Unveiling the order of the high temperature superconductors

Weizmann Institute of Science
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Talk online: sachdev.physics.harvard.edu

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

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Cornell / BNL

Stephen Edkins
Cornell / St Andrews

Michael Lawler

J. C. Seamus Davis

Eun-Ah Kim

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 to appear, arXiv:1404.0362

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

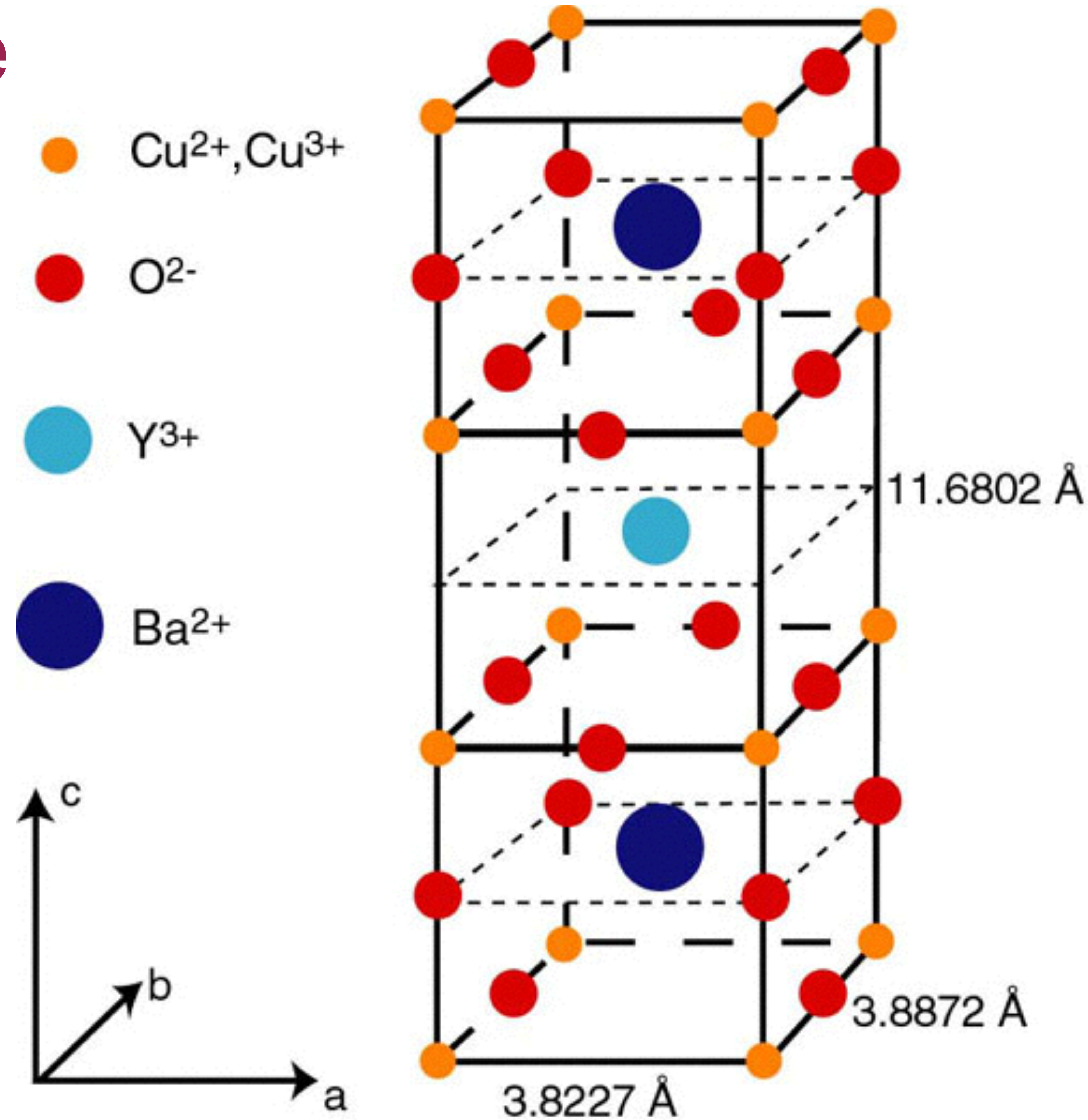
Anjan Soumyanarayanan

Ilija Zelkovic

Michael Yee

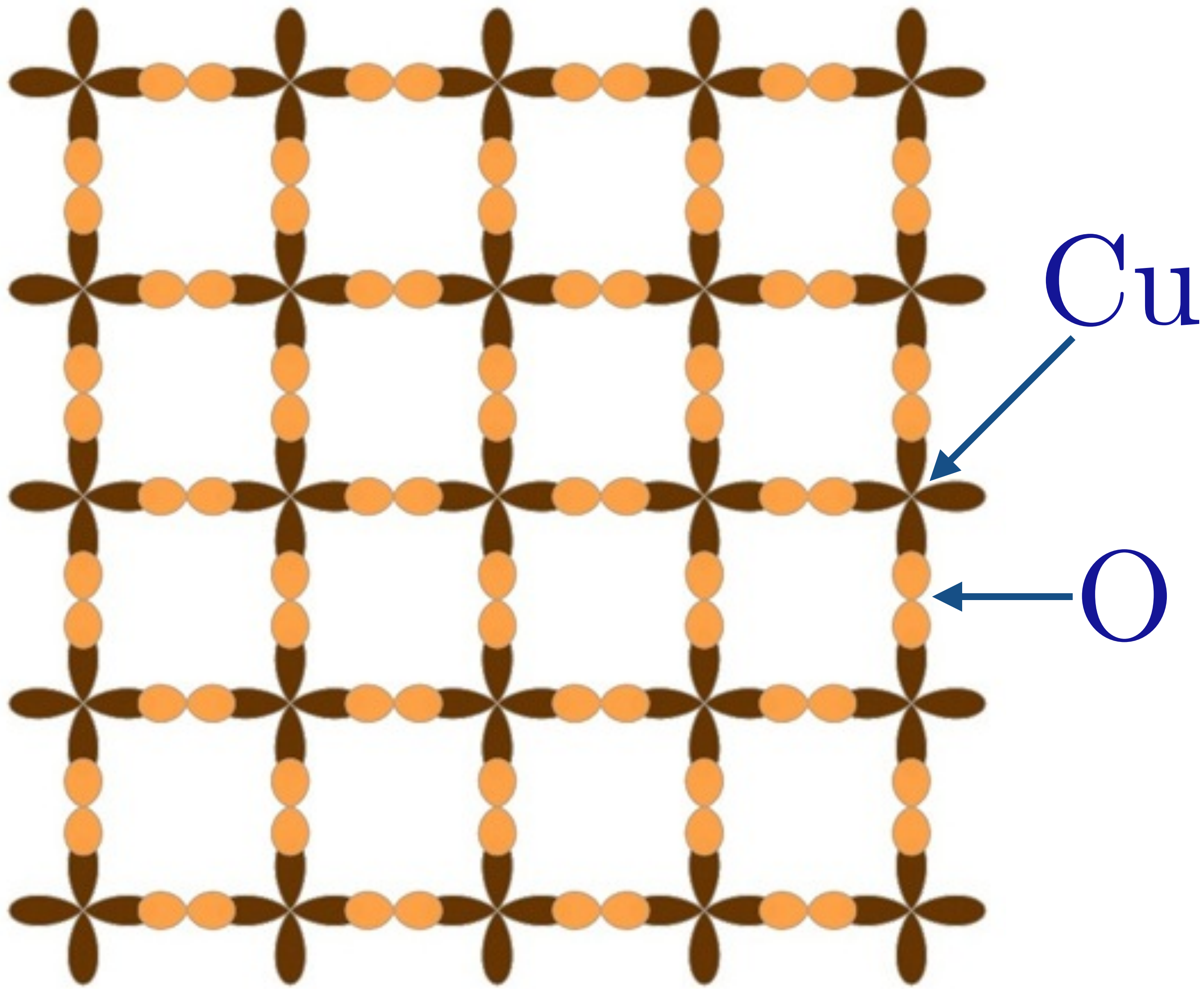
Jennifer Hoffman

High temperature superconductors

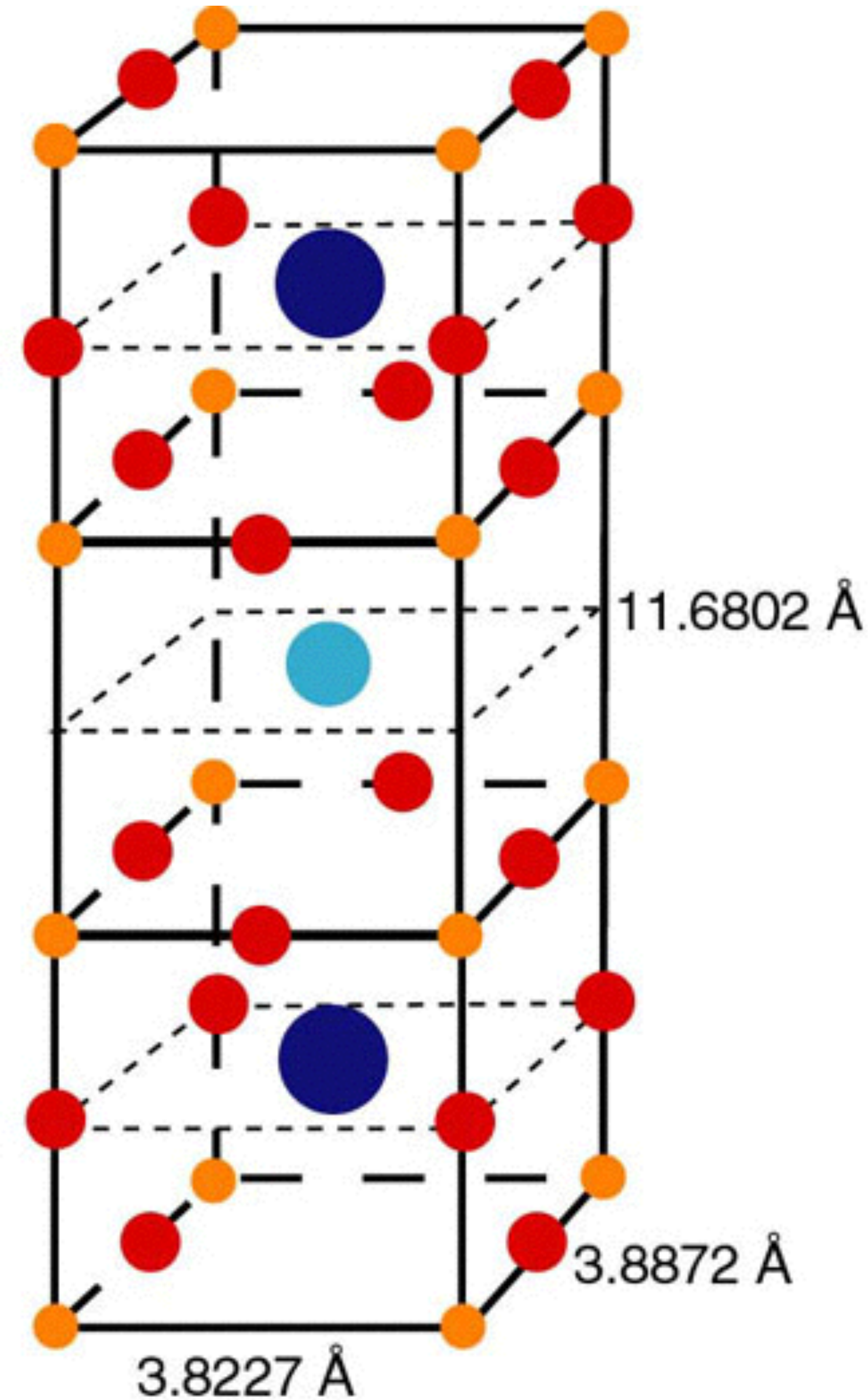


$$\mathrm{YBa_2Cu_3O}_{6+x}$$

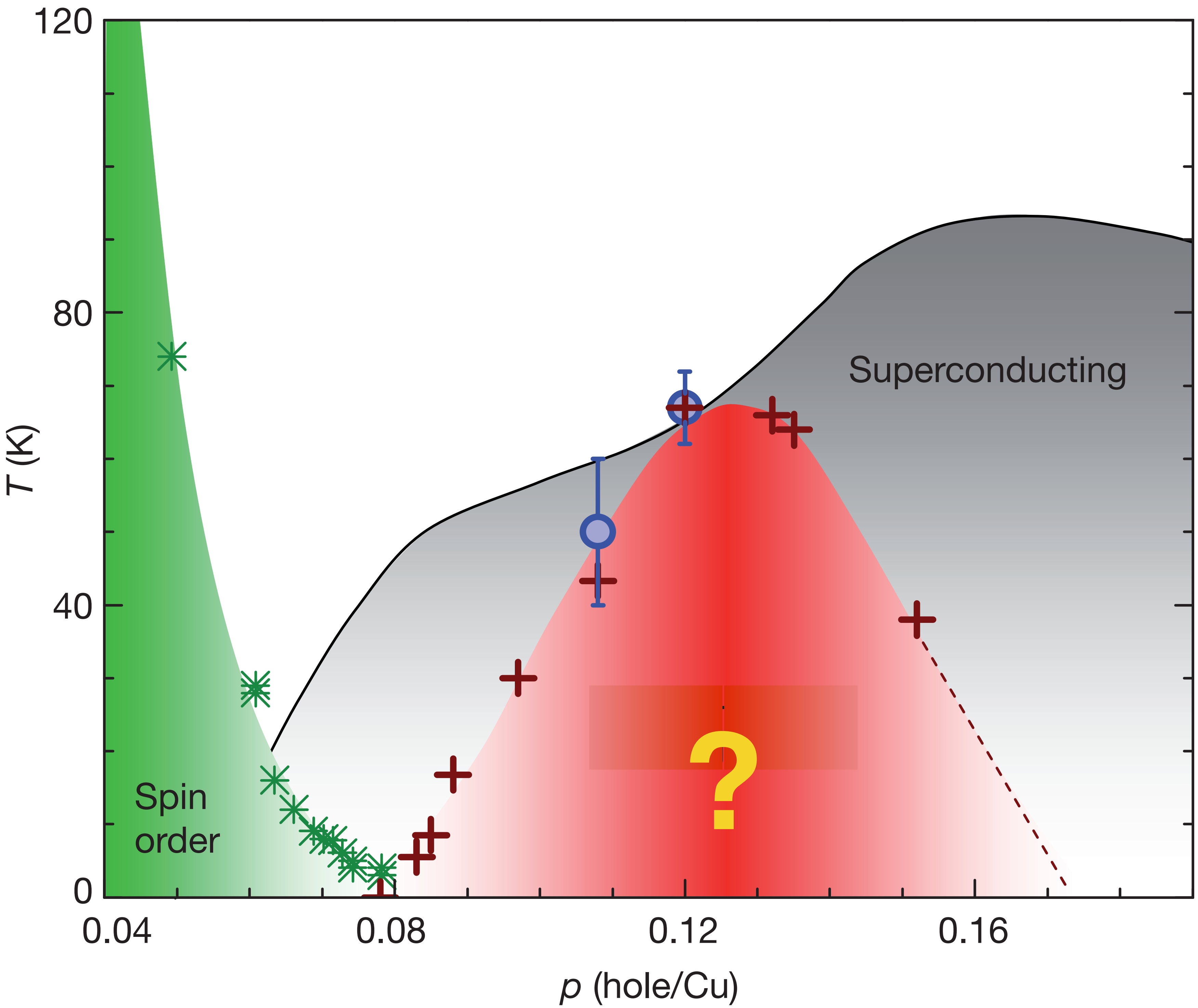
High temperature superconductors

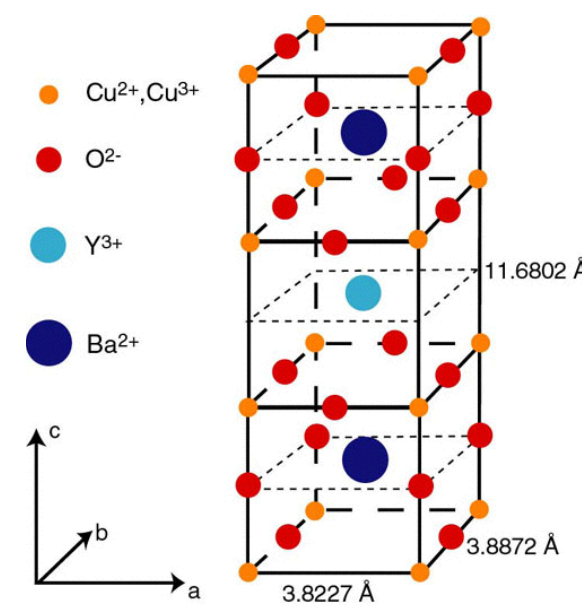


CuO_2 plane



$YBa_2Cu_3O_{6+x}$





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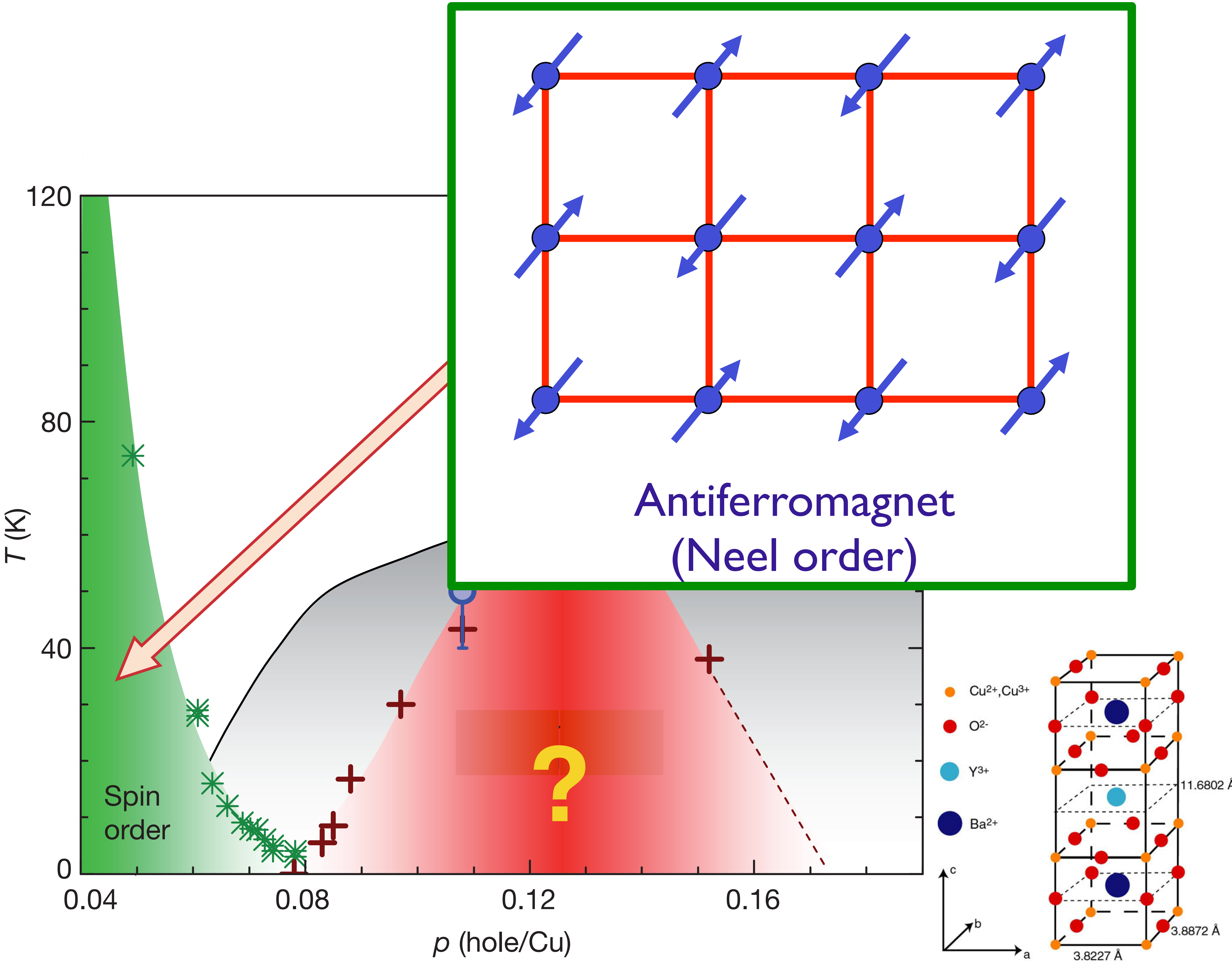

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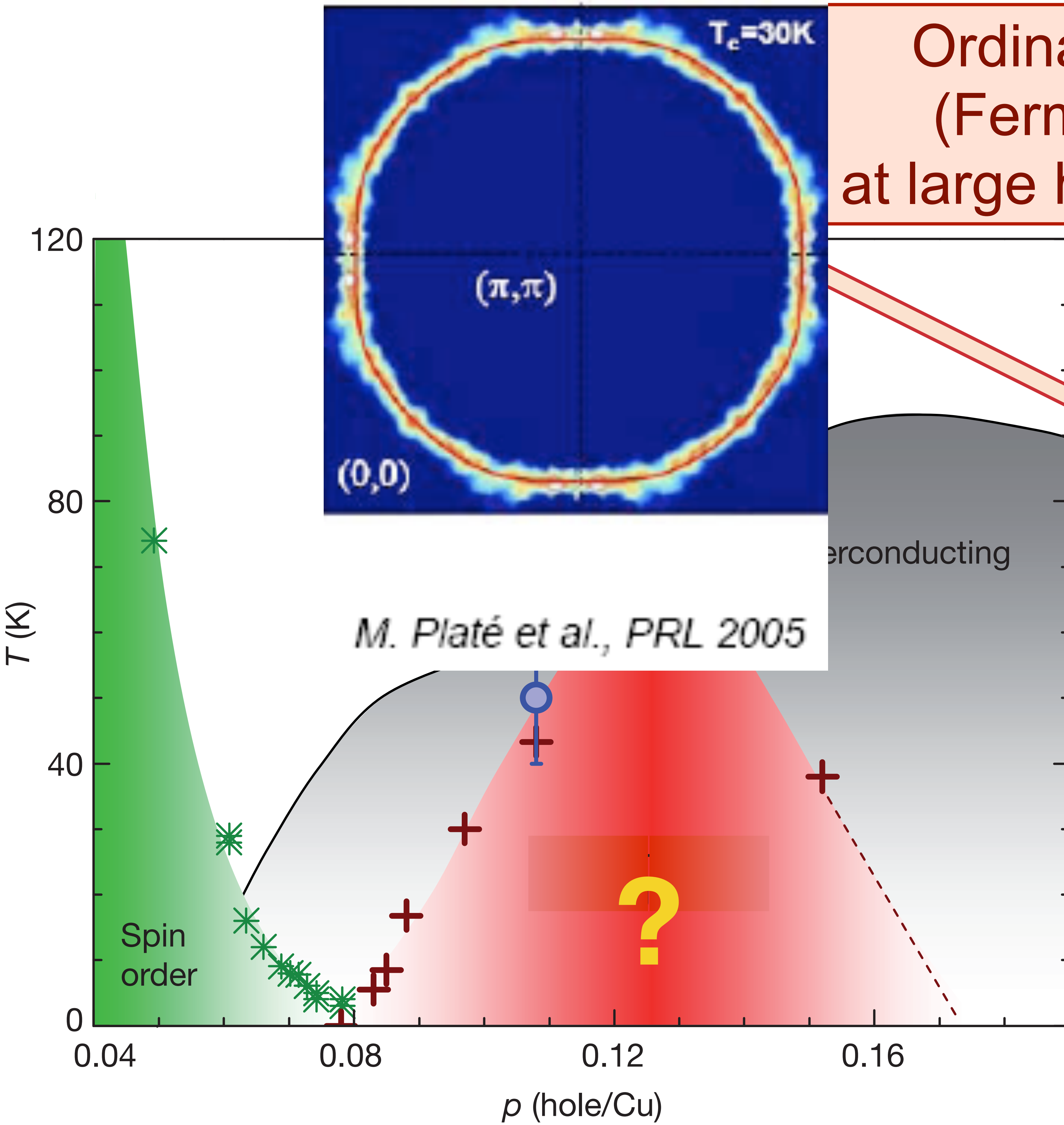
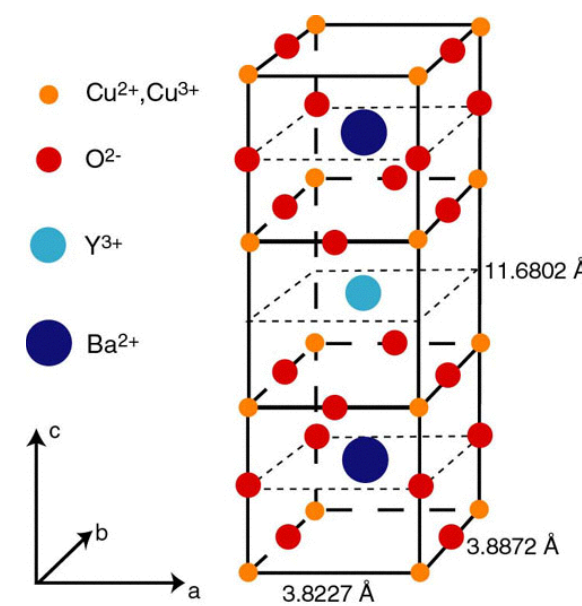
Ordinary metal
(Fermi liquid)
at large hole density





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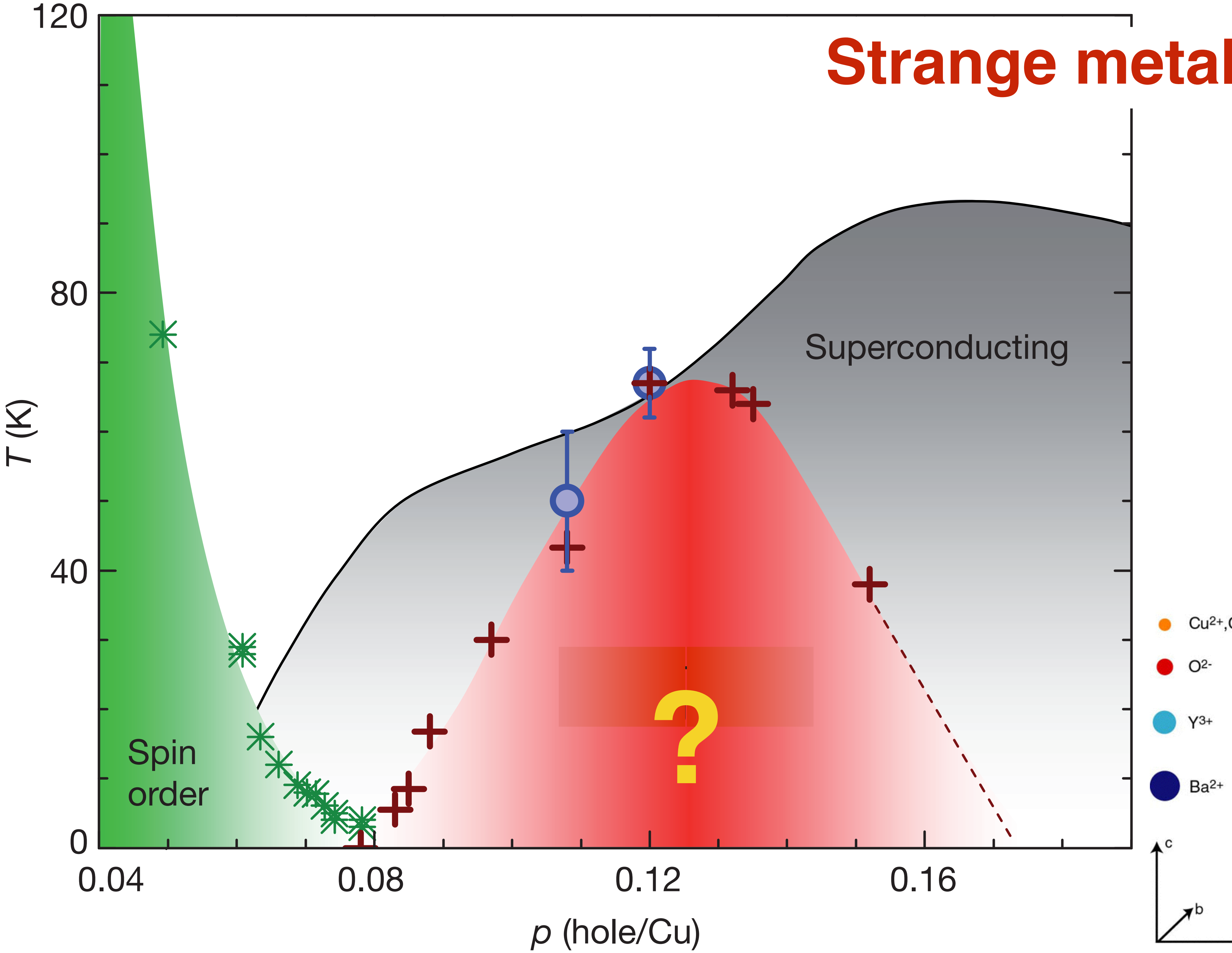

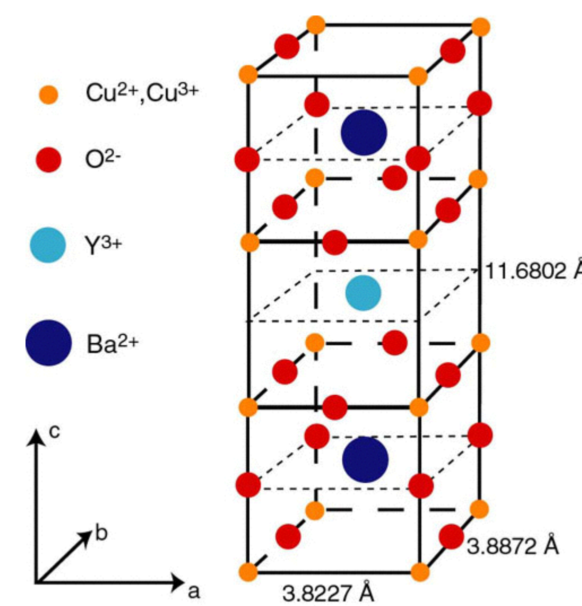

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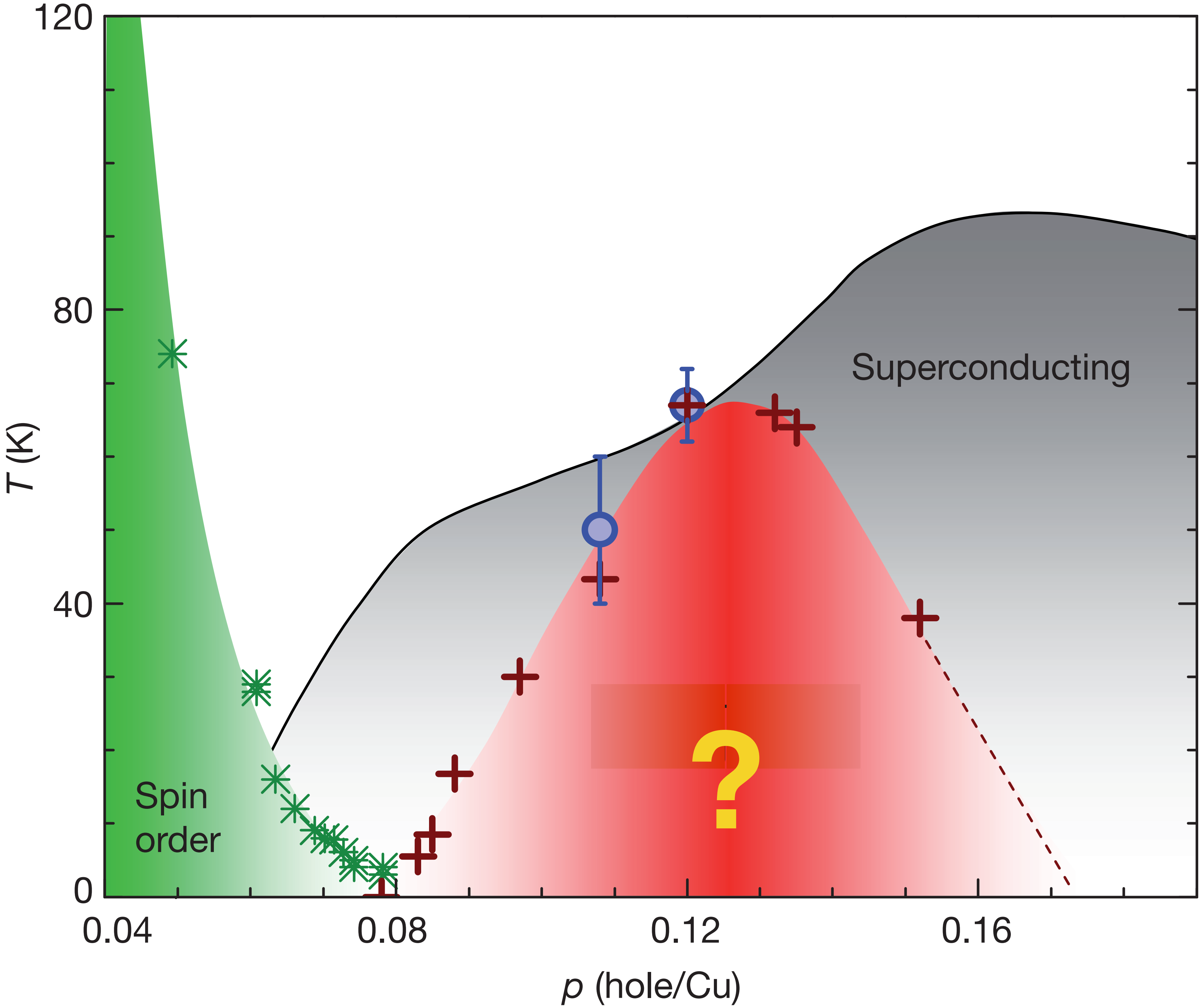
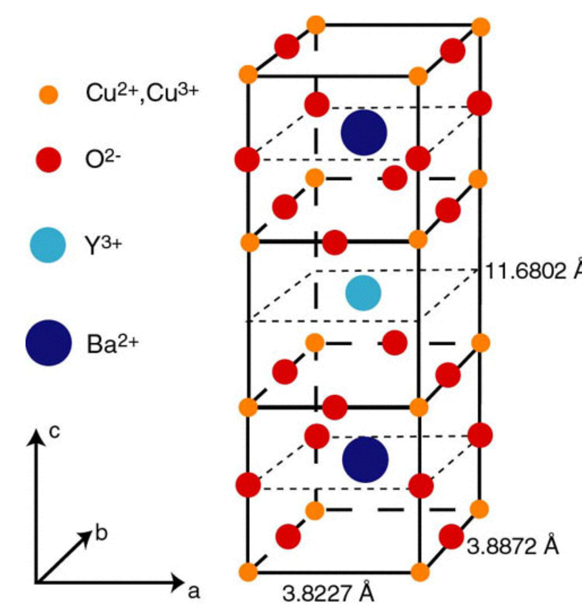
In the La-based superconductors, the region with magnetic order overlaps with the red region - I will not discuss these materials: see S. A. Kivelson, I.P. Bindloss, E. Fradkin, V. Oganesyan, J. M. Tranquada, A. Kapitulnik, and C. Howald, *Rev. Mod. Phys.* **75**, 1201(2003)





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Outline

1. Unconventional *d*-wave superconductivity

2. Low hole density state:
   An unconventional density wave

3. Outline of theoretical prediction

4. Evolution of Fermi surface

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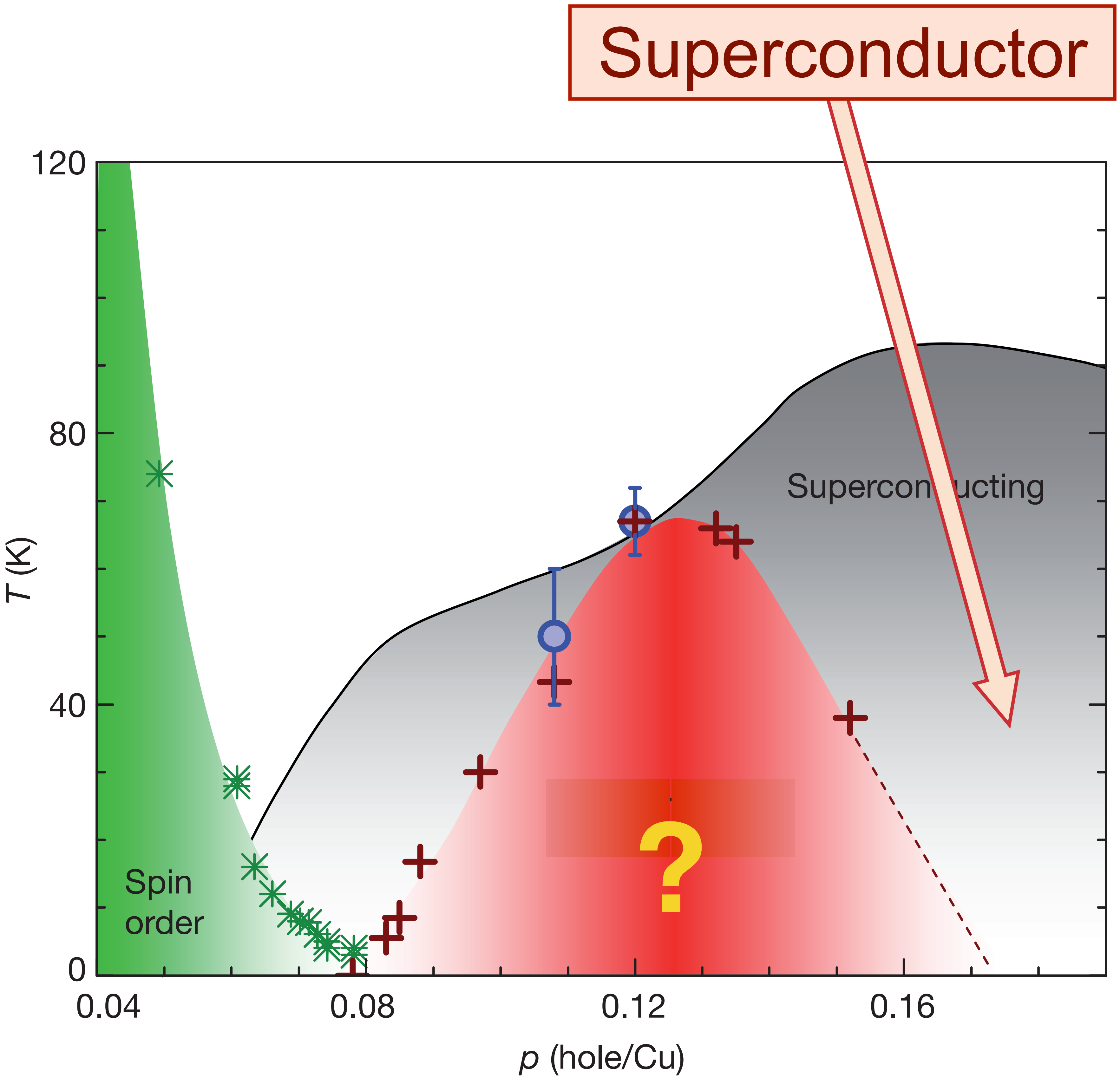

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Superconductivity:
Bose condensation of Cooper pairs of electrons

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

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

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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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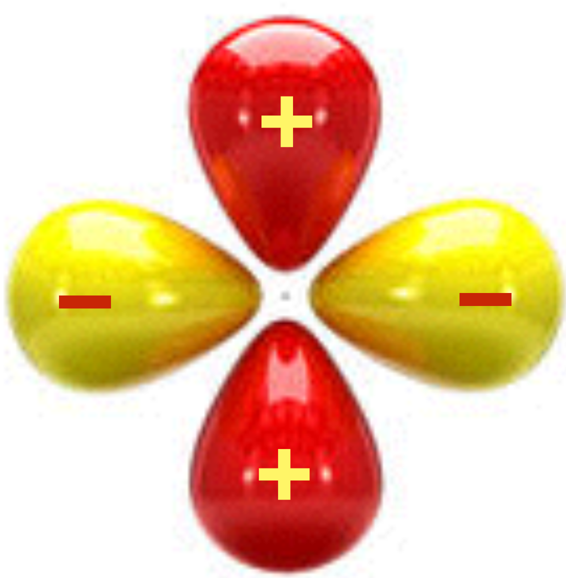
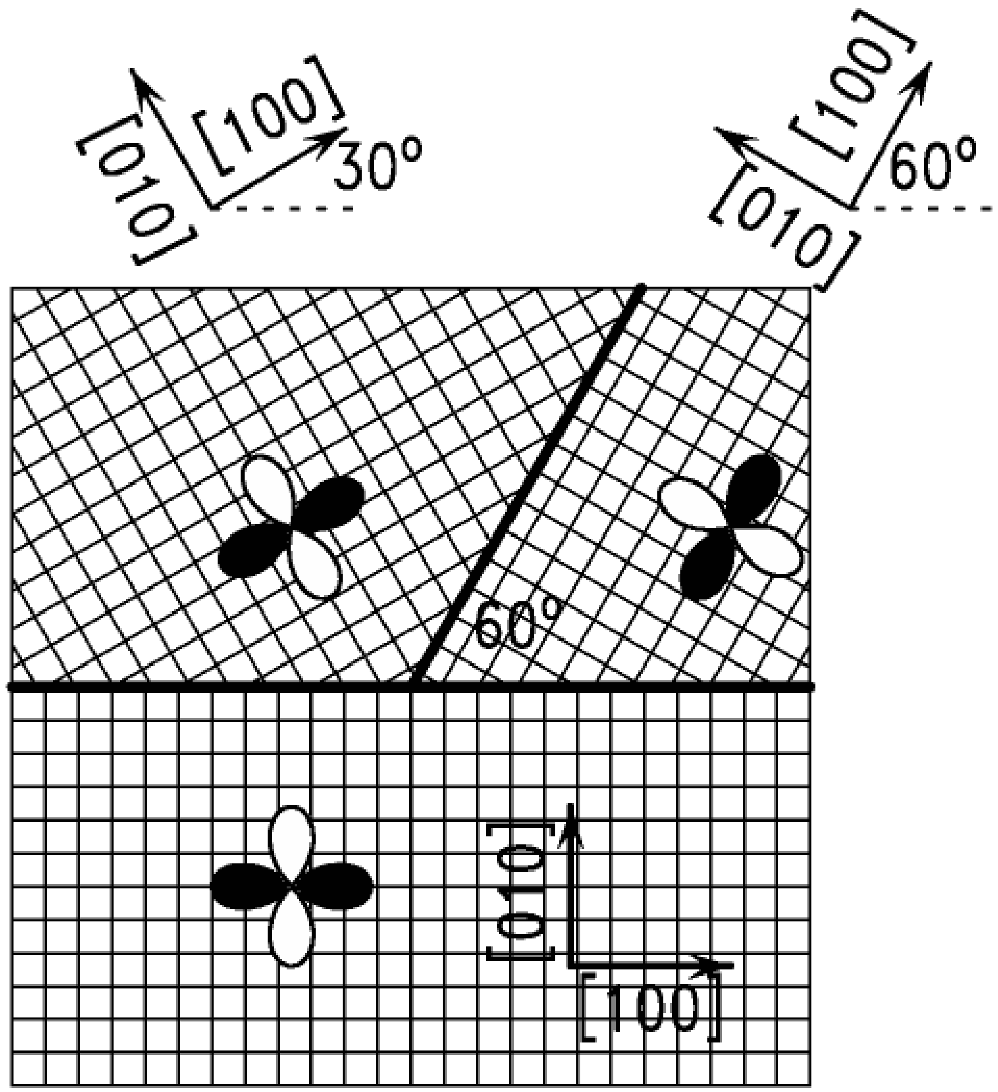
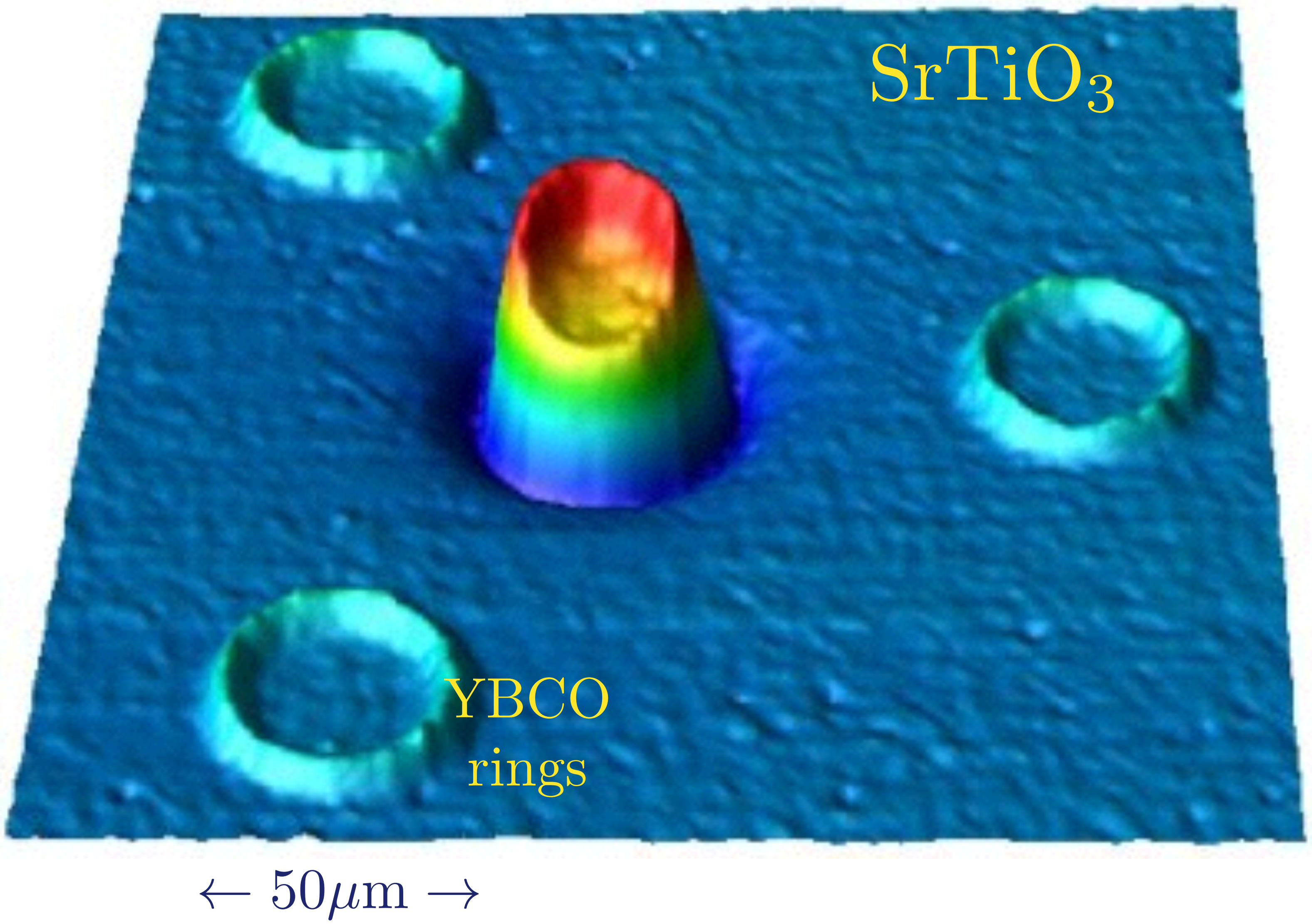


Internal Cooper-pair wavefunction has *d*-wave form in cuprates: ***Unconventional*** superconductivity

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

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





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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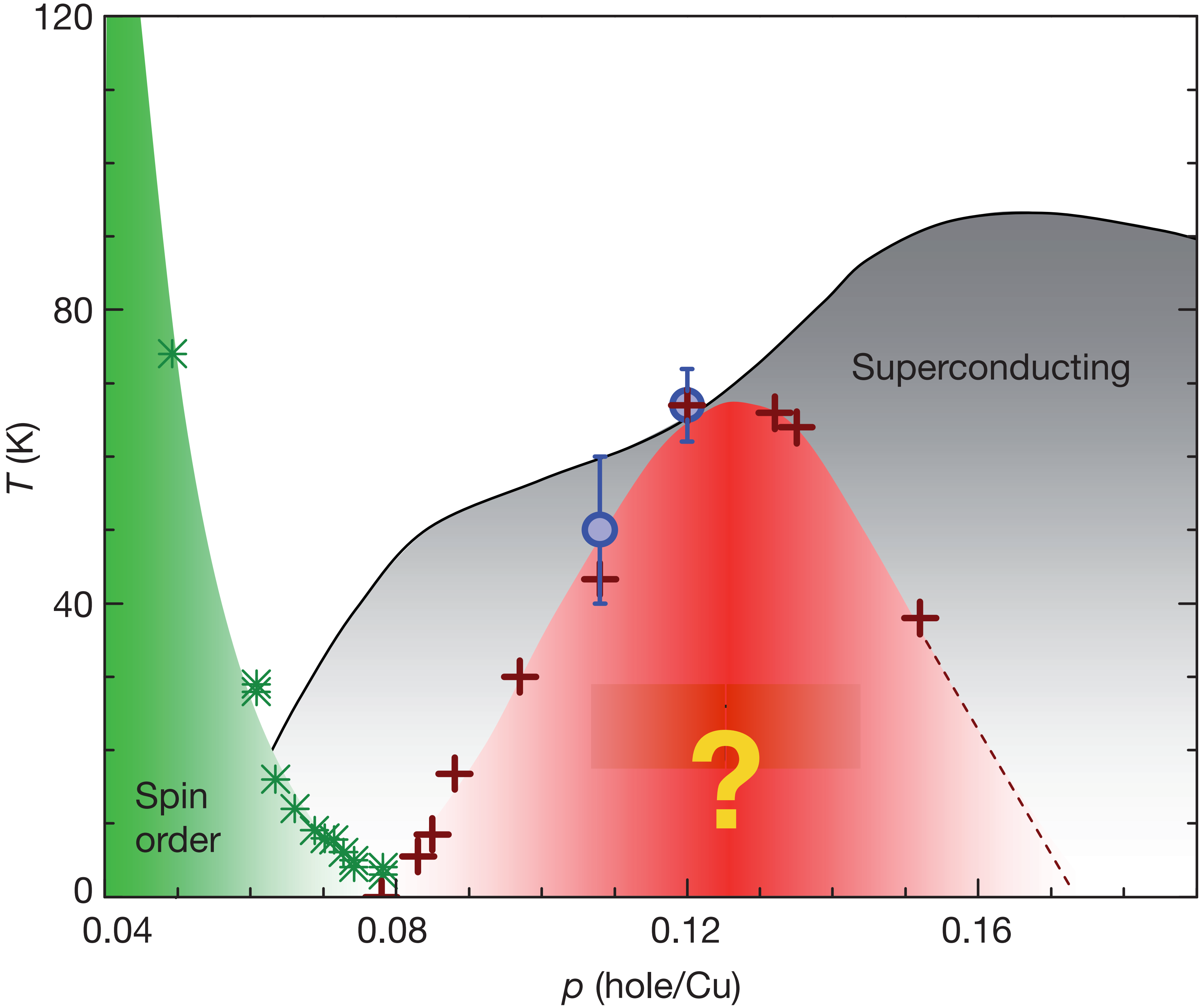

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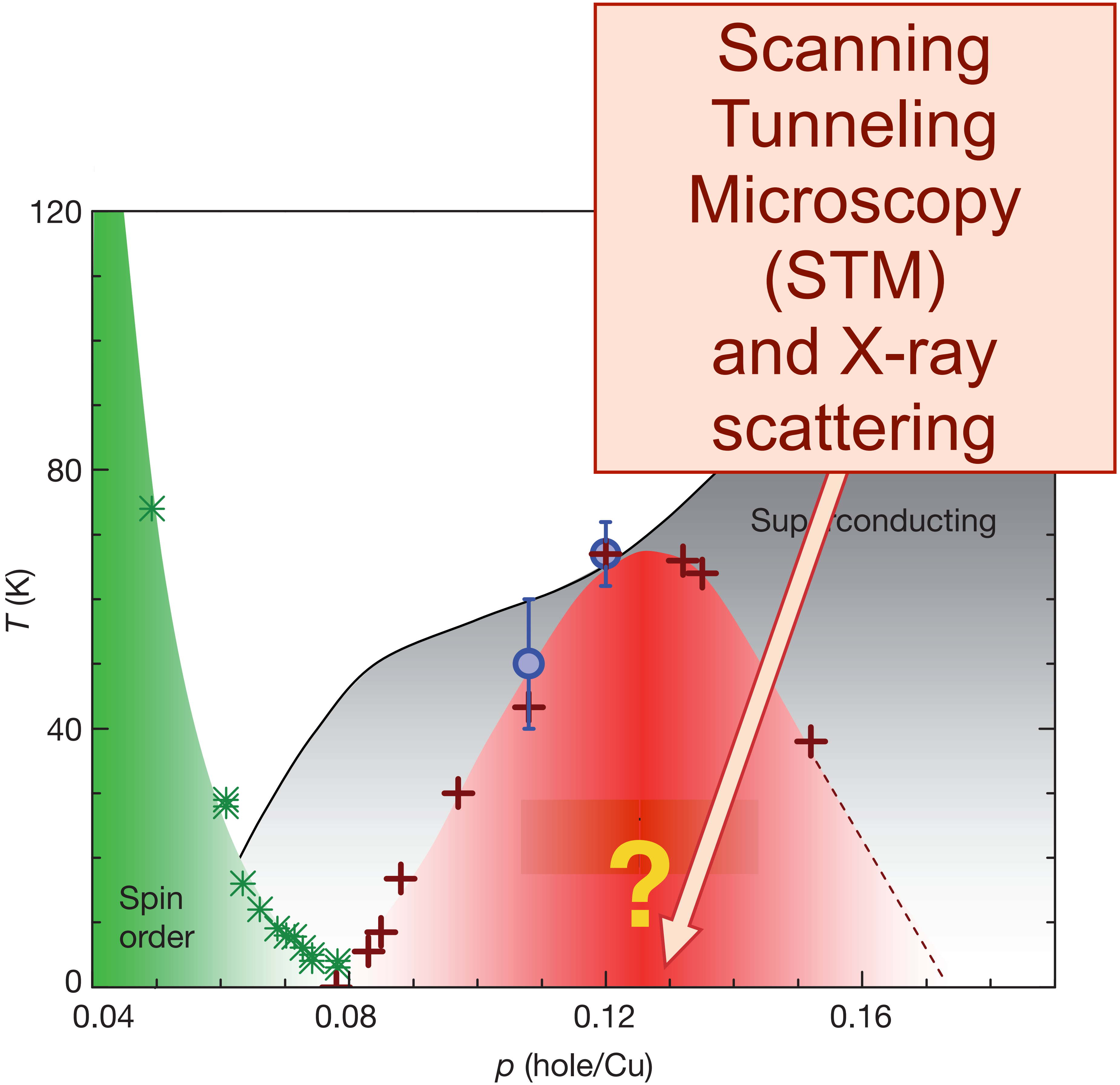

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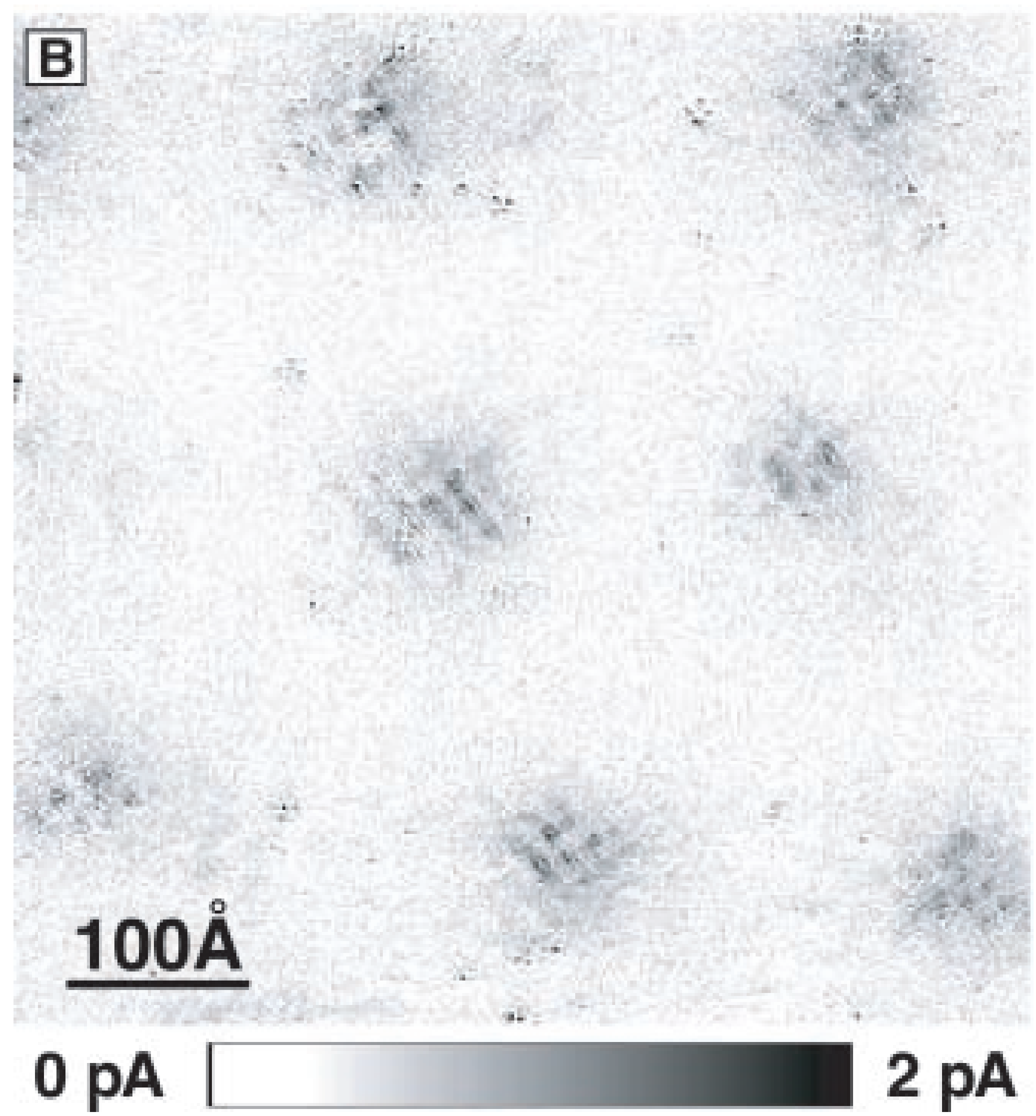
A Four Unit Cell Periodic Pattern of Quasi-Particle States Surrounding Vortex Cores in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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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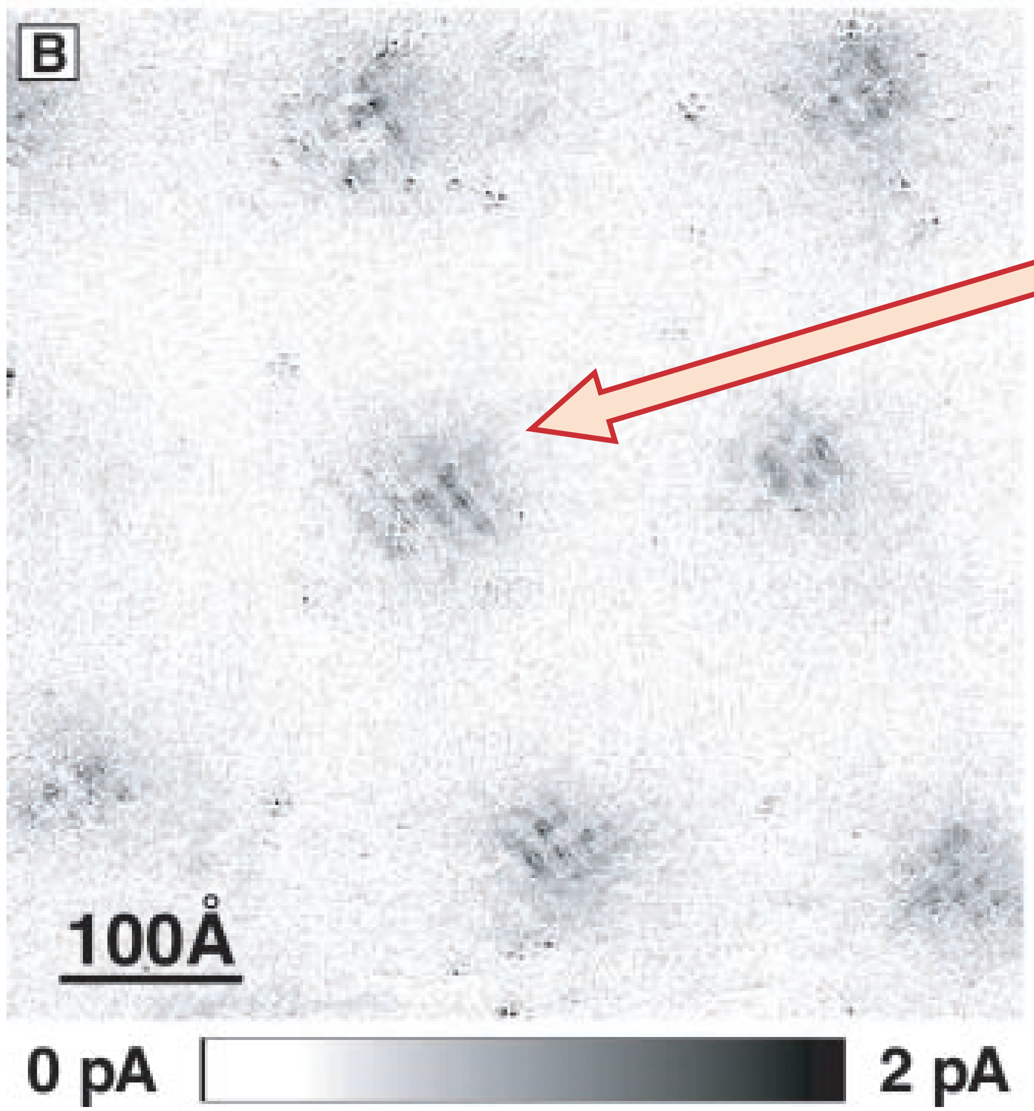

A density wave with wavelength ≈ 4 lattice spacings around vortex cores ?

See also
C. Howald, H. Eisaki, N. Kaneko, M. Greven, and A. Kapitulnik, Phys. Rev. B **67**, 014533 (2003);

M. Vershinin, S. Misra, S. Ono, Y. Abe, Yoichi Ando, and A. Yazdani, Science **303**, 1995 (2004).

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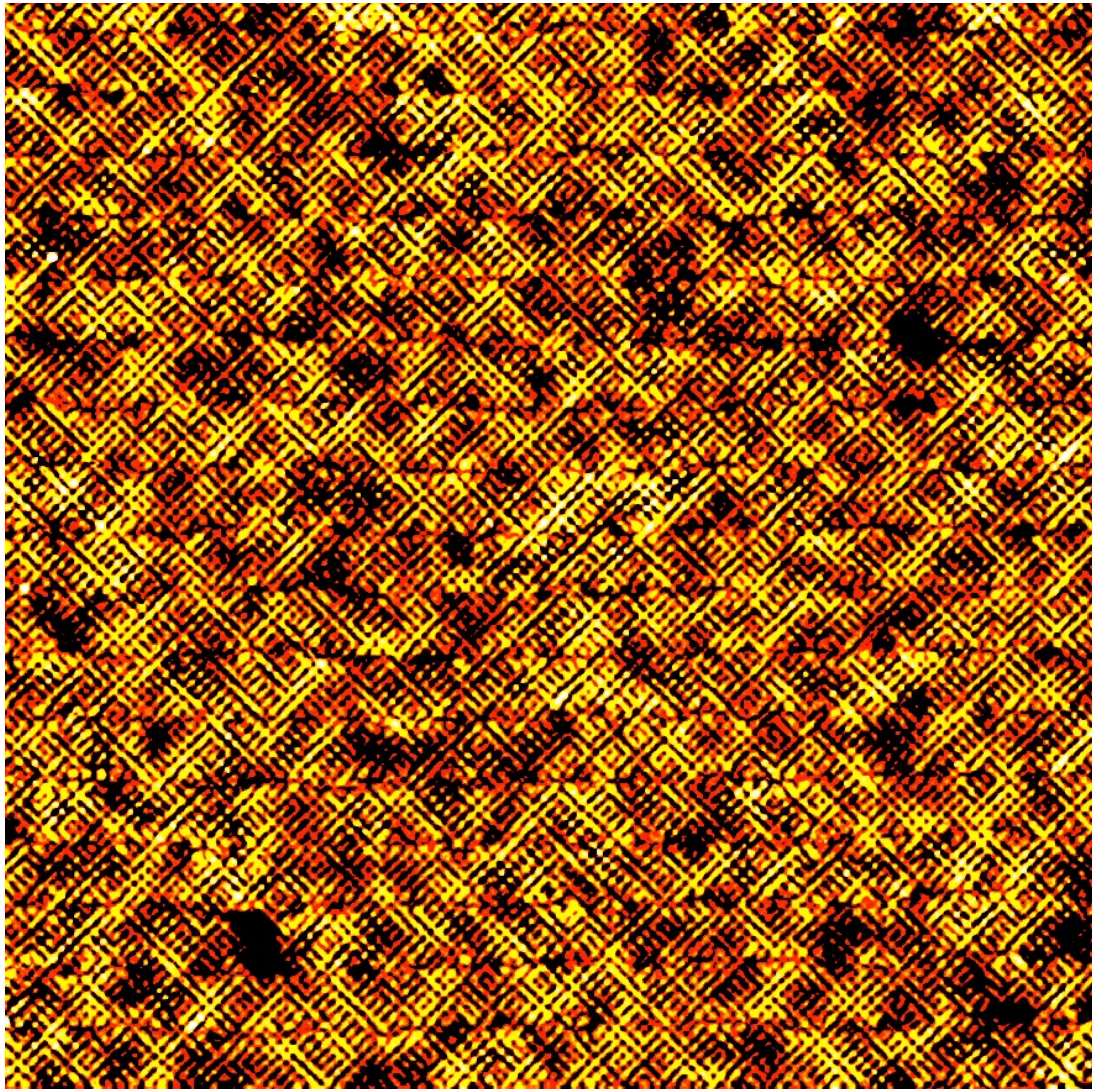

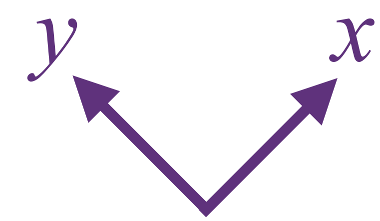

"R-map" of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007).

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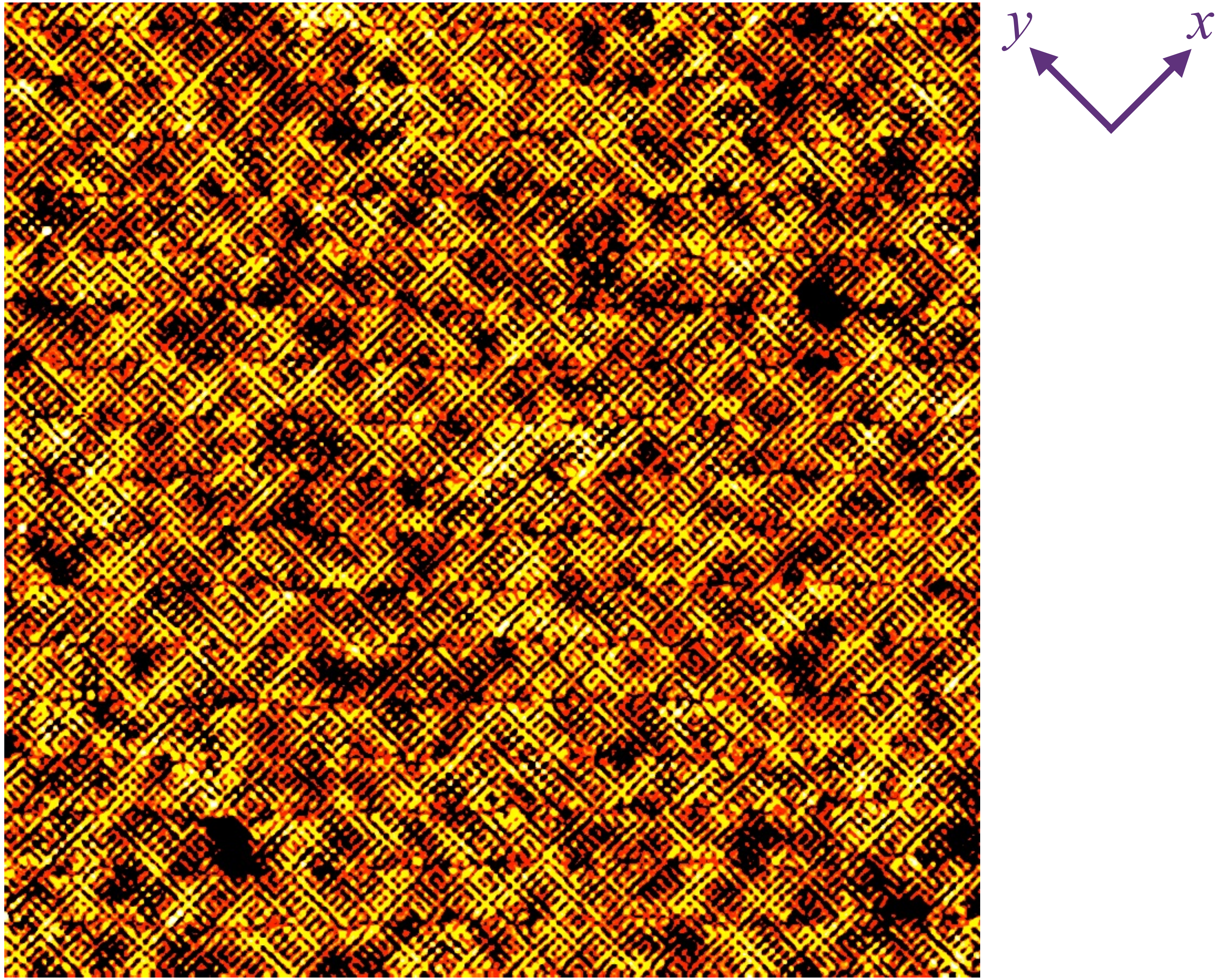

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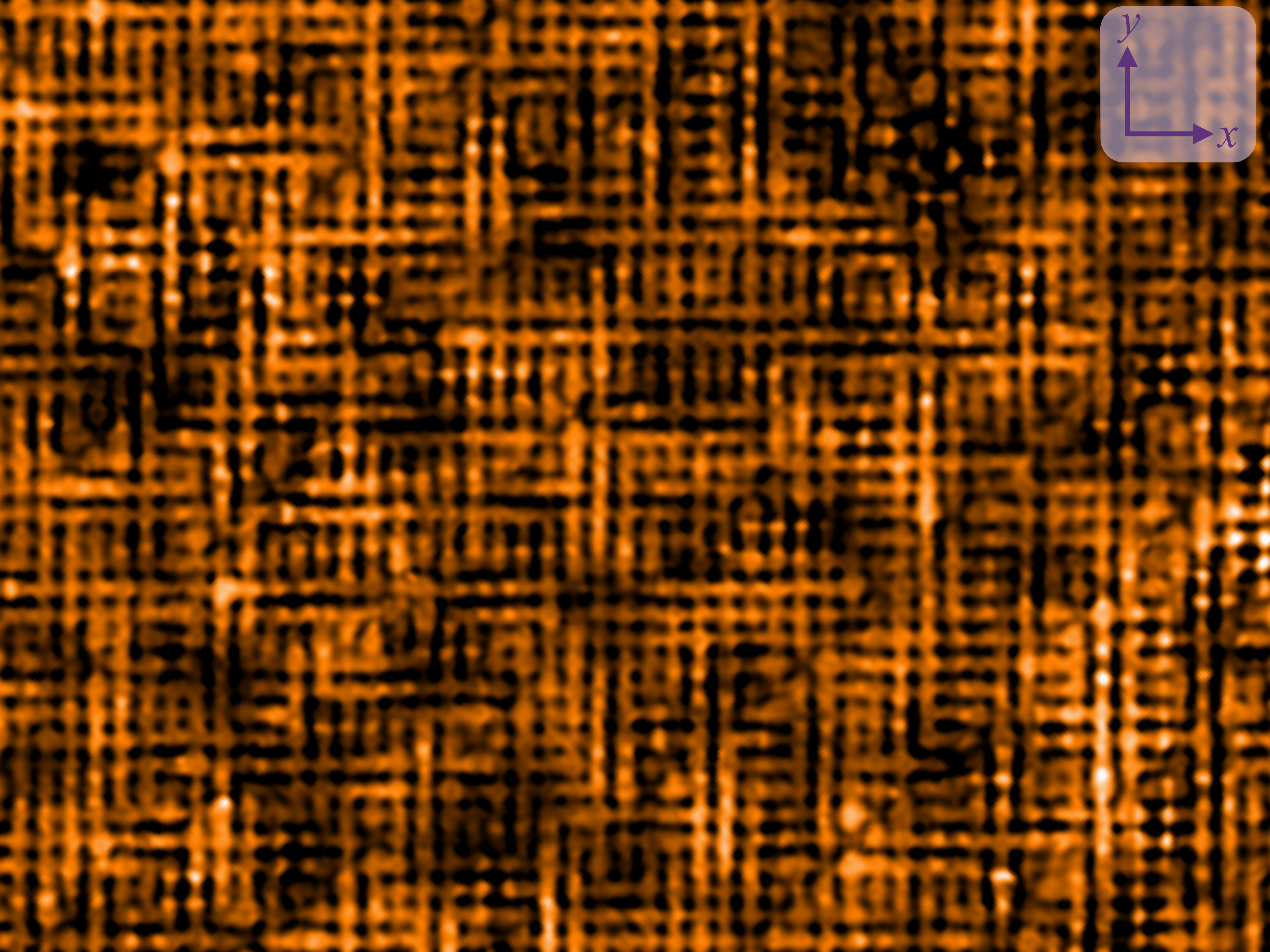
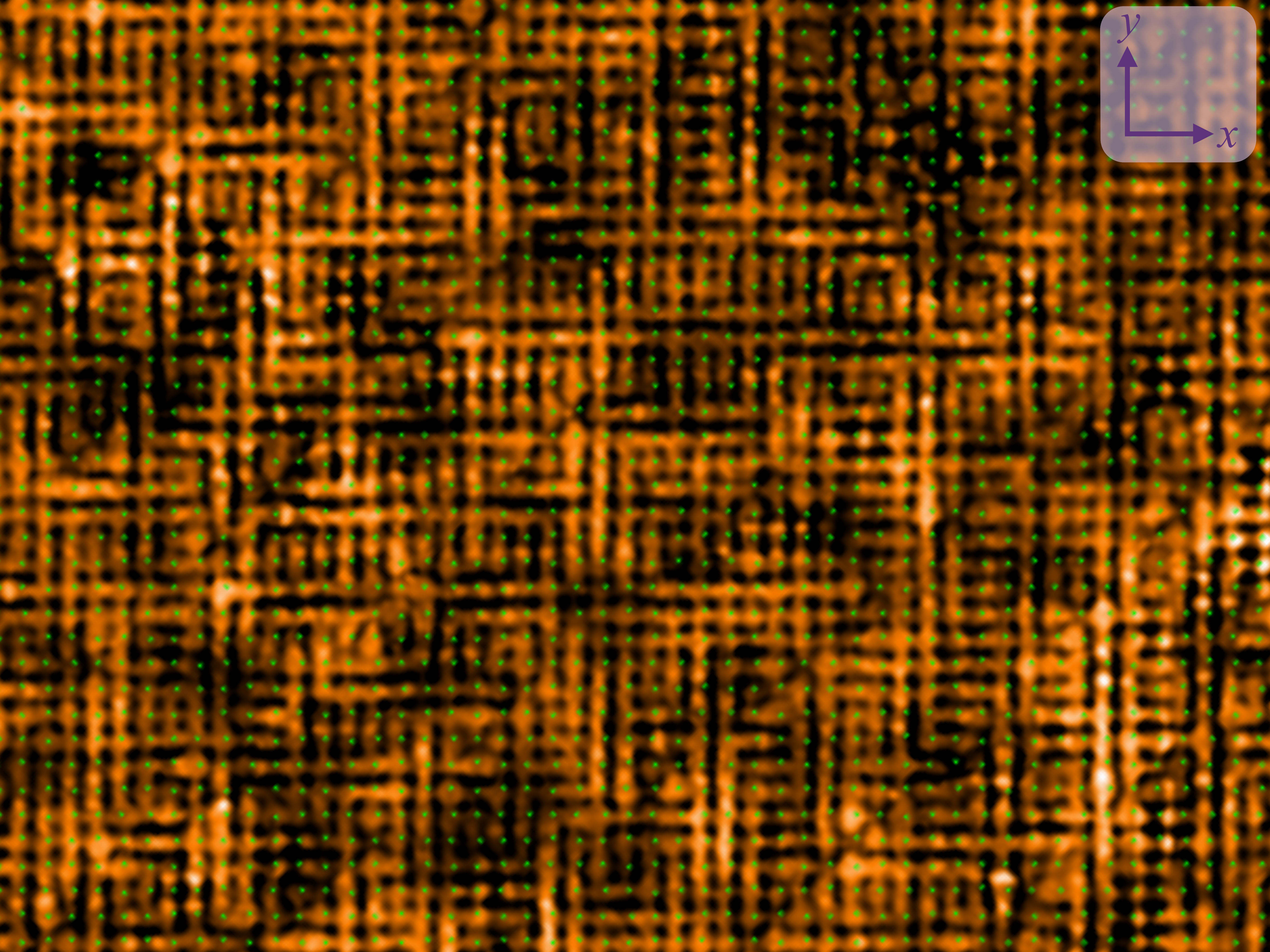

y
x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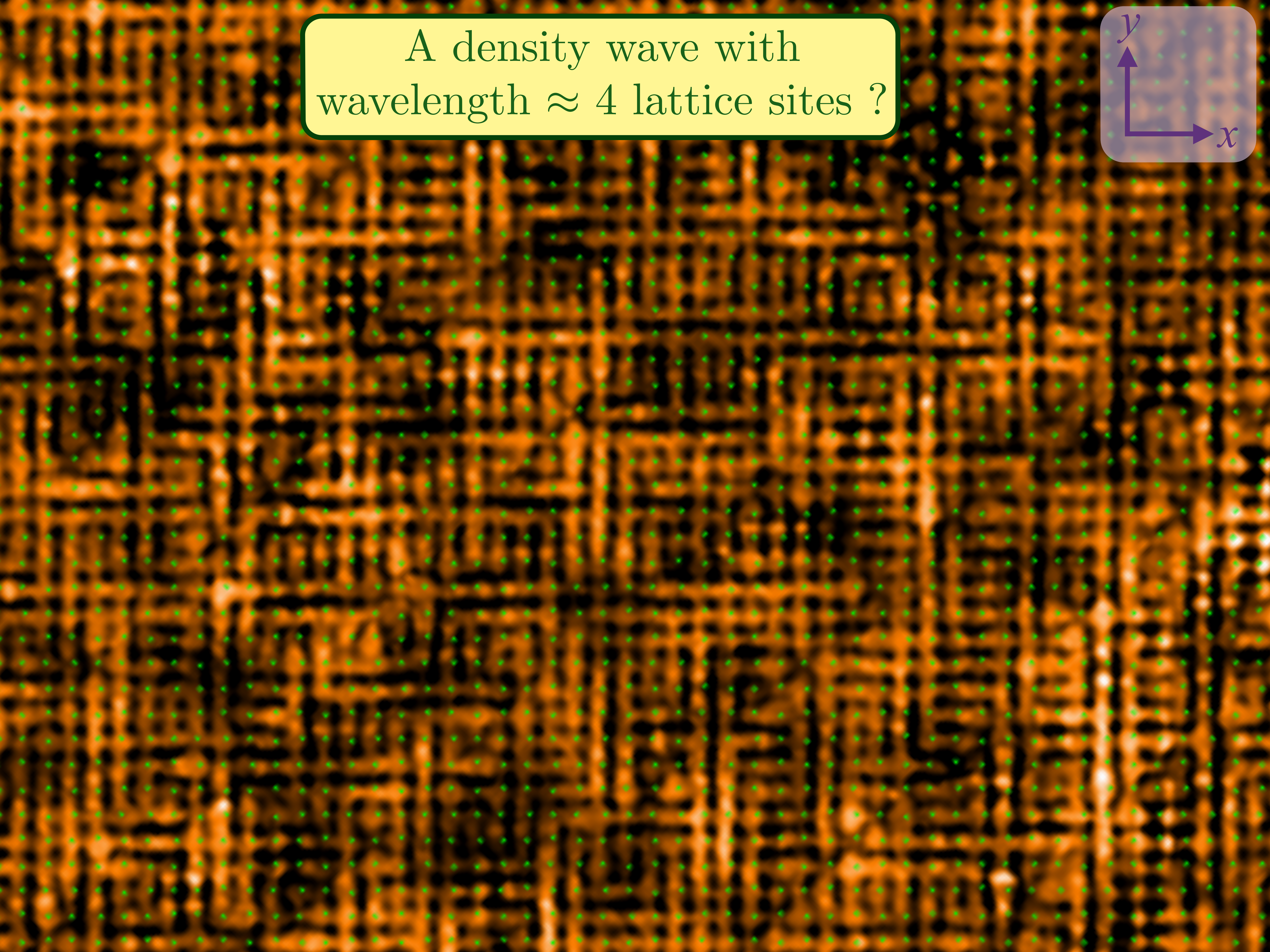
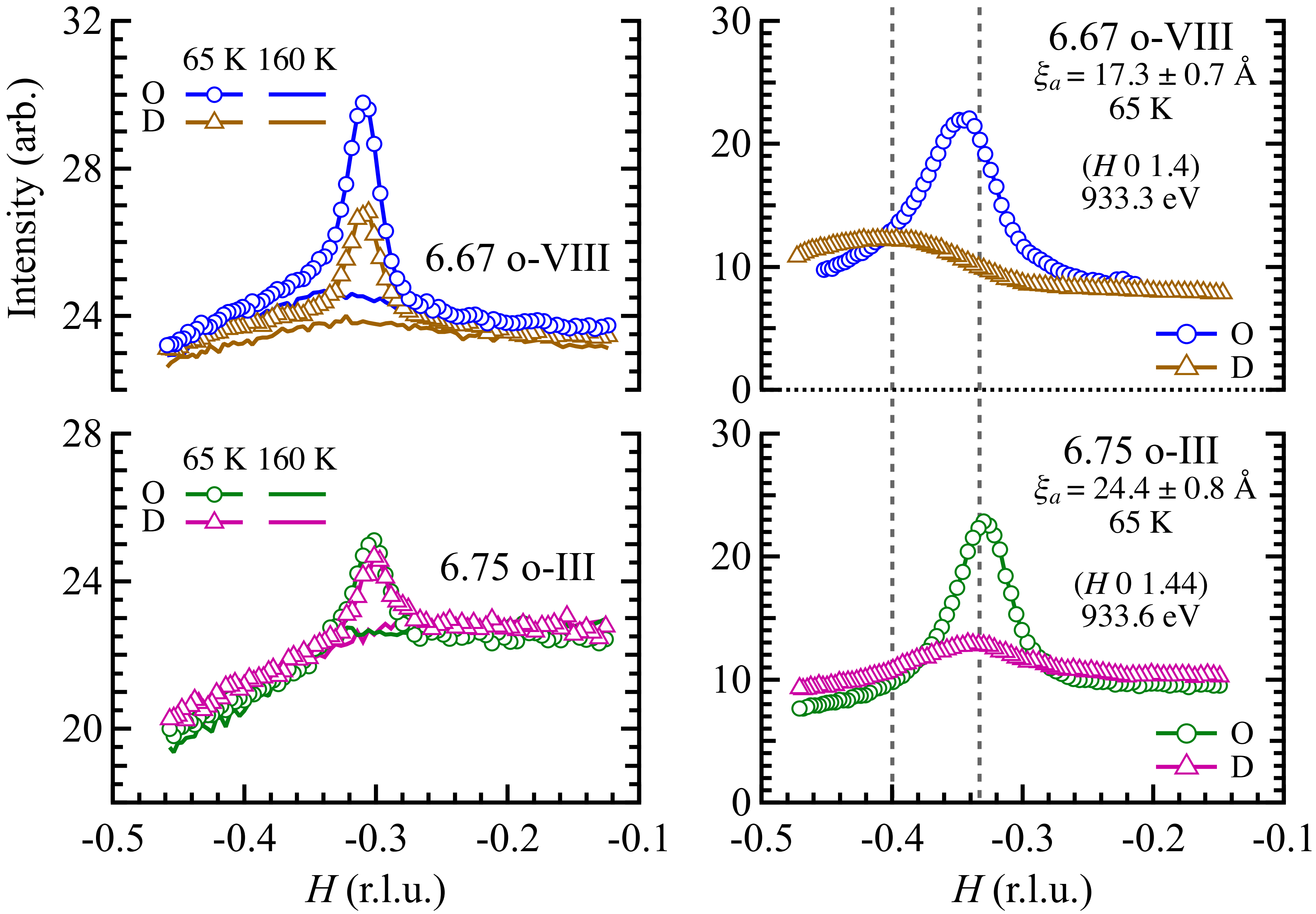

A density wave with
wavelength ≈ 4 lattice sites ?
y
x



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 "charge" density 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

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

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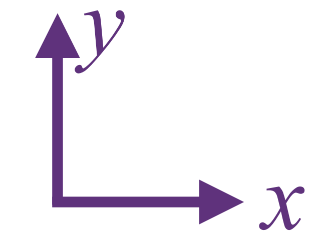
CDW wavevector $\mathbf{Q}$

Charge density wave (CDW) order

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

Nearly constant CDW order parameter

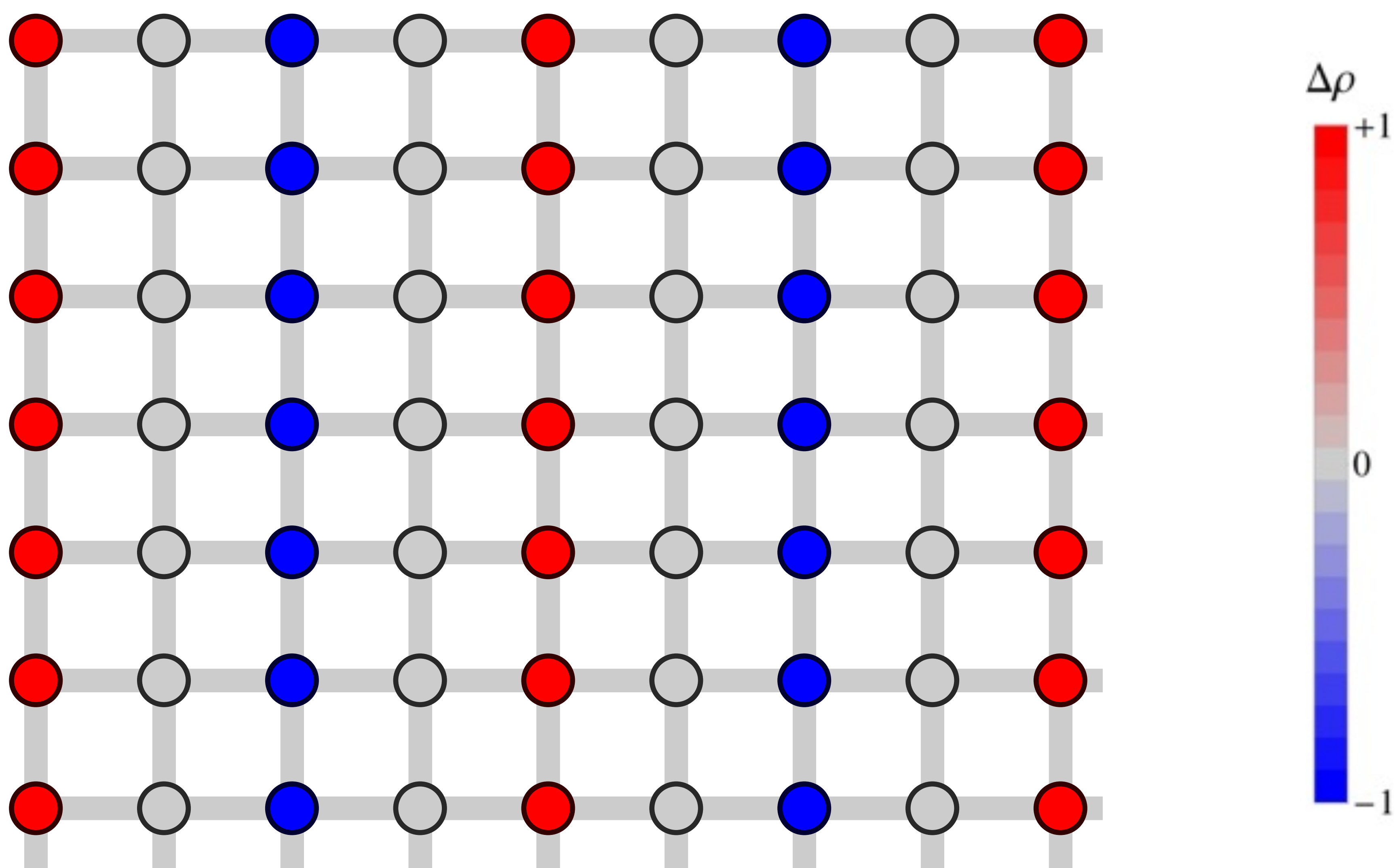
CDW order.

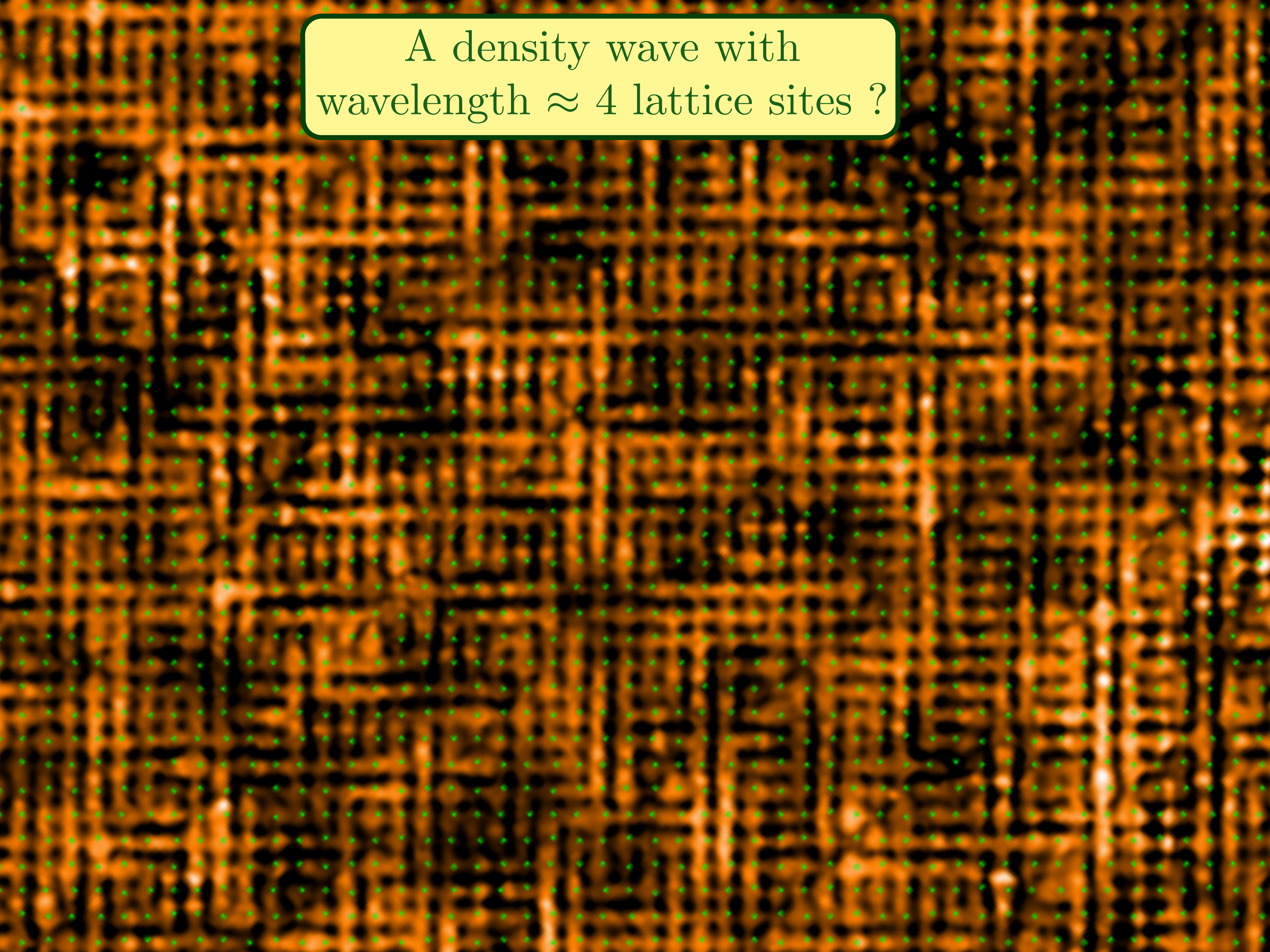


Plot of $P_{ii} = \left\langle c^\dagger_{i\alpha} c_{i\alpha} \right\rangle$ with

$$P_{ii} = e^{i\mathbf{Q}\cdot\mathbf{r}_i} + \text{c.c.}$$

$$\text{with} \quad \mathbf{Q} = 2\pi(1/4, 0)$$




A density wave with
wavelength ≈ 4 lattice sites ?

Charge density wave (CDW) order

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Unconventional density wave (DW) :
Bose condensation of particle-hole pairs

$$\left\langle c_\alpha^\dagger(\mathbf{r}_1) c_\alpha(\mathbf{r}_2) \right\rangle$$

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

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DW wavevector $\mathbf{Q}$

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Nearly constant DW order parameter

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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 (using reflection symmetry for $\mathbf{Q}$ along axes or diagonals)

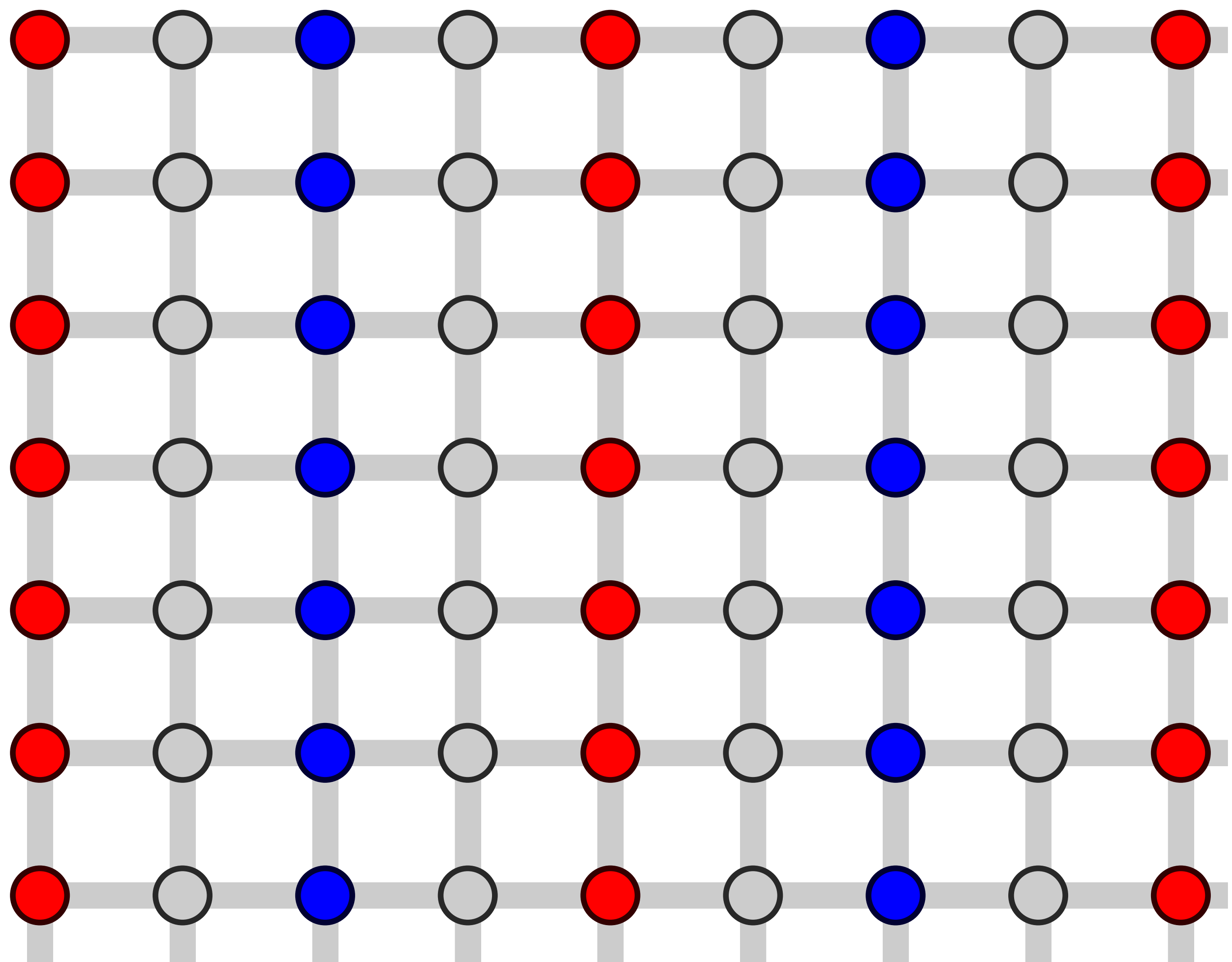
$$\mathcal{P}(\mathbf{k}) = \mathcal{P}_s + \mathcal{P}_{s'}(\cos k_x + \cos k_y) + \mathcal{P}_d(\cos k_x - \cos k_y)$$

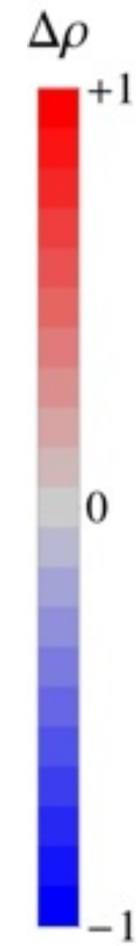
Conventional CDW order: s-wave

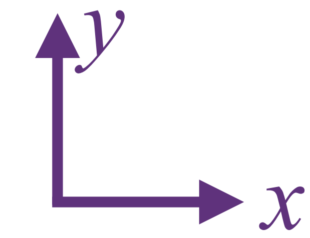
Plot of $P_{ij} = \left\langle c^\dagger_{i\alpha} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

$$\mathcal{P}(\mathbf{k}) = 1 \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$







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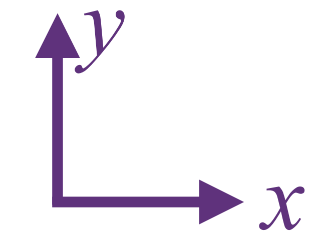

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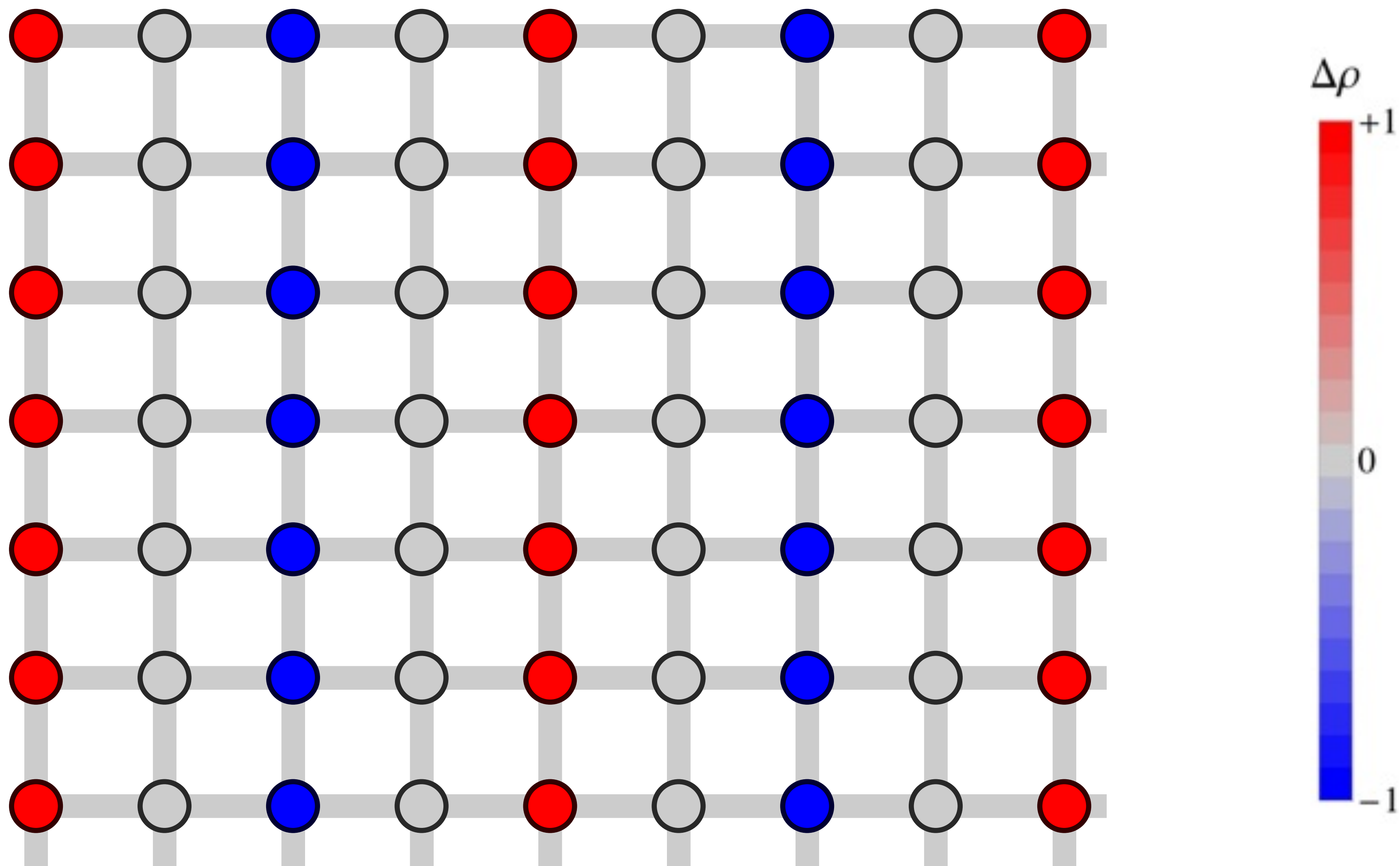
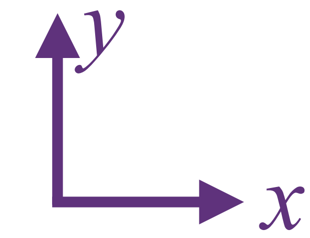


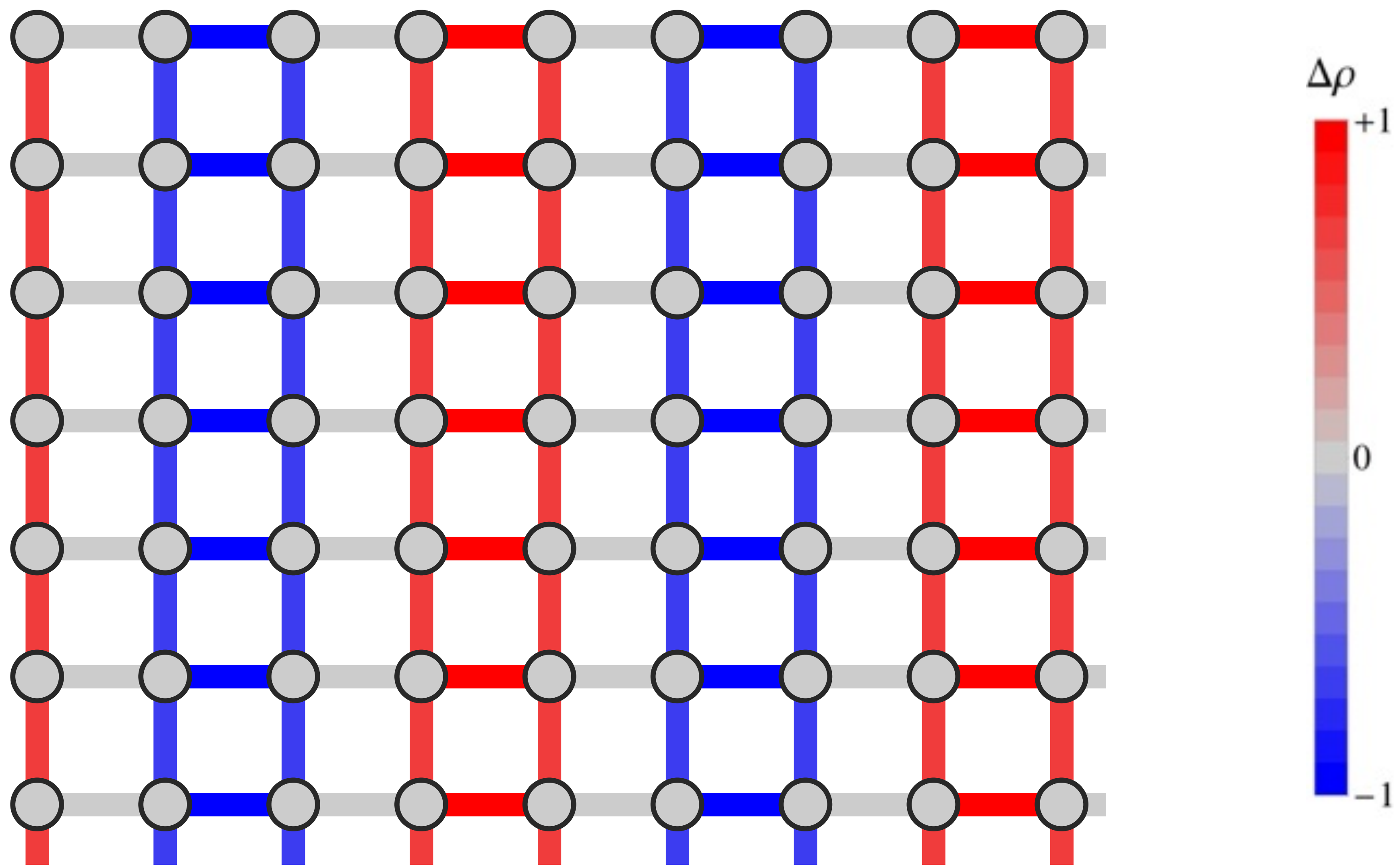
Unconventional DW order: s'-wave



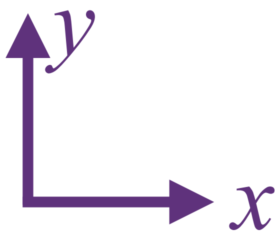
Plot of $P_{ij} = \left\langle c_{i\alpha}^\dagger c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) + \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$



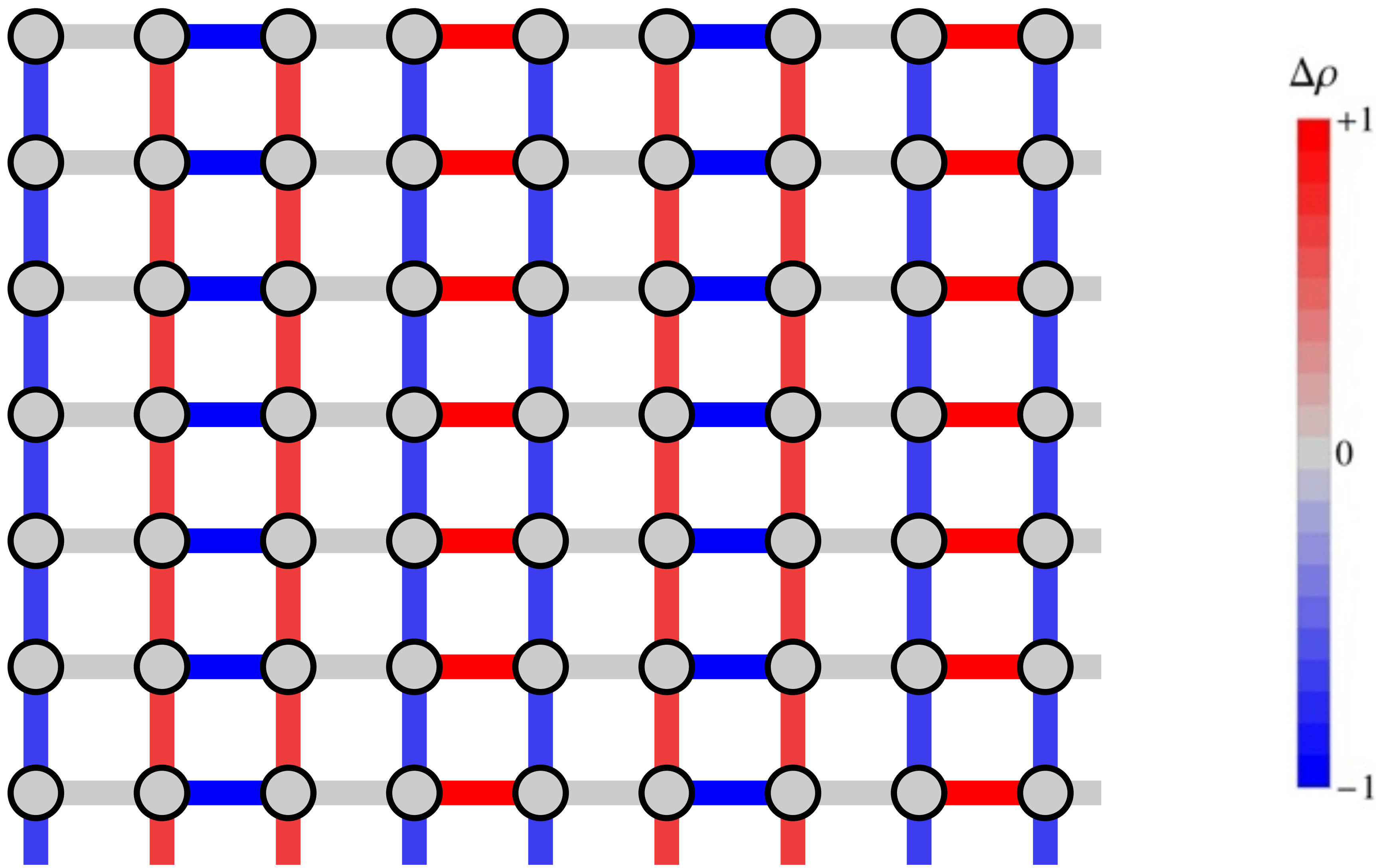
Unconventional DW order: d-wave



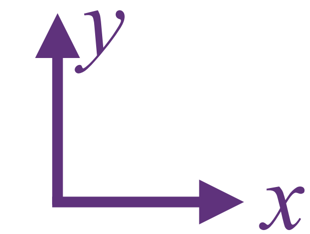
Plot of $P_{ij} = \left\langle c^\dagger_{i\alpha} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) - \cos(k_y)\right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$



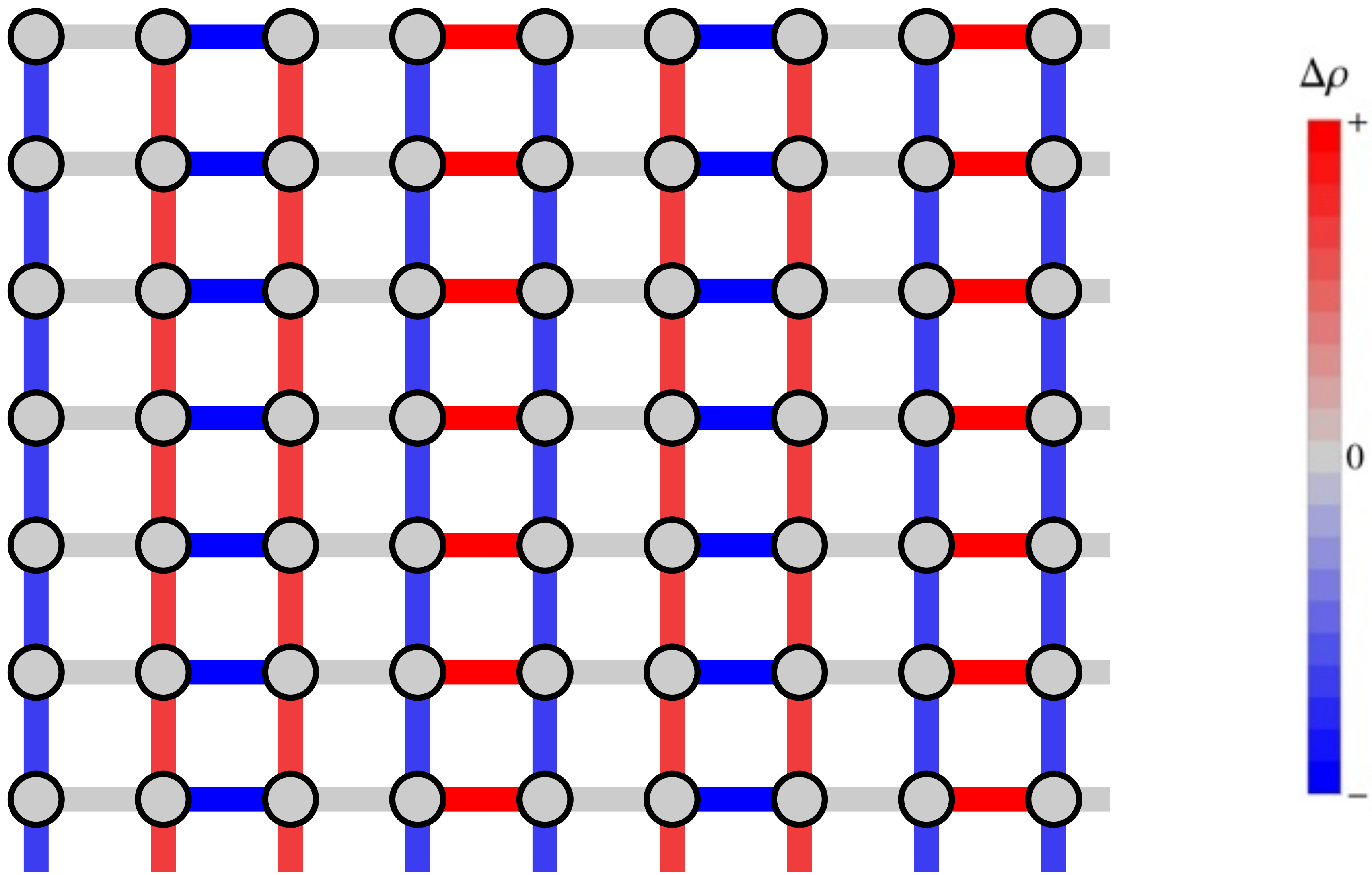
Unconventional DW order: d-wave



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

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

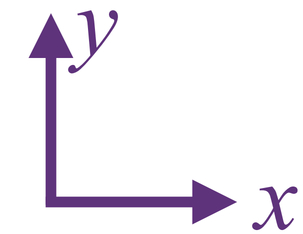
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) - \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$



A DW with d-wave predominant is nearly degenerate with d-wave SC near the quantum-critical point for antiferromagnetism in a metal.

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

Unconventional DW order: d-wave

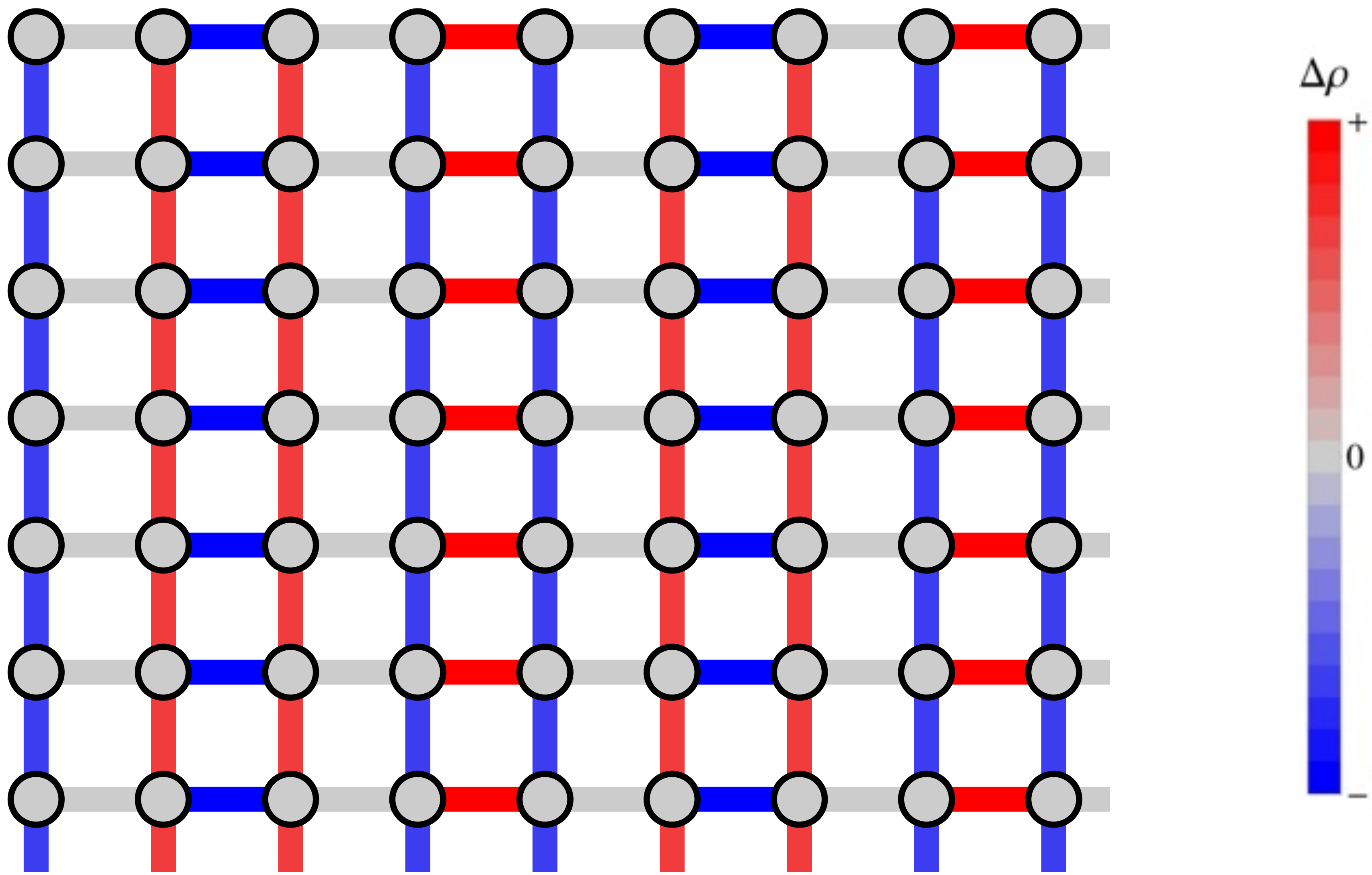


Plot of $P_{ij} = \left\langle c_{i\alpha}^\dagger c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

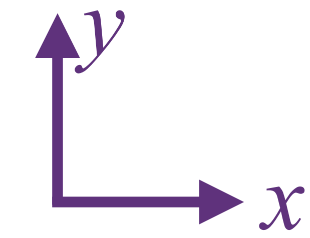
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) - \cos(k_y)\right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$

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



This specific d-wave bond order (with $\mathbf{Q}$ along the axes) was first predicted in S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).

Unconventional CDW order: d-wave

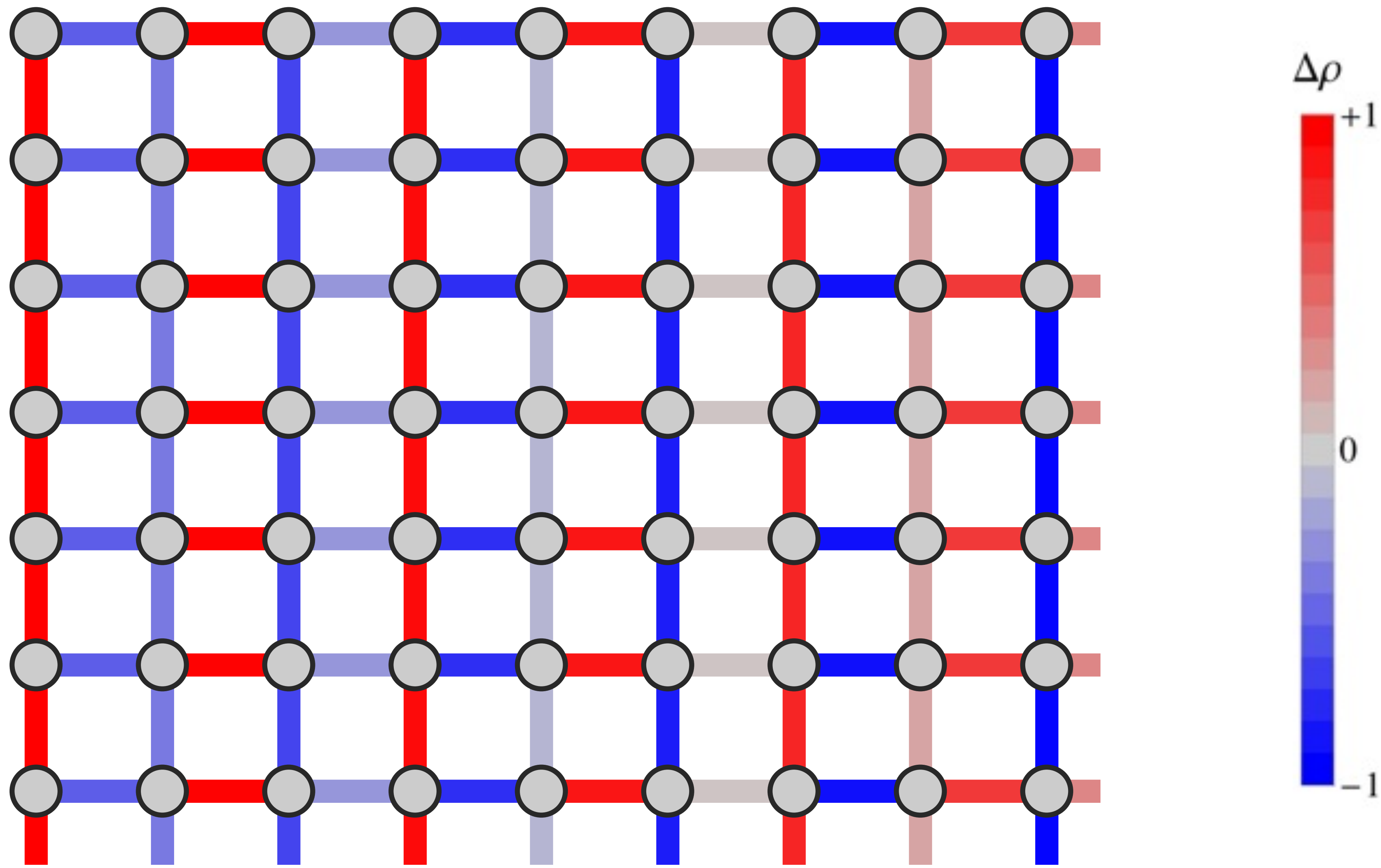


Plot of $P_{ij} = \left\langle c^\dagger_{i\alpha} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

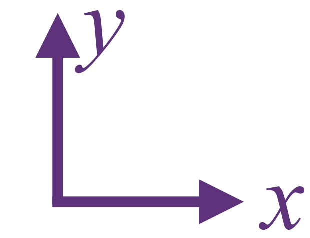
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) - \cos(k_y)\right] \quad \text{and} \quad \mathbf{Q} = 2\pi(0.317, 0)$$

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



This specific d-wave bond order (with $\mathbf{Q}$ along the axes) was first predicted in S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).

Unconventional DW order: $d + s$-wave

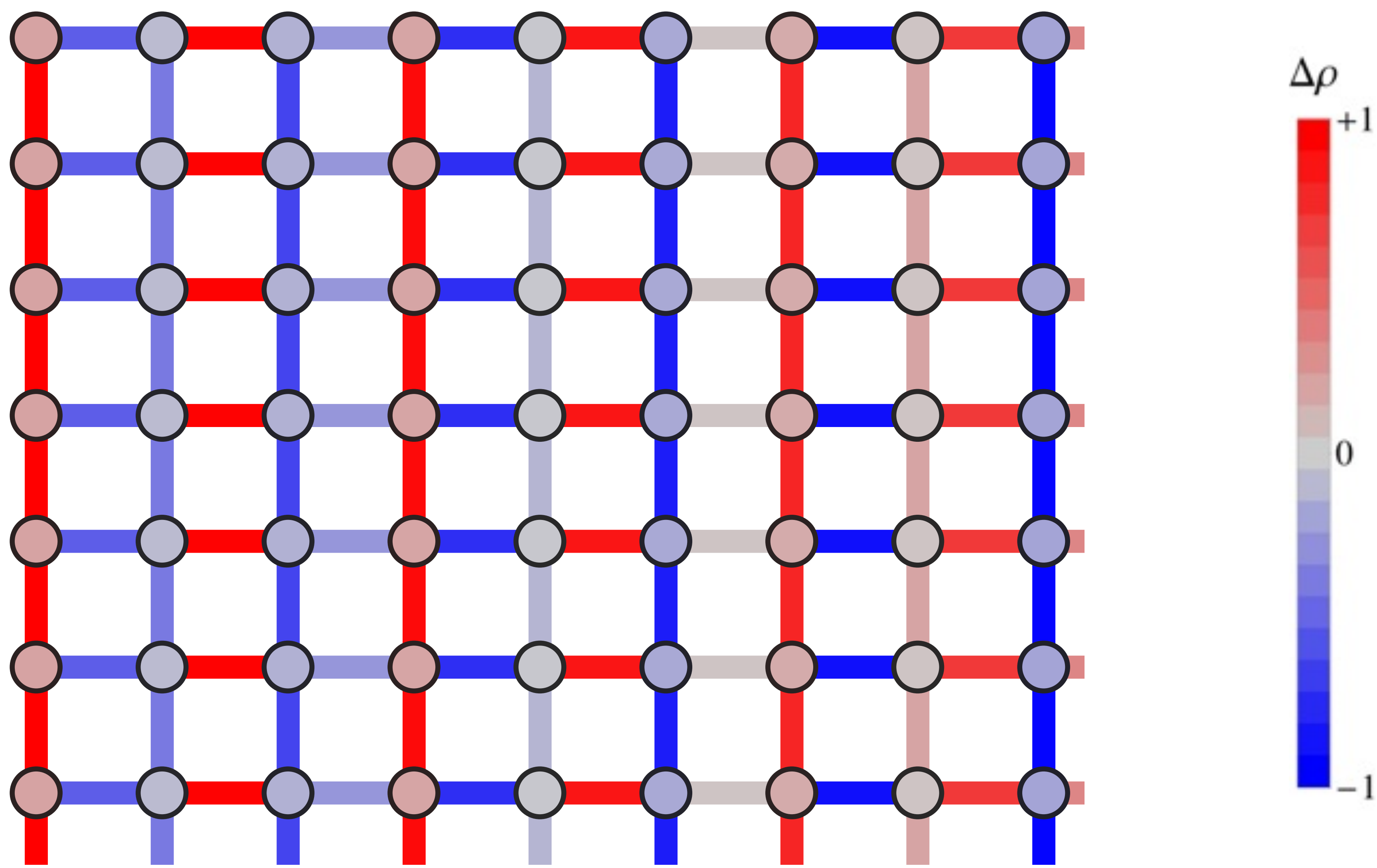


Plot of $P_{ij} = \left\langle c_{i\alpha}^\dagger c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[0.2 + \cos(k_x) - \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = 2\pi(0.317, 0)$$

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



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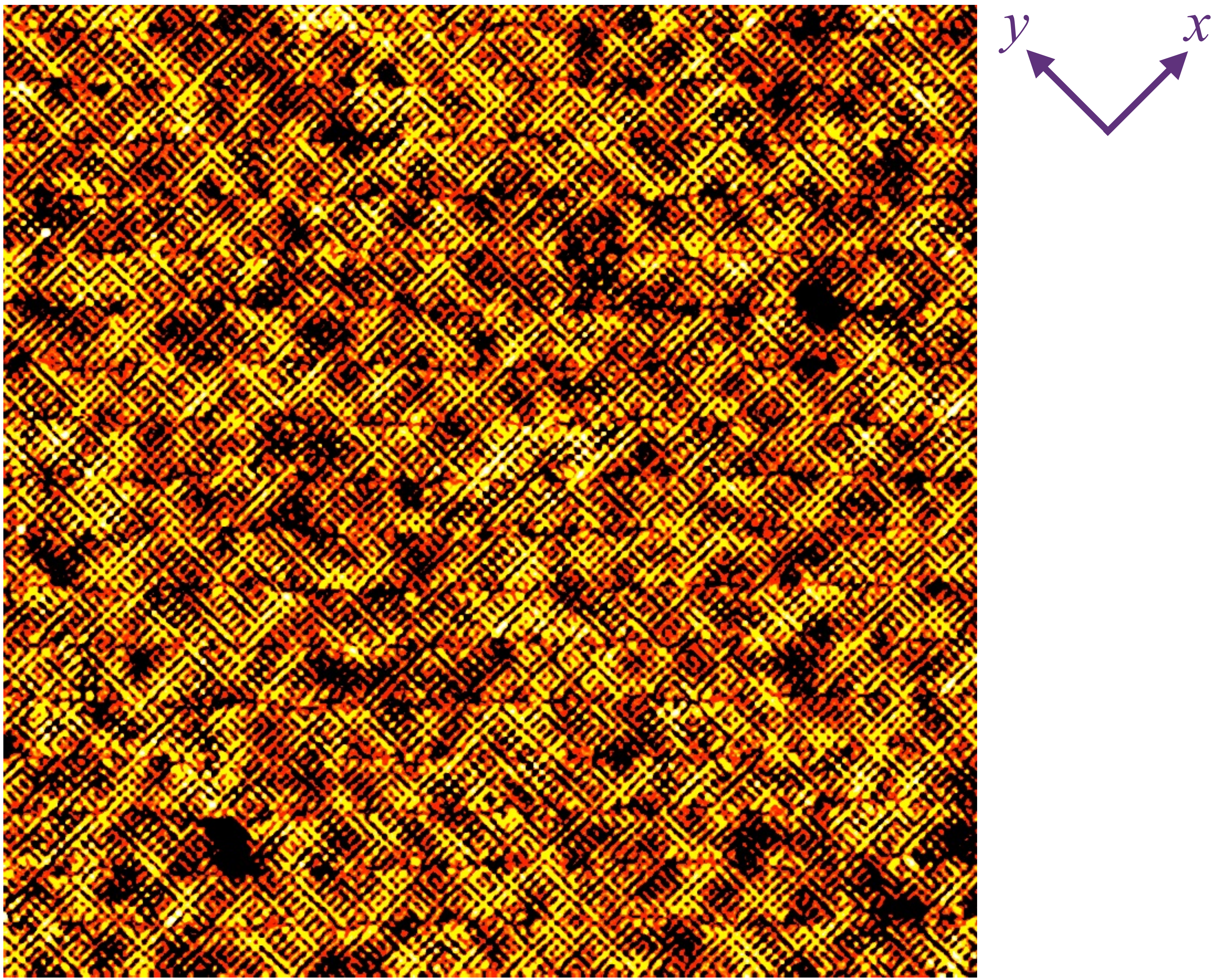
See also
C. Howald, H. Eisaki, N. Kaneko, M. Greven, and A. Kapitulnik, Phys. Rev. B **67**, 014533 (2003);

M. Vershinin, S. Misra, S. Ono, Y. Abe, Yoichi Ando, and A. Yazdani, Science **303**, 1995 (2004).

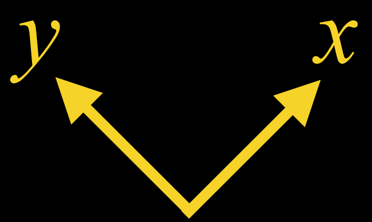
W. D. Wise, M. C. Boyer, K. Chatterjee, T. Kondo, T. Takeuchi, H. Ikuta, Y. Wang, and E. W. Hudson, Nature Phys. **4**, 696 (2008).



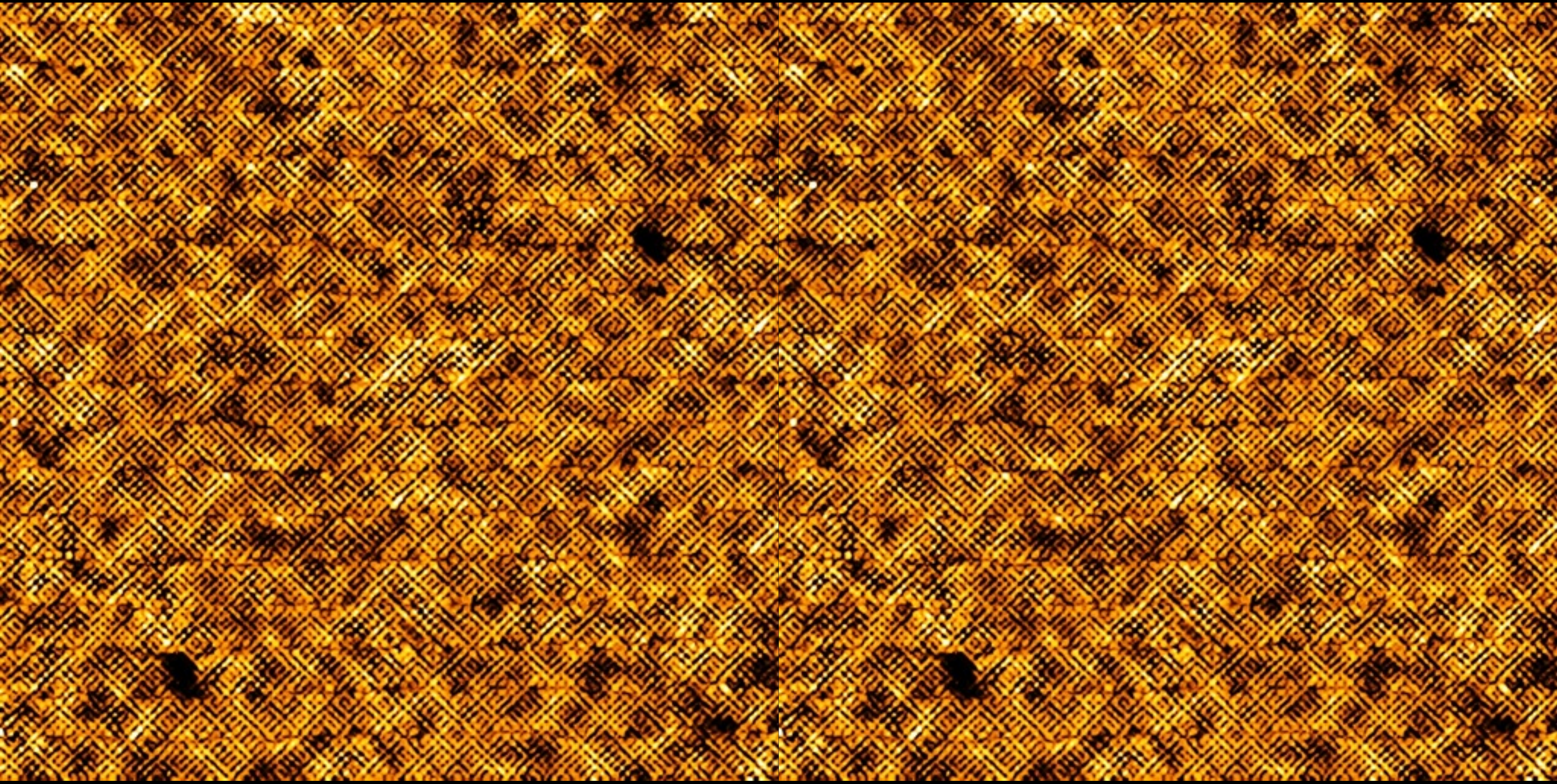
"R-map" of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007).

UD45K
BSCCO

R(r,150mV)

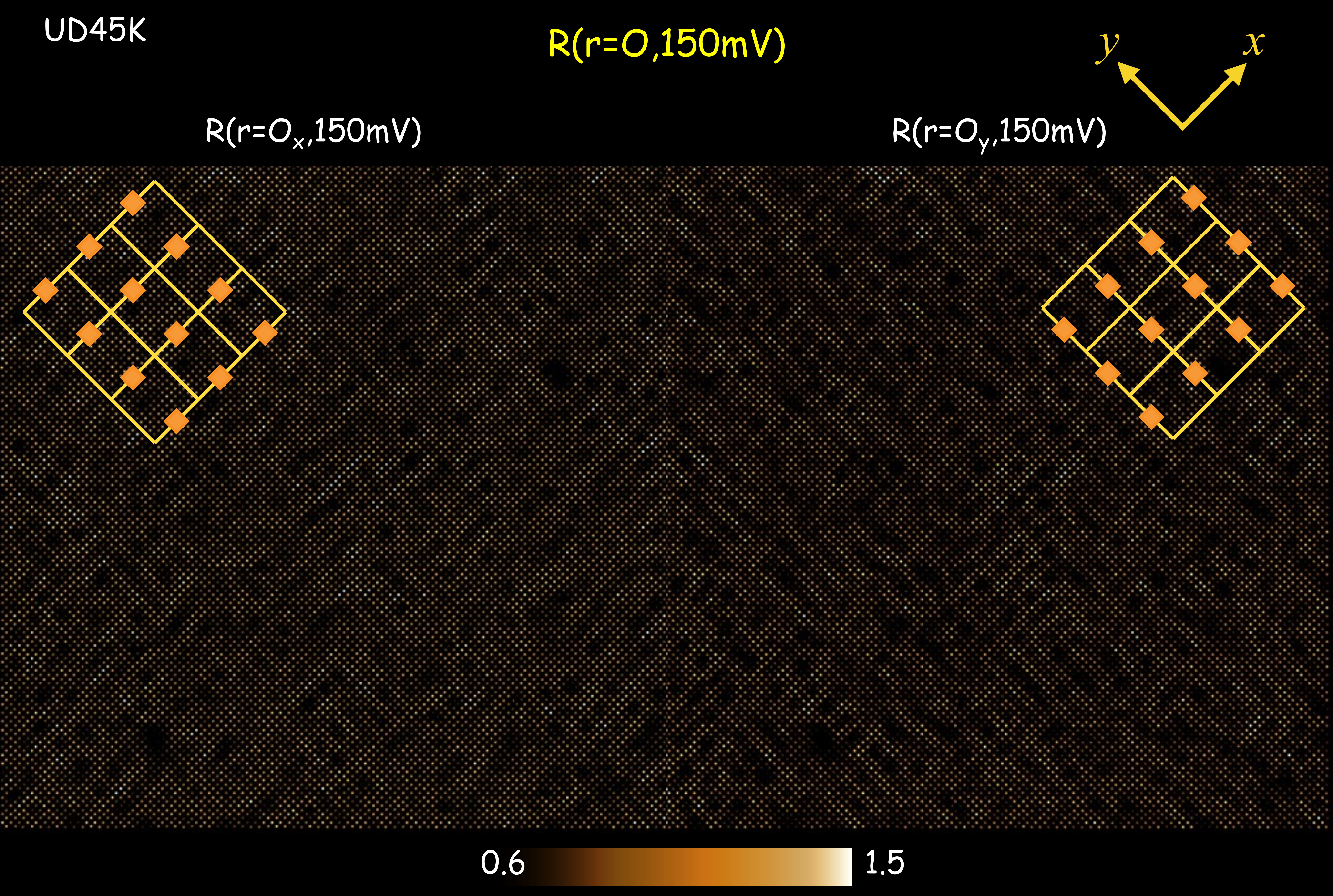


R(r,150mV) R(r,150mV)



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, PNAS to appear, arXiv:1404.0362



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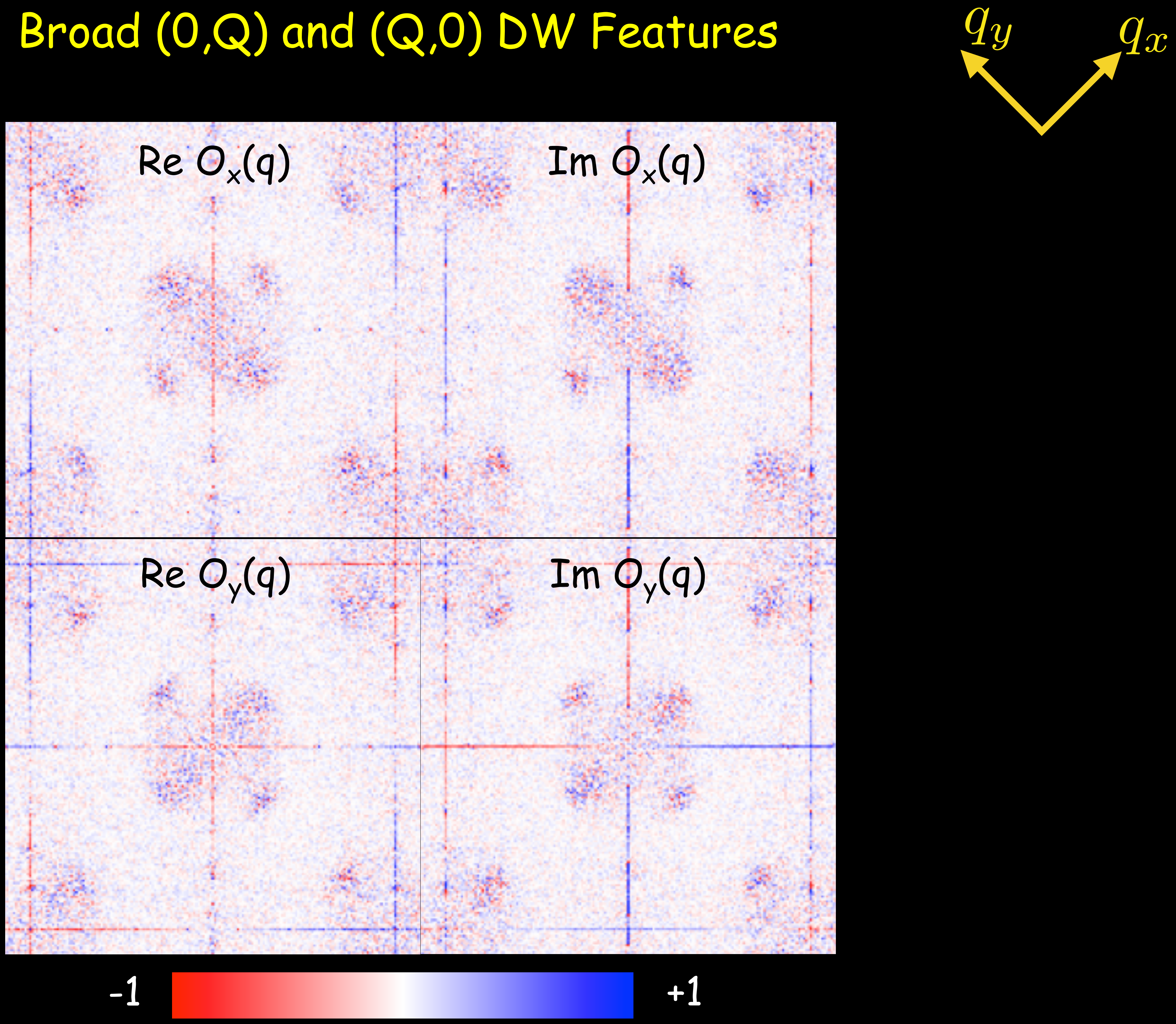
UD45K

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



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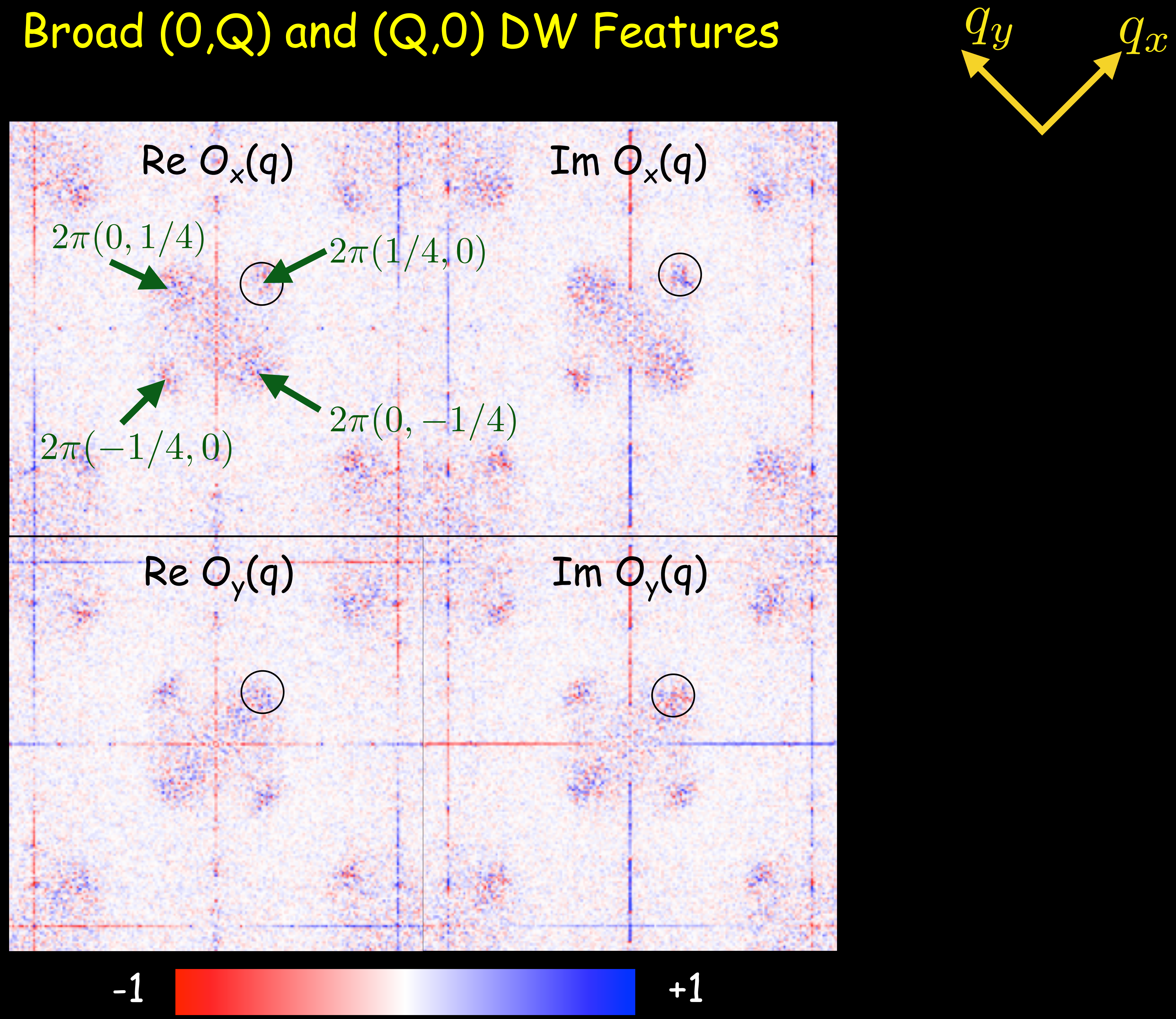

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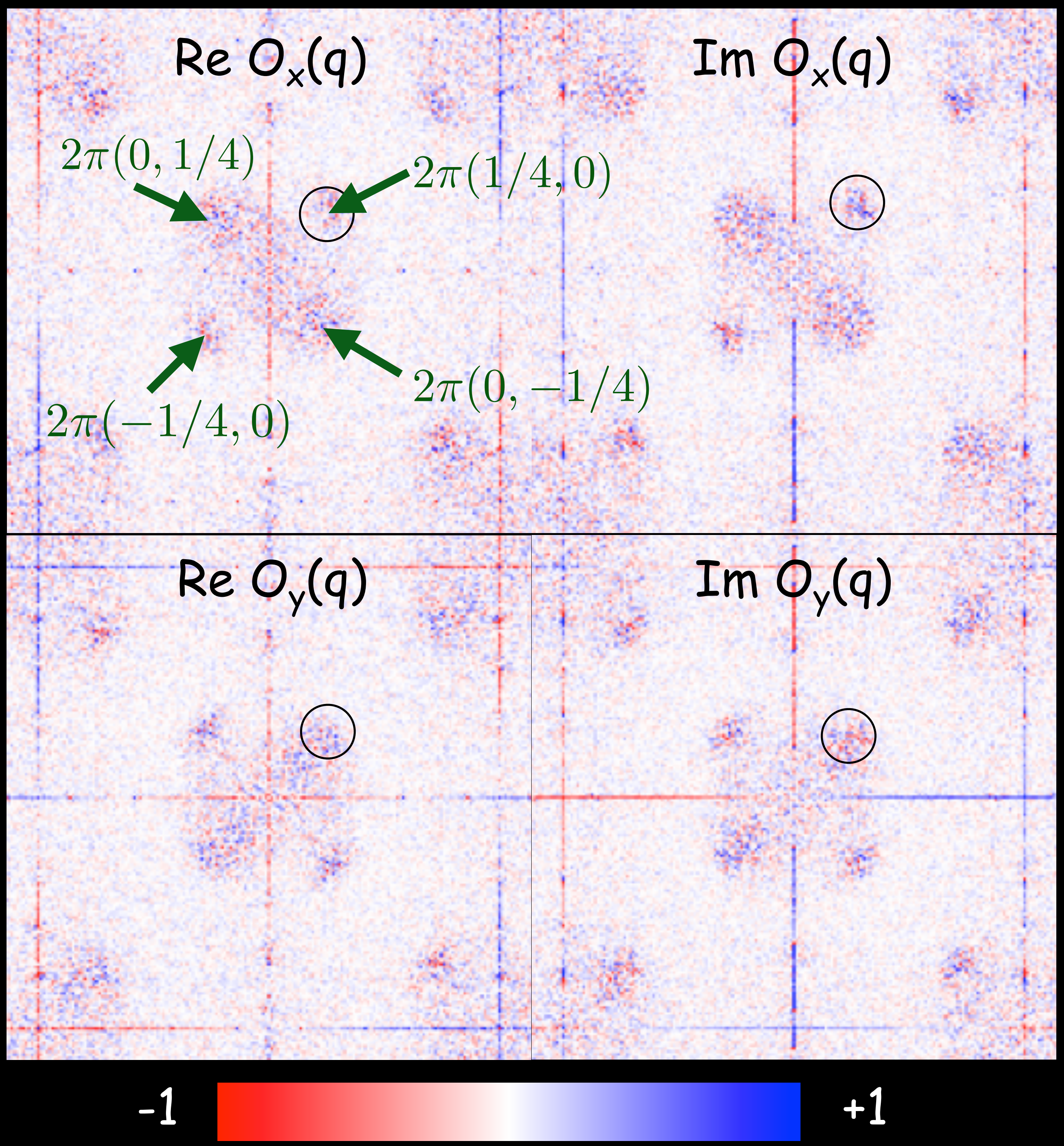
UD45K

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

For each pixel in the circles, we obtain 2 complex numbers, $O_x(q)$ and $O_y(q)$.



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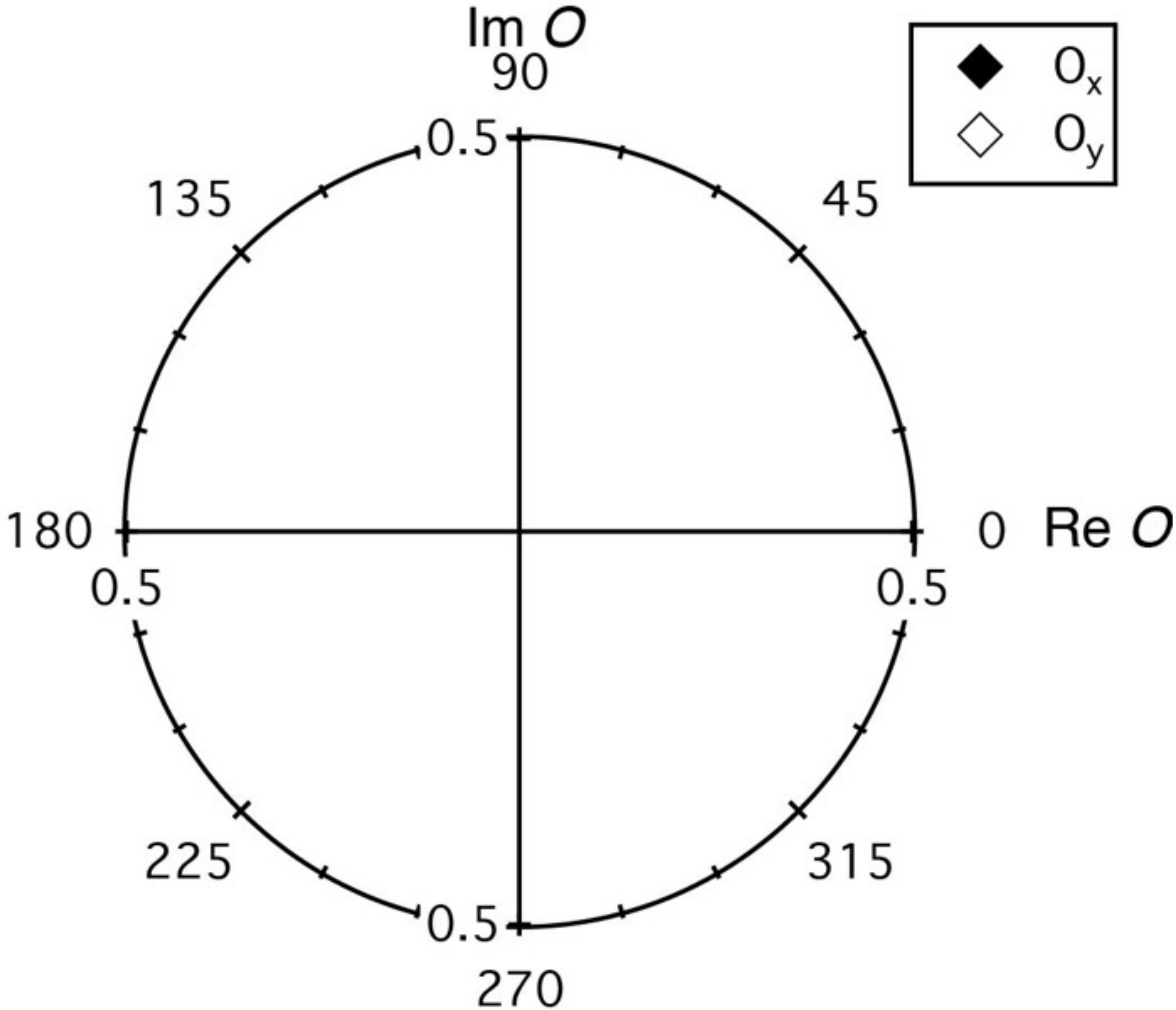

Phase-sensitive measurement of the *d* symmetry of density wave order

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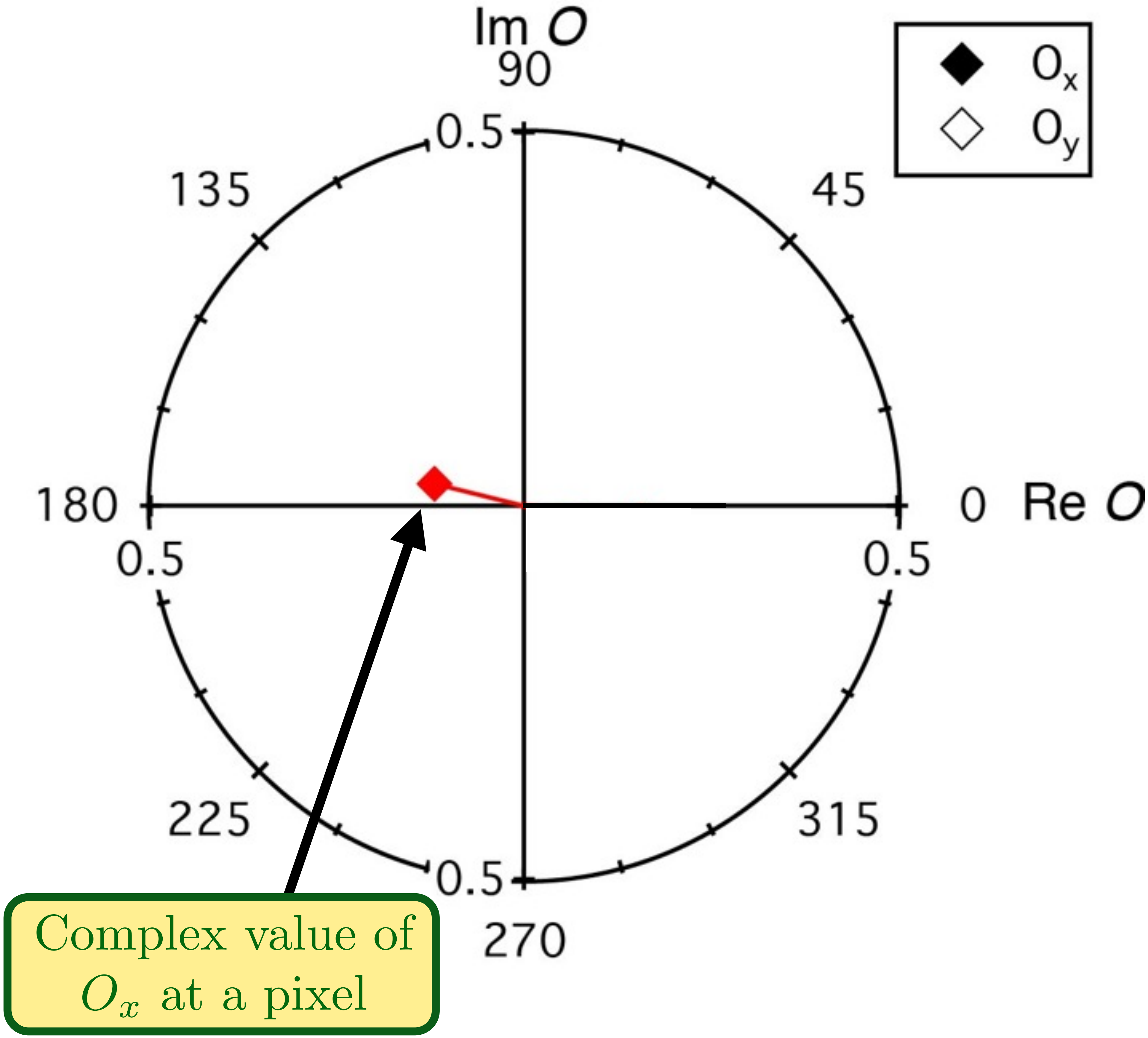

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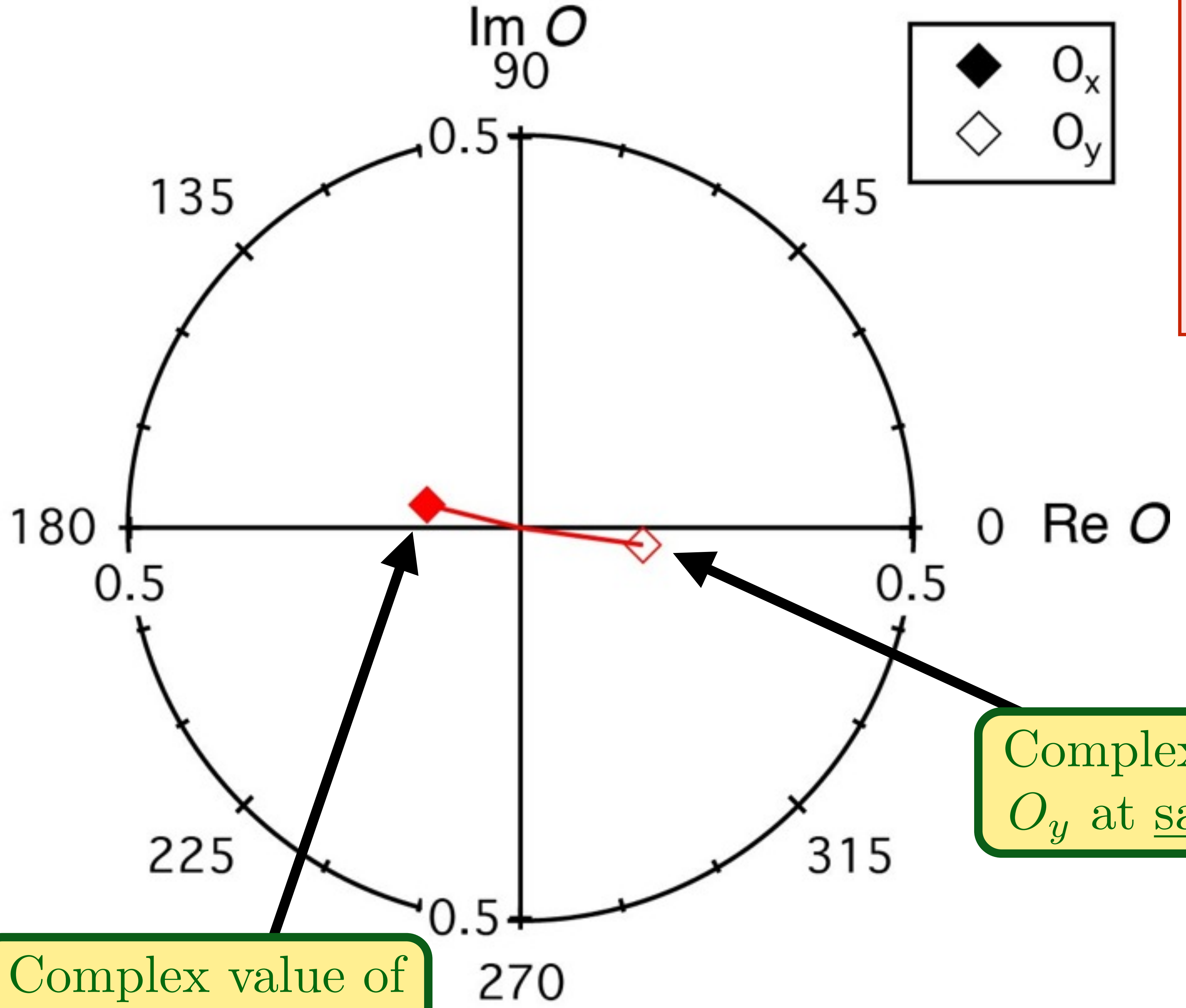

Complex value of O_y at <u>same</u> pixel

Complex value of O_x at a pixel

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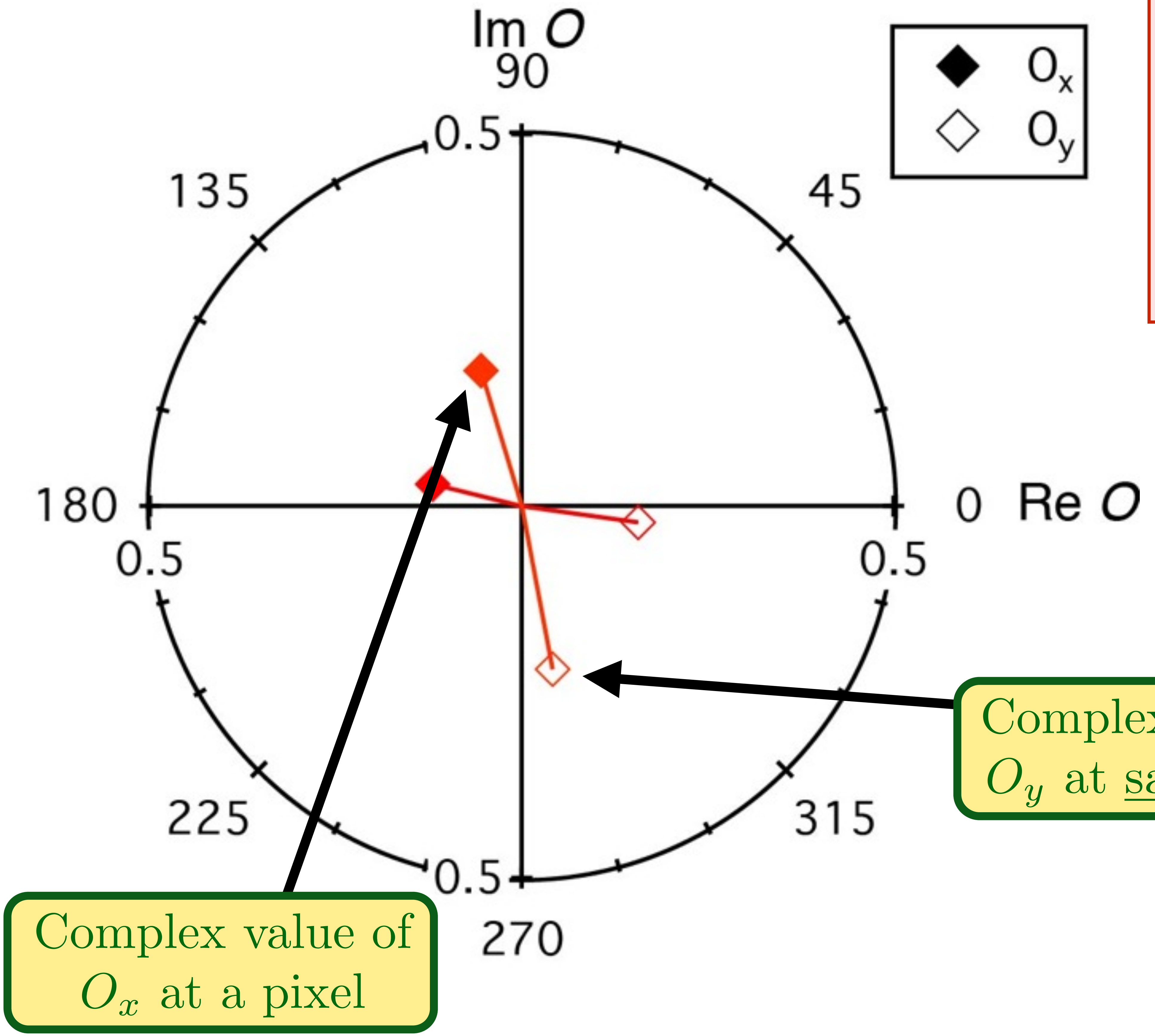

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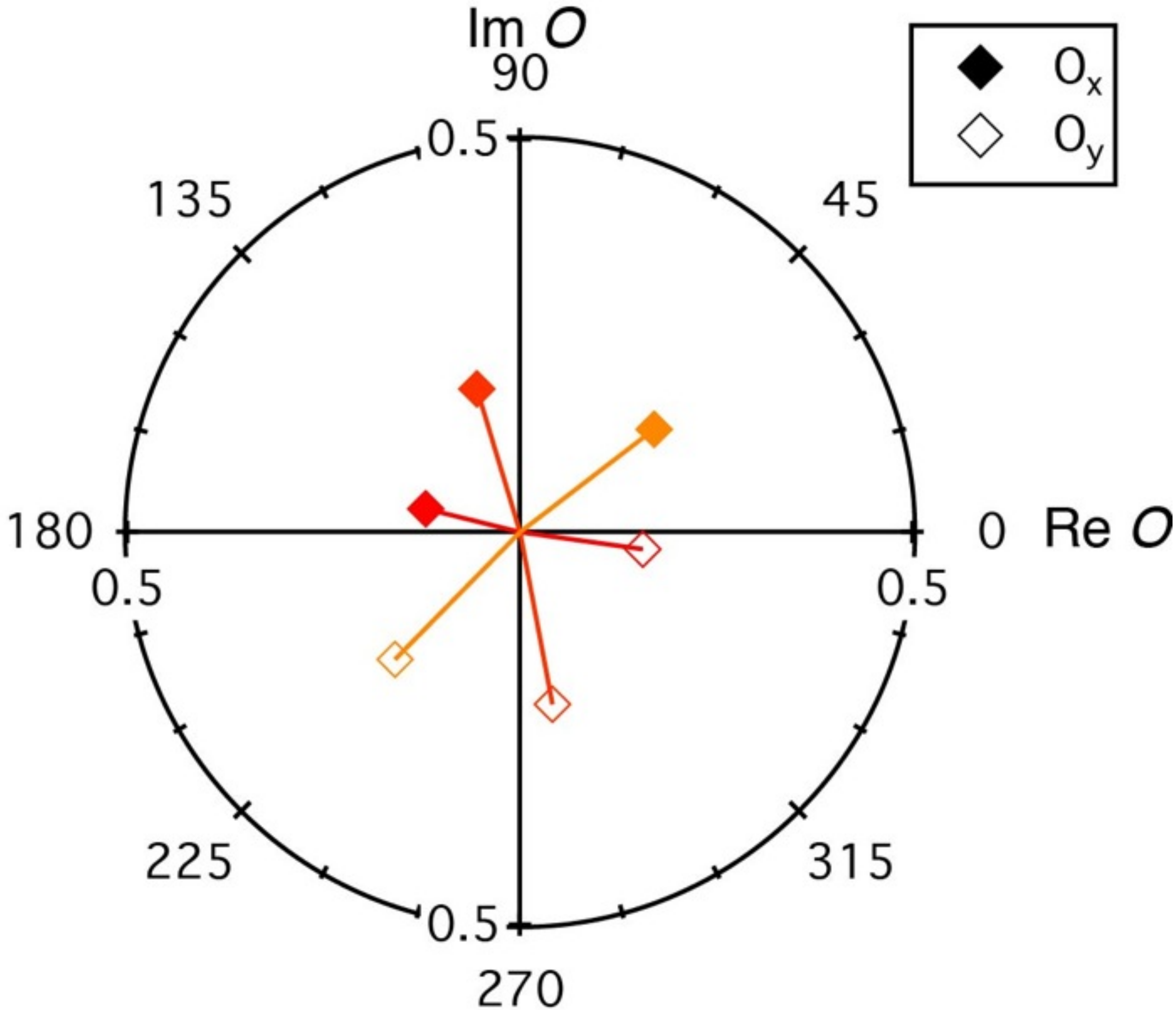

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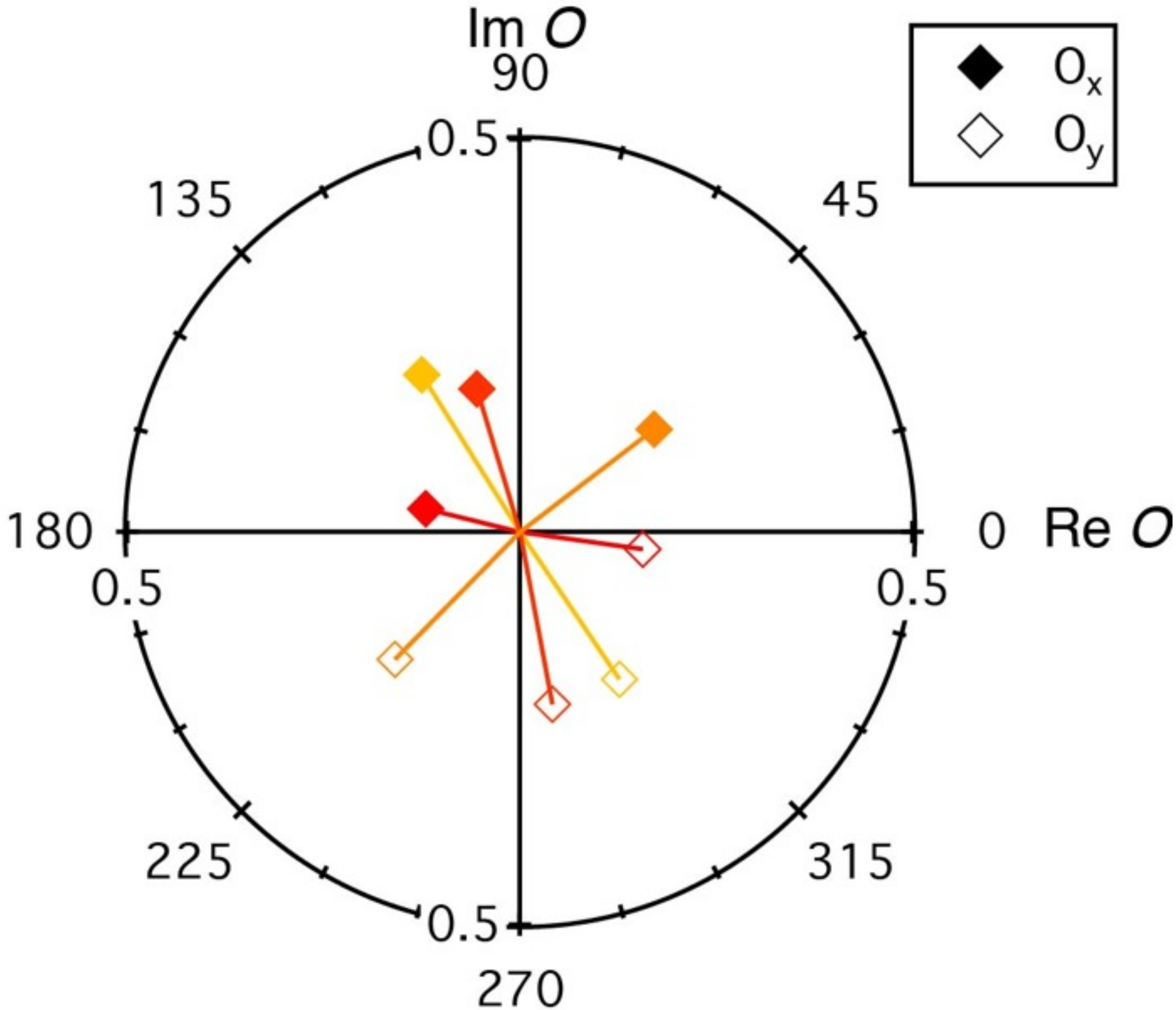

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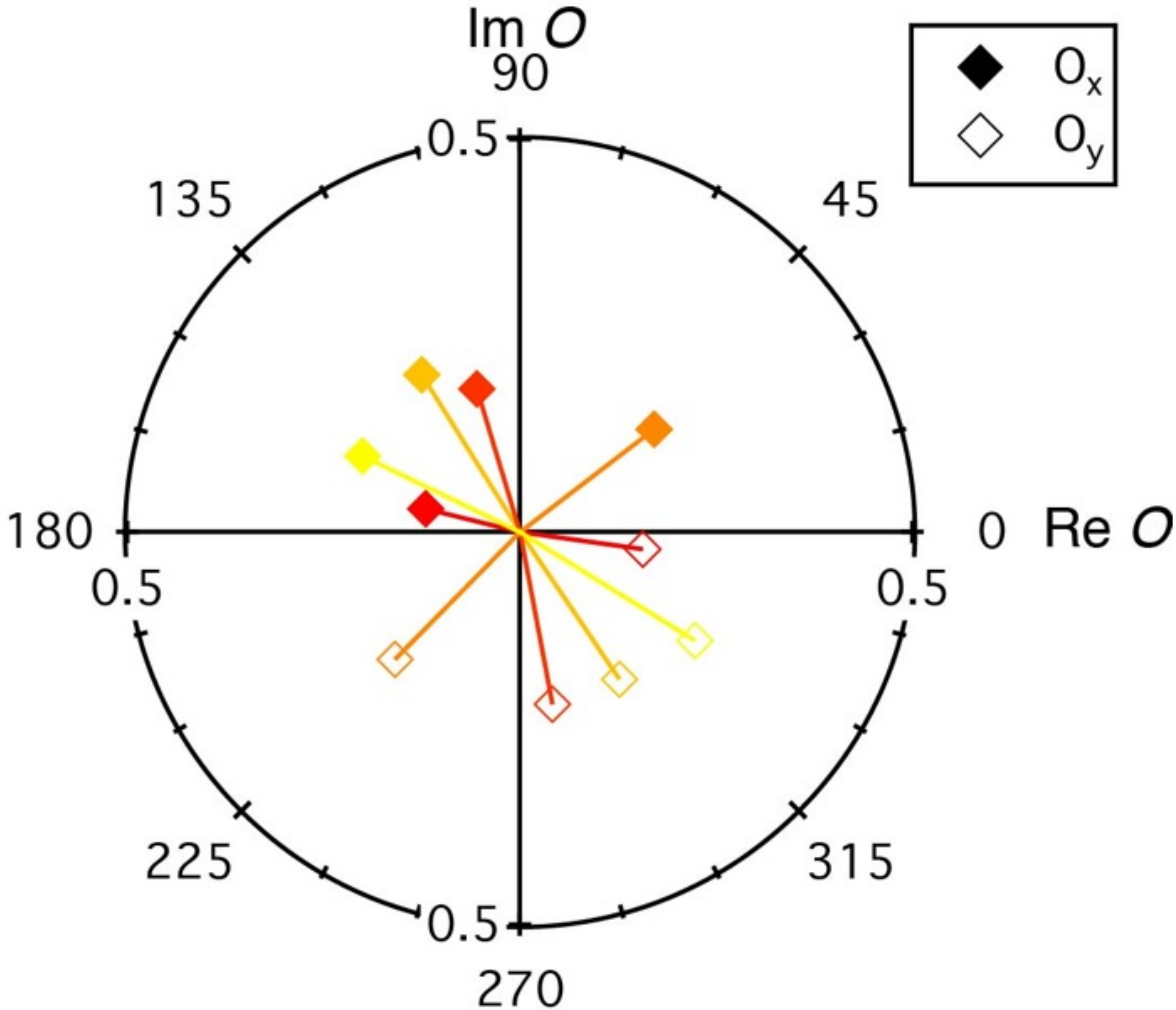

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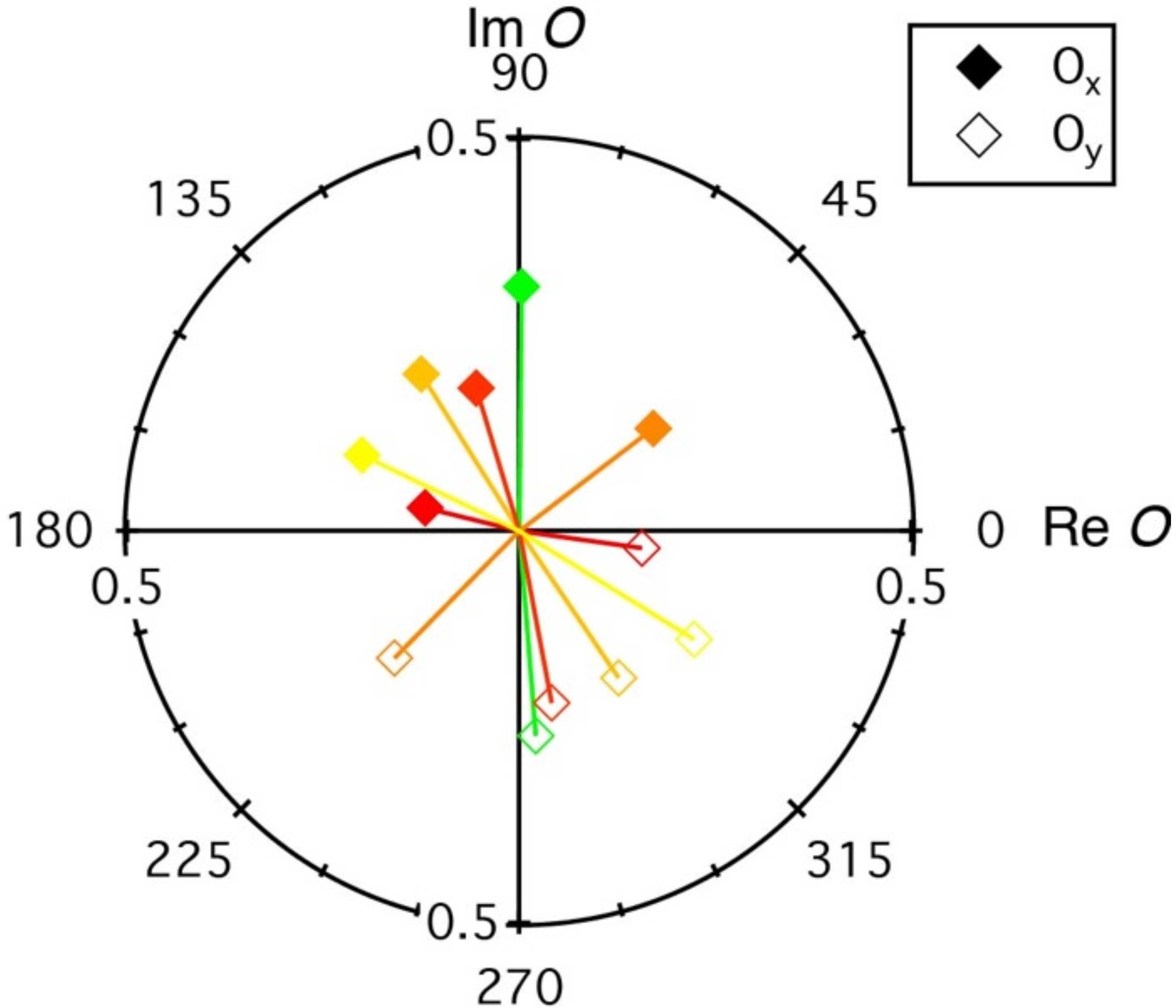

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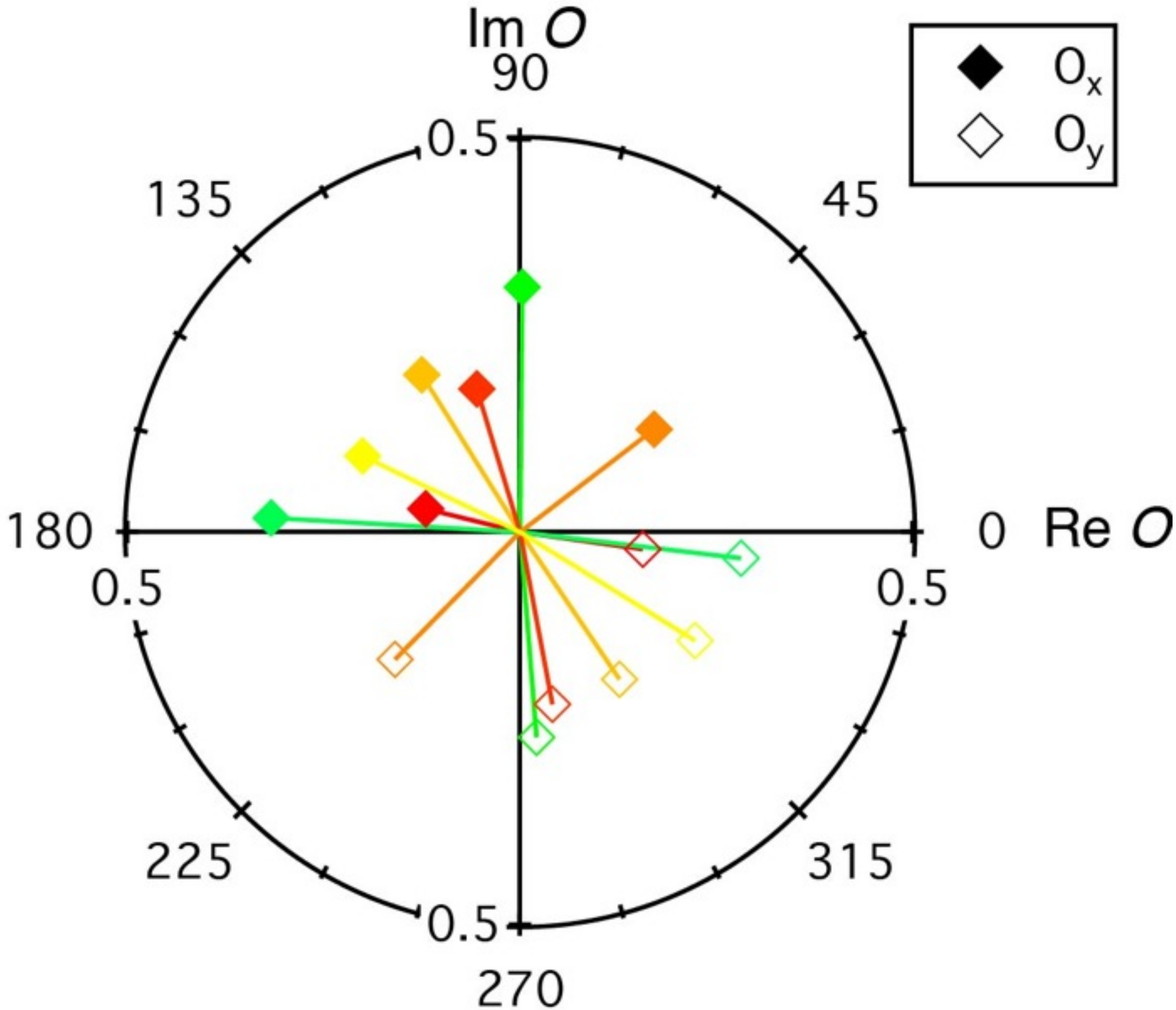

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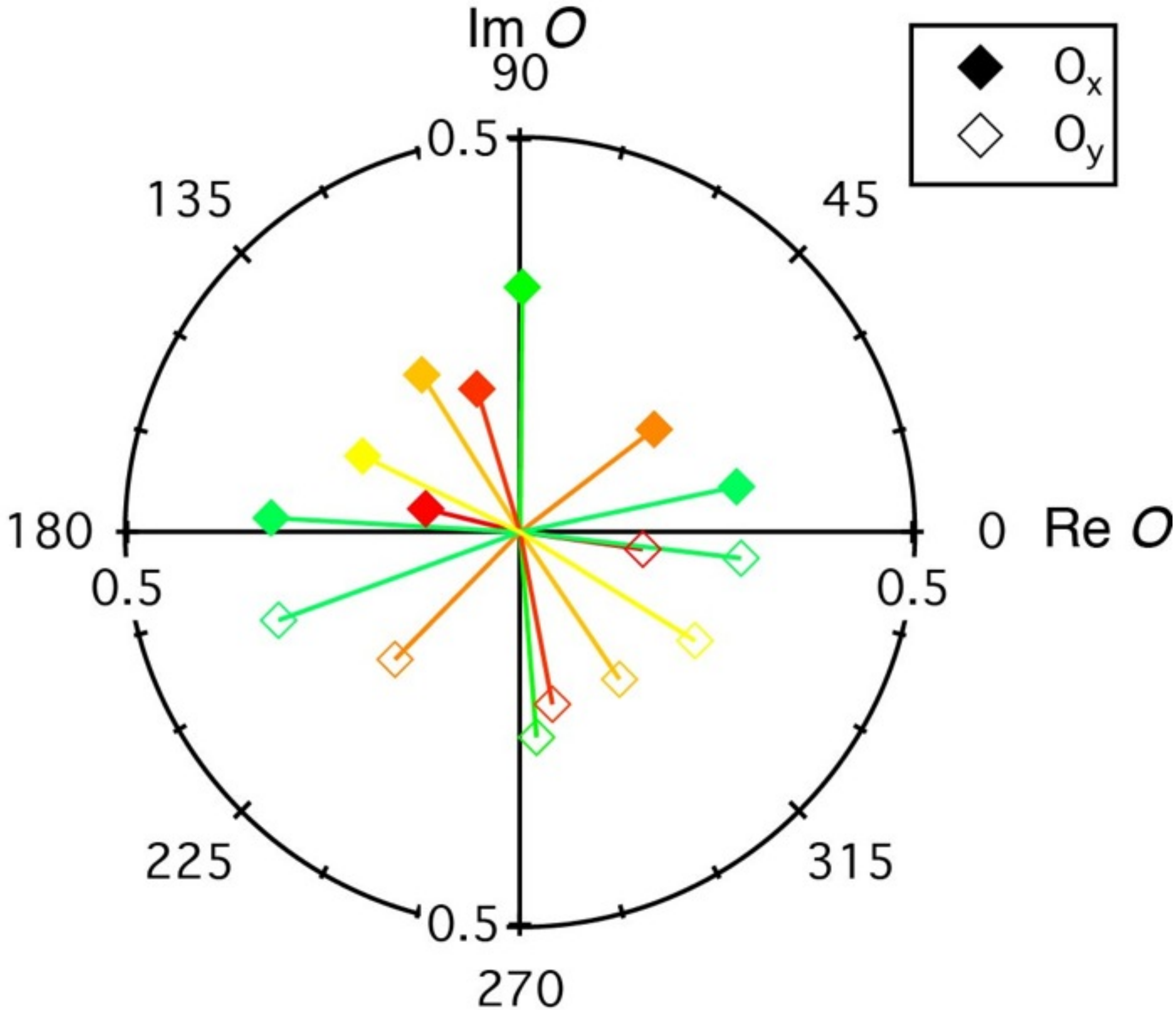

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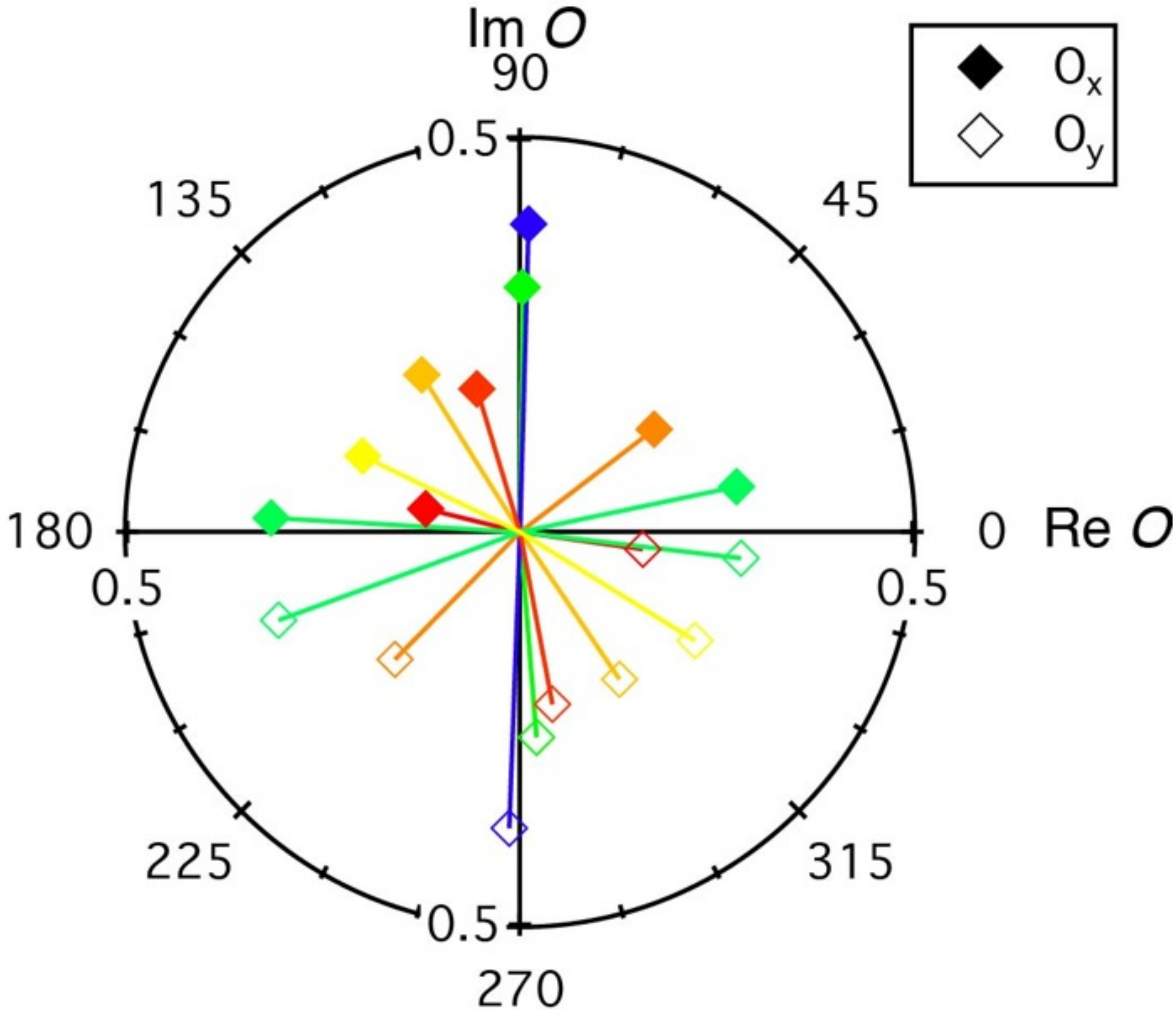

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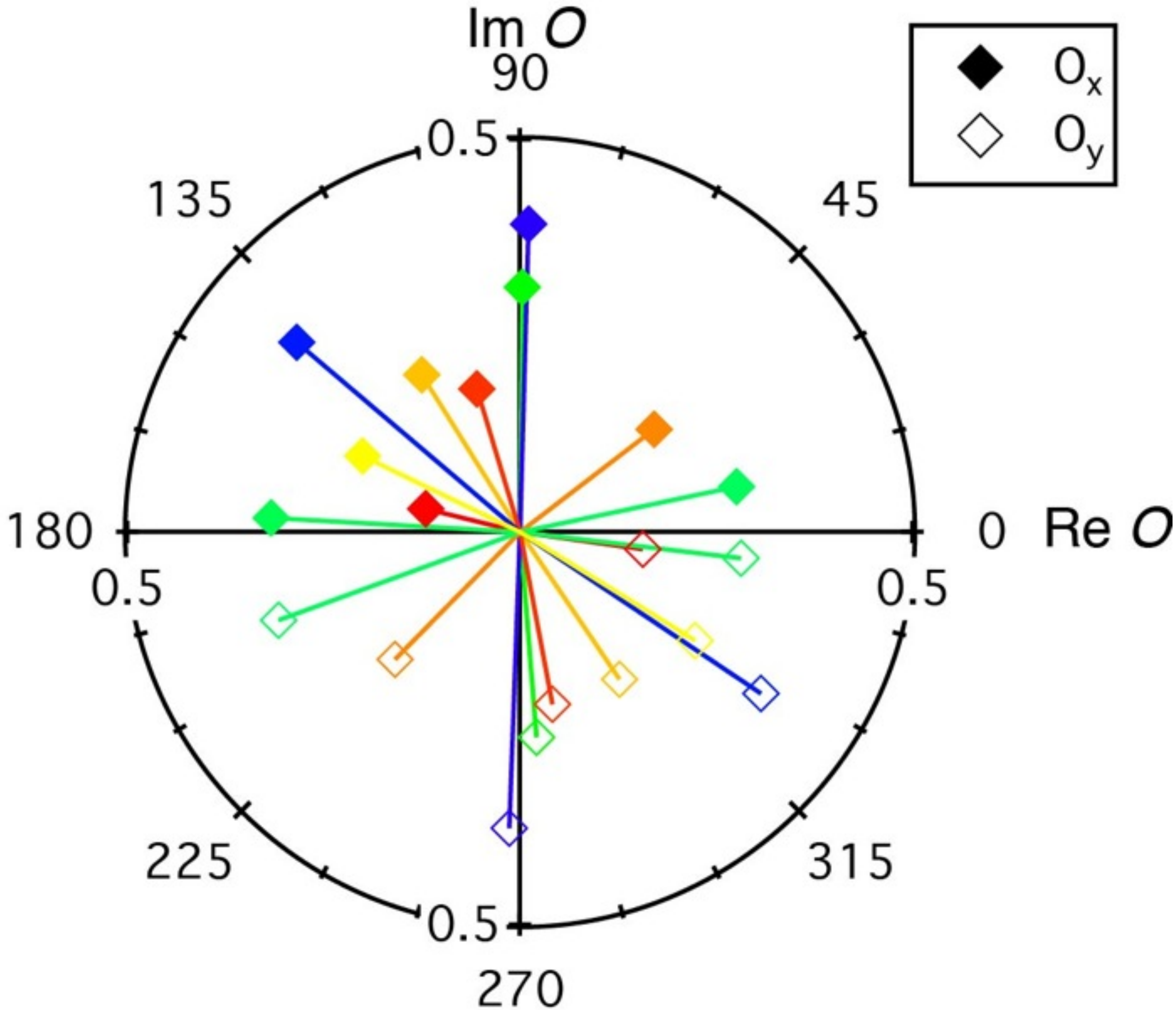

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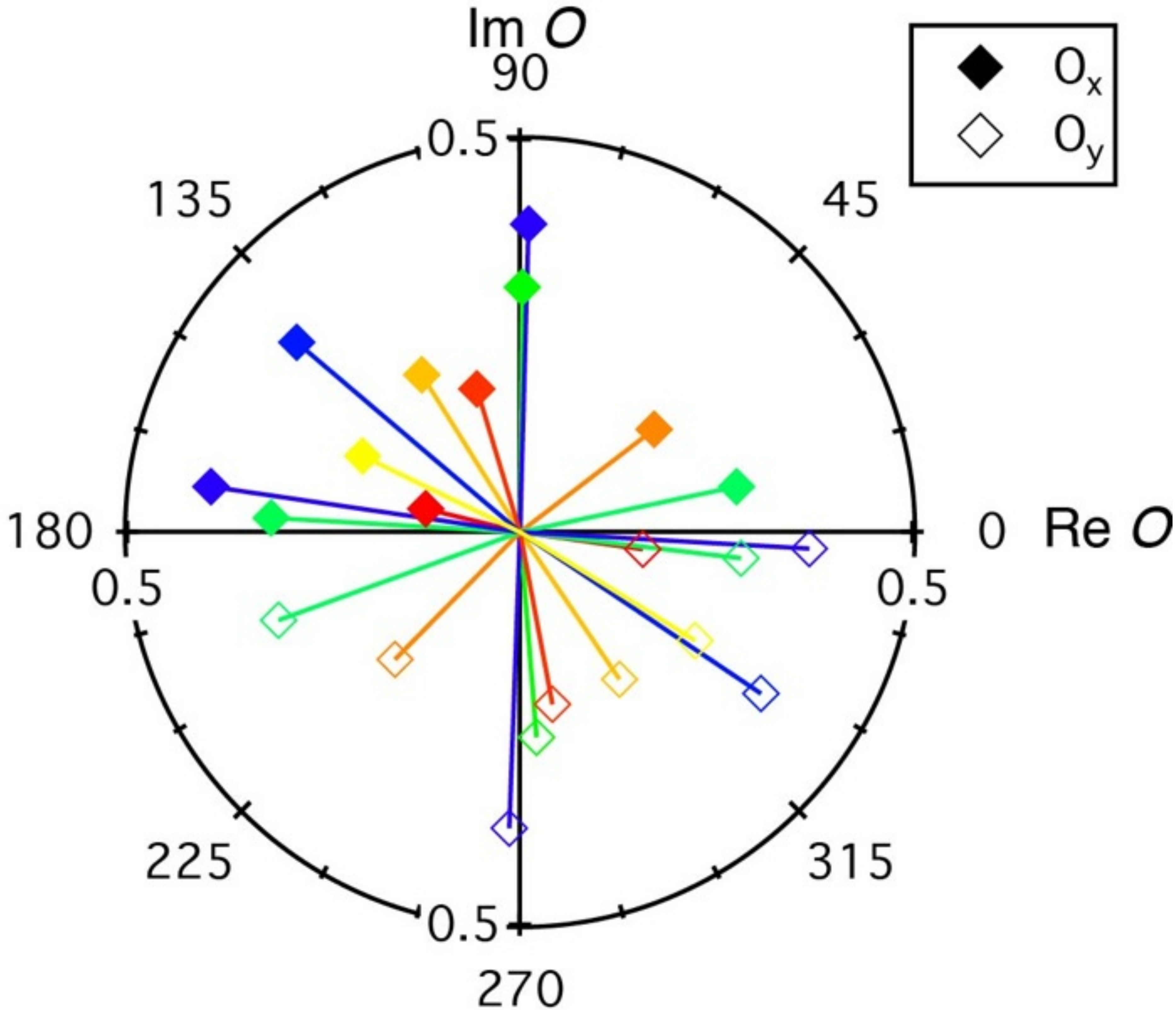

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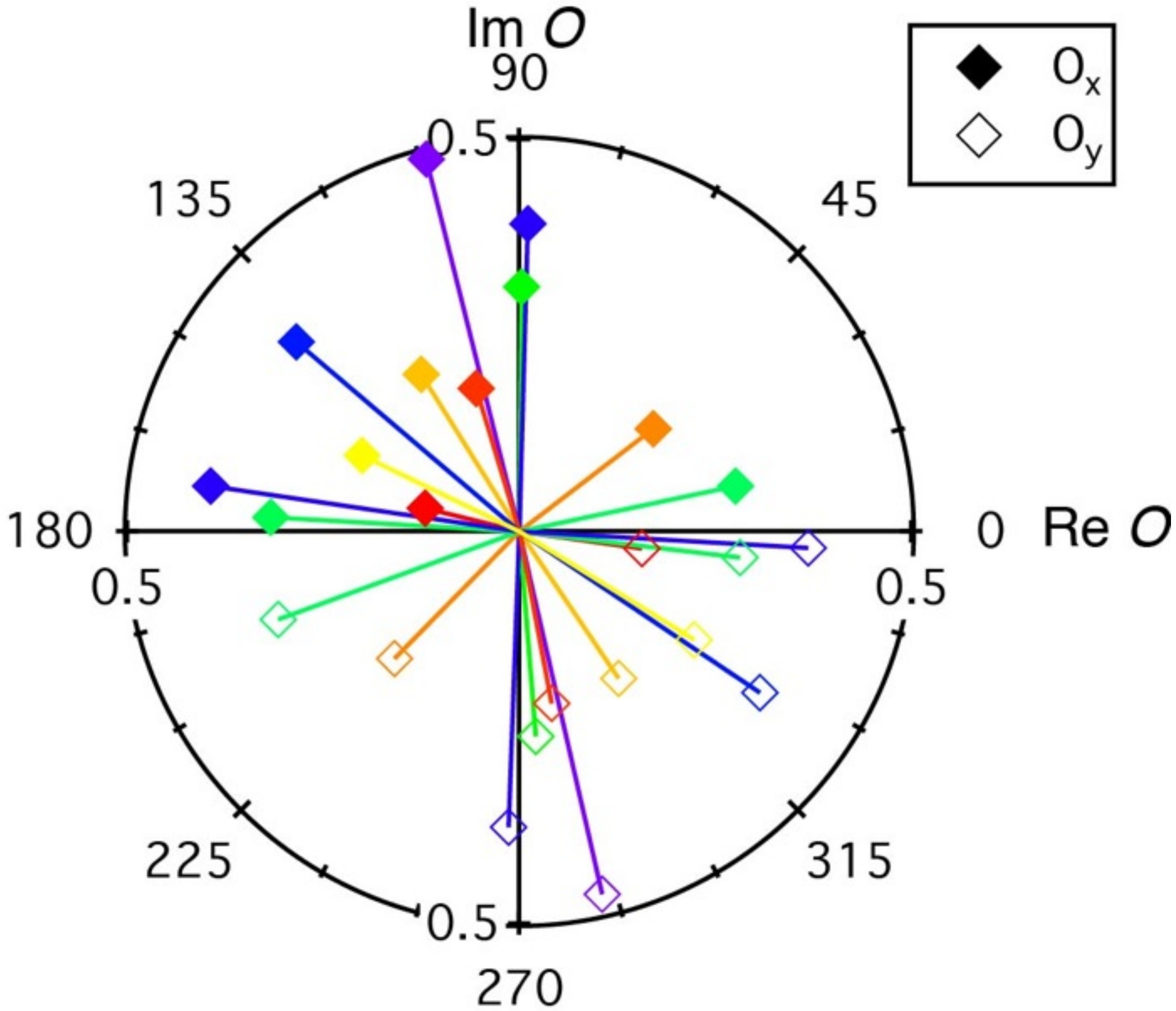

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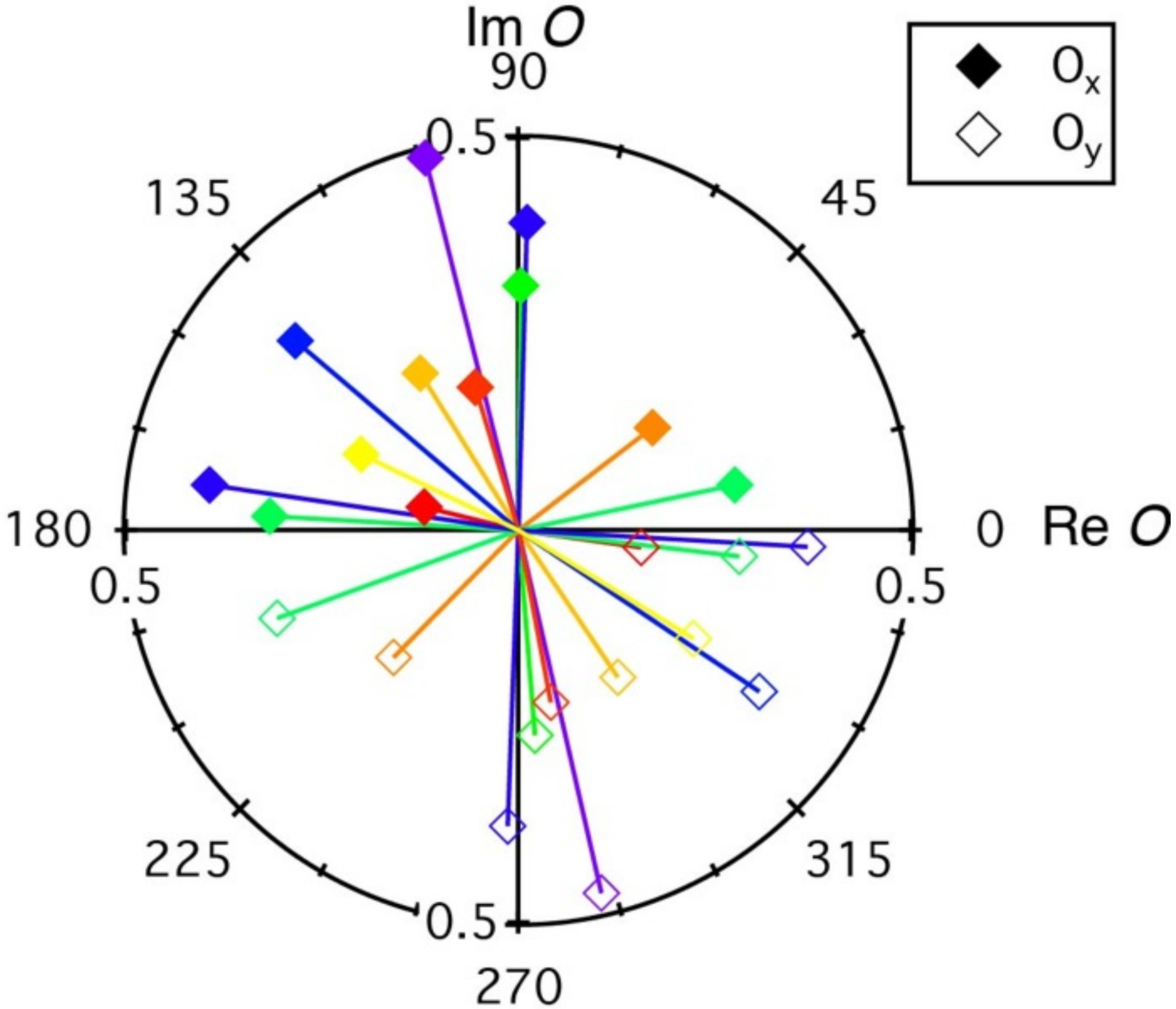

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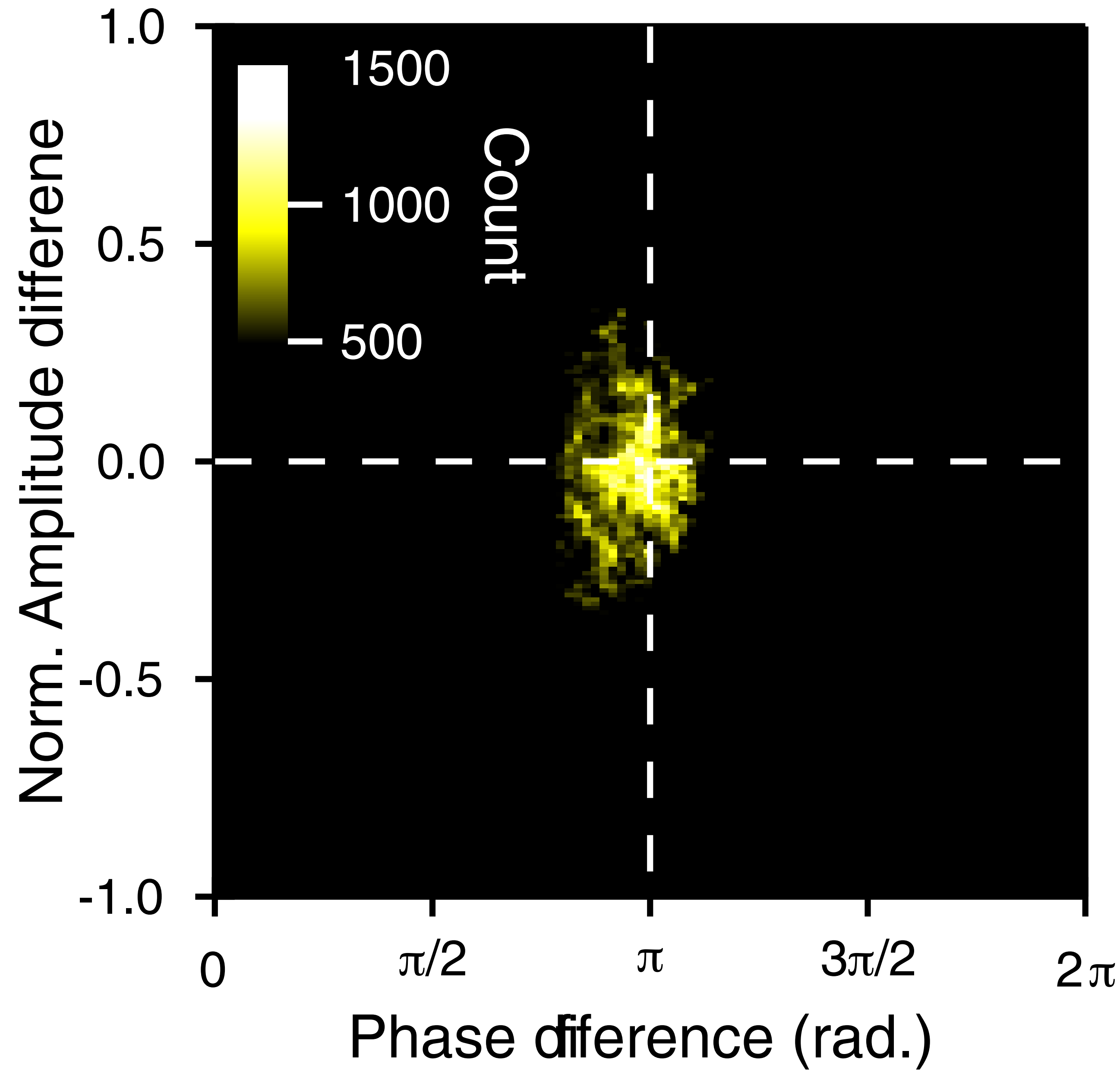

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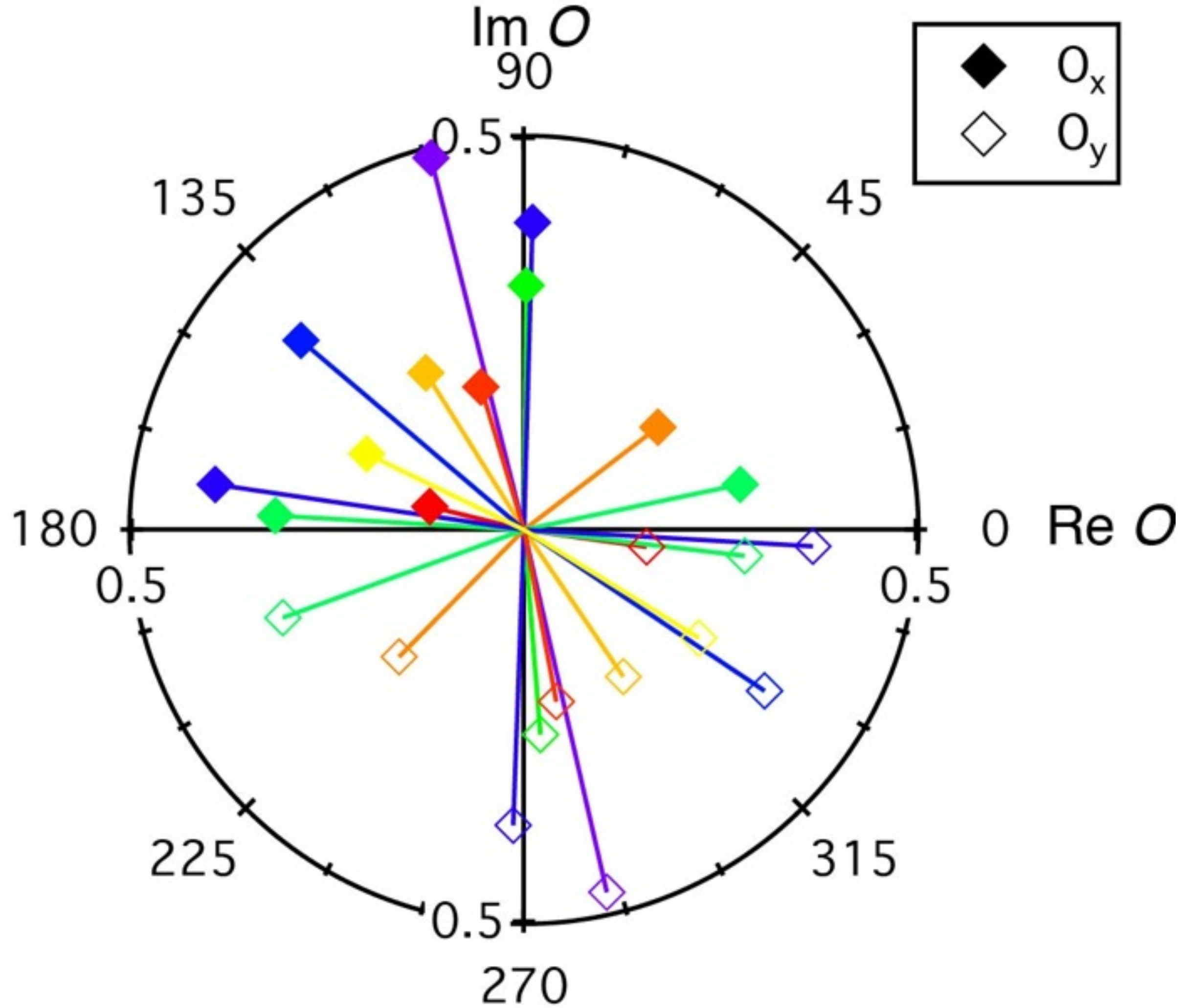

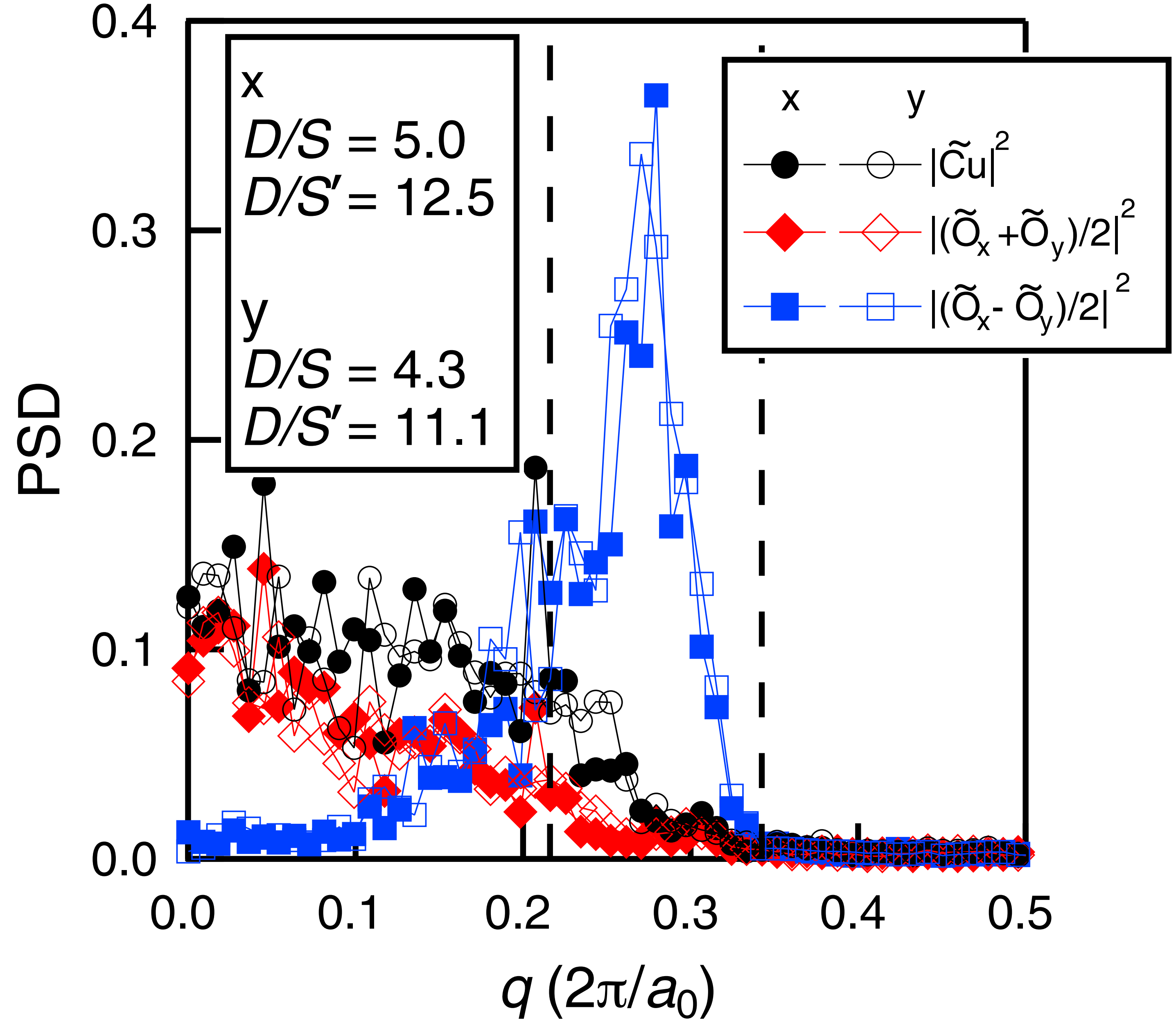

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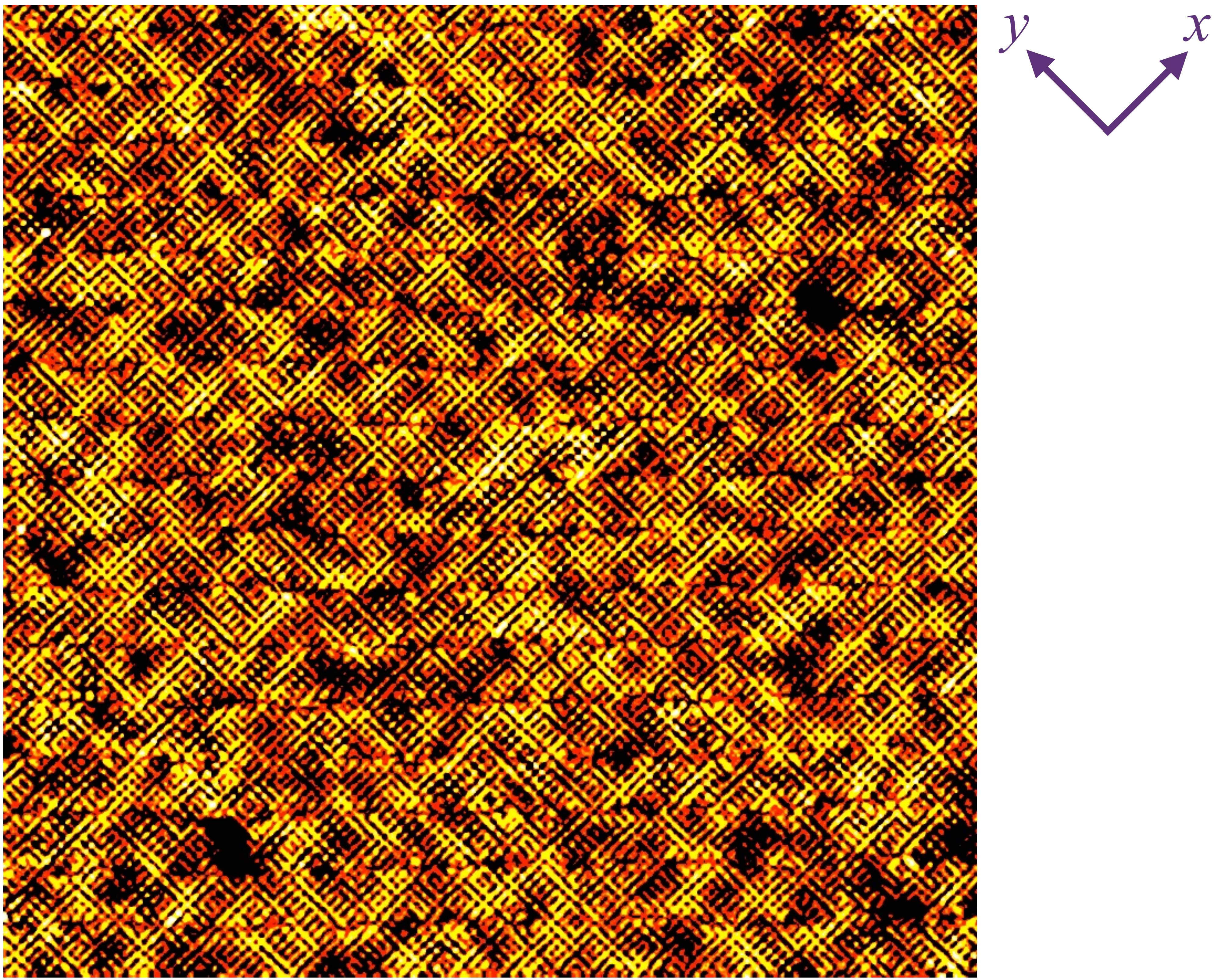
M. Vershinin, S. Misra, S. Ono, Y. Abe, Yoichi Ando, and A. Yazdani, Science **303**, 1995 (2004).

W. D. Wise, M. C. Boyer, K. Chatterjee, T. Kondo, T. Takeuchi, H. Ikuta, Y. Wang, and E. W. Hudson, Nature Phys. **4**, 696 (2008).



"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).

See also

C. Howald, H. Eisaki, N. Kaneko, M. Greven, and A. Kapitulnik, Phys. Rev. B **67**, 014533 (2003);

M. Vershinin, S. Misra, S. Ono, Y. Abe, Yoichi Ando, and A. Yazdani, Science **303**, 1995 (2004).

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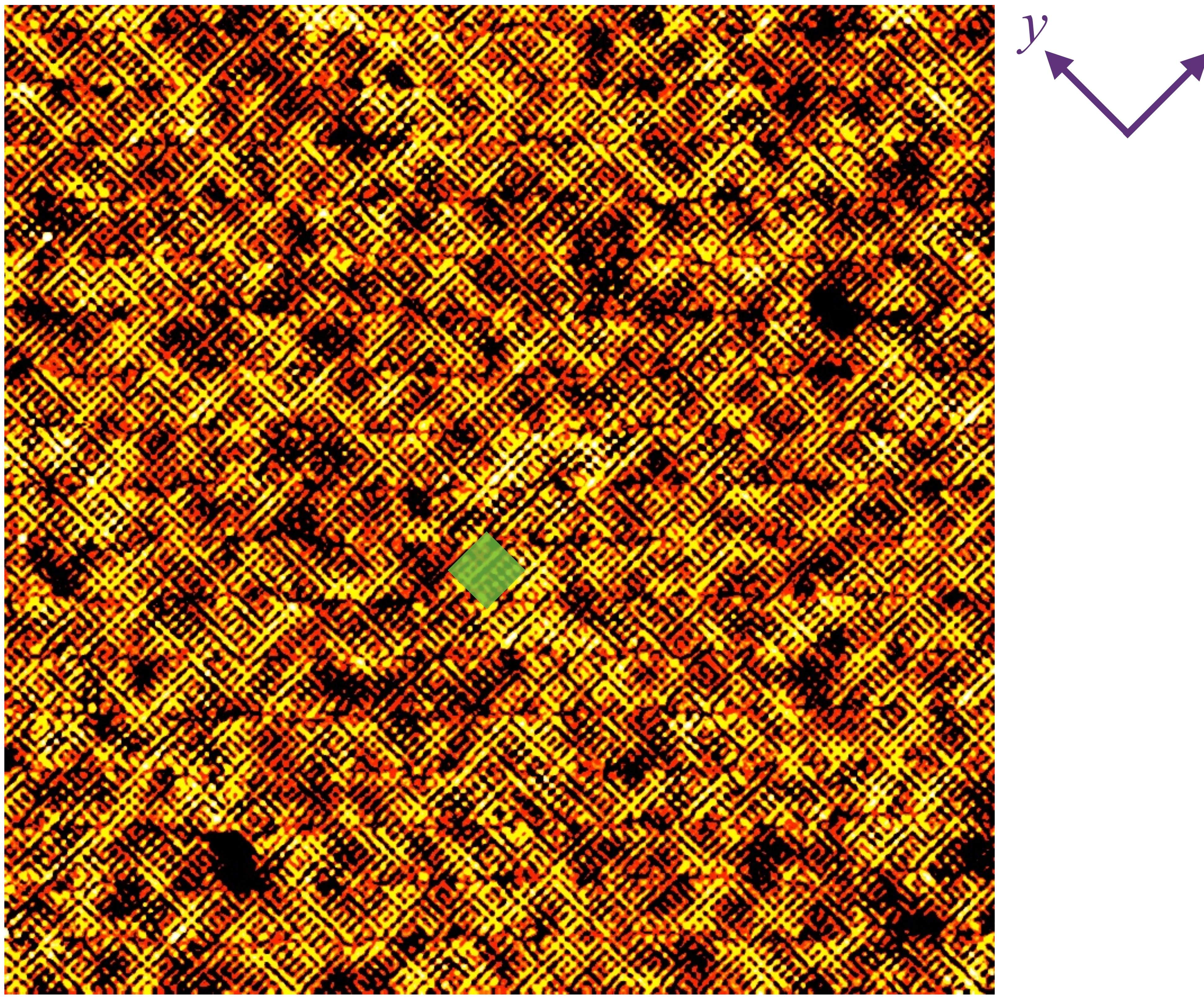

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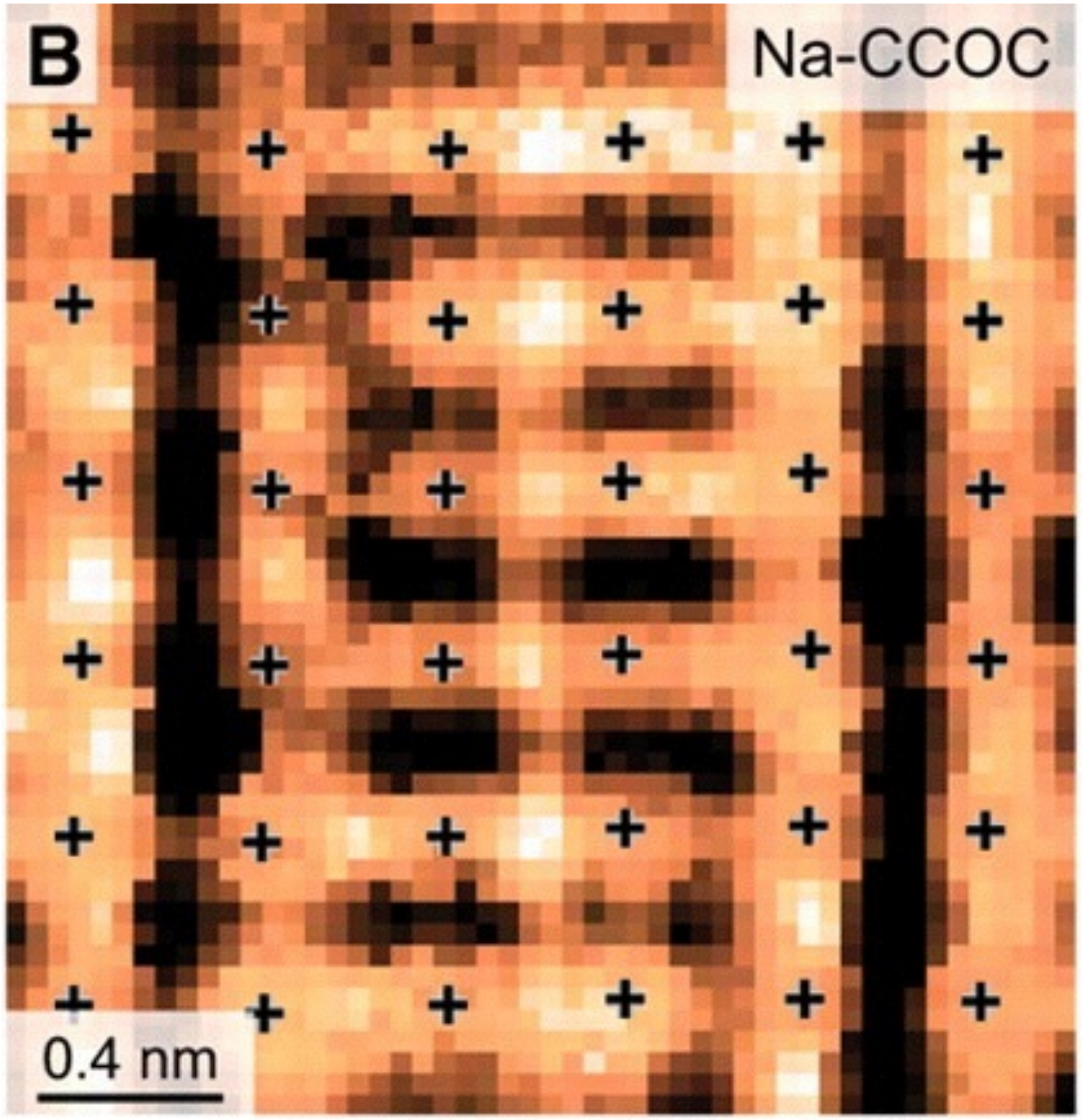
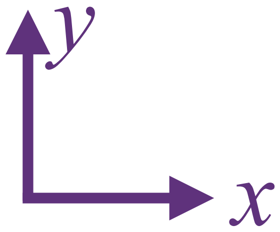
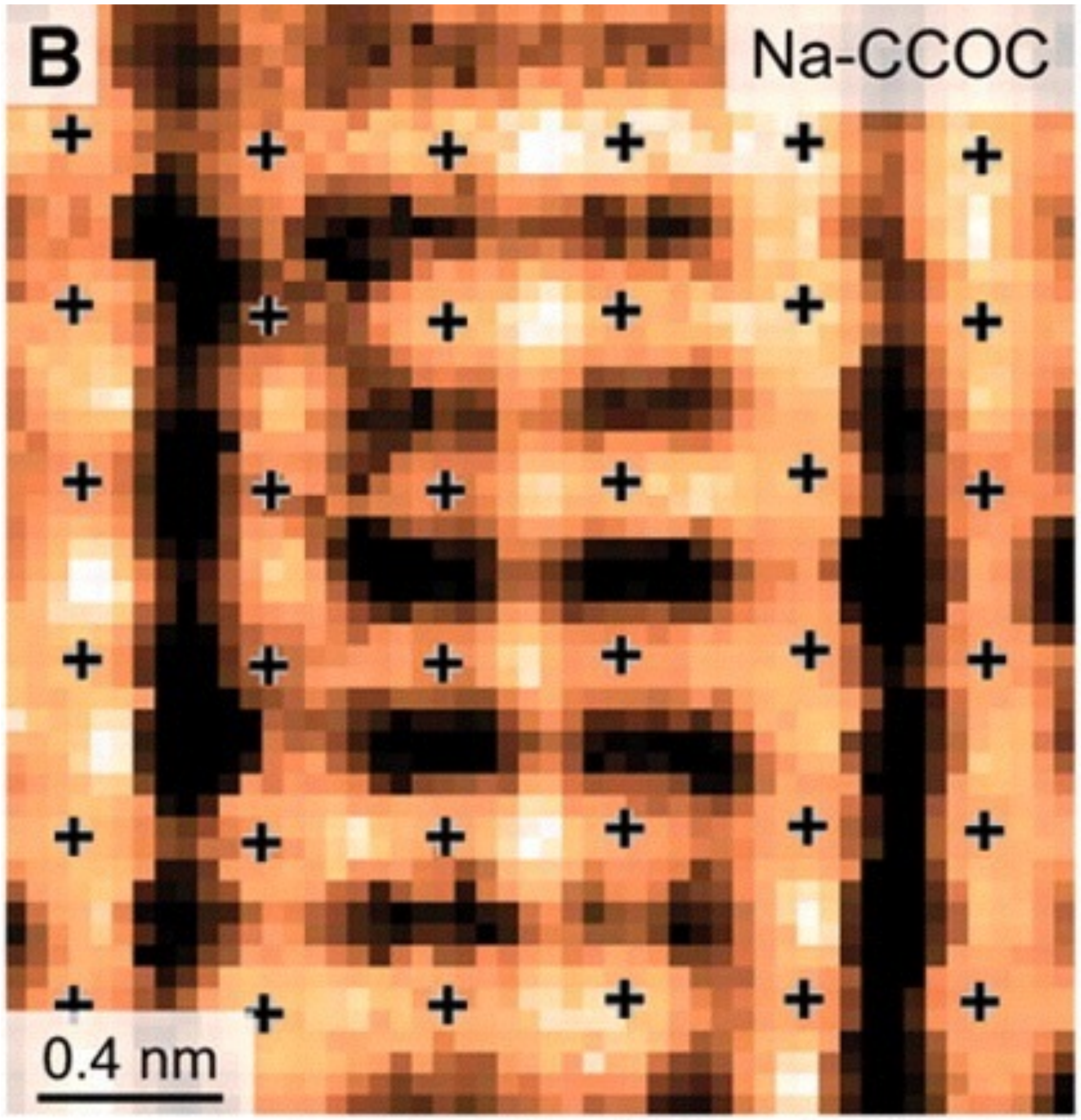
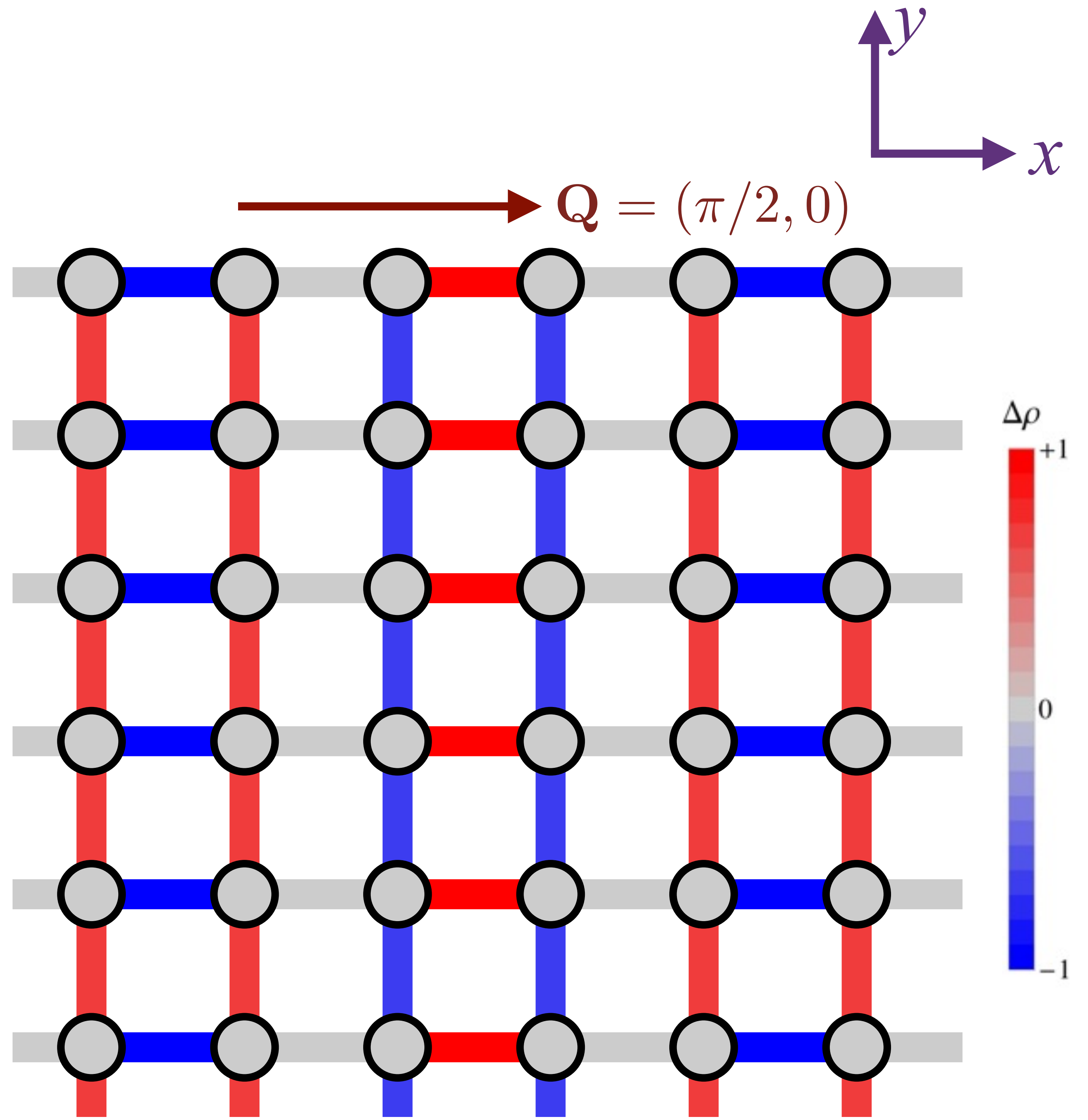


Y. Kohsaka *et al.*, Science **315**, 1380 (2007)



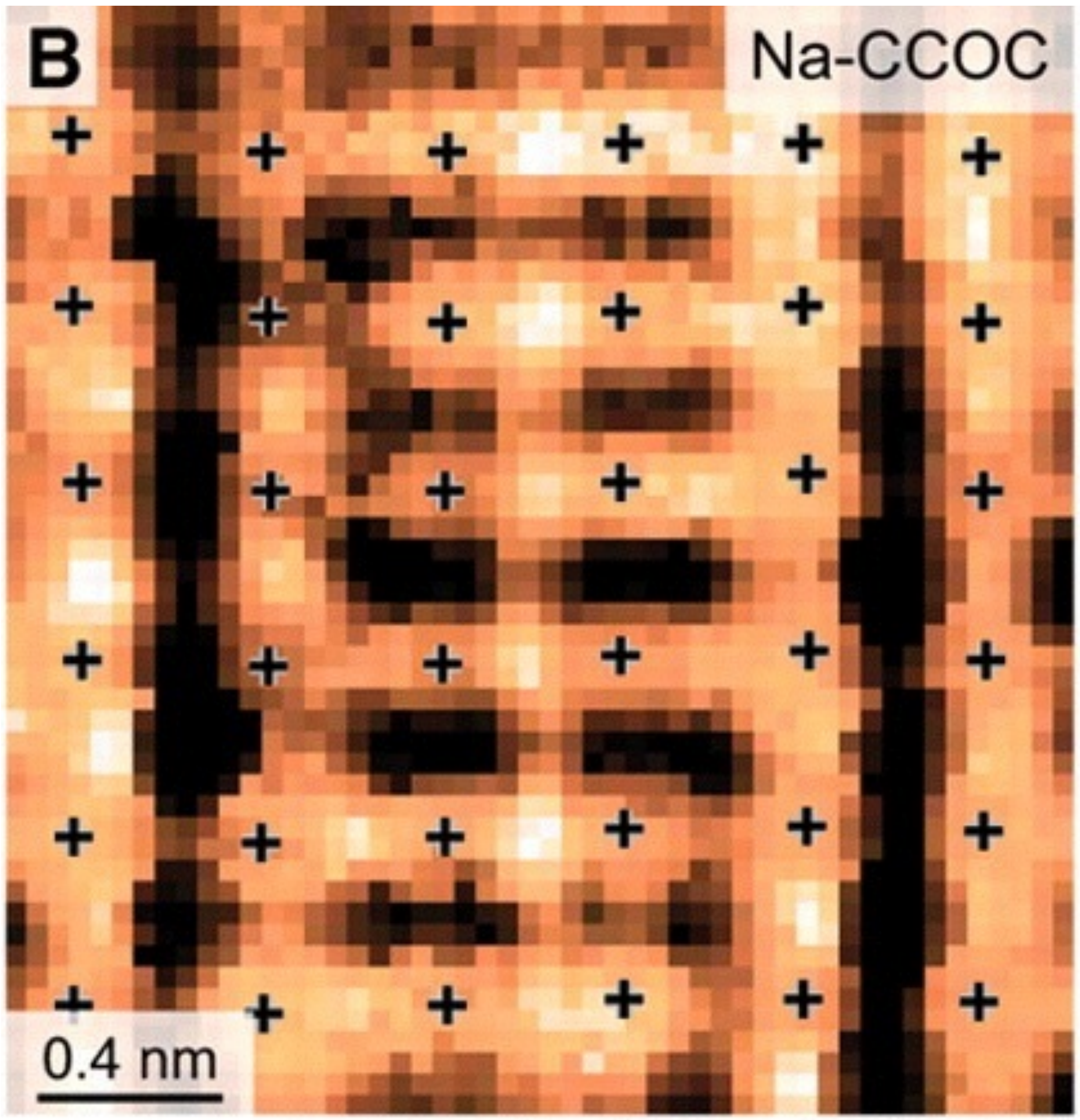


Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)

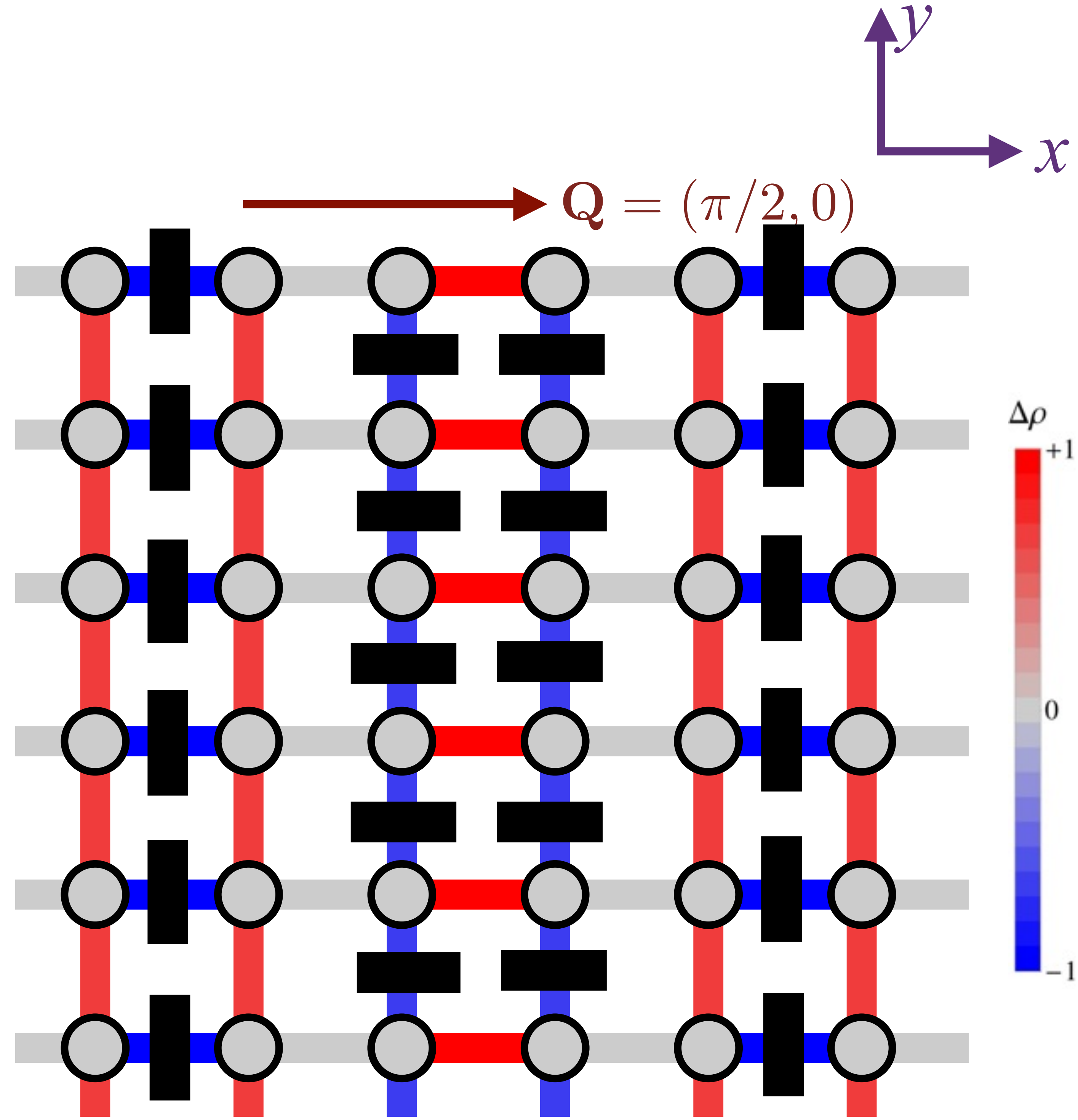


d-wave bond order

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



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



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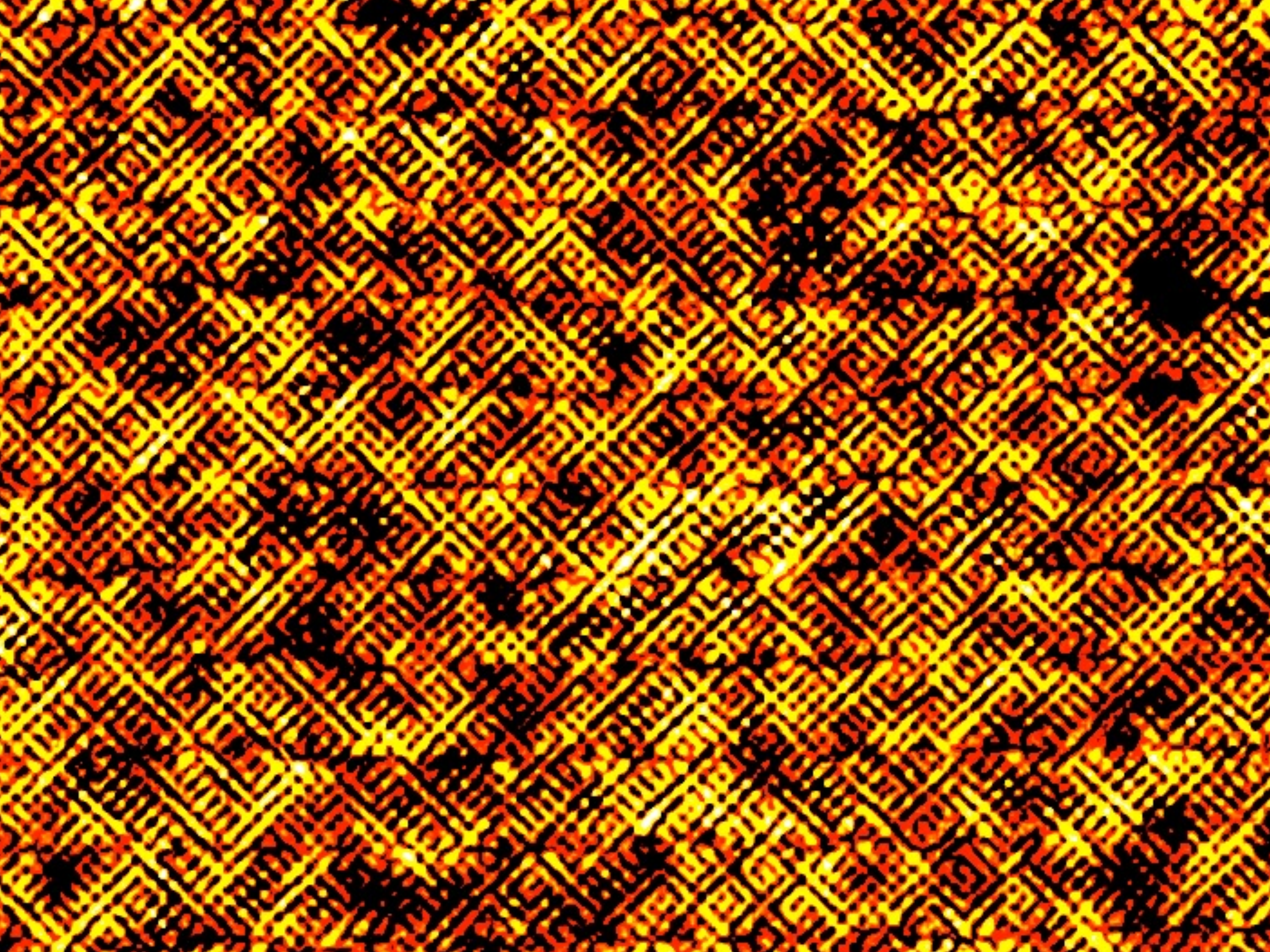

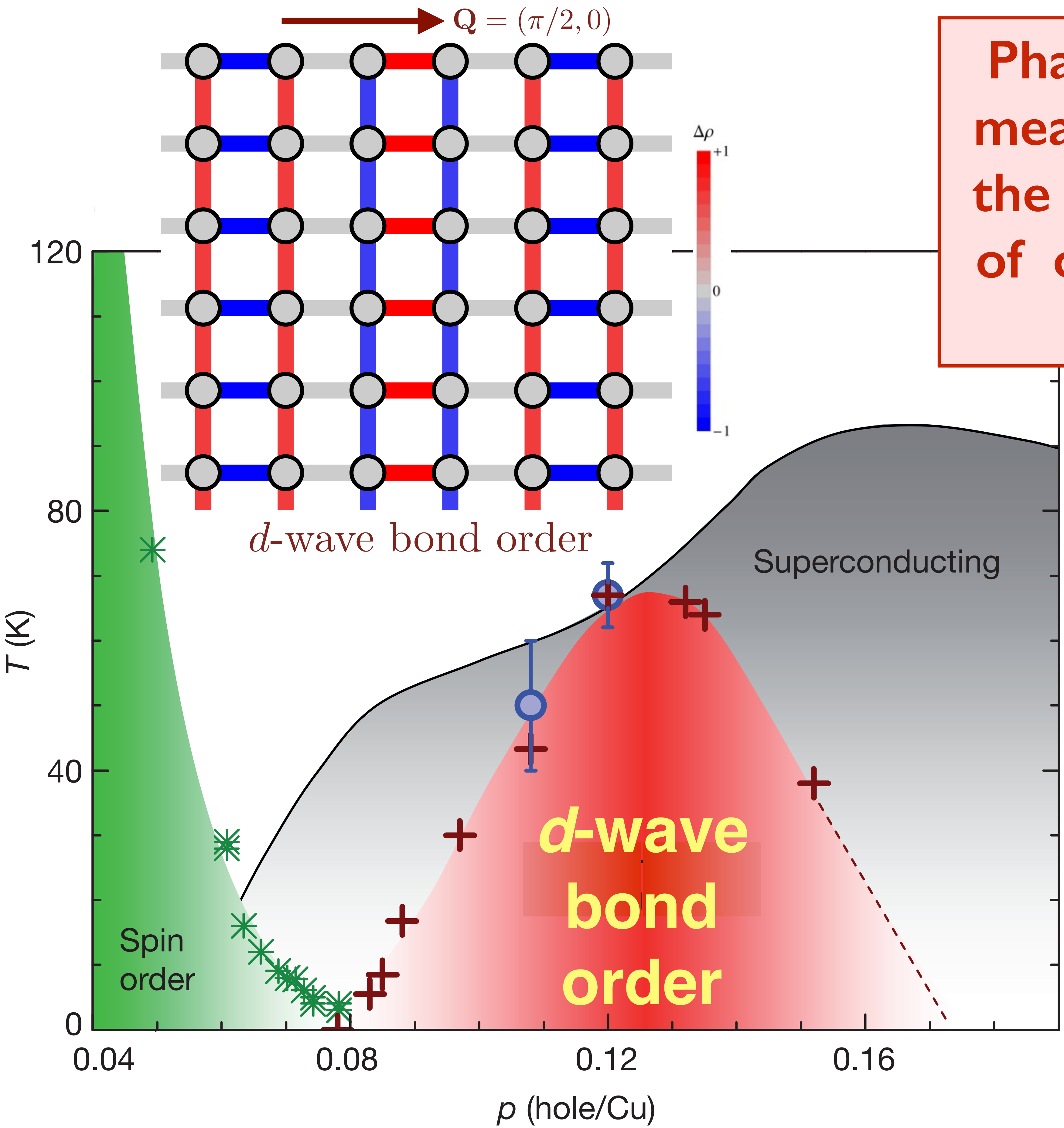

Phase-sensitive measurement of the *d* symmetry of density wave order

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, PNAS to appear, arXiv:1404.0362

Outline

1. Unconventional *d*-wave superconductivity

2. Low hole density state:
   An unconventional density wave

3. Outline of theoretical prediction

4. Evolution of Fermi surface

Outline

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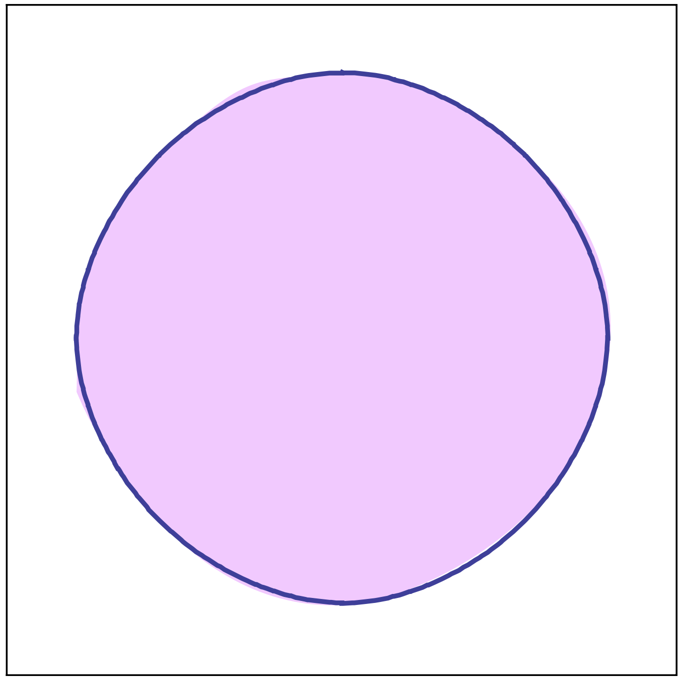
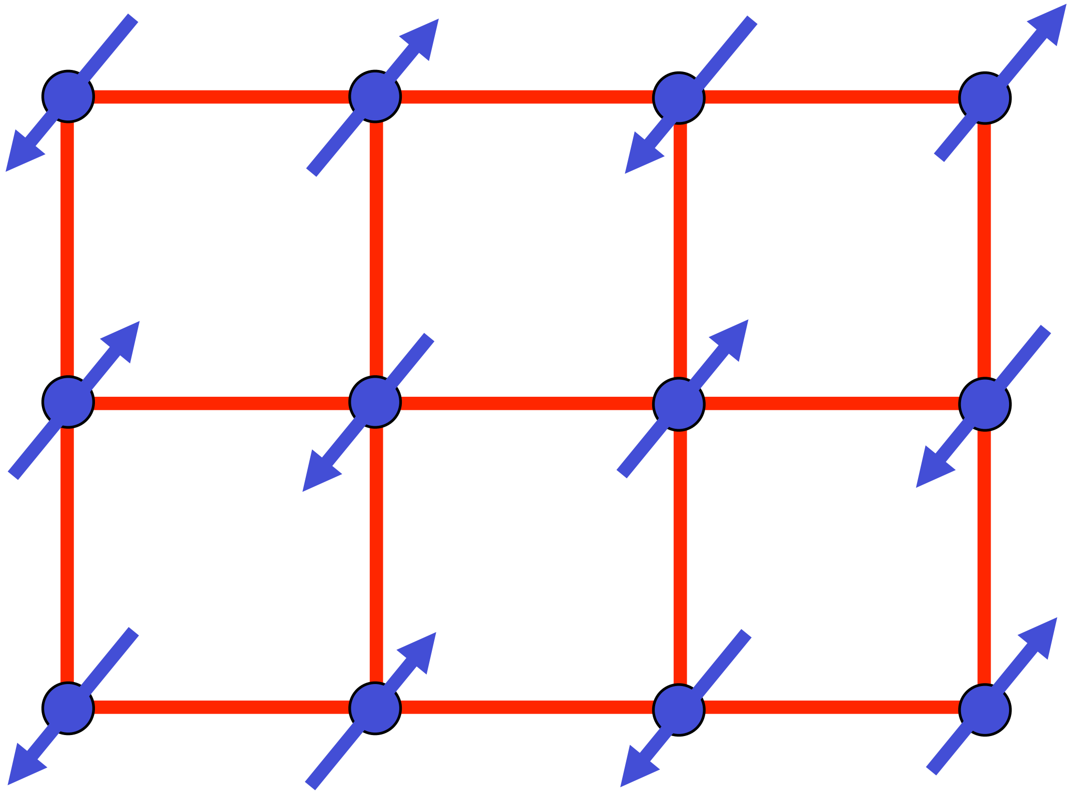
Fermi surface+antiferromagnetism

Metal with "large" Fermi surface



+

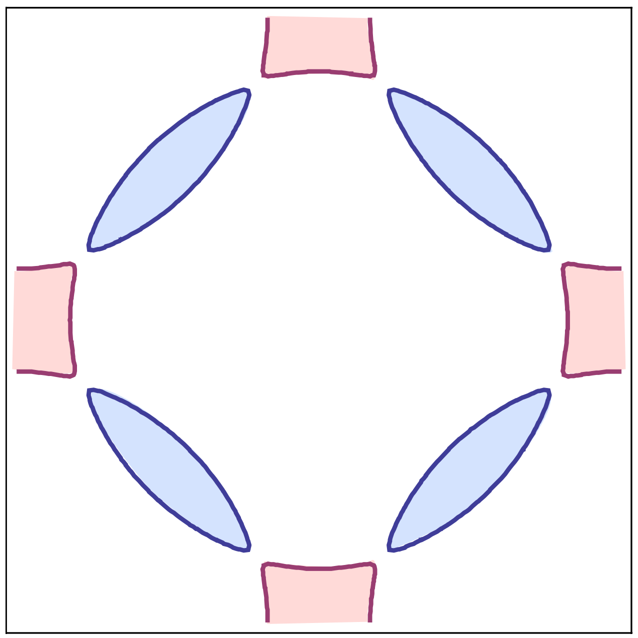


The electron spin polarization obeys

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

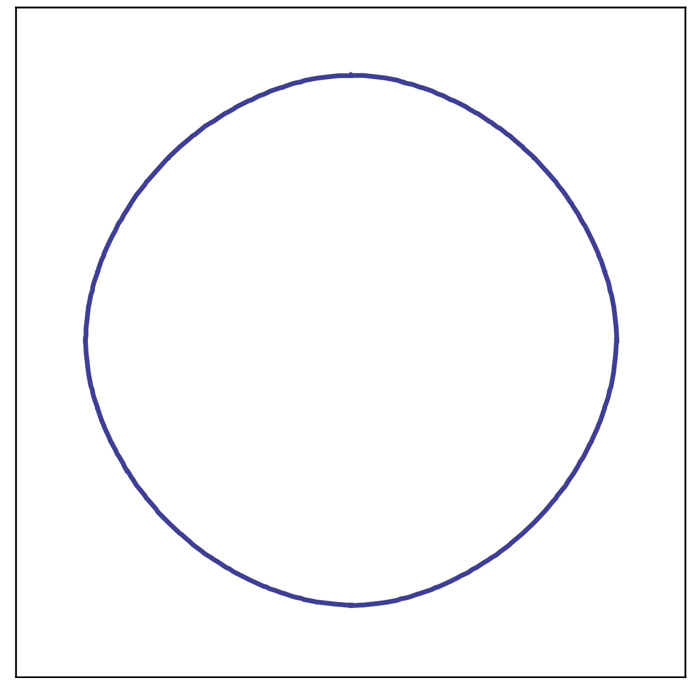
where $\mathbf{K} = (\pi, \pi)$ is the ordering wavevector.

Quantum phase transition with onset of antiferromagnetism in a metal



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

Metal with electron and hole pockets

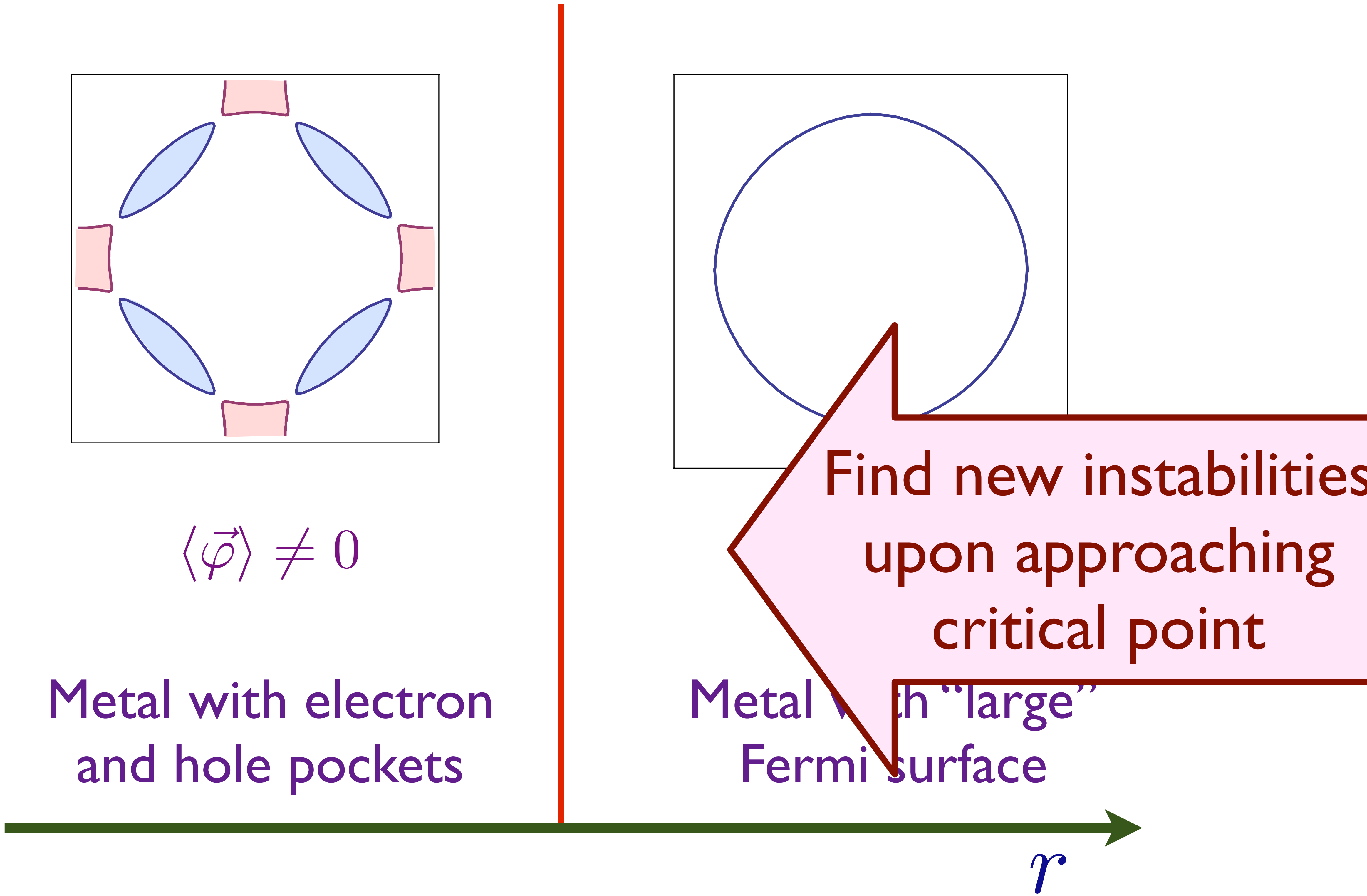


$\langle \vec{\varphi} \rangle = 0$

Metal with "large" Fermi surface

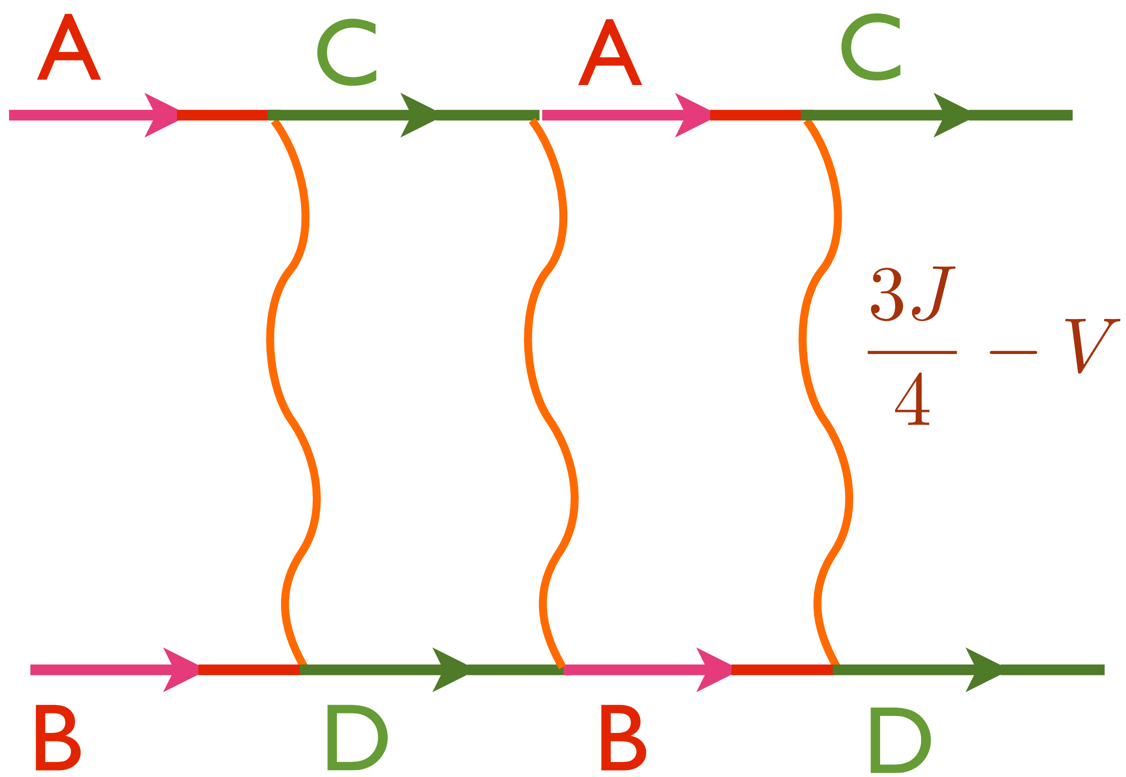
r

Quantum phase transition with onset of antiferromagnetism in a metal



Pairing "glue" from antiferromagnetic fluctuations

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



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

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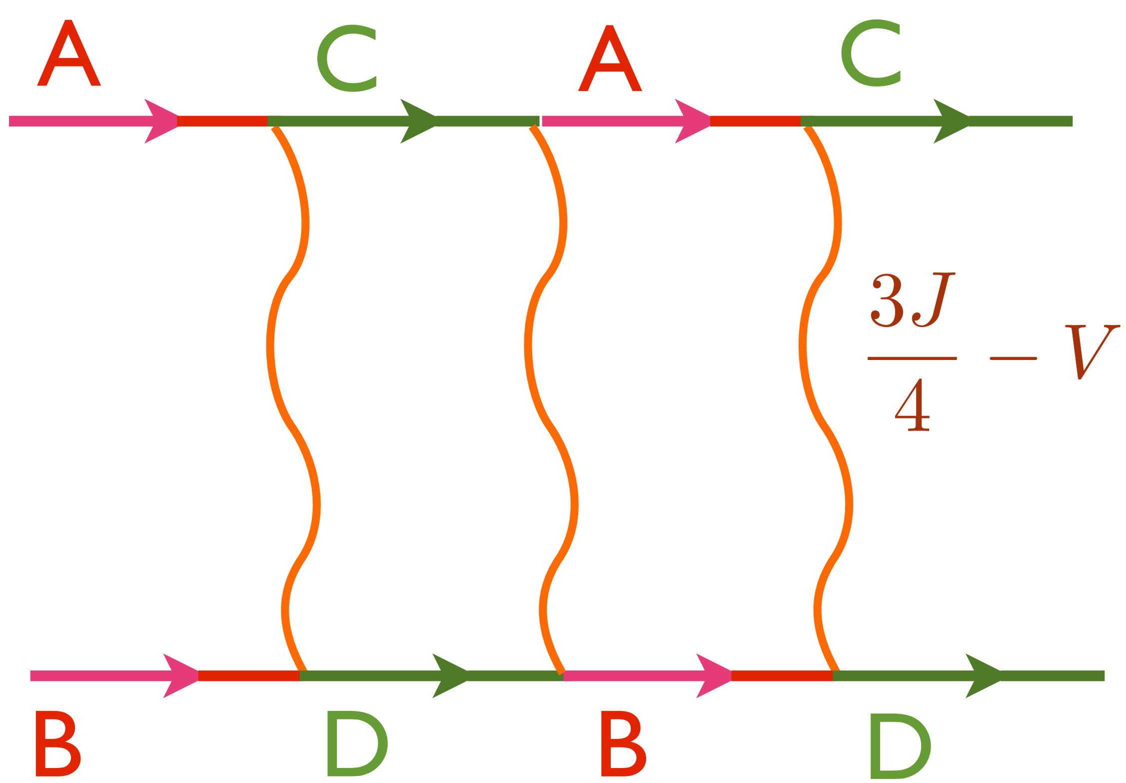

V. J. Emery, *J. Phys. (Paris) Colloq.* **44**, C3-977 (1983)
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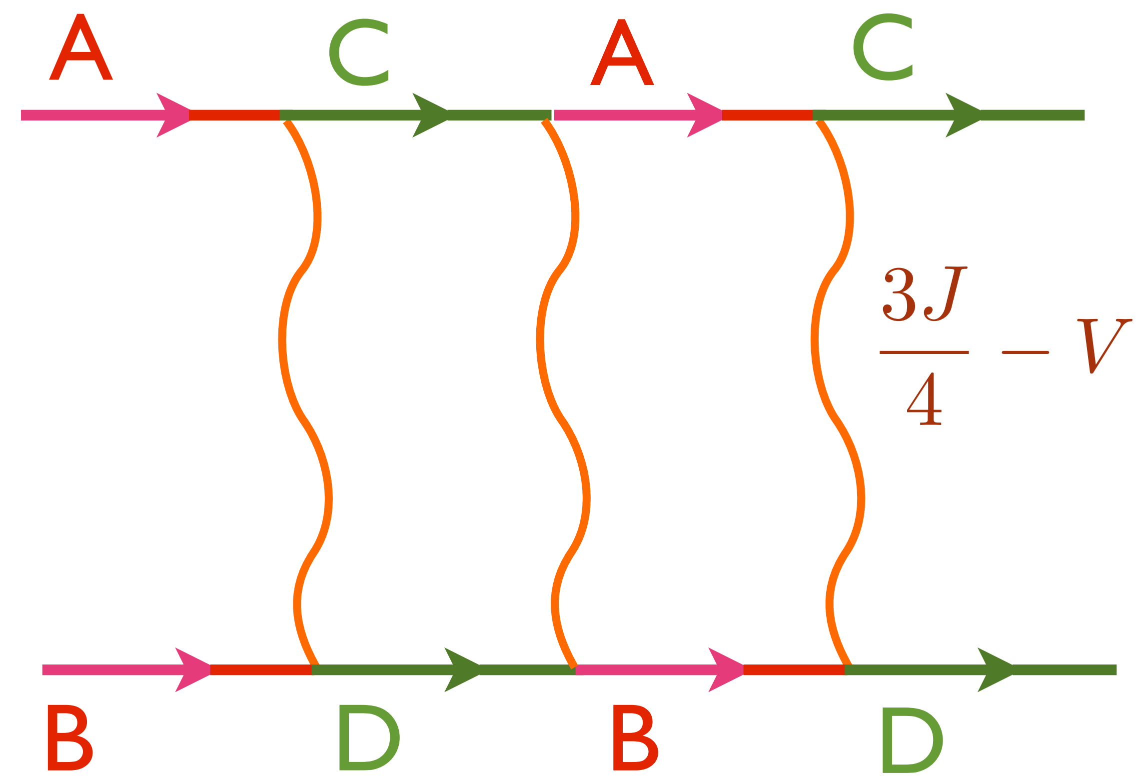

Antiferromagnetic exchange interaction

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

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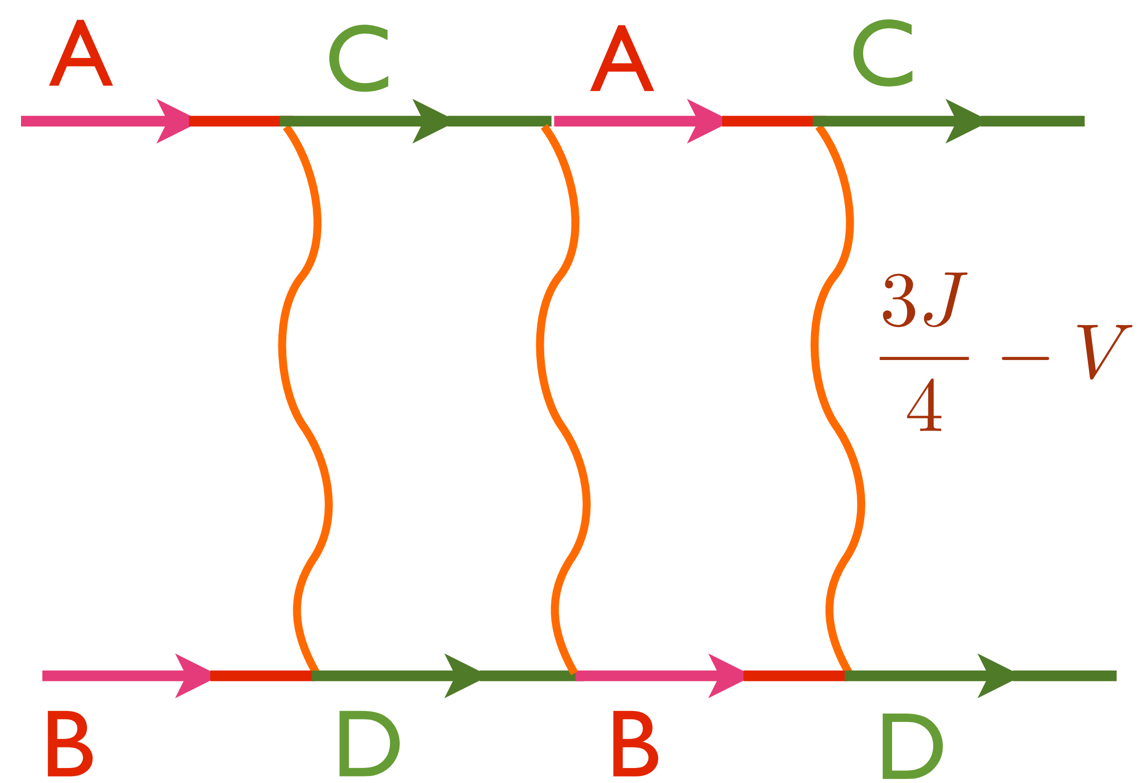
Coulomb repulsion



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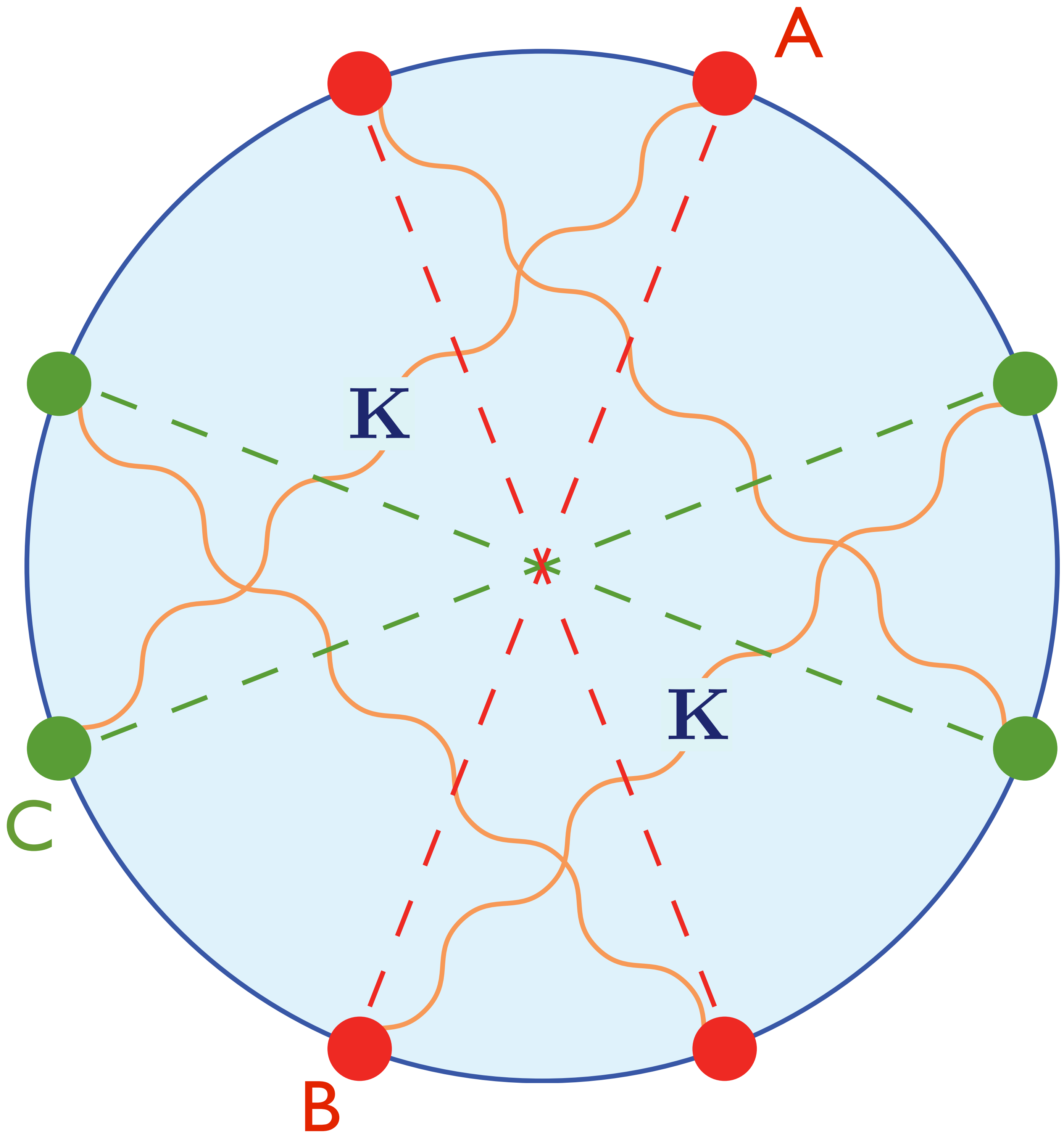

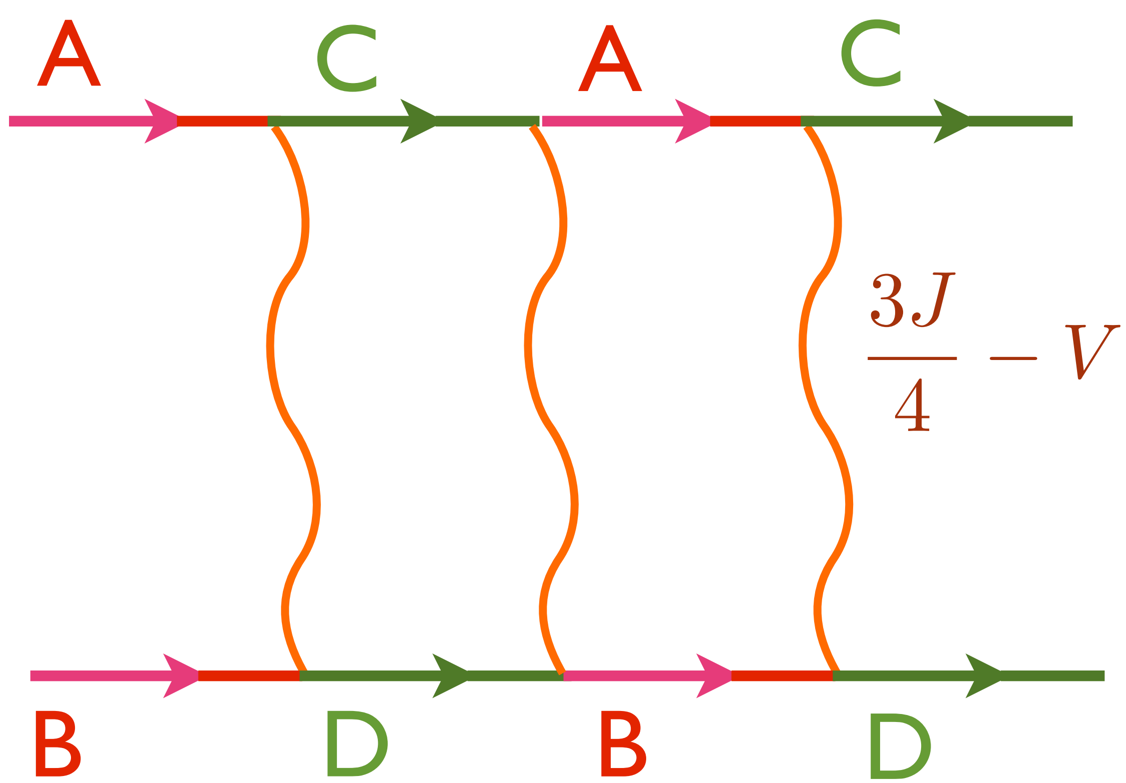

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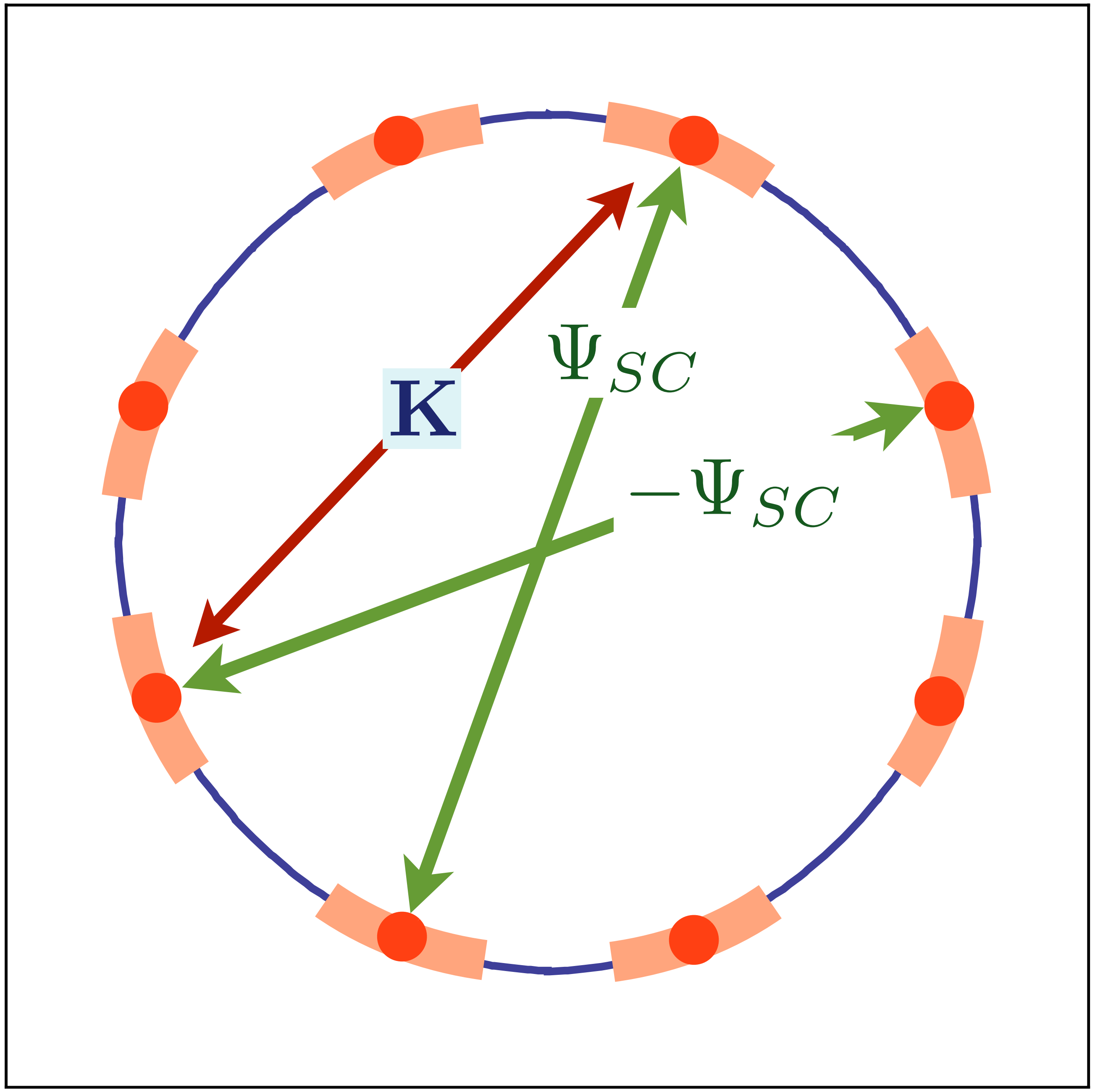
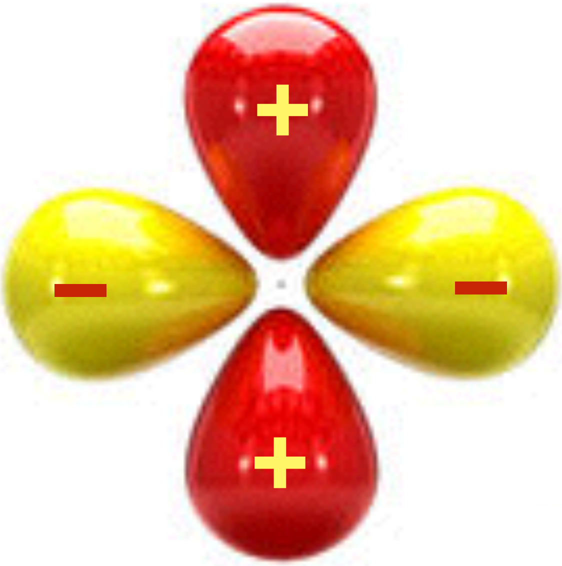
$$\left\langle c^\dagger_{\mathbf{k}\alpha} c^\dagger_{-\mathbf{k}\beta} \right\rangle = \varepsilon_{\alpha\beta}(\cos k_x - \cos k_y)\Psi_{SC}$$





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 $\Psi_{i\alpha a} \to U_{i,ab} \Psi_{i\alpha b}$

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)

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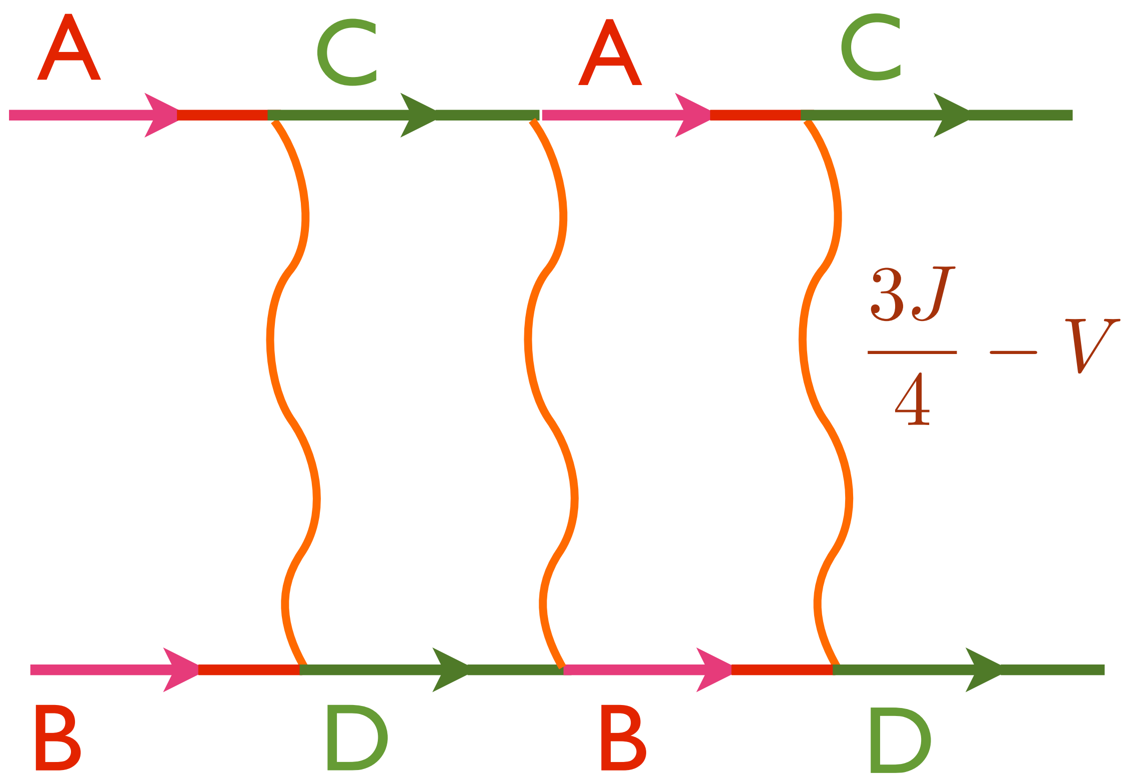

V. J. Emery, *J. Phys. (Paris) Colloq.* **44**, C3-977 (1983)
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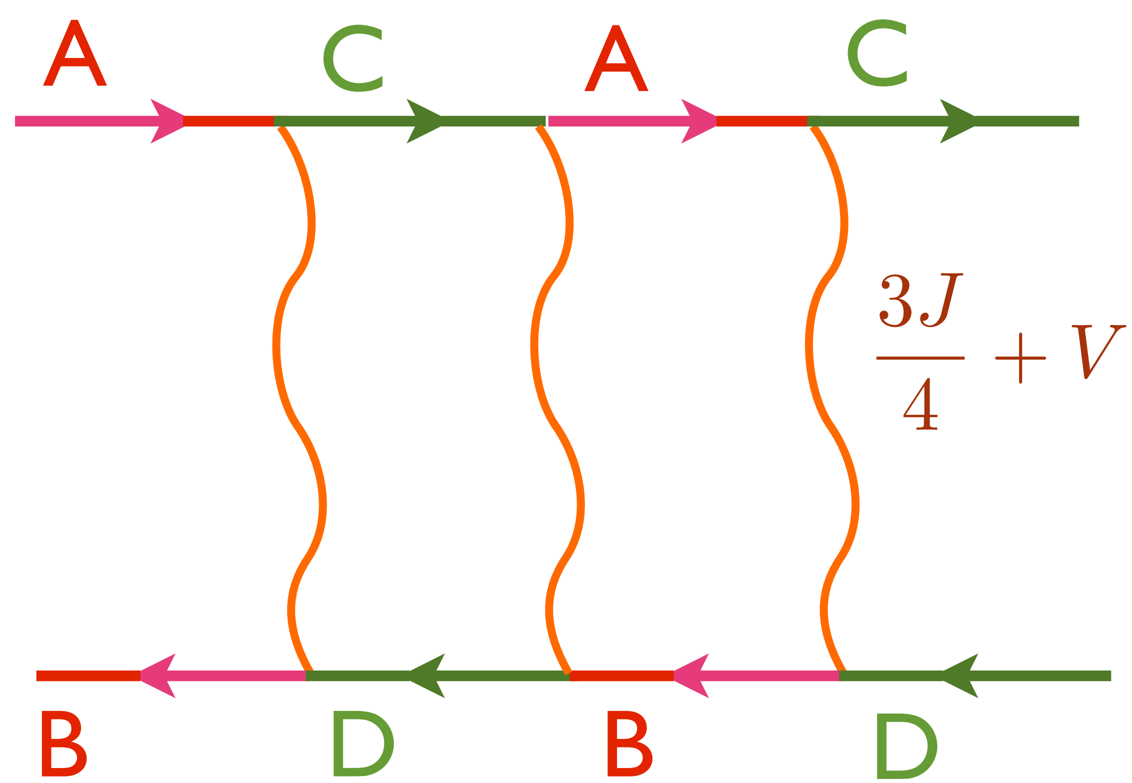
K. Miyake, S. Schmitt-Rink, and C. M. Varma, *Phys. Rev. B* **34**, 6554 (1986)

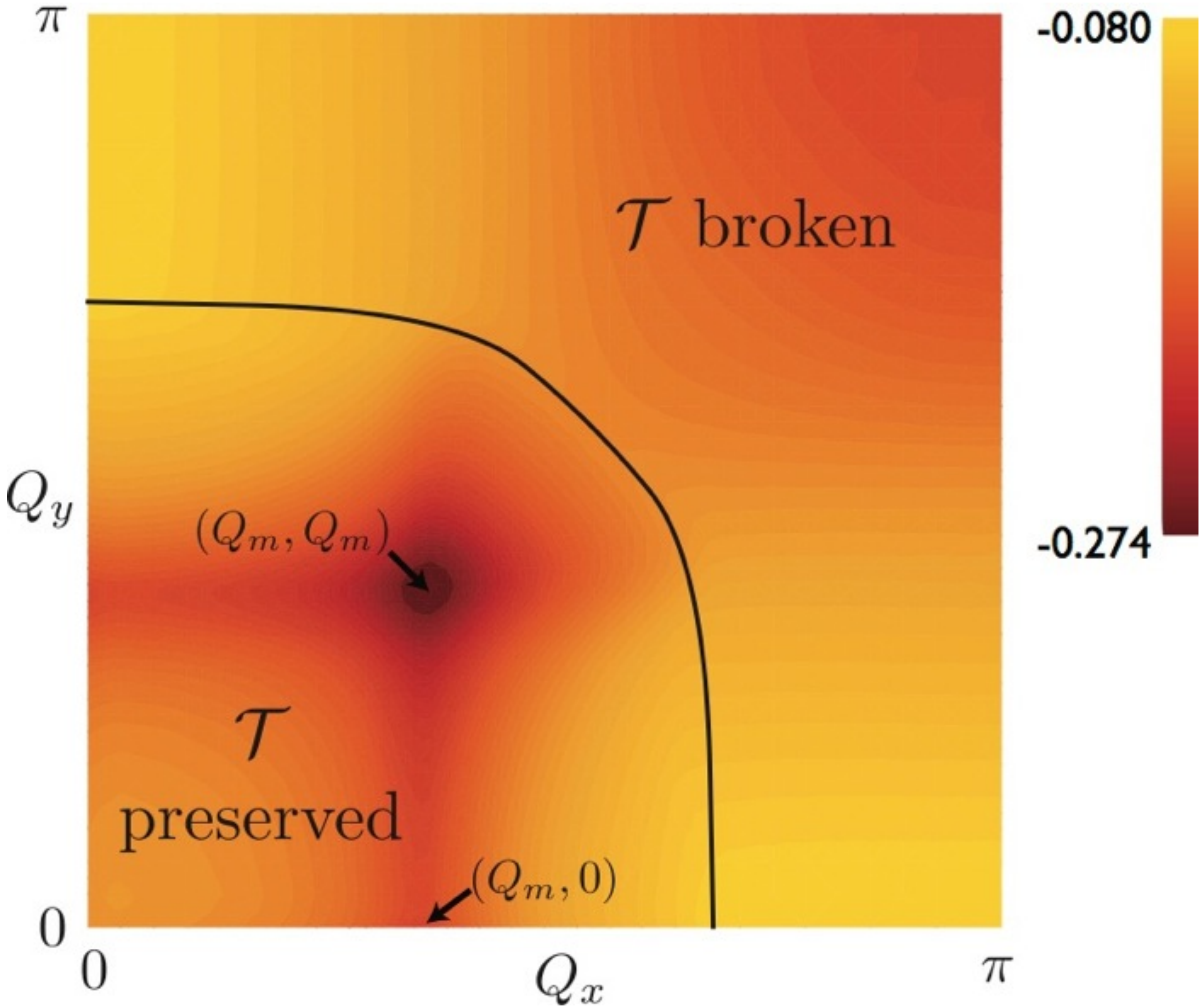
Same "glue" leads to *d*-wave particle-hole pairing !

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



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)

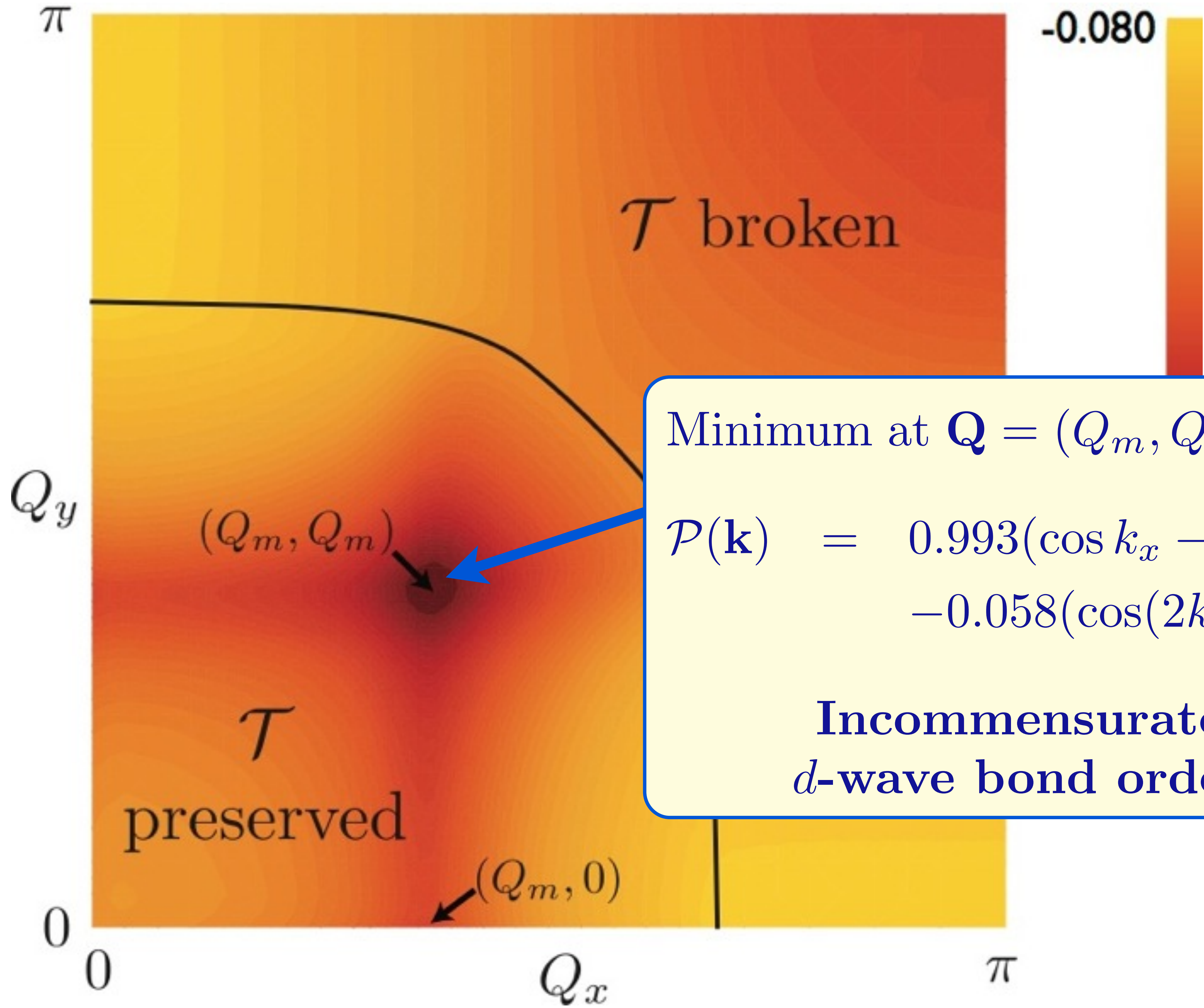
S. Sachdev and R. La Placa, Phys. Rev. Lett. 111, 027202 (2013); A. Allais, J. Bauer, and S. Sachdev, arXiv:1402.6311



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

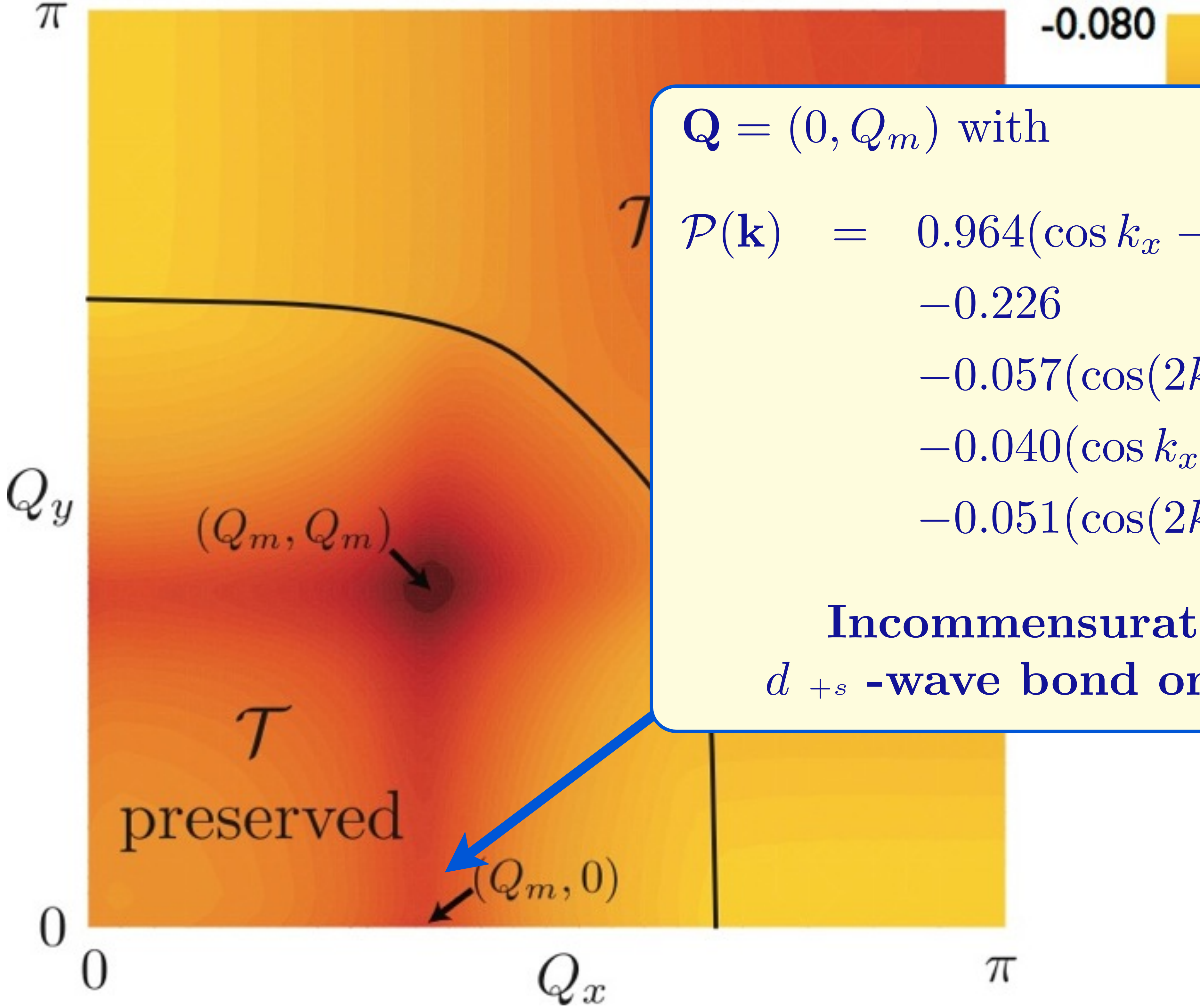
$$\begin{aligned}\mathcal{P}(\mathbf{k}) &= 0.993(\cos k_x - \cos k_y) \\ &\quad -0.058(\cos(2k_x) - \cos(2k_y))\end{aligned}$$

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



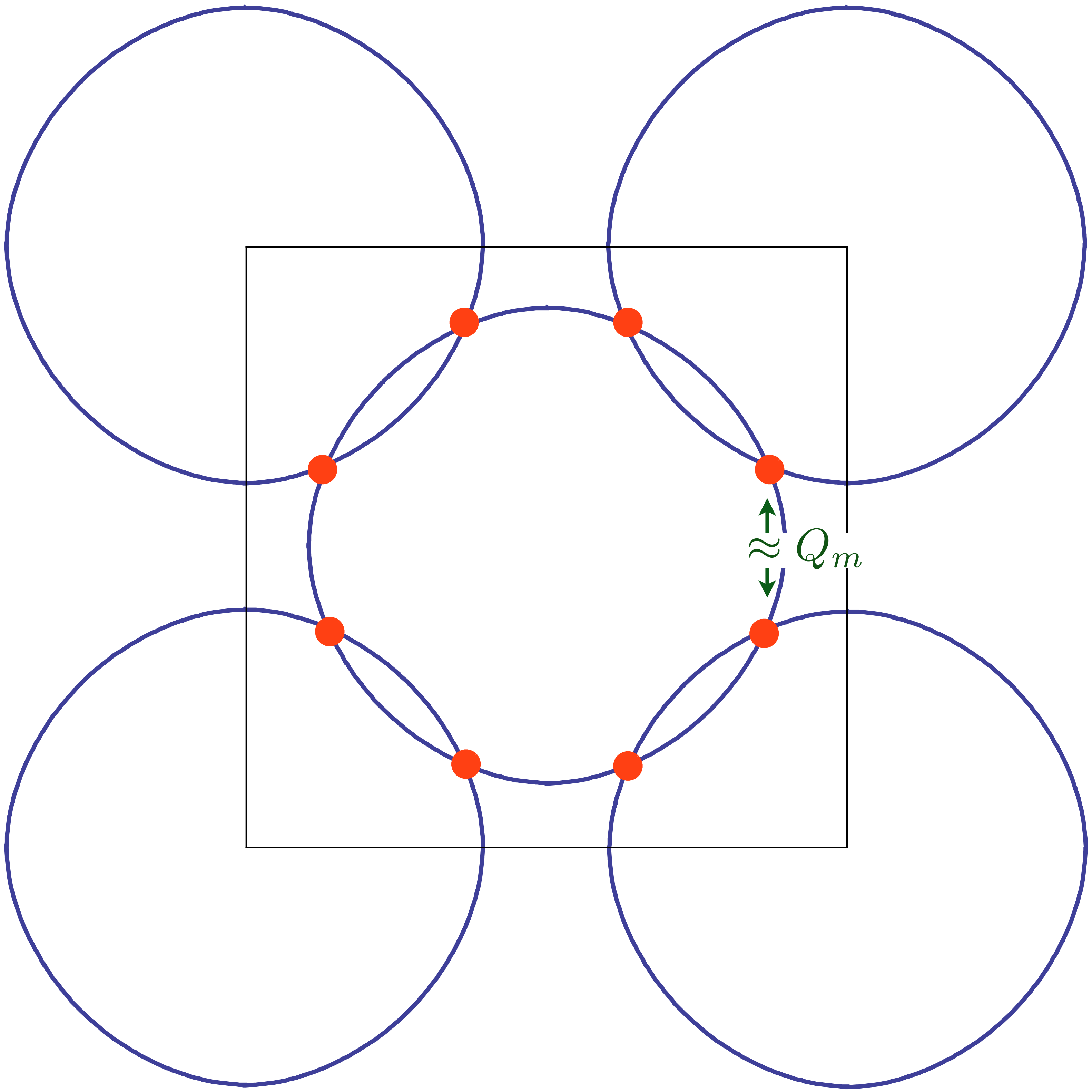
$\mathbf{Q} = (0, Q_m)$ with

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

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



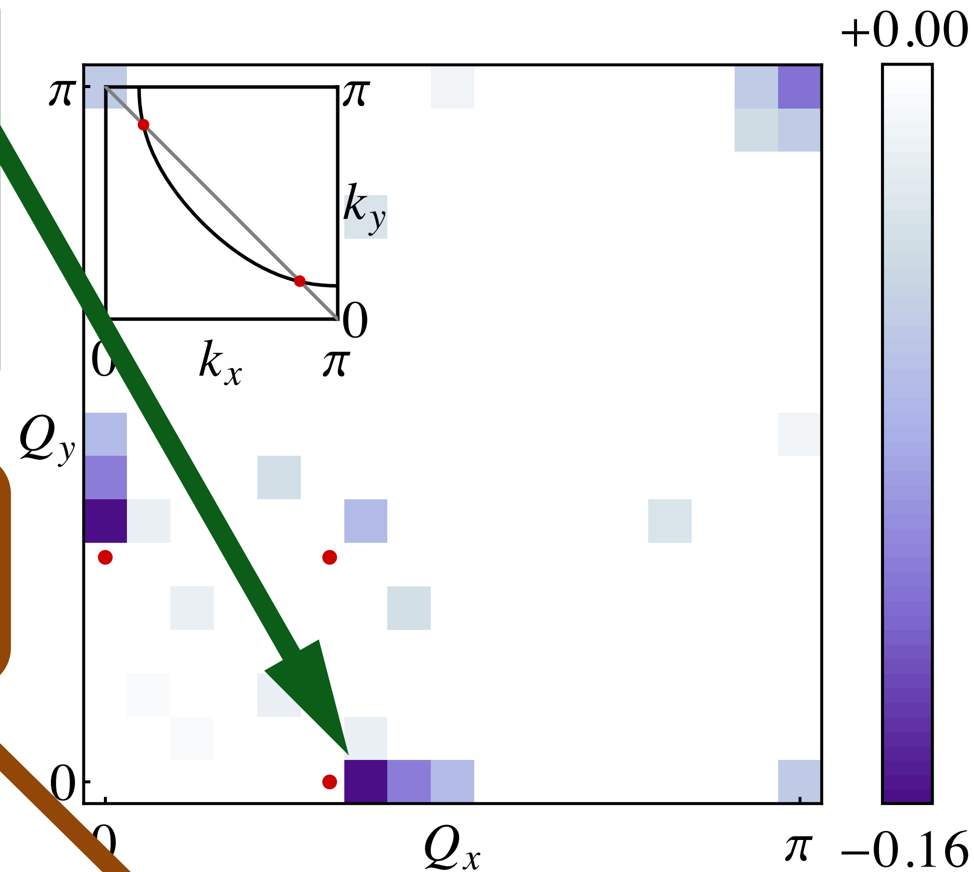
Q_m is approximately the separation between hotspots.

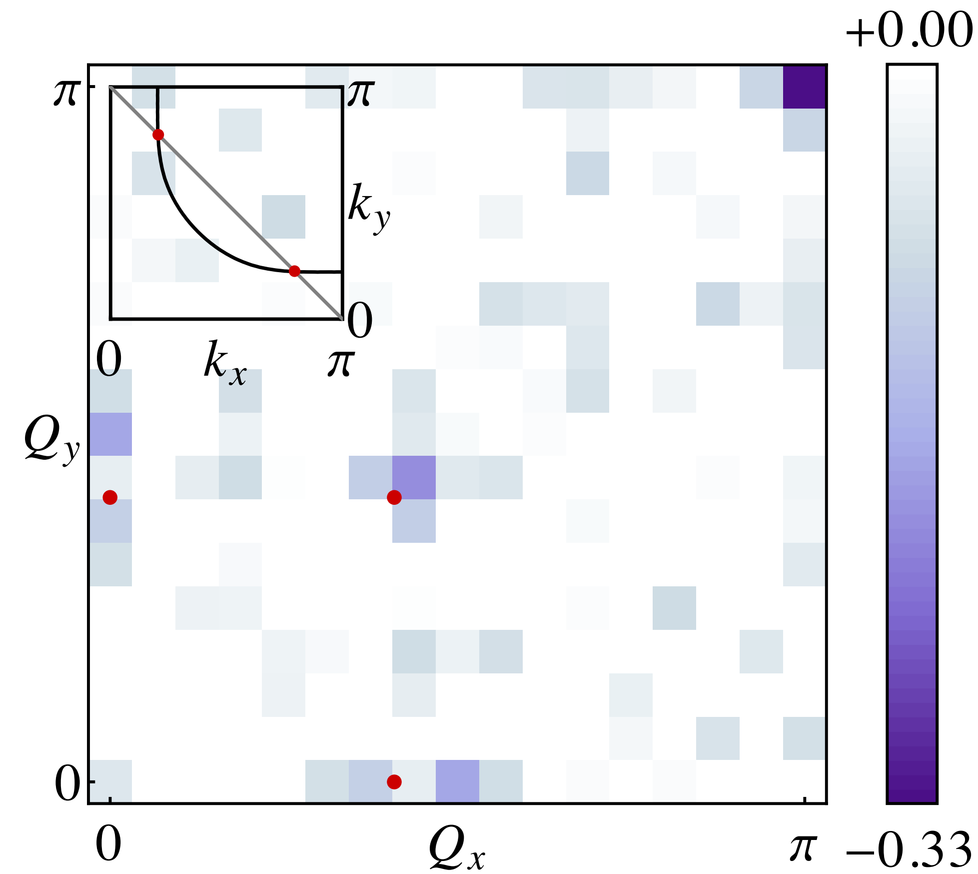
Results of a variational Monte Carlo computation on a wavefunction with double-occupancy projected out.

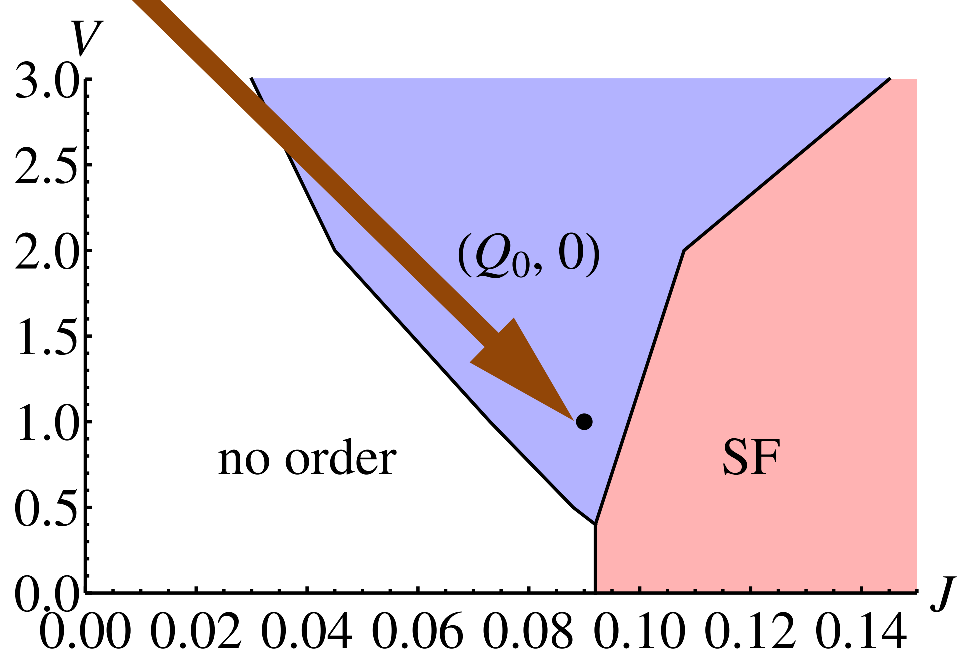
A. Allais, J. Bauer, and S. Sachdev, arXiv:1402.4807

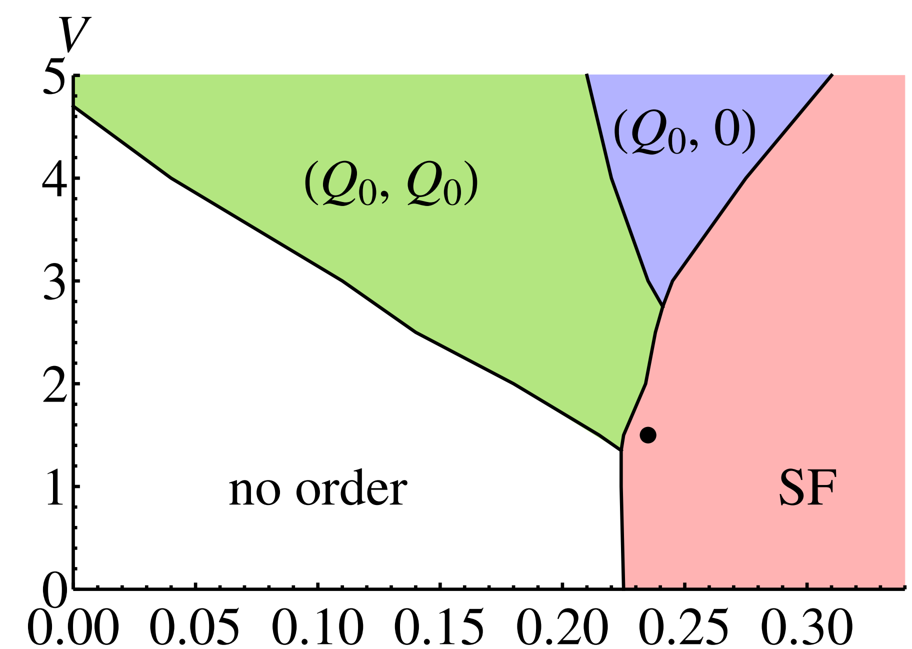
Q of the lowest energy state. Predominantly *d* wave

Q-plot above at this value of J,V



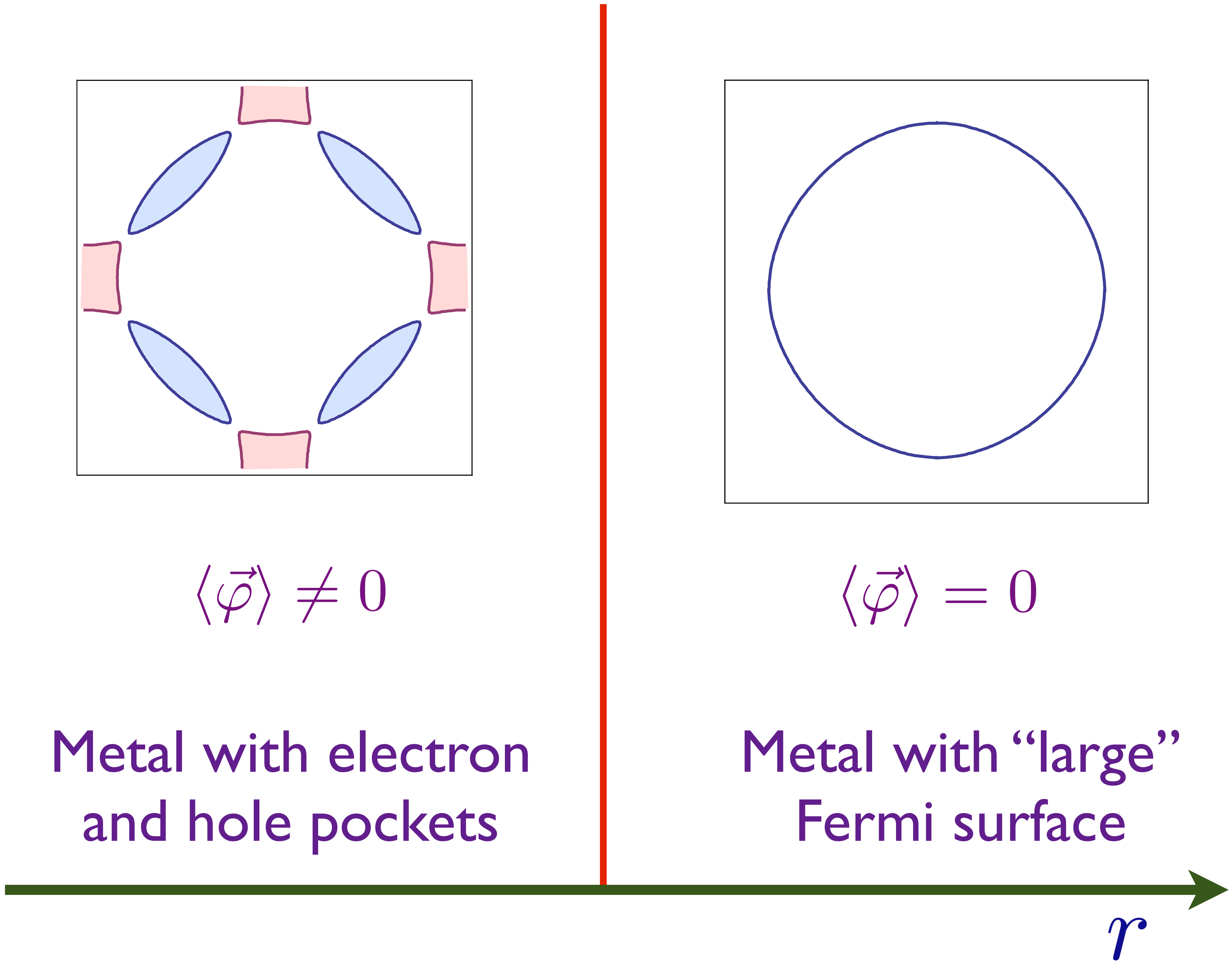






Andrea Allais

Quantum phase transition with onset of antiferromagnetism in a metal



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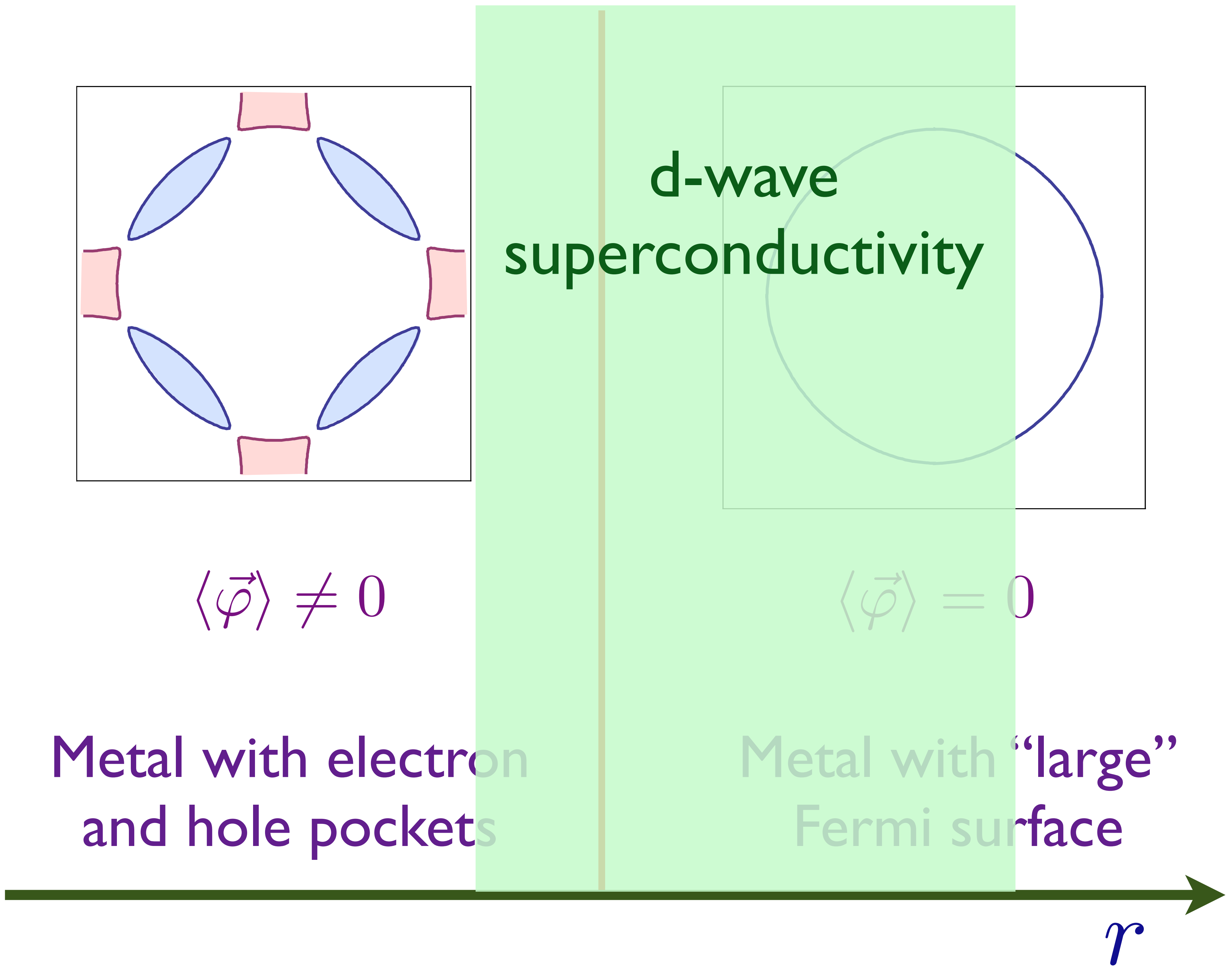
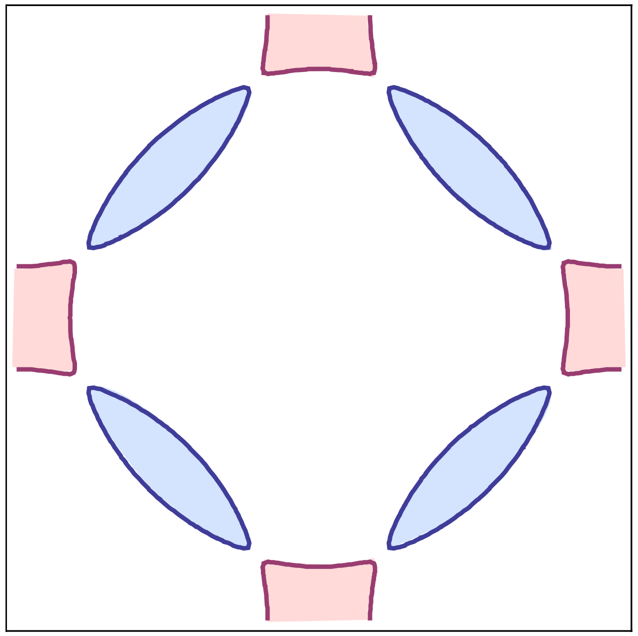
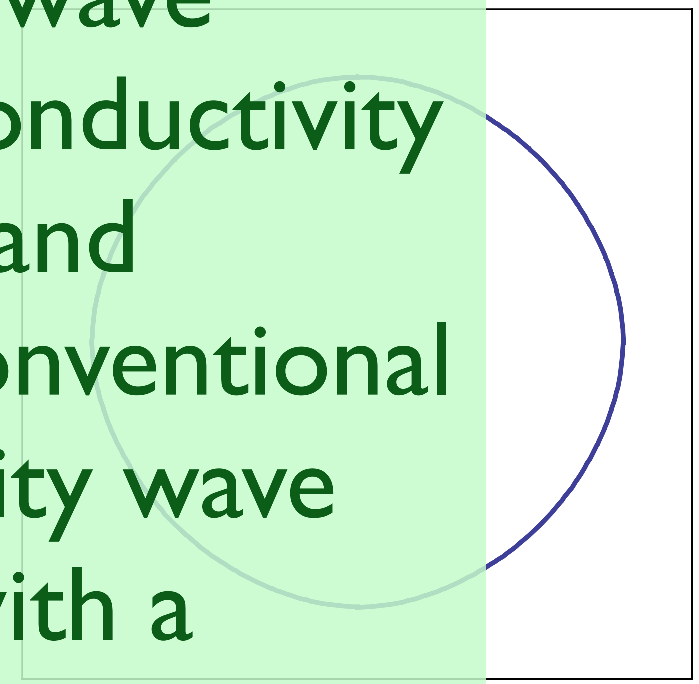


Quantum phase transition with onset of antiferromagnetism in a metal





d-wave superconductivity and an unconventional density wave with a d-wave form factor

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

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

Metal with electron and hole pockets

Metal with "large" Fermi surface

r

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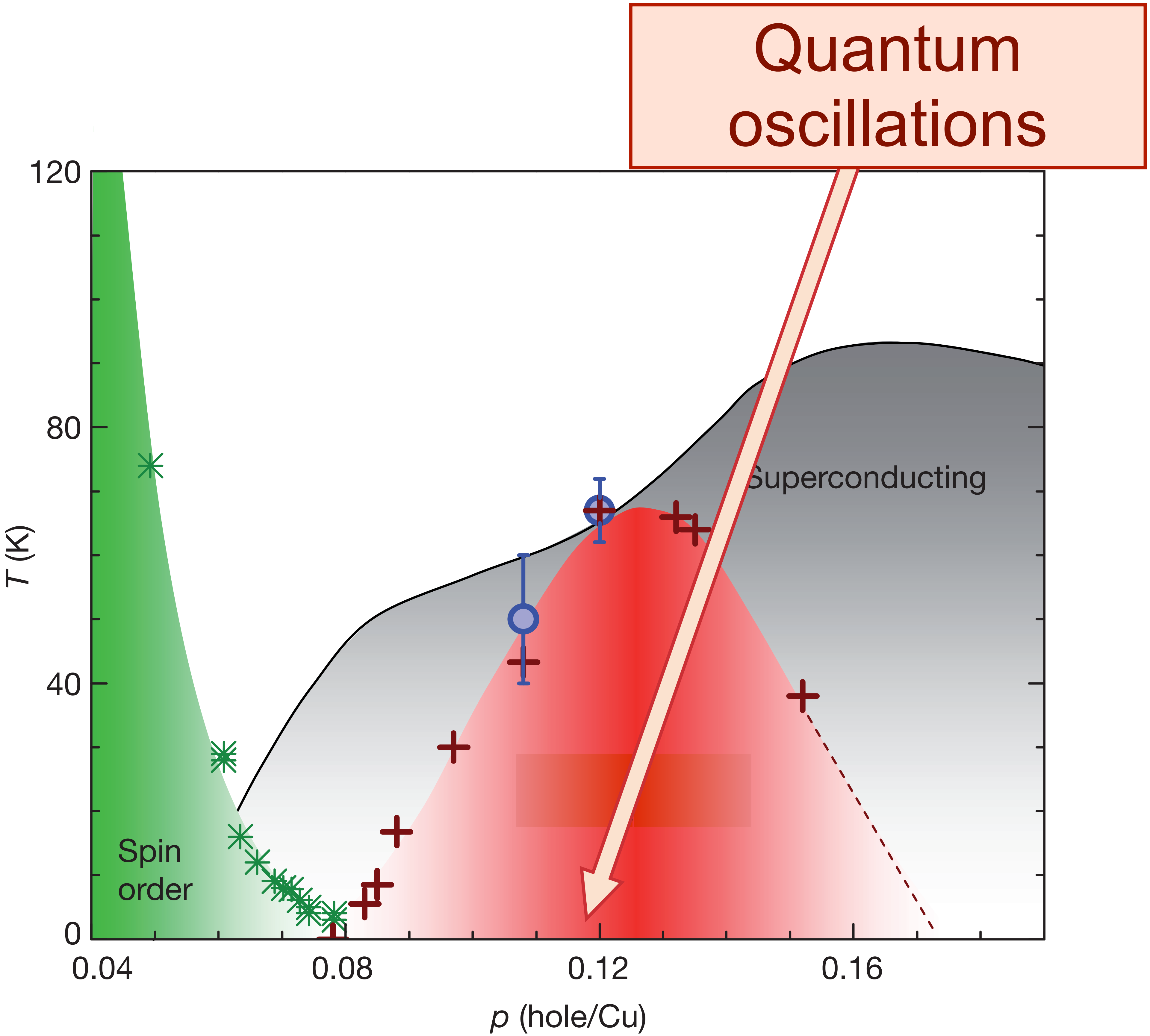

T. Wu, H. Mayaffre, S. Kramer, M. Horvatic, C. Berthier, W.N. Hardy, R. Liang, D.A. Bonn, and M.-H. Julien, Nature **477**, 191 (2011).

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)

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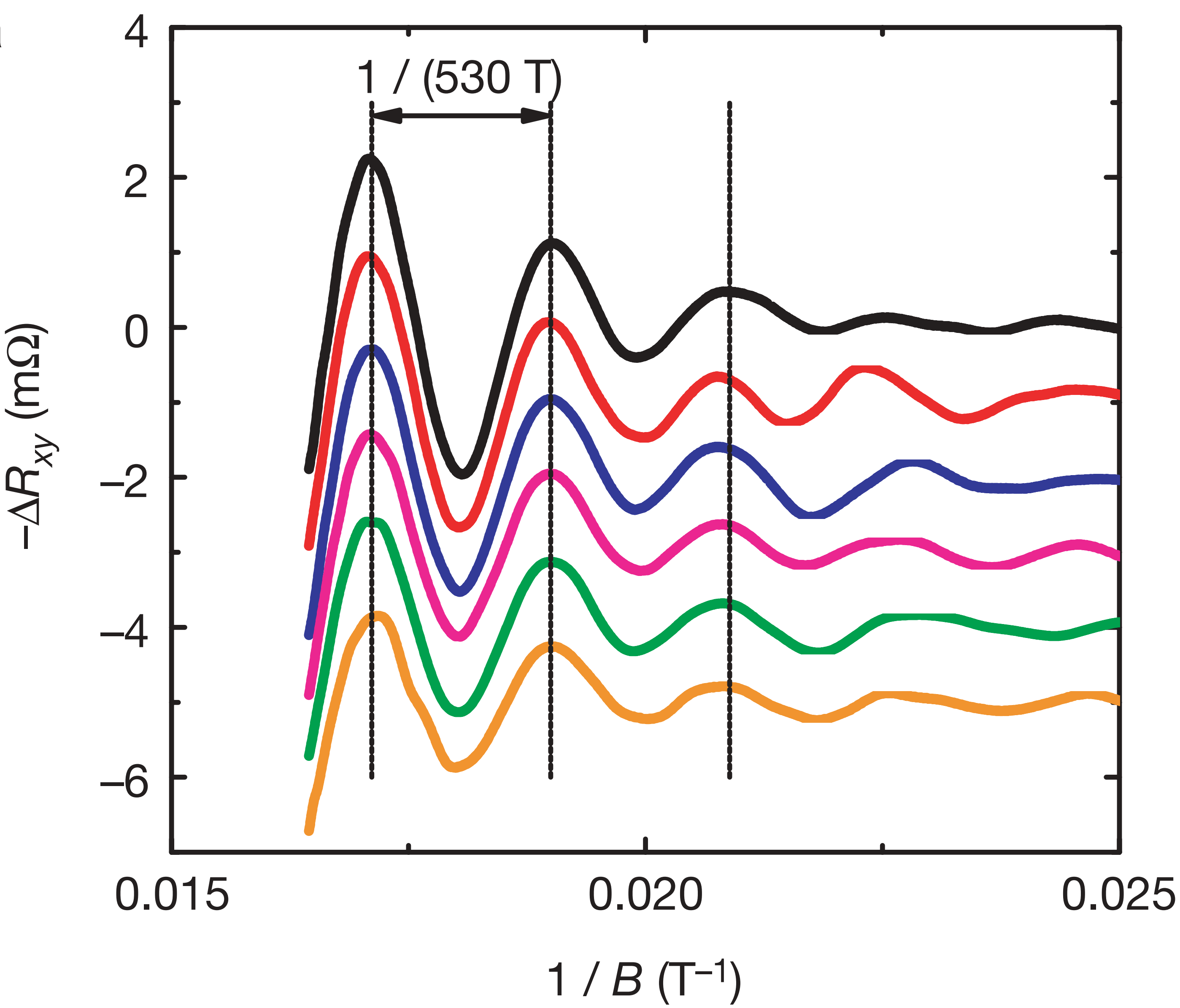
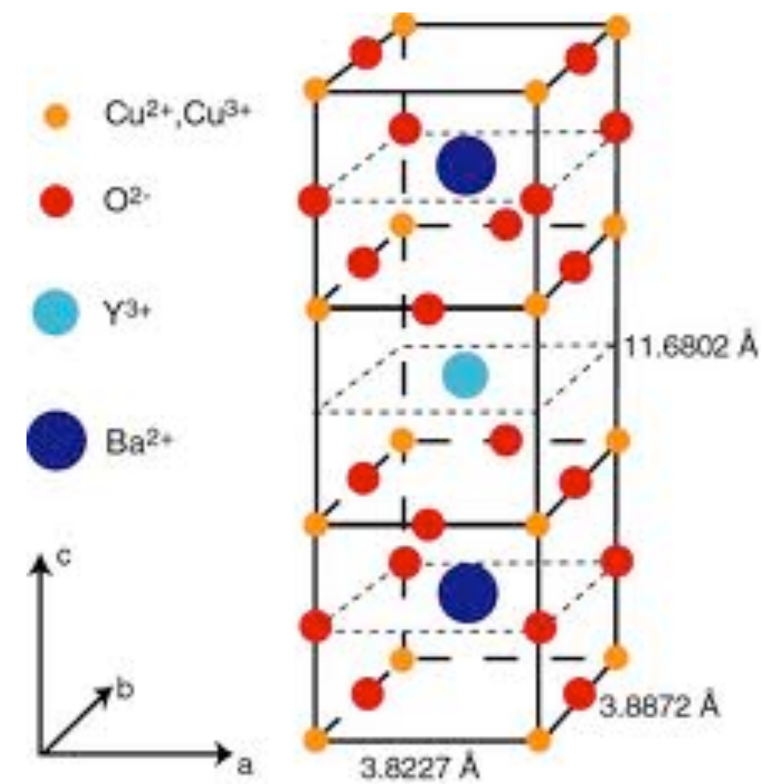
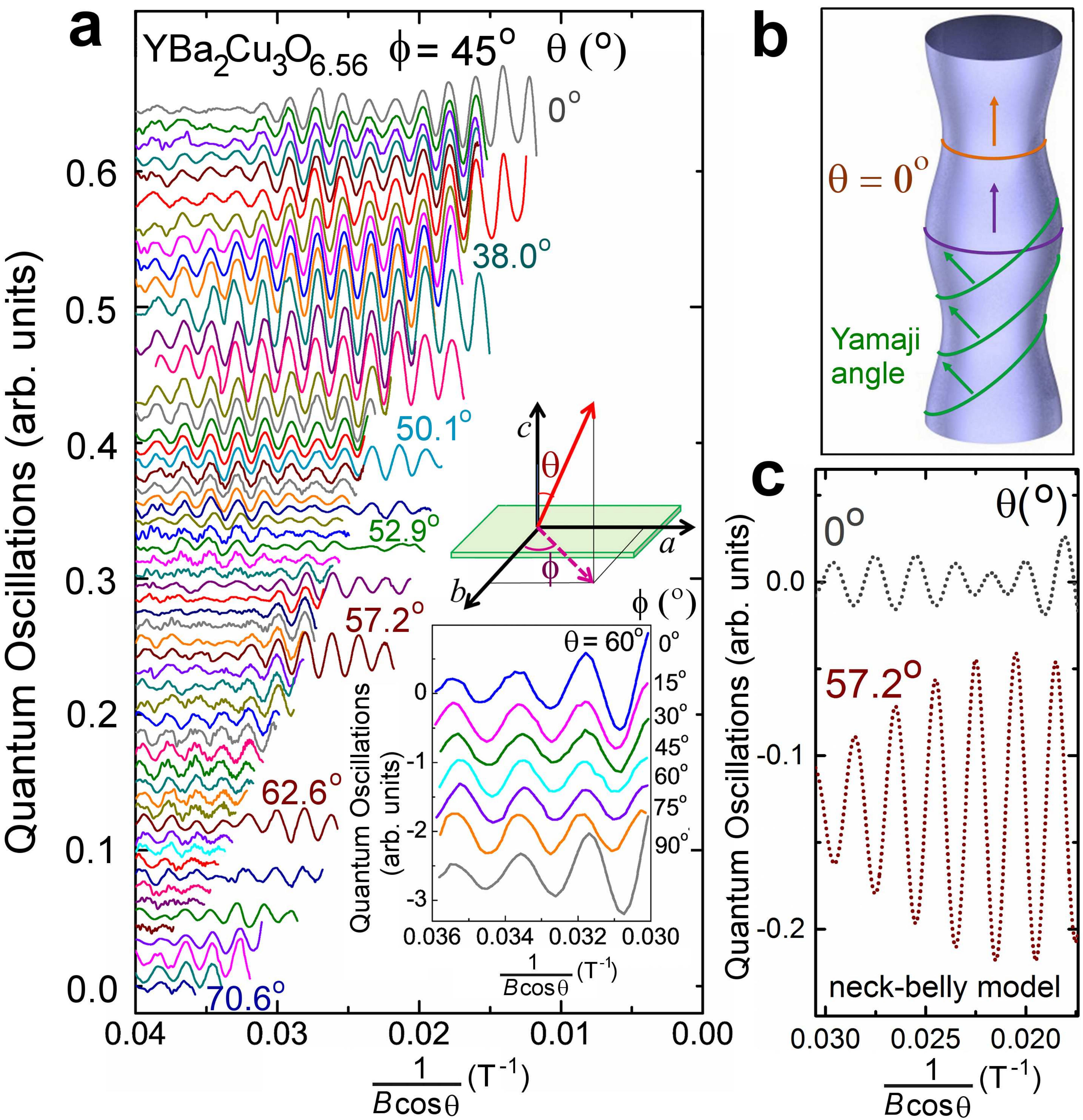


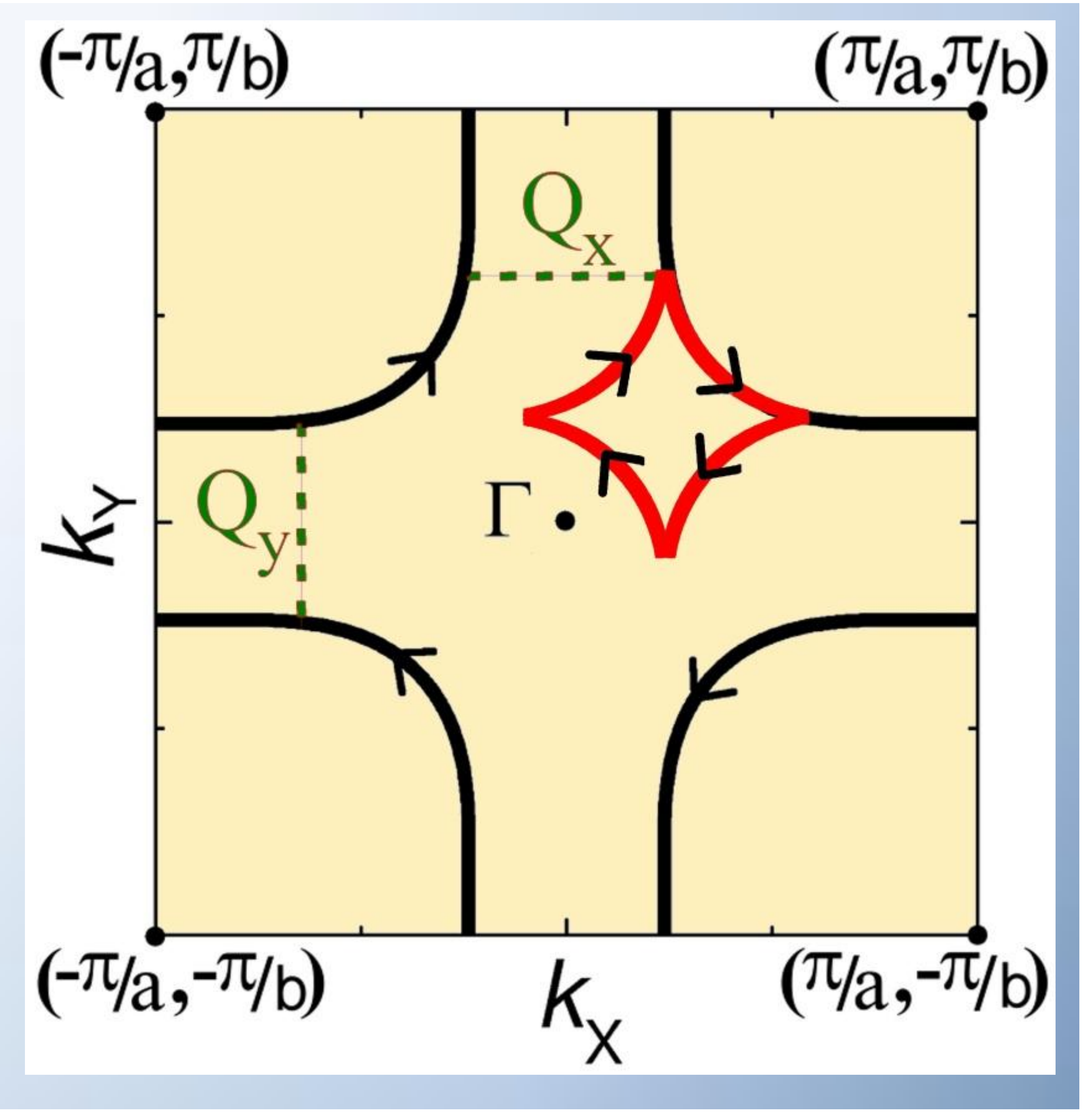




Normal-state nodal electronic structure in underdoped high-T_c copper oxides

Suchitra E. Sebastian, N. Harrison, F. F. Balakirev, M. M. Altarawneh, P. A. Goddard, Ruixing Liang, D. A. Bonn, W. N. Hardy, and G. G. Lonzarich

Nature, to appear



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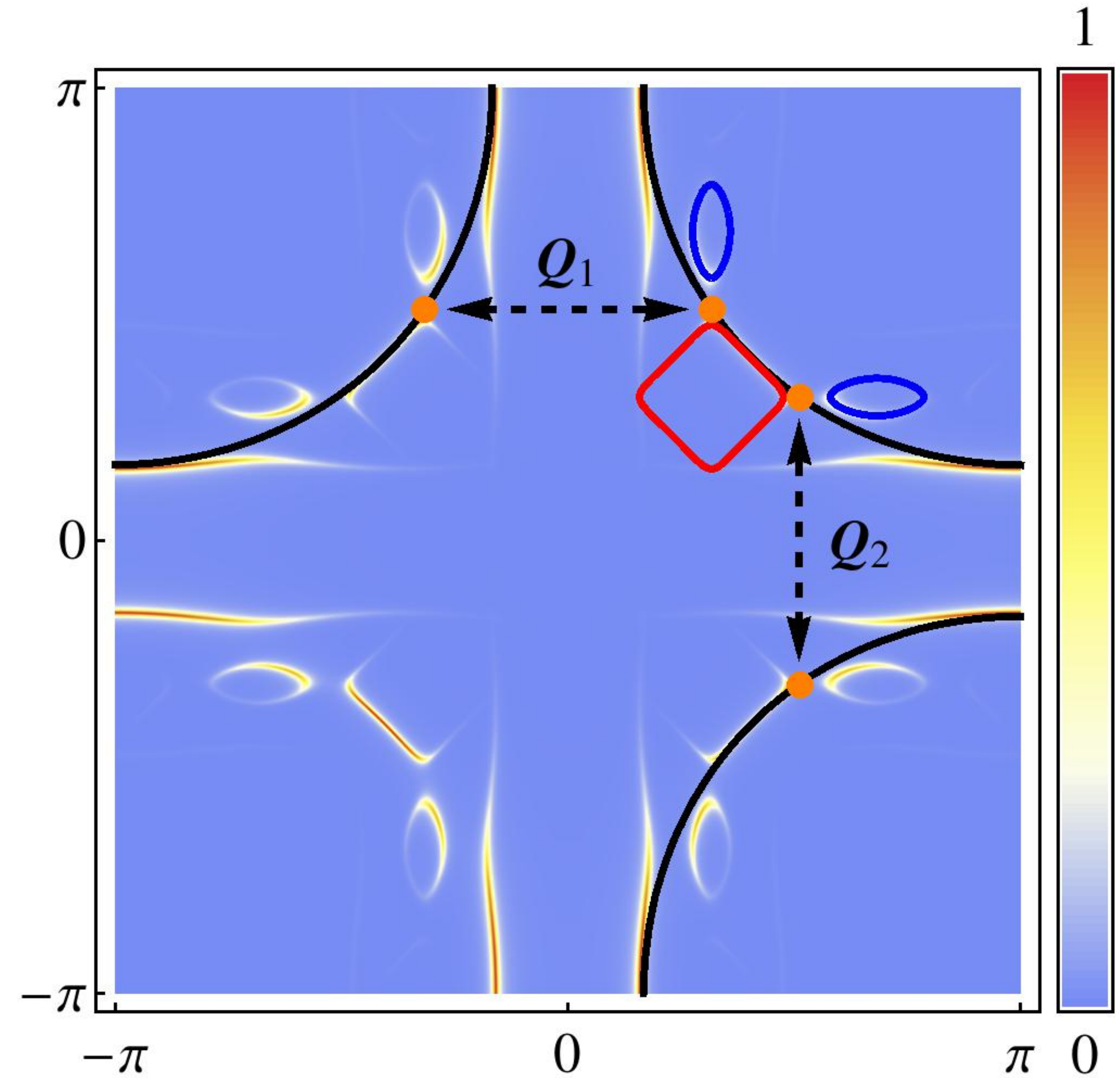
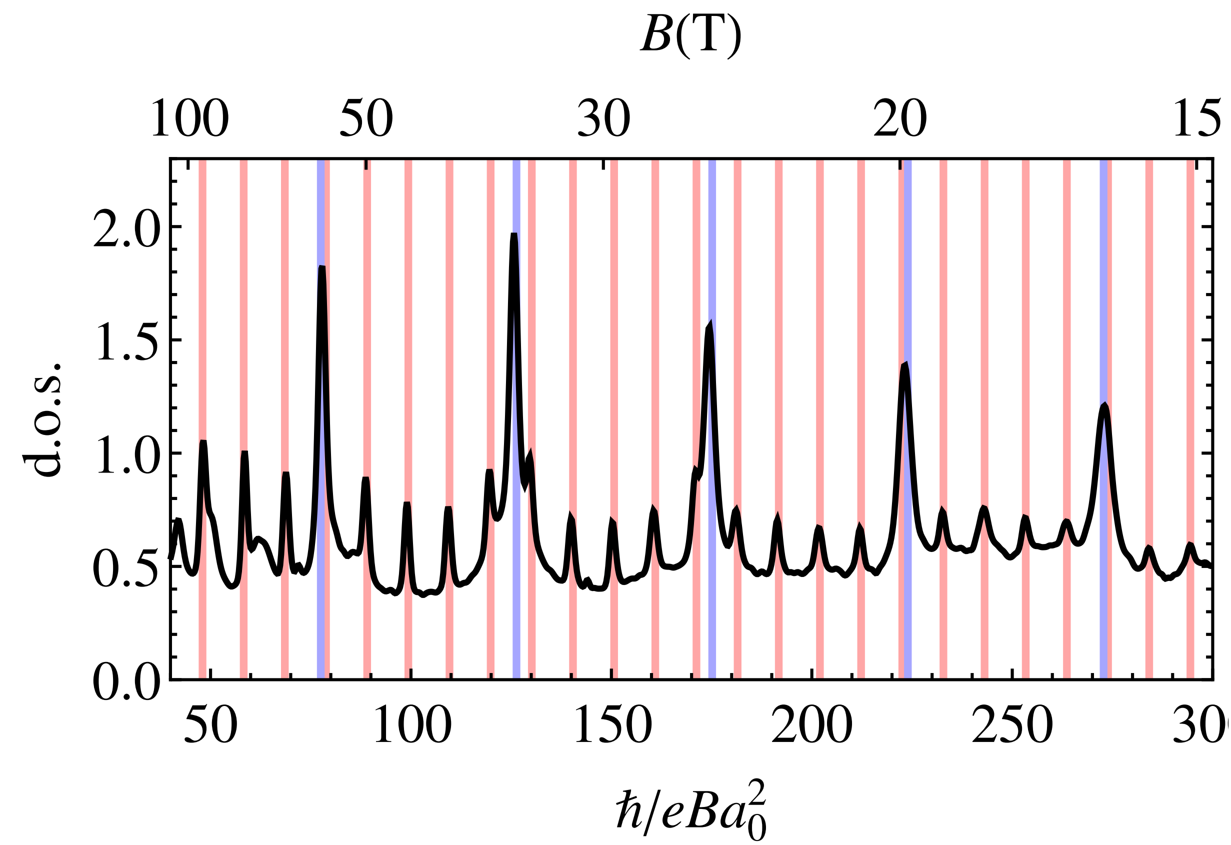
Electron spectral density
and
quantum oscillations
from bi-directional
density wave order

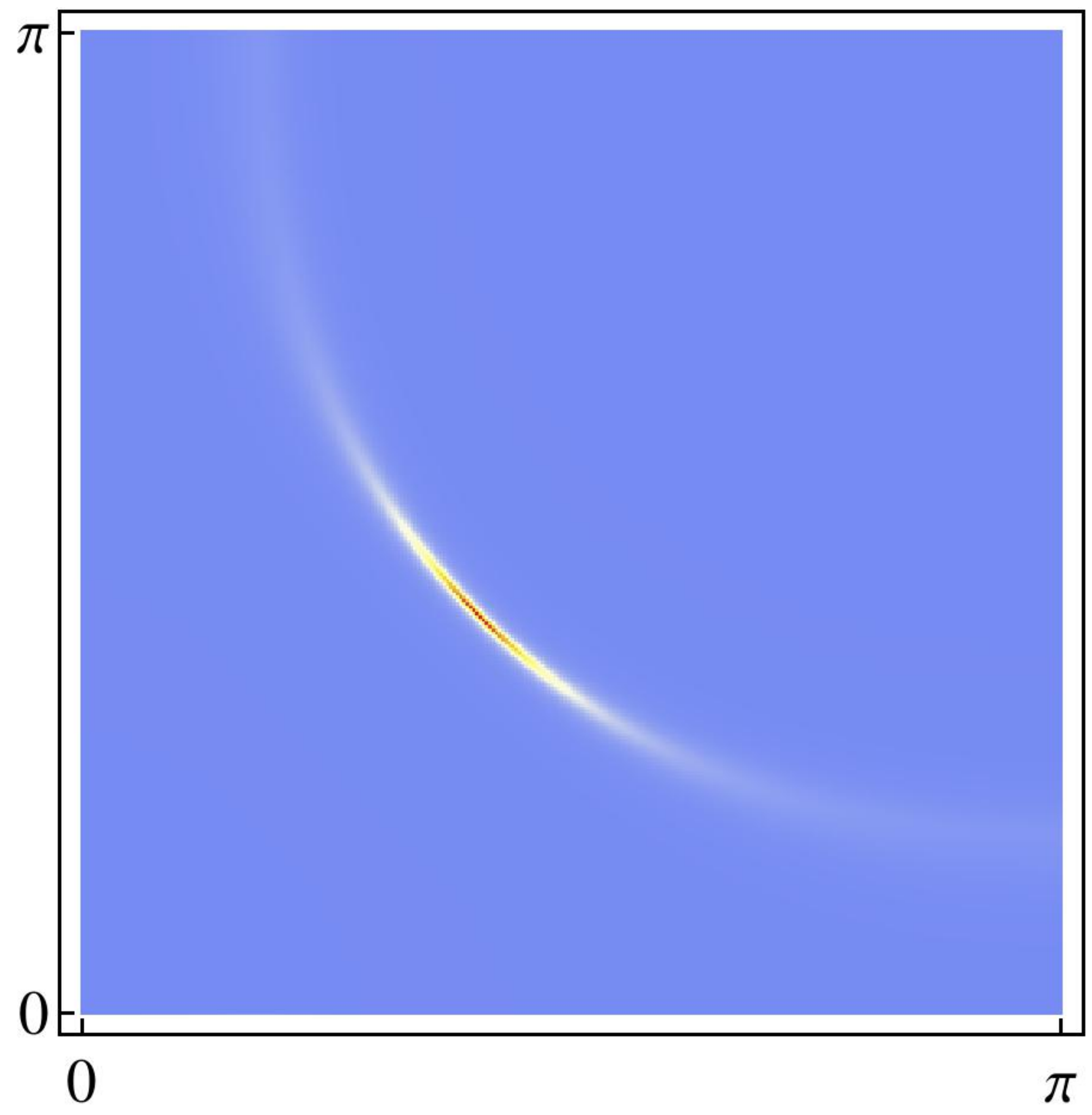
Andrea Allais,
Debanjan Chowdhury,
and Subir Sachdev,
arXiv:1406.0503

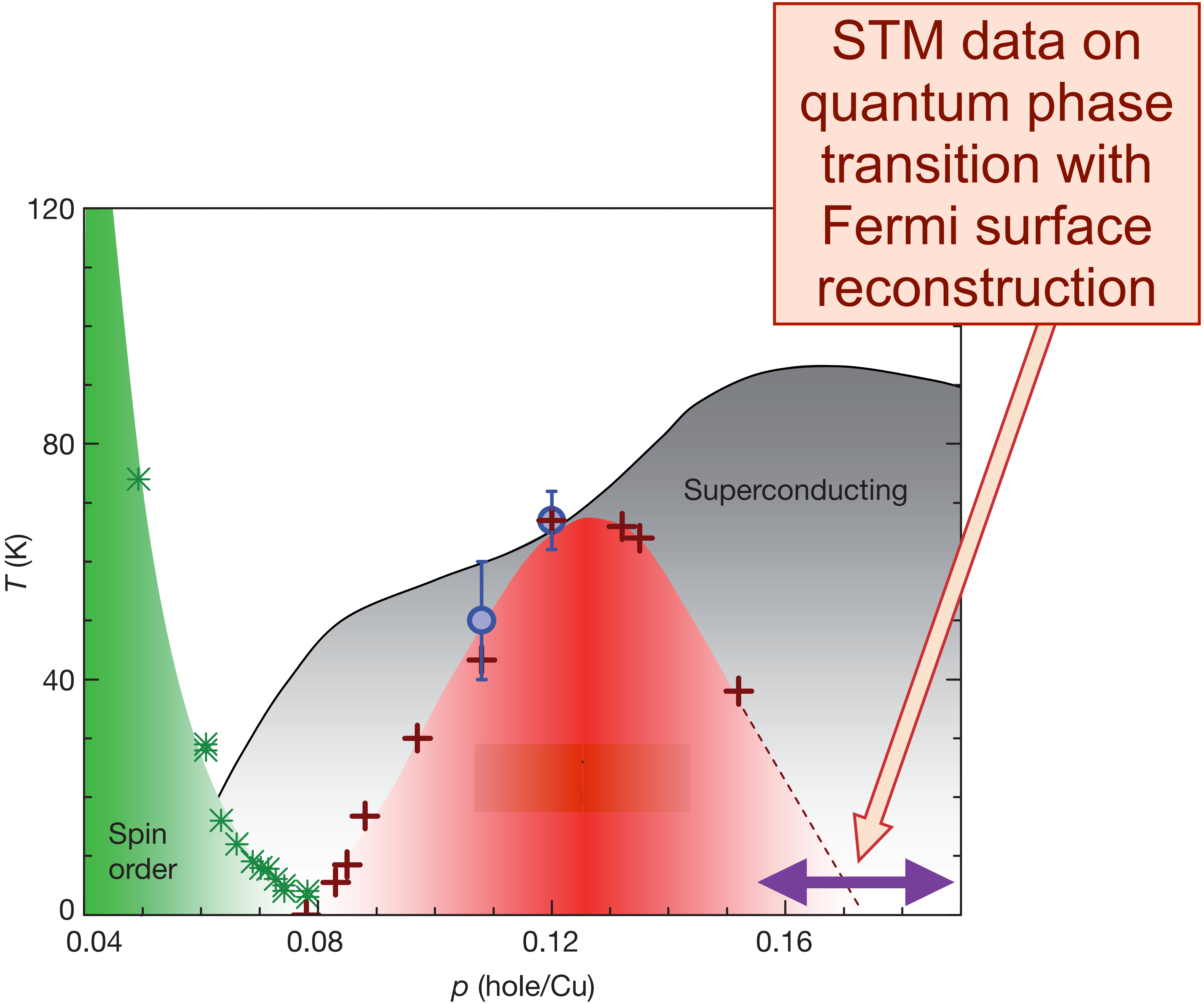




Electron spectral density from fluctuating superconducting *and* density wave orders

Andrea Allais, Debanjan Chowdhury, and Subir Sachdev, arXiv:1406.0503





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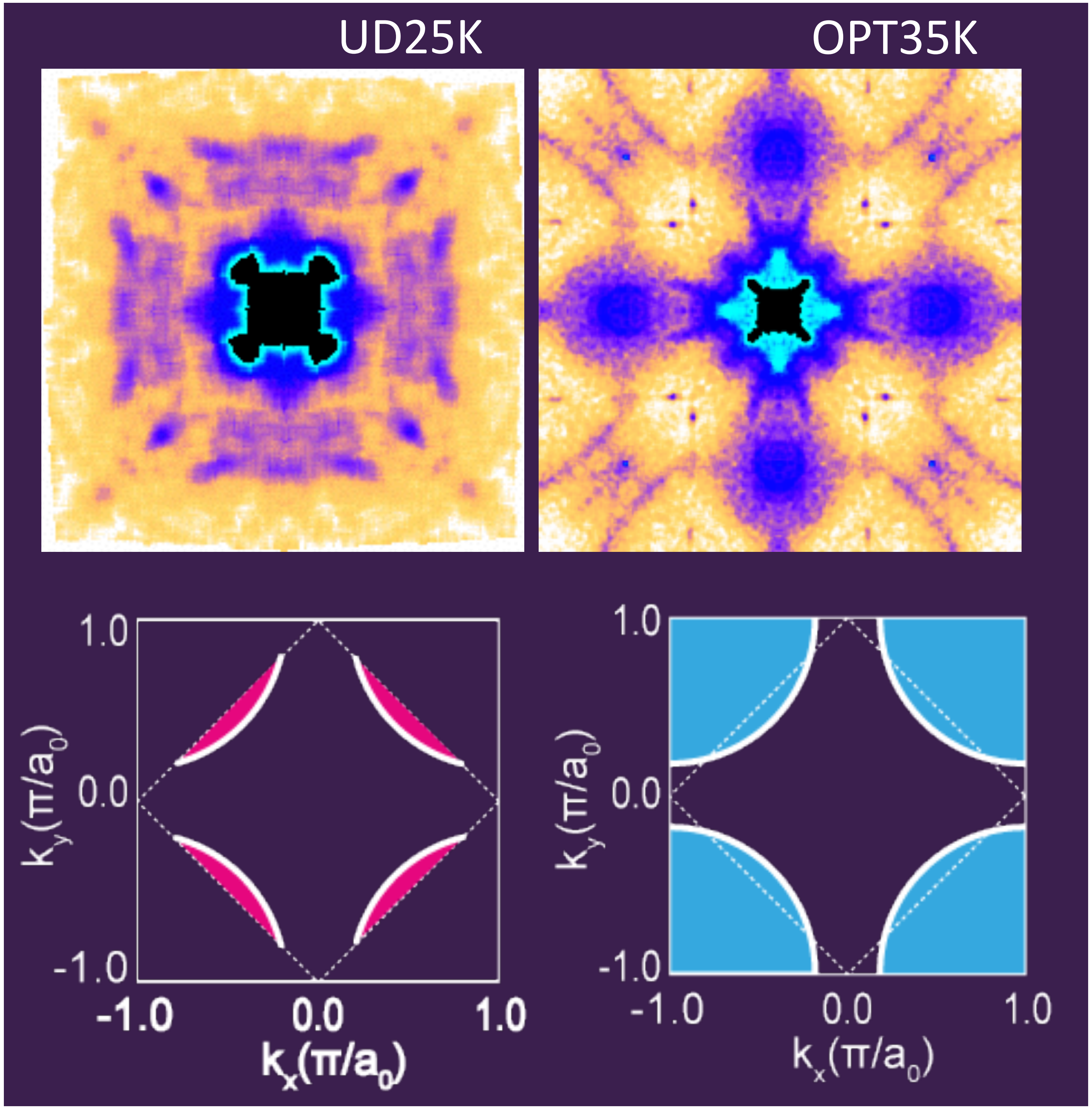
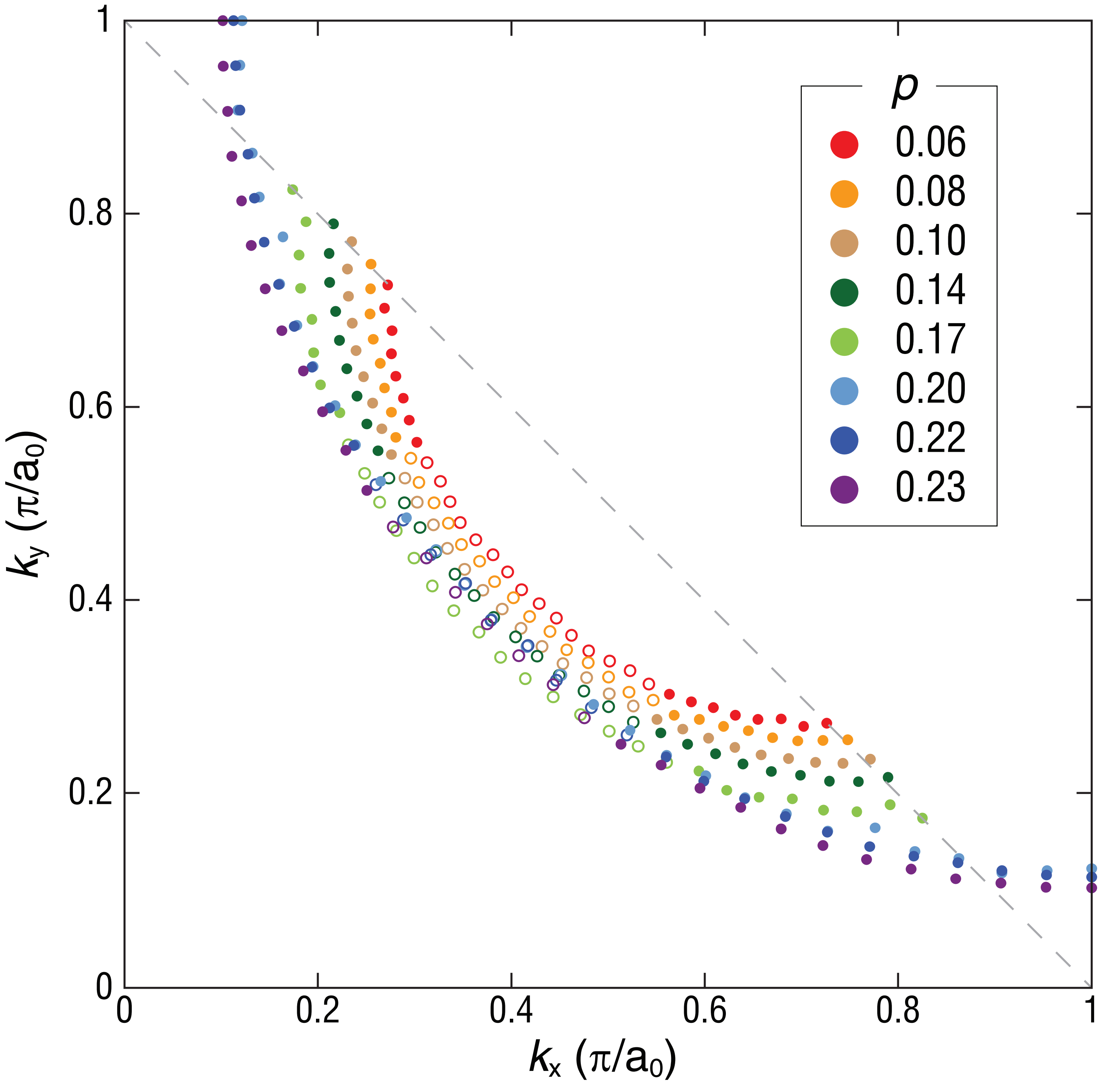


Yang He, Yi Yin, M. Zech, A. Soumyanarayanan, I. Zeljkovic, M. M. Yee, M. C. Boyer, K. Chatterjee, W. D. Wise, Takeshi Kondo, T. Takeuchi, H. Ikuta, P. Mistark, R. S. Markiewicz, A. Bansil, S. Sachdev, E. W. Hudson, J. E. Hoffman, *Science* **344**, 608 (2014).



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Conclusions

1. *d*-wave superconductivity

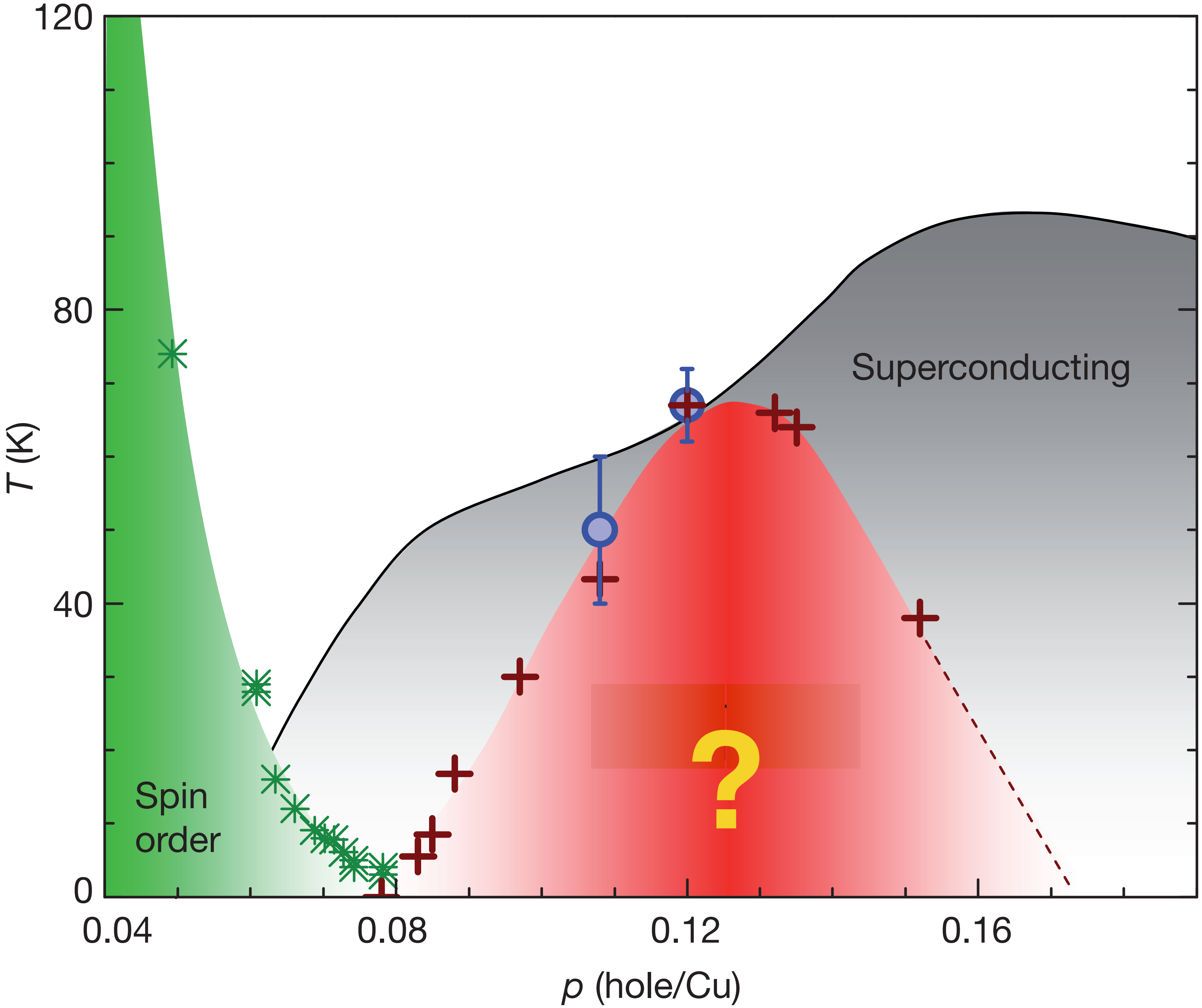
2. Low hole density state:

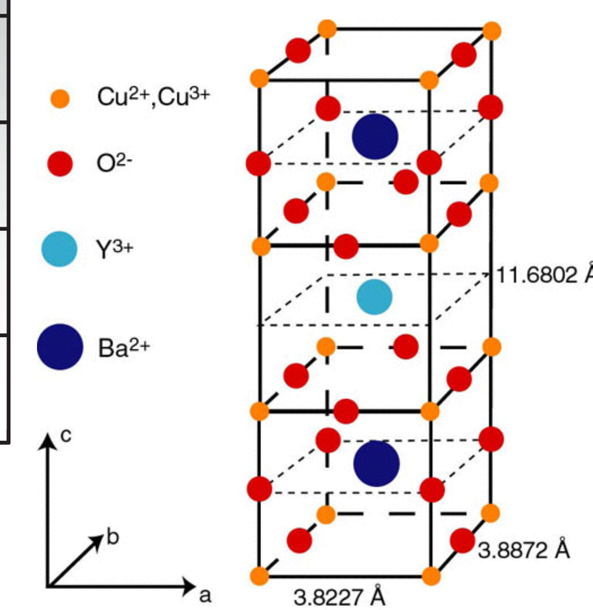
   An unconventional density wave:

   d-wave bond order

3. Theoretical background

4. Evolution of Fermi surface





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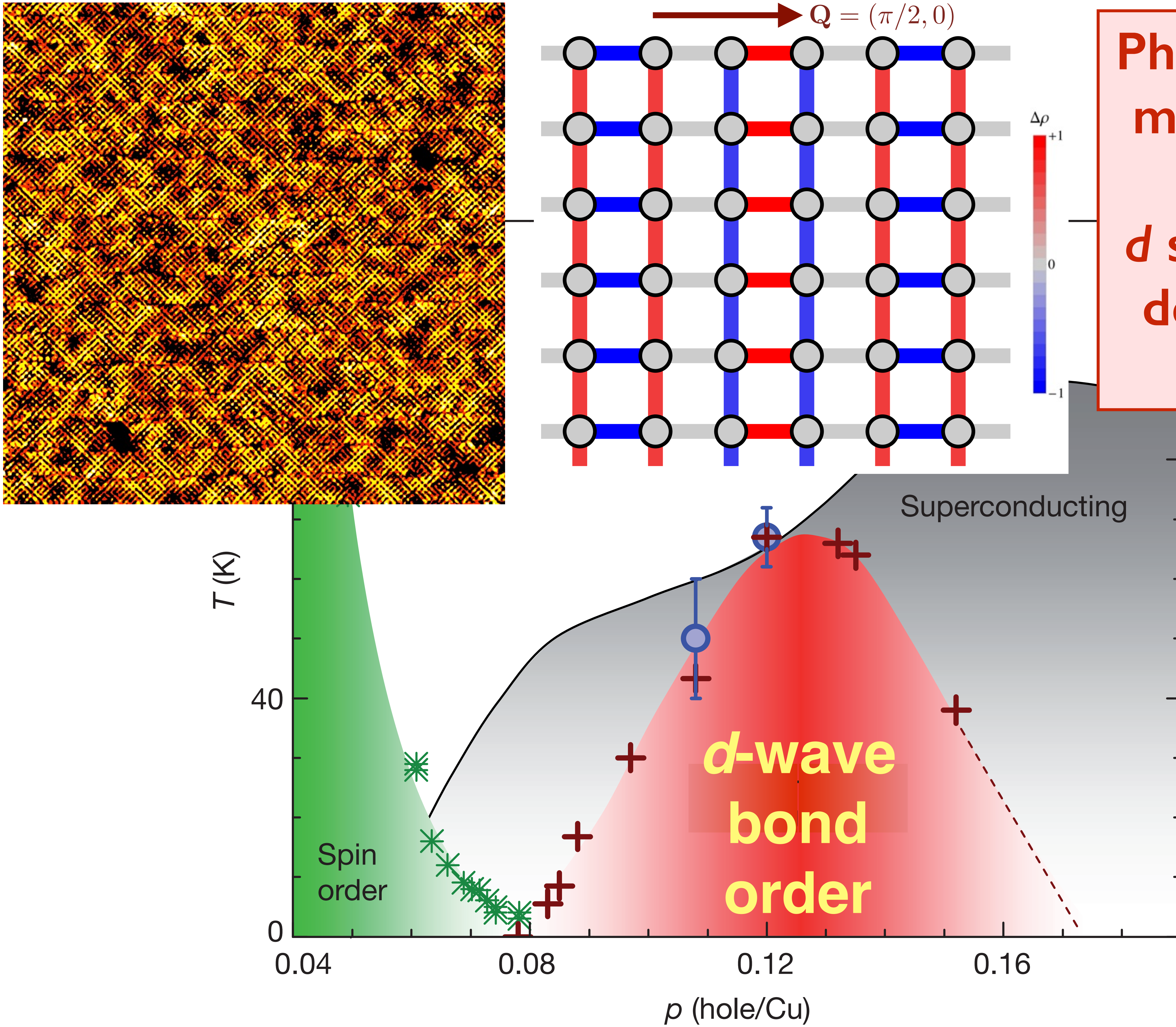
Phase-sensitive measurement of the *d* symmetry of density wave order



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