The "pseudogap" phase of the high temperature superconductors

ITAMP, Harvard
September 4, 2014

Subir Sachdev

Talk online: sachdev.physics.harvard.edu

PHYSICS
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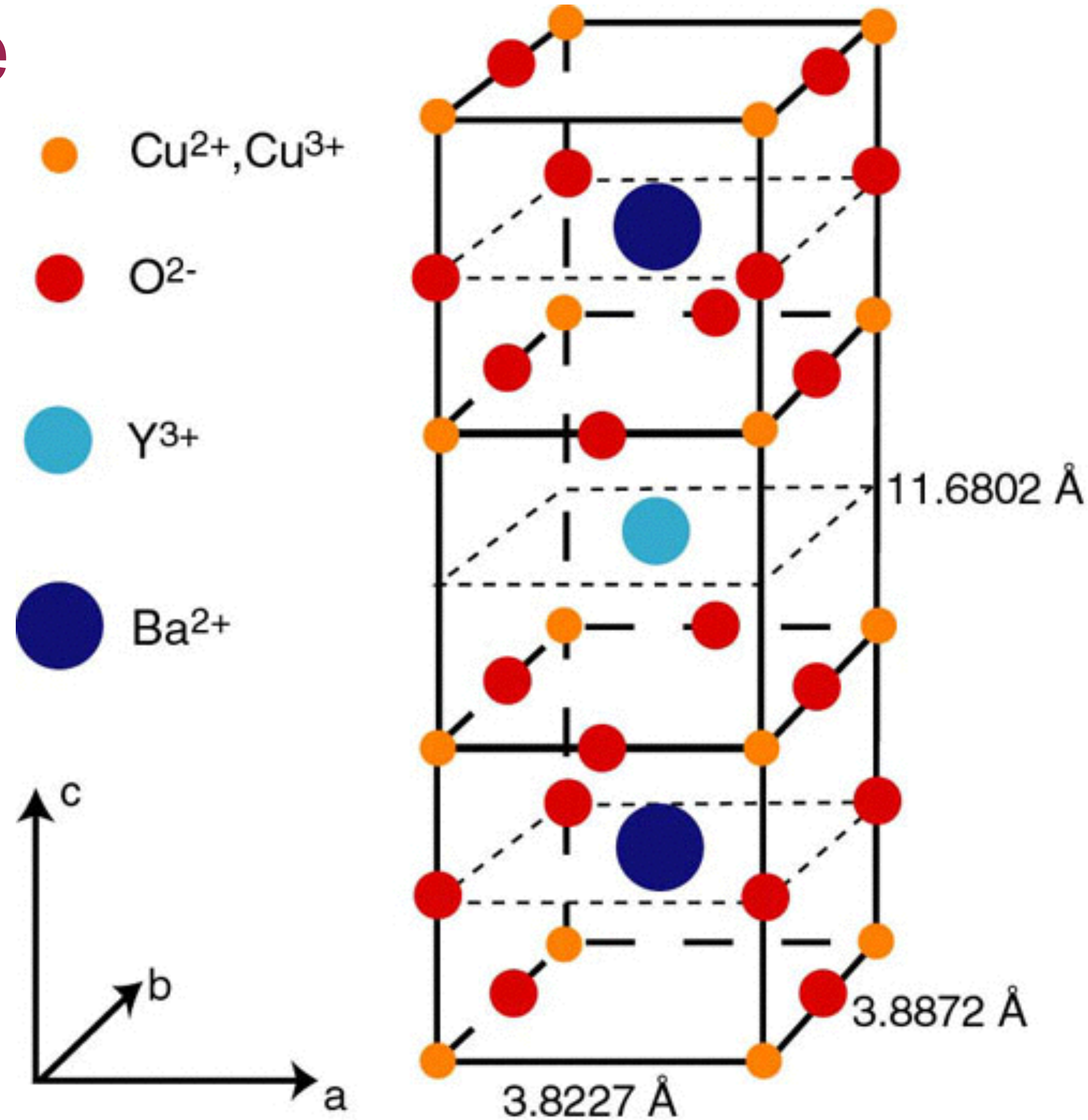
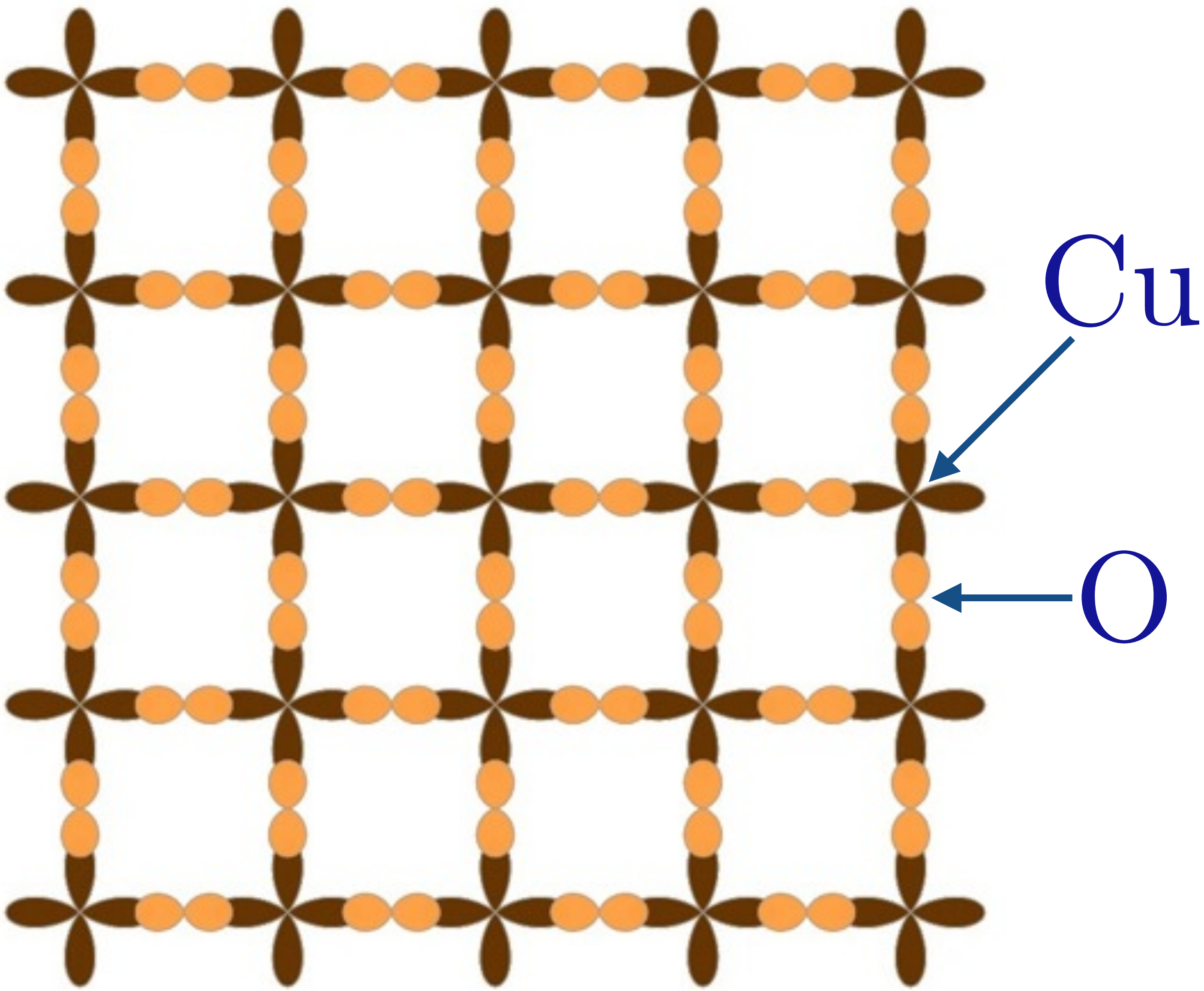
High temperature superconductors

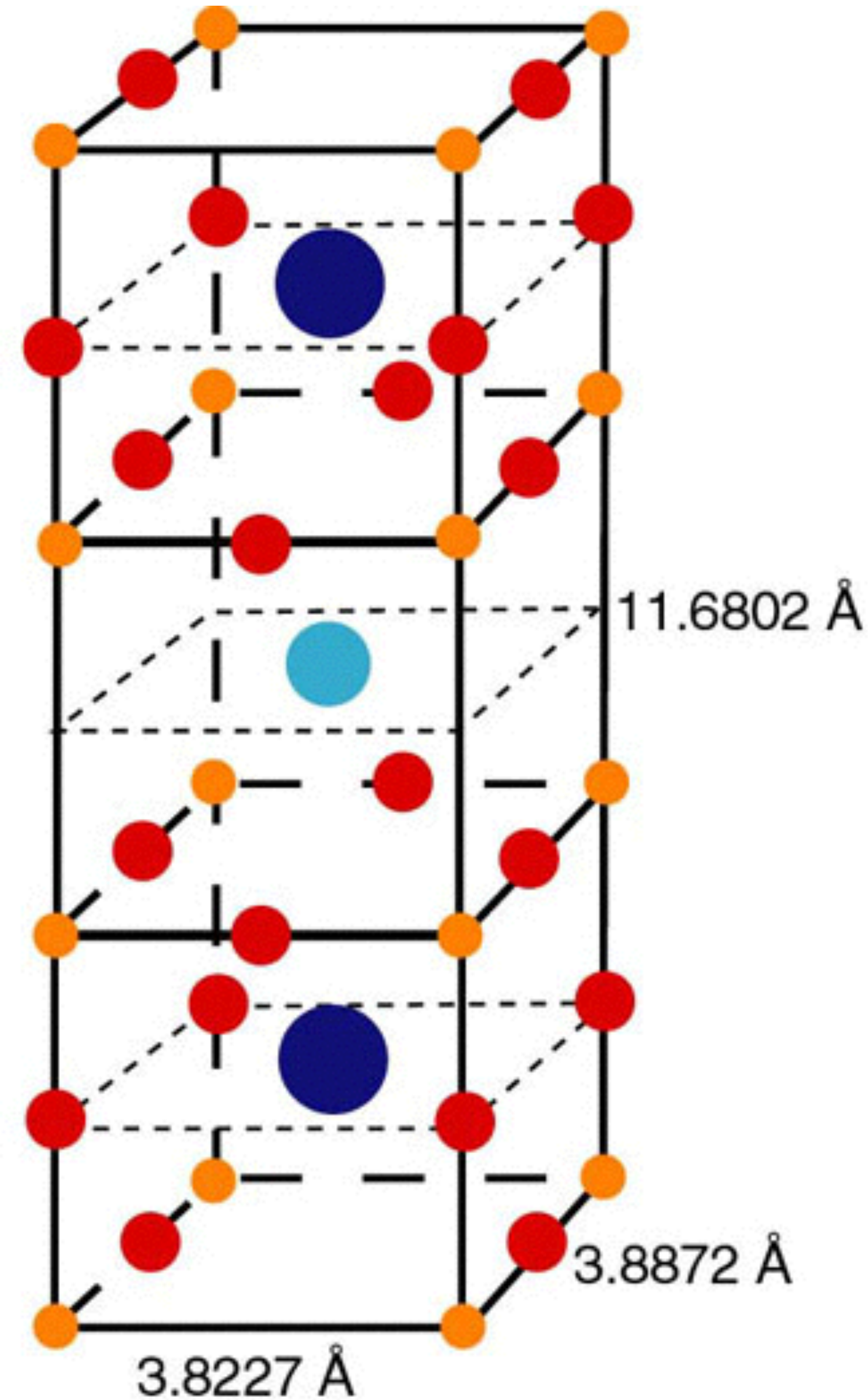


$$YBa_2Cu_3O_{6+x}$$

High temperature superconductors



CuO_2 plane



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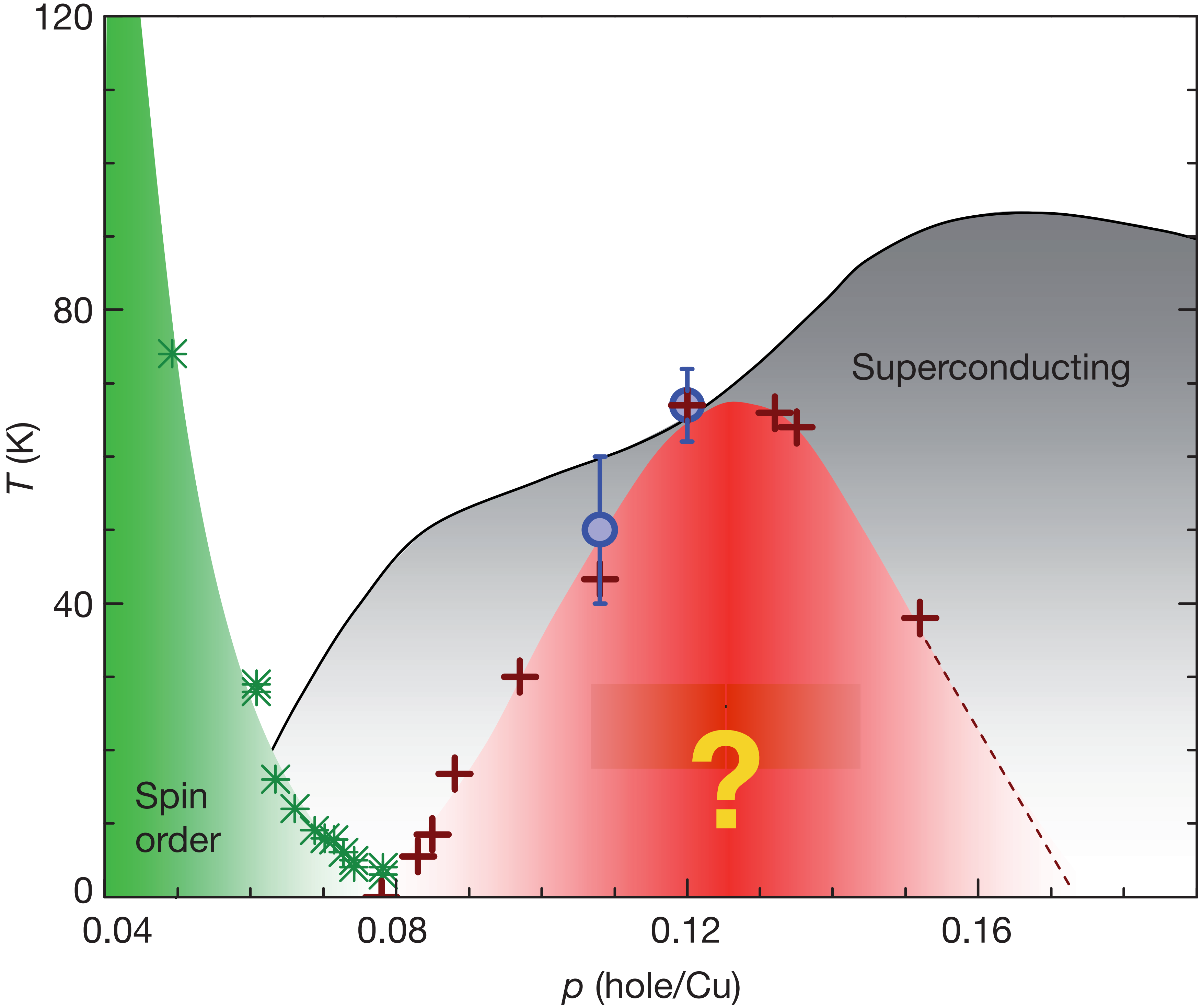
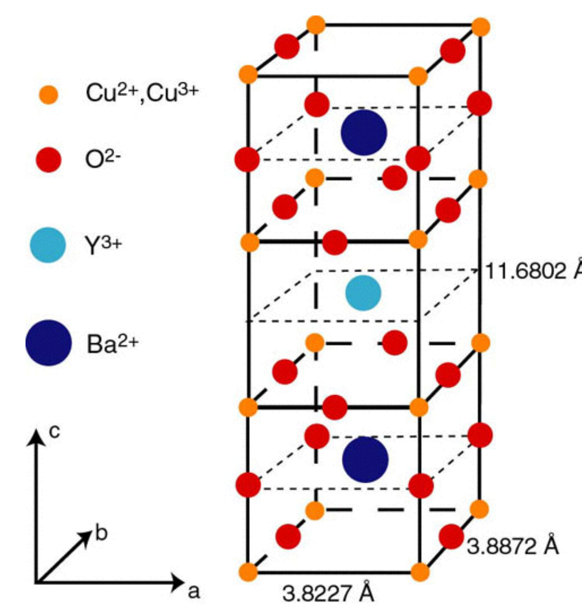
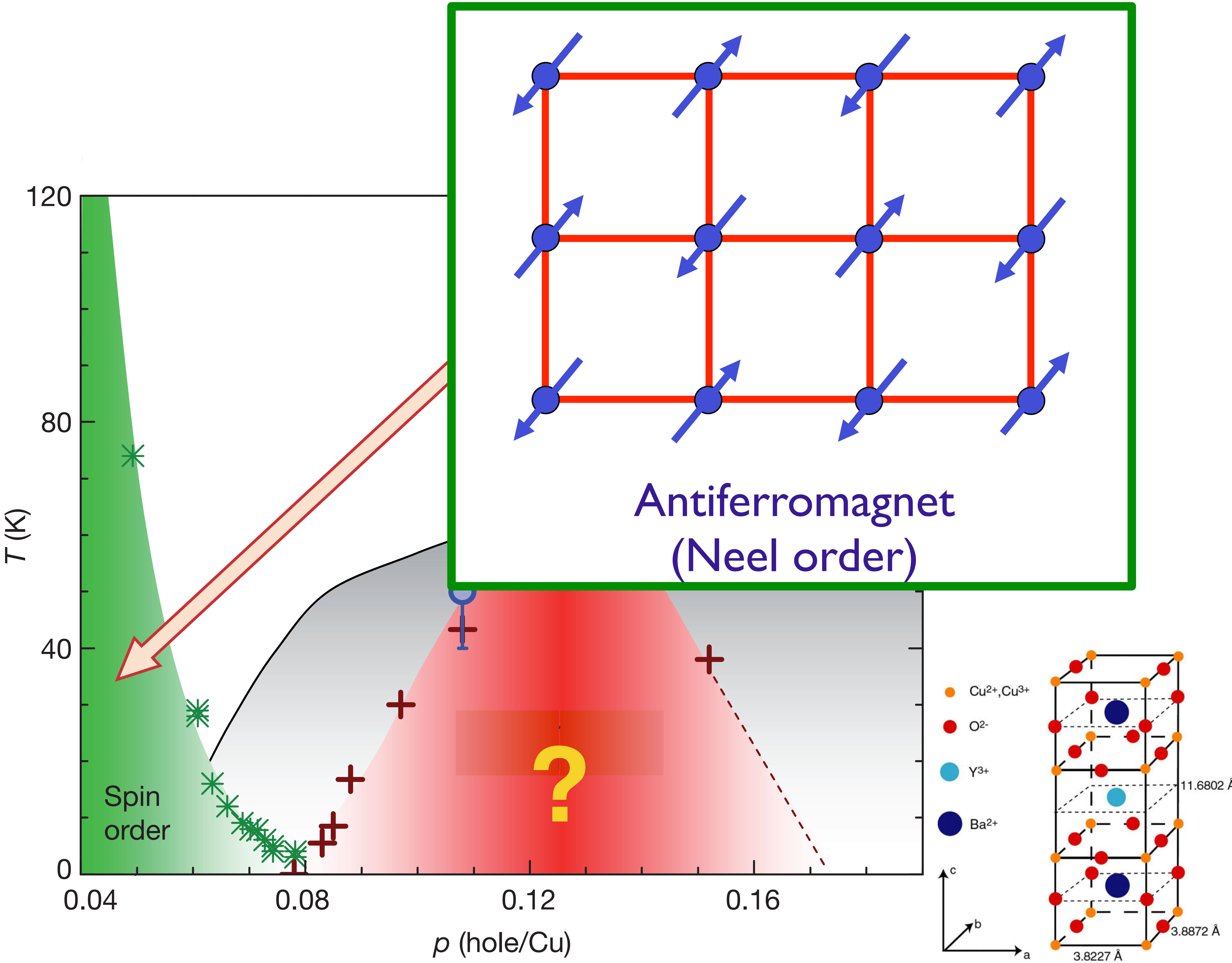




T. Wu, H. Mayaffre, S. Kramer, M. Horvatic, C. Berthier, W.N. Hardy, R. Liang, D.A. Bonn, and M.-H. Julien, Nature **477**, 191 (2011).



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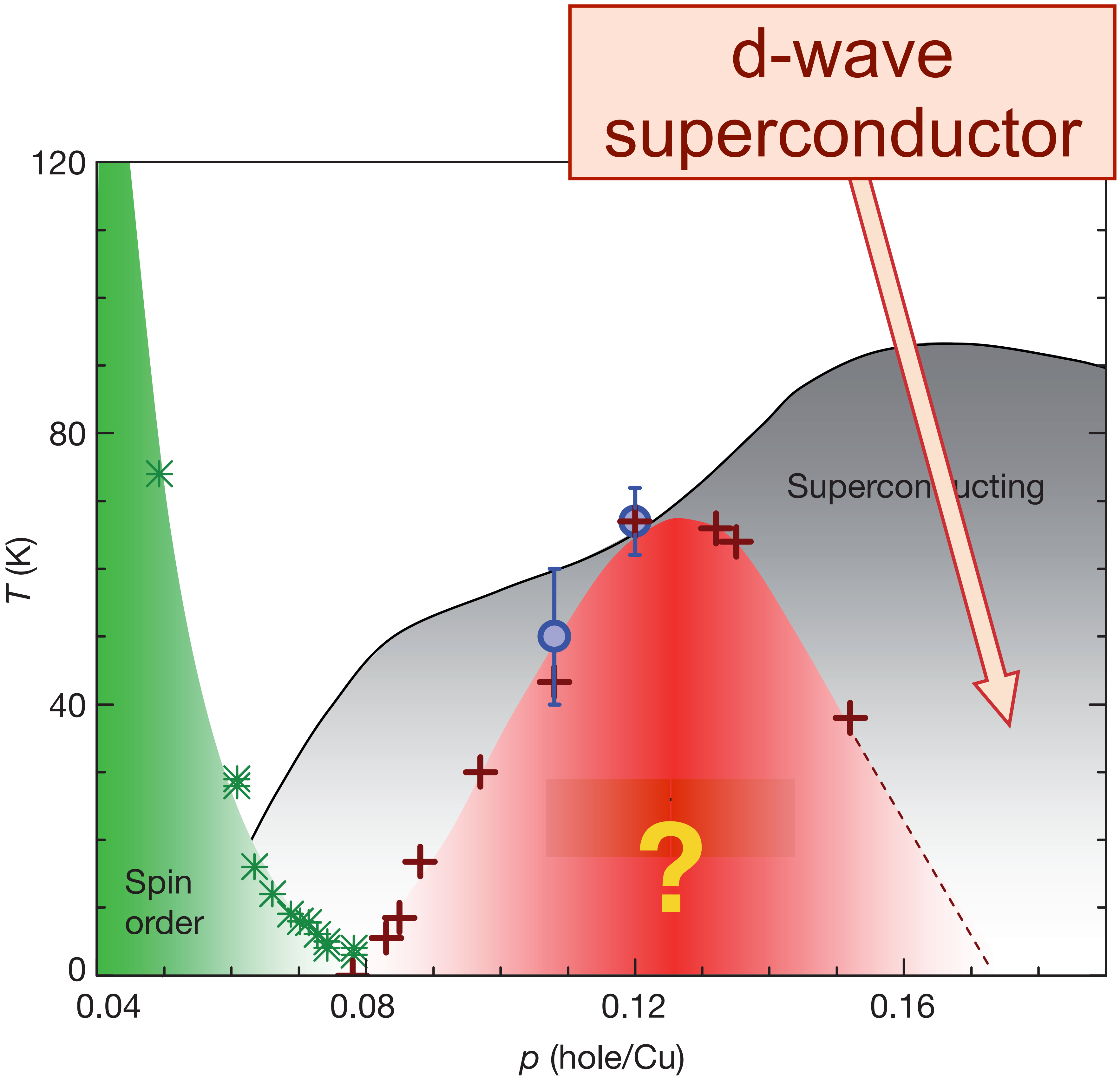

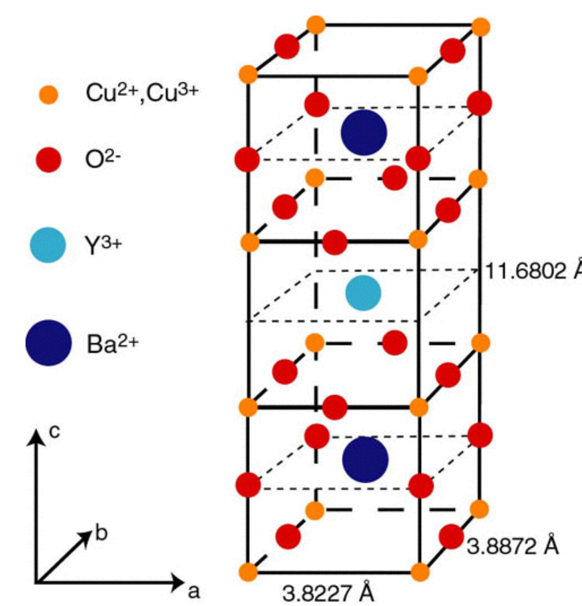

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Superconductivity:
Bose condensation of Cooper pairs of electrons

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

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

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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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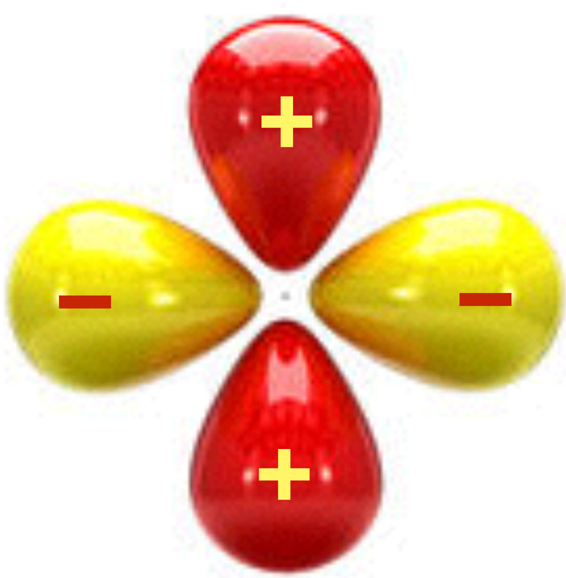
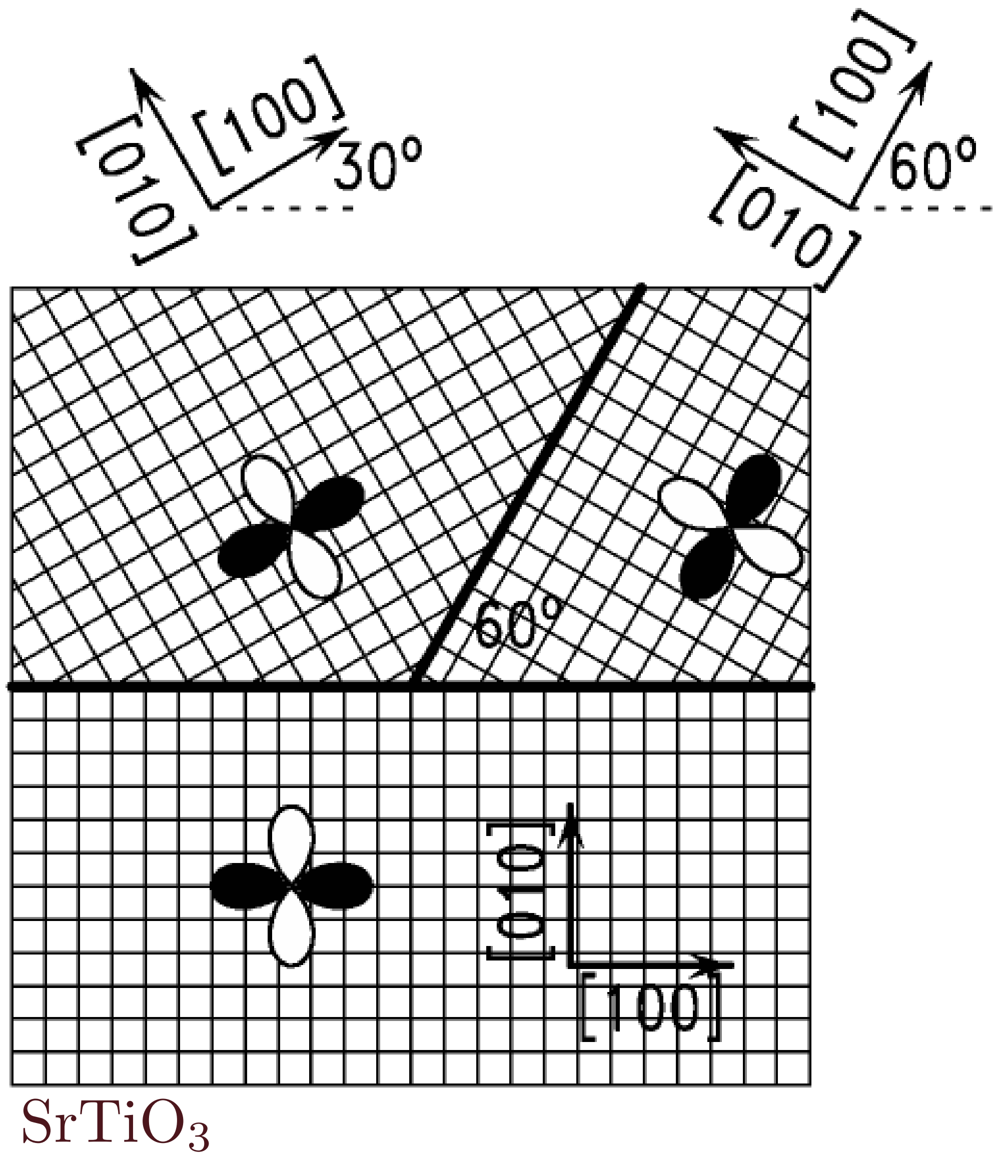
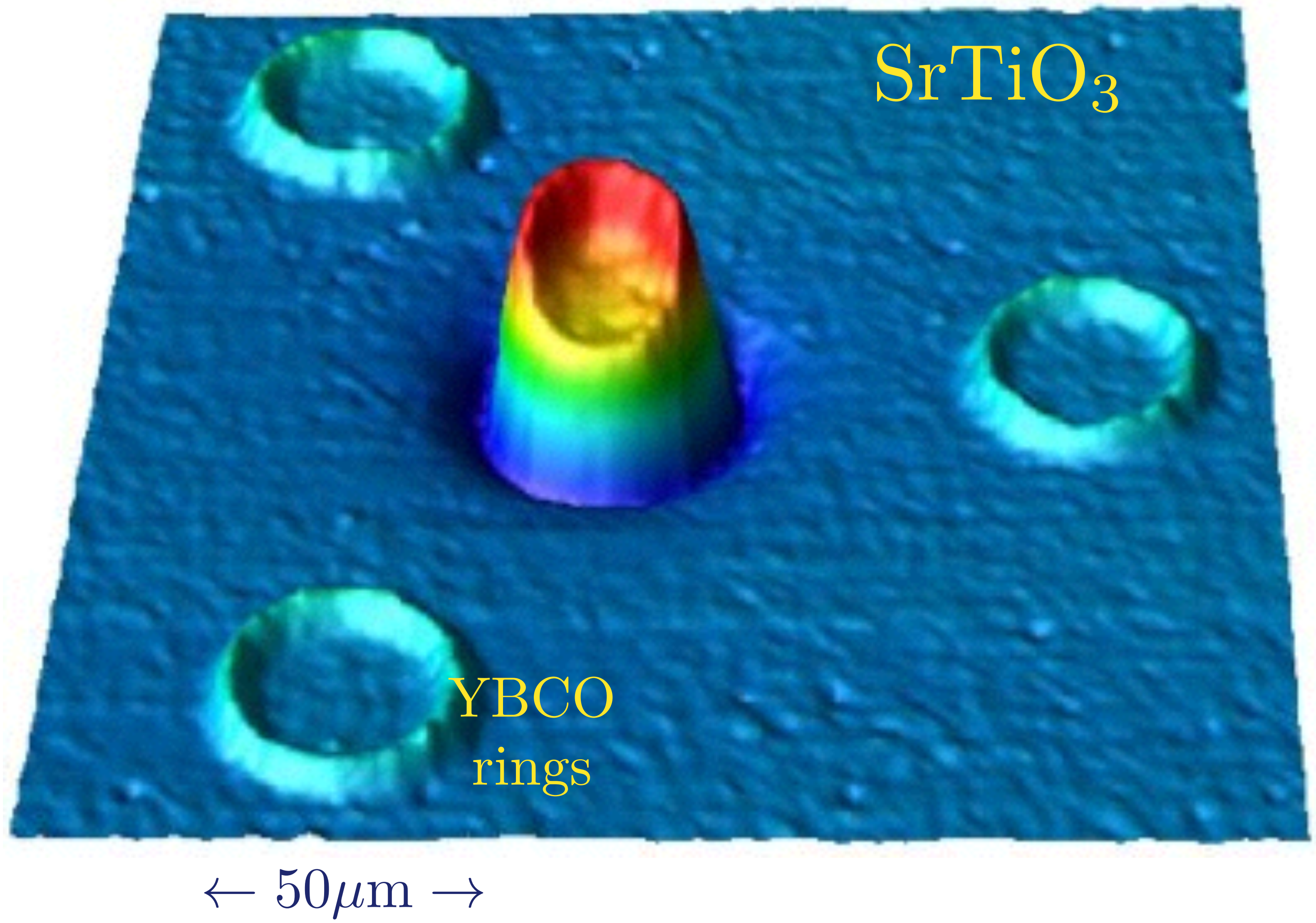


Internal Cooper-pair wavefunction.
Has *d*-wave form in cuprates

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

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



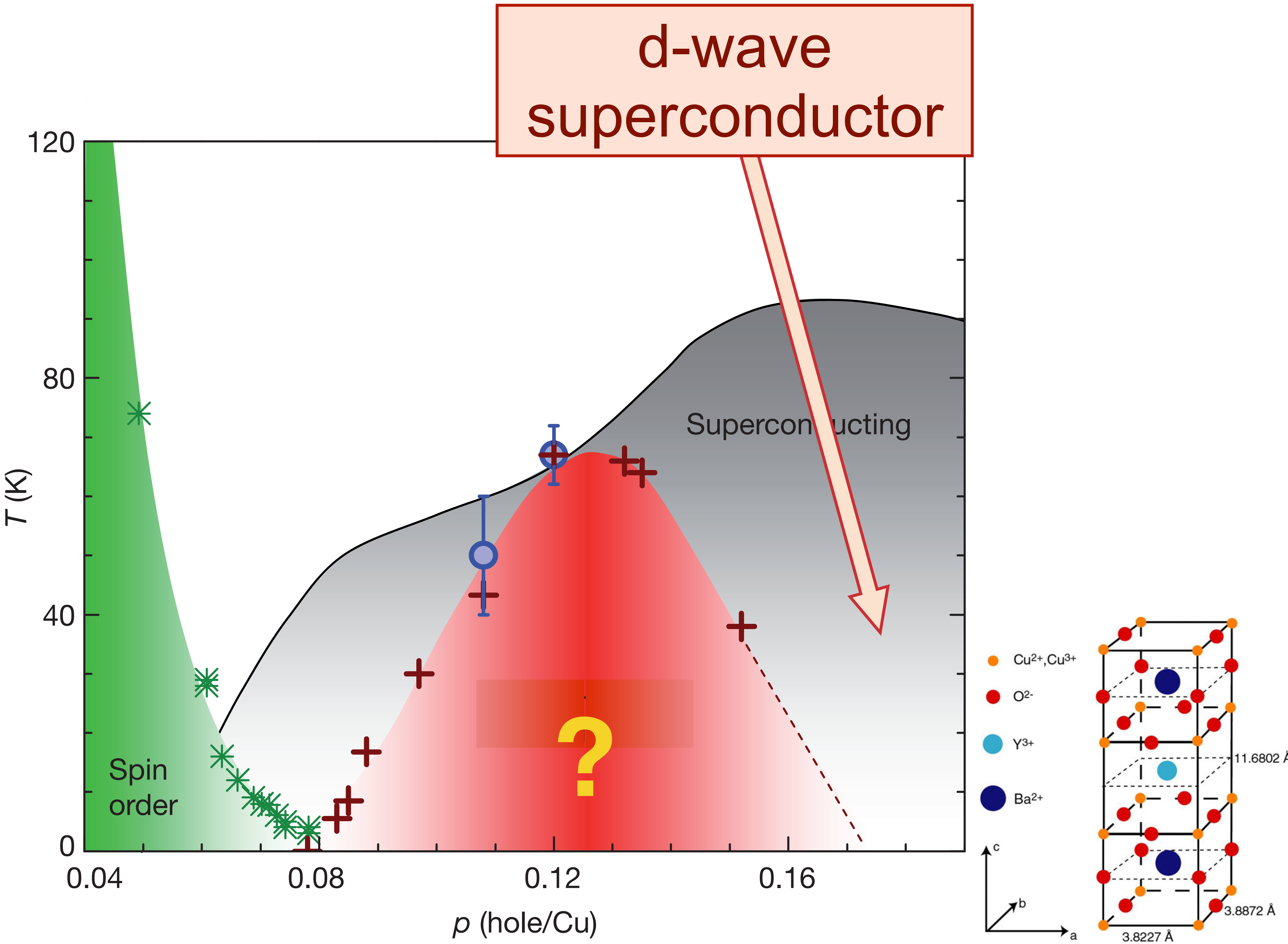


Pairing Symmetry and Flux Quantization in a Tricrystal Superconducting Ring of $YBa_2Cu_3O_{7-\delta}$

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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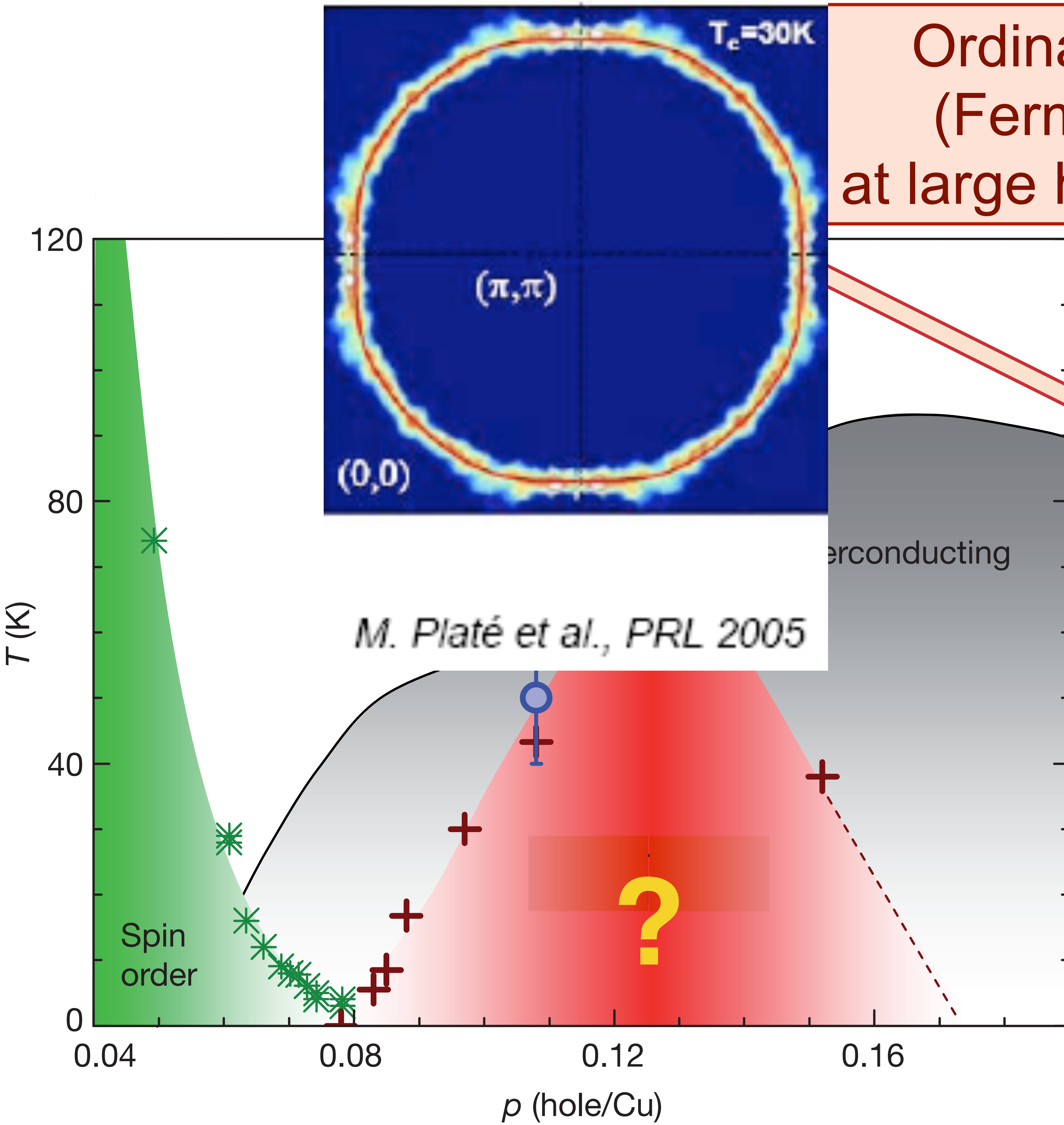
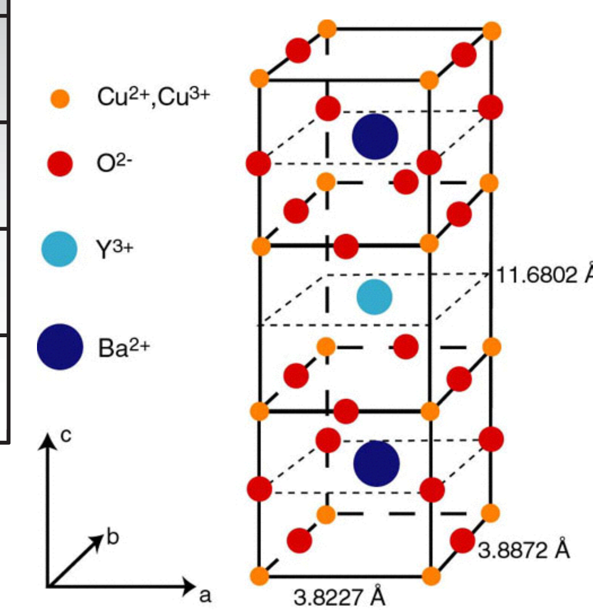
Ordinary metal
(Fermi liquid)
at large hole density





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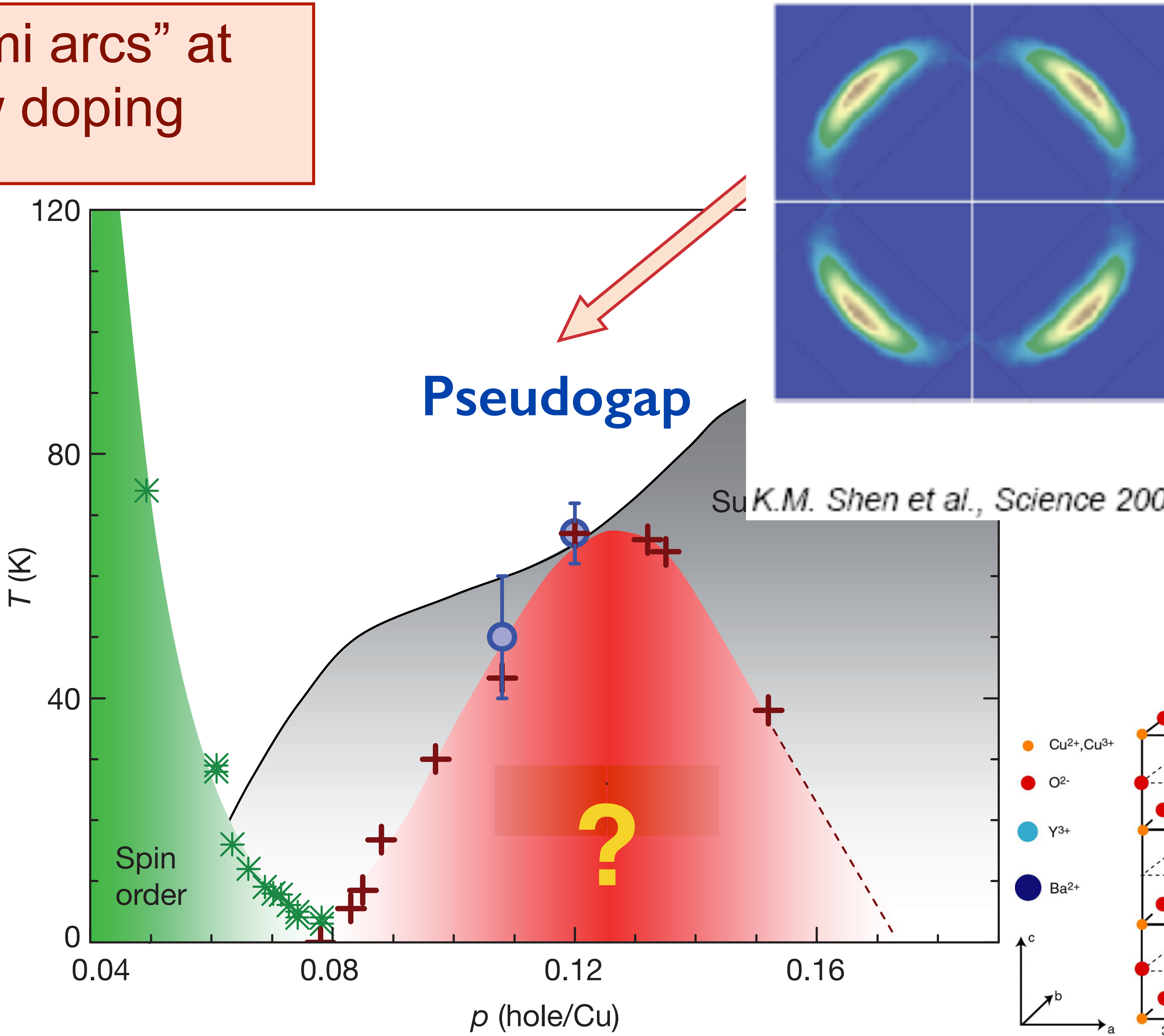
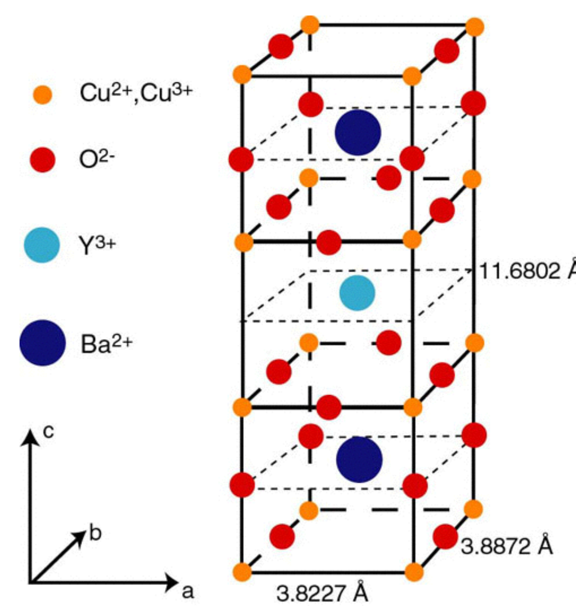
“Fermi arcs” at low doping





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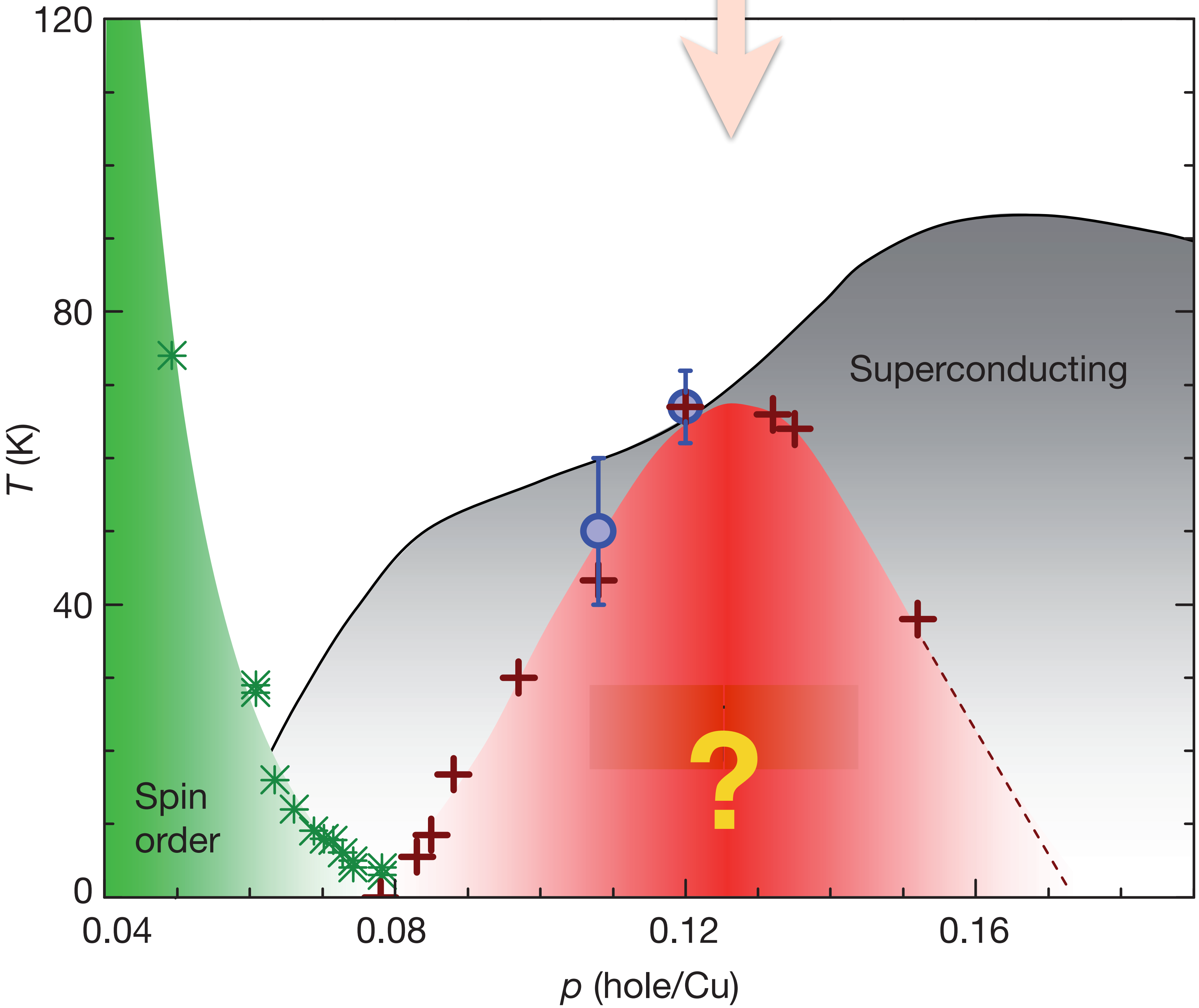
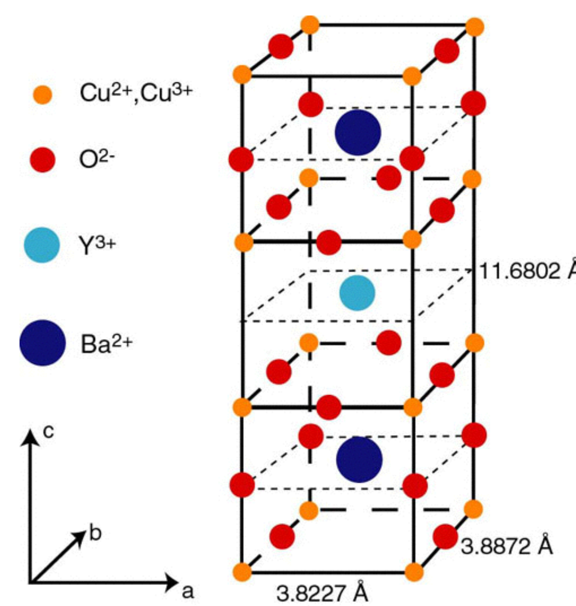
X-ray scattering





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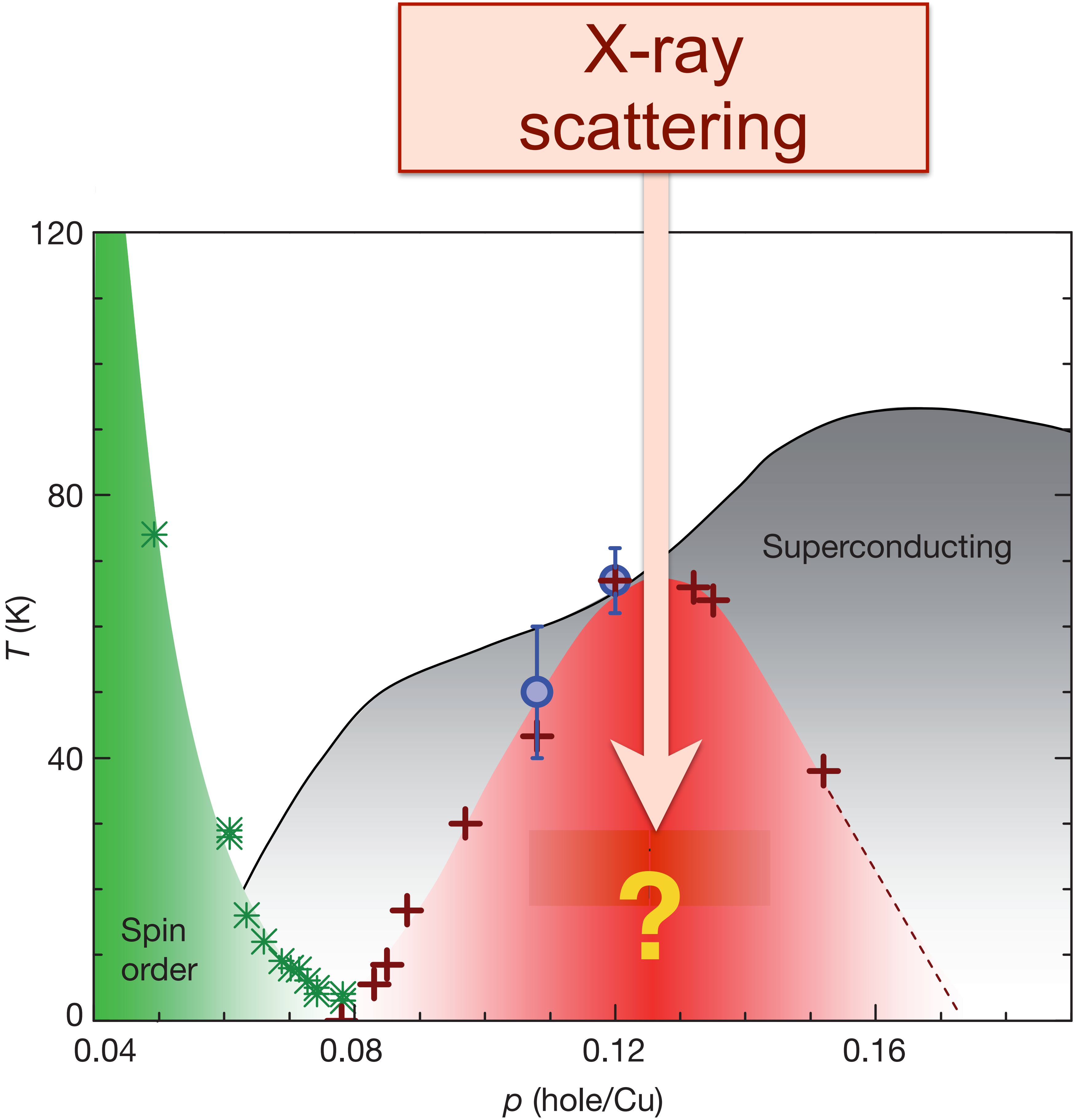

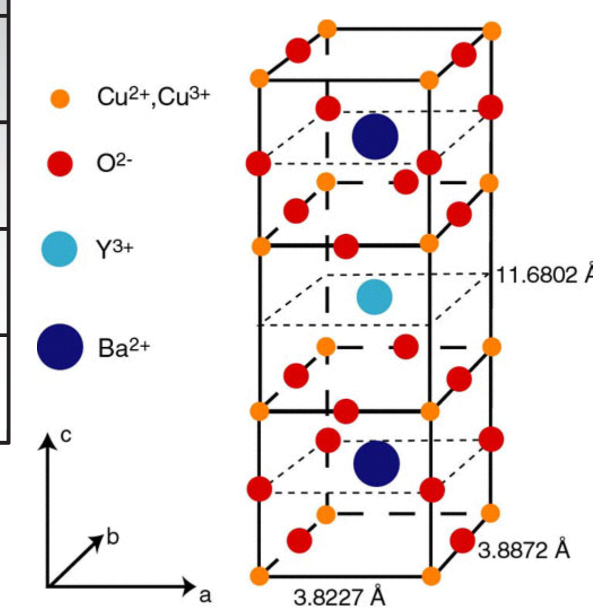

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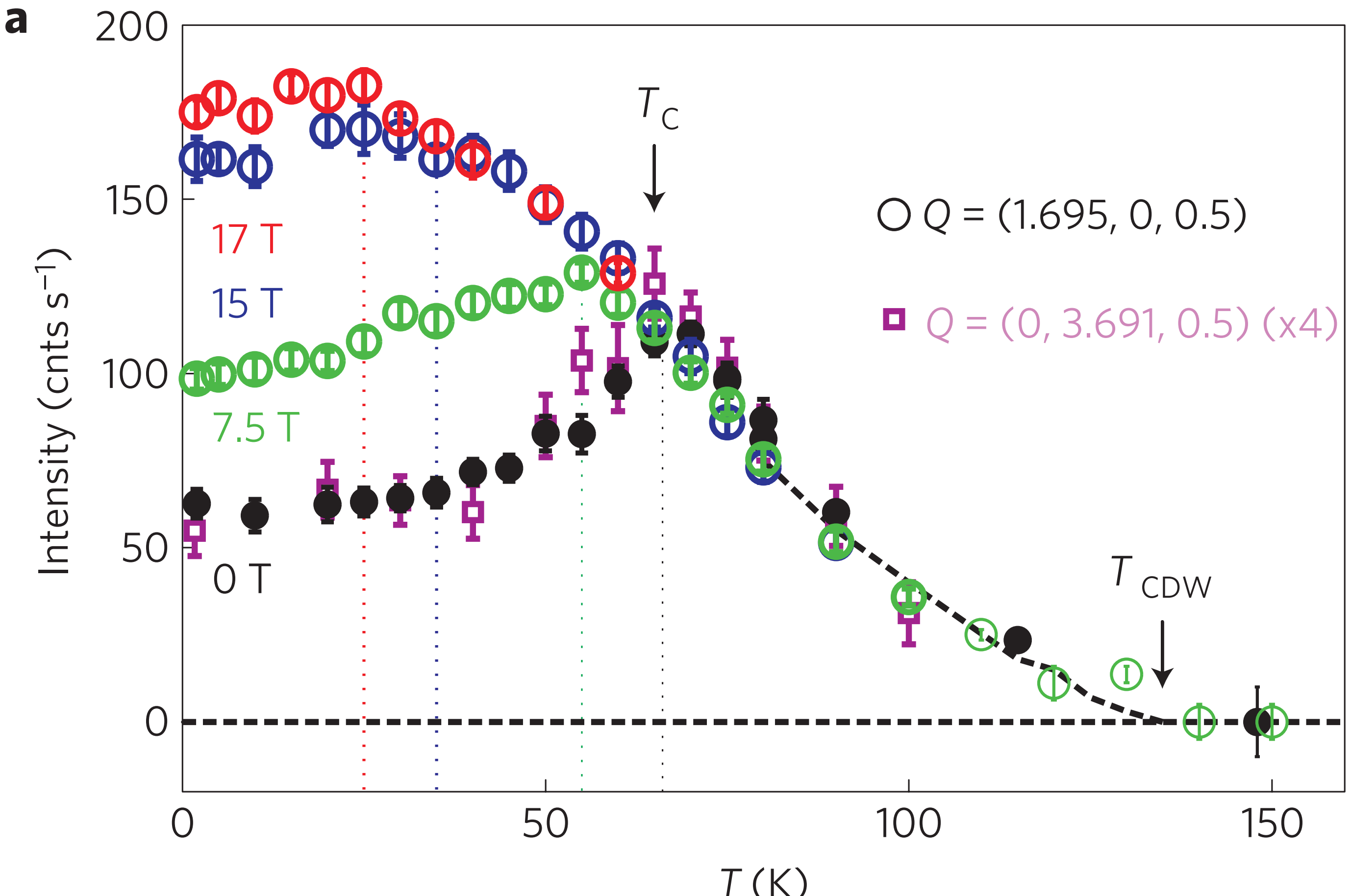
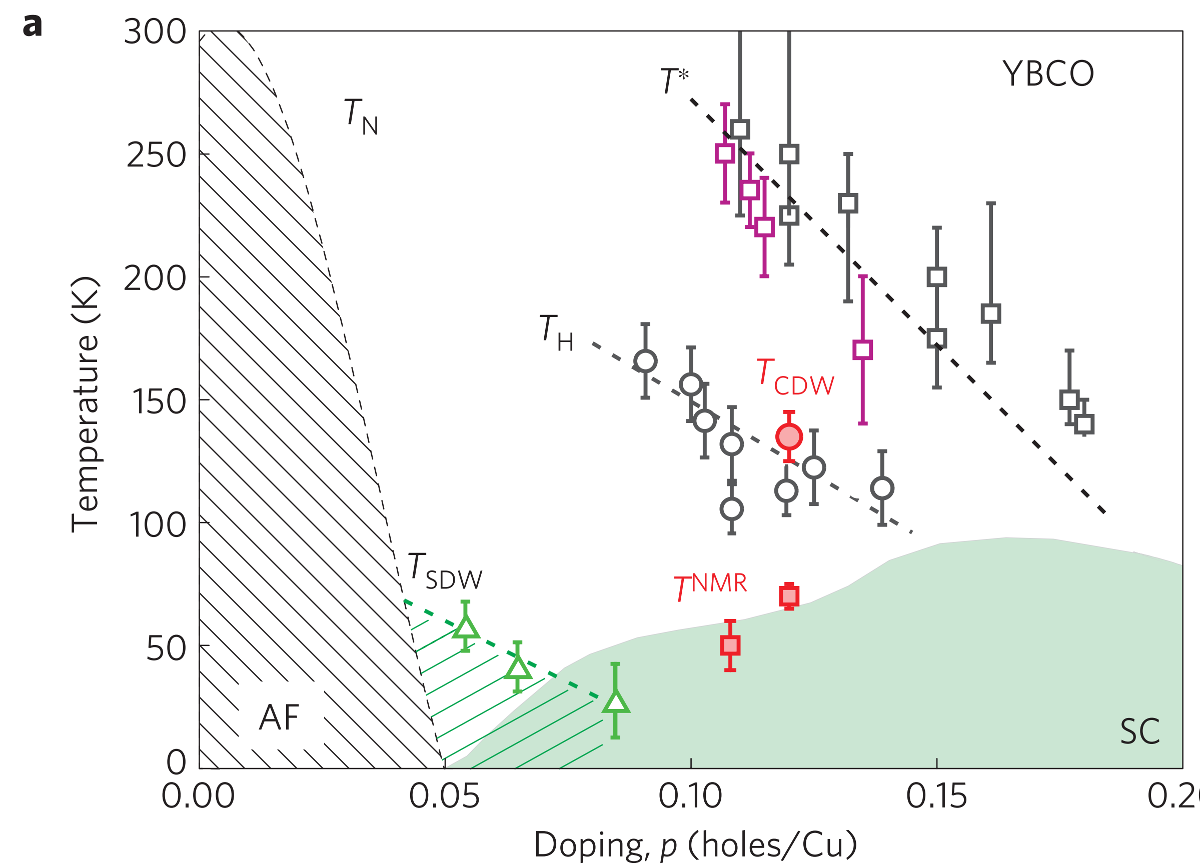
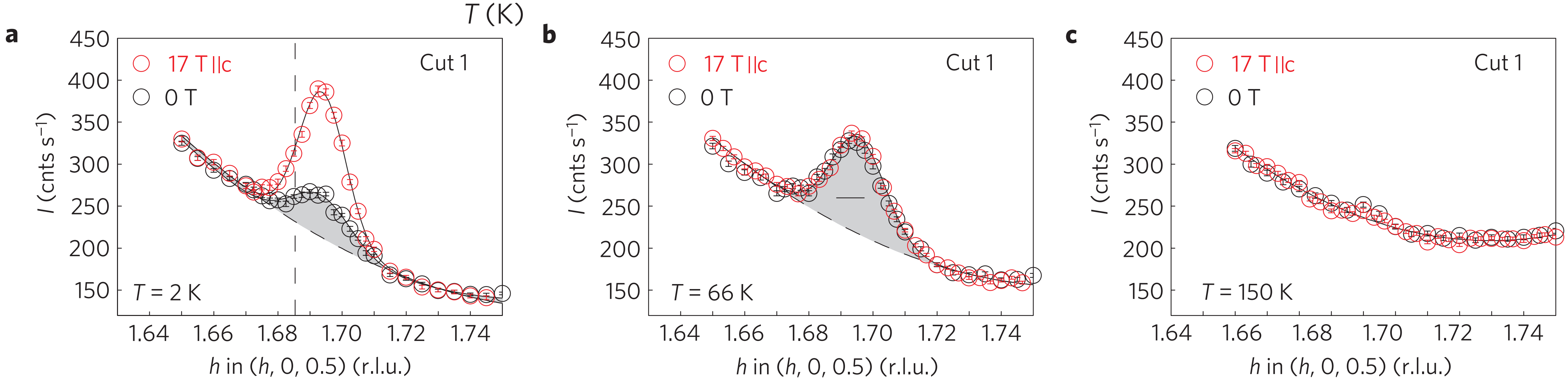
Direct observation of competition between superconductivity and charge density wave order in $YBa_2Cu_3O_{6.67}$

NATURE PHYSICS | VOL 8 | DECEMBER 2012 |

J. Chang[1,2]★, E. Blackburn[3], A. T. Holmes[3], N. B. Christensen[4], J. Larsen[4,5], J. Mesot[1,2], Ruixing Liang[6,7], D. A. Bonn[6,7], W. N. Hardy[6,7], A. Watenphul[8], M. v. Zimmermann[8], E. M. Forgan[3] and S. M. Hayden[9]



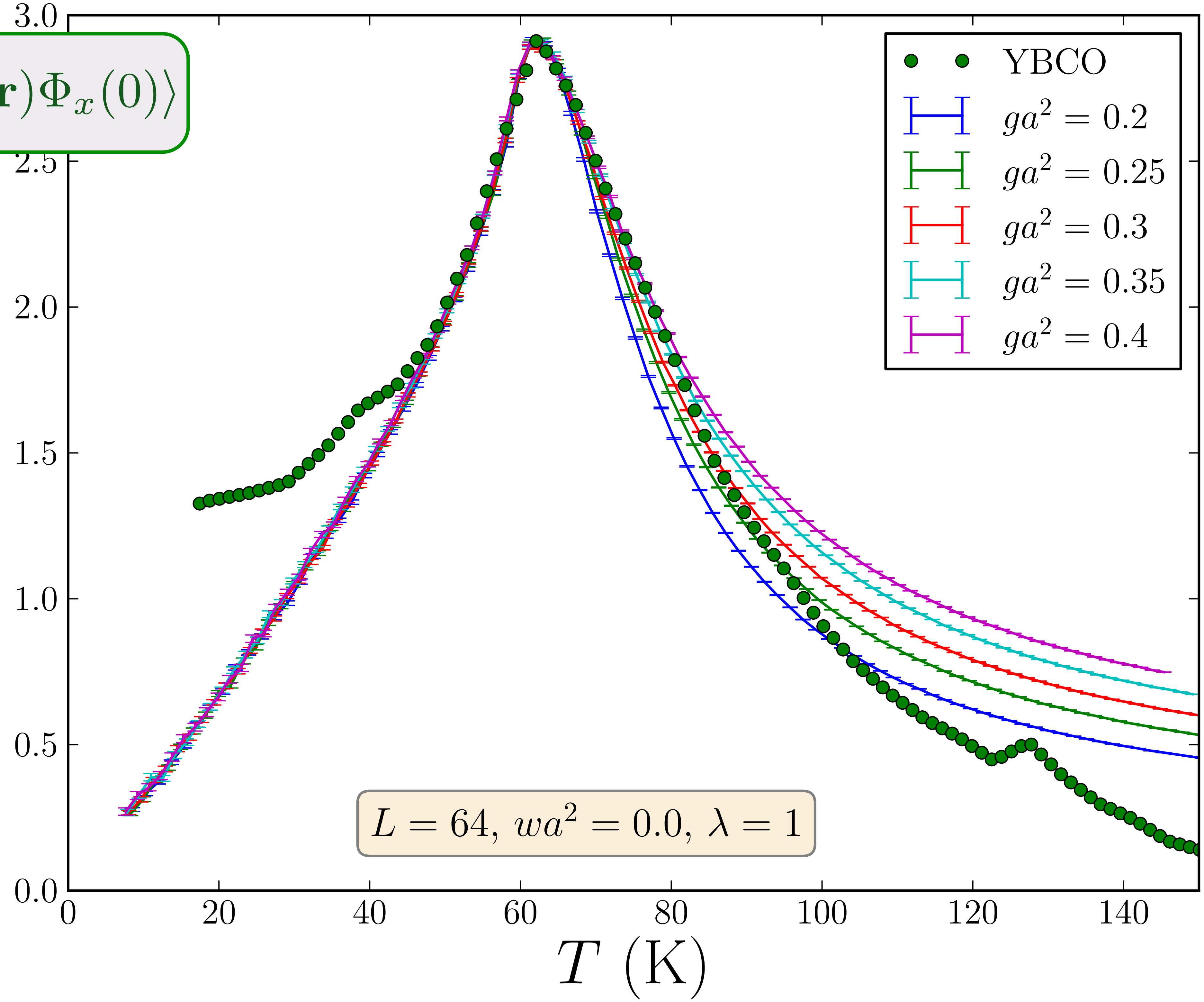




Comparison of Monte Carlo with experiments

$$S_{\Phi_x} = \int d^2r \, \langle \Phi_x(\mathbf{r}) \Phi_x(0) \rangle$$

Charge order structure factor S_{Φ_x}



For $ga^2 = 0.30$ and $wa^2 = 0.0$ we have $\rho_s = 160\text{K}$.

The height was also rescaled to make the peak heights match.

L. E. Hayward, D. G. Hawthorn, R. G. Melko, and S. Sachdev, Science **343**, 1336 (2014)

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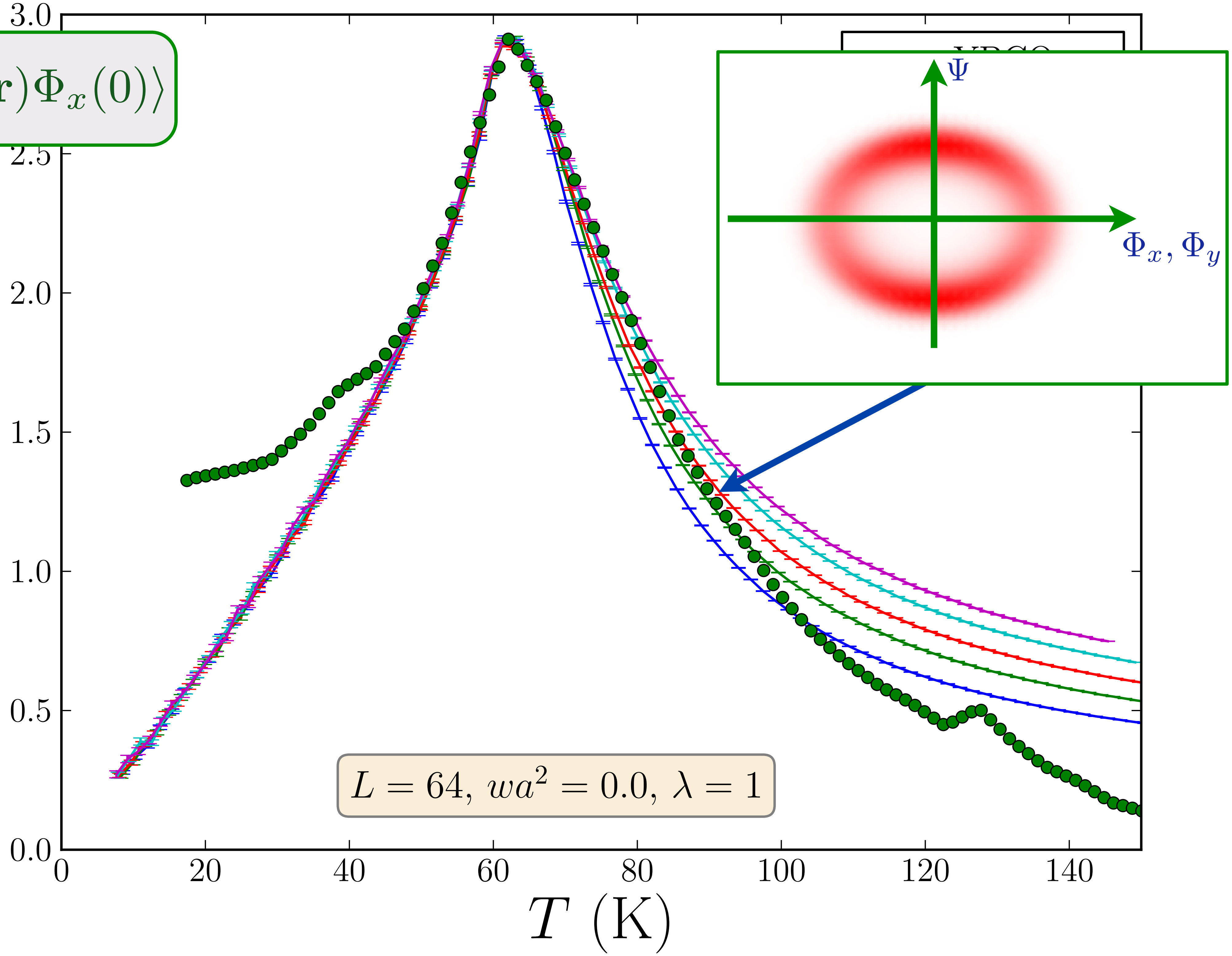

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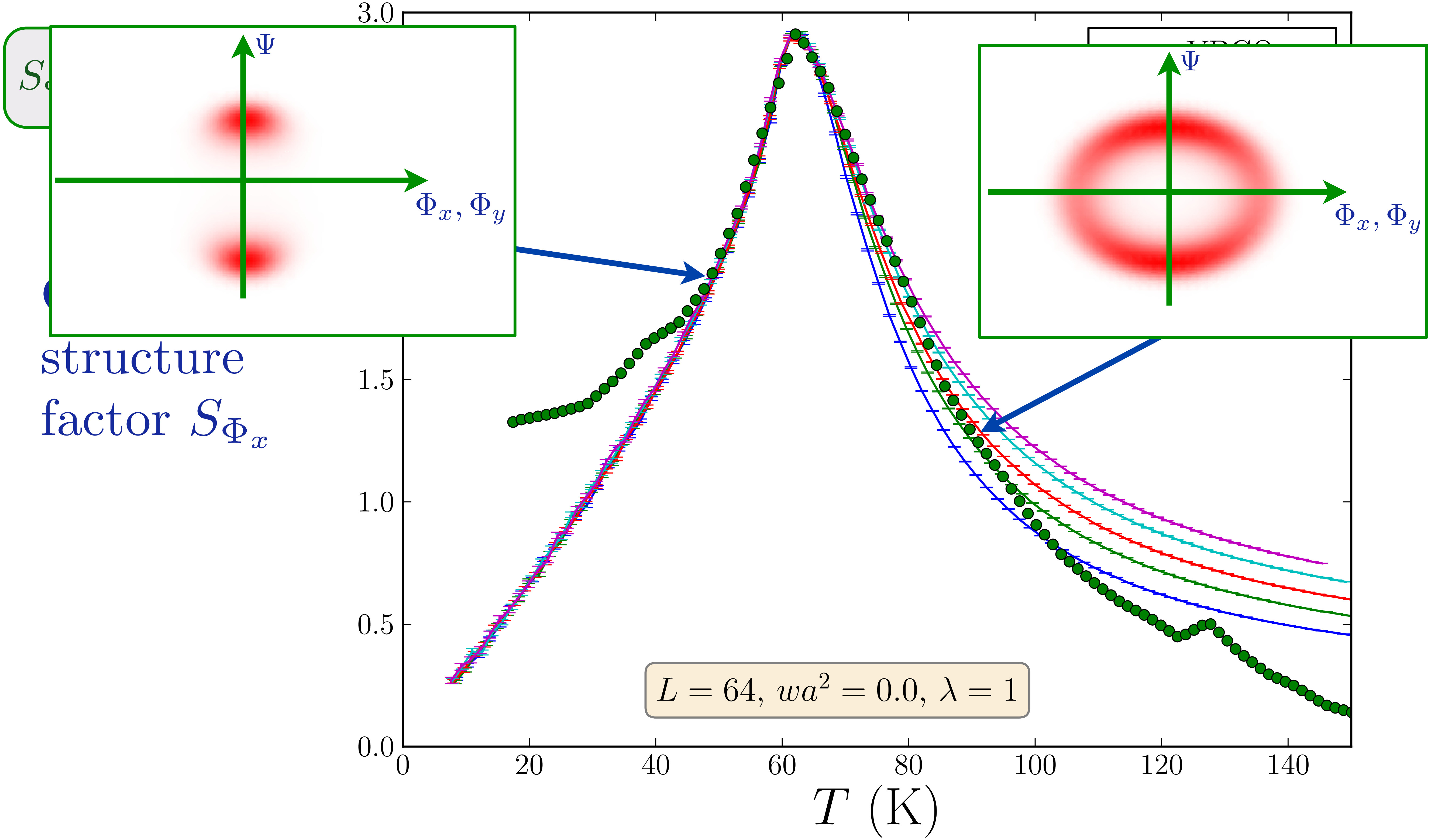

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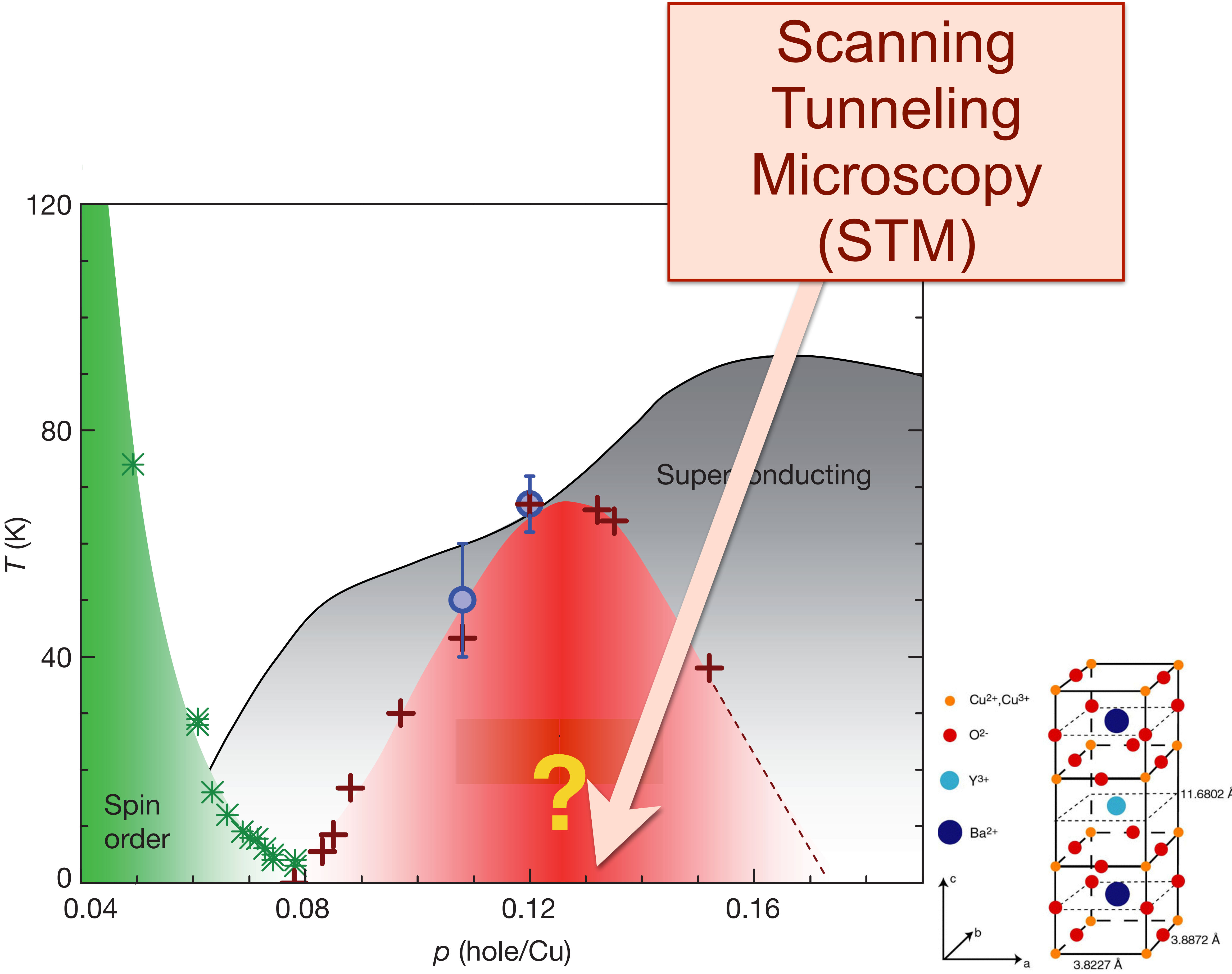

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A Four Unit Cell Periodic Pattern of Quasi-Particle States Surrounding Vortex Cores in $Bi_2Sr_2CaCu_2O_{8+\delta}$

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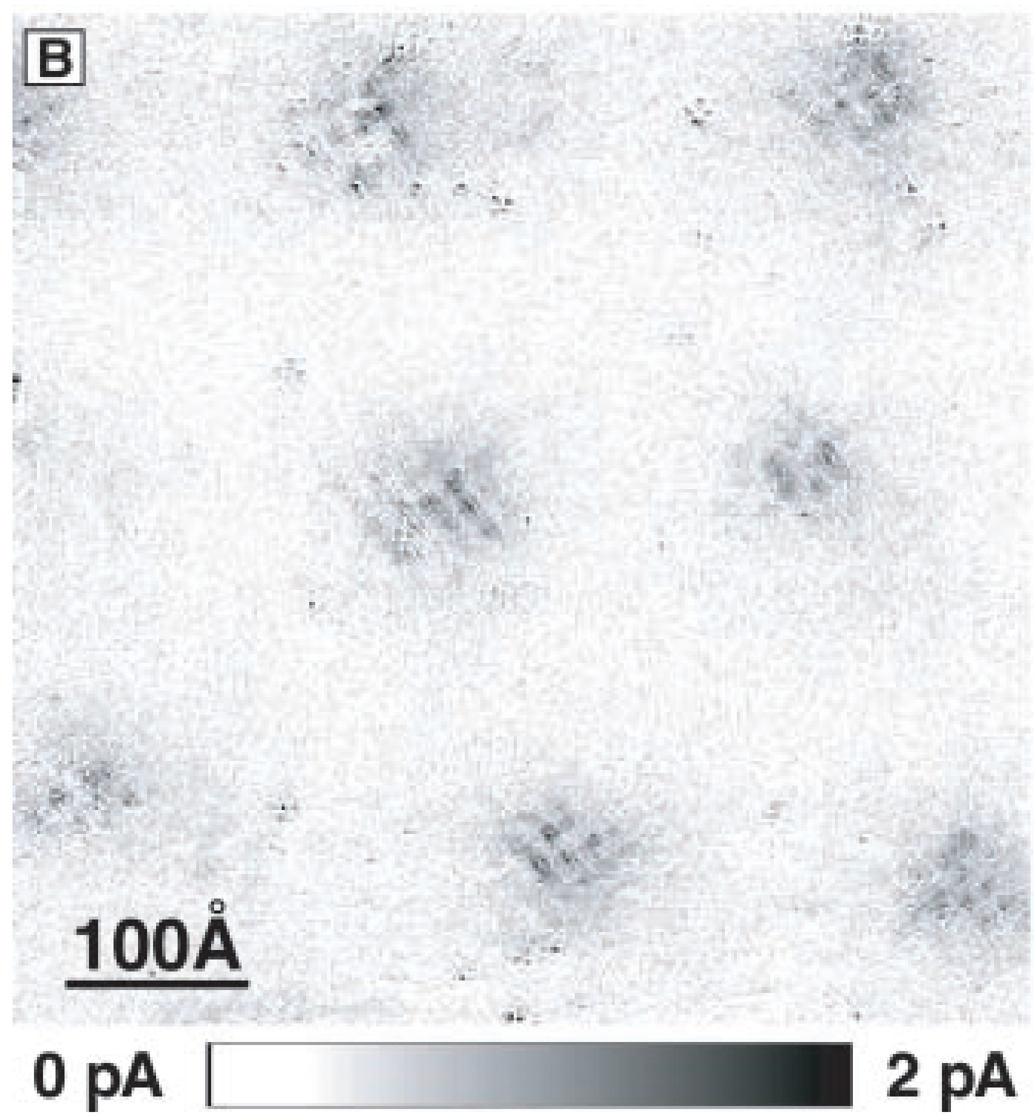

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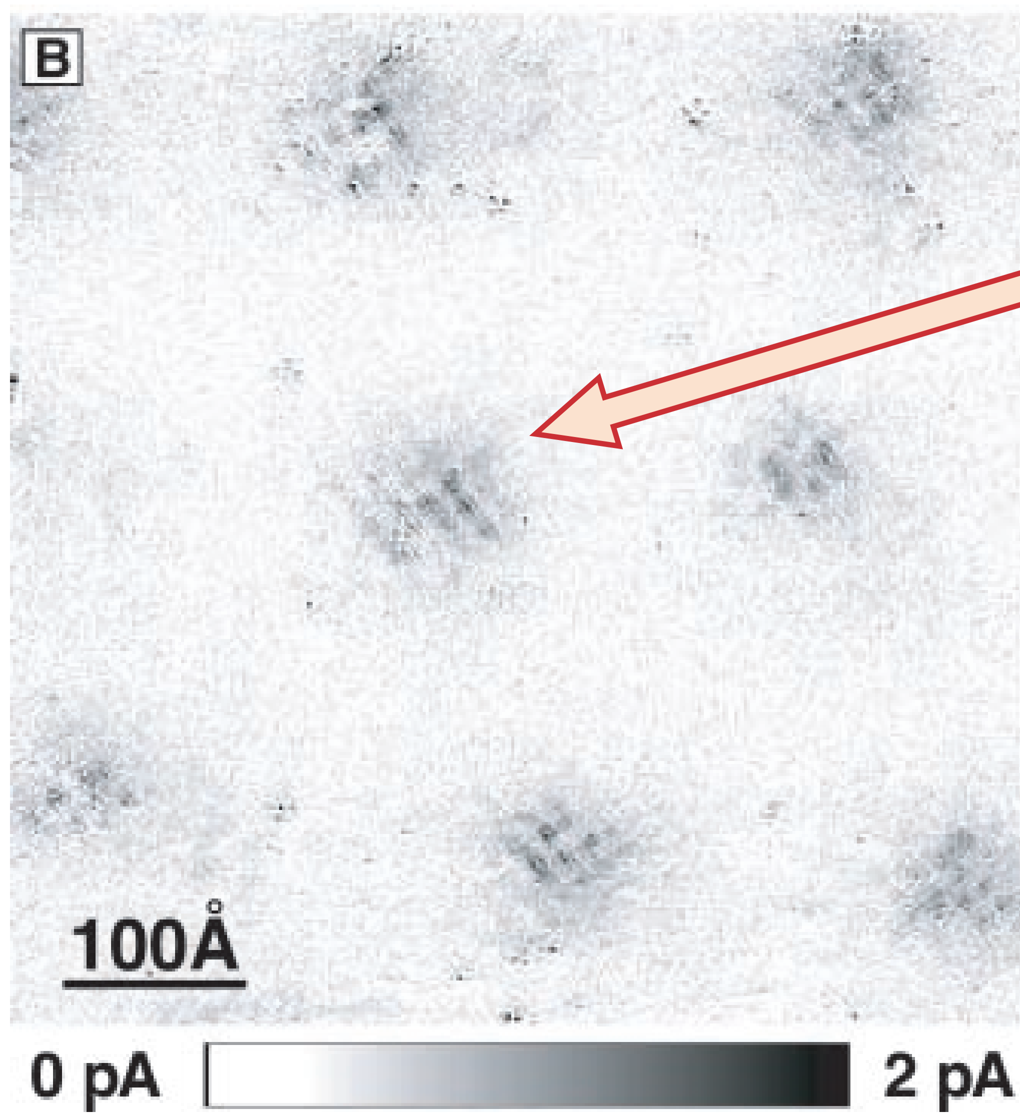

A charge density wave (CDW) with wavelength ≈ 4 lattice spacings around vortex cores ?

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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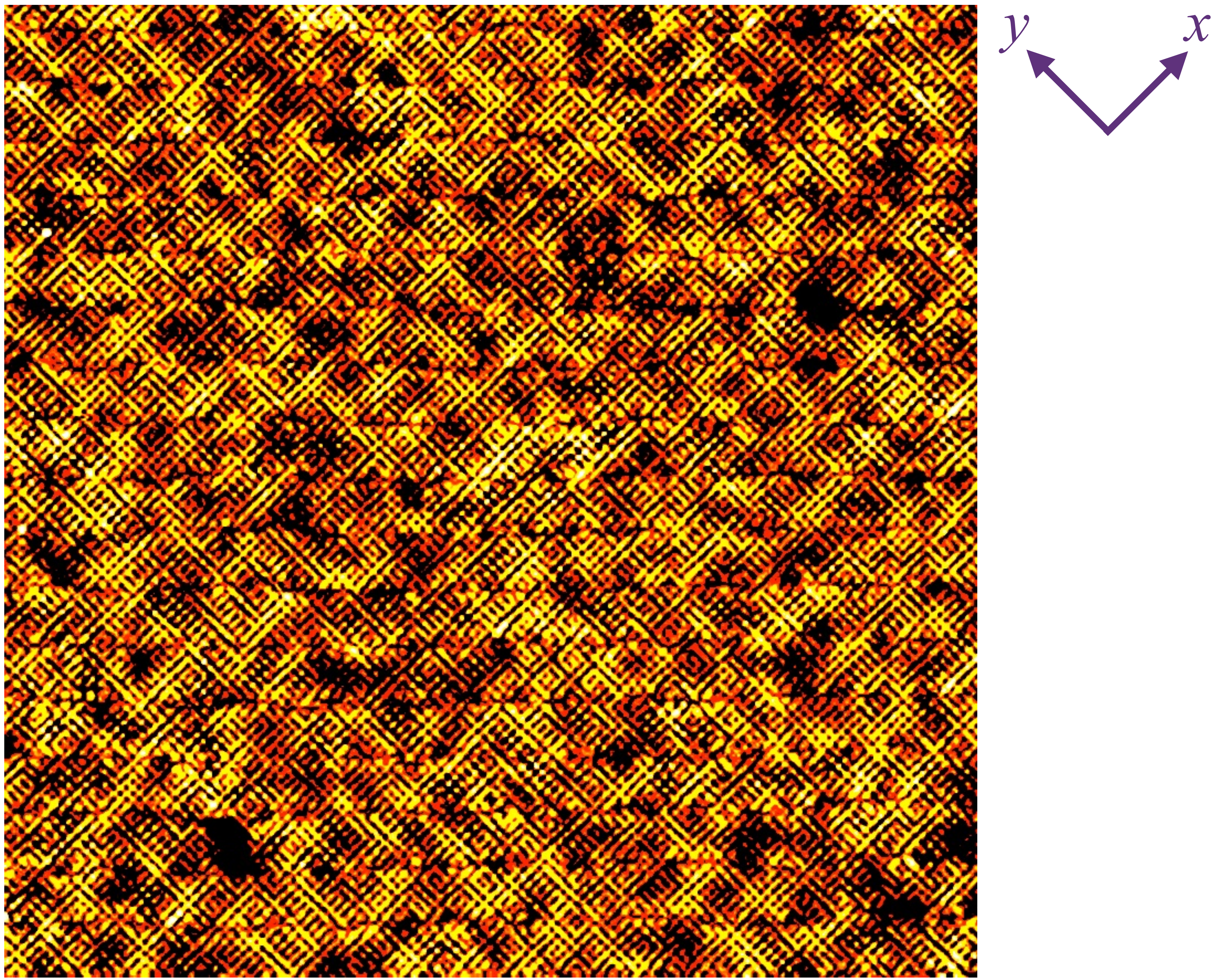

"R-map" of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007). Davis group has sub-angstrom resolution capabilities, with lattice drift corrections, which make sublattice phase-resolved STM possible.

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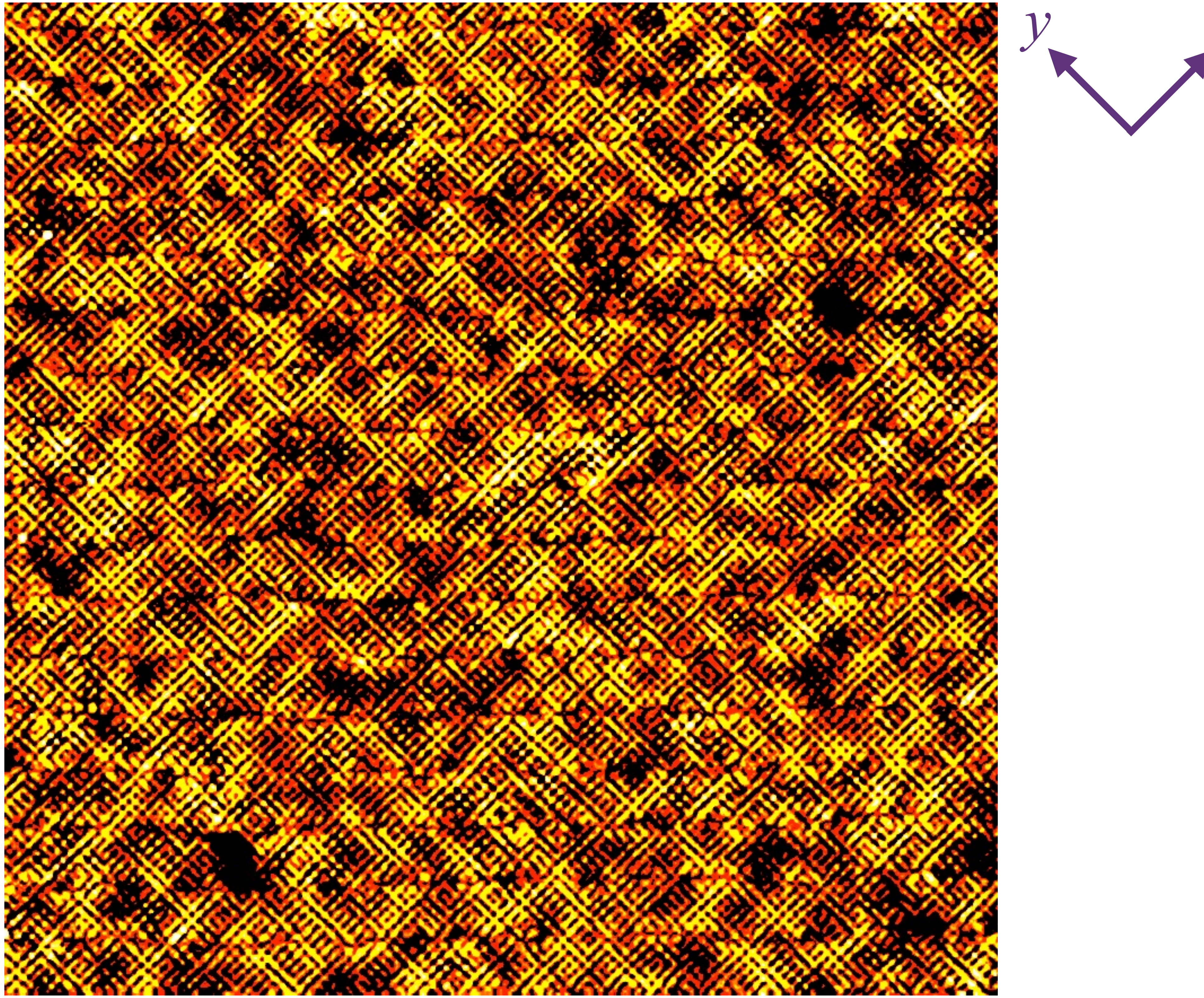

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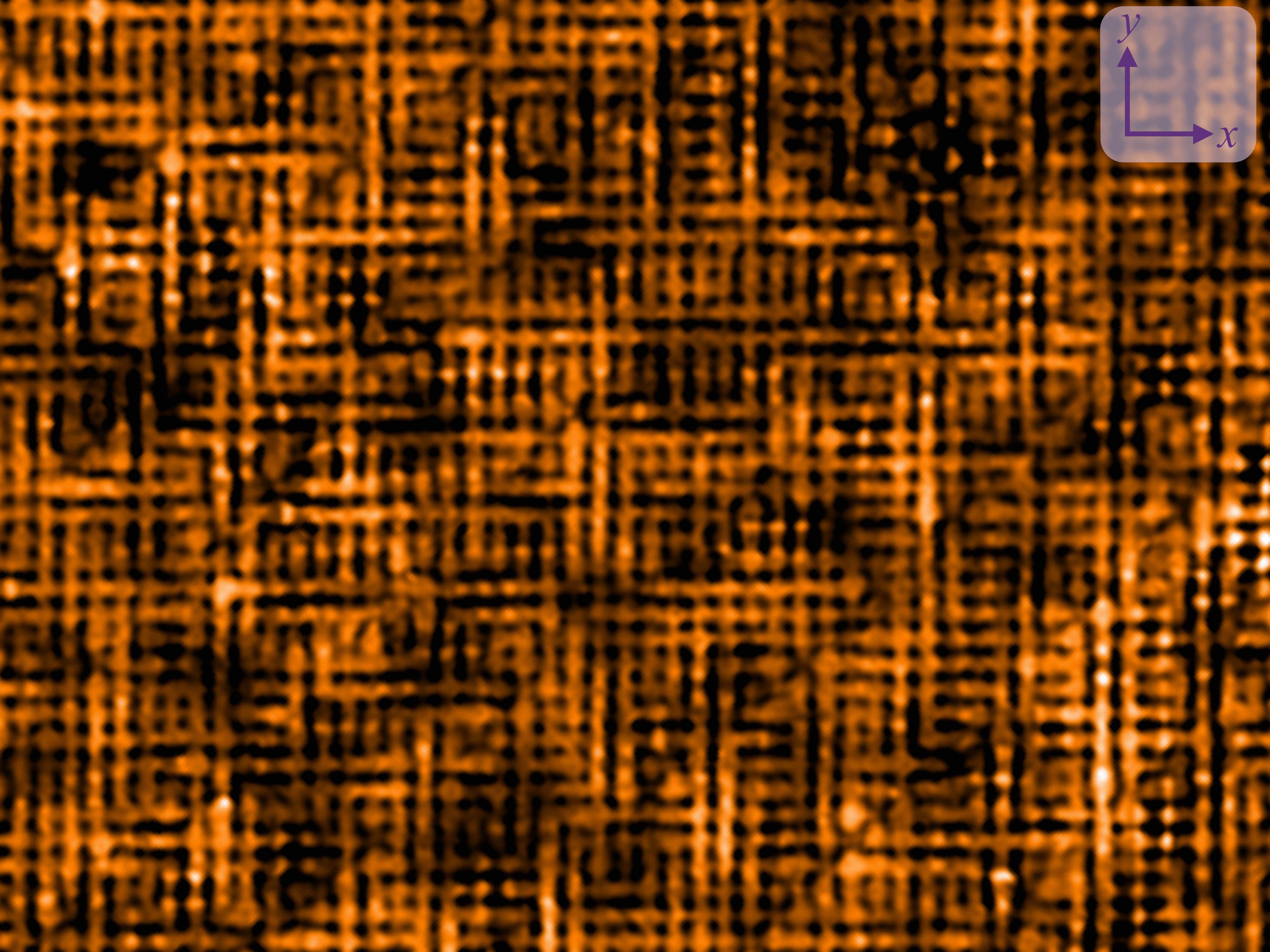
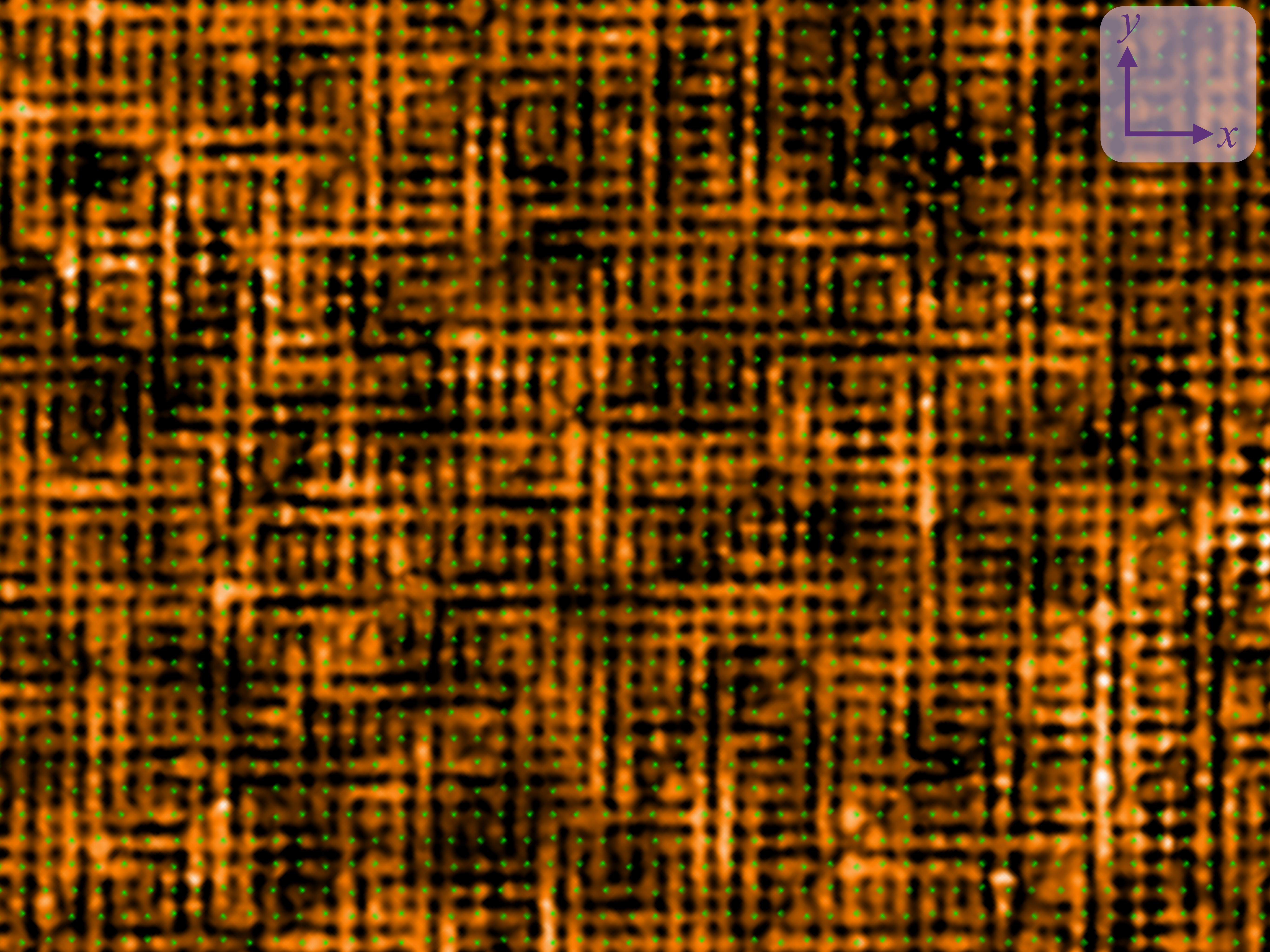

y
x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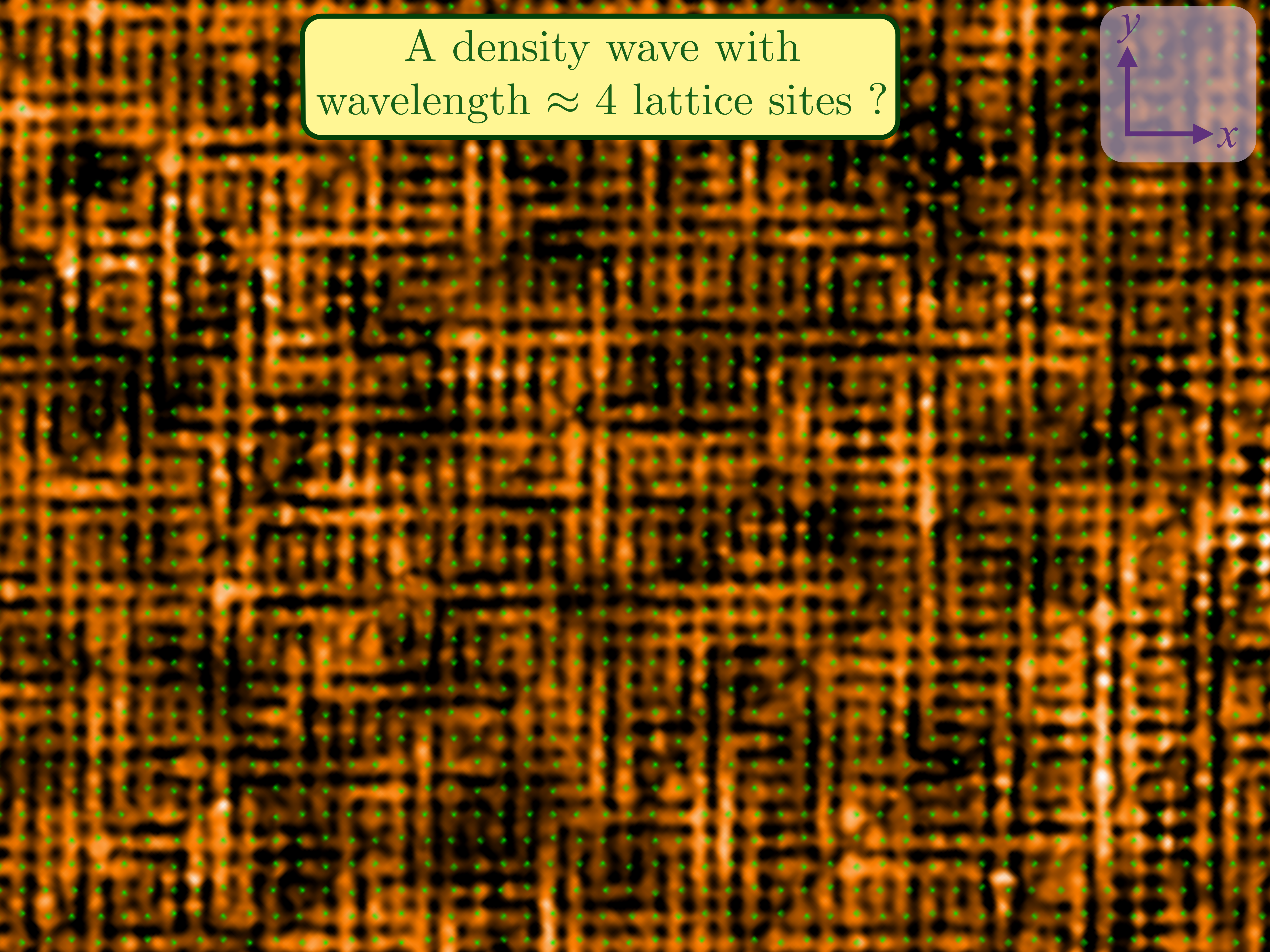
A density wave with
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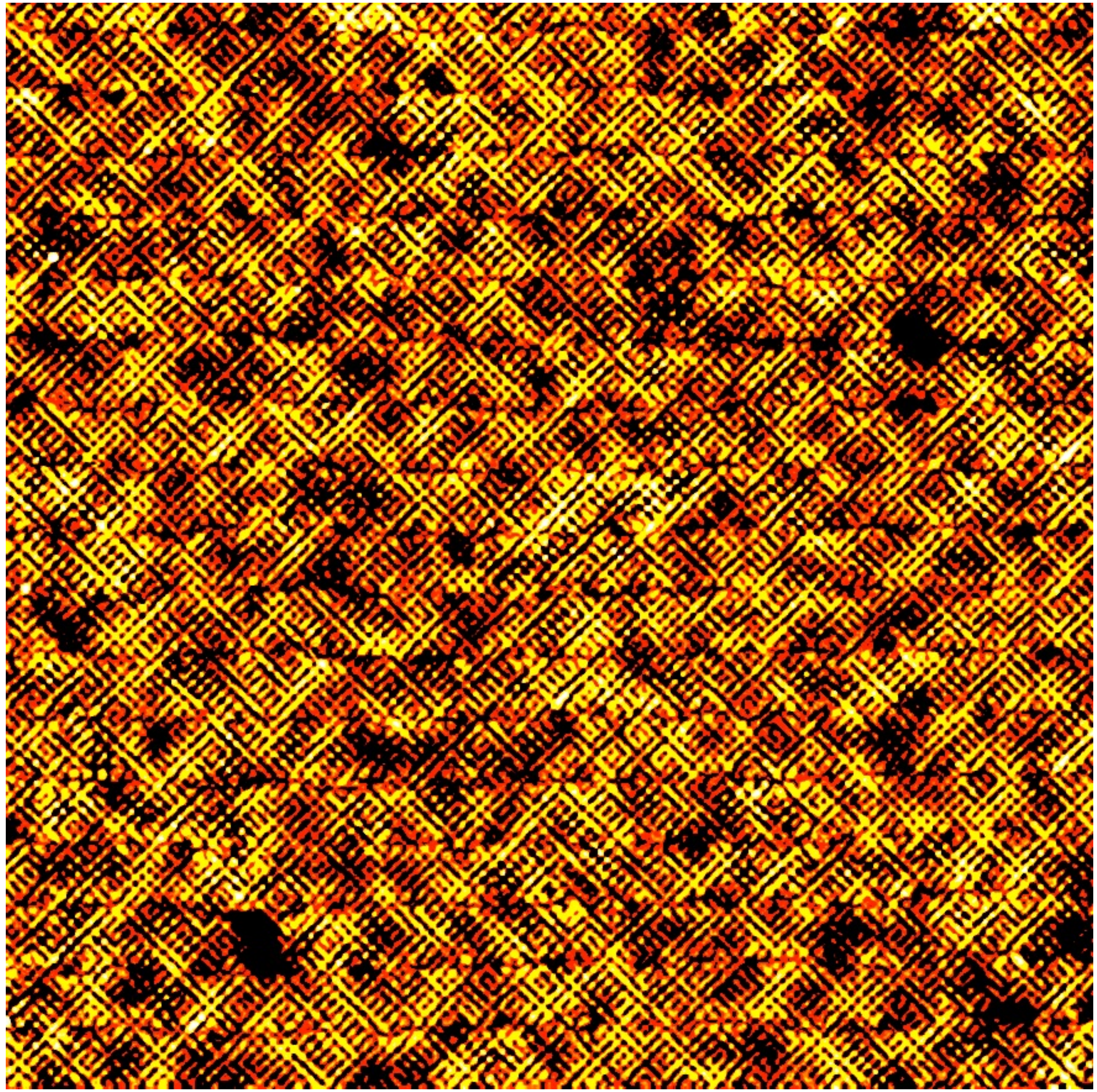

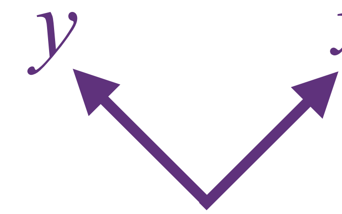

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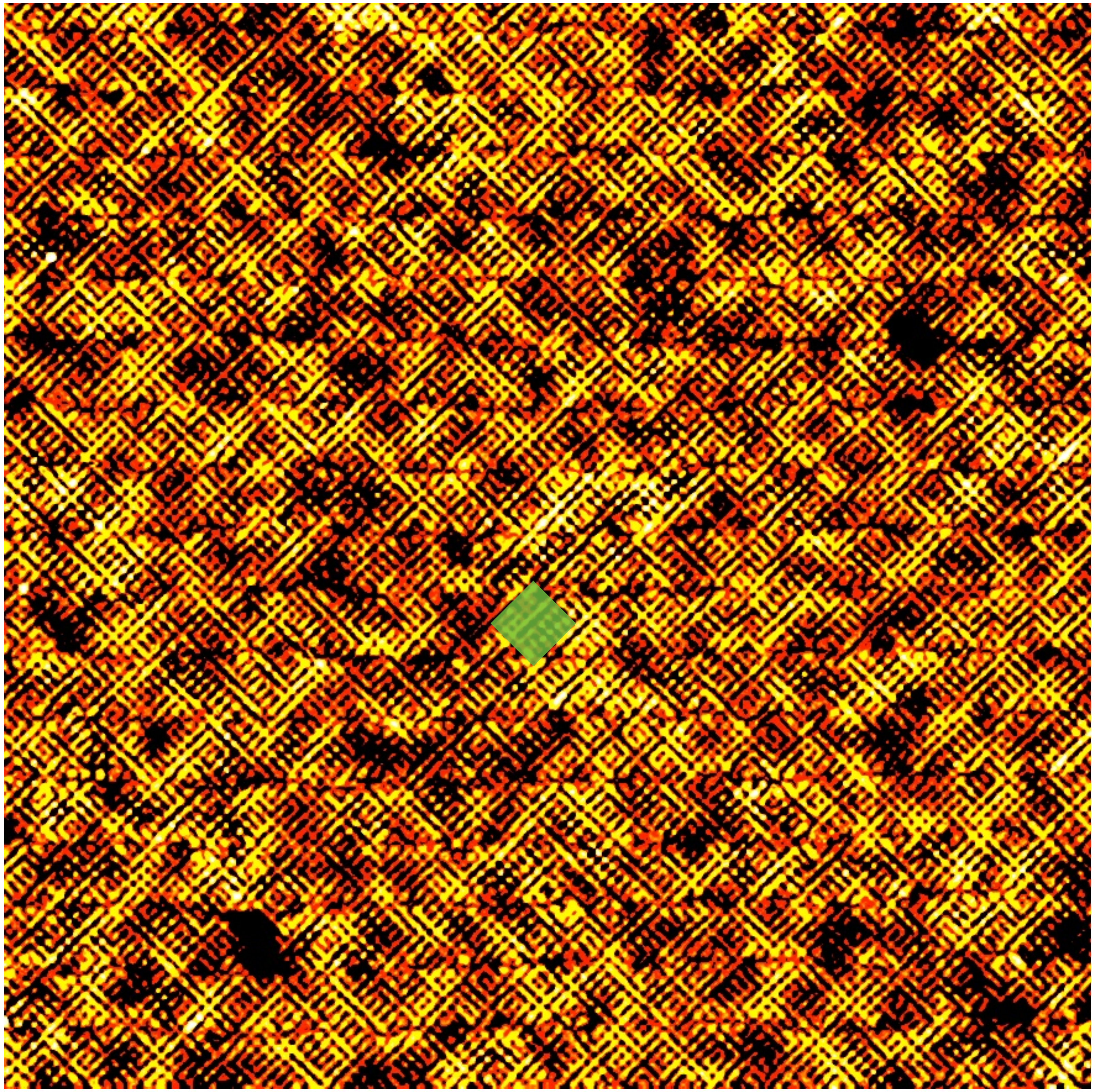

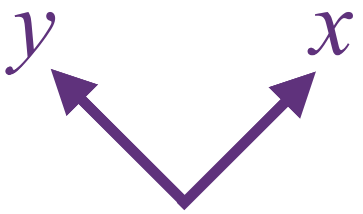

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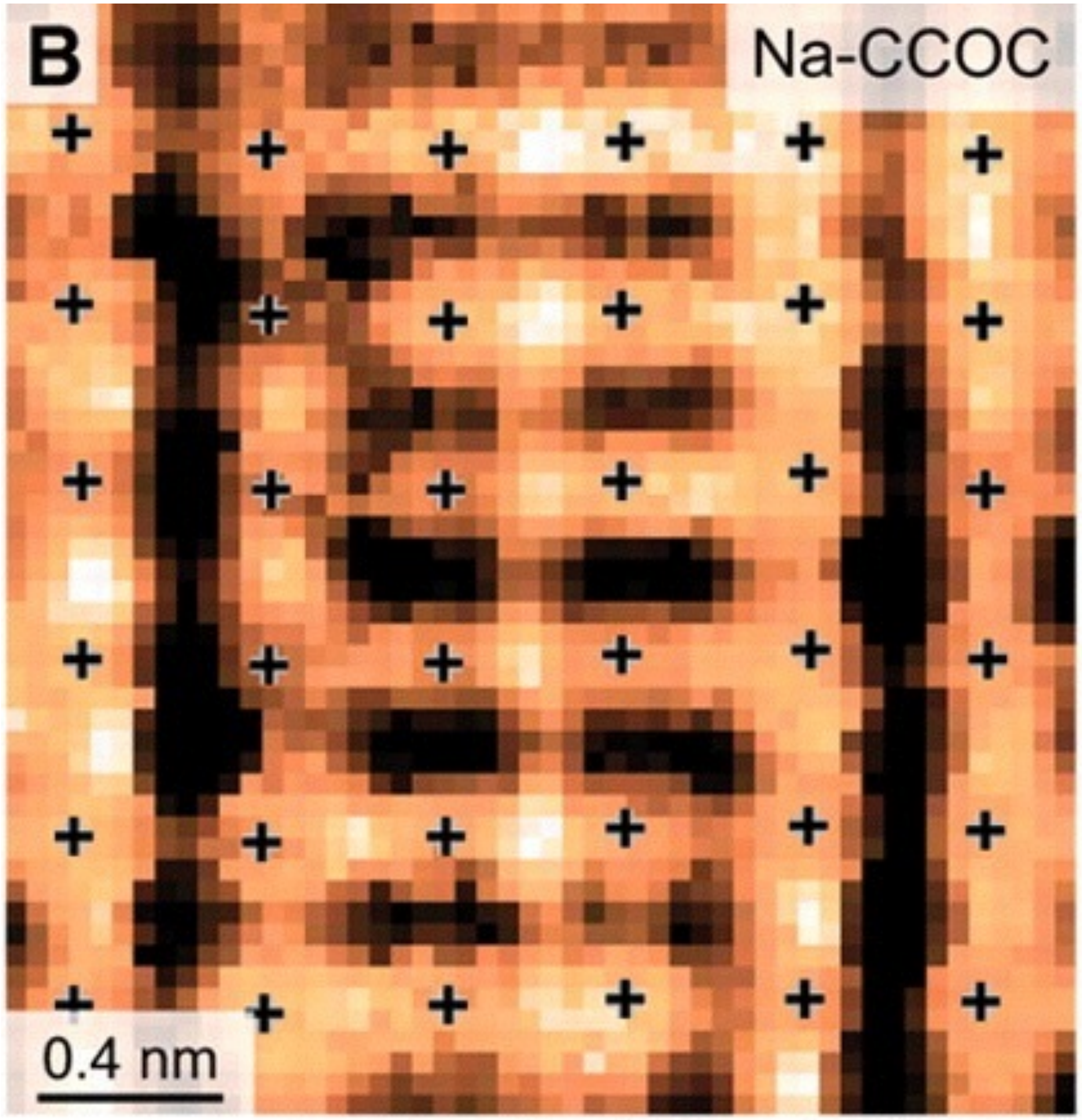

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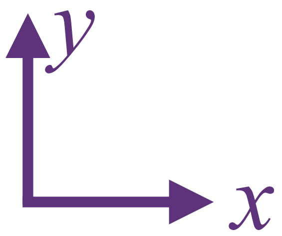


Charge density wave (CDW) order

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

Charge density wave (CDW) order

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

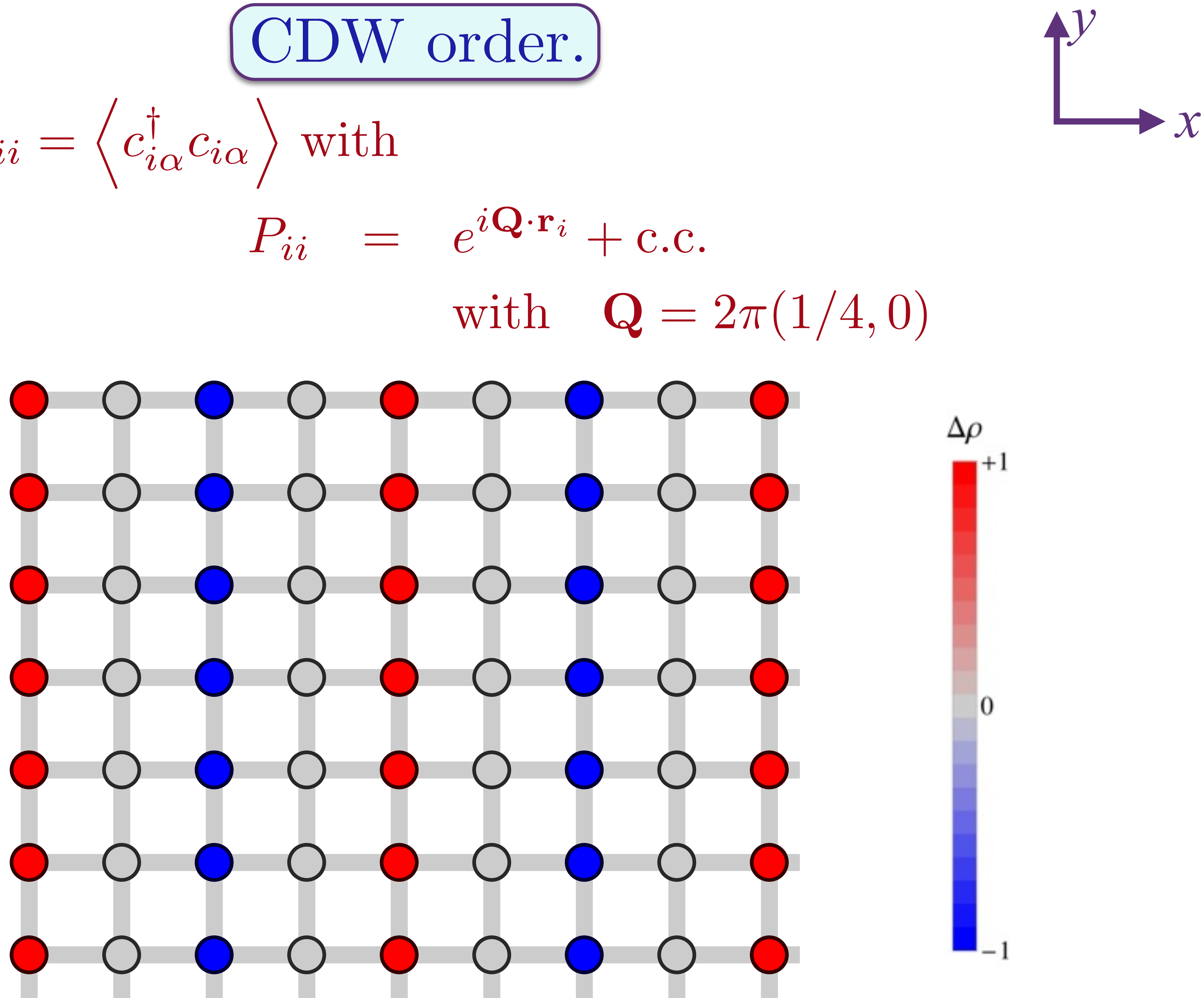
Nearly constant CDW order parameter

CDW order.

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

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

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



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

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

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

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

$$\langle c^\dagger_\alpha(\mathbf{r}_1) c_\alpha(\mathbf{r}_2) \rangle$$

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

Crucial "center-of-mass" co-ordinate.
(Not used in previous work)
Simplifies action of time-reversal

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

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

Nearly constant CDW order parameter

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

$$\langle c^\dagger_\alpha(\mathbf{r}_1) c_\alpha(\mathbf{r}_2) \rangle$$

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

Density wave **form factor** (internal particle-hole pair wavefunction)

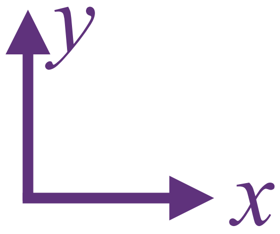
$$\mathcal{P}(\mathbf{r}) = \int \frac{d^2 k}{4\pi^2} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot\mathbf{r}}$$

Time-reversal symmetry requires $\mathcal{P}(\mathbf{k}) = \mathcal{P}(-\mathbf{k})$.

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

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

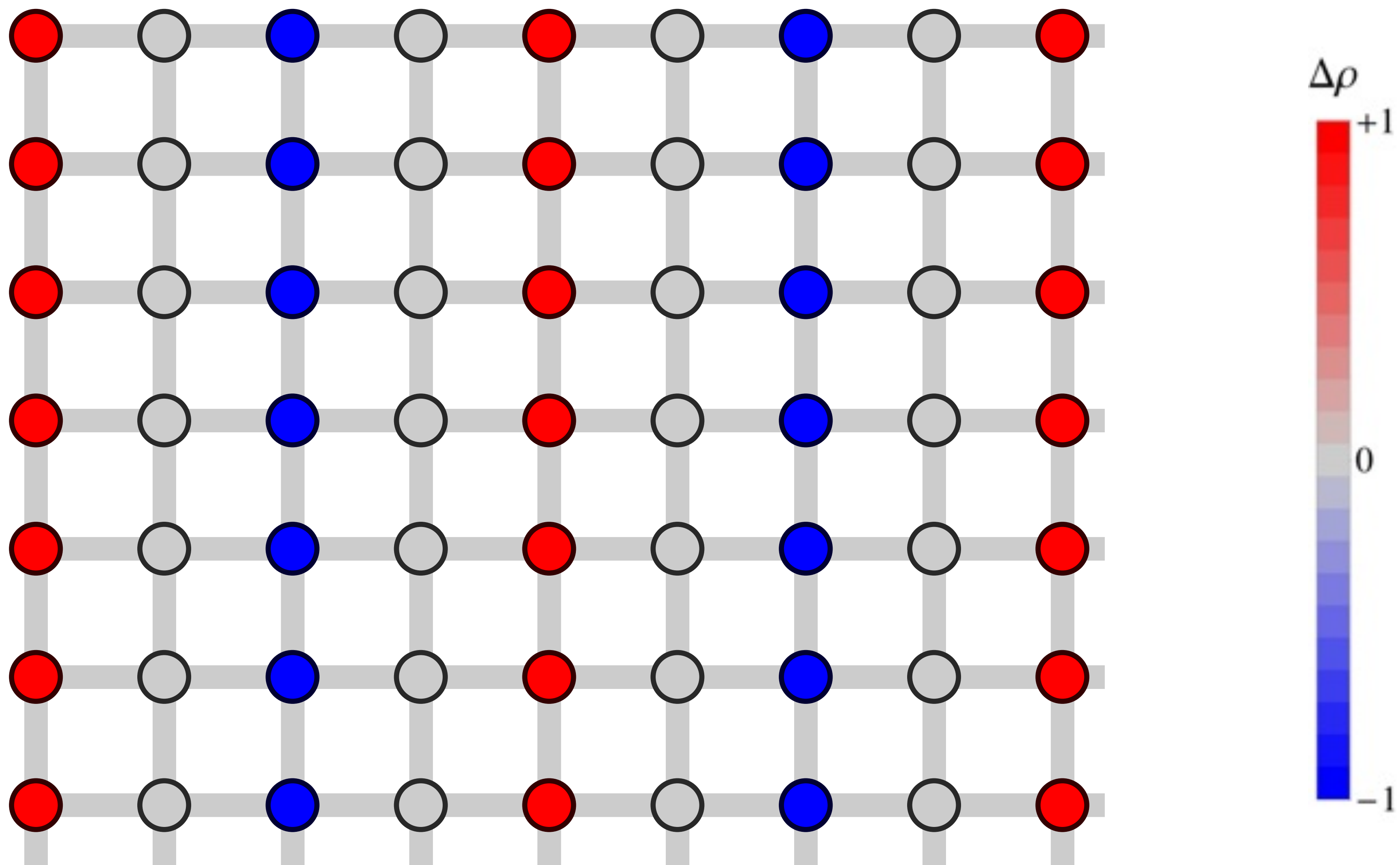
Conventional CDW order: s-form factor



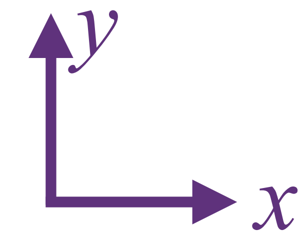
Plot of $P_{ij} = \left\langle c^\dagger_{i\alpha} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

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



Unconventional DW order: s'-form factor



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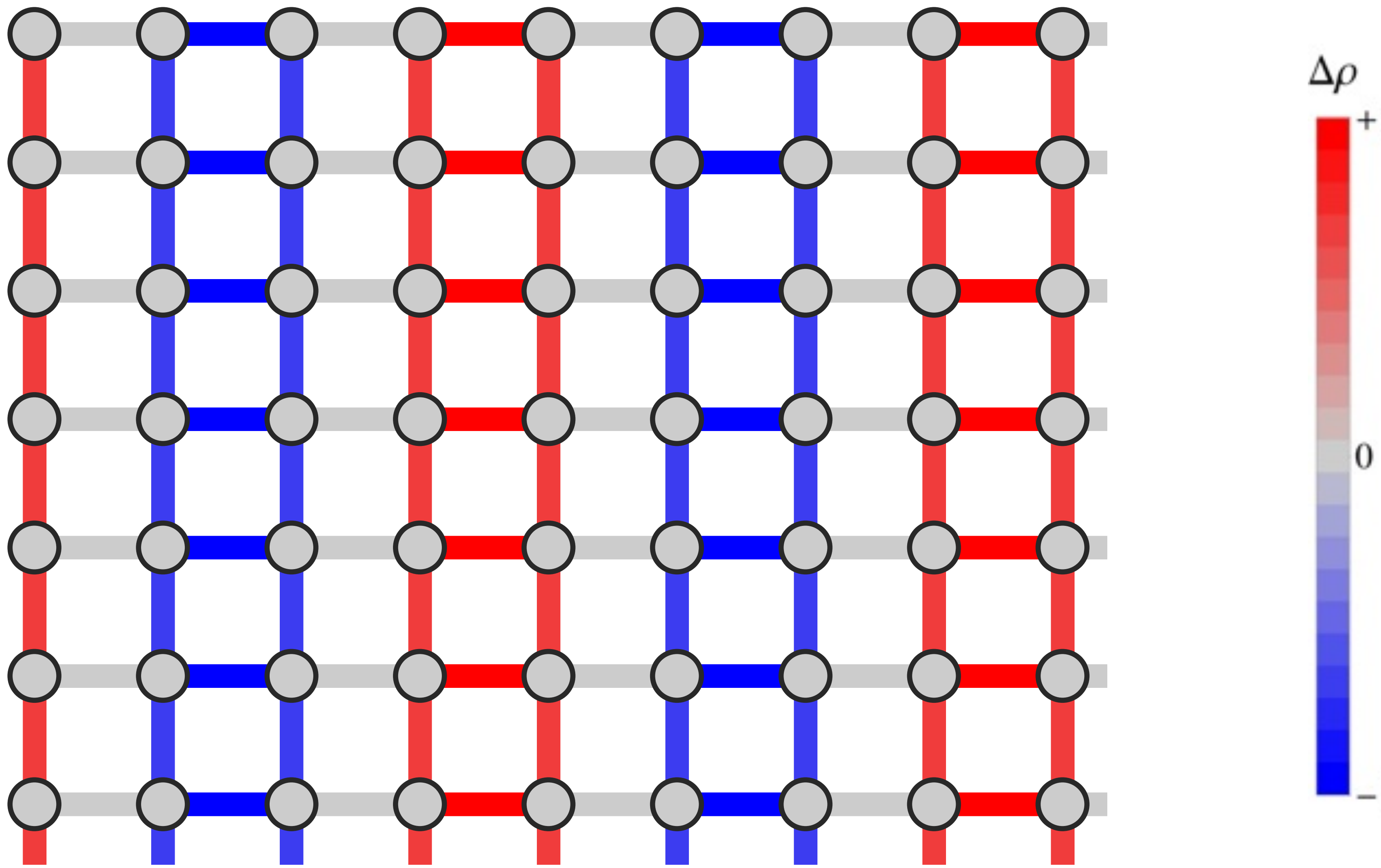
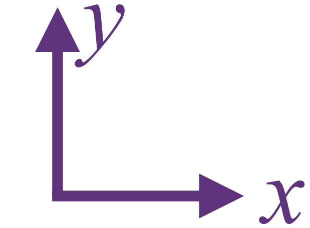
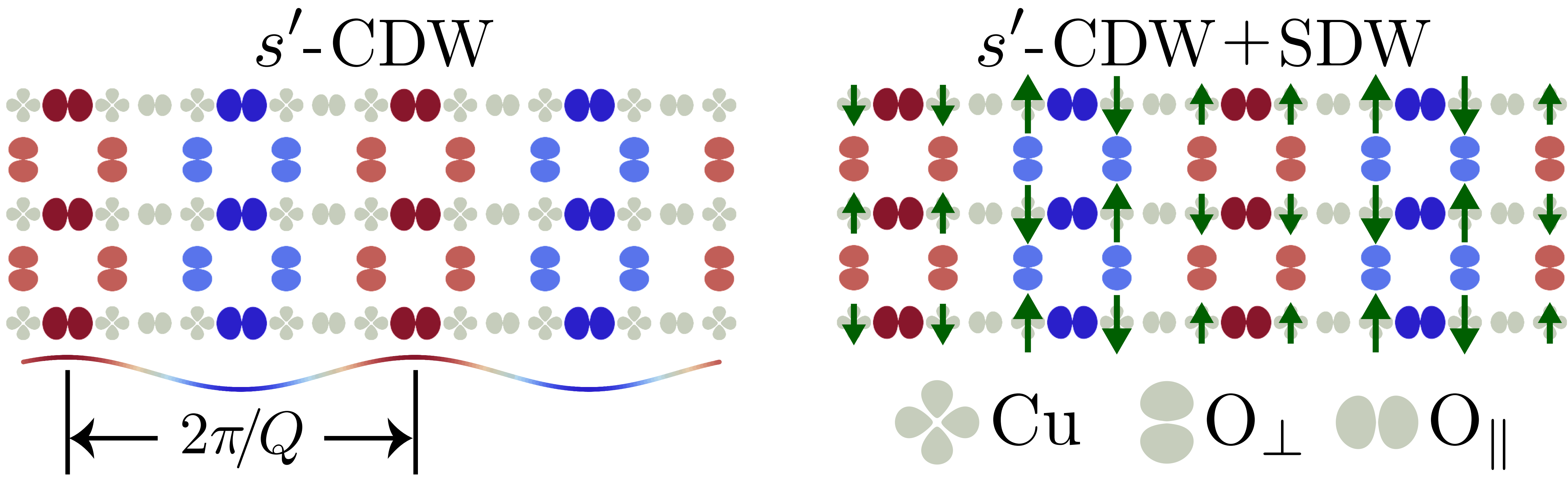
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) + \cos(k_y)\right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$



Unconventional DW order: s'-form factor



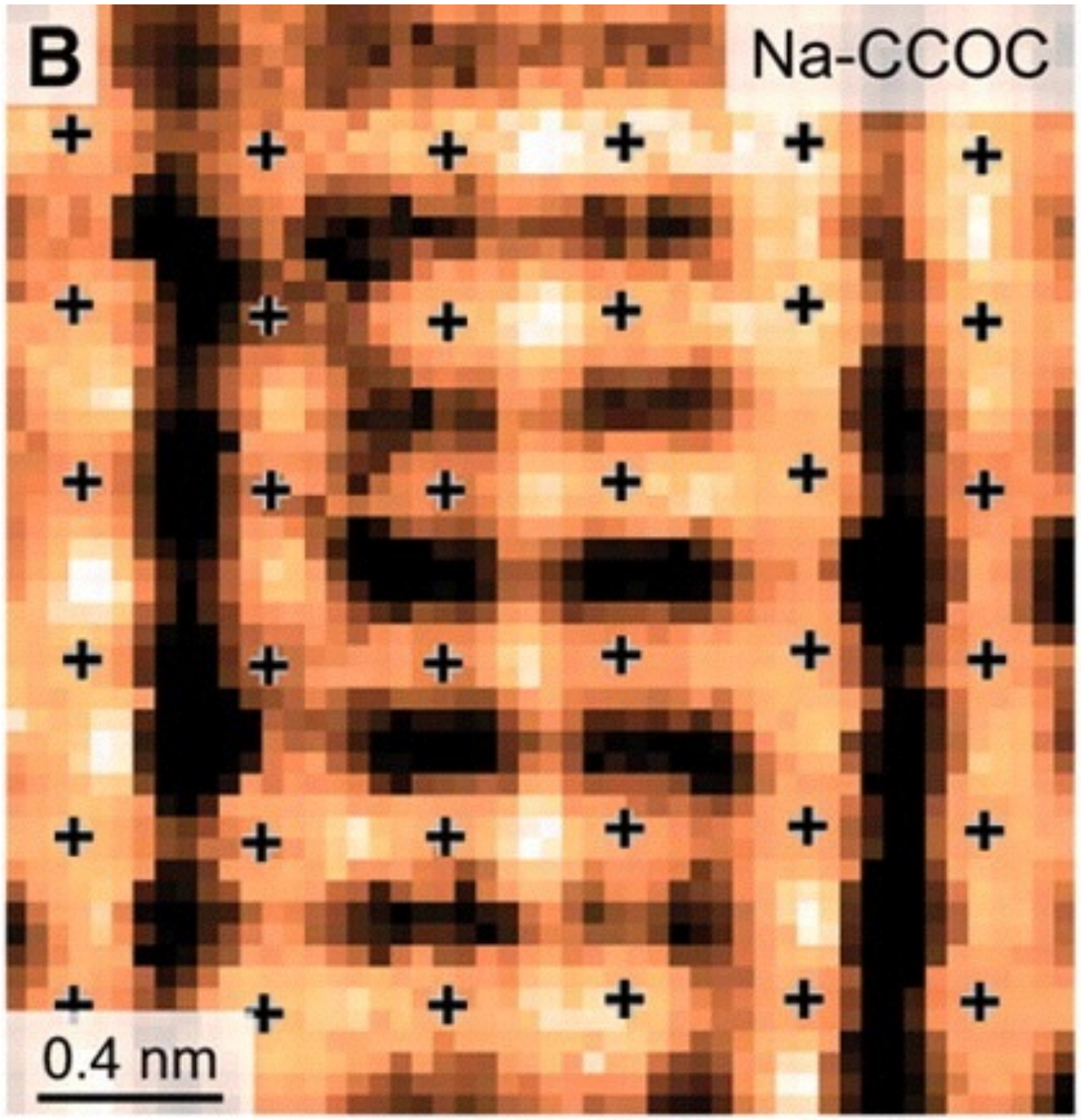
Compatible with "stripe" model, and spin-density-wave (SDW) order



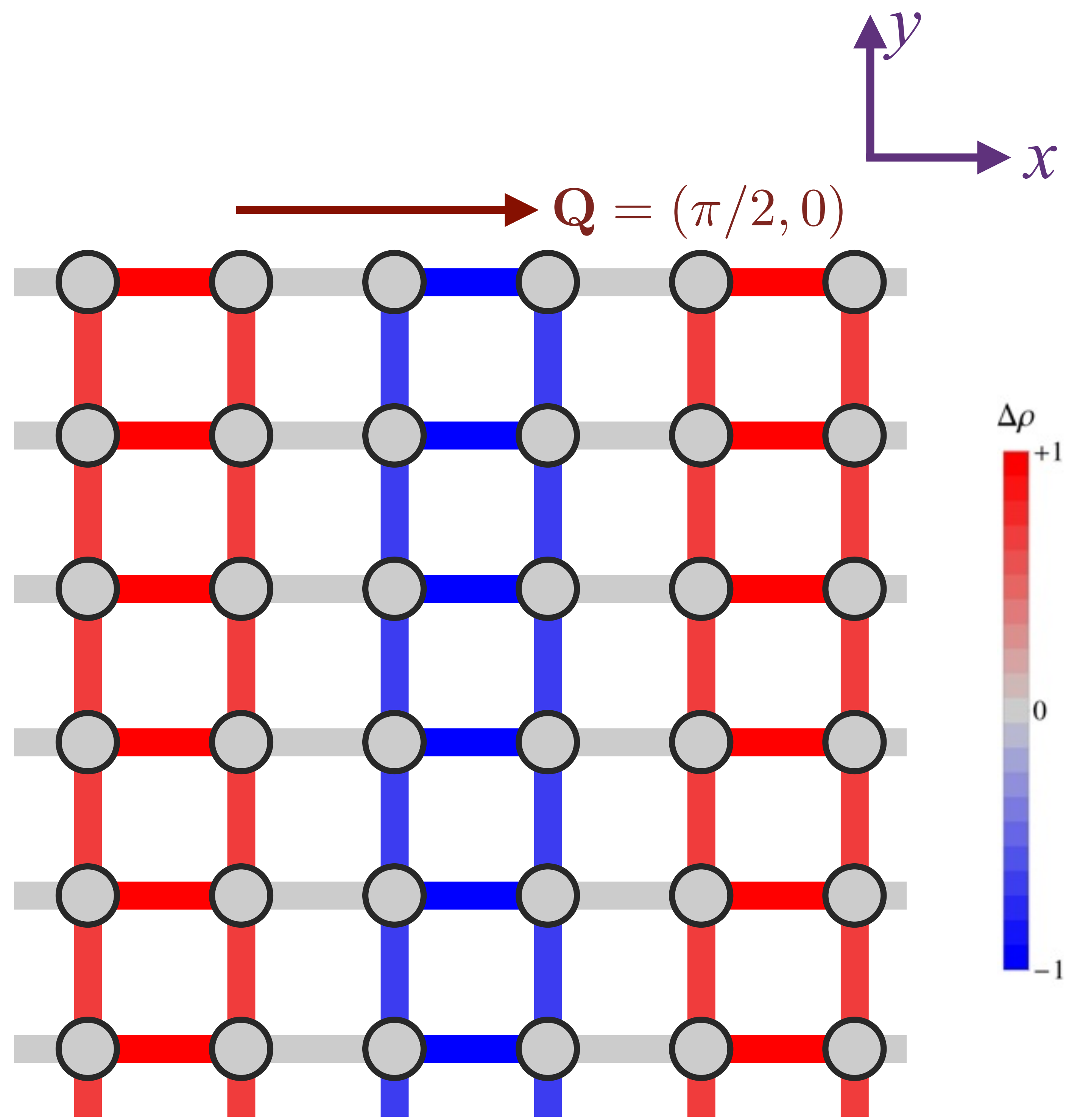
Orbital symmetry of charge density wave order in $La_{1.88}Ba_{0.12}CuO_4$ and $YBa_2Cu_3O_{6.67}$

A. J. Achkar,[1] F. He,[2] R. Sutarto,[2] Christopher McMahon,[1] M. Zwiebler,[3] M. Hücker,[4]
G. Gu,[4] Ruixing Liang,[5] D. A. Bonn,[5] W. N. Hardy,[5] J. Geck,[3] and D. G. Hawthorn[1]

X-ray observations indicate strong s' component in LBCO



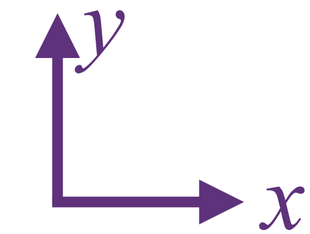
Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)



s'-form factor density wave order

s' form factor is incompatible with STM measurements on BSCCO, Na-CCOC.

Unconventional DW order: s'-form factor



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

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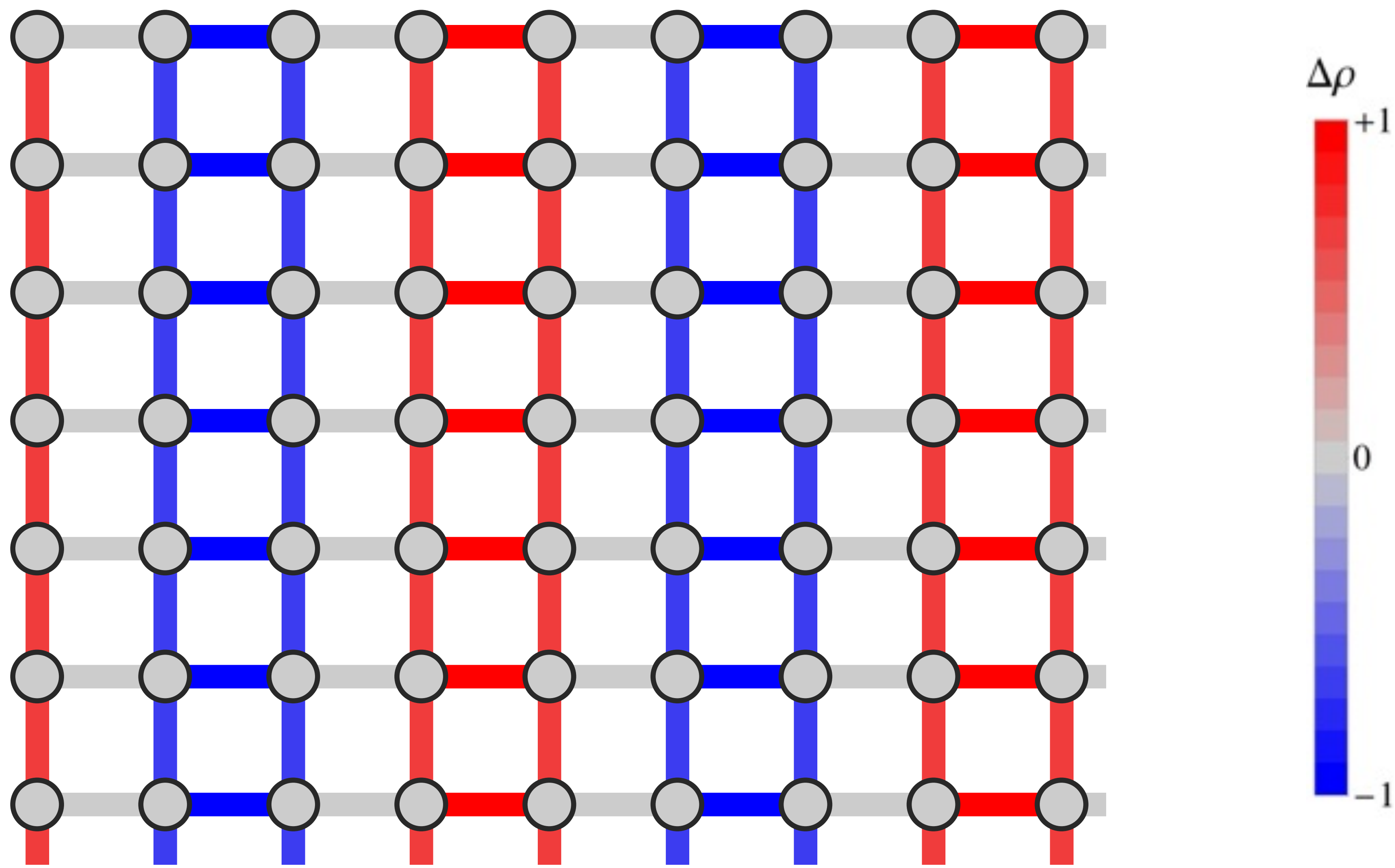
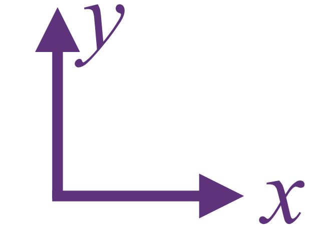
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) + \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$



Unconventional DW order: d-form factor

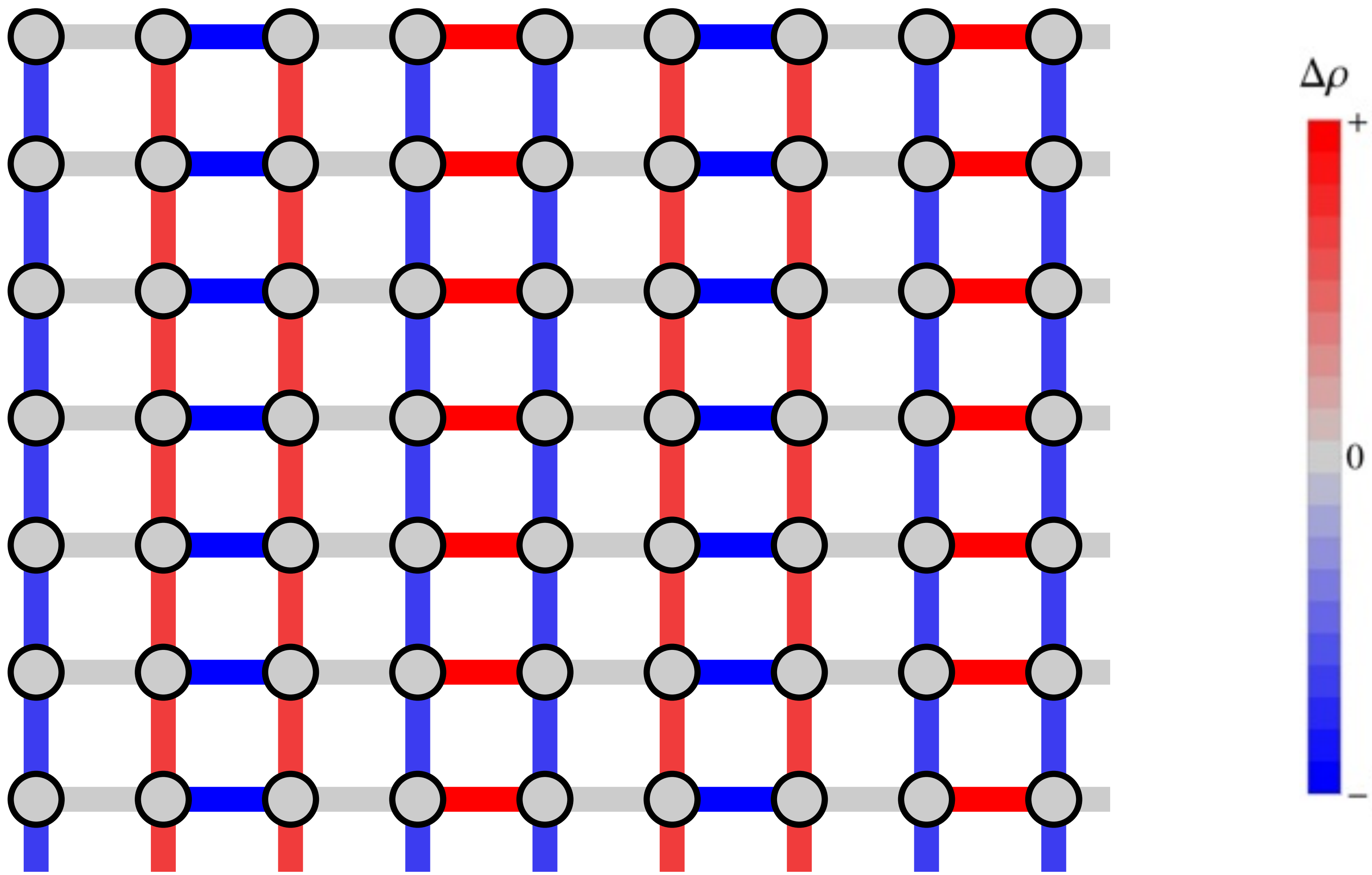


Plot of $P_{ij} = \left\langle c^\dagger_{i\alpha} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

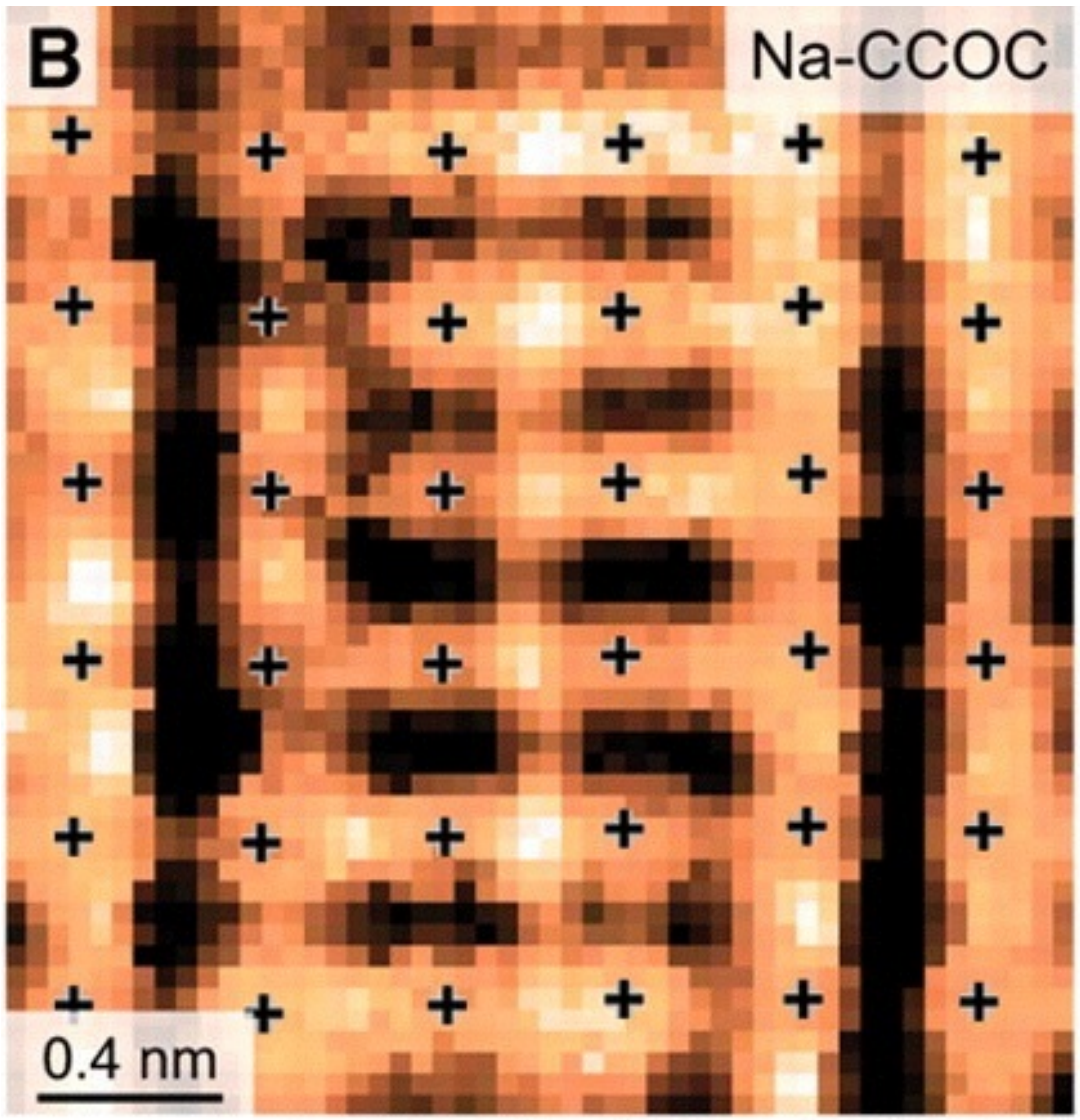
$$P_{ij} = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2} + \text{c.c.}$$

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

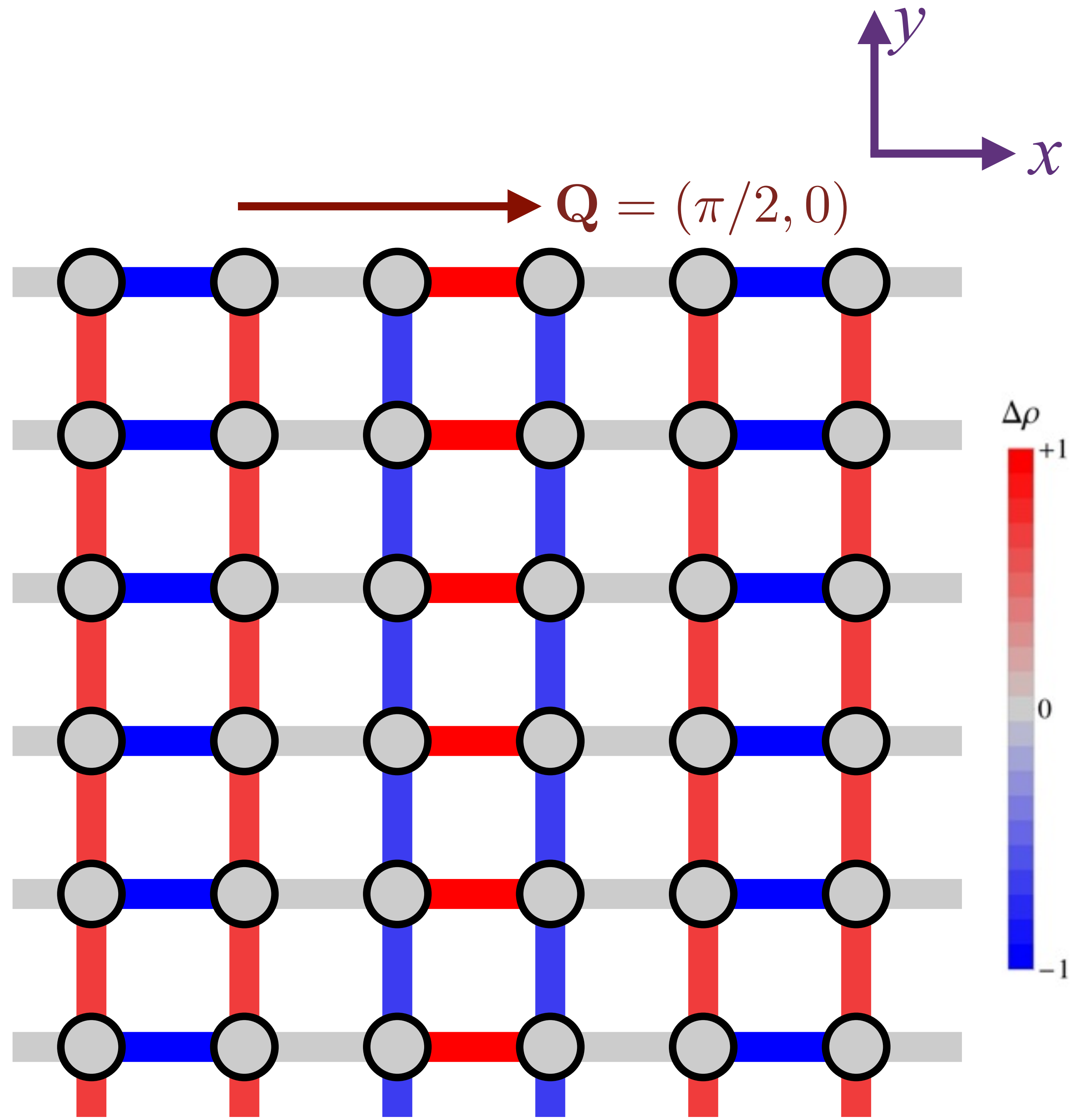
Density wave on horizontal bonds has a phase-shift of π relative to the wave on vertical bonds



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

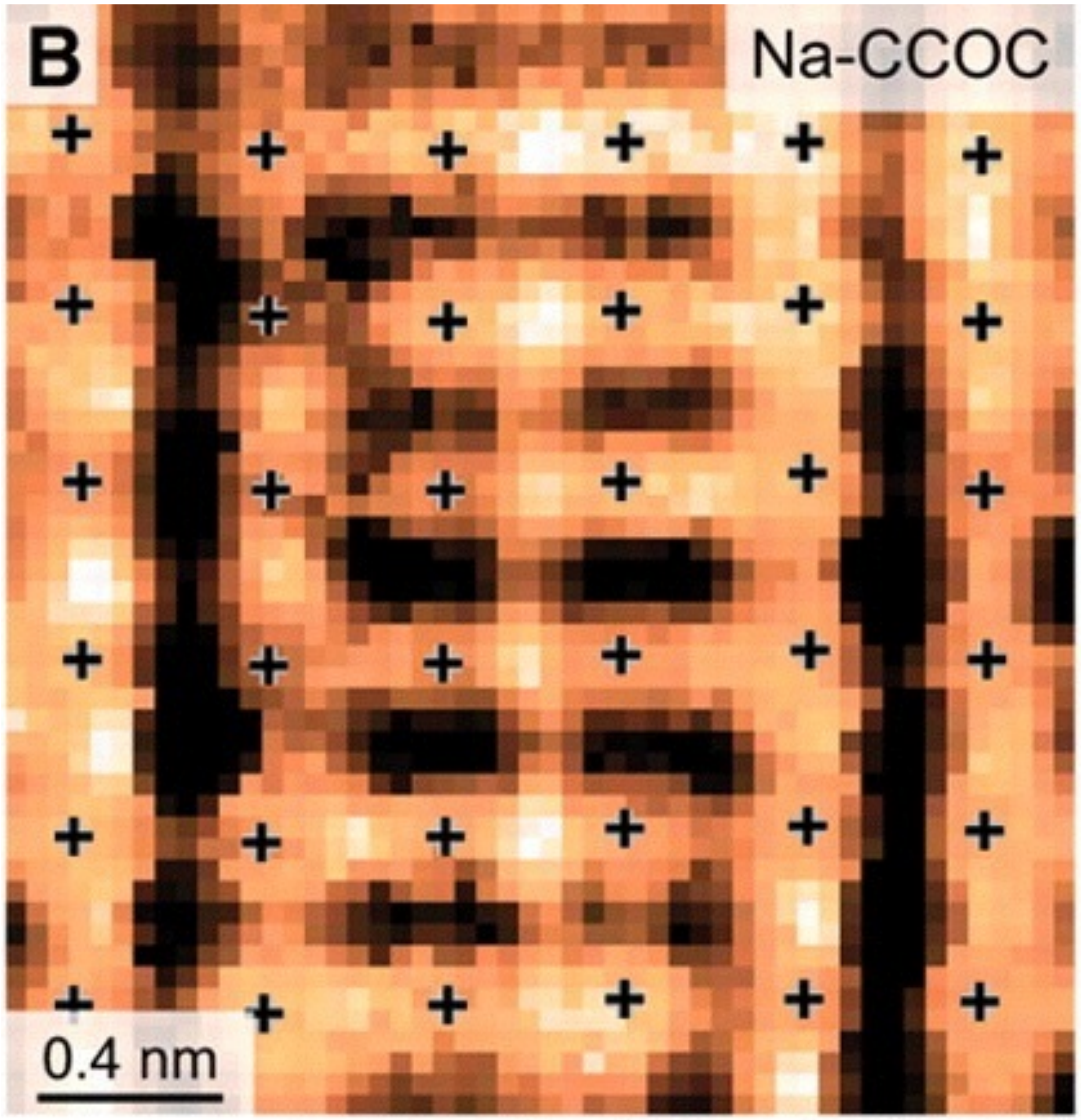


Y. Kohsaka *et al.*, Science **315**, 1380 (2007)

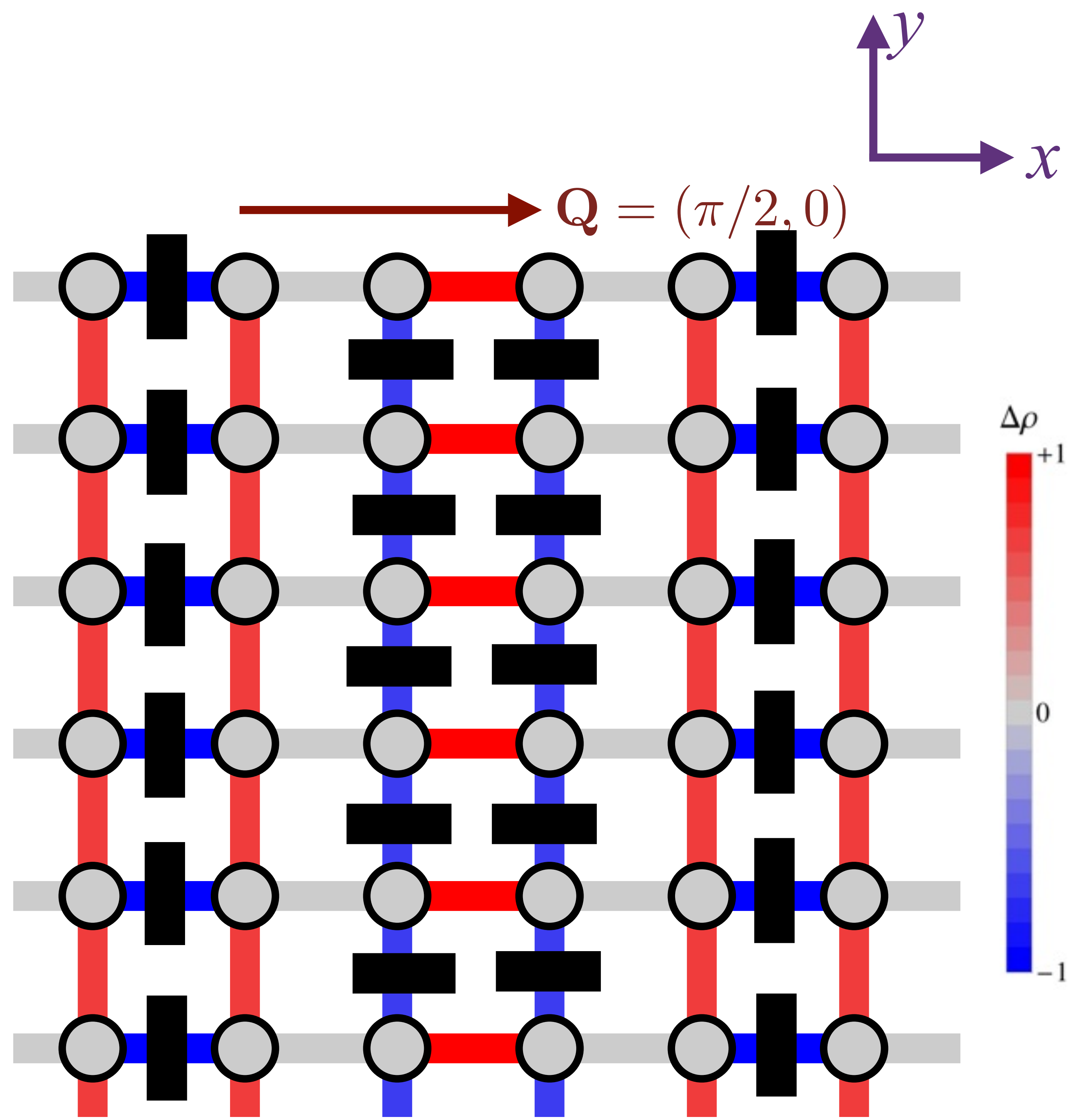


d-form factor density wave order

This specific *d*-form factor density wave order (with **Q** along the axes) was first predicted in S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).



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



d-form factor density wave order

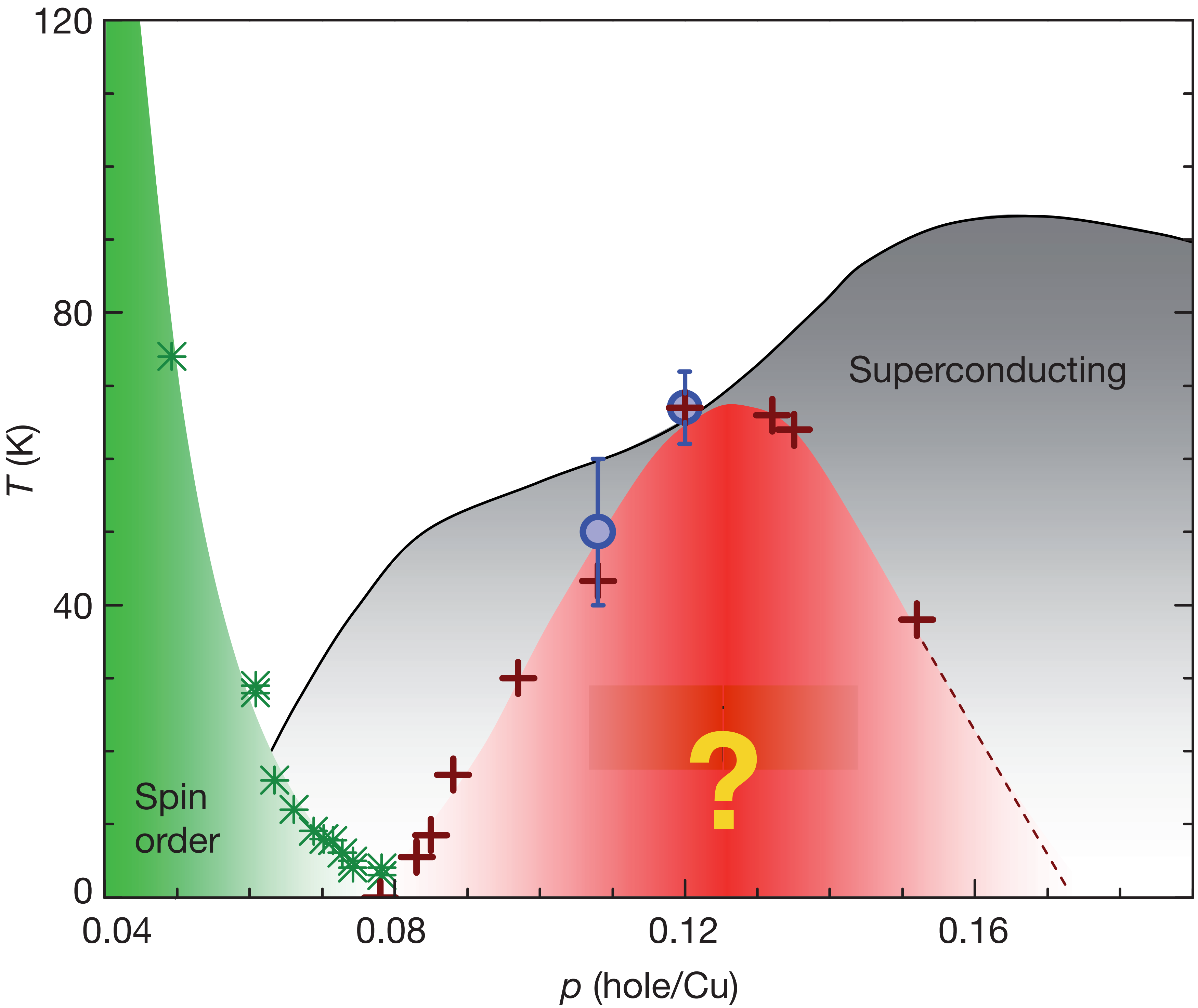
d form factor is compatible with STM measurements on BSCCO, Na-CCOC !

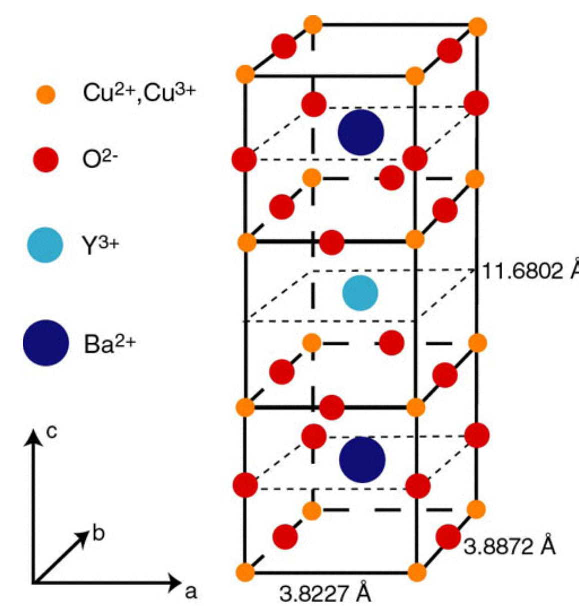
Direct phase-sensitive identification of a *d*-form factor density wave in underdoped cuprates

Kazuhiro Fujita[a,b,c,1], Mohammad H. Hamidian[a,b,1], Stephen D. Edkins[b,d], Chung Koo Kim[a], Yuhki Kohsaka[e], Masaki Azuma[f], Mikio Takano[g], Hidenori Takagi[c,h,i], Hiroshi Eisaki[j], Shin-ichi Uchida[c], Andrea Allais[k], Michael J. Lawler[b,l], Eun-Ah Kim[b], Subir Sachdev[k,m], and J. C. Séamus Davis[a,b,d,2]

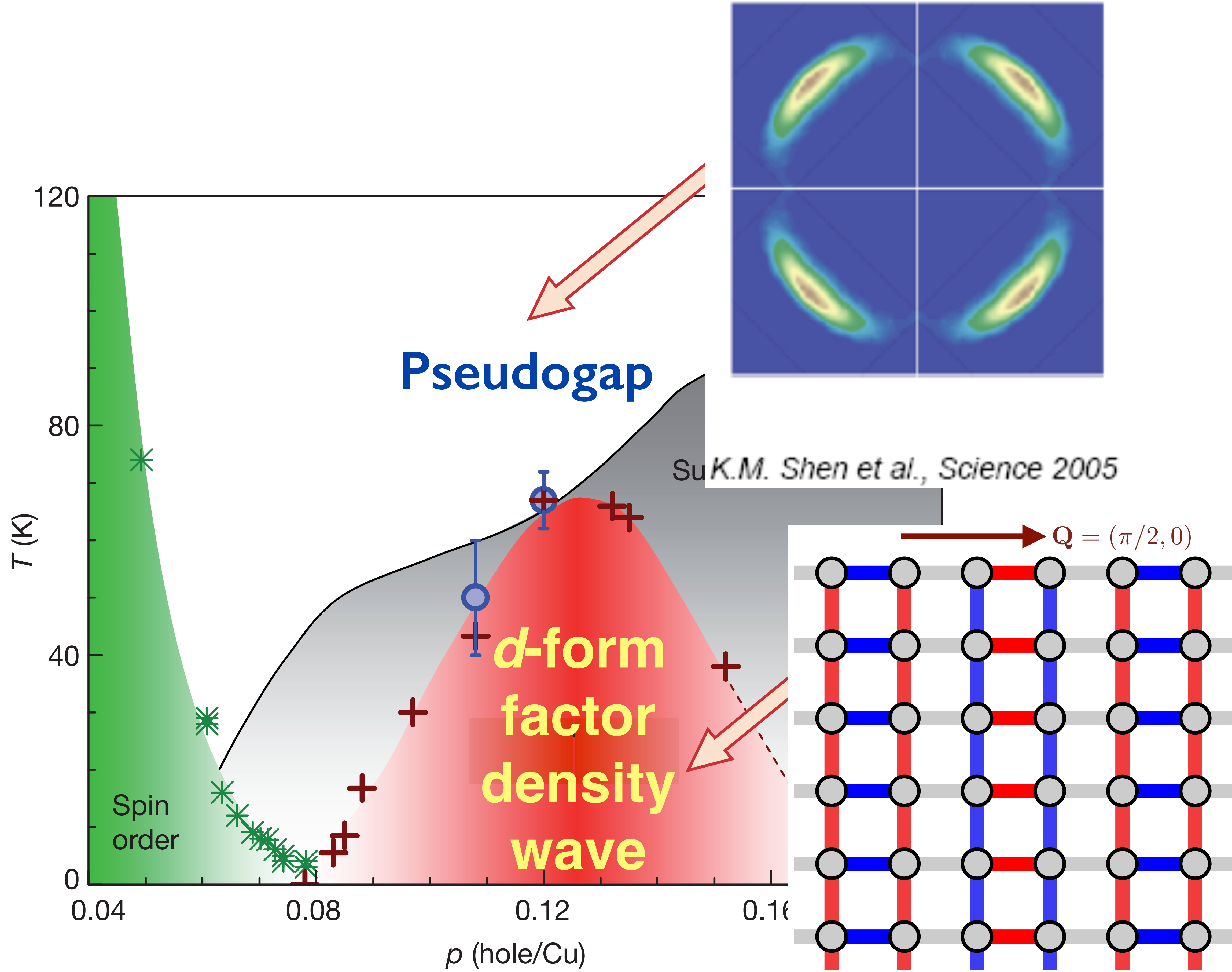
The identity of the fundamental broken symmetry (if any) in the underdoped cuprates is unresolved. However, evidence has been accumulating that this state may be an unconventional density wave. Here we carry out site-specific measurements within each CuO_2 unit cell, segregating the results into three separate electronic structure images containing only the Cu sites [$Cu(r)$] and only the x/y axis O sites [$O_x(r)$ and $O_y(r)$]. Phase-resolved Fourier analysis reveals directly that the modulations in the $O_x(r)$ and $O_y(r)$ sublattice images consistently exhibit a relative phase of π. We confirm this discovery on two highly distinct cuprate compounds, ruling out tunnel matrix-element and materials-specific systematics. These observations demonstrate by direct sublattice phase-resolved visualization that the density wave found in underdoped cuprates consists of modulations of the intraunit-cell states that exhibit a predominantly *d*-symmetry form factor.

Proceedings of the National Academy of Sciences **111**, E3026 (2014)





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).



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