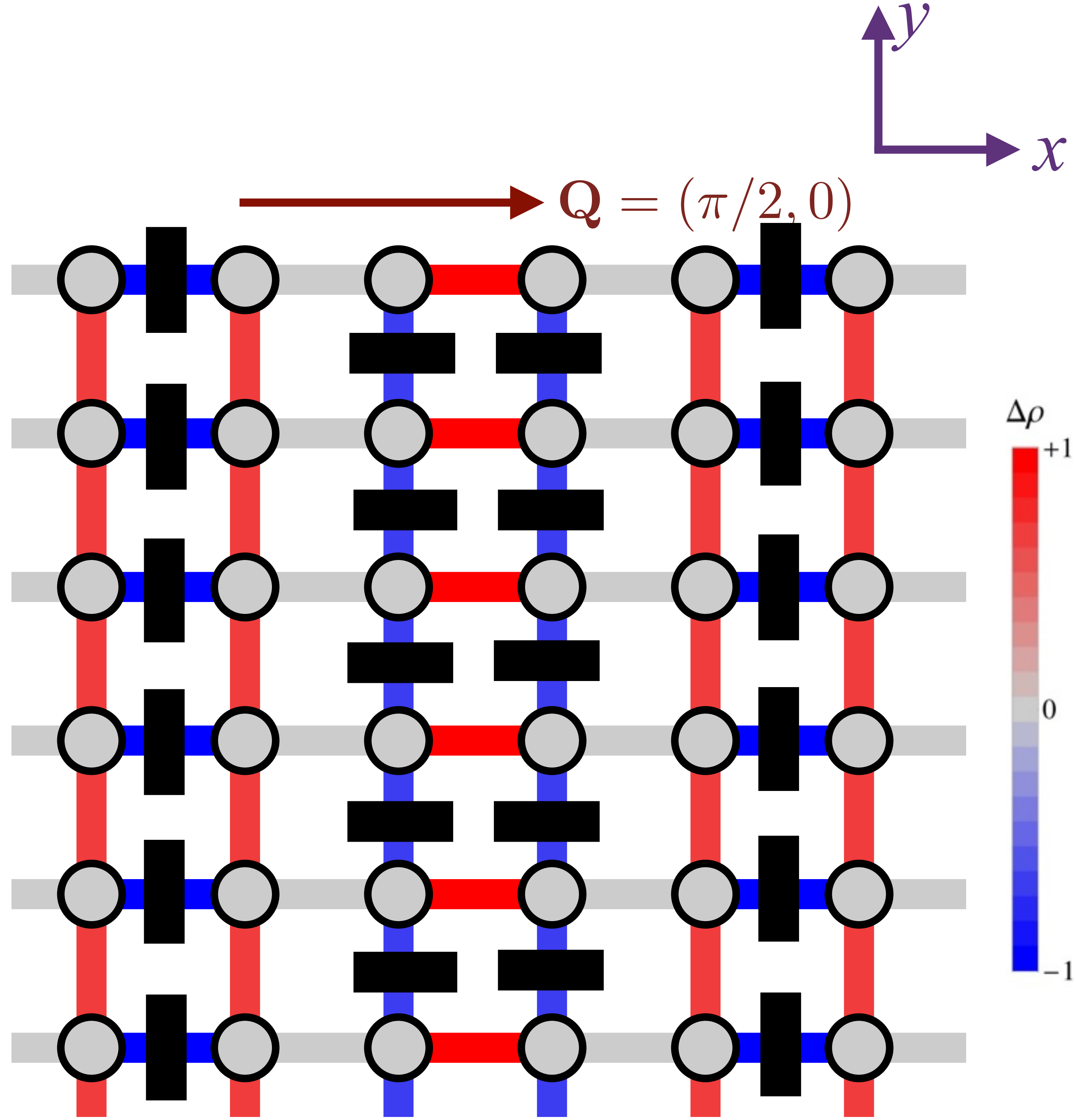


Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)



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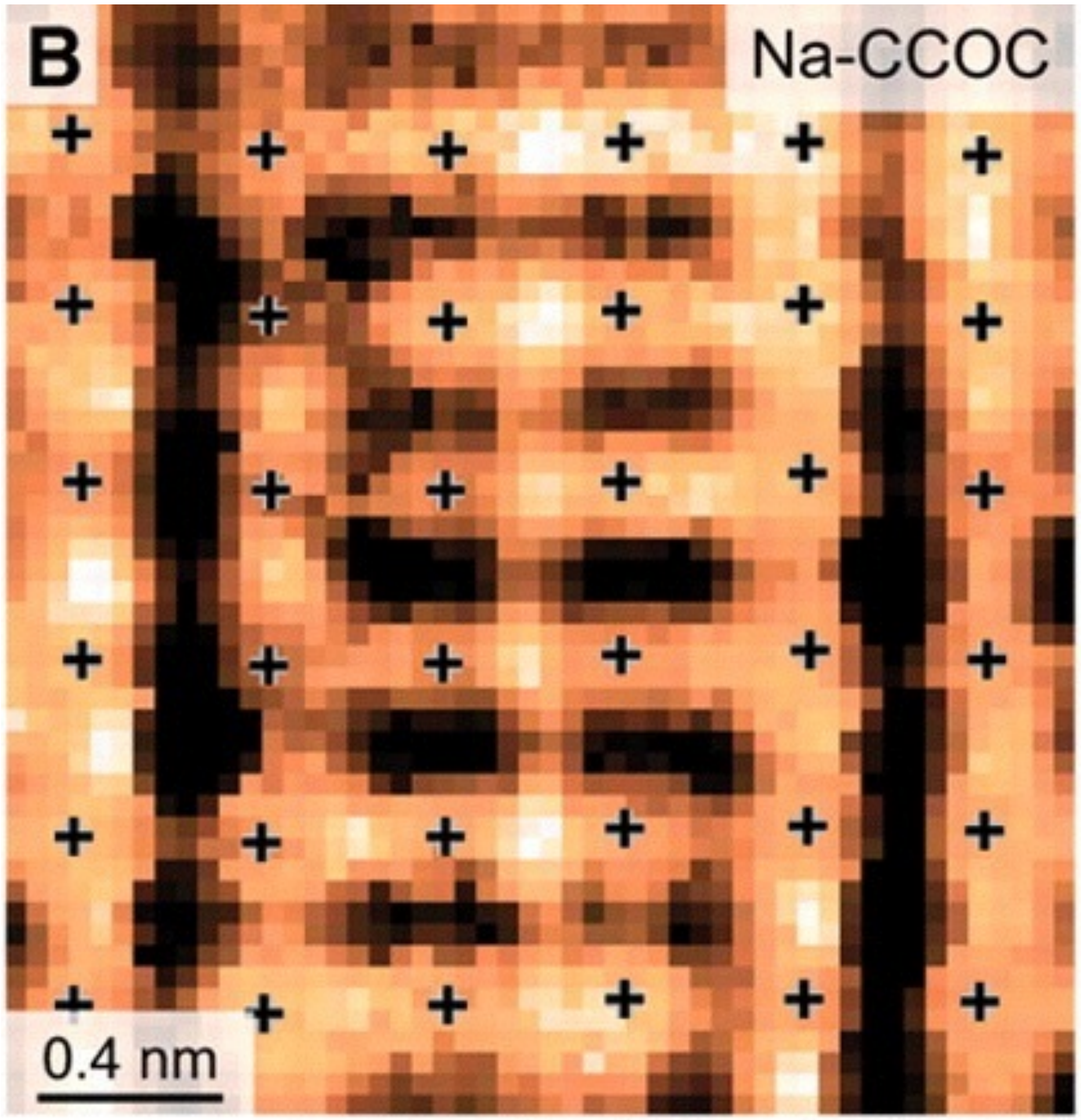

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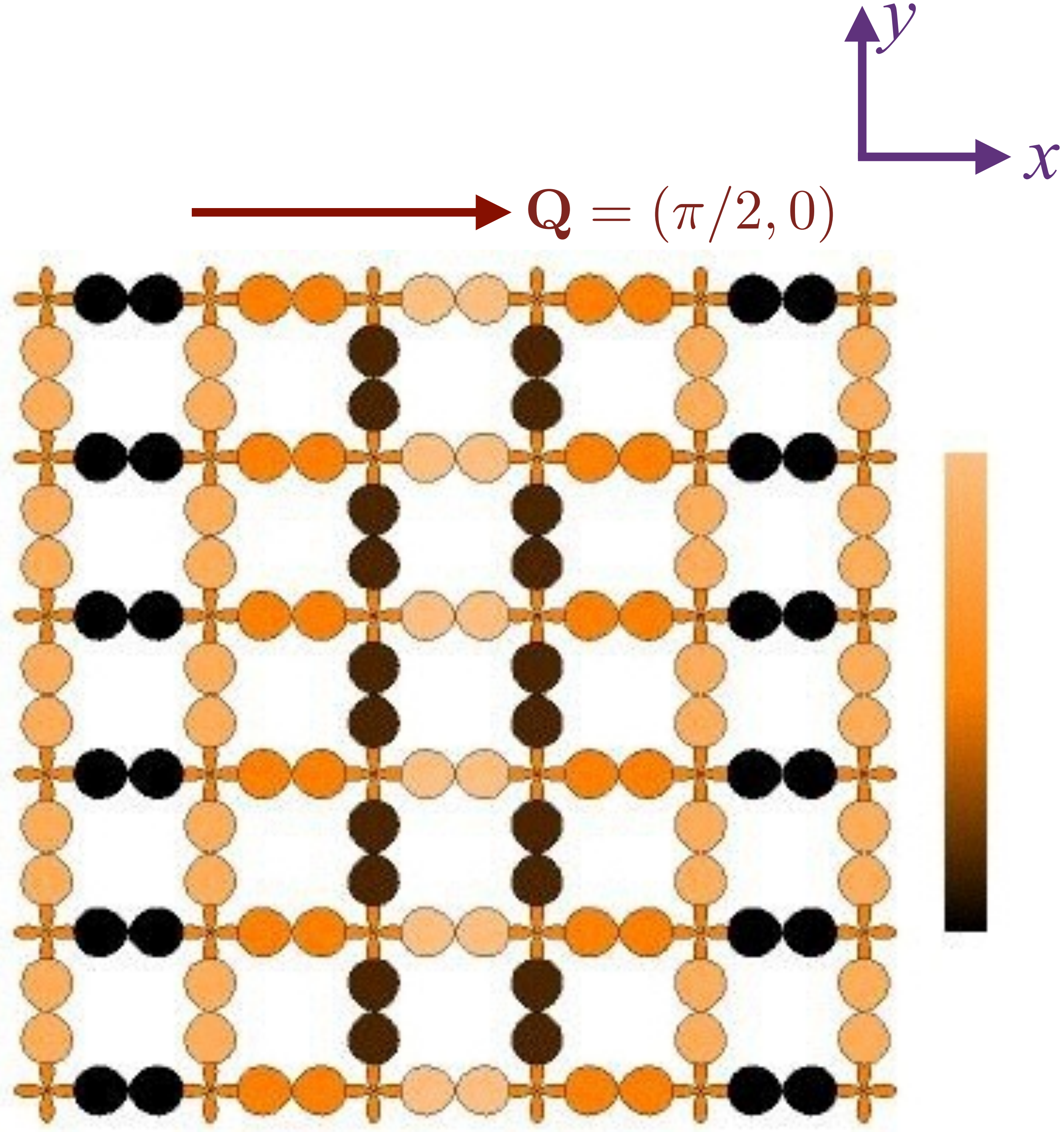

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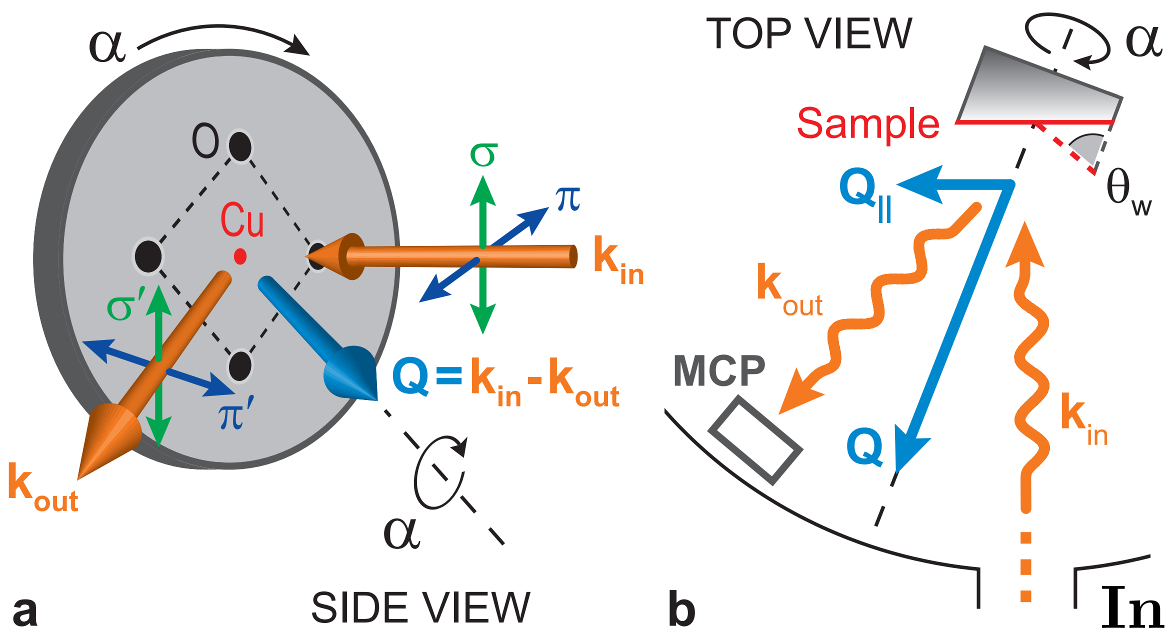
The symmetry of charge order in the cuprates

R. Comin, R. Sutarto, F. He, E. da Silva Neto, L. Chauviere, A. Frano, R. Liang, W.N. Hardy, D.A. Bonn, Y. Yoshida, H. Eisaki, J. E. Hoffman, B. Keimer, G.A. Sawatzky, and A. Damascelli, arXiv:1402.5415



Polarization and angular analysis of X-ray scattering at $\mathbf{Q} = (Q_0, 0)$ in Bi2201 and YBCO

In addition, by adopting a special experimental geometry, we also resolve the *intra-unit-cell* symmetry of the charge ordered state, which is revealed to be a *d*-wave bond-order. These results represent a fundamental advancement in our microscopic description of charge order in cuprates, and provide crucial insights for the understanding of its origin and interplay with superconductivity and magnetism.

The symmetry of charge order in the cuprates

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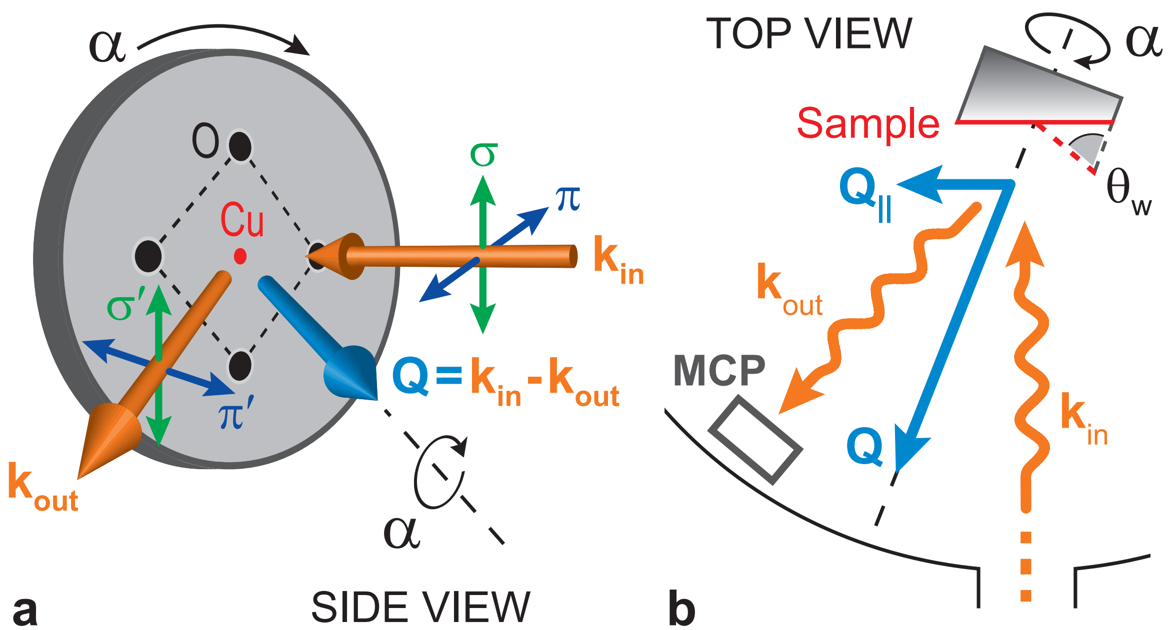
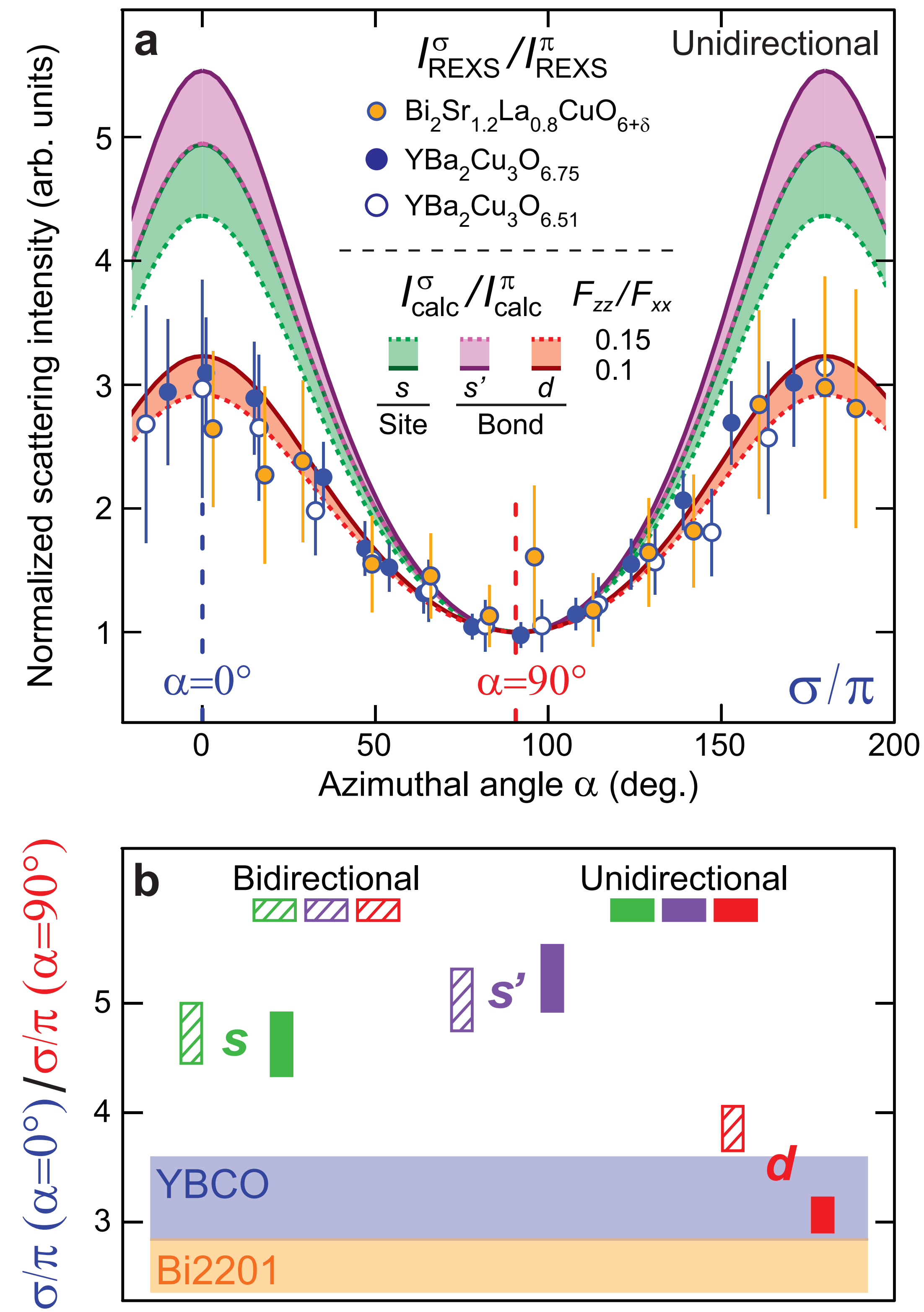
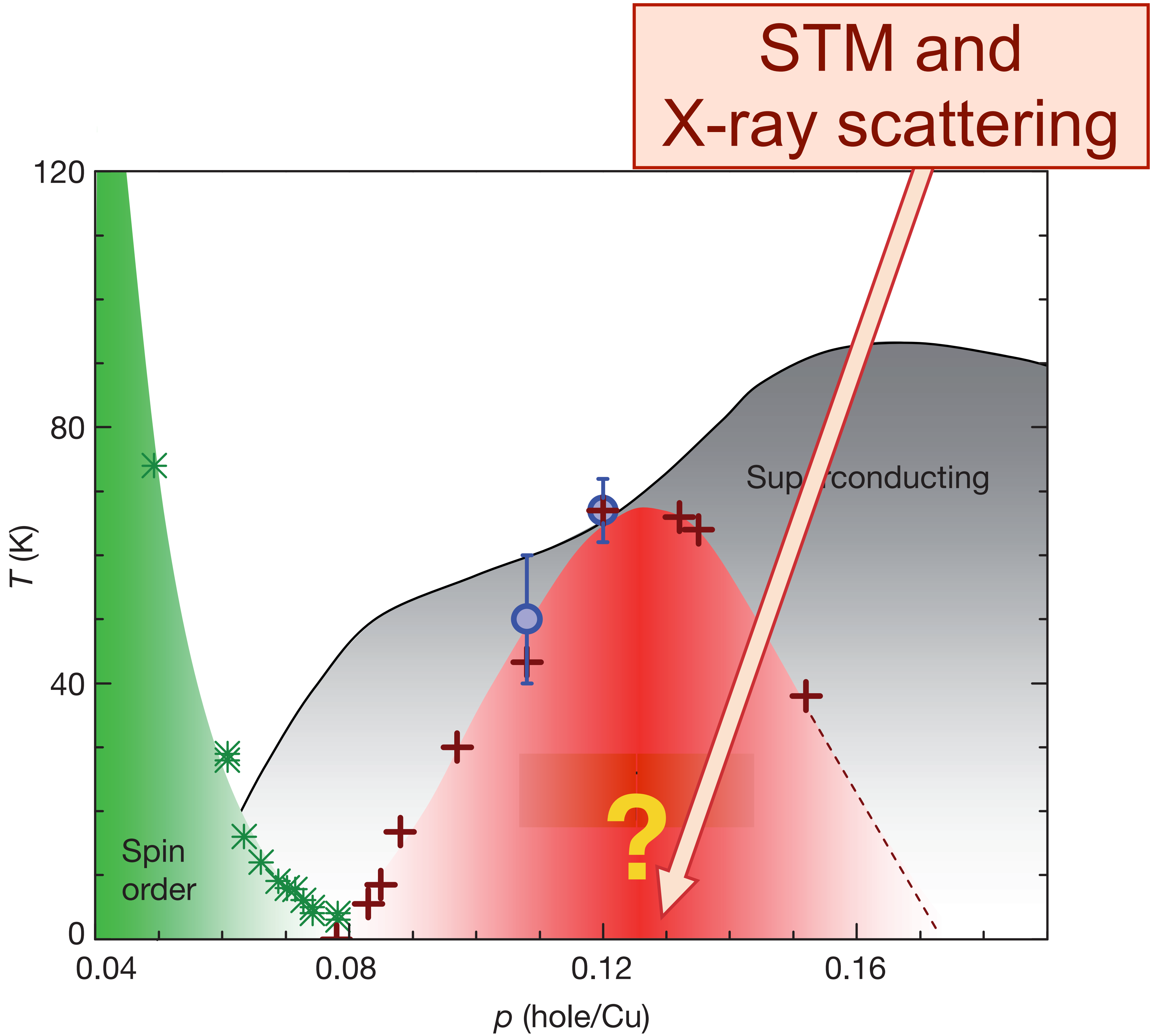
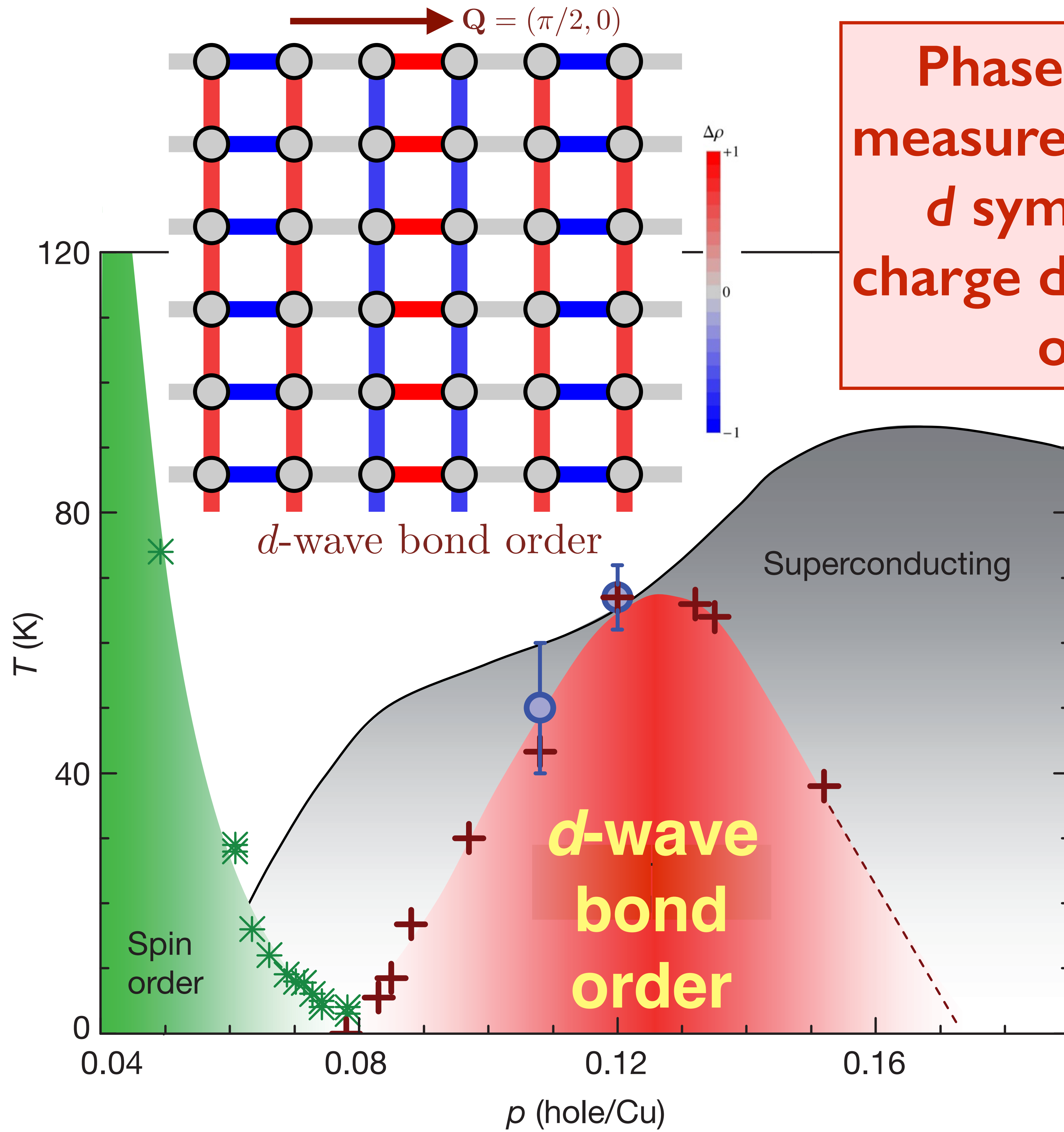




Δ_{CDW}	Probability levels P (%)	
	Bidirectional	Unidirectional
Δ_s	30.3	38.8
$\Delta_{s'}(\cos k_x + \cos k_y)$	12.0	6.0
$\Delta_d\,(\cos k_x - \cos k_y)$	**81.8**	**87.6**



T. Wu, H. Mayaffre, S. Kramer, M. Horvatic, C. Berthier, W.N. Hardy, R. Liang, D.A. Bonn, and M.-H. Julien, Nature **477**, 191 (2011).



Phase-sensitive measurement of the *d* symmetry of charge density wave order

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, arXiv:1404.0362

Outline

1. *d*-wave superconductivity

2. Low hole density state:
   d-wave bond order

3. Theoretical background

4. Evolution of Fermi surface

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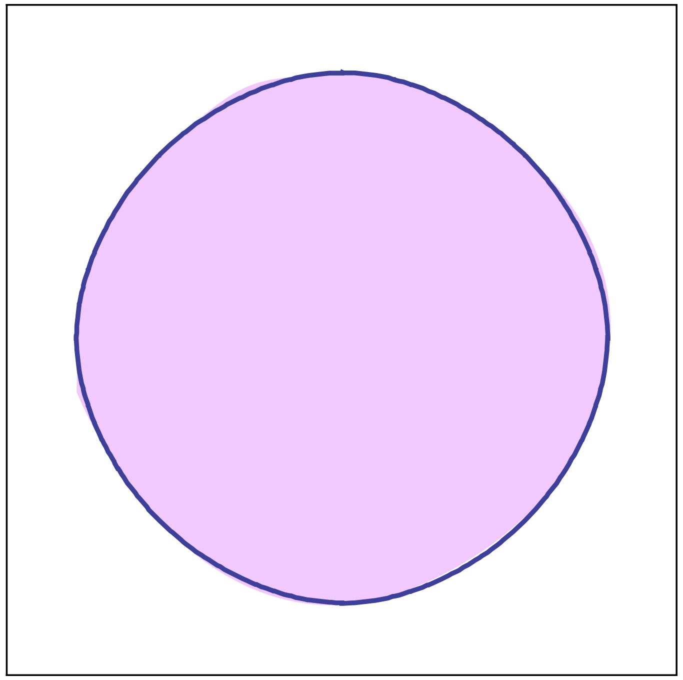
Fermi surface+antiferromagnetism

Metal with "large"
Fermi surface



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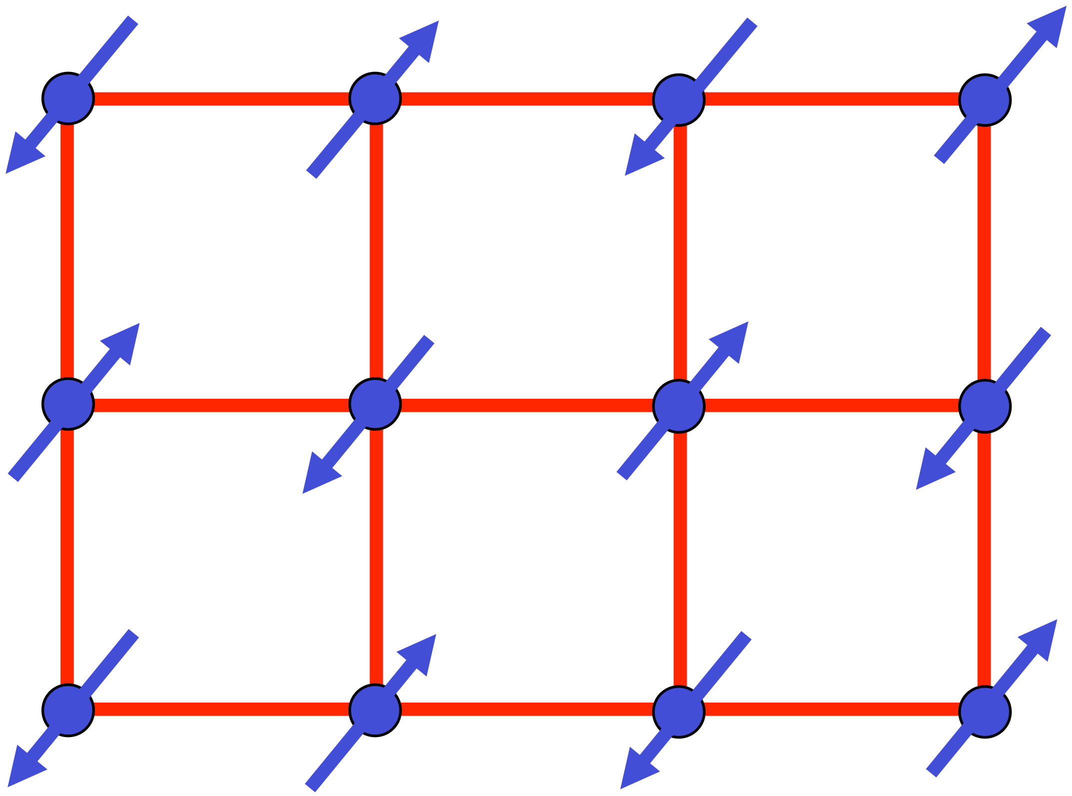
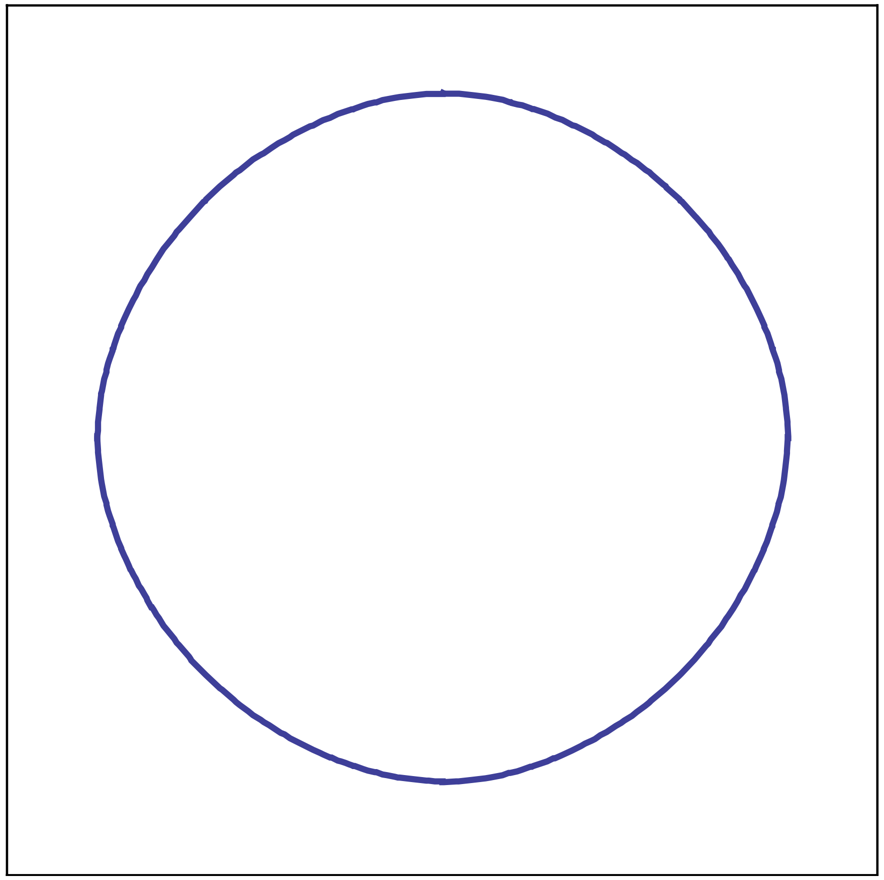


The electron spin polarization obeys

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

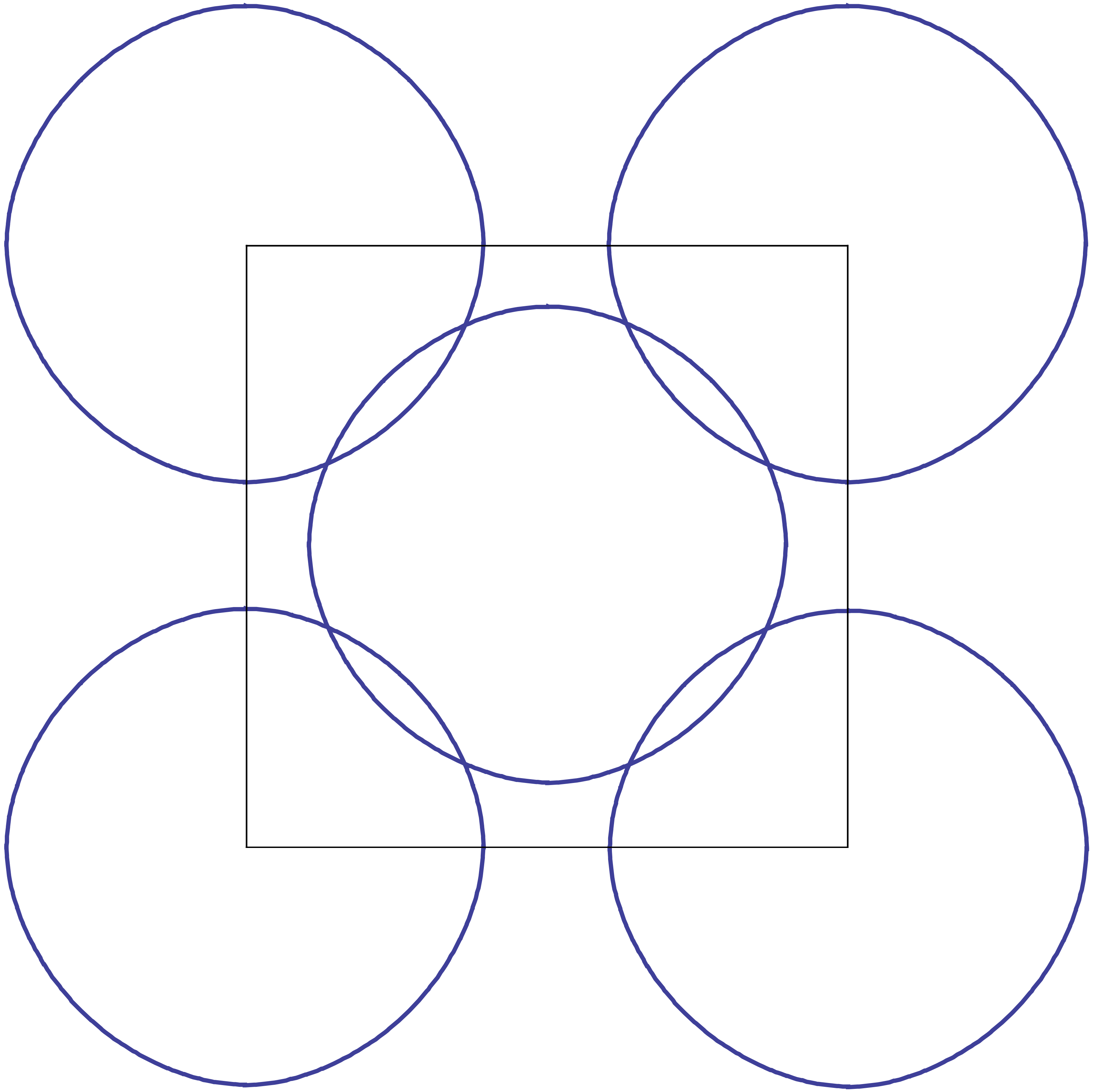
where $\mathbf{K} = (\pi, \pi)$ is the ordering wavevector.

Fermi surface+antiferromagnetism



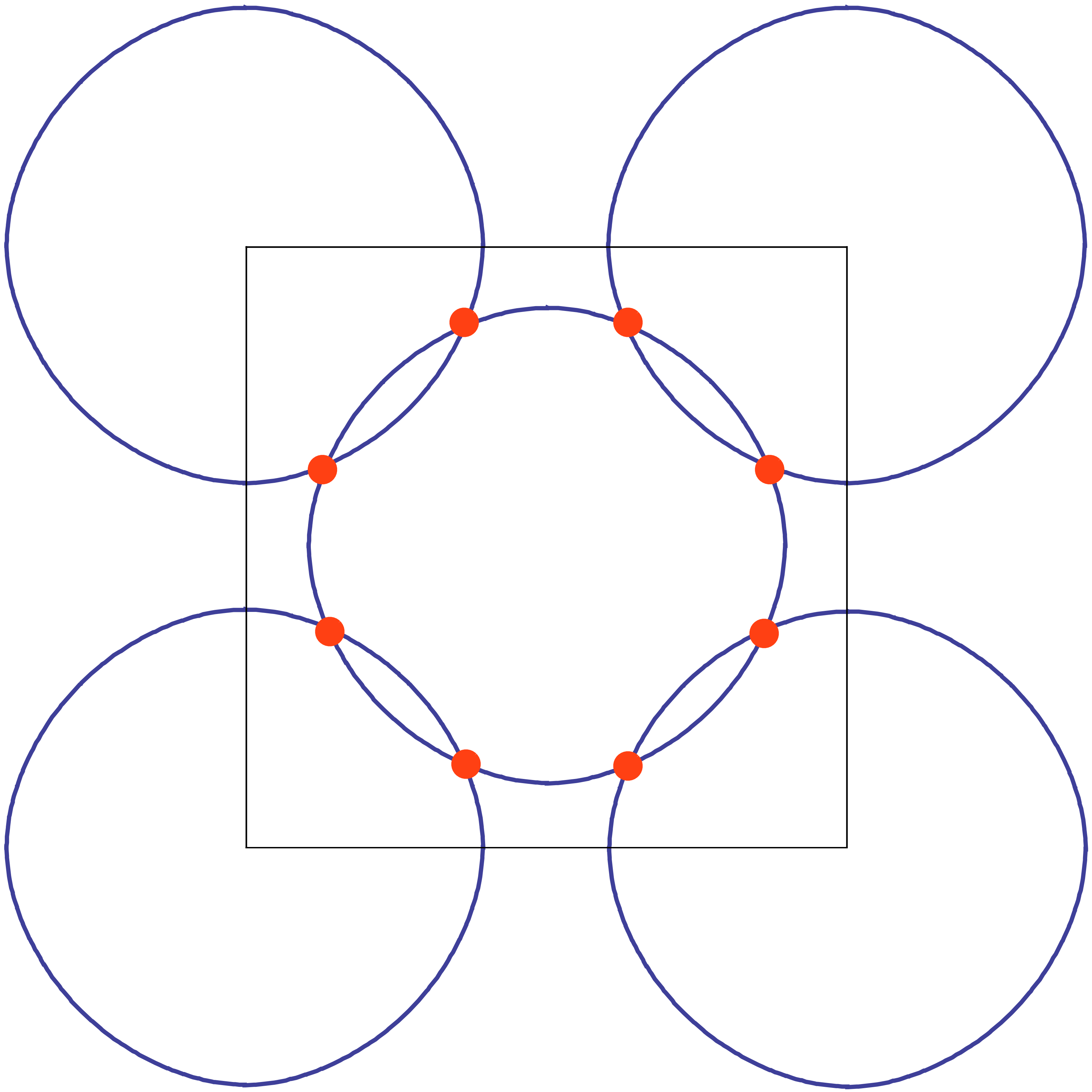
Metal with "large" Fermi surface

Fermi surface+antiferromagnetism



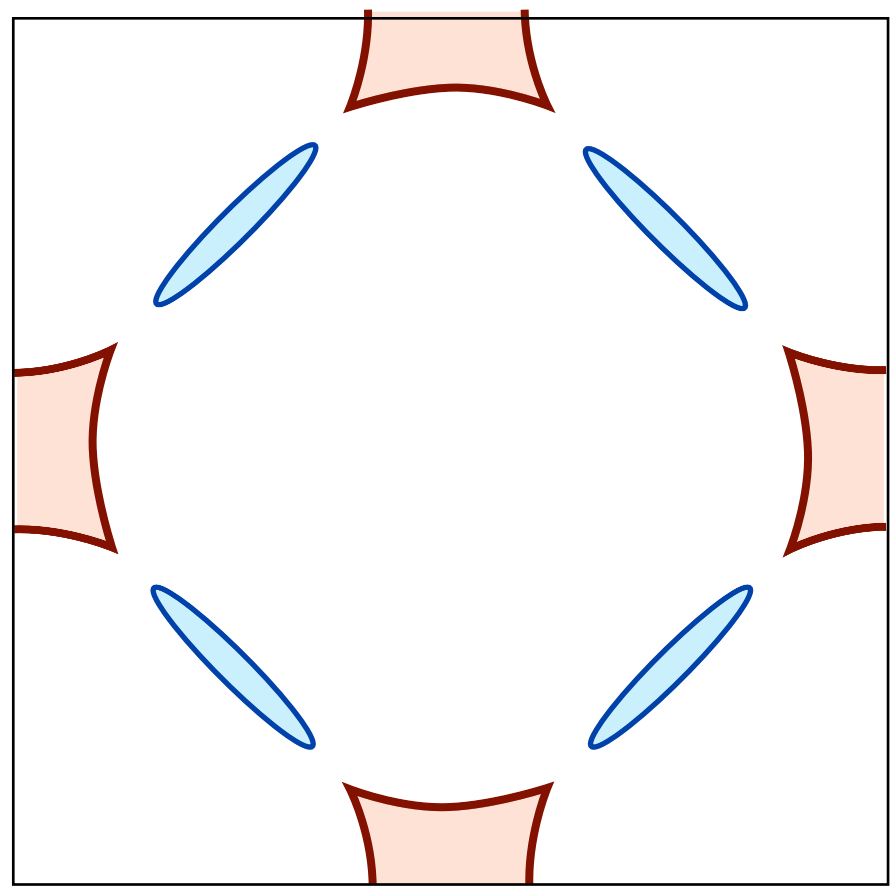
Fermi surfaces translated by $\mathbf{K} = (\pi, \pi)$.

Fermi surface+antiferromagnetism



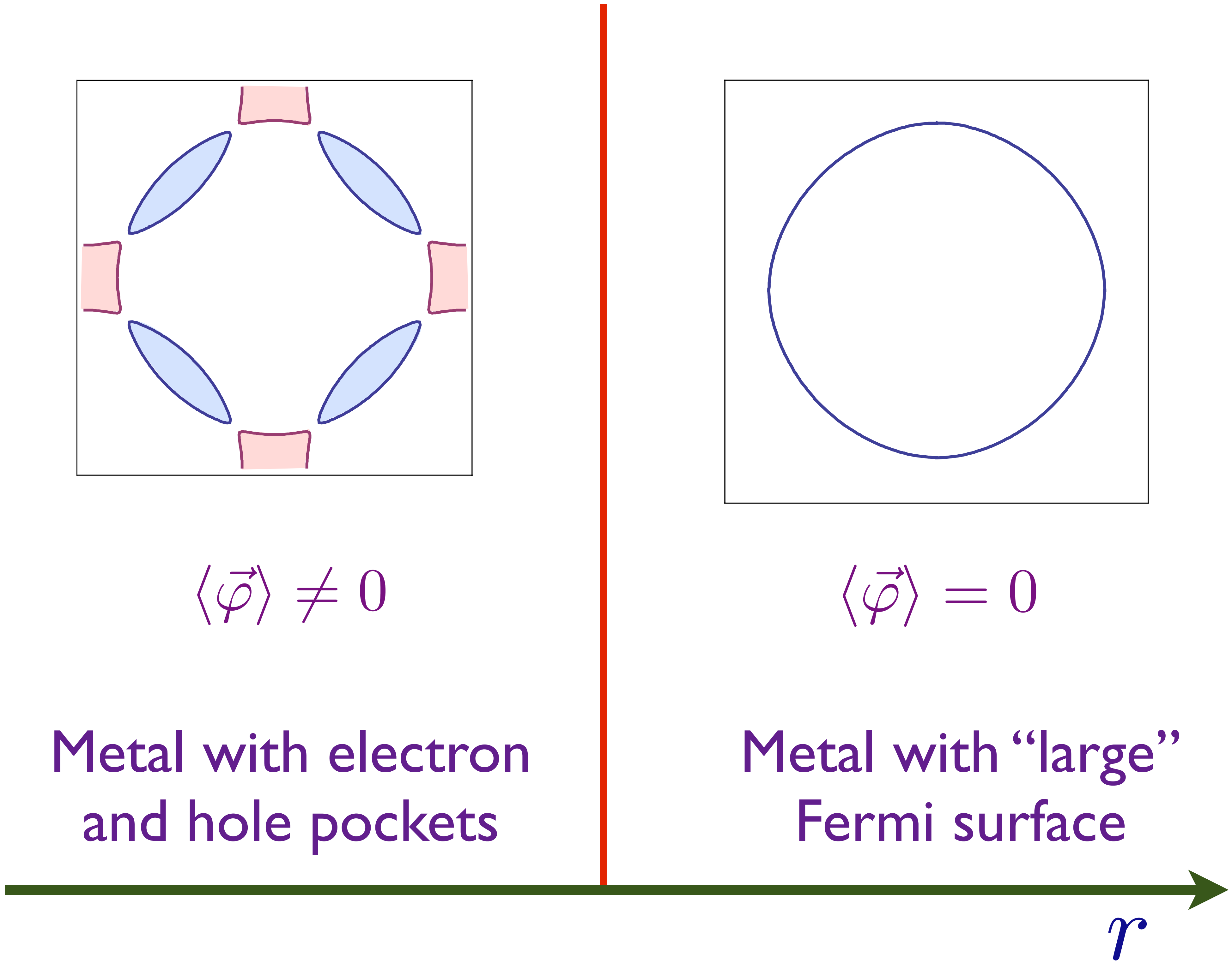
“Hot” spots

Fermi surface+antiferromagnetism

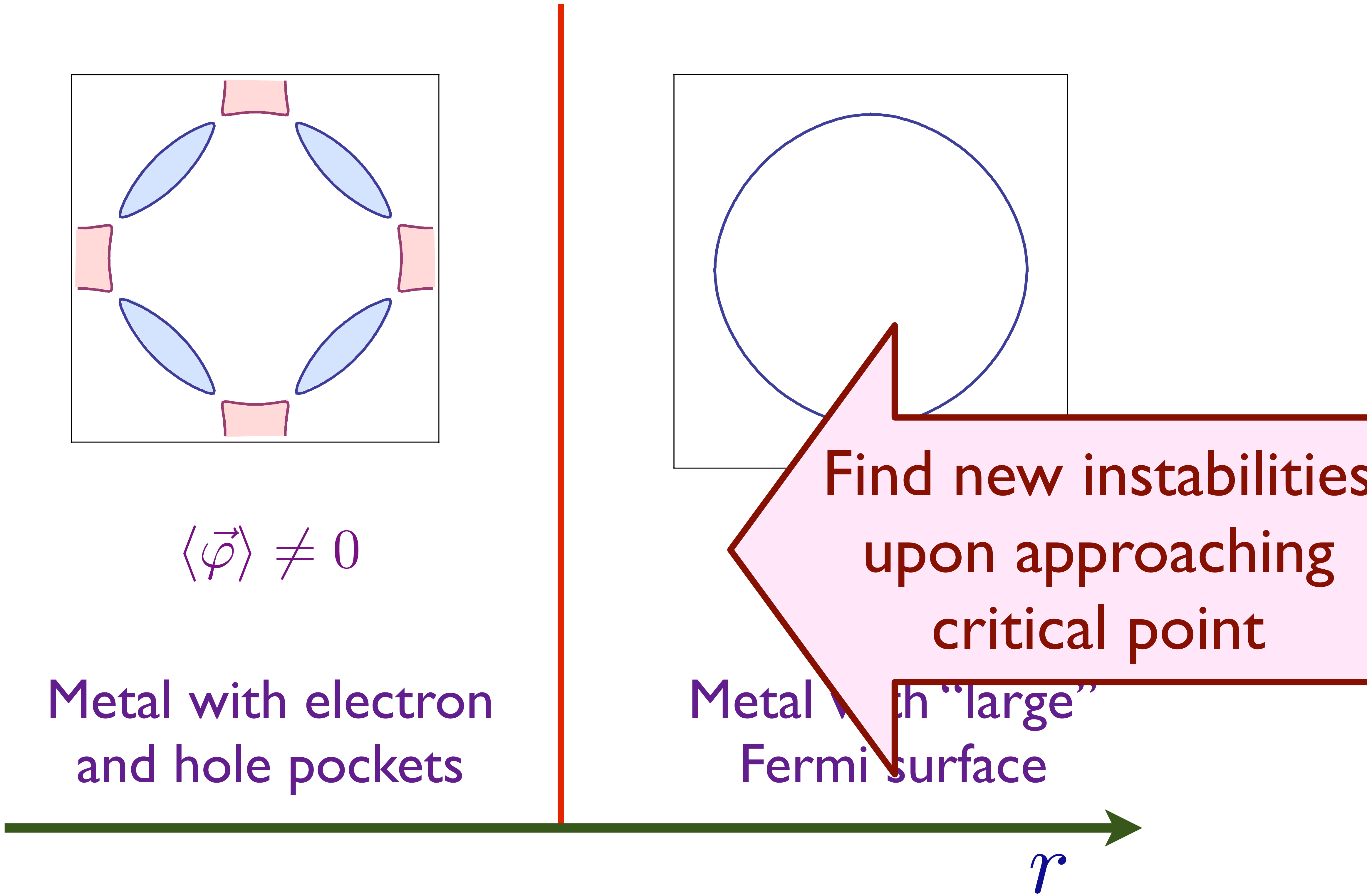


Electron and hole pockets in antiferromagnetic phase with $\langle\vec{\varphi}\rangle \neq 0$

Quantum phase transition with onset of antiferromagnetism in a metal

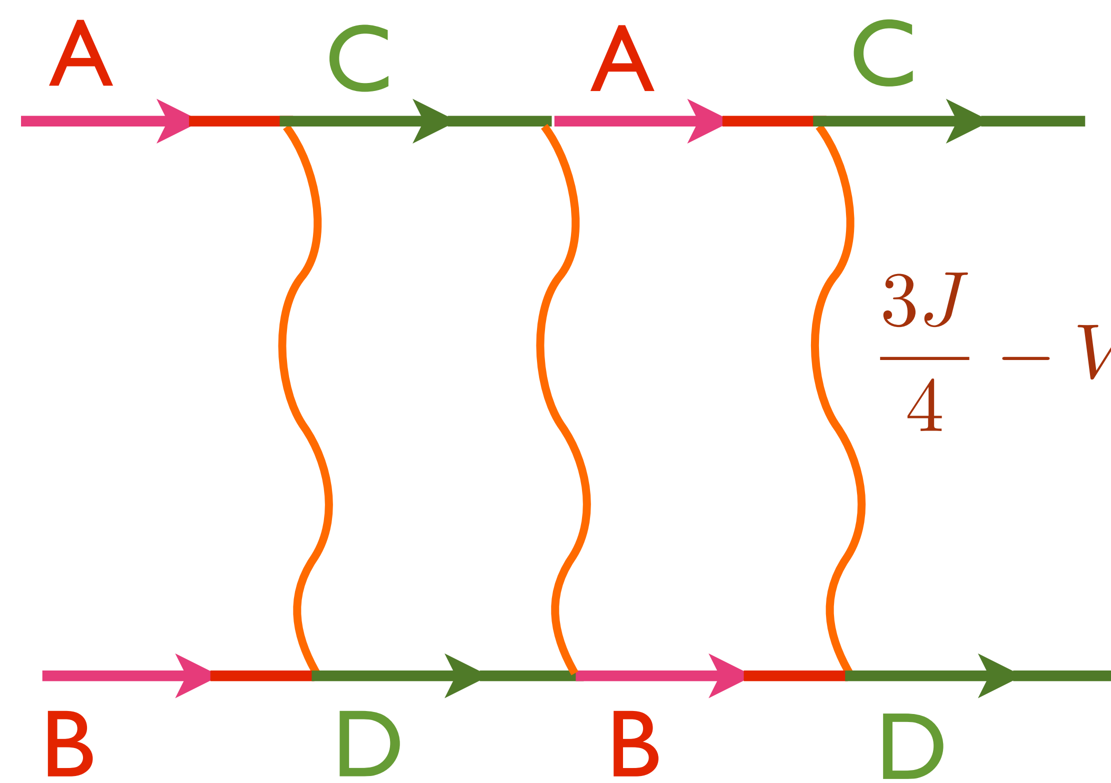


Quantum phase transition with onset of antiferromagnetism in a metal



Pairing "glue" from antiferromagnetic fluctuations

$$H = -\sum_{i,j} t_{ij} c^{\dagger}_{i\alpha} c_{j\alpha} + J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j + V \sum_{\langle ij \rangle} n_i \, n_j + \ldots$$



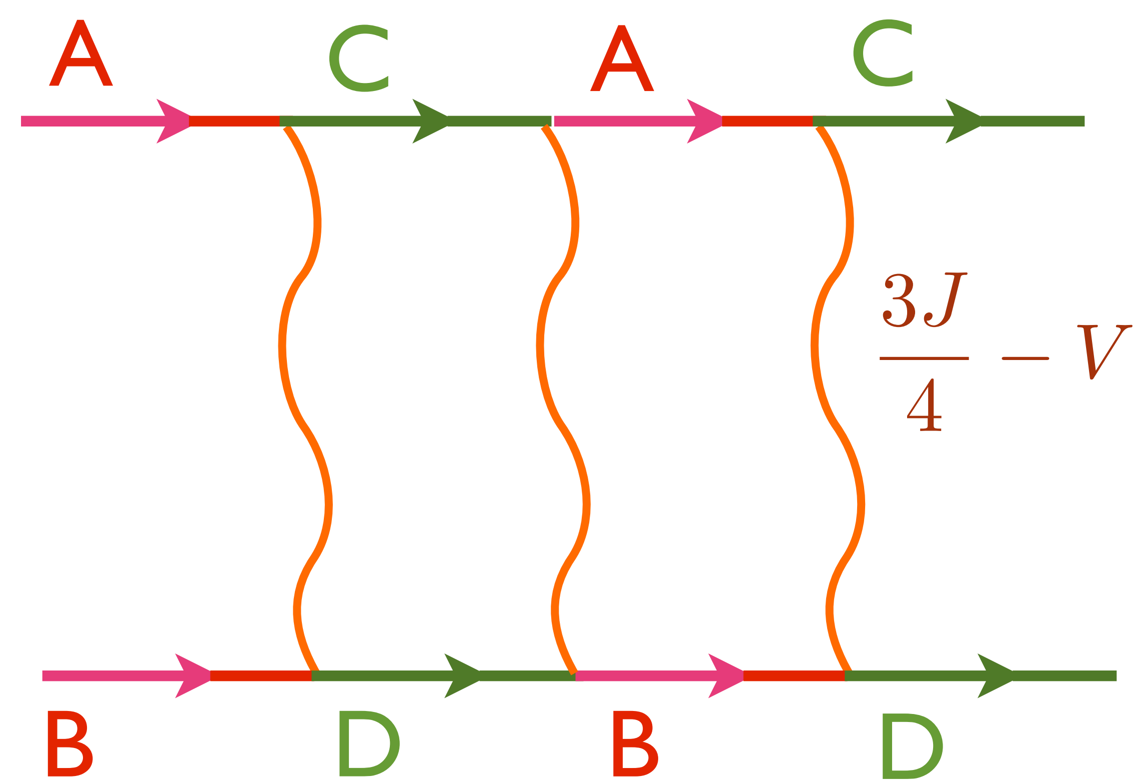
Theory

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)

Pairing "glue" from antiferromagnetic fluctuations

Electron hopping

$$H = -\sum_{i,j} t_{ij} c^{\dagger}_{i\alpha} c_{j\alpha} + J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j + V \sum_{\langle ij \rangle} n_i \, n_j + \ldots$$



Theory

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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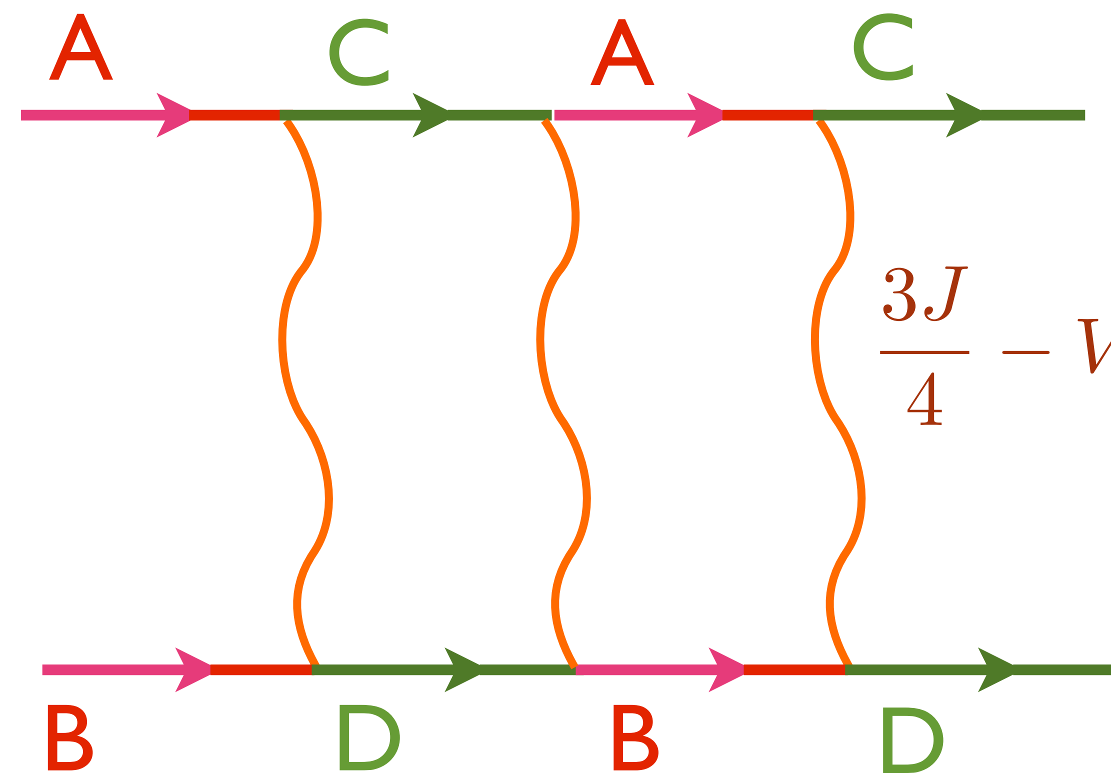


Antiferromagnetic exchange interaction

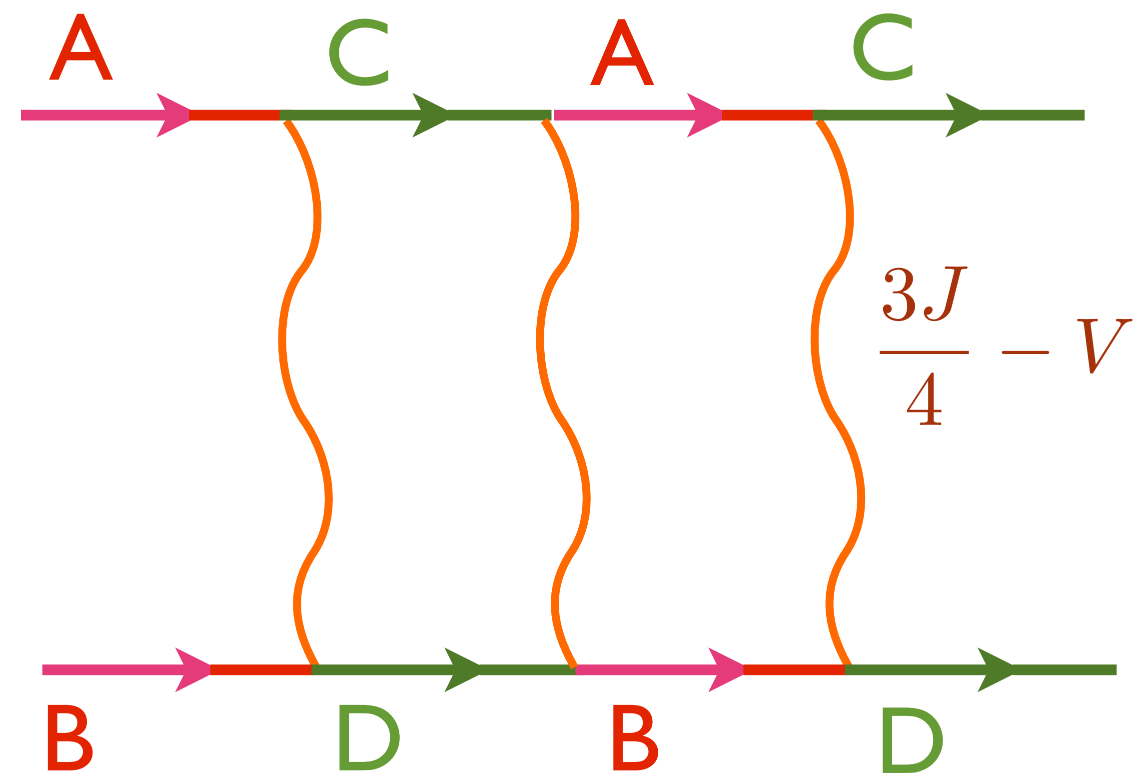
Theory

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)

Pairing "glue" from antiferromagnetic fluctuations

$$H = -\sum_{i,j} t_{ij} c^\dagger_{i\alpha} c_{j\alpha} + J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j + V \sum_{\langle ij \rangle} n_i n_j + \ldots$$

Coulomb repulsion



Theory

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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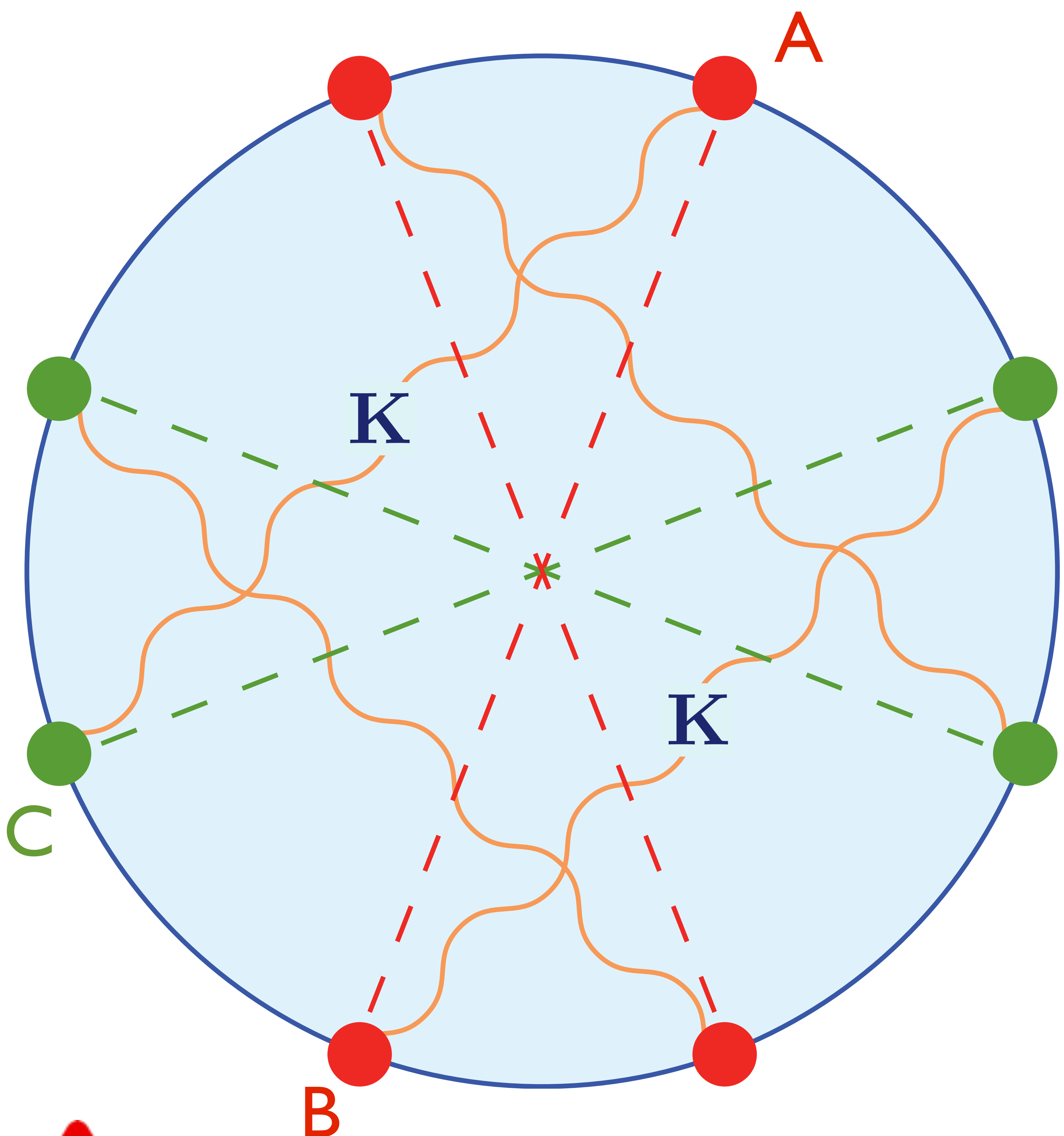
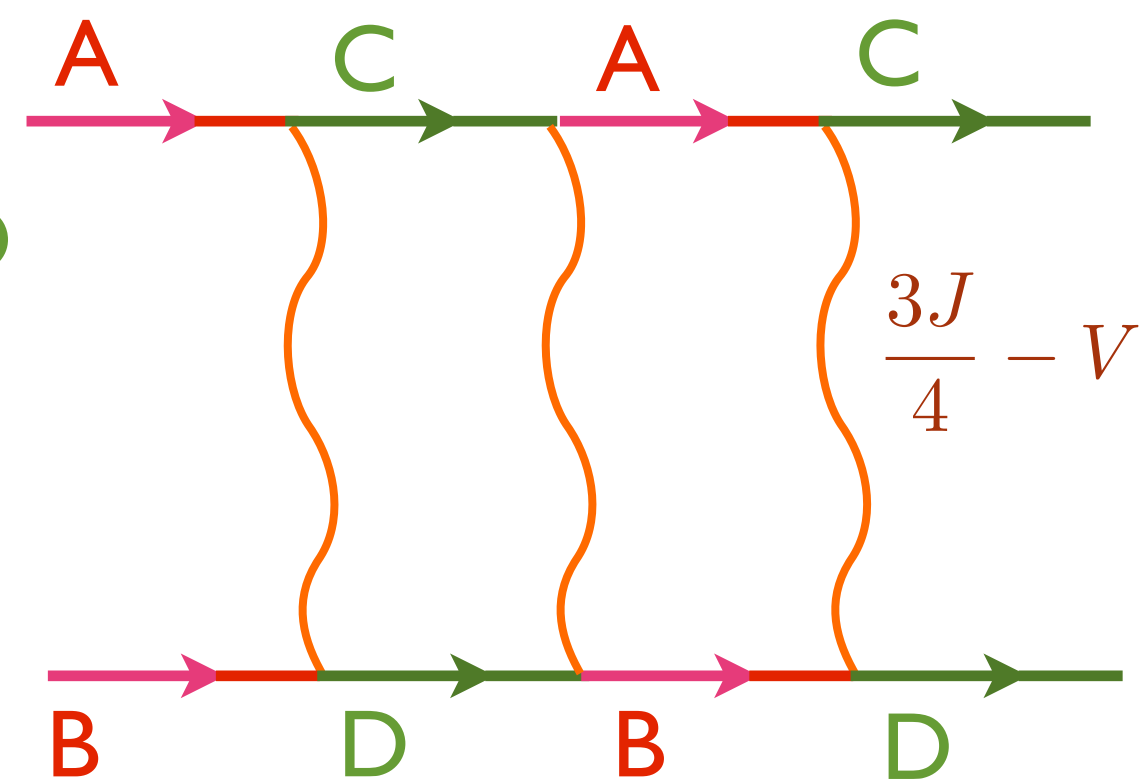
Pairing "glue" from antiferromagnetic fluctuations

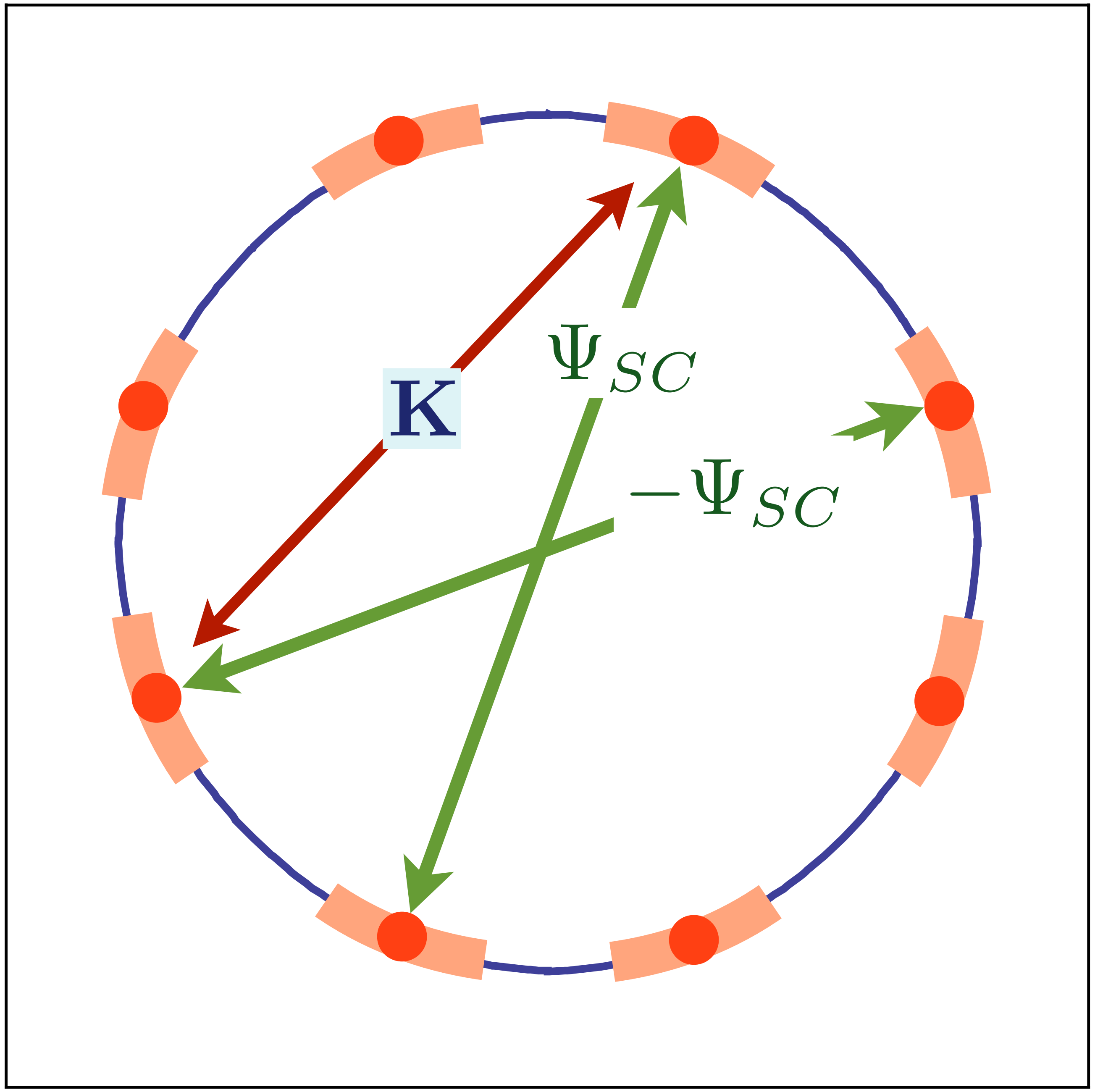


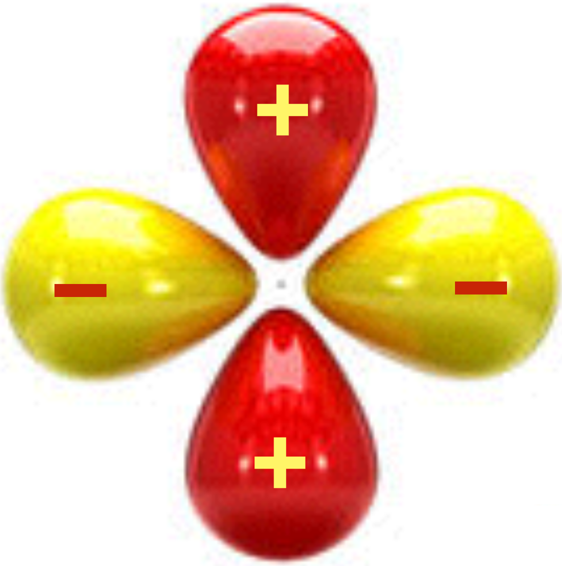


Theory

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)

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





d-wave superconductor:
sign-changing pairing amplitude

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)

Pseudospin symmetry of the exchange interaction

$$H_J = J\,\vec{S}_1 \cdot \vec{S}_2$$

with $\vec{S}_i = \frac{1}{2} c^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} c_{i\beta}$ is the antiferromagnetic exchange interaction. Introduce the Nambu spinor

$$\Psi_{i\uparrow} = \begin{pmatrix} c_{i\uparrow} \\ c^\dagger_{i\downarrow} \end{pmatrix} \quad , \quad \Psi_{i\downarrow} = \begin{pmatrix} c_{i\downarrow} \\ -c^\dagger_{i\uparrow} \end{pmatrix}$$

Then we can write

$$H_J = \frac{1}{8} J \left(\Psi^\dagger_{1\alpha a} \vec{\sigma}_{\alpha\beta} \Psi_{1\beta a} \right) \cdot \left(\Psi^\dagger_{2\gamma b} \vec{\sigma}_{\gamma\delta} \Psi_{2\delta b} \right)$$

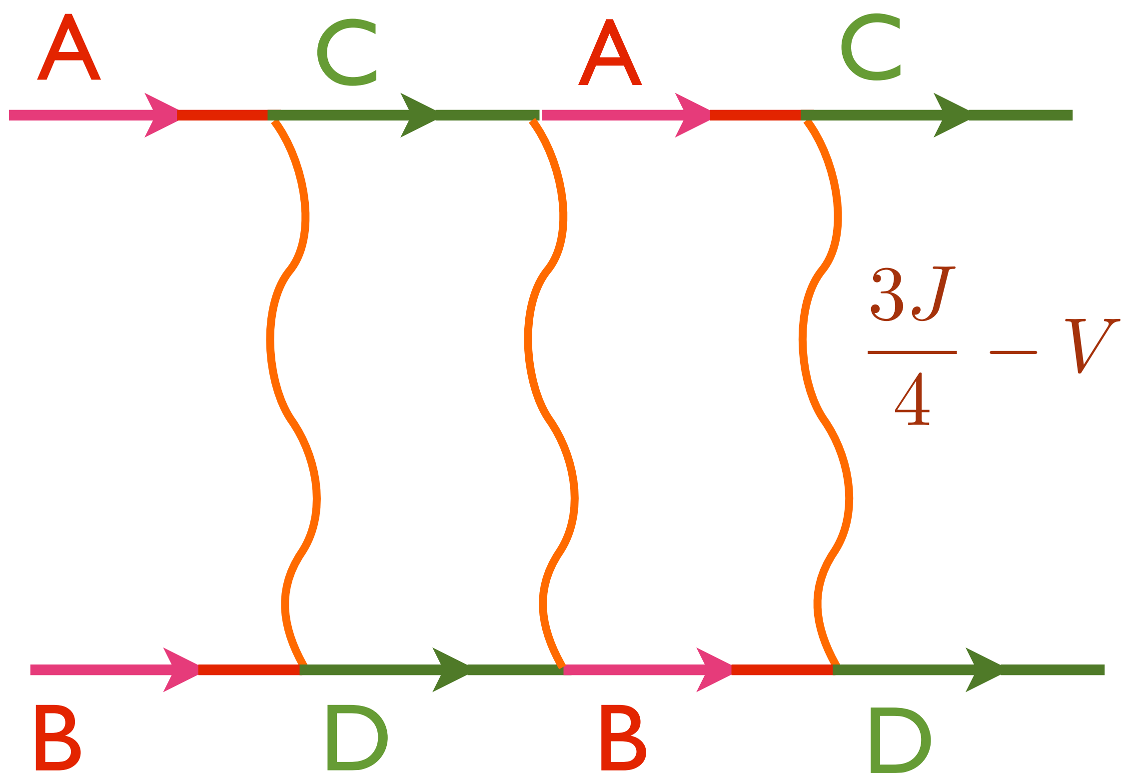
where a, b are the Nambu indices. This form makes explicit the symmetry under *independent* SU(2) pseudospin transformations on each site $\Psi_{i\alpha a} \to U_{i,ab} \Psi_{i\alpha b}$

Theory

I. Affleck, Z. Zou, T. Hsu, and P. W. Anderson, Phys. Rev. B **38**, 745 (1988)
E. Dagotto, E. Fradkin, and A. Moreo, Phys. Rev. B **38**, 2926 (1988)
P. A. Lee, N. Nagaosa, and X.-G. Wen, Rev. Mod. Phys. **78**, 17 (2006)

Pairing "glue" from antiferromagnetic fluctuations

$$H = -\sum_{i,j} t_{ij} c^\dagger_{i\alpha} c_{j\alpha} + J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j + V \sum_{\langle ij \rangle} n_i n_j + \ldots$$

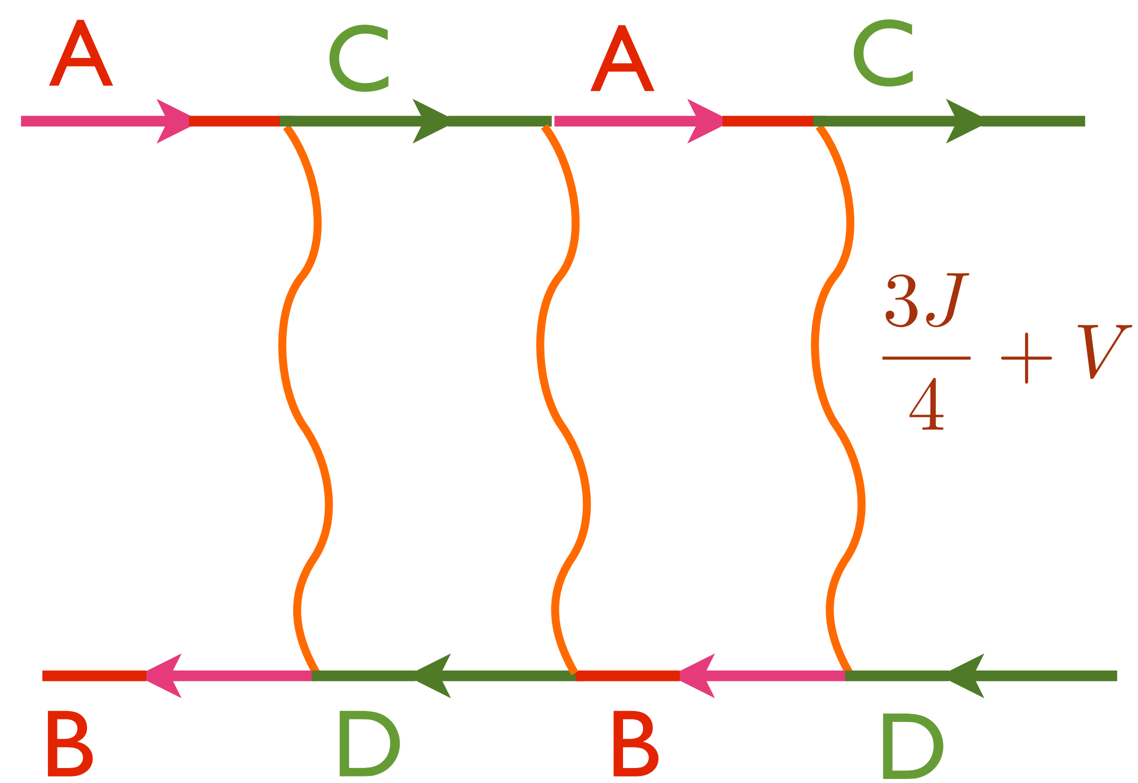


Theory

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)

<u>*Same*</u> "glue" leads to *d*-wave particle-hole pairing !

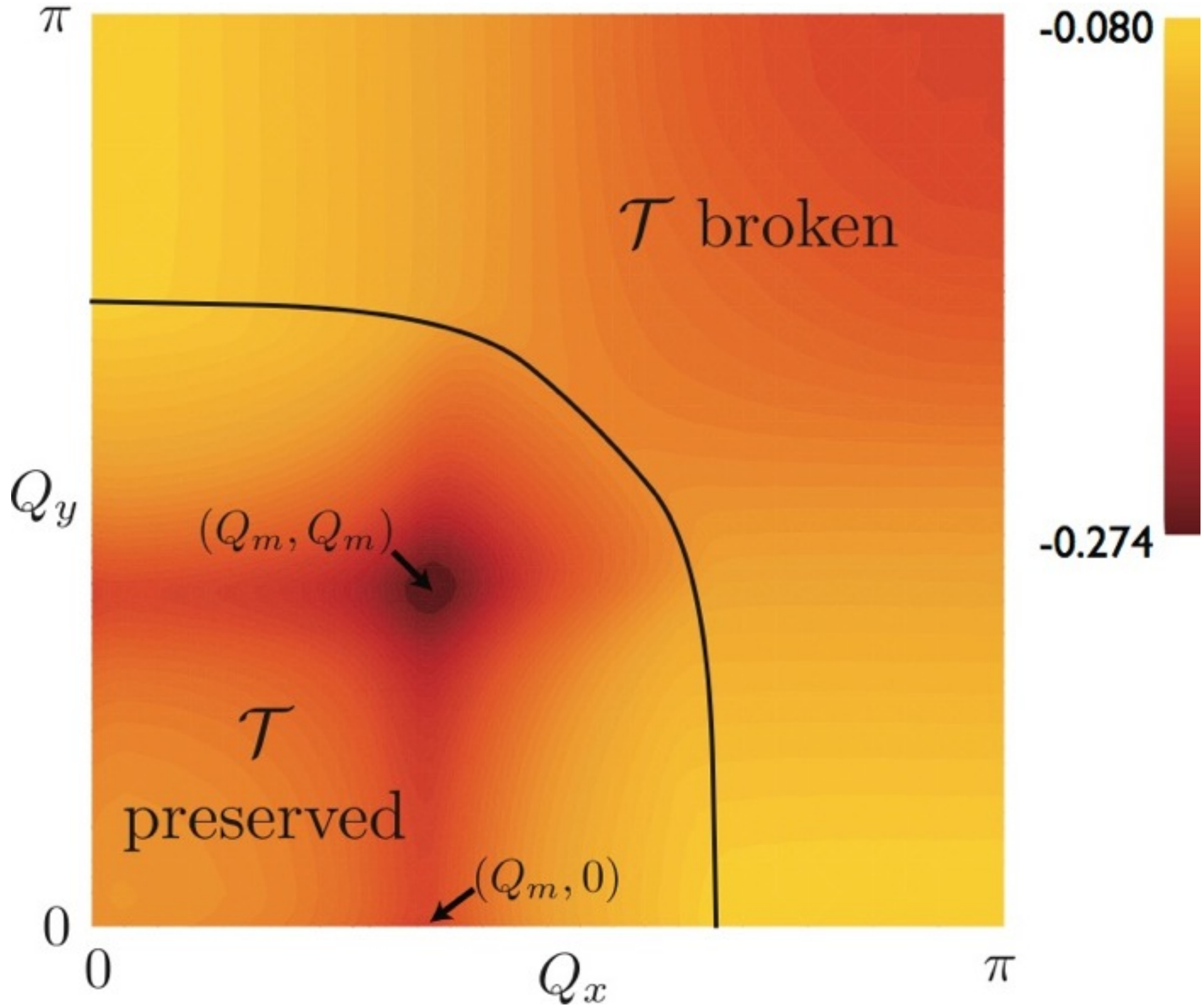
$$H = -\sum_{i,j} t_{ij} c_{i\alpha}^{\dagger} c_{j\alpha} + J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j + V \sum_{\langle ij \rangle} n_i n_j + \ldots$$



M. A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)
S. Sachdev and R. LaPlaca *Phys. Rev. Lett.* **111**, 027202 (2013)
J. C. Davis and Dung-Hai Lee, Proc. Natl. Acad. Sci. **110**, 17623 (2013)
J. D. Sau and S. Sachdev, *Phys. Rev. B* **89**, 075129 (2014)

Theory

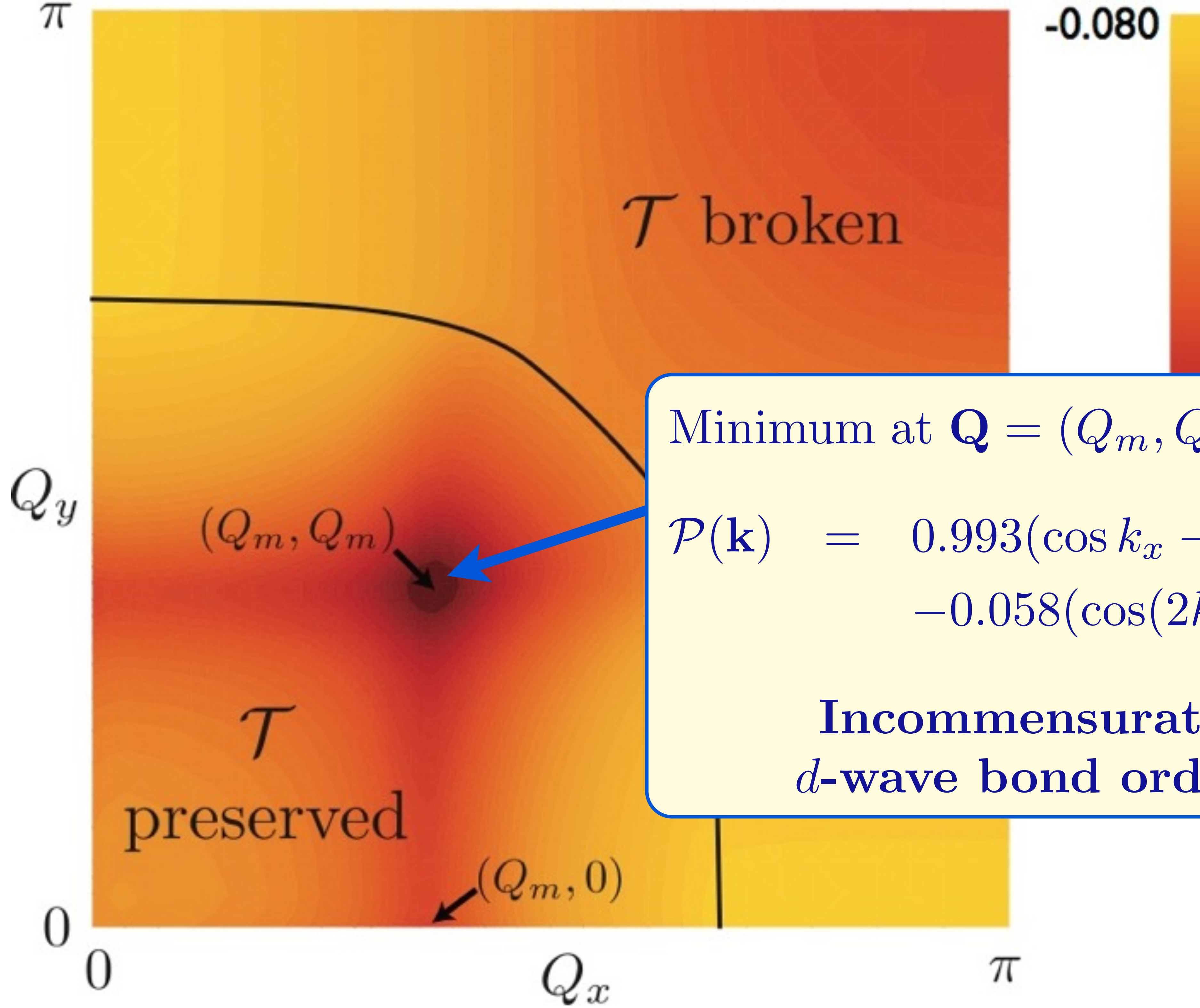
S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013); A. Allais, J. Bauer, and S. Sachdev, arXiv:1402.6311



Eigenvalues, $\lambda(\mathbf{Q})$, of the spin-singlet, particle-hole propagator. The corresponding eigenvector is $\mathcal{P}(\mathbf{k})$ and this leads to the order

$$\left\langle c_{i\alpha}^{\dagger} c_{j\alpha} \right\rangle = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2}$$

S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013); A. Allais, J. Bauer, and S. Sachdev, arXiv:1402.6311



Minimum at $\mathbf{Q} = (Q_m, Q_m)$ with

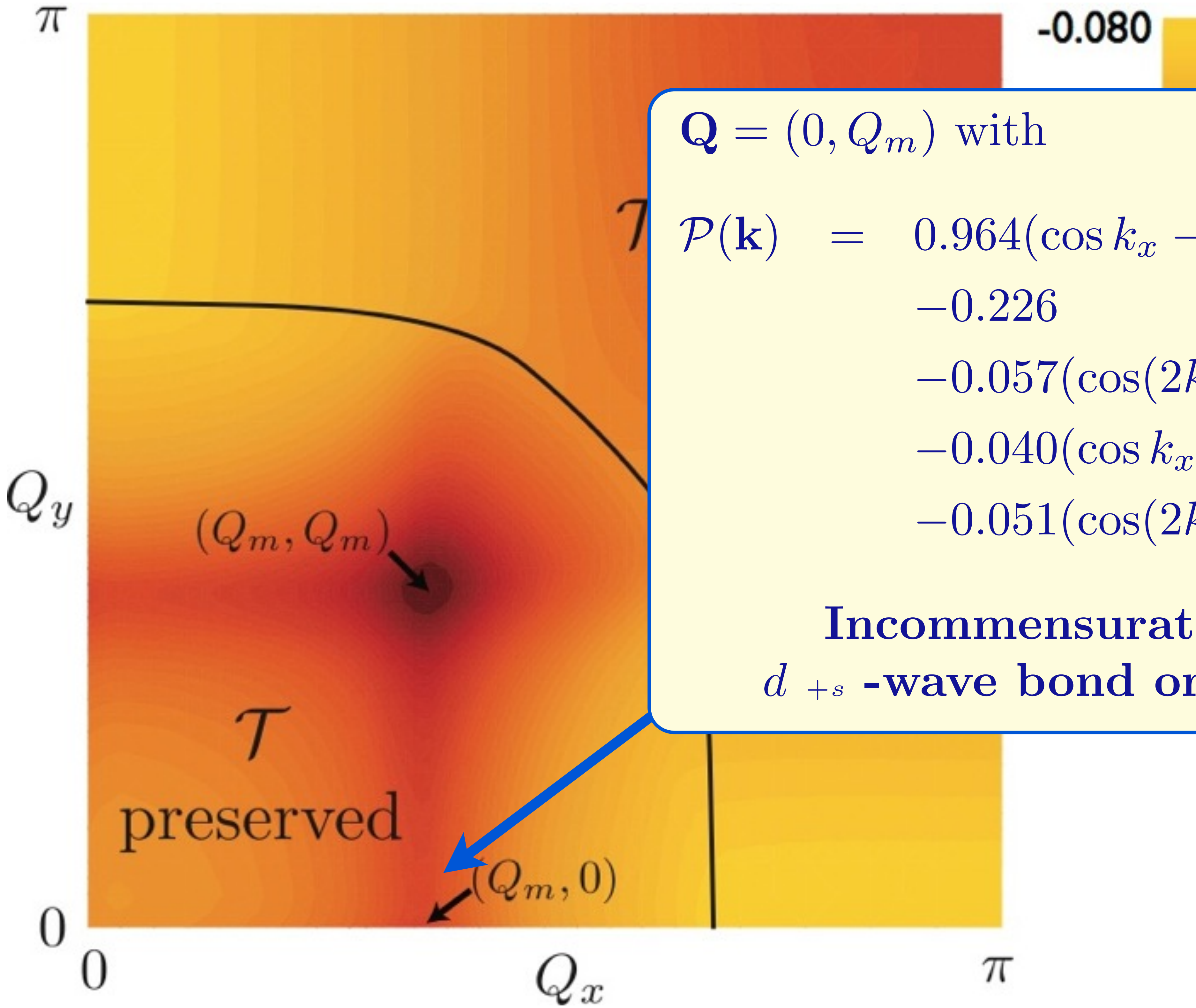
$$\begin{aligned} \mathcal{P}(\mathbf{k}) &= 0.993(\cos k_x - \cos k_y) \\ &\quad -0.058(\cos(2k_x) - \cos(2k_y)) \end{aligned}$$

Incommensurate
d-wave bond order

Eigenvalues, $\lambda(\mathbf{Q})$, of the spin-singlet, particle-hole propagator. The corresponding eigenvector is $\mathcal{P}(\mathbf{k})$ and this leads to the order

$$\left\langle c_{i\alpha}^{\dagger} c_{j\alpha} \right\rangle = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)}\right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2}$$

S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013); A. Allais, J. Bauer, and S. Sachdev, arXiv:1402.6311



$\mathbf{Q} = (0, Q_m)$ with

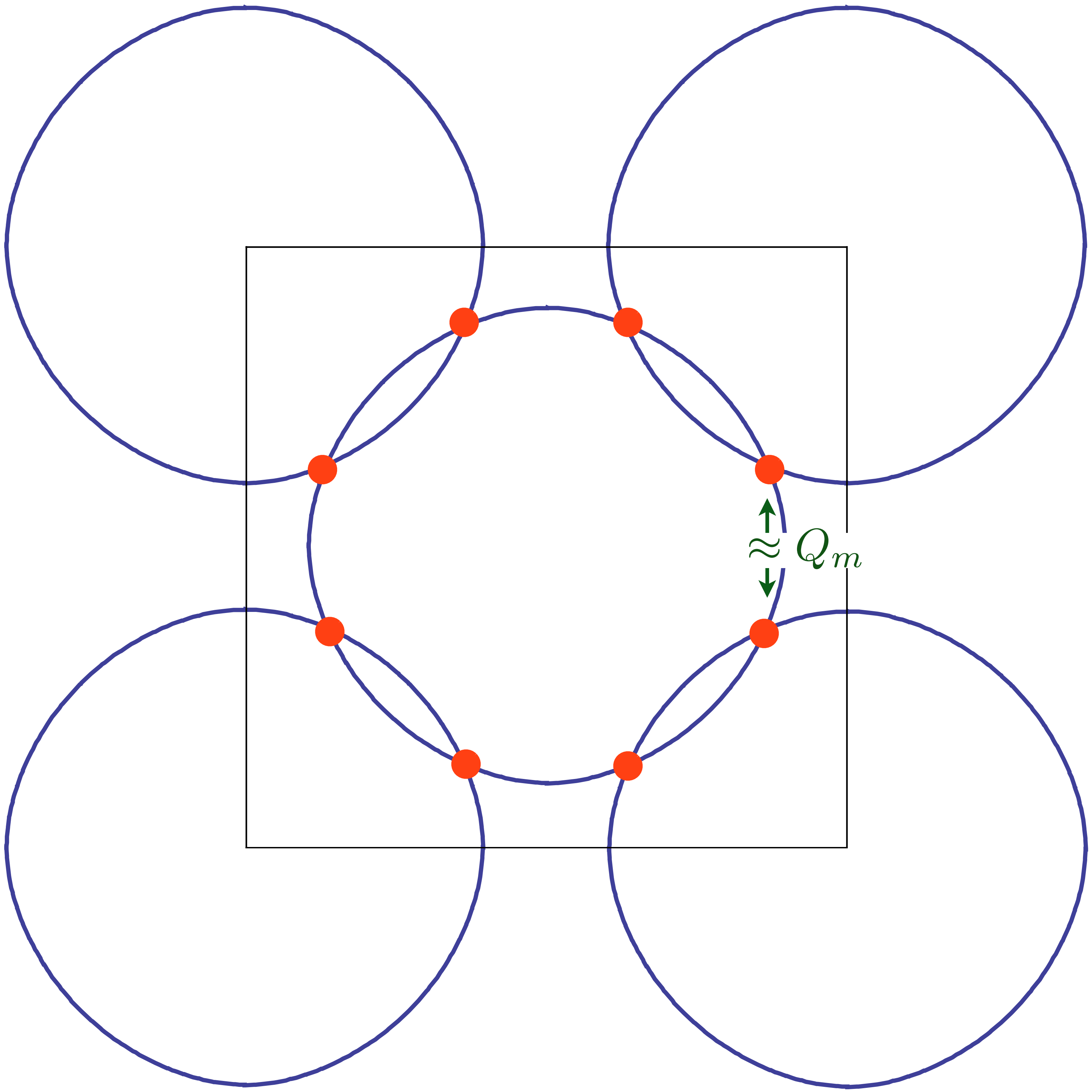
$$
\begin{aligned}
\mathcal{P}(\mathbf{k}) \;=\; & 0.964(\cos k_x - \cos k_y) \\
& -0.226 \\
& -0.057(\cos(2k_x) - \cos(2k_y)) \\
& -0.040(\cos k_x + \cos k_y) \\
& -0.051(\cos(2k_x) + \cos(2k_y))
\end{aligned}
$$

Incommensurate
d $_{+s}$ -wave bond order

Eigenvalues, $\lambda(\mathbf{Q})$, of the spin-singlet, particle-hole propagator. The corresponding eigenvector is $\mathcal{P}(\mathbf{k})$ and this leads to the order

$$\left\langle c_{i\alpha}^{\dagger} c_{j\alpha} \right\rangle = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2}$$

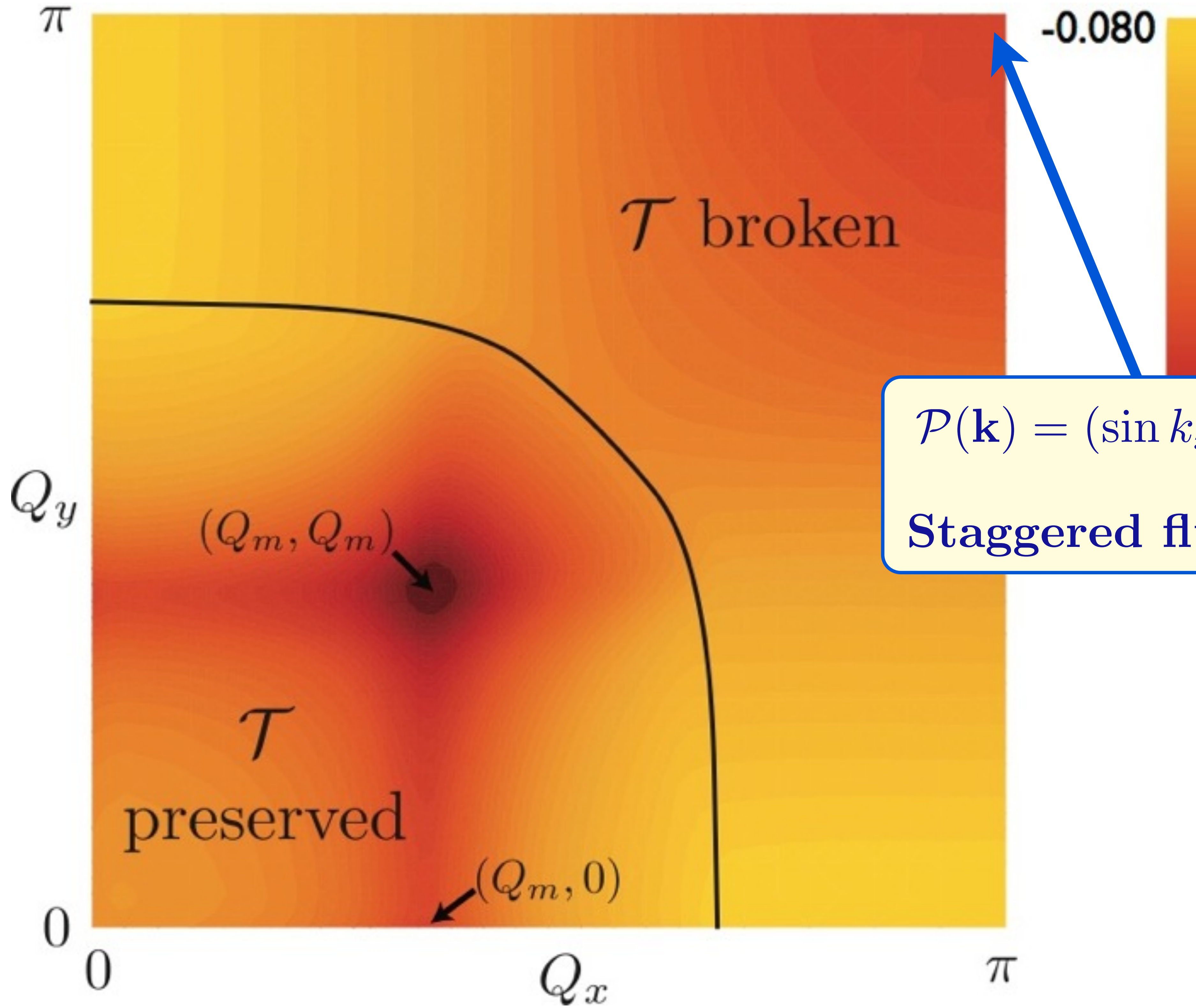
Fermi surface+antiferromagnetism



Q_m is approximately the separation between hotspots.

Theory

S. Sachdev and R. La Placa, Phys. Rev. Lett. 111, 027202 (2013); A. Allais, J. Bauer, and S. Sachdev, arXiv:1402.6311



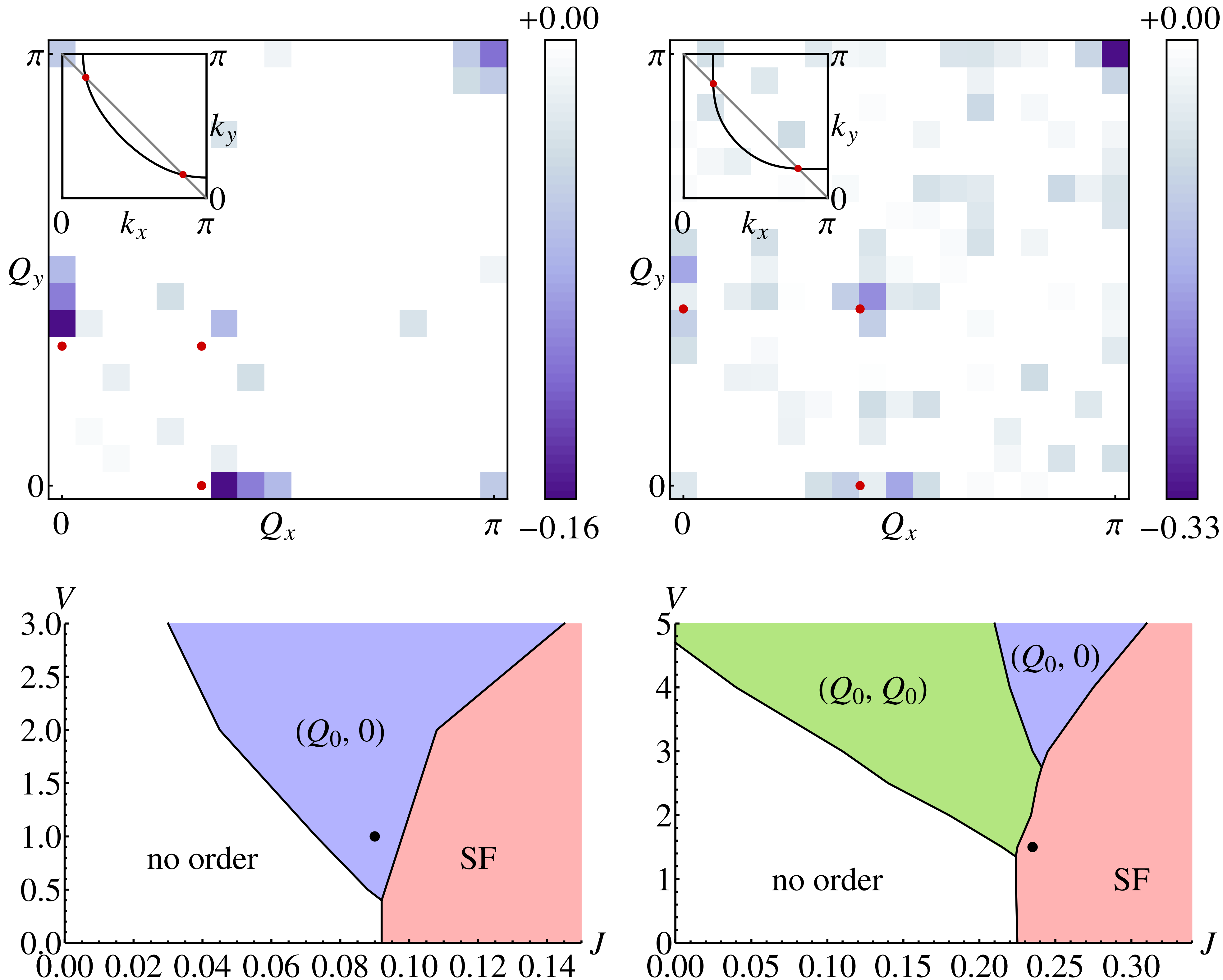
$\mathcal{P}(\mathbf{k}) = (\sin k_x - \sin k_y)$

Staggered flux (SF) state

Eigenvalues, $\lambda(\mathbf{Q})$, of the spin-singlet, particle-hole propagator. The corresponding eigenvector is $\mathcal{P}(\mathbf{k})$ and this leads to the order

$$\left\langle c_{i\alpha}^{\dagger} c_{j\alpha} \right\rangle = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2}$$

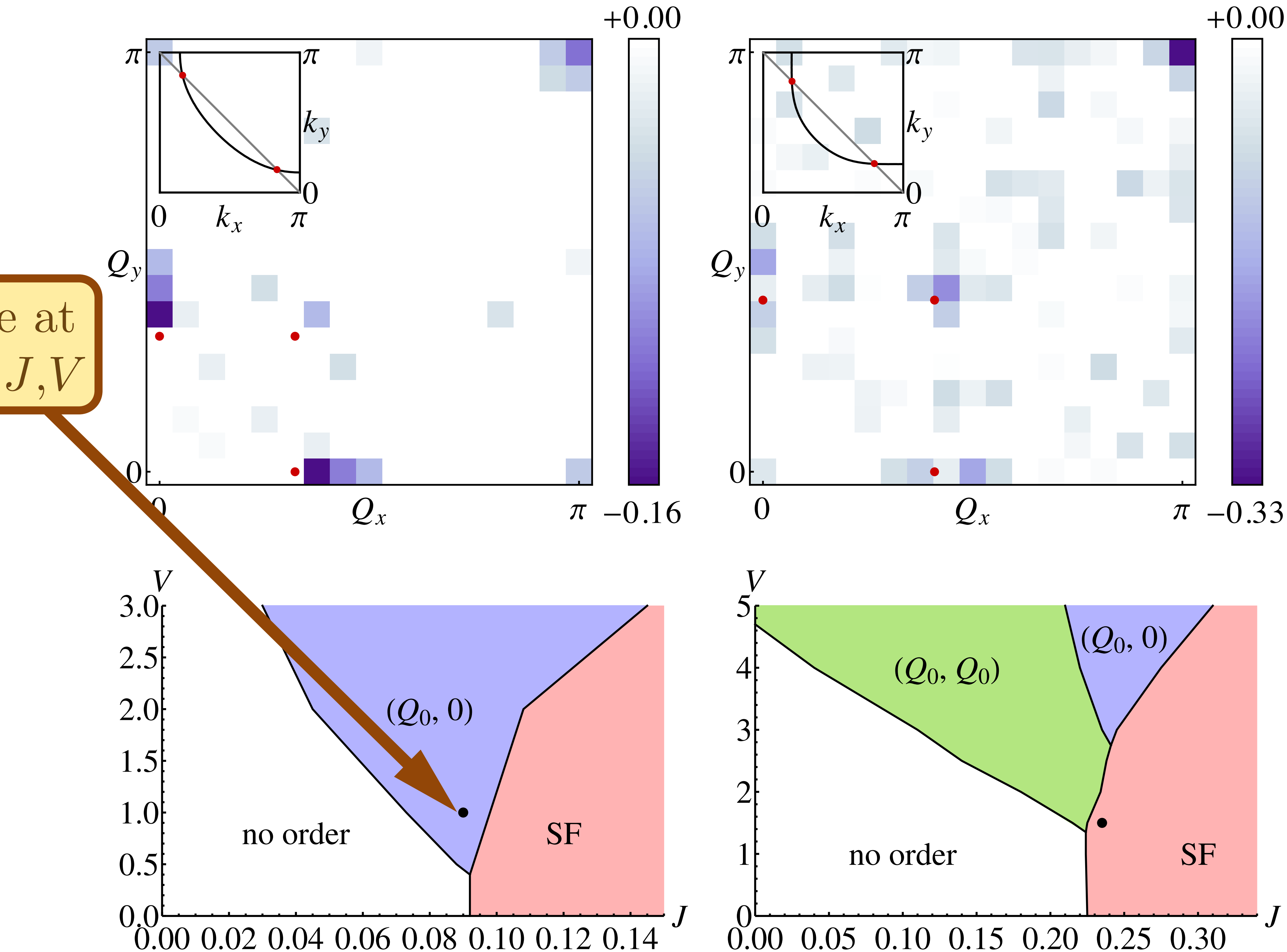
Results of a variational Monte Carlo computation on a wavefunction with double-occupancy projected out.
A. Allais, J. Bauer, and S. Sachdev, arXiv:1402.4807



Andrea Allais

Theory

Results of a variational Monte Carlo computation on a wavefunction with double-occupancy projected out.
A. Allais, J. Bauer, and S. Sachdev, arXiv:1402.4807

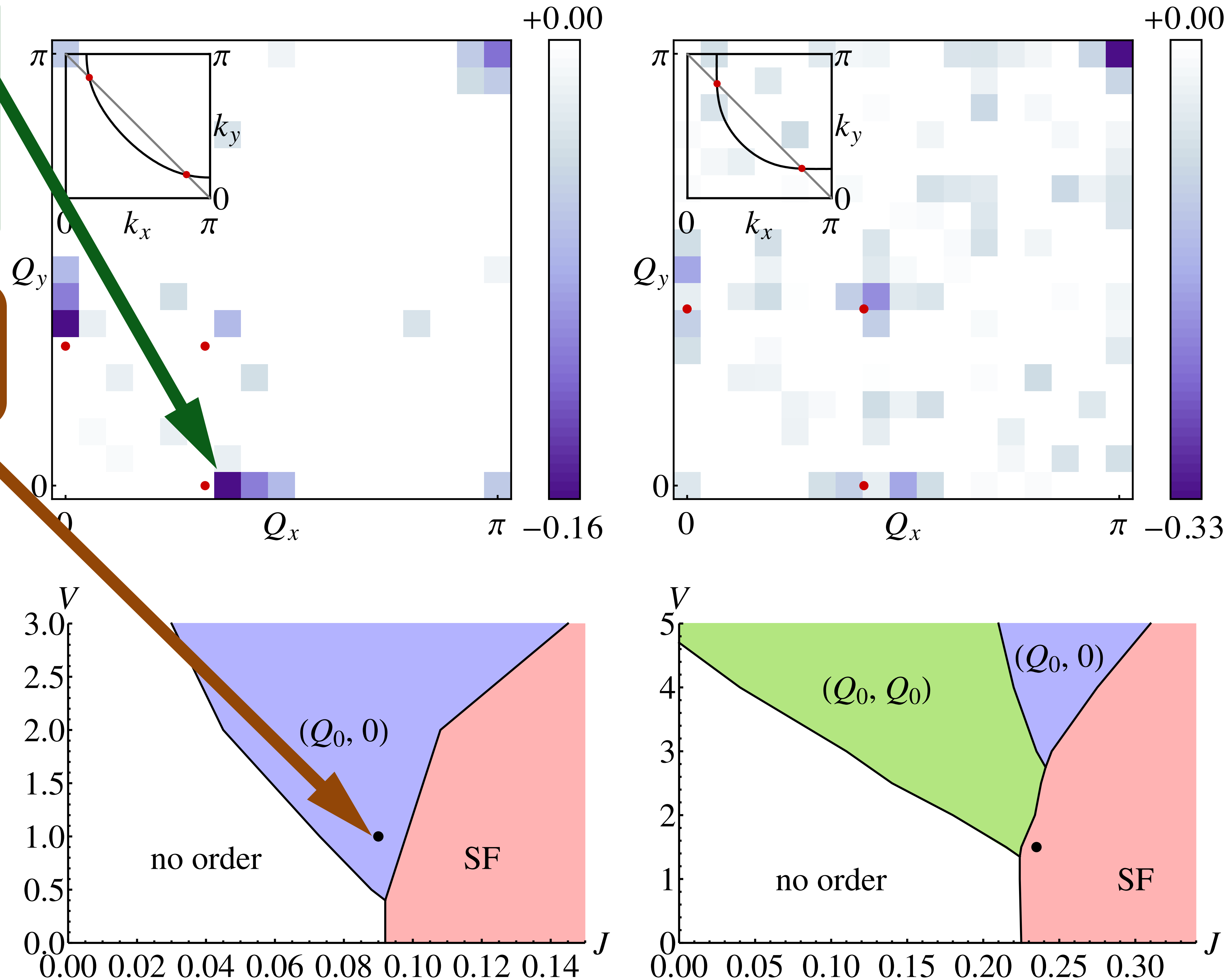


Andrea Allais

Results of a variational Monte Carlo computation on a wavefunction with double-occupancy projected out.
A. Allais, J. Bauer, and S. Sachdev, arXiv:1402.4807

Q of the lowest energy state. Predominantly d wave

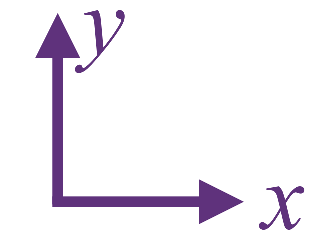
Q-plot above at this value of J,V



Andrea Allais

Theory

d-wave bond order.

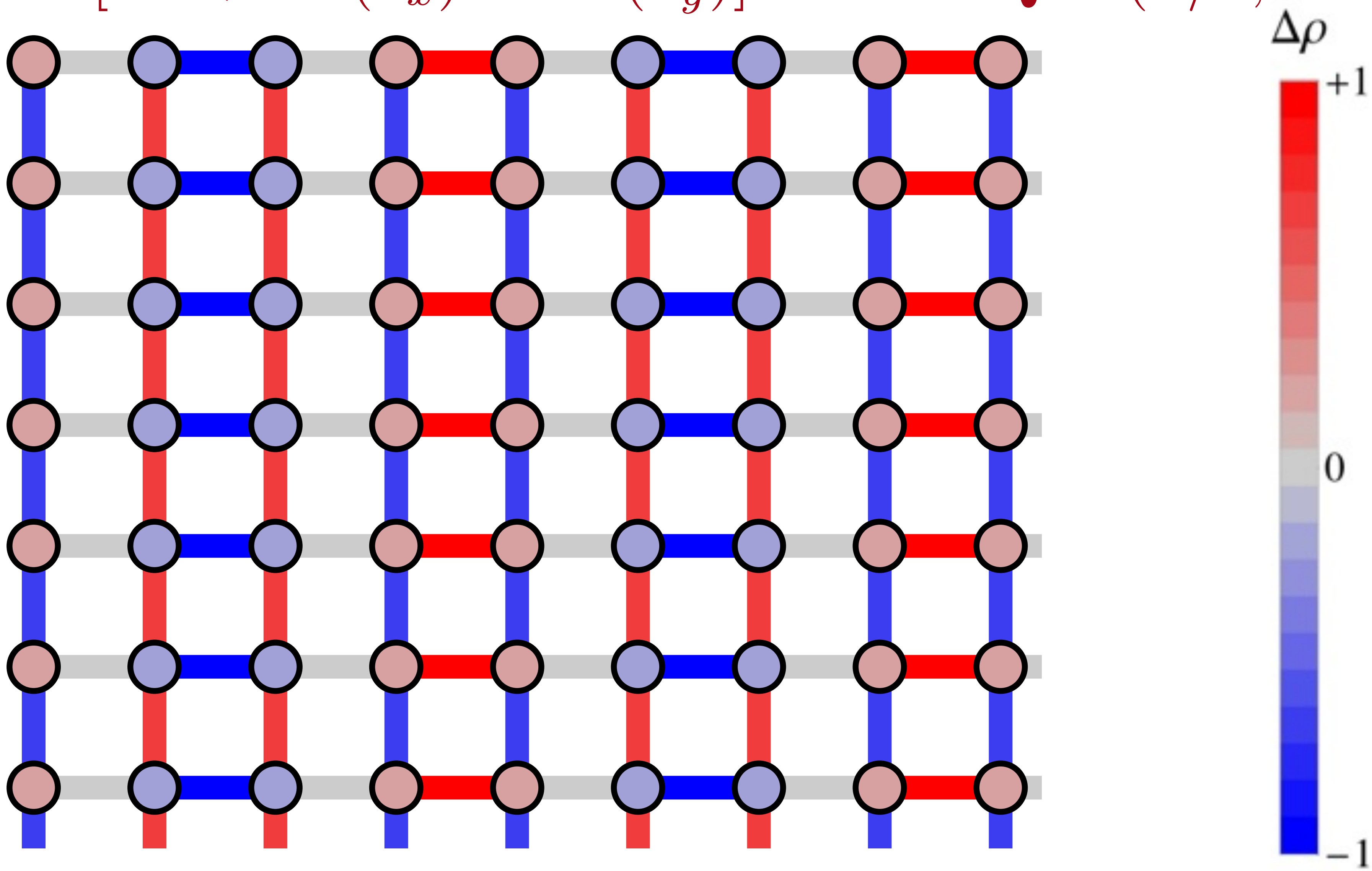


Plot of $P_{ij} = \left\langle c^\dagger_{i\alpha} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

$$P_{ij} = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2} + \text{c.c.}$$

$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[0.3 + \cos(k_x) - \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = (\pi/2, 0)$$

Density wave on horizontal bonds has a phase-shift of π relative to the wave on vertical bonds



This d-wave bond order was first discussed in
S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).

Outline

1. *d*-wave superconductivity

2. Low hole density state:
   d-wave bond order

3. Theoretical background

4. Evolution of Fermi surface

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   d-wave bond order

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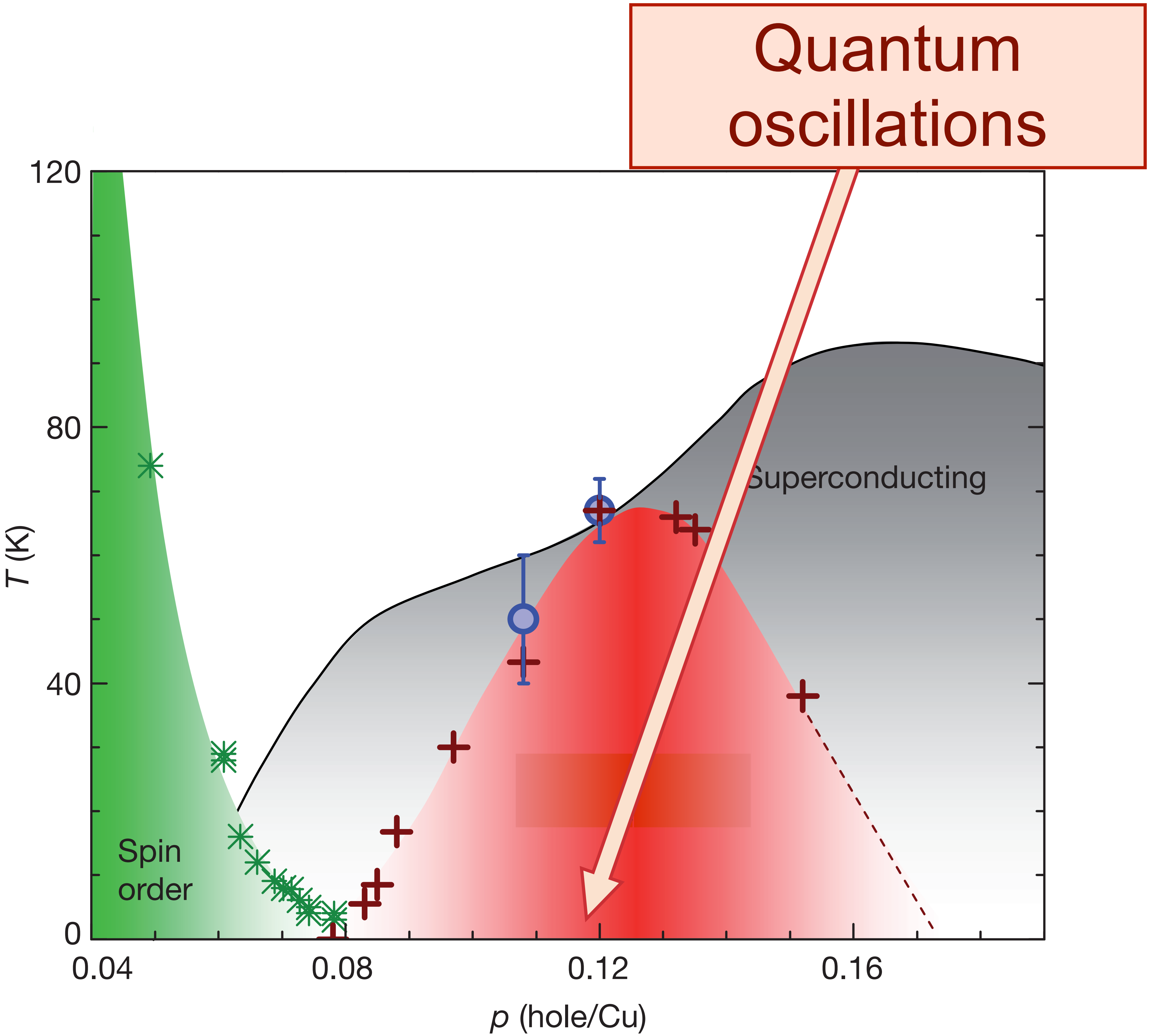
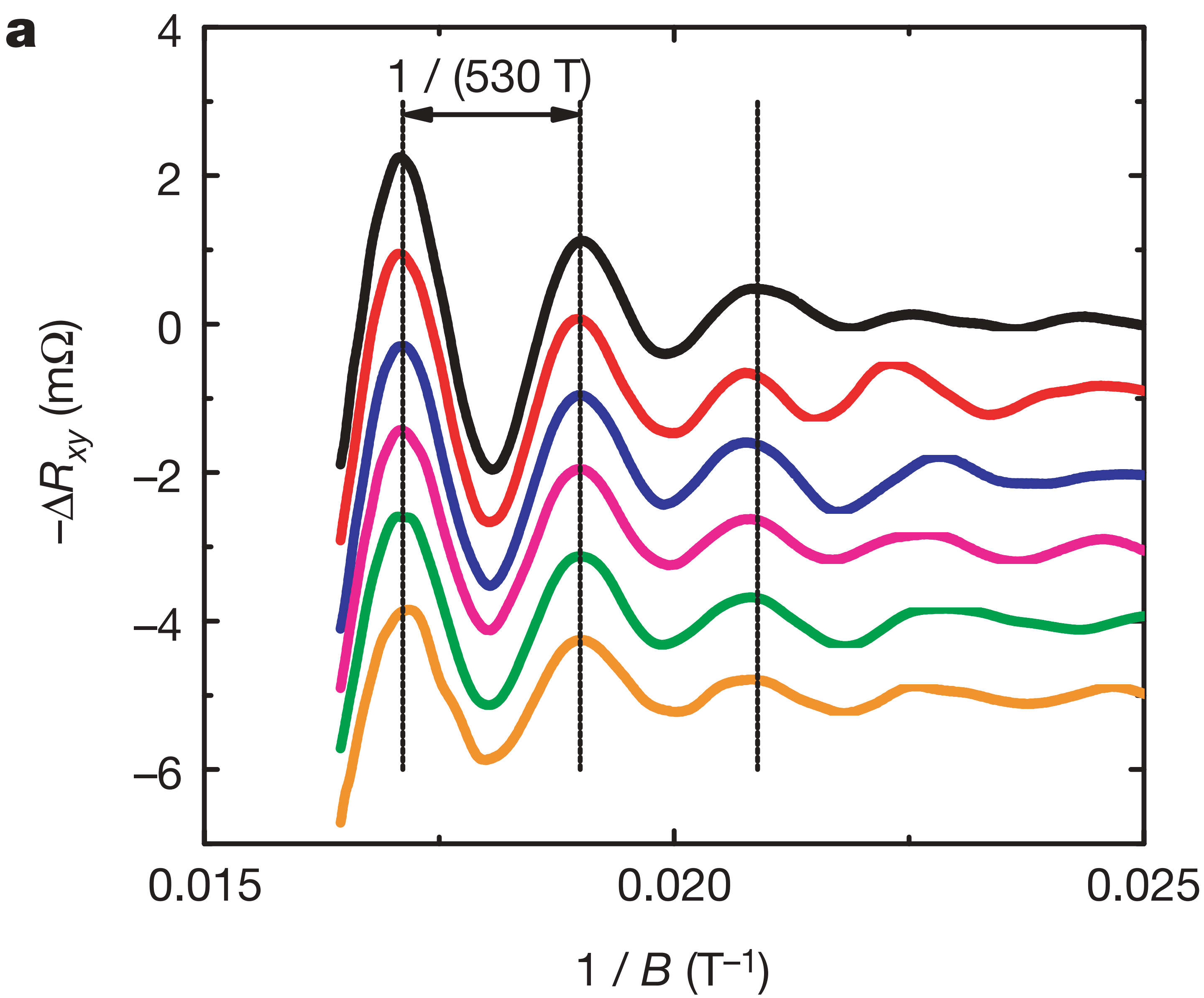


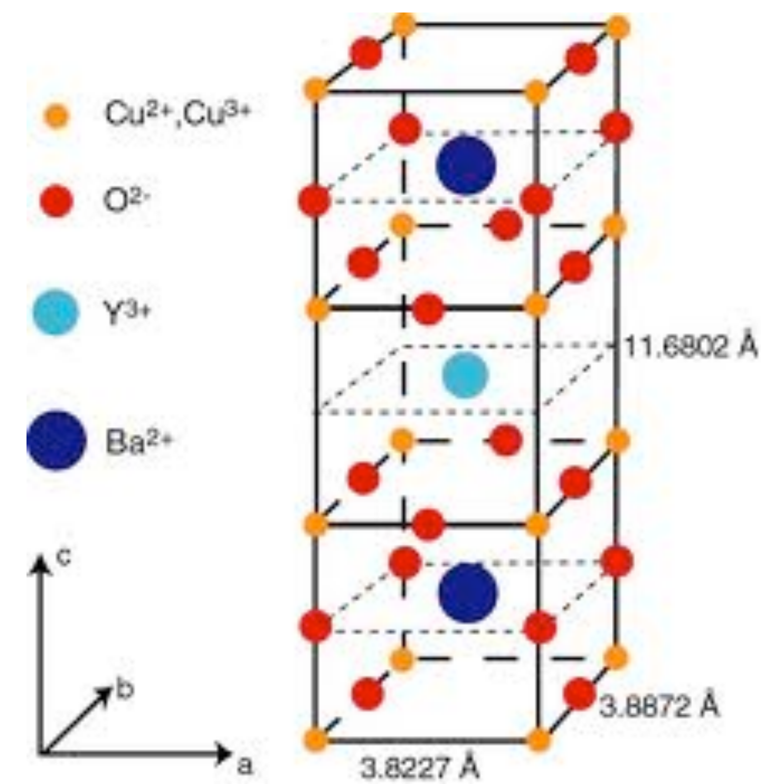
T. Wu, H. Mayaffre, S. Kramer, M. Horvatic, C. Berthier, W.N. Hardy, R. Liang, D.A. Bonn, and M.-H. Julien, Nature **477**, 191 (2011).

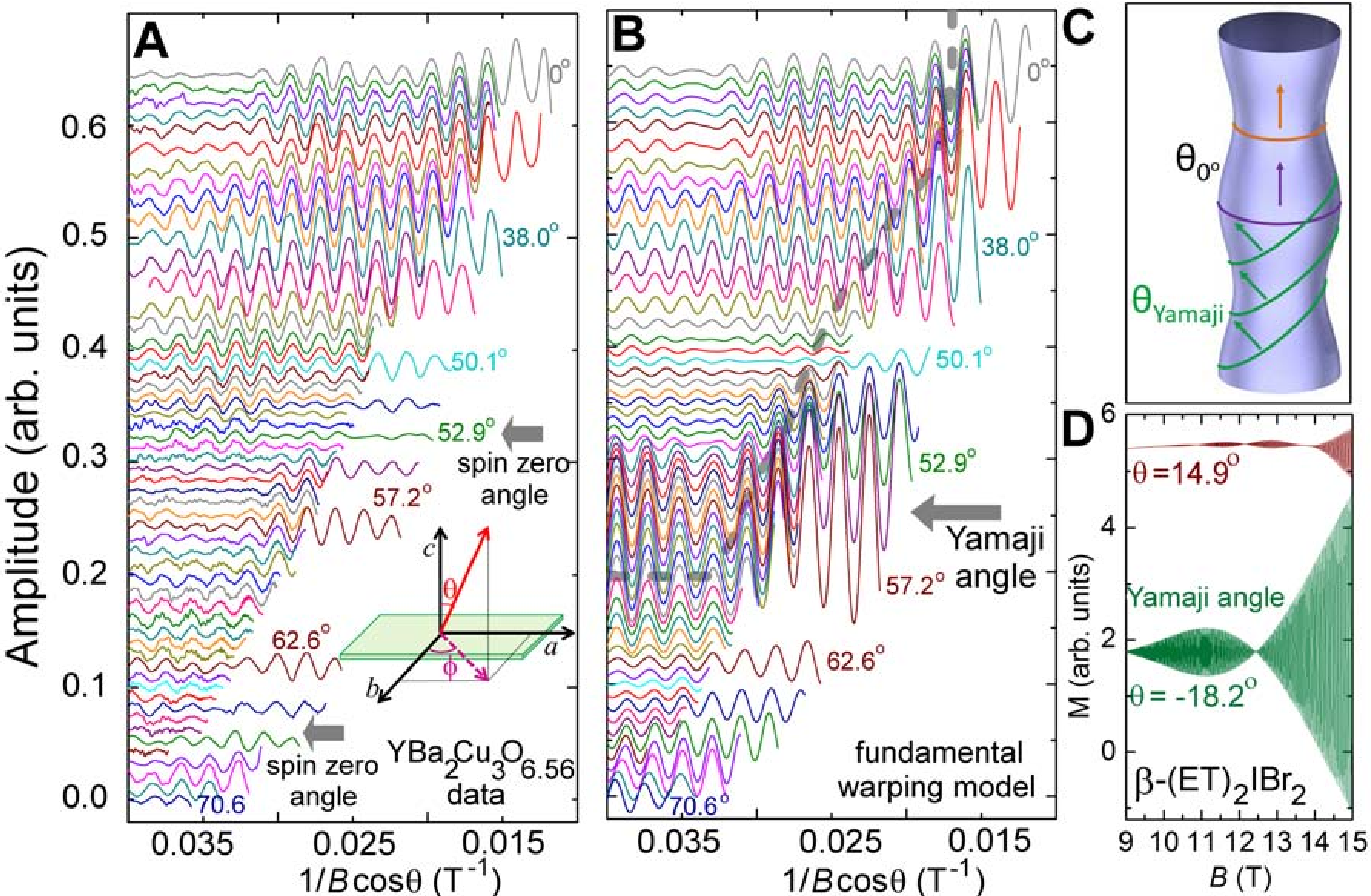
Quantum oscillations and the Fermi surface in an underdoped high-T_c superconductor

Nicolas Doiron-Leyraud[1], Cyril Proust[2], David LeBoeuf[1], Julien Levallois[2], Jean-Baptiste Bonnemaison[1], Ruixing Liang[3,4], D. A. Bonn[3,4], W. N. Hardy[3,4] & Louis Taillefer[1,4]

Nature **447**, 565 (2007)



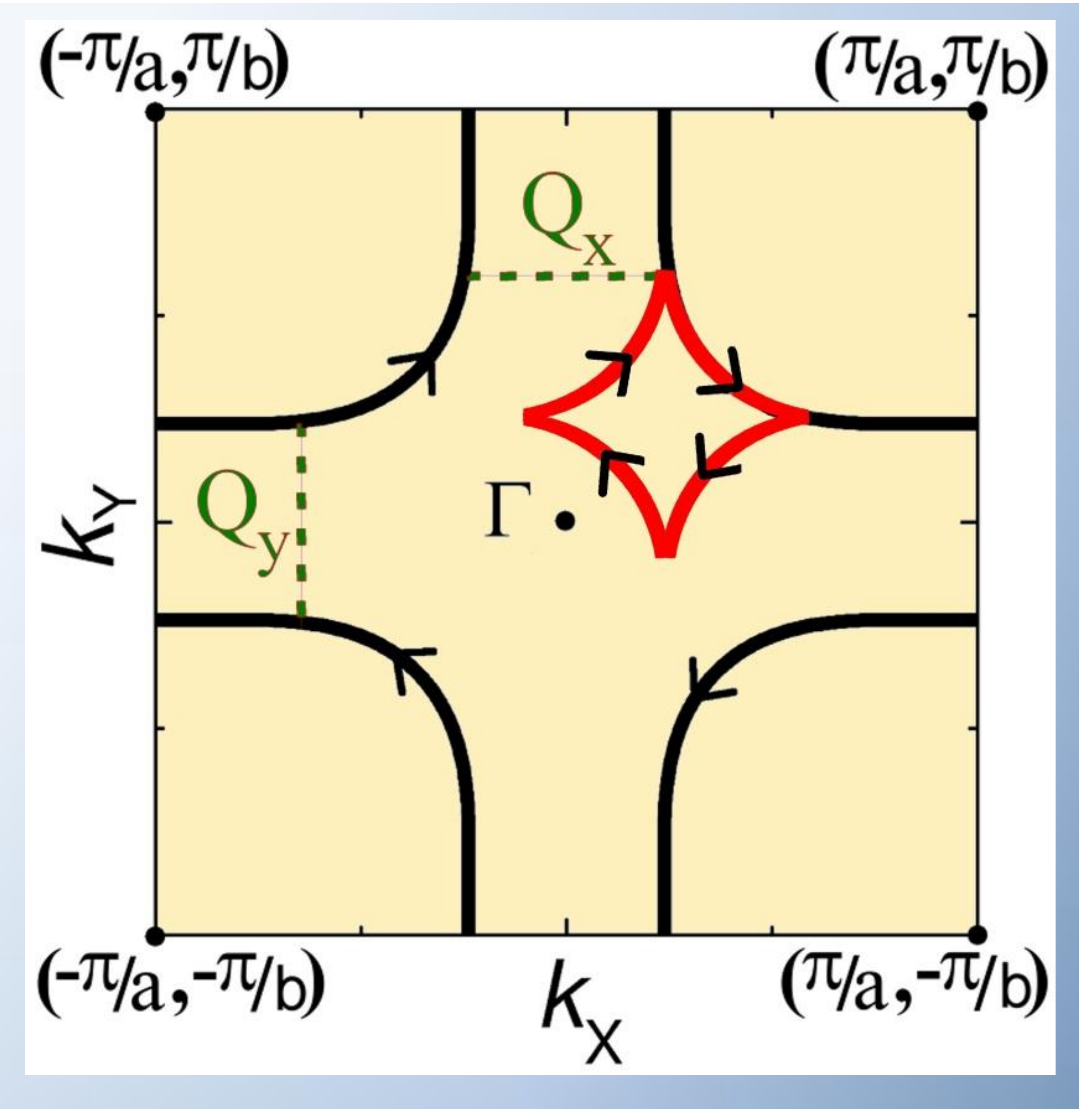




Twofold twisted Fermi surface from staggered order in an underdoped high T_c superconductor

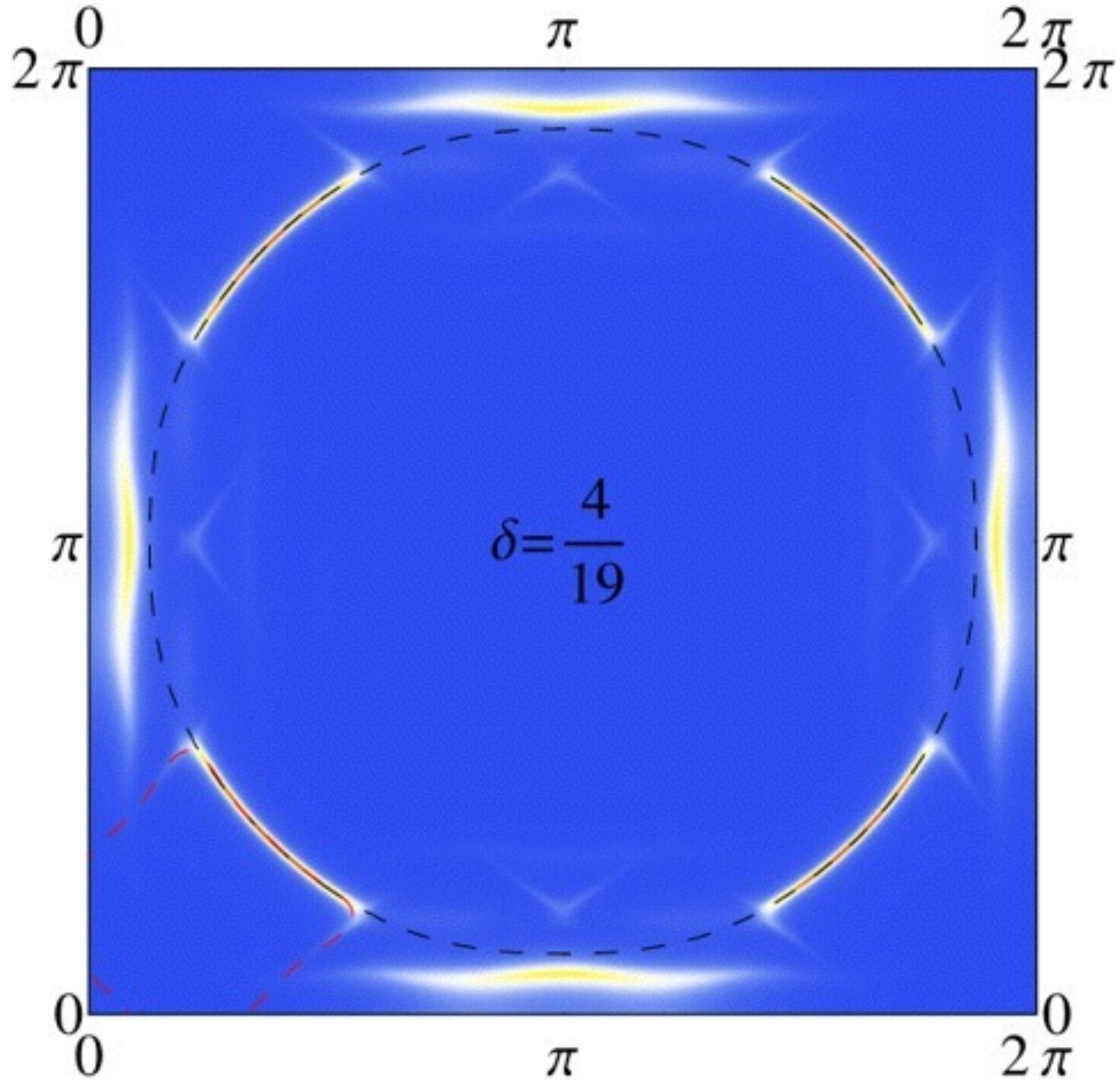
Suchitra E. Sebastian,[1*] N. Harrison,[2] F. F. Balakirev,[2] M. M. Altarawneh,[2,3] Ruixing Liang,[4,5] D. A. Bonn,[4,5] W. N. Hardy,[4,5] G. G. Lonzarich,[1]

APS March meeting 2013 B2.00004, Nature, to appear



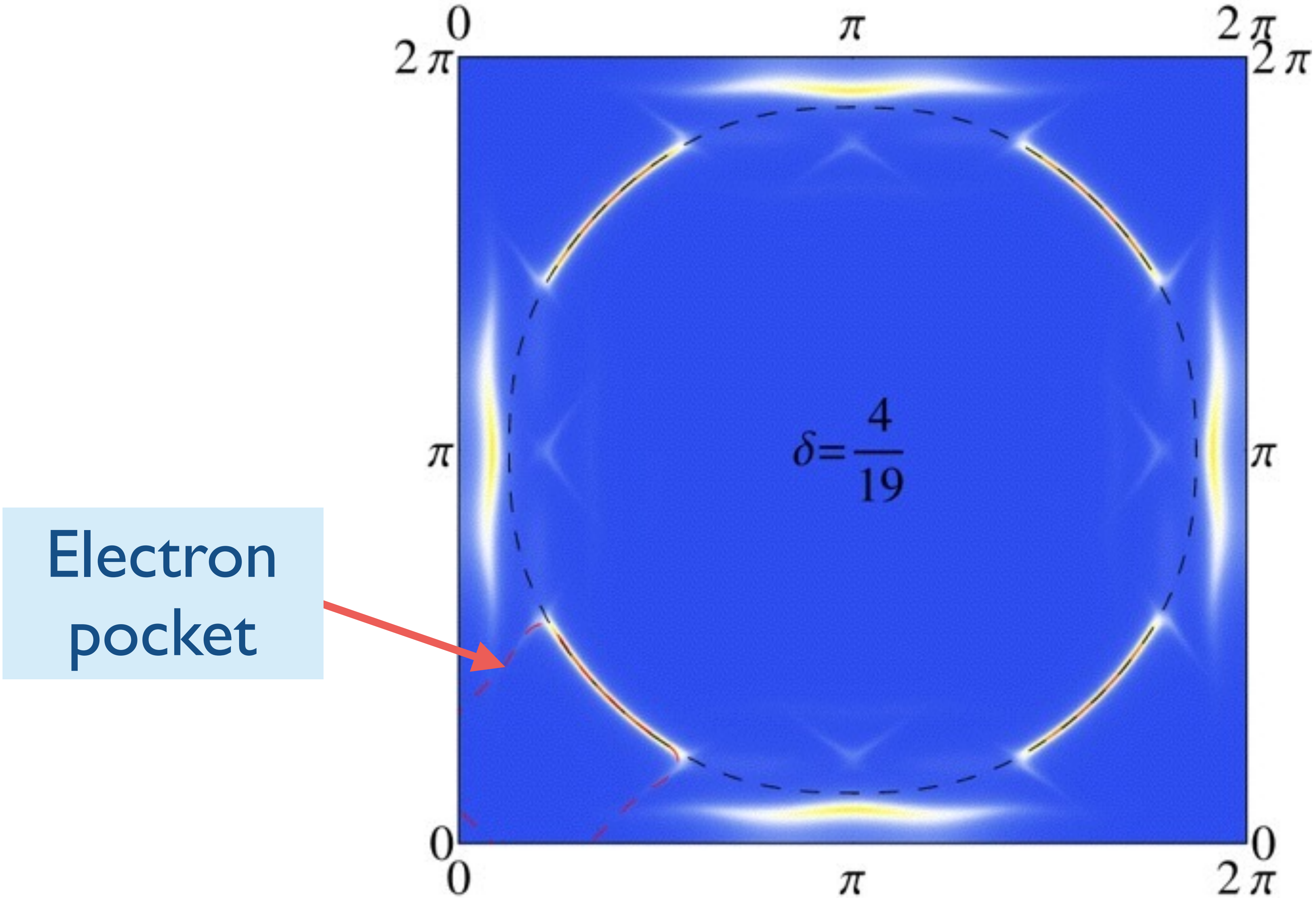
N. Harrison and S. E. Sebastian, Phys. Rev. Lett. **106**, 226402 (2011).

Electron spectral function in the presence of charge order at $\mathbf{Q} = 2\pi(\delta, 0)$ and $\mathbf{Q} = 2\pi(0, \delta)$



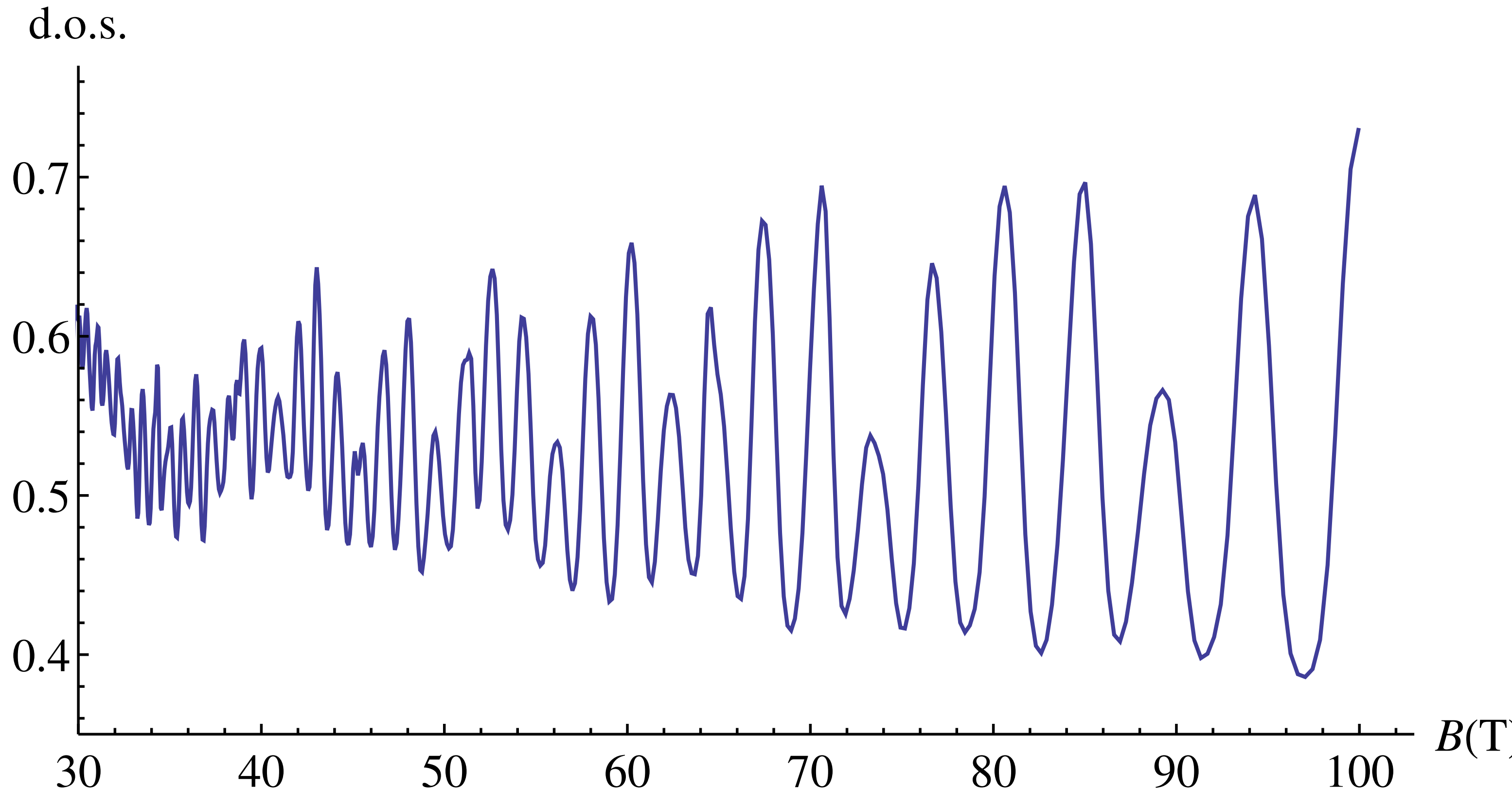
S. Sachdev and R. LaPlaca *Phys. Rev. Lett.* **111**, 027202 (2013)
A. Allais, D. Chowdhury, and S. Sachdev, to appear

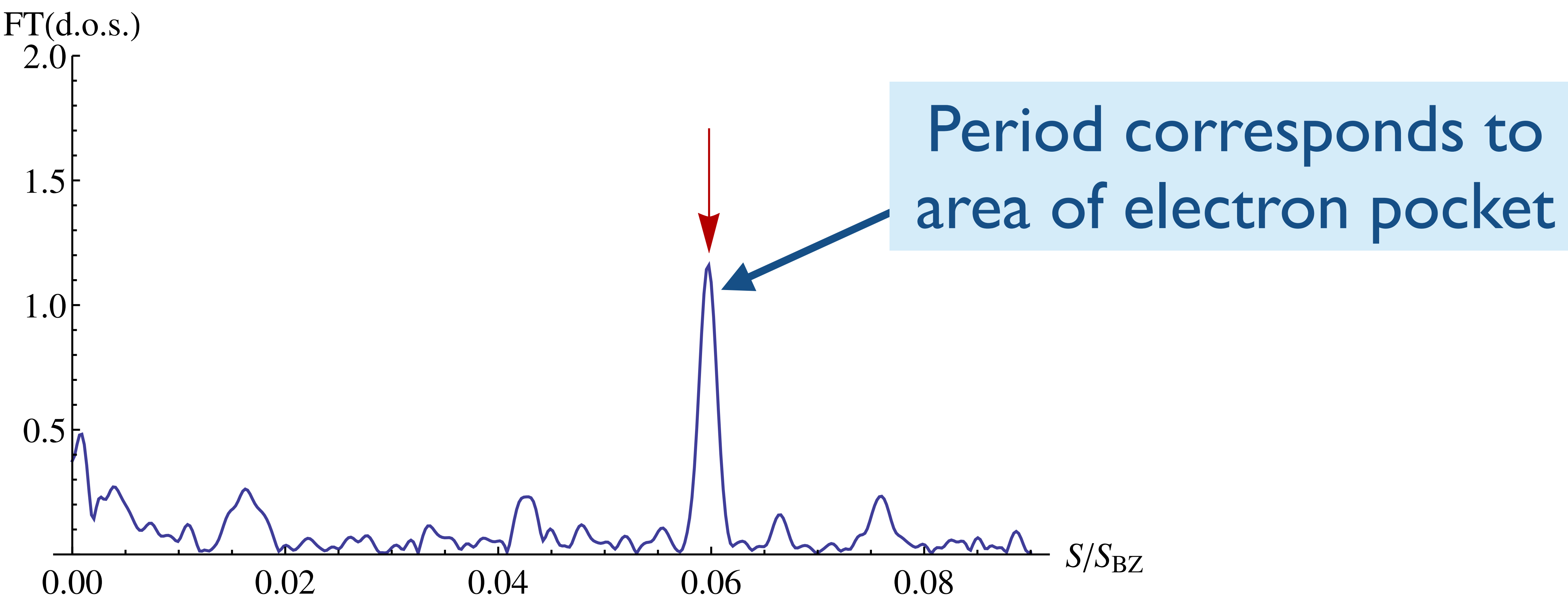
Electron spectral function in the presence of charge order at $\mathbf{Q} = 2\pi(\delta, 0)$ and $\mathbf{Q} = 2\pi(0, \delta)$



S. Sachdev and R. LaPlaca *Phys. Rev. Lett.* **111**, 027202 (2013)
A. Allais, D. Chowdhury, and S. Sachdev, to appear

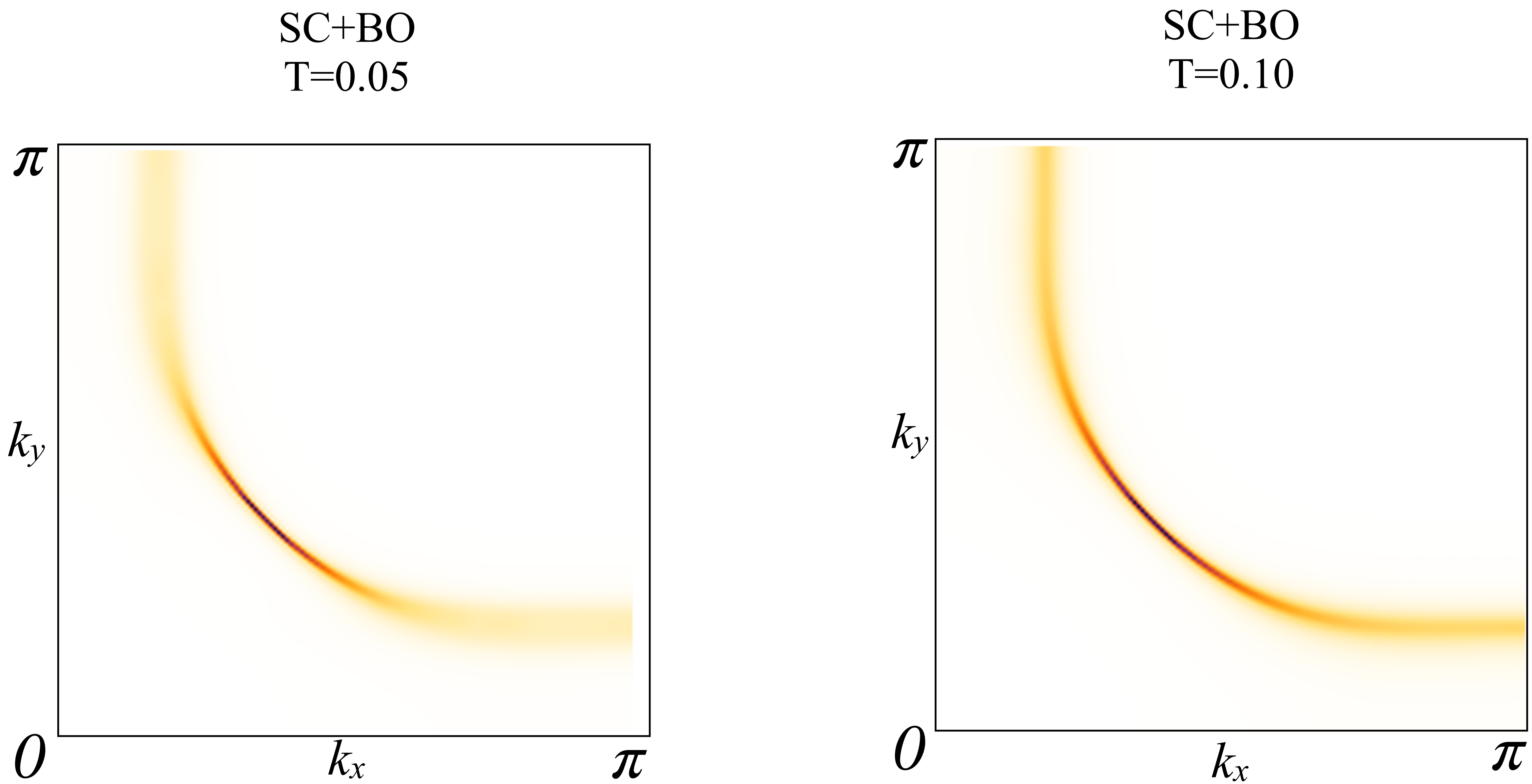
Quantum oscillation in the presence of charge order at $\mathbf{Q} = 2\pi(\delta, 0)$ and $\mathbf{Q} = 2\pi(0, \delta)$





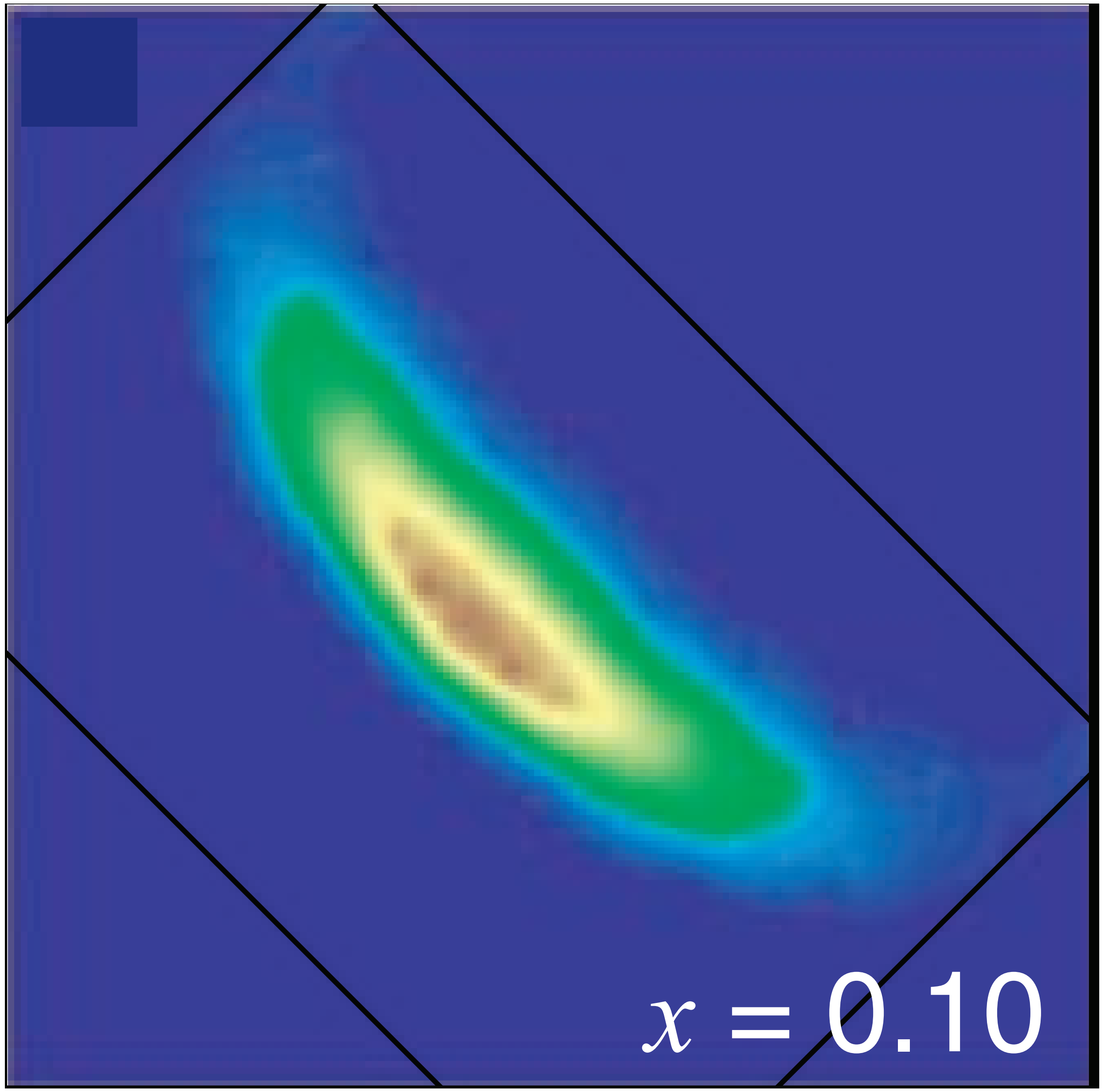
A. Allais, D. Chowdhury, and S. Sachdev, to appear

Electron spectral function with fluctuating charge order and superconductivity at temperatures above T_c.



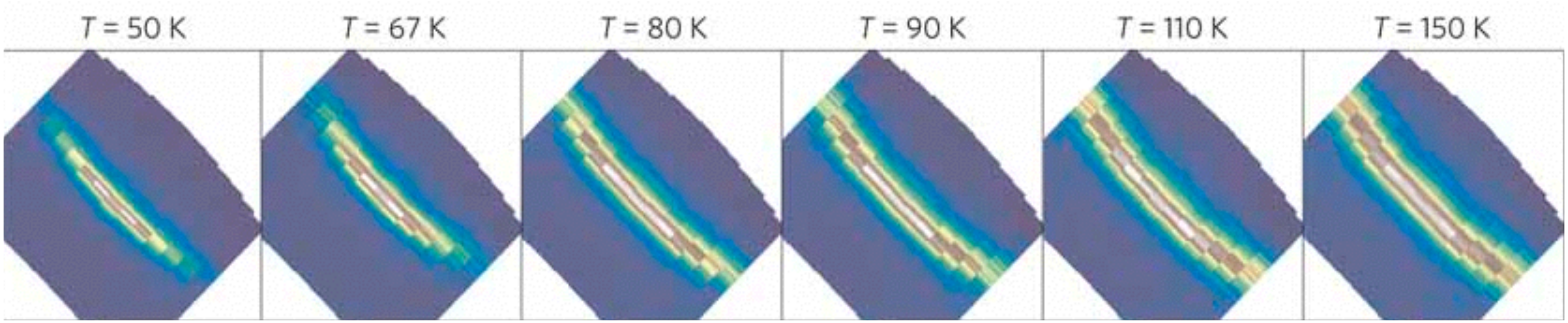
Spectral functions A(k,ω=0) in the presence of fluctuating SC and BO (with wave vectors (Q,0), (0,Q)) at two different temperatures. Notice how spectral weight fills up in the antinodal regions as a function of increasing temperature.

A. Allais, D. Chowdhury, and S. Sachdev, to appear

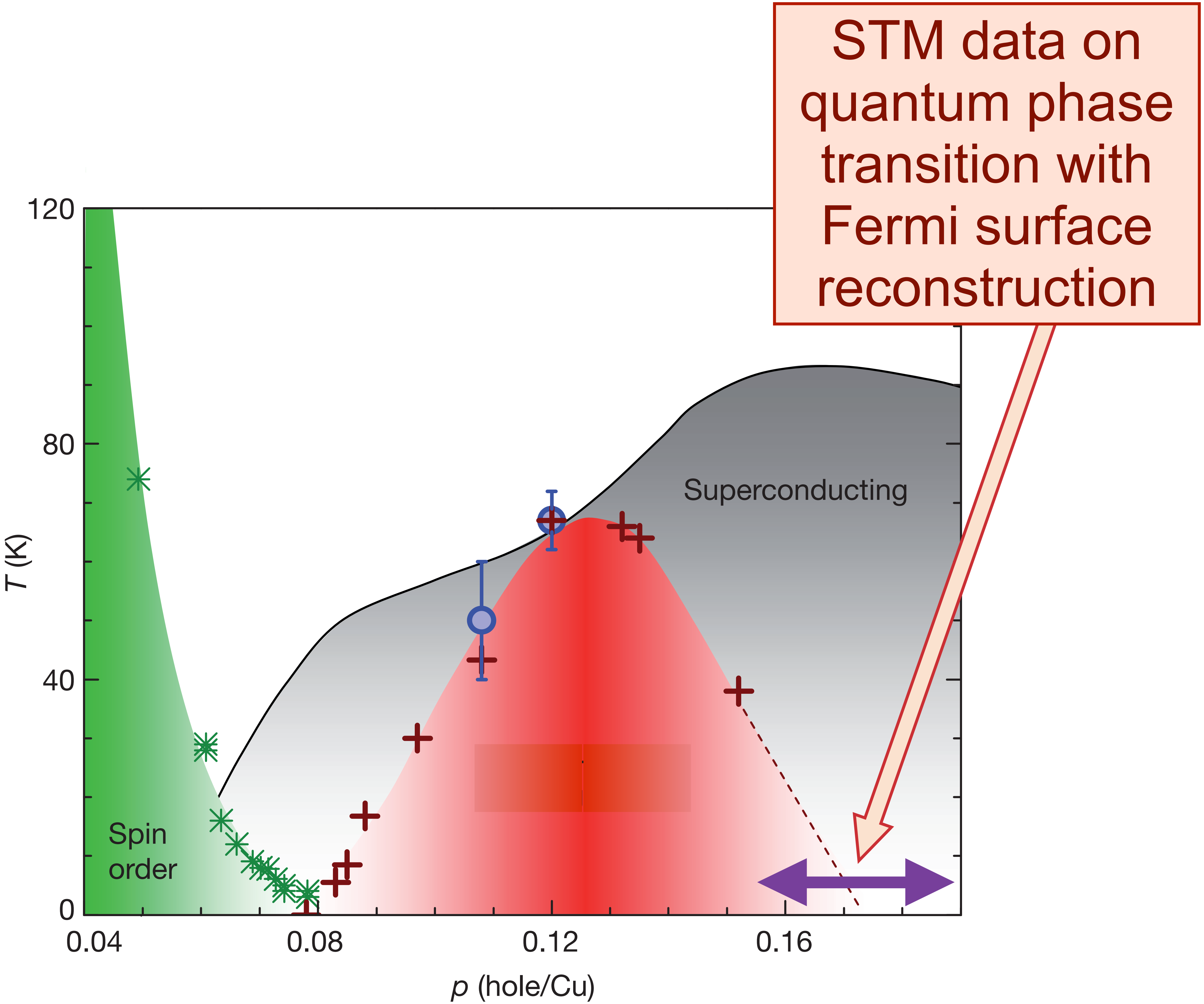


Nodal Quasiparticles and Antinodal Charge Ordering in $Ca_{2-x}Na_xCuO_2Cl_2$

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).



T. J. Reber, N. C. Plumb, Z. Sun, Y. Cao, Q. Wang, K. McElroy, H. Iwasawa, M. Arita, J. S. Wen, Z. J. Xu, G. Gu, Y. Yoshida, H. Eisaki, Y. Aiura, and D. S. Dessau, *Nature Physics* **8**, 606 (2012)



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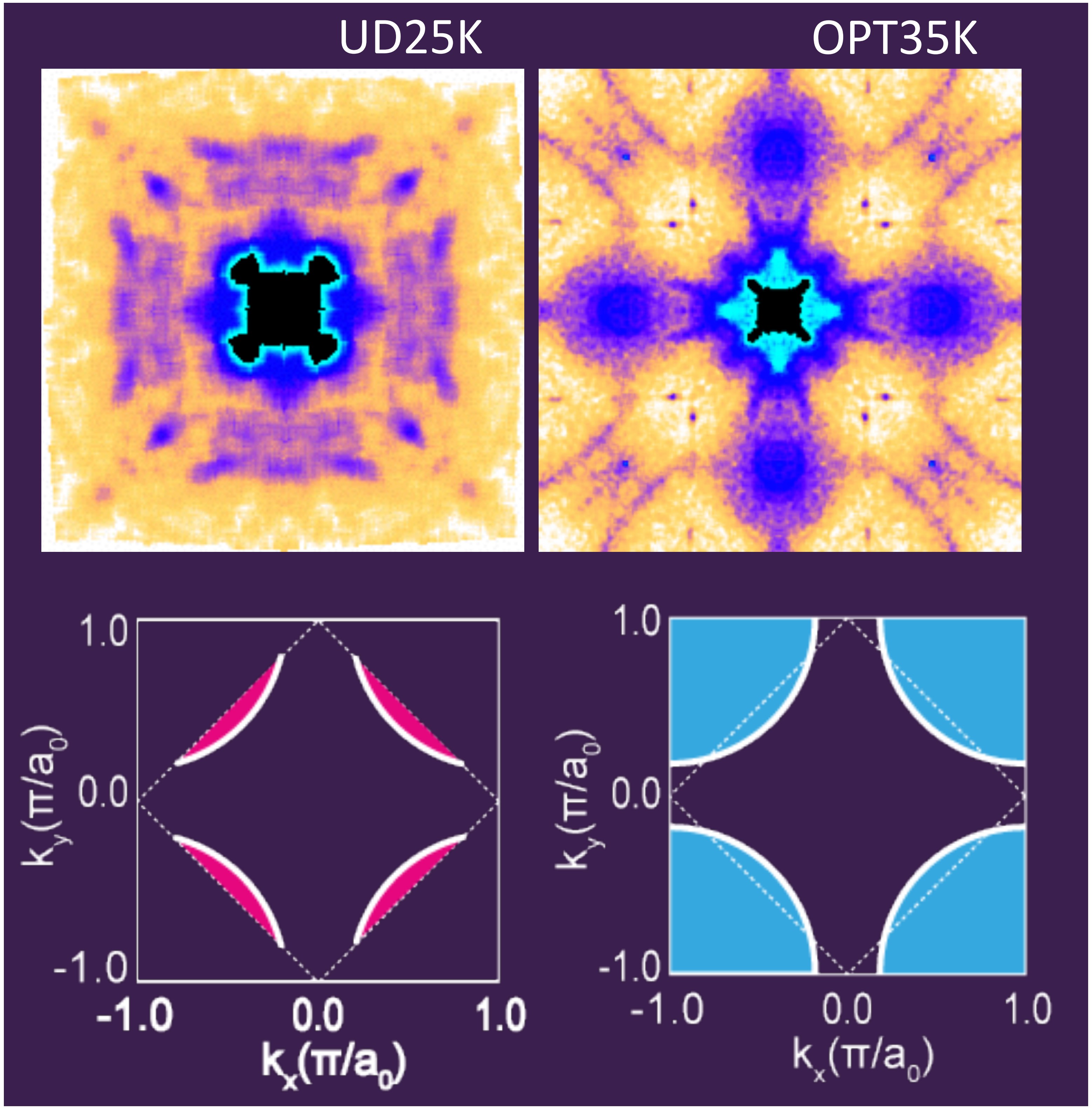

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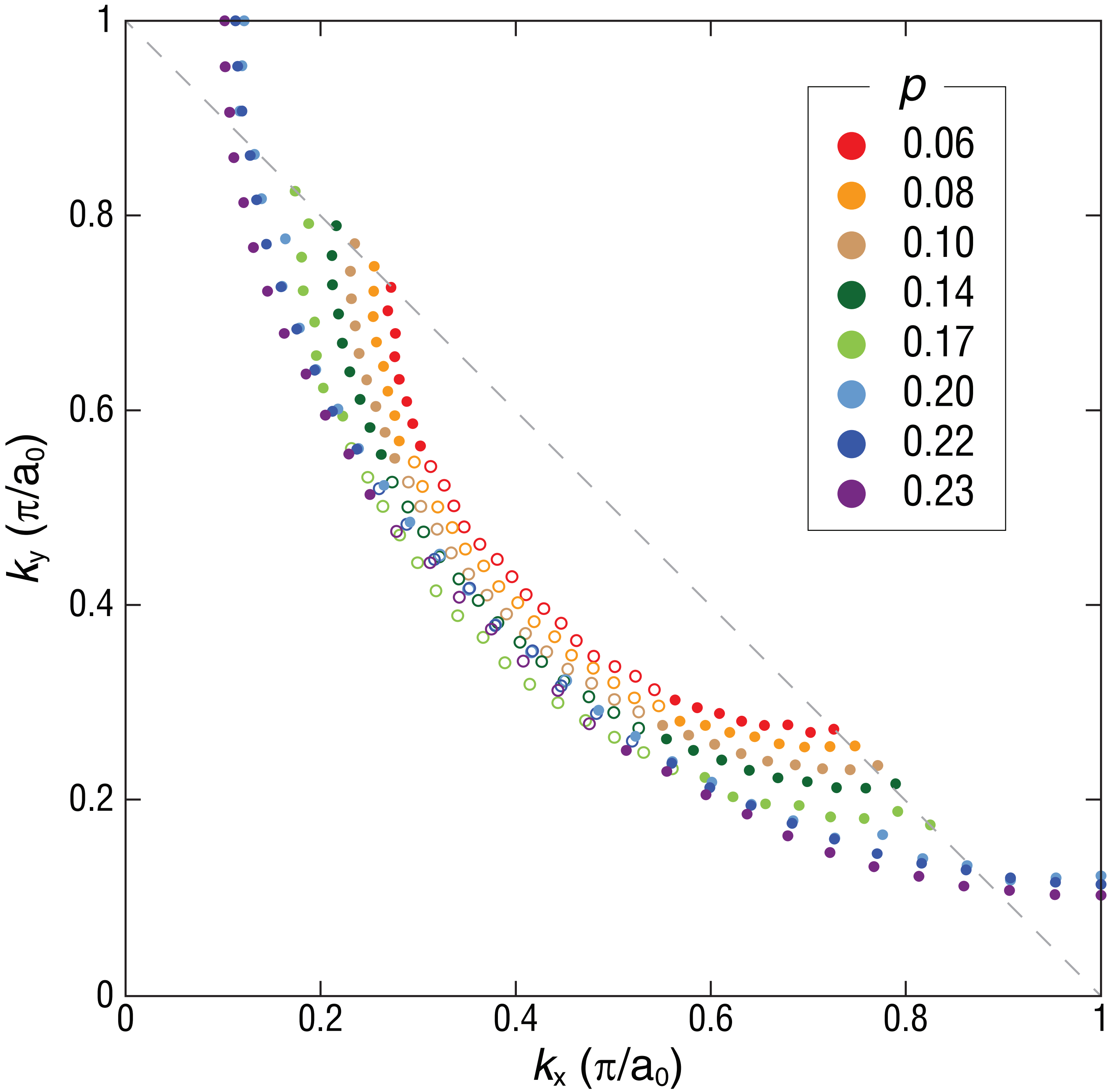

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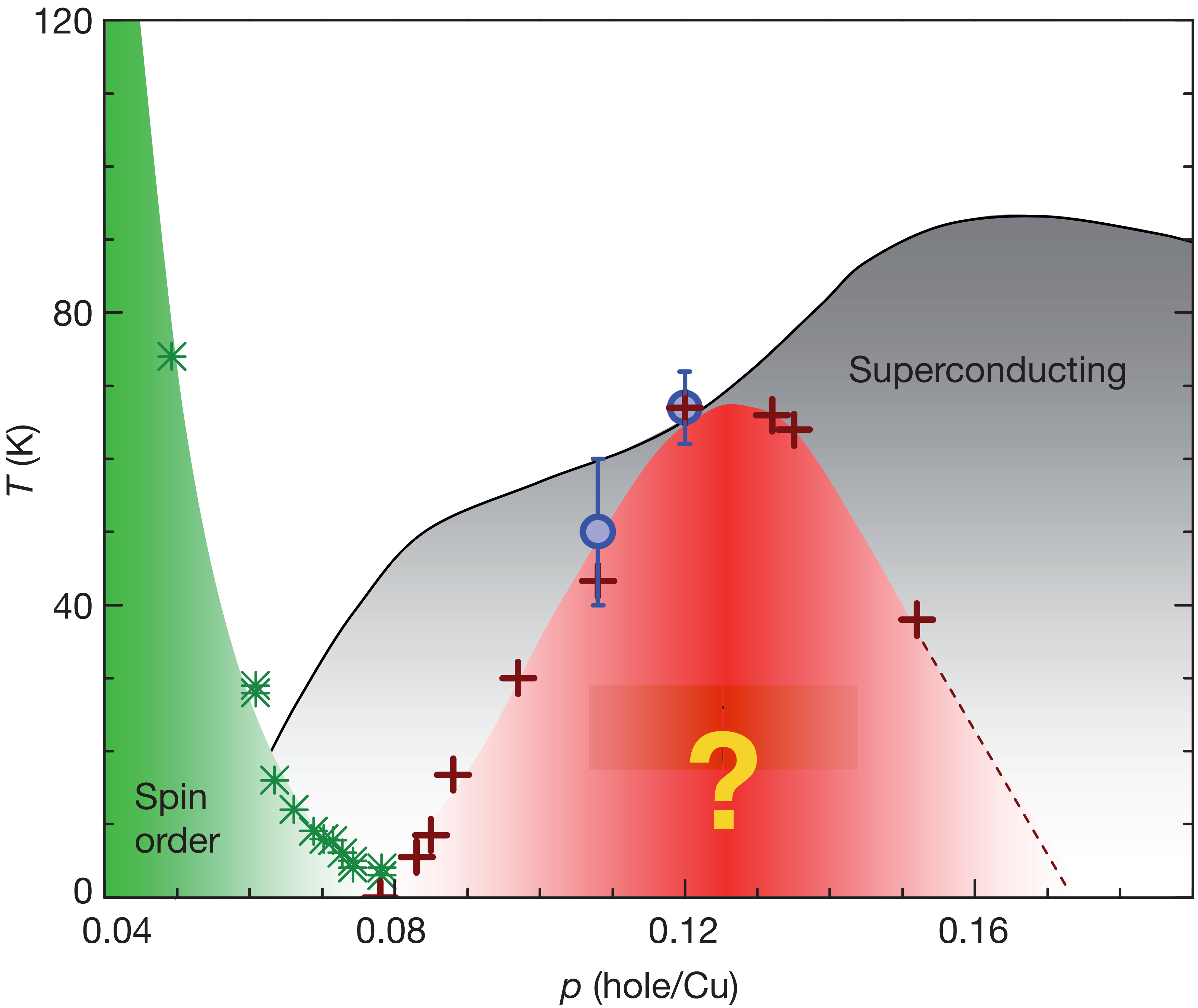
Conclusions

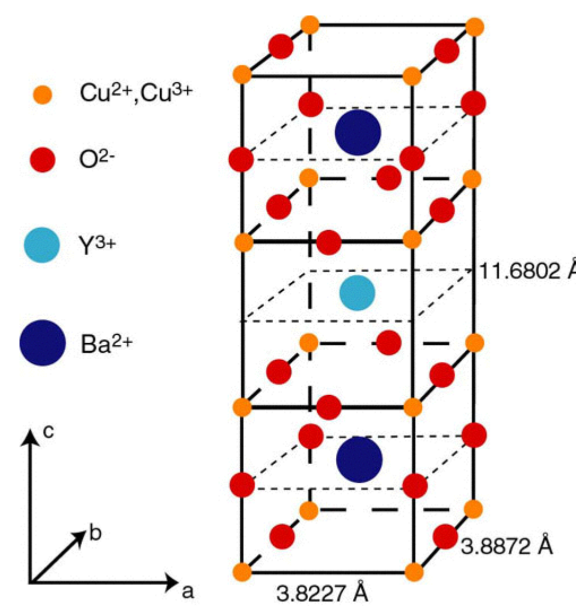
1. *d*-wave superconductivity

2. Low hole density state:
   d-wave bond order

3. Theoretical background

4. Evolution of Fermi surface





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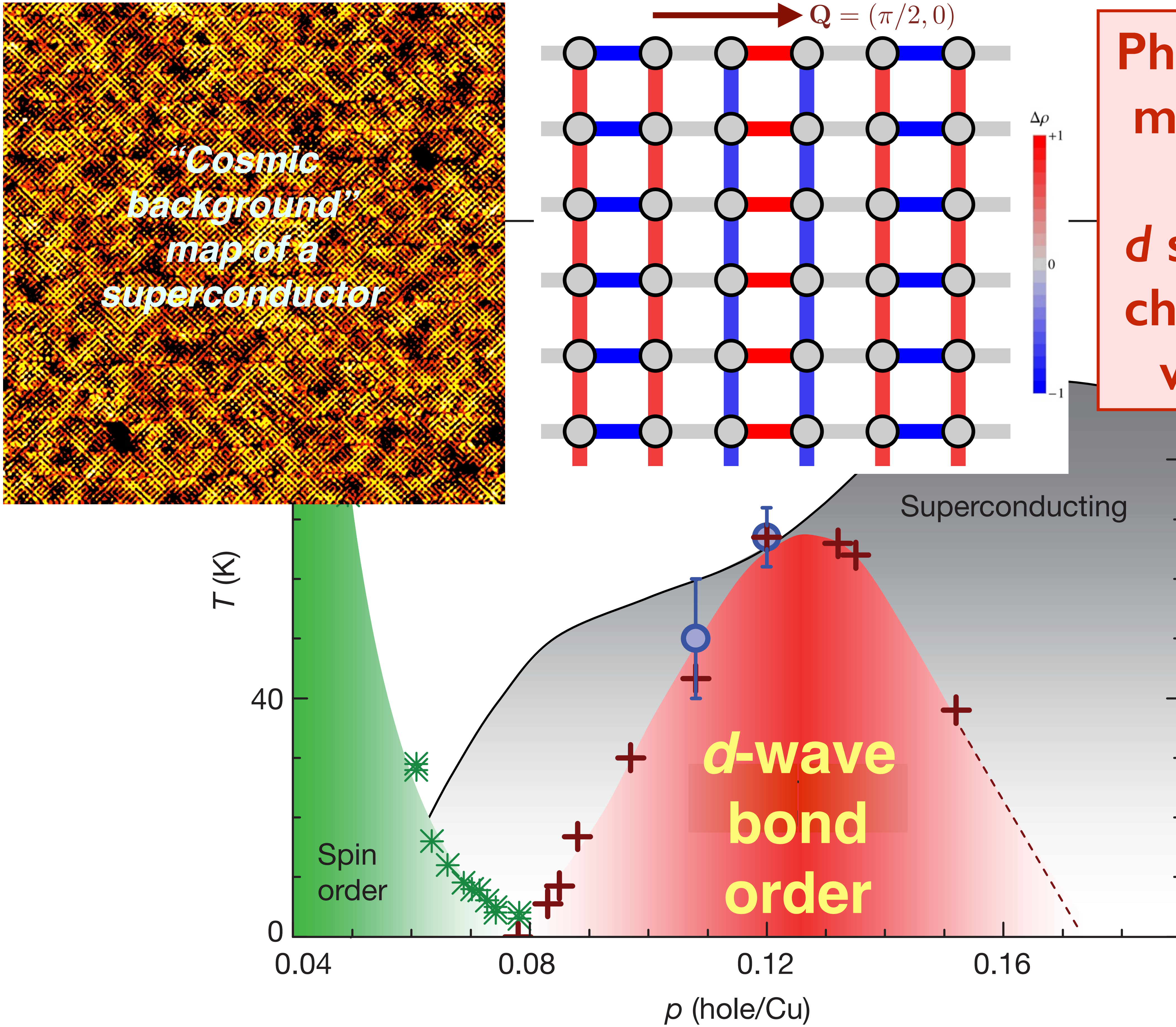

Phase-sensitive measurement of the *d* symmetry of charge density wave order

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