Unveiling the order of the high temperature superconductors

City College of New York
October 22, 2014

Subir Sachdev

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

NSF

JOHN TEMPLETON FOUNDATION

PHYSICS

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Talk online: sachdev.physics.harvard.edu

Theorists at Harvard

Max Metlitski
(KITP, UCSB)

Andrea Allais

Matthias Punk
(Innsbruck)

Debanjan
Chowdhury

Alexandra
Thomson

Cornell

Kazuhiro Fujita
Cornell/ BNL

Mohammad Hamidian
Cornell / BNL

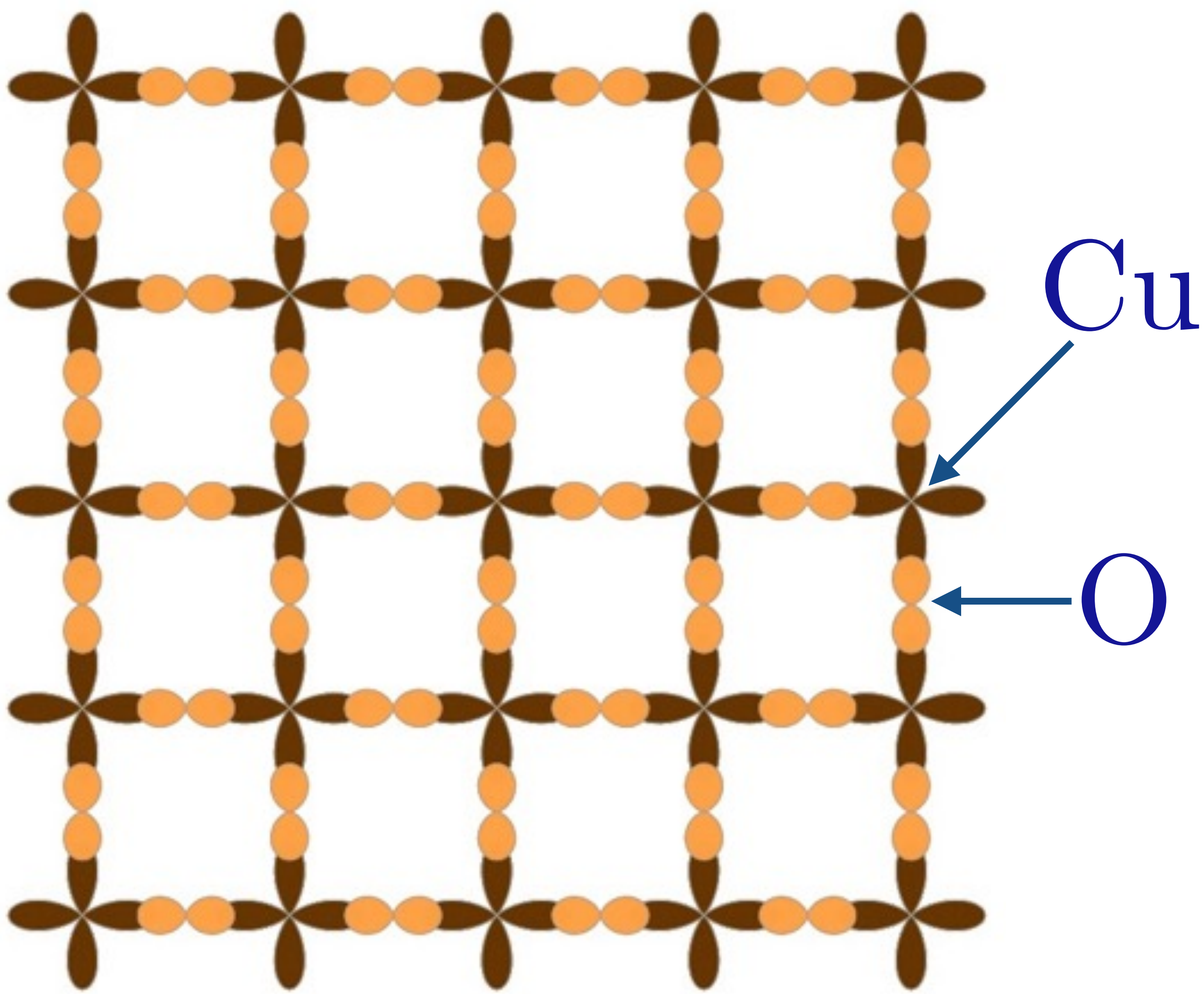
Stephen Edkins
Cornell / St Andrews

Michael Lawler

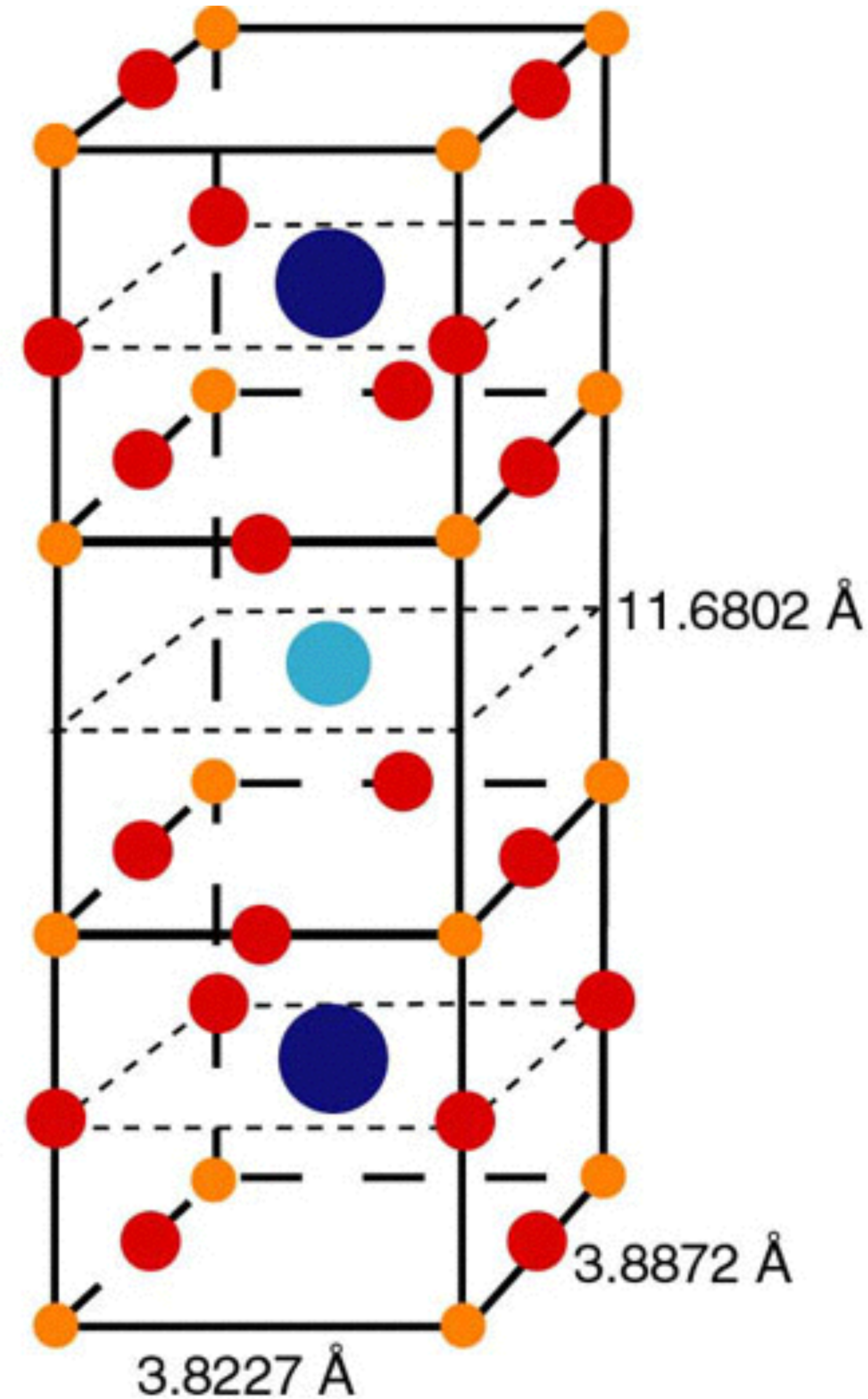
J. C. Seamus Davis

Eun-Ah Kim

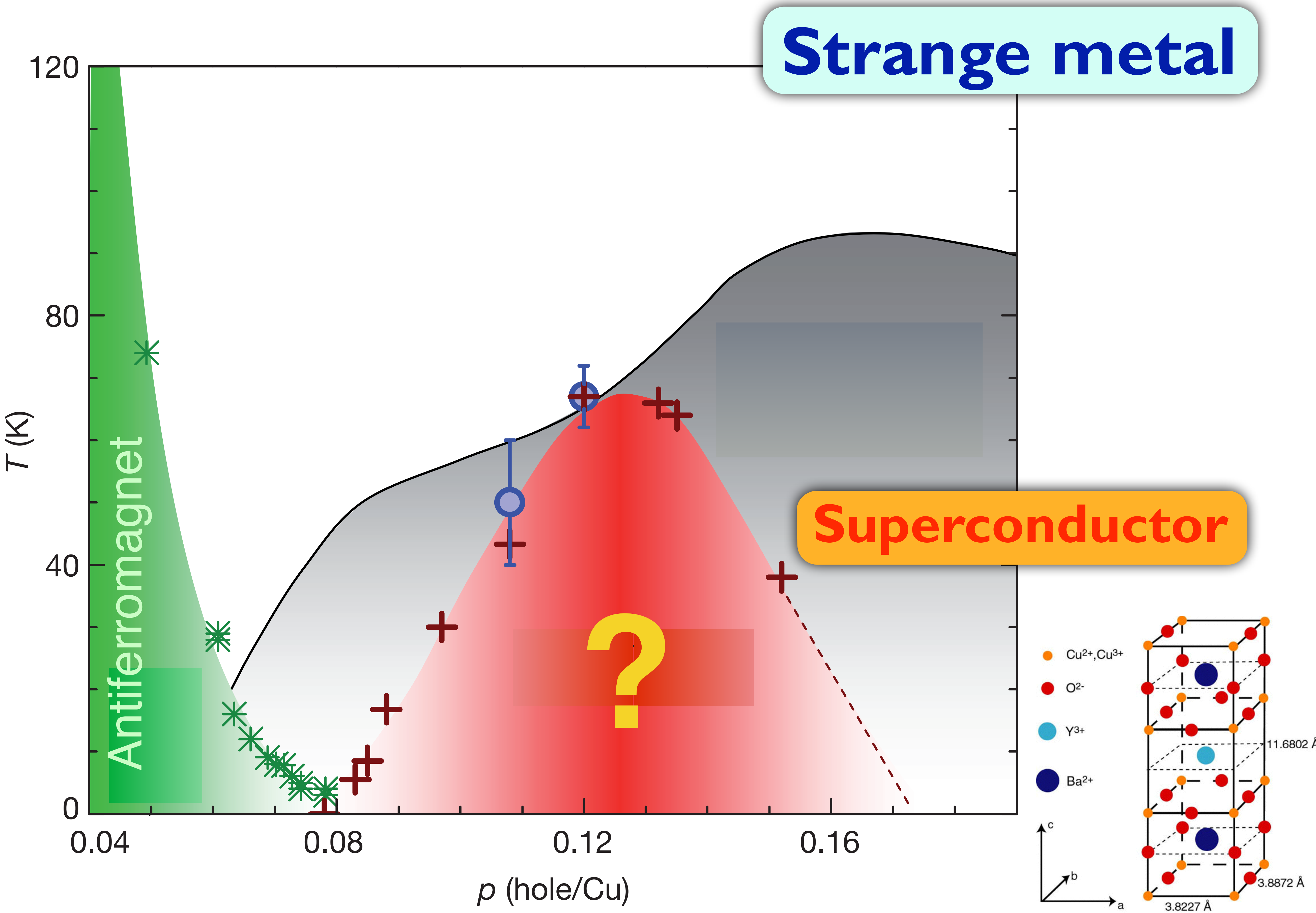
High temperature superconductors



CuO_2 plane



$YBa_2Cu_3O_{6+x}$



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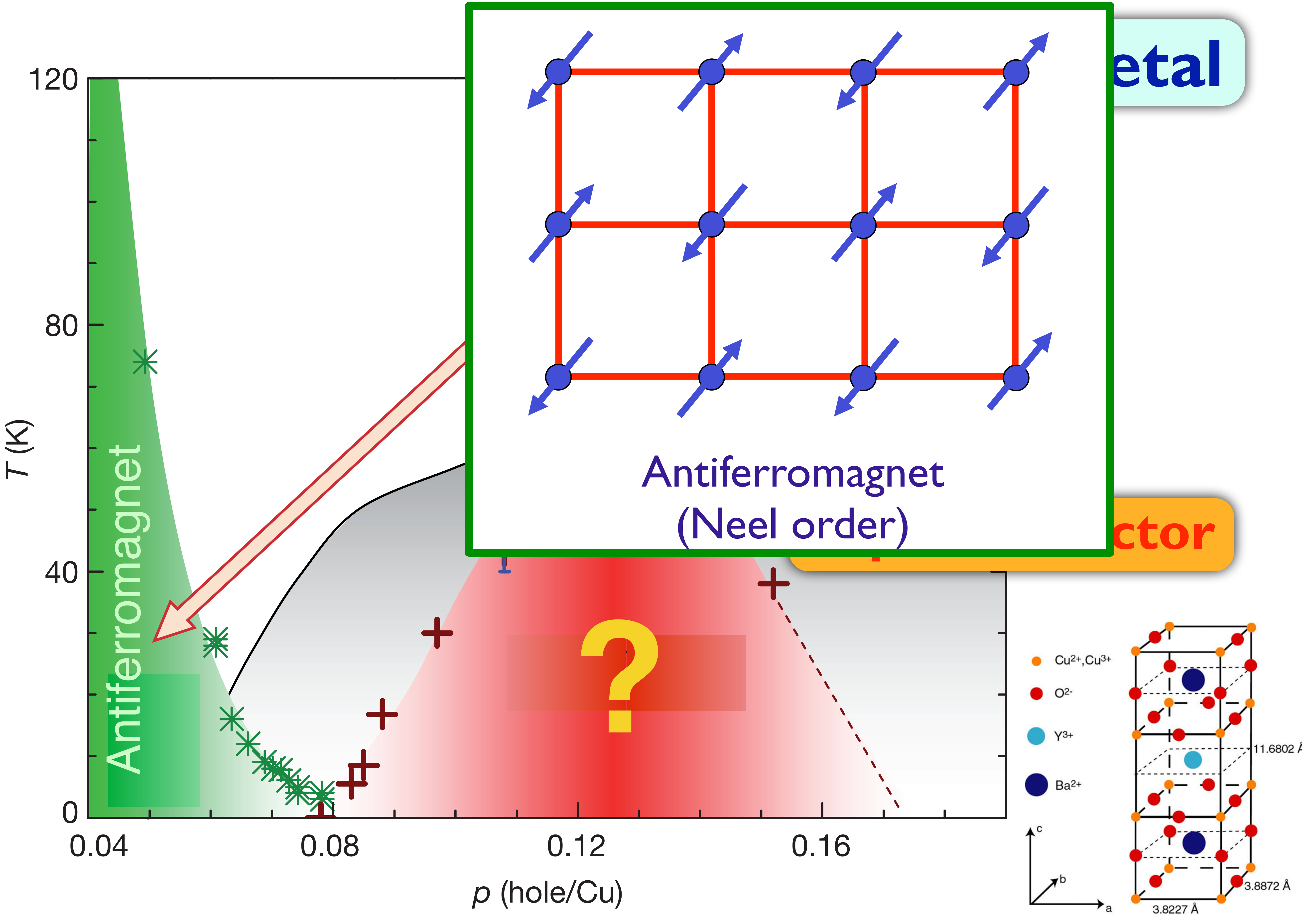

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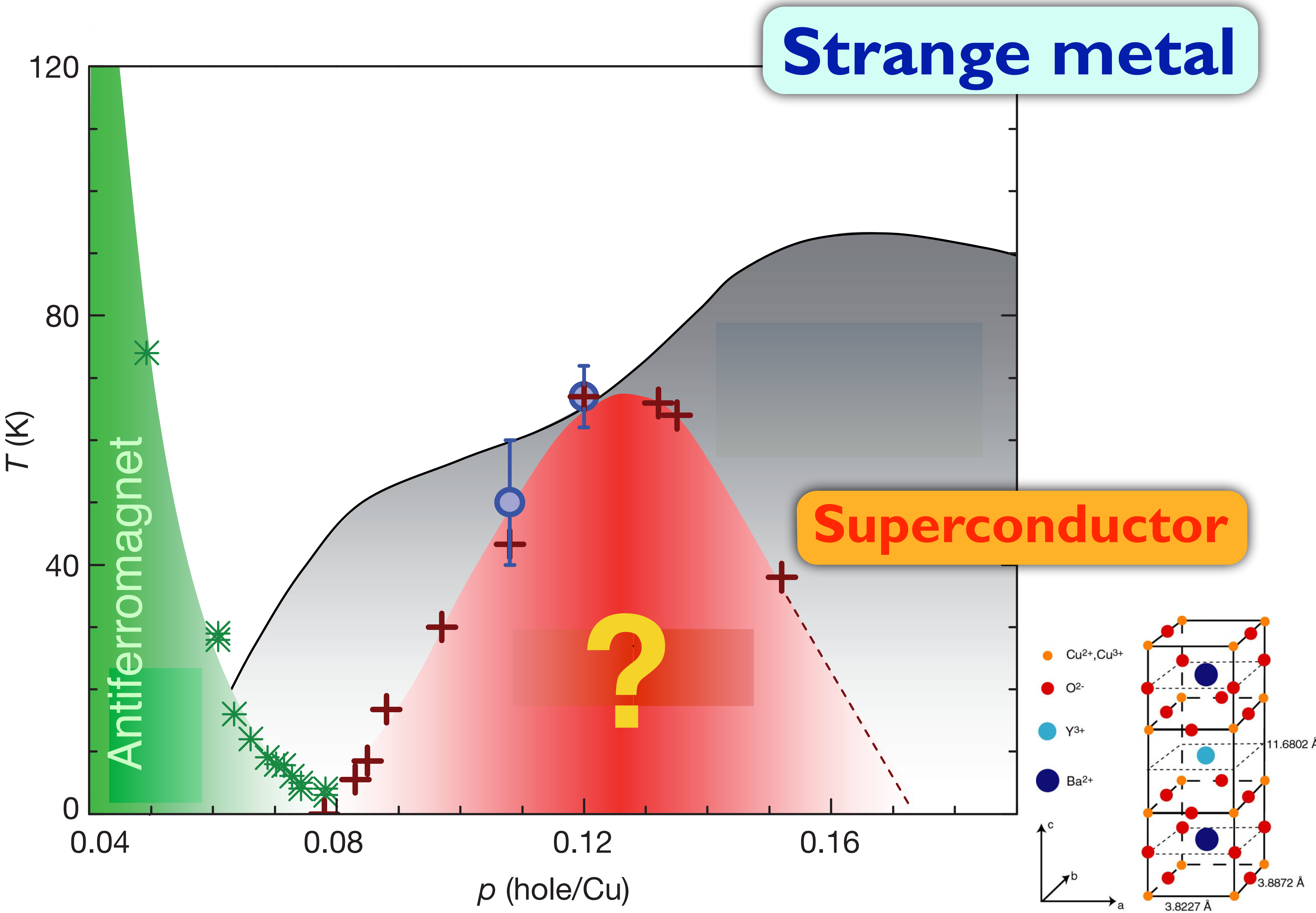

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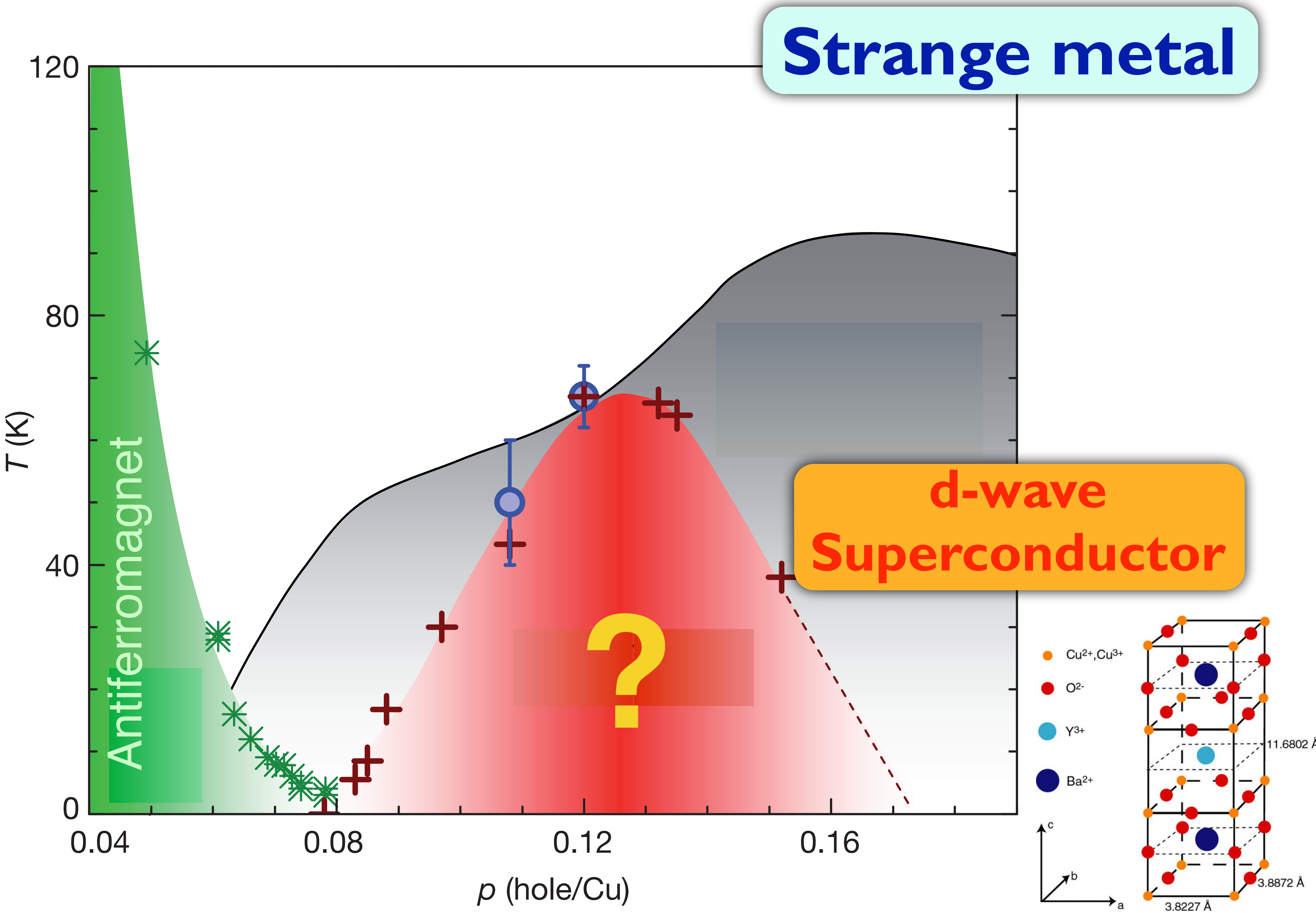

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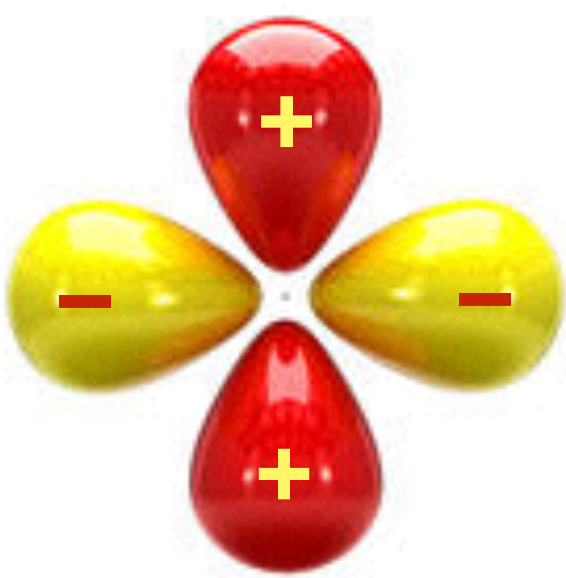
Superconductivity:
Bose condensation of Cooper pairs of electrons

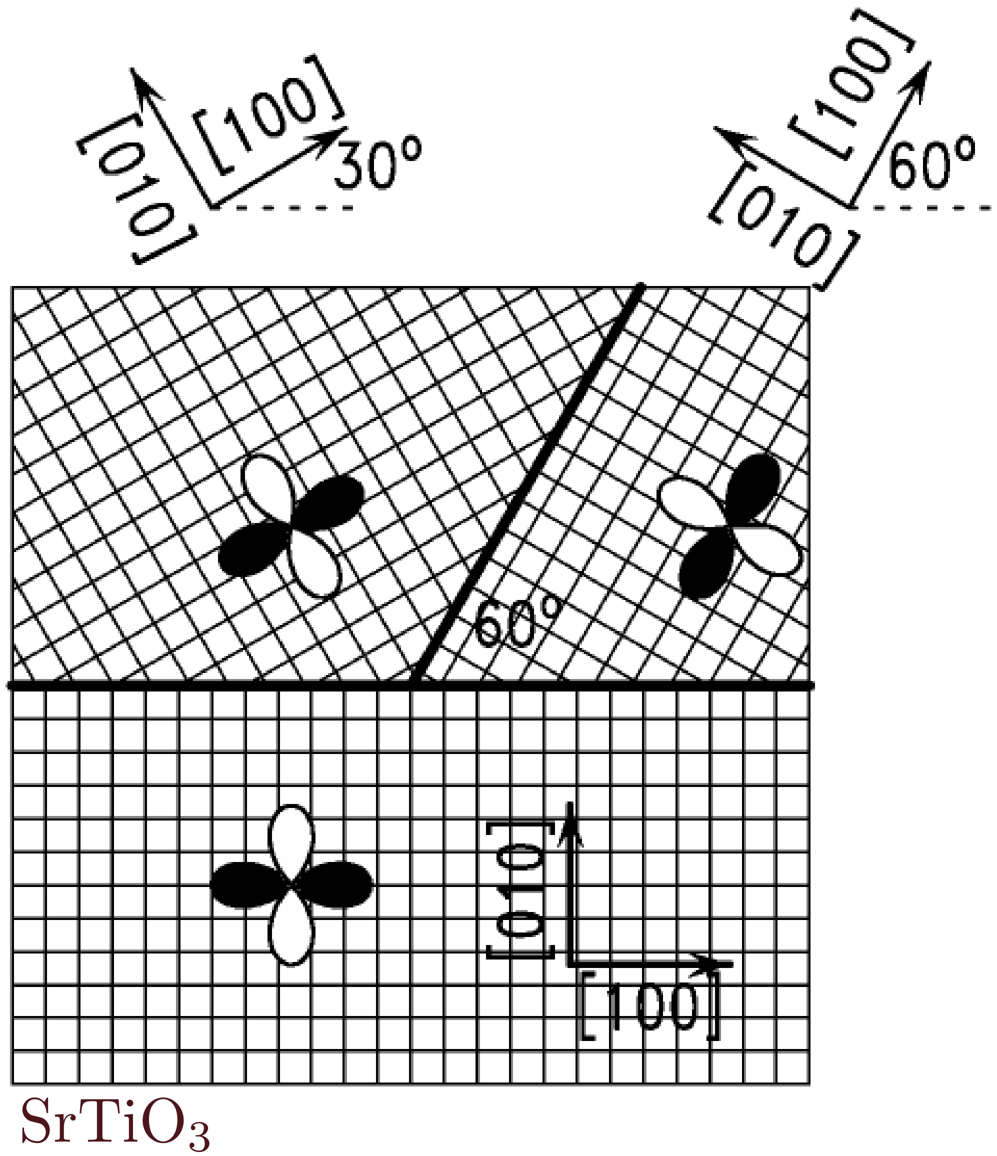
$$\varepsilon^{\alpha\beta}\left\langle c^\dagger_\alpha(\mathbf{r}_1)c^\dagger_\beta(\mathbf{r}_2)\right\rangle = \Big[P(\mathbf{r}_1-\mathbf{r}_2)\Big] \times \Psi_{SC}\left(\frac{\mathbf{r}_1+\mathbf{r}_2}{2}\right)$$

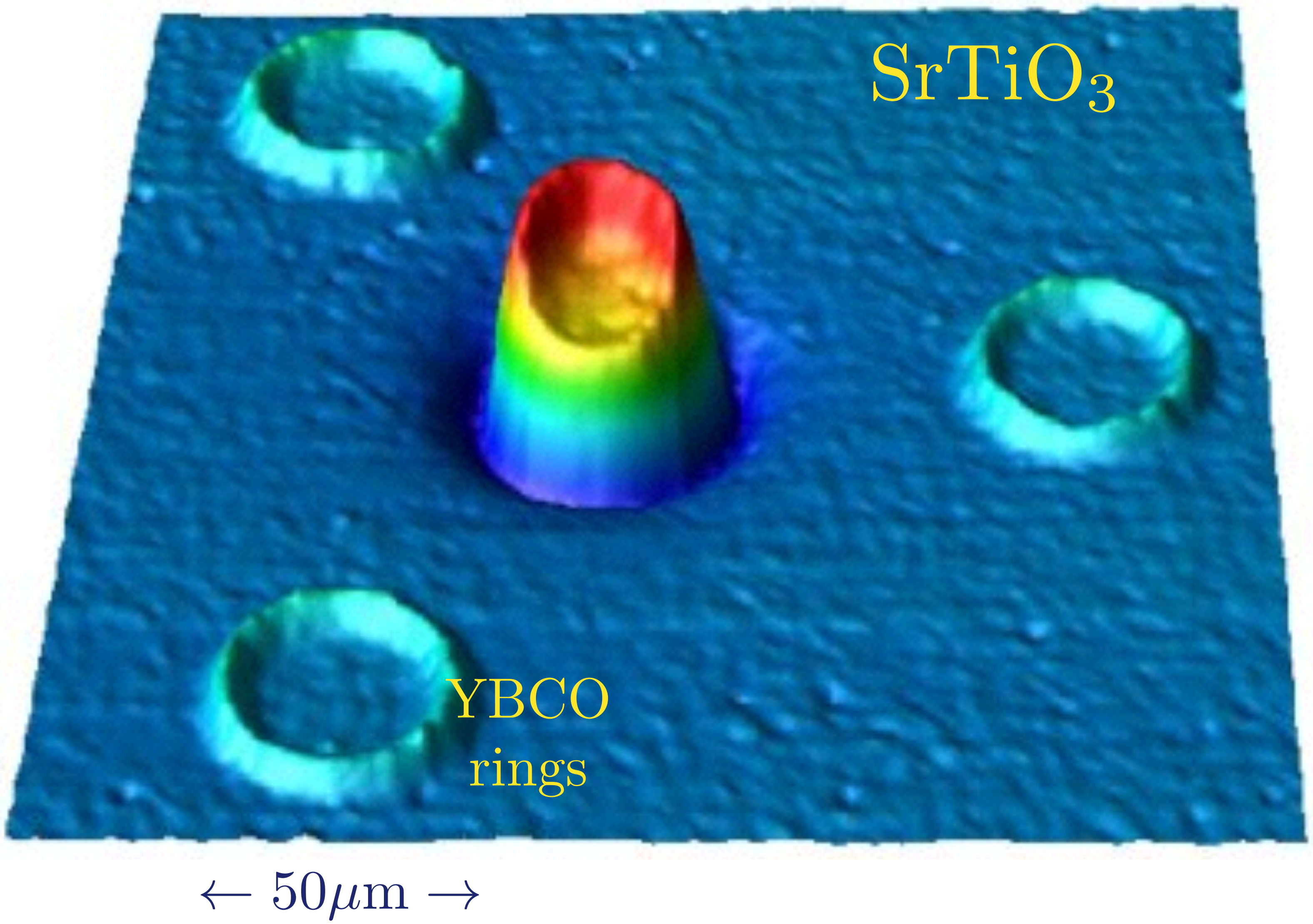


Internal Cooper-pair wavefunction.
Has *d*-wave form in cuprates

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

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

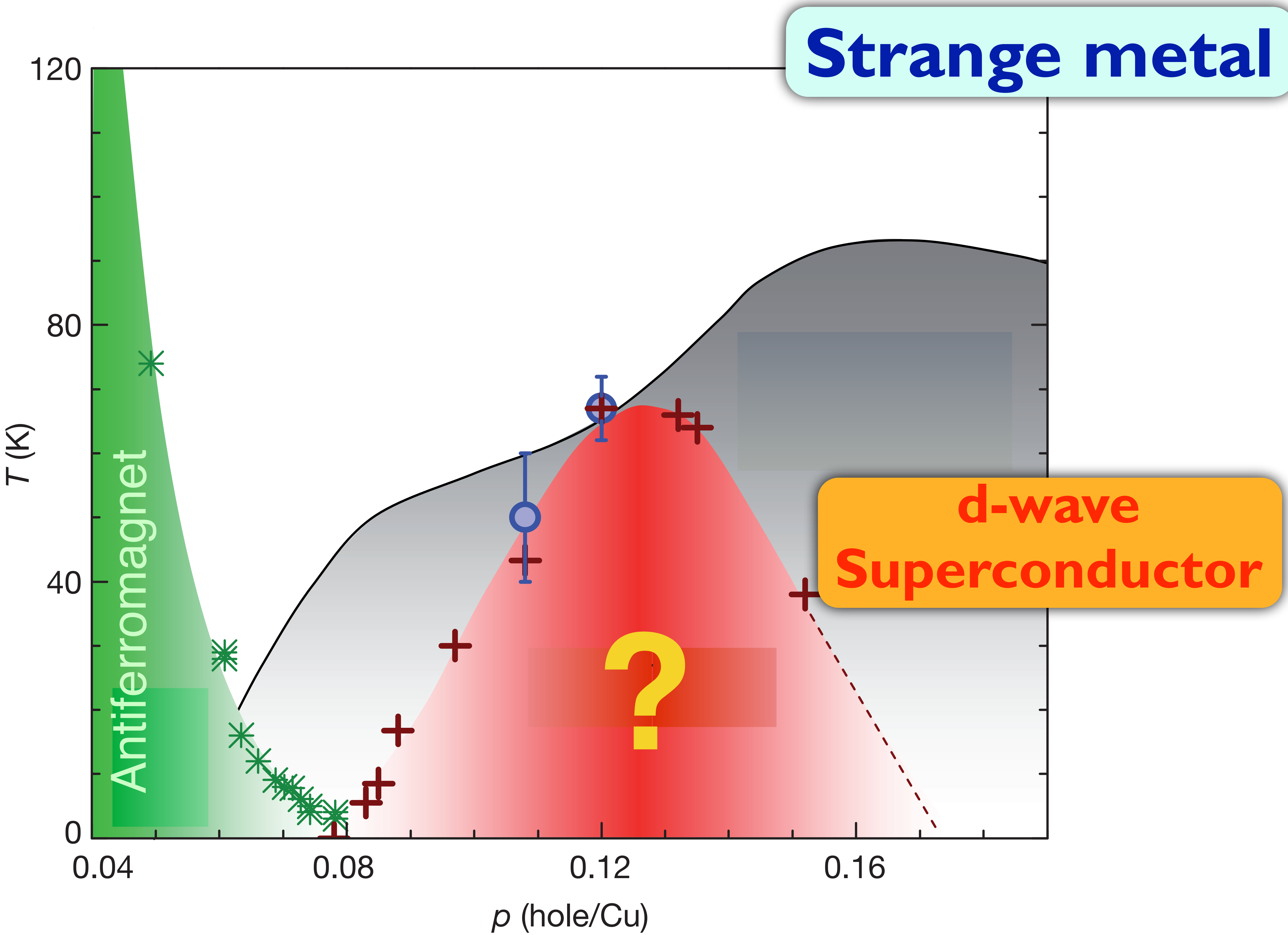




Pairing Symmetry and Flux Quantization in a Tricrystal Superconducting Ring of $YBa_2Cu_3O_{7-\delta}$

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)


Strange metal
120
80
40
0
T (K)
Antiferromagnet
?
d-wave
Superconductor
0.04
0.08
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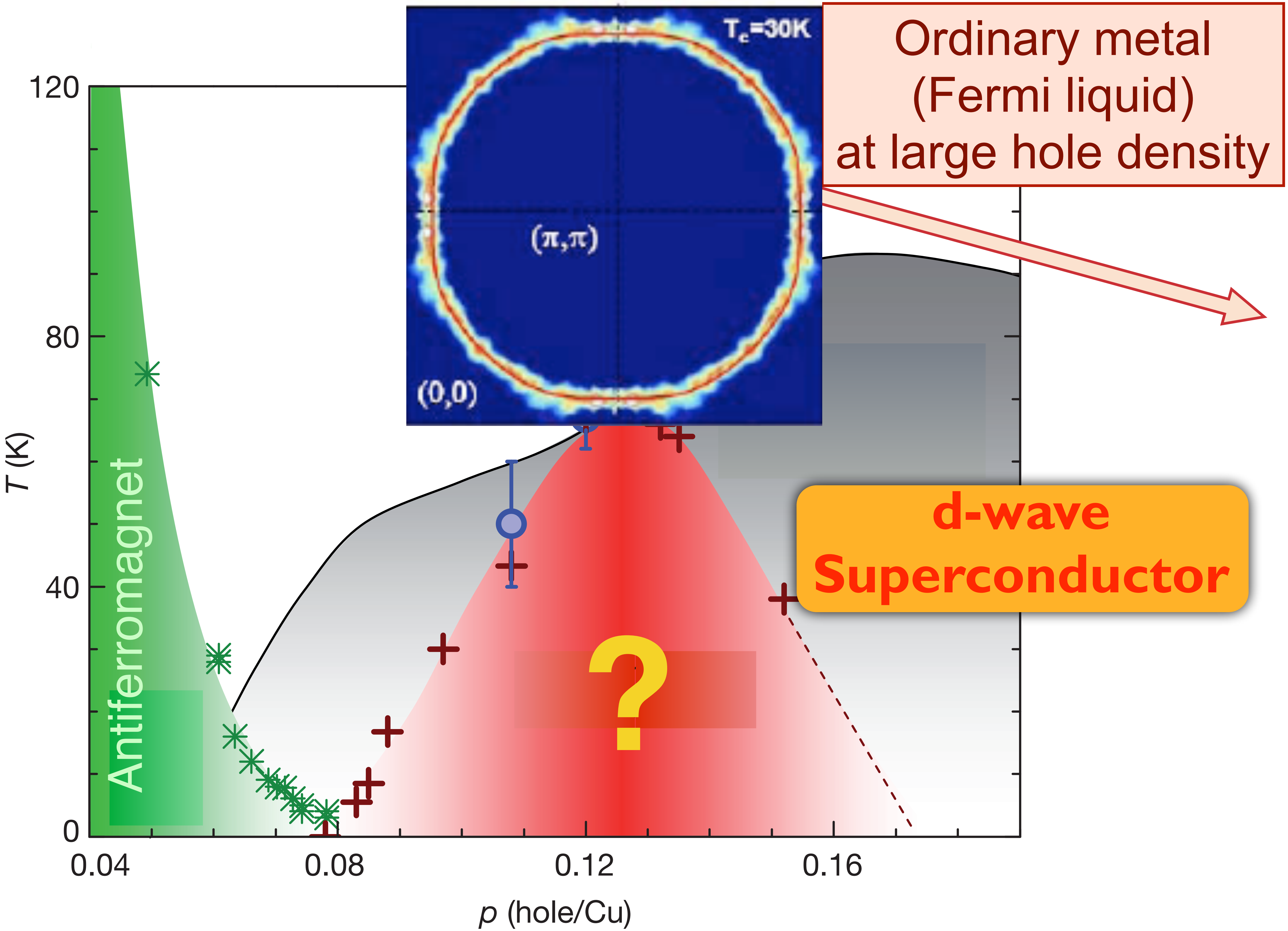
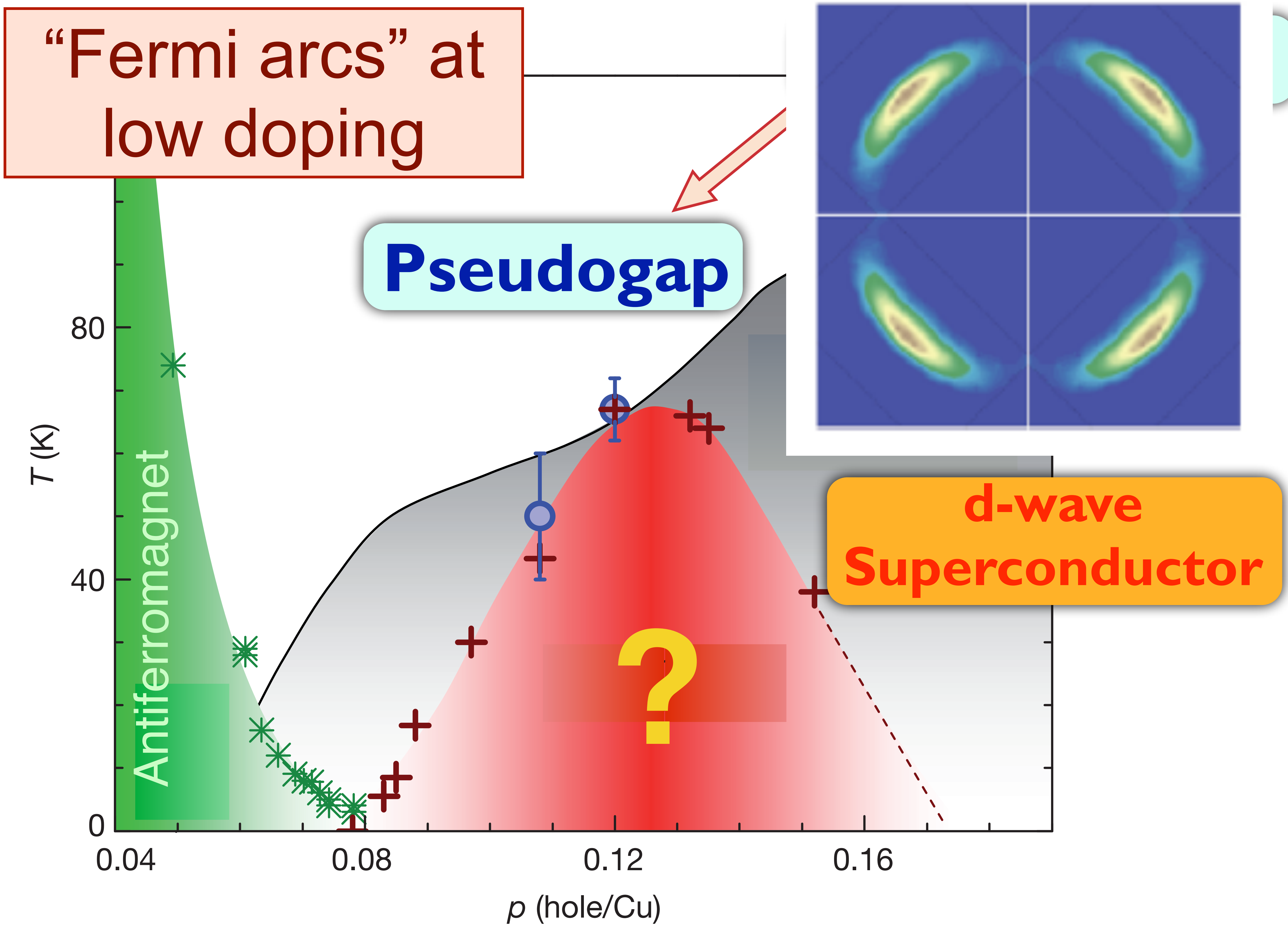
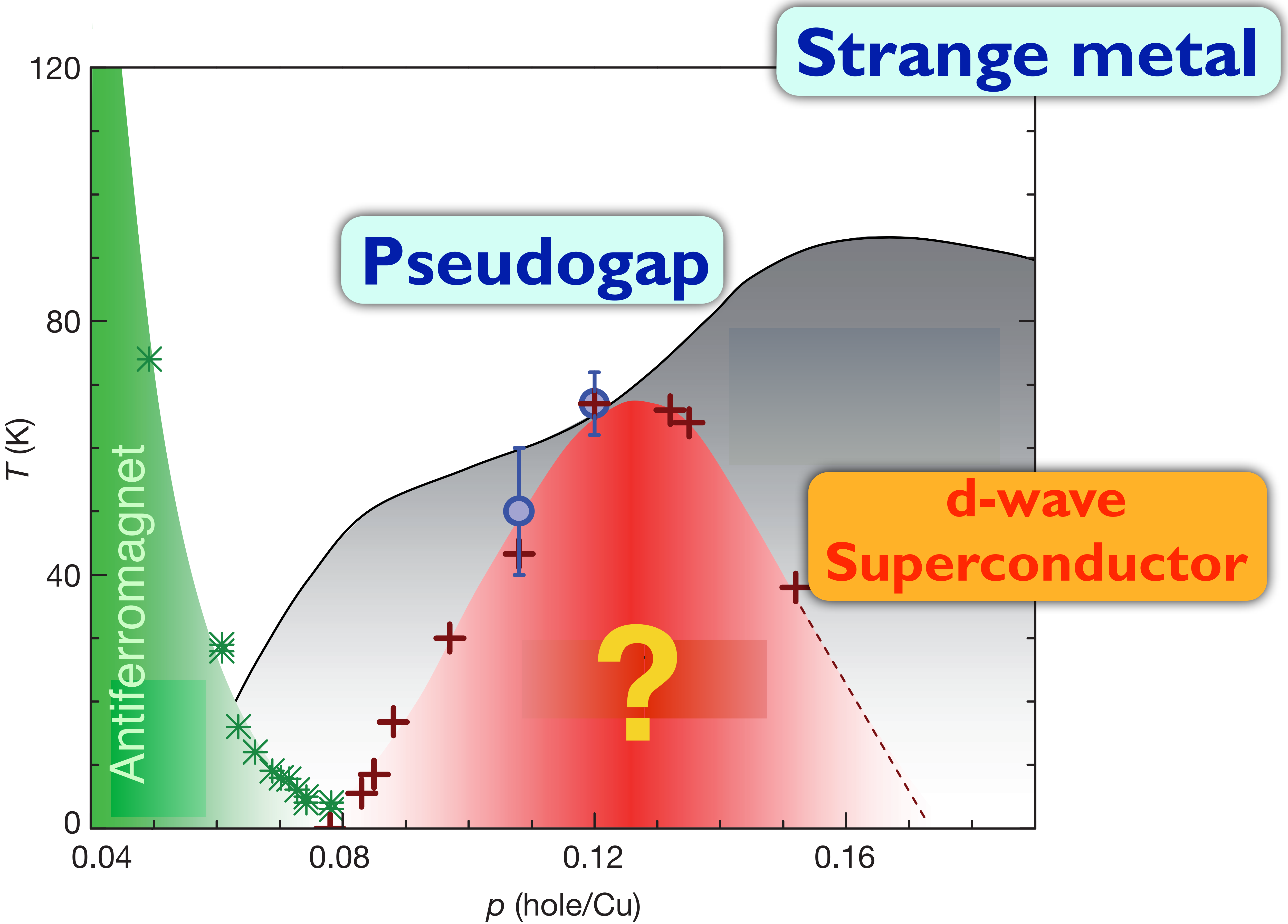
0.16
p (hole/Cu)



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



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)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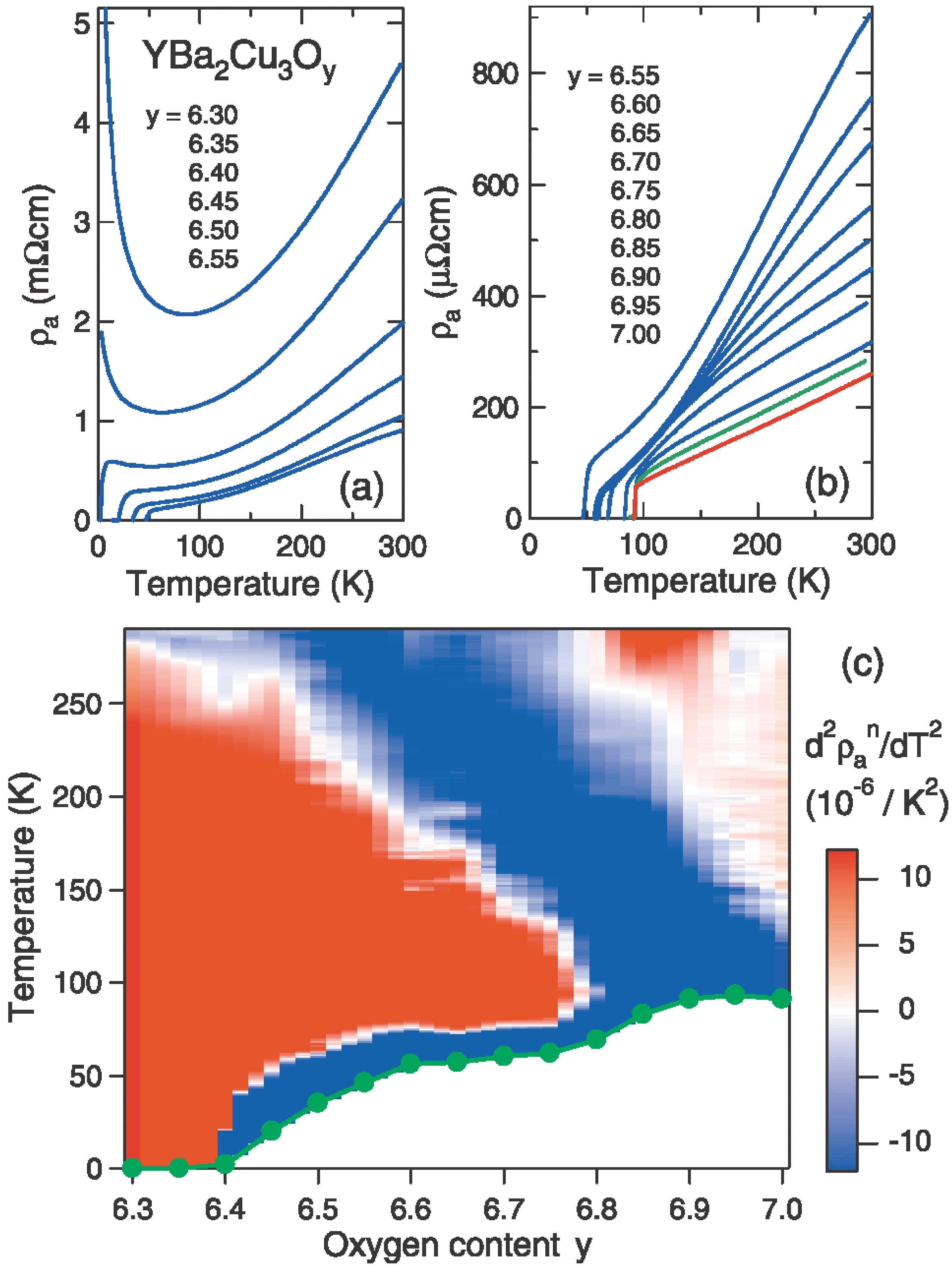
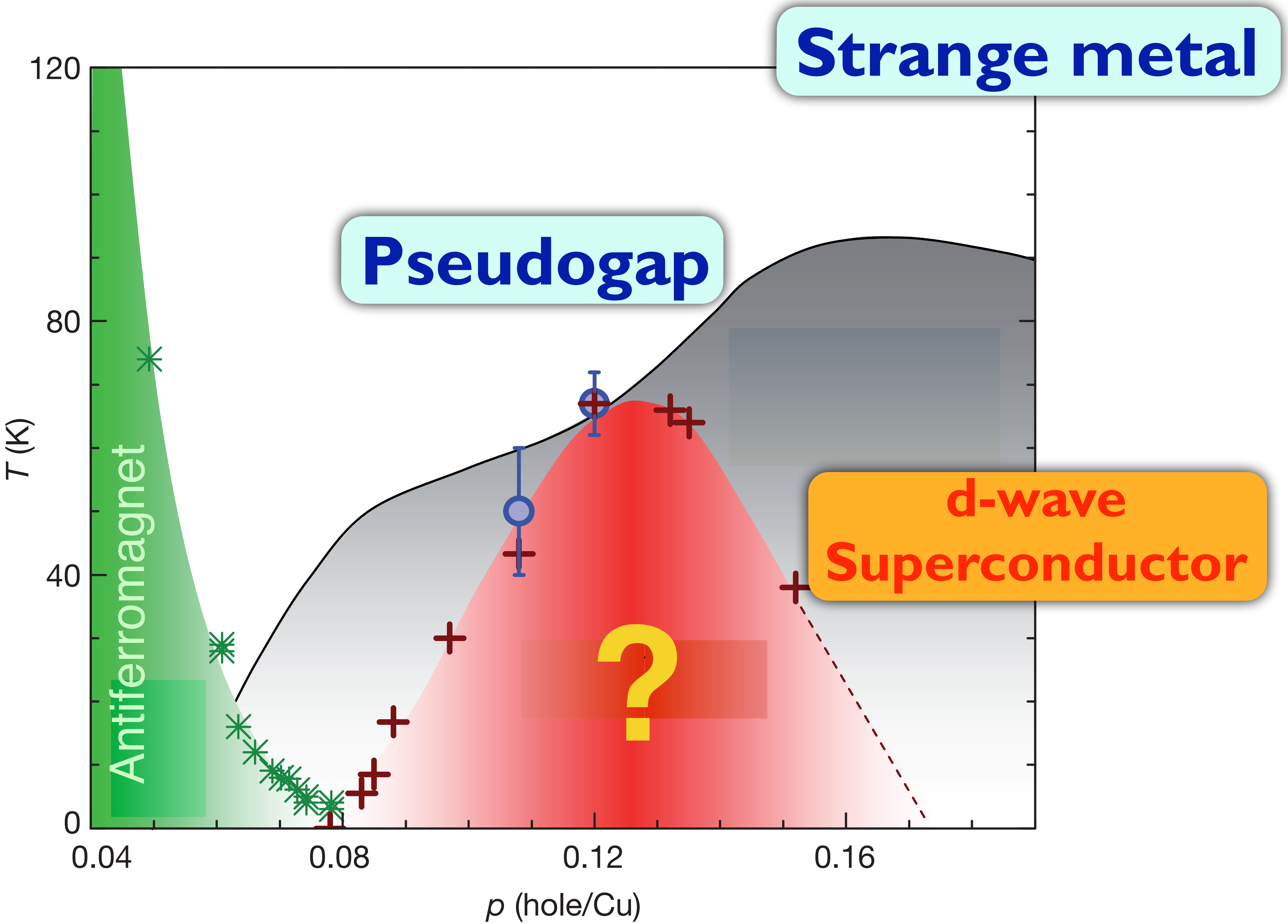
Strange metal



YBCO at optimal doping has resistivity $\rho(T) \sim T$.

Yoichi Ando, Seiki Komiya, Kouji Segawa, S. Ono, and Y. Kurita, Phys. Rev. Lett. **93**, 267001 (2004)



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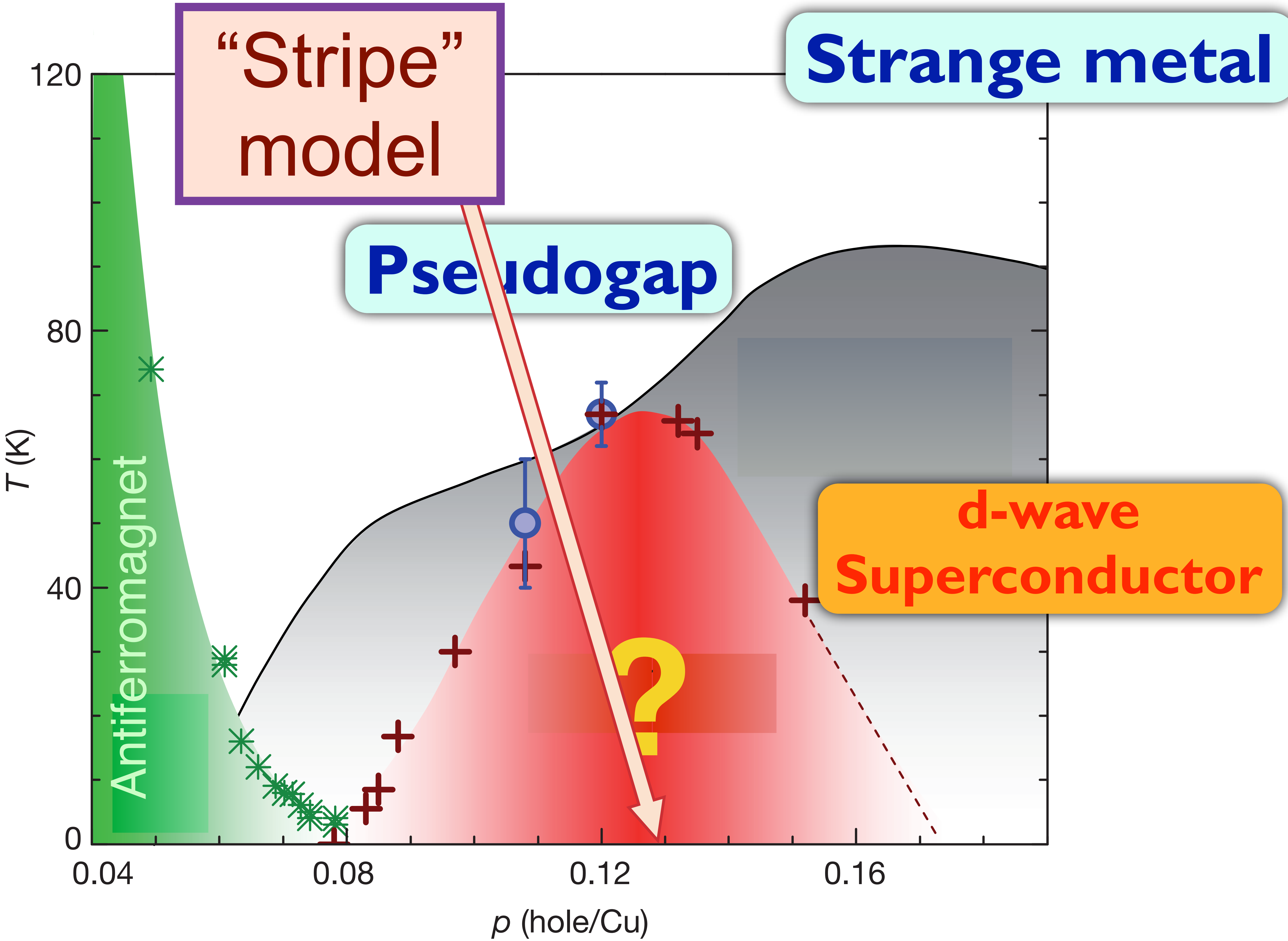

"Stripe" model
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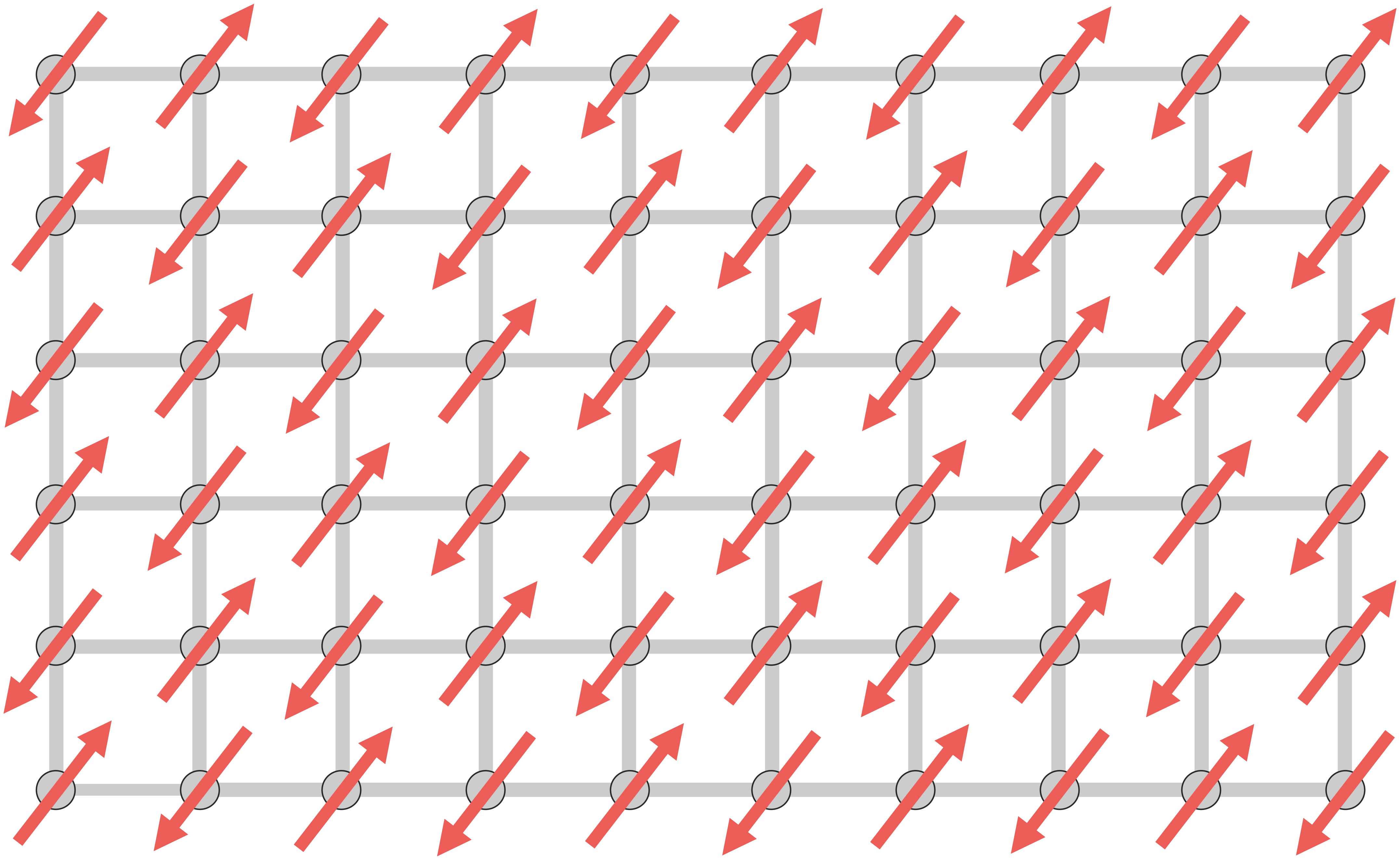
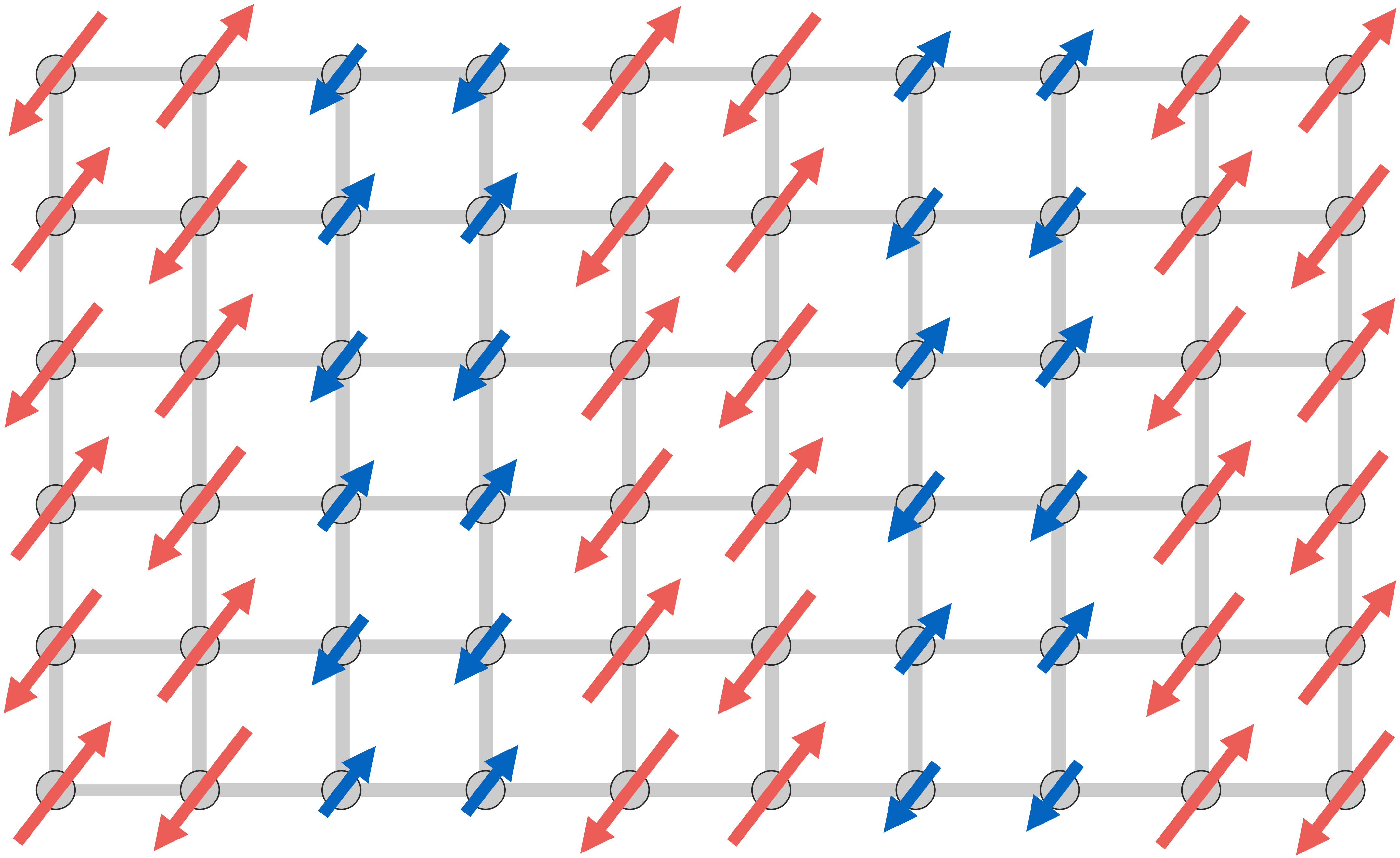
“Stripe” model



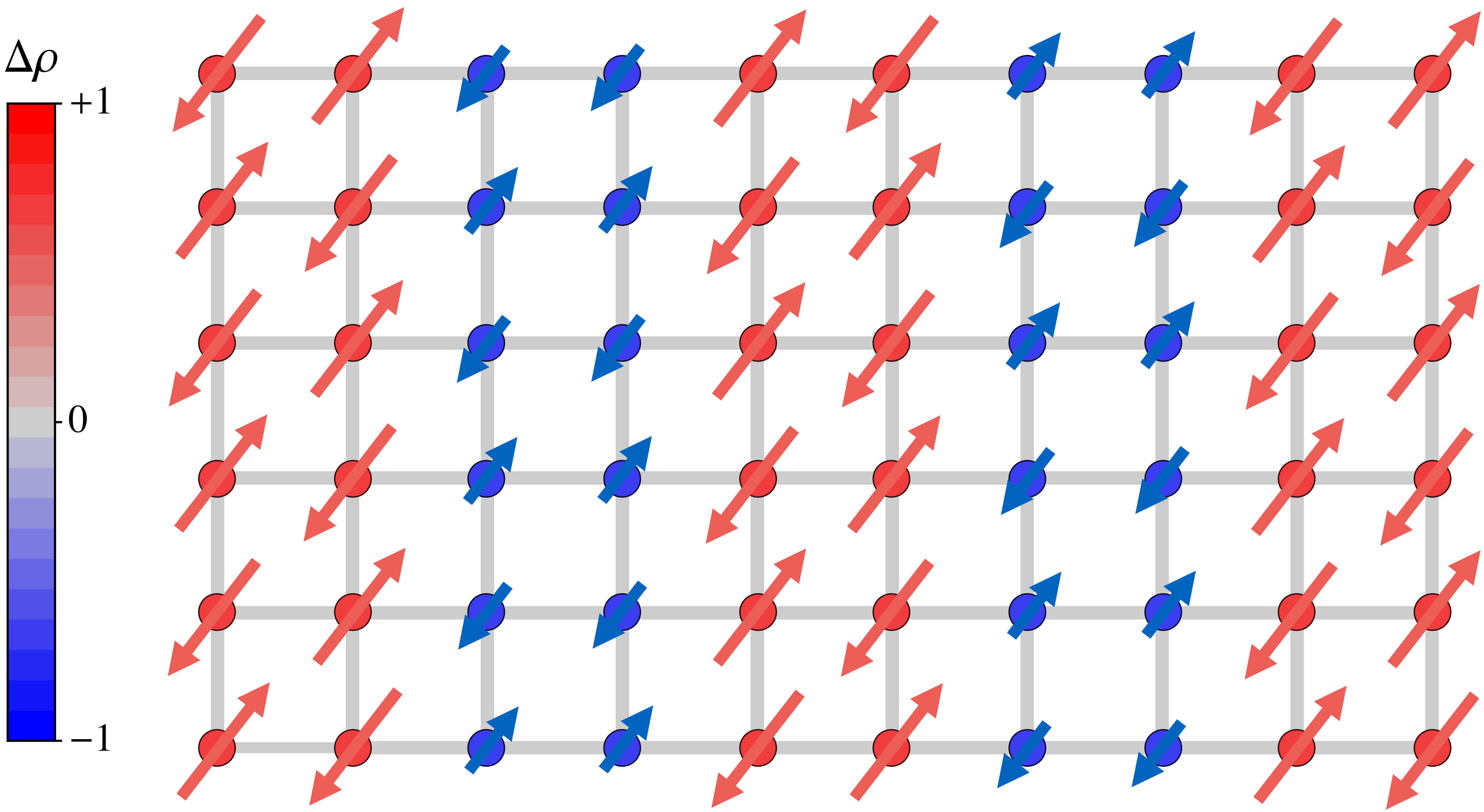
Start with an antiferromagnet

“Stripe” model



Domain walls 4 lattice spacings apart

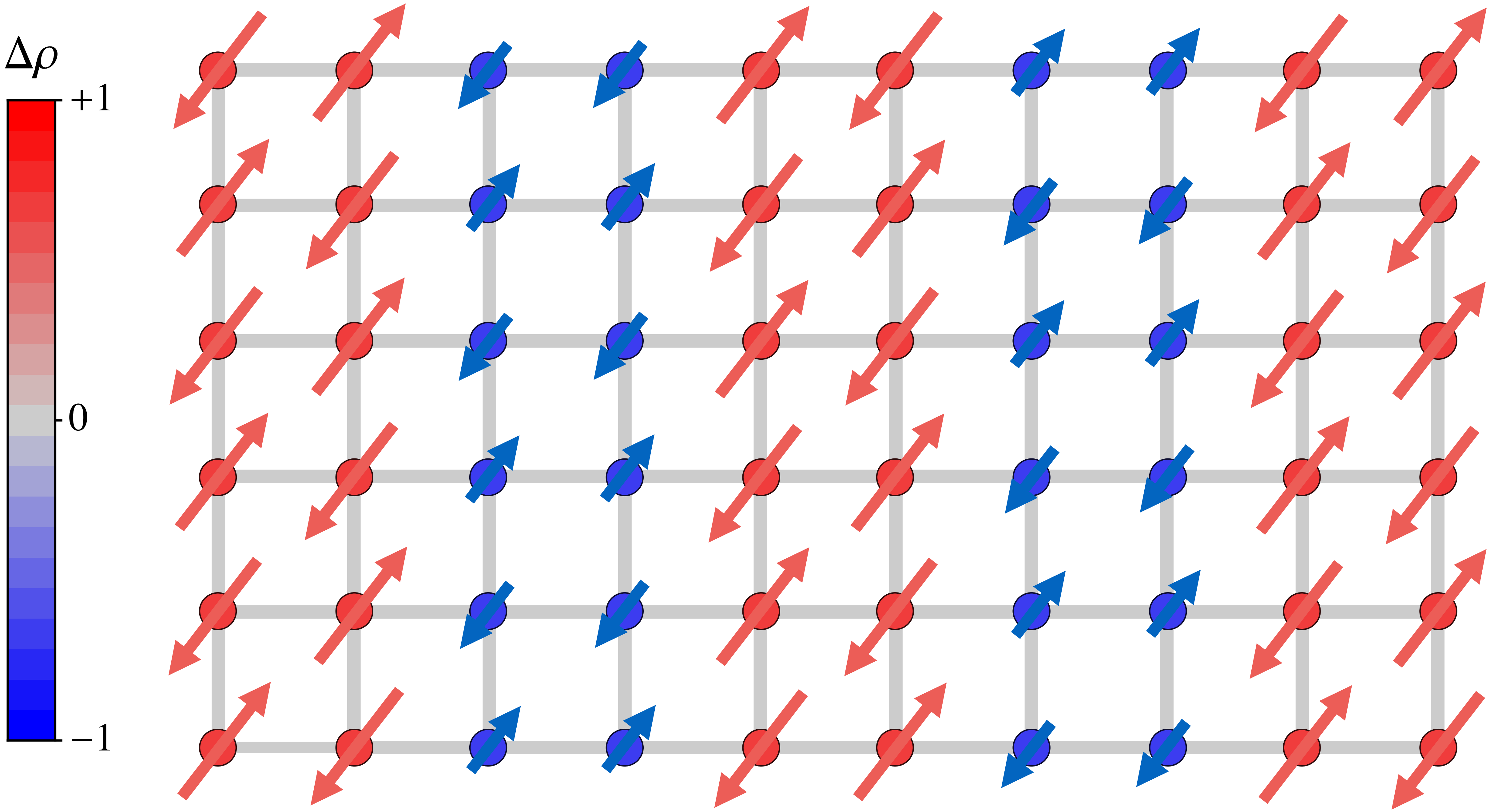
“Stripe” model



Put the holes in the domain walls

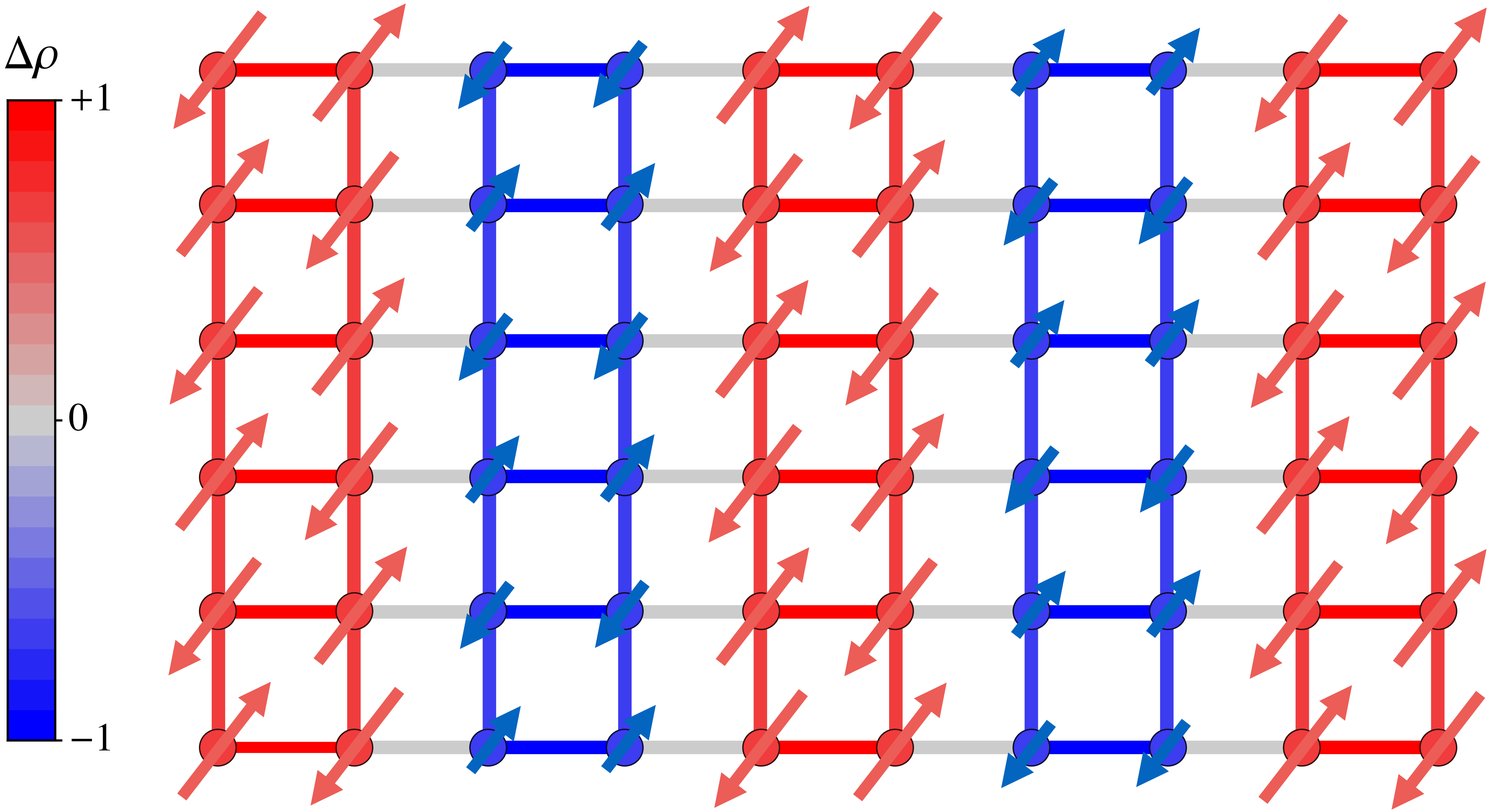
Observed in La-based compounds (Tranquada..)
Theory: Zaanen, Kivelson, Fradkin….

"Stripe" model

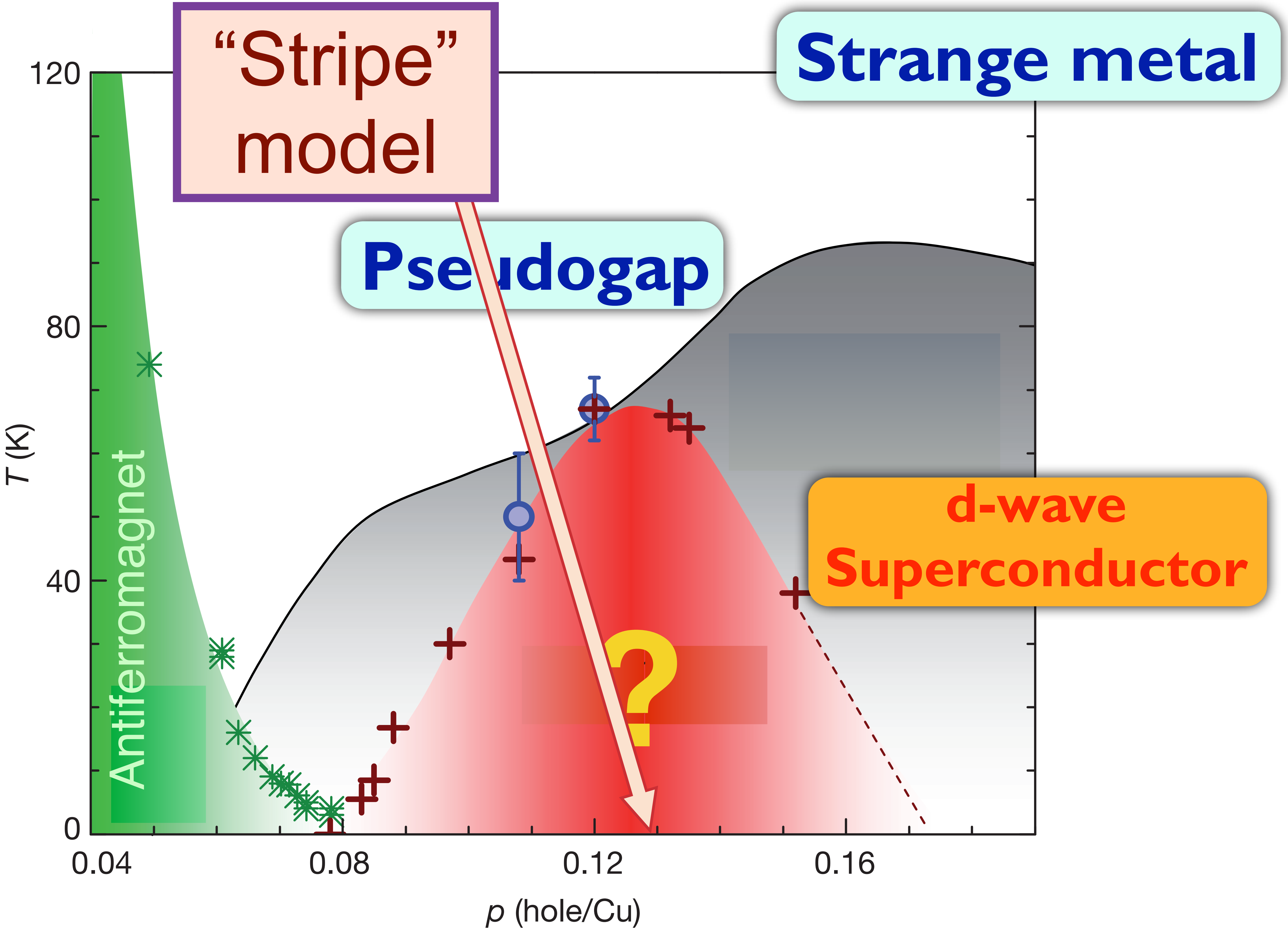


Put the holes in the domain walls

"Stripe" model



Colors on the bonds map the local exchange energy



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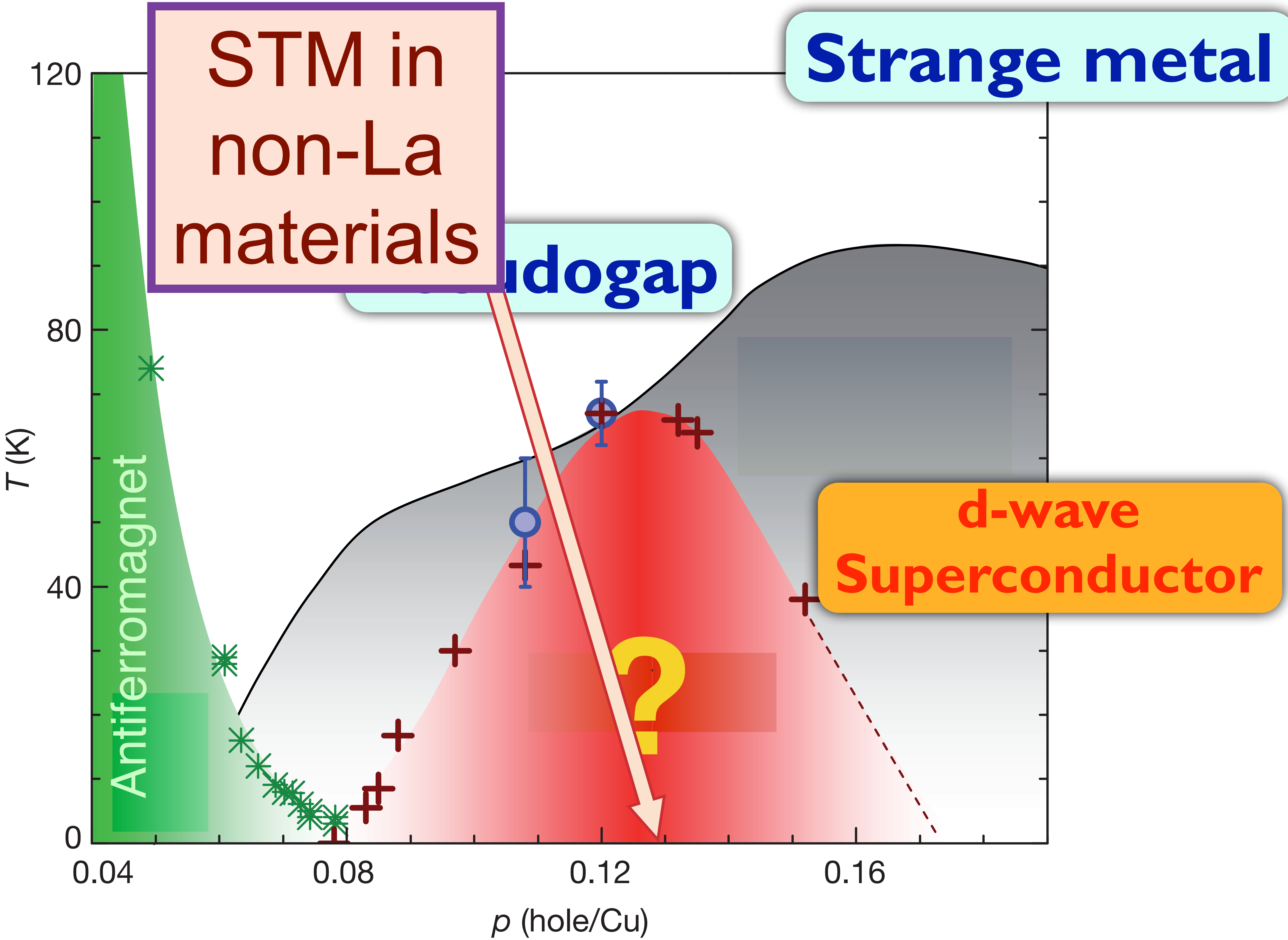

STM in non-La materials
Strange metal
Pseudogap
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See also
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M. Vershinin, S. Misra, S. Ono, Y. Abe, Yoichi Ando, and A. Yazdani, Science **303**, 1995 (2004).

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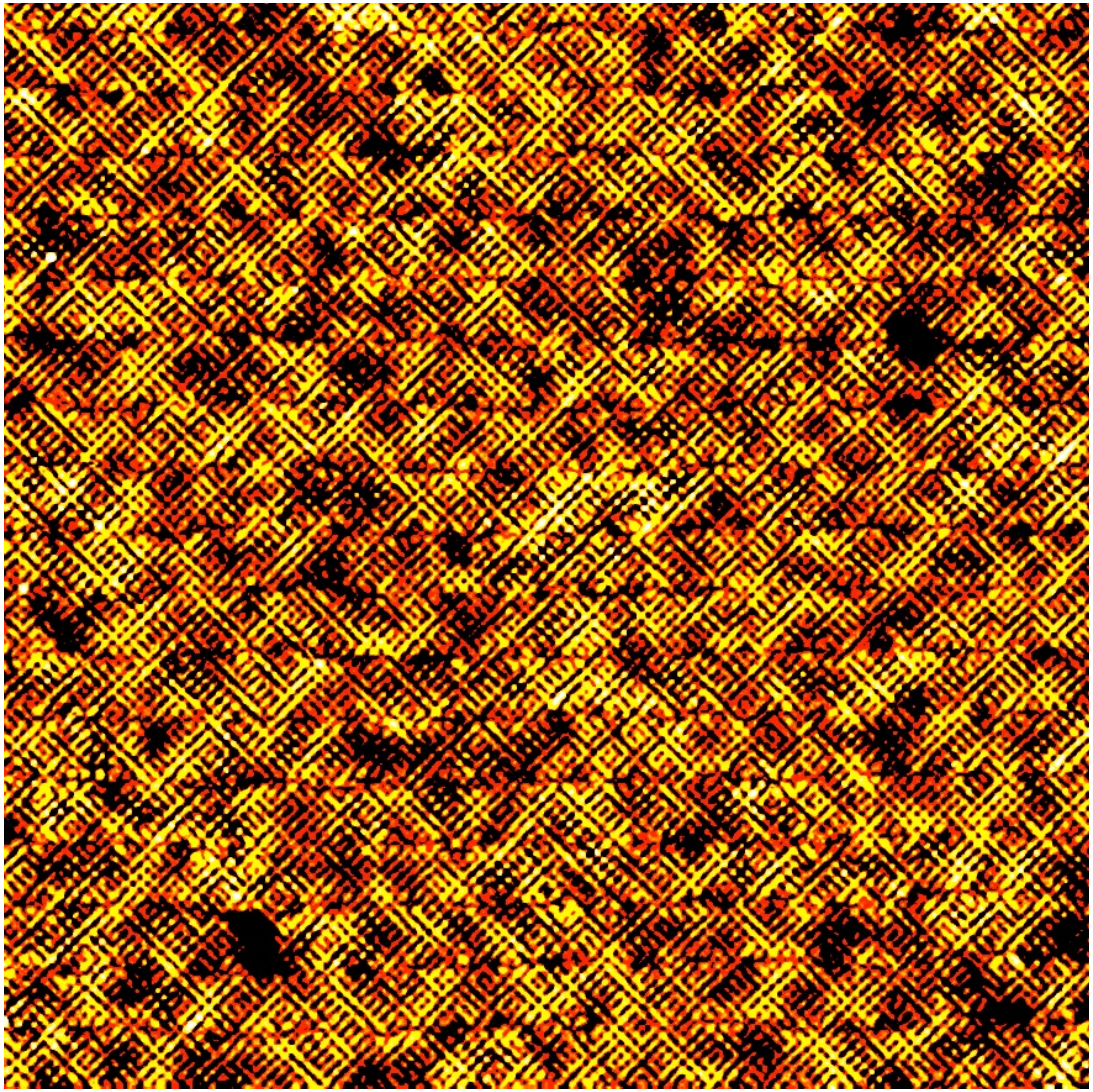

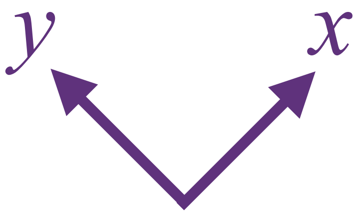

"R-map" of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007). Davis group has sub-angstrom resolution capabilities, with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

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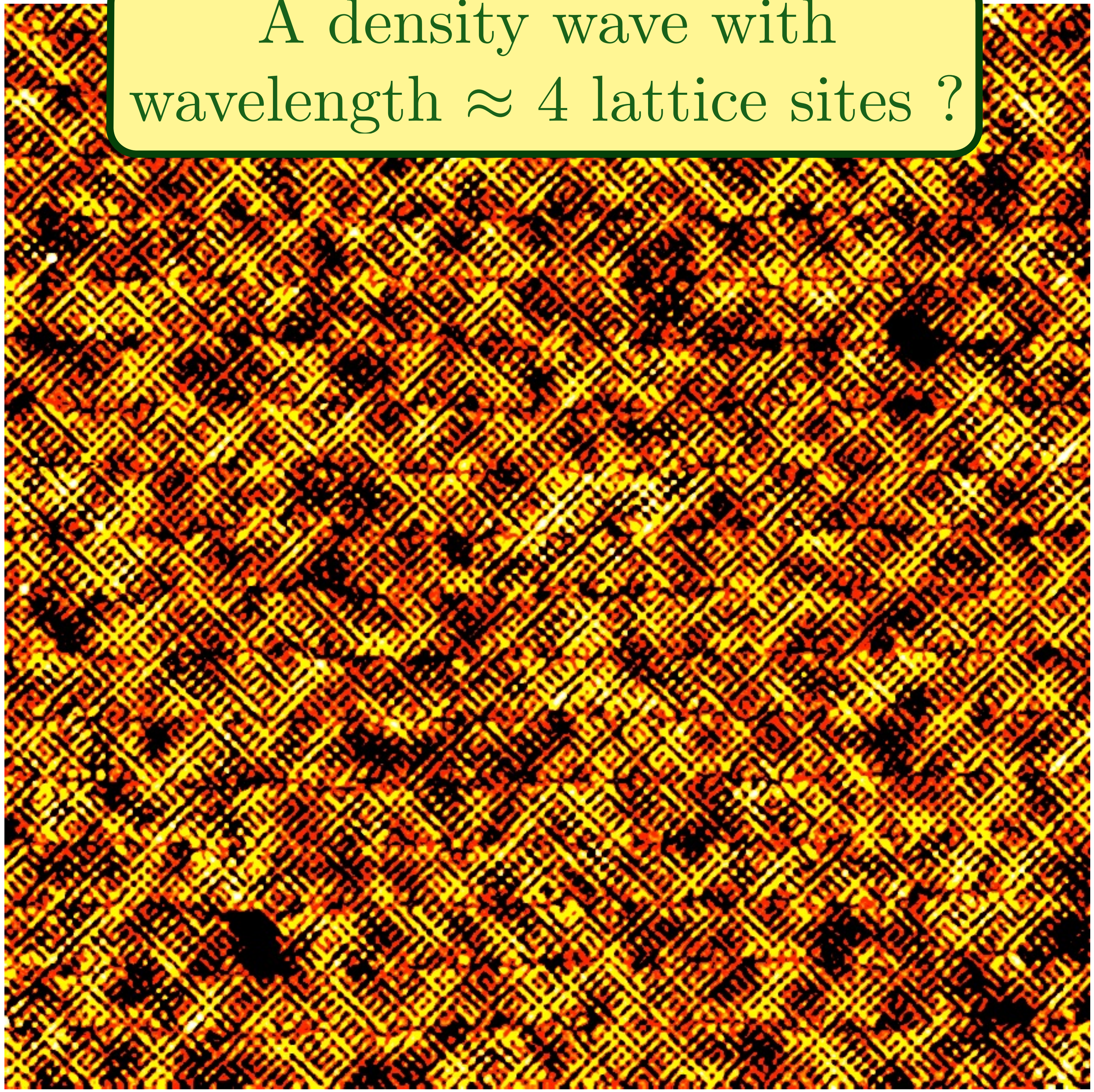
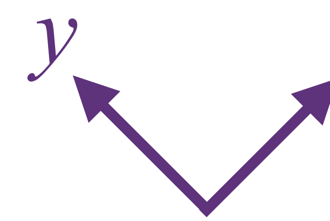
A density wave with wavelength ≈ 4 lattice sites ?





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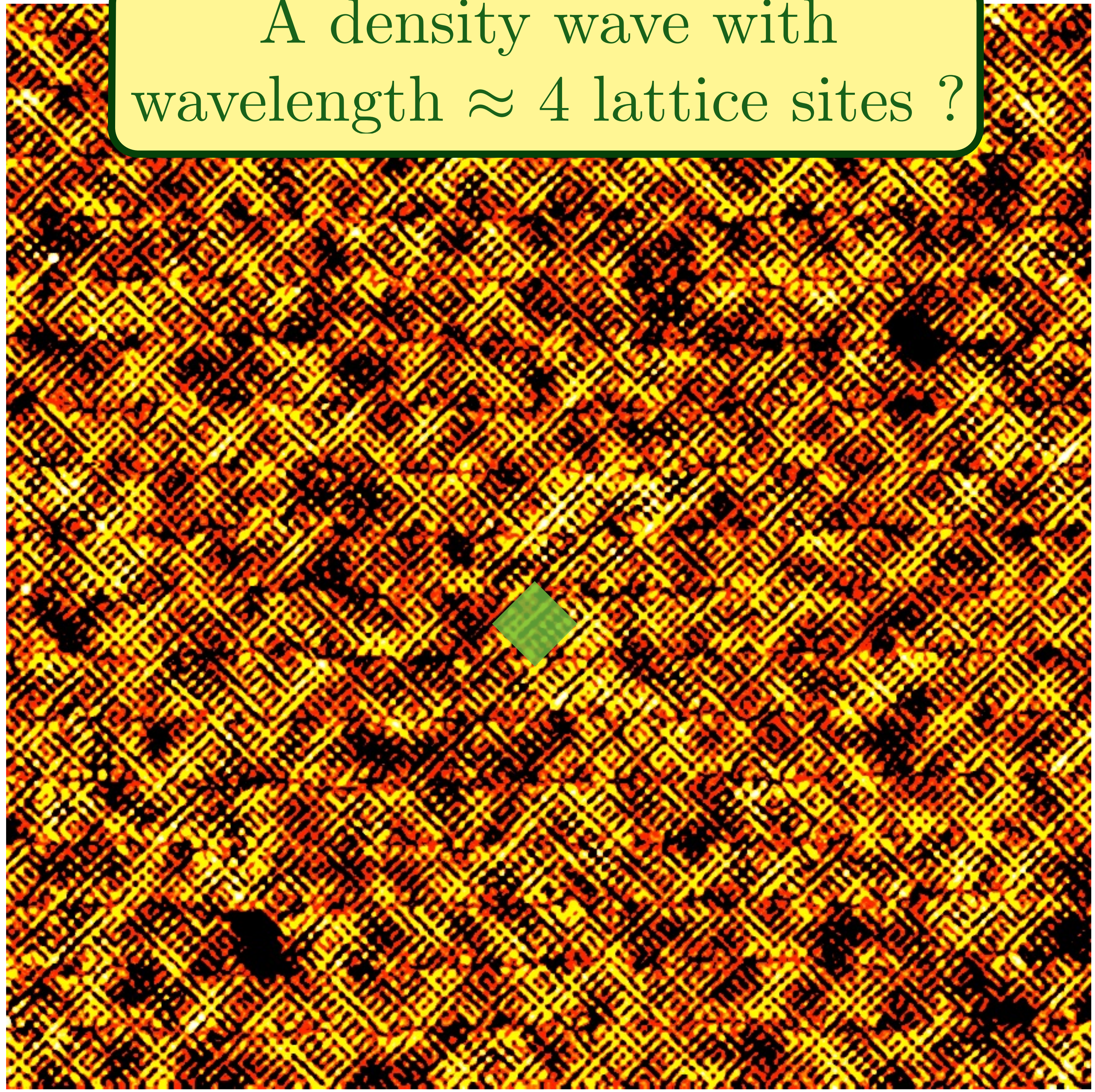
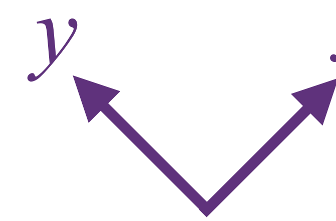
A density wave with wavelength $\approx$ 4 lattice sites ?





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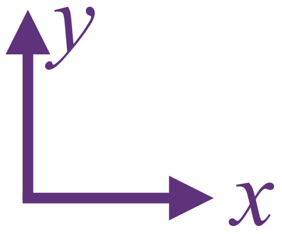
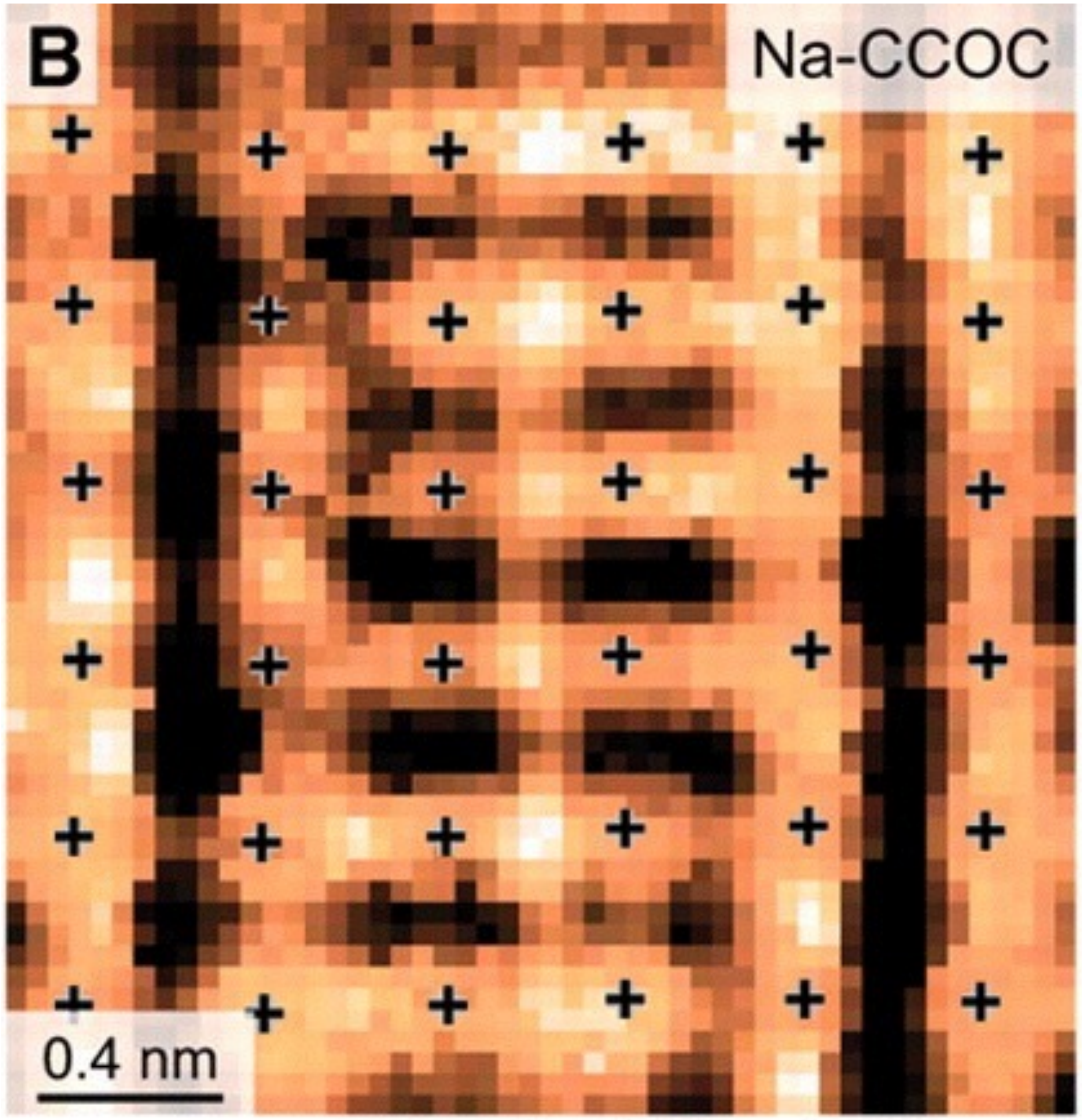
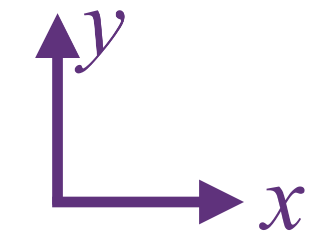
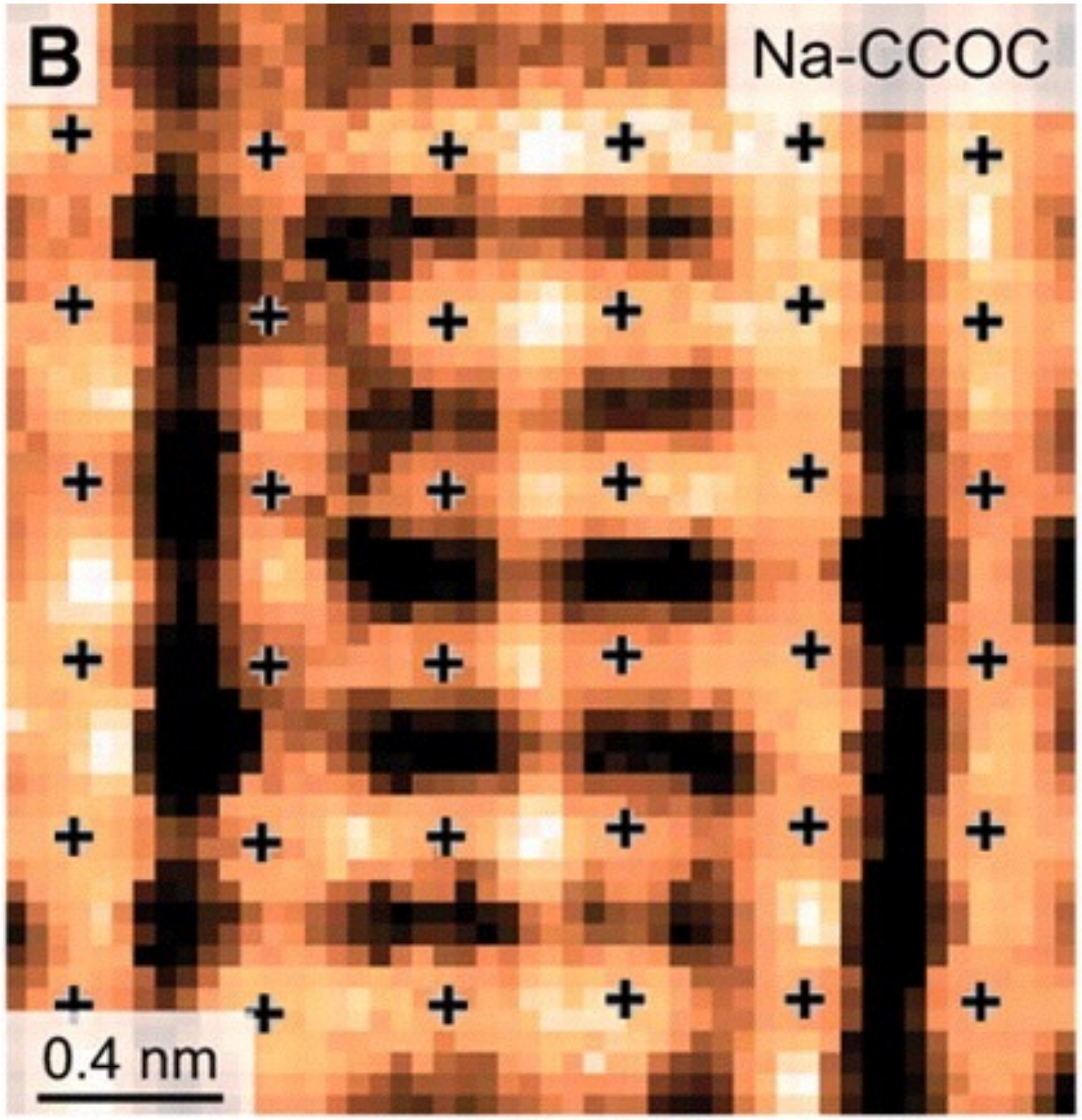




Y. Kohsaka *et al.*, Science **315**, 1380 (2007)





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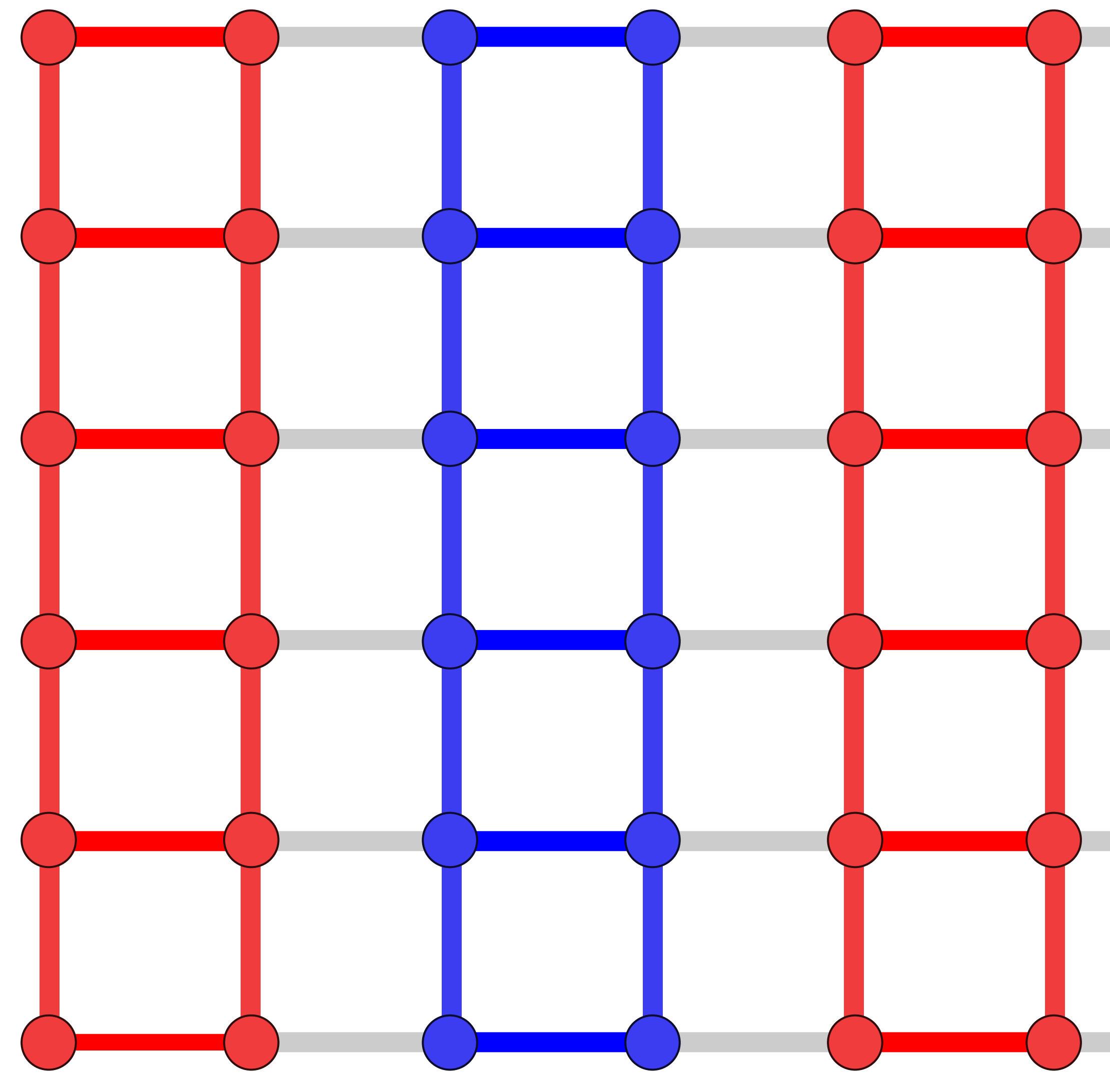
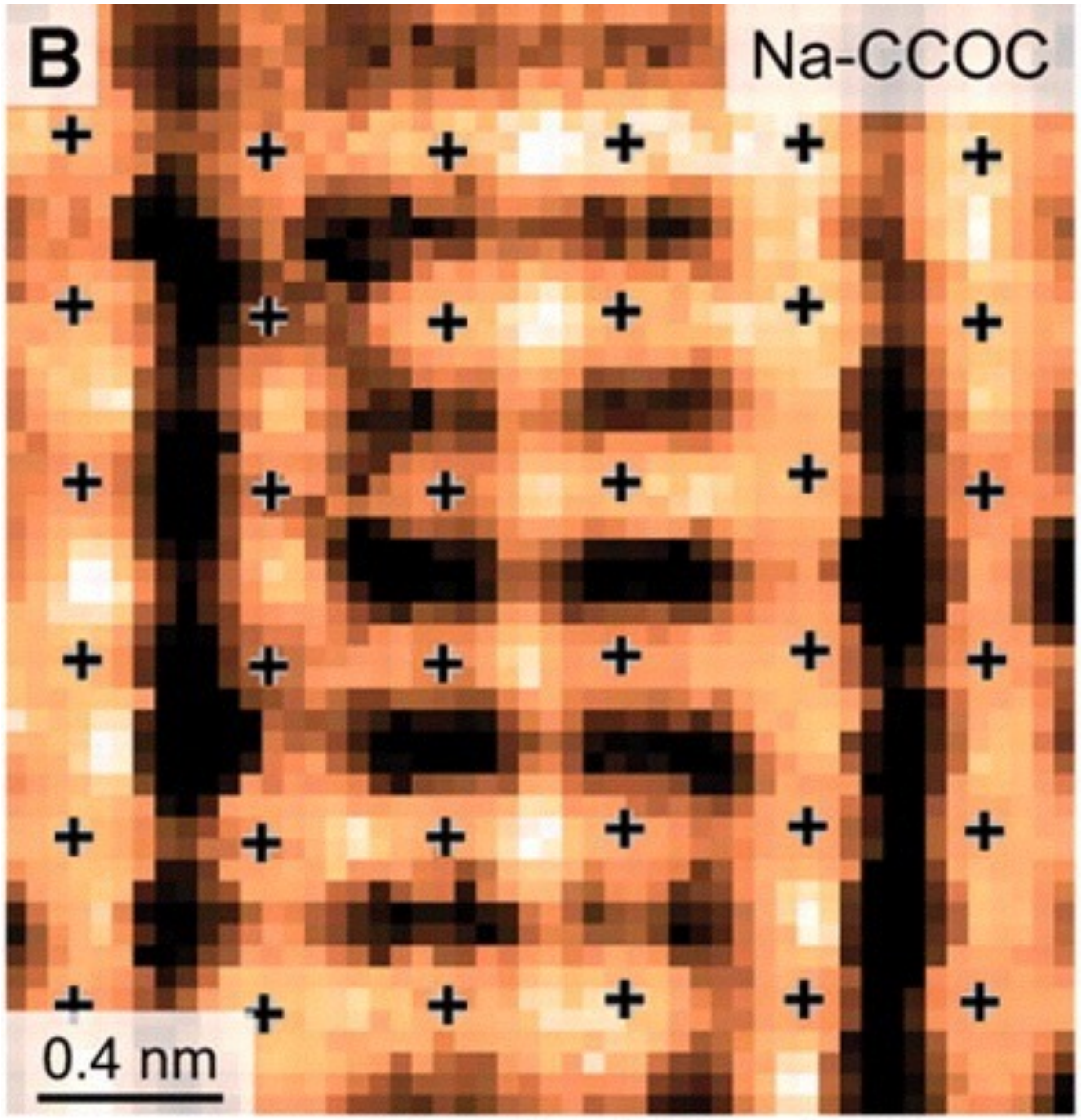


"Stripe" model



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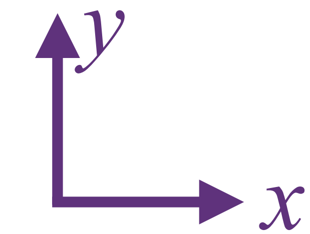

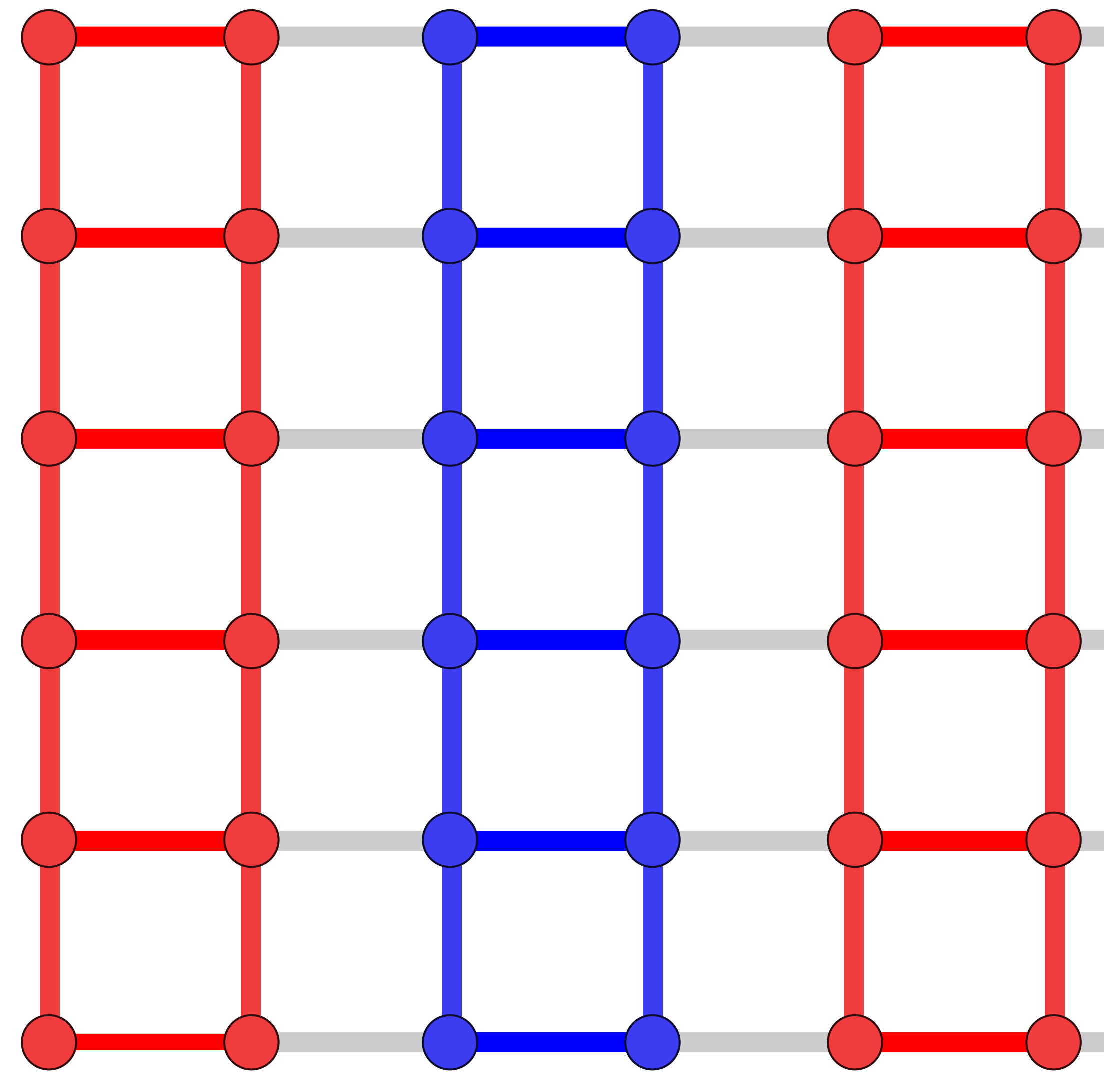

“Stripe” model

Microstructure of STM picture does not match “stripe” model

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

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

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

M. A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)

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

M.A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)

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

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

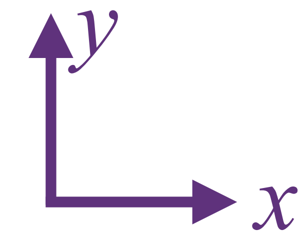
Time-reversal symmetry requires $\mathcal{P}(\mathbf{k}) = \mathcal{P}(-\mathbf{k})$.

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

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

M.A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)

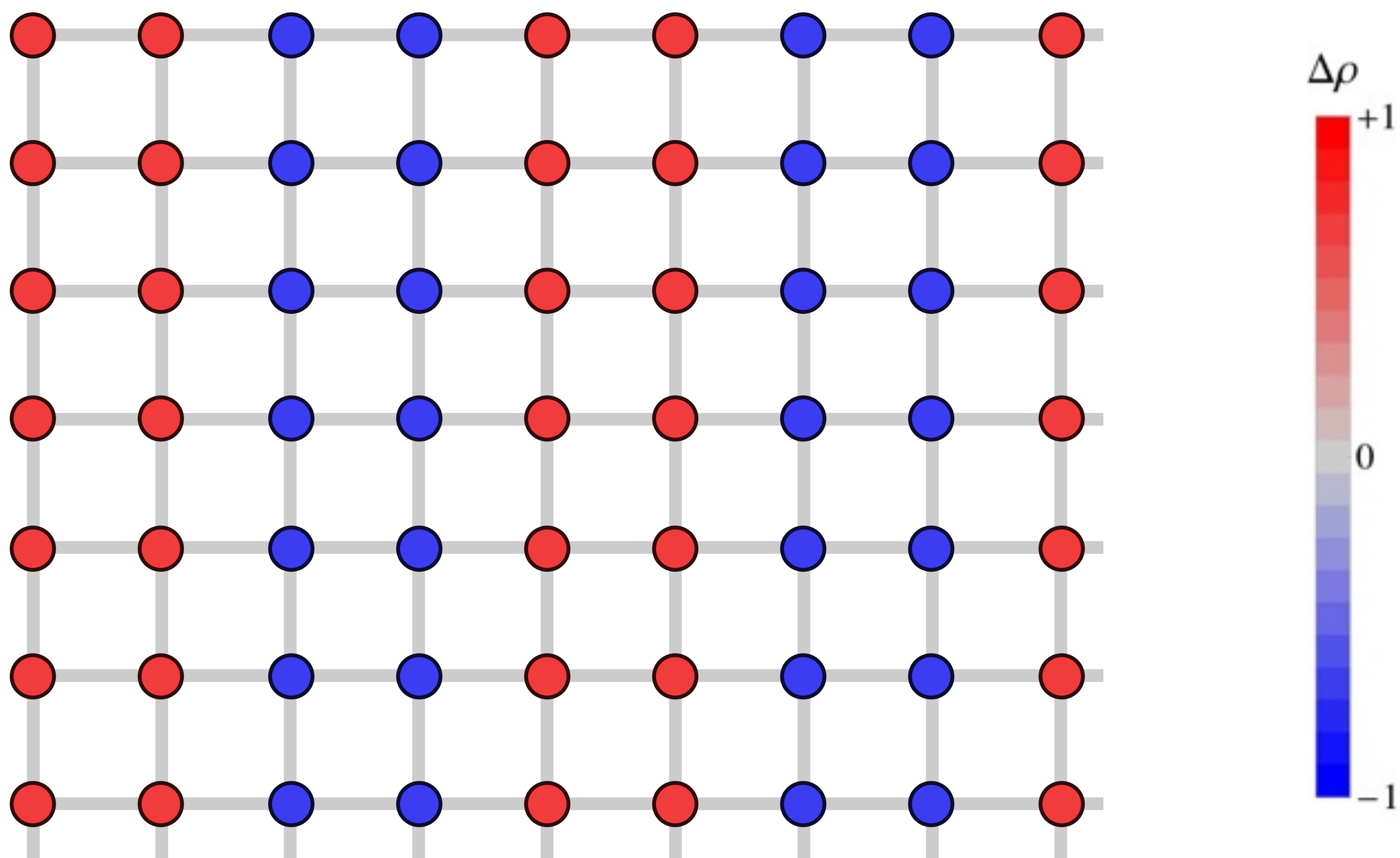
Conventional CDW order: s-form factor



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

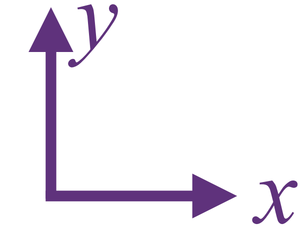
$$P_{ij} = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2} + \text{c.c.}$$

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



$\mathbf{Q} = (\pi/2, 0)$

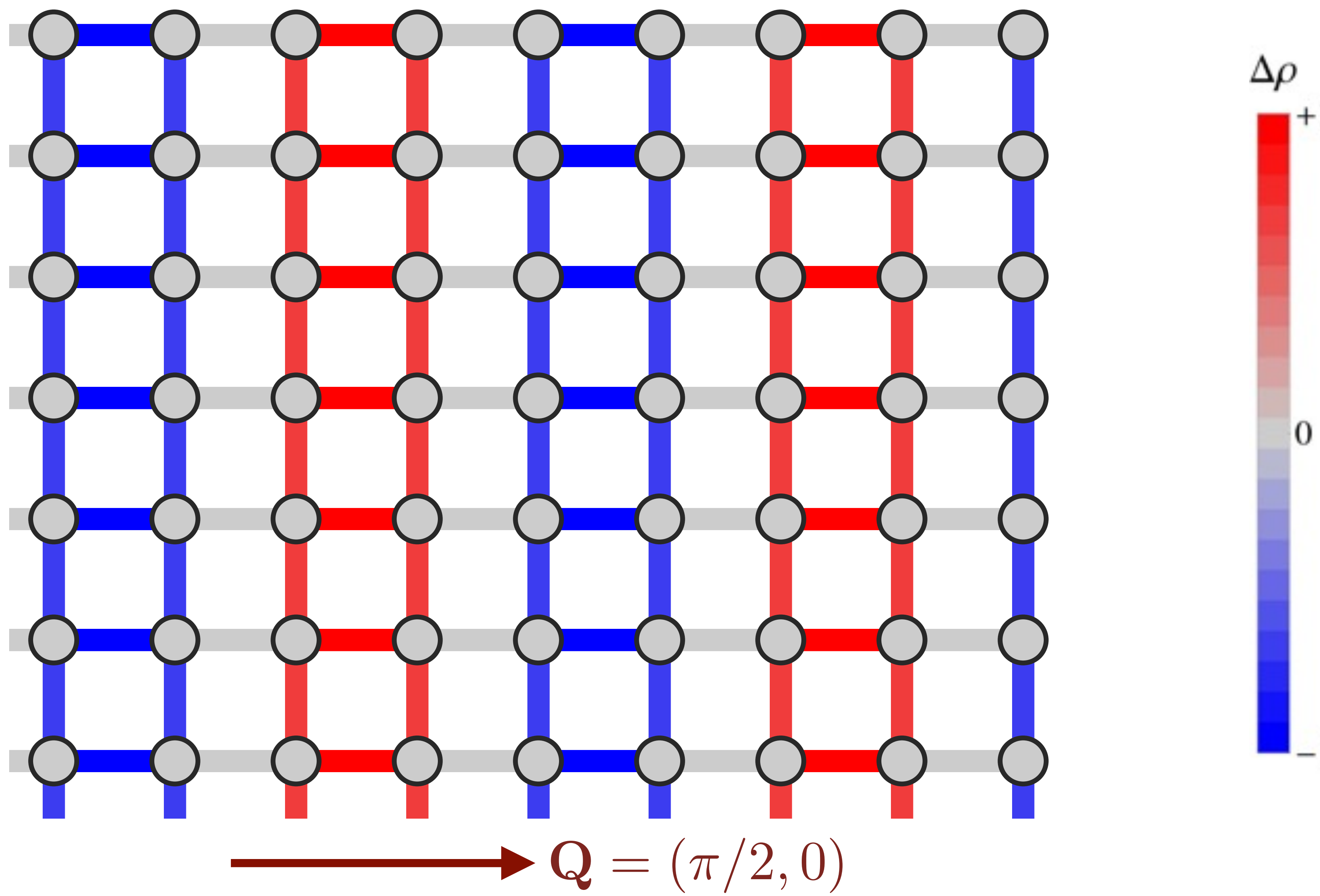
Unconventional DW order: s'-form factor



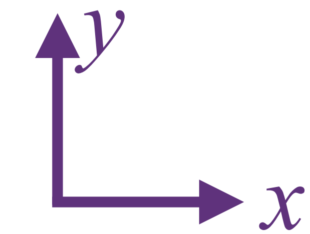
Plot of $P_{ij} = \left\langle c_{i\alpha}^{\dagger} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

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



Unconventional DW order: s'-form factor

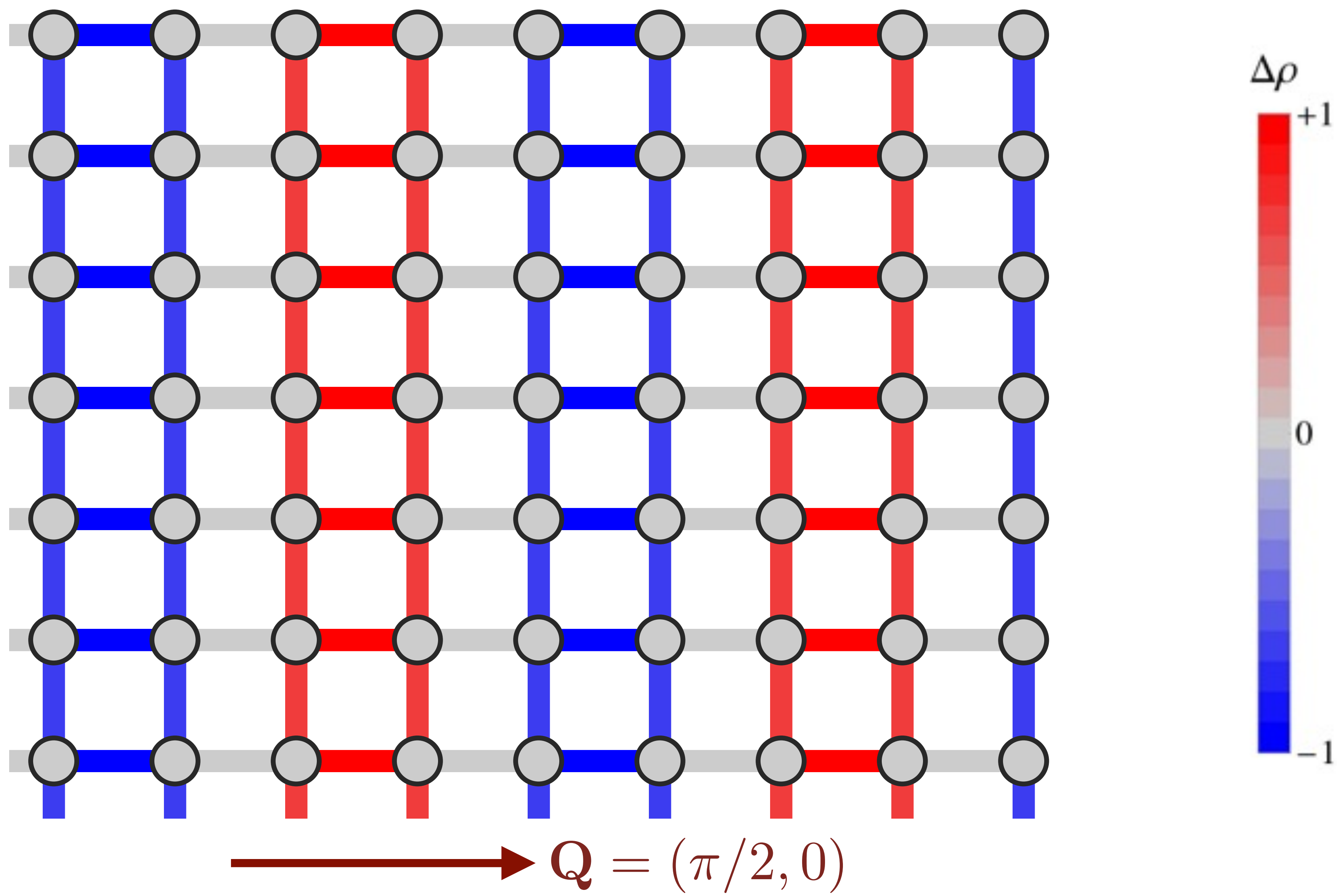


Plot of $P_{ij} = \left\langle c^\dagger_{i\alpha} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

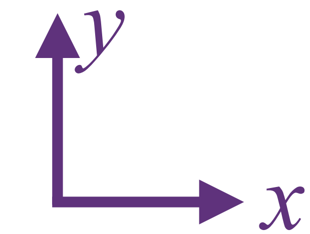
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) + \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$

"Stripe" model !



M. H. Fischer, Si Wu, M. Lawler, A. Paramekanti, and Eun-Ah Kim, arXiv:1406.2711

Unconventional DW order: s'-form factor



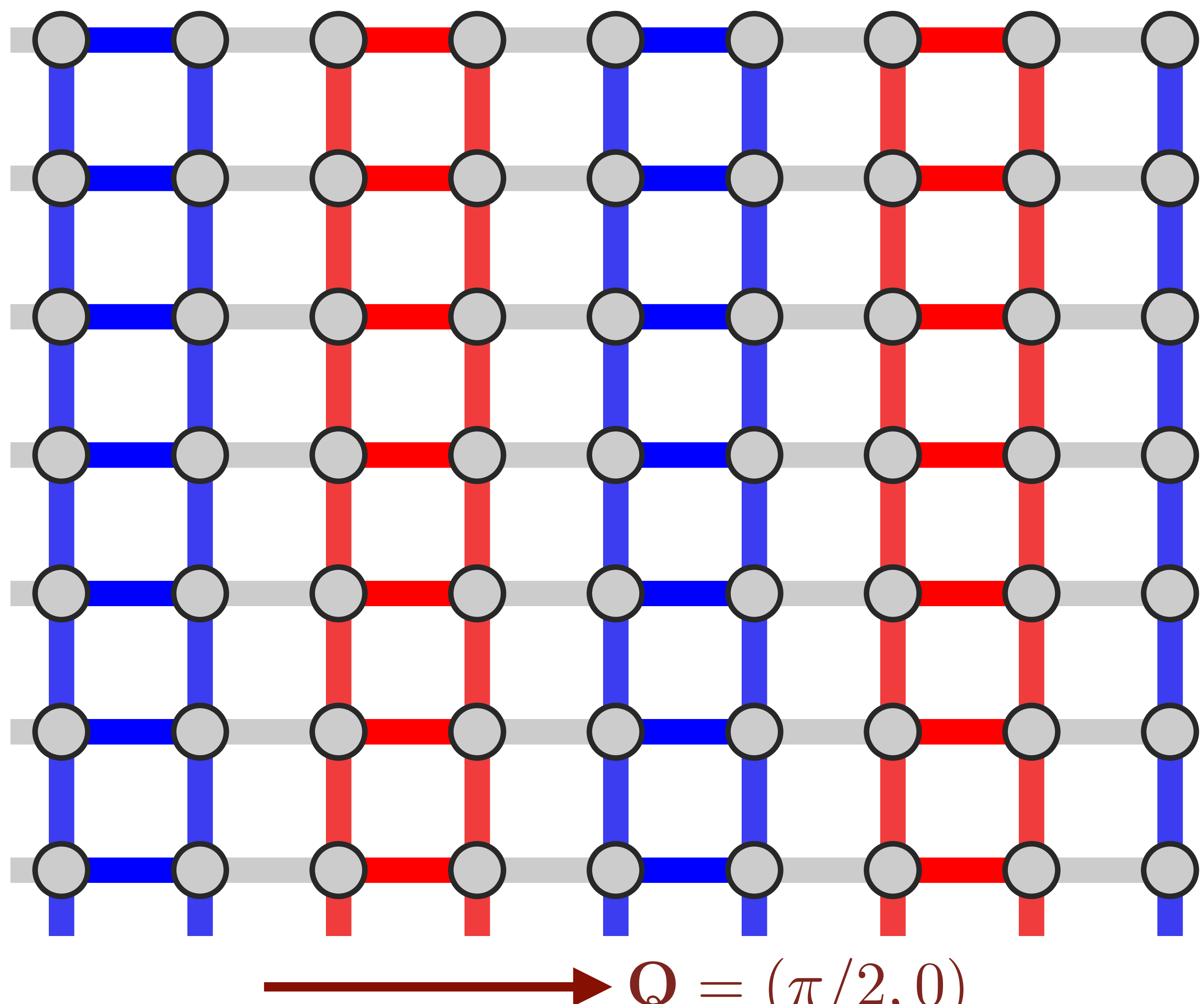
Plot of $P_{ij} = \left\langle c_{i\alpha}^{\dagger} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

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

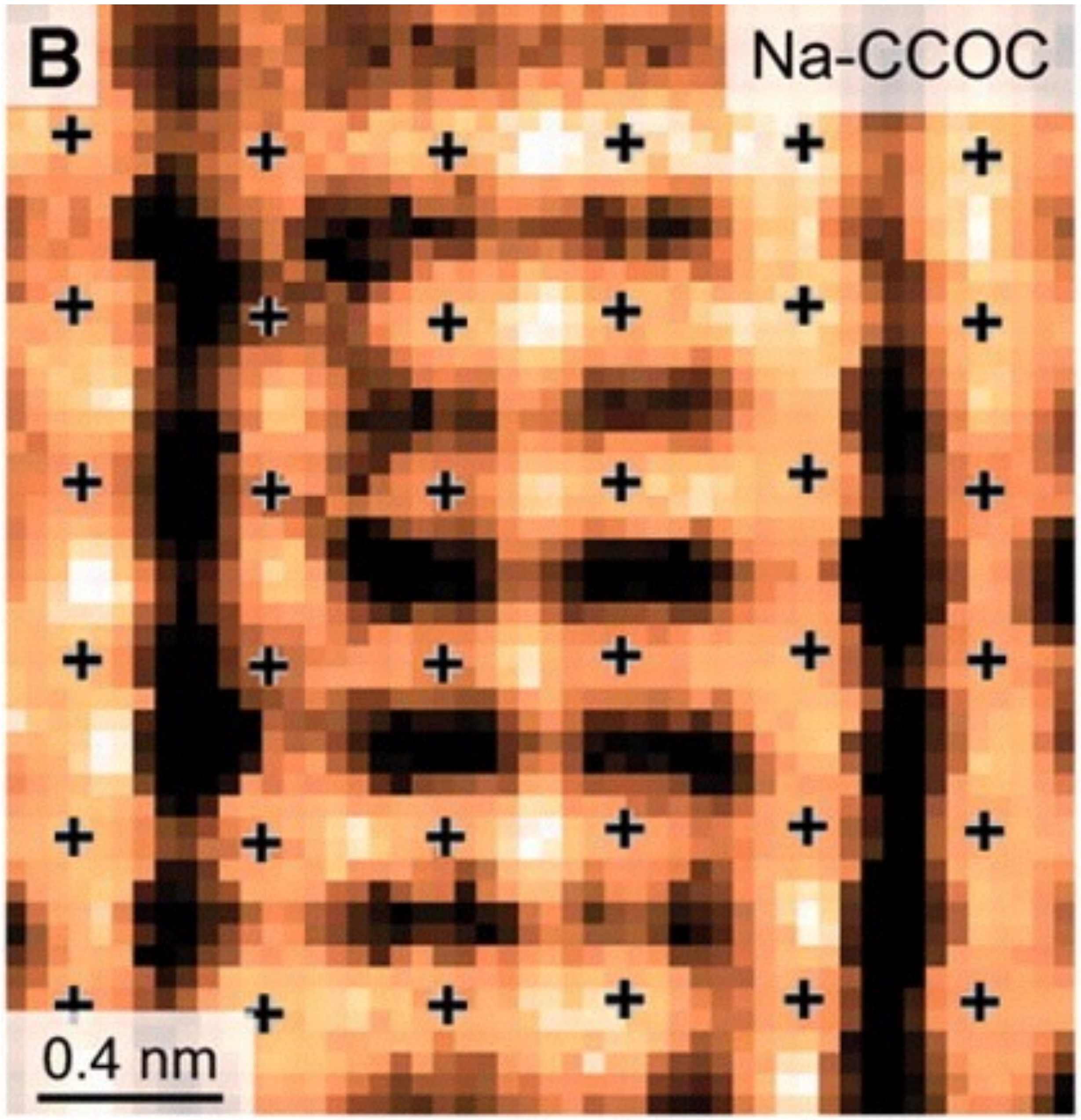
"Stripe" model !

X-ray observations indicate strong s' component in LBCO

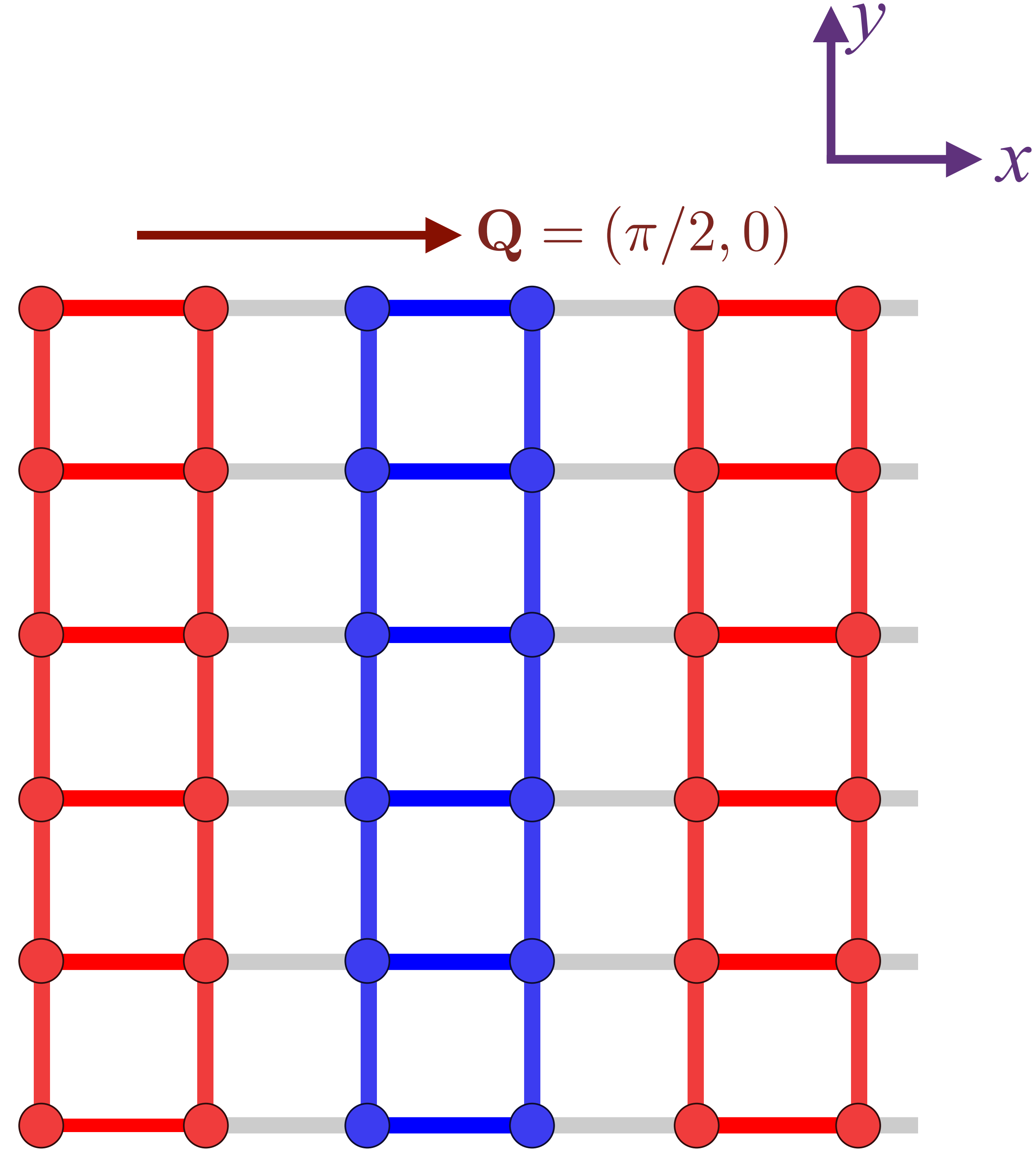


David Hawthorn, Waterloo

A. J. Achkar, F. He, R. Sutarto, Christopher McMahon, M. Zwiebler, M. Hucker, G. D. Gu, Ruixing Liang, D. A. Bonn, W. N. Hardy, J. Geck, and D. G. Hawthorn, arXiv:1409.6787



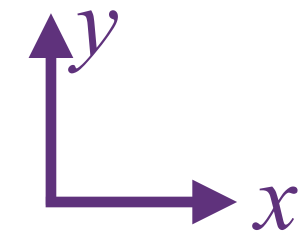
Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)



$s + s'$-form factor density wave

$s + s'$ form factor does not match STM measurements on BSCCO, Na-CCOC.

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.

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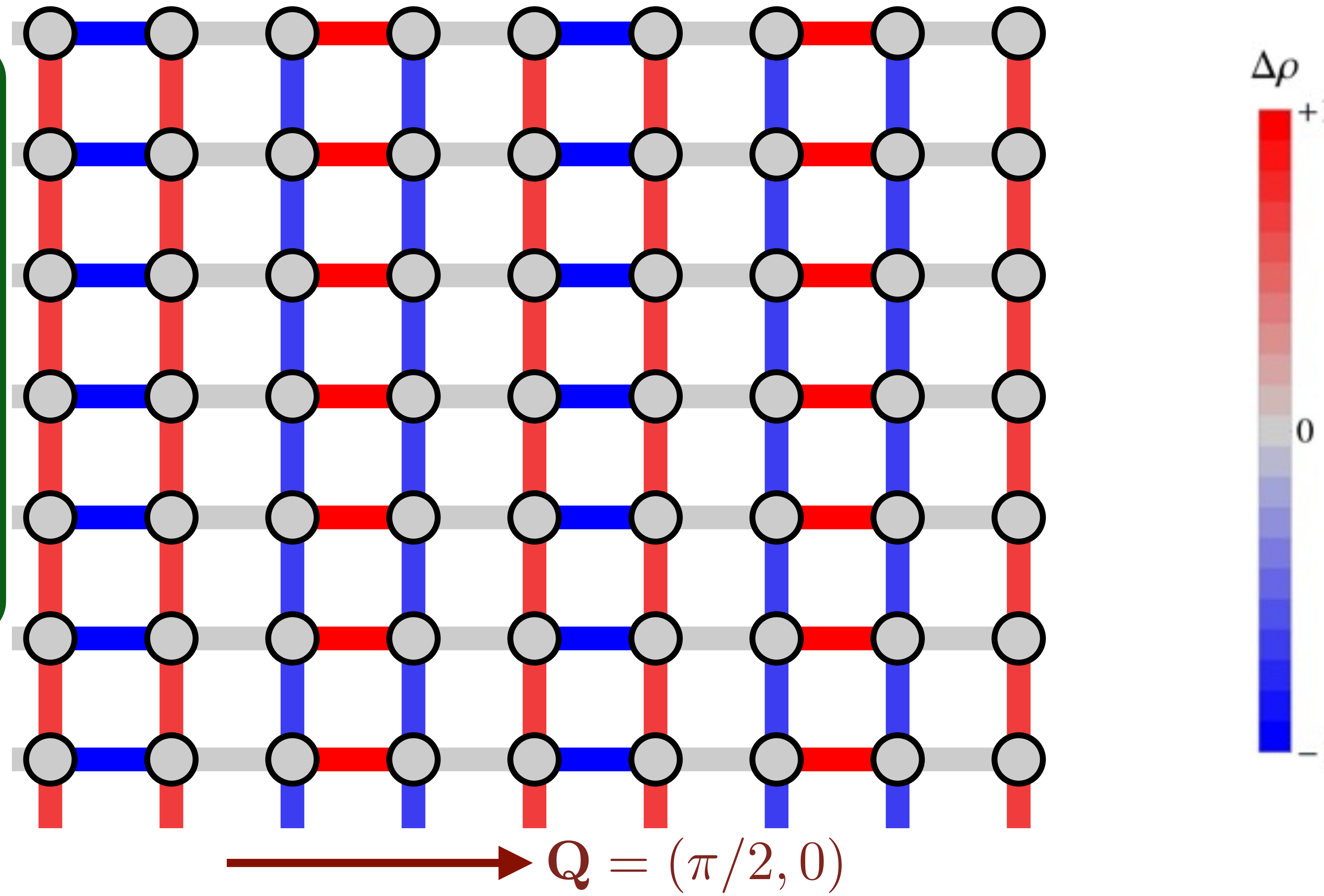
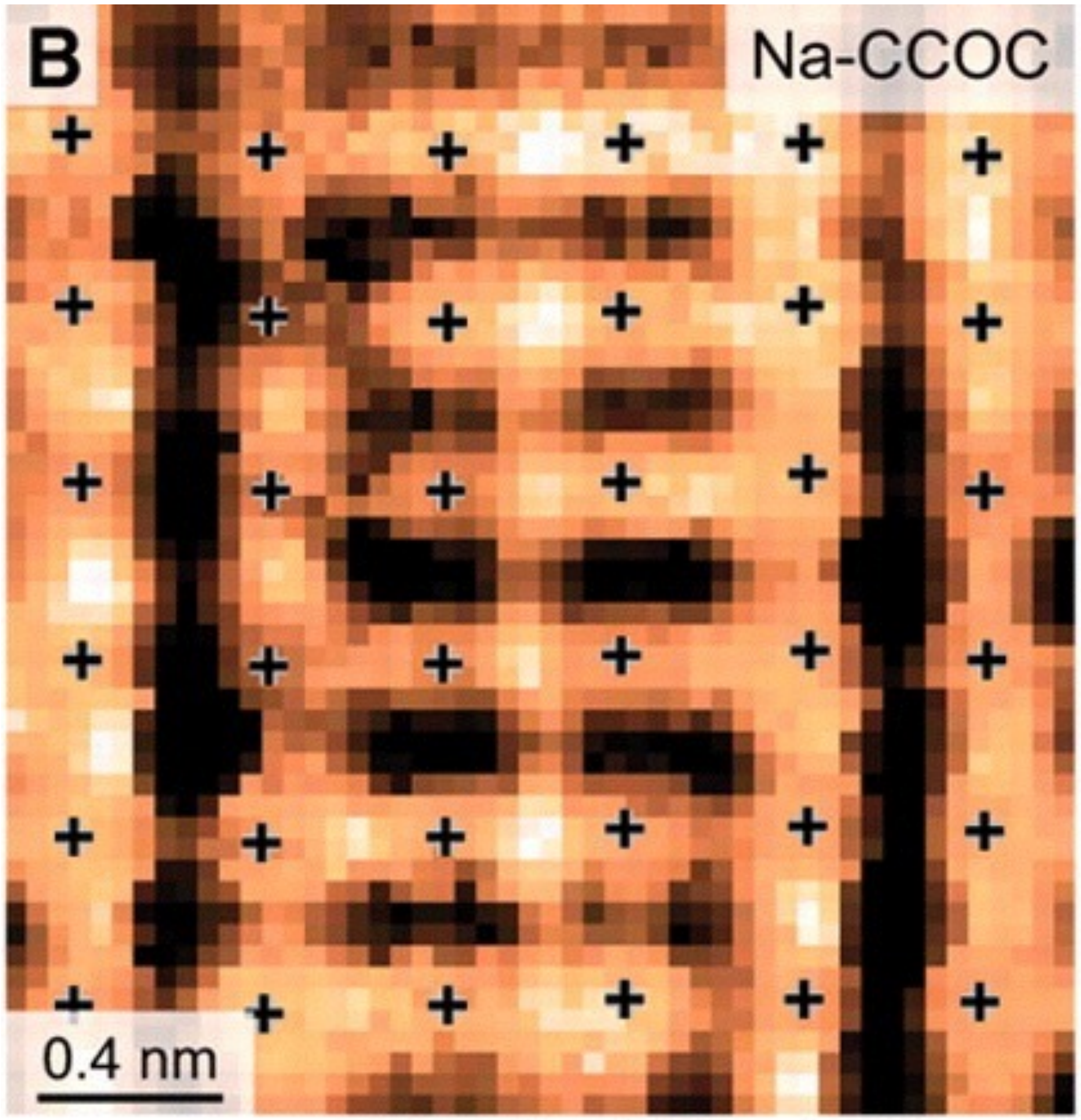
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) - \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$

Our prediction:

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



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



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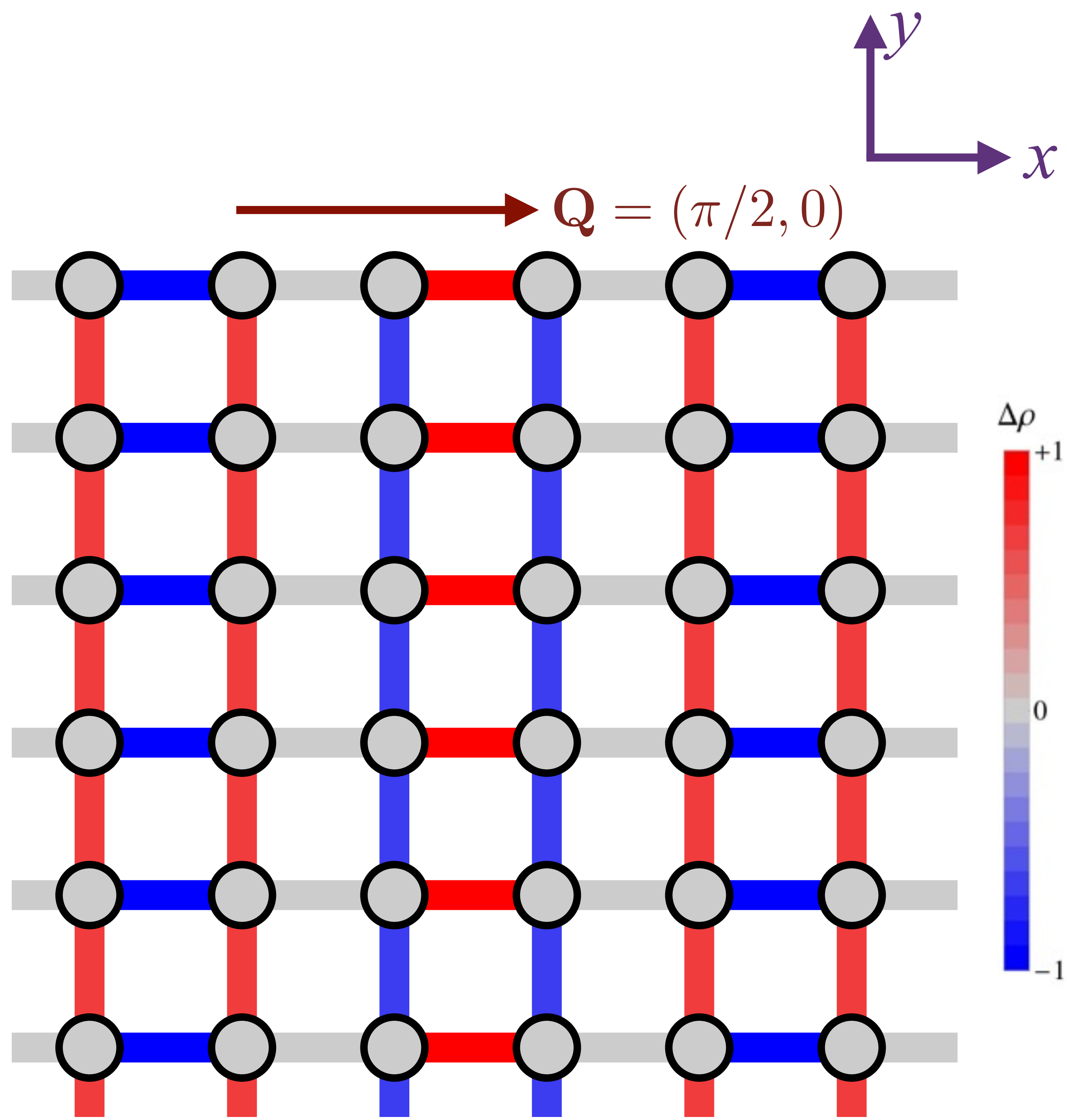
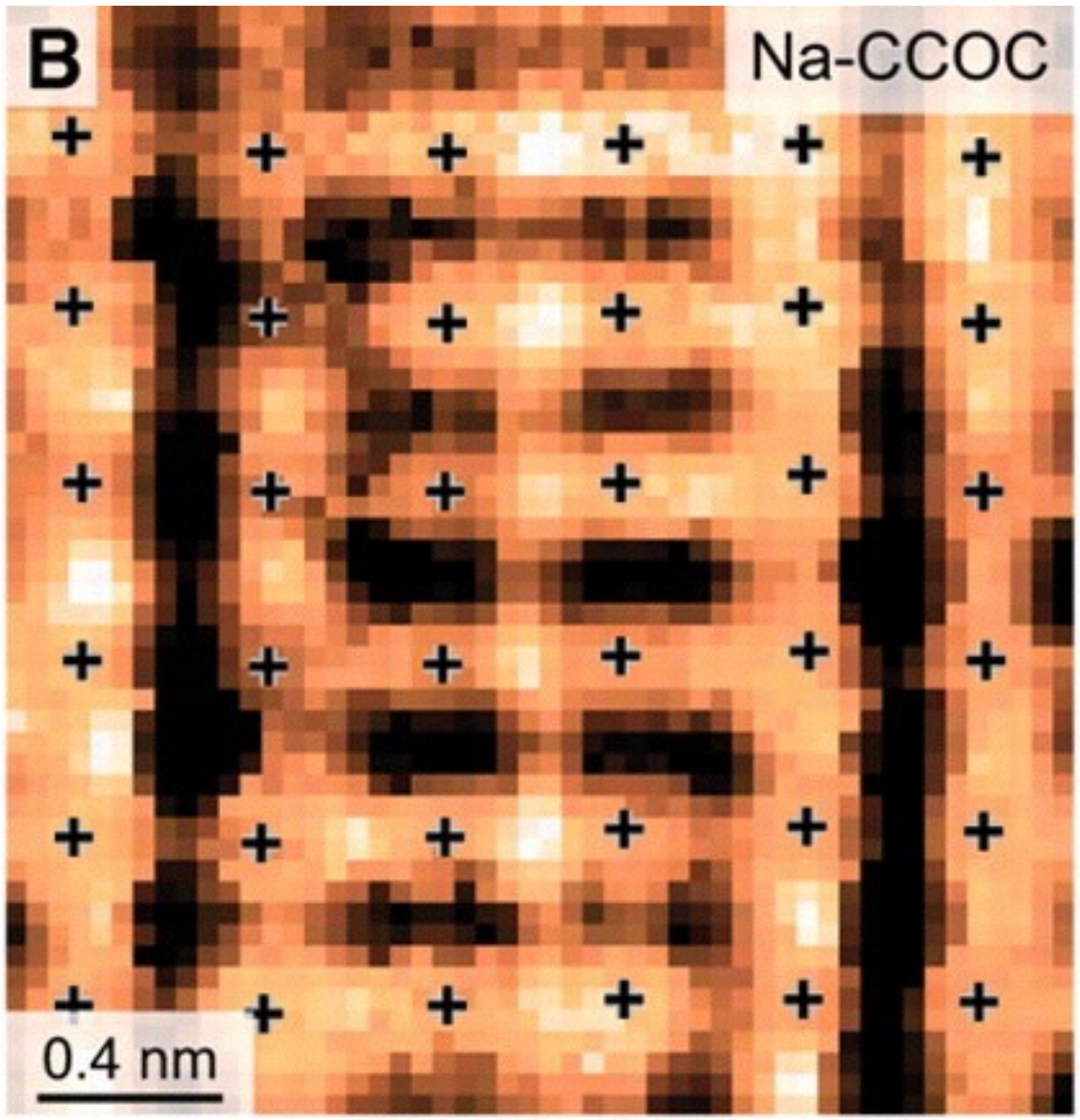
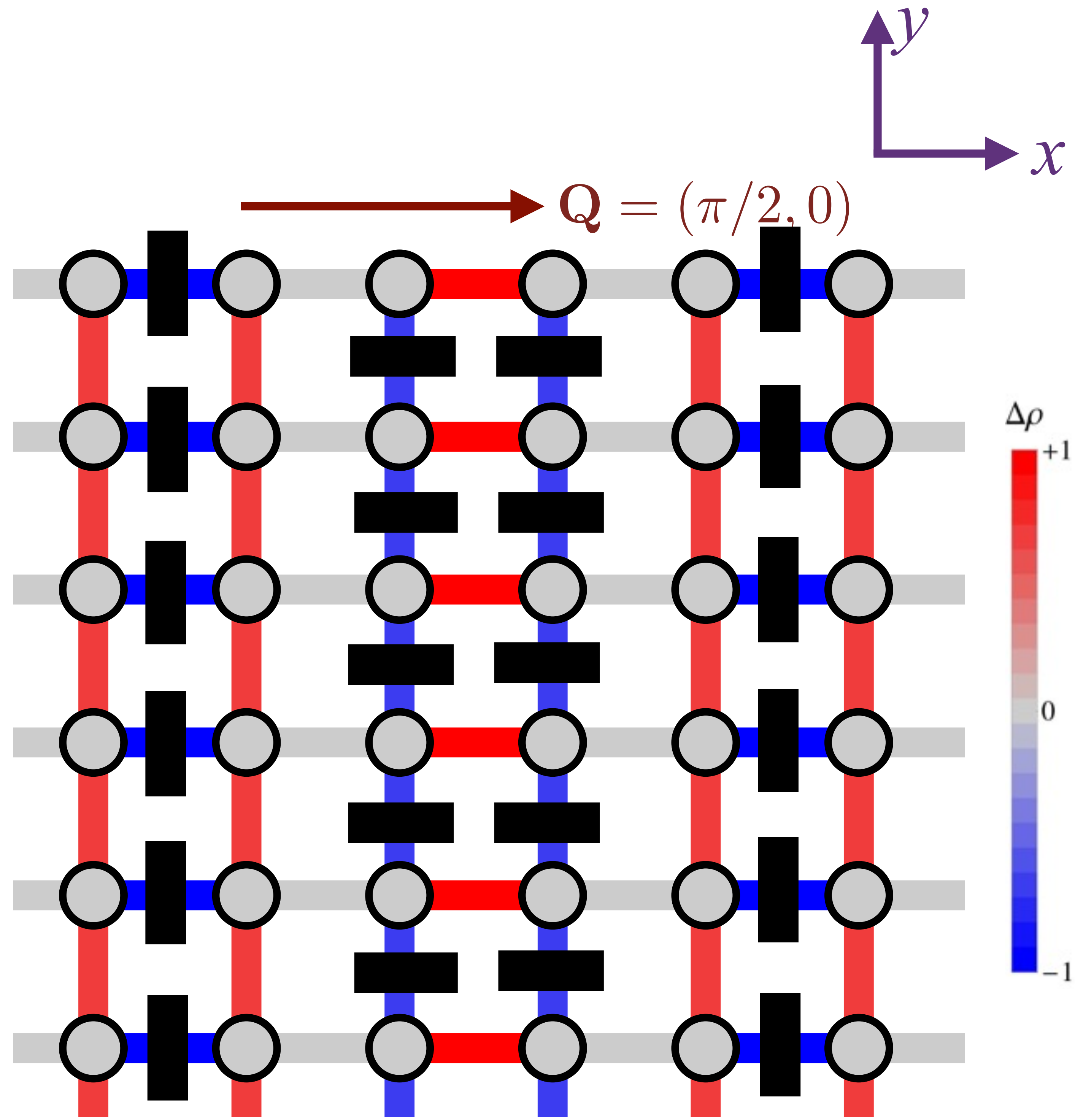


d-form factor density wave order

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



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



d-form factor density wave order

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]

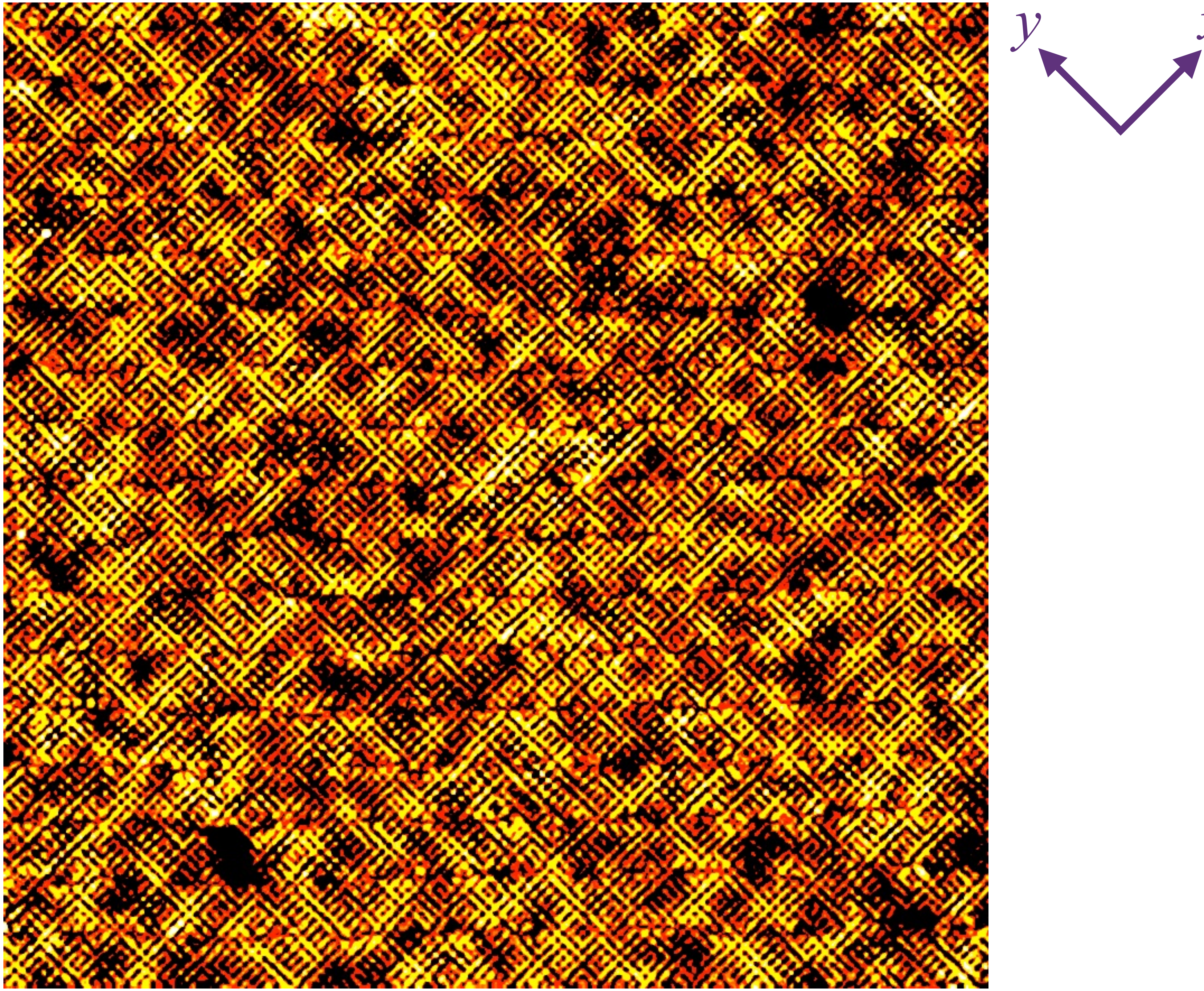
The identity of the fundamental broken symmetry (if any) in the underdoped cuprates is unresolved. However, evidence has been accumulating that this state may be an unconventional density wave. Here we carry out site-specific measurements within each CuO_2 unit cell, segregating the results into three 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)

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).

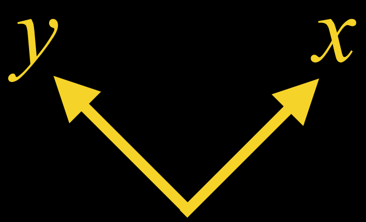
W. D. Wise, M. C. Boyer, K. Chatterjee, T. Kondo, T. Takeuchi, H. Ikuta, Y. Wang, and E. W. Hudson, Nature Phys. **4**, 696 (2008).



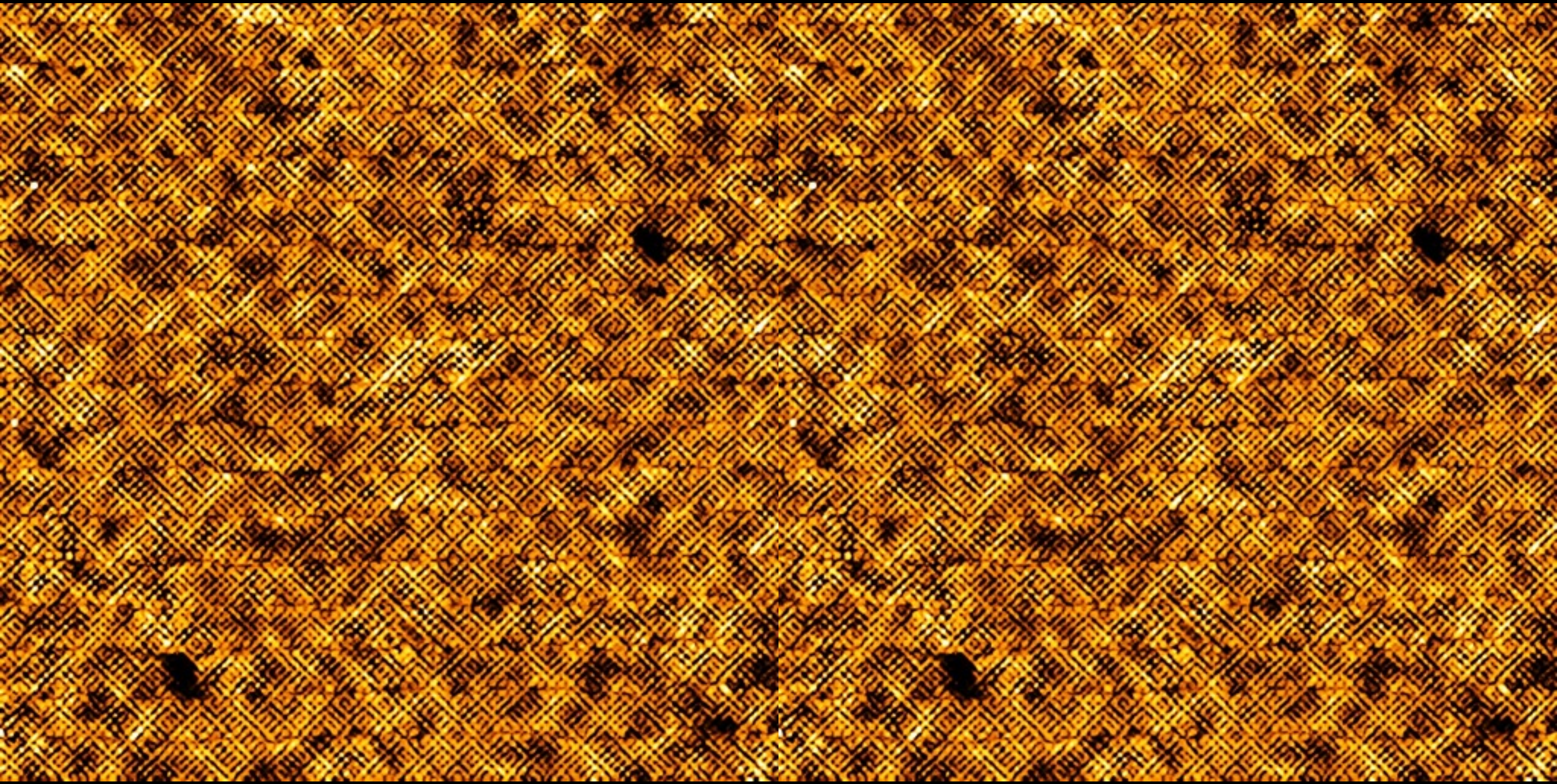
"R-map" of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007). Davis group has sub-angstrom resolution capabilities, with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

UD45K
BSCCO

R(r,150mV)

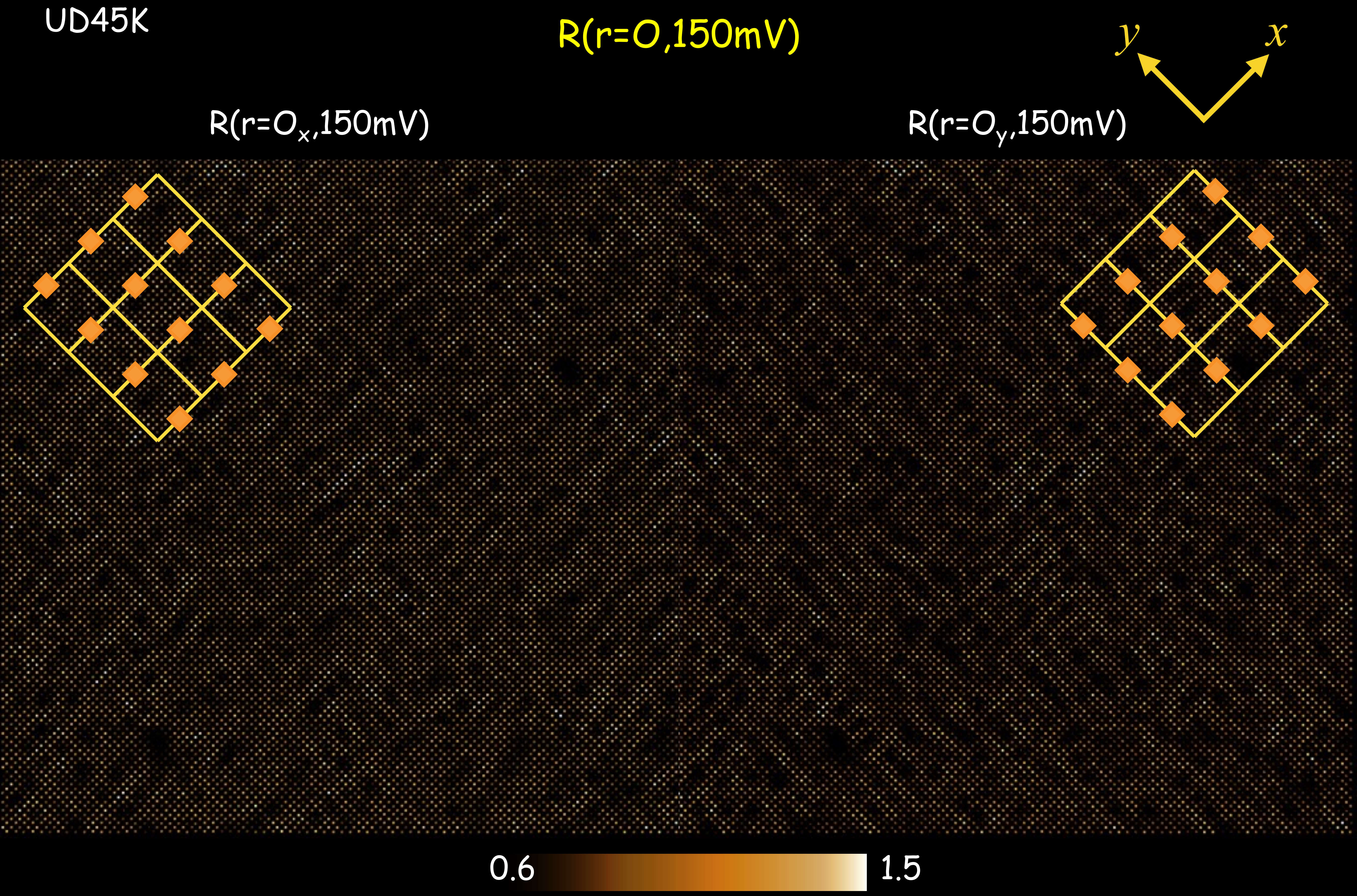


R(r,150mV) R(r,150mV)



Note that these are identical images.

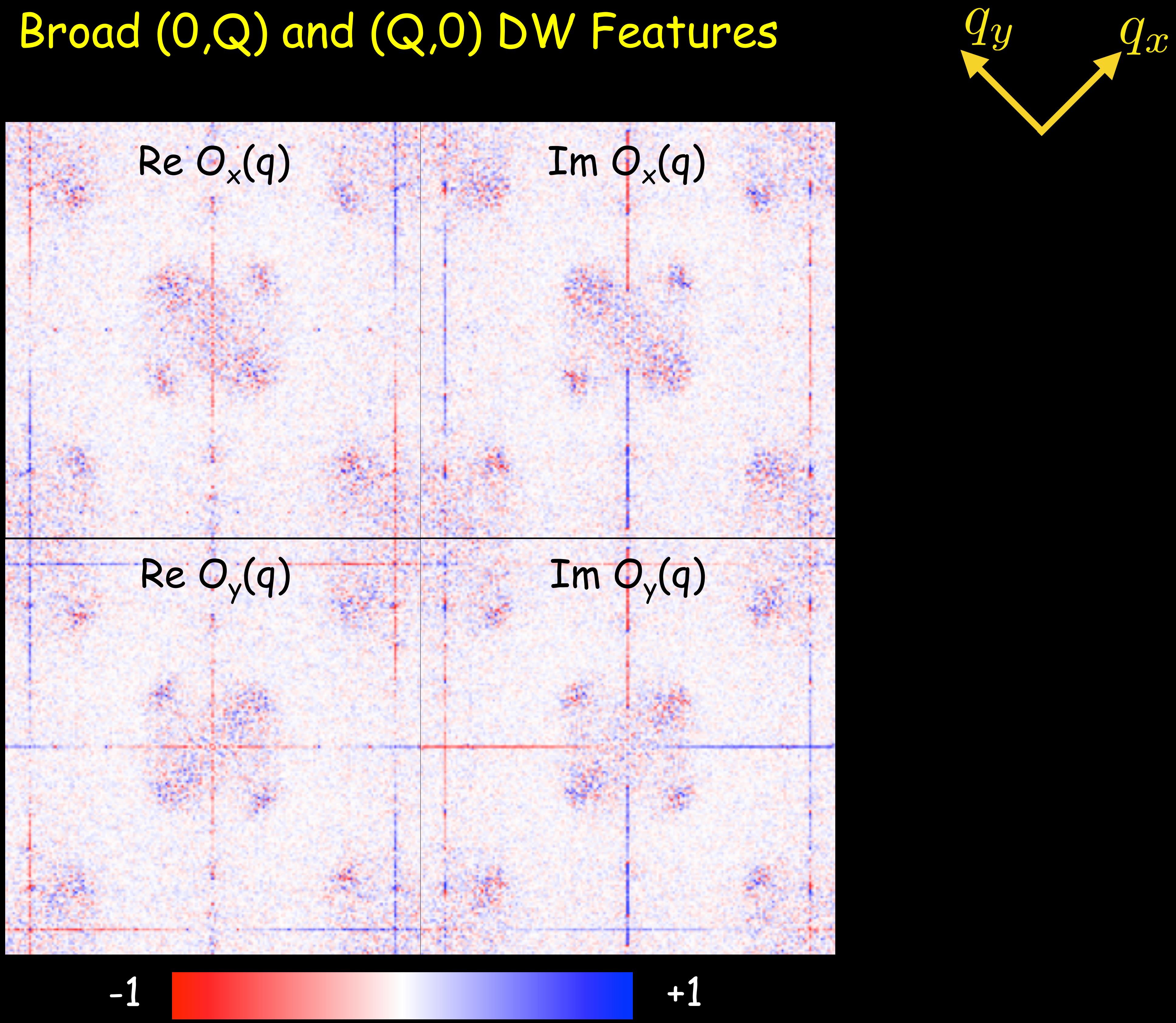
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)



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)

UD45K

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



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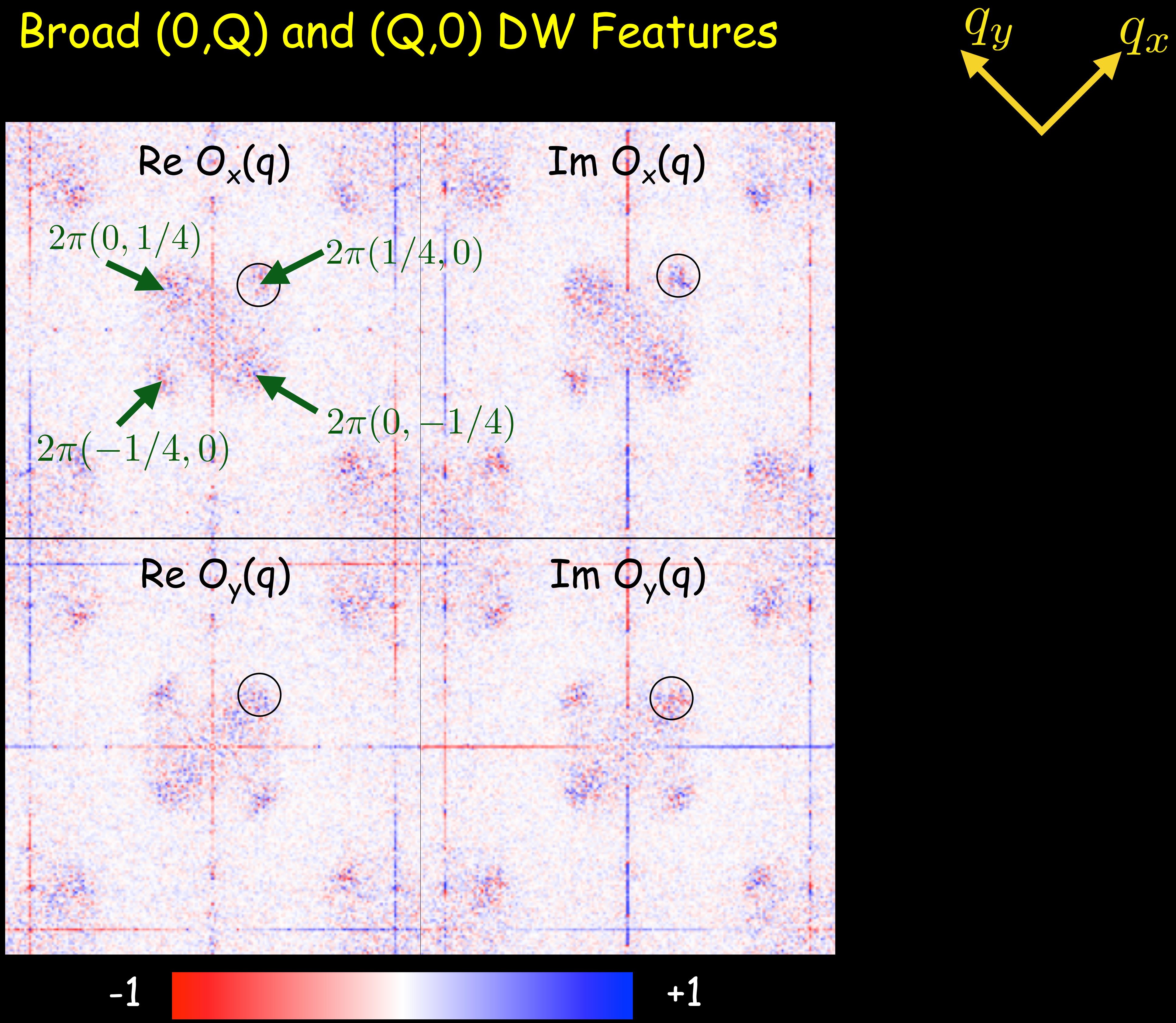

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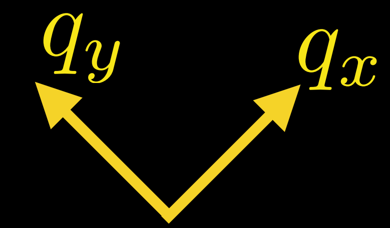
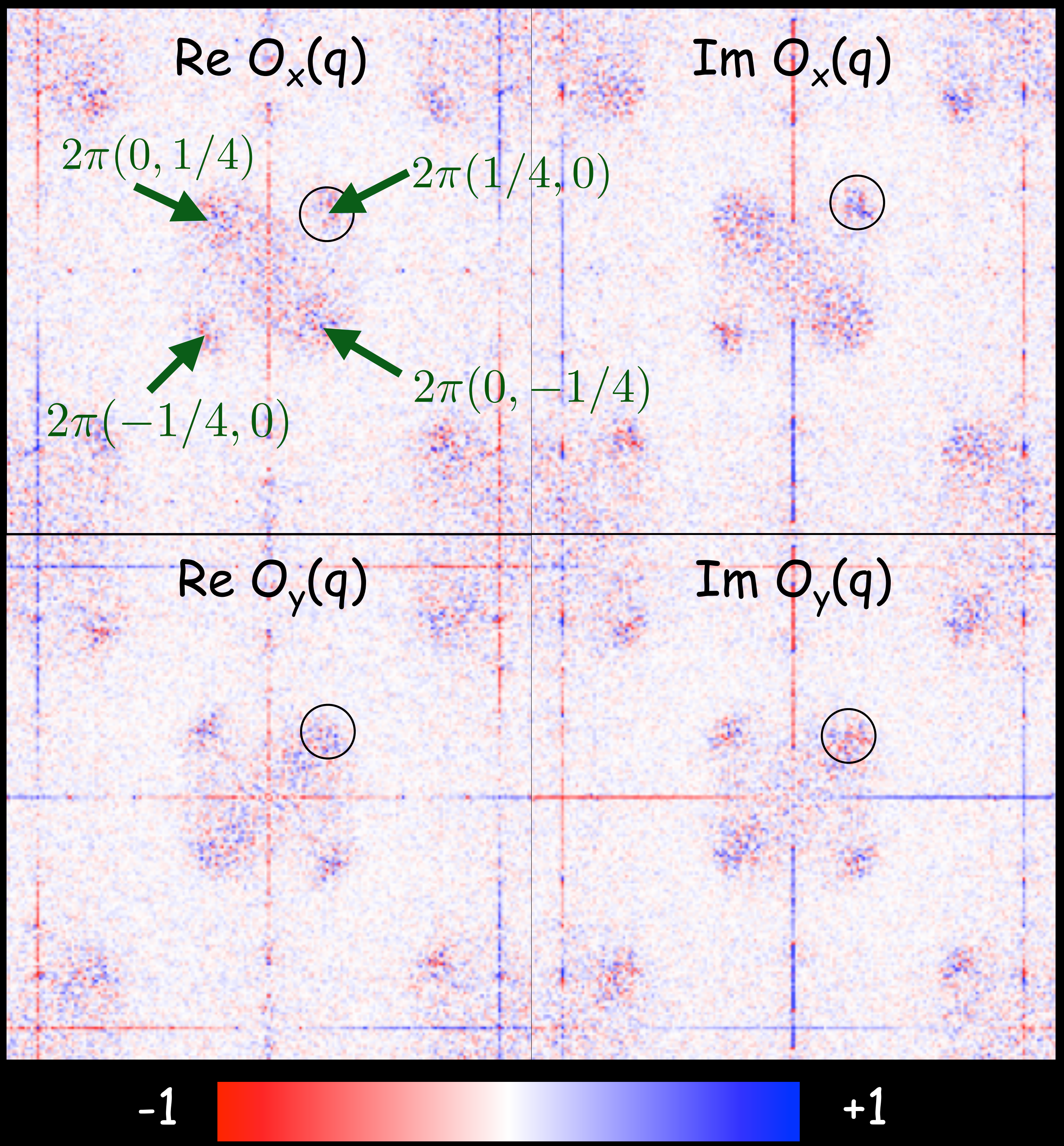


For each pixel in the circles, we obtain 2 complex numbers, $O_x(q)$ and $O_y(q)$.



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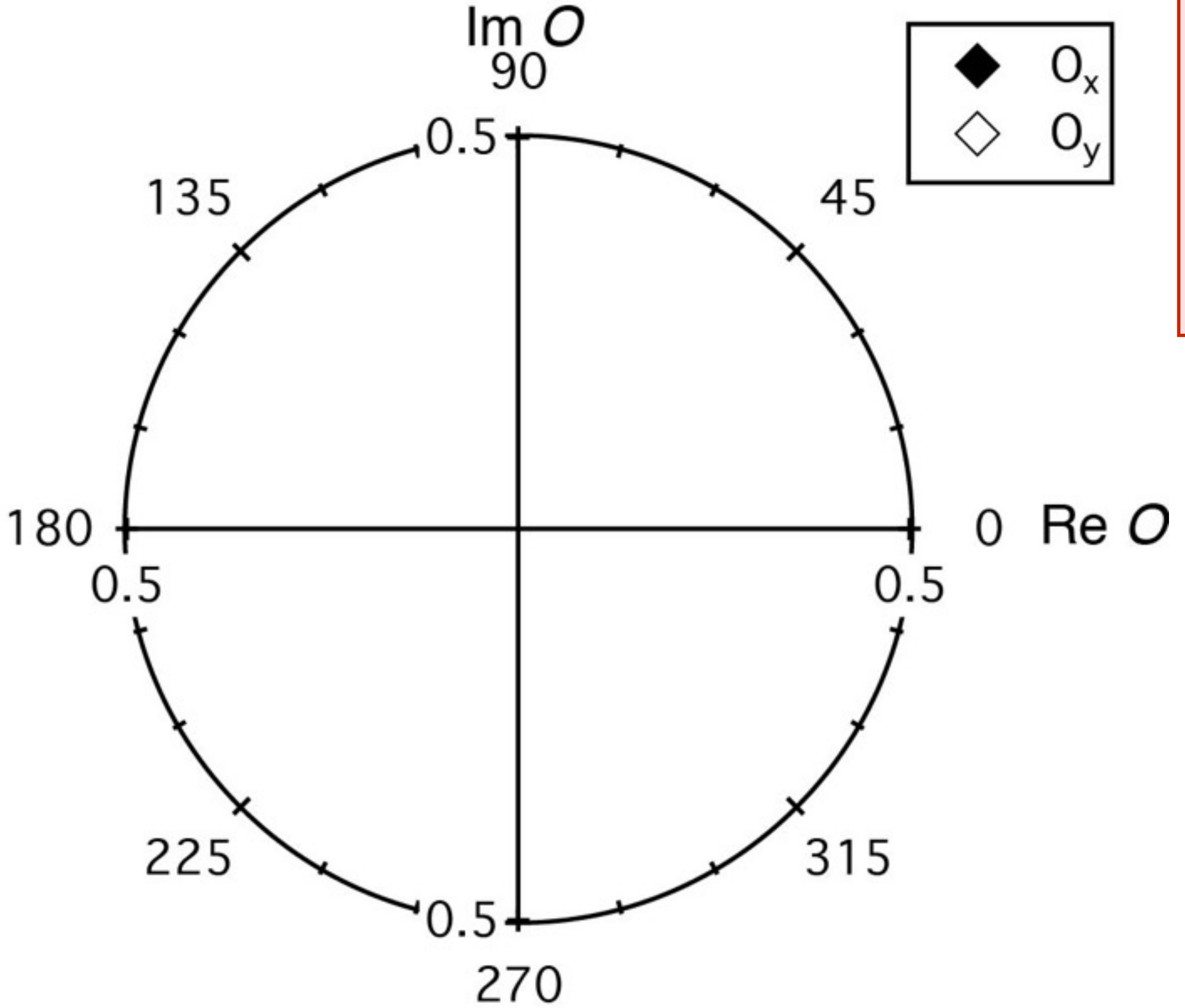
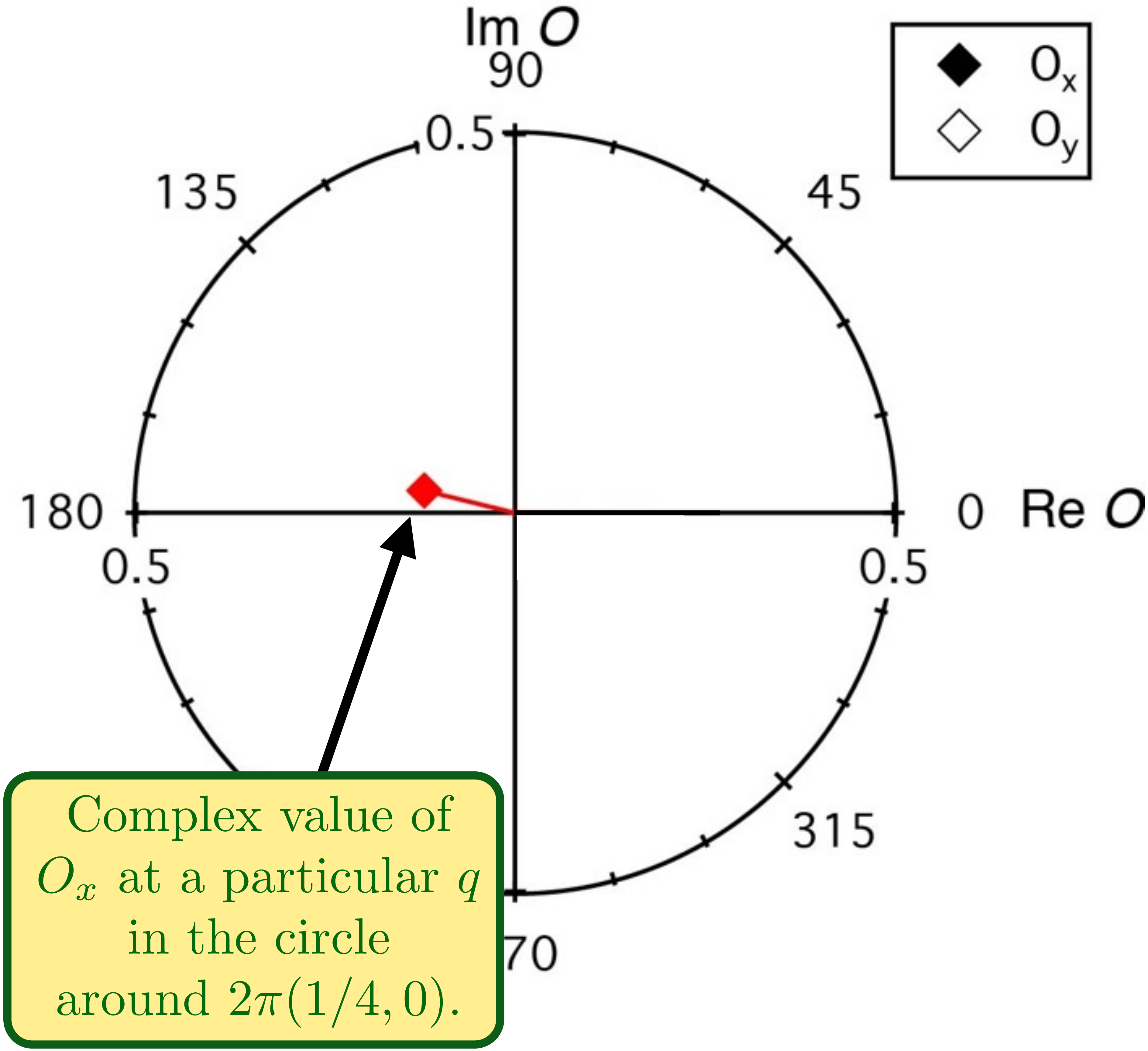


Phase-sensitive measurement of the *d*-form factor of density wave order

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 **111**, E3026 (2014)



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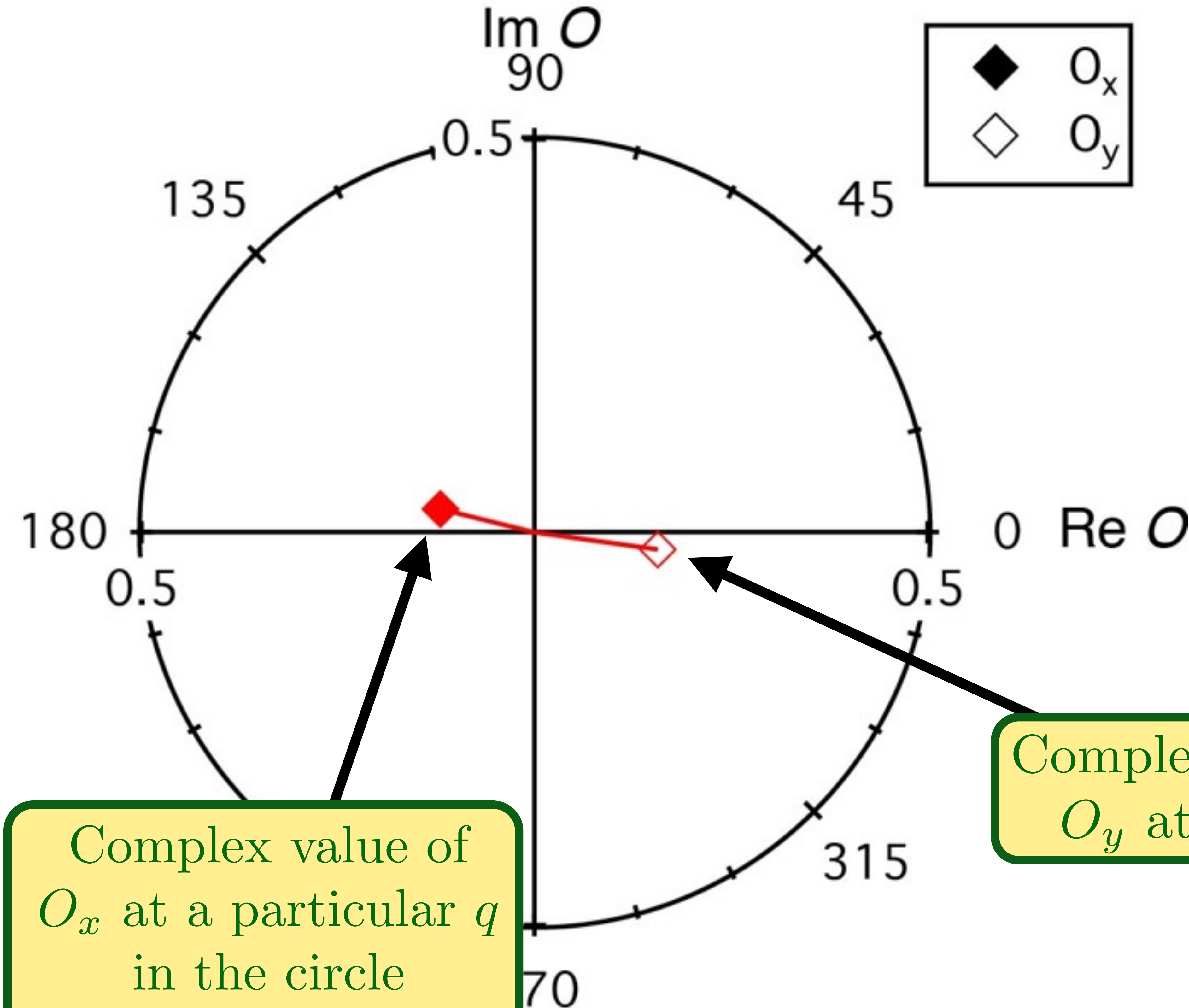

Complex value of O_x at a particular q in the circle around $2\pi(1/4, 0)$.

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

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)

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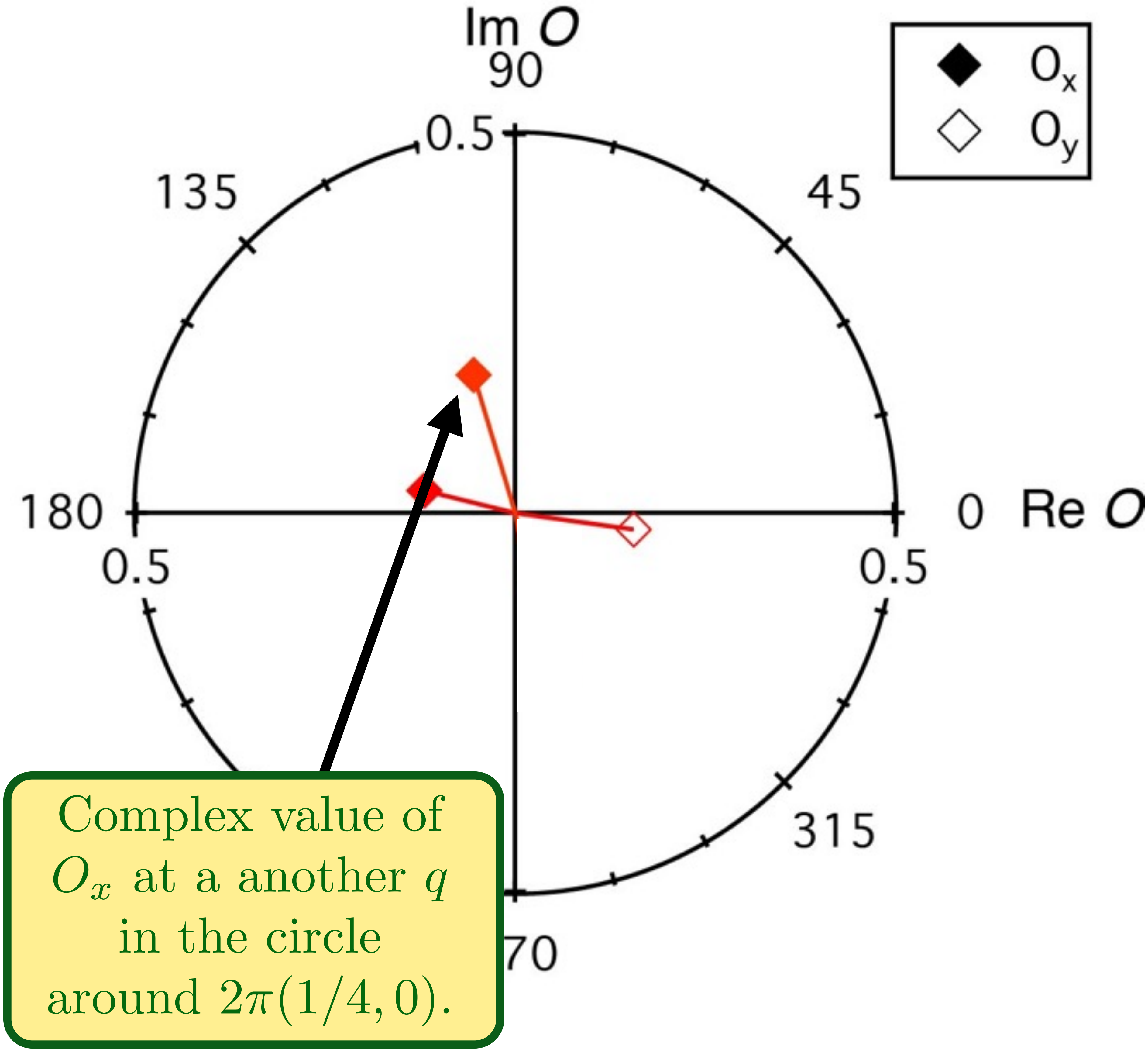

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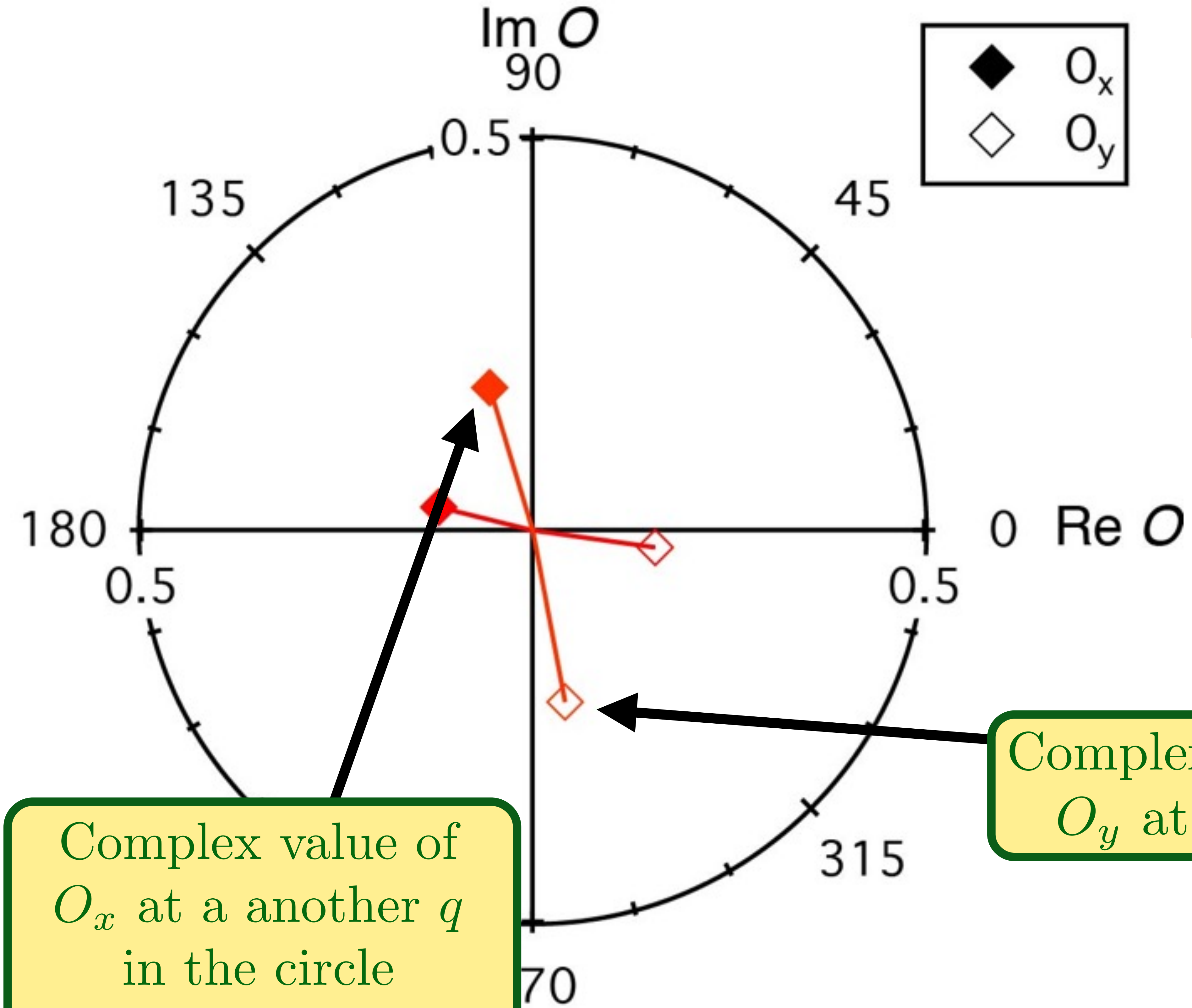

Complex value of O_x at a another q in the circle around $2\pi(1/4,0)$.

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

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)

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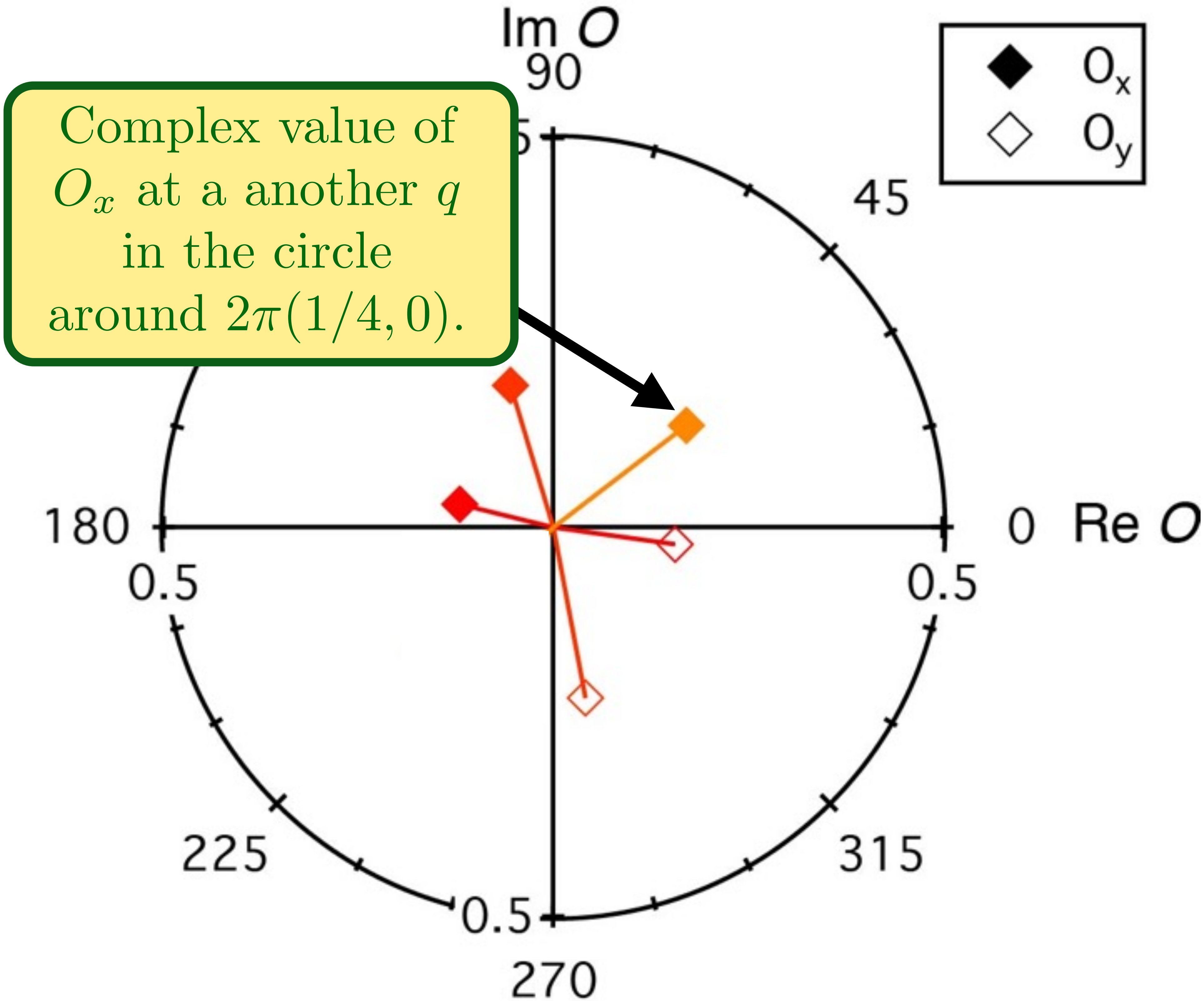

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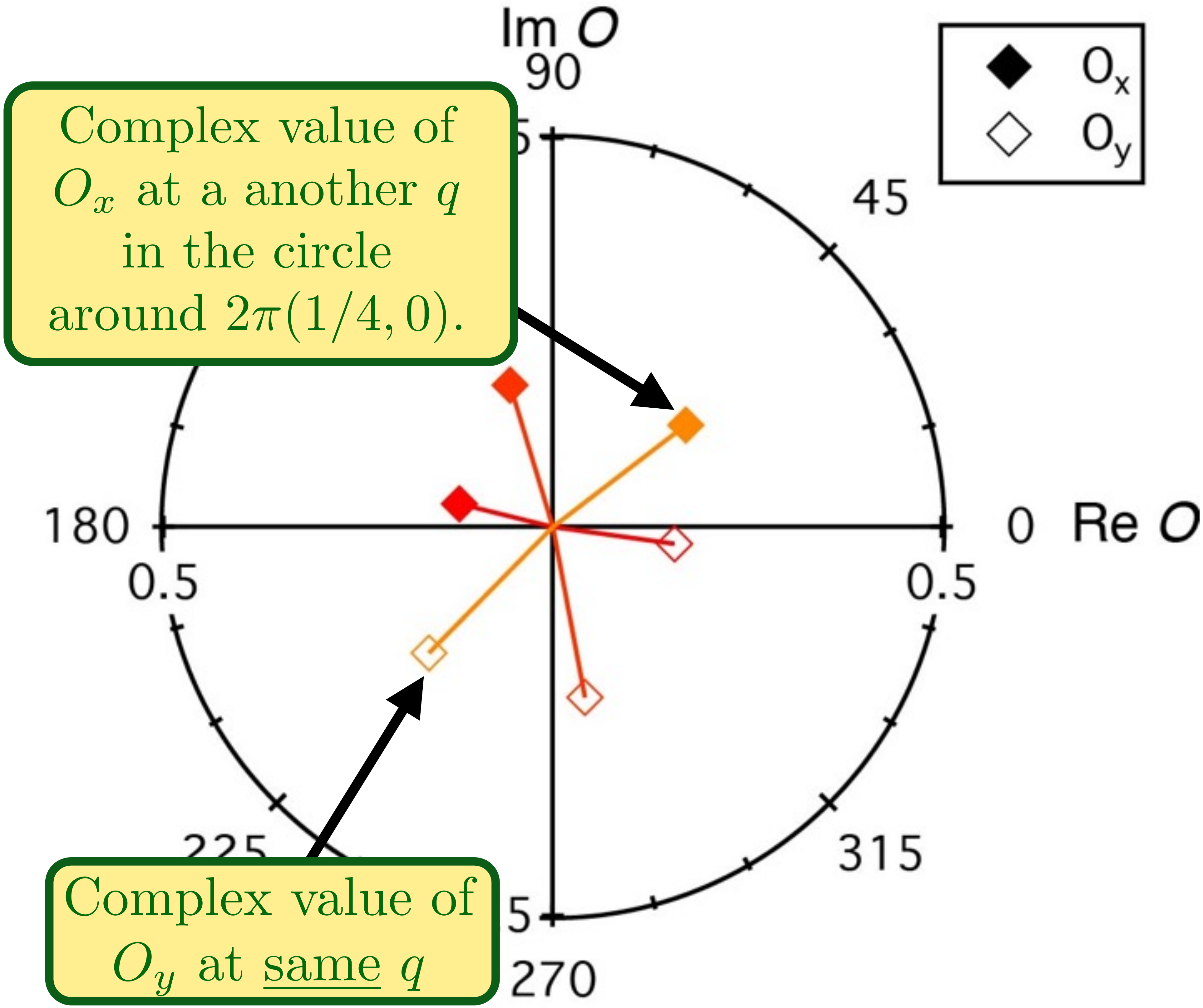

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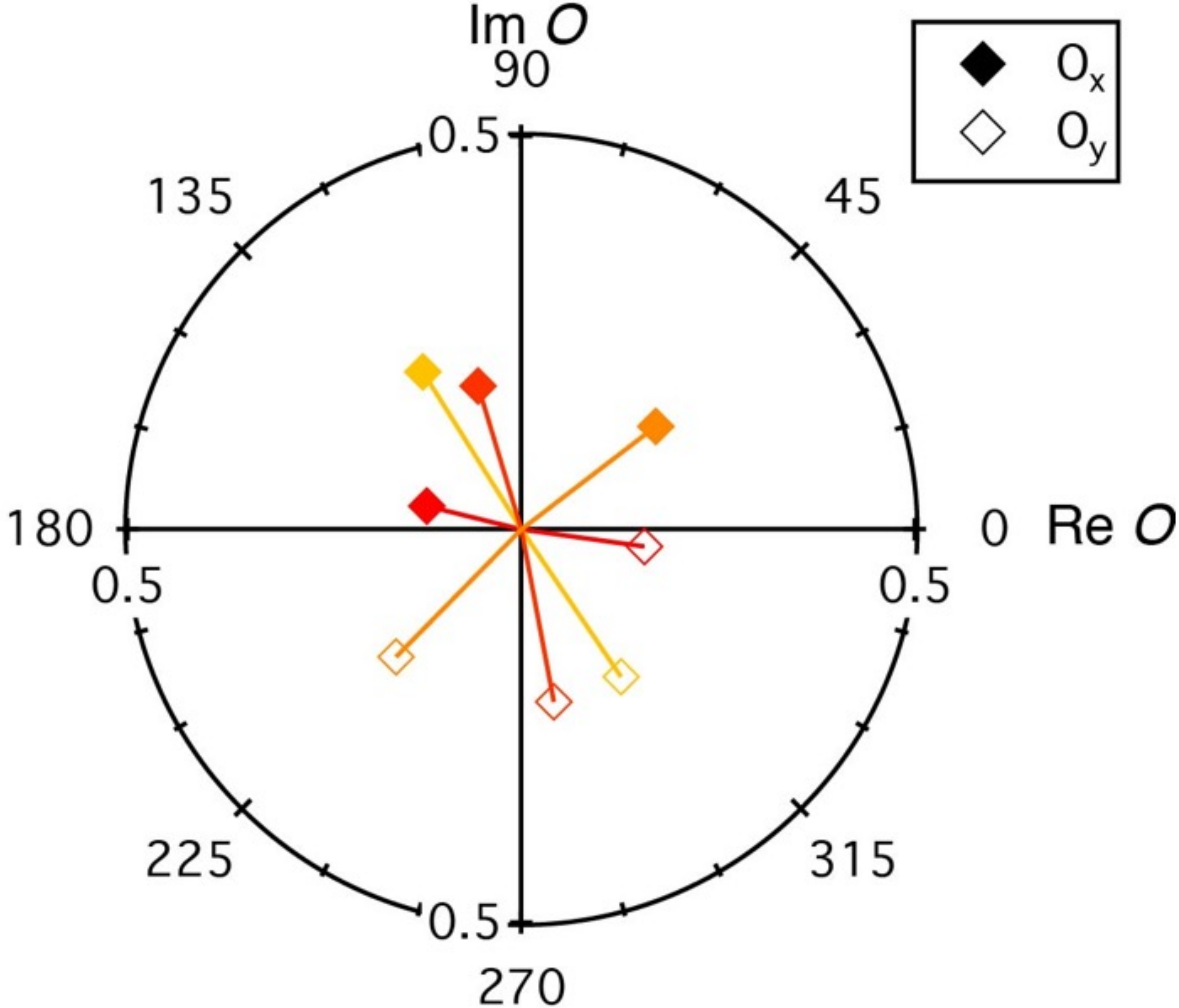

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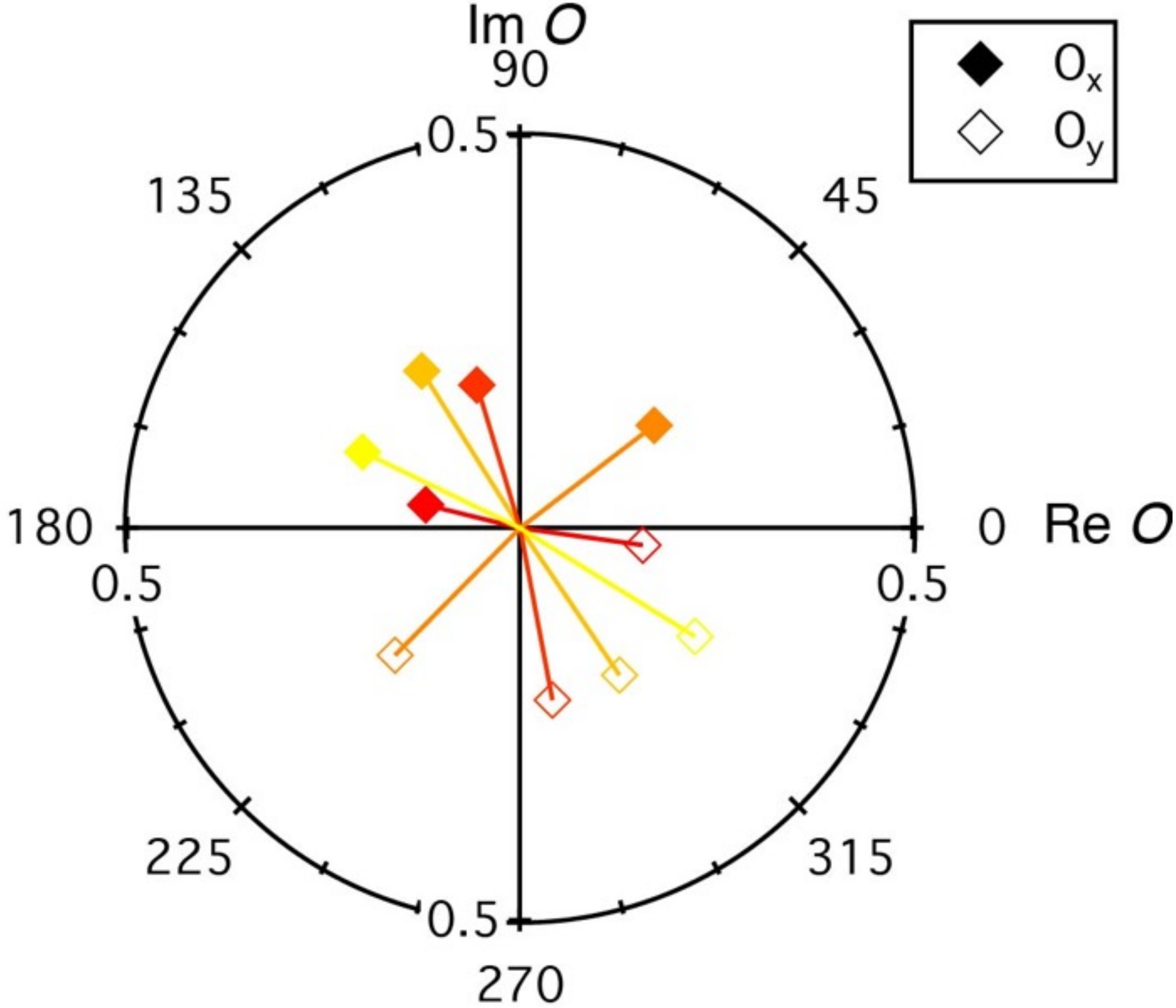

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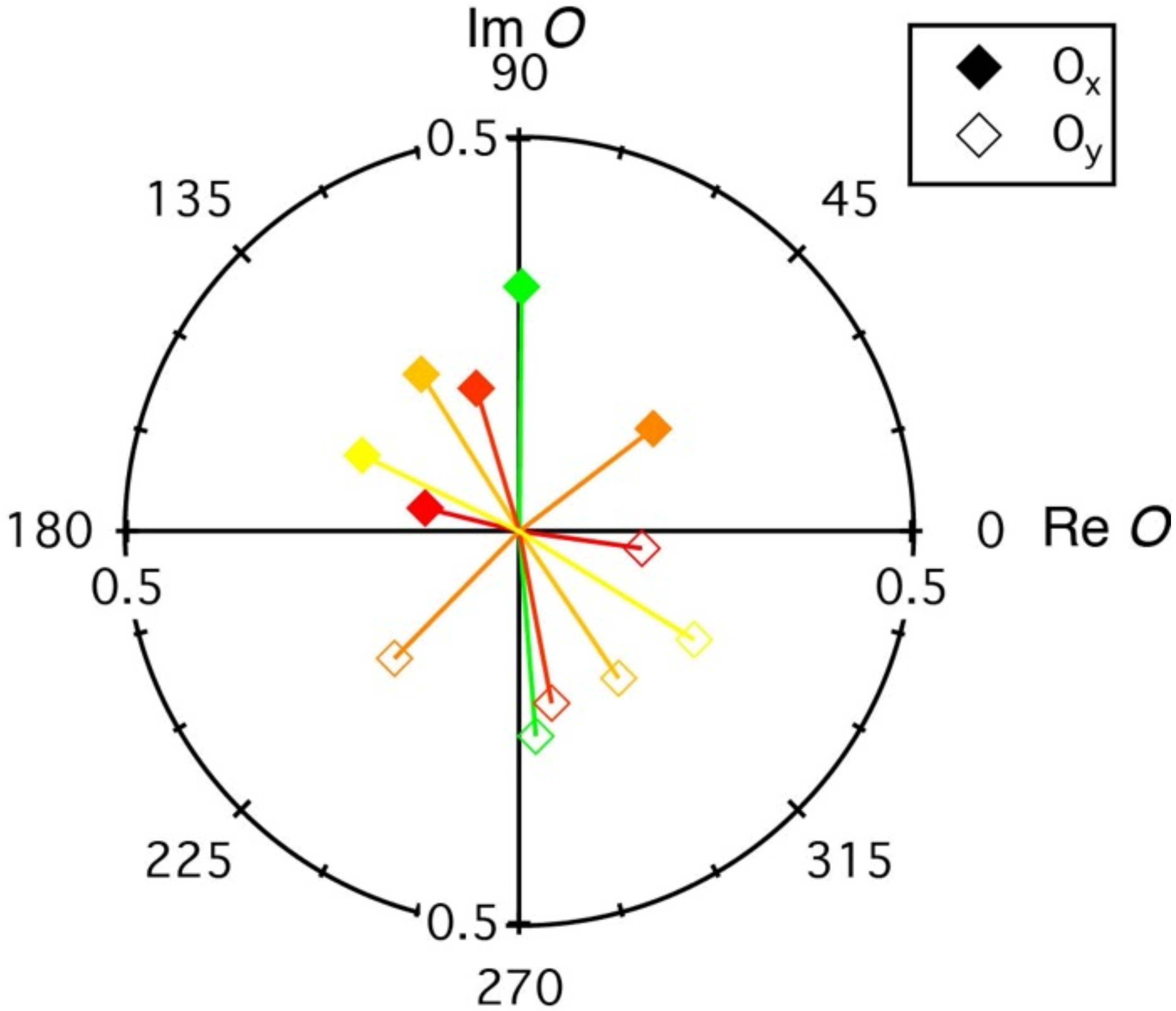

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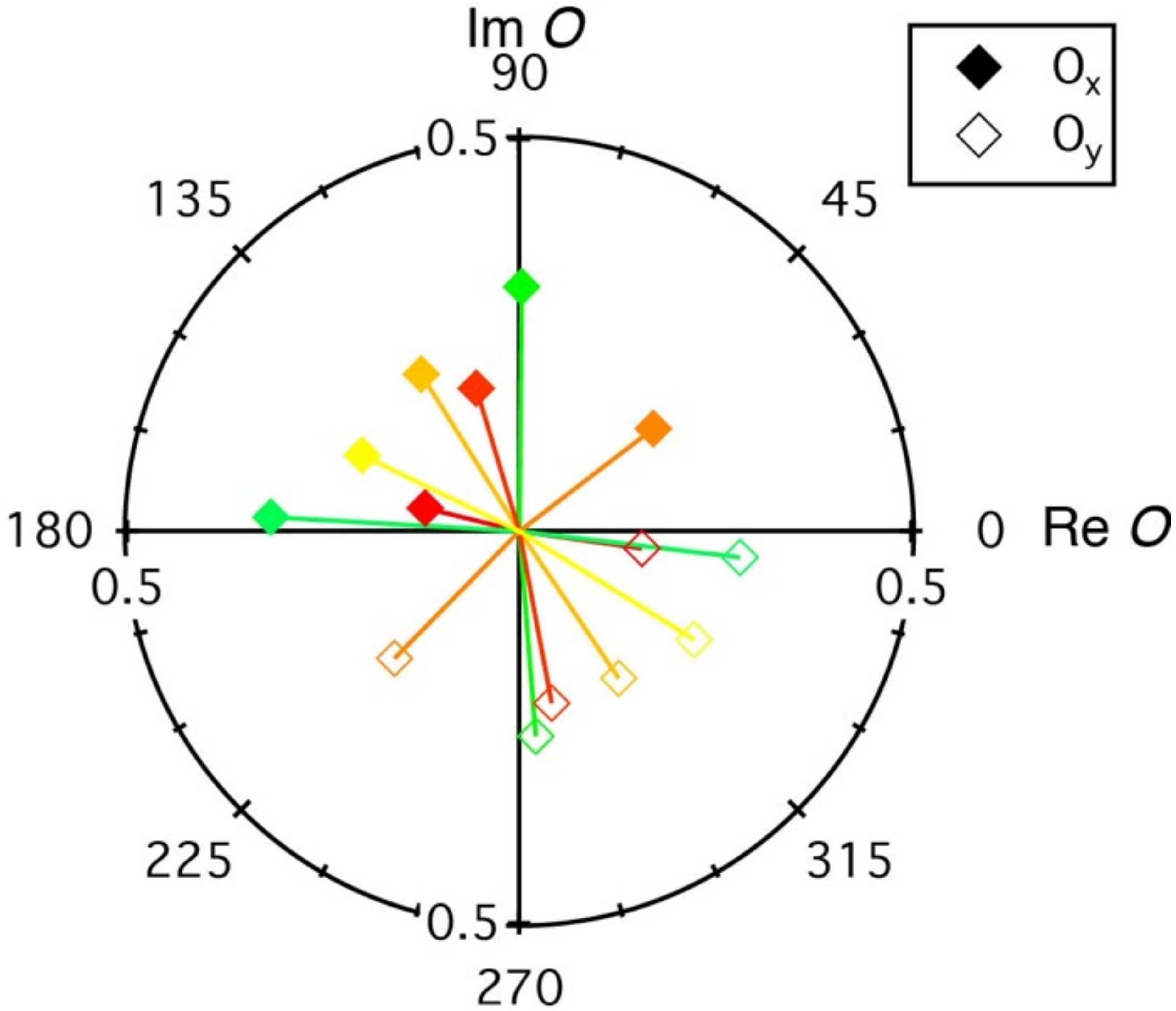

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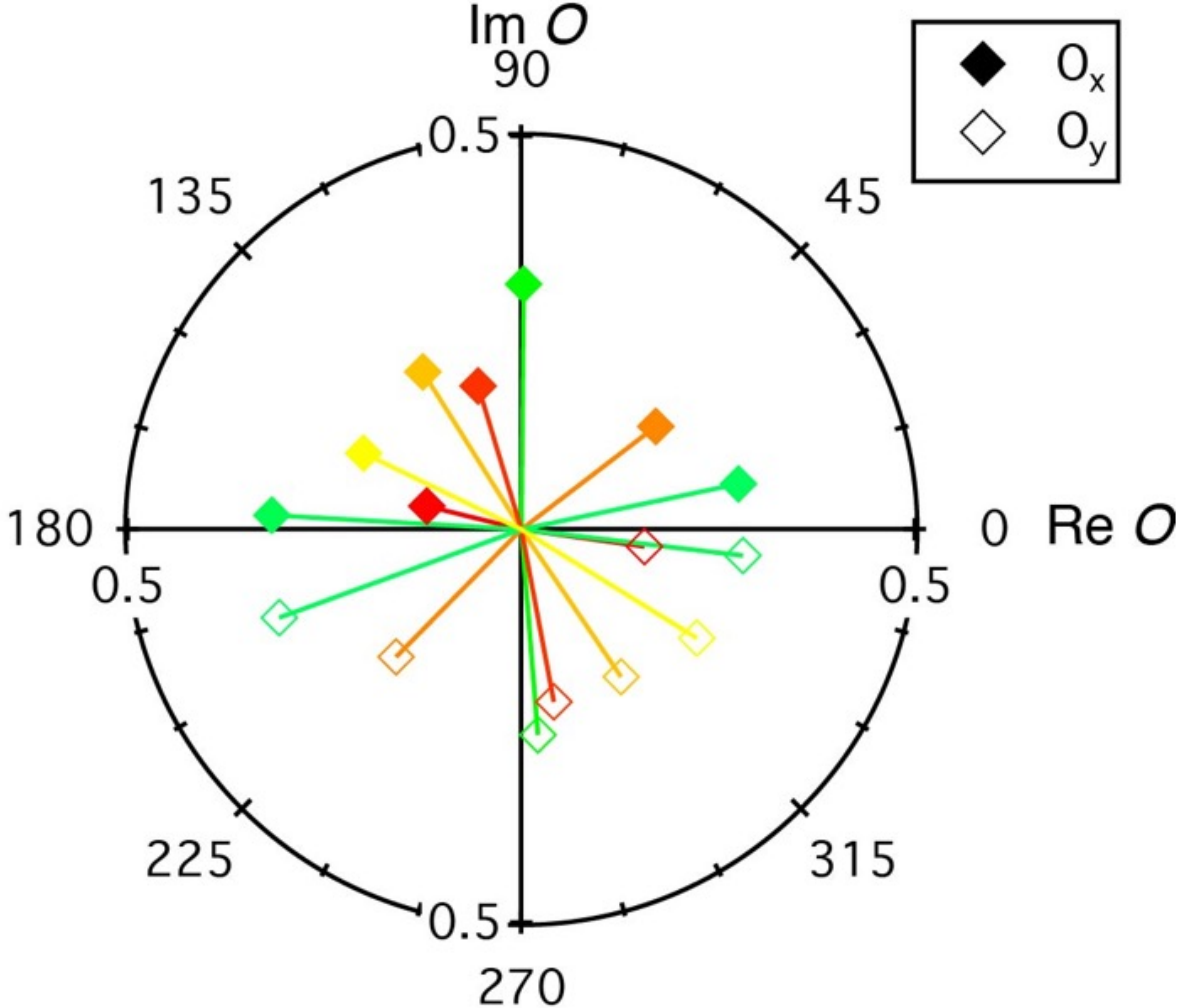

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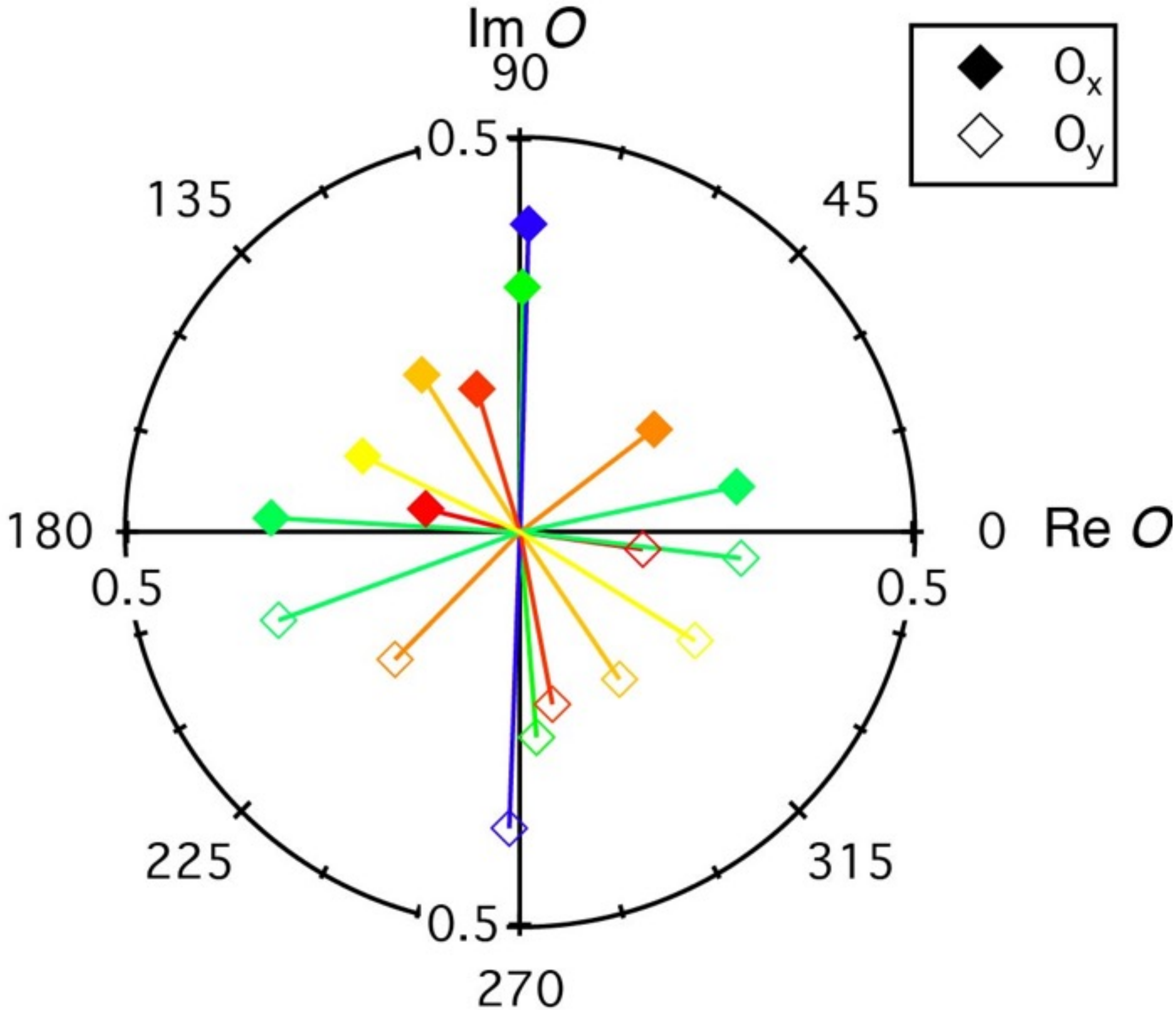

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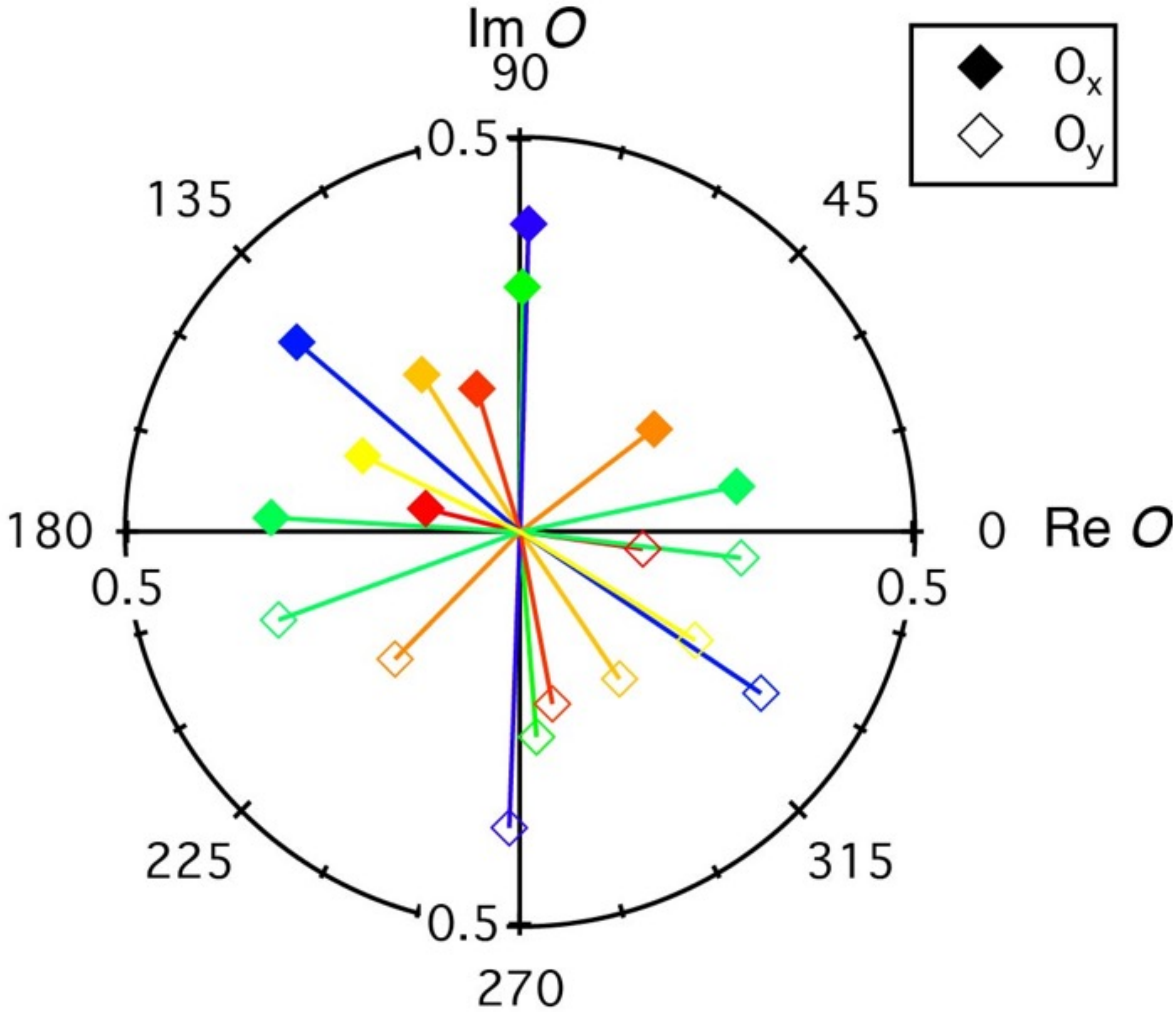

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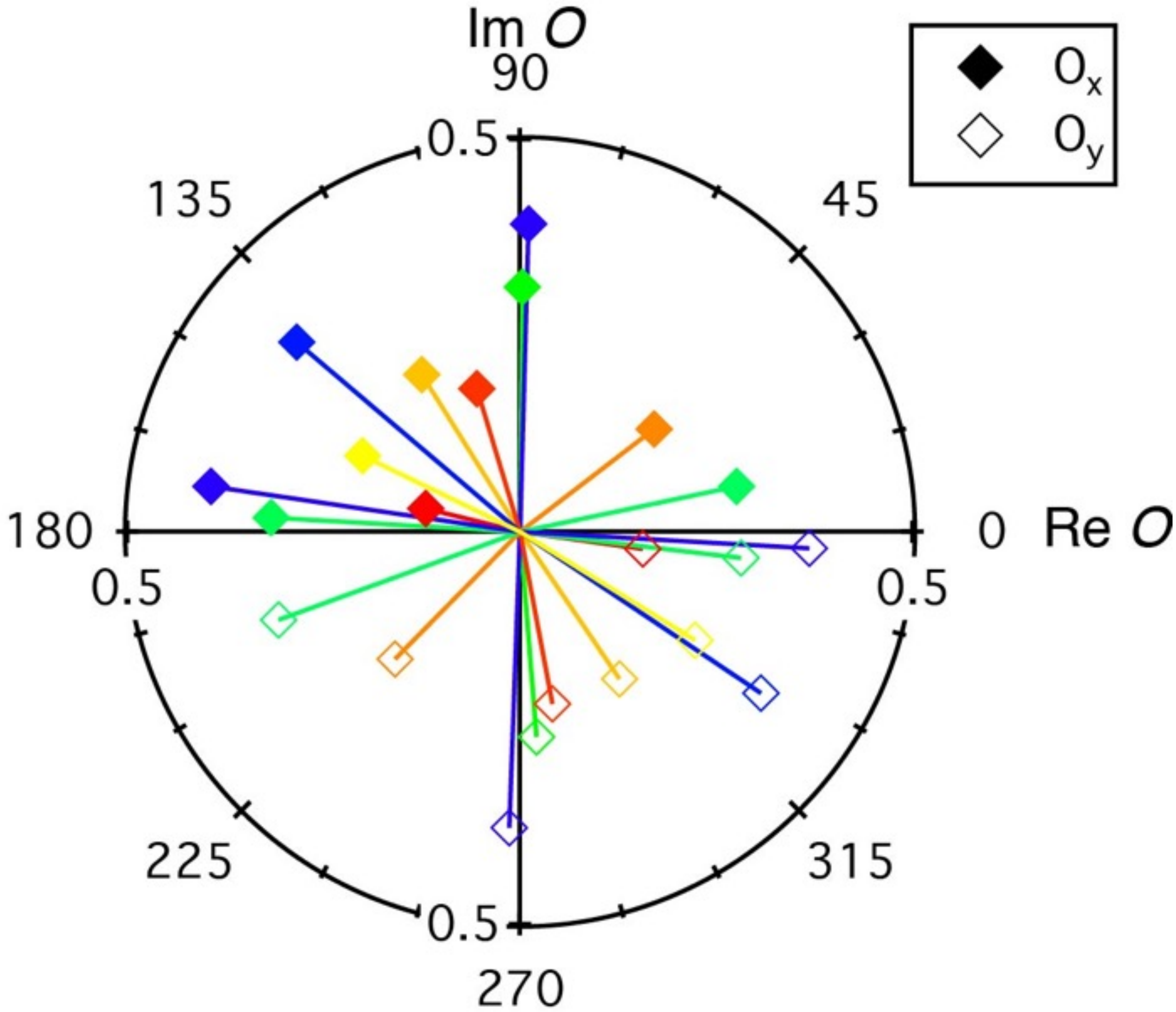

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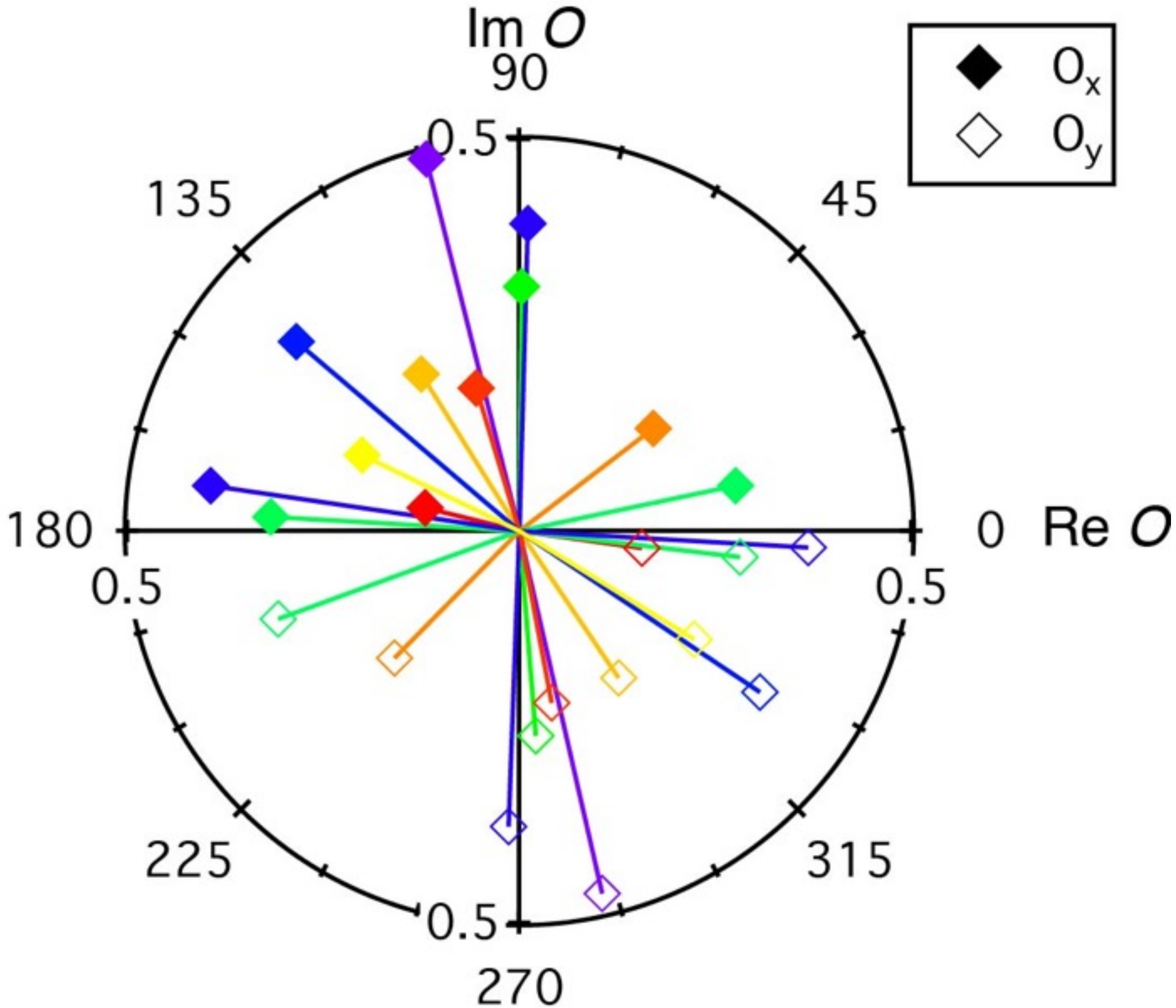

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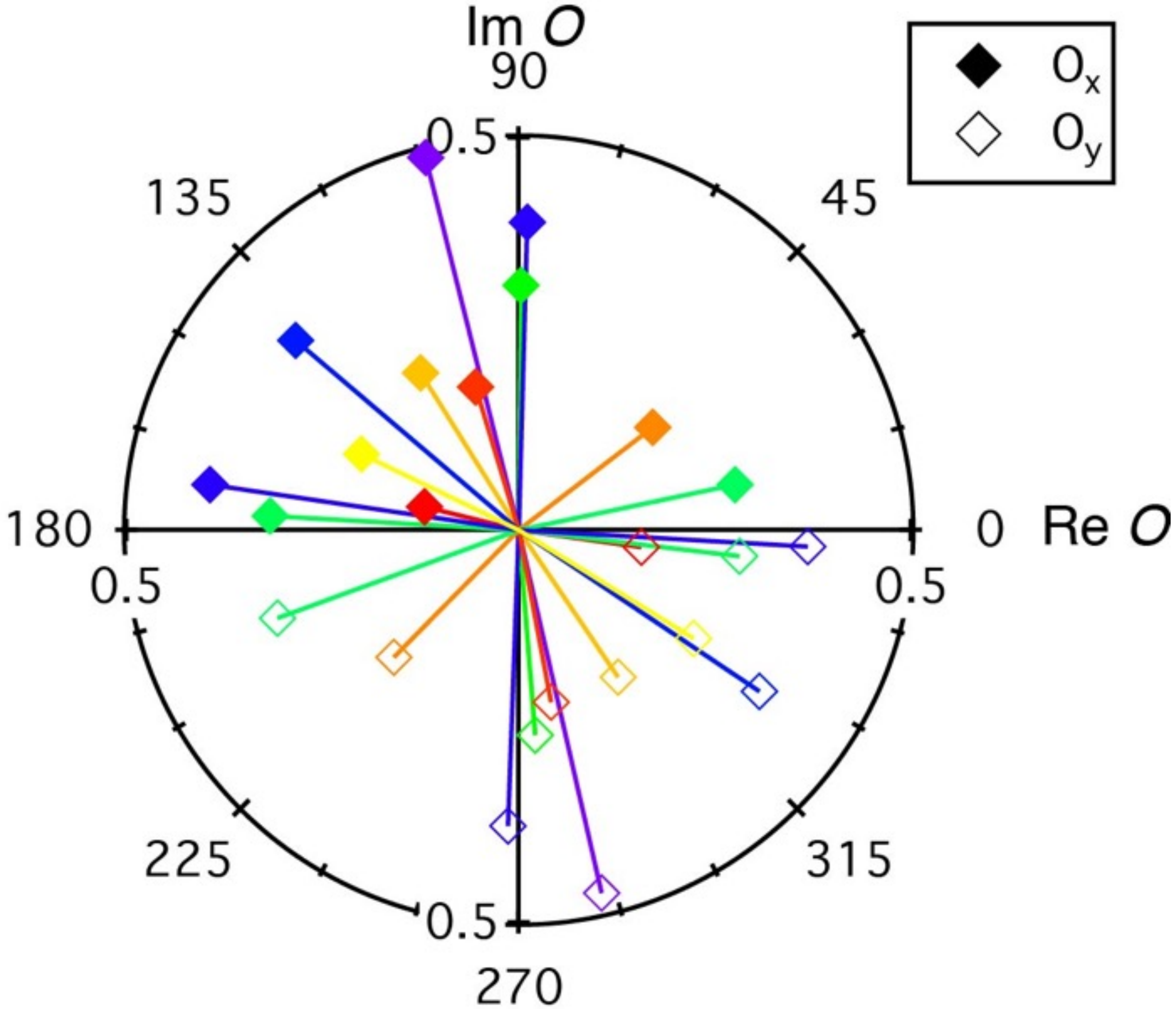
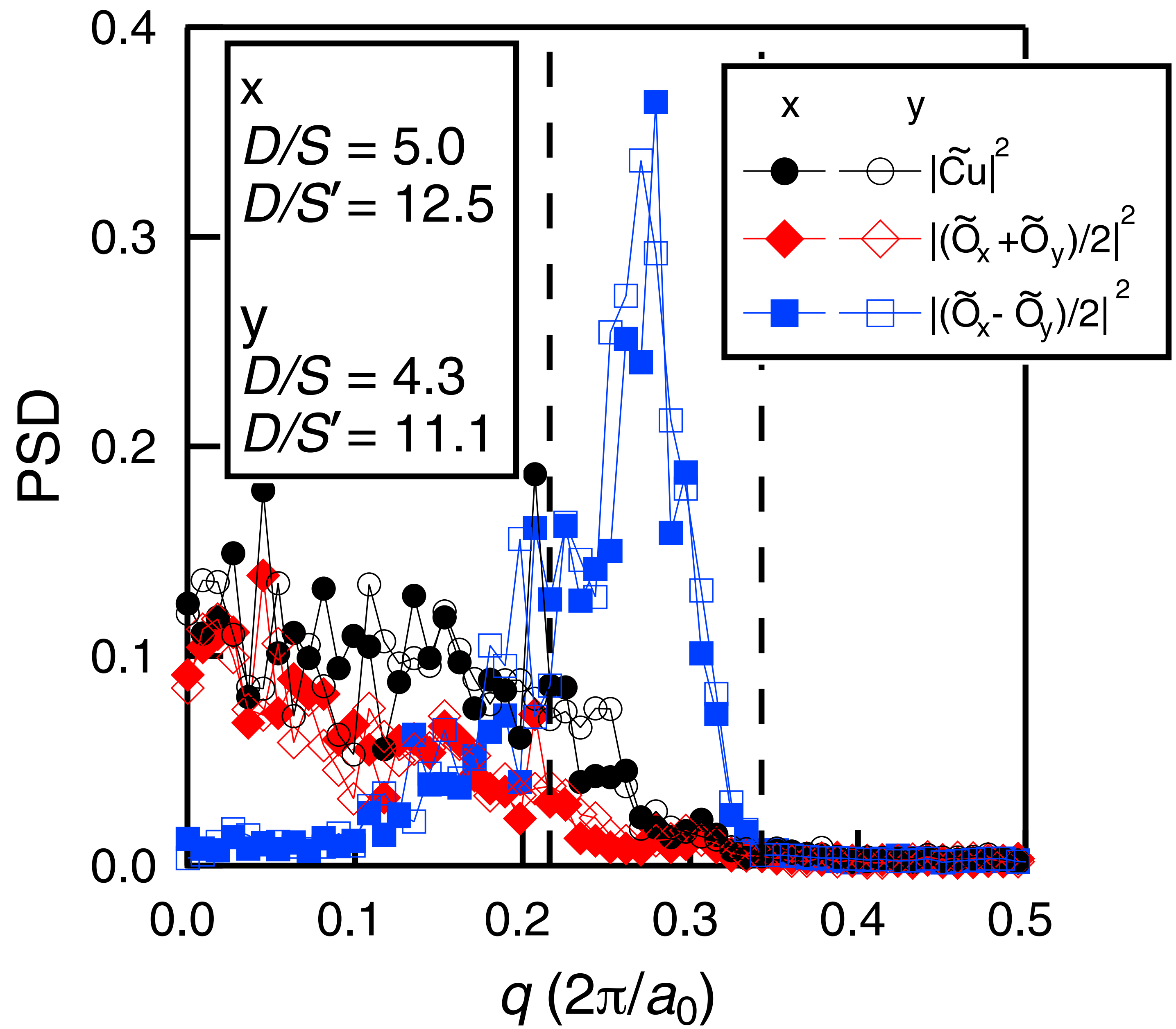
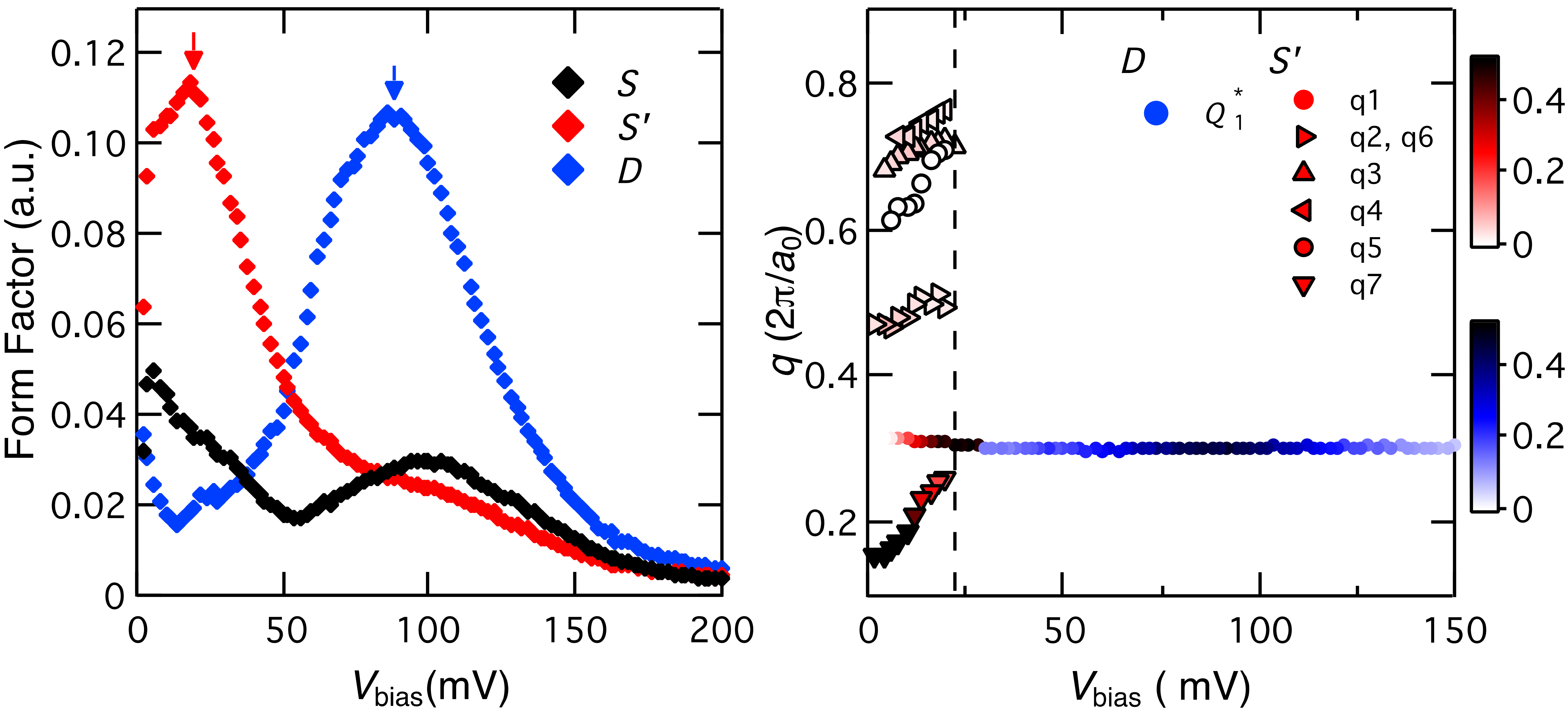
Phase-sensitive measurement of the *d*-form factor of density wave order



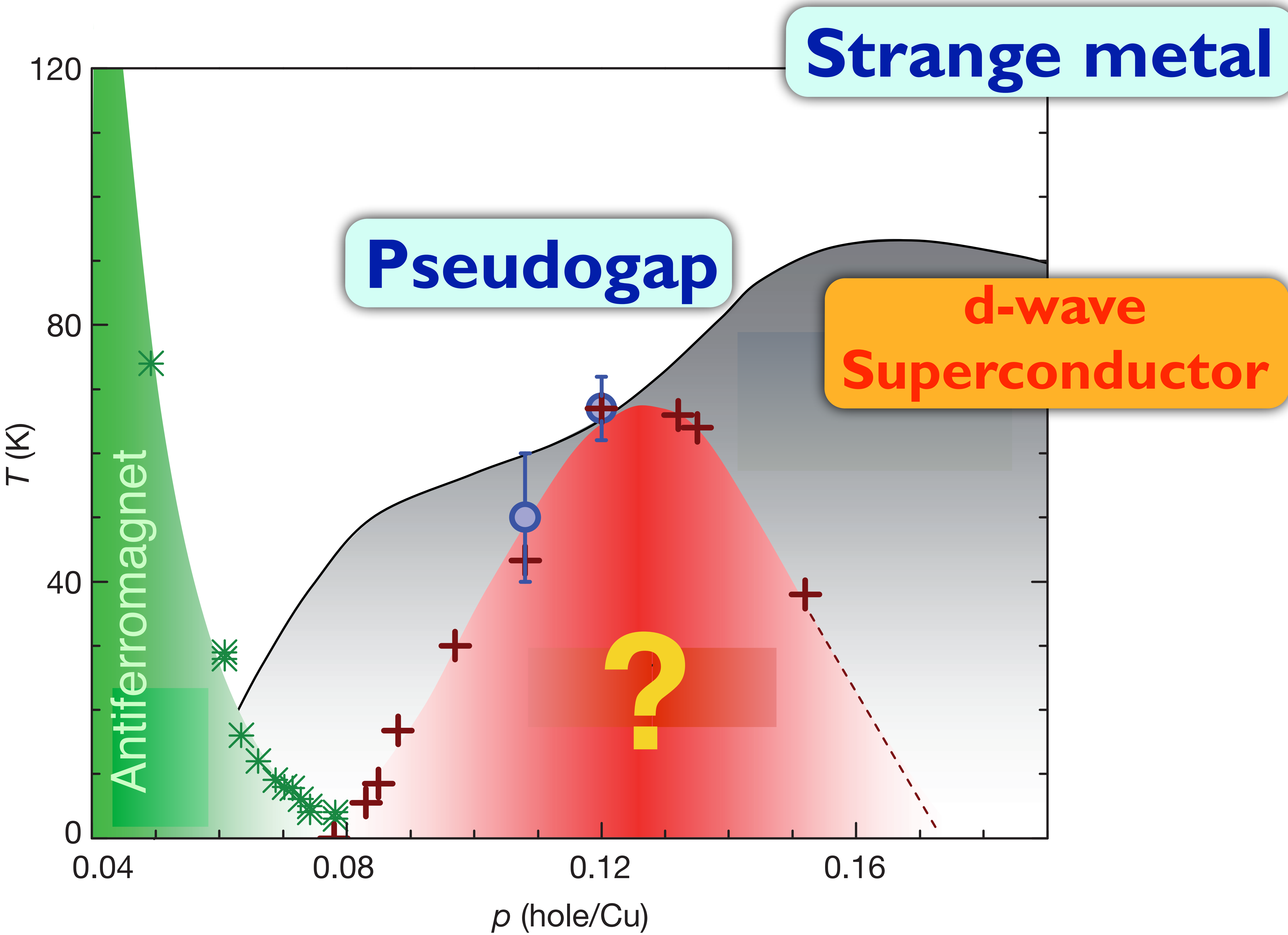


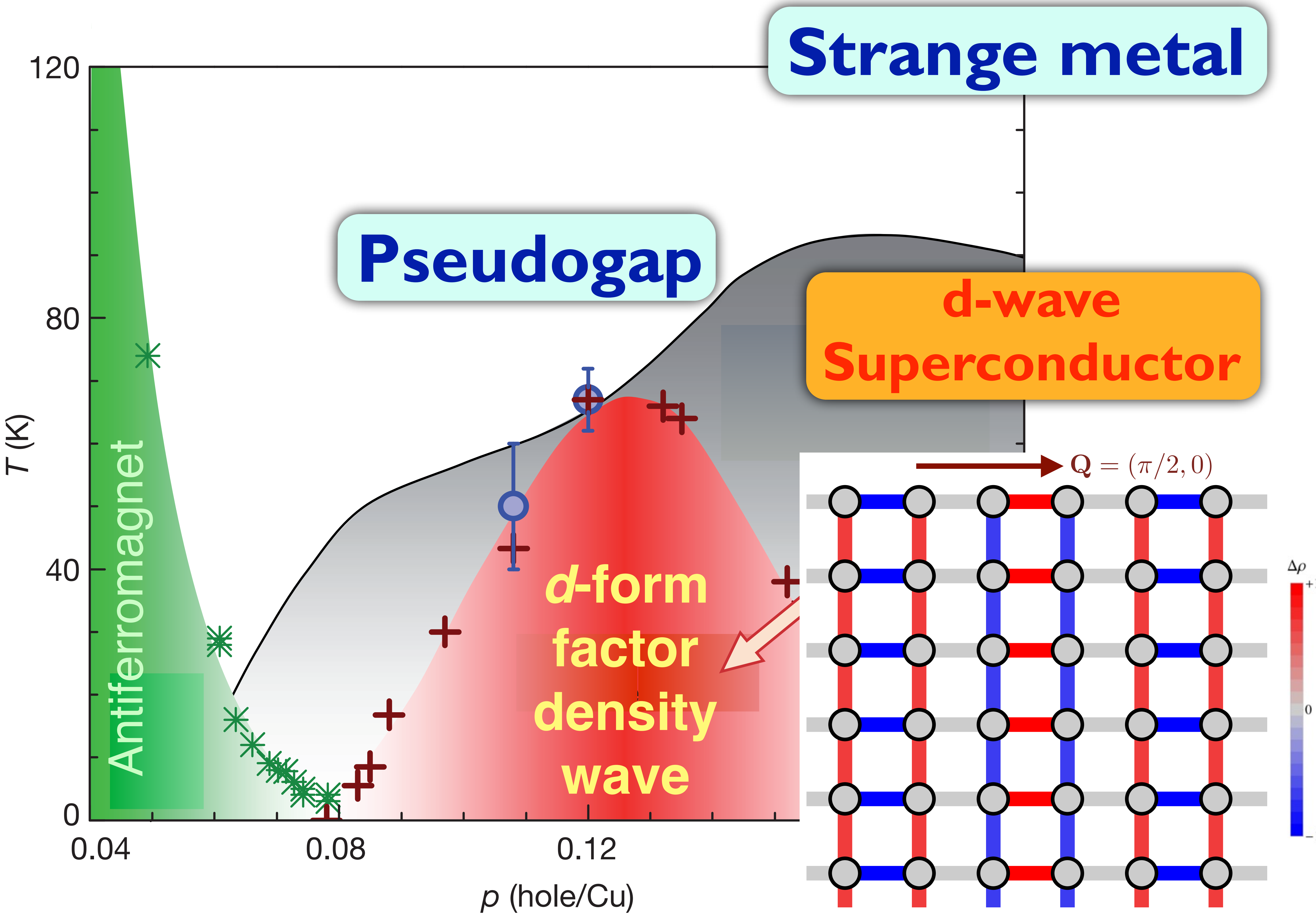
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

d-form factor is peaked at the pseudogap energy, and does not disperse as a function of wavevector



K. Fujita, M. H. Hamidian, S. D. Edkins, Chung Koo Kim, A. P. MacKenzie, H. Eisaki, S. Uchida, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, to appear


Strange metal
Pseudogap
d-wave
Superconductor
Antiferromagnet
?
120
80
40
0
T (K)
0.04
0.08
0.12
0.16
p (hole/Cu)



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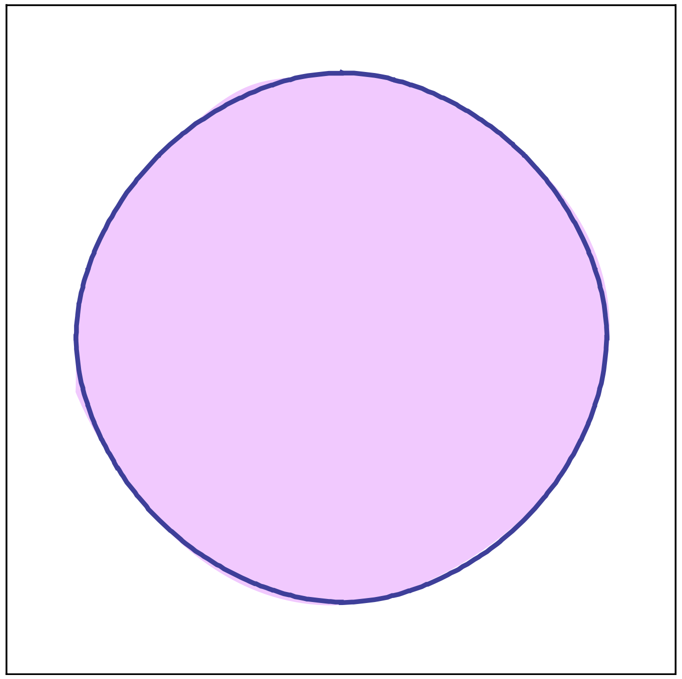
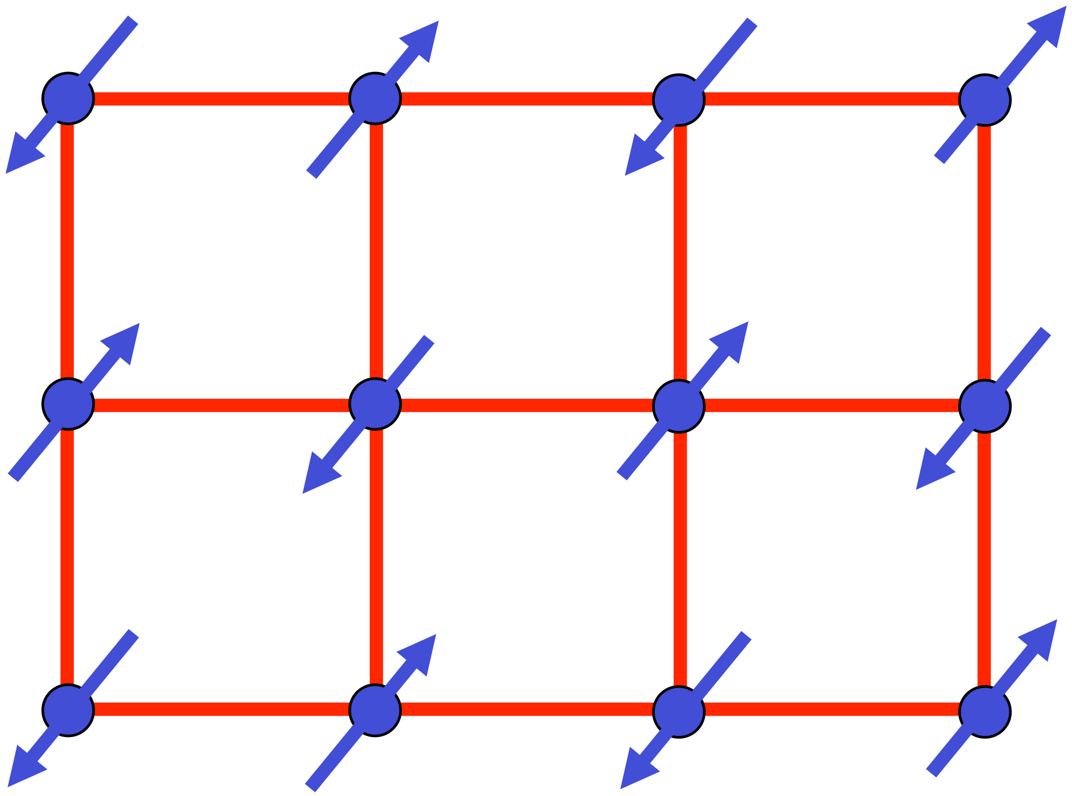
Theory

Fermi surface+antiferromagnetism

Metal with "large"
Fermi surface



+

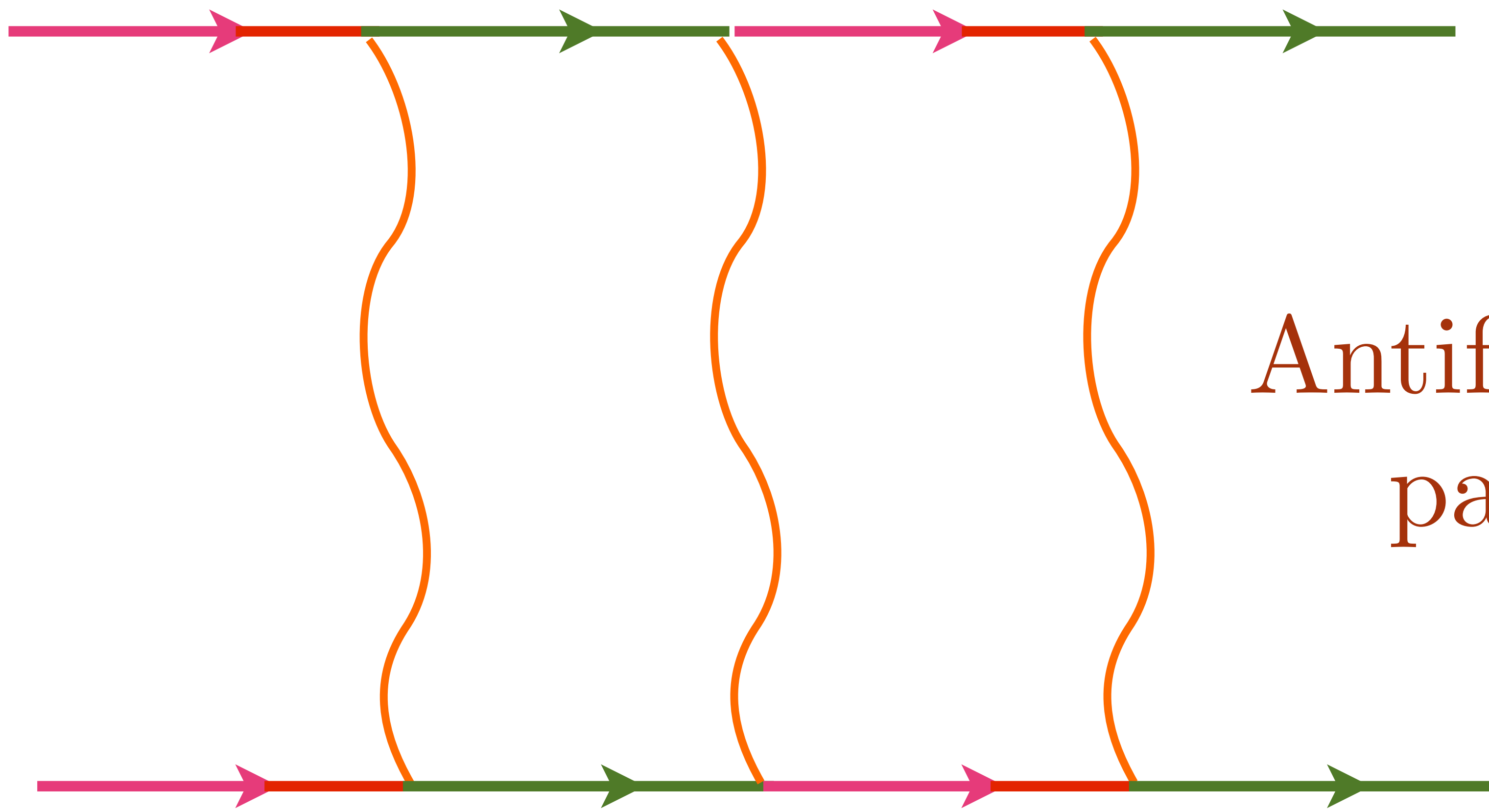


The electron spin polarization obeys

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

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

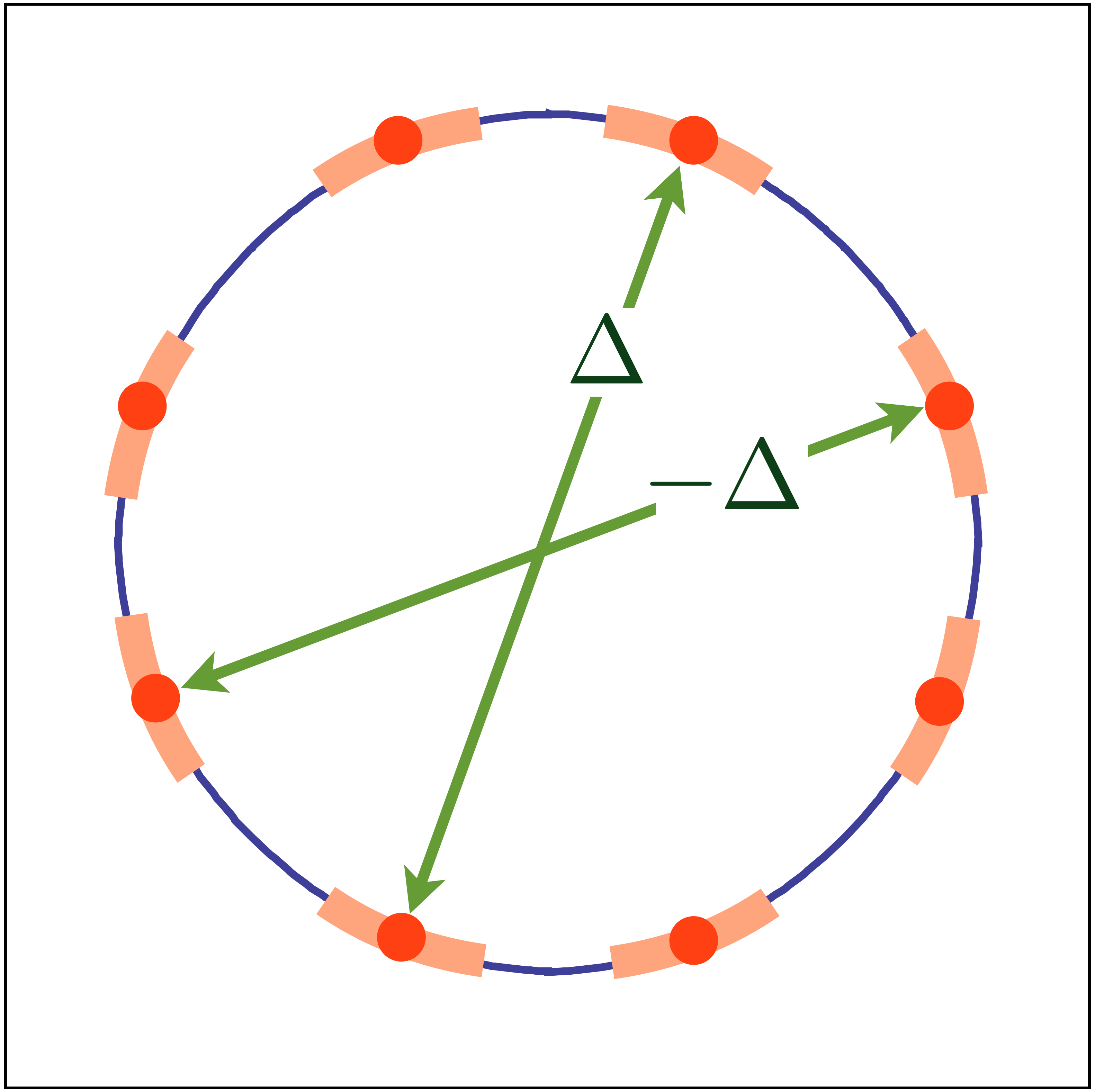
Pairing "glue" for d-wave superconductivity from antiferromagnetic fluctuations



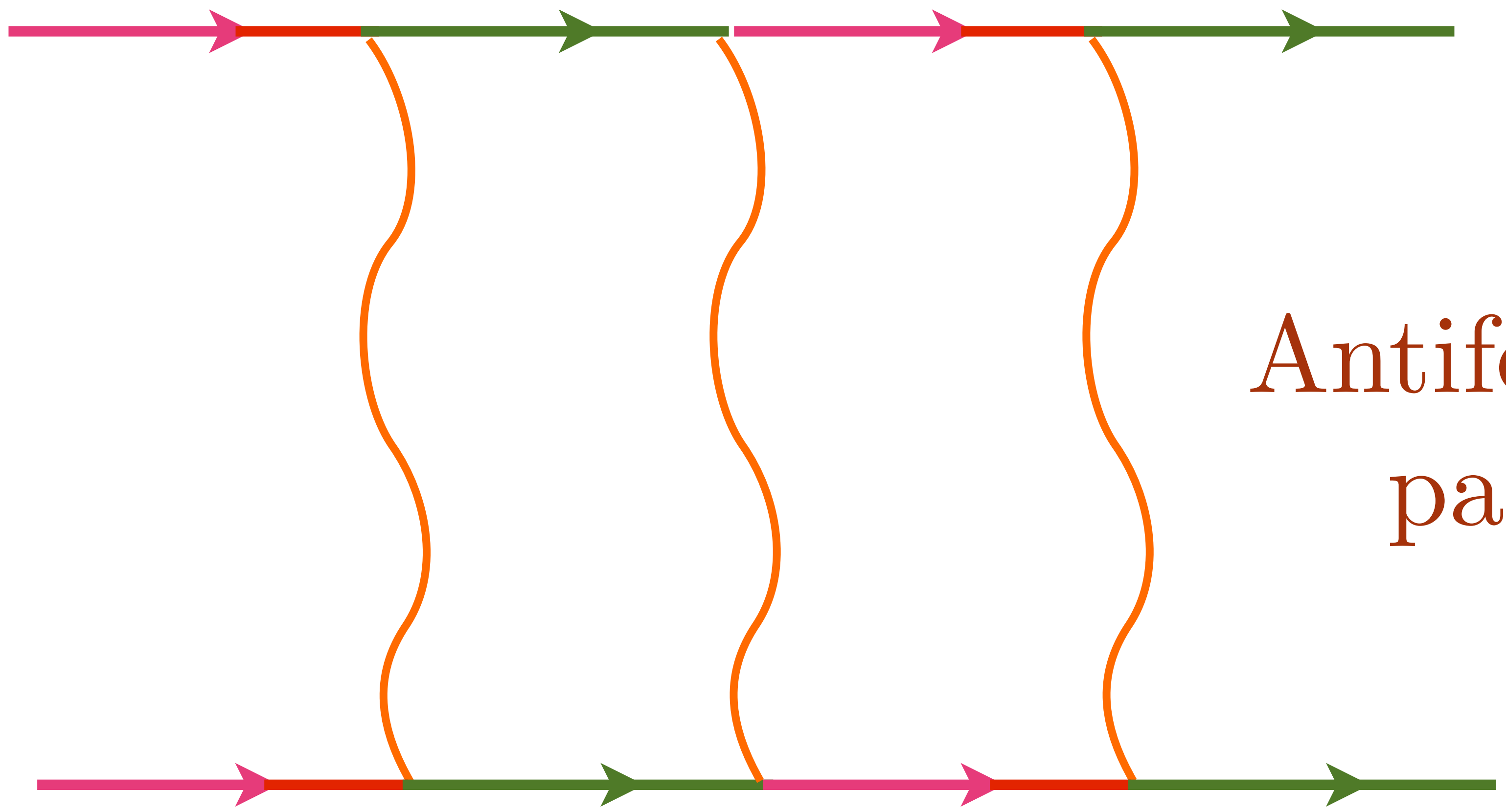
Antiferromagnetic paramagnon

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)
P. Monthoux, A.V. Balatsky, and D. Pines, *Phys. Rev. Lett.* **67**, 3448 (1991)

$$\left\langle c^{\dagger}_{\mathbf{k}\alpha} c^{\dagger}_{-\mathbf{k}\beta} \right\rangle = \varepsilon_{\alpha\beta} \Delta (\cos k_x - \cos k_y)$$



Pairing “glue” for d-wave superconductivity from antiferromagnetic fluctuations



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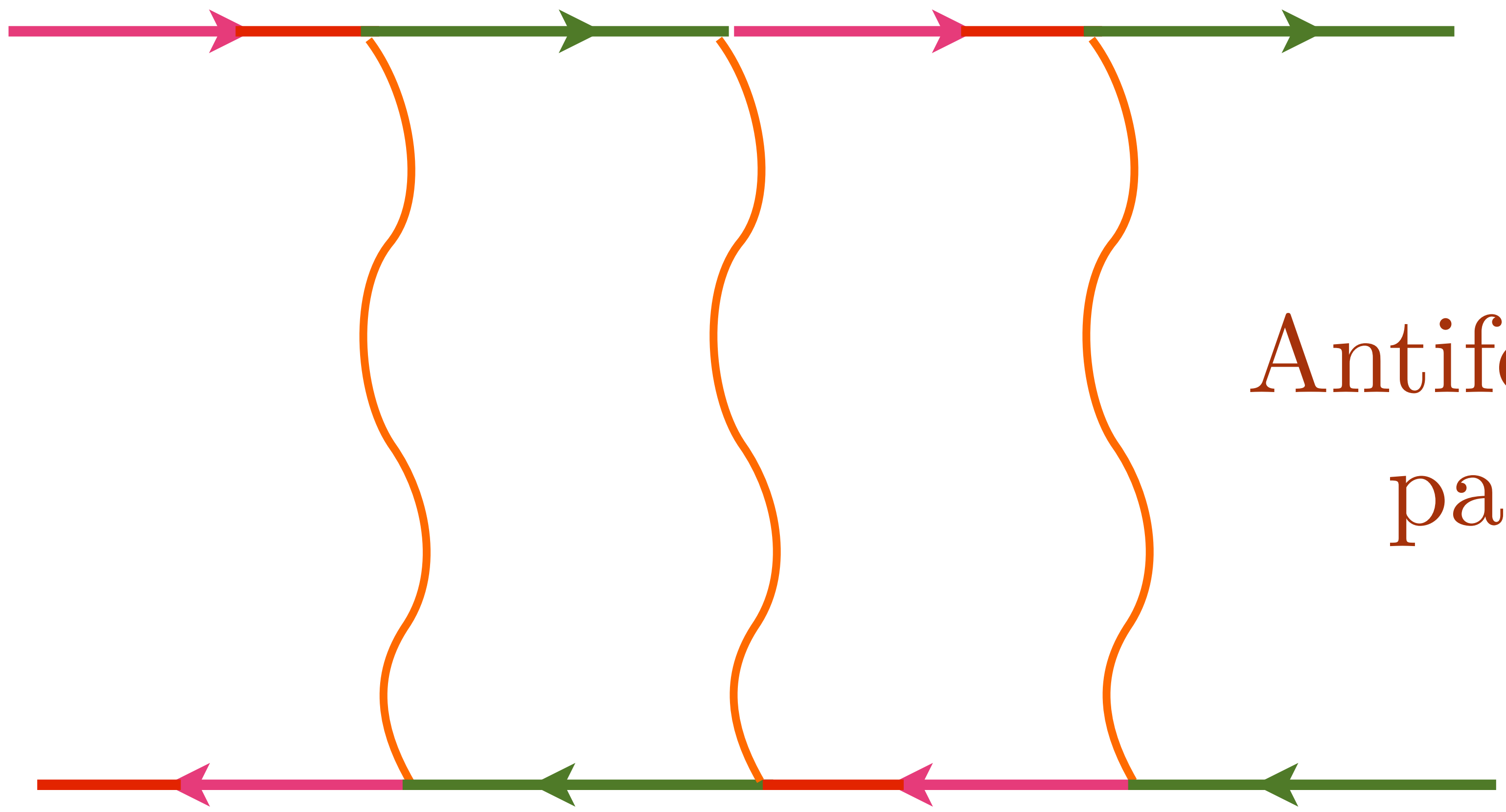
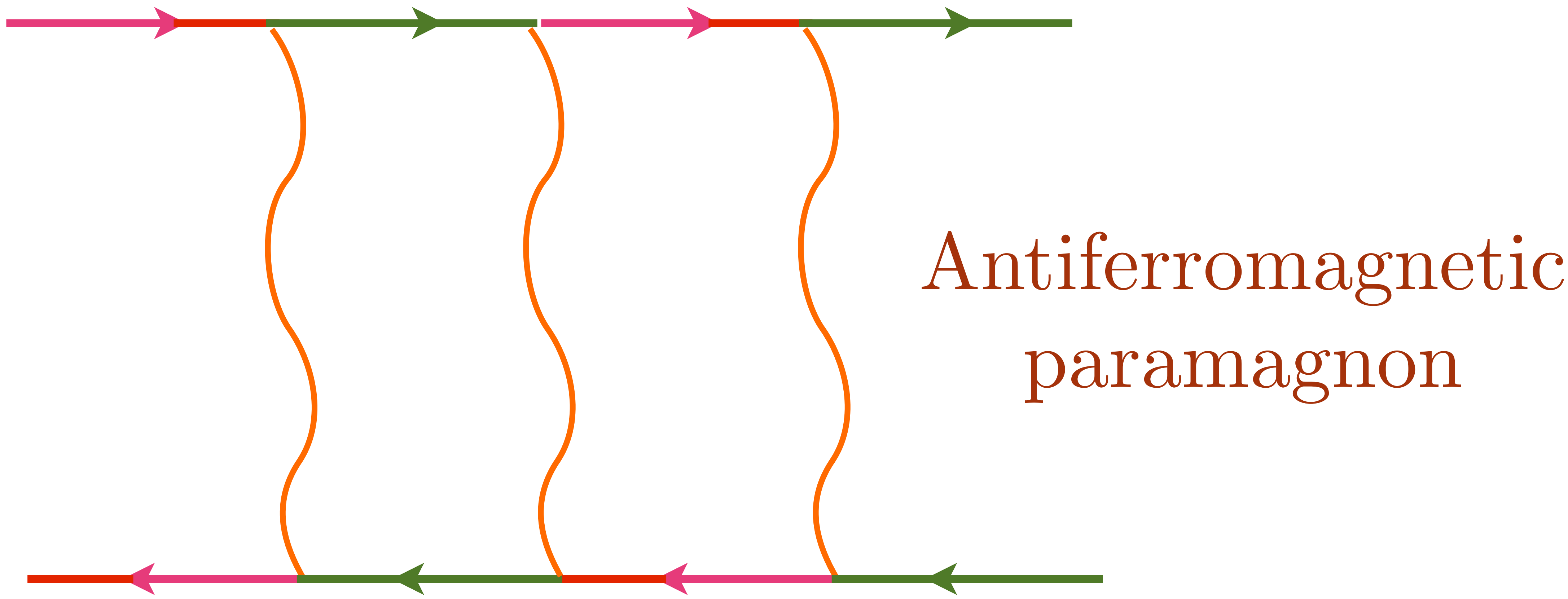
Same glue can lead to "d-wave" particle-hole pairing !



Antiferromagnetic paramagnon

M. A. Metlitski and S. Sachdev, Phys. Rev. B **85**, 075127 (2010)
T. Holder and W. Metzner, Phys. Rev. B **85**, 165130 (2012)
M. Bejas, A. Greco, and H. Yamase, Phys. Rev. B **86**, 224509 (2012)
S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013)
K. B. Efetov, H. Meier, and C. Pépin, Nat. Phys. **9**, 442 (2013)
Y. Wang and A. V. Chubukov, Phys. Rev. B **90**, 035149 (2014)

Same glue can lead to "d-wave" particle-hole pairing !

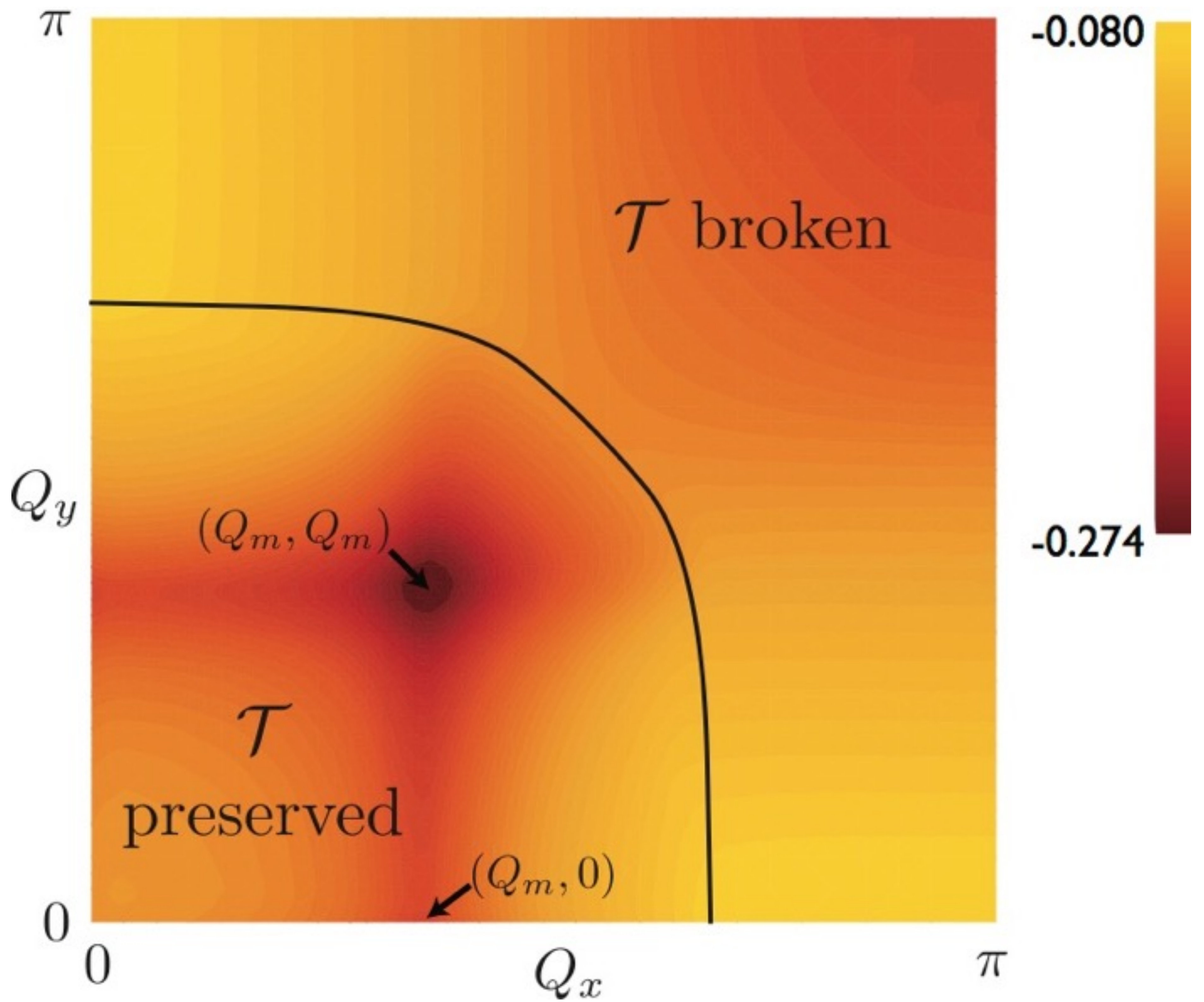


Compute eigenvalues, $\lambda(\mathbf{Q})$, of the spin-singlet, particle-hole propagator. The corresponding eigenvector is $\mathcal{P}(\mathbf{k})$ and this leads to the order

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

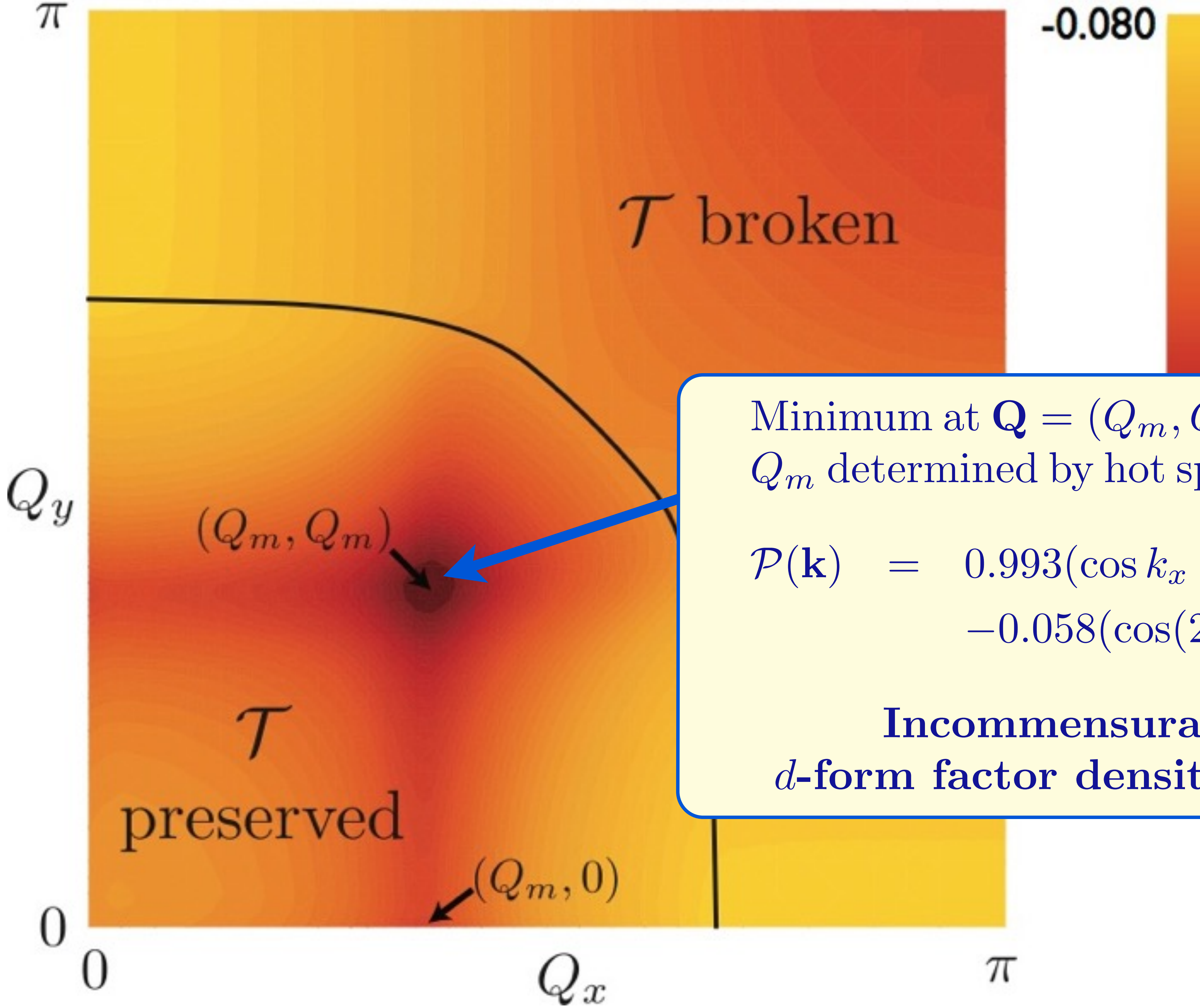
S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013)

S. Sachdev and R. La Placa, Phys. Rev. Lett. 111, 027202 (2013)



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

S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013)



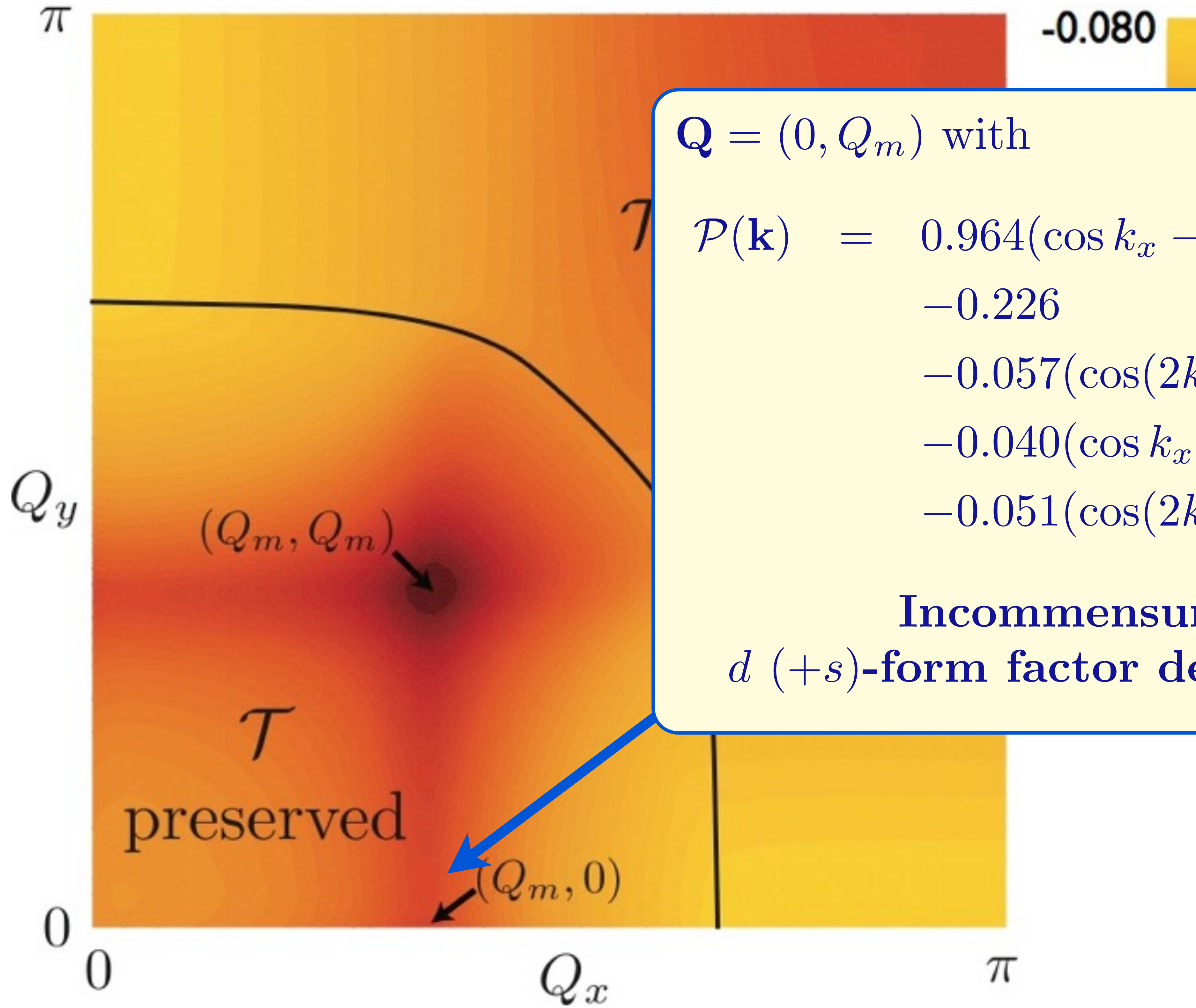
Minimum at $\mathbf{Q} = (Q_m, Q_m)$ (with Q_m determined by hot spots) with

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

Incommensurate
d-form factor density wave

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

S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013)



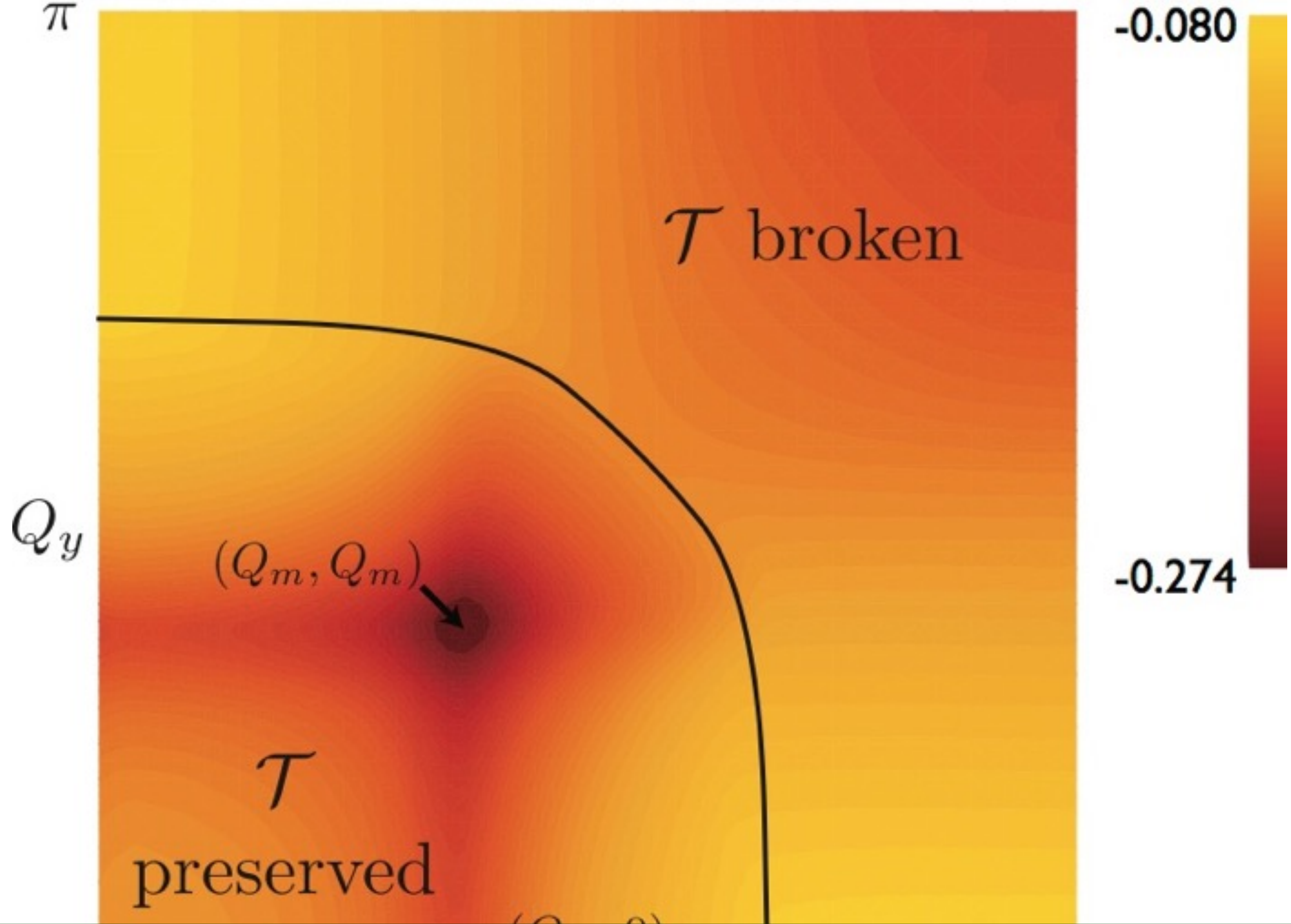
$\mathbf{Q} = (0, Q_m)$ with

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

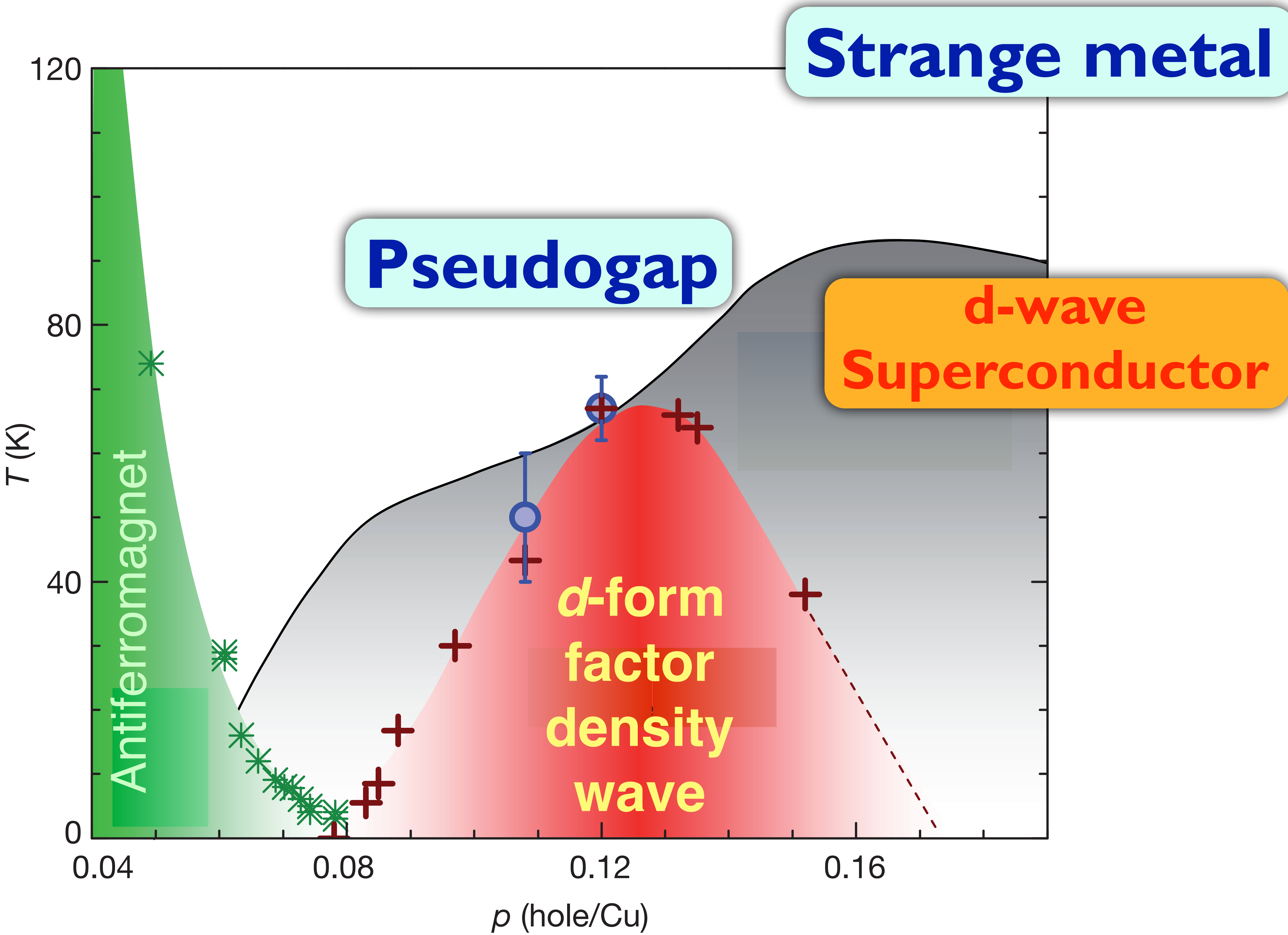
Incommensurate
d $(+s)$**-form factor density wave**

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

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



This theory yields the correct form factor, but the incorrect **Q**. We have found the same features in all theories (one- and three-band) with a large Fermi surface



Strange metal
Pseudogap
d-wave
Superconductor
Antiferromagnet
d-form
factor
density
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120
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T (K)
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0.08
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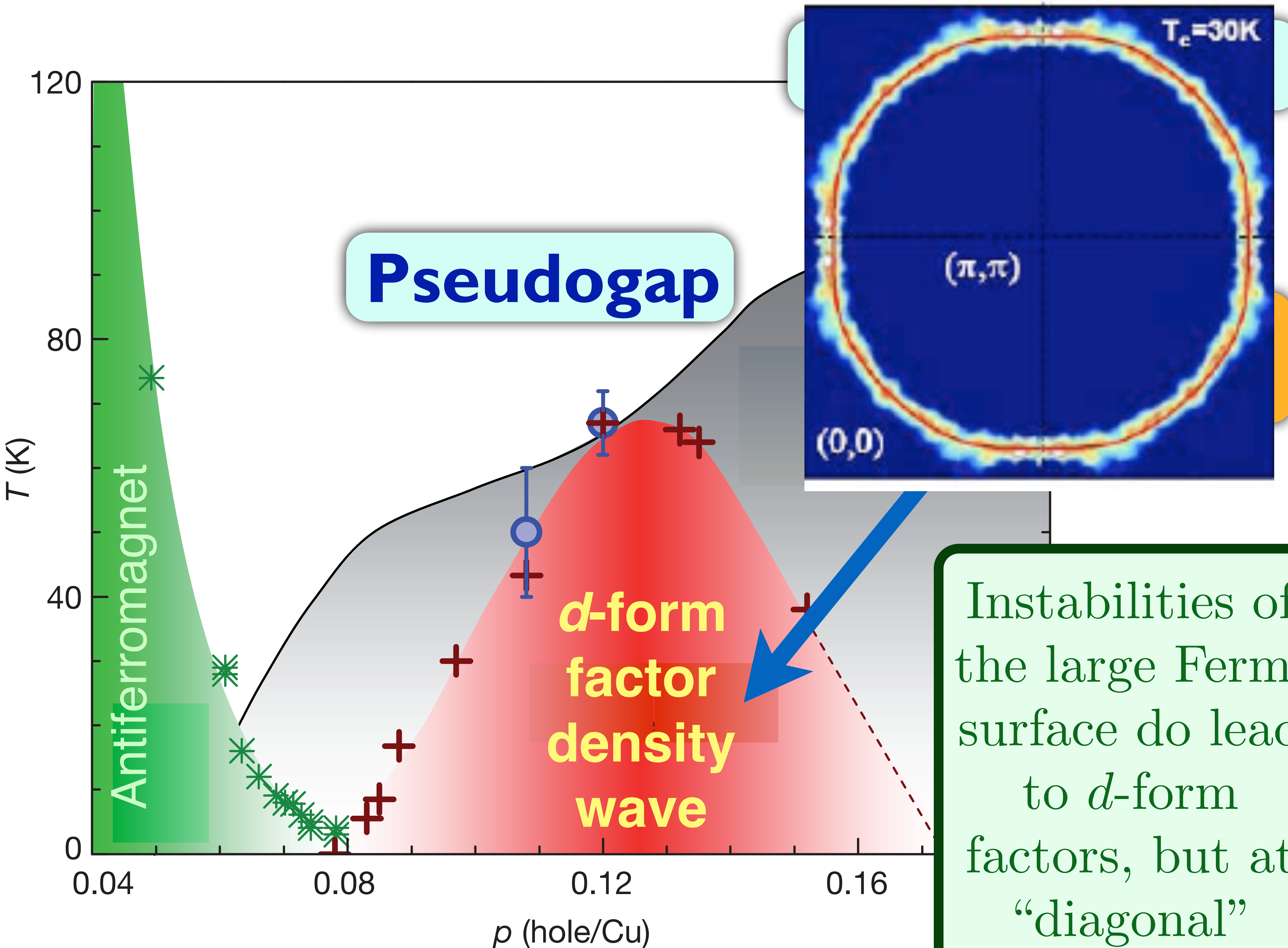
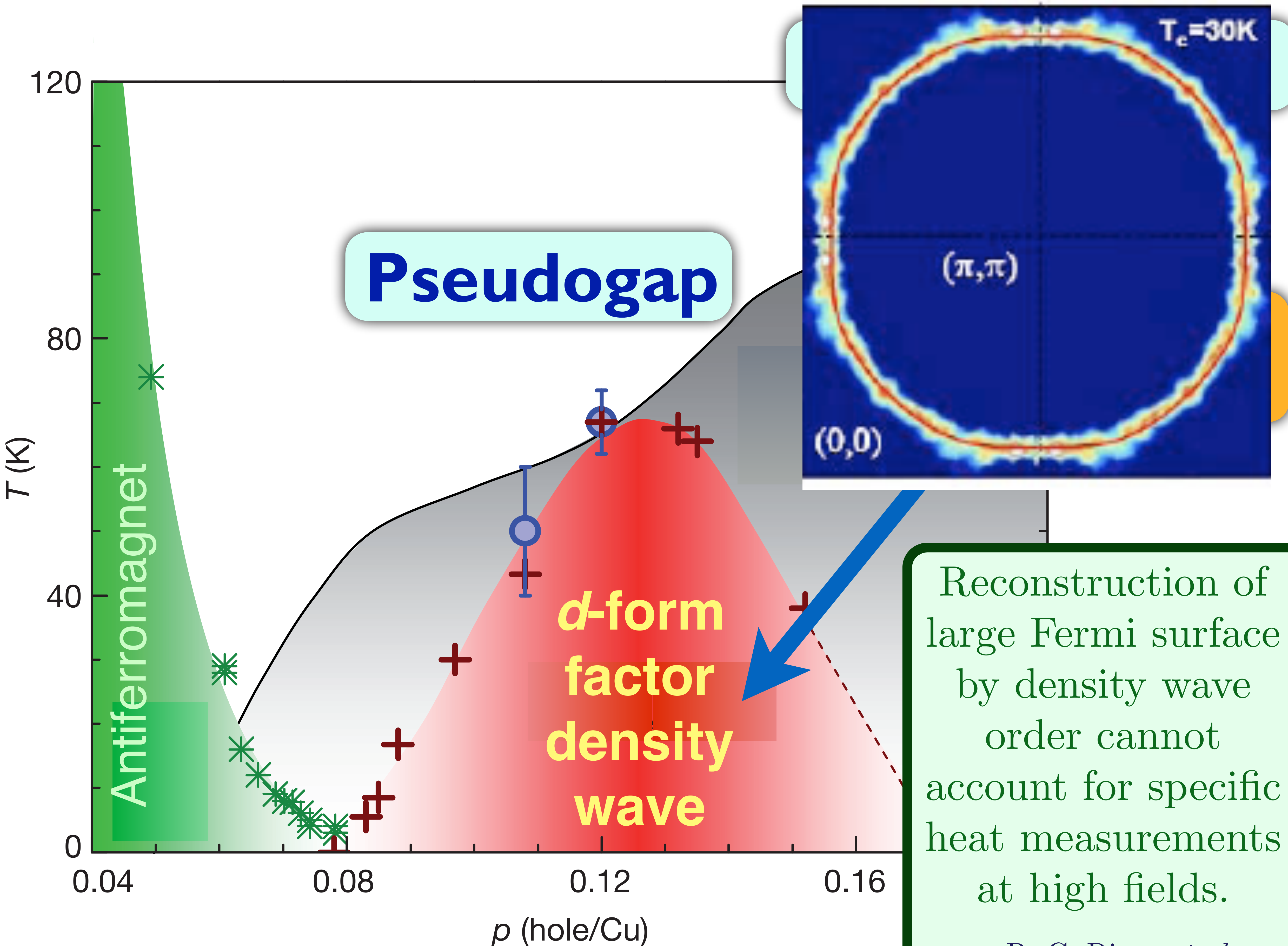
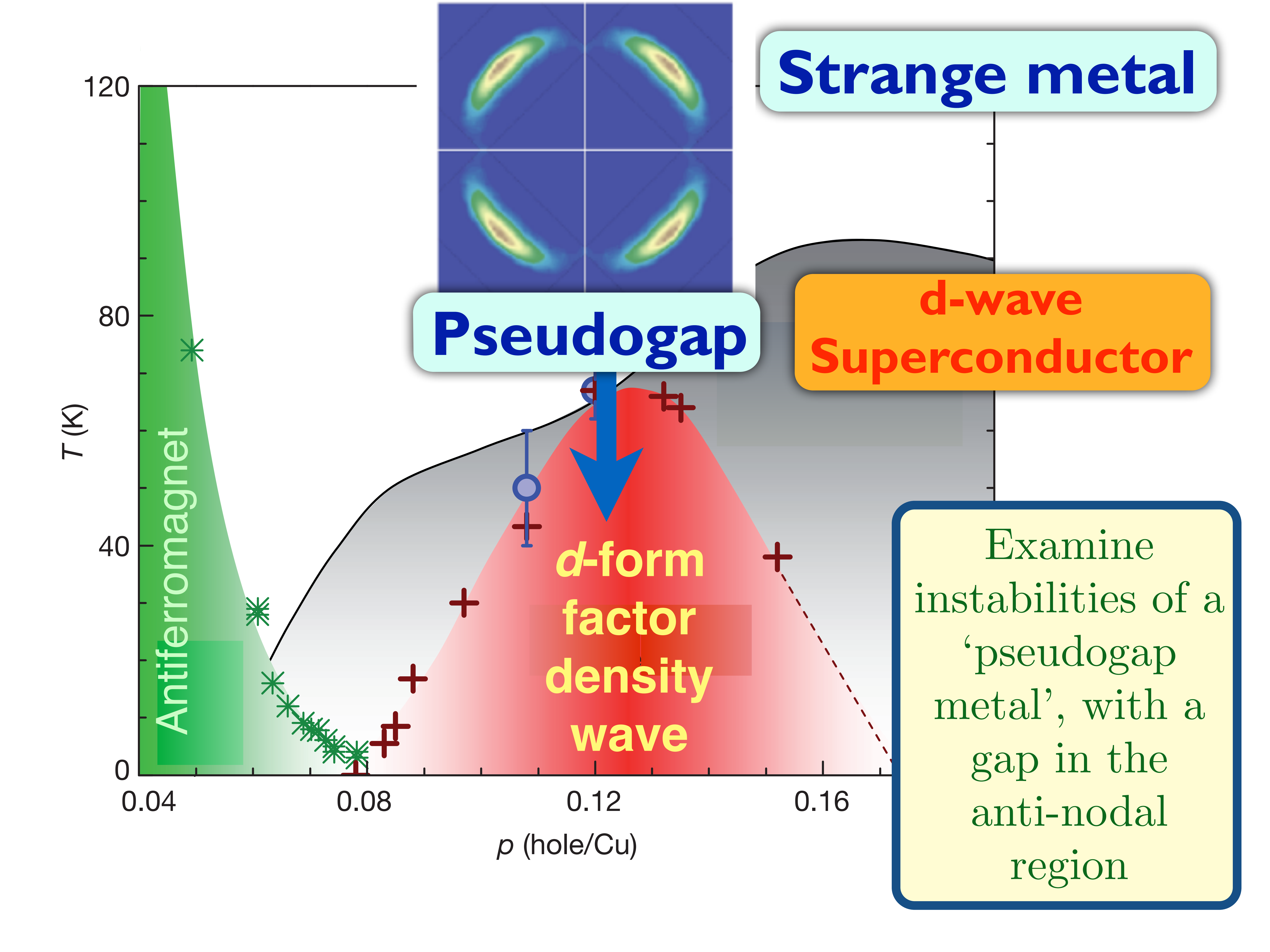


Instabilities of the large Fermi surface do lead to *d*-form factors, but at "diagonal" wavevectors.



Reconstruction of large Fermi surface by density wave order cannot account for specific heat measurements at high fields.

R. C. Riggs *et al.*, Nature Physics **7**, 332 (2011).


Strange metal
Pseudogap
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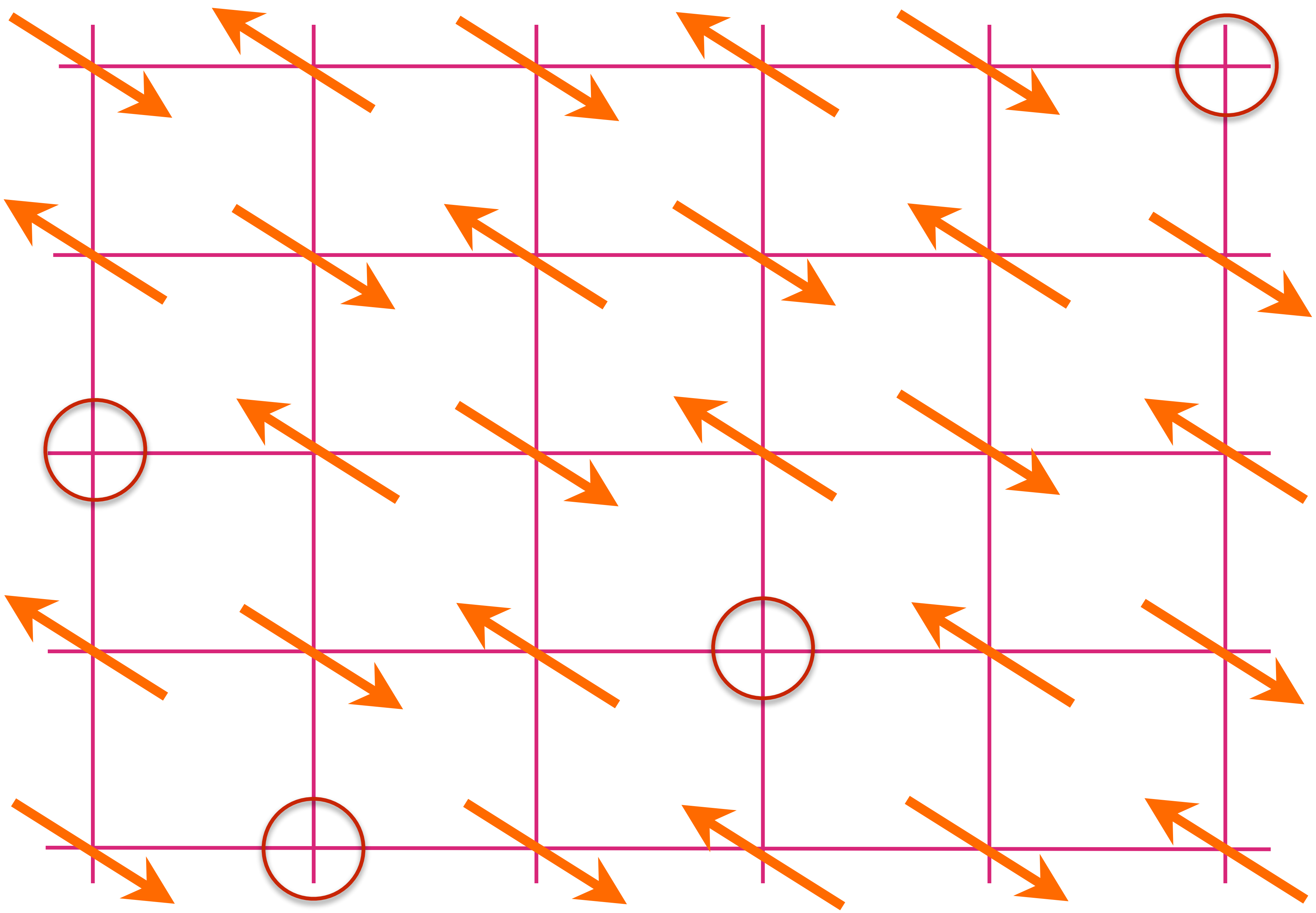
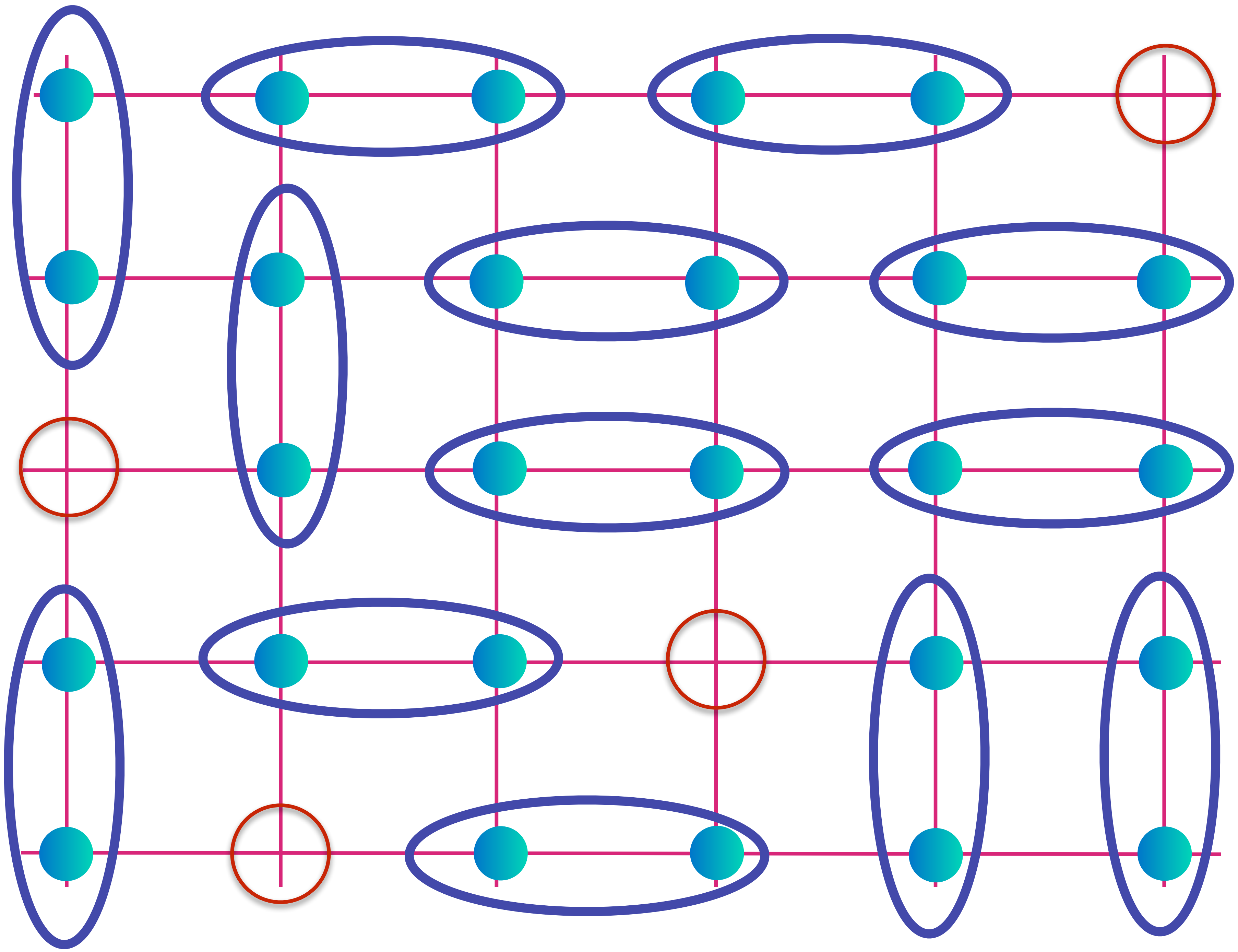
0.04
0.08
0.12
0.16
p (hole/Cu)
Examine instabilities of a 'pseudogap metal', with a gap in the anti-nodal region

Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)



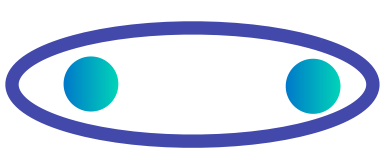
Doped anti-ferromagnet

Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)



Spin liquid

Spinless charge +e holons

 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Baskaran, Zou, Anderson, Fradkin, Kivelson…

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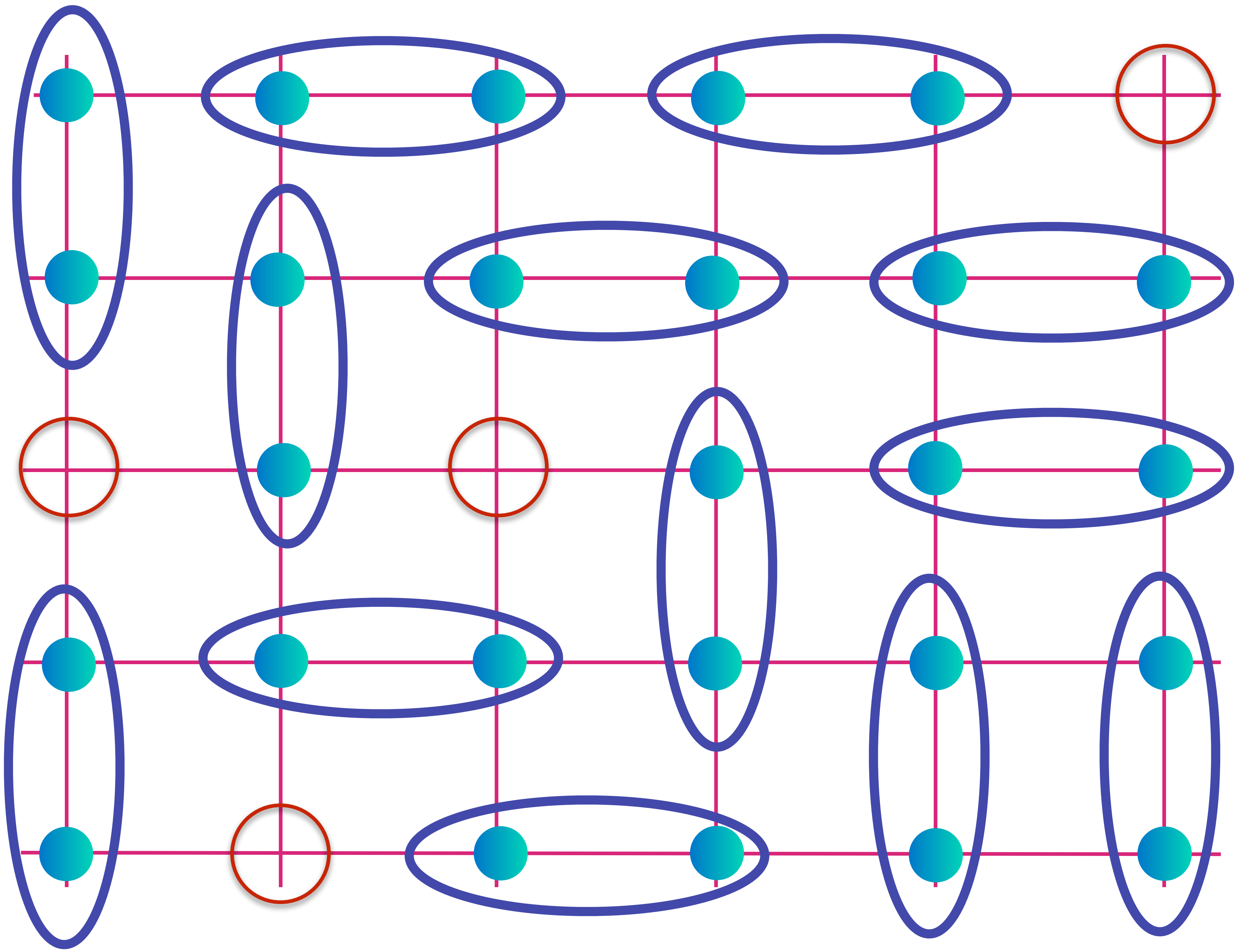

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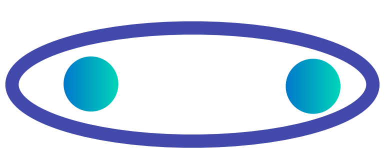
Spinless charge +e holons

 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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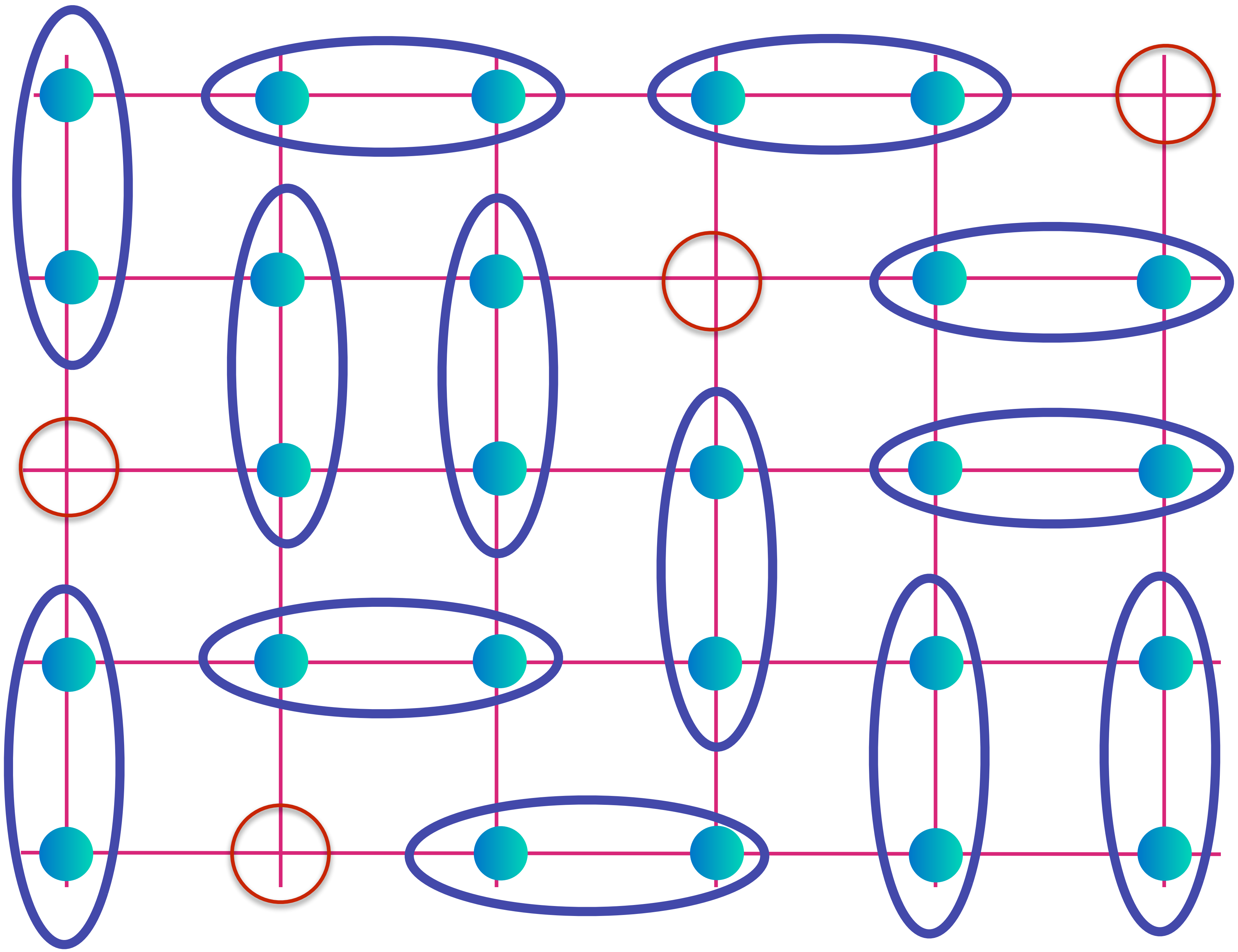

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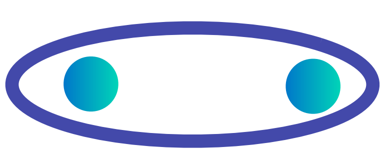 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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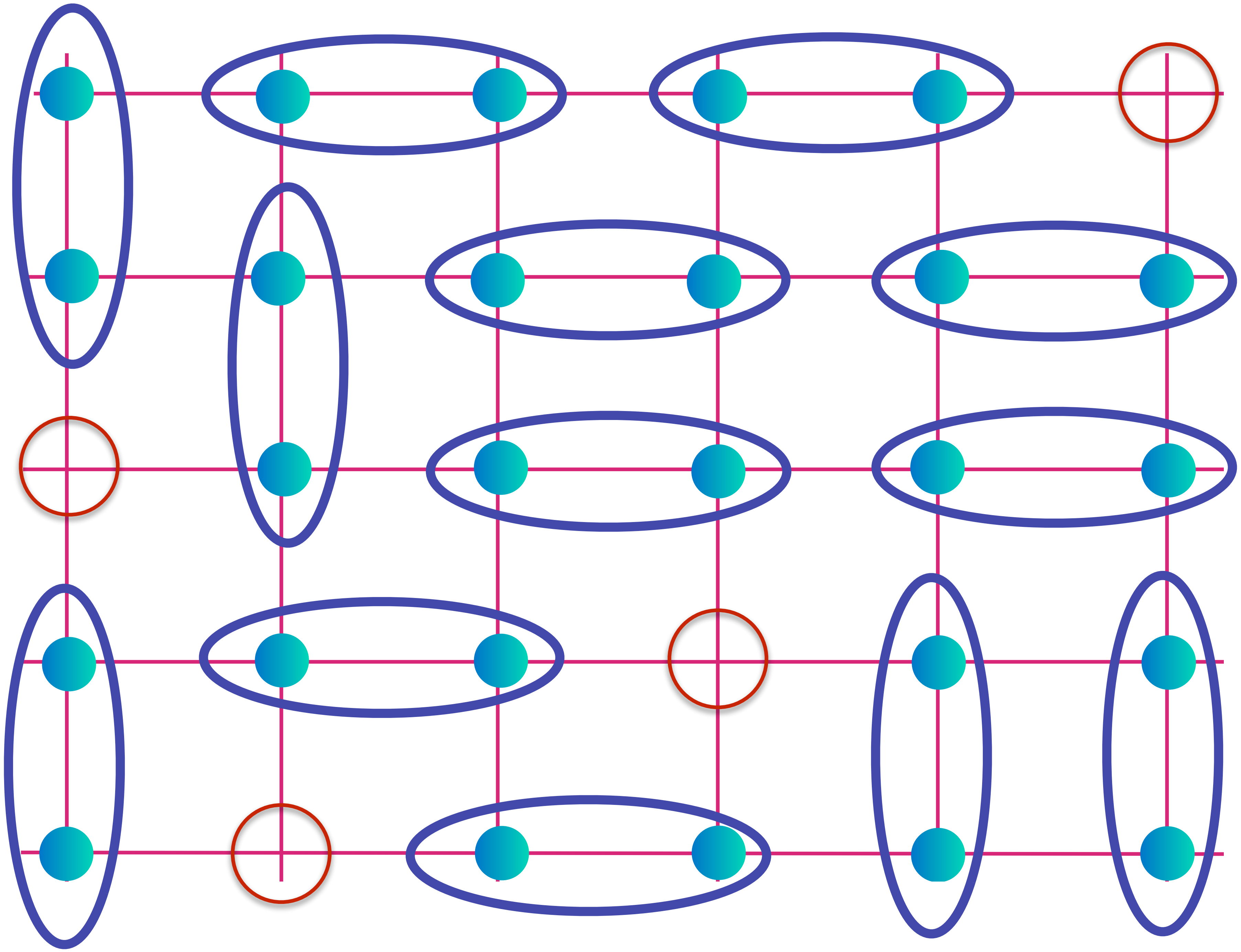

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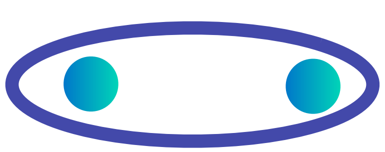 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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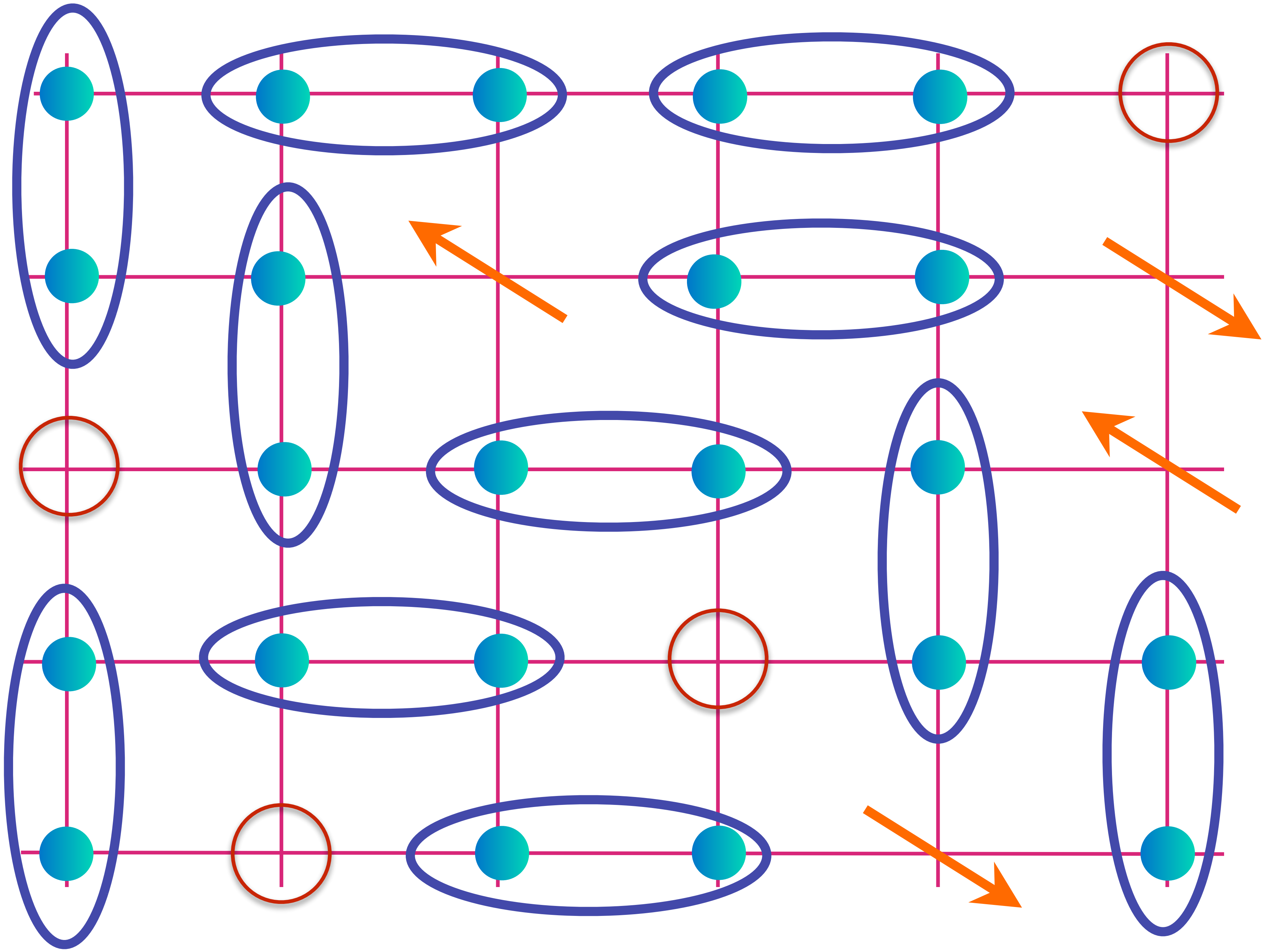
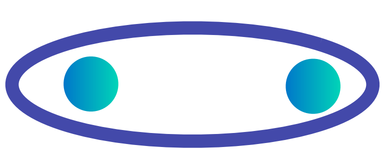


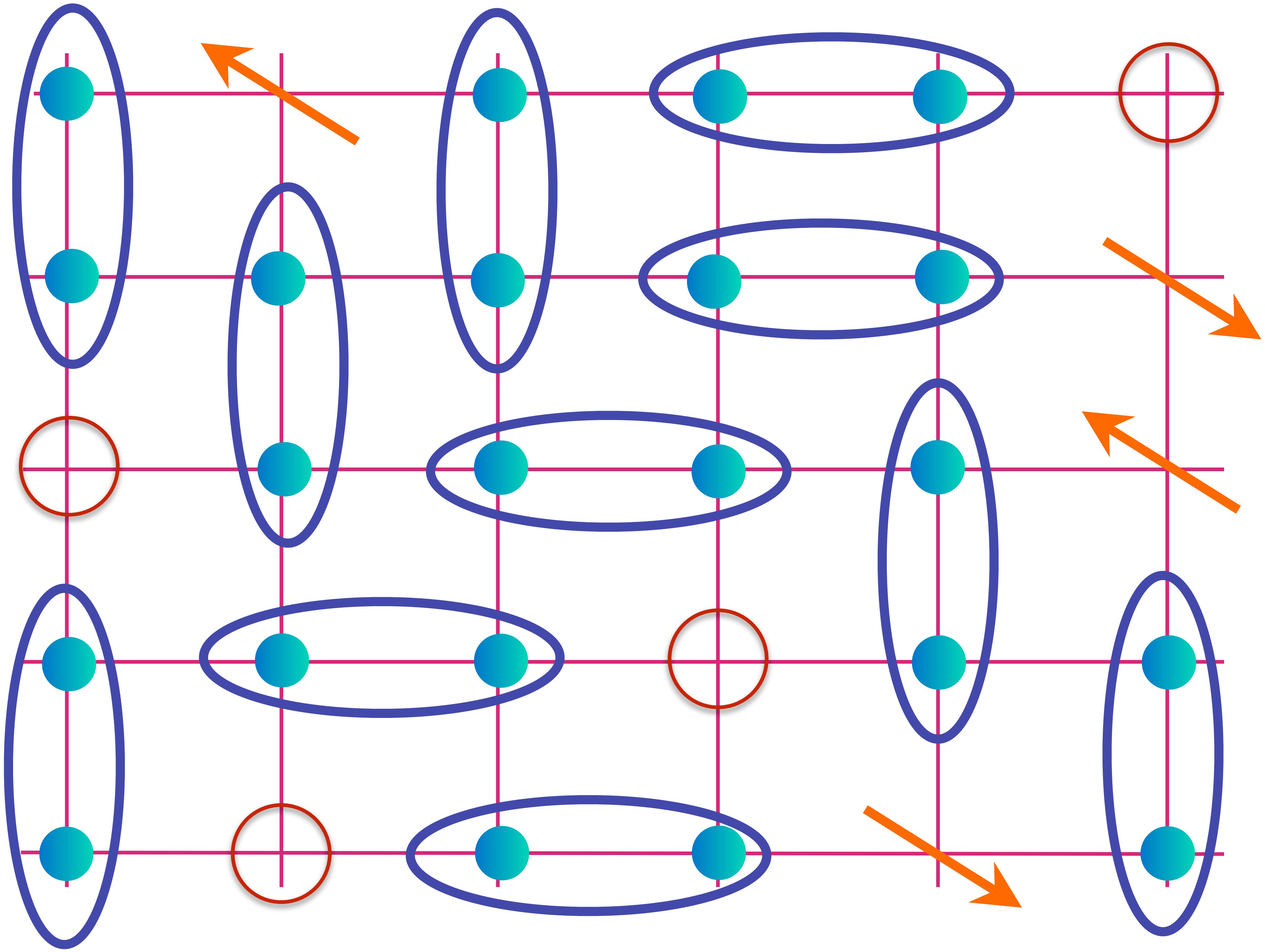
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

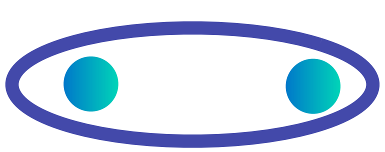
Spin liquid

Spinless charge +e holons *and* S=1/2 neutral spinons

Baskaran, Zou, Anderson, Fradkin, Kivelson…

Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)



 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Spin liquid

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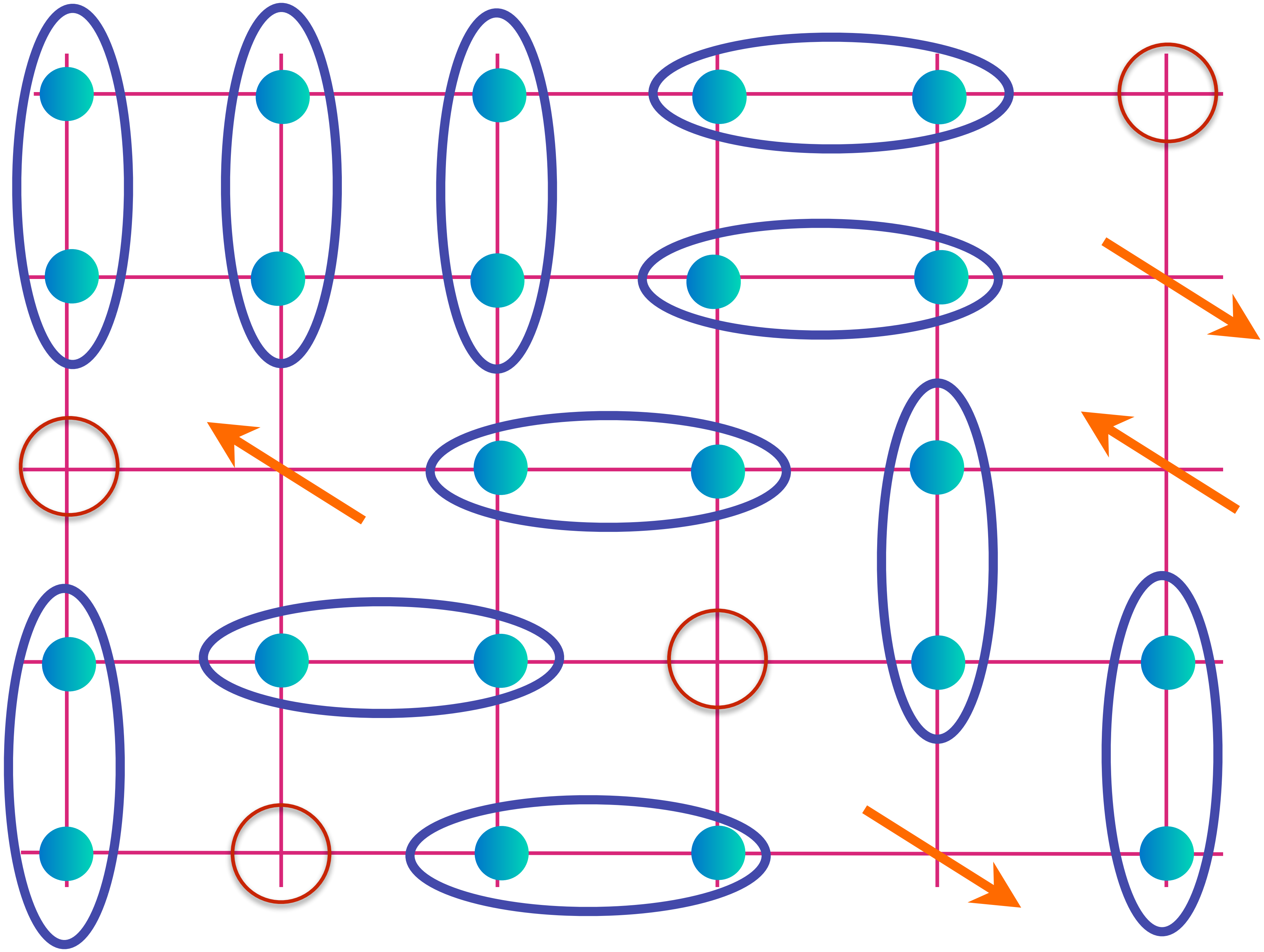

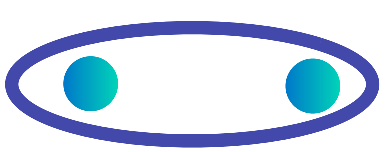 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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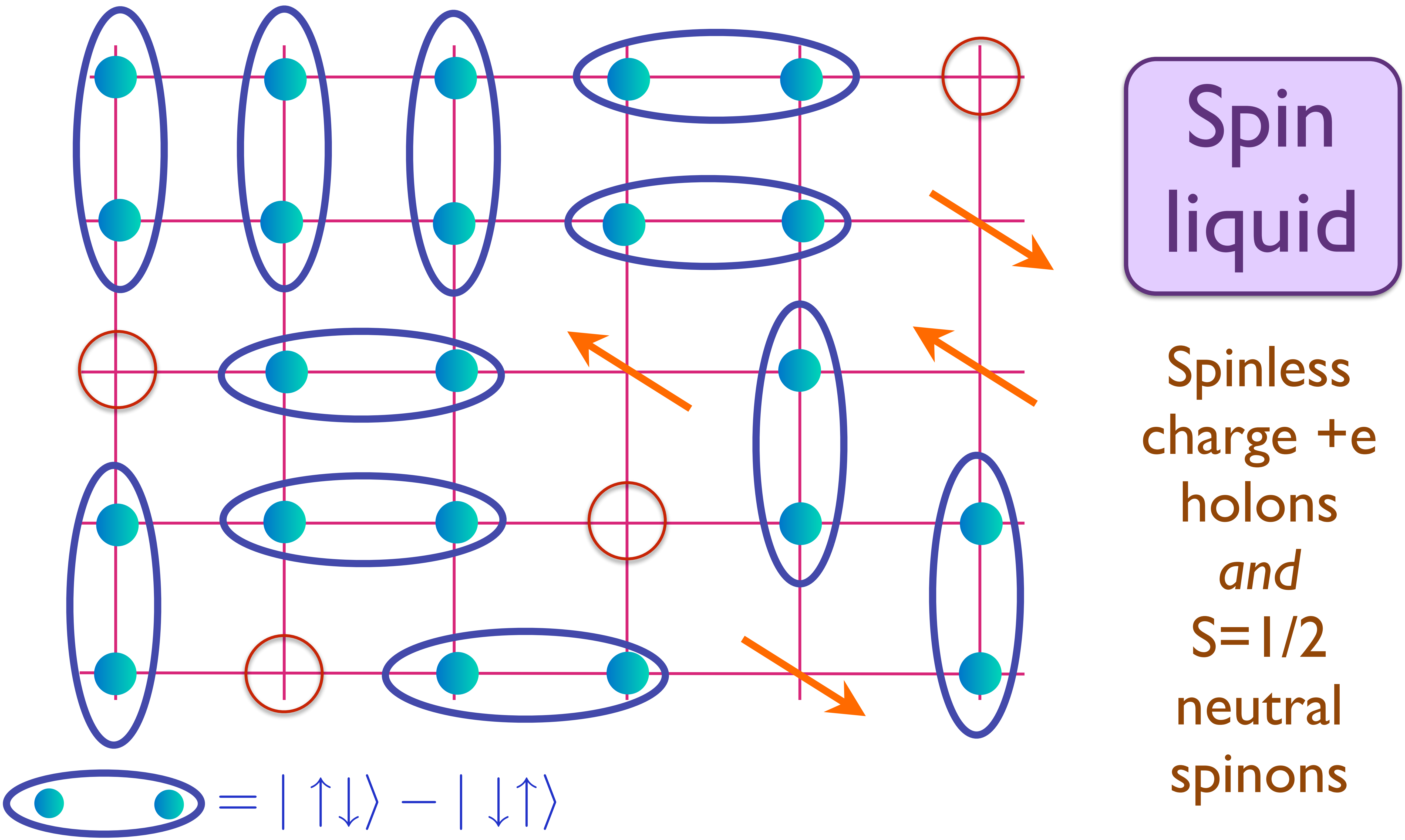

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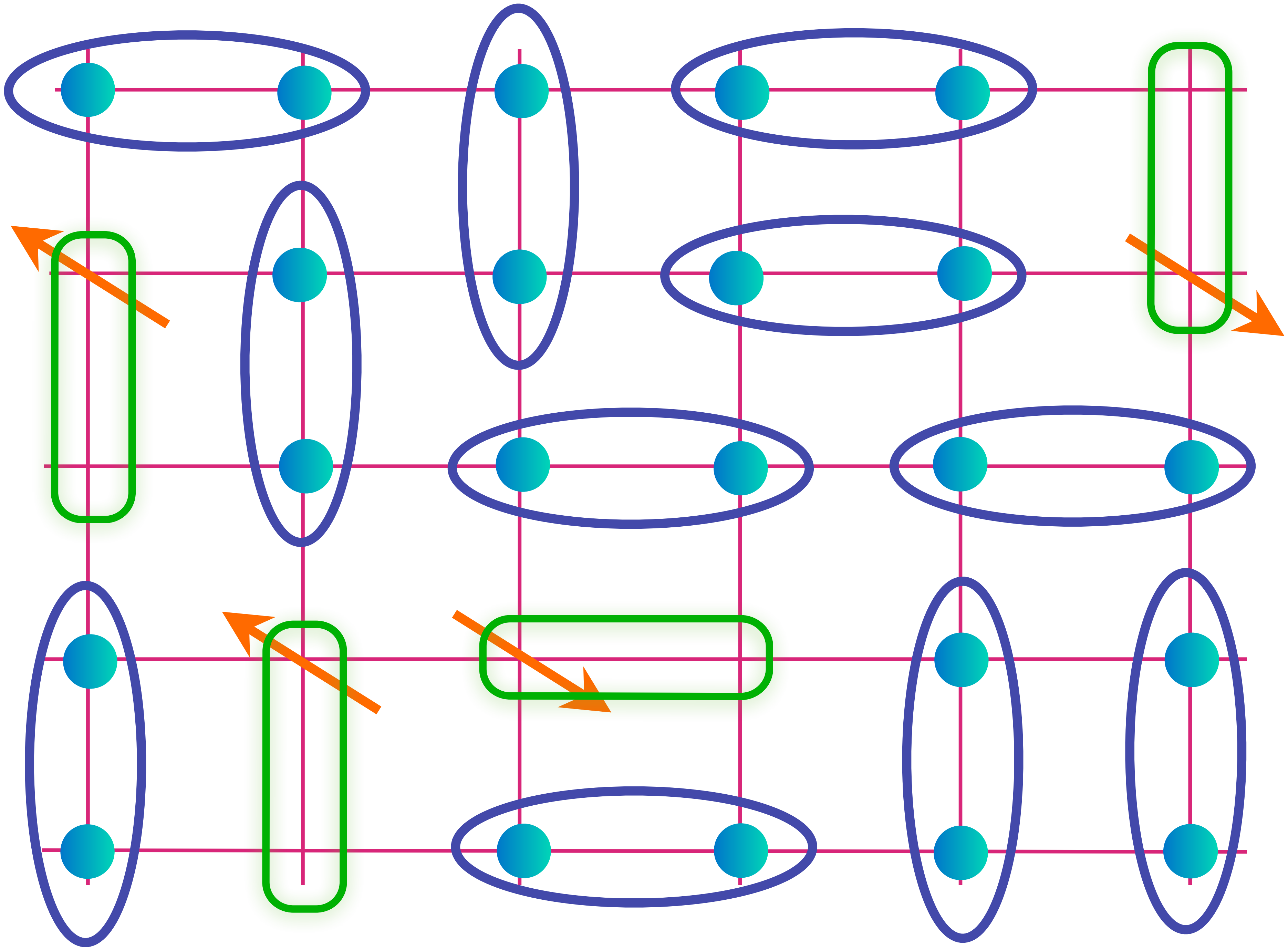
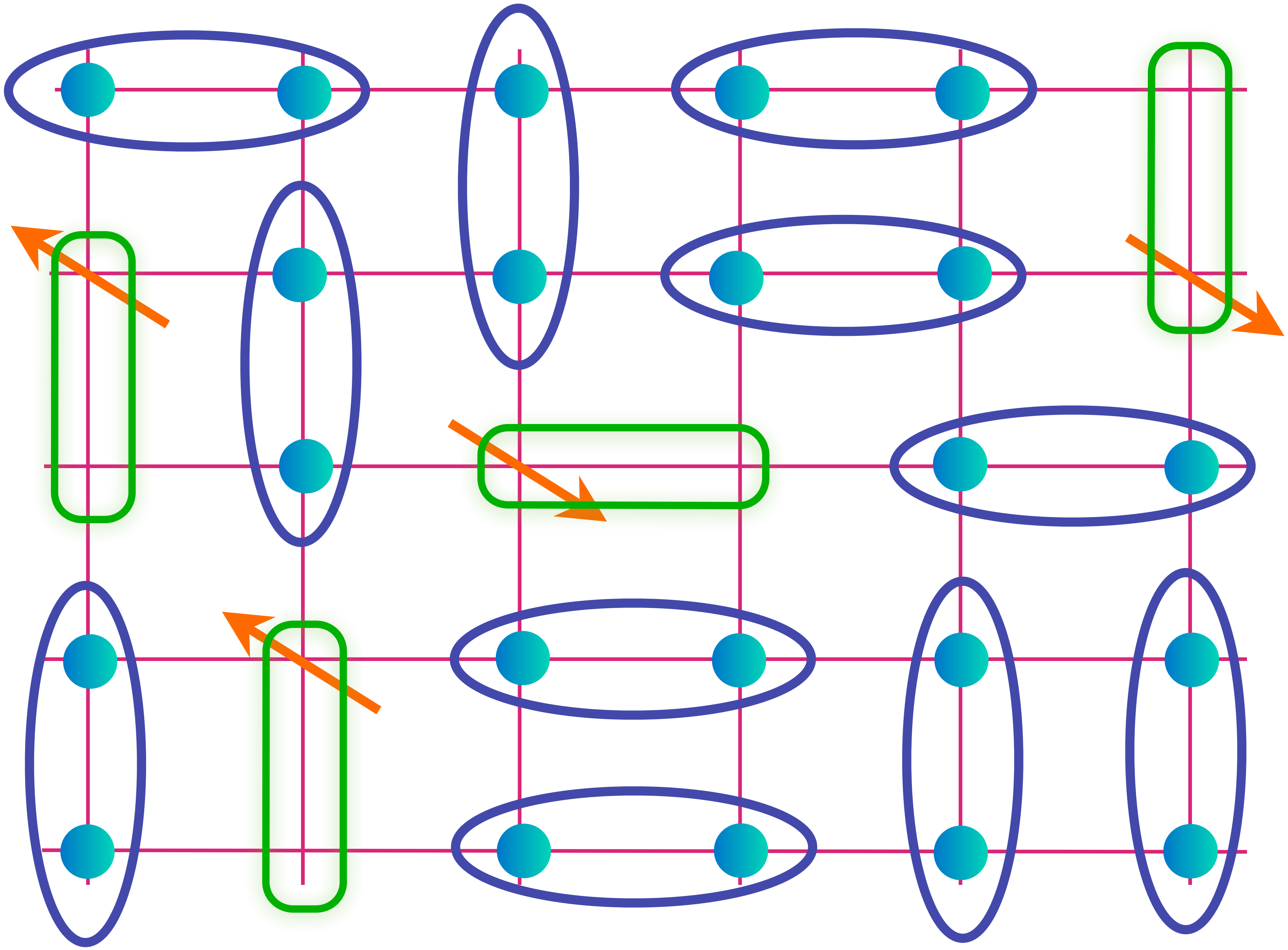


FL* !

Spin singlets *and* charge +e S=1/2 holes of density *p*

T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)
M. Punk and S. Sachdev, *Phys. Rev. B* **85**, 195123 (2012).

Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)



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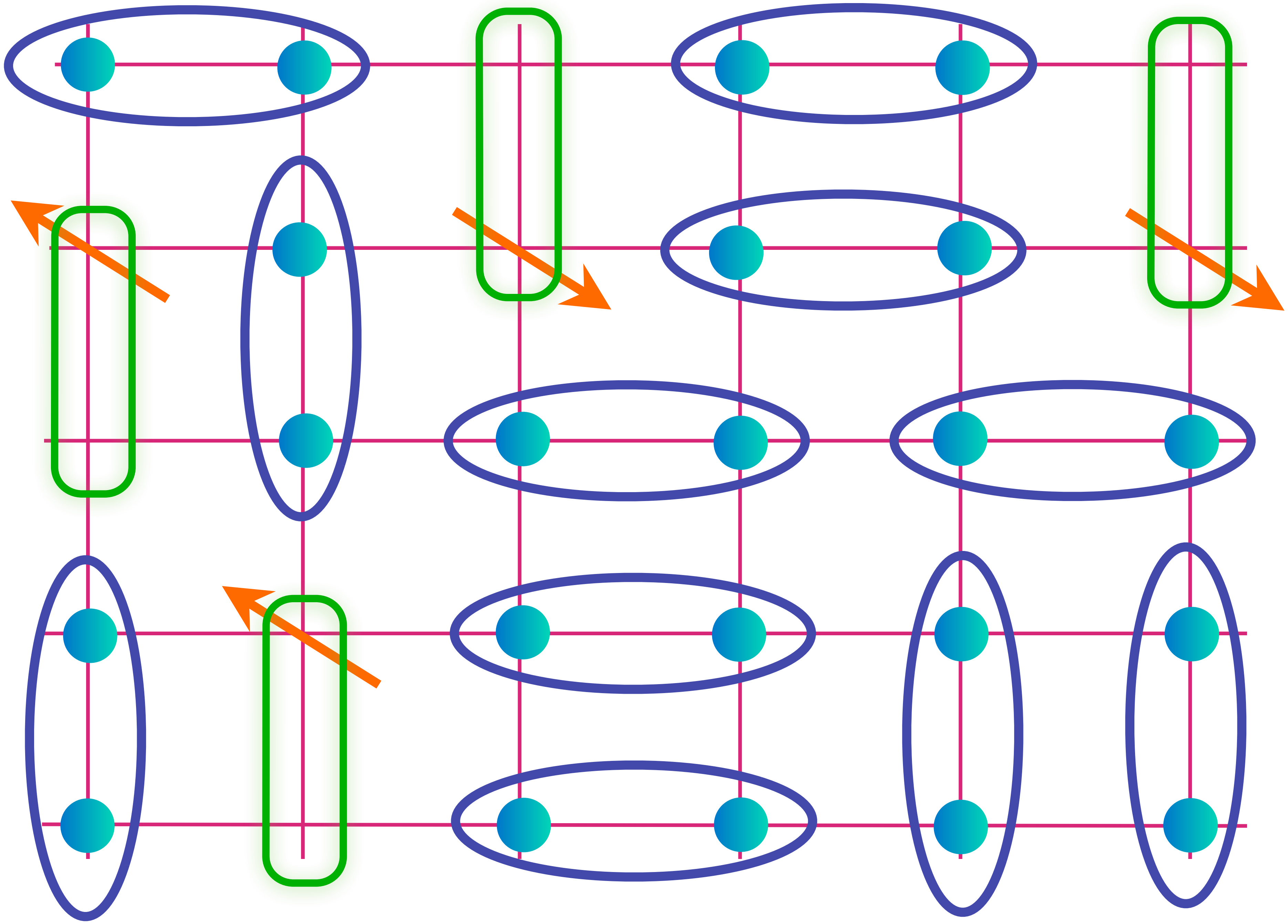

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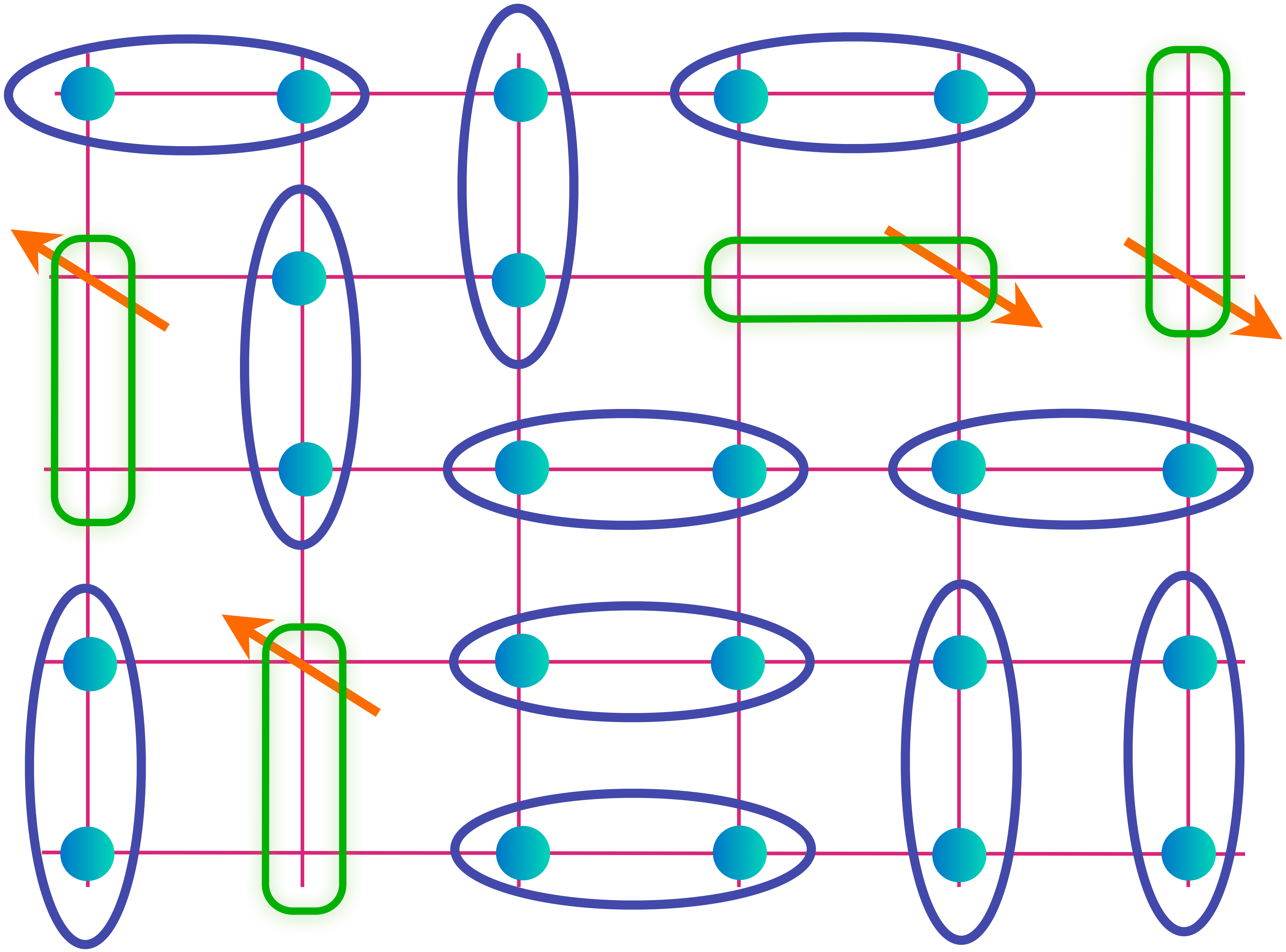

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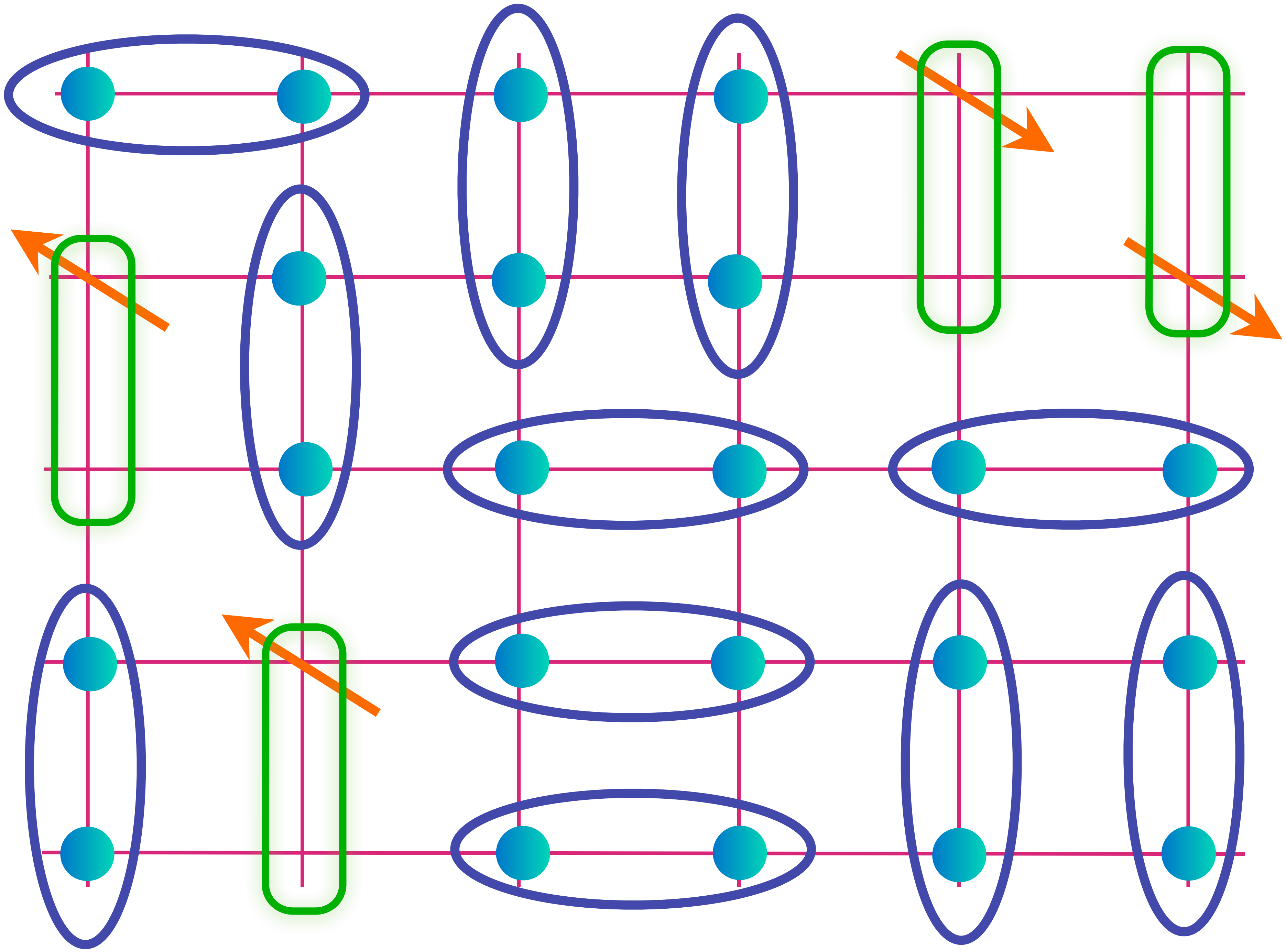

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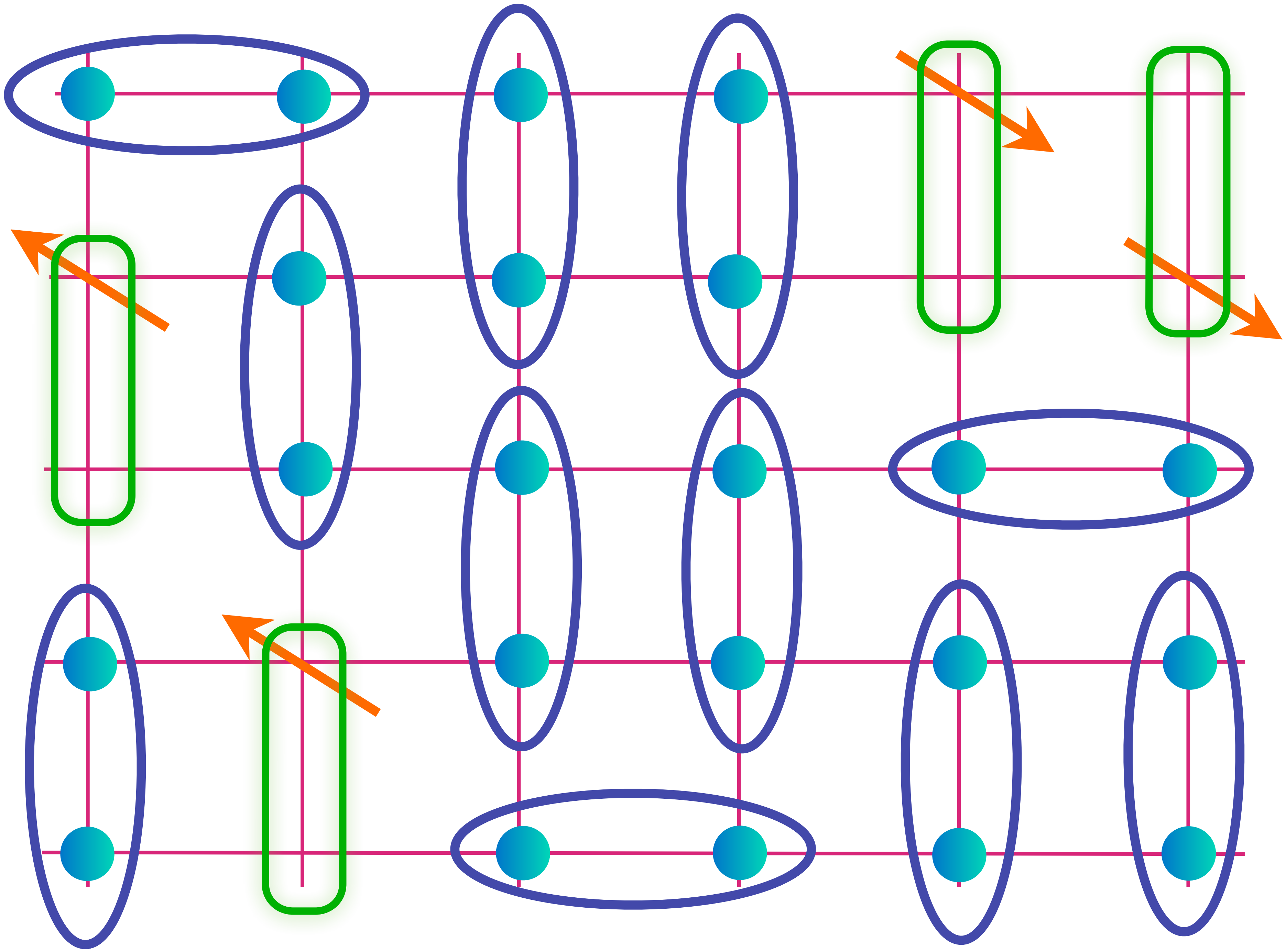

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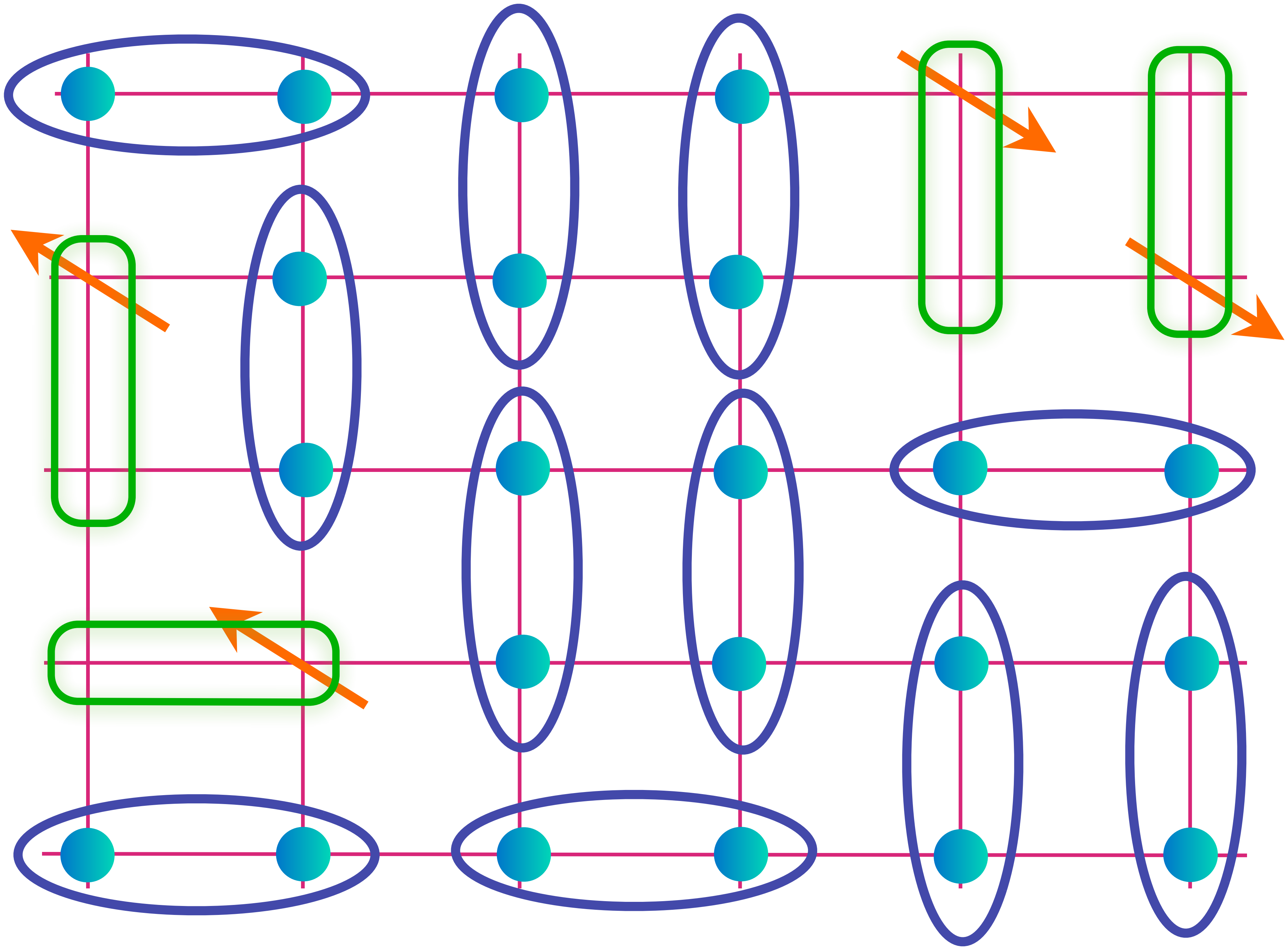

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Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)

- Fermi surface of electron/hole-like quasiparticles (the green dimers) enclosing area p. Contrast this with the area $1+p$ in a Fermi liquid.

T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)
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Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)

- Fermi surface of electron/hole-like quasiparticles (the green dimers) enclosing area p. Contrast this with the area $1+p$ in a Fermi liquid.

- The green dimers can only move by resonating with a background of blue dimers. An *emergent gauge field* describes the dynamics of the blue dimers.

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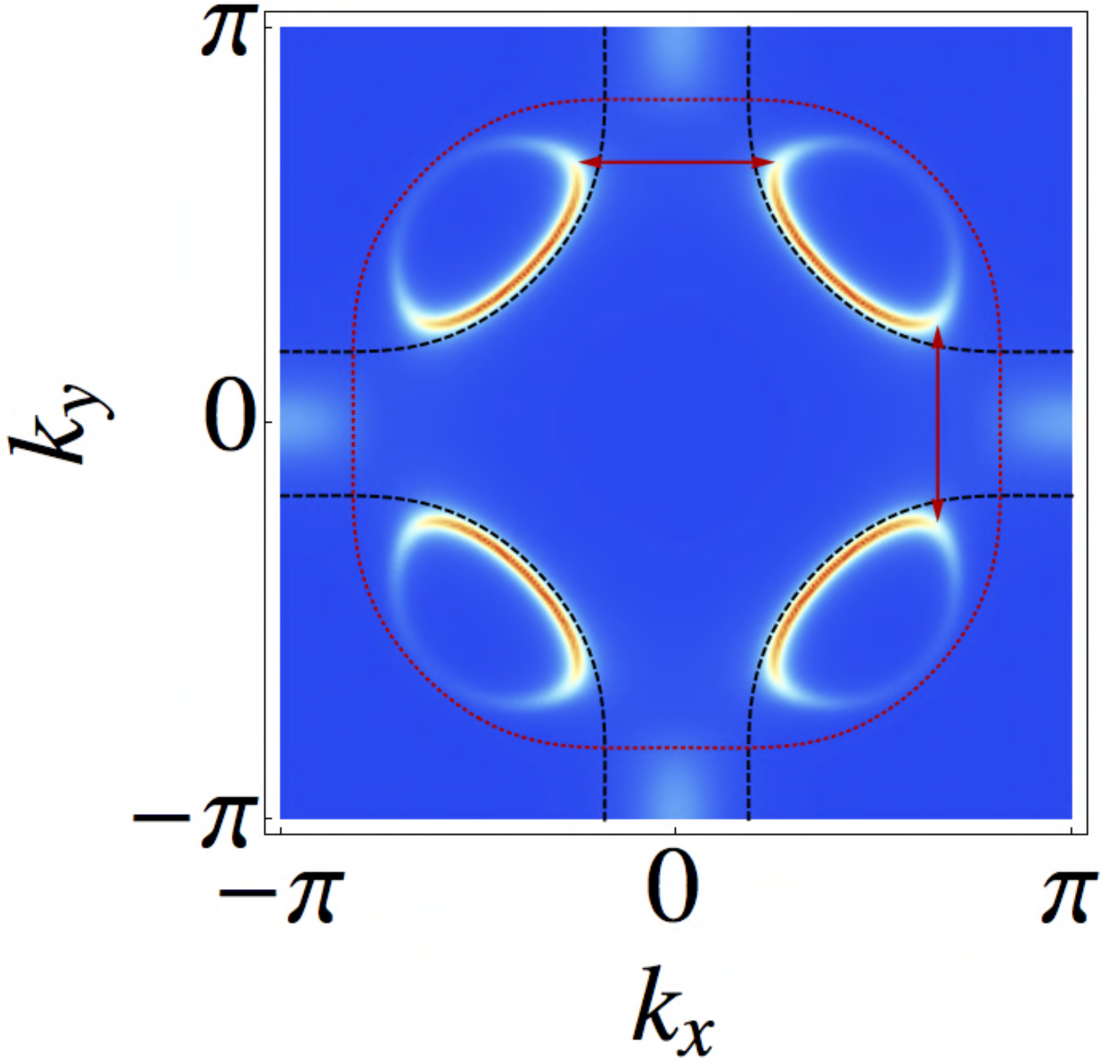
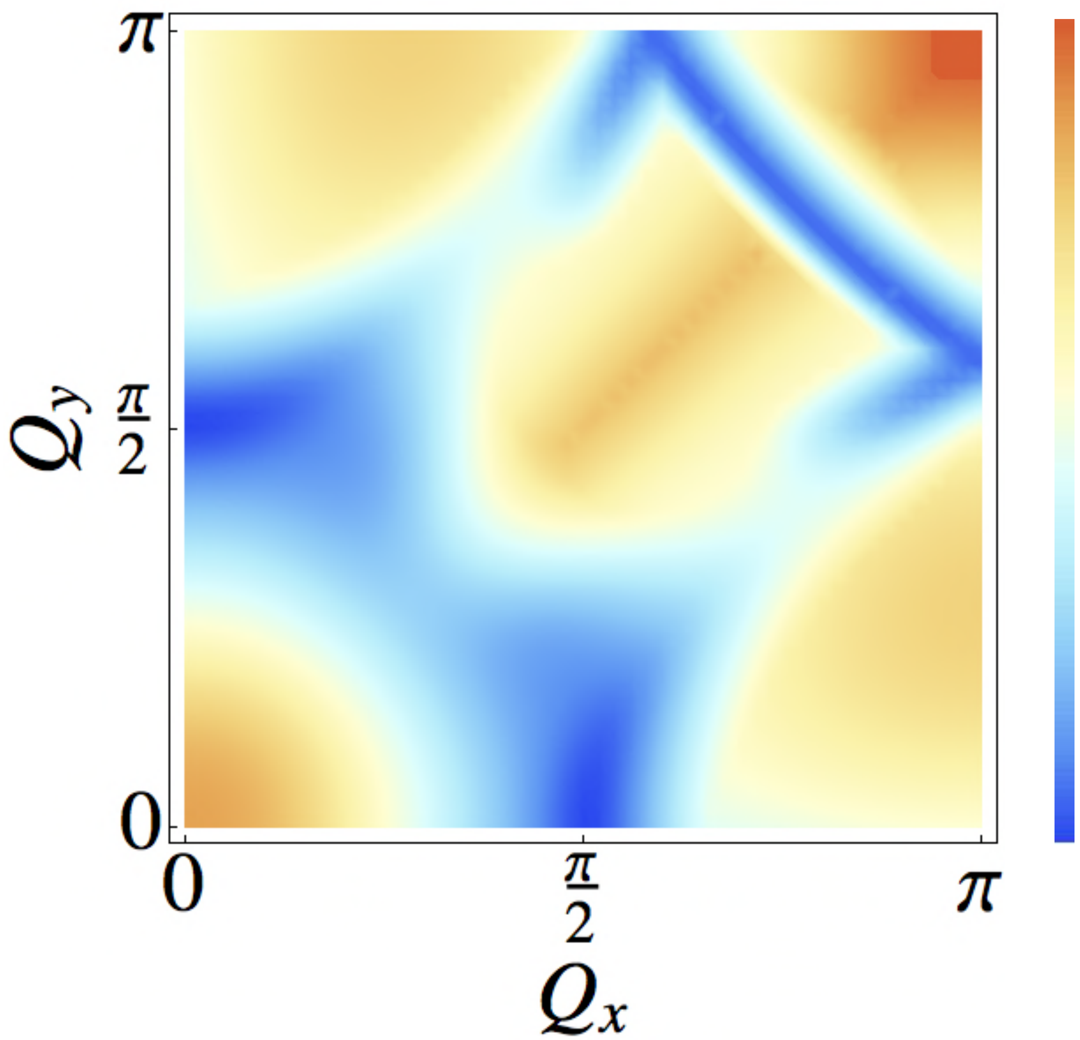


Electron spectral function of FL*

Semi-phenomenological theory of a FL* state with hole pockets of volume p, along with a background spin liquid with an emergent U(1) gauge field. Note that the quasiparticle excitations around the Fermi surface do not carry U(1) gauge charges.

Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
M. Punk and S. Sachdev, Phys. Rev. B **85**, 195123 (2012)
D. Chowdhury and S. Sachdev, arXiv:1409.5430



Eigenvalues of spin-singlet, time-reversal-preserving particle-hole propagator

The dominant density wave instability of this FL* is a predominantly d-form factor density wave with a wavevector $\mathbf{Q}$ along the $(1,0)$ and $(0,1)$ square lattice directions, in agreement with observations on the non-La-based cuprates.

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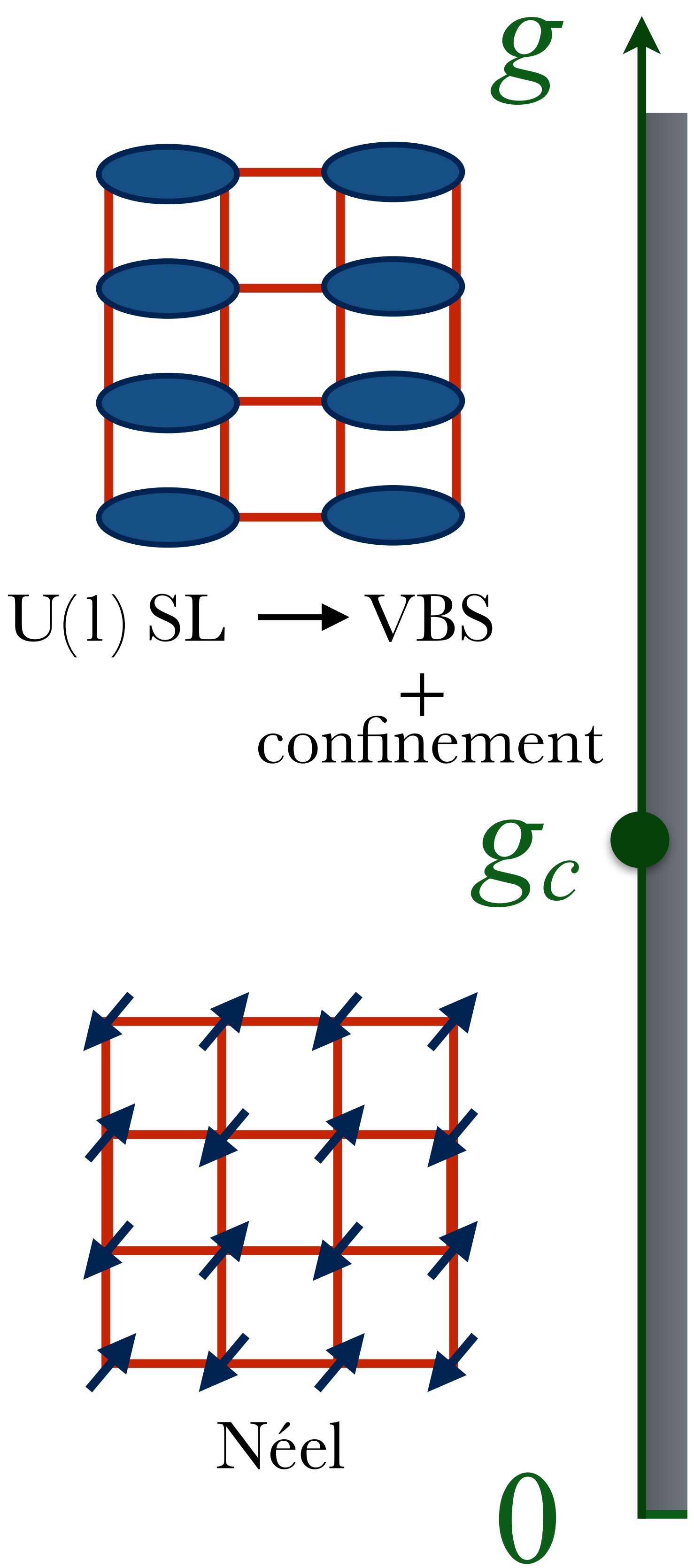

g
U(1) SL → VBS
+
confinement
g_c
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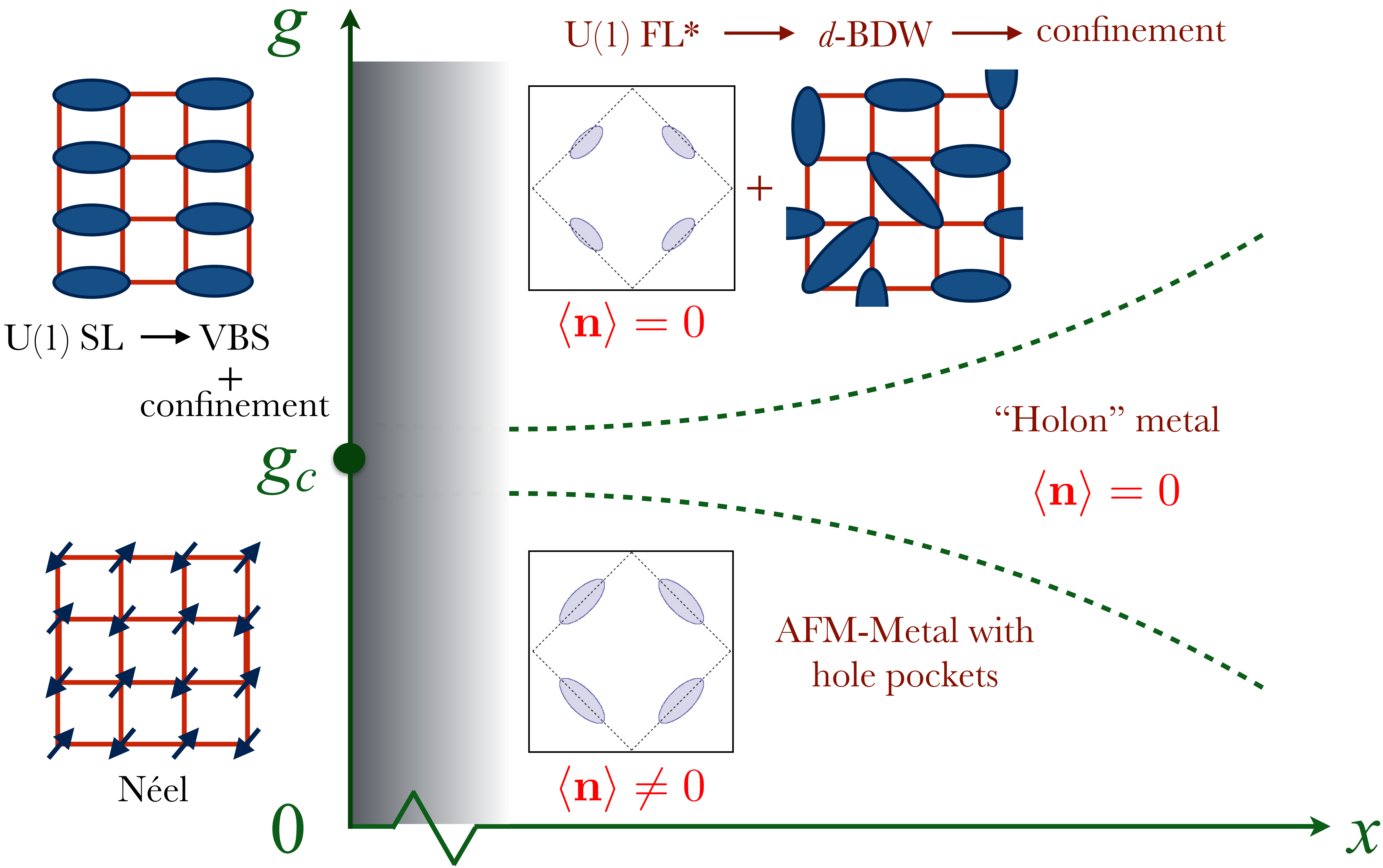
0



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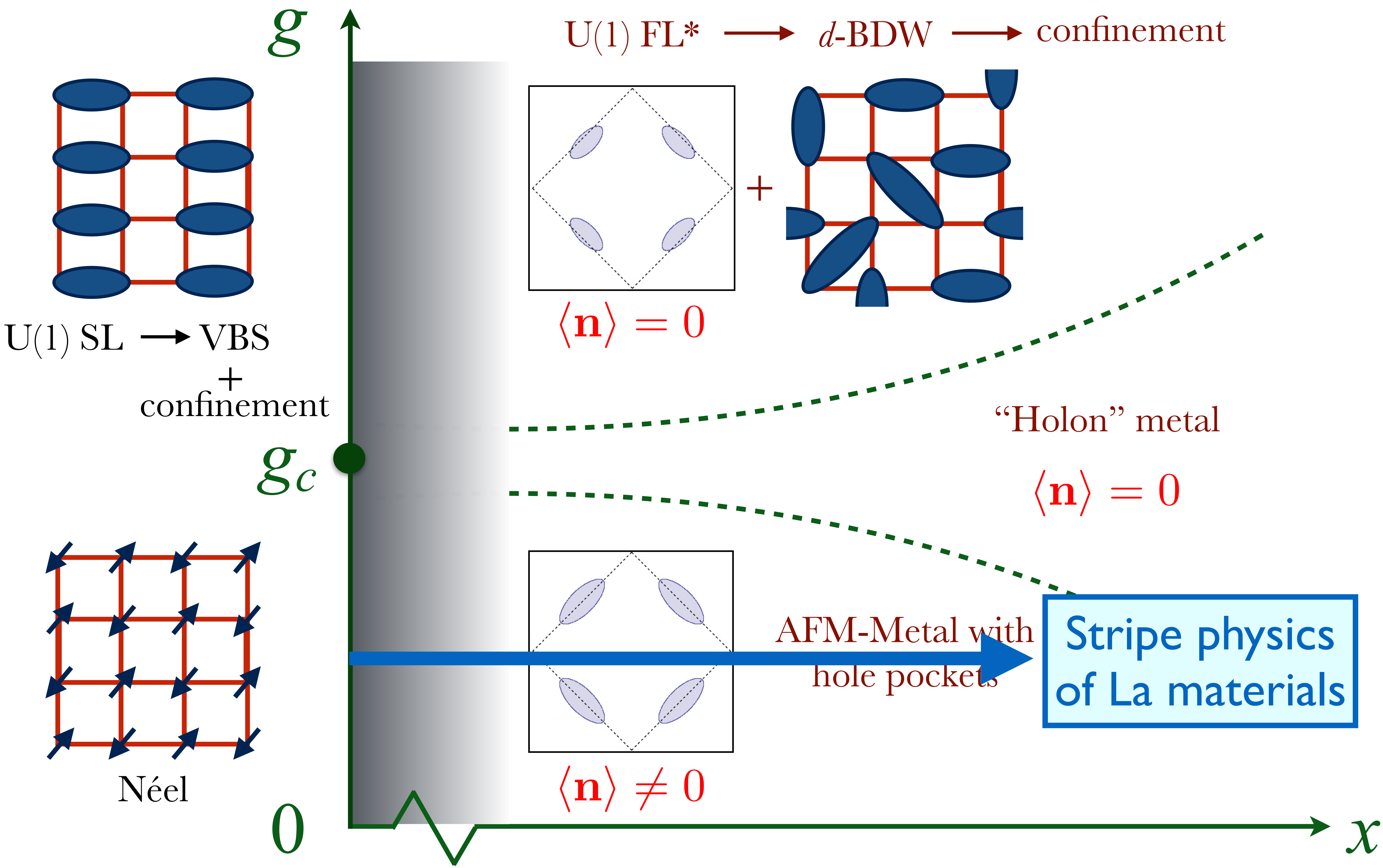

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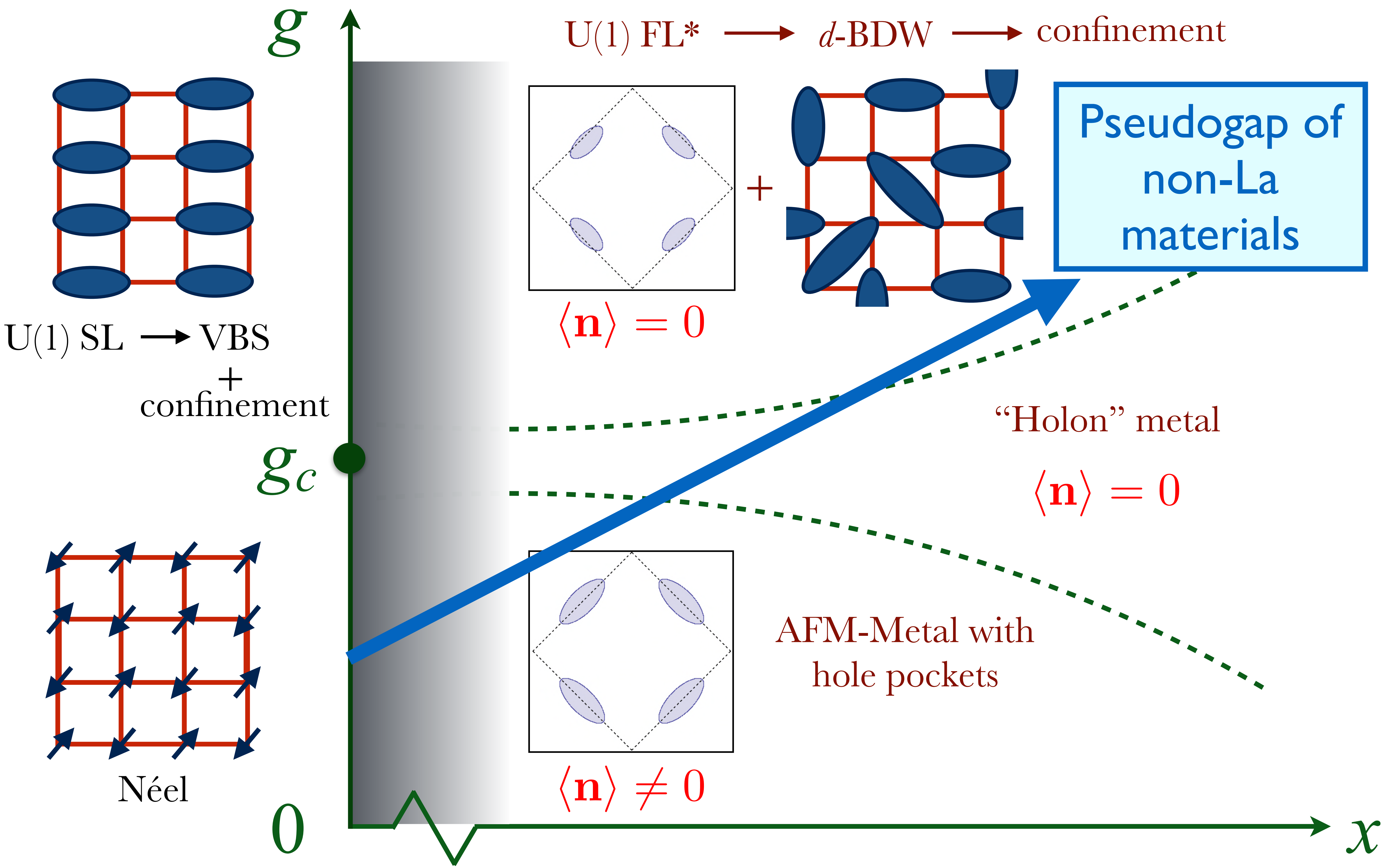

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Conclusions

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Conclusions

1. *d*-form factor density wave order observed in the non-La hole-doped cuprate superconductors.

2. The “stripe” model corresponds to a *s*’-form factor, and this describes the La-based, lower T_c, hole-doped cuprate superconductors.

3. The *d*-form factor is an unexpected window into the electronic structure of the pseudogap, with evidence for a fractionalized Fermi liquid (FL*) model.