Unveiling the order of the high temperature superconductors

University of Innsbruck
October 10, 2014

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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

NSF

JOHN TEMPLETON FOUNDATION

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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

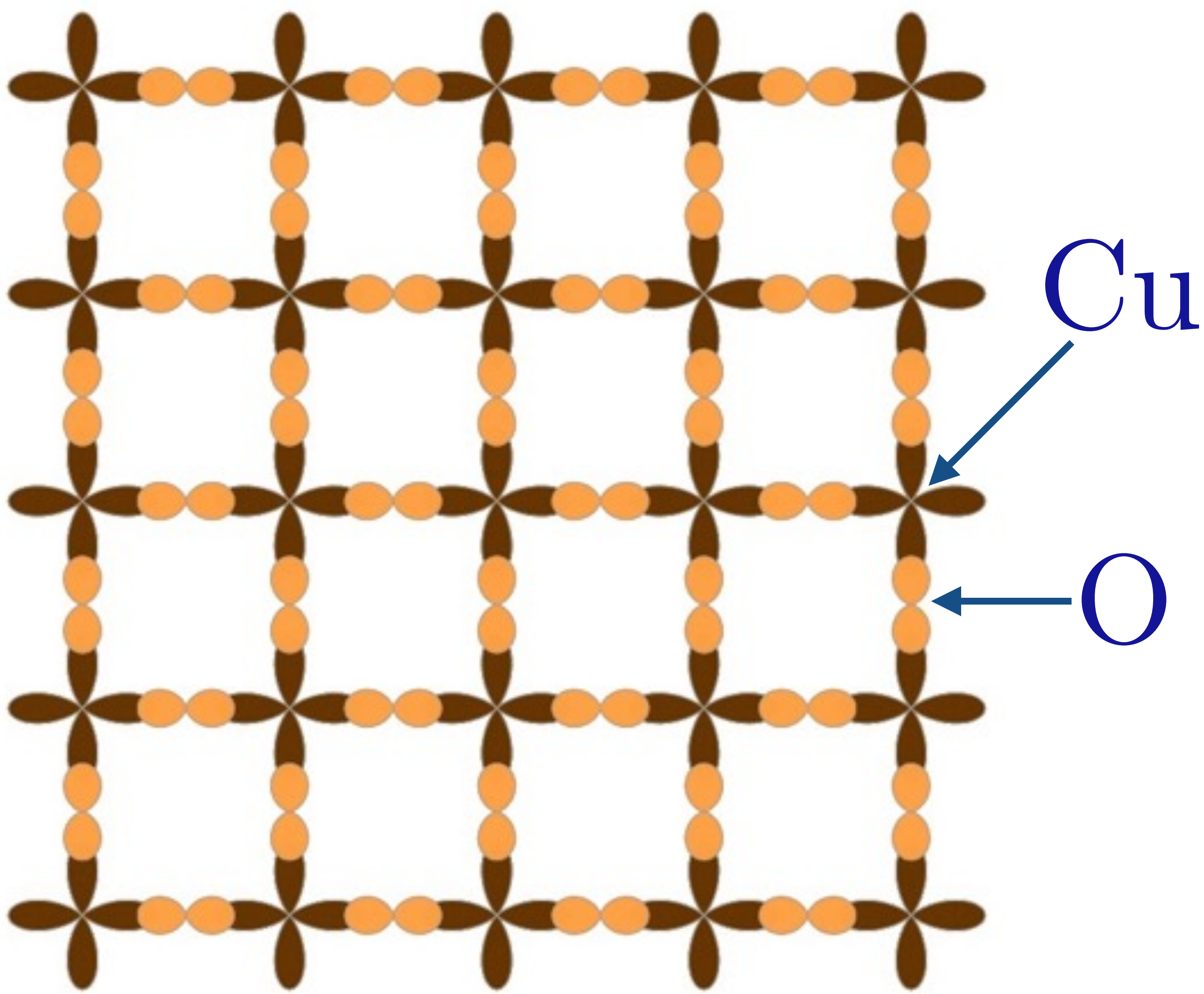
Stephen Edkins
Cornell / St Andrews

Michael Lawler

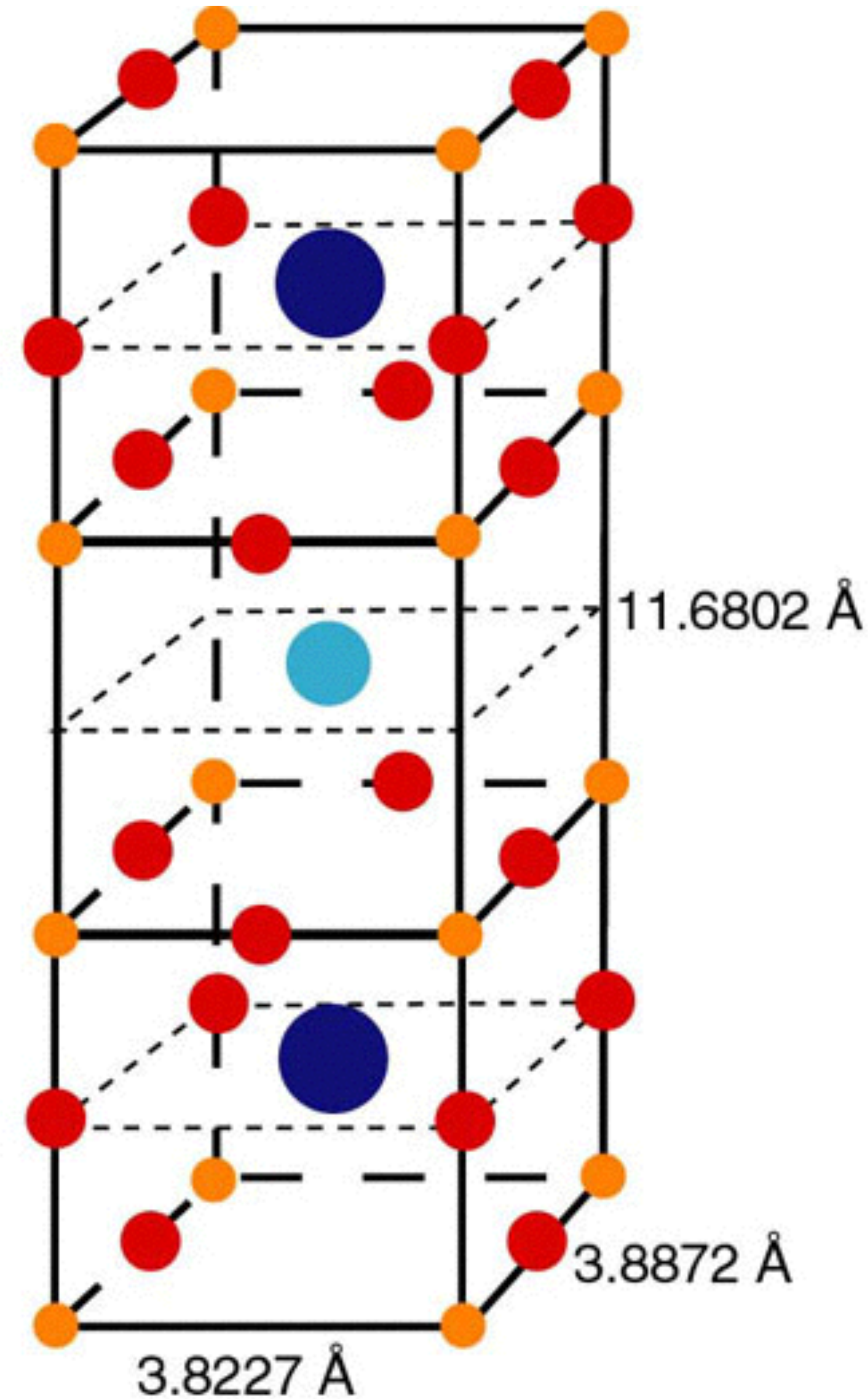
J. C. Seamus Davis

Eun-Ah Kim

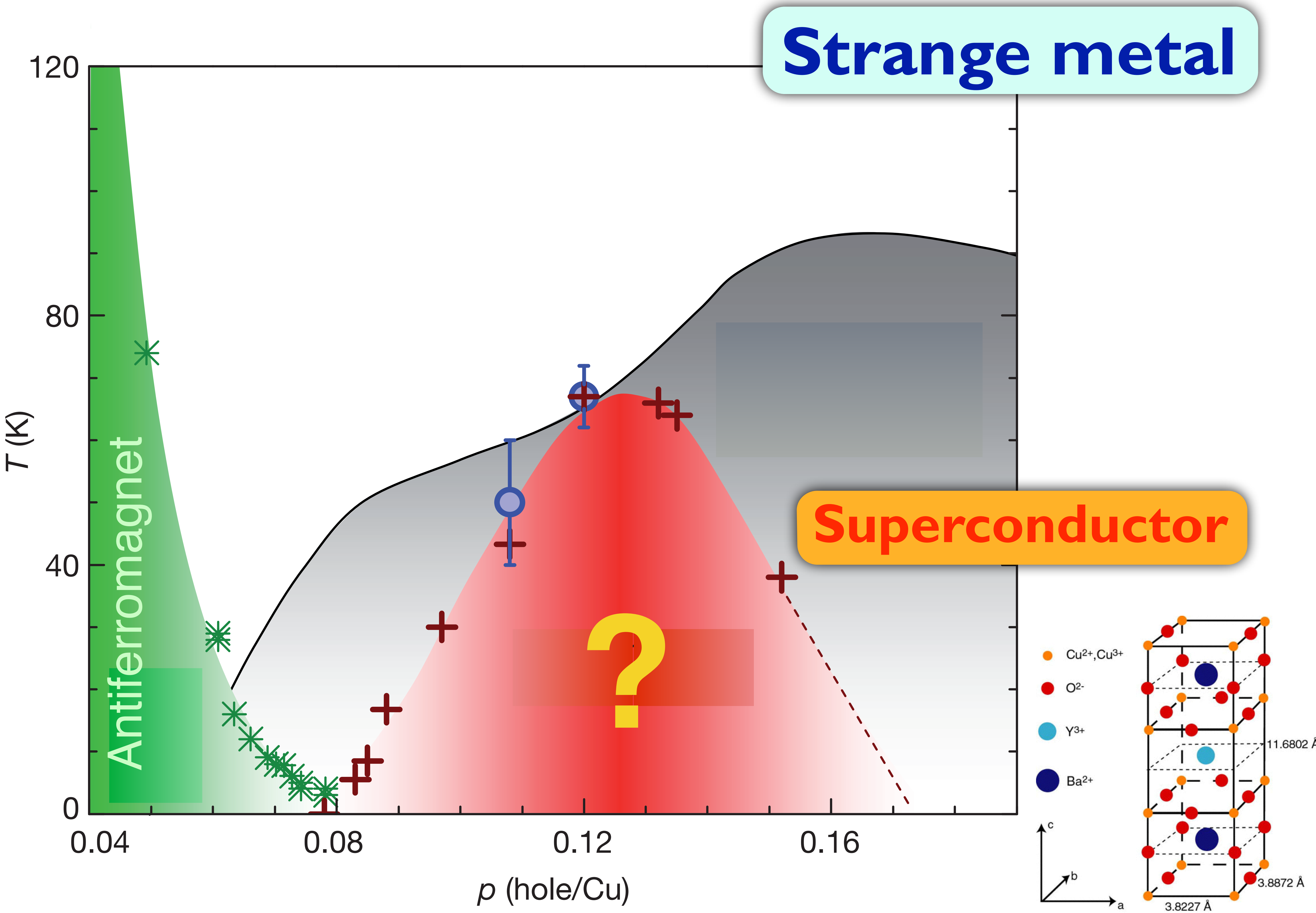
High temperature superconductors



CuO_2 plane



$YBa_2Cu_3O_{6+x}$



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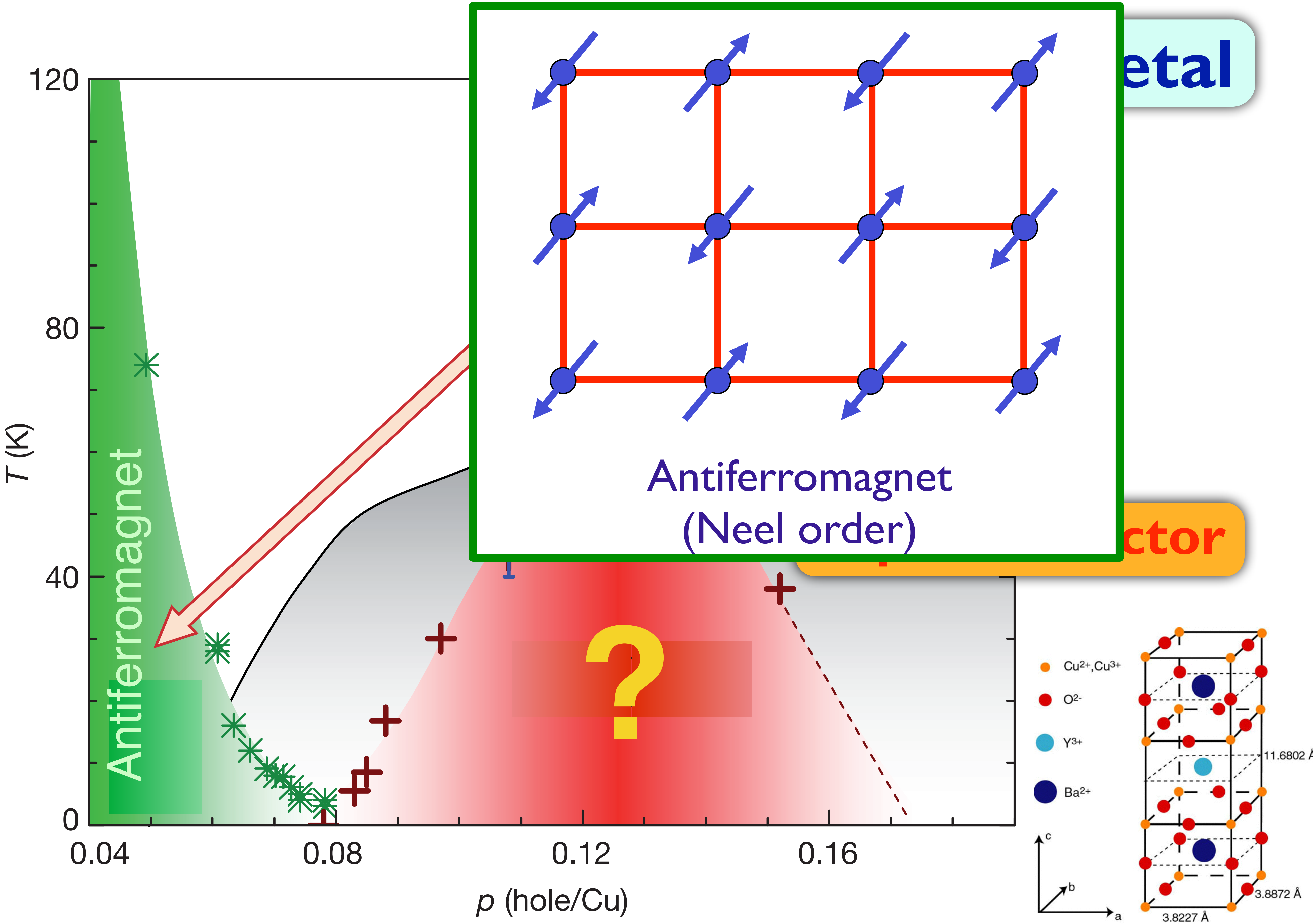

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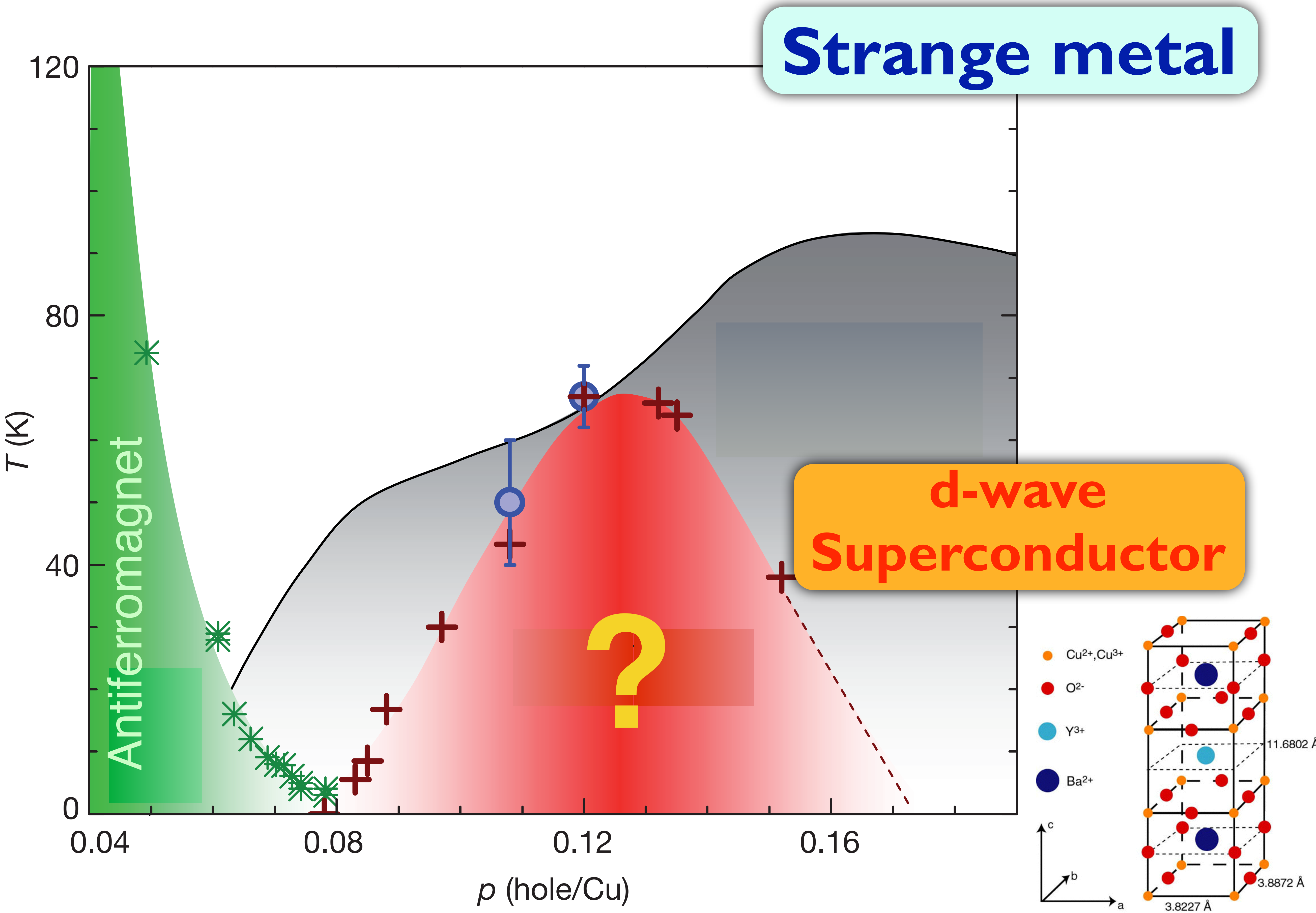

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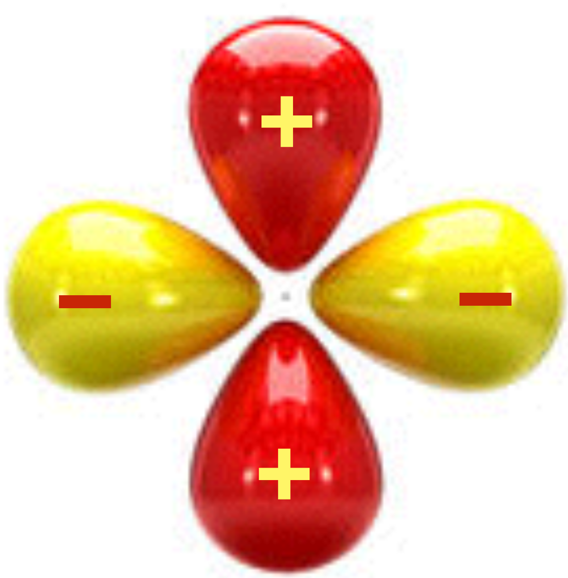
Superconductivity:
Bose condensation of Cooper pairs of electrons

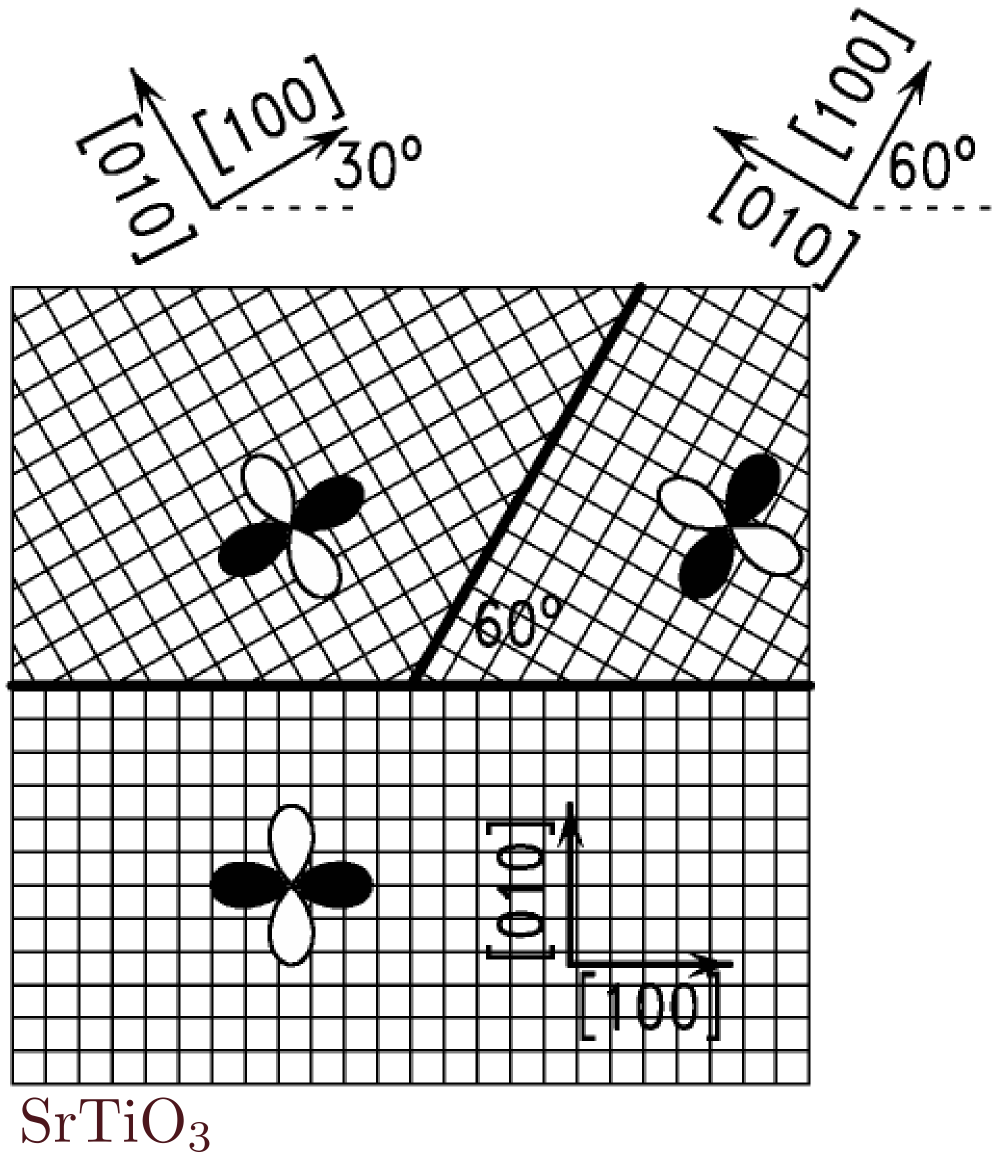
$$\varepsilon^{\alpha\beta} \left\langle c_\alpha^\dagger(\mathbf{r}_1) c_\beta^\dagger(\mathbf{r}_2) \right\rangle = \left[P(\mathbf{r}_1 - \mathbf{r}_2) \right] \times \Psi_{SC}\left(\frac{\mathbf{r}_1 + \mathbf{r}_2}{2} \right)$$

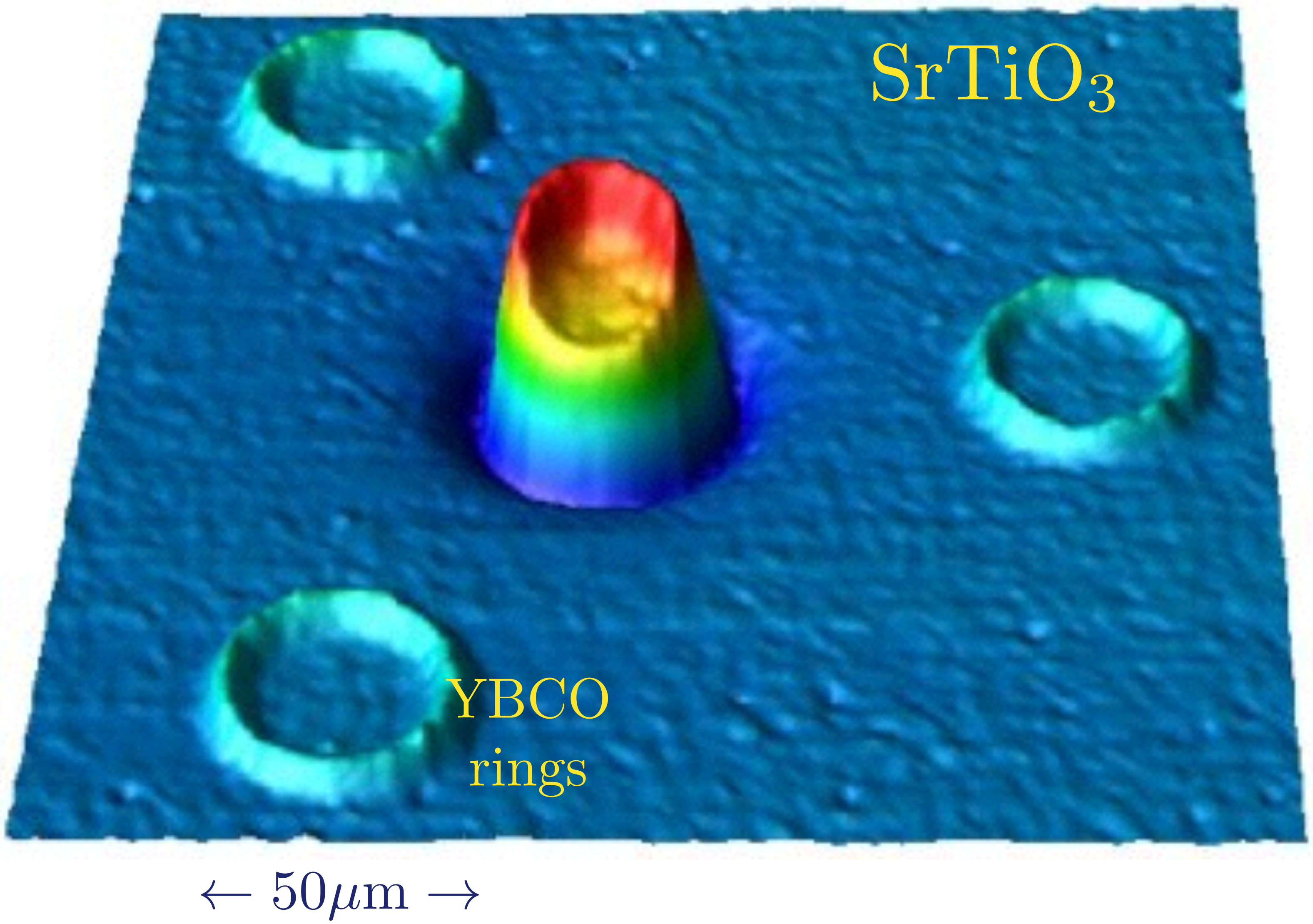


Internal Cooper-pair wavefunction. Has *d*-wave form in cuprates

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

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

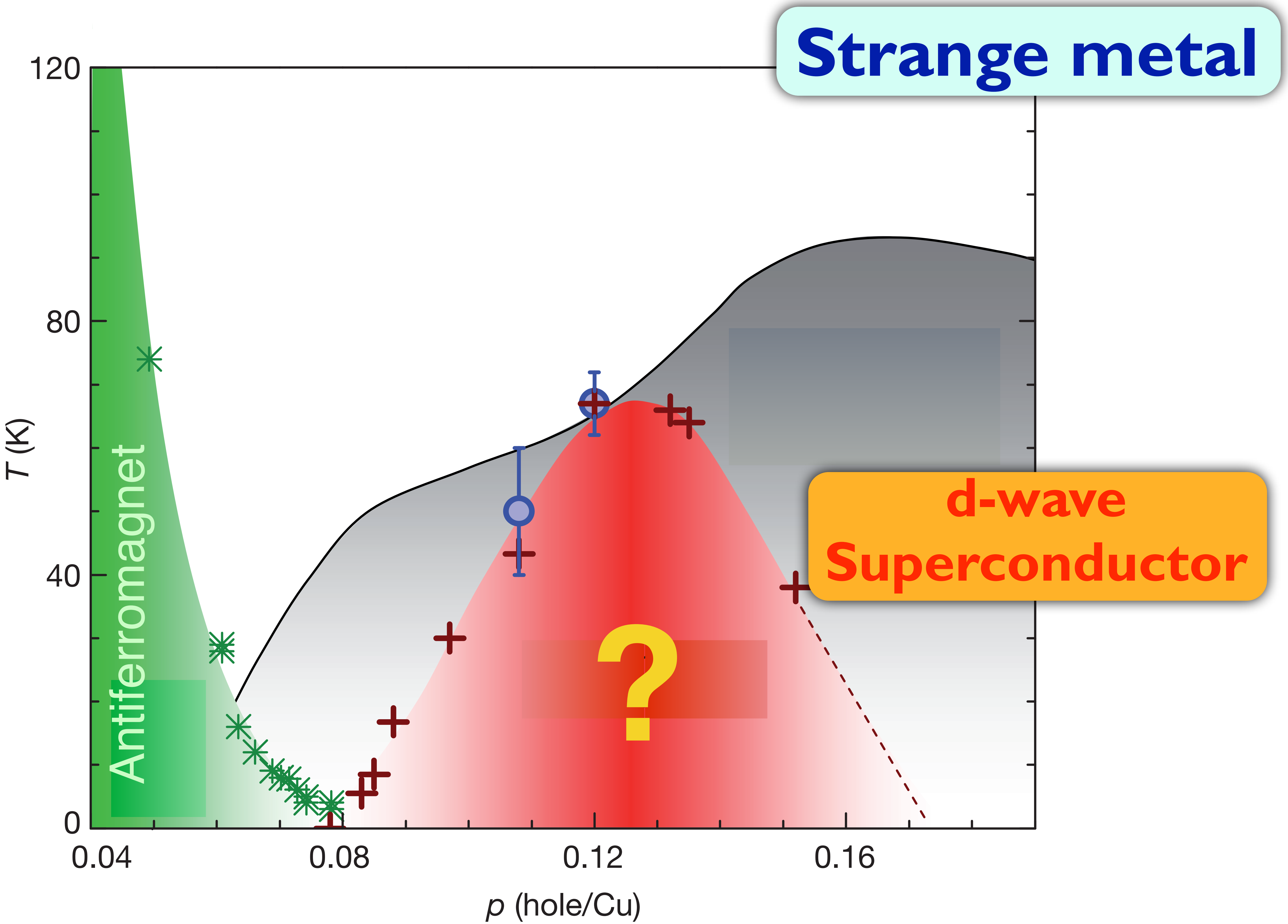




Pairing Symmetry and Flux Quantization in a Tricrystal Superconducting Ring of $YBa_2Cu_3O_{7-\delta}$

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
d-wave
Superconductor
Antiferromagnet
?
T (K)
120
80
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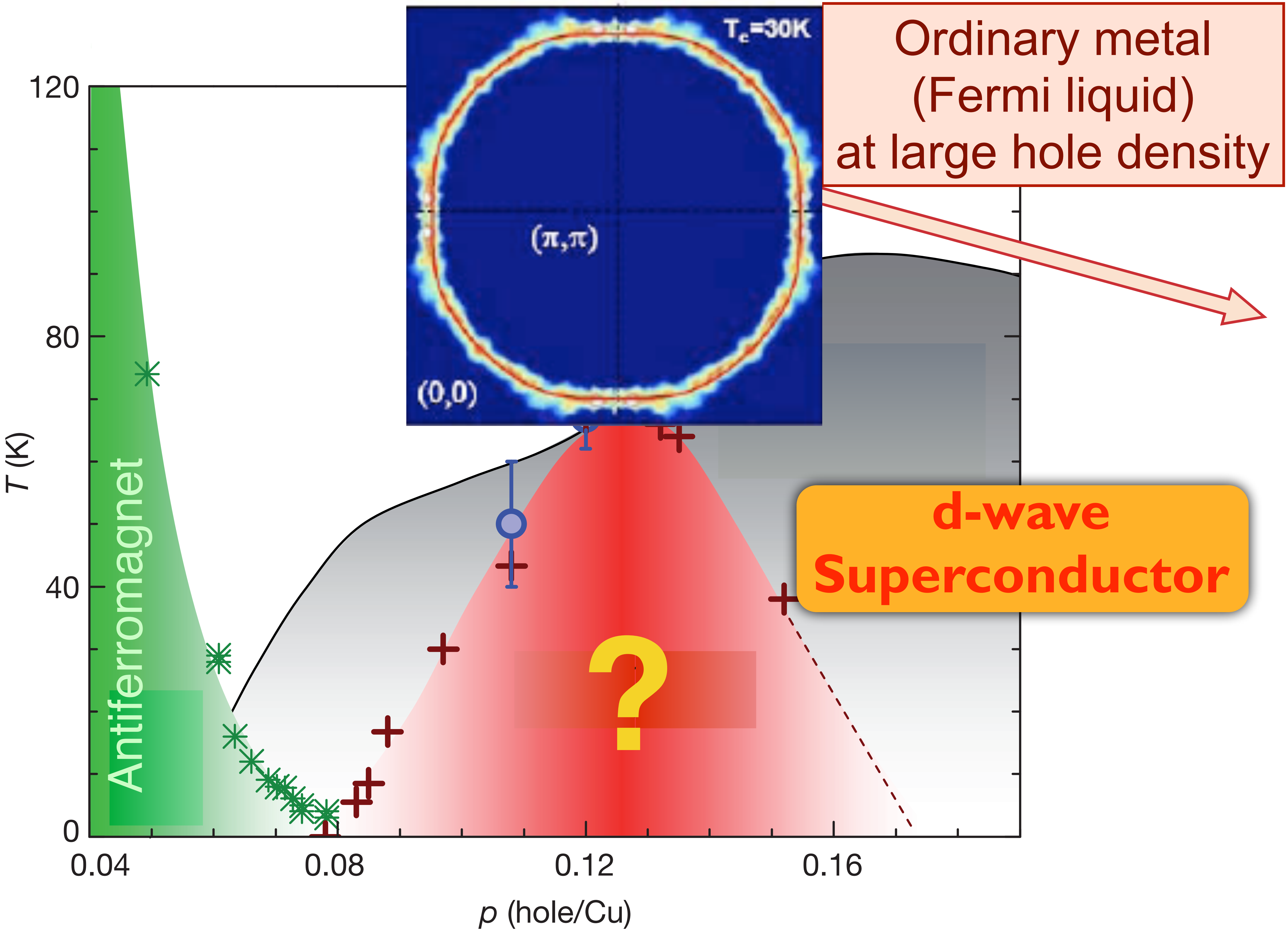
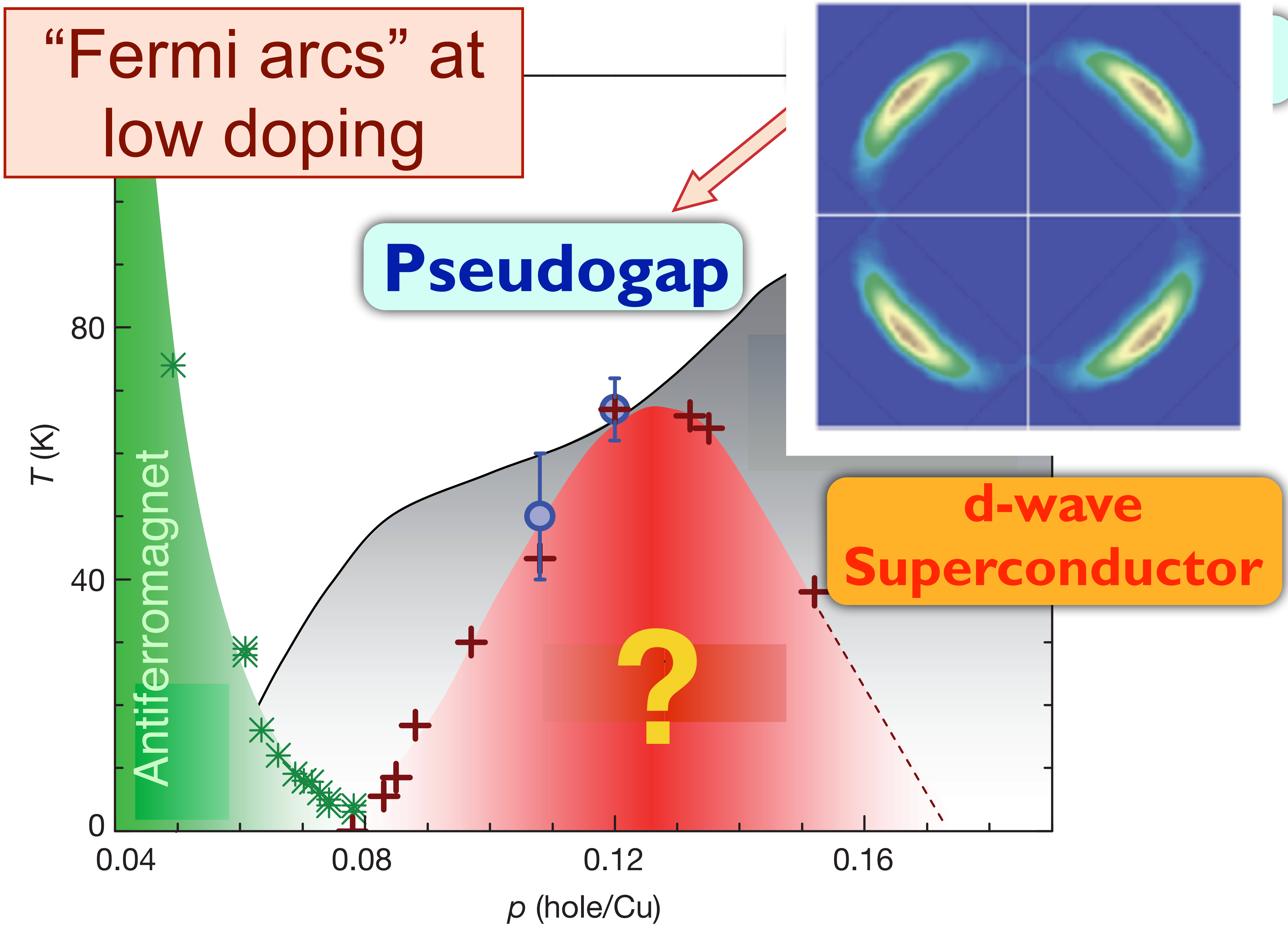
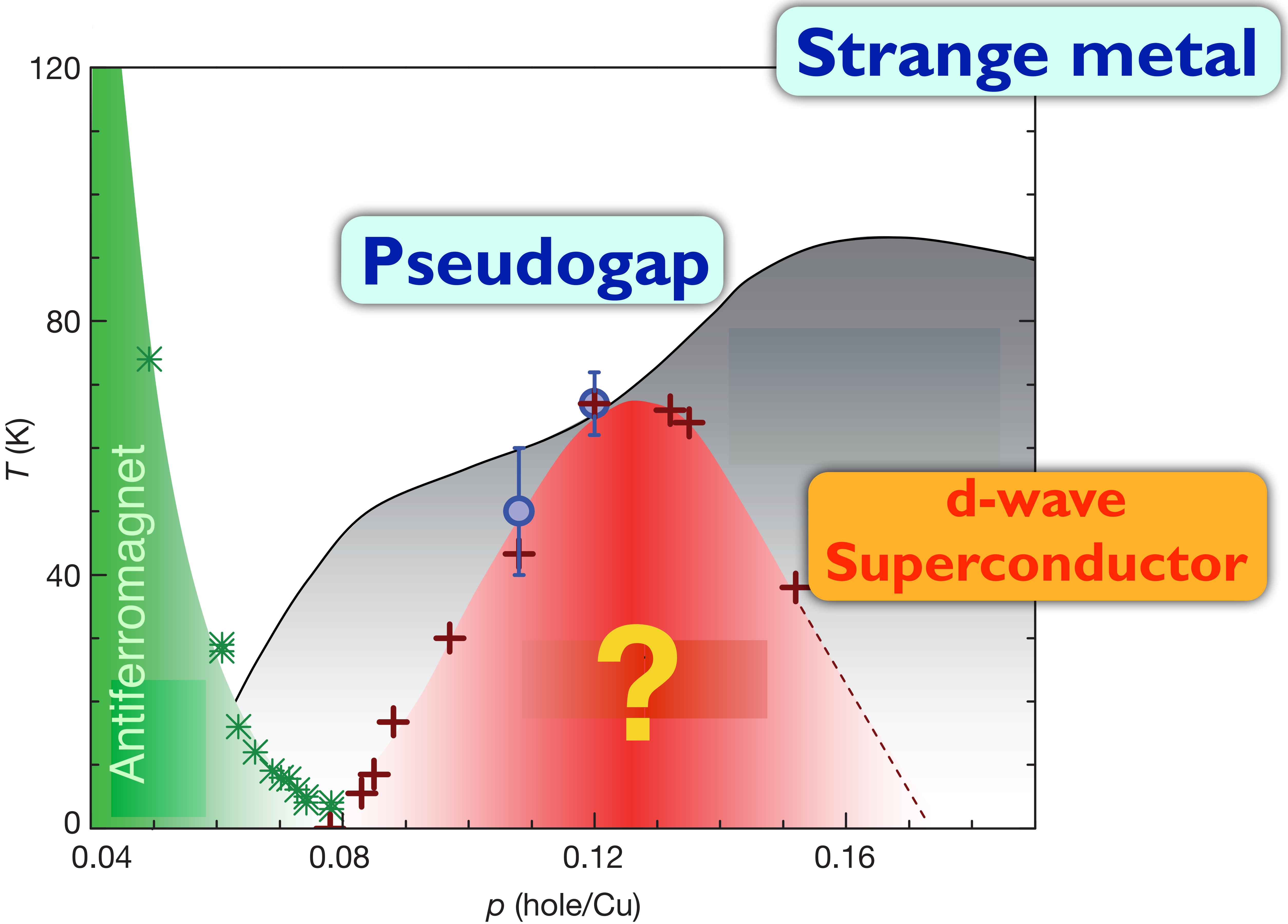
0.16
p (hole/Cu)



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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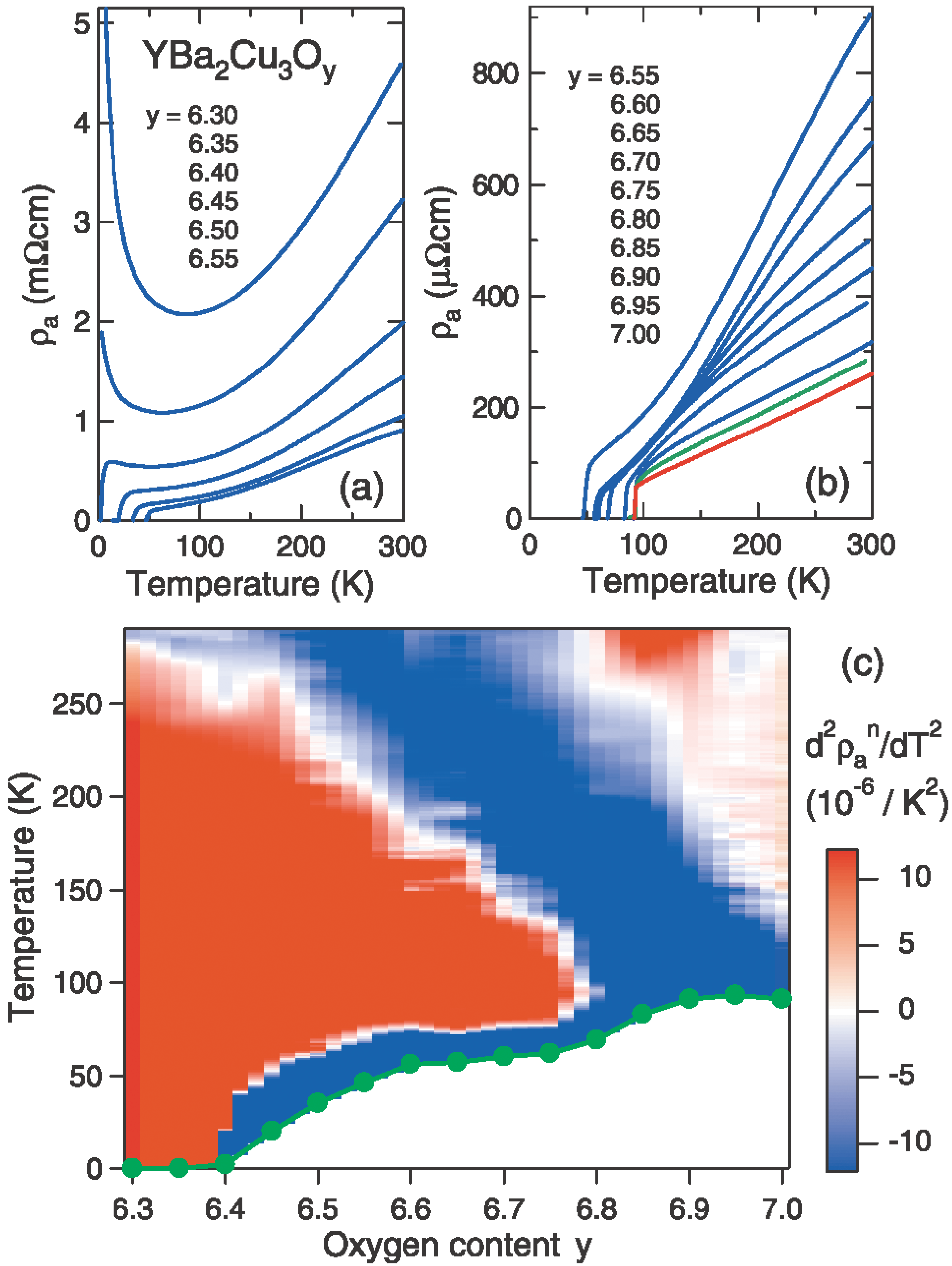
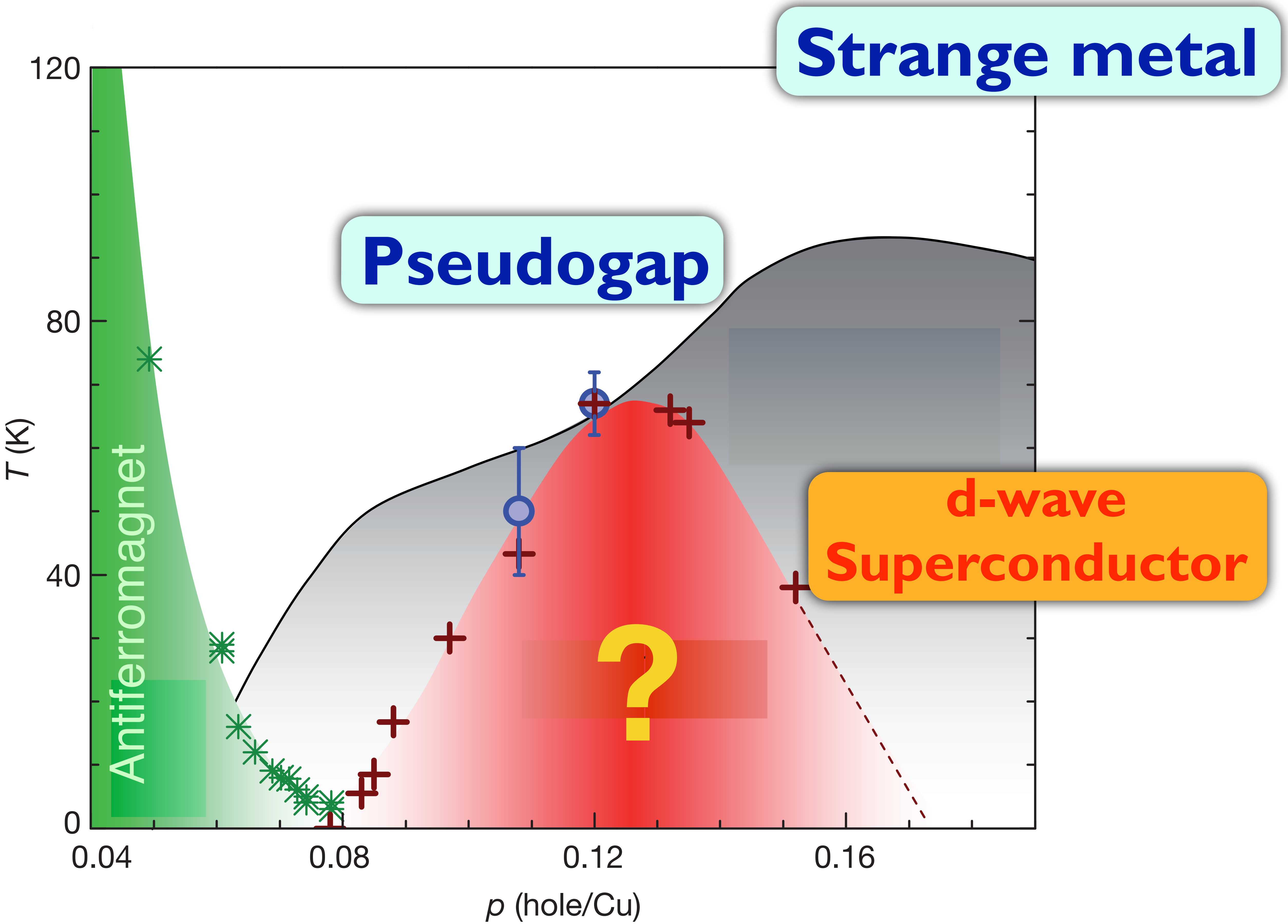
Strange metal



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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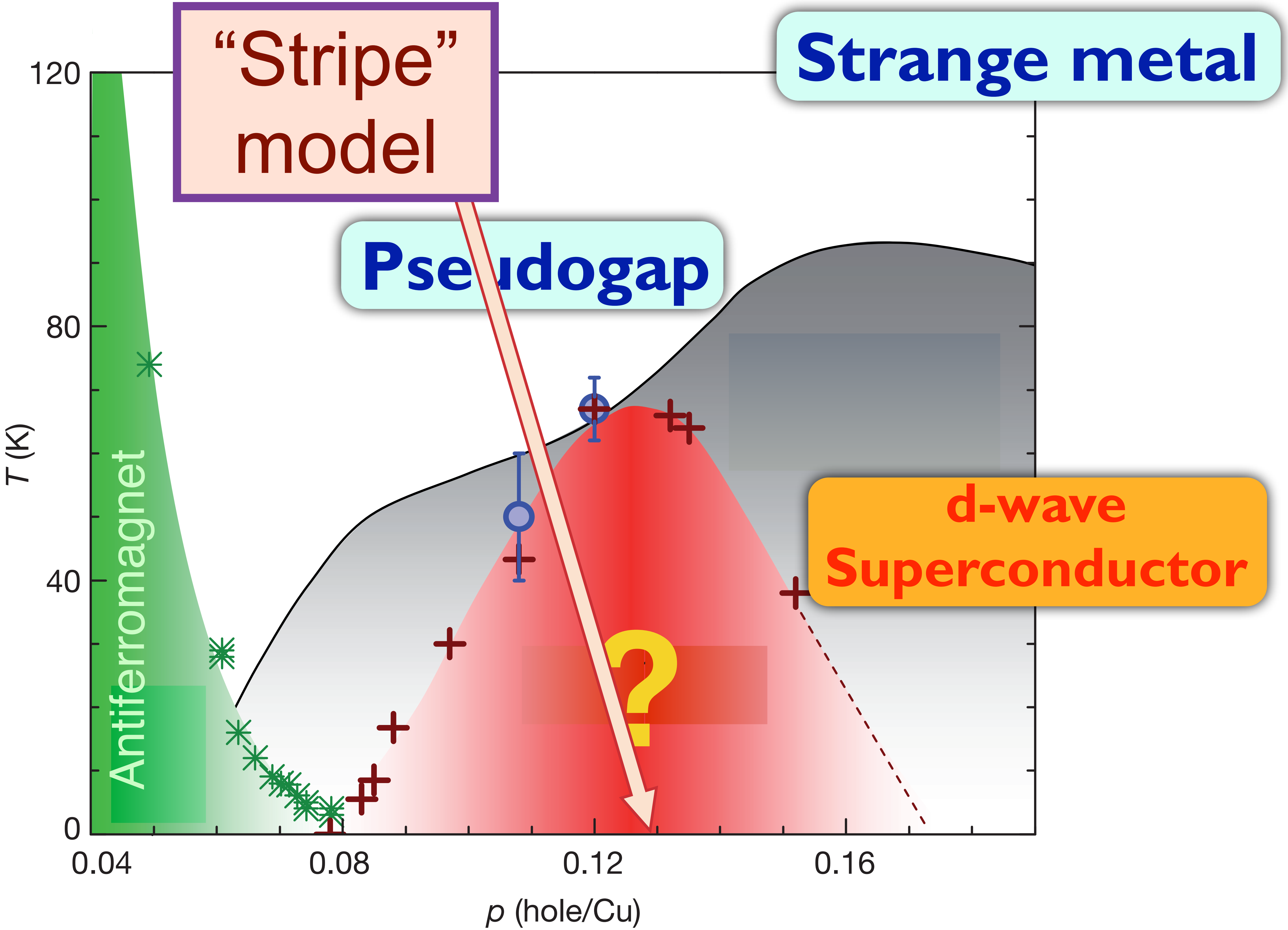

“Stripe” model
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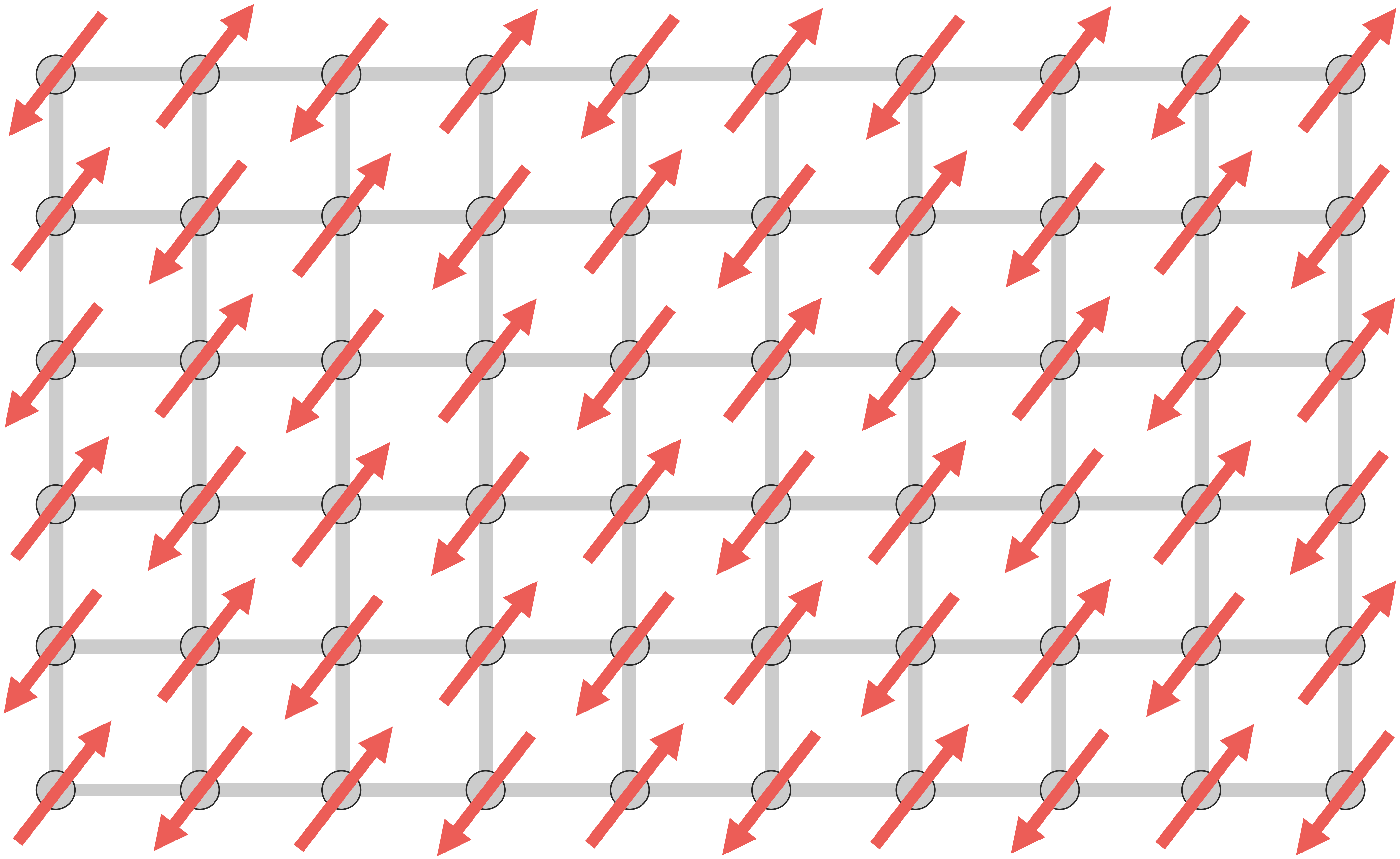
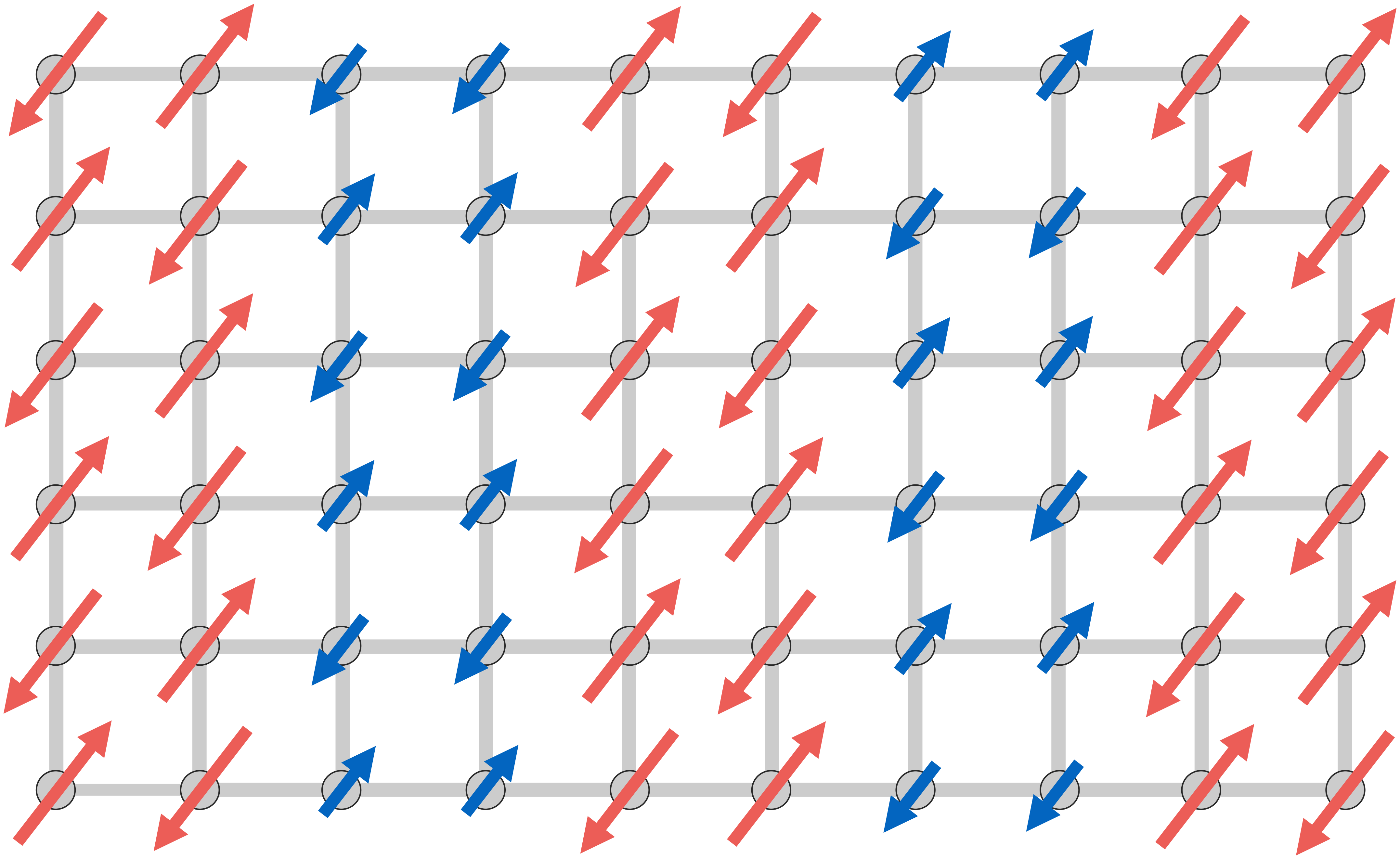


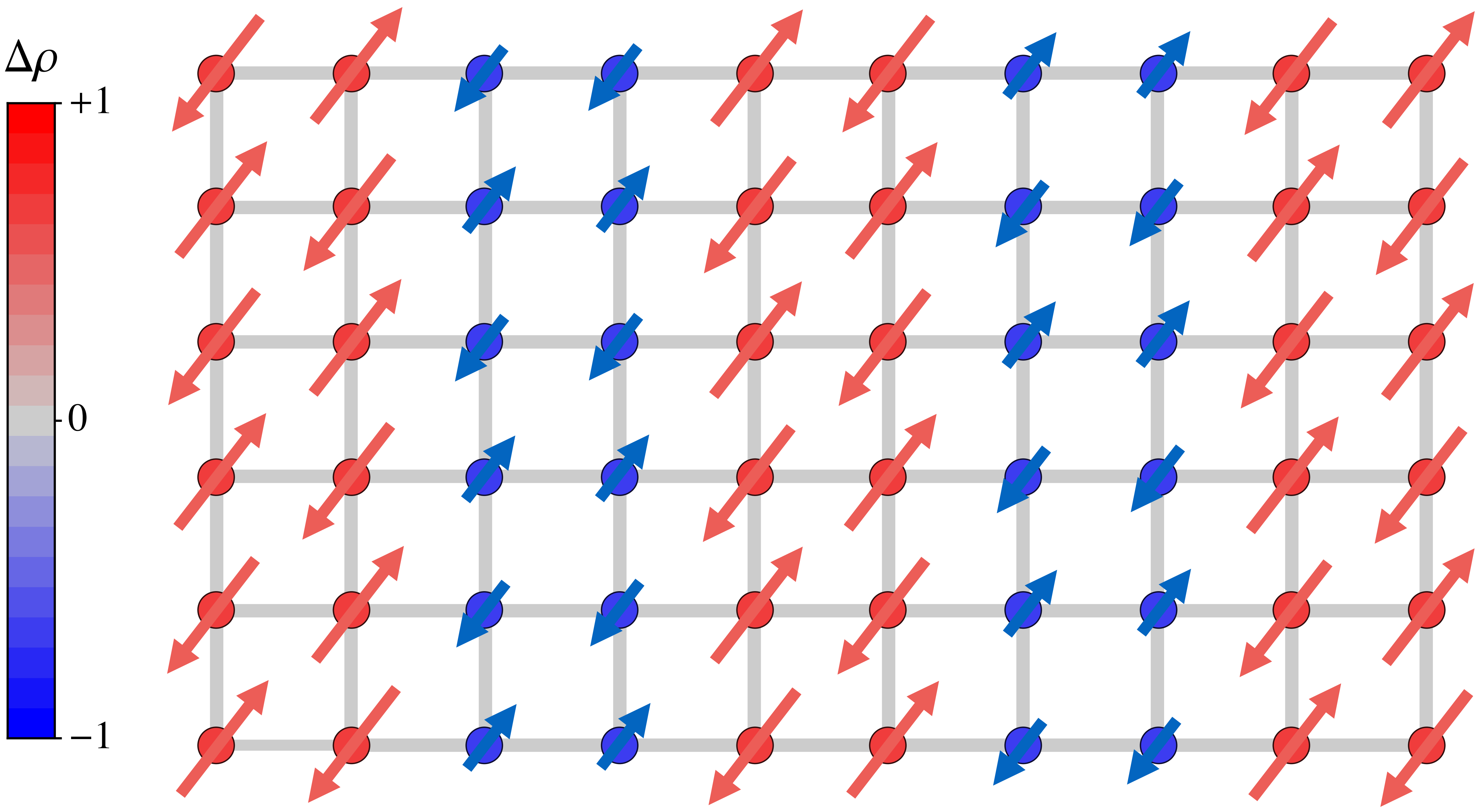
Start with an antiferromagnet

“Stripe” model



Domain walls 4 lattice spacings apart

“Stripe” model

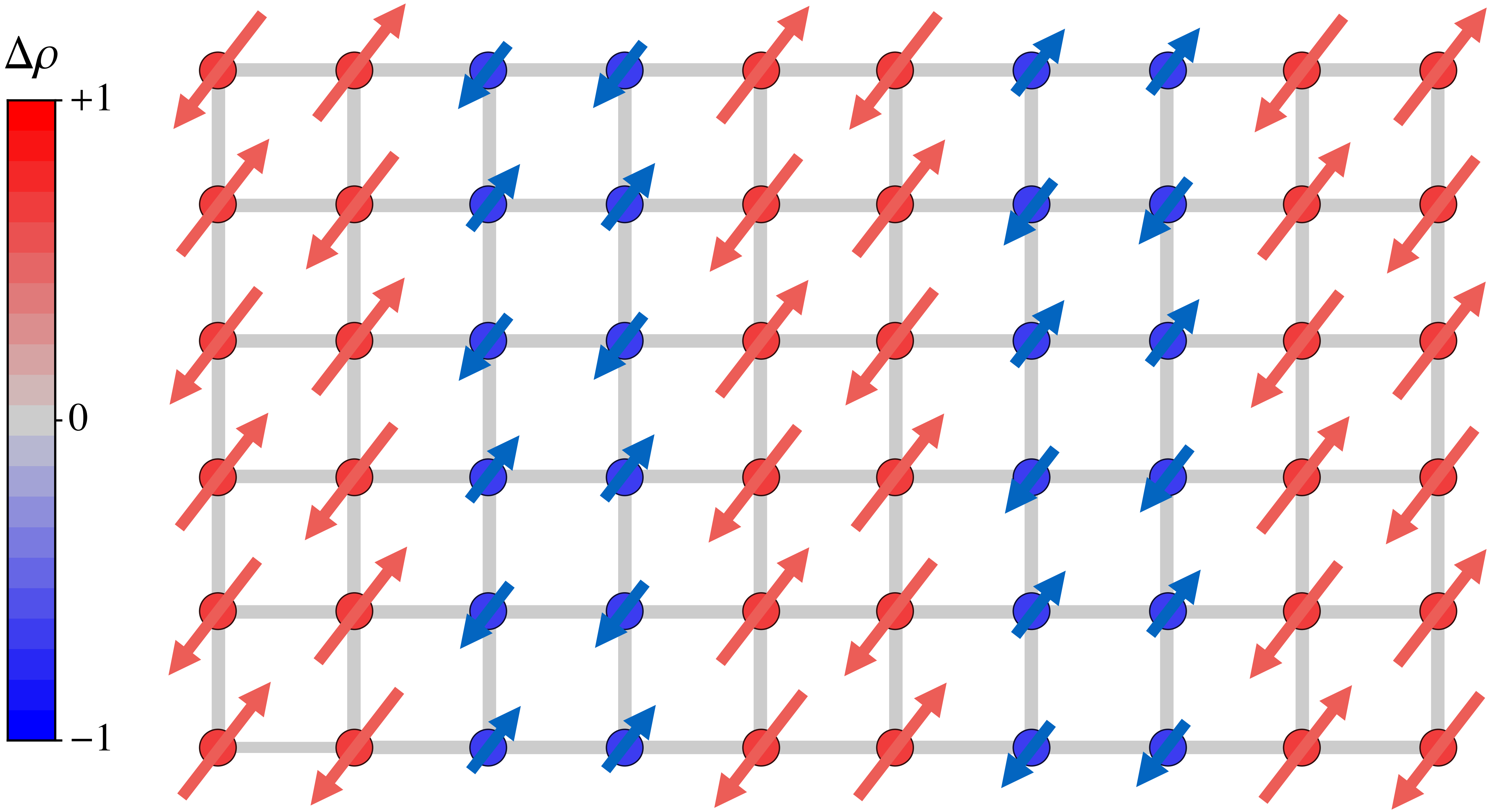


Put the holes in the domain walls

Observed in La-based compounds (Tranquada..)

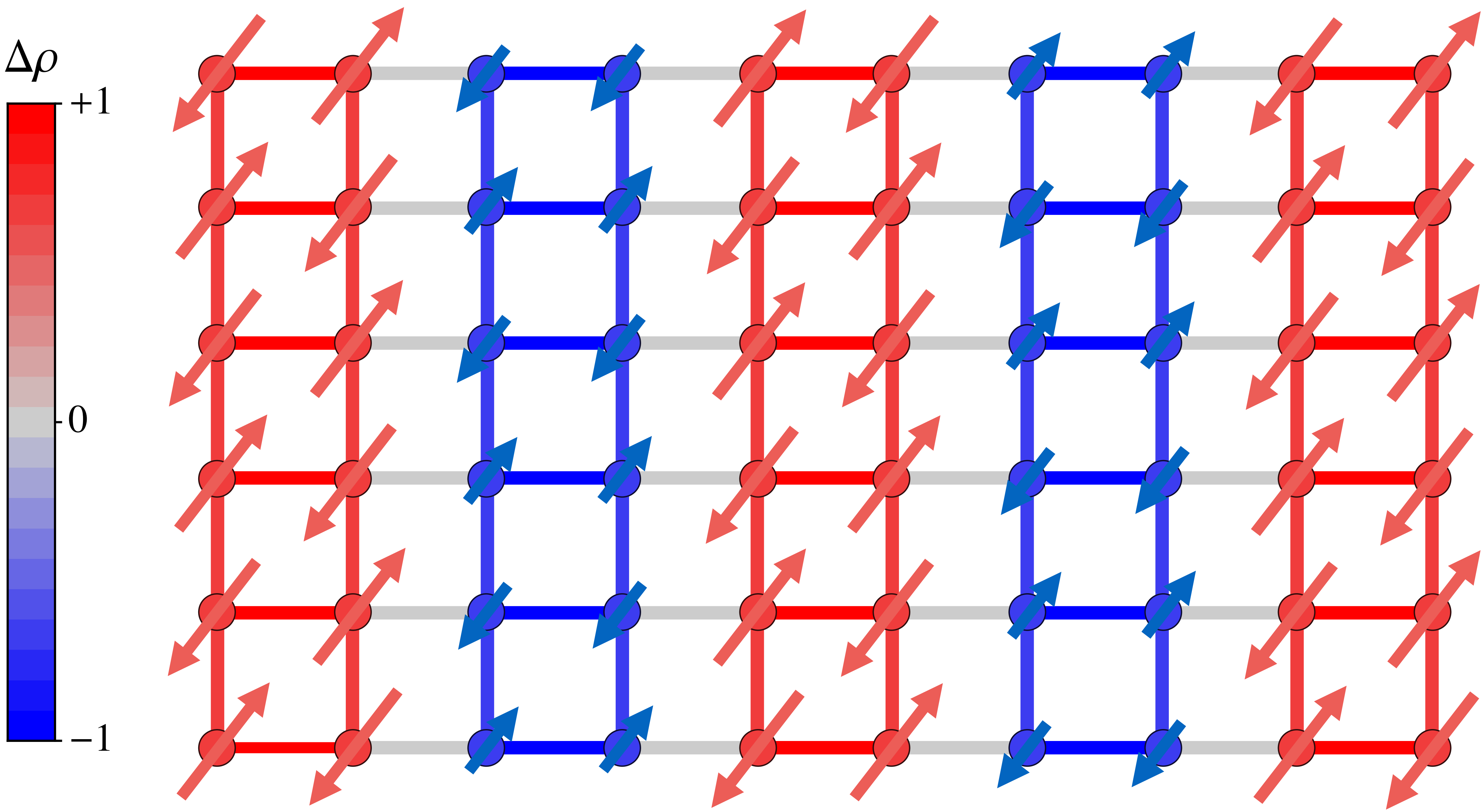
Theory: Zaanen, Kivelson, Fradkin….

“Stripe” model

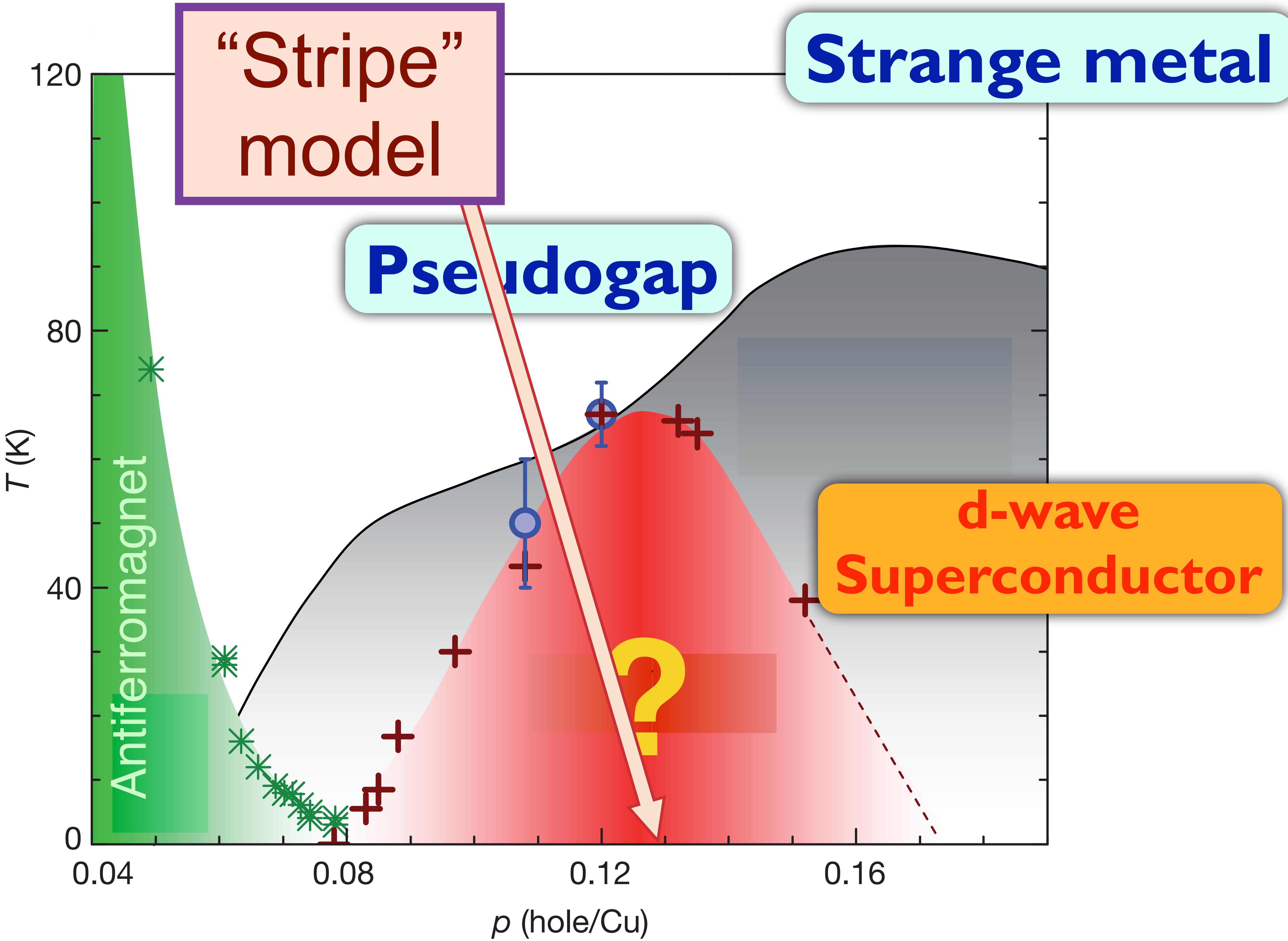


Put the holes in the domain walls

“Stripe” model



Colors on the bonds map the local exchange energy



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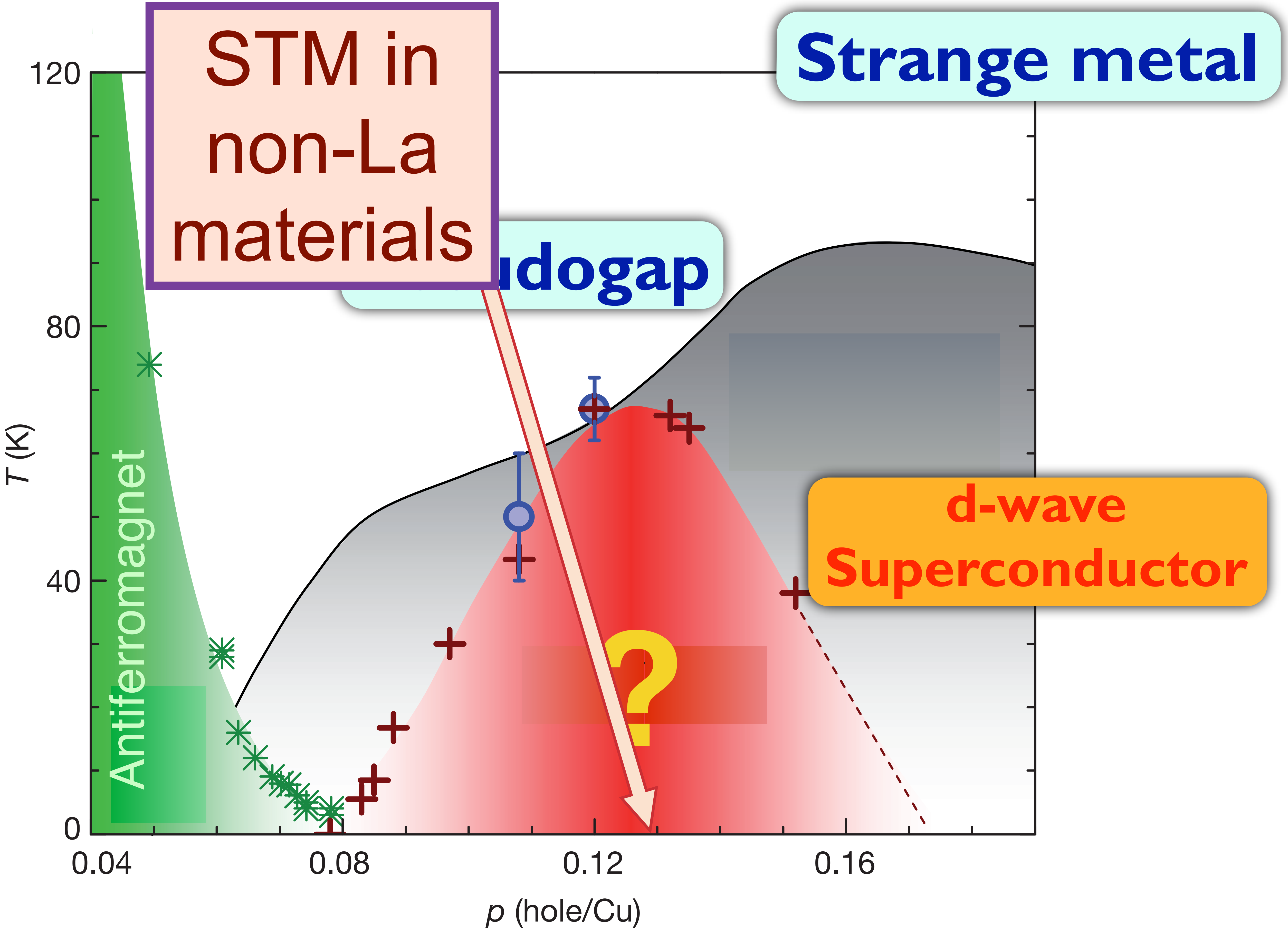

STM in non-La materials
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See also
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M. Vershinin, S. Misra, S. Ono, Y. Abe, Yoichi Ando, and A. Yazdani, Science **303**, 1995 (2004).

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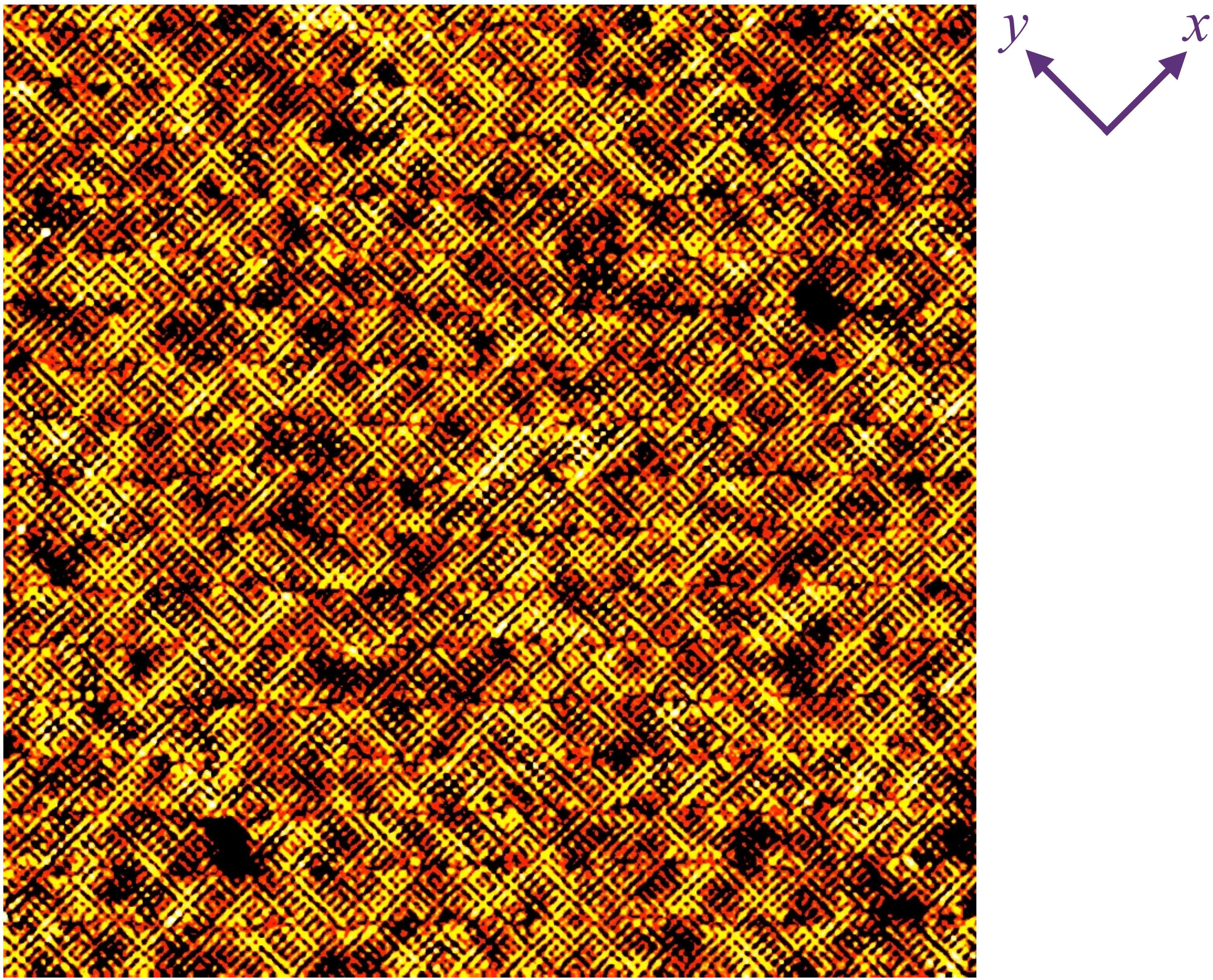

"R-map" of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007). Davis group has sub-angstrom resolution capabilities, with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

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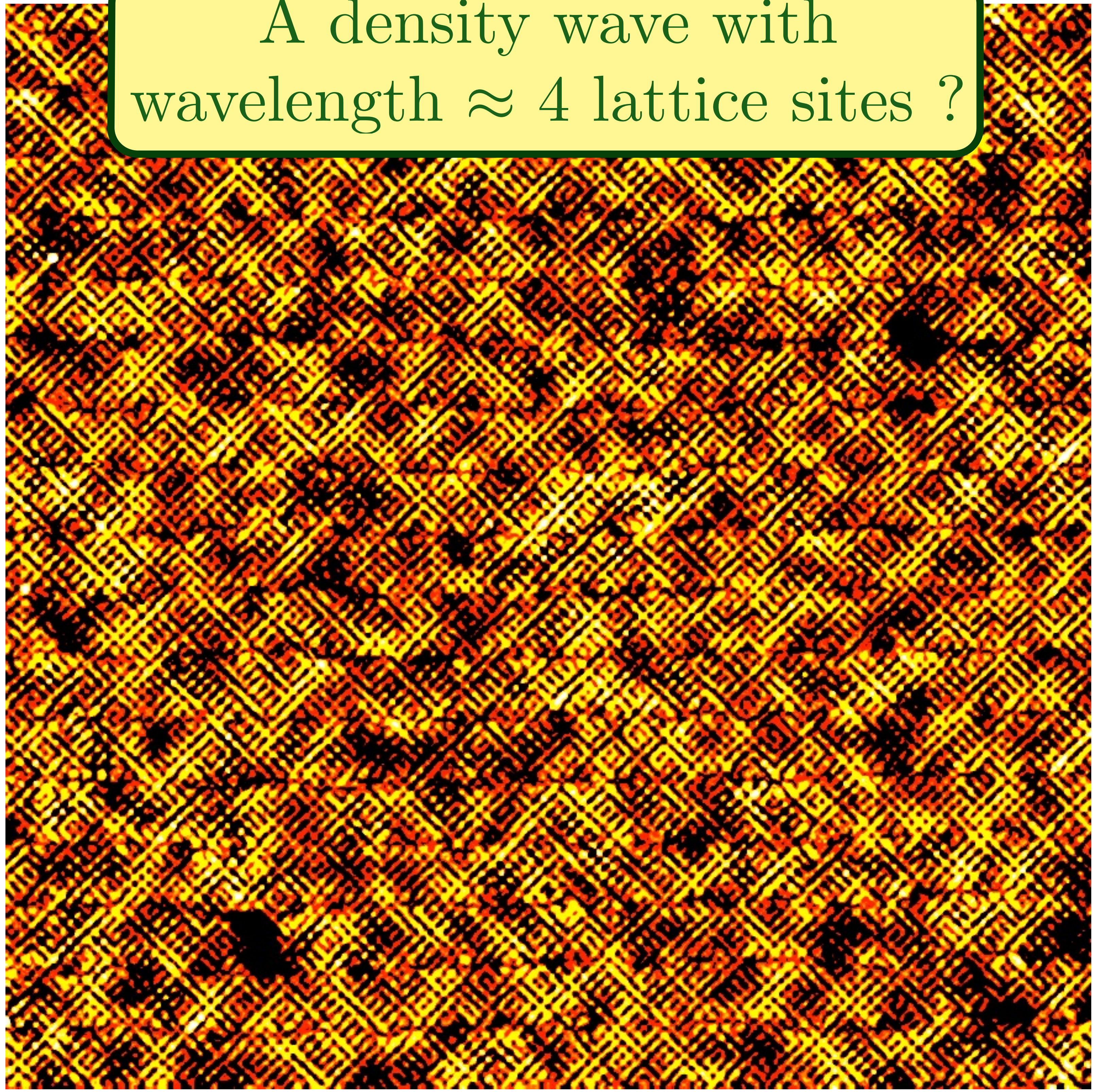
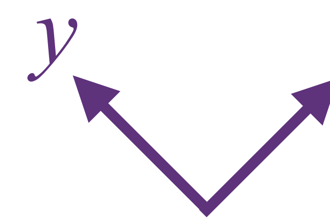
A density wave with wavelength ≈ 4 lattice sites ?





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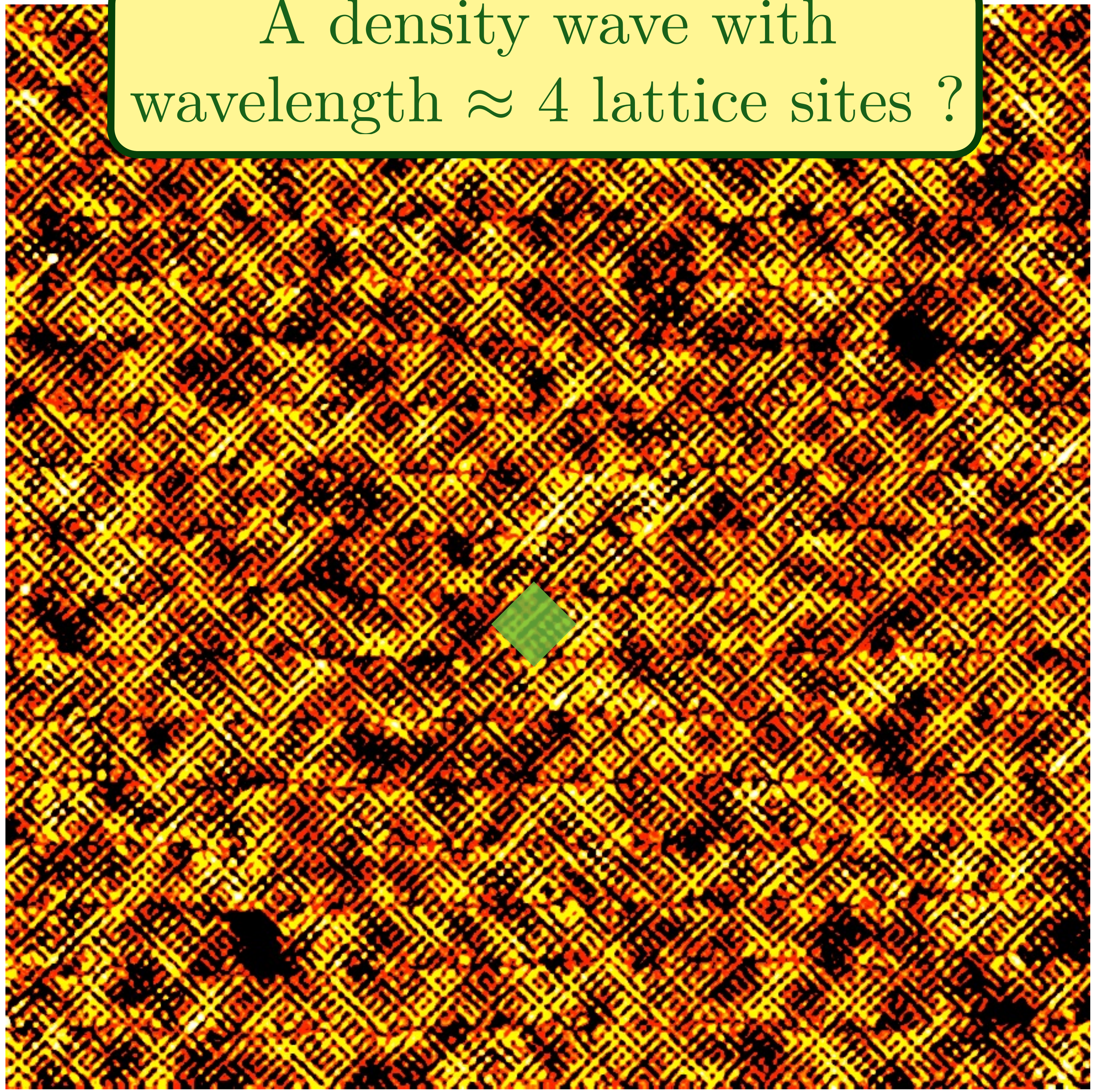

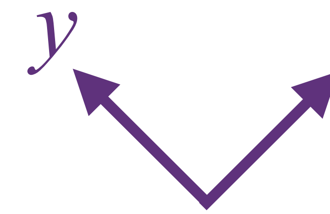

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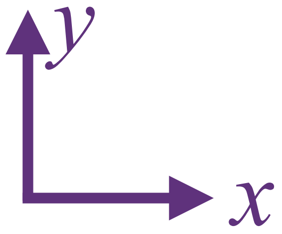

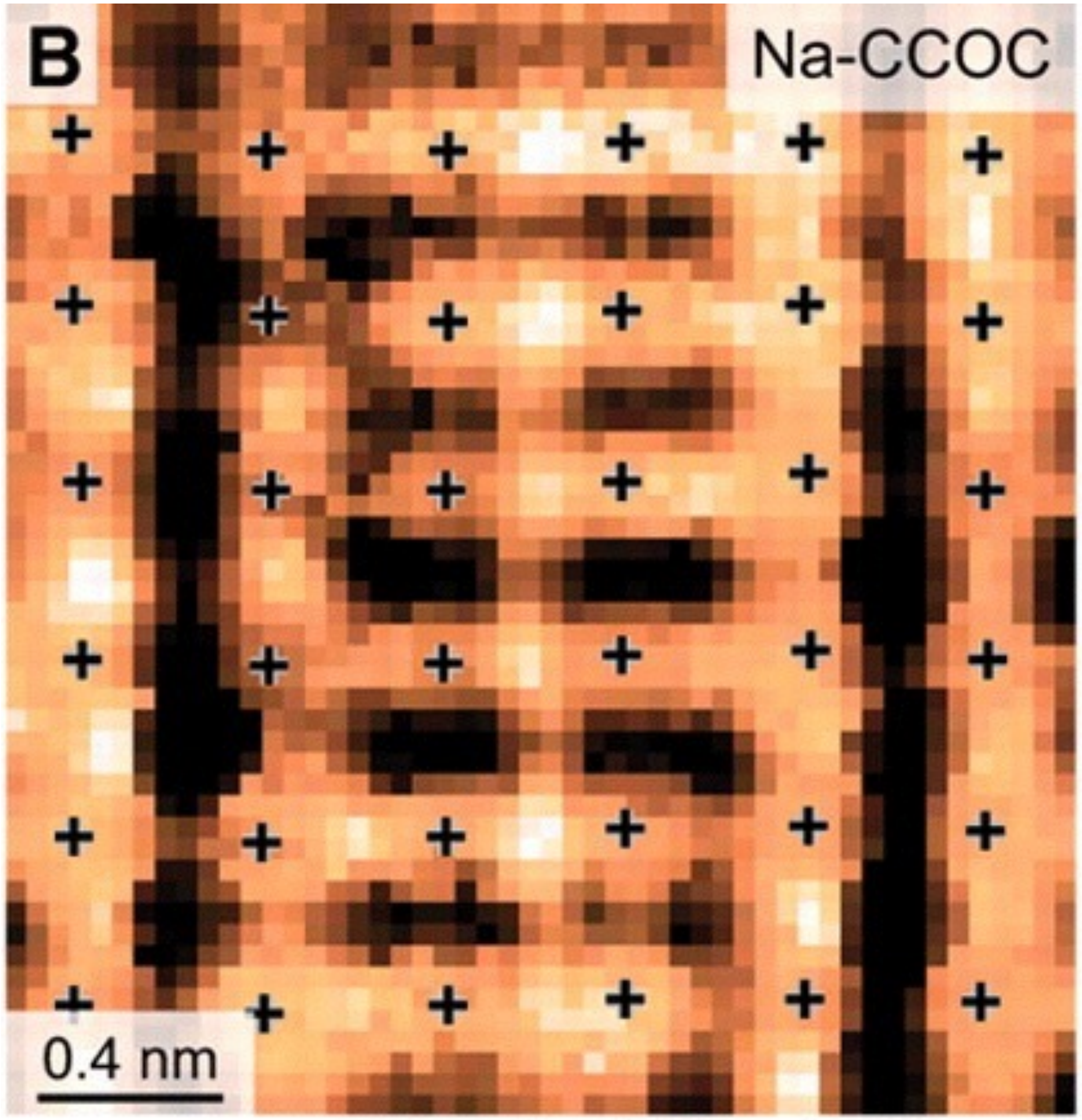

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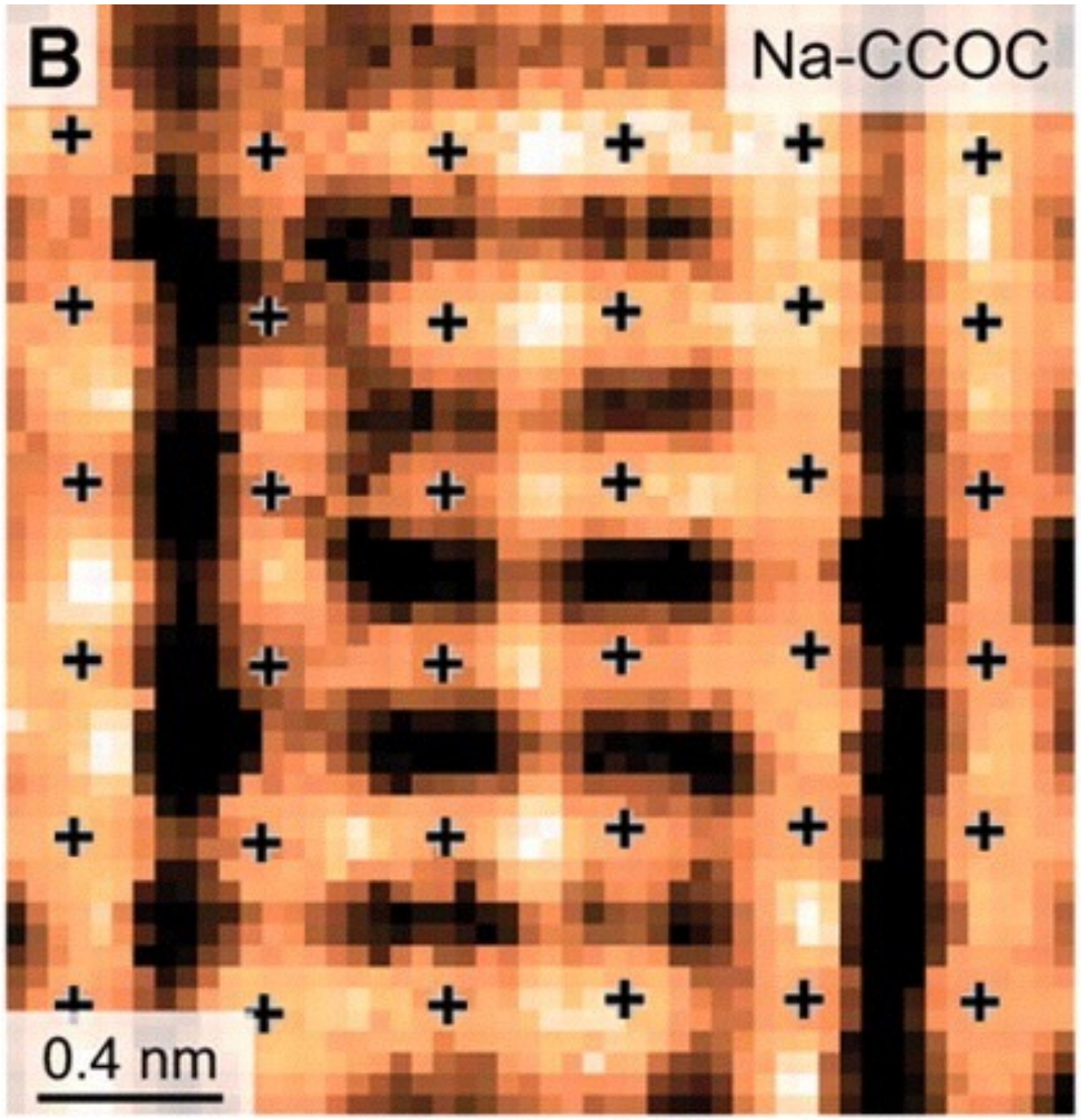

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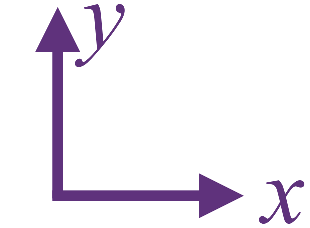
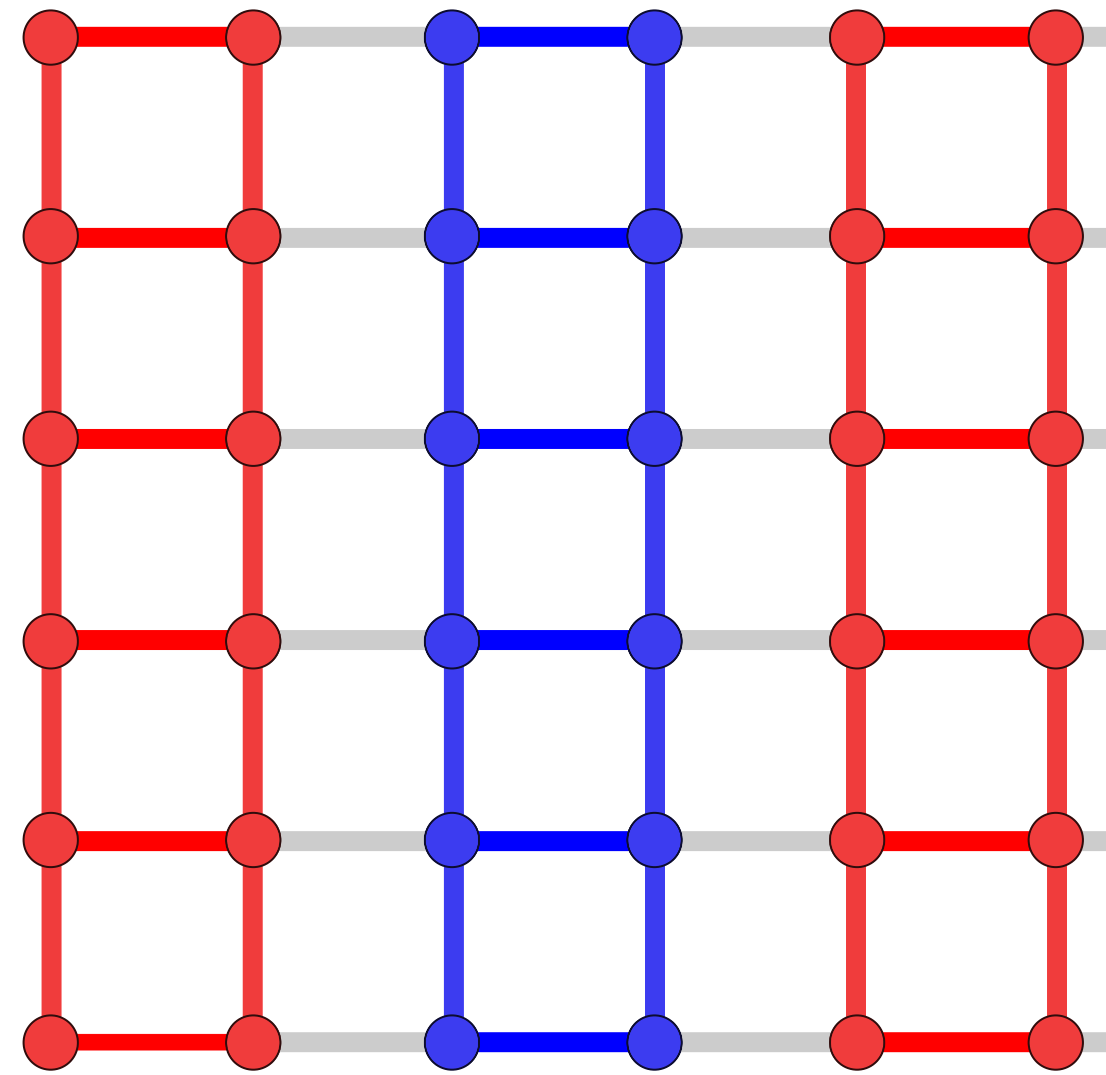
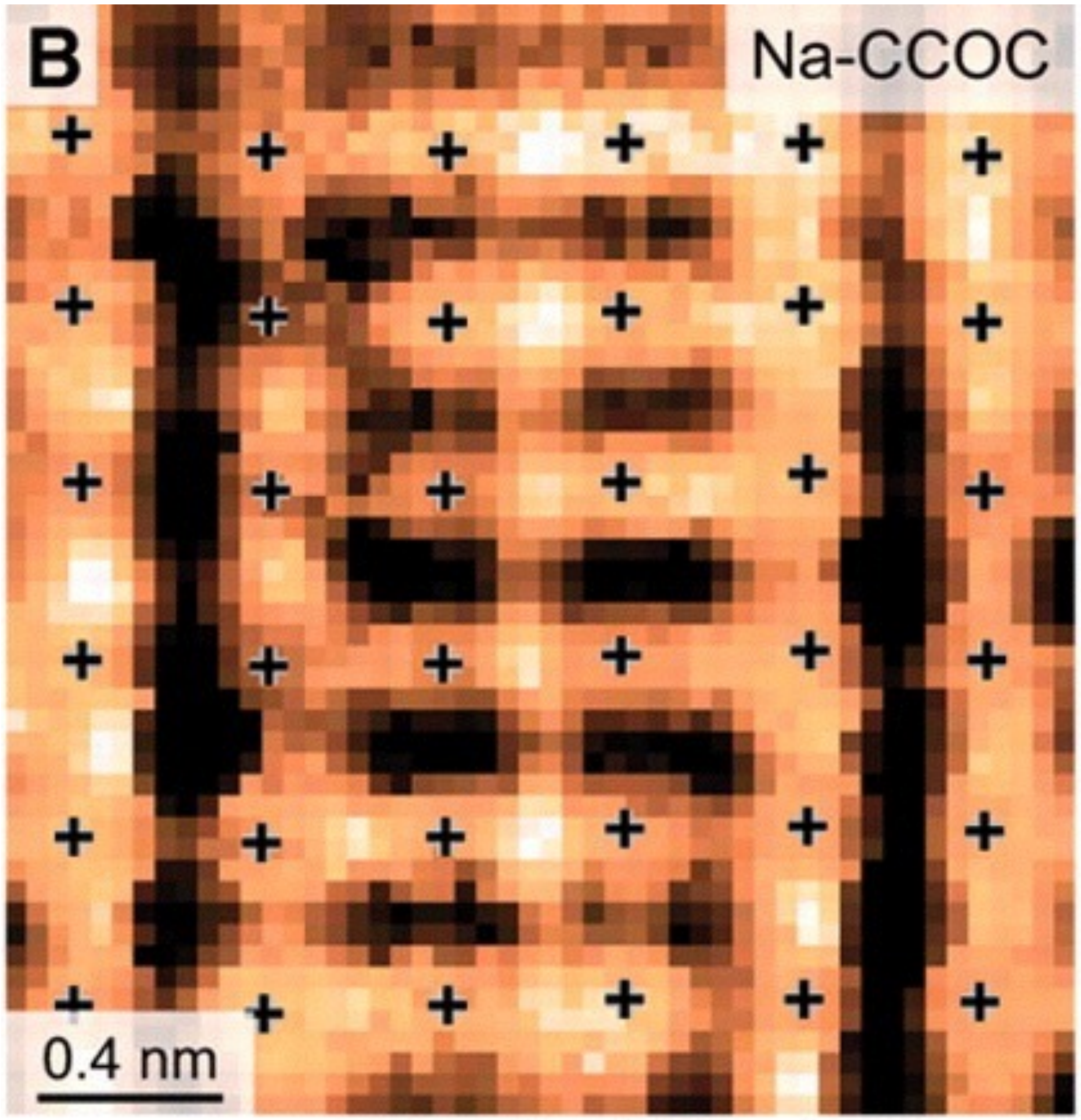




“Stripe” model



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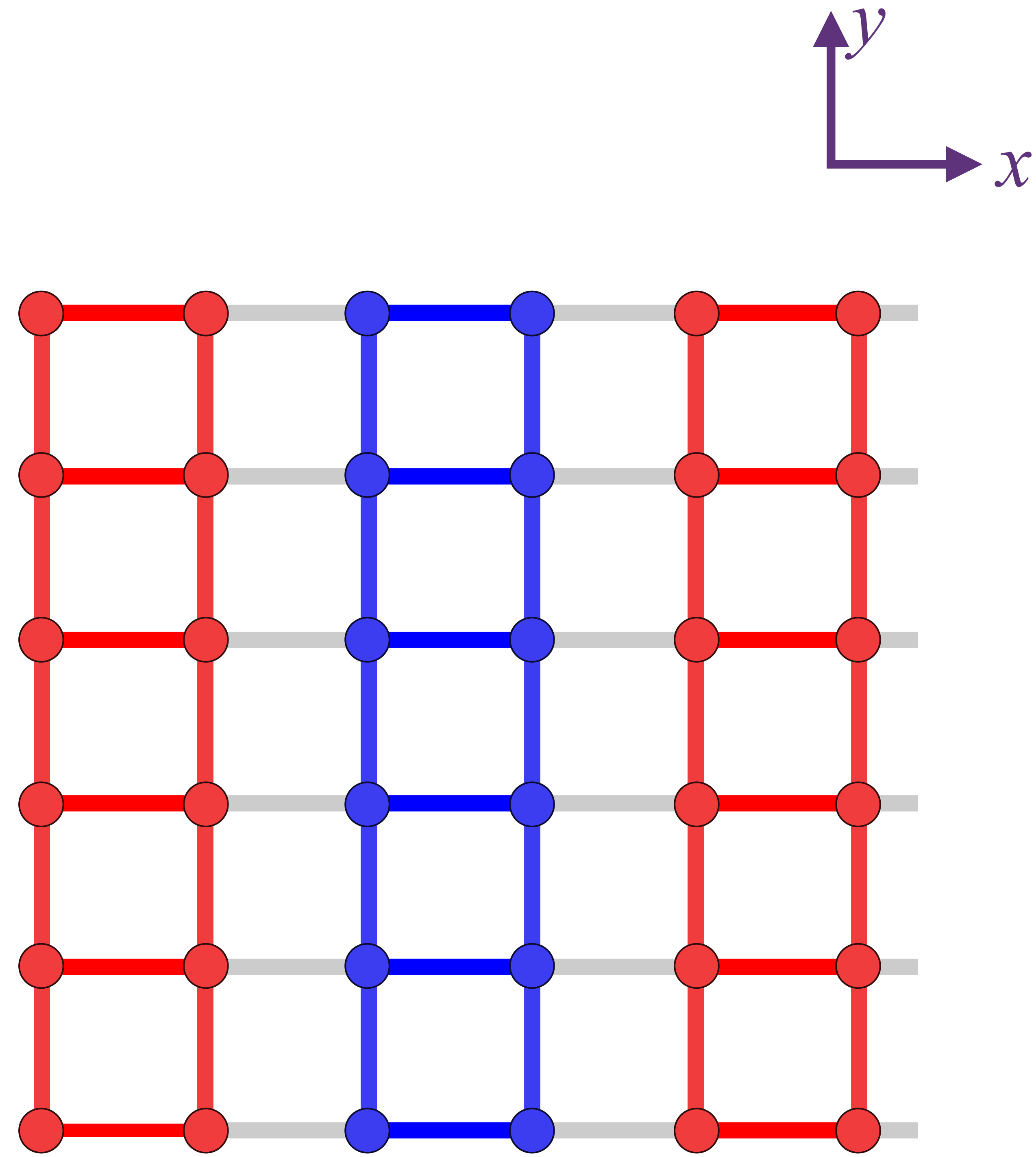

“Stripe” model

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)

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

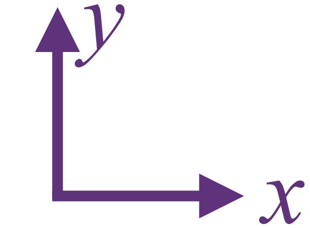
Time-reversal symmetry requires $\mathcal{P}(\mathbf{k}) = \mathcal{P}(-\mathbf{k})$.

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)

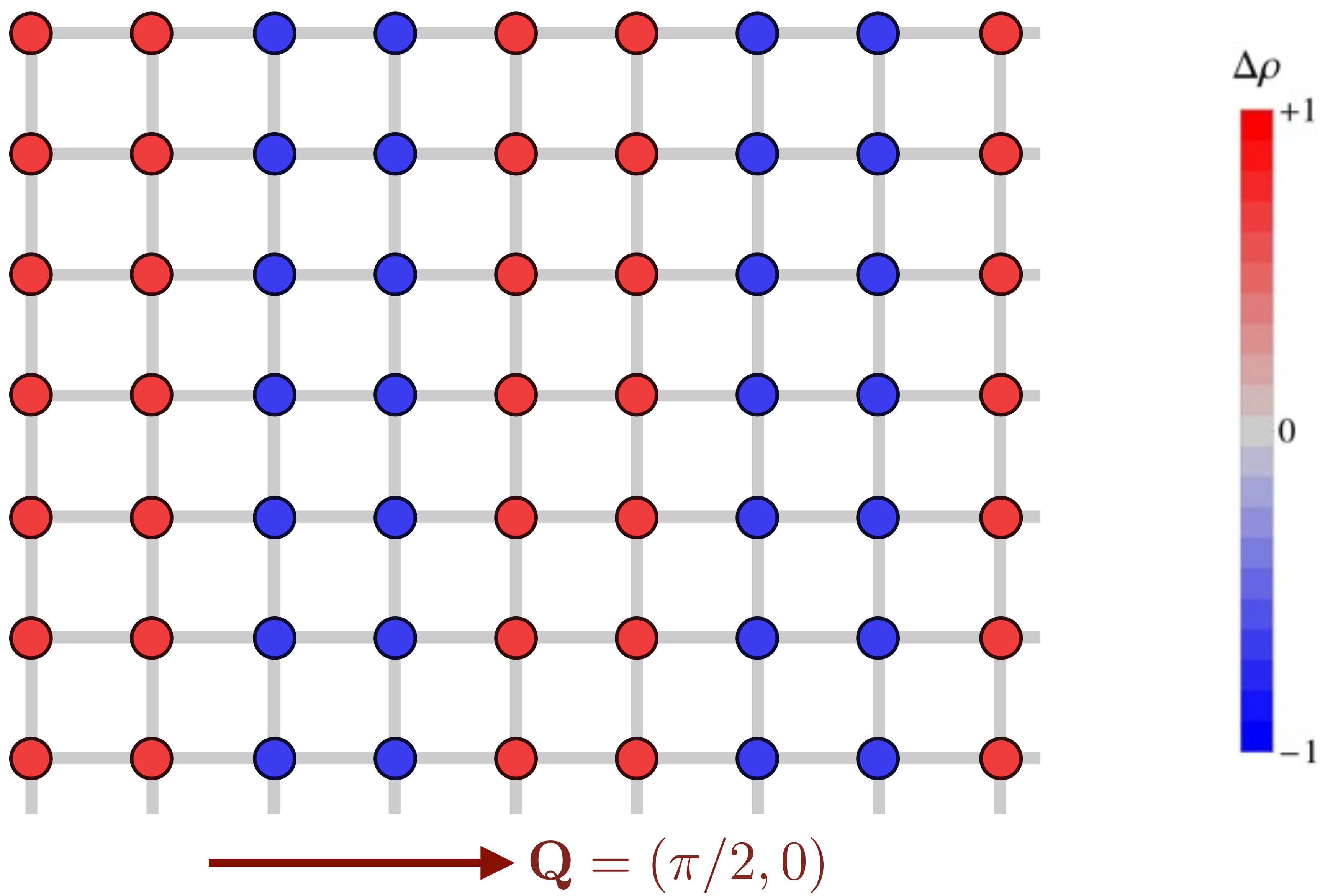
Conventional CDW order: s-form factor



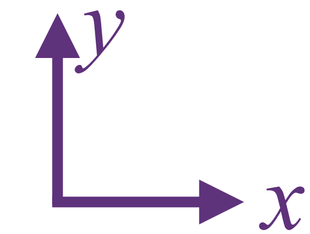
Plot of $P_{ij} = \left\langle c_{i\alpha}^{\dagger} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

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



Unconventional DW order: s'-form factor



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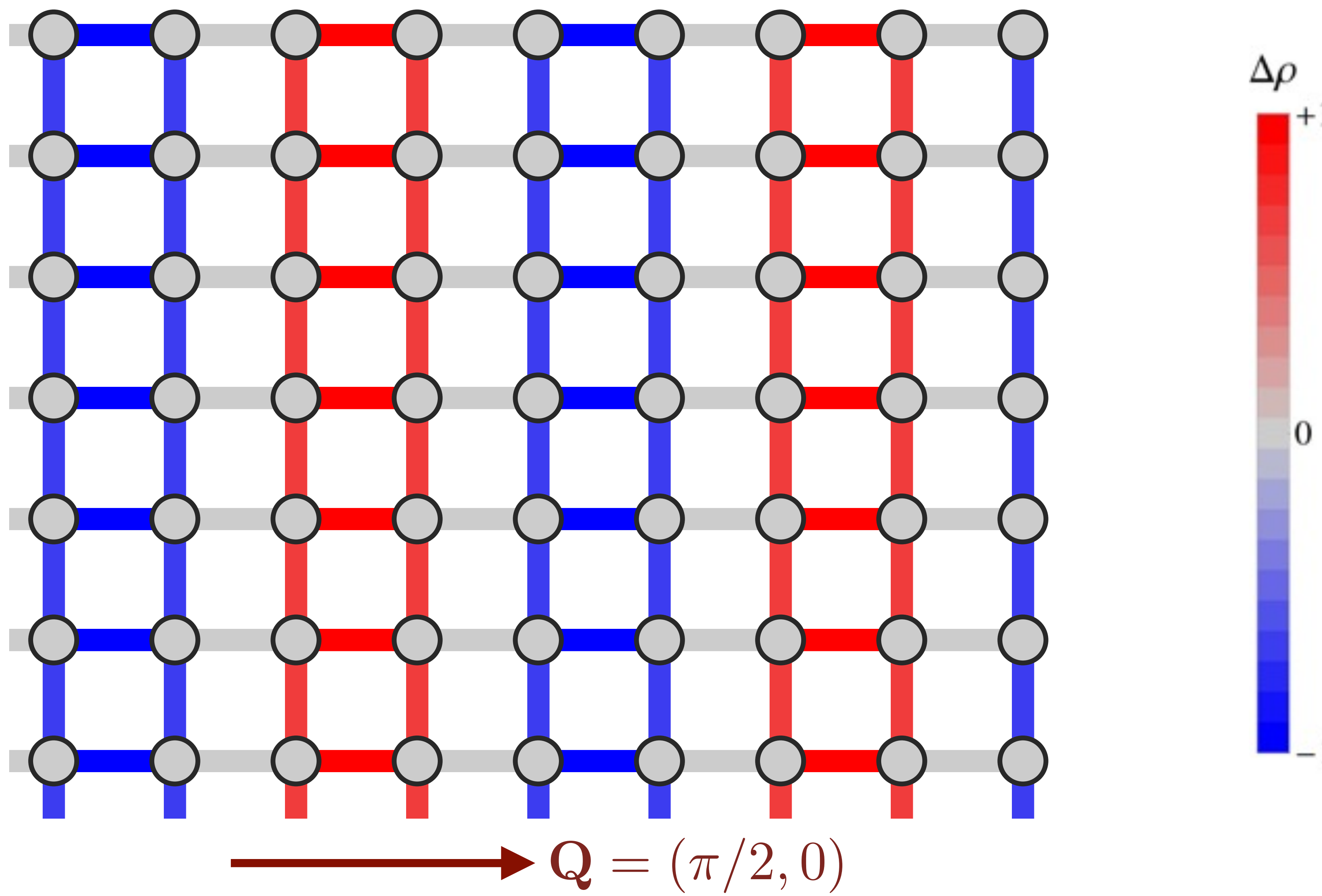
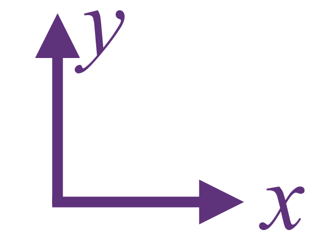
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) + \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$



Unconventional DW order: s'-form factor



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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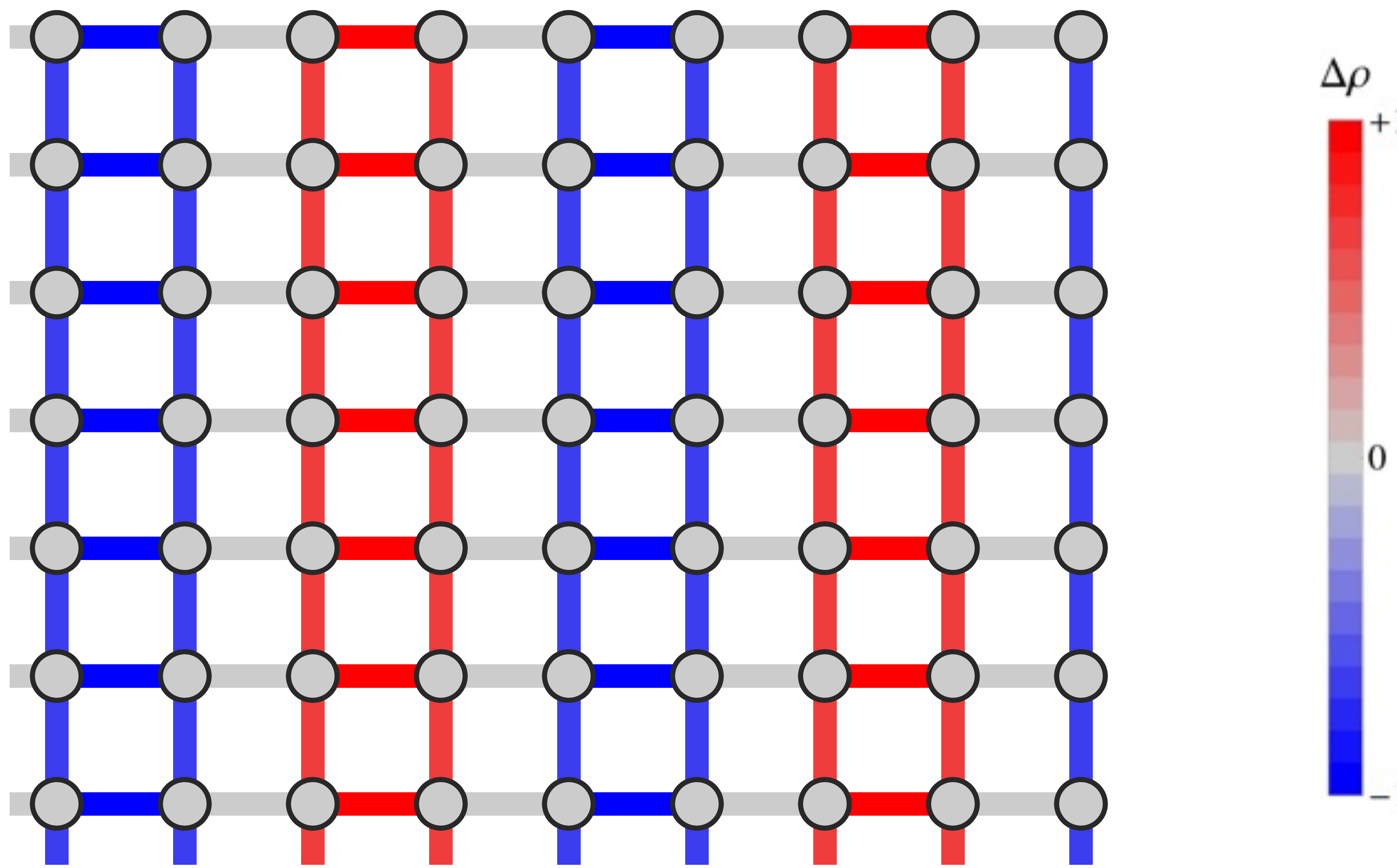
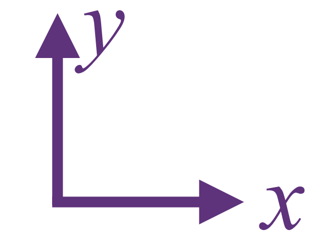
"Stripe" model !



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

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

Unconventional DW order: s'-form factor



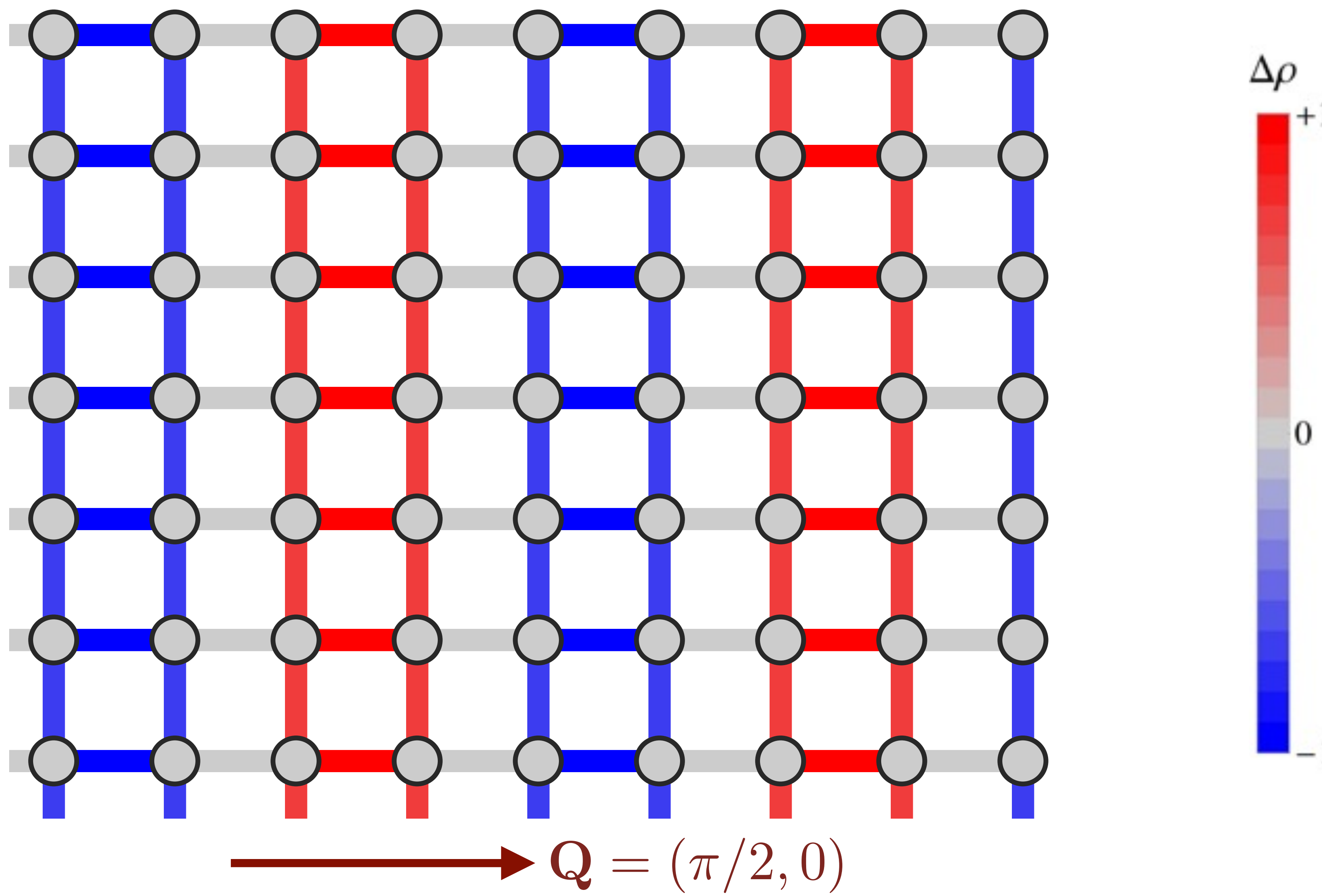
Plot of $P_{ij} = \left\langle c_{i\alpha}^{\dagger} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

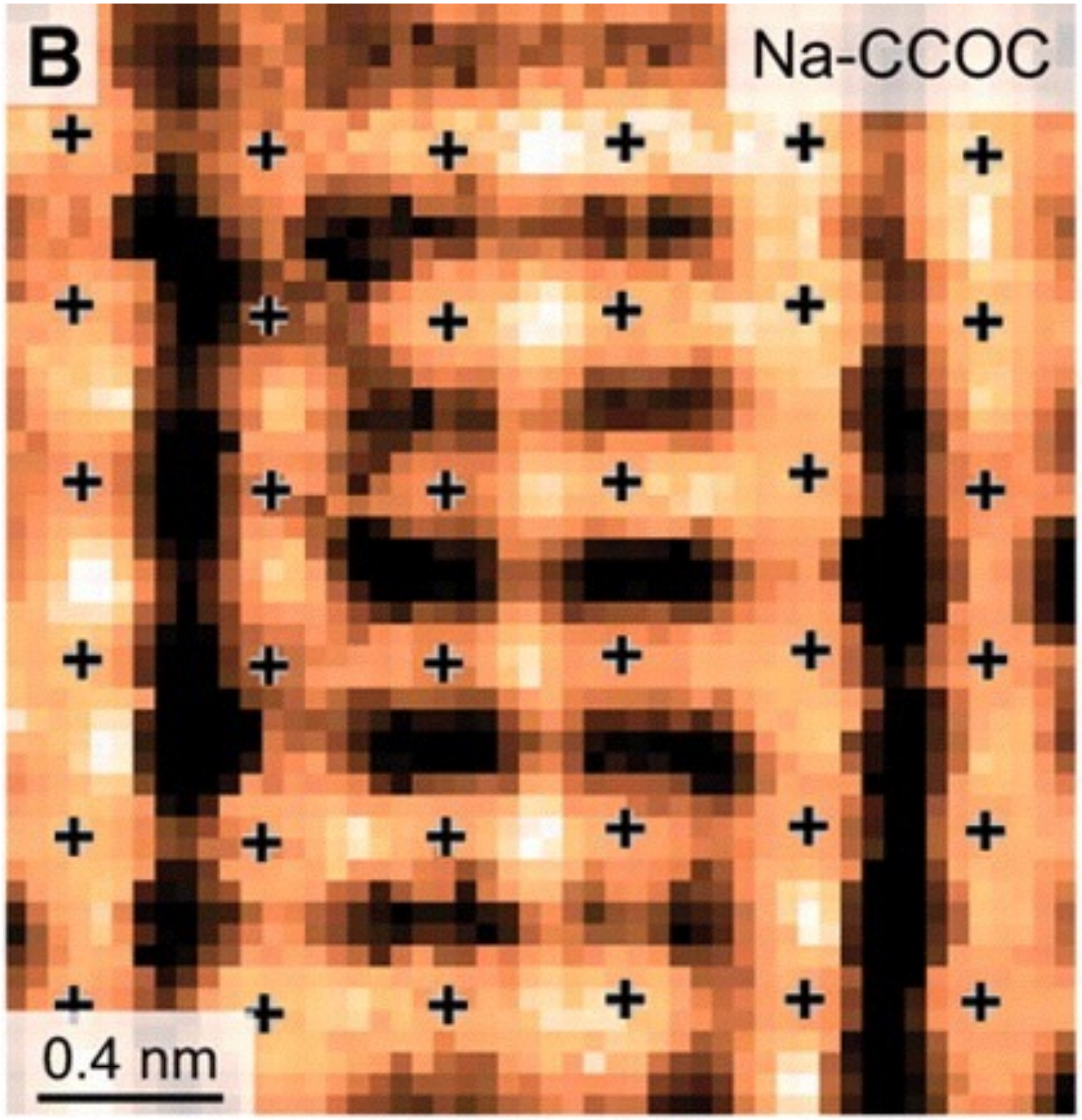
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) + \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$

“Stripe” model !

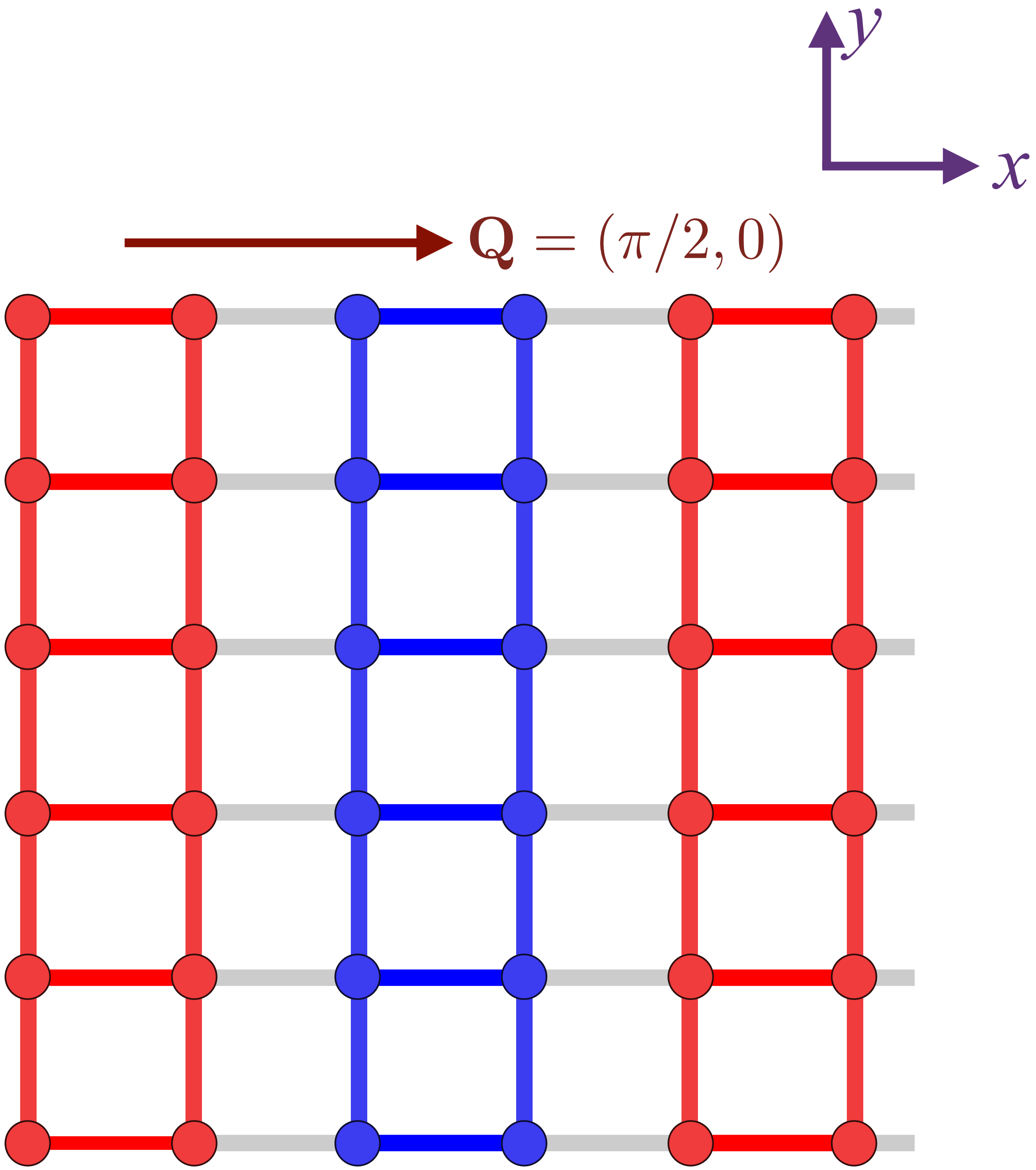
X-ray observations indicate strong s' component in LBCO



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



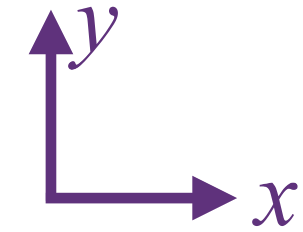
Y. Kohsaka *et al.*, Science **315**, 1380 (2007)



$s + s'$-form factor density wave

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

Unconventional DW order: d-form factor

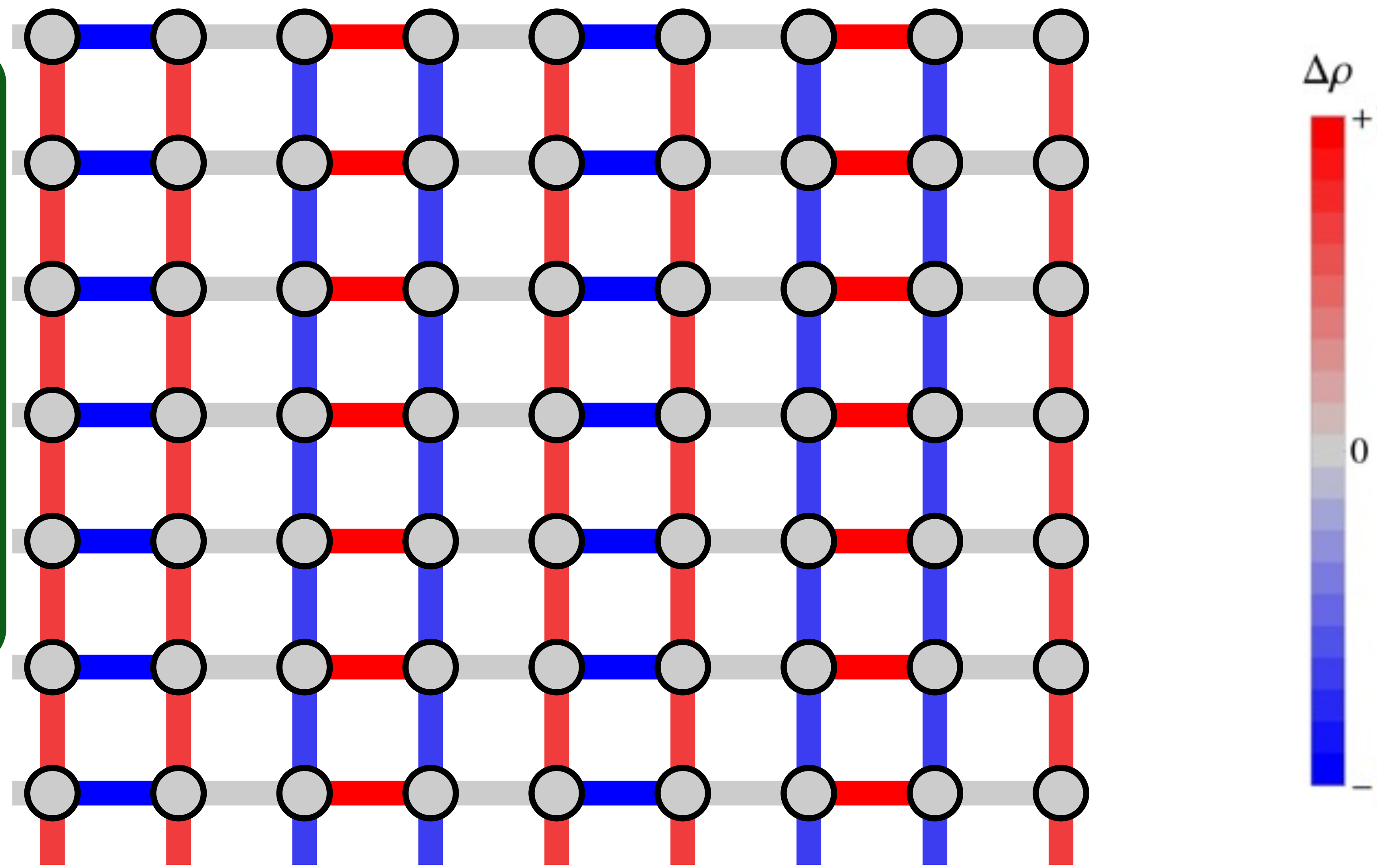


Plot of $P_{ij} = \left\langle c^{\dagger}_{i\alpha} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

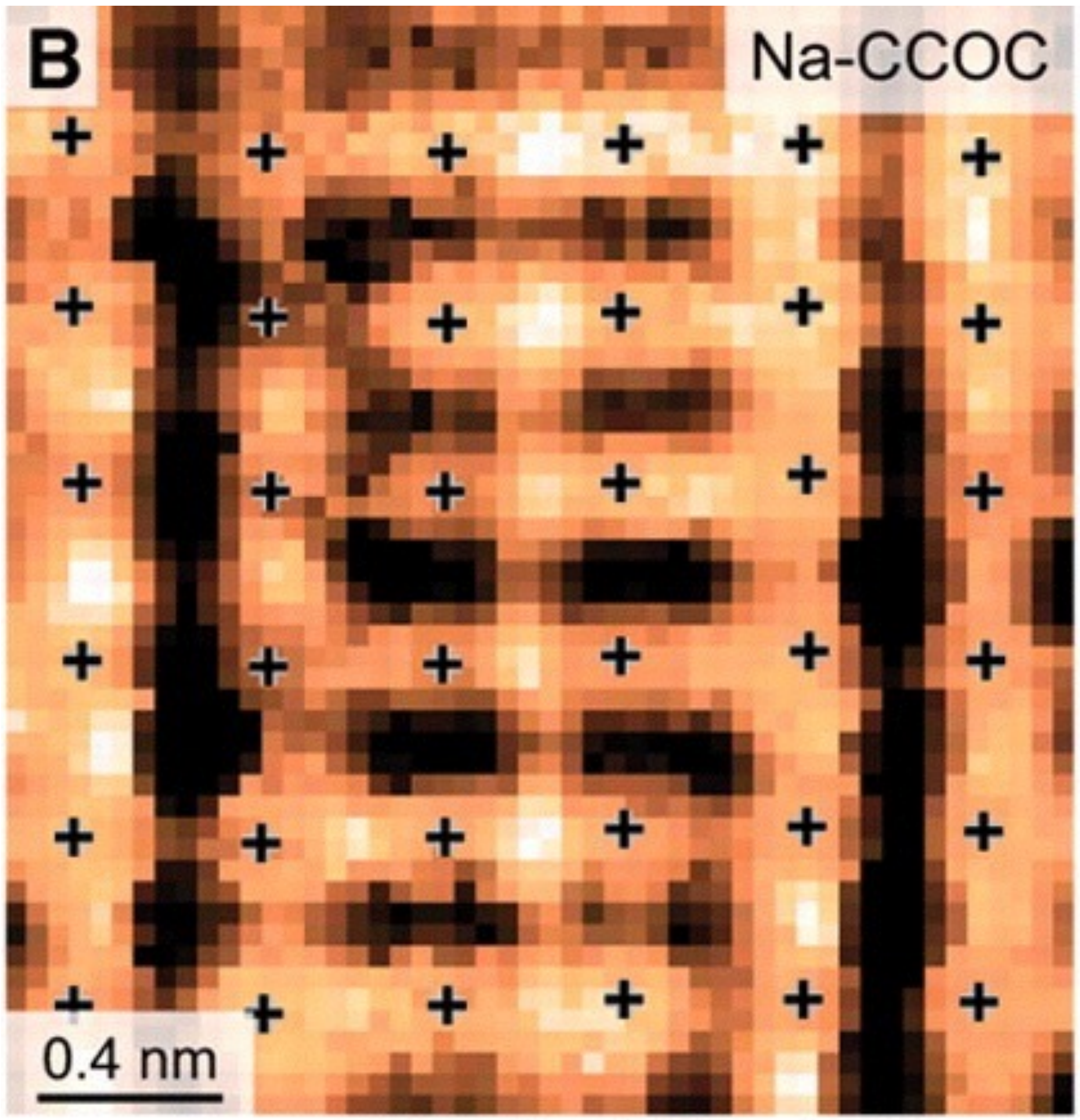
$$\mathcal{P}(\mathbf{k}) = e^{i\phi}\left[\cos(k_x) - \cos(k_y)\right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$

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

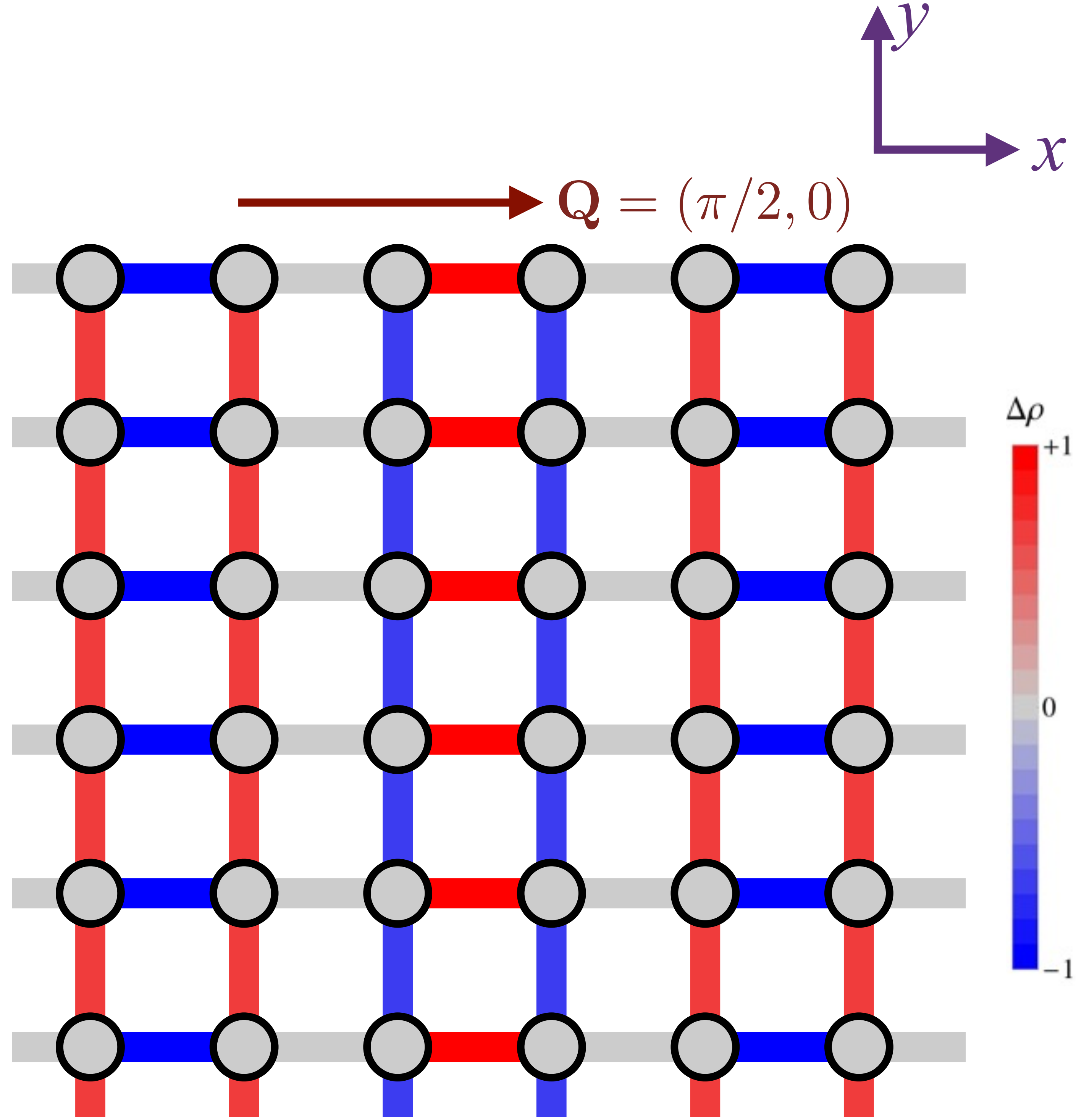


$\mathbf{Q} = (\pi/2, 0)$

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

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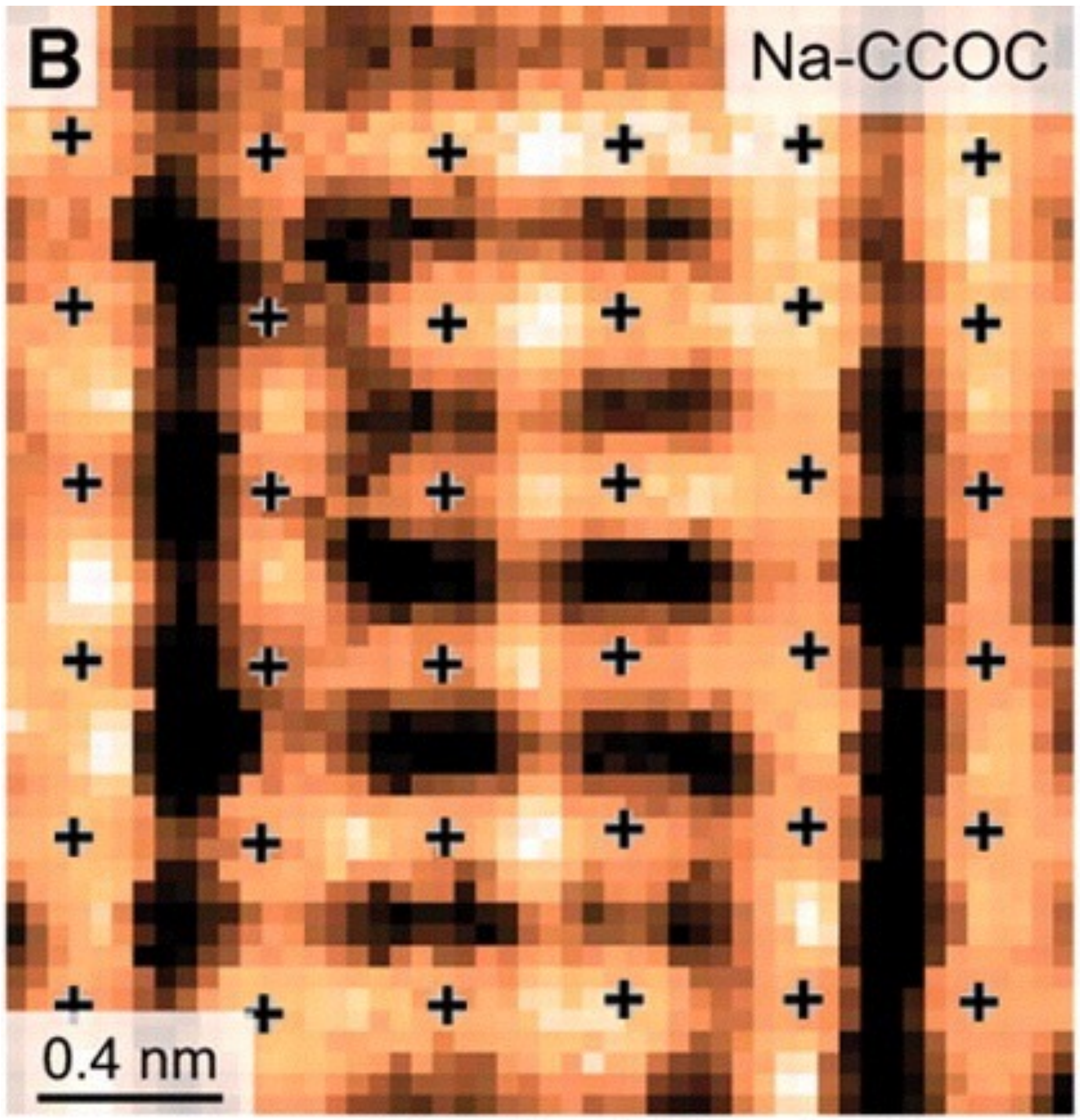
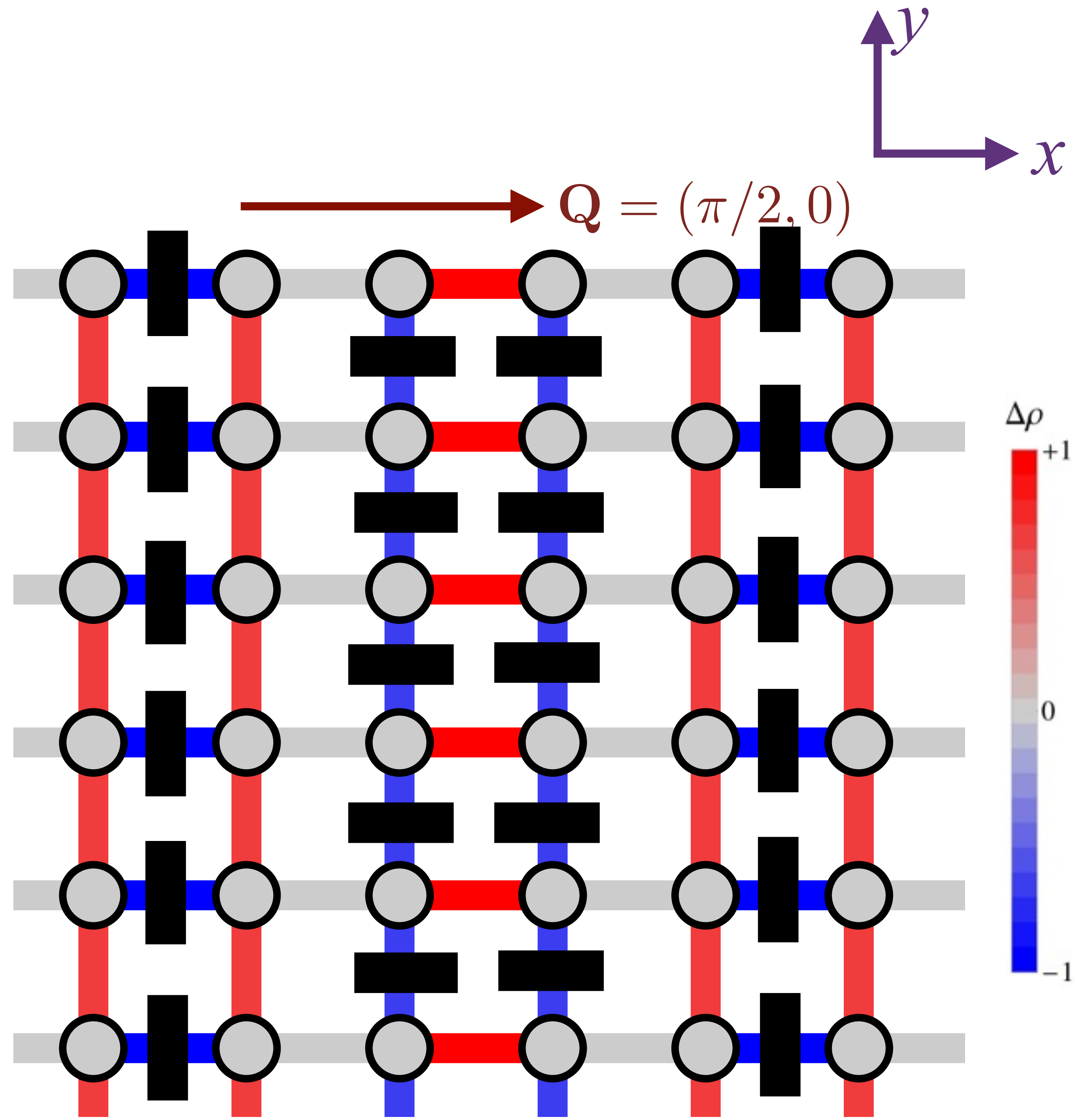


Y. Kohsaka *et al.*, Science **315**, 1380 (2007)



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]

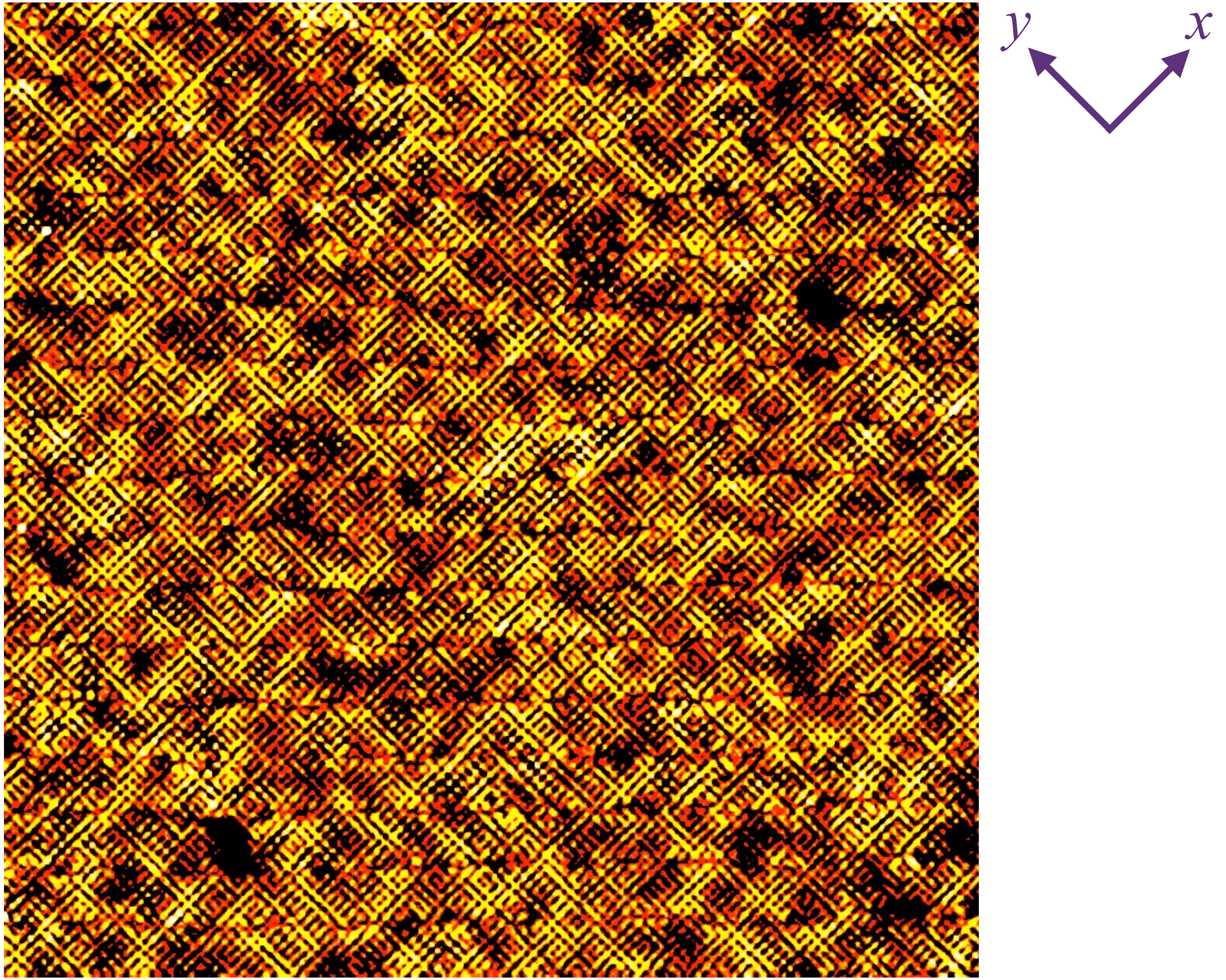
The identity of the fundamental broken symmetry (if any) in the underdoped cuprates is unresolved. However, evidence has been accumulating that this state may be an unconventional density wave. Here we carry out site-specific measurements within each CuO_2 unit cell, segregating the results into three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

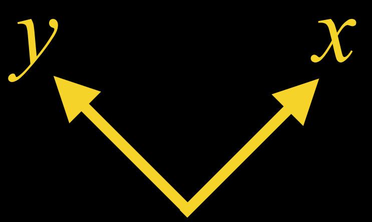
W. D. Wise, M. C. Boyer, K. Chatterjee, T. Kondo, T. Takeuchi, H. Ikuta, Y. Wang, and E. W. Hudson, Nature Phys. **4**, 696 (2008).



"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.

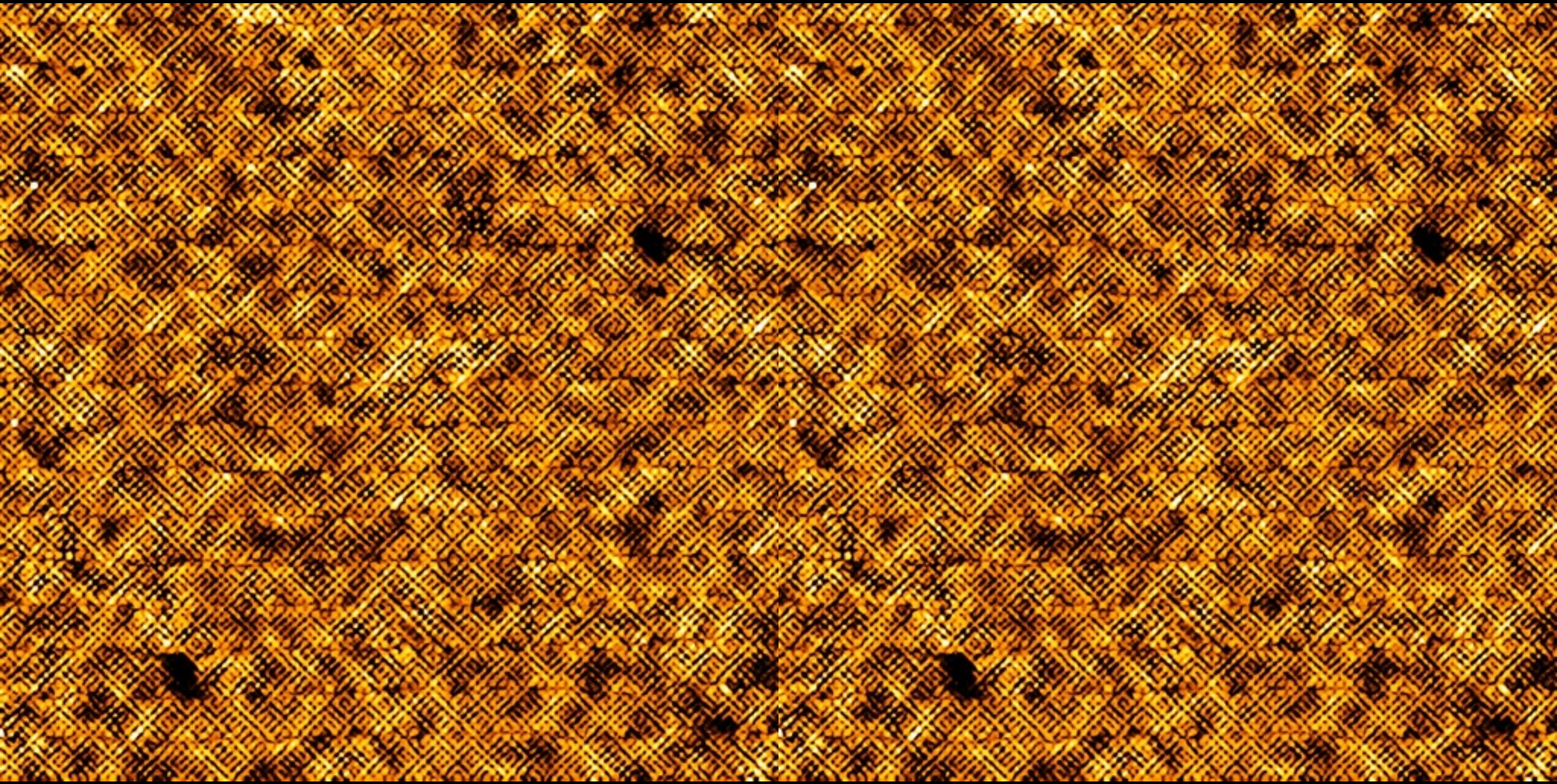
UD45K
BSCCO

R(r,150mV)



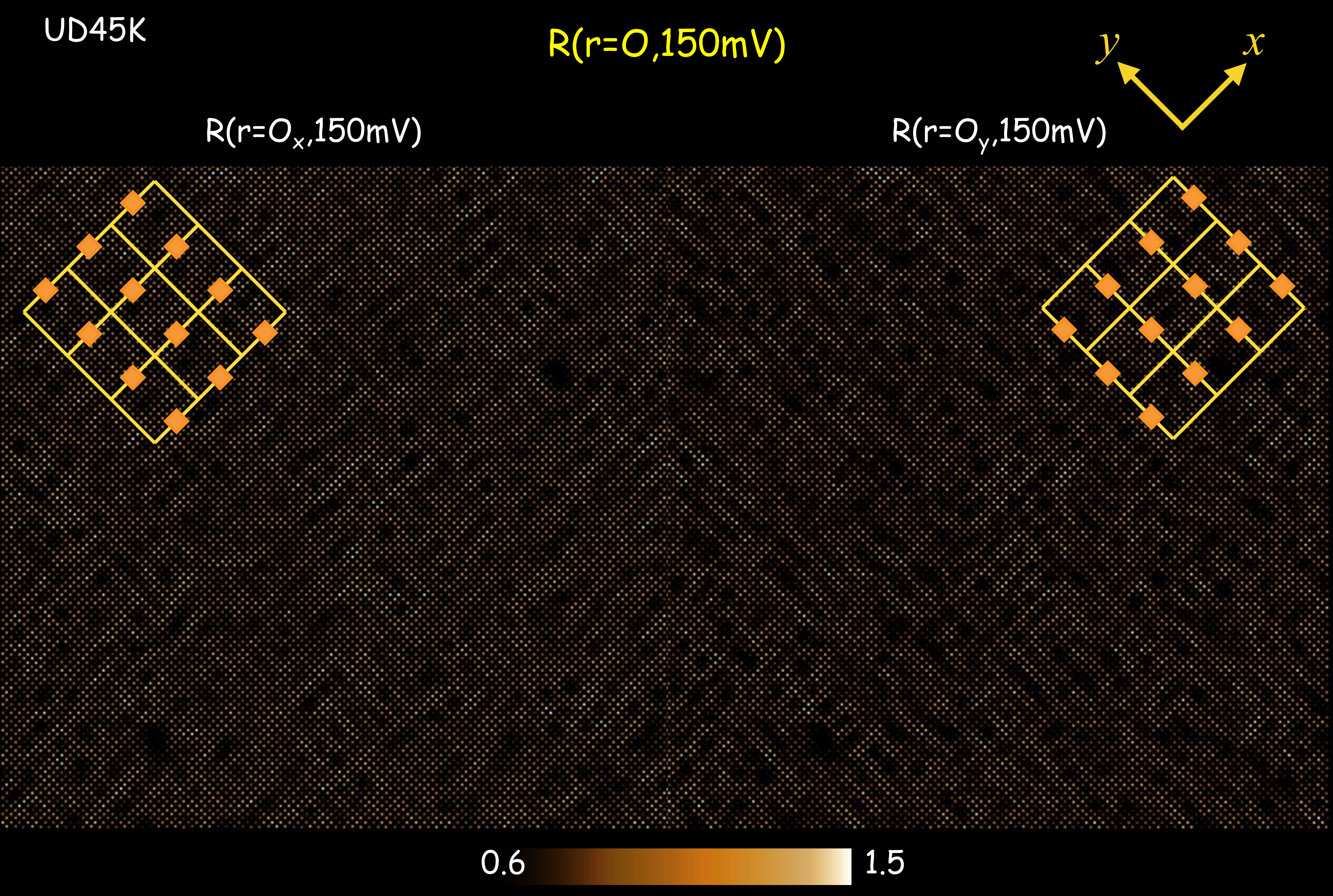
R(r,150mV)

R(r,150mV)



Note that these are identical images.

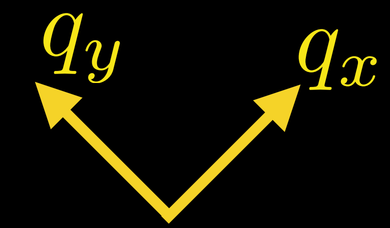
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

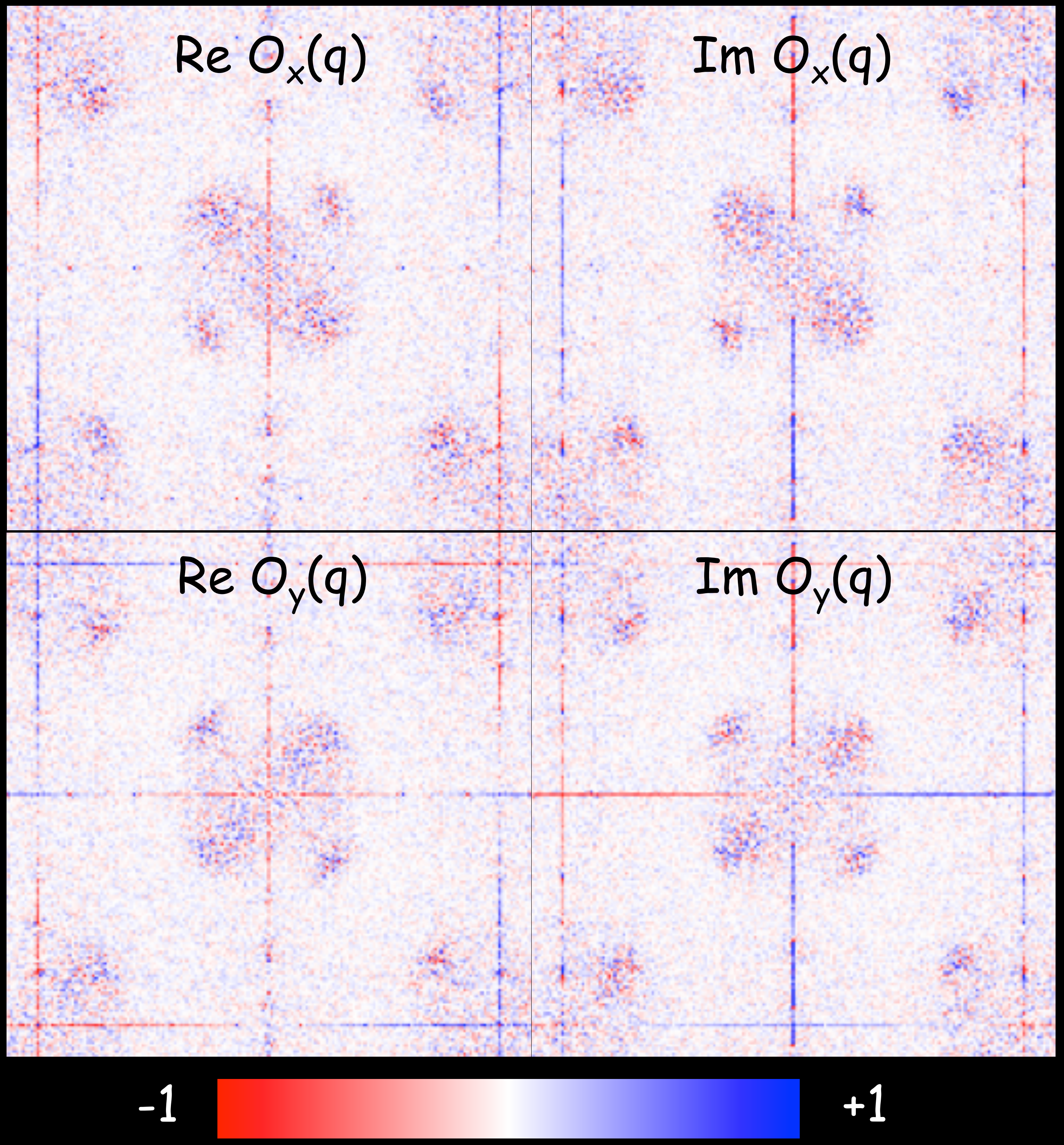


K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

UD45K

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





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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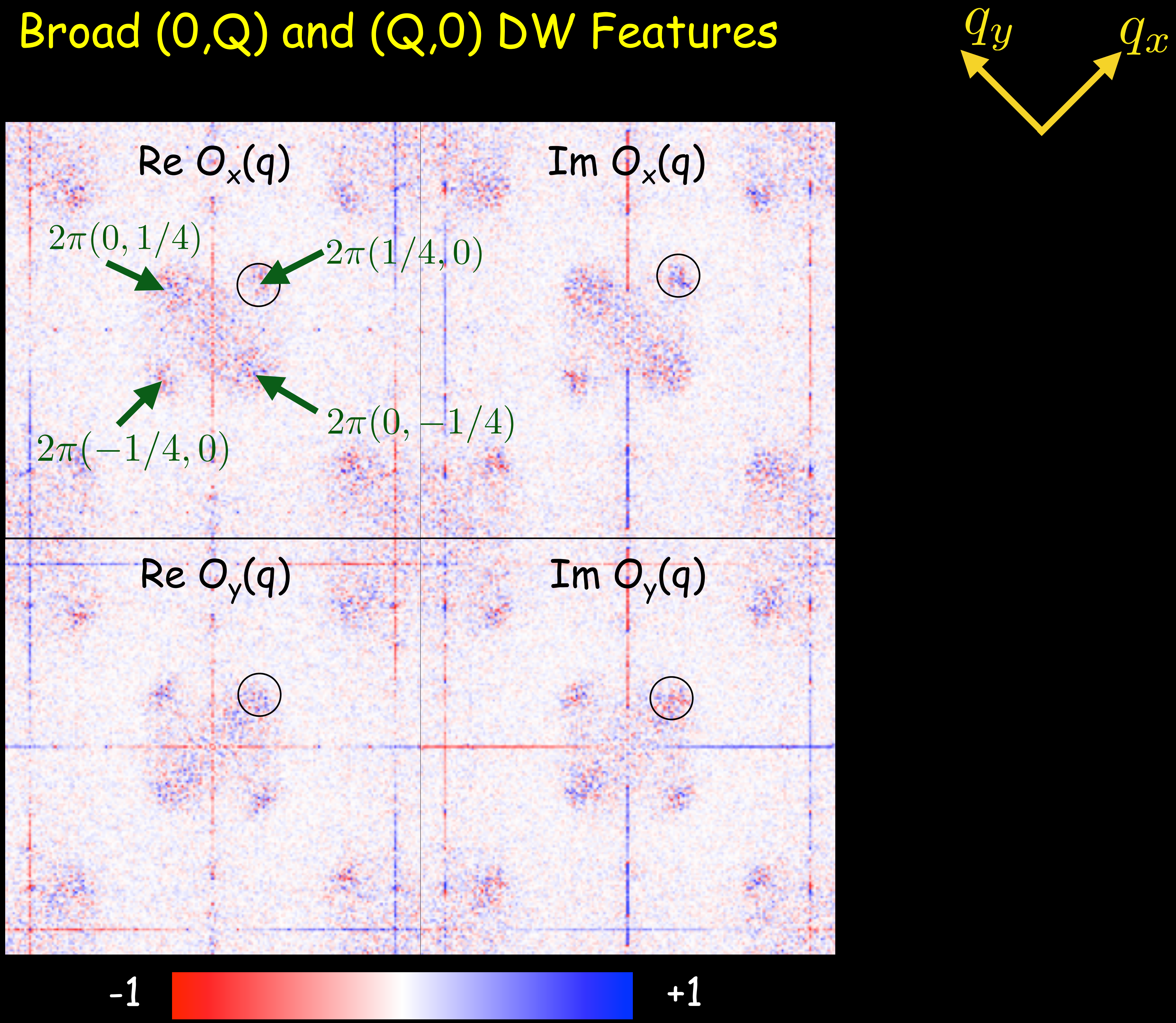

K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

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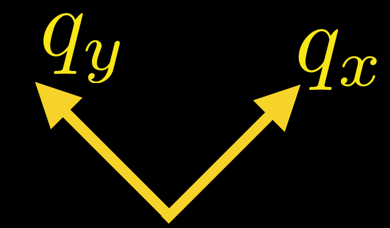
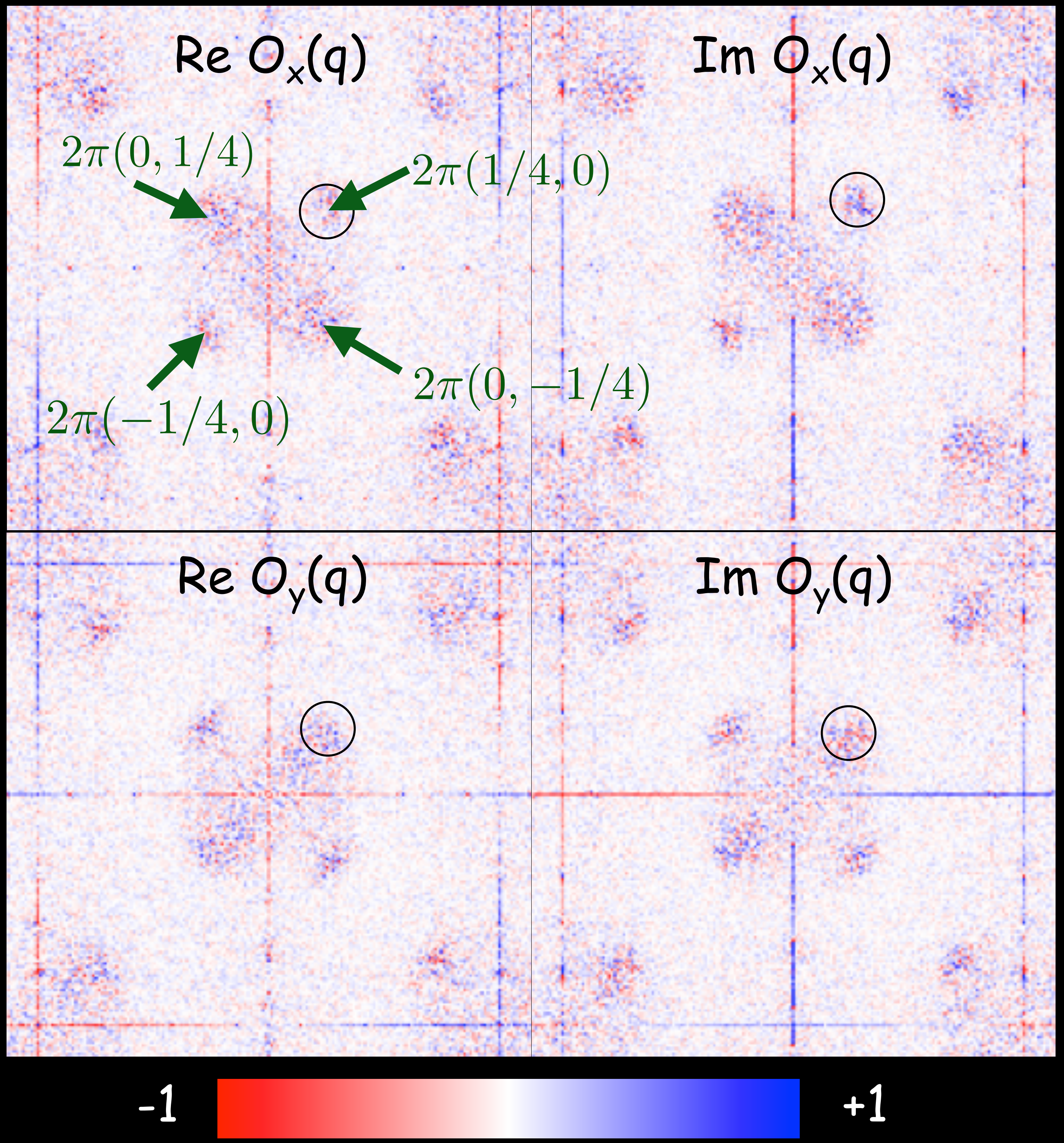
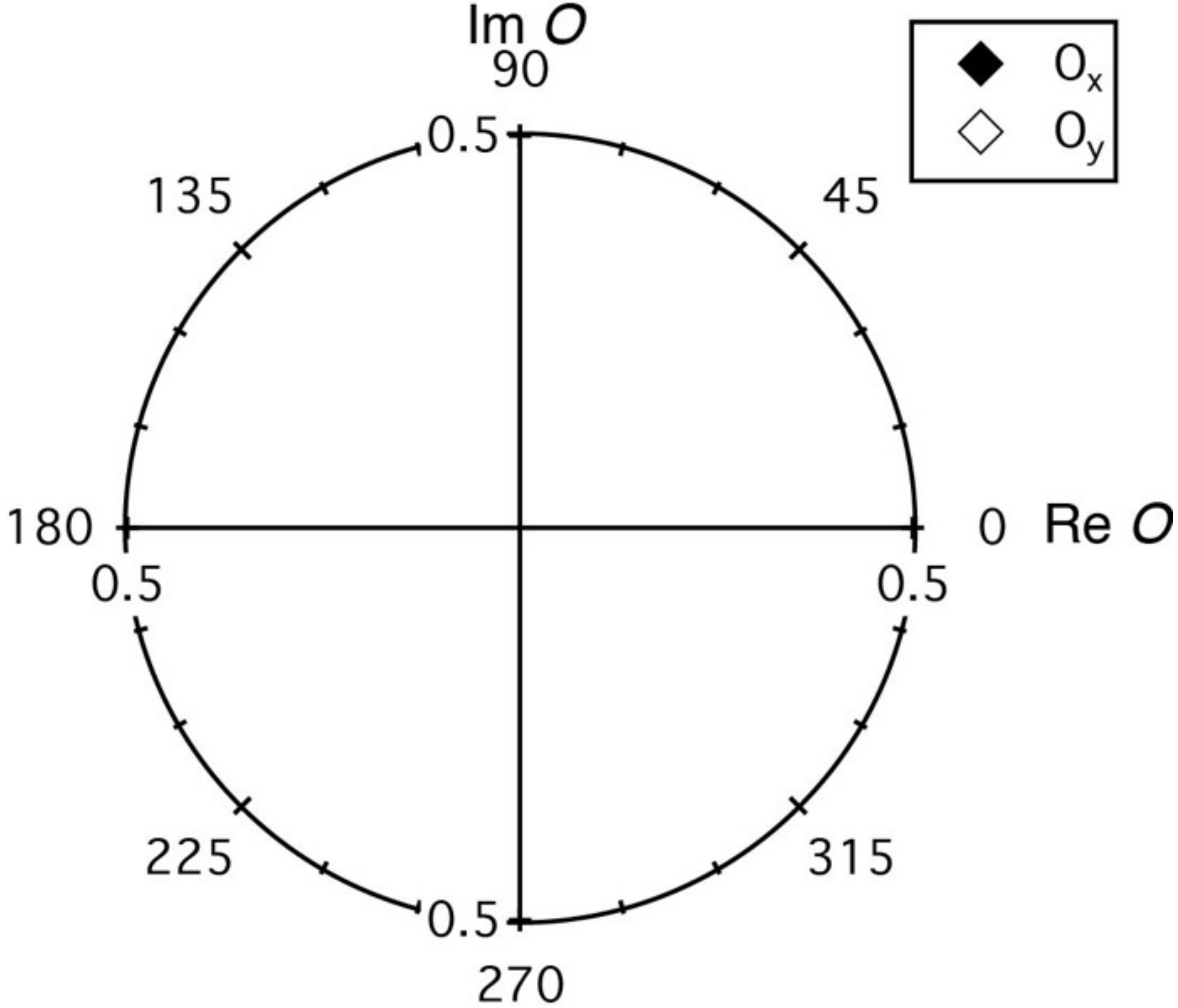


For each pixel in the circles, we obtain 2 complex numbers, $O_x(q)$ and $O_y(q)$.



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)



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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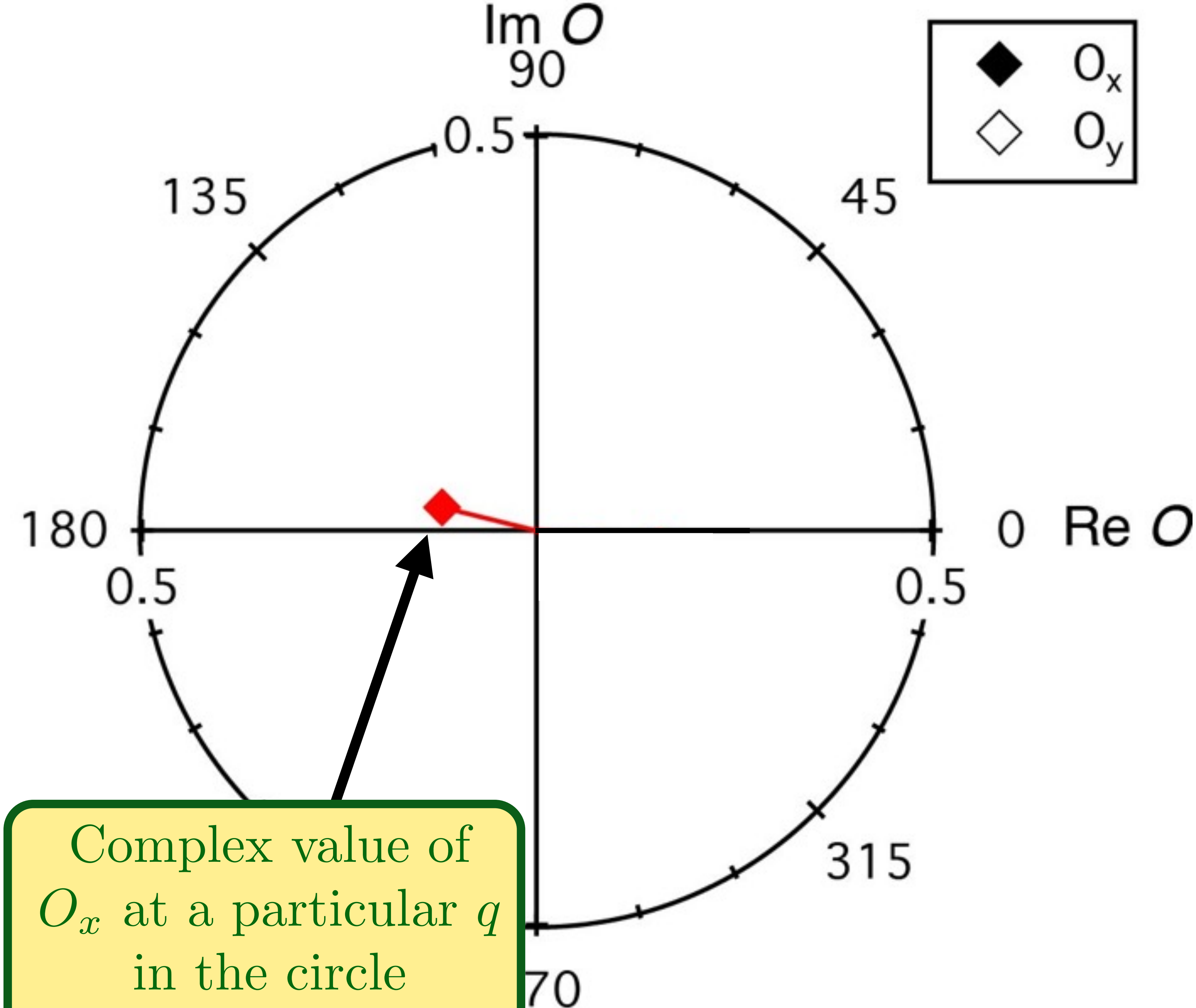

Complex value of O_x at a particular q in the circle around $2\pi(1/4, 0)$.

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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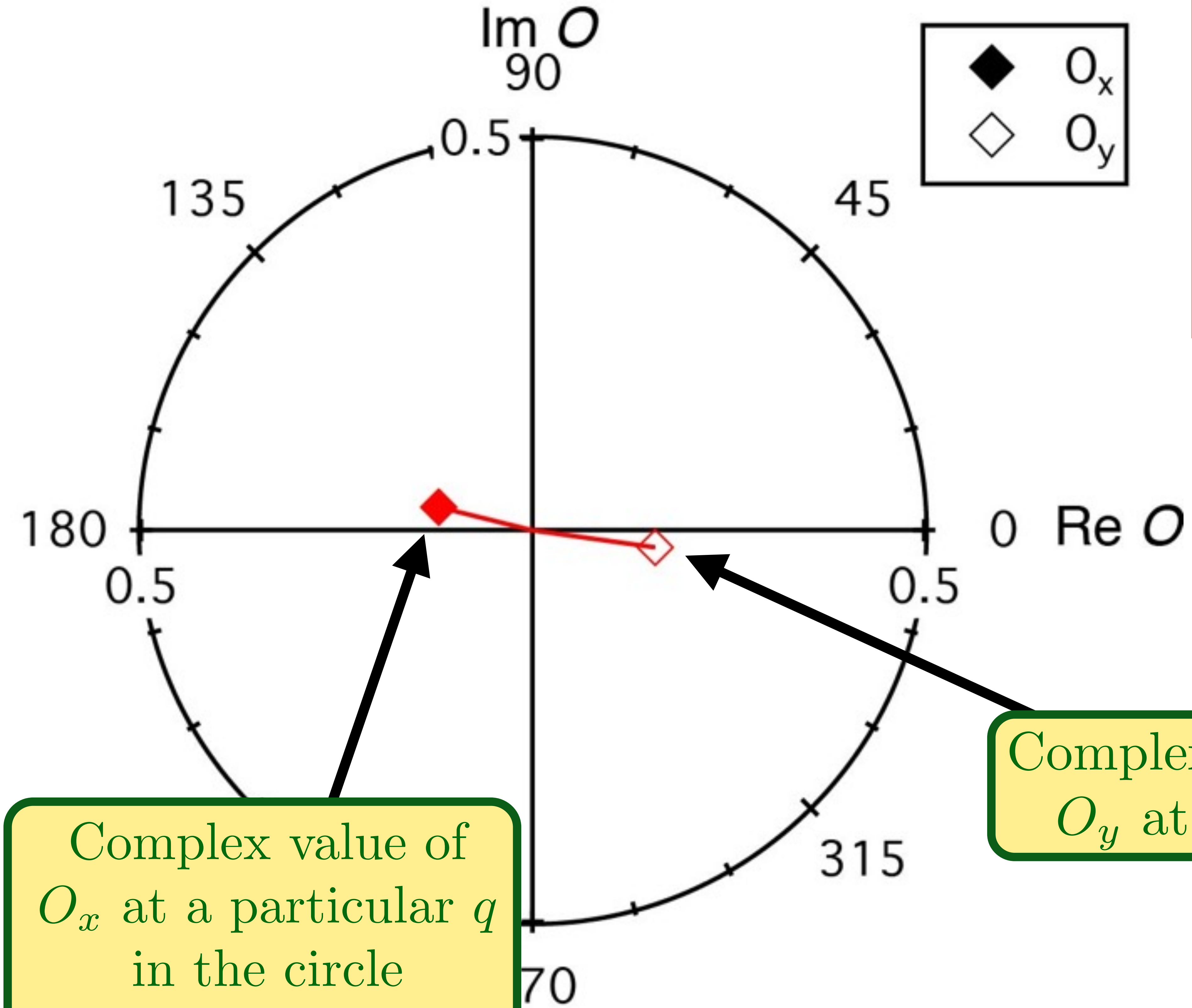

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Complex value of O_y at <u>same</u> q

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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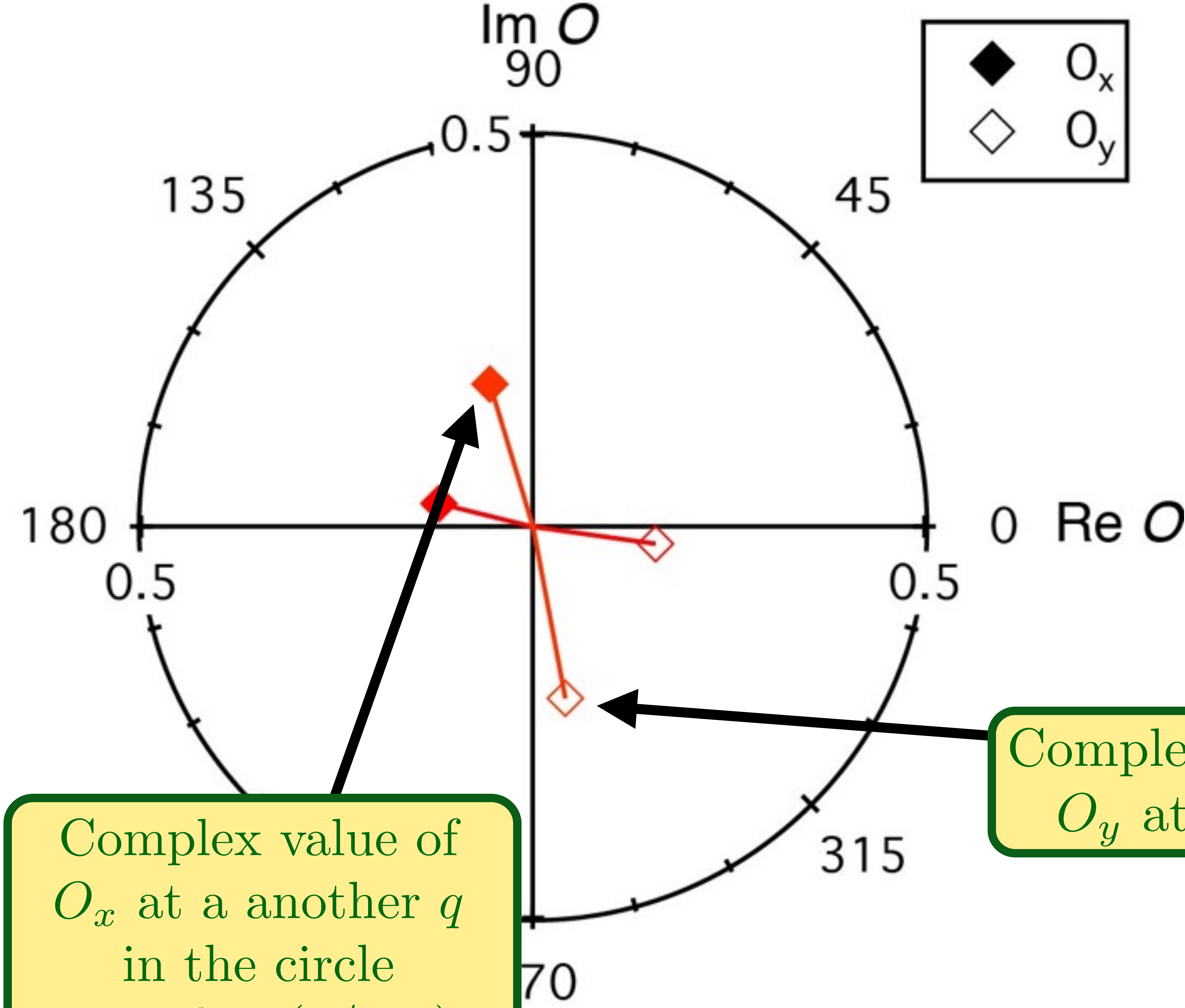
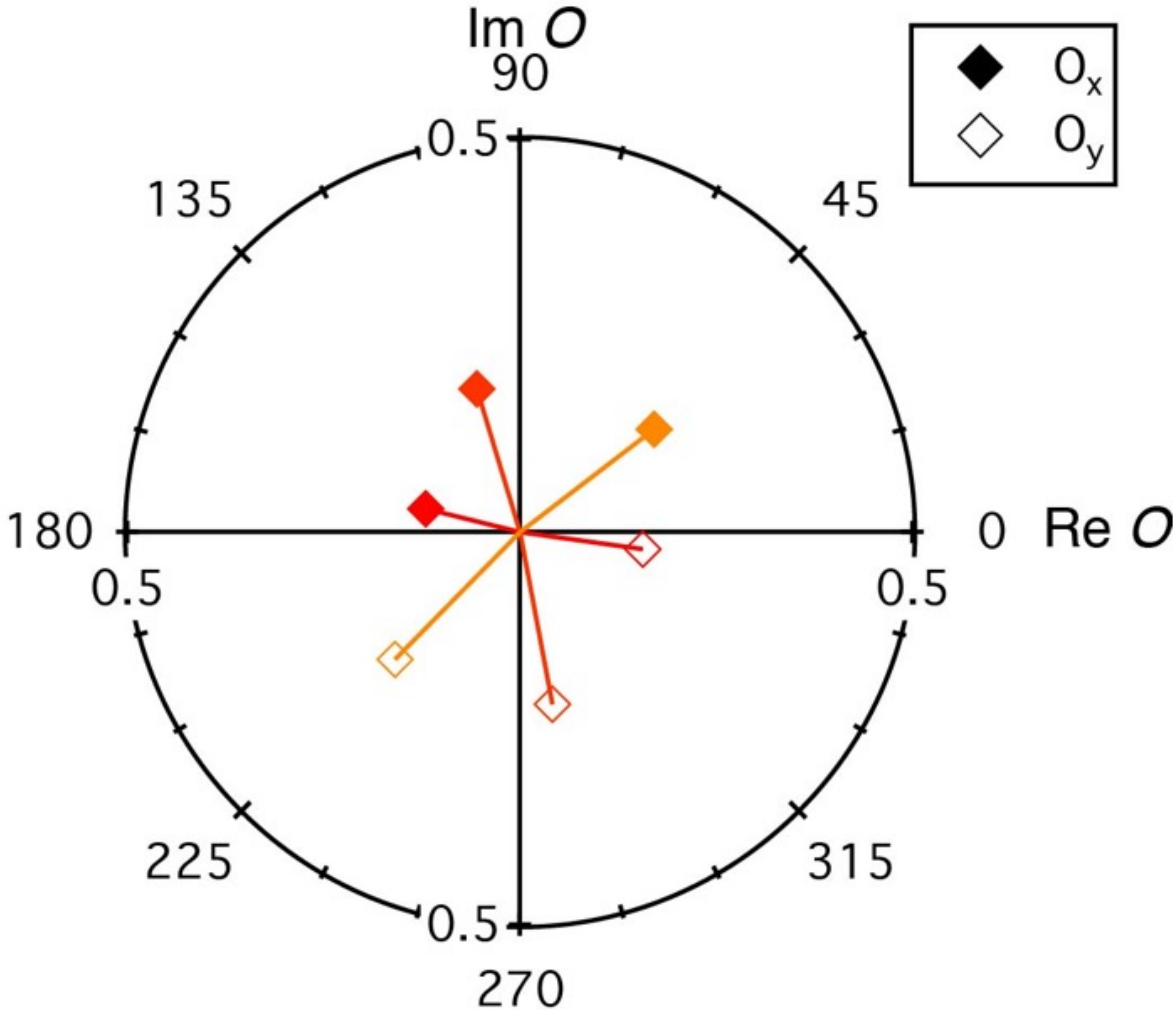


Complex value of O_x at a another q in the circle around $2\pi(1/4, 0)$.

Complex value of O_y at same 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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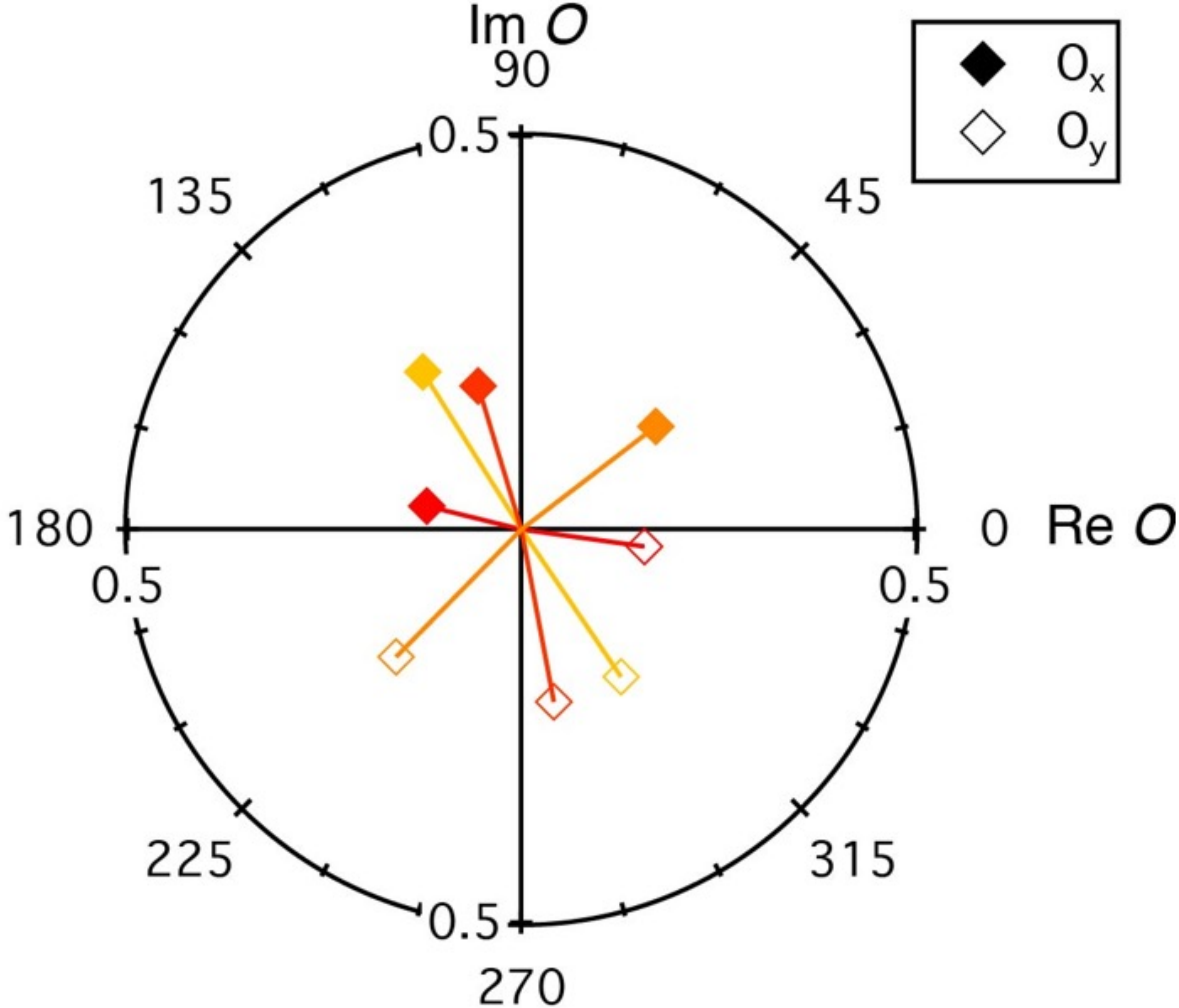

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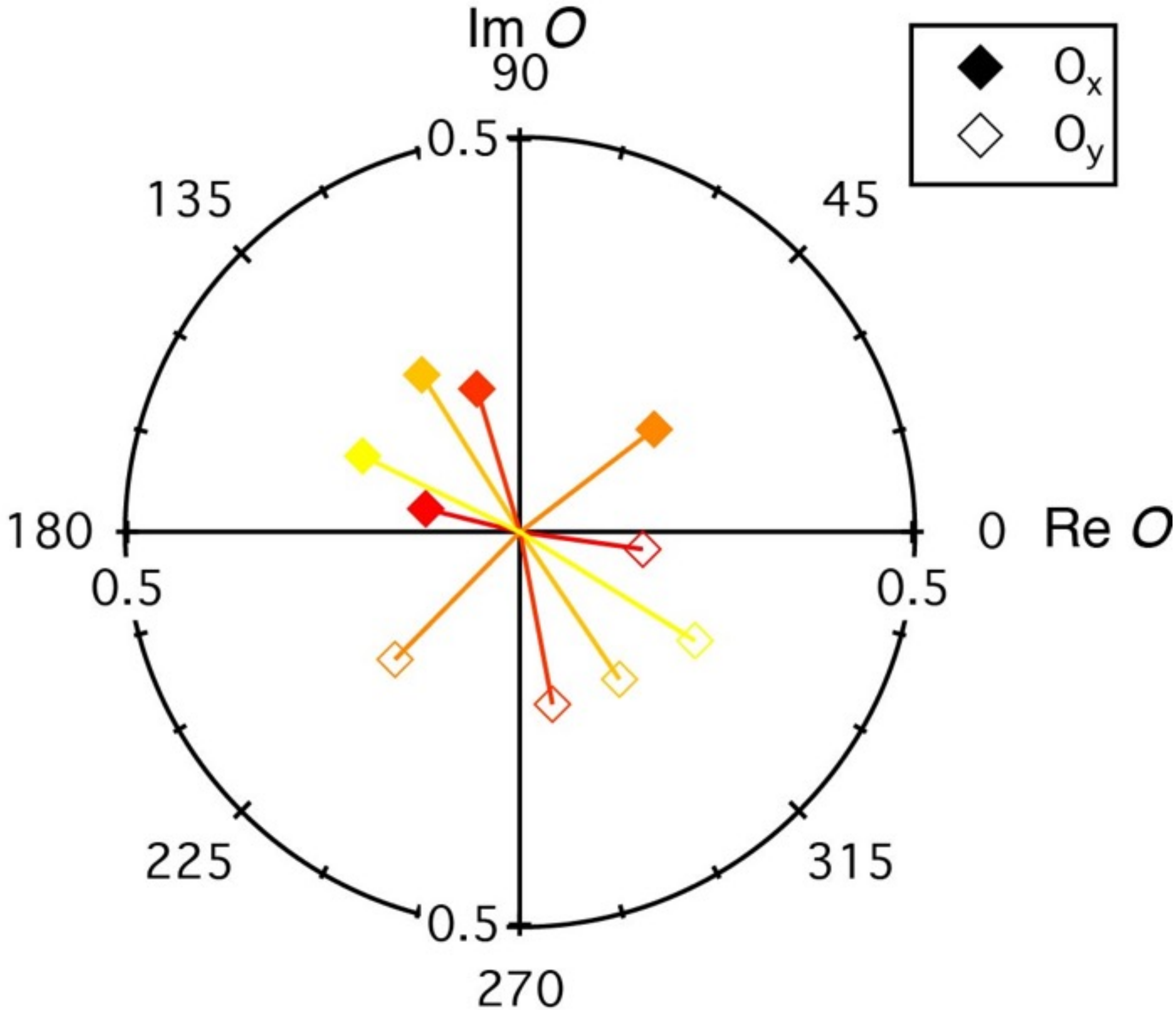

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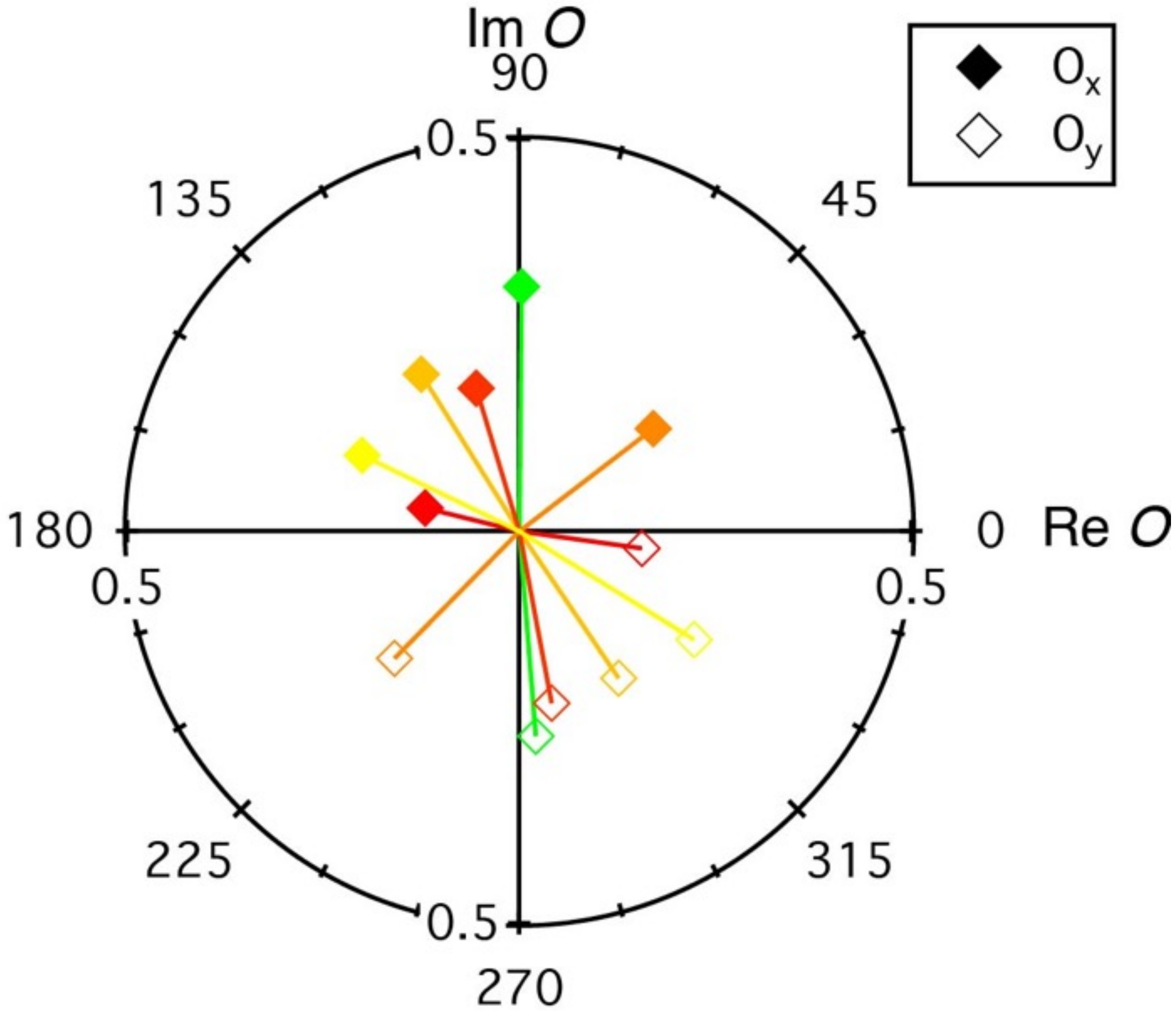

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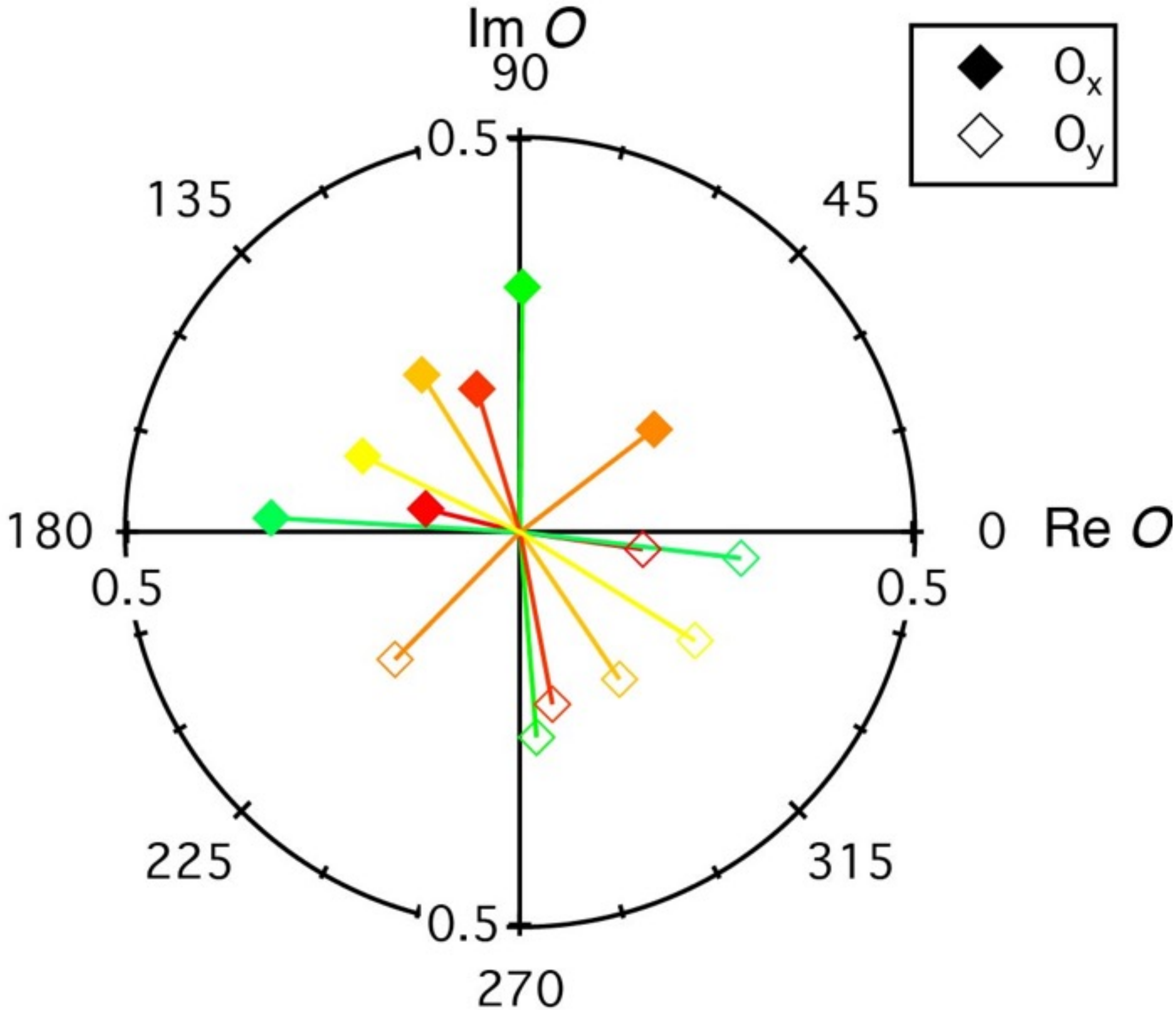

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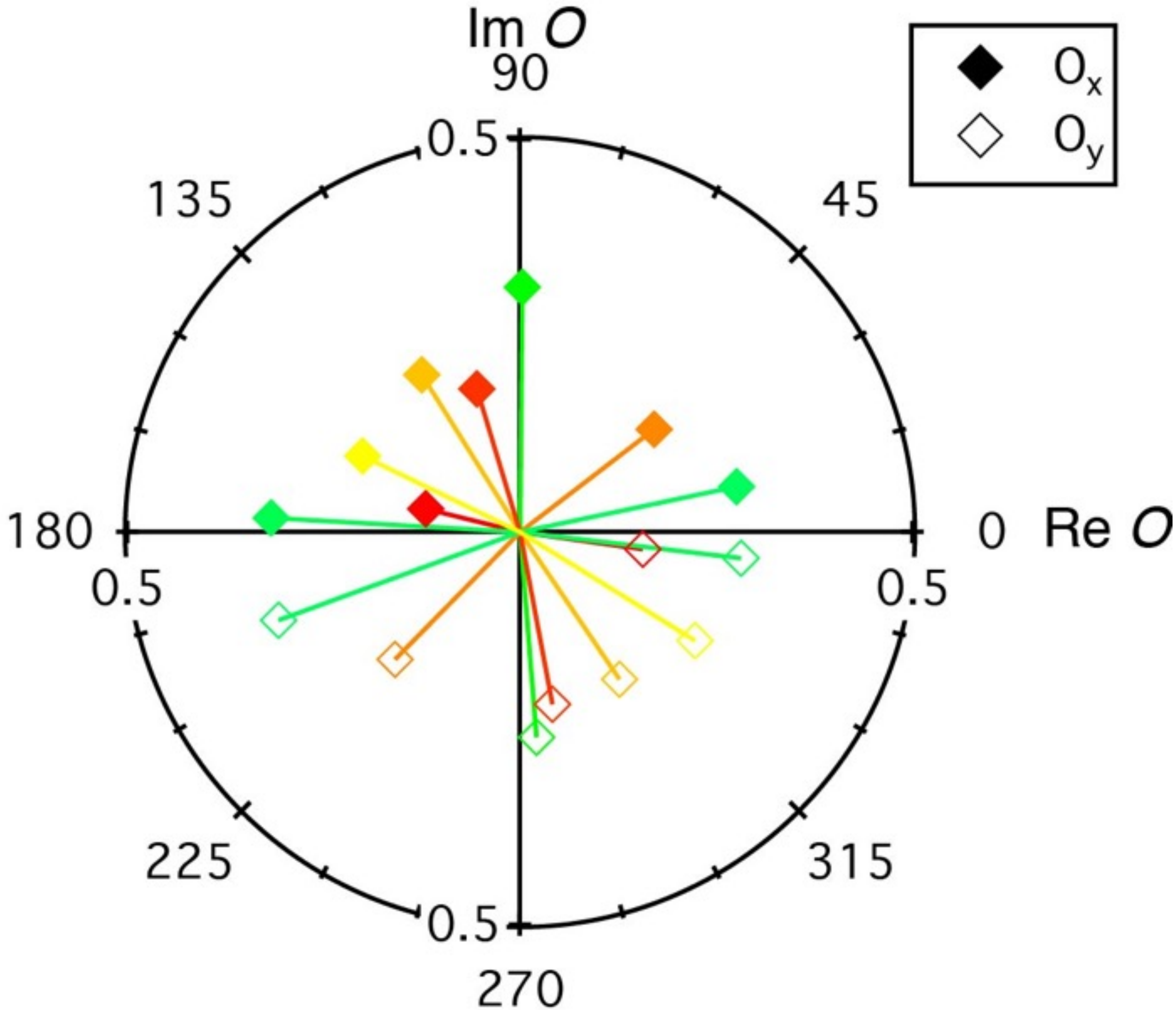

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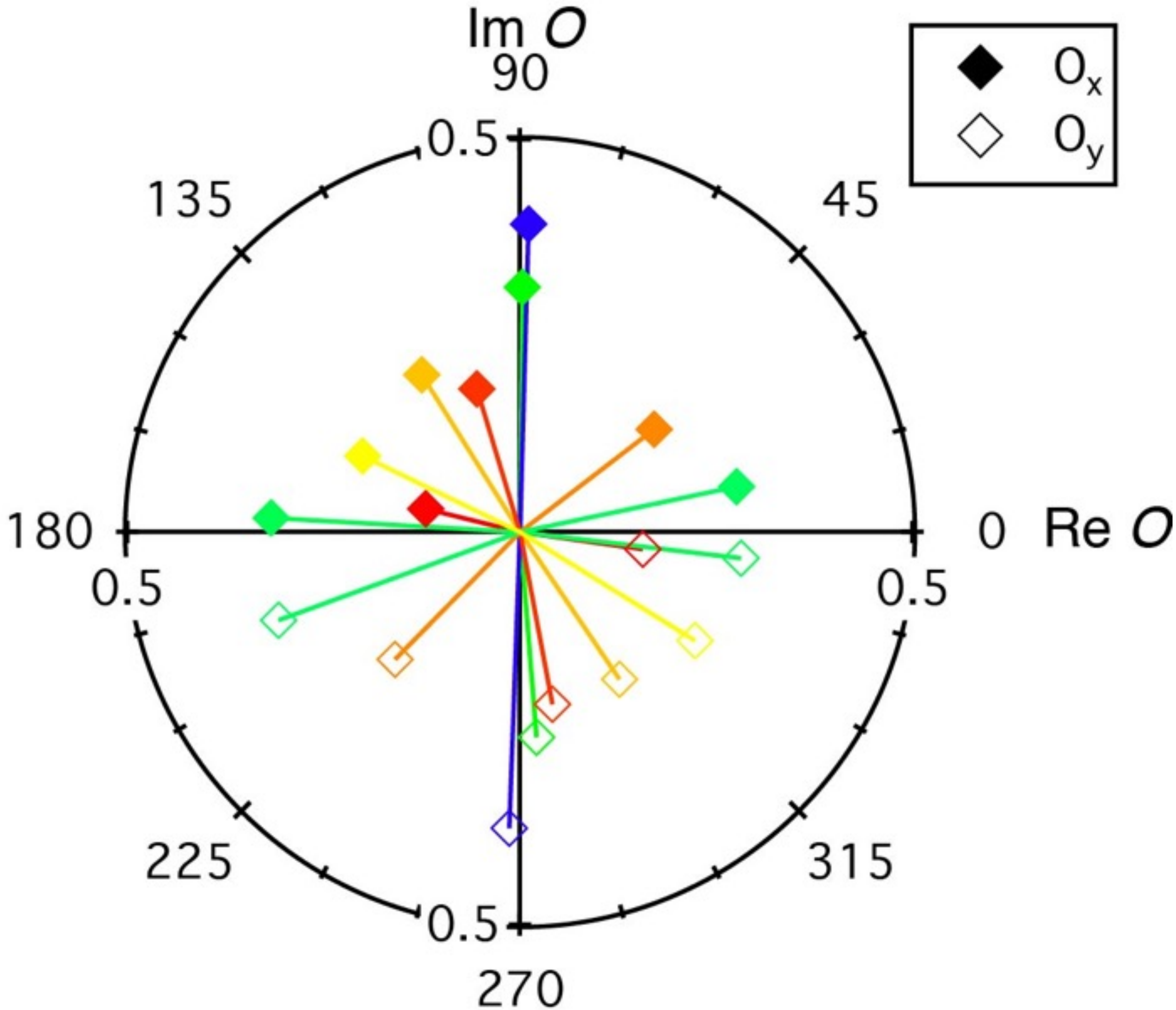

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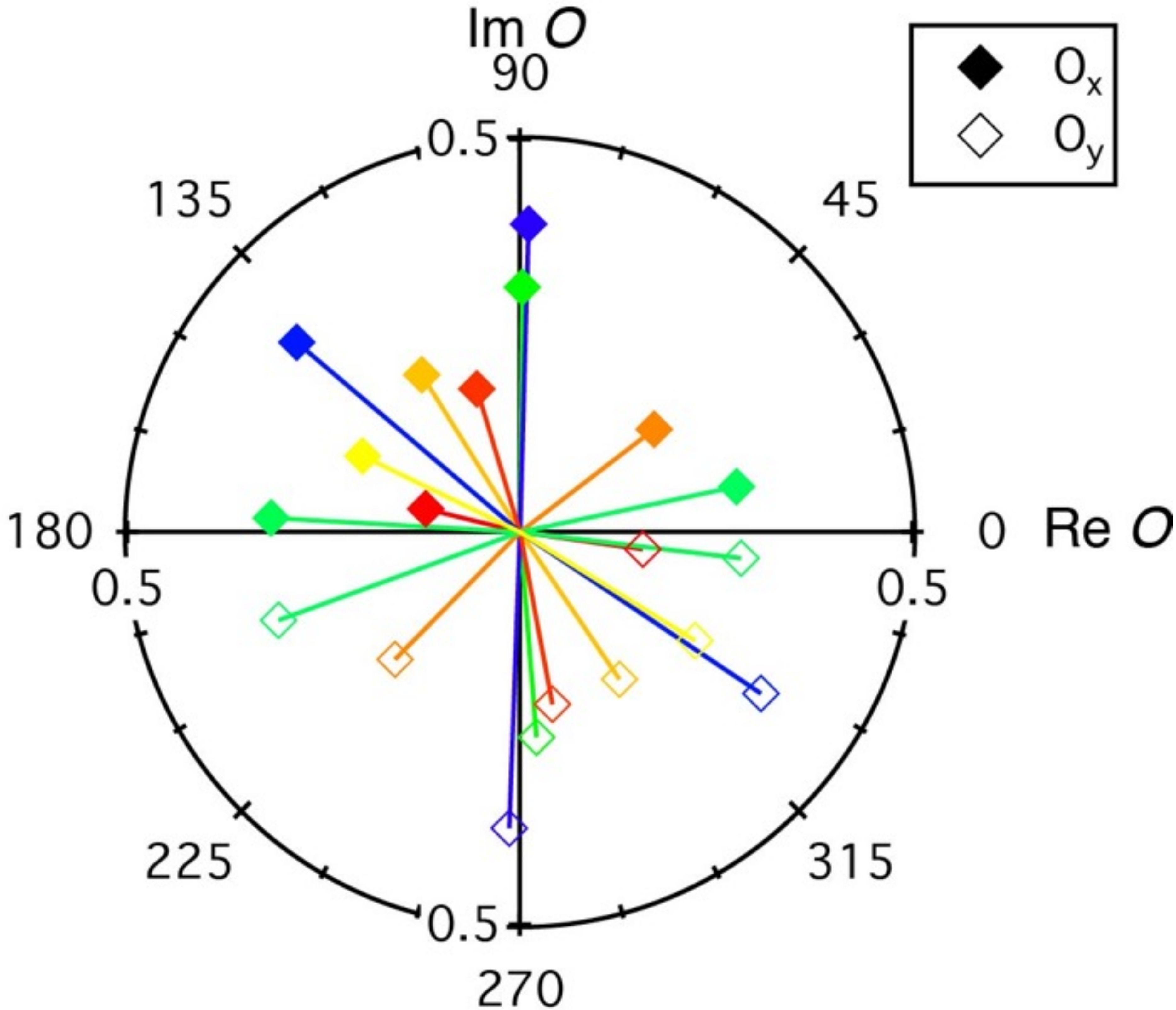

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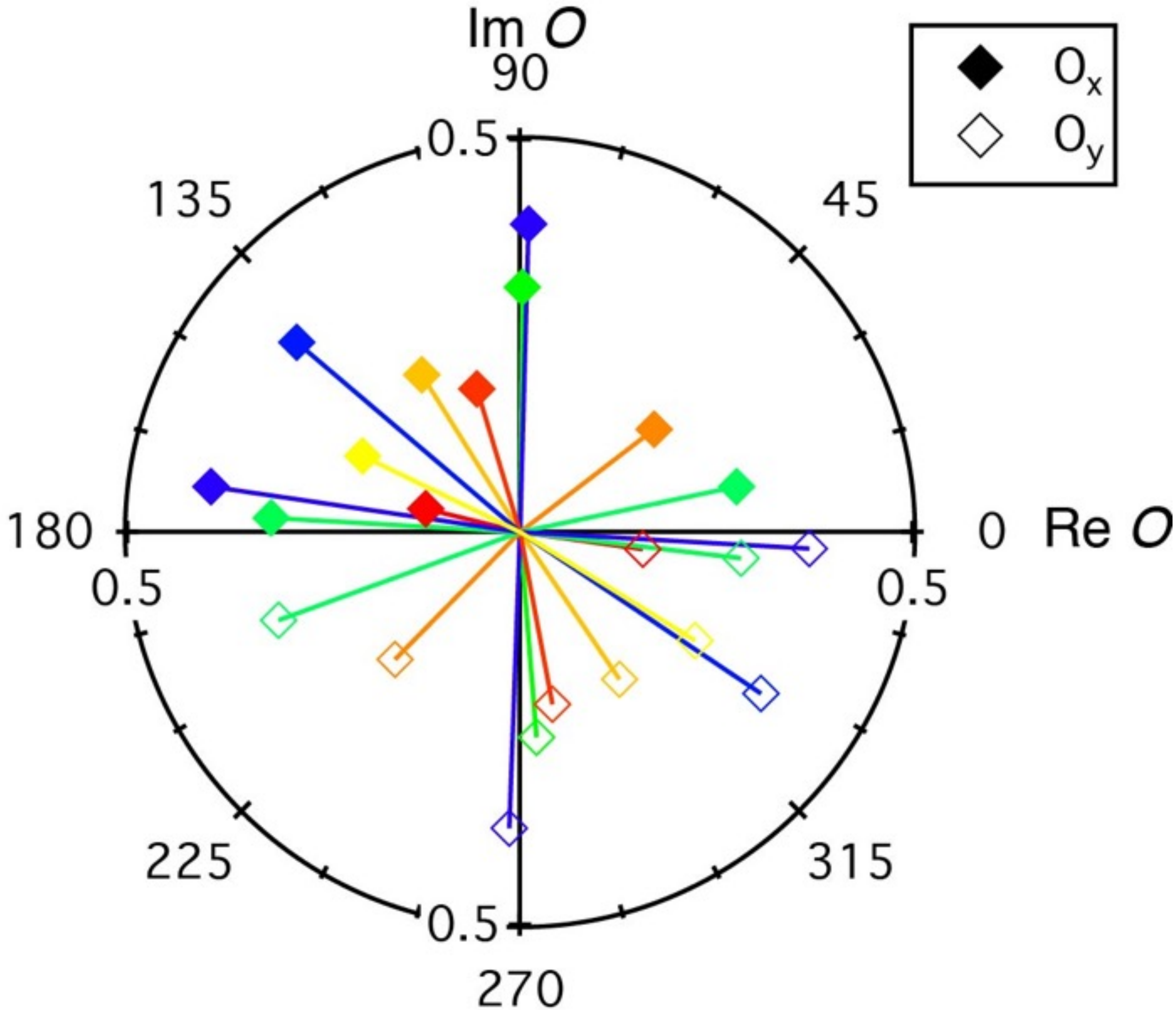

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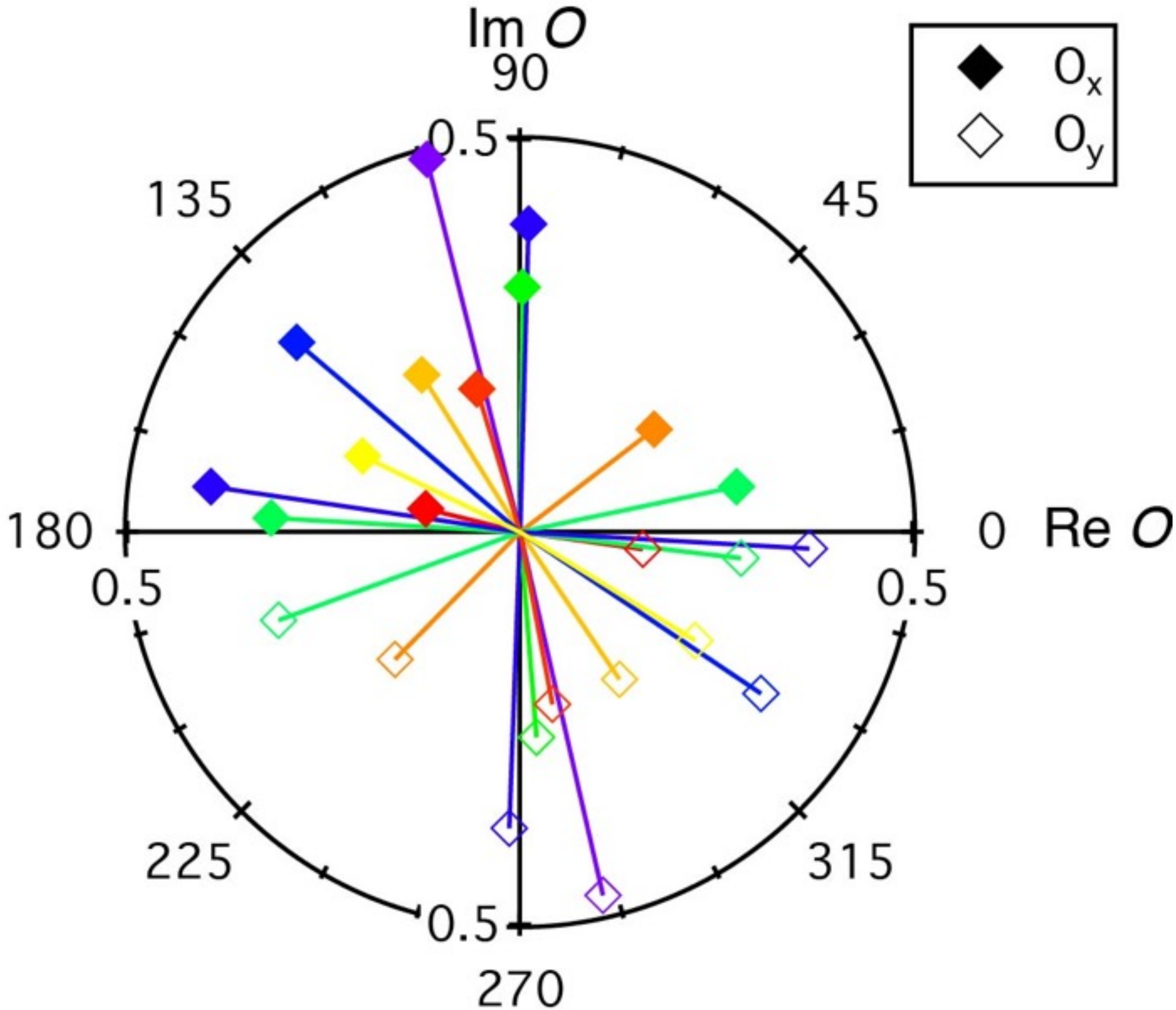

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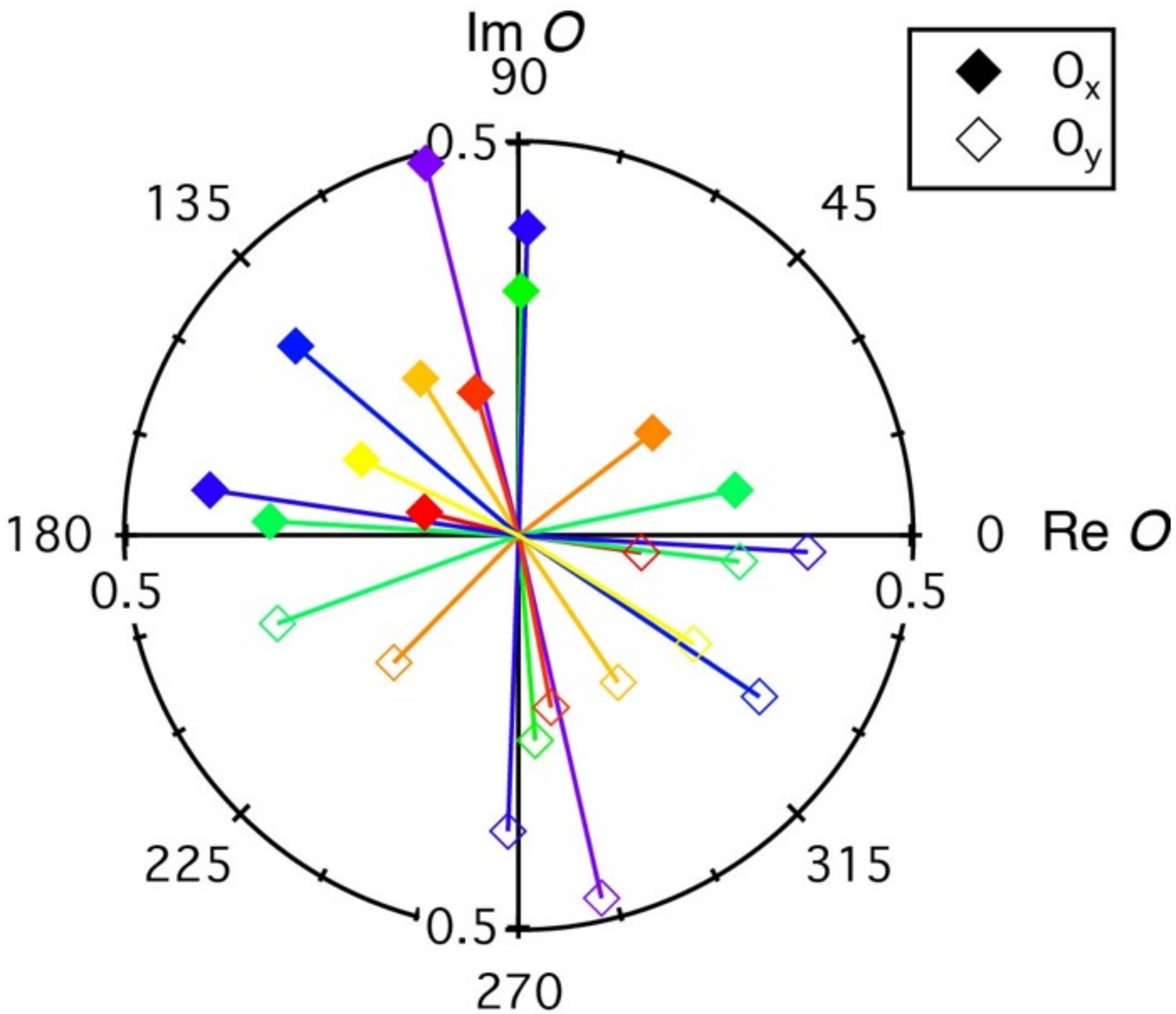

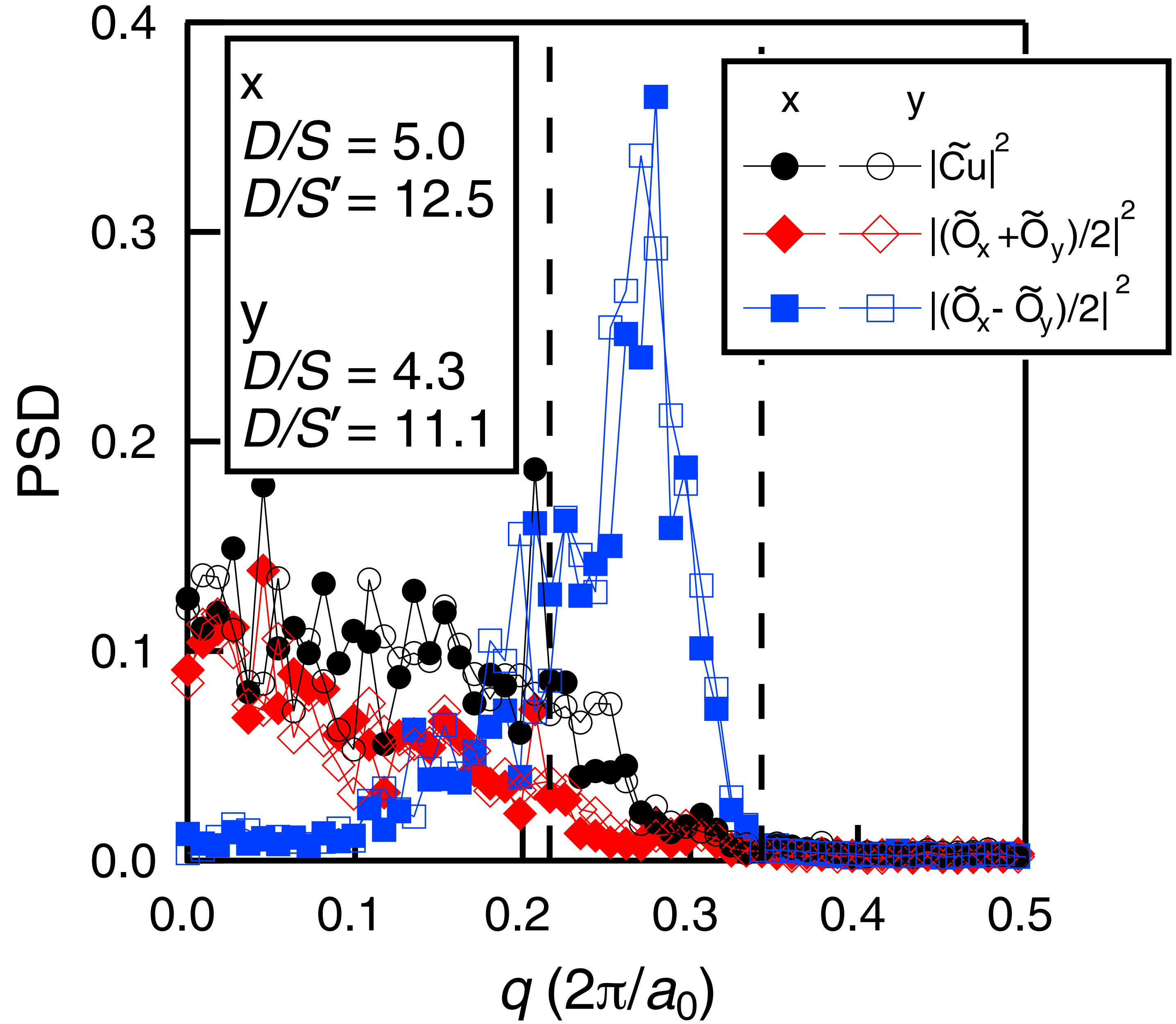

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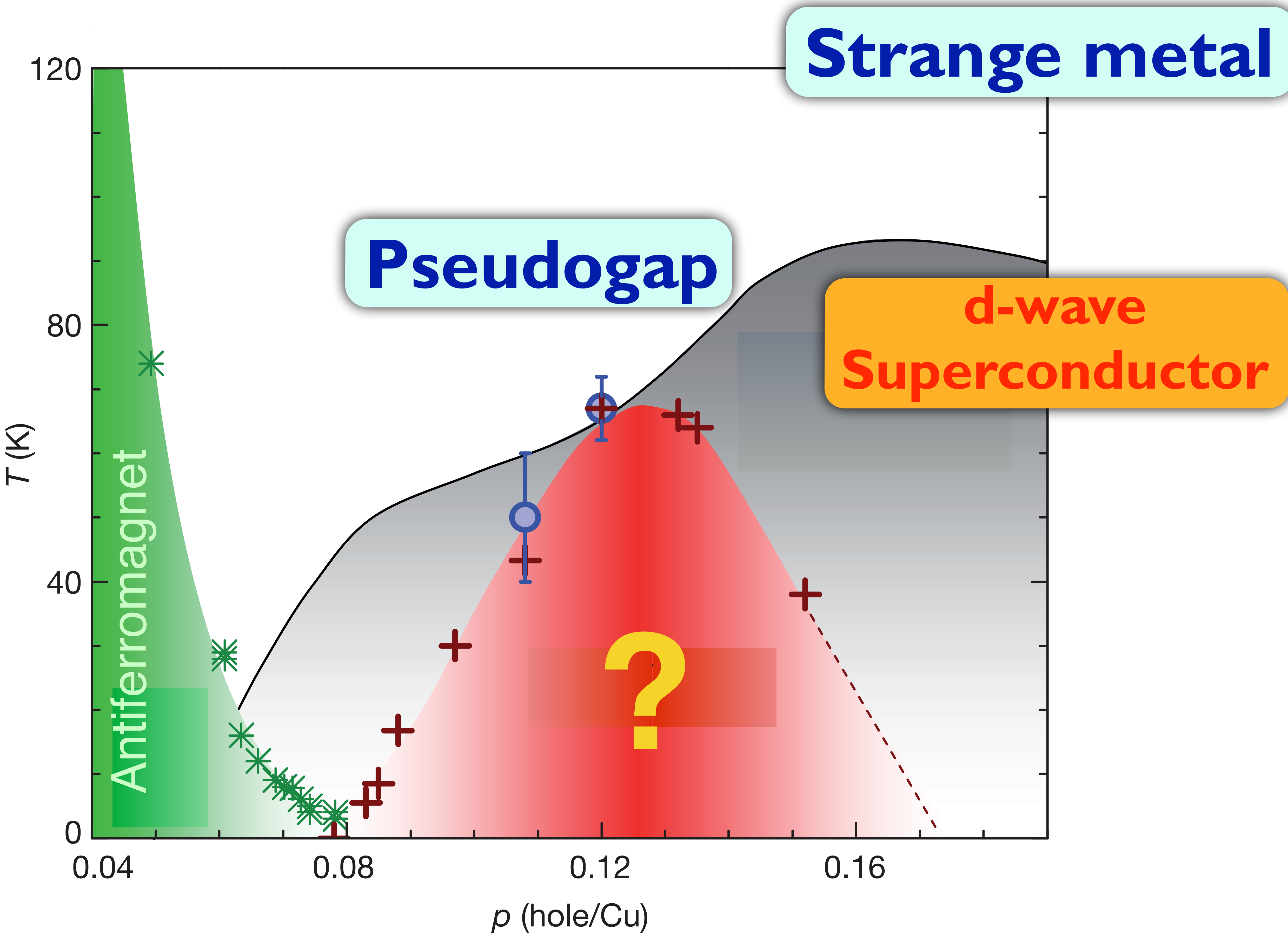
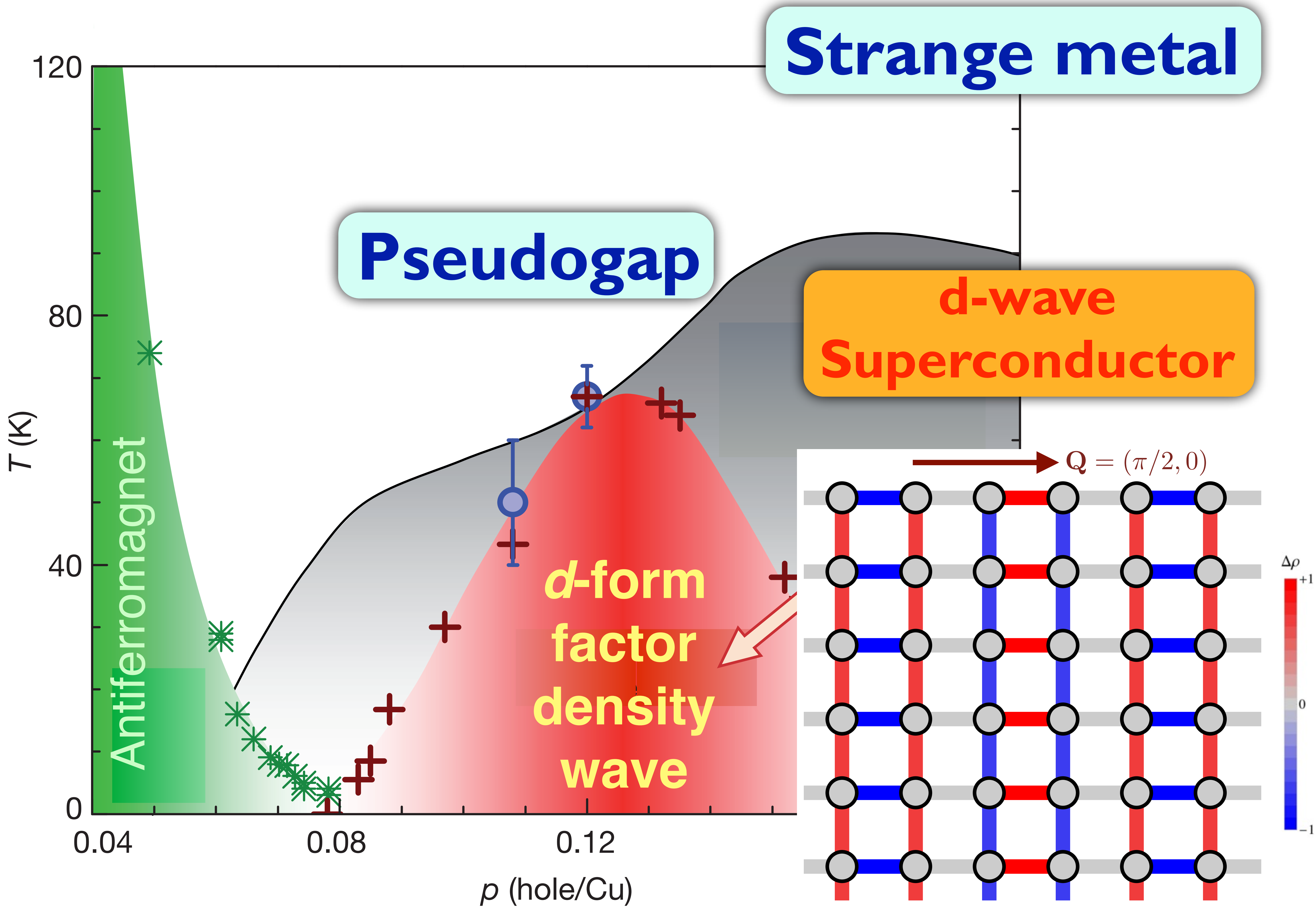

Strange metal
Pseudogap
d-wave
Superconductor
Antiferromagnet
?
120
80
40
0
T (K)
0.04
0.08
0.12
0.16
p (hole/Cu)



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Outline

1. Density waves in the underdoped cuprates

   STM observation of d-form factor density wave

2. RPA theory of density waves

3. Fractionalized Fermi liquids (FL*) in doped square lattice antiferromagnets

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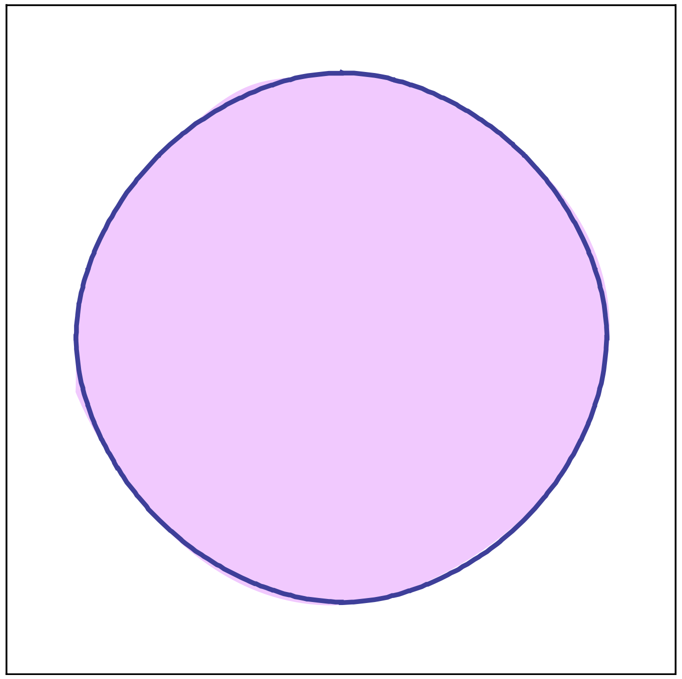
3. Fractionalized Fermi liquids (FL*) in doped square lattice antiferromagnets

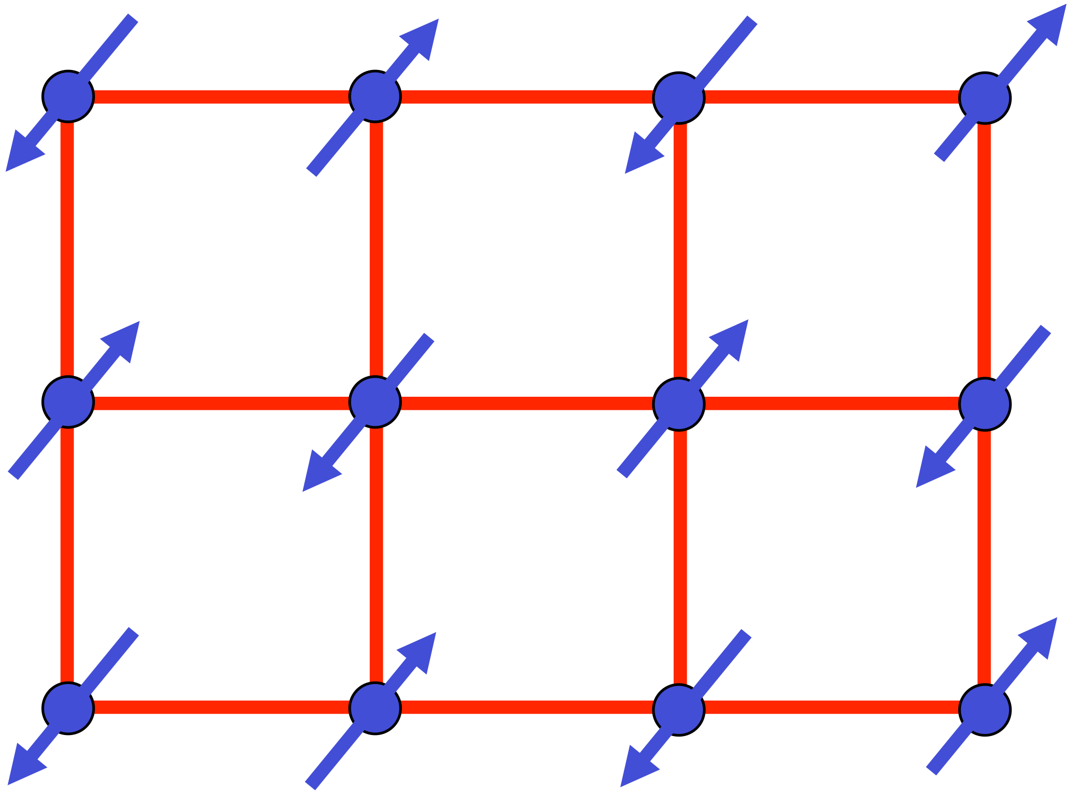
d-form factor density waves with the correct wavevector

Fermi surface+antiferromagnetism

Metal with "large"
Fermi surface



+



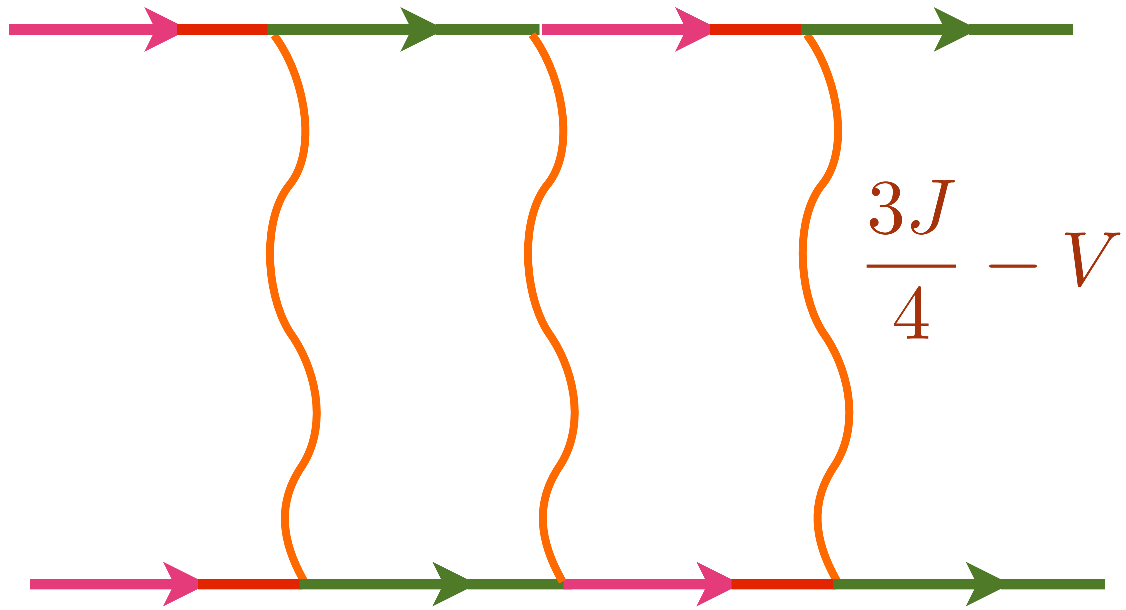
The electron spin polarization obeys

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

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

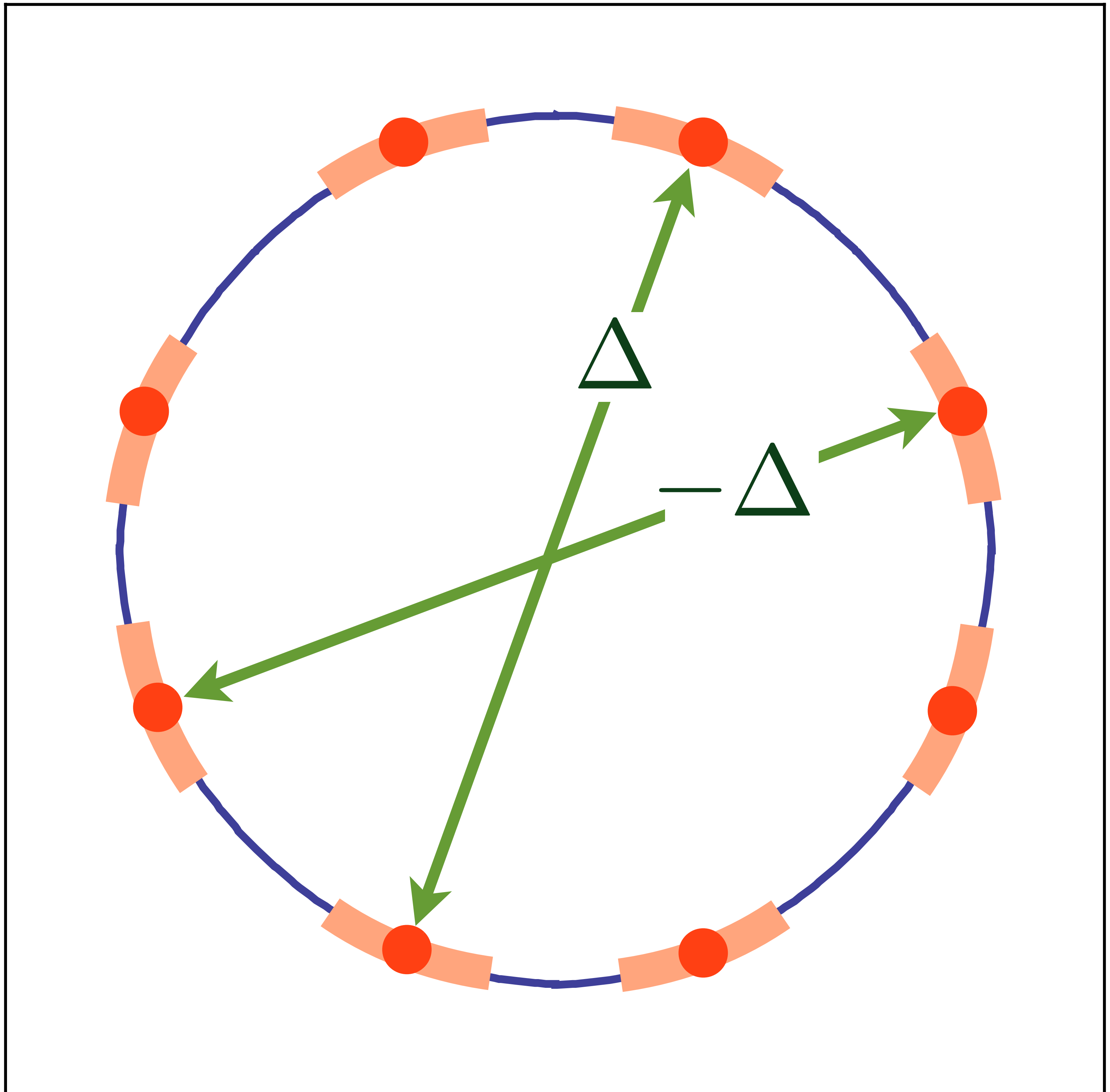
Pairing "glue" from antiferromagnetic fluctuations

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



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)

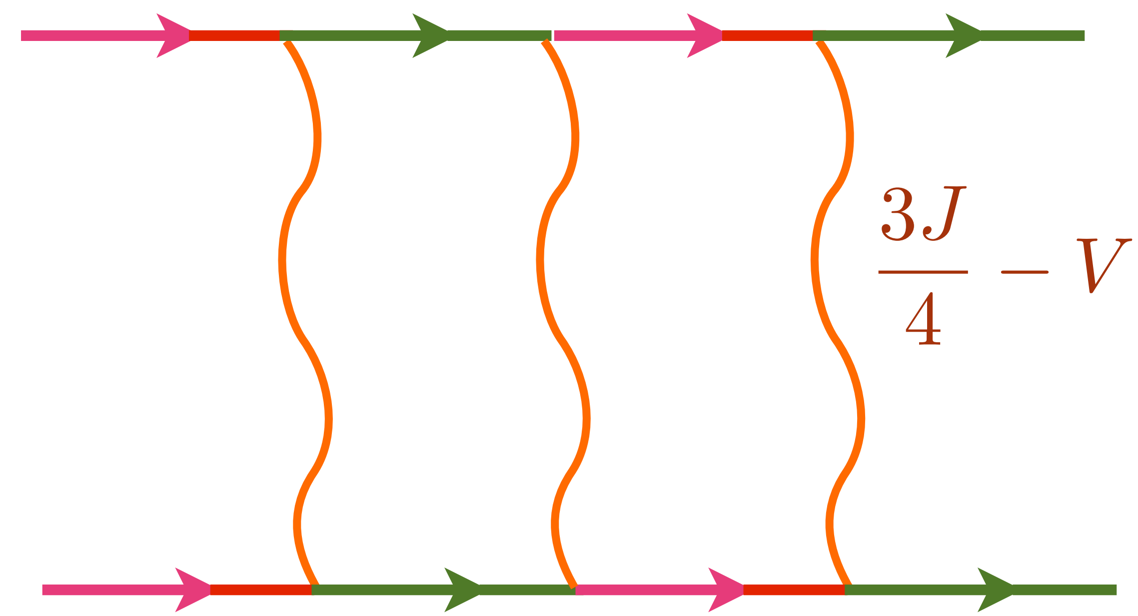
$$\left\langle c^\dagger_{\mathbf{k}\alpha} c^\dagger_{-\mathbf{k}\beta} \right\rangle = \varepsilon_{\alpha\beta} \Delta (\cos k_x - \cos k_y)$$



Unconventional pairing at *and near* hot spots

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)
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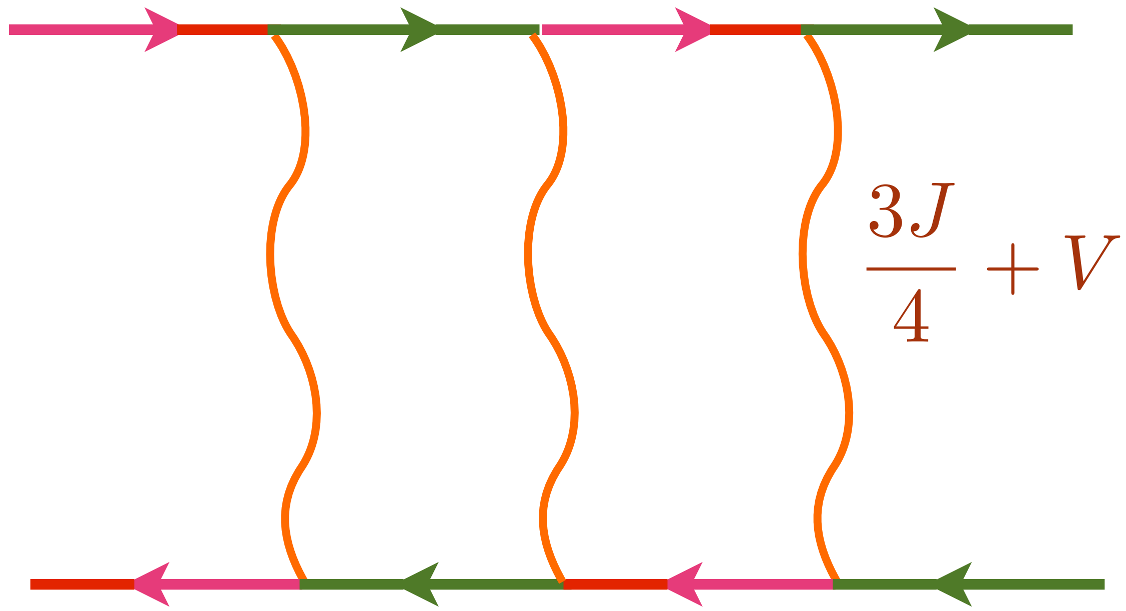
K. Miyake, S. Schmitt-Rink, and C. M. Varma, *Phys. Rev. B* **34**, 6554 (1986)

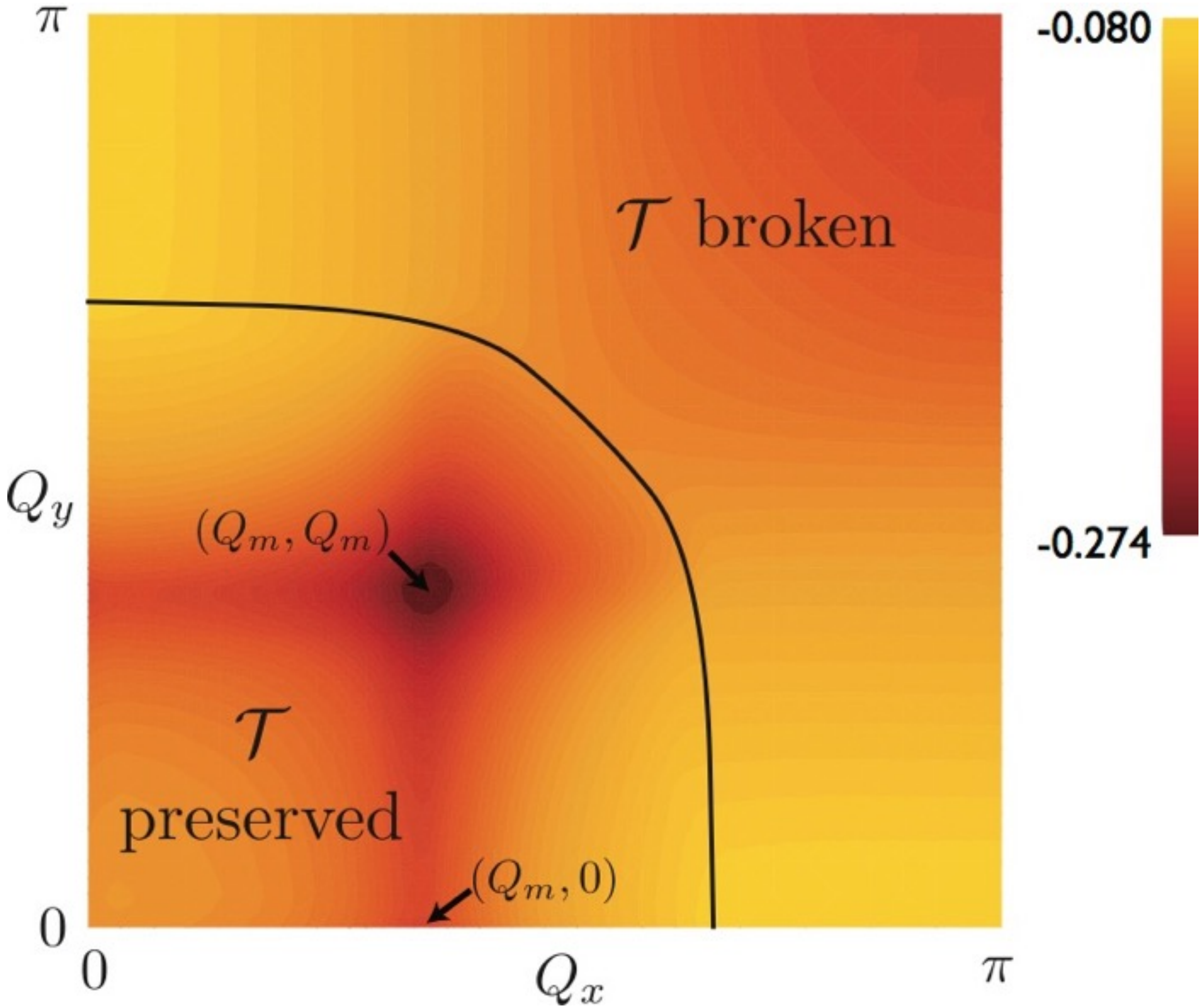
Same "glue" can lead to particle-hole pairing

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



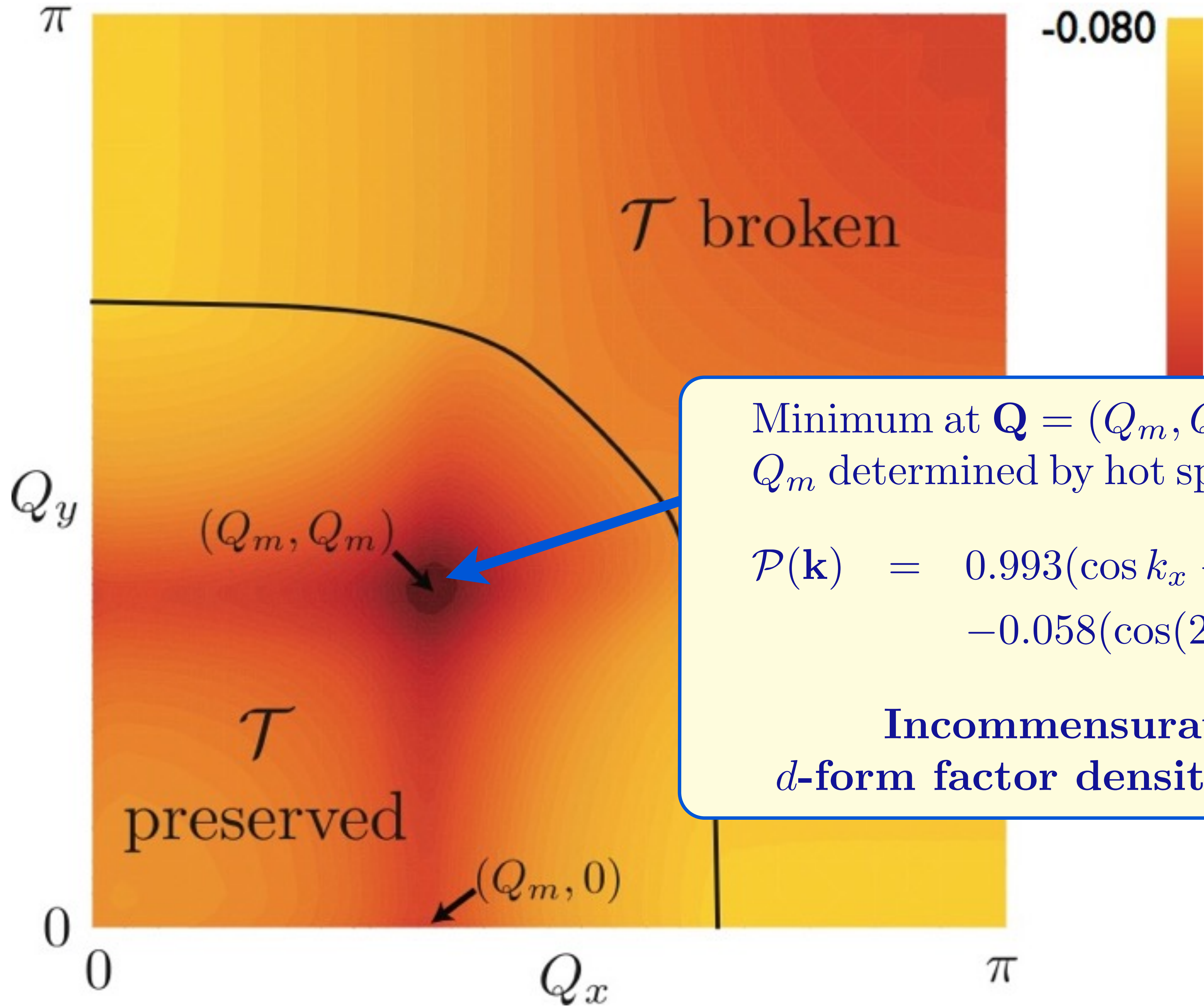
M.A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)
S. Sachdev and R. La Placa, *Phys. Rev. Lett.* **111**, 027202 (2013)

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



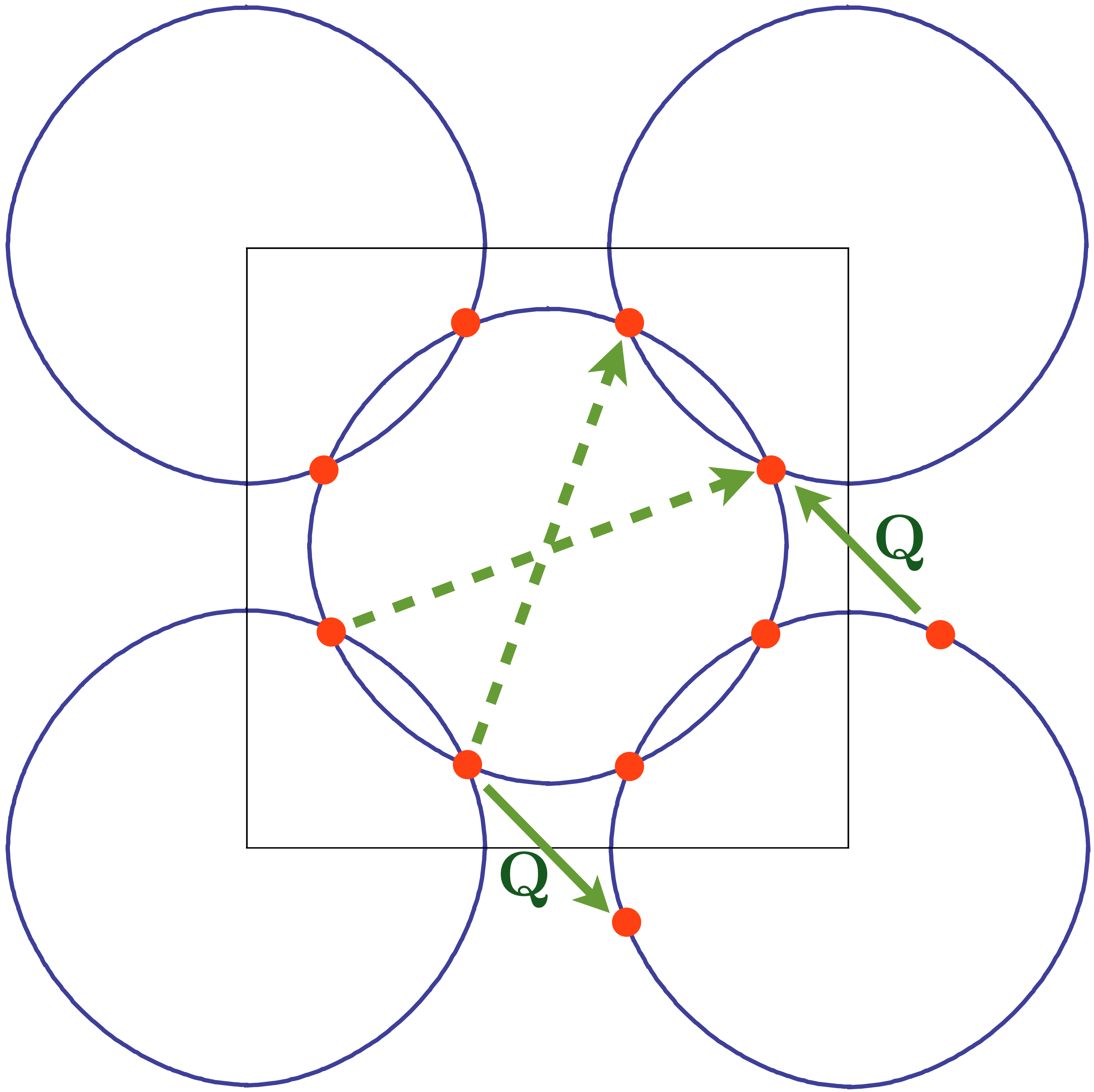
Minimum at $\mathbf{Q} = (Q_m, Q_m)$ (with Q_m determined by hot spots) with

$$\mathcal{P}(\mathbf{k}) = 0.993(\cos k_x - \cos k_y) - 0.058(\cos(2k_x) - \cos(2k_y))$$

Incommensurate
***d*-form factor density wave**

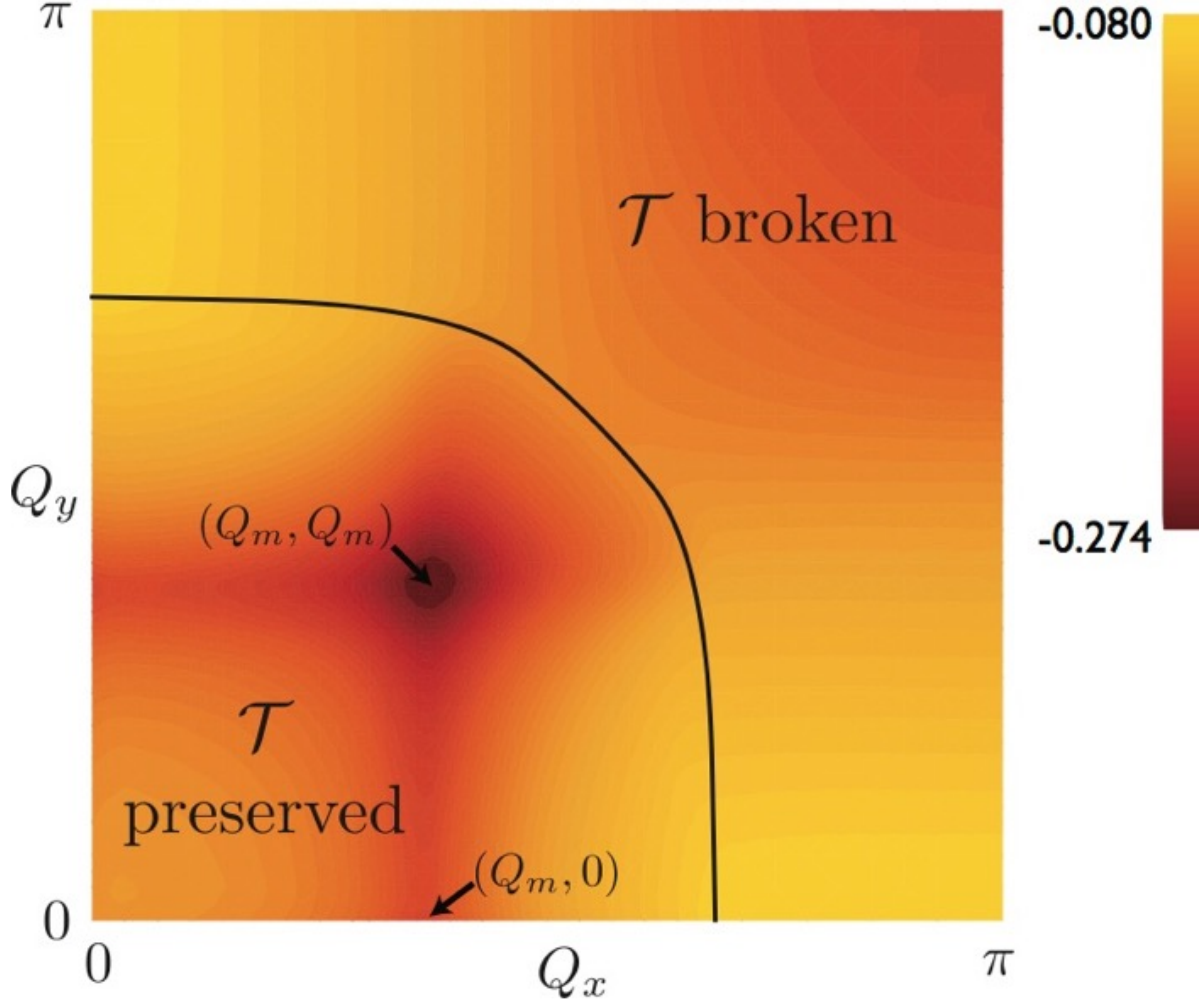
Eigenvalues, $\lambda(\mathbf{Q})$, of the spin-singlet, particle-hole propagator. The corresponding eigenvector is $\mathcal{P}(\mathbf{k})$ and this leads to the order $\left\langle c_{i\alpha}^\dagger c_{j\alpha} \right\rangle = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)}\right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2}$

d-form factor density wave



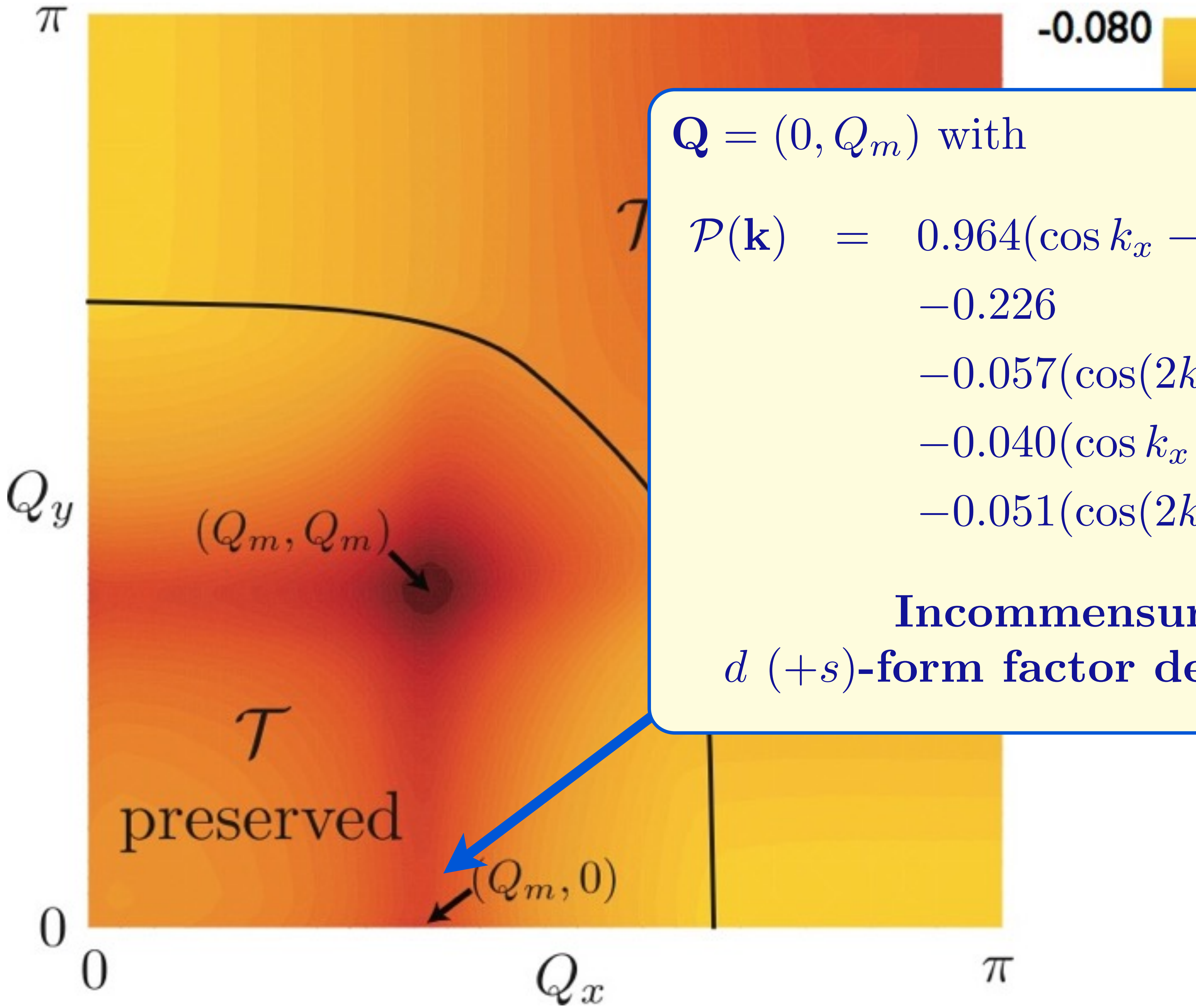
$$\left\langle c^{\dagger}_{\mathbf{k}-\mathbf{Q}/2,\alpha} c_{\mathbf{k}+\mathbf{Q}/2,\alpha} \right\rangle = \mathcal{P}_d (\cos k_x - \cos k_y)$$

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



$\mathbf{Q} = (0, Q_m)$ 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 $\mathcal{P}(\mathbf{k})$ and this leads to the order $\left\langle c_{i\alpha}^{\dagger} c_{j\alpha} \right\rangle = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)}\right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2}$

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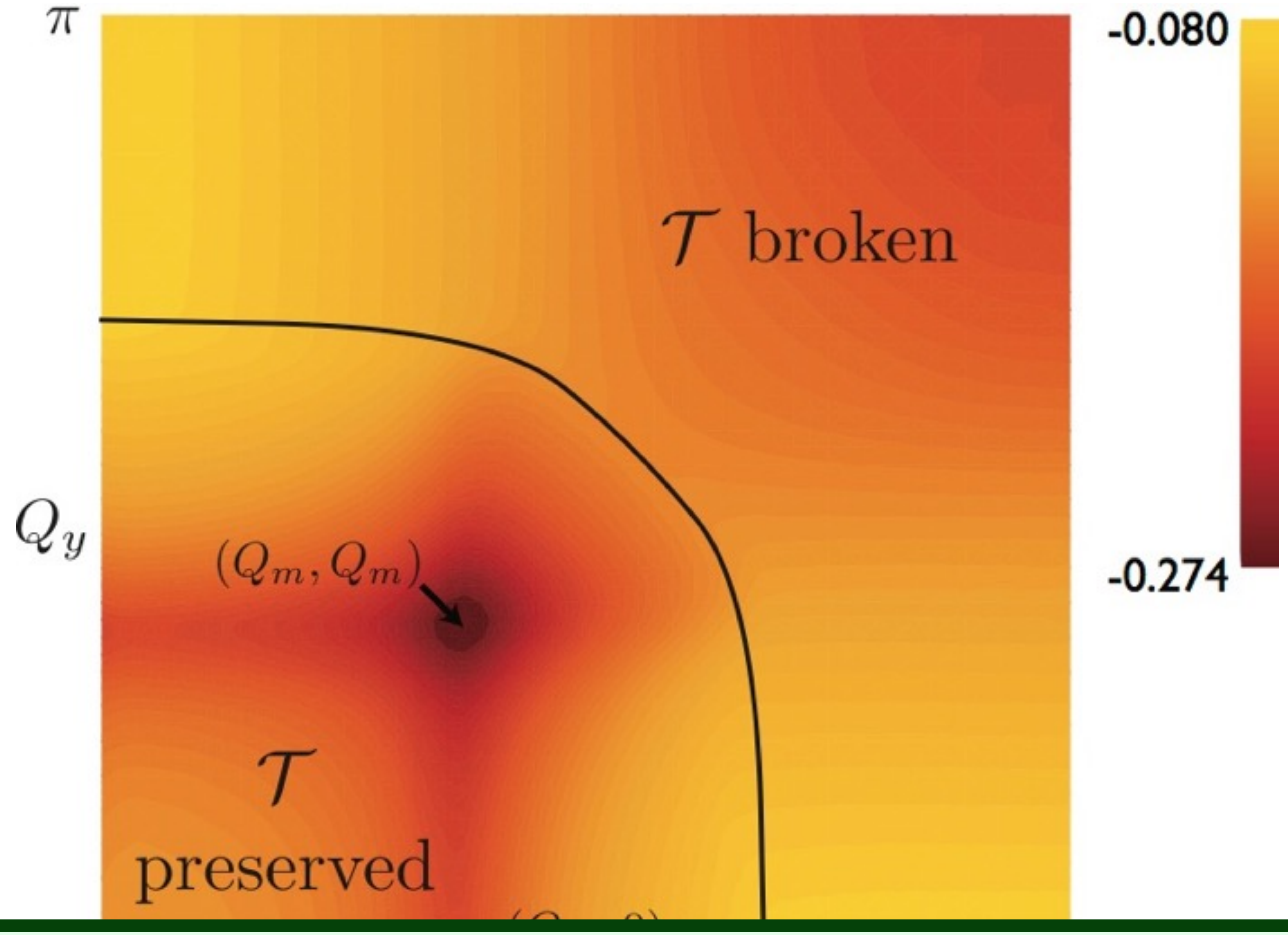
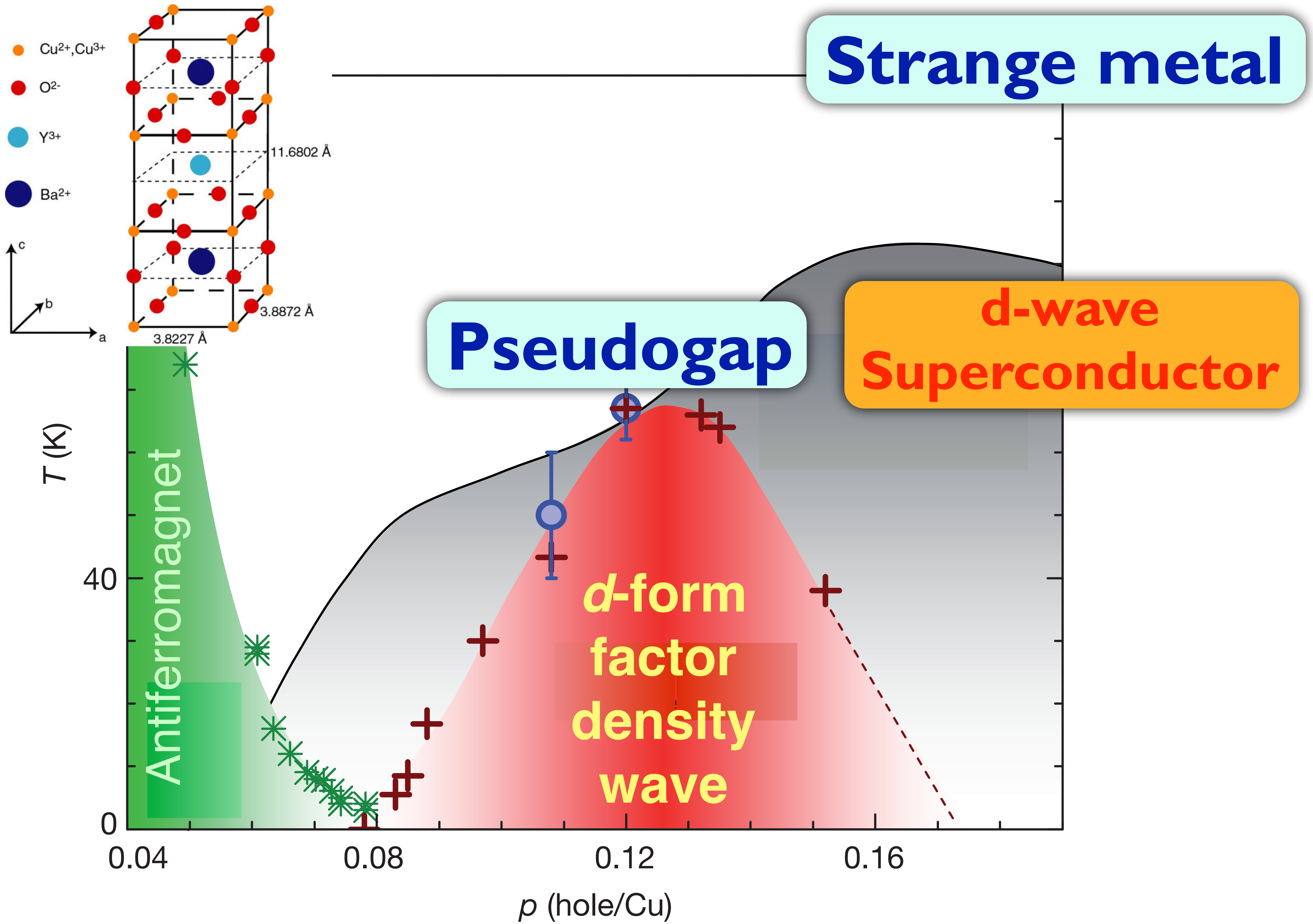
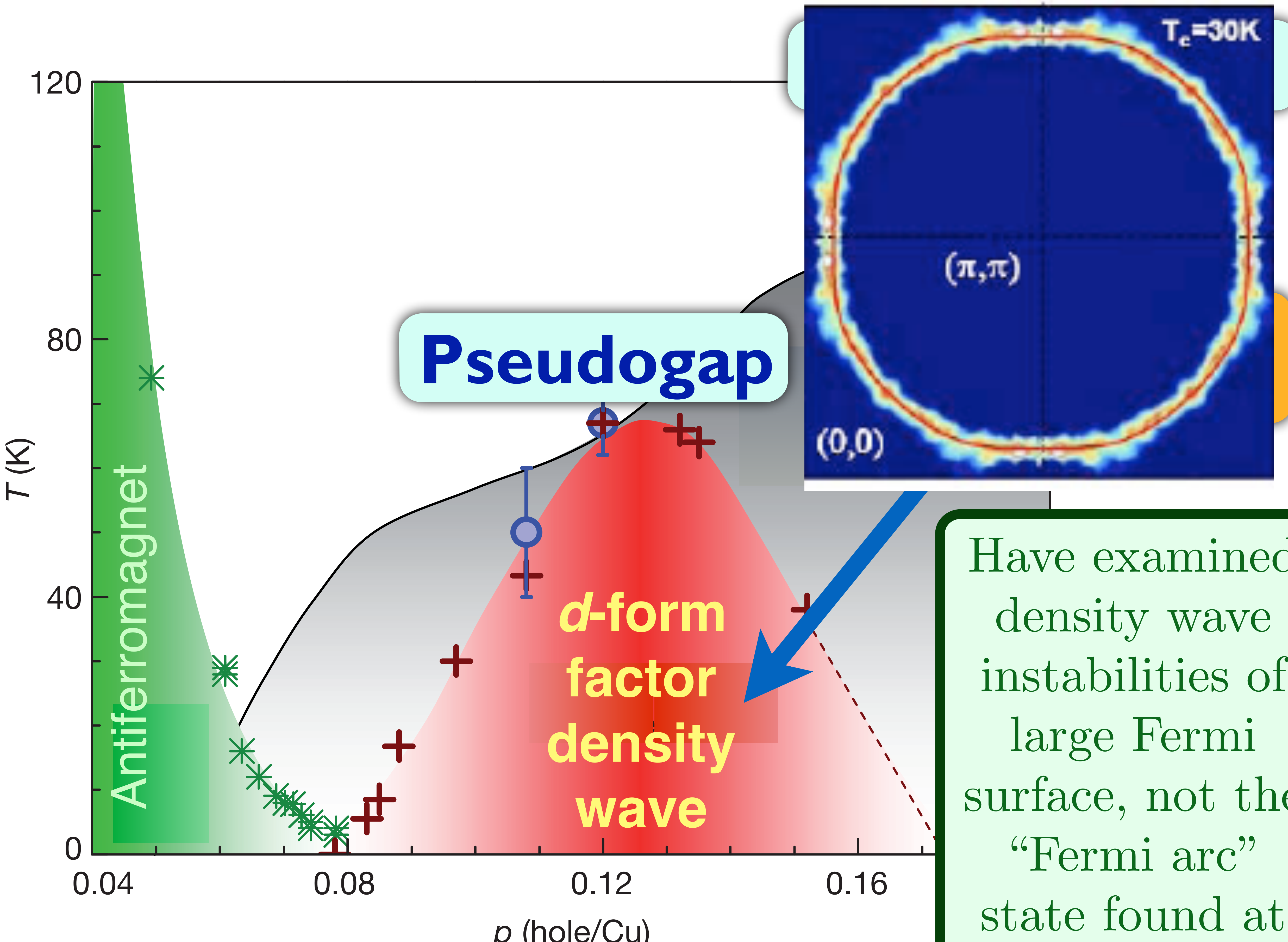


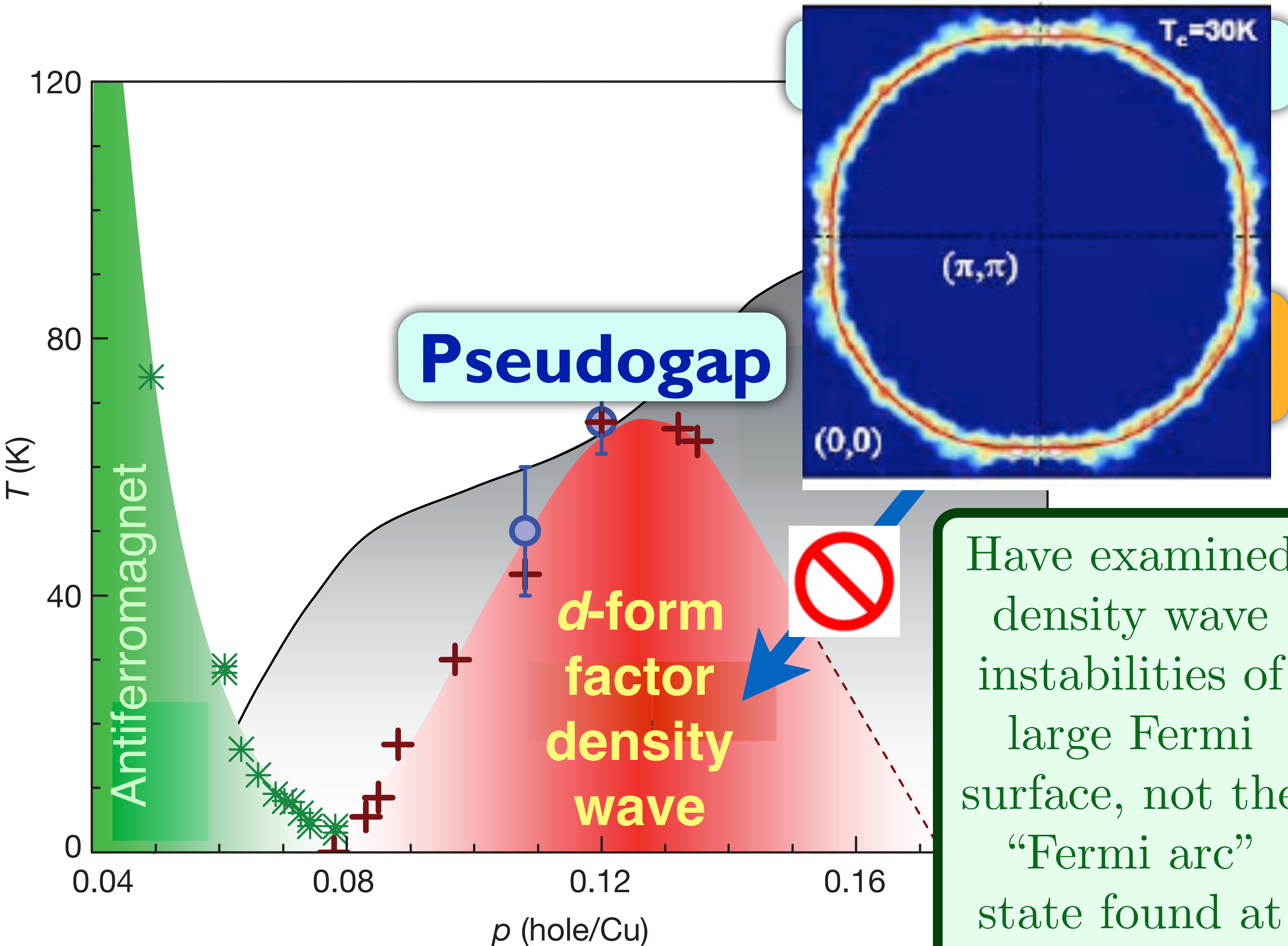
This theory yields the correct form factor, but the incorrect $\mathbf{Q}$. We have found the same features in all theories (one- and three-band) with a large Fermi surface



Cu2+,Cu3+
O2-
Y3+
Ba2+
c
b
a
11.6802 Å
3.8872 Å
3.8227 Å
Strange metal
Pseudogap
d-wave
Superconductor
Antiferromagnet
d-form
factor
density
wave
T (K)
40
0
0.04
0.08
0.12
0.16
p (hole/Cu)



Have examined density wave instabilities of large Fermi surface, not the "Fermi arc" state found at low doping.



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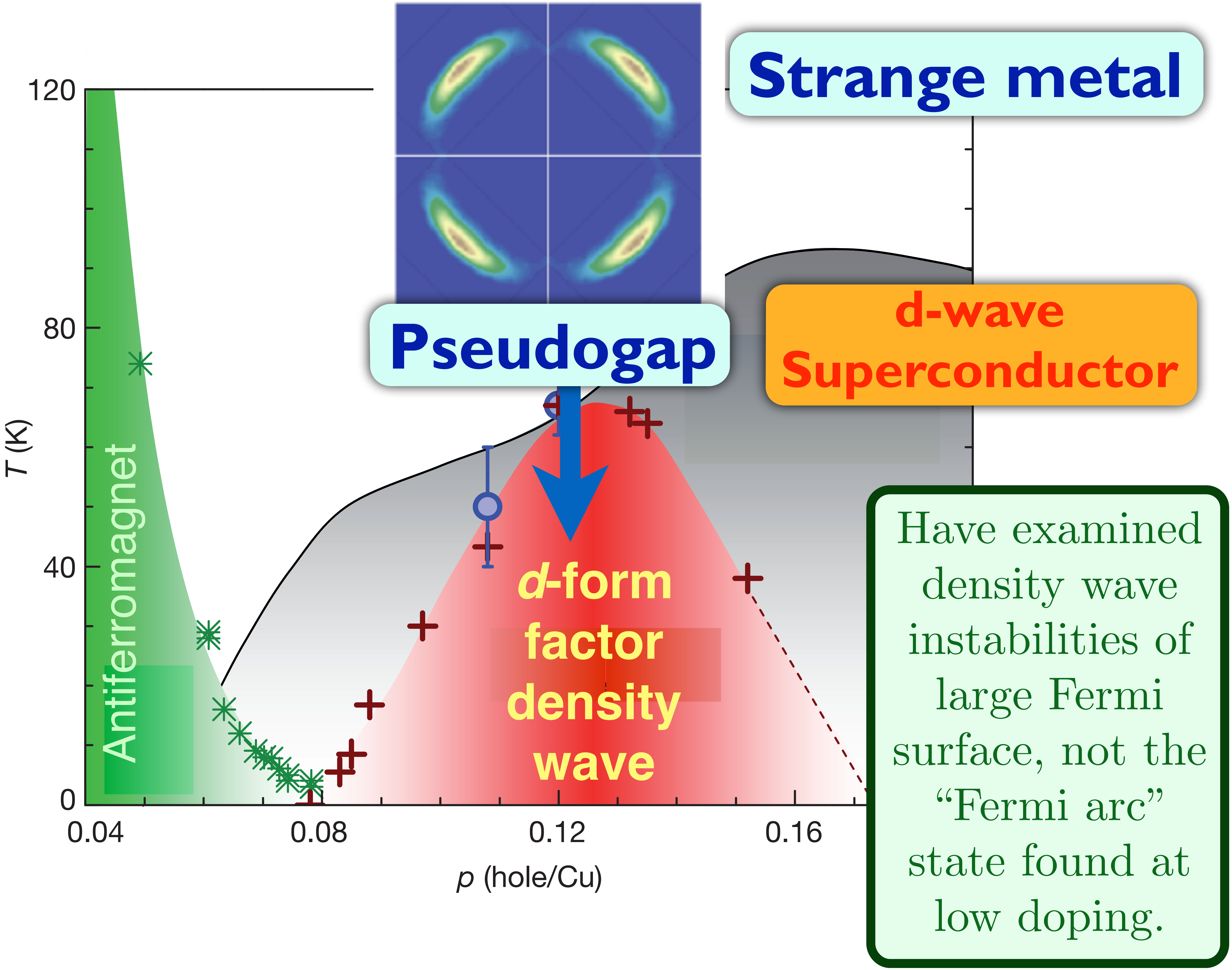
Strange metal
Pseudogap
d-wave Superconductor
Antiferromagnet
d-form factor density wave
120
80
40
0
T (K)
0.04
0.08
0.12
0.16
p (hole/Cu)
Have examined density wave instabilities of large Fermi surface, not the "Fermi arc" state found at low doping.

Outline

1. Density waves in the underdoped cuprates

   STM observation of d-form factor density wave

2. RPA theory of density waves

3. Fractionalized Fermi liquids (FL*) in doped square lattice antiferromagnets

   d-form factor density waves with the correct wavevector

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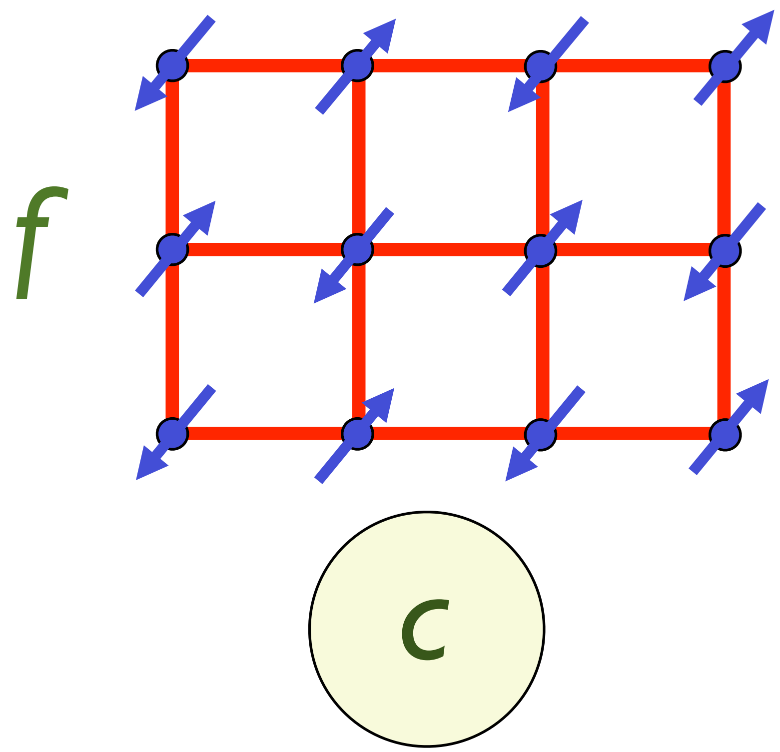
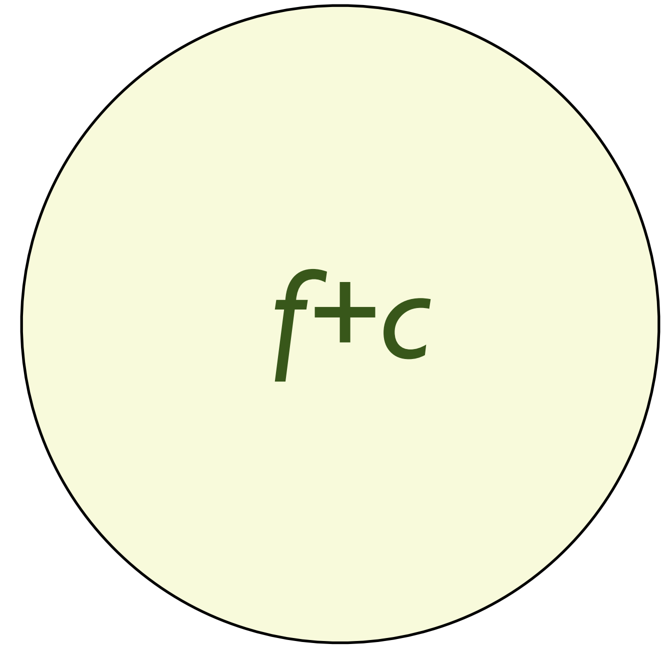
Magnetic order and the heavy Fermi liquid in the Kondo lattice



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

Magnetic Metal:
f-electron moments
and
c-conduction electron
Fermi surface

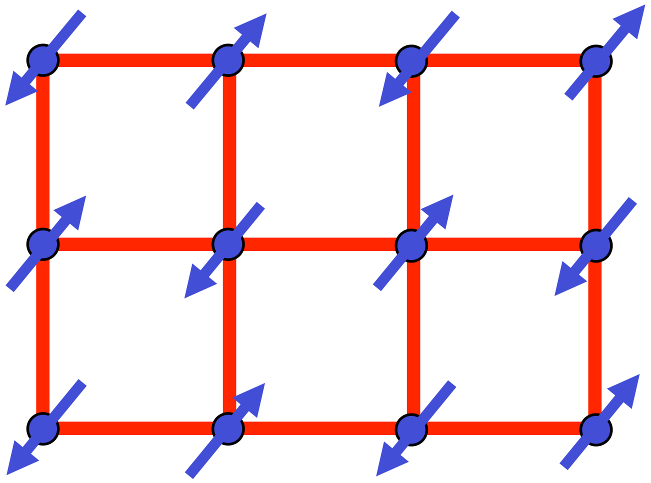


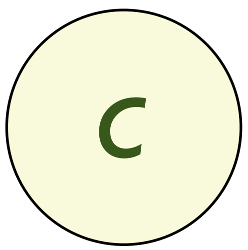
$$\langle \vec{\varphi} \rangle = 0$$

Heavy Fermi liquid
with "large" Fermi
surface of
hydridized *f* and
c-conduction
electrons

Separating onset of SDW order and the heavy Fermi liquid in the Kondo lattice

f





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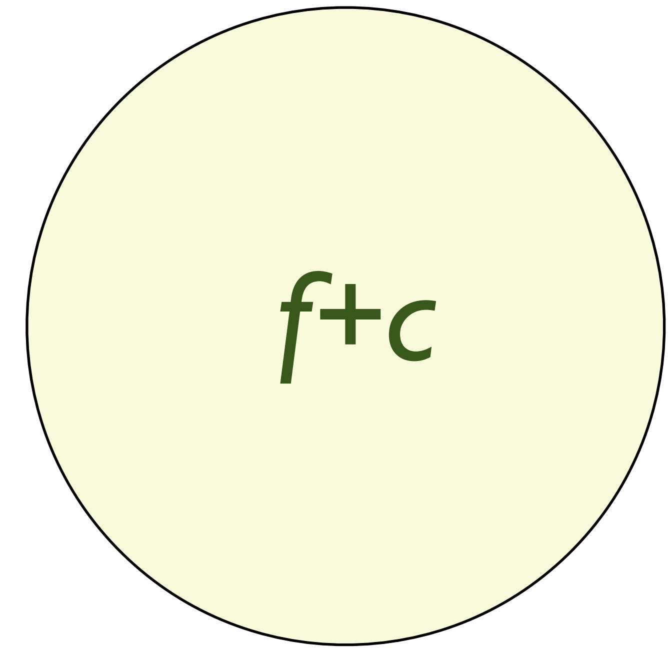

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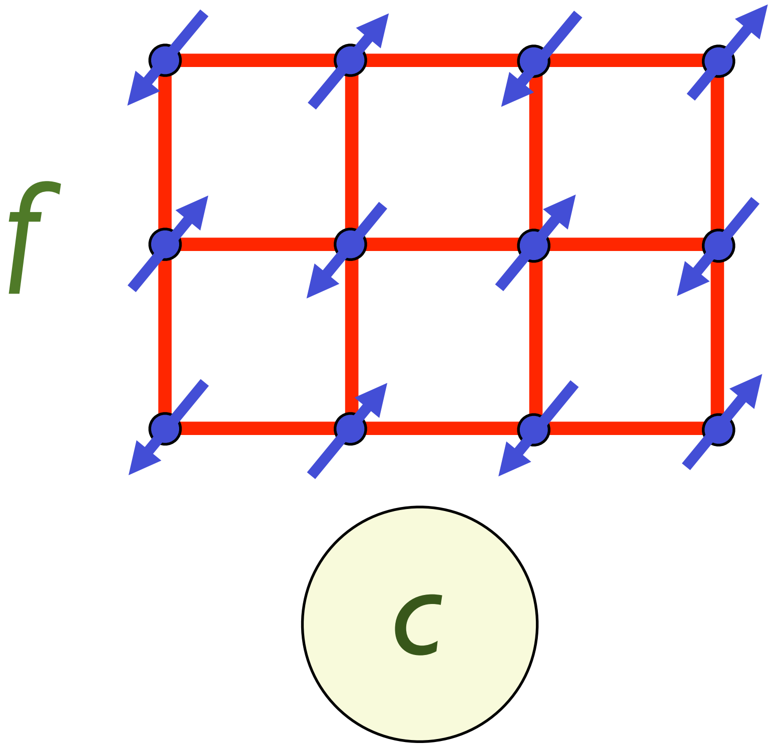

$$\langle \vec{\varphi} \rangle \neq 0$$

Magnetic Metal:
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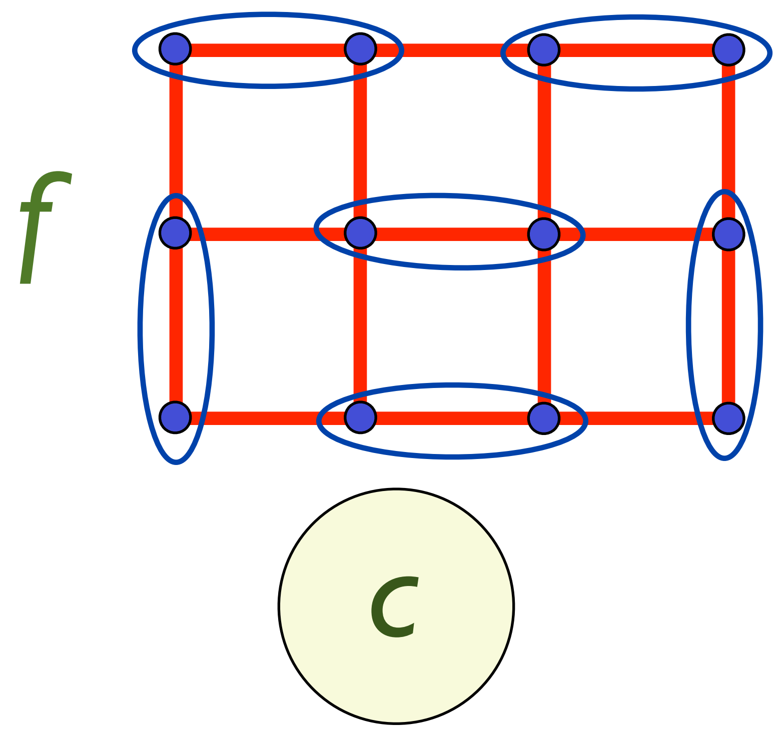
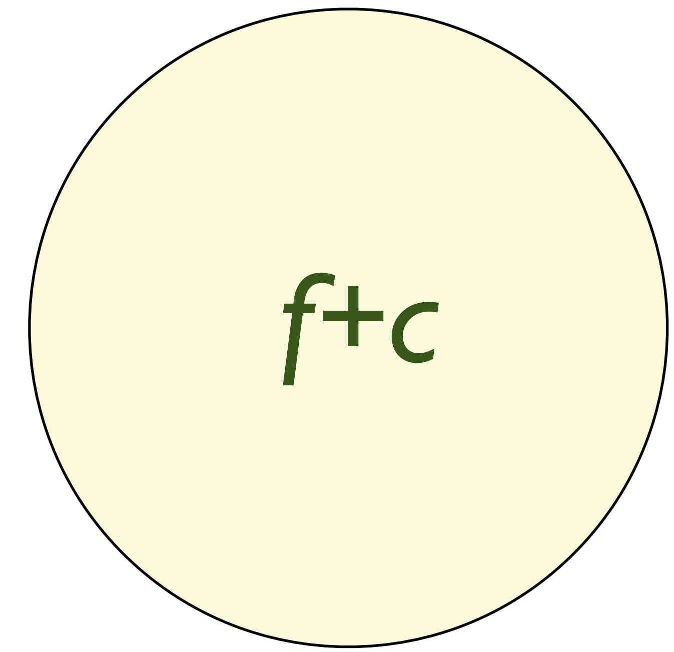


$$\langle \vec{\varphi} \rangle = 0$$

Conduction electron
Fermi surface
and
spin-liquid of
f-electrons



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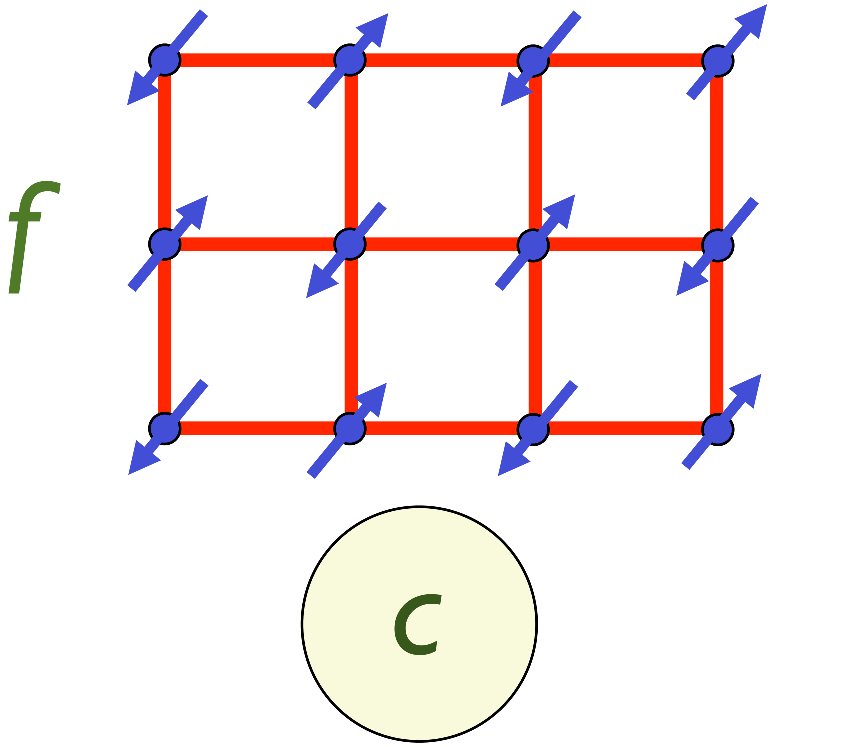

$\langle \vec{\varphi} \rangle \neq 0$

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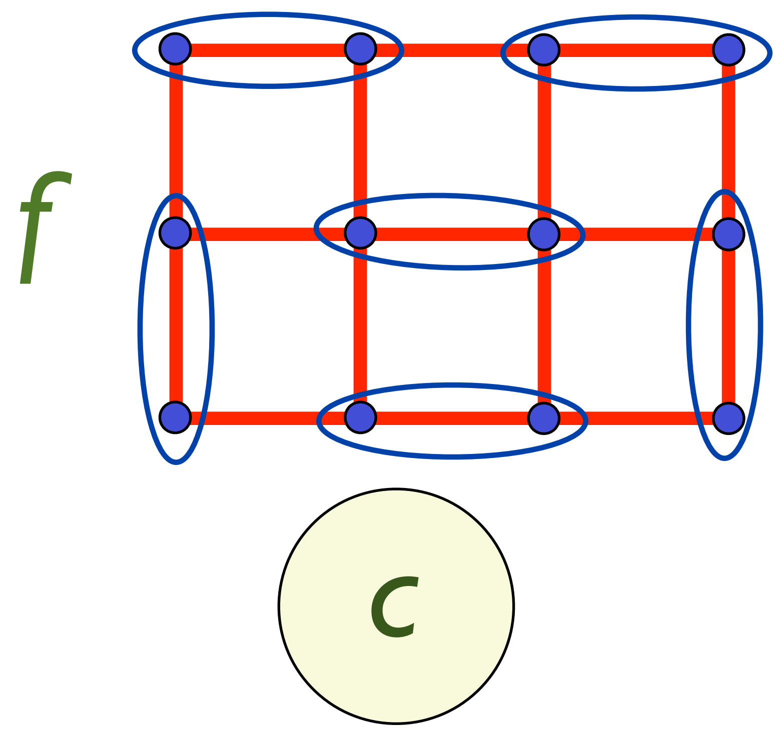
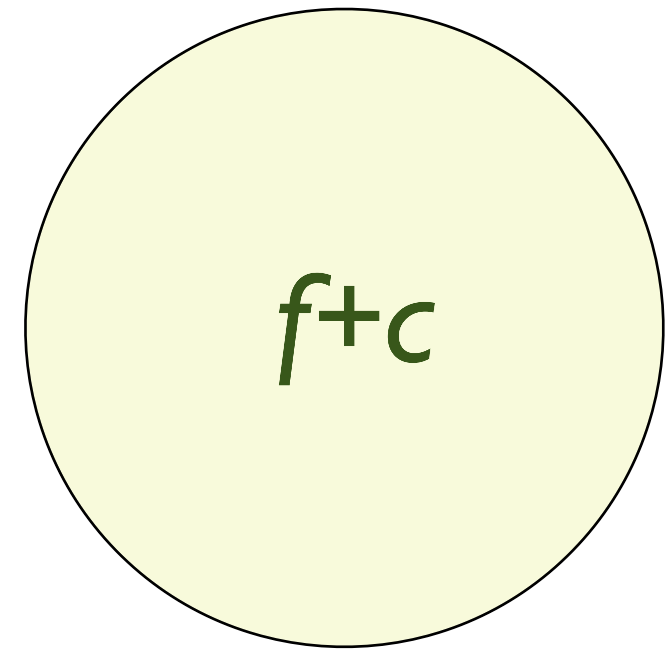


$\langle \vec{\varphi} \rangle = 0$

Fractionalized Fermi liquid (FL*) phase with no symmetry breaking and "small" Fermi surface



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

Heavy Fermi liquid
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surface of
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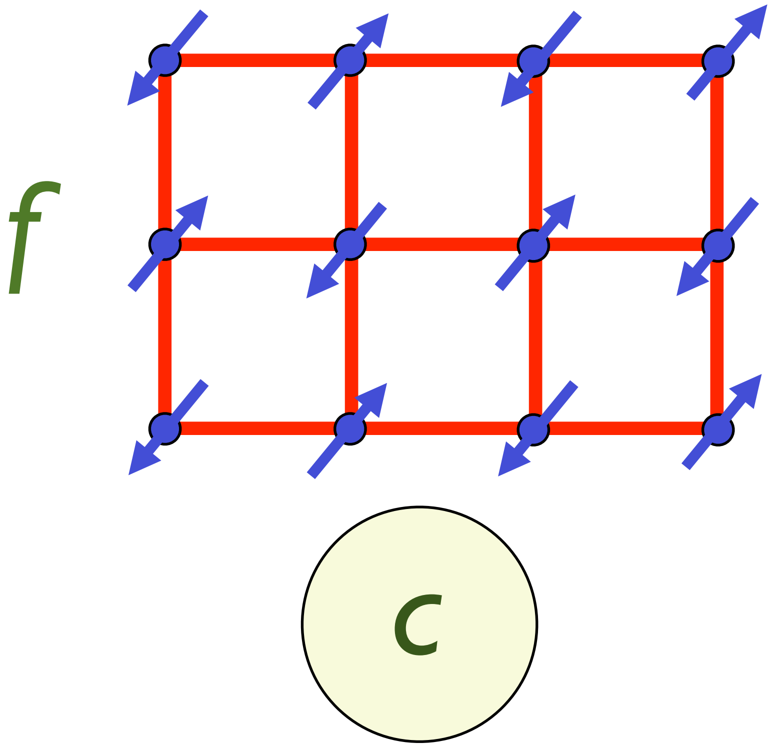
T. Senthil, S. Sachdev, and M. Vojta, *Phys. Rev. Lett.* **90**, 216403 (2003)

Separating onset of SDW order and the heavy Fermi liquid in the Kondo lattice



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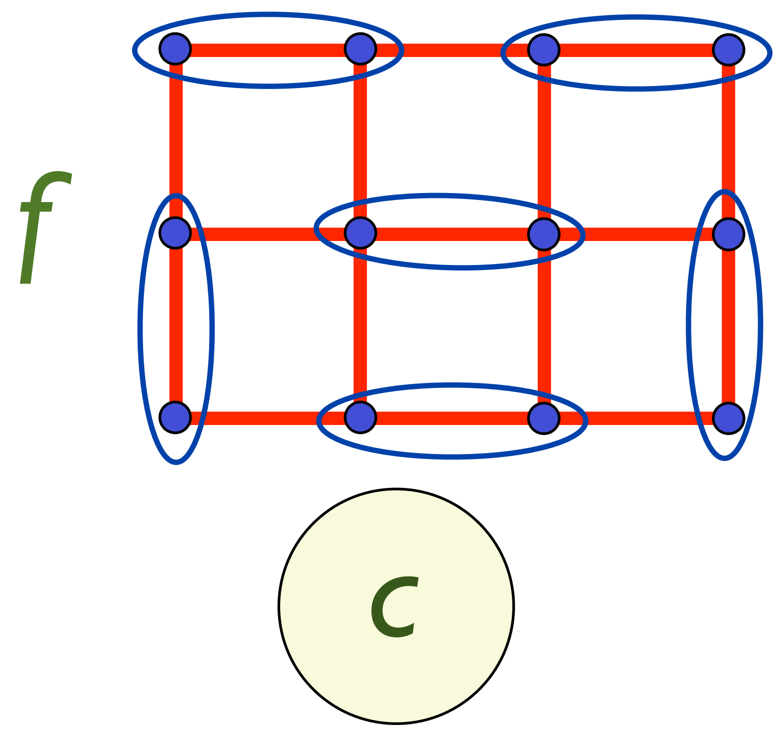

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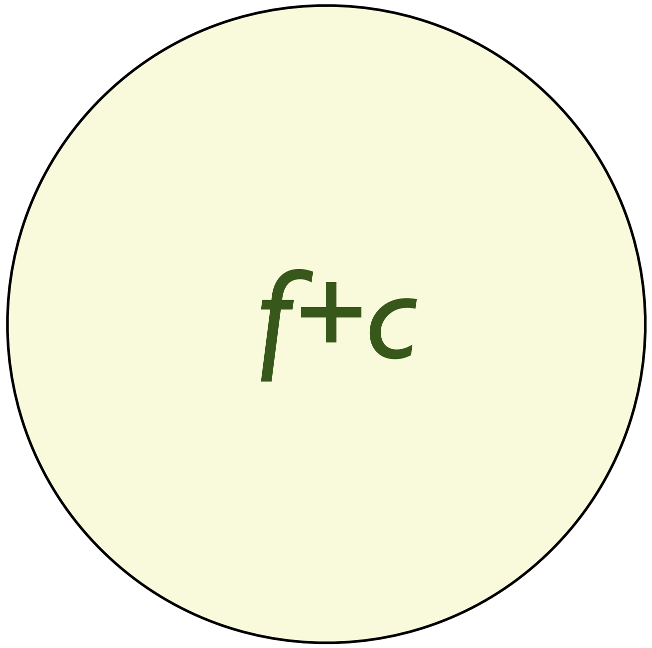


$\langle \vec{\varphi} \rangle = 0$

A "topological" phase transition with no conventional order parameter

T. Senthil, S. Sachdev, and M. Vojta, *Phys. Rev. Lett.* **90**, 216403 (2003)

Characteristics of FL* phase

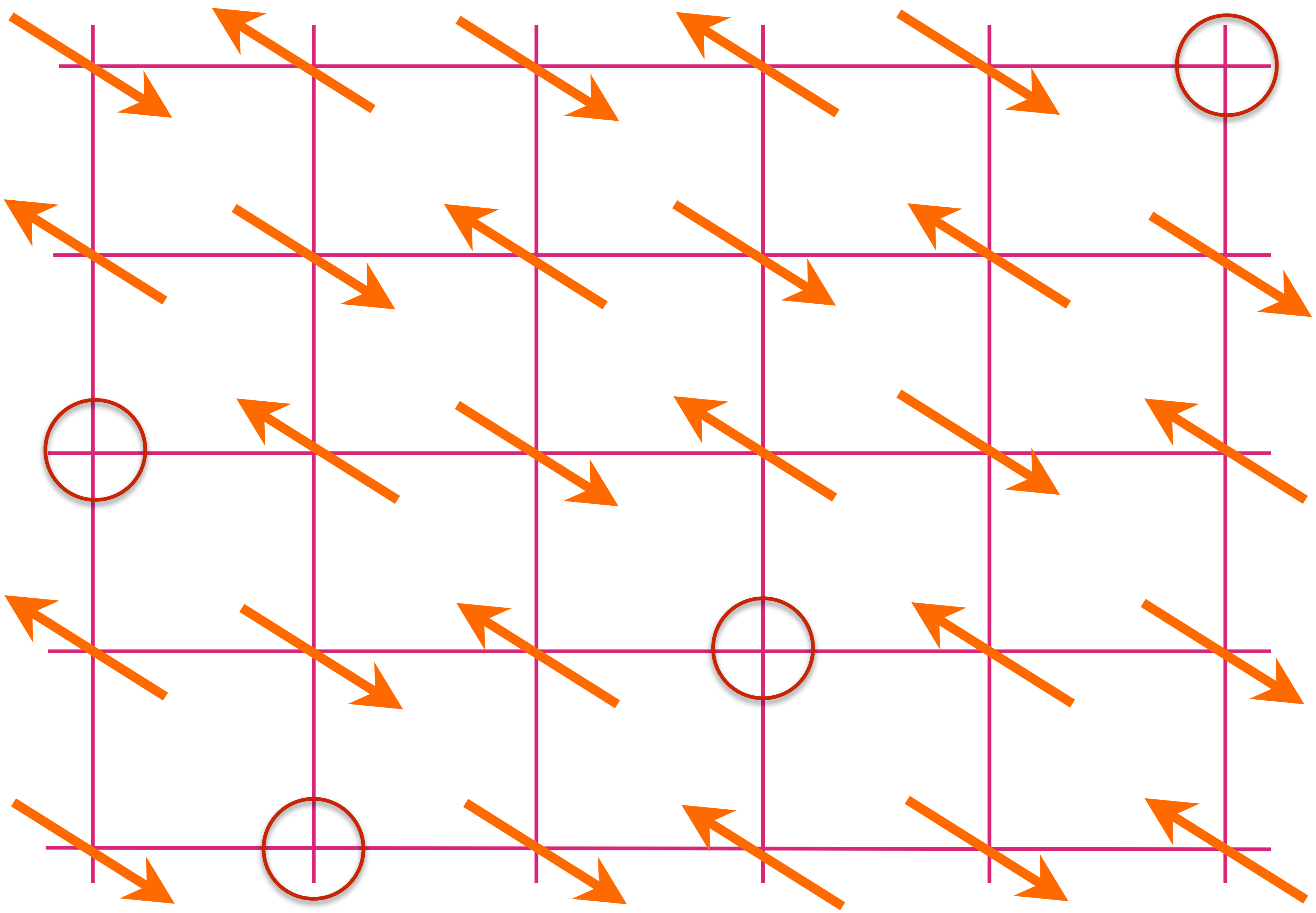
- Fermi surface volume does not count all electrons.

- Such a phase *must* have low energy collective gauge excitations ("topological" order).

- These low energy gauge excitations are needed to account for the deficit in the Fermi surface volume, in M. Oshikawa's proof of the Luttinger theorem.

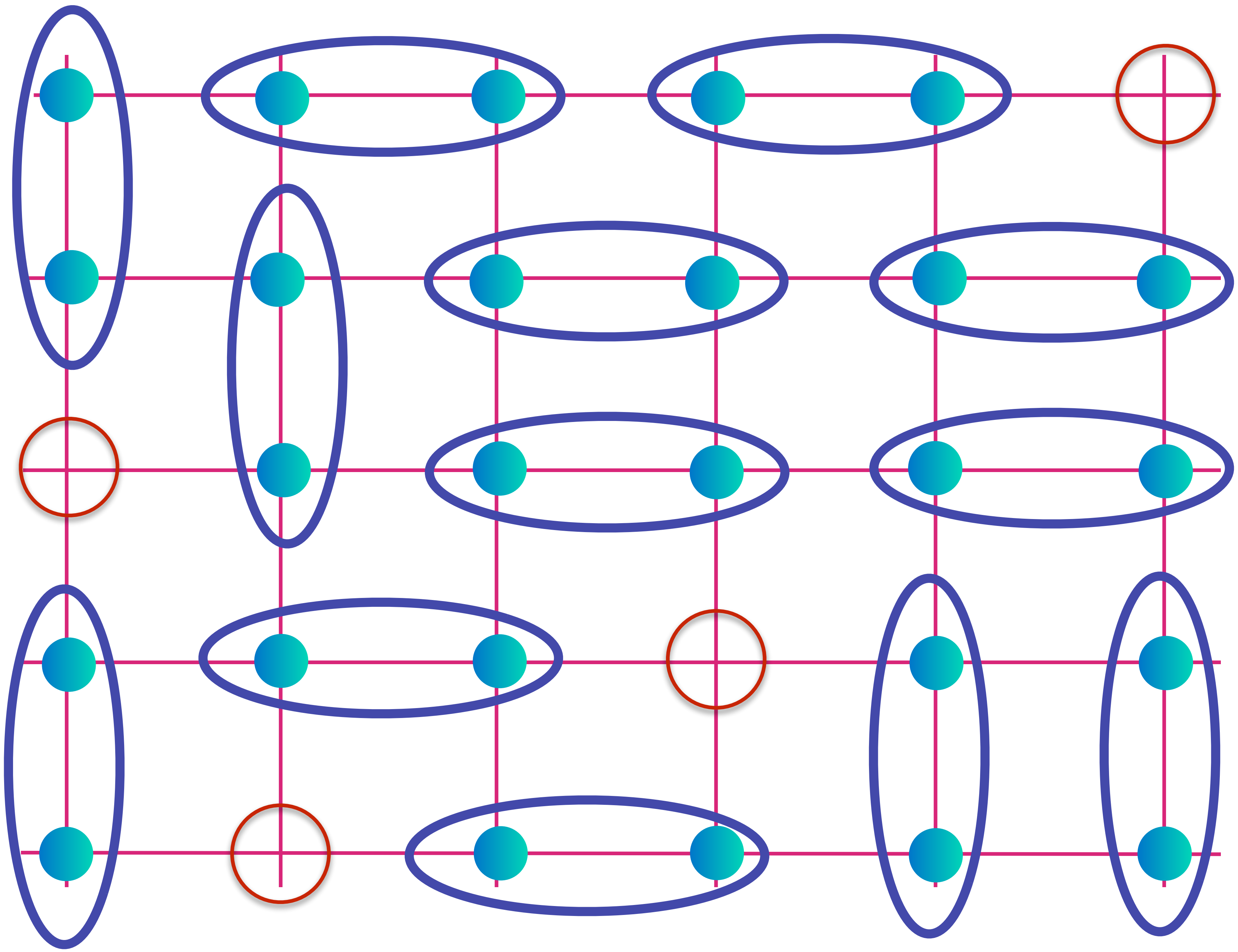
T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)

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



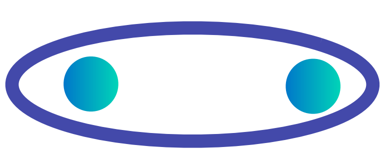
Doped anti-ferromagnet

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



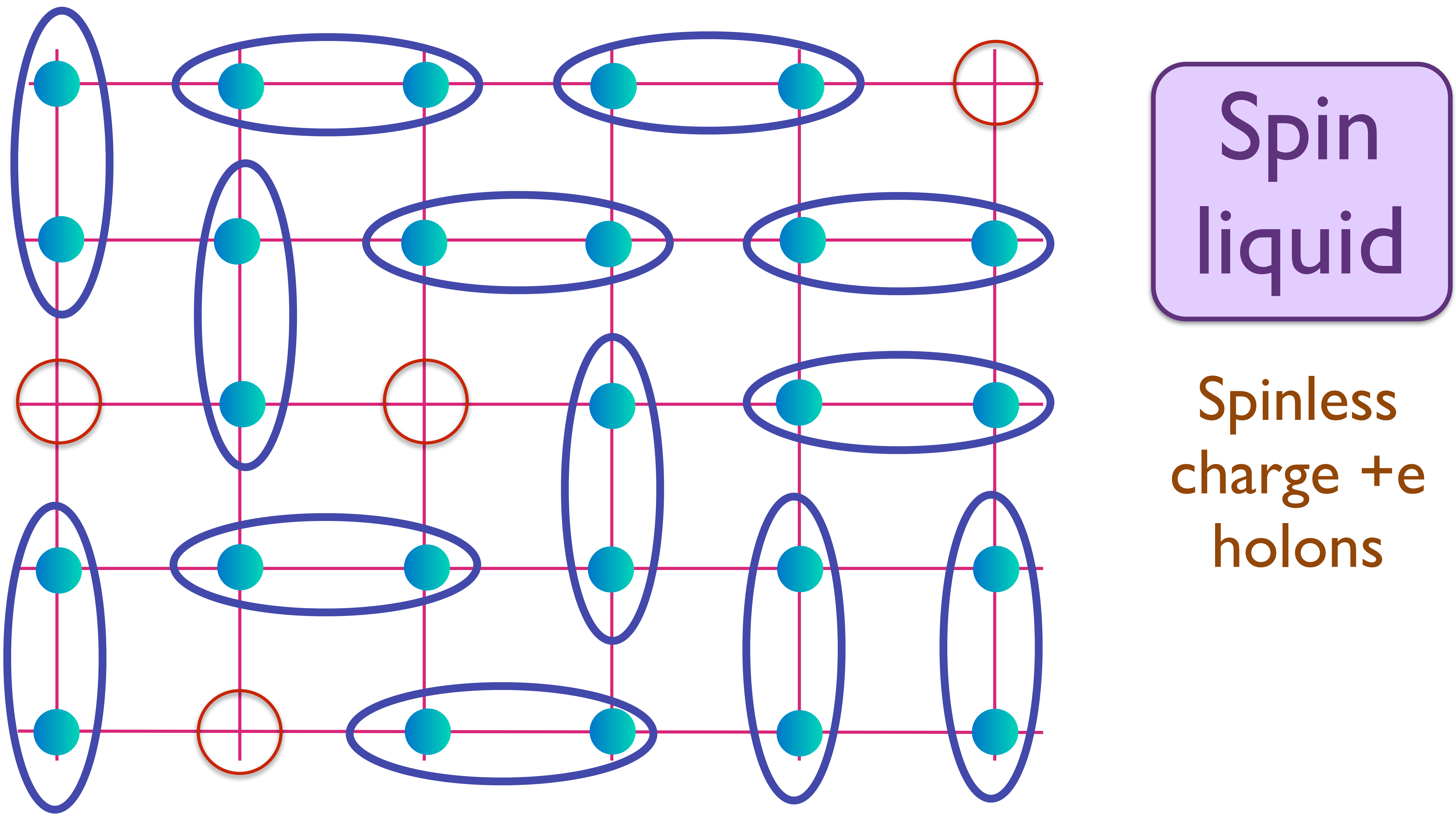
Spin liquid

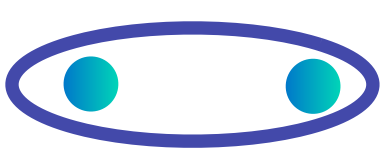
Spinless charge +e holons

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

Baskaran, Zou, Anderson, Fradkin, Kivelson…

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





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

Baskaran, Zou, Anderson, Fradkin, Kivelson…

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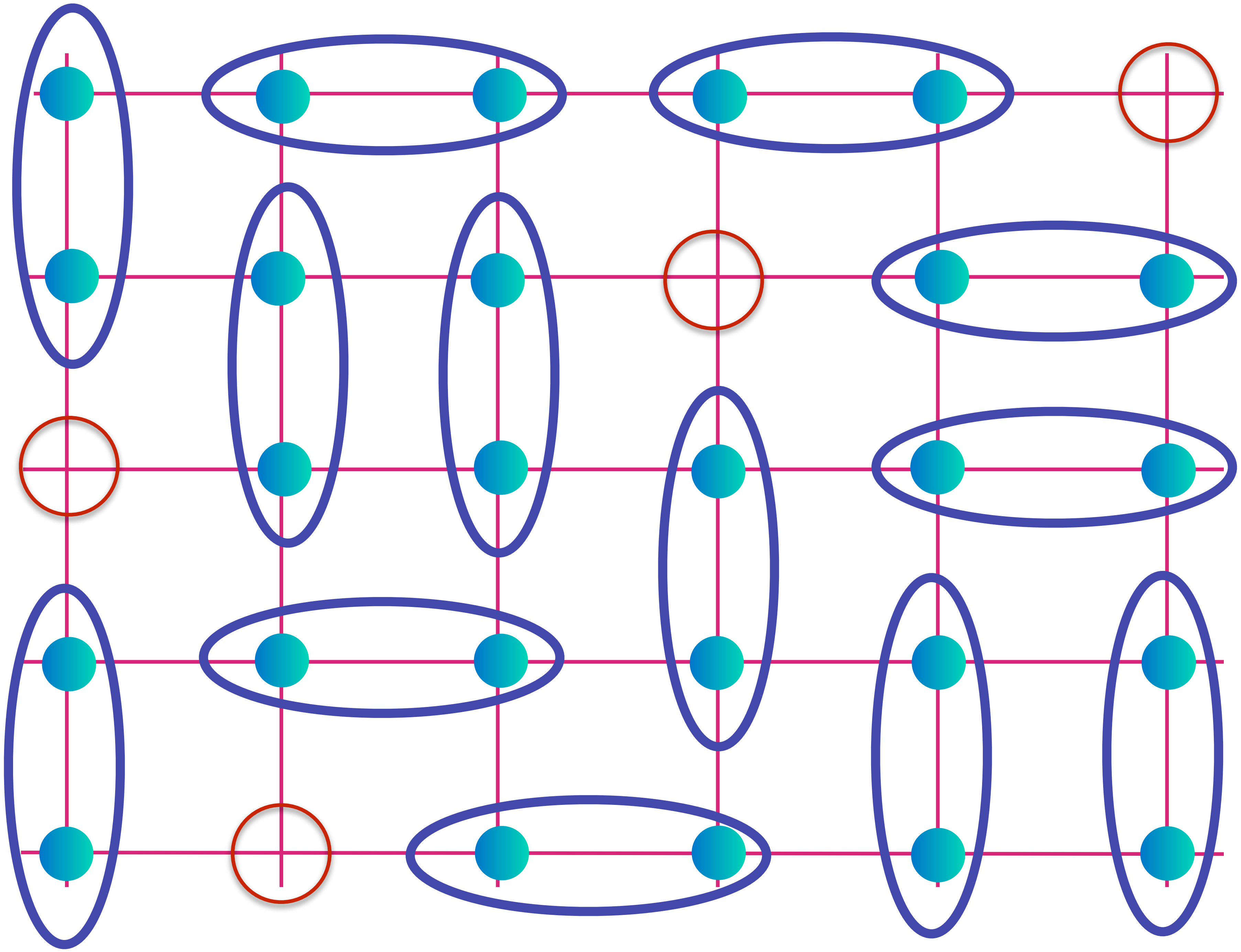

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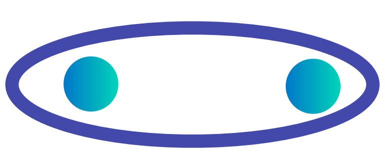
Spinless charge +e holons

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

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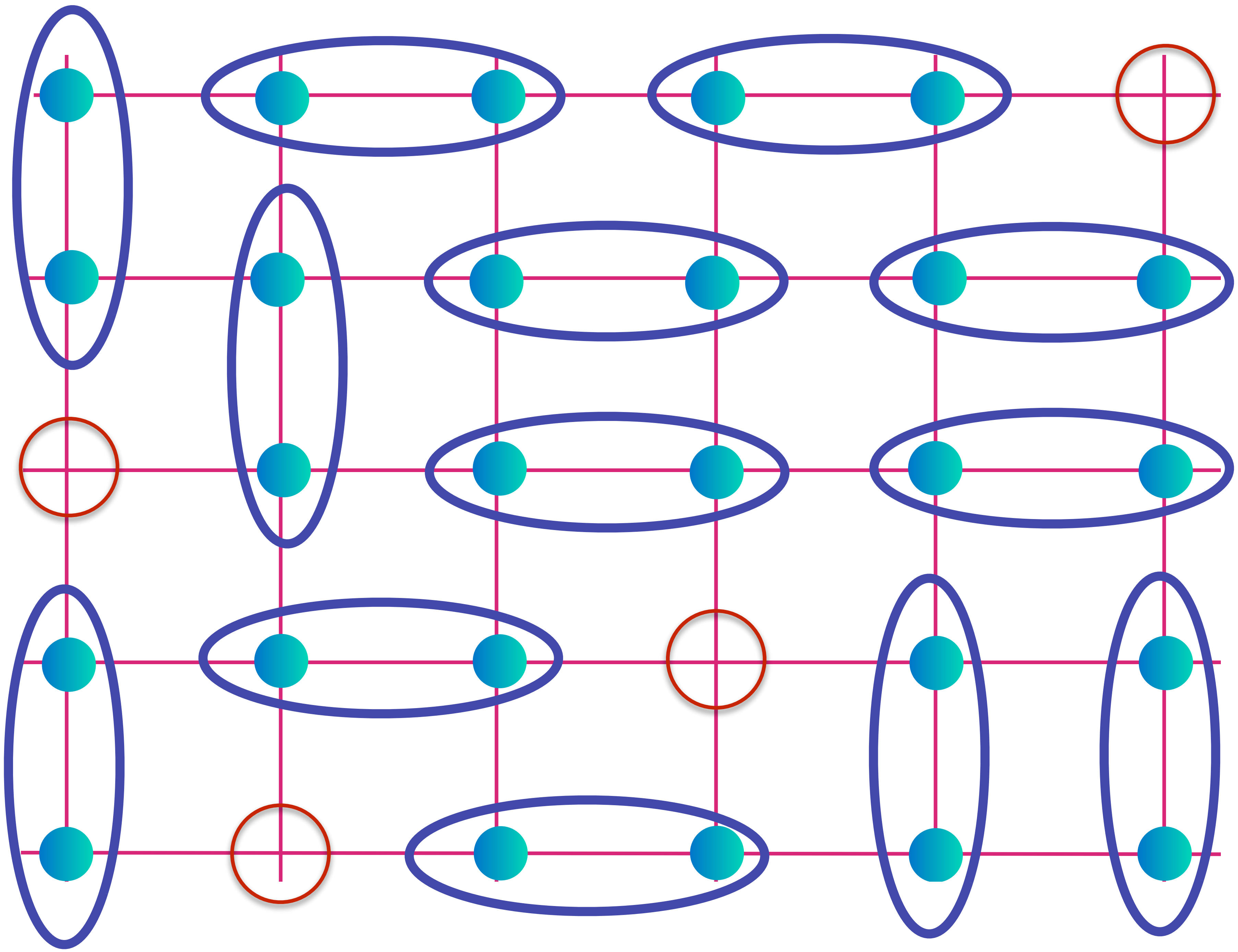
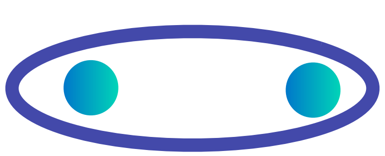


Spin liquid

Spinless charge +e holons

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

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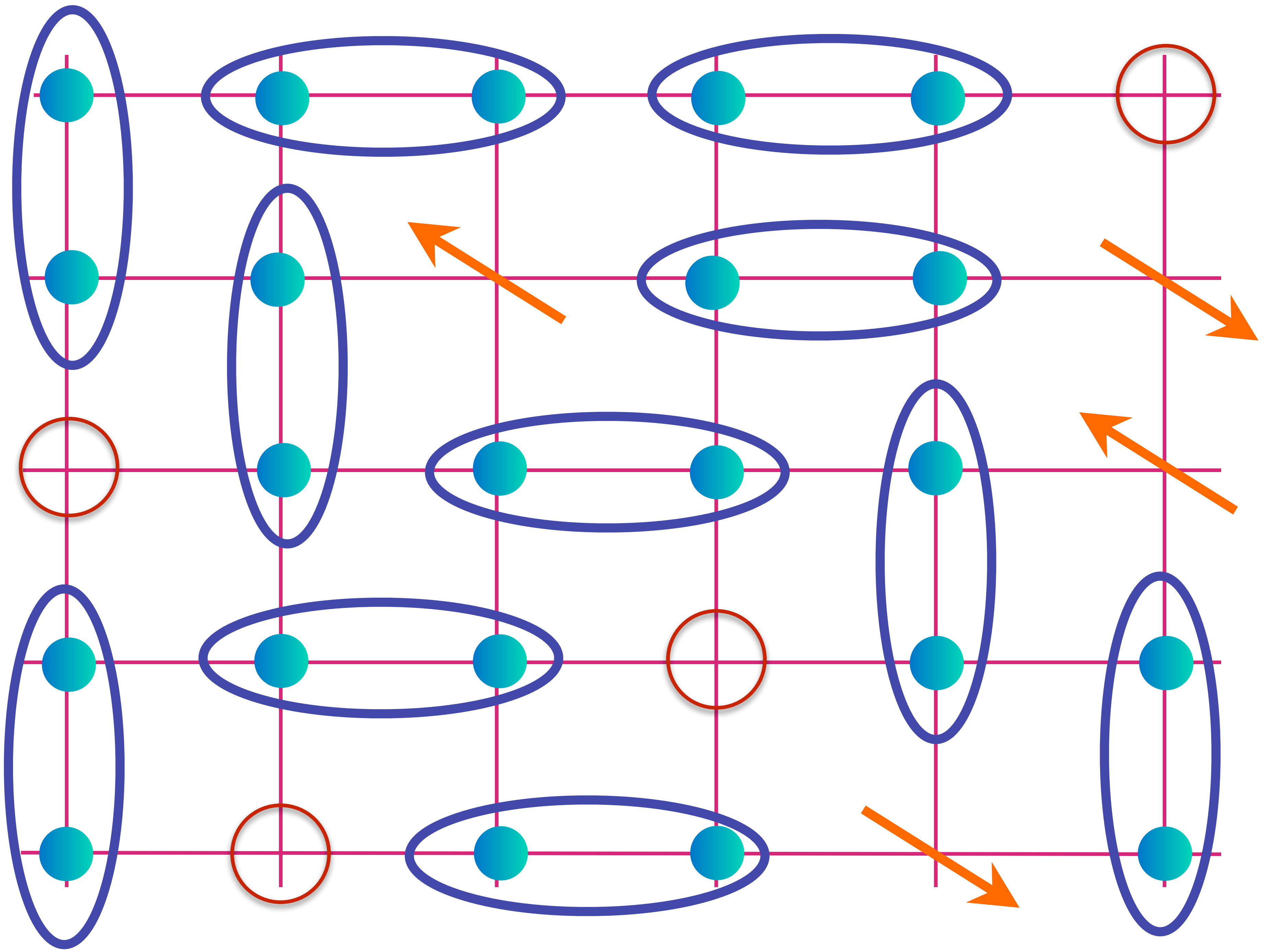
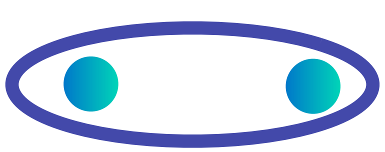


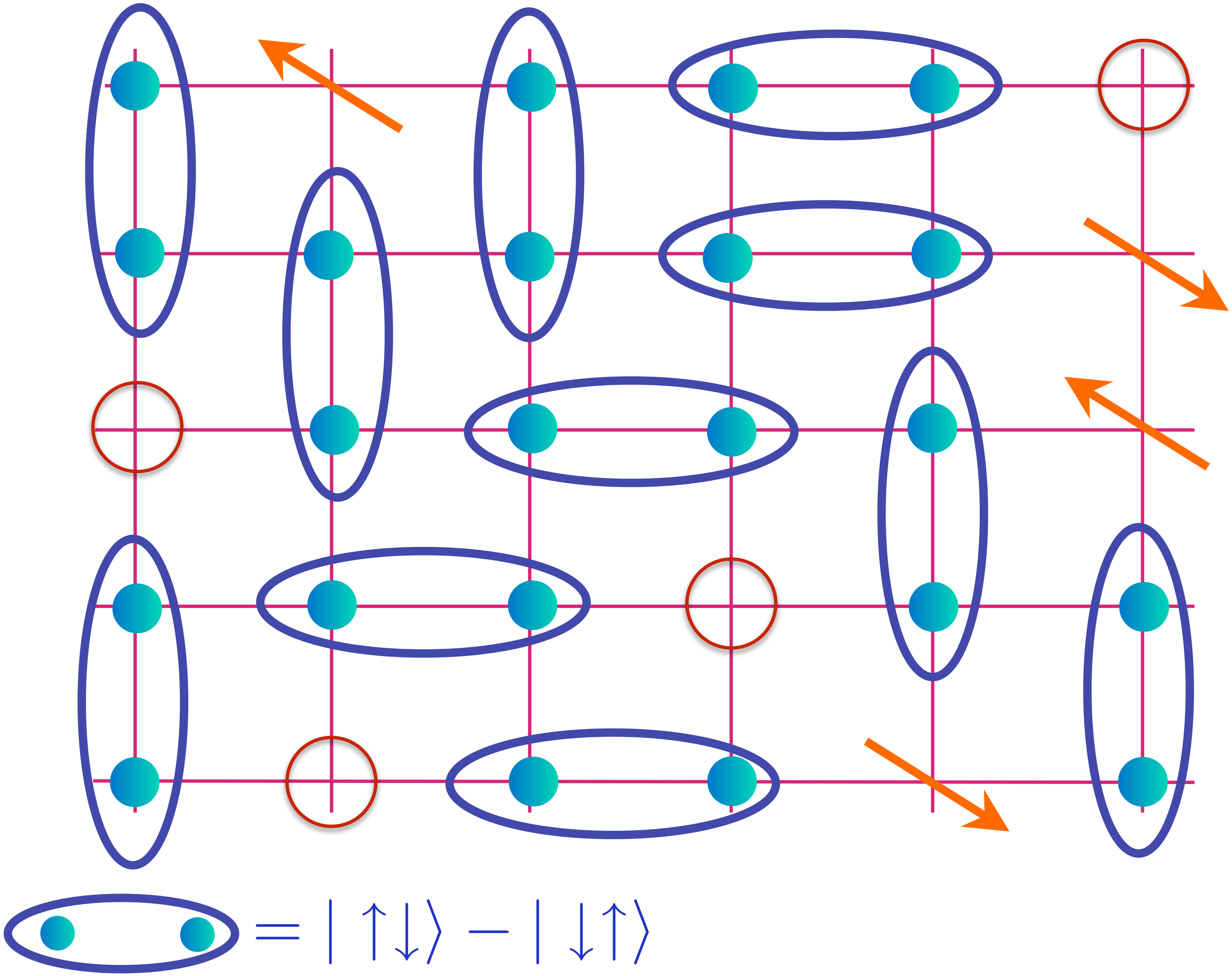
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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*)



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

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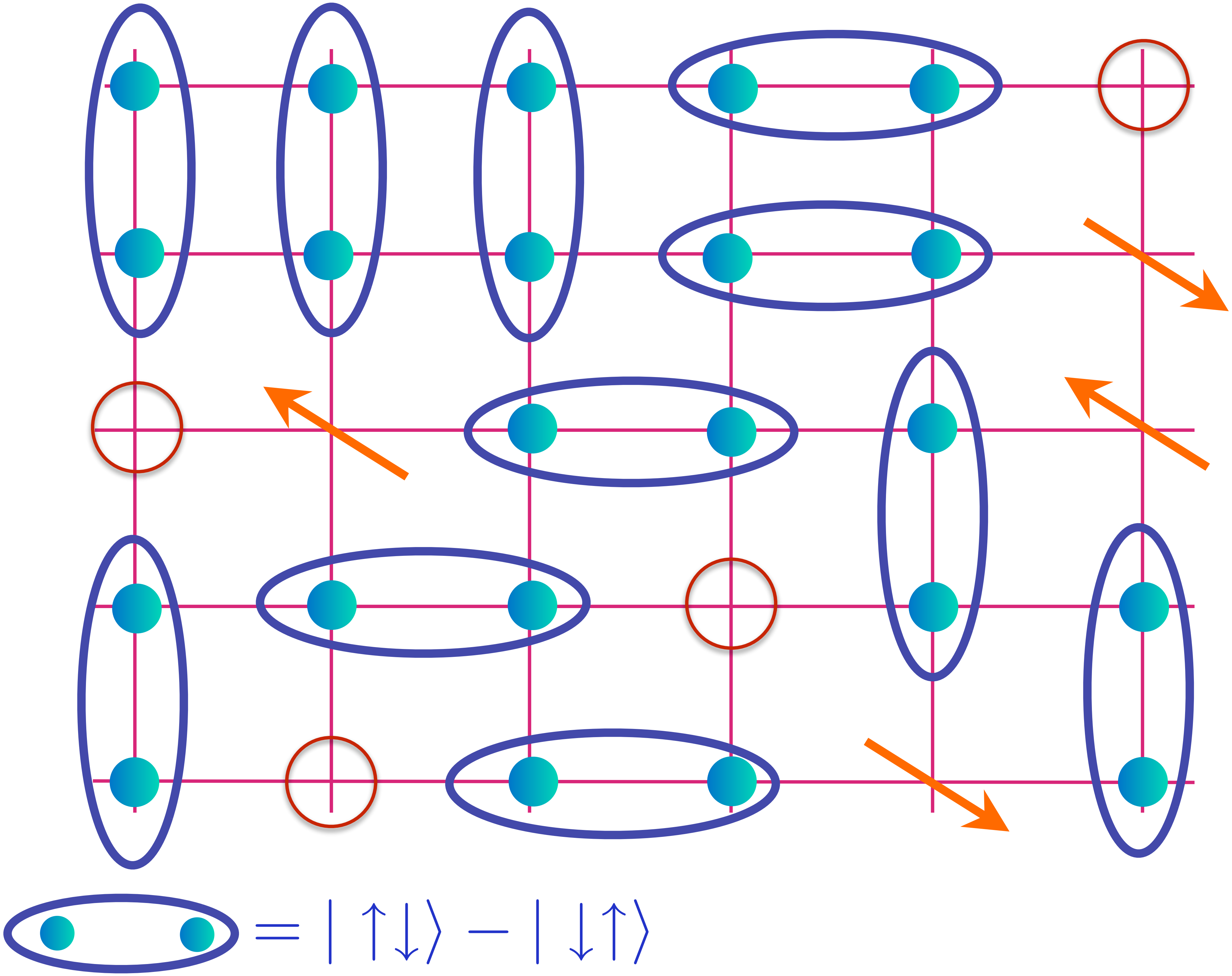

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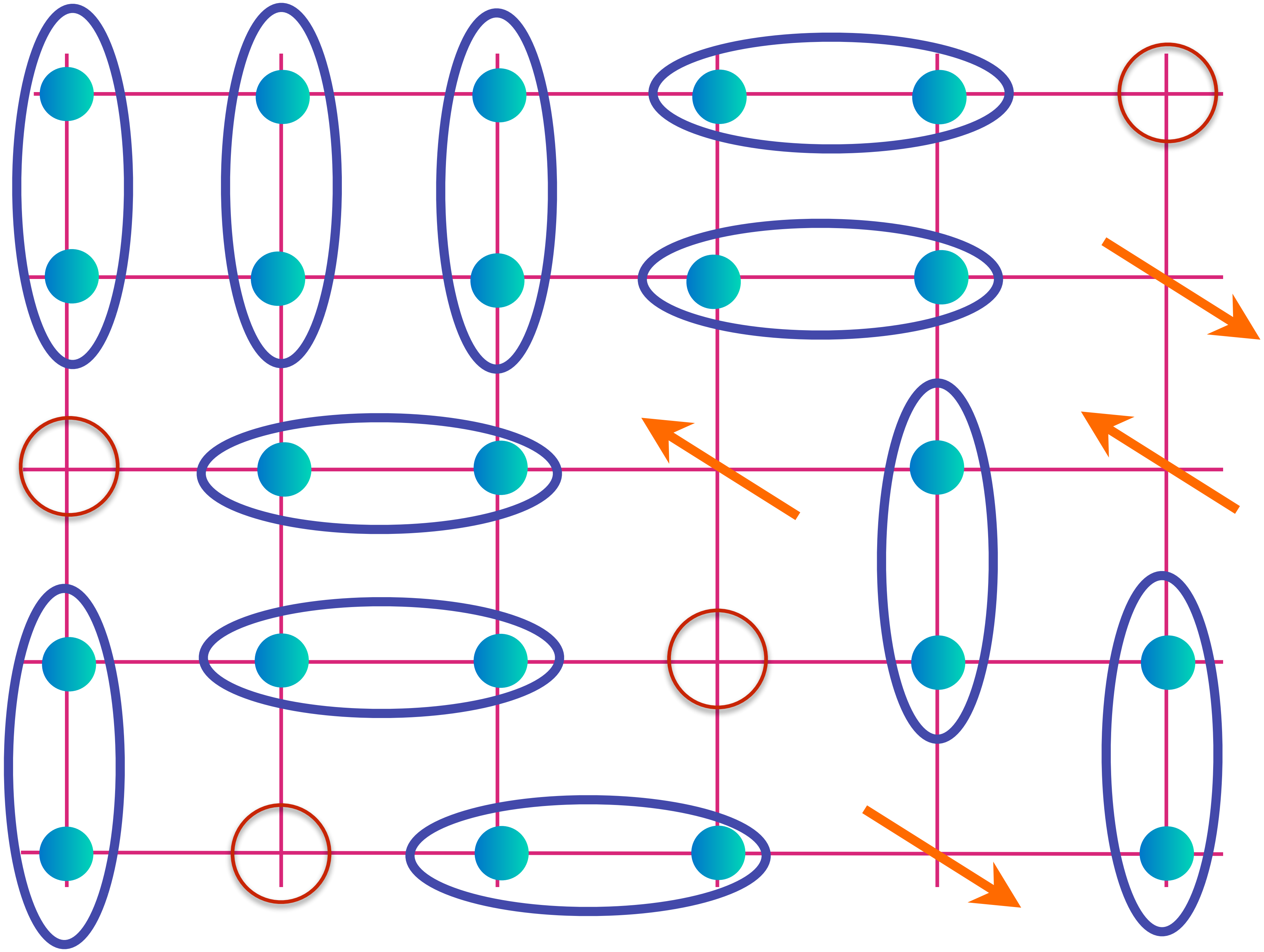
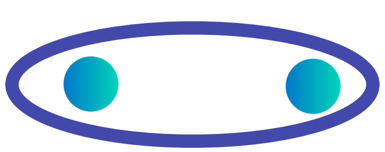
Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)



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

Spin liquid

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

Baskaran, Zou, Anderson, Fradkin, Kivelson…

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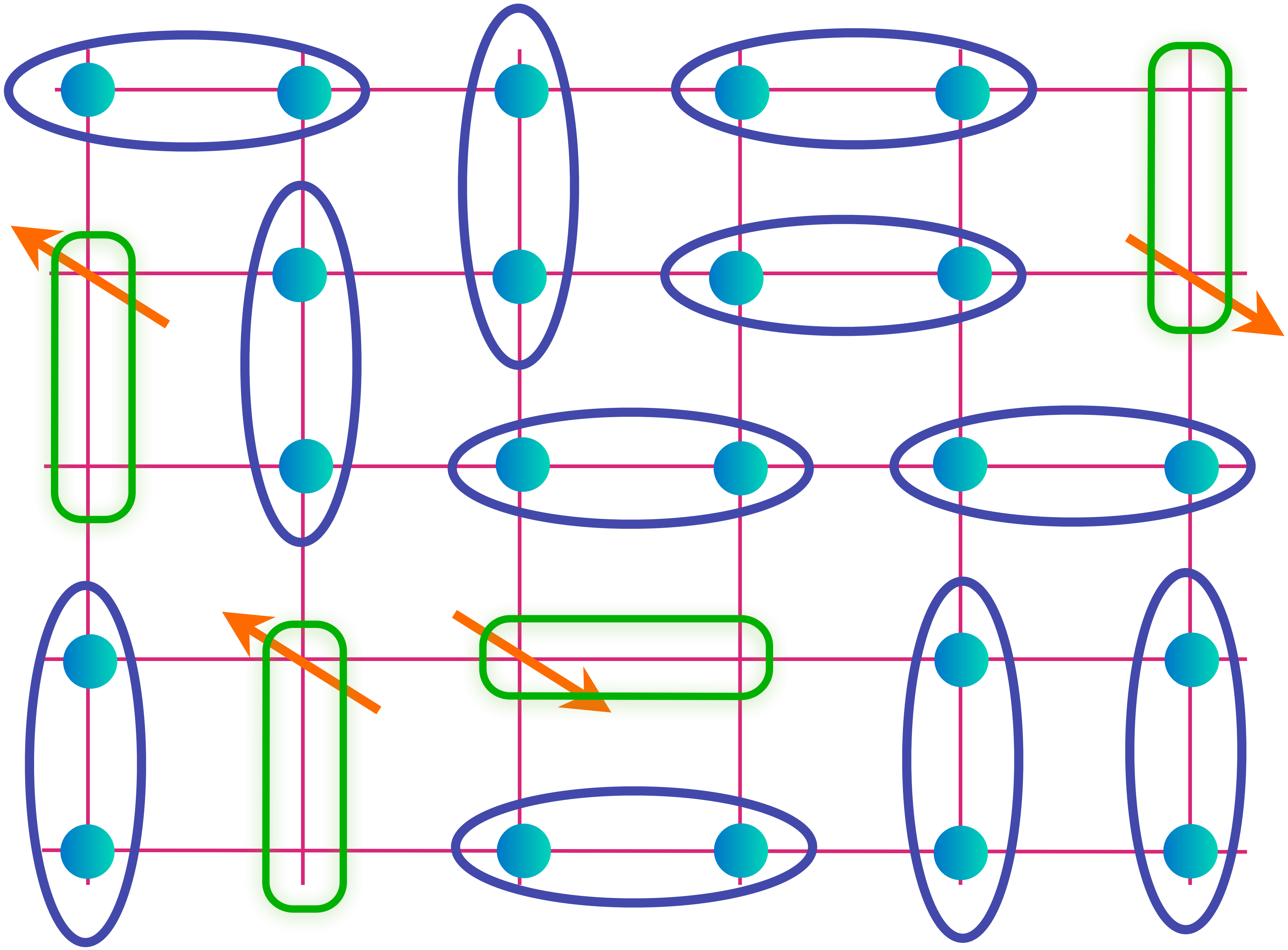

FL* !

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

Charge $+e$, spin $S = 1/2$ holes form Fermi surfaces of total volume p (and not $1 + p$ as in a Fermi liquid).

M. Punk and S. Sachdev, *Phys. Rev. B* **85**, 195123 (2012)

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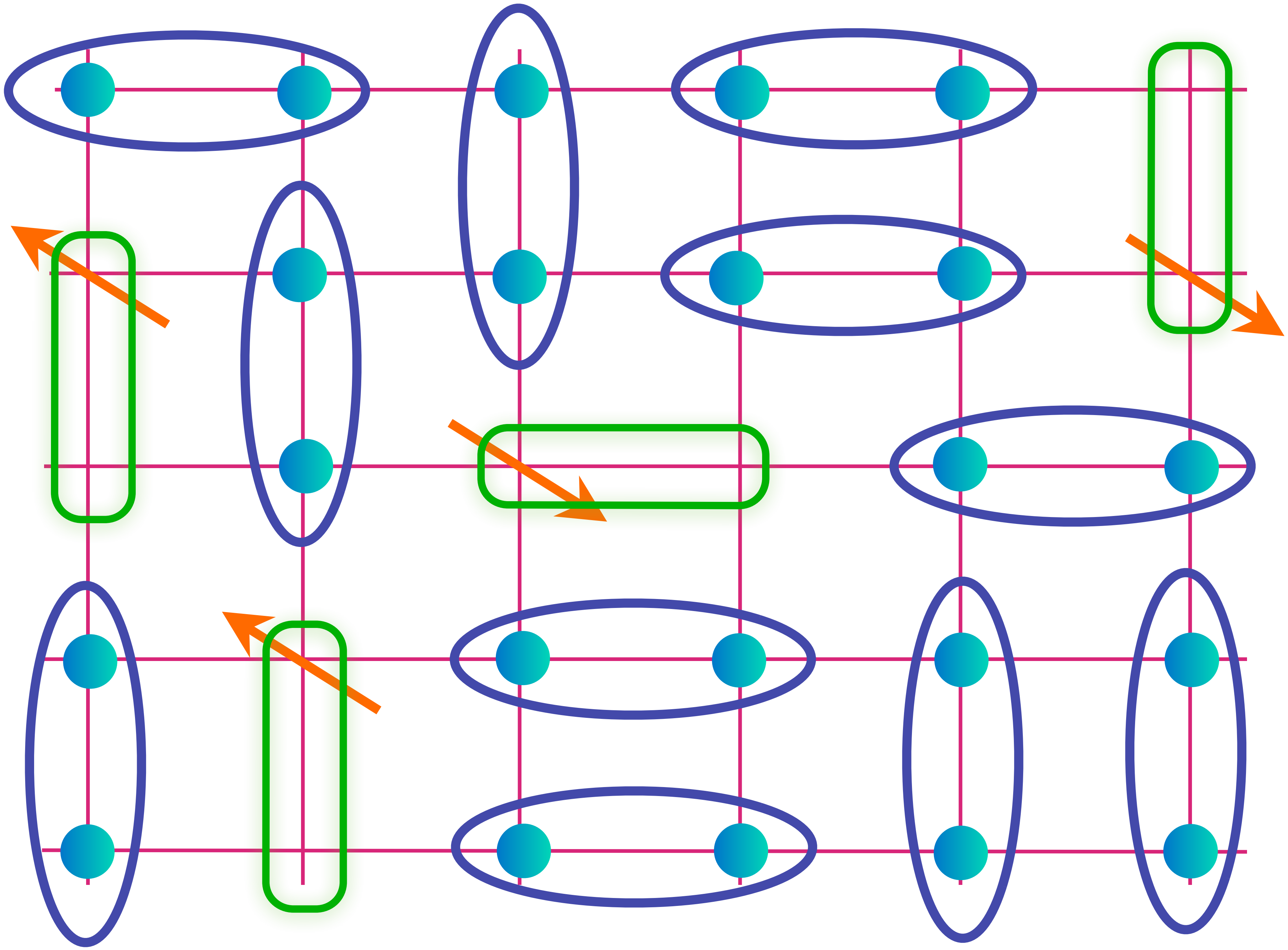

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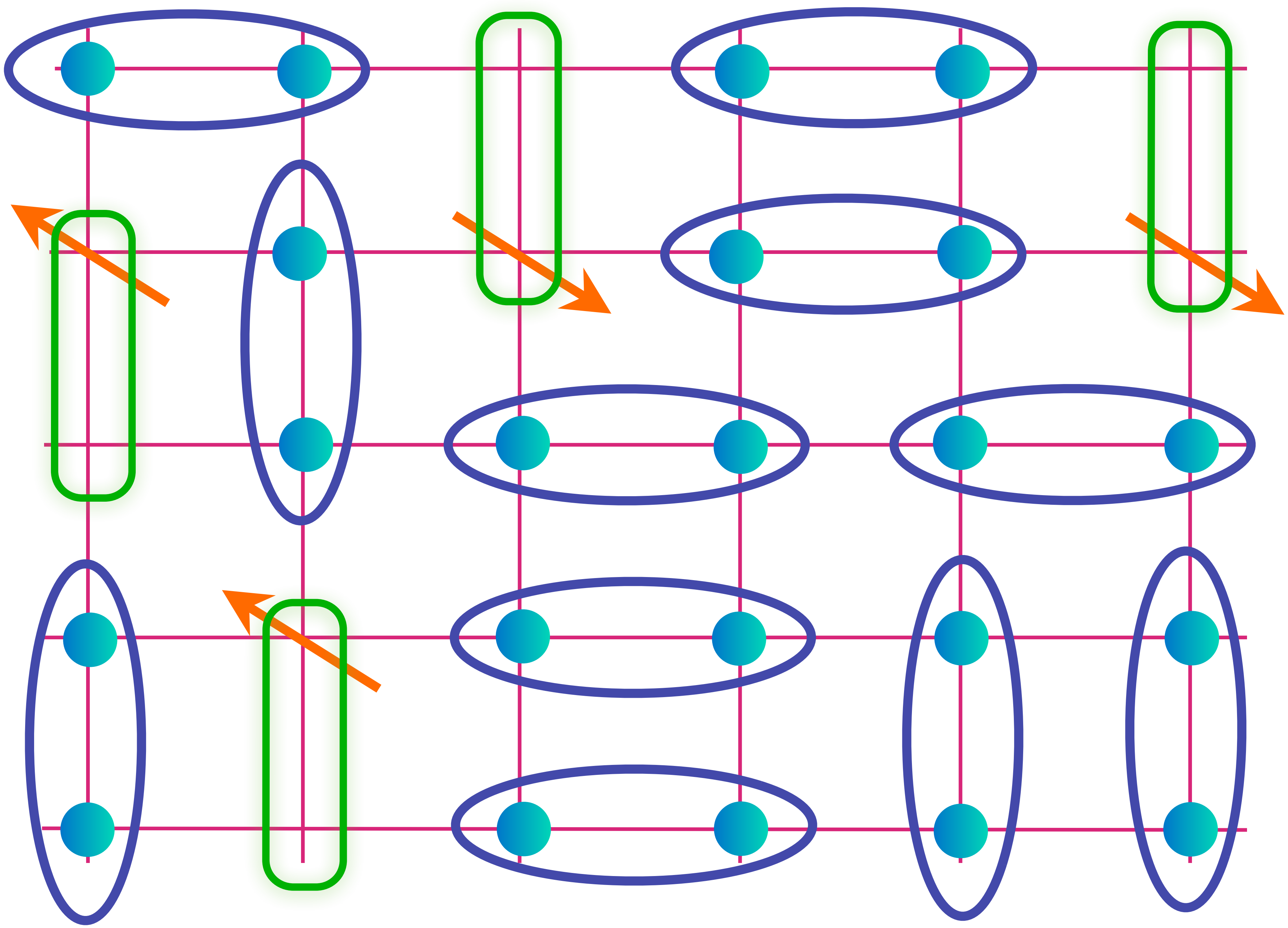

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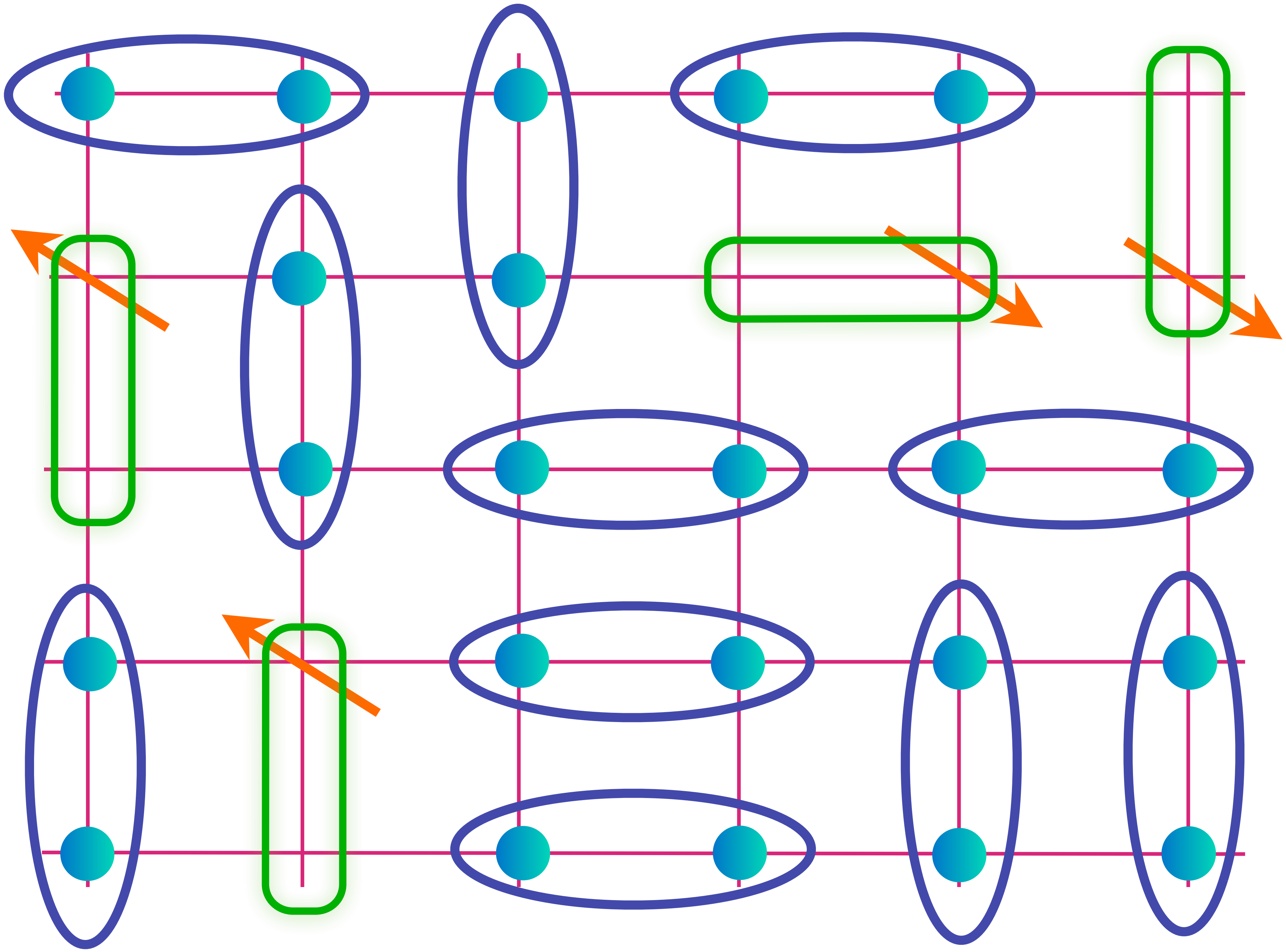

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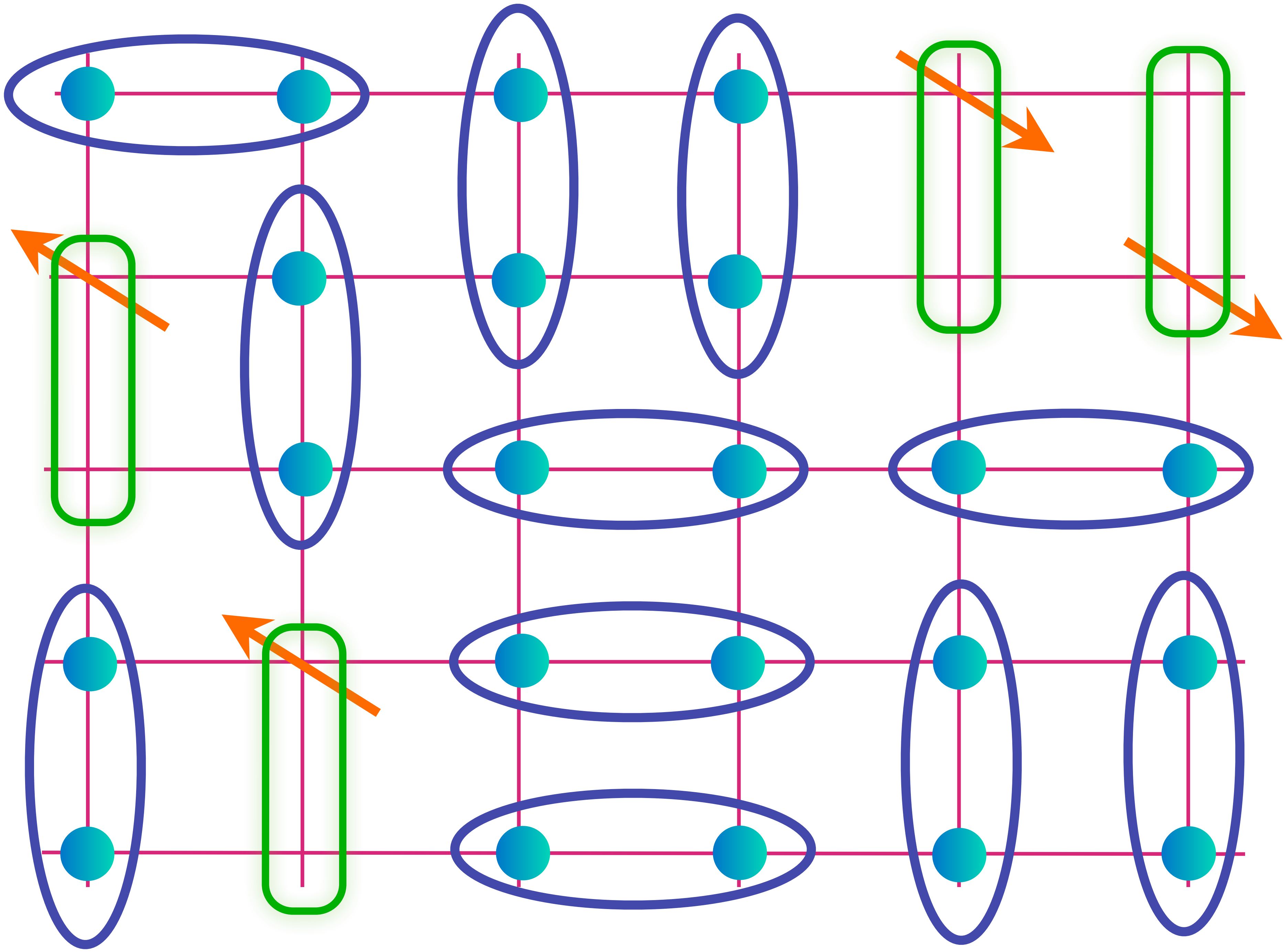

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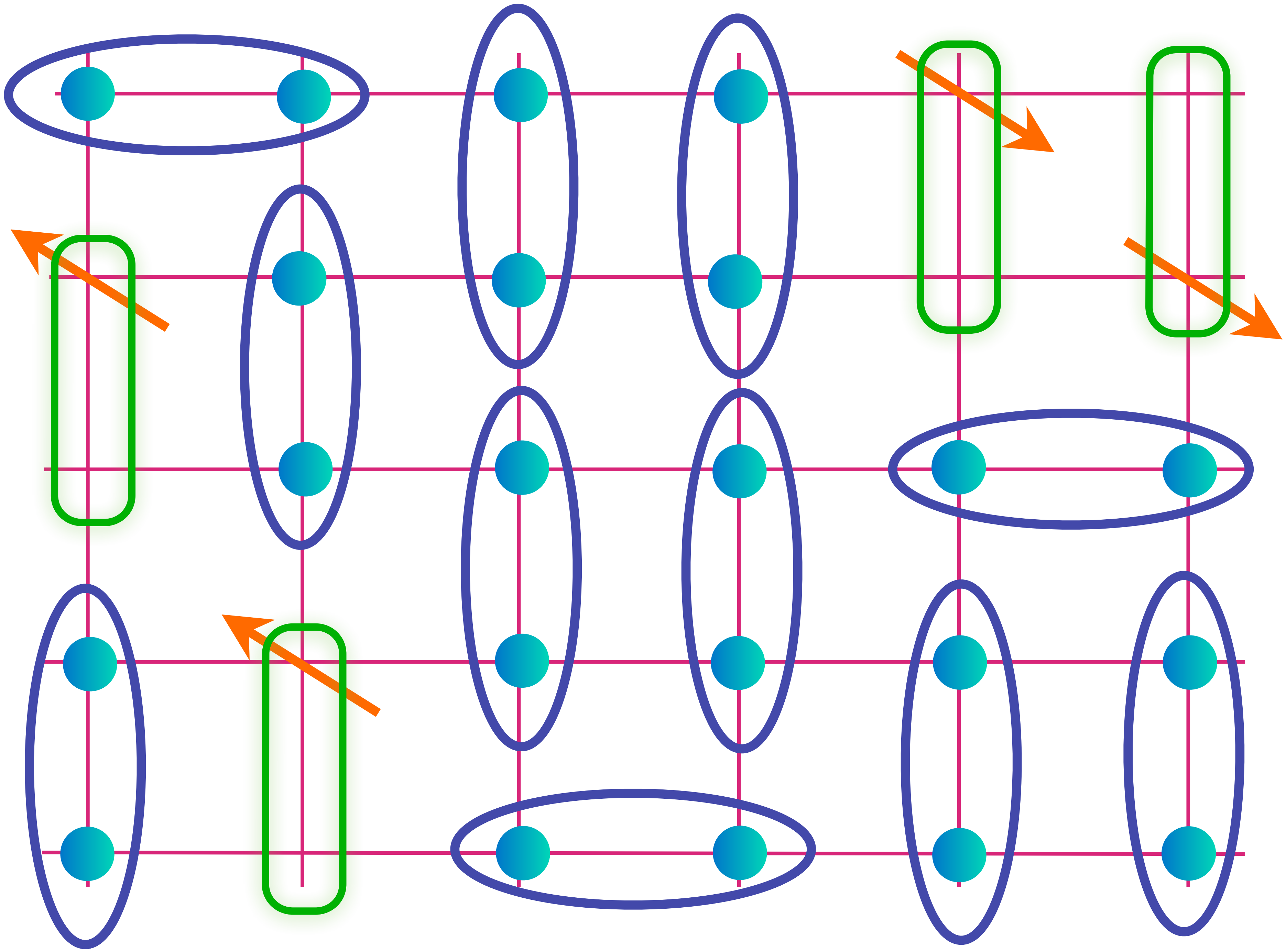

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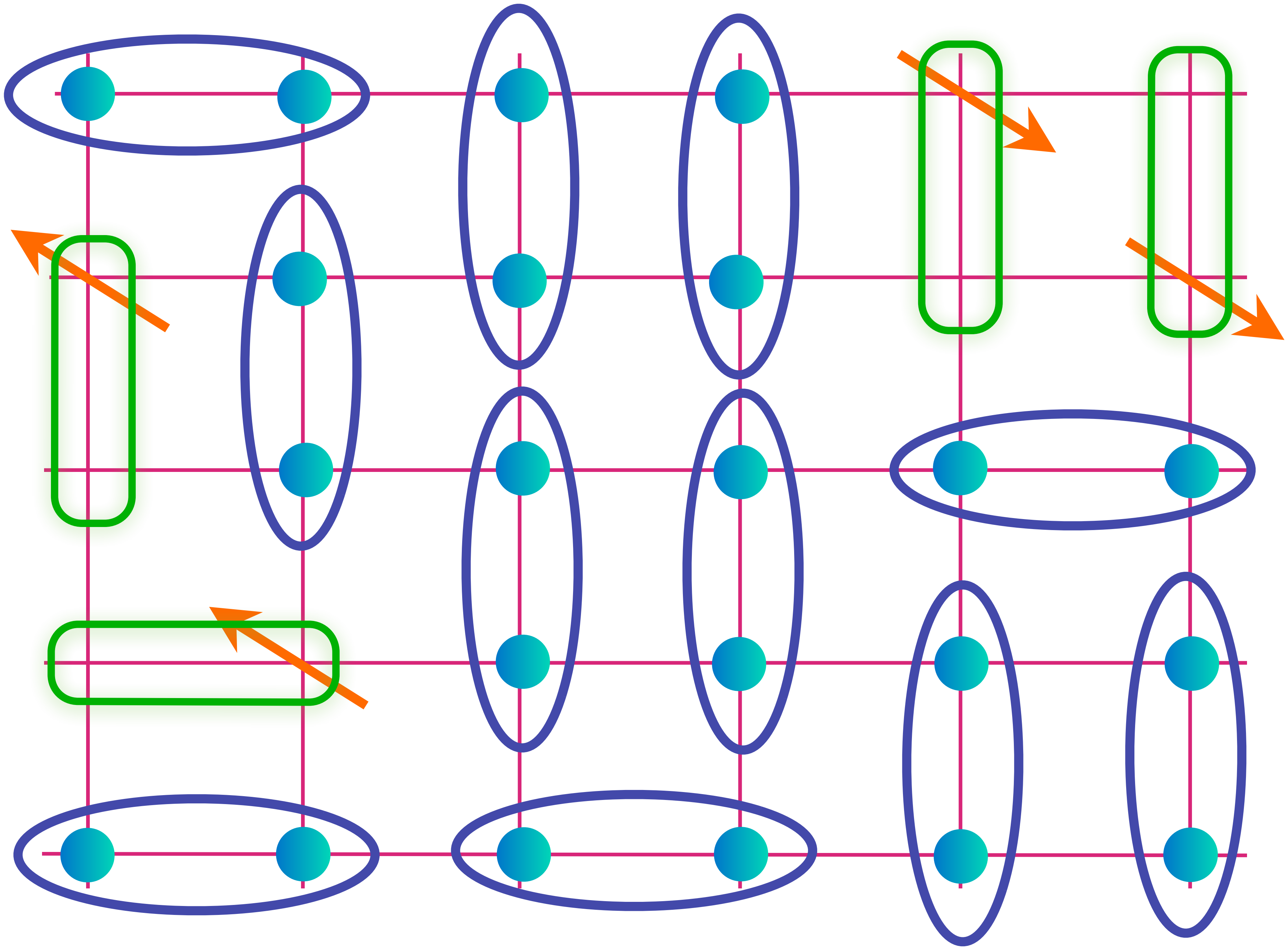

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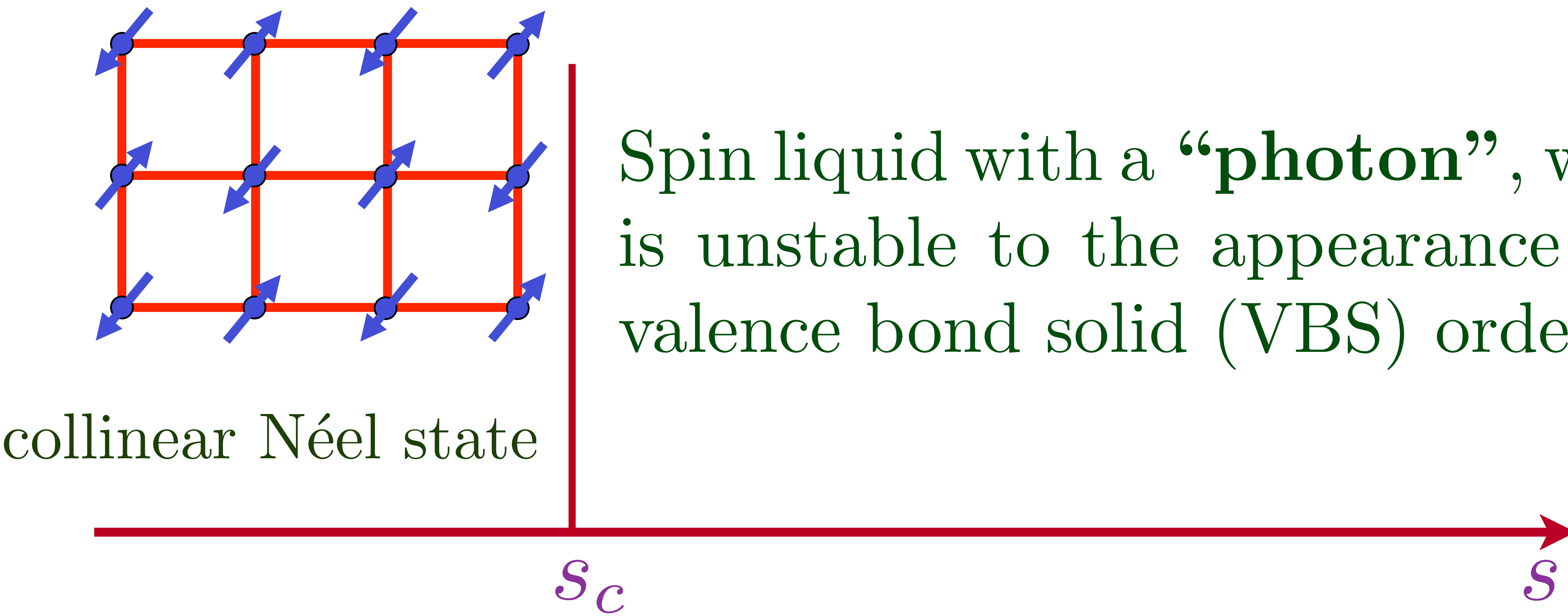
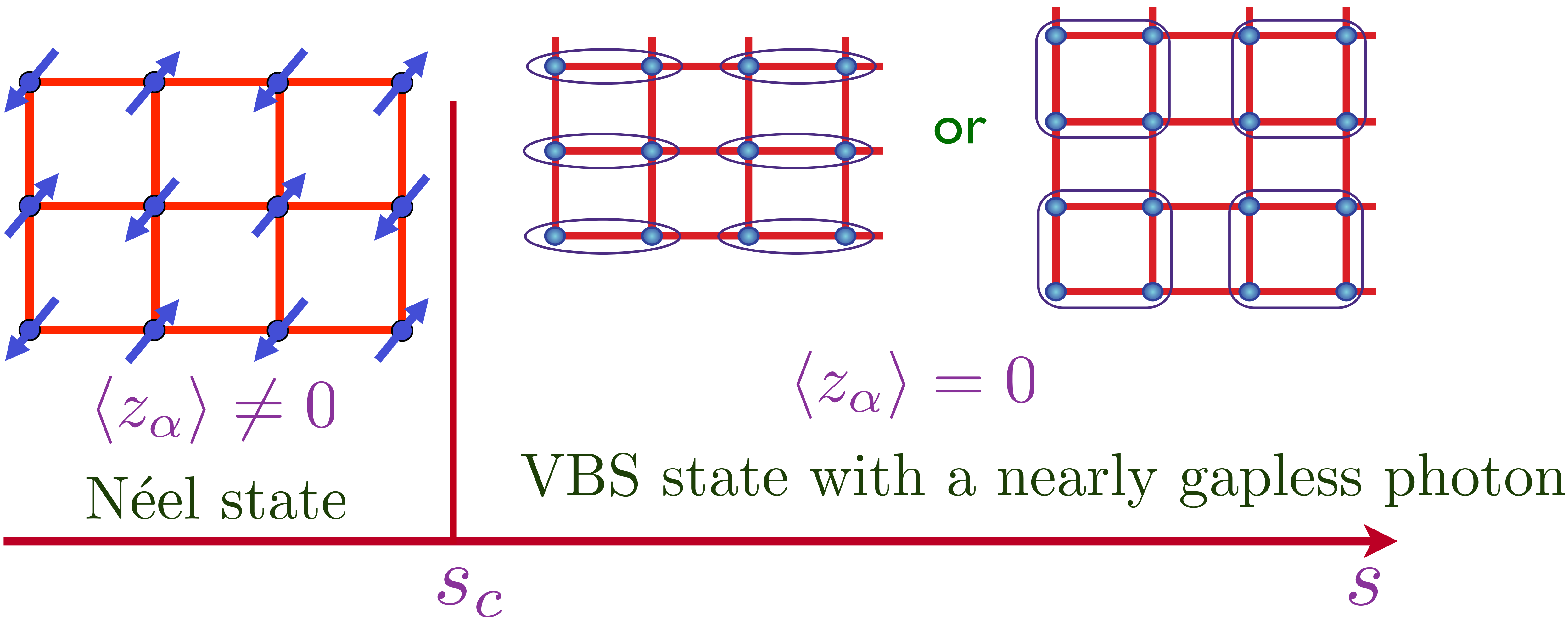
M. Punk and S. Sachdev, *Phys. Rev. B* **85**, 195123 (2012)

Quantum "disordering" magnetic order



N. Read and S. Sachdev, *Phys. Rev. Lett.* **62**, 1694 (1989).

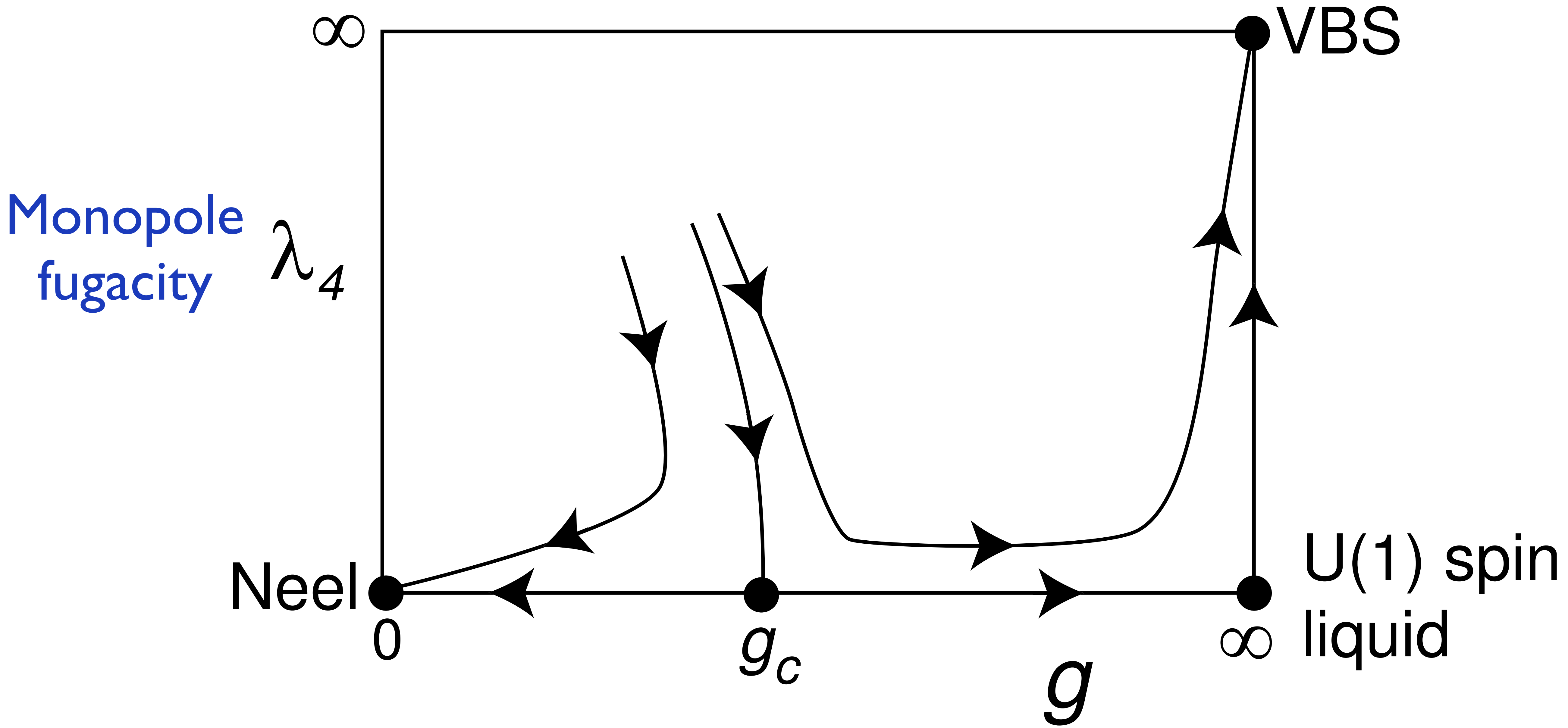
Neel-VBS quantum transition



Critical theory for photons and deconfined spinons:

$$\mathcal{S}_z = \int d^2r d\tau \left[|(\partial_\mu - iA_\mu) z_\alpha|^2 + s|z_\alpha|^2 + u(|z_\alpha|^2)^2 + \frac{1}{2e_0^2}(\epsilon_{\mu\nu\lambda}\partial_\nu A_\lambda)^2 \right]$$

O.I. Motrunich and A. Vishwanath, *Phys. Rev. B* **70**, 075104 (2004).
T. Senthil, A. Vishwanath, L. Balents, S. Sachdev and M.P.A. Fisher, *Science* **303**, 1490 (2004).



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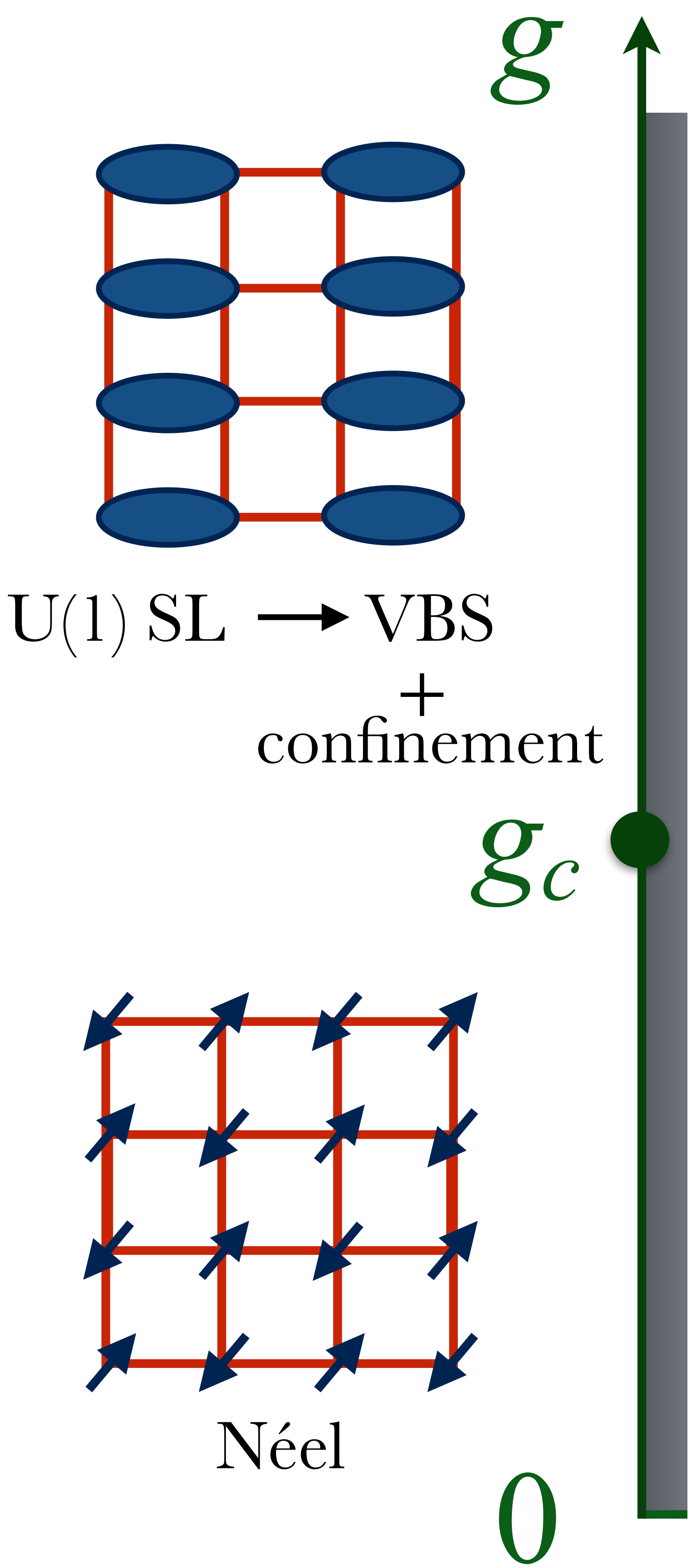
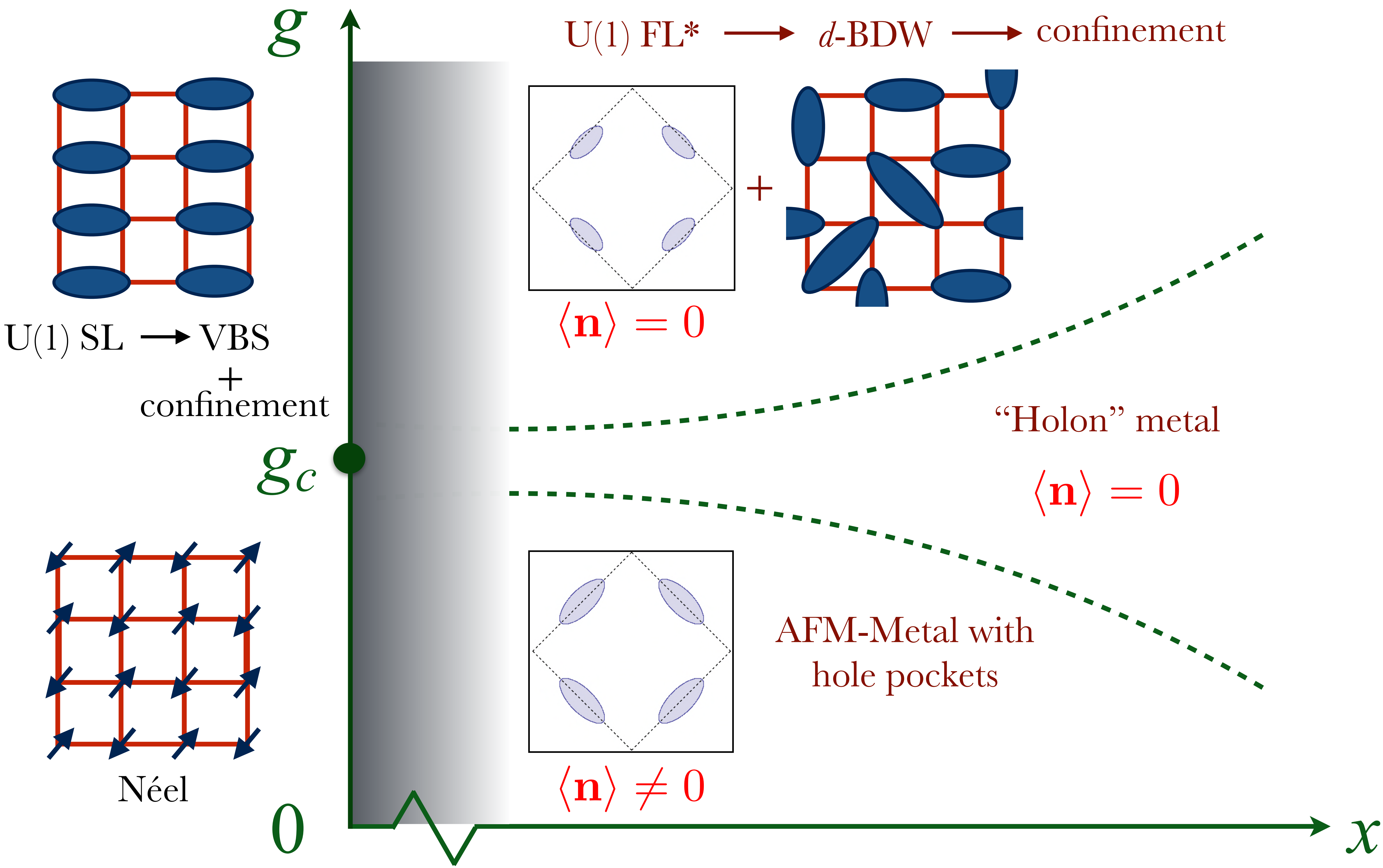
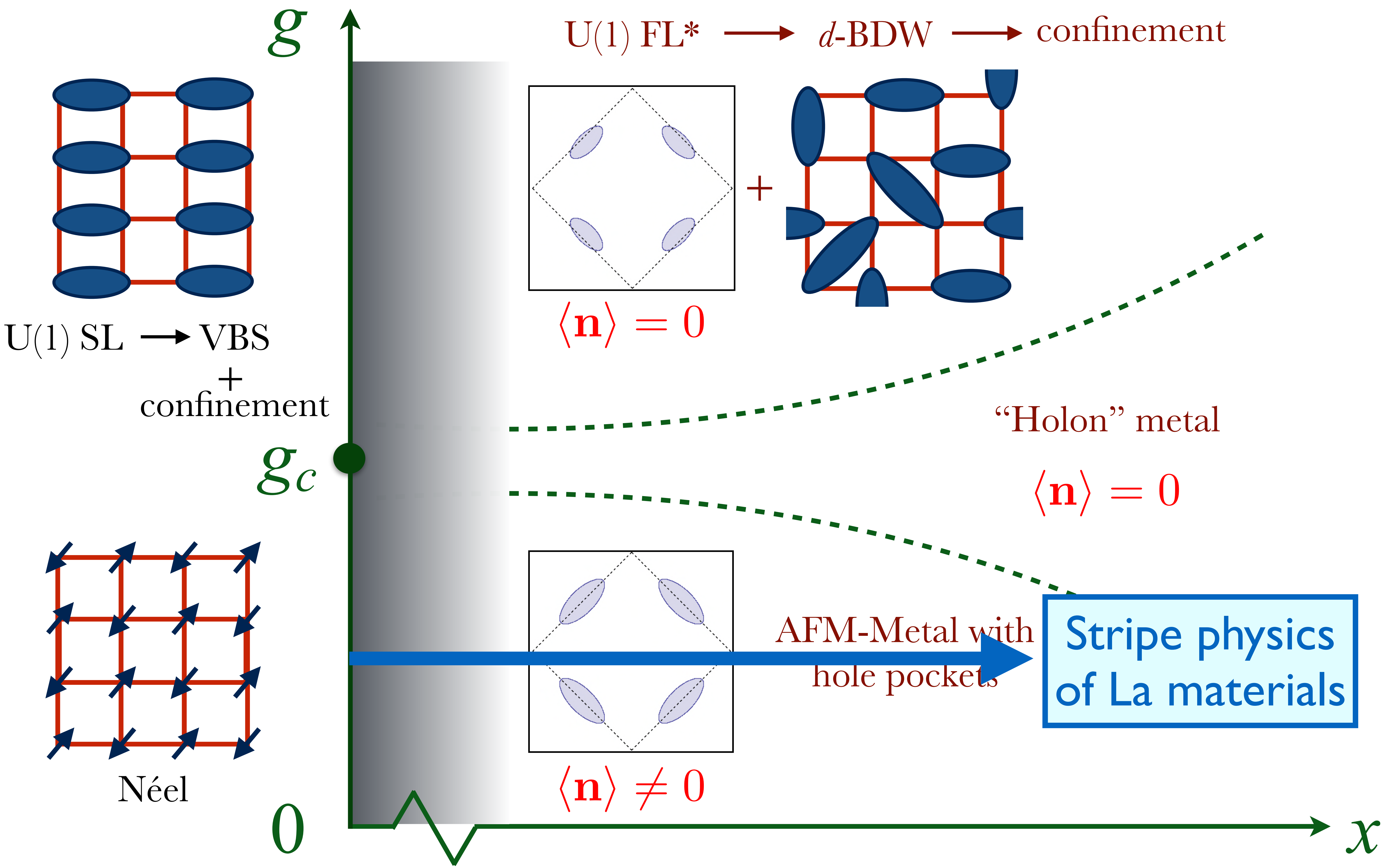


g
U(1) SL → VBS
+
confinement
g_c
Néel
0



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)
D. Chowdhury and S. Sachdev, arXiv:1409.5430



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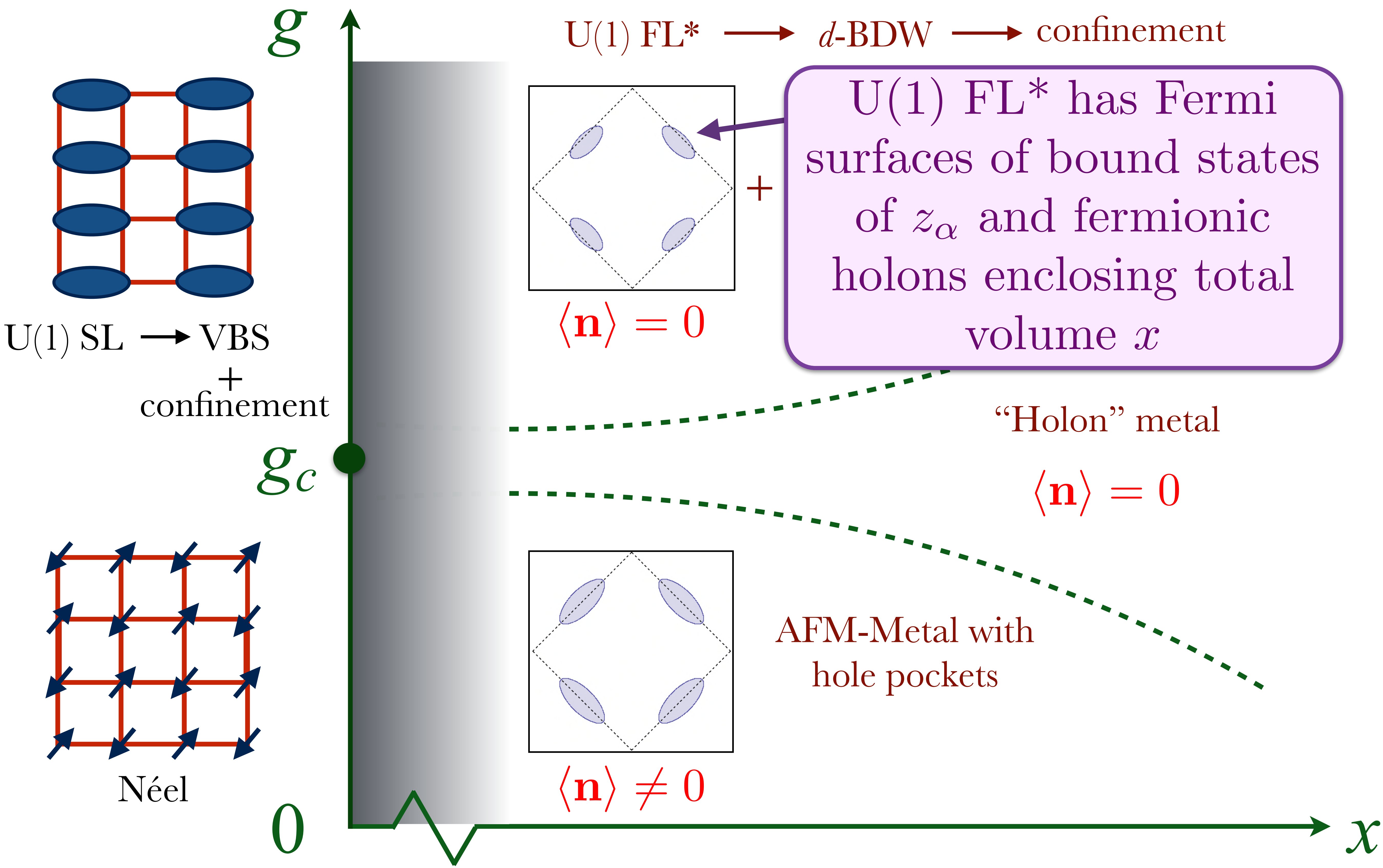

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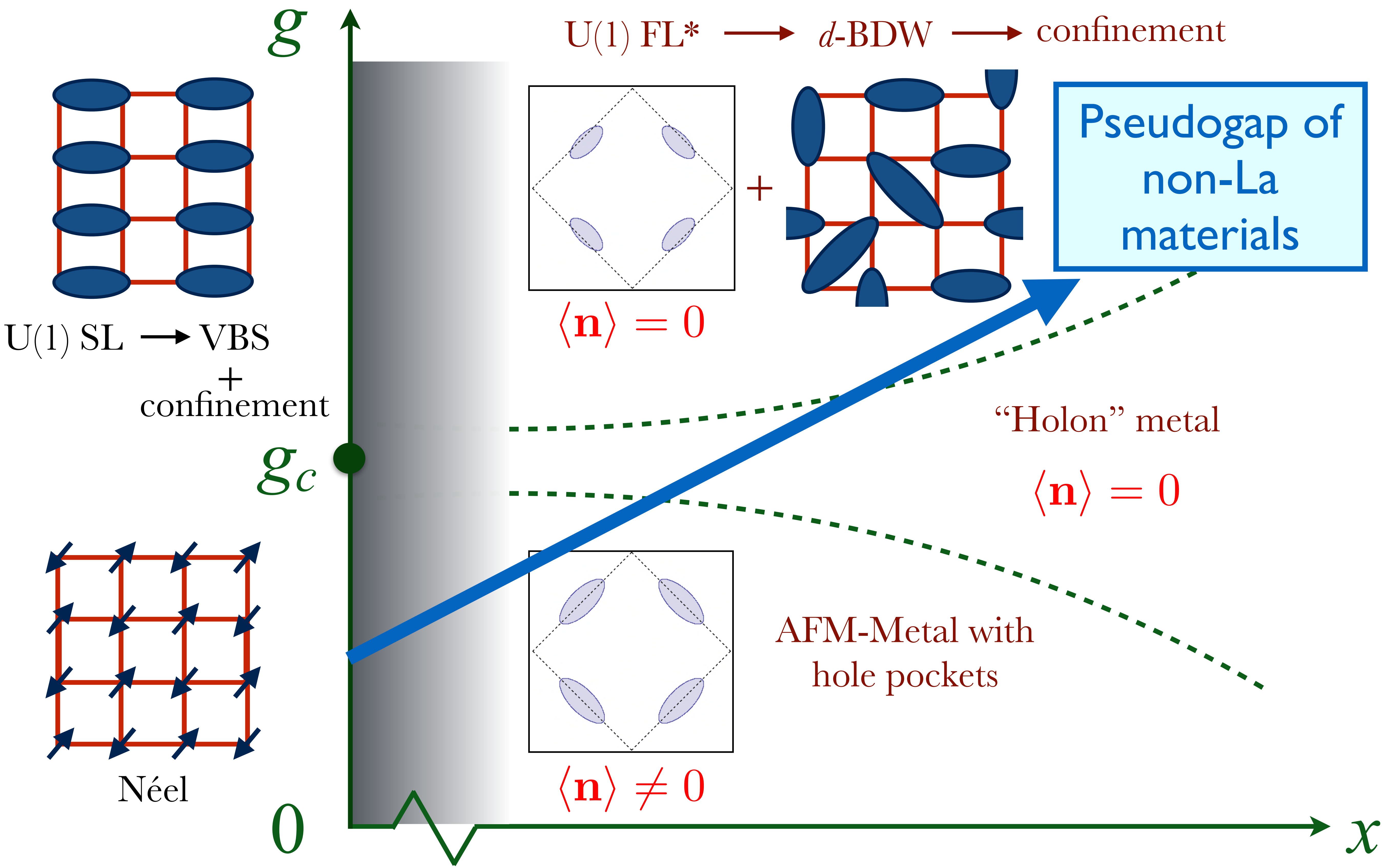

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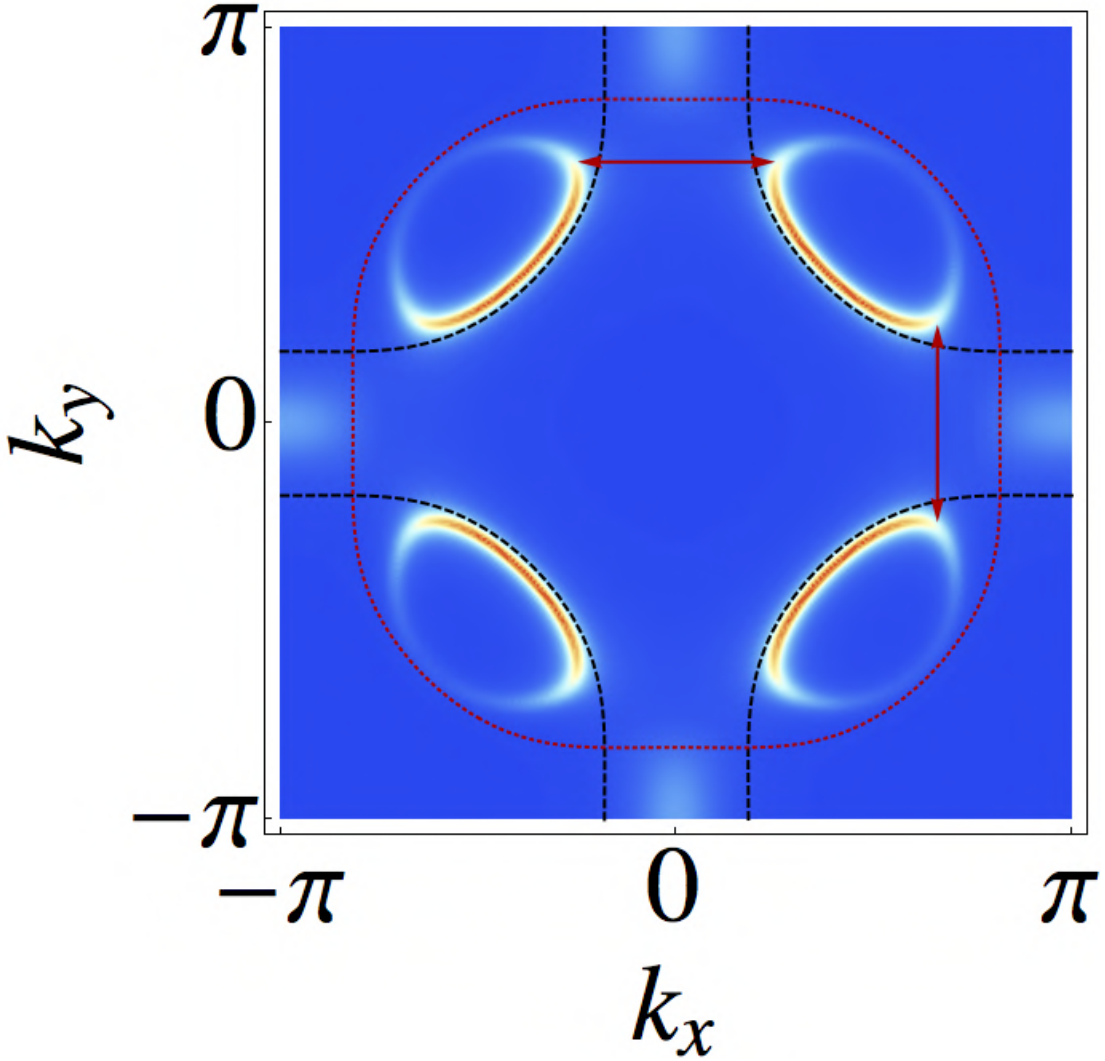

Electron spectral function of FL*

The pseudogap is described by the U(1)-FL*: a state with hole pockets on a background of a spin-liquid described by a U(1) gauge theory. Its dominant density wave instability 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.

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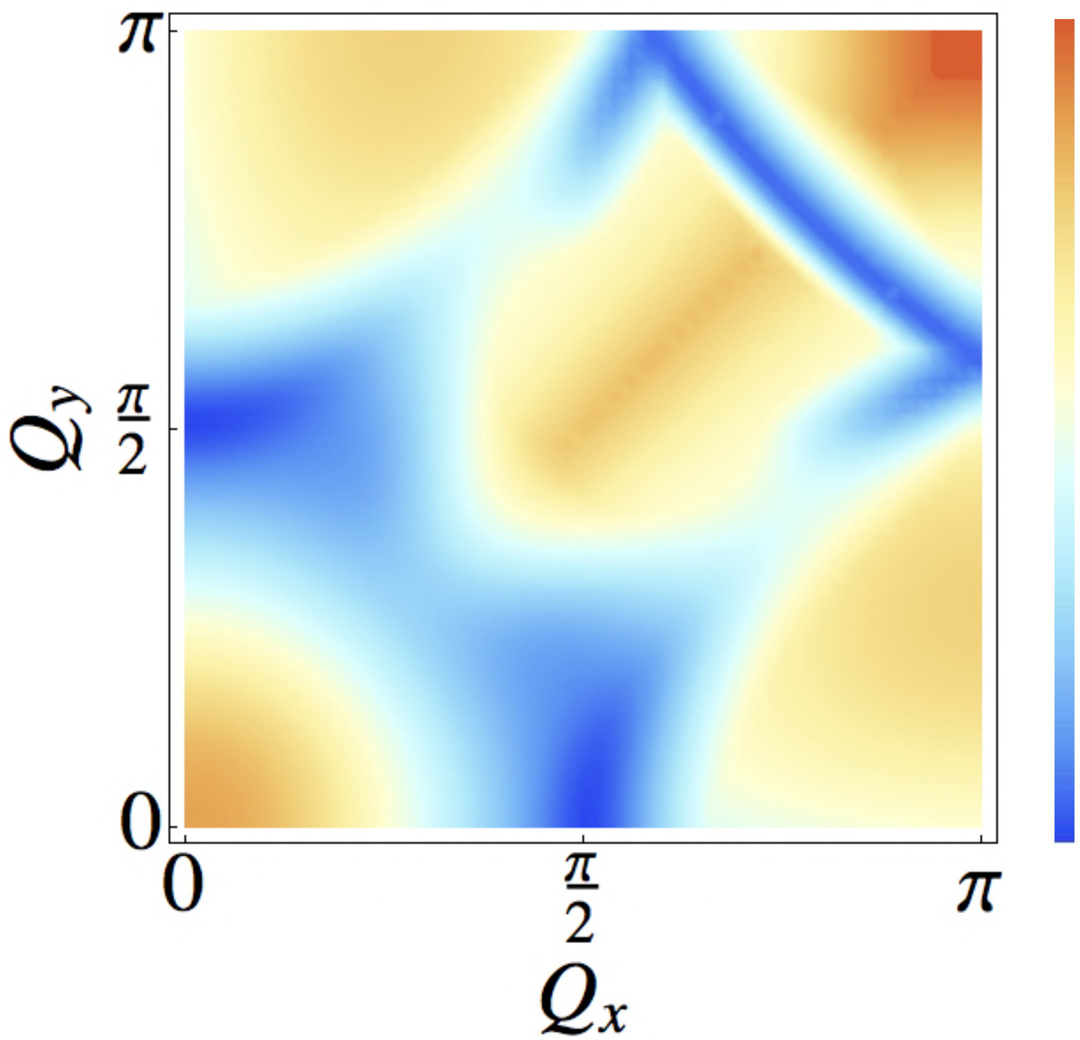

Eigenvalues of spin-singlet, time-reversal-preserving particle-hole propagator

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Conclusions

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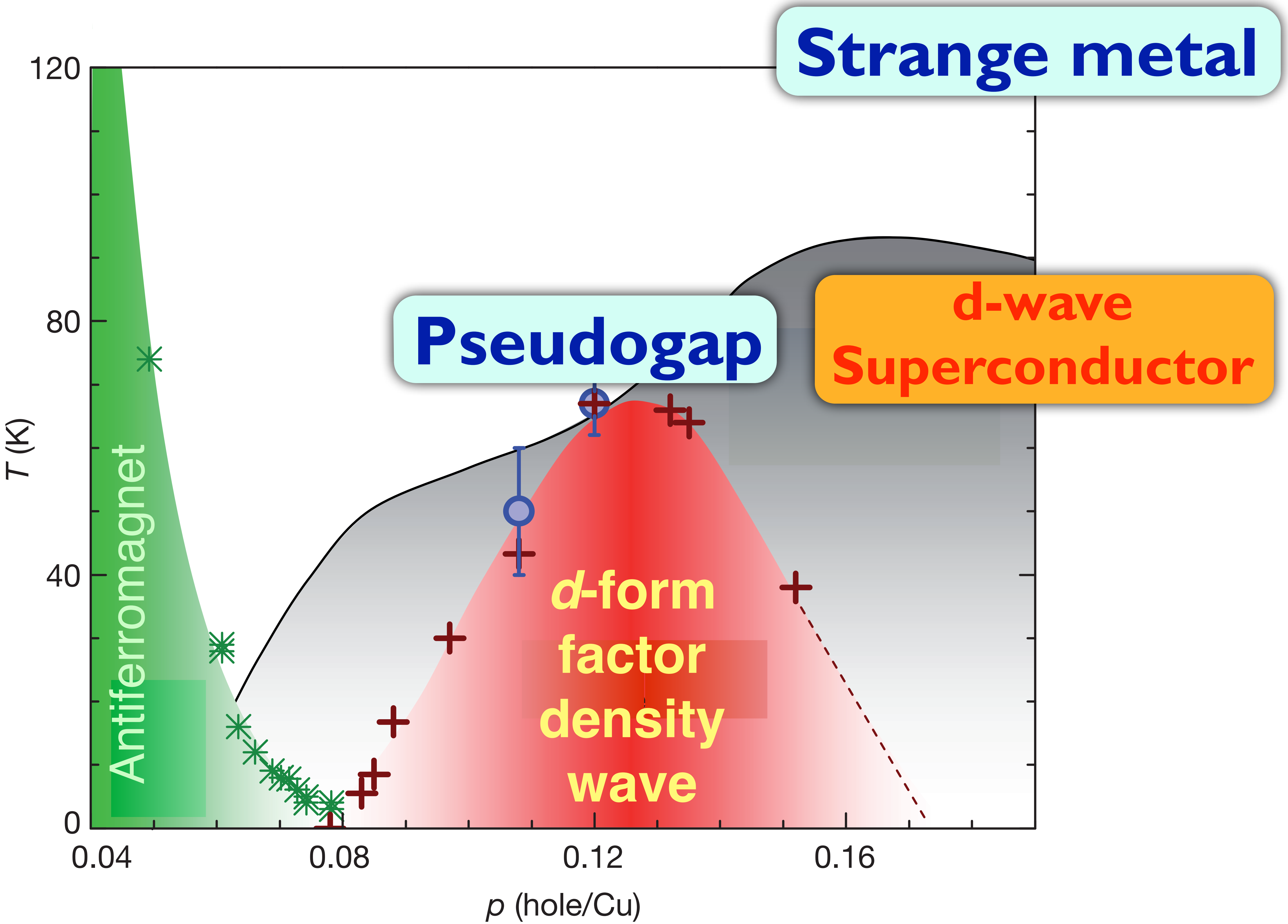
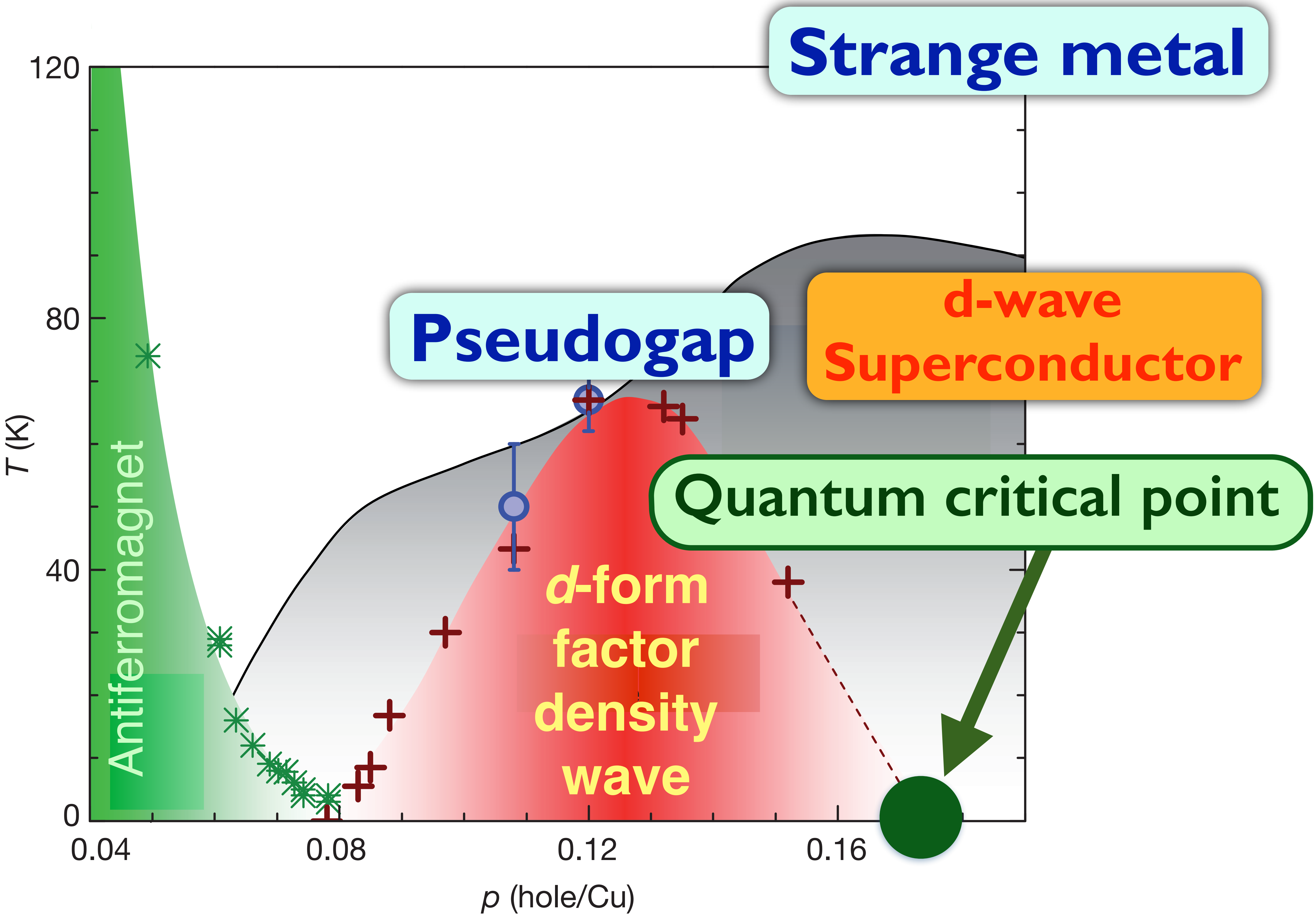
1. *d*-form factor density wave order observed in the non-La hole-doped cuprate superconductors.

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 appears to be an unexpected window into the spin-liquid physics of the pseudogap.


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



Y. He *et al.*, Science **344**, 608 (2014)
K. Fujita *et al.*, Science **344**, 612 (2014)