Adventures with the spin-fermion model, and beyond

Pines@90, SCES@60

University of Illinois, Urbana

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PHYSICS

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

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Talk online: sachdev.physics.harvard.edu

Spin-fermion model @25

PHYSICAL REVIEW B VOLUME 42, NUMBER 1 1 JULY 1990

Phenomenological model of nuclear relaxation in the normal state of $YBa_2Cu_3O_7$

A. J. Millis
AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

Hartmut Monien and David Pines
Physics Department, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801
(Received 27 November 1989; revised manuscript received 7 March 1990)

A phenomenological model of a system of antiferromagnetically correlated spins is shown to give a good quantitative description of NMR, nuclear-quadrupole-resonance, and Knight-shift measurements on yttrium, planar copper, and planar oxygen sites in $YBa_2Cu_3O_7$. The antiferromagnetic correlation length is estimated to be ~ 2.5 lattice constants at $T=100$ K. The temperature dependence of the correlation length ceases at $T_x \simeq 100$ K. The enhancement of the observed relaxation rates over what is expected for weakly interacting electrons is calculated and shown to be large. Extension of the calculation to other cuprate superconductors is discussed.

Spin-fermion model @25

VOLUME 67, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1991

Toward a Theory of High-Temperature Superconductivity in the Antiferromagnetically Correlated Cuprate Oxides

P. Monthoux,[1] A. V. Balatsky,[1],[2],[a] and D. Pines[1]
[1] *Department of Physics, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801*
[2] *Landau Institute for Theoretical Physics, Moscow, U.S.S.R.*
(Received 17 July 1991)

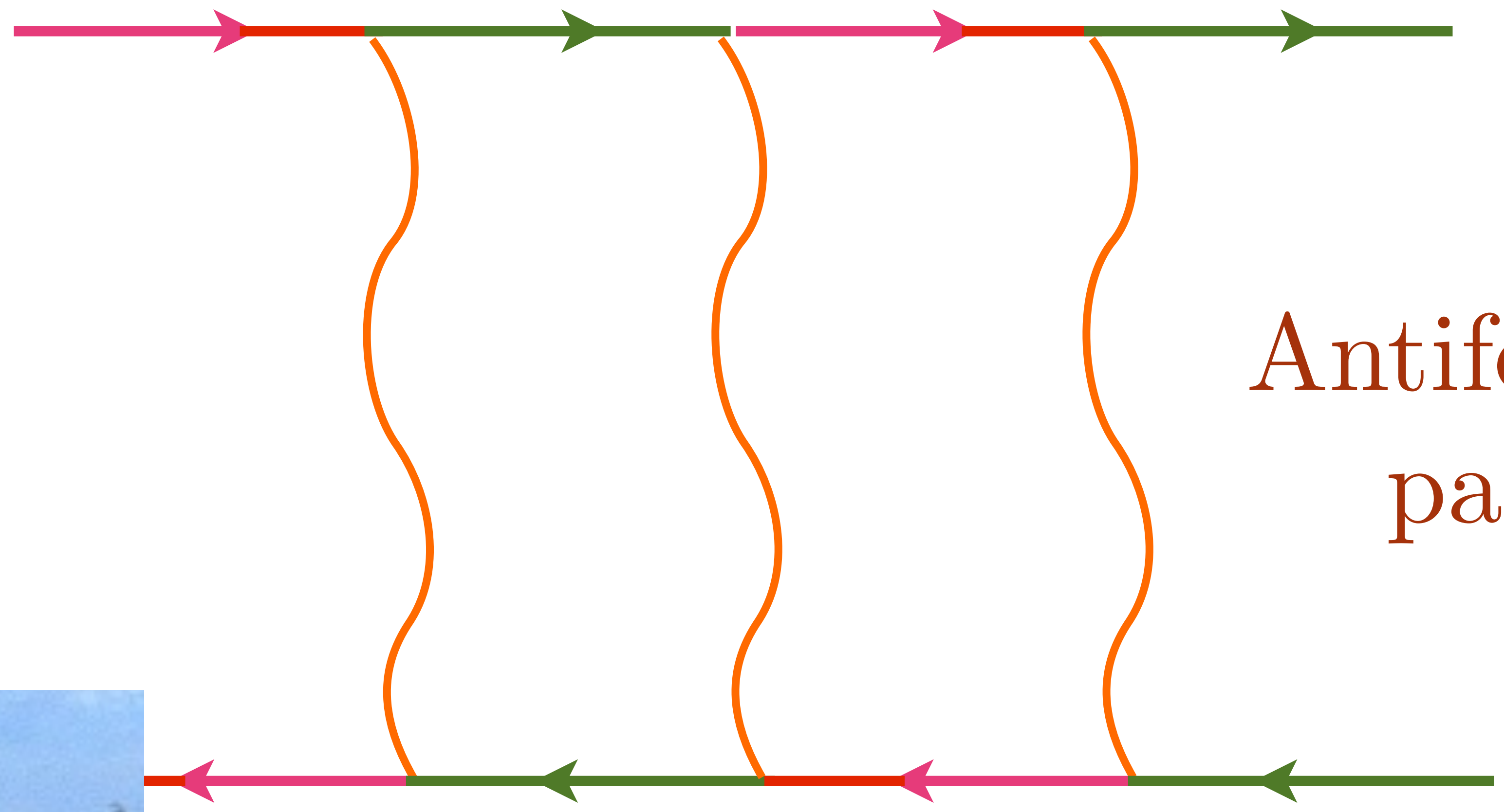
We show that the retarded interaction between quasiparticles on a 2D square lattice induced by the exchange of antiferromagnetic paramagnons leads uniquely to a transition to a superconducting state with $d_{x^2-y^2}$ symmetry. With a spin-excitation spectrum and a quasiparticle-paramagnon coupling determined by fits to normal-state experiments, we obtain high transition temperatures and energy-gap behaviors comparable to those measured for $YBa_2Cu_3O_7$, $YBa_2Cu_3O_{6.63}$, and $La_{1.85}Sr_{0.15}CuO_4$.

Spin-fermion model @25

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

Spin-fermion model @25

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



Antiferromagnetic paramagnon

Max Metlitski

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)

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

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

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

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)

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

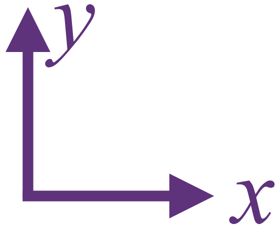
Time-reversal symmetry requires $\mathcal{P}(\mathbf{k}) = \mathcal{P}(-\mathbf{k})$.

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)

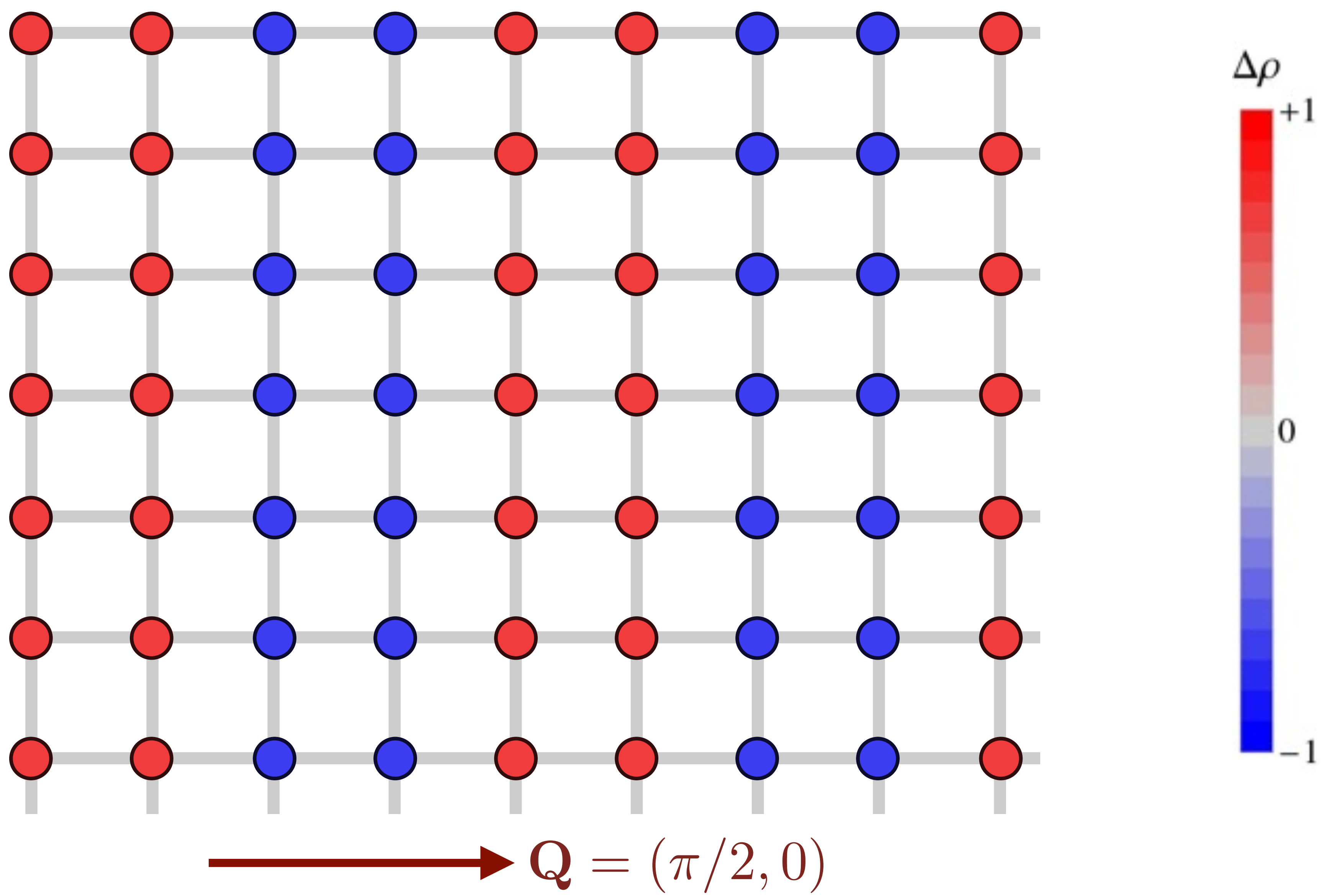
Conventional CDW order: s-form factor



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

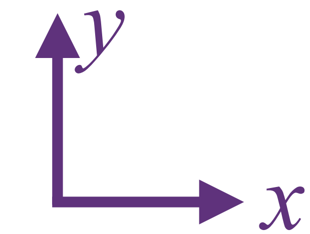
$$P_{ij} = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2} + \text{c.c.}$$

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



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

Unconventional DW order: s'-form factor



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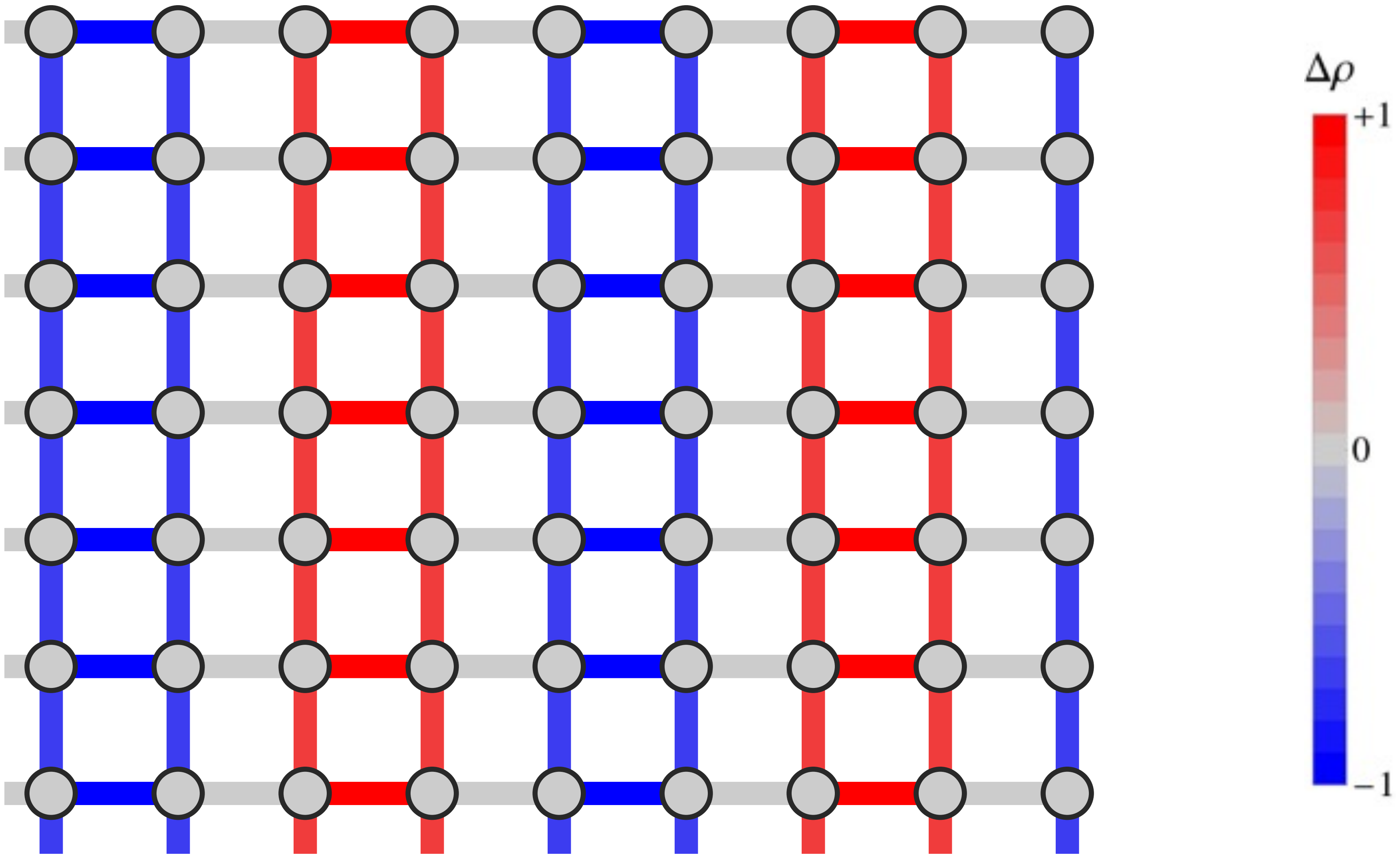
$$P_{ij} = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2} + \text{c.c.}$$

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



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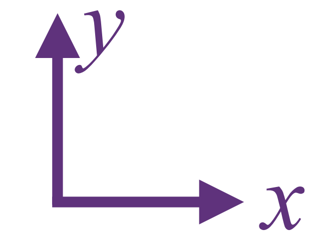
Unconventional DW order: s'-form factor



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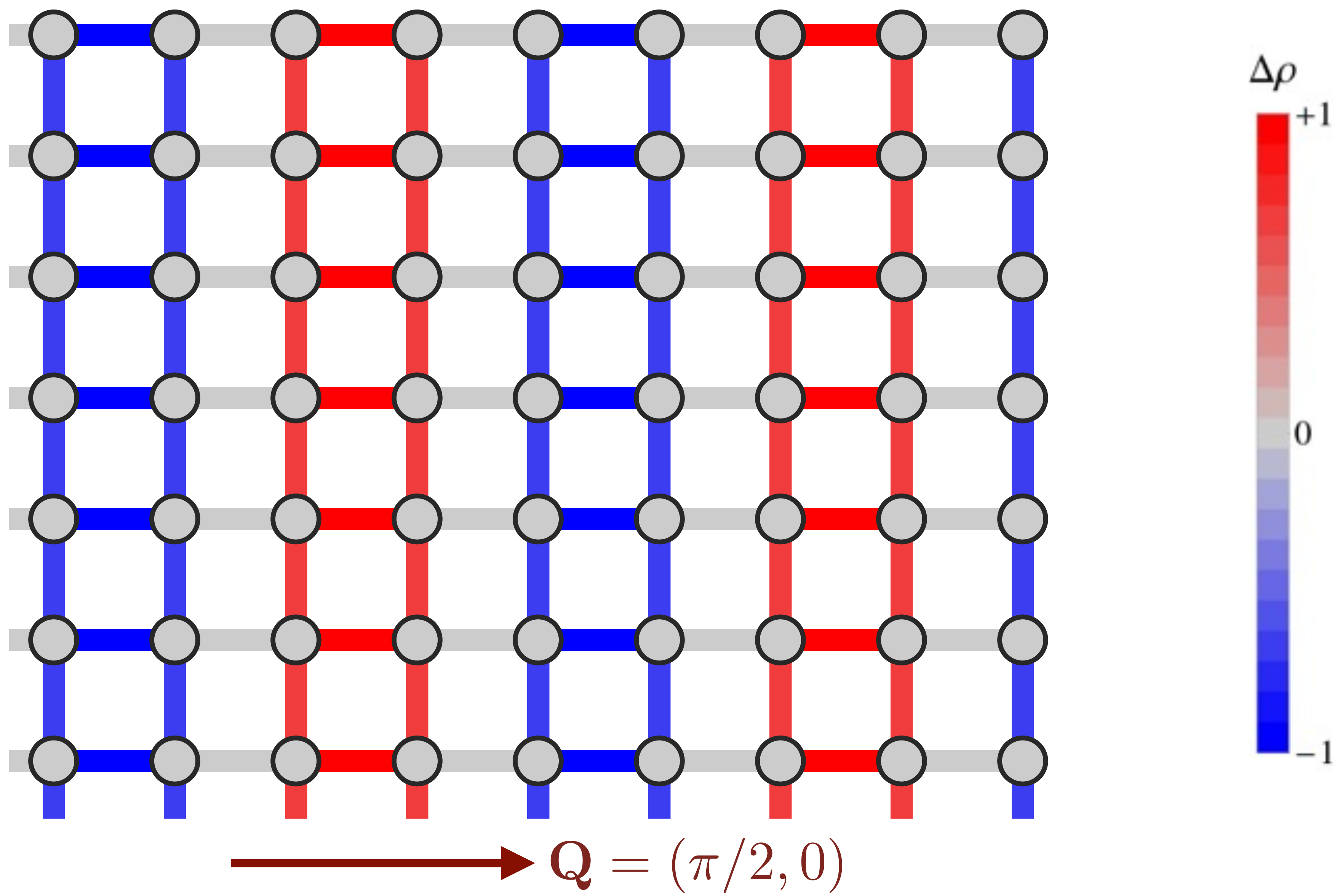
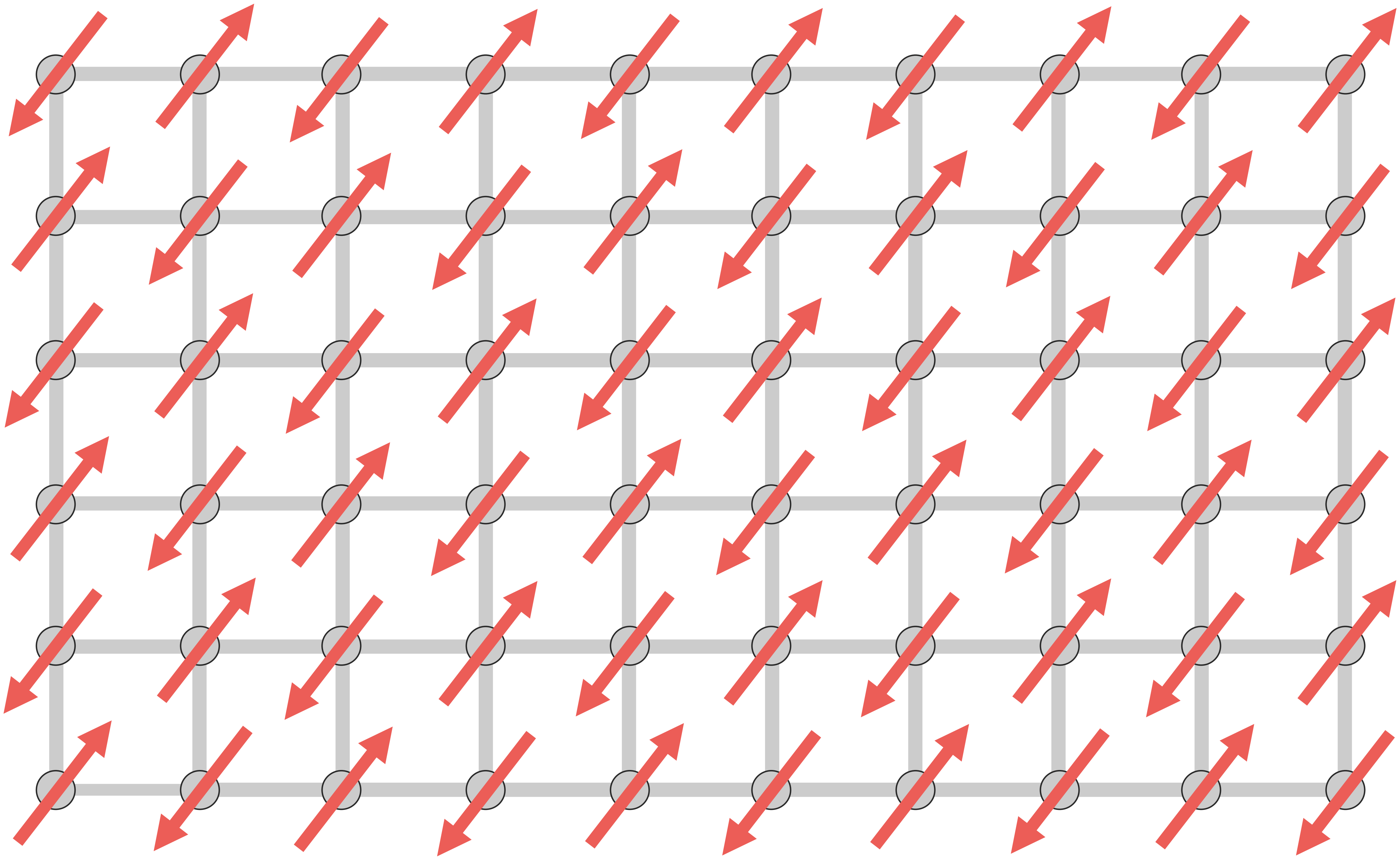
"Stripe" model !



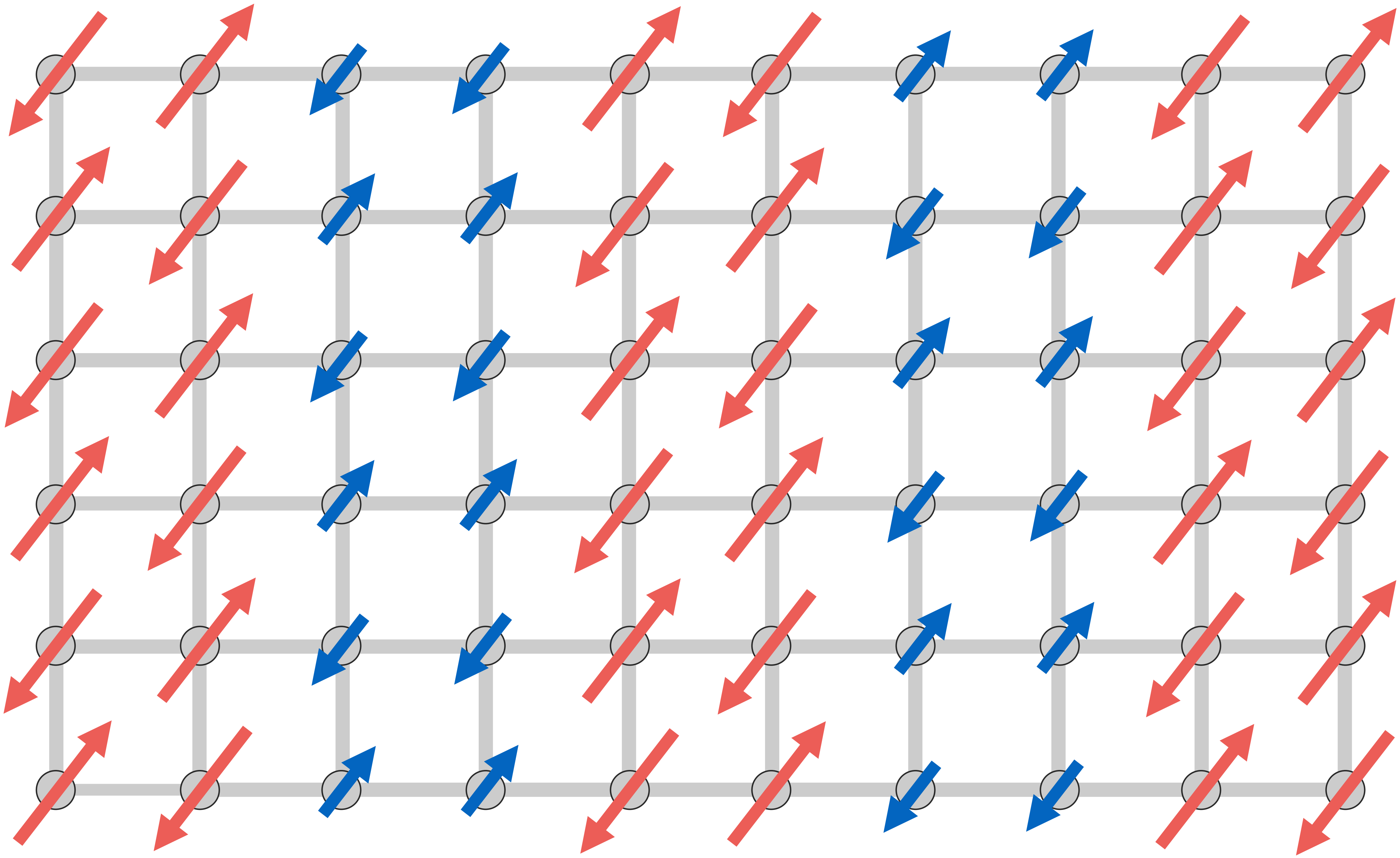
M. H. Fischer, Si Wu, M. Lawler, A. Paramekanti, and Eun-Ah Kim, arXiv:1406.2711

“Stripe” model



Start with an antiferromagnet

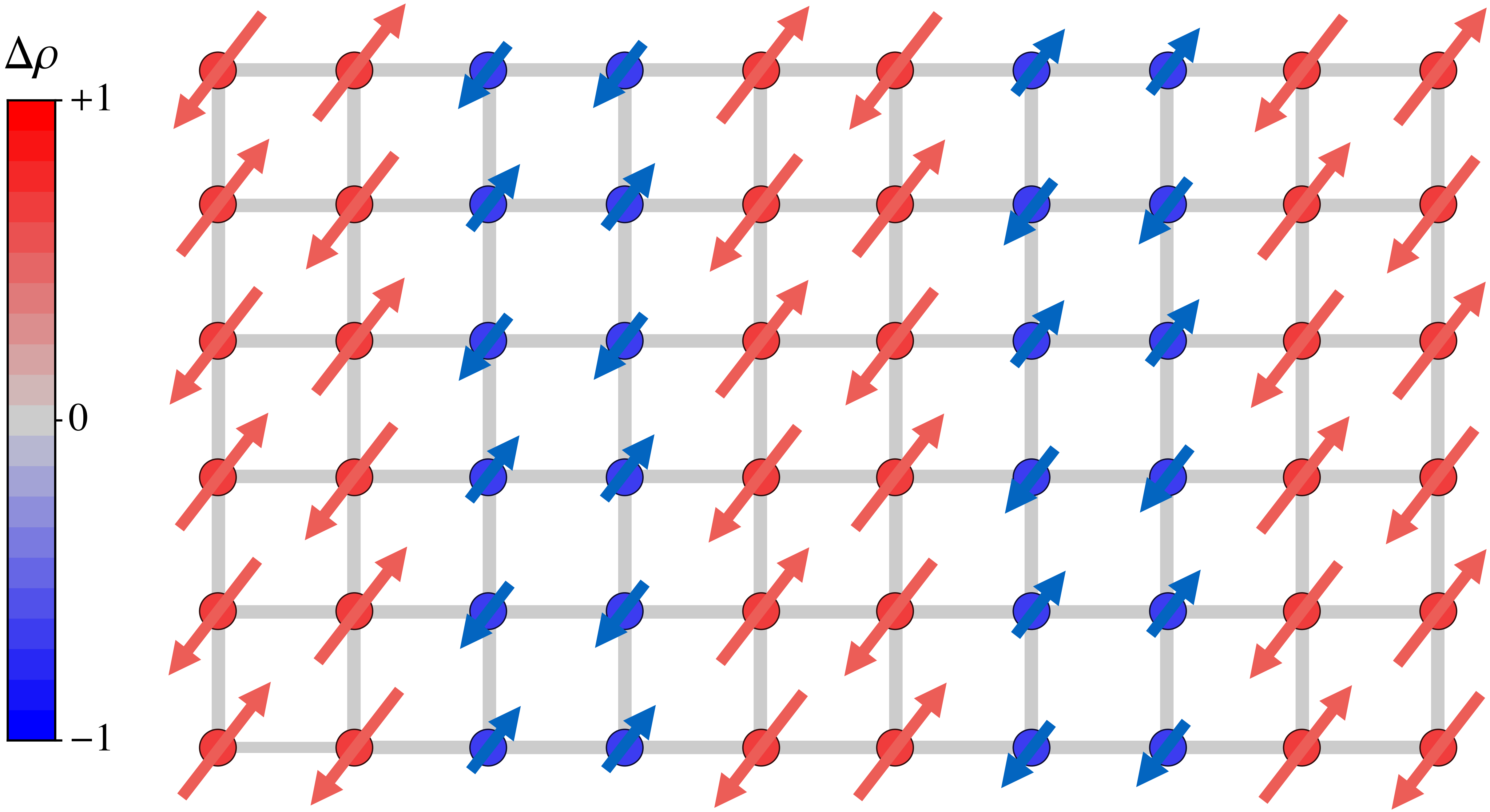
“Stripe” model



Domain walls 4 lattice spacings apart

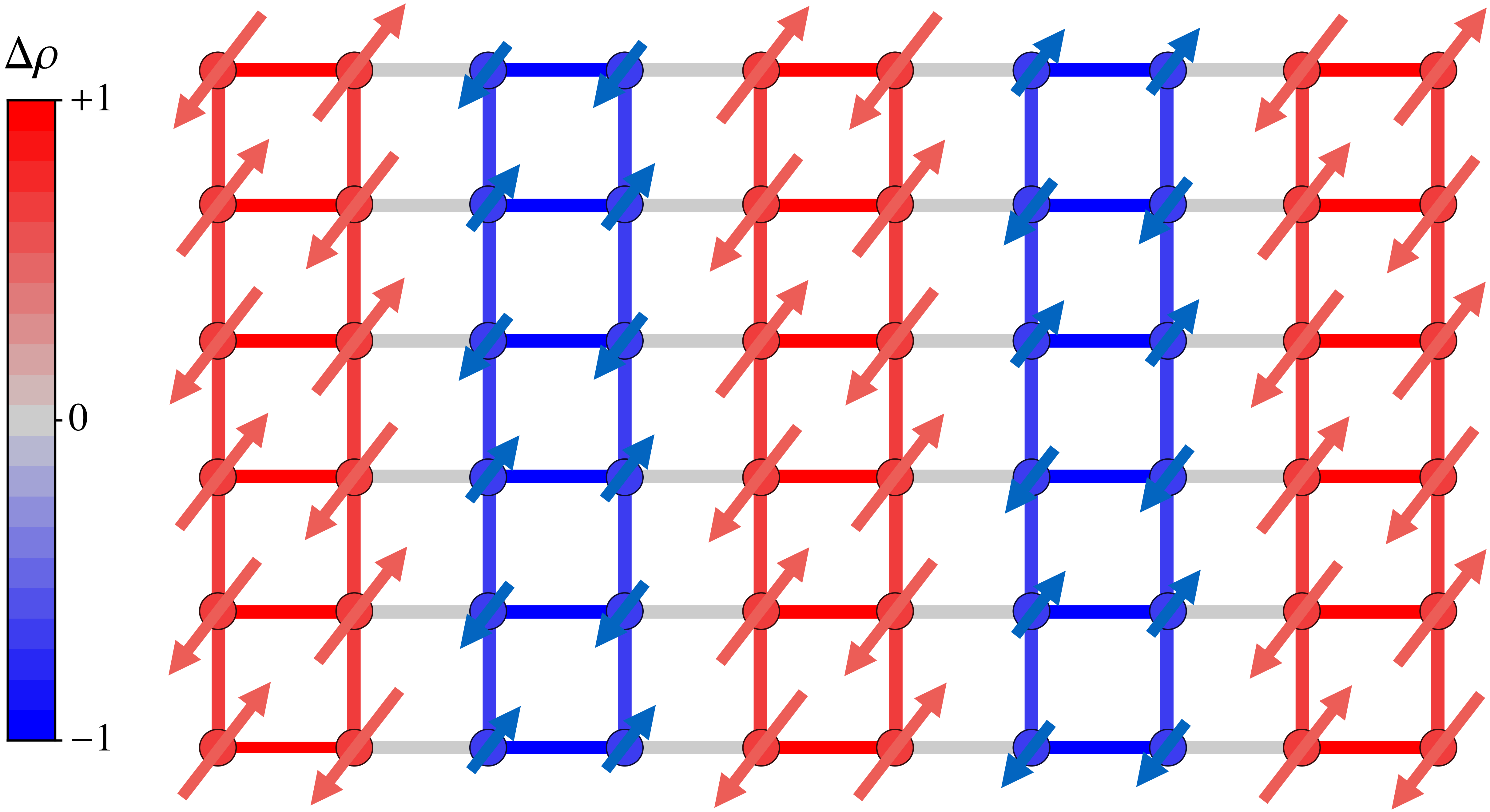
Observed in La-based compounds (Tranquada..)
Theory: Zaanen, Kivelson, Fradkin….

"Stripe" model



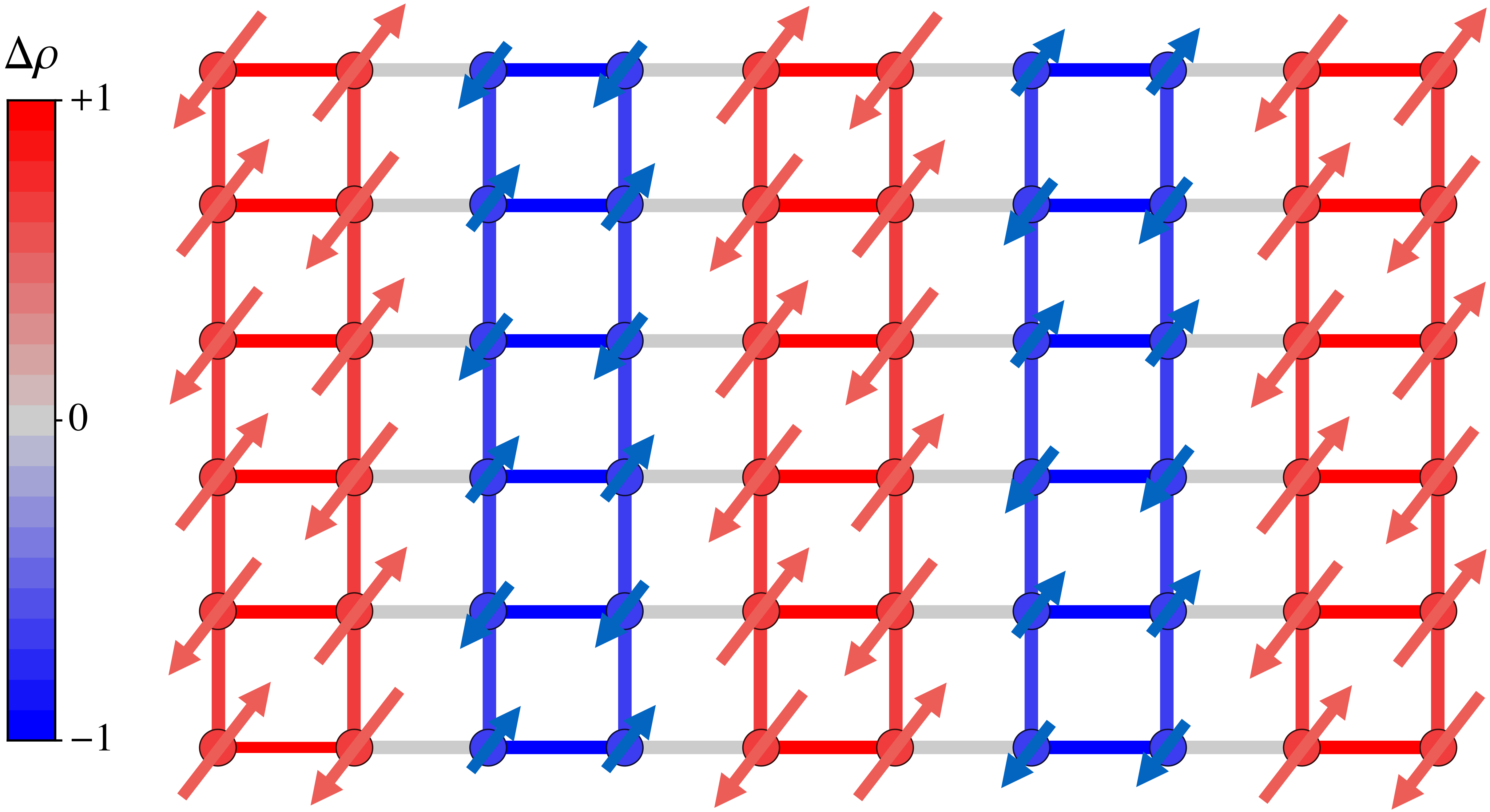
Put the holes in the domain walls

“Stripe” model



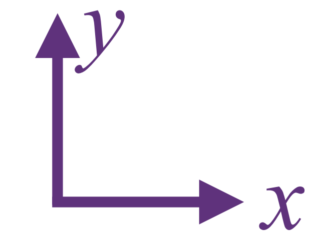
Colors on the bonds map the local exchange energy

“Stripe” model



Stripe model described by large $s + s'$ form factor

Unconventional DW order: s'-form factor



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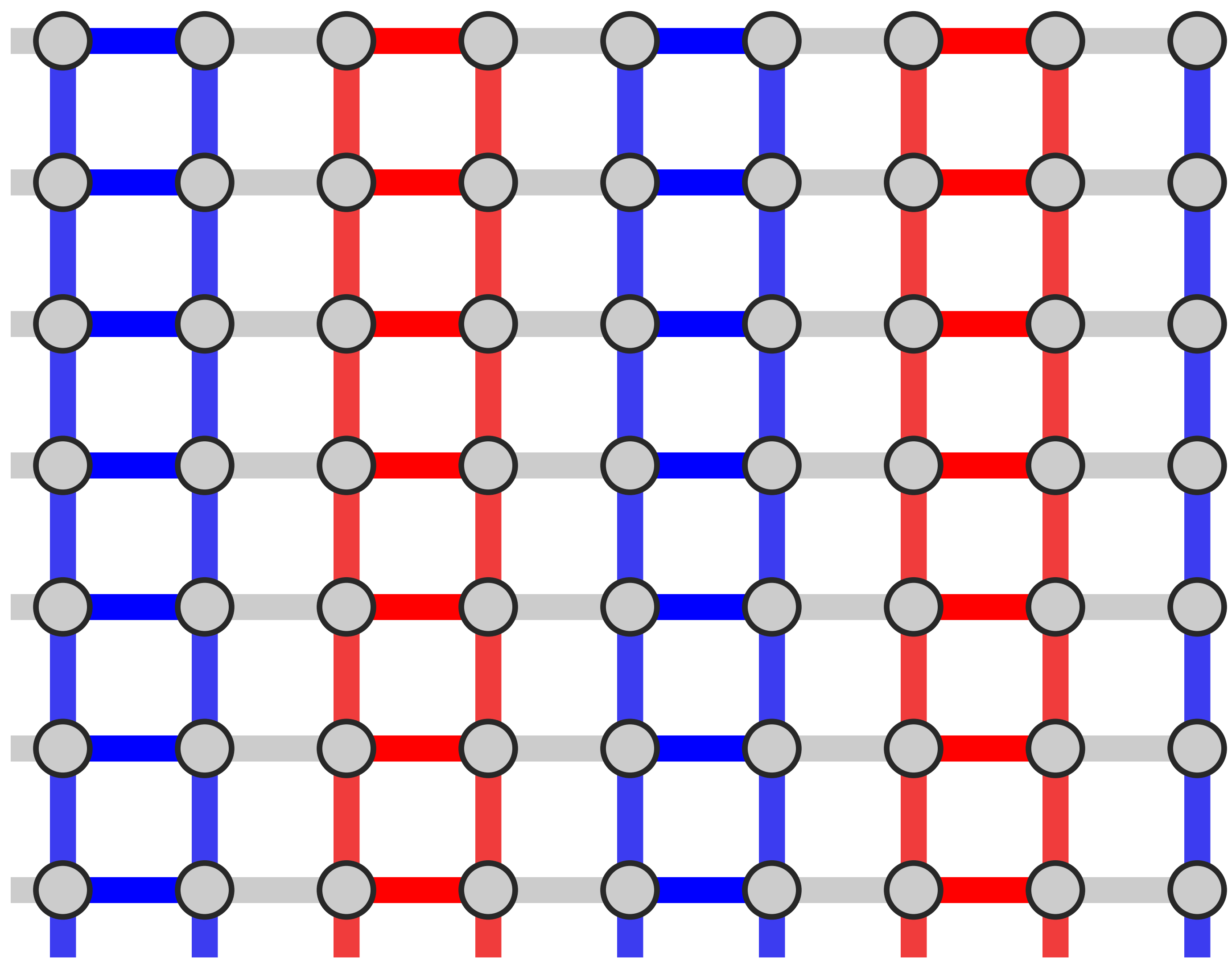
$$P_{ij} = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2} + \text{c.c.}$$

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

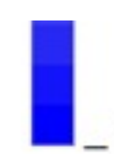
"Stripe" model !

X-ray observations indicate strong s' component in LBCO



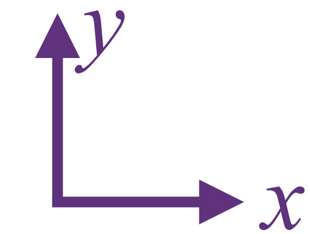
$\mathbf{Q} = (\pi/2, 0)$

David Hawthorn



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

Current order: p-form factor



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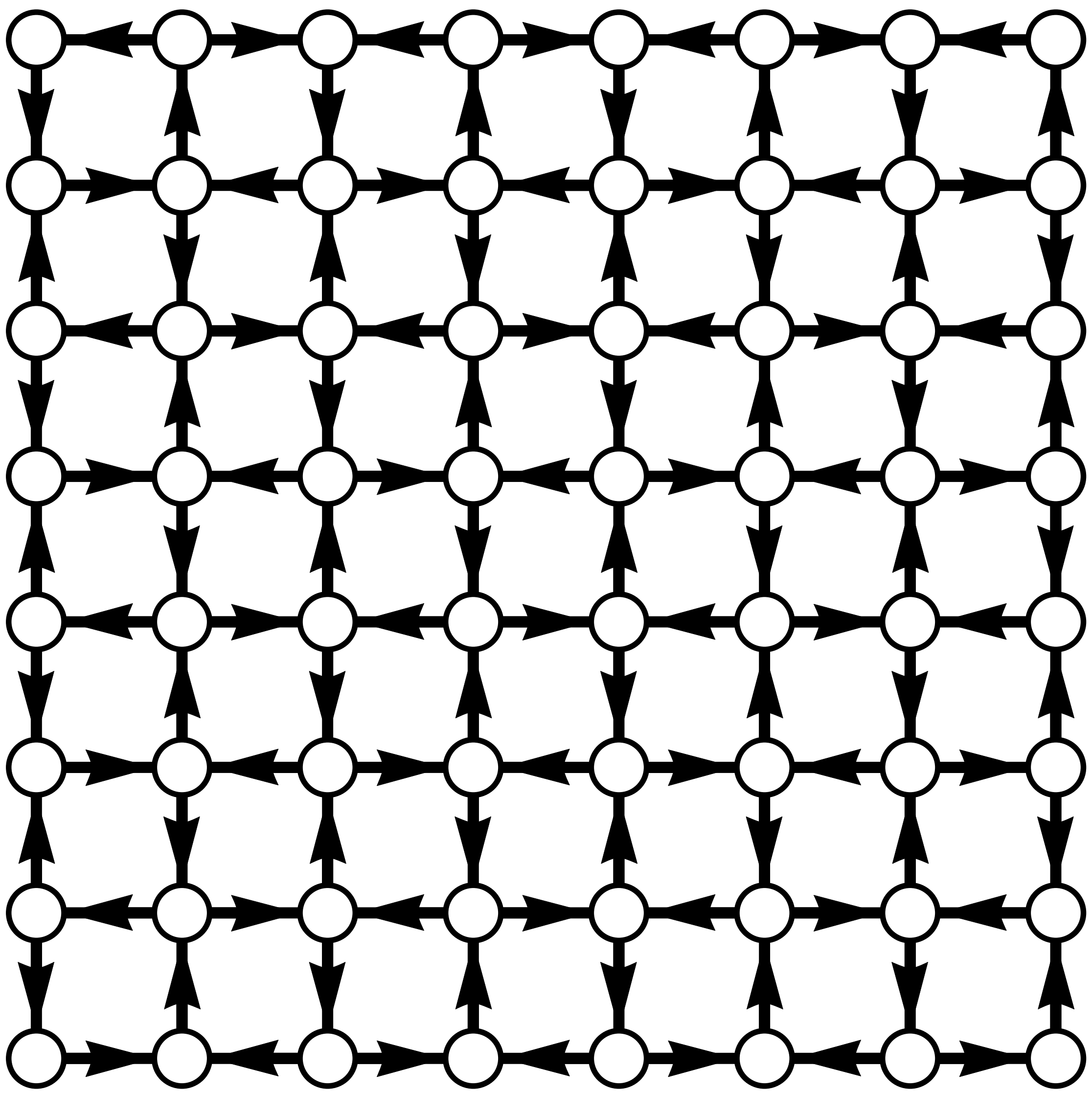
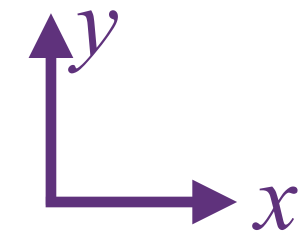
$$\mathcal{P}(\mathbf{k}) = \sin(k_x) - \sin(k_y) \quad \text{and} \quad \mathbf{Q} = (\pi, \pi)$$



This state breaks time-reversal and is also known as "d-density wave" (*but is p-form factor in our notation*), and "staggered-flux (SF)". (Similar comments apply to "loop" orders of Varma and others.)

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

Unconventional DW order: d-form factor



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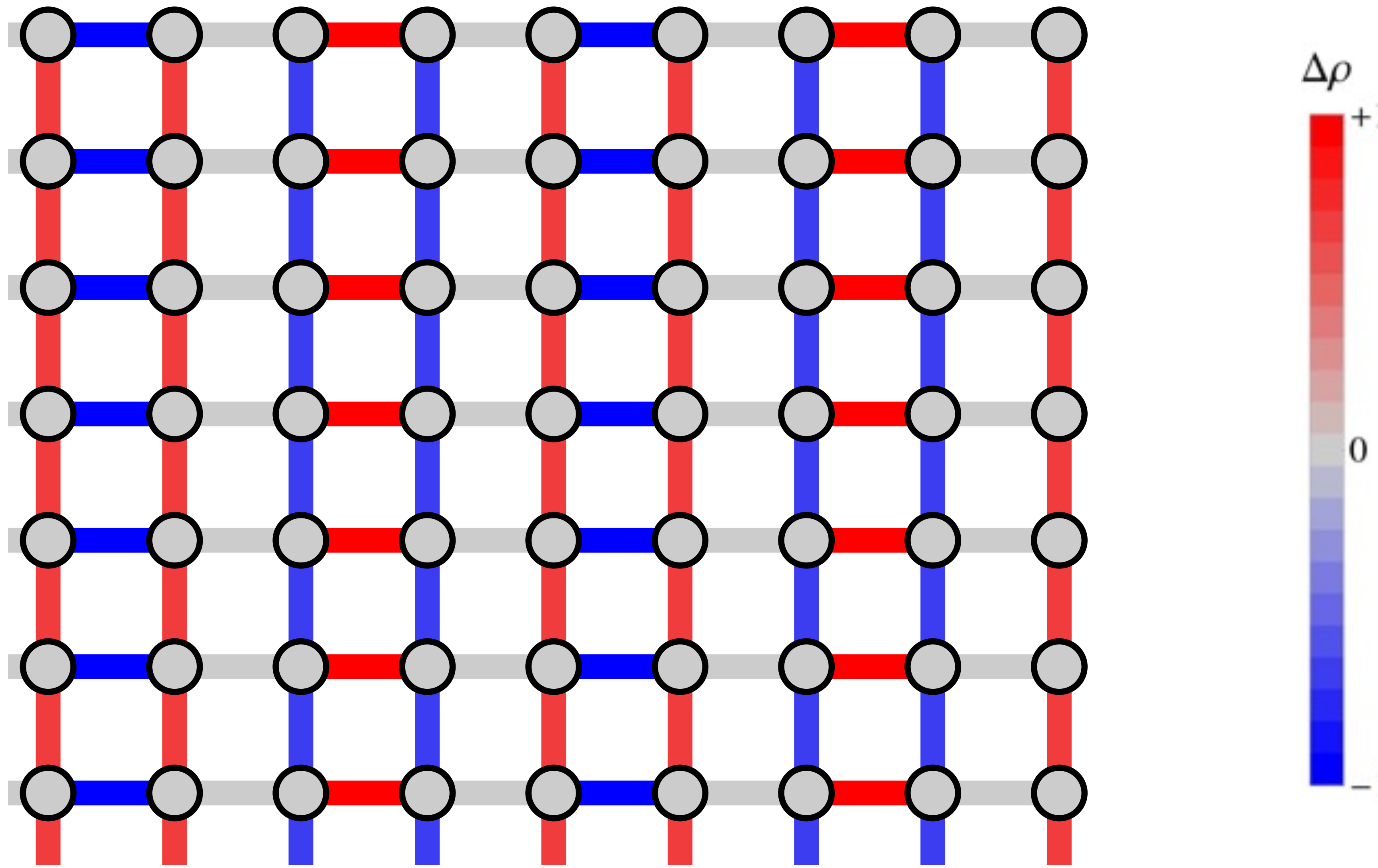

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M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075128 (2010).
S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).

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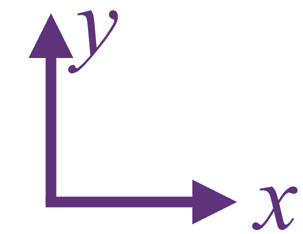

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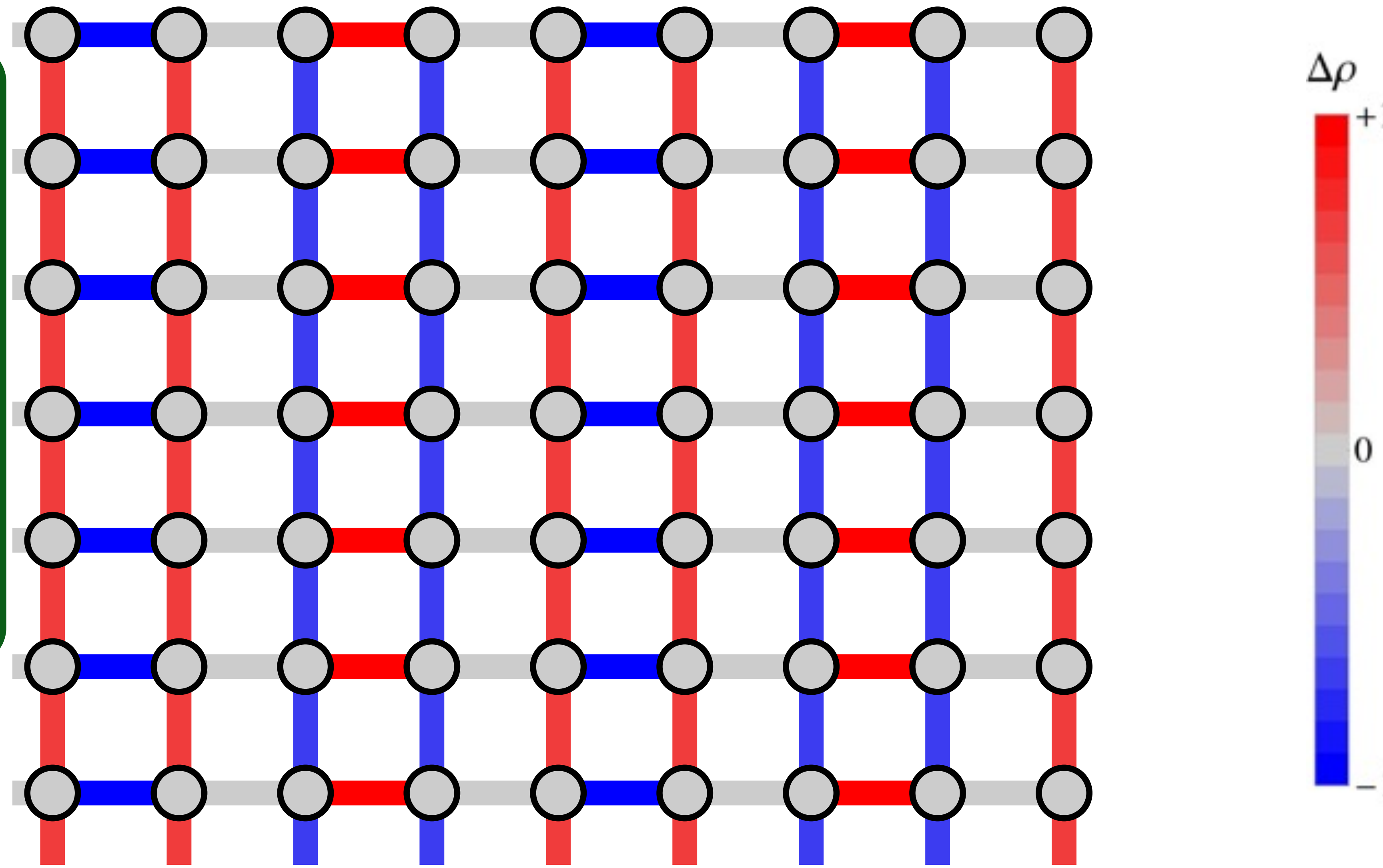
Our prediction: Density wave on horizontal bonds has a phase-shift of π relative to the wave on vertical bonds



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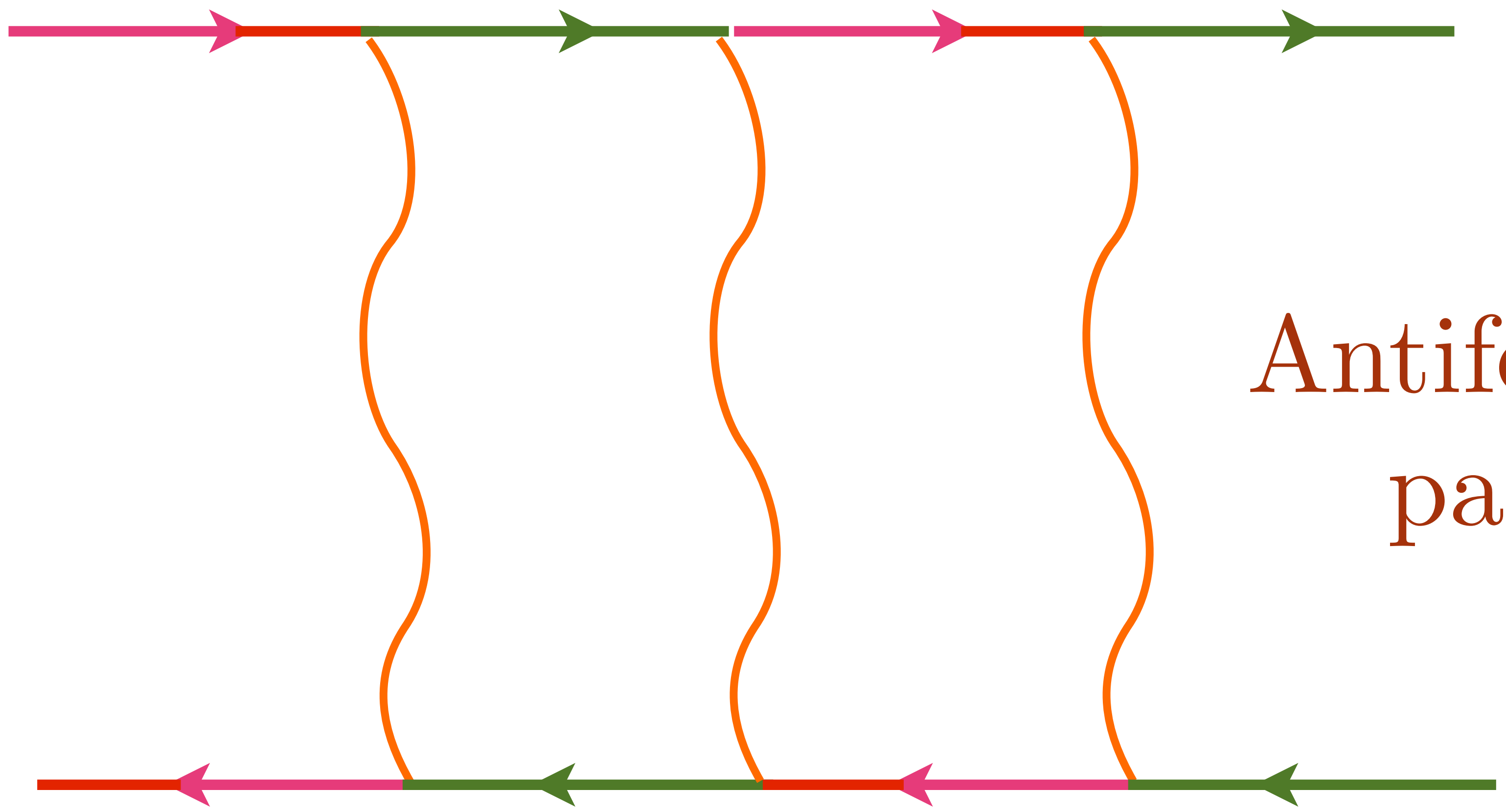
Spin-fermion model @25

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)

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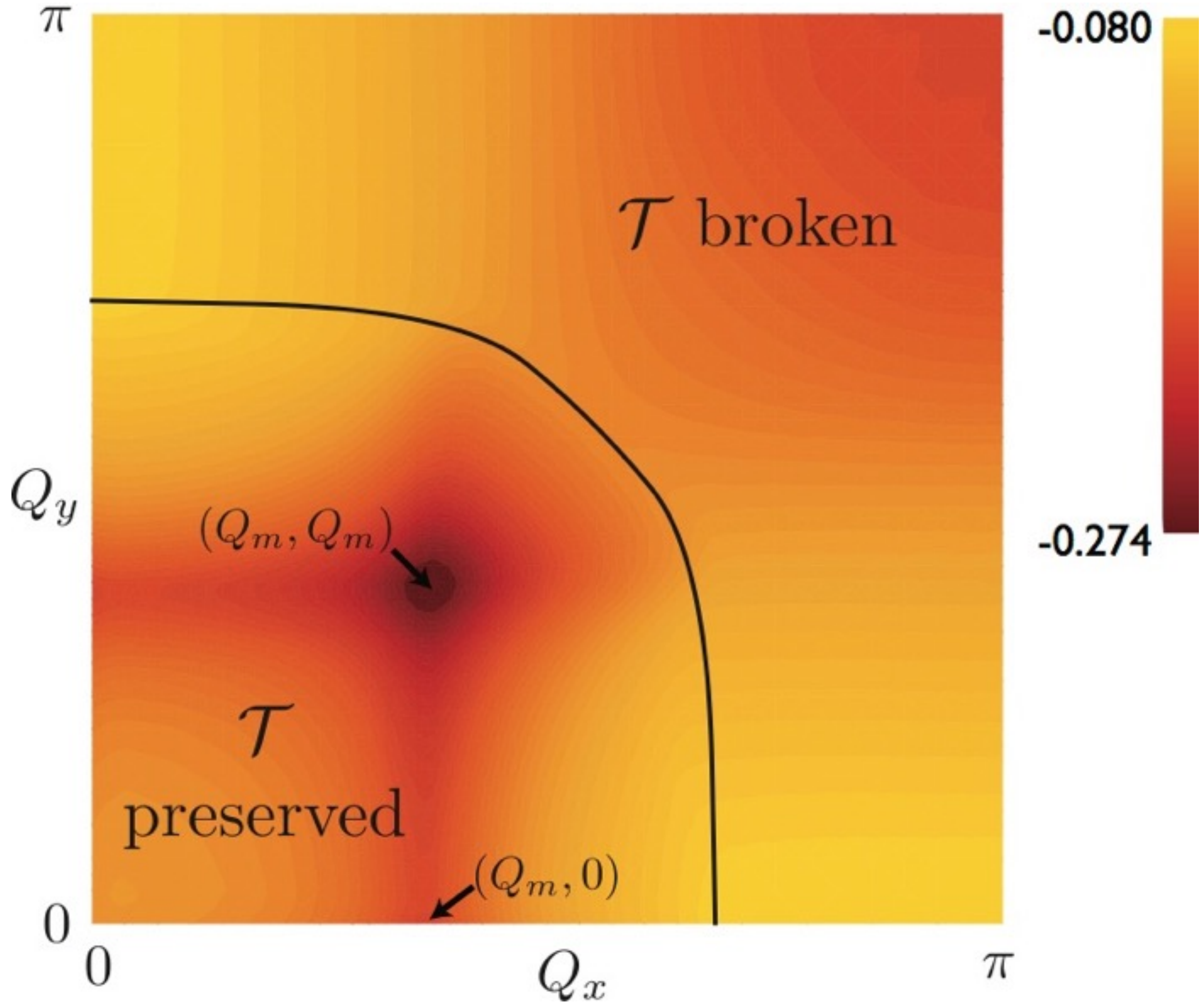
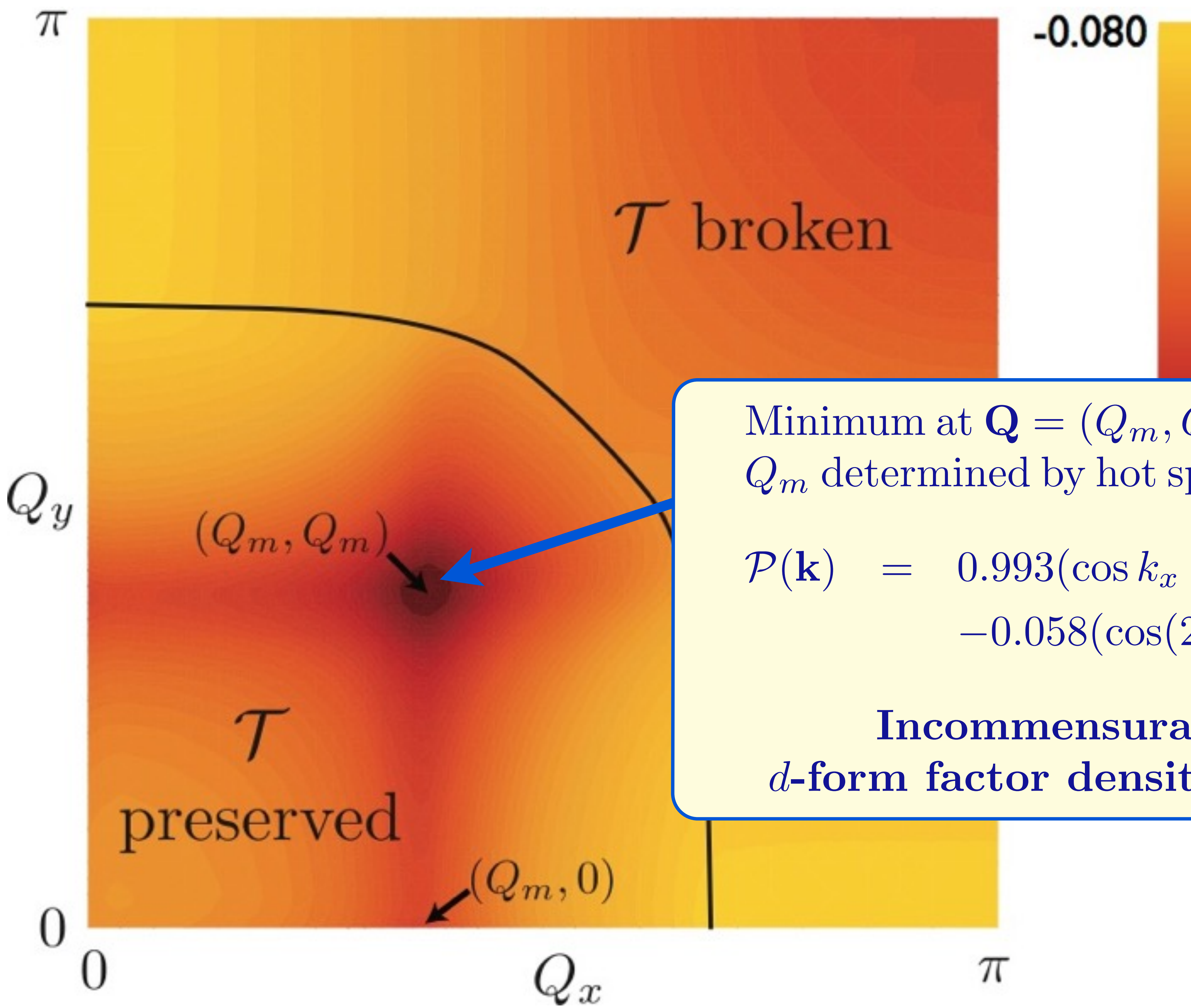


Eigenvalues, $\lambda(\mathbf{Q})$, of the spin-singlet, particle-hole propagator. The corresponding eigenvector is $\mathcal{P}(\mathbf{k})$.

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



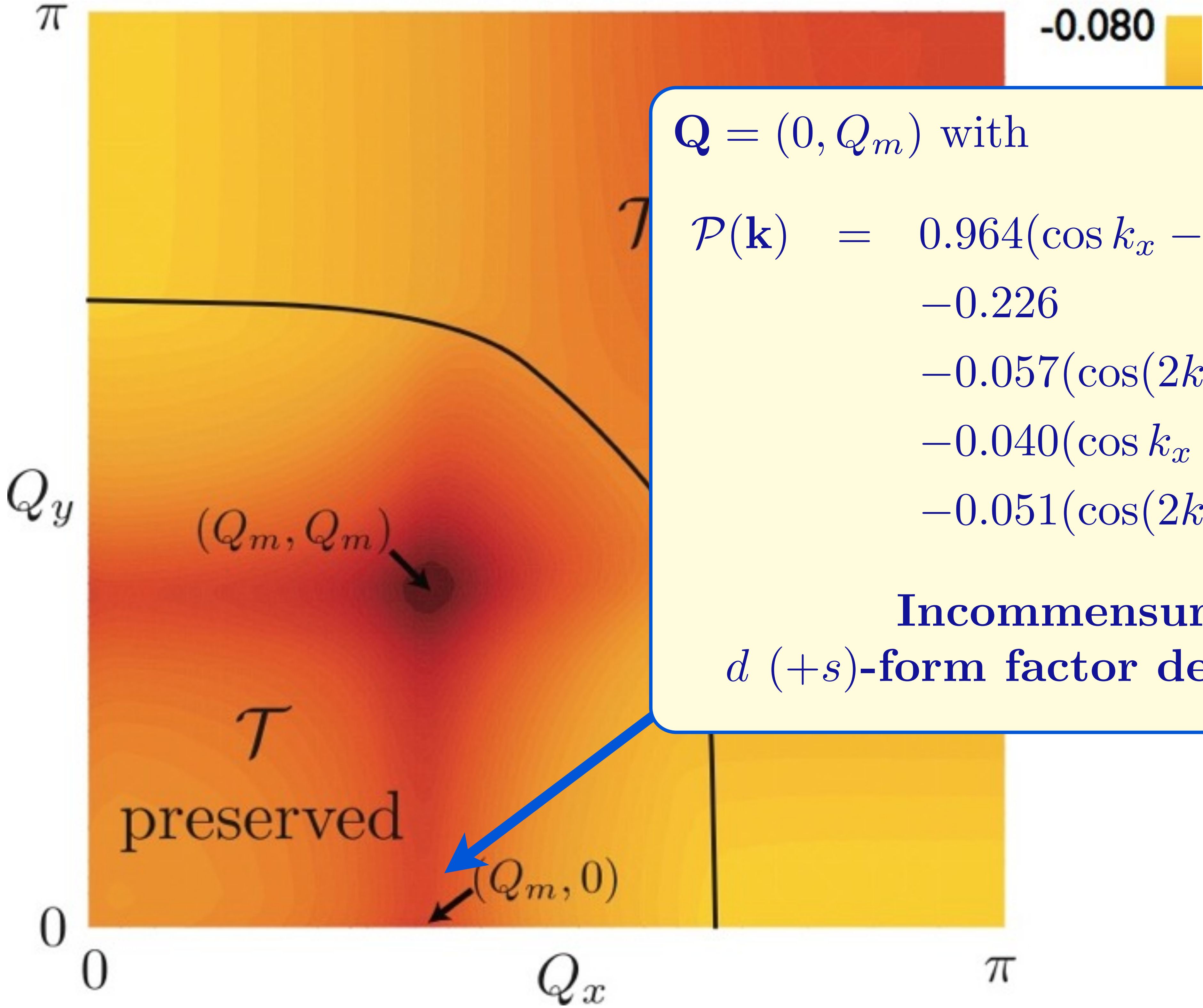
Minimum at $\mathbf{Q} = (Q_m, Q_m)$ (with Q_m determined by hot spots) with

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

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

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

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**

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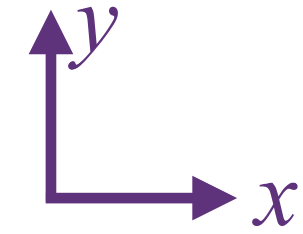
Unconventional DW order: d-form factor



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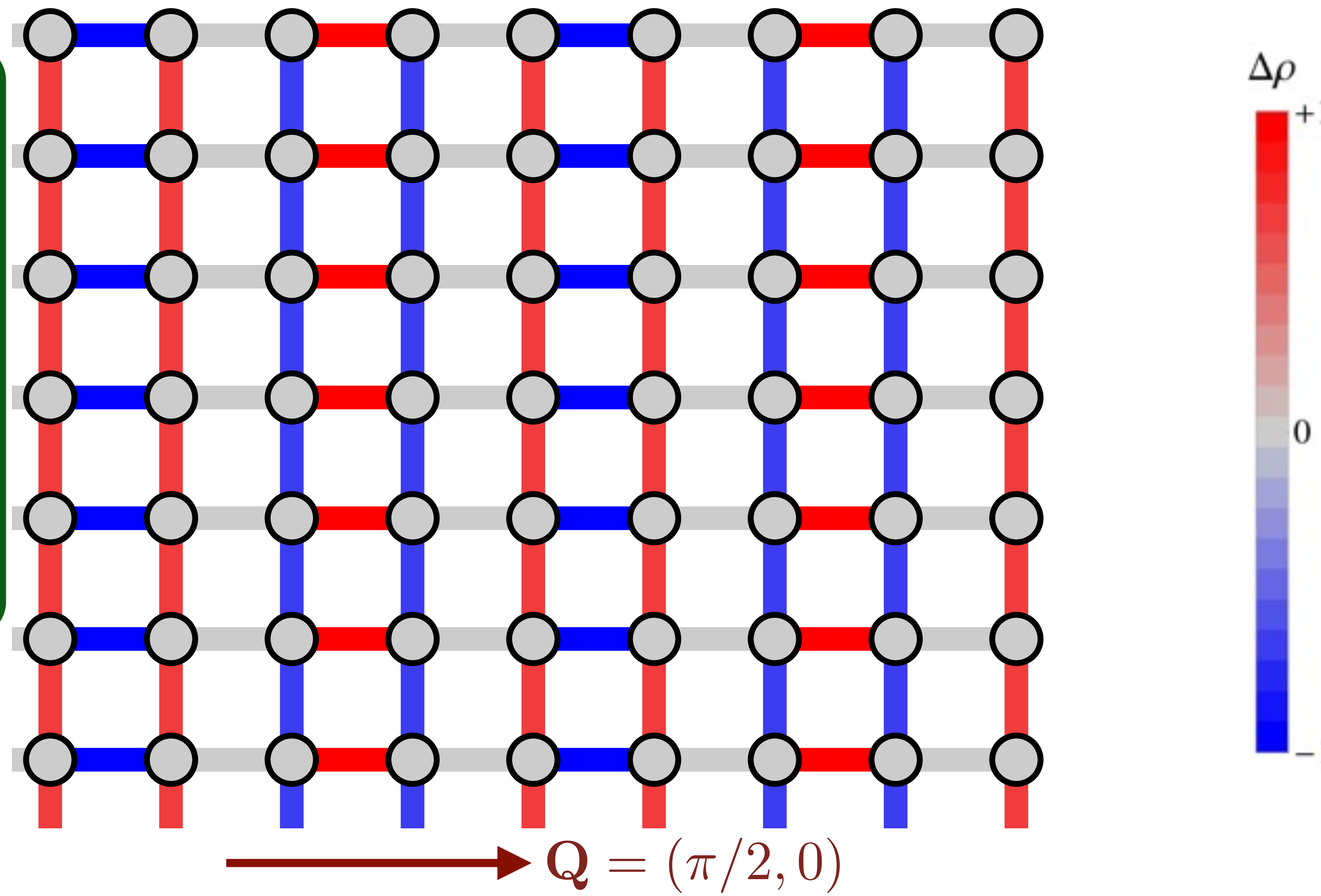

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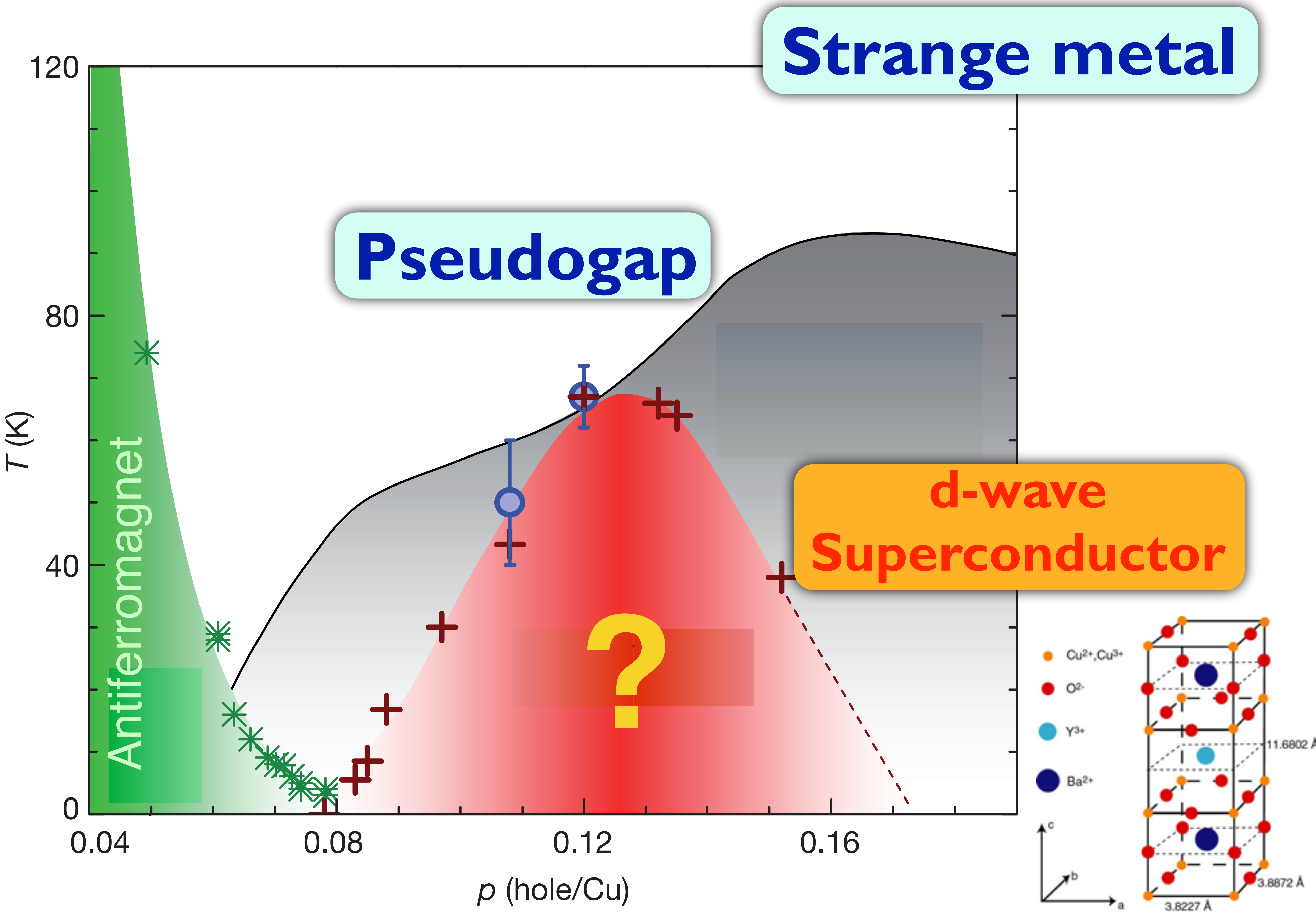
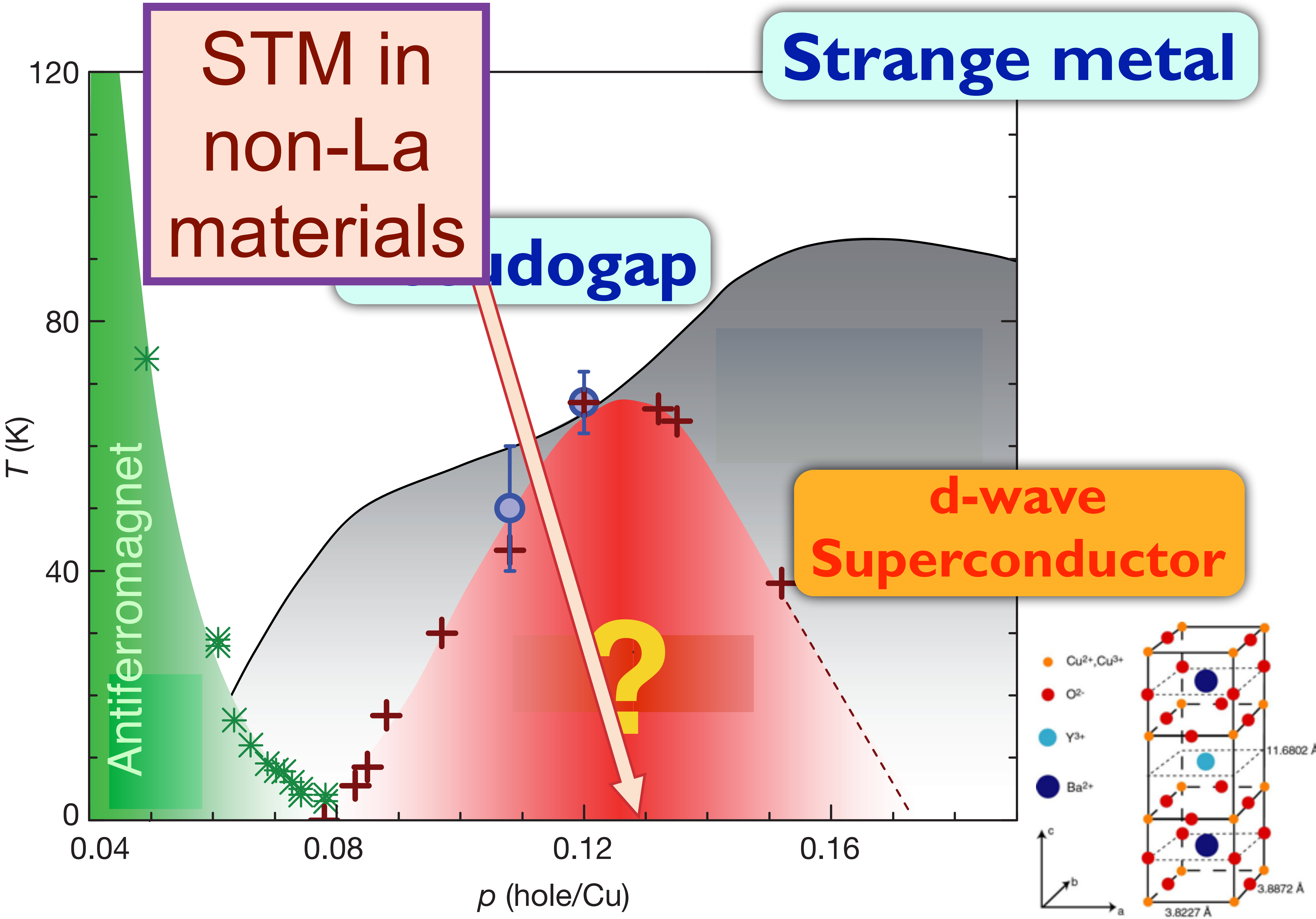


T. Wu, H. Mayaffre, S. Kramer, M. Horvatic, C. Berthier, W.N. Hardy, R. Liang, D.A. Bonn, and M.-H. Julien, Nature **477**, 191 (2011).



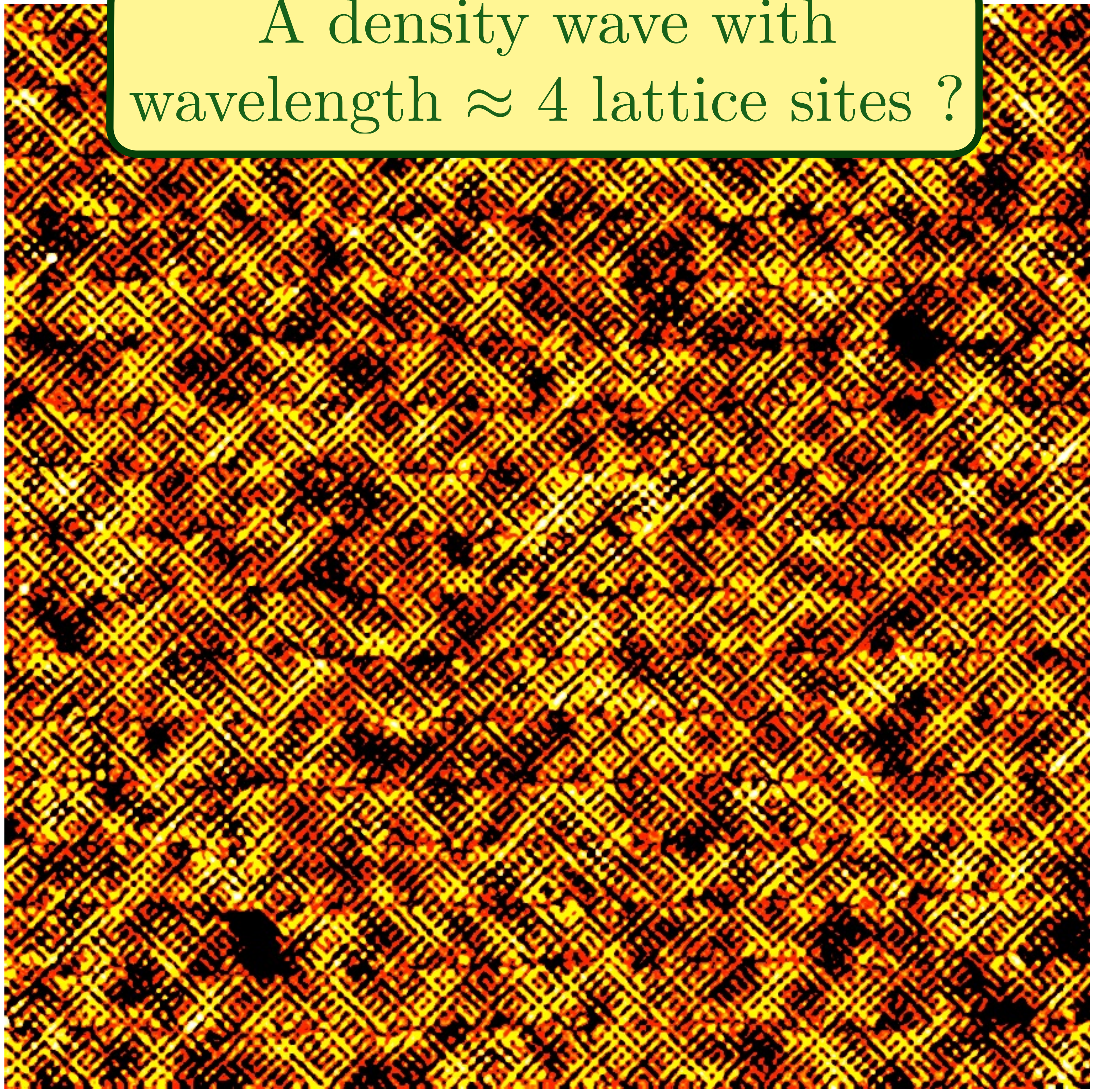
STM in non-La materials
Strange metal
Pseudogap
d-wave Superconductor
Antiferromagnet
?
120
80
40
0
T (K)
0.04
0.08
0.12
0.16
p (hole/Cu)
Cu2+,Cu3+
O2-
Y3+
Ba2+
11.6802 Å
3.8872 Å
3.8227 Å
a
b
c

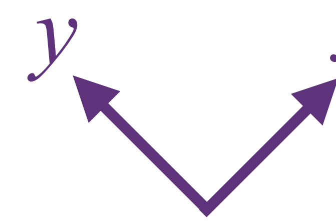
See also
C. Howald, H. Eisaki, N. Kaneko, M. Greven, and A. Kapitulnik, Phys. Rev. B **67**, 014533 (2003);

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).

A density wave with wavelength ≈ 4 lattice sites ?





"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.

A density wave with wavelength ≈ 4 lattice sites ?

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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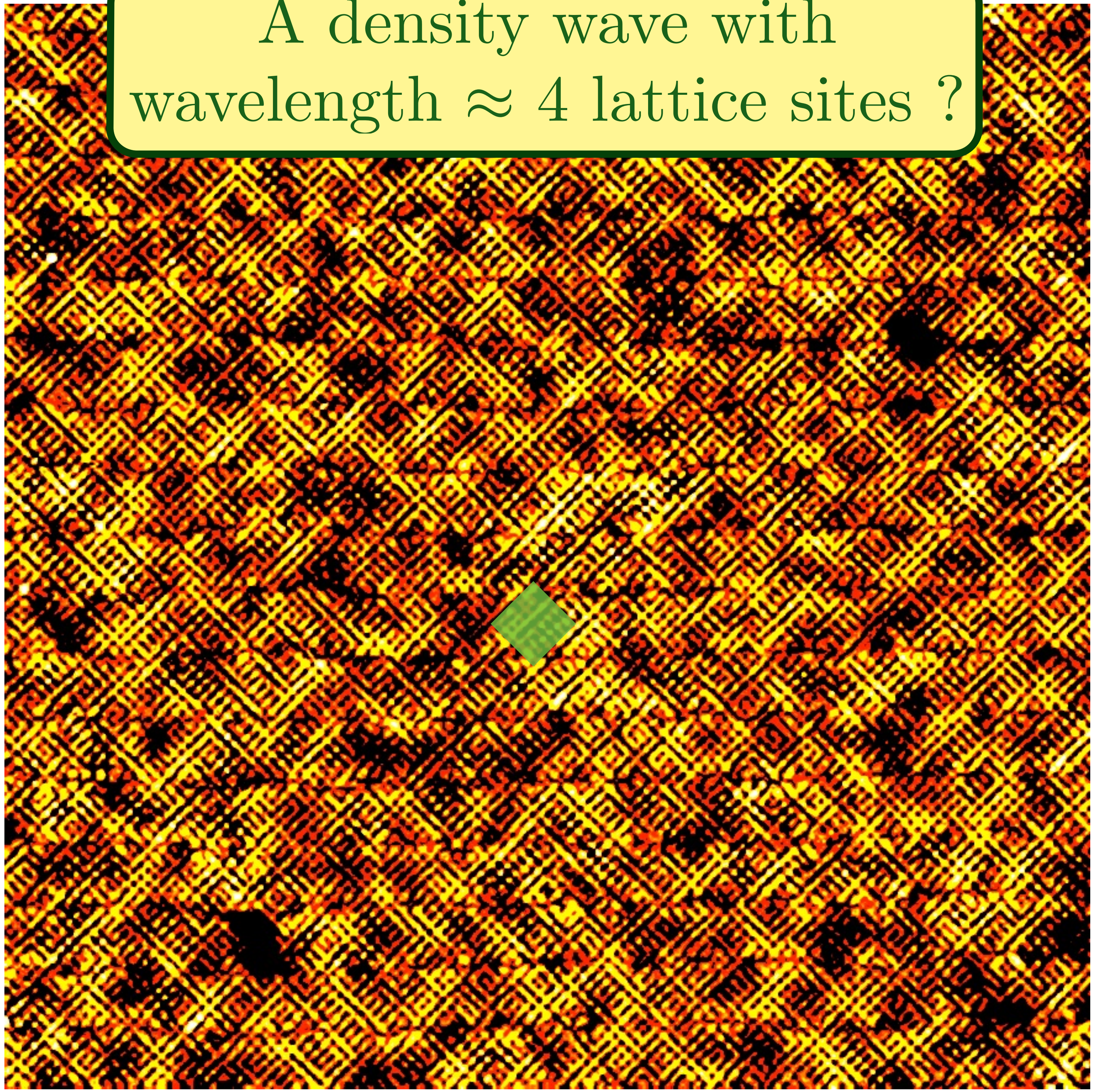

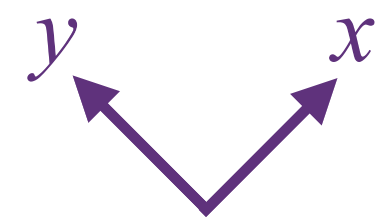

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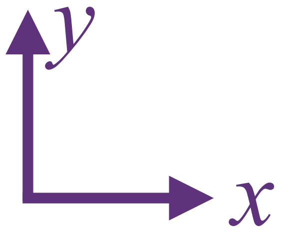

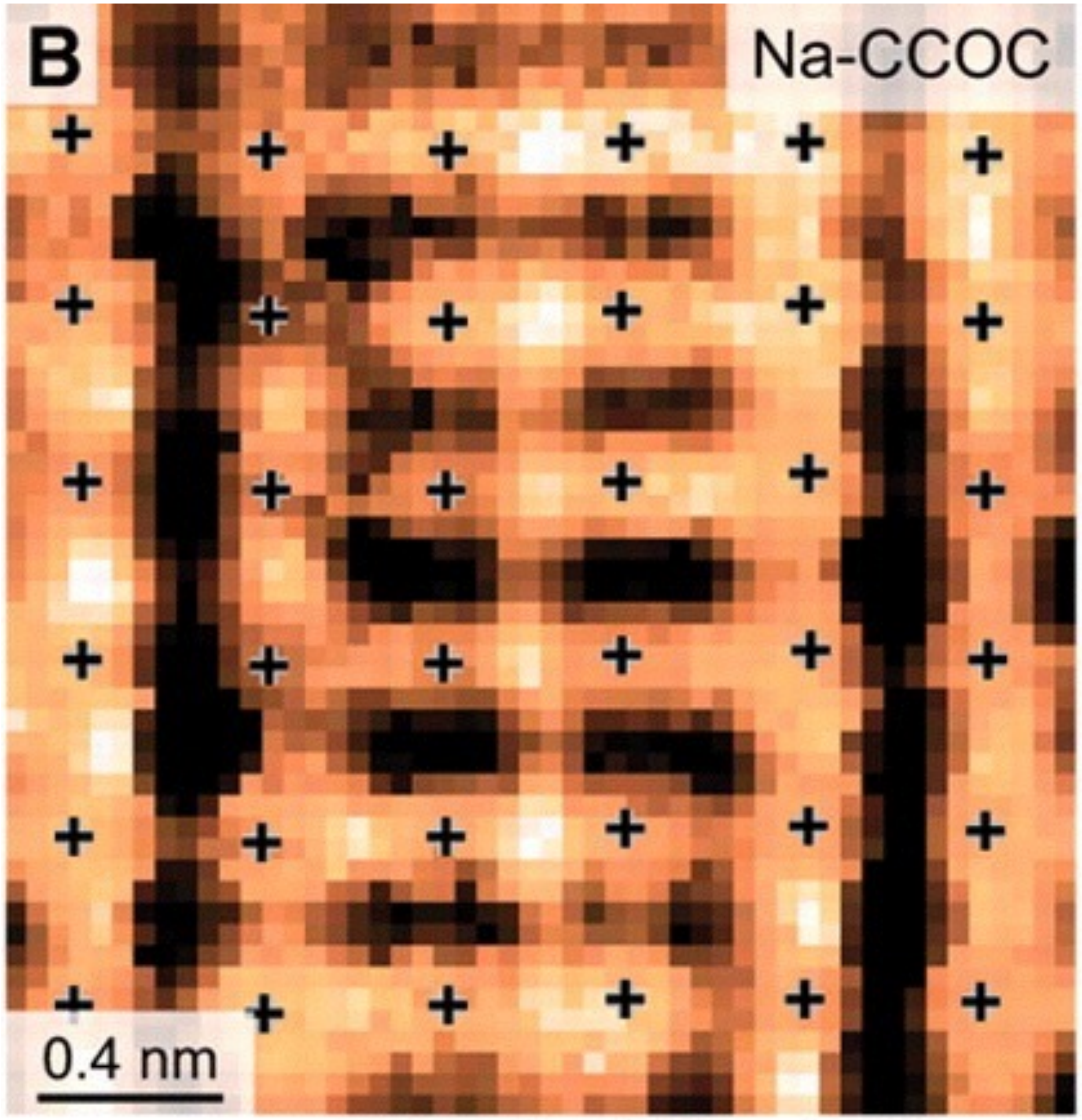

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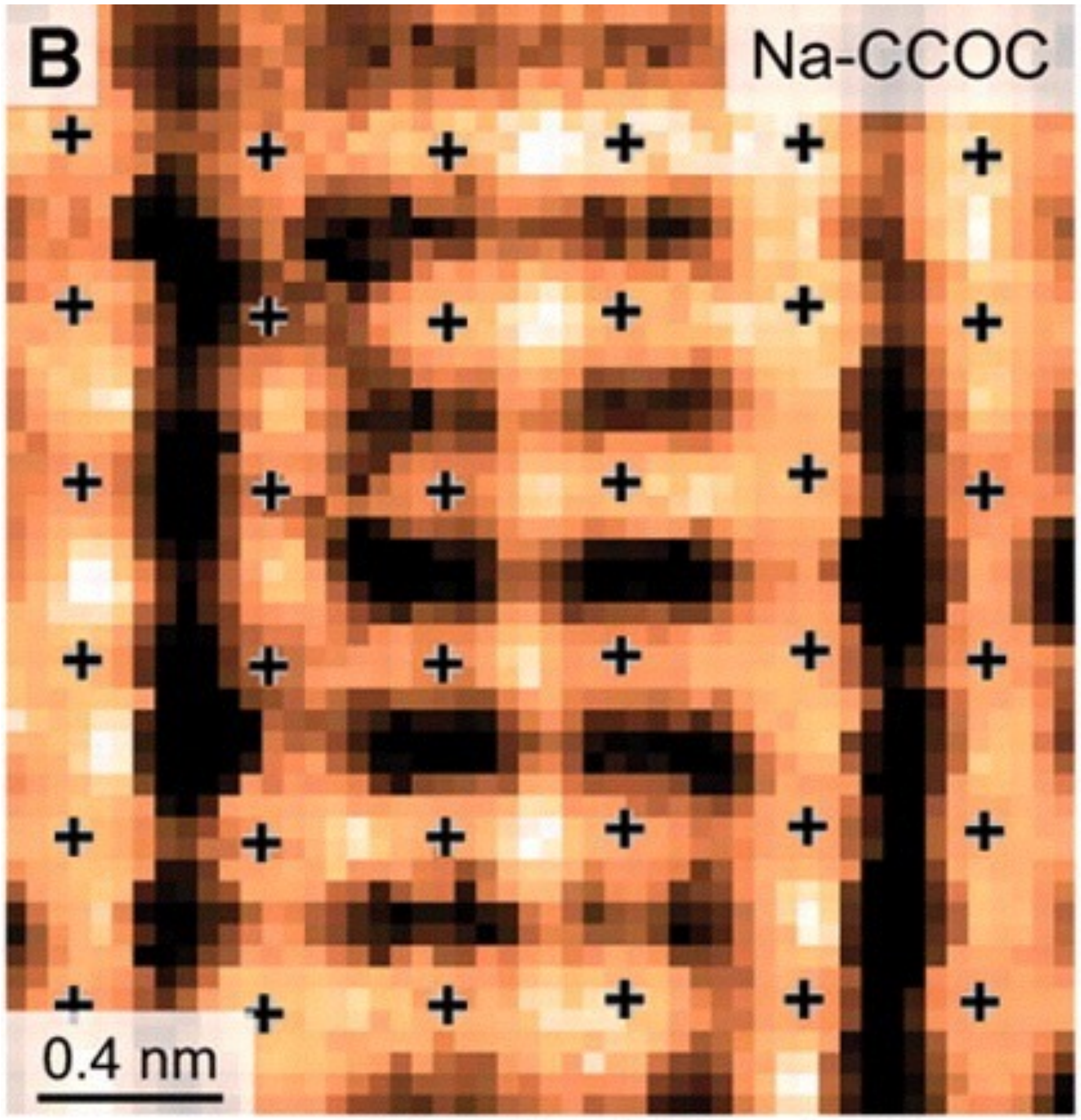

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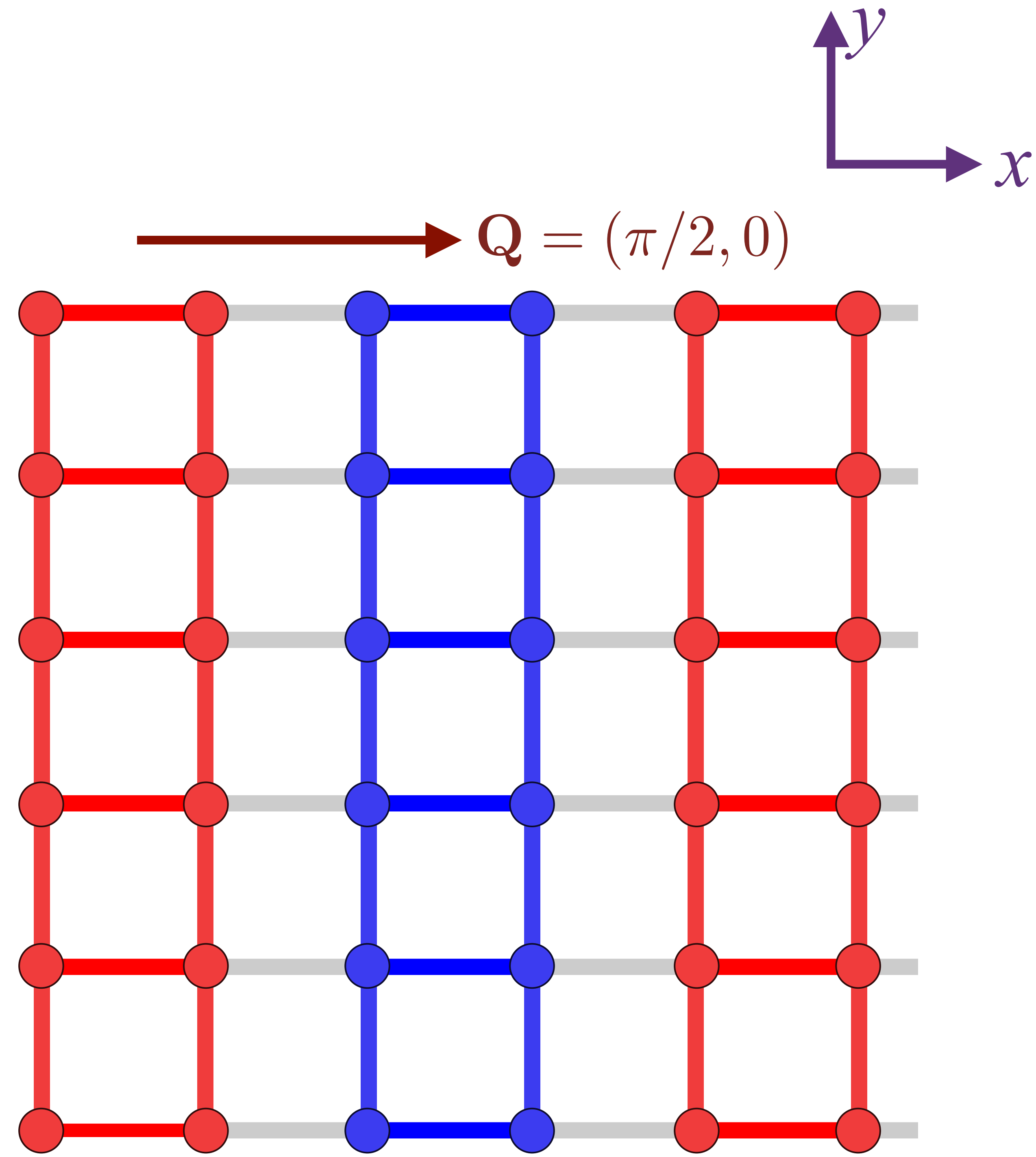
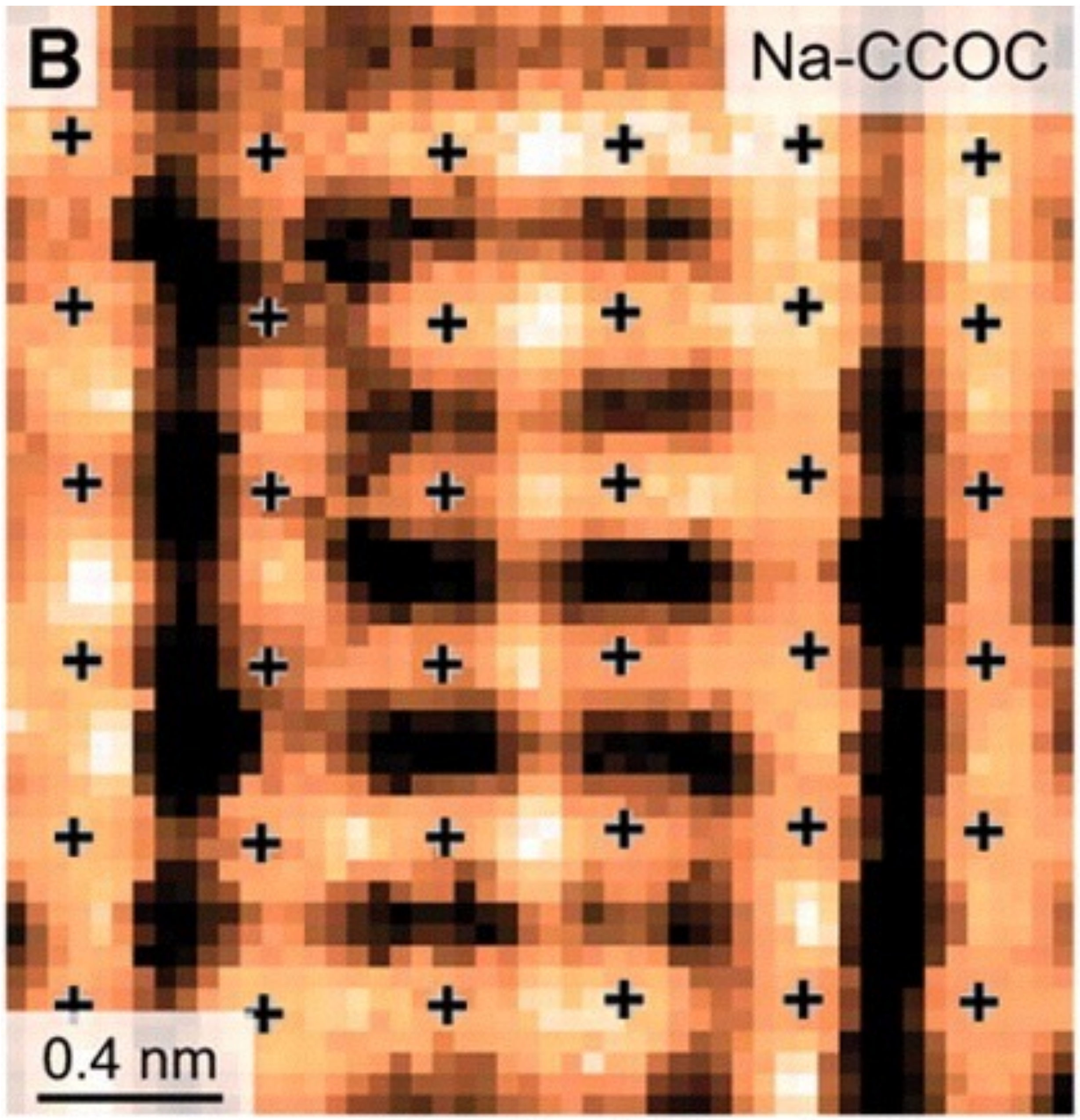


$s + s'$-form factor density wave

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



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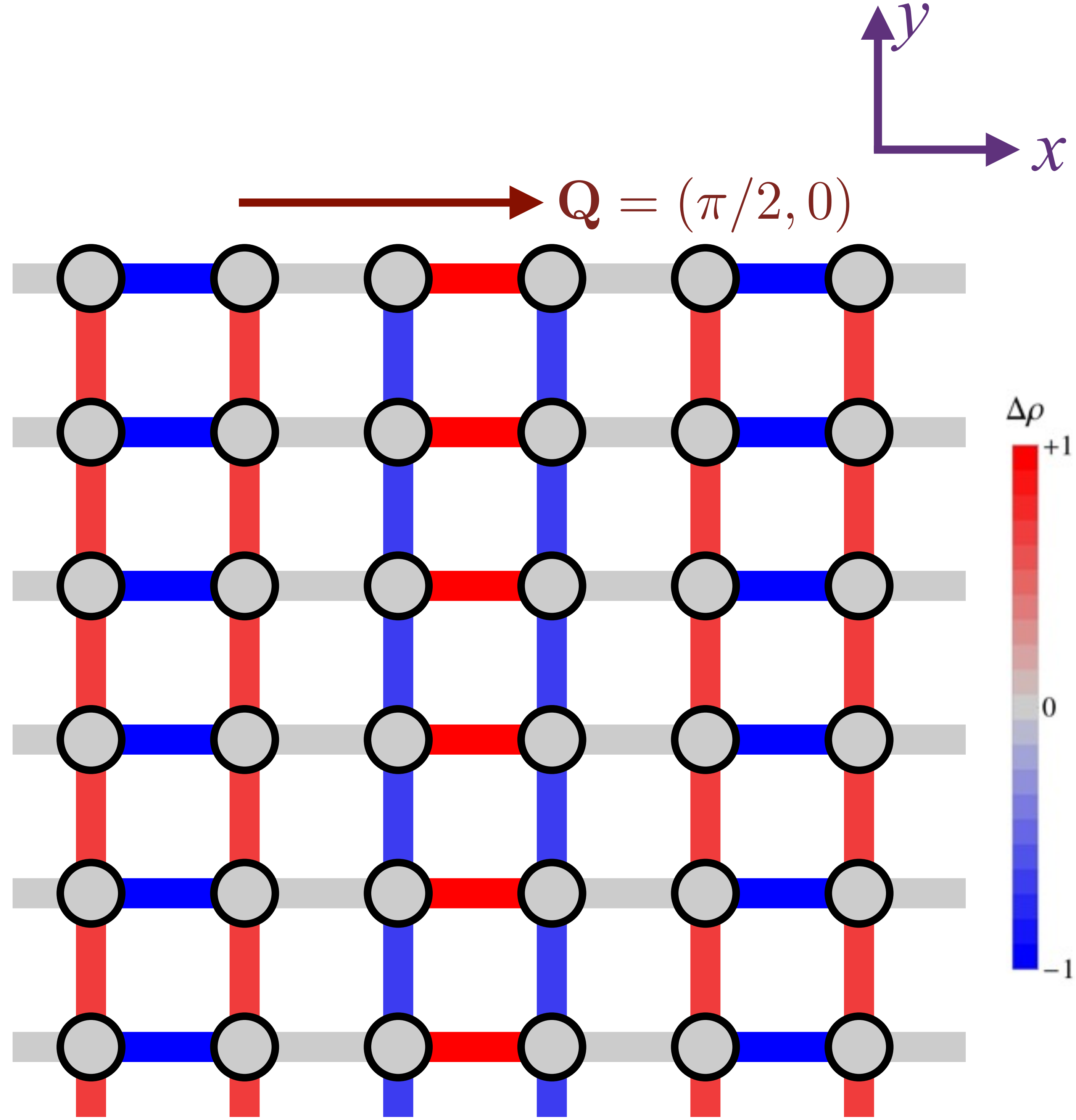
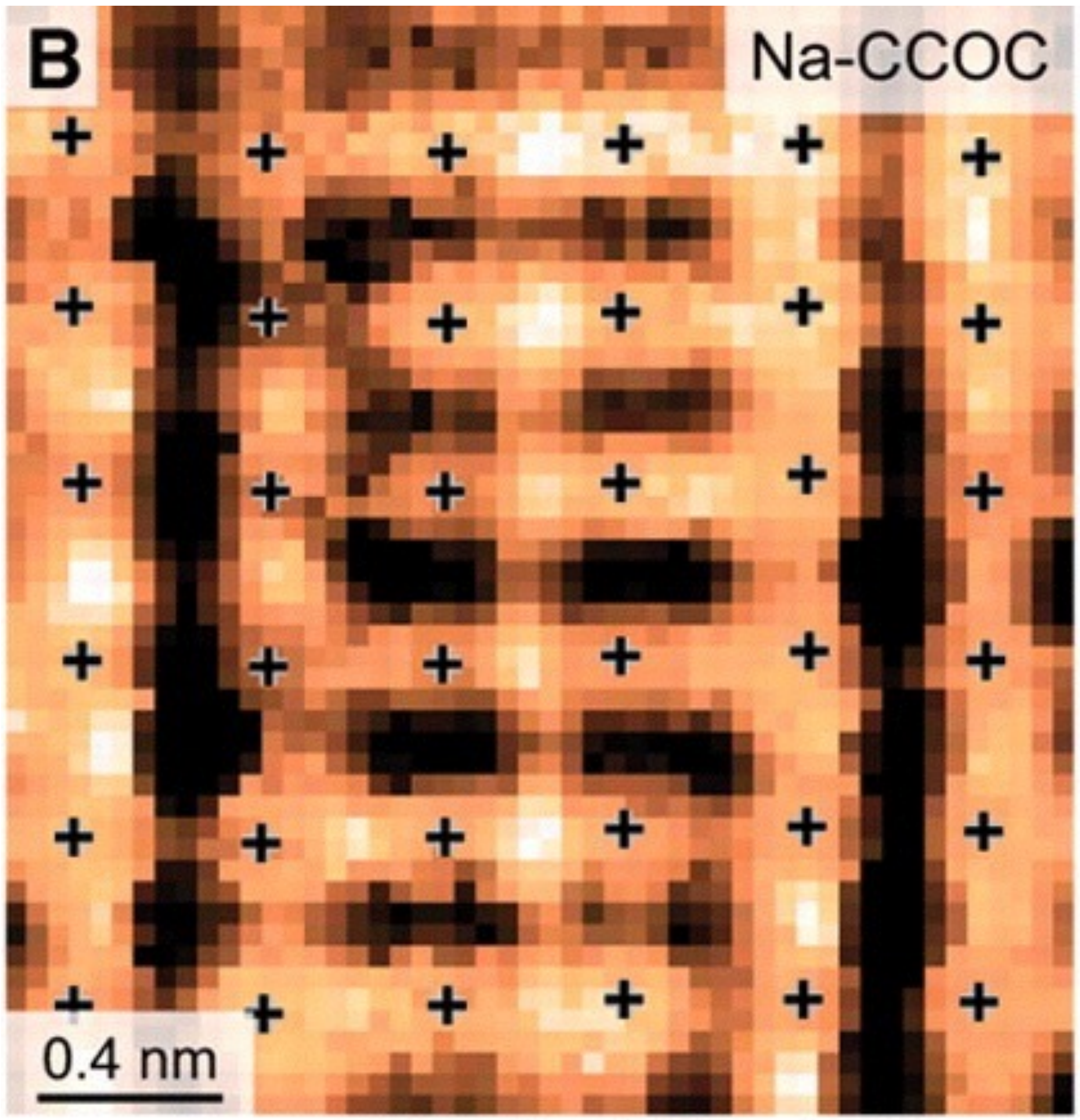


d-form factor density wave order

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



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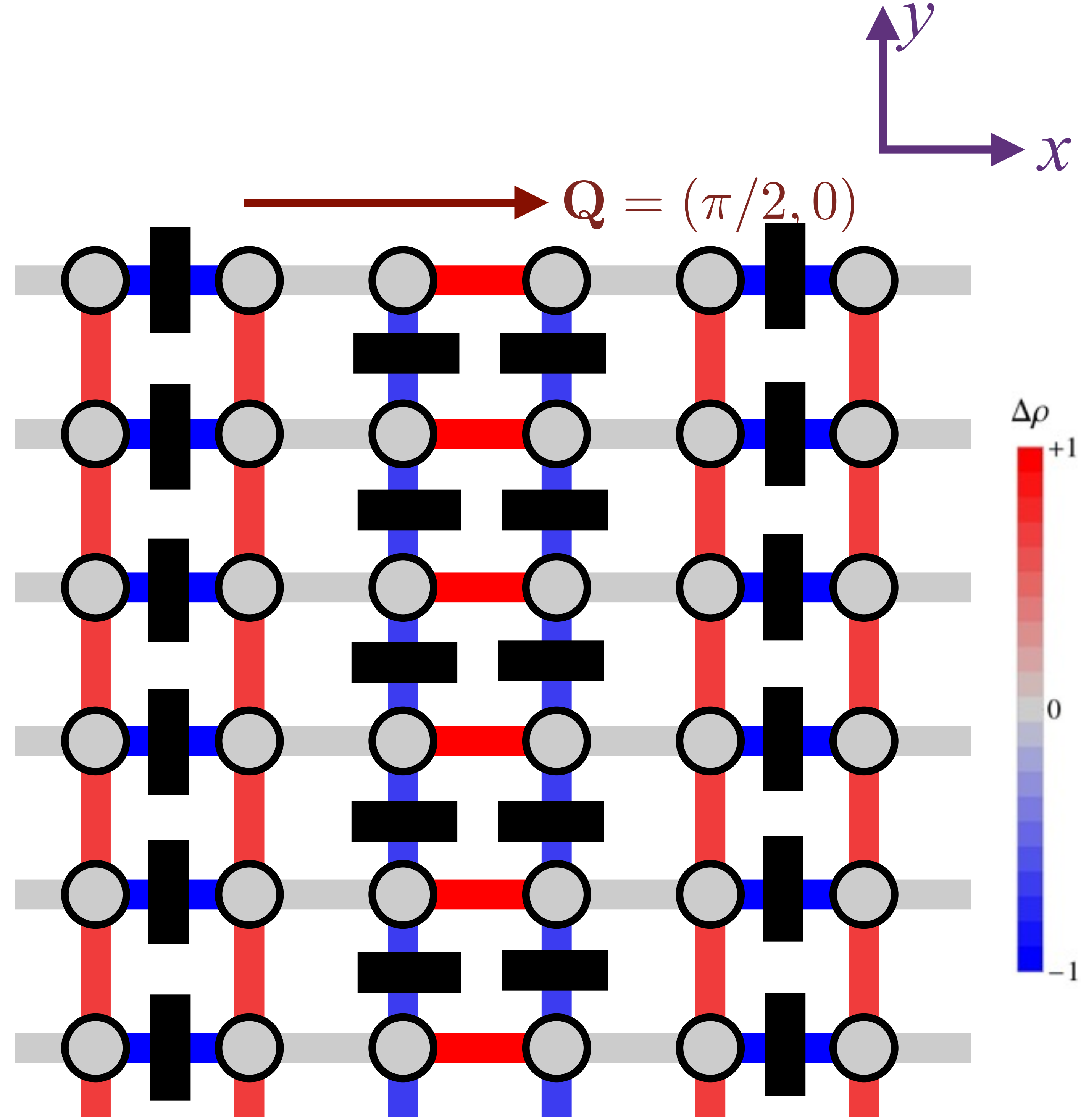

d-form factor density wave order

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

Cornell

Kazuhiro Fujita
Cornell/ BNL

Mohammad Hamidian
Cornell / BNL

Stephen Edkins
Cornell / St Andrews

Michael Lawler

J. C. Seamus Davis

Eun-Ah Kim

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)

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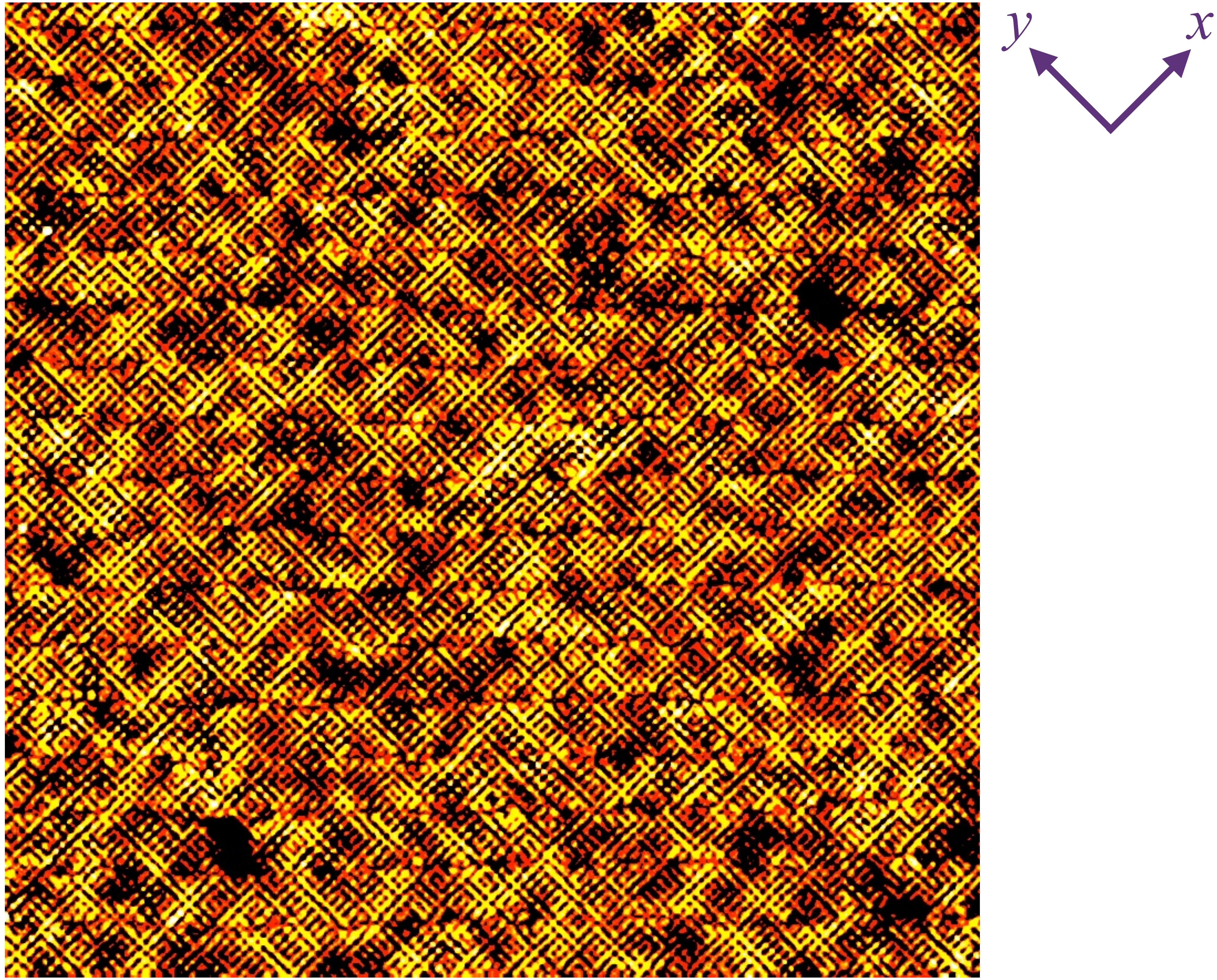

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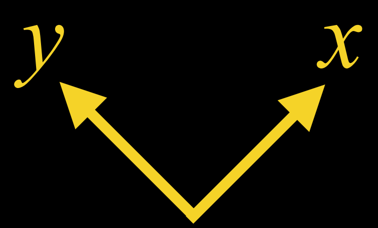
UD45K
BSCCO

R(r,150mV)



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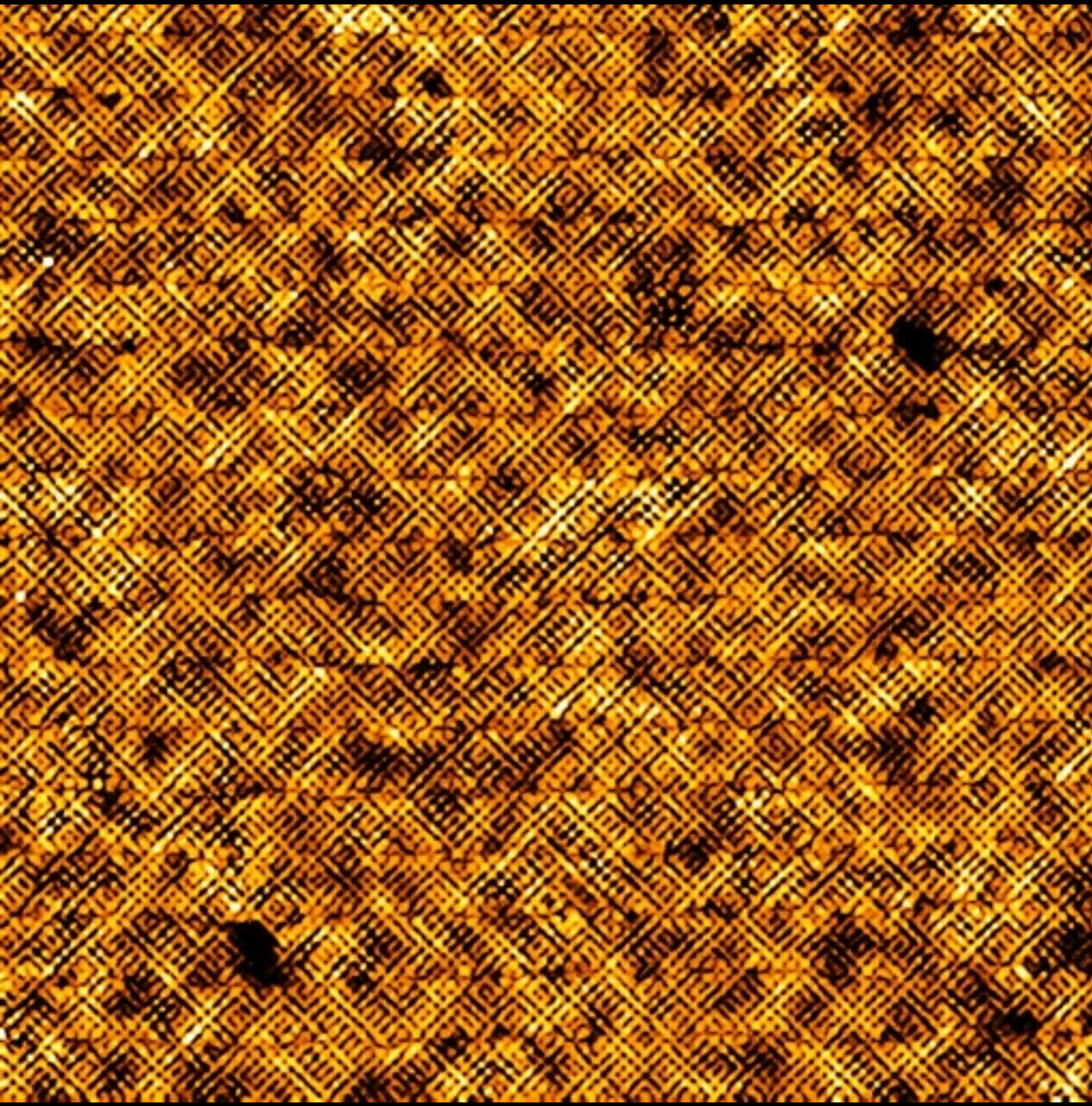

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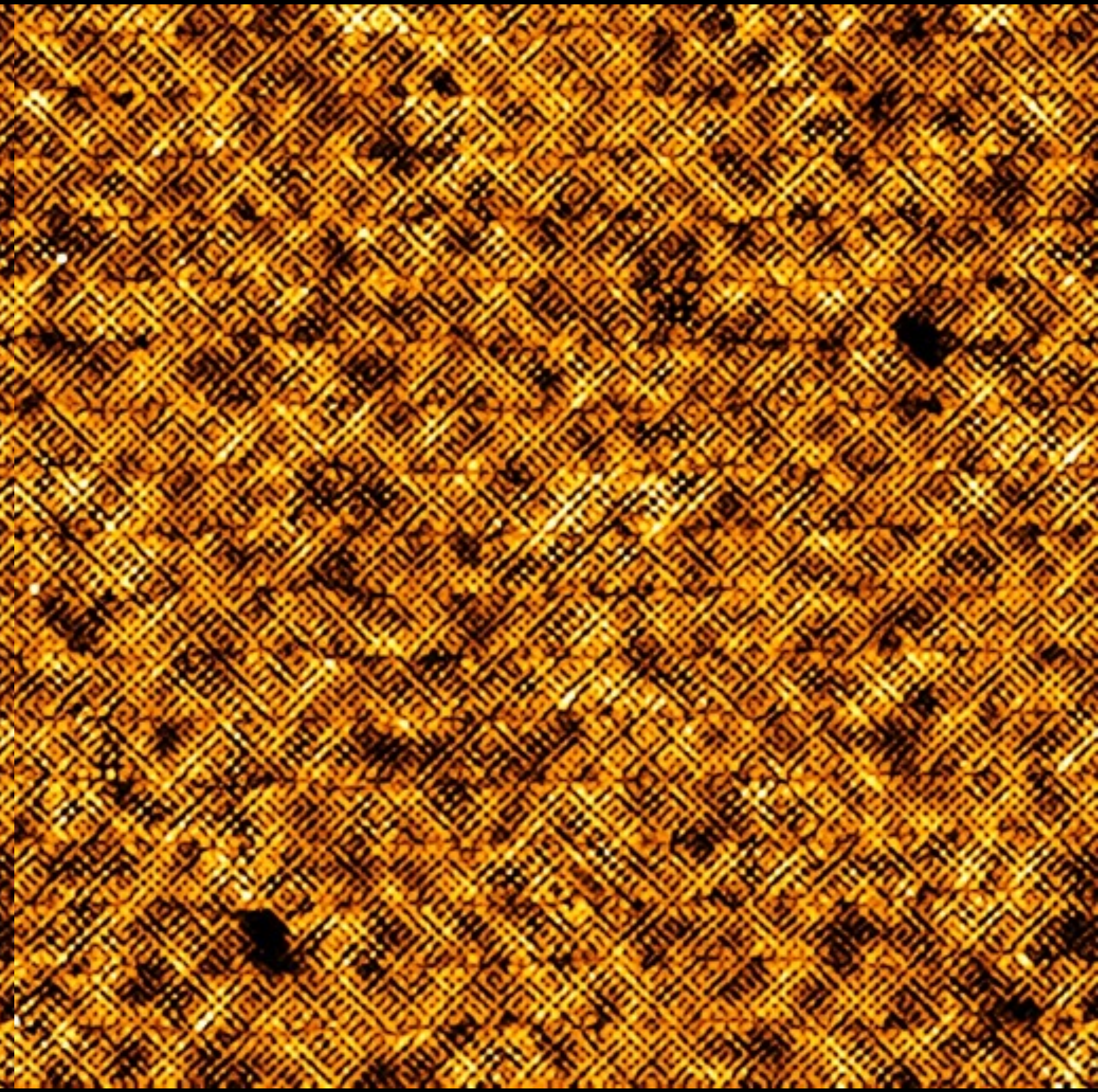
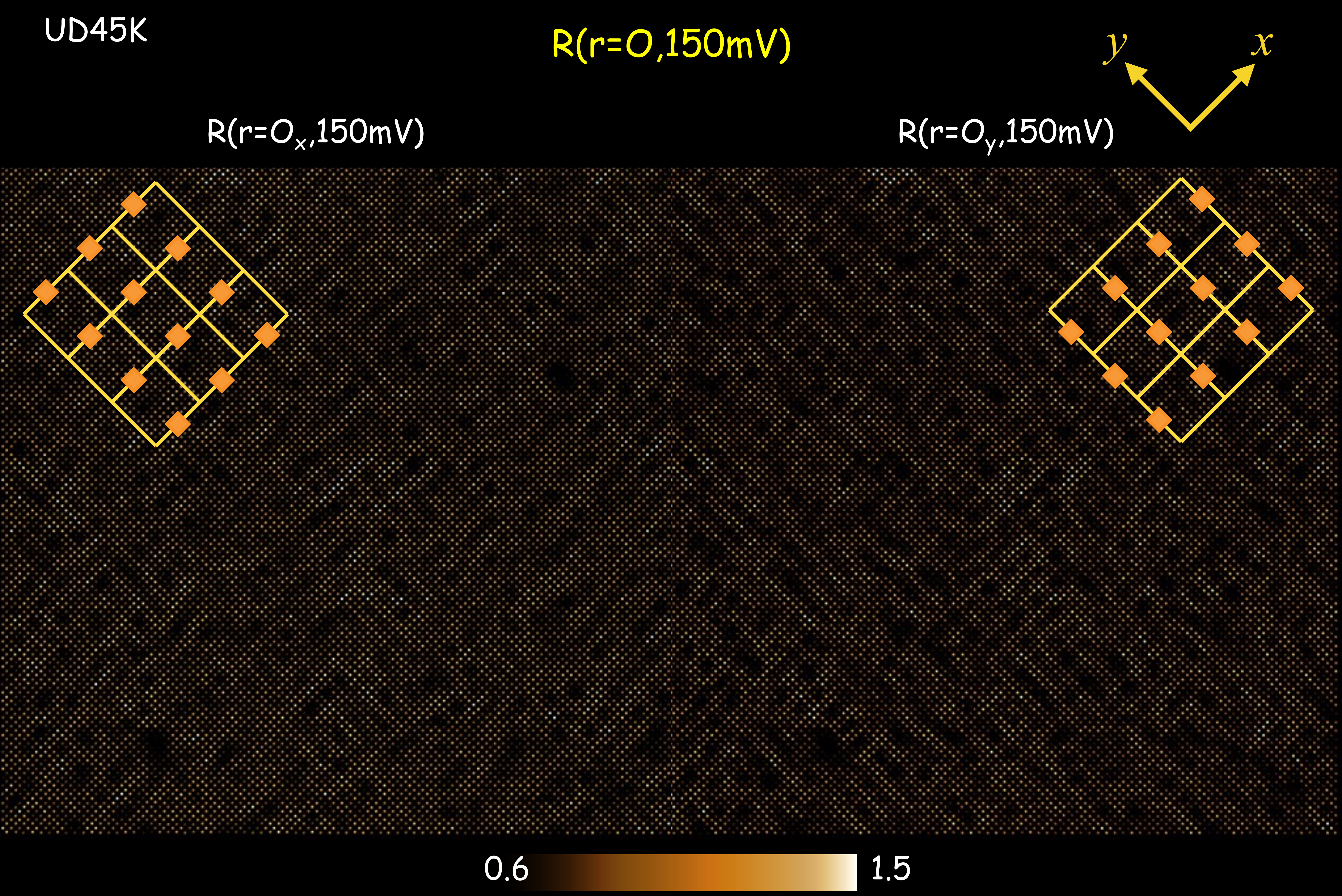


Note that these are identical images.

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)



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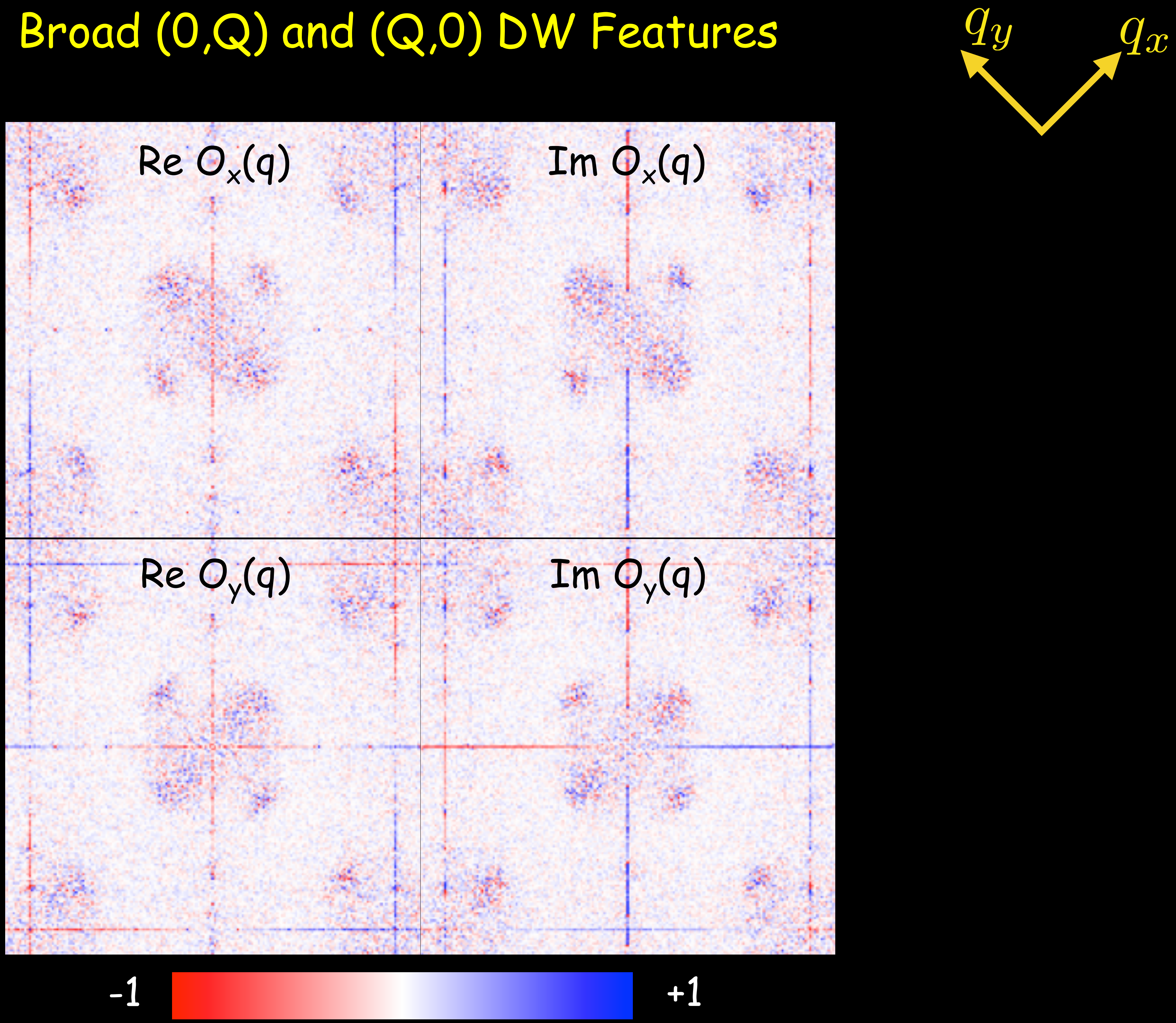
UD45K

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



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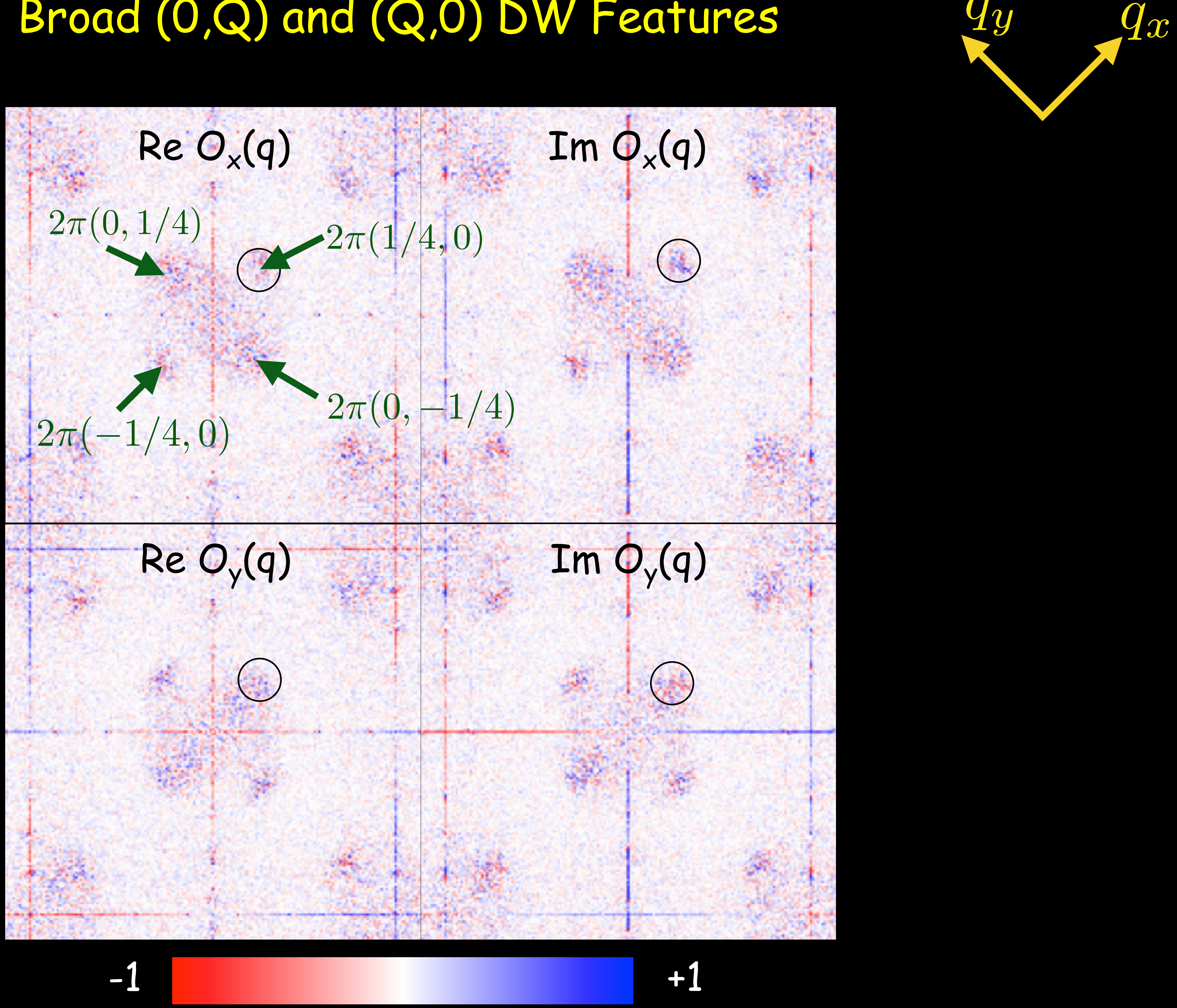

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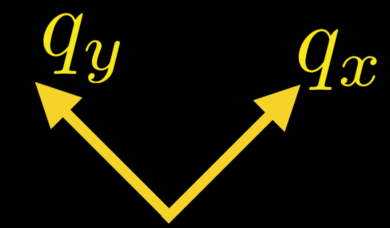
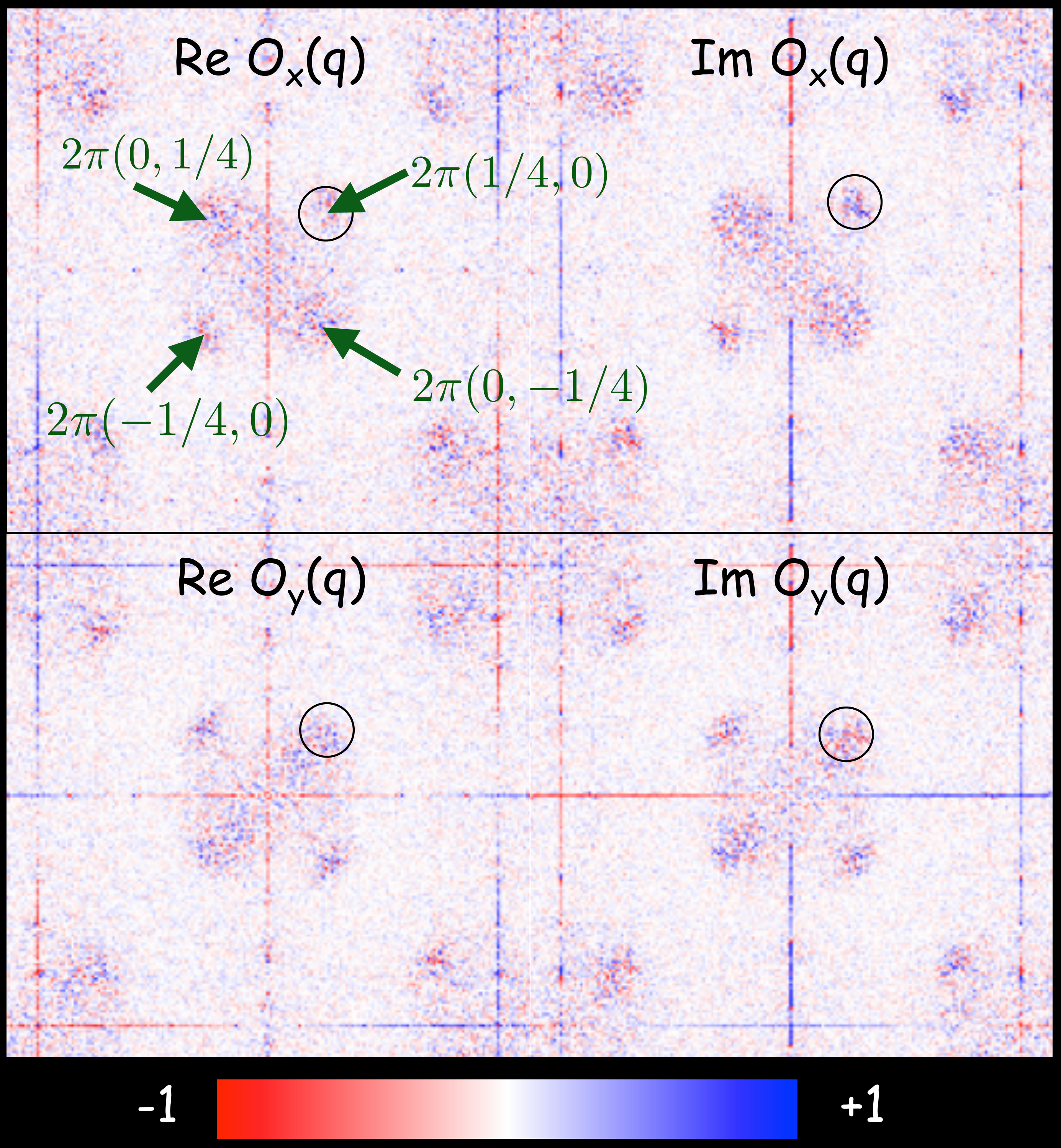


For each pixel in the circles, we obtain 2 complex numbers, $O_x(q)$ and $O_y(q)$.



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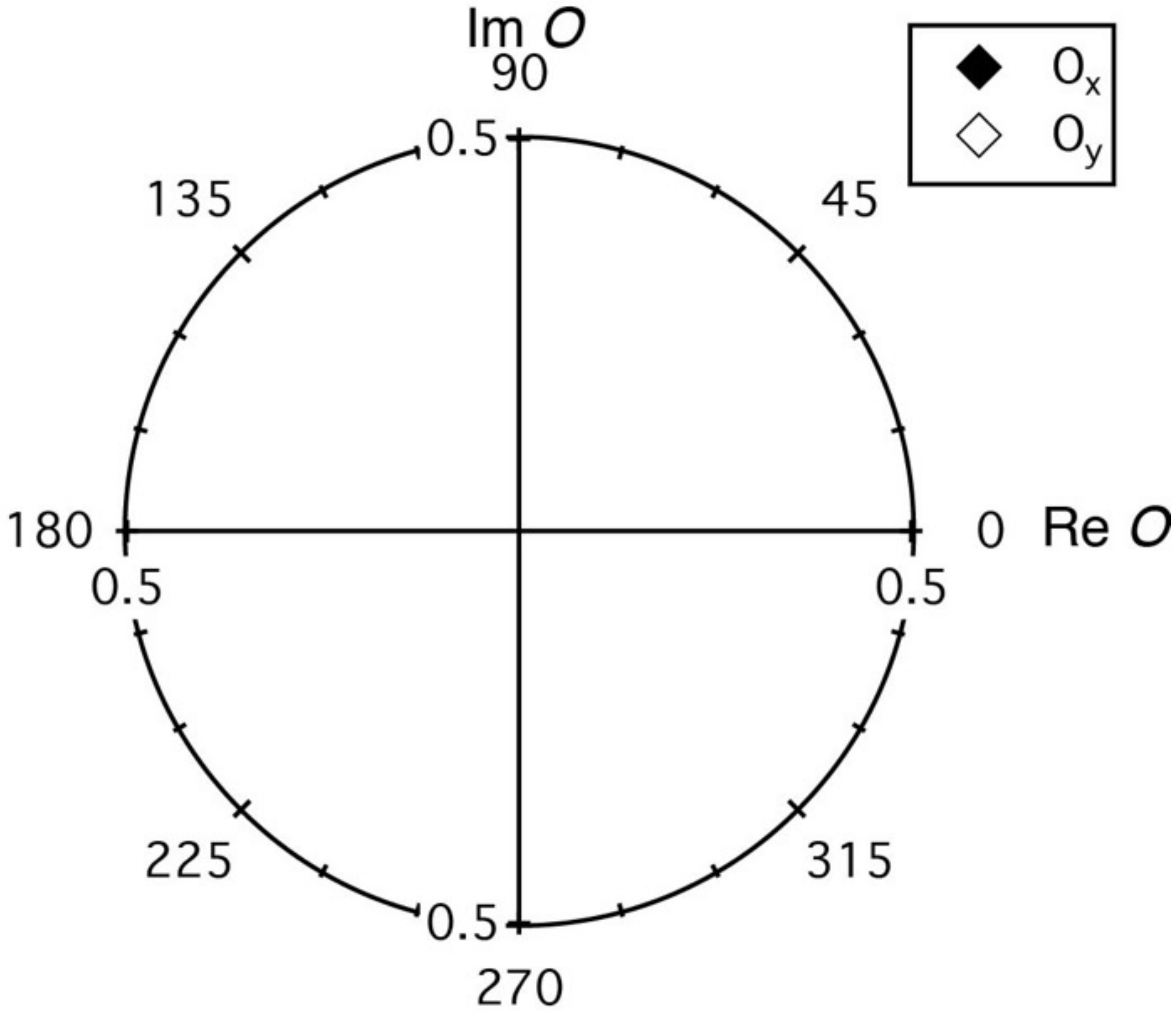

Phase-sensitive measurement of the *d*-form factor of density wave order

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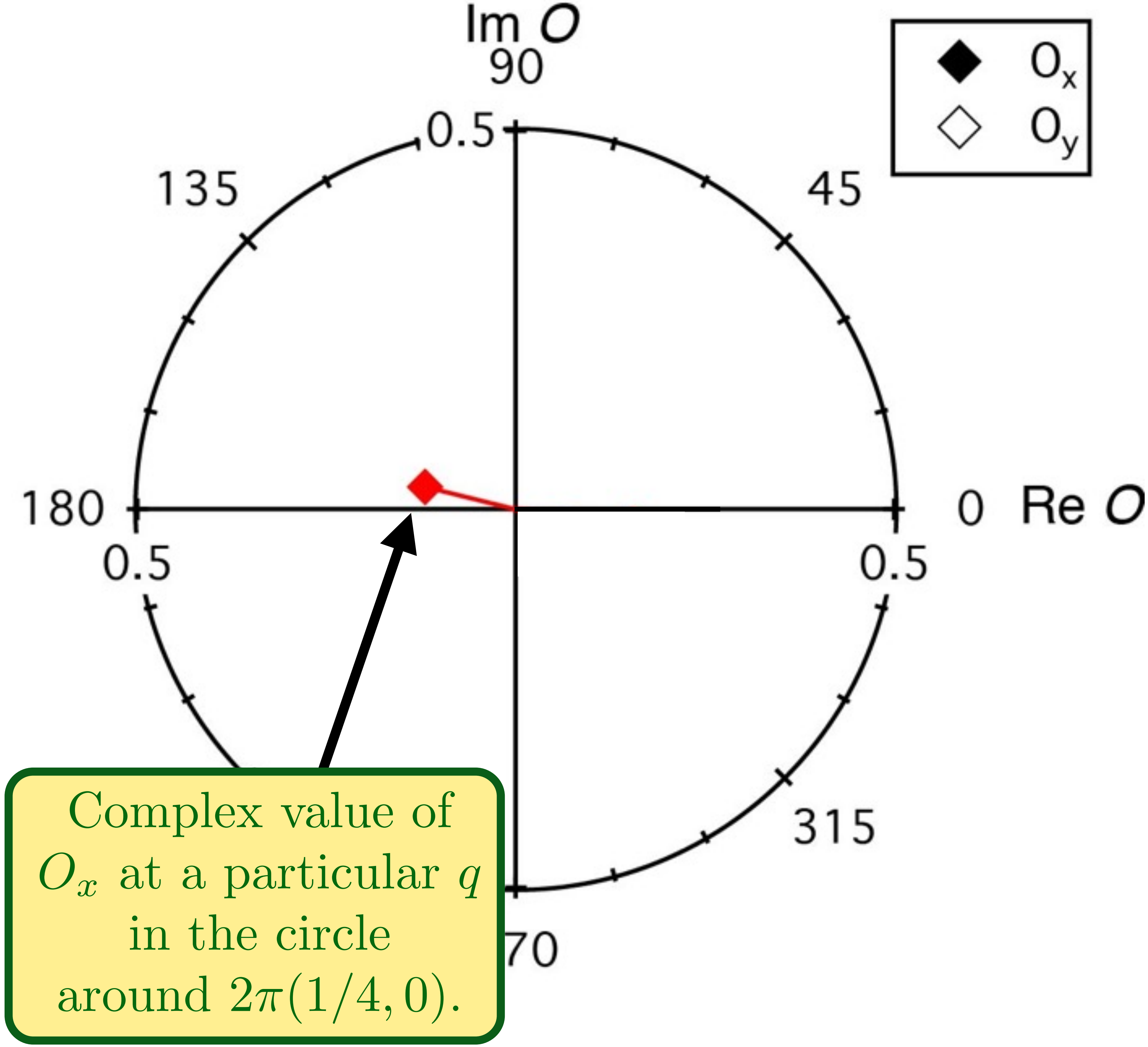

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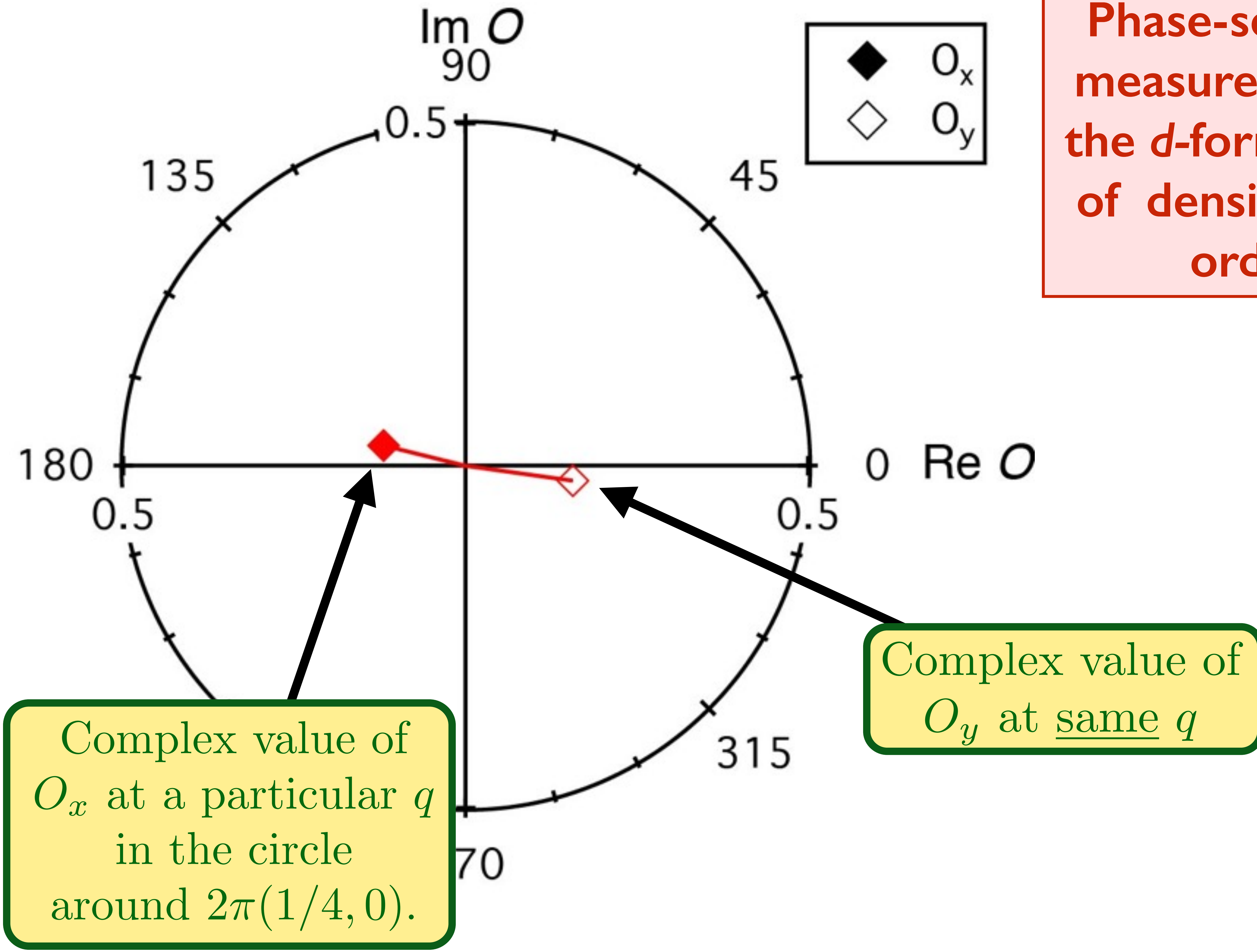

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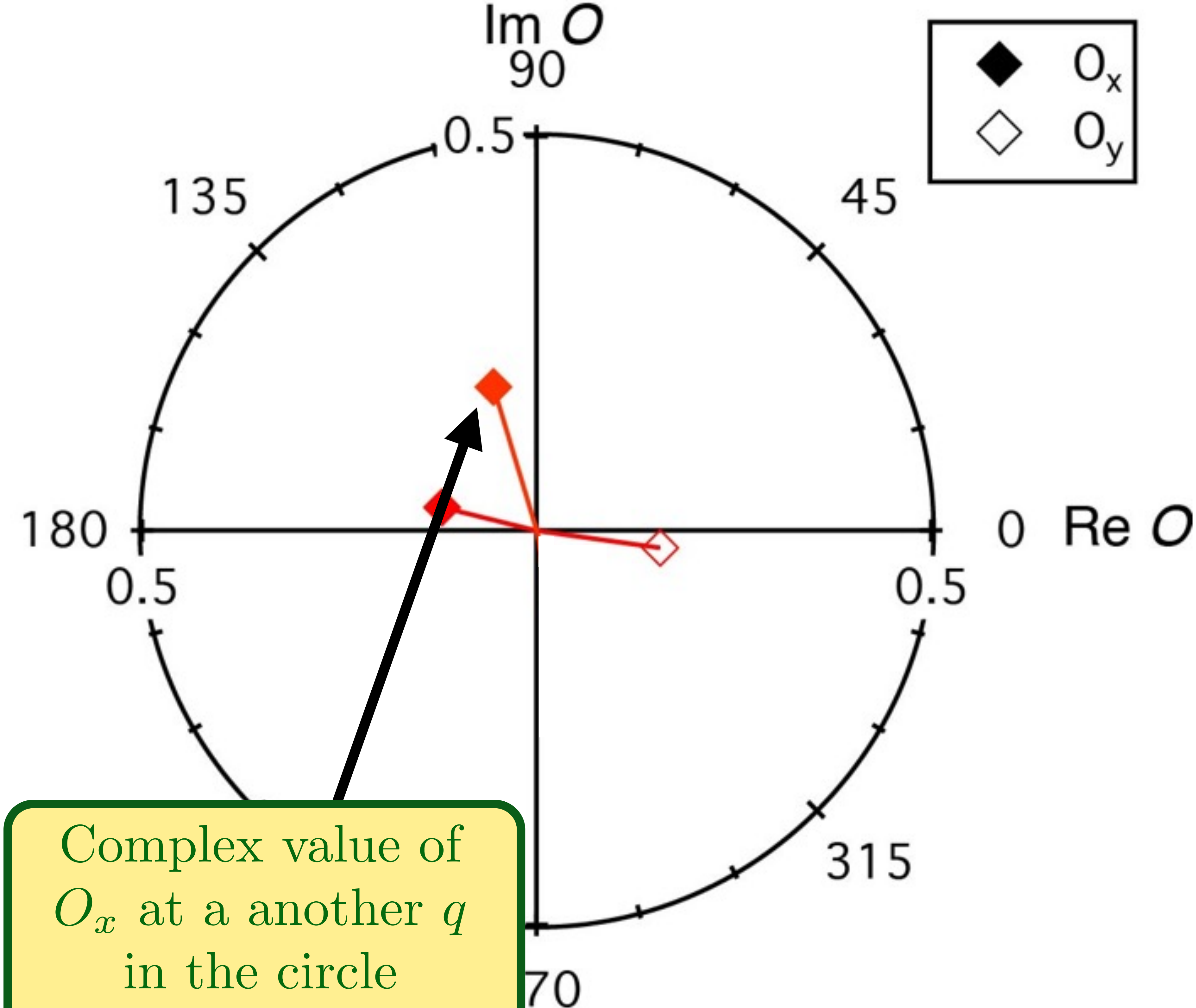

Complex value of O_x at a another q in the circle around $2\pi(1/4, 0)$.

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

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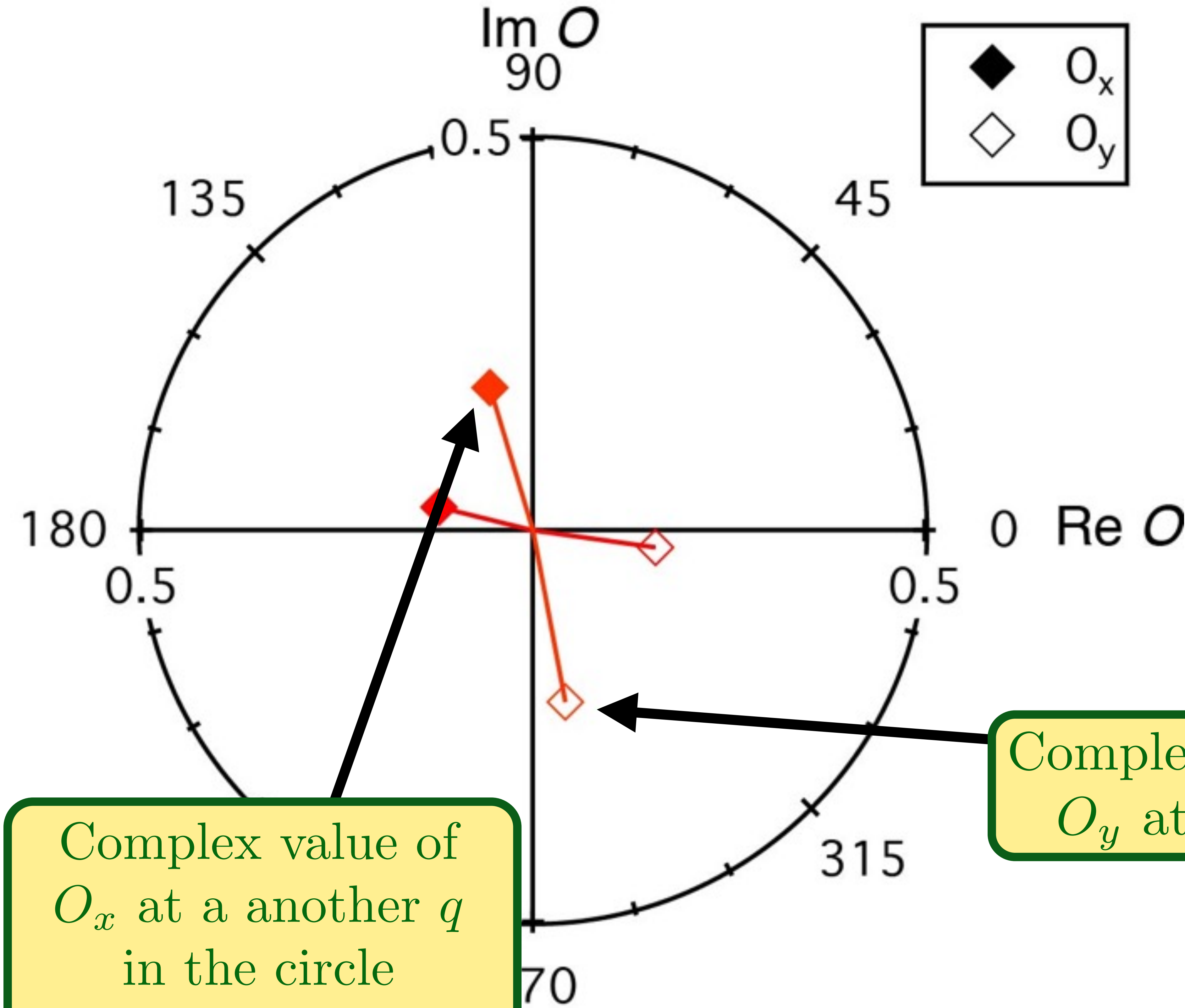

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Complex value of O_y at <u>same</u> q

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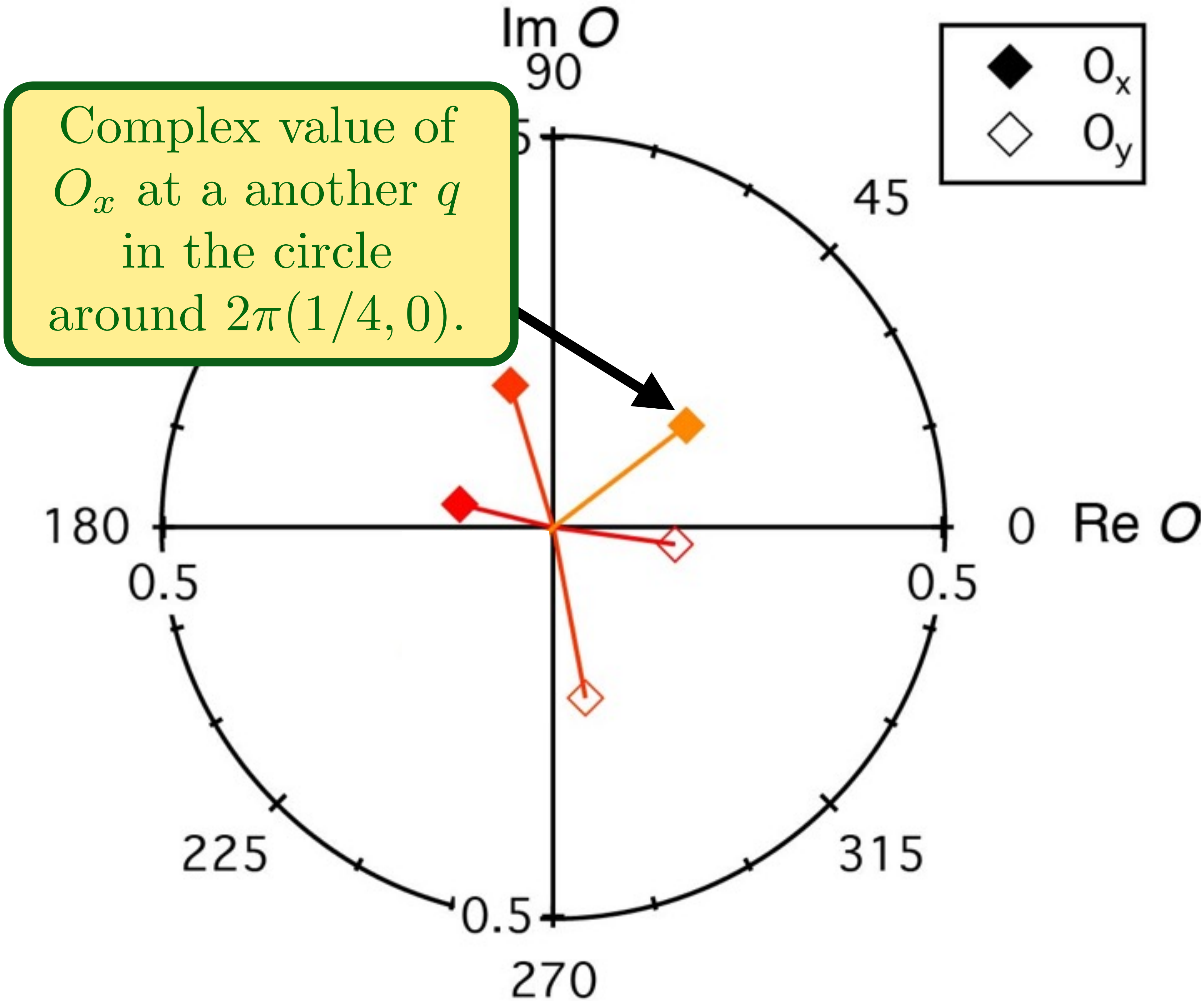

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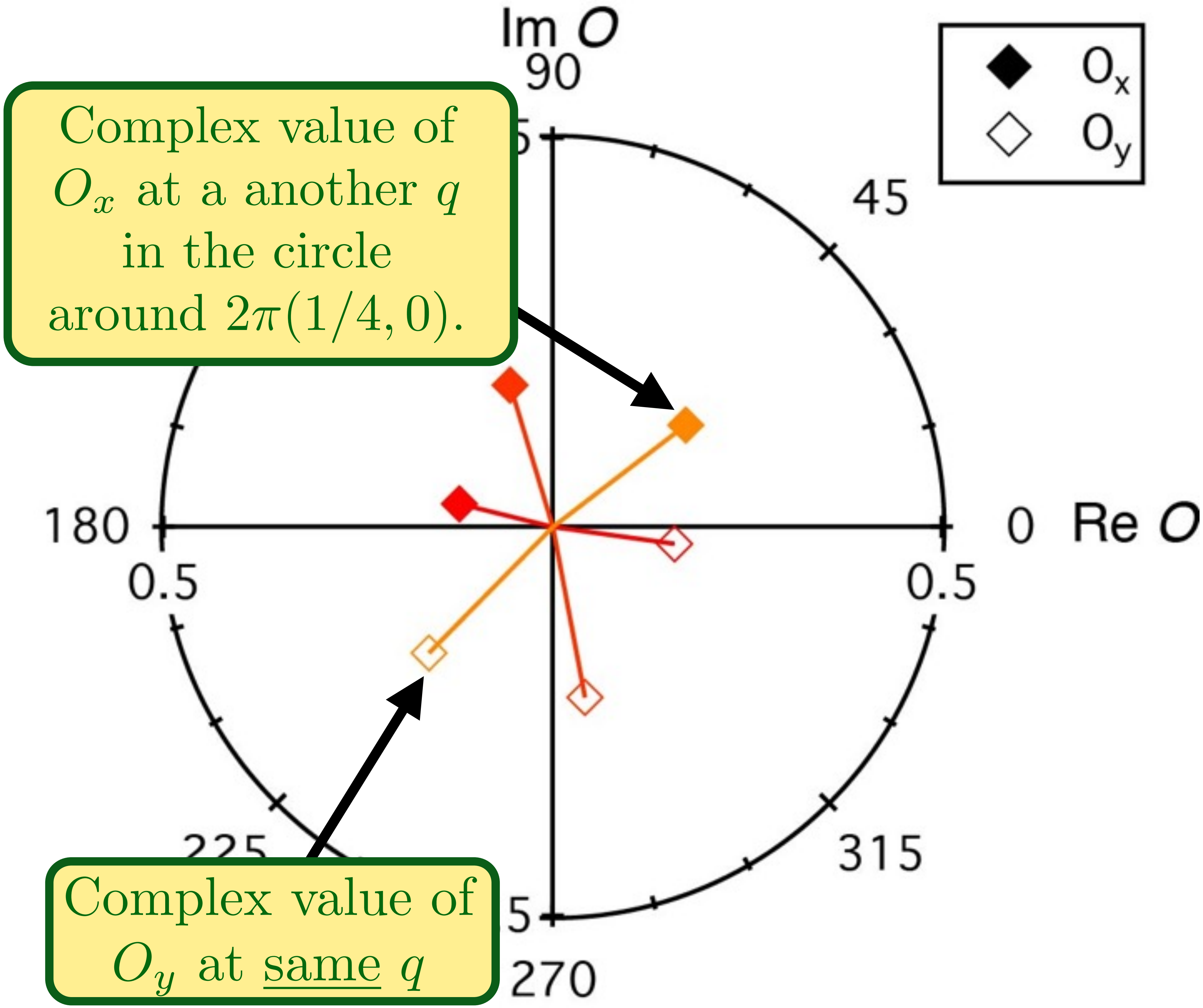

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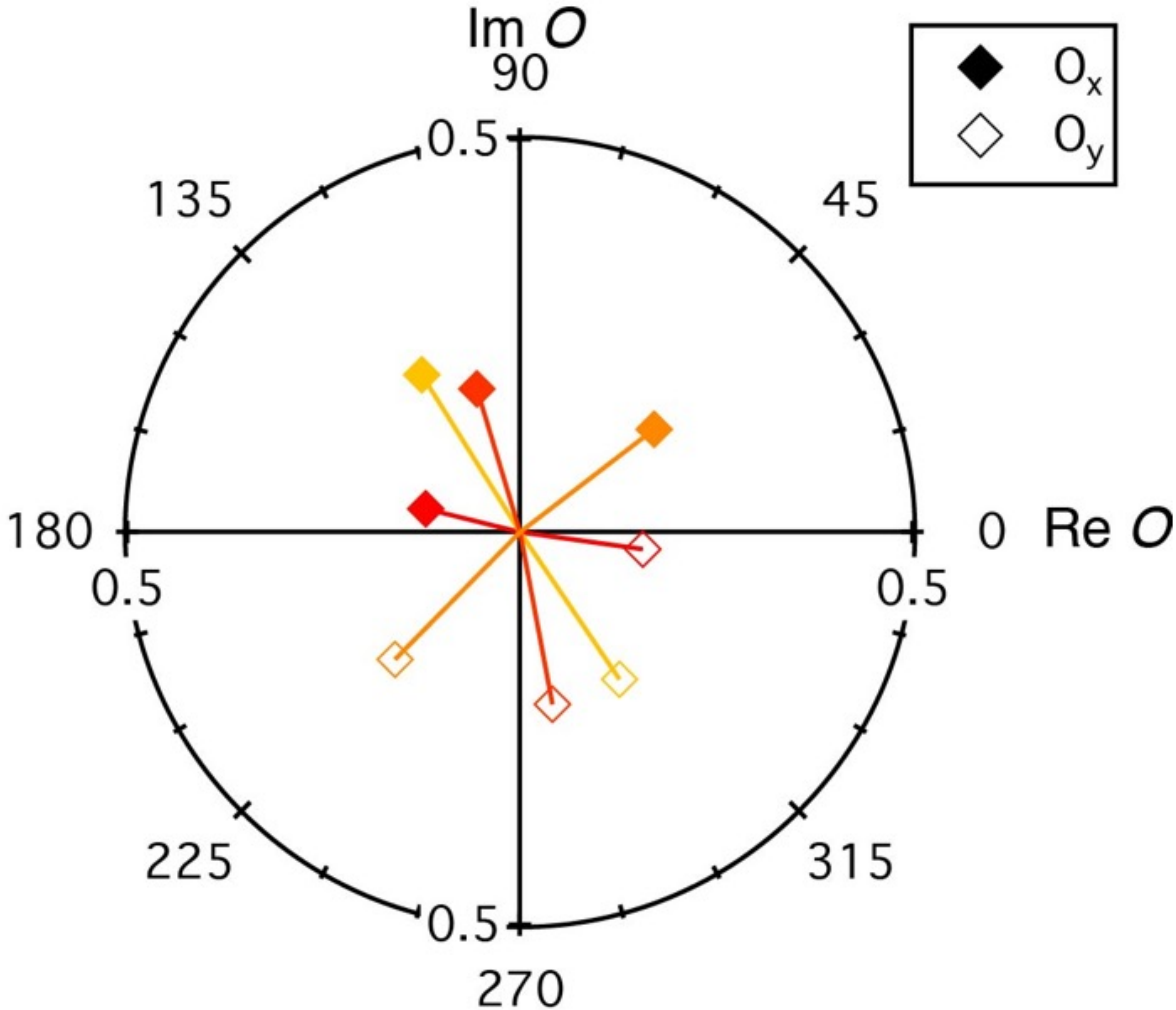

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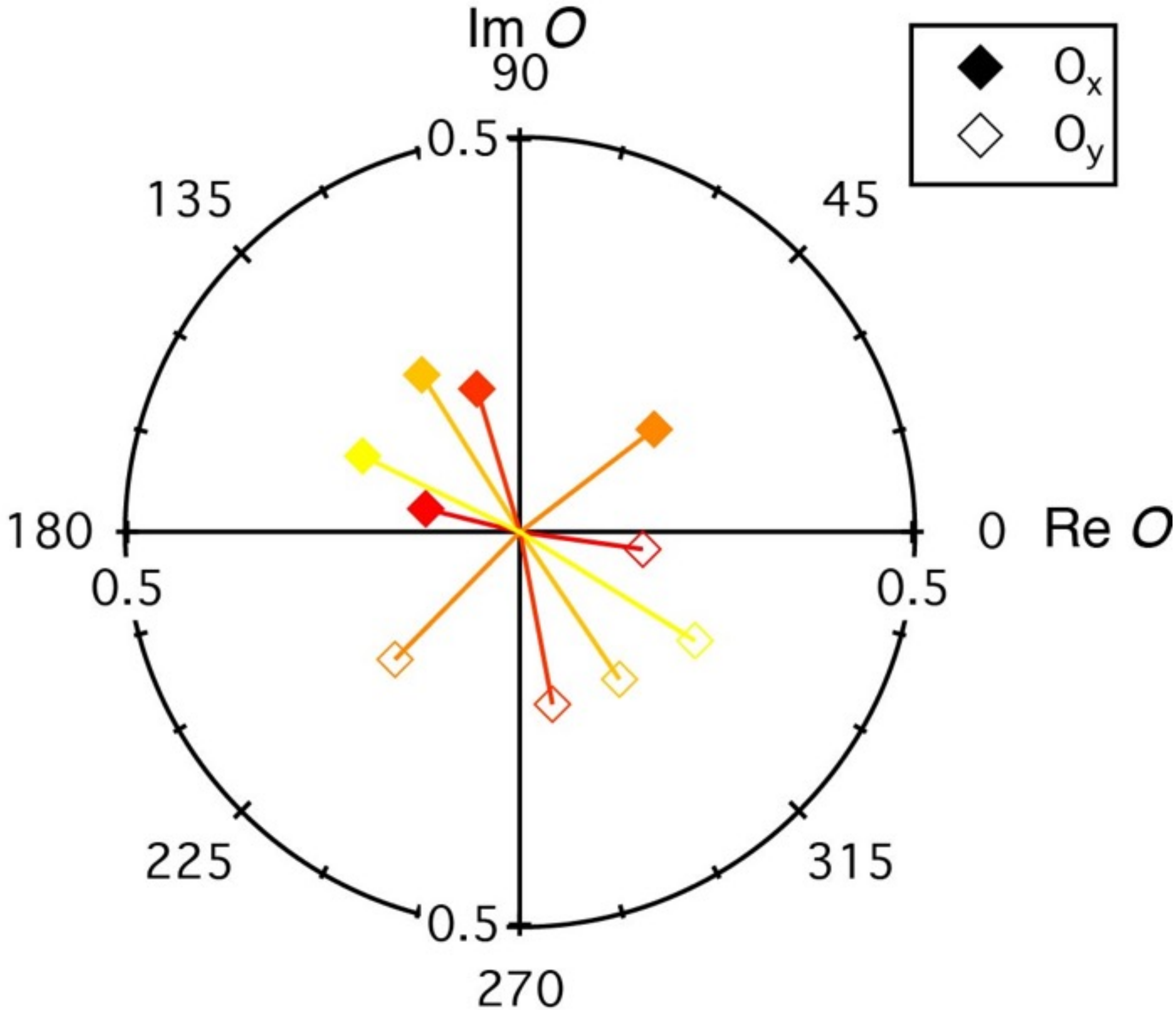

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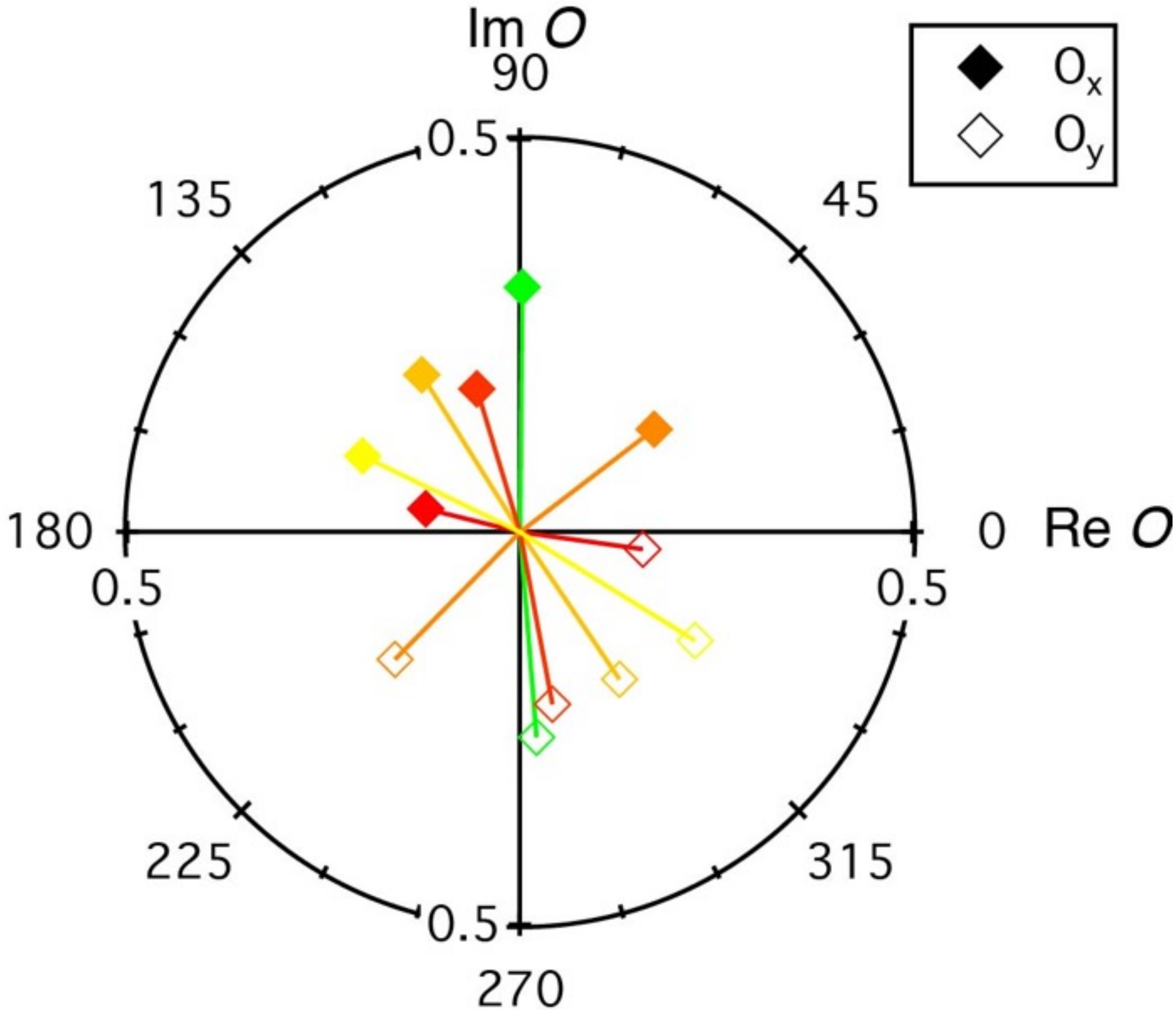

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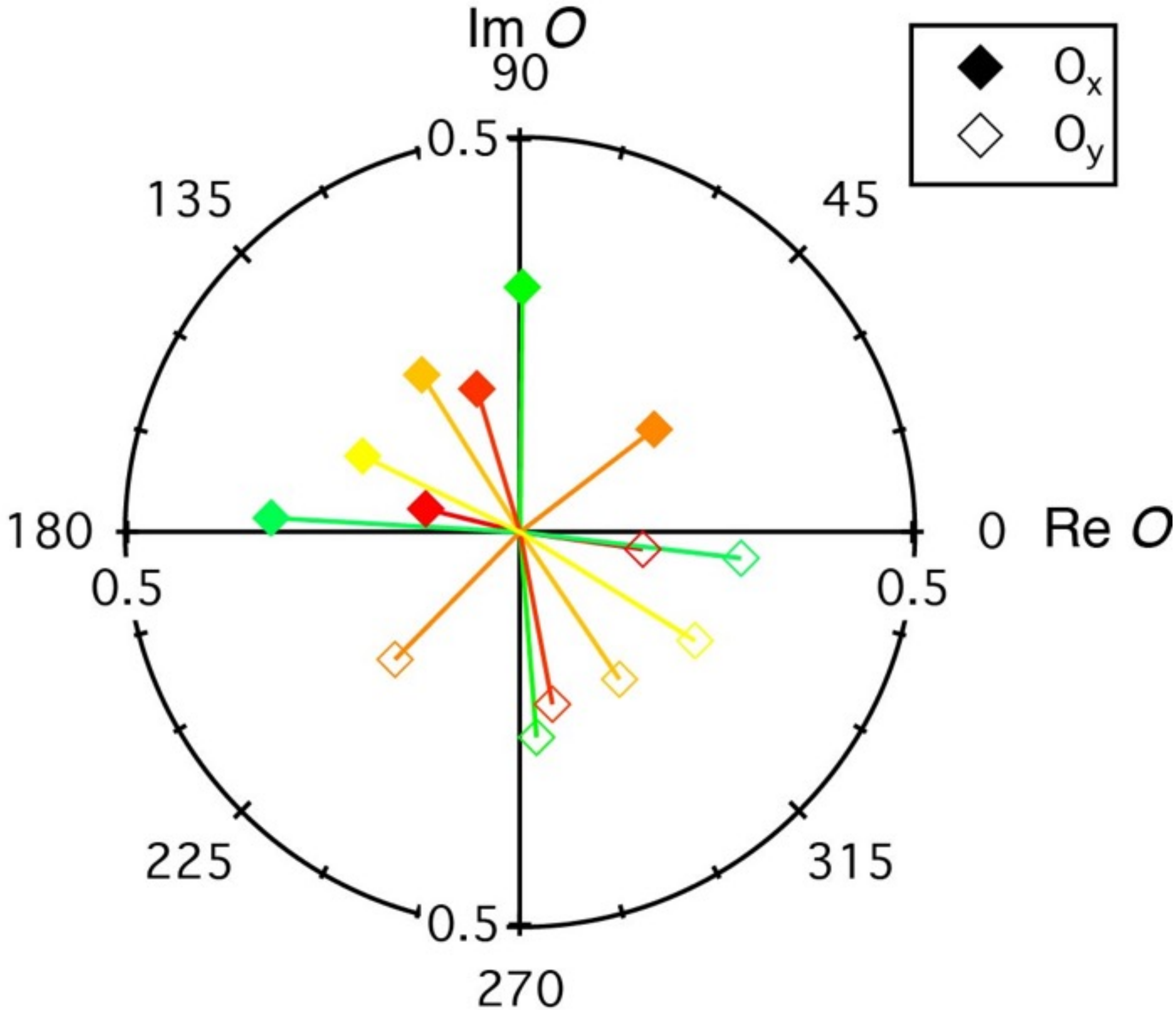

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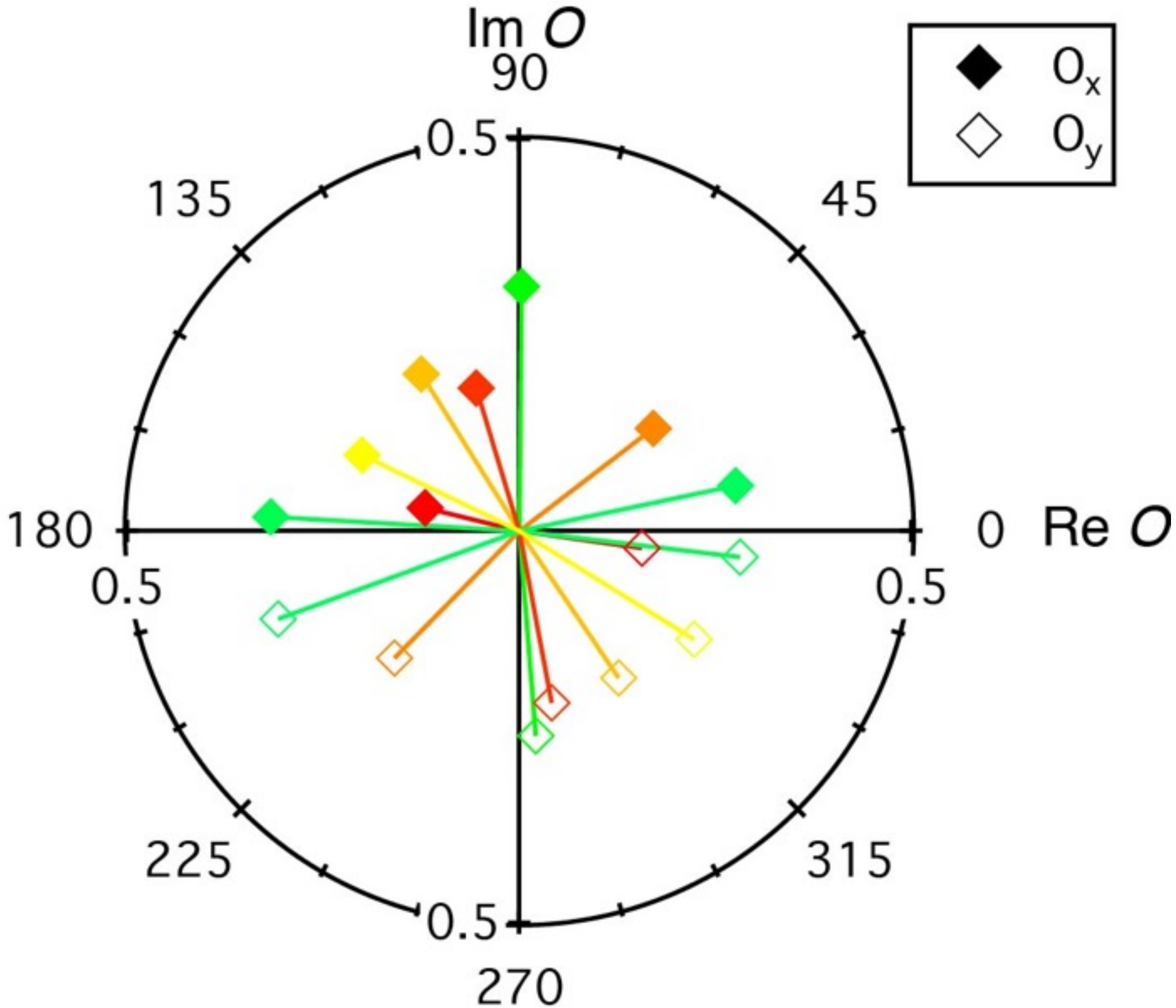

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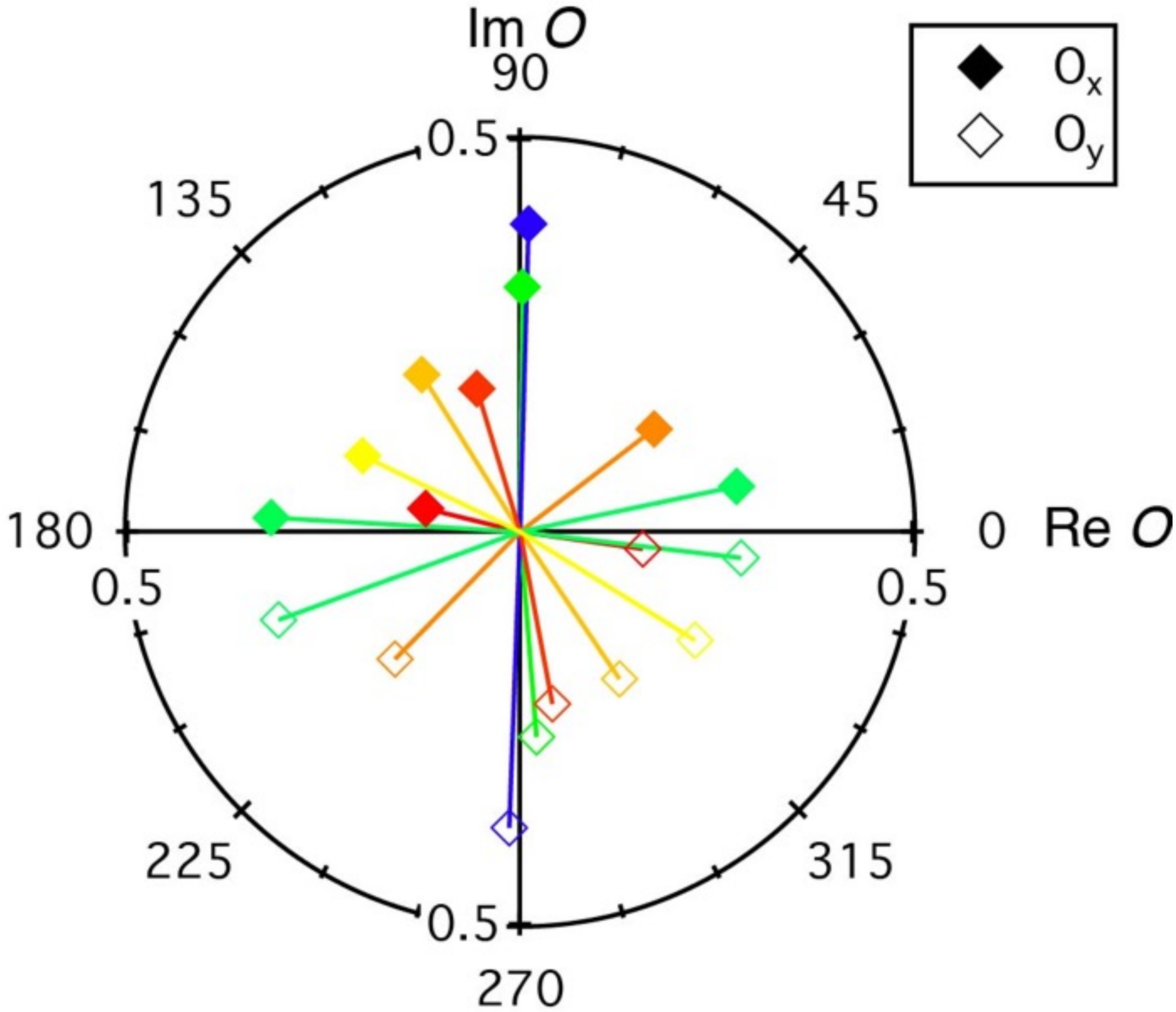

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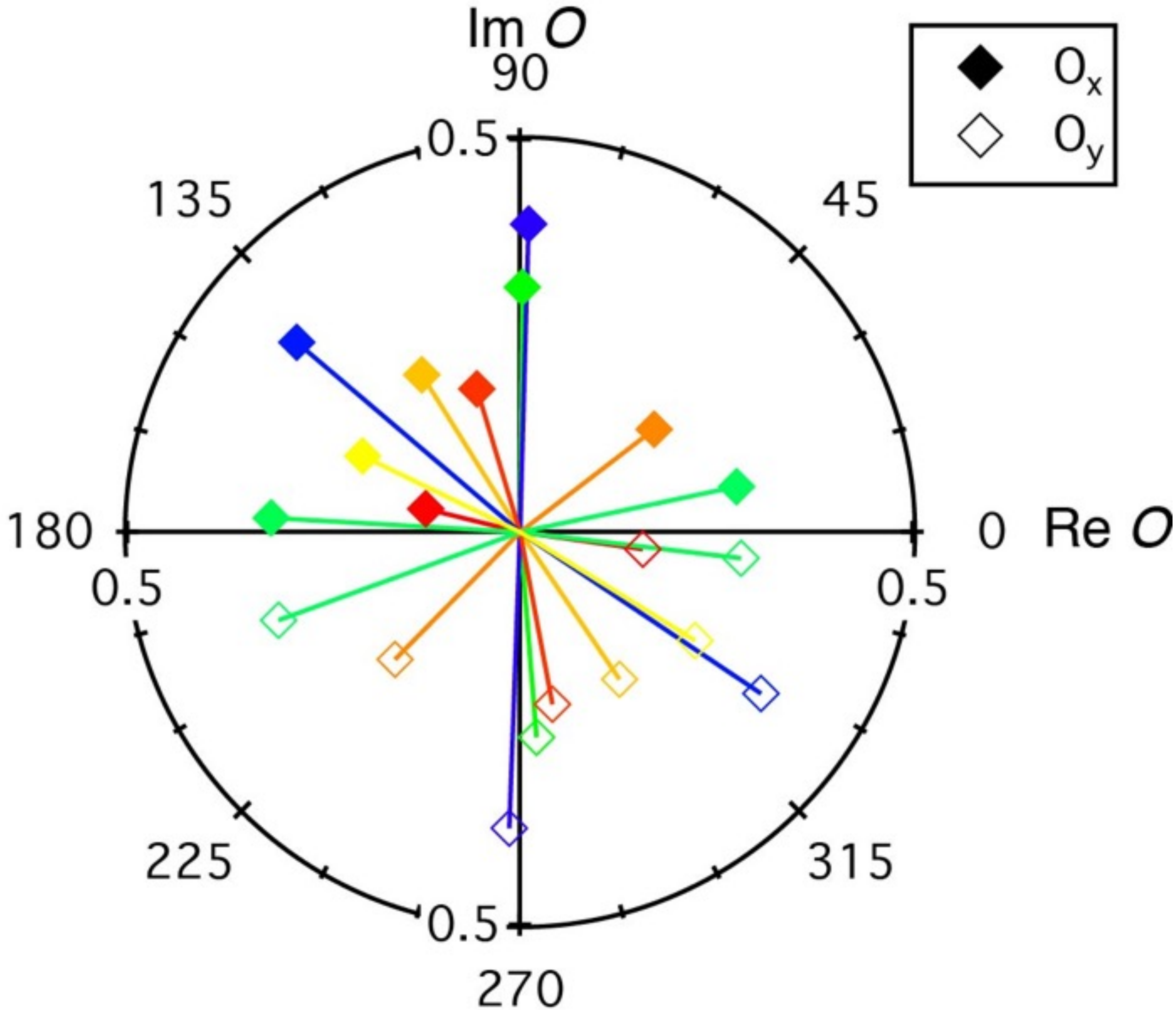

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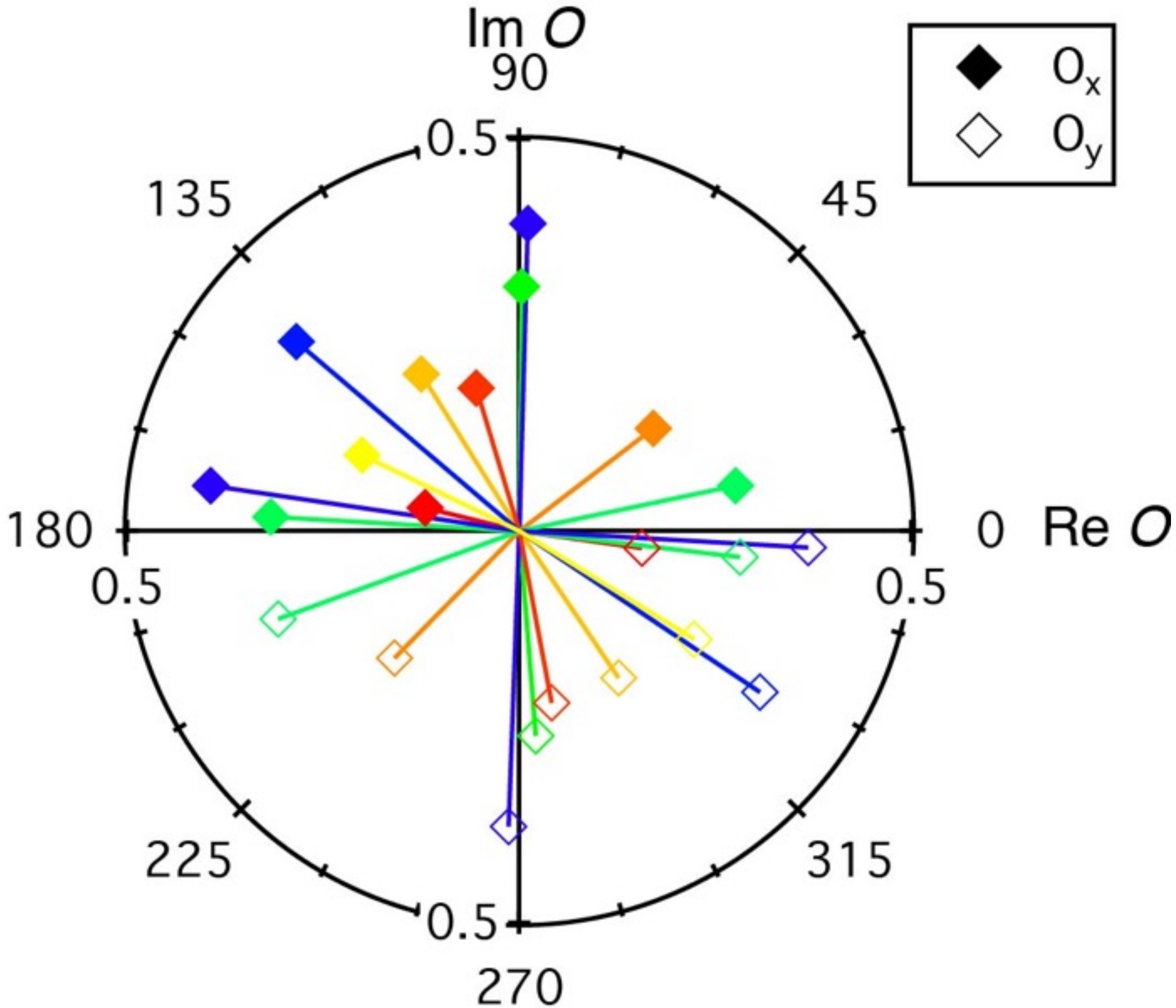

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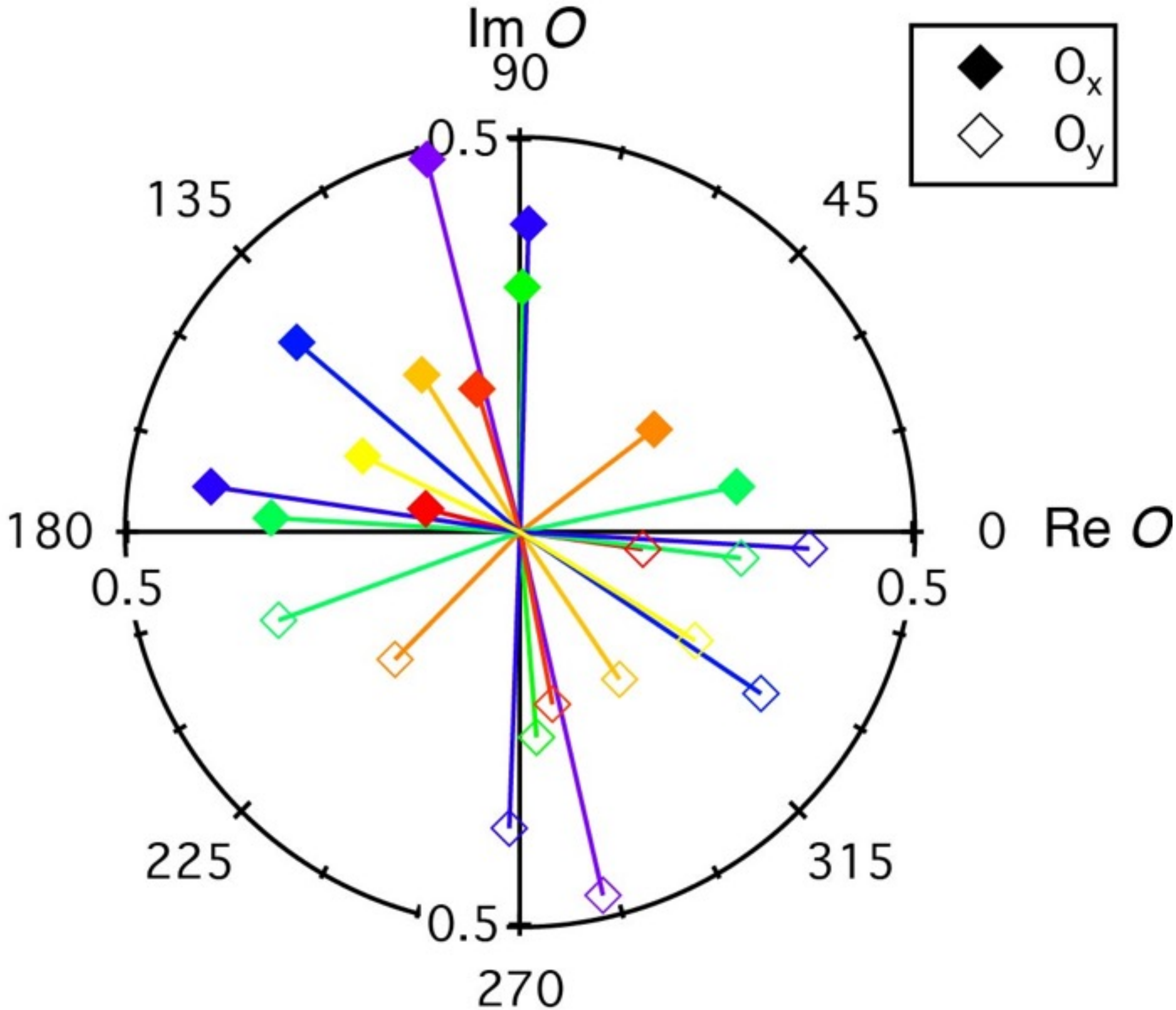

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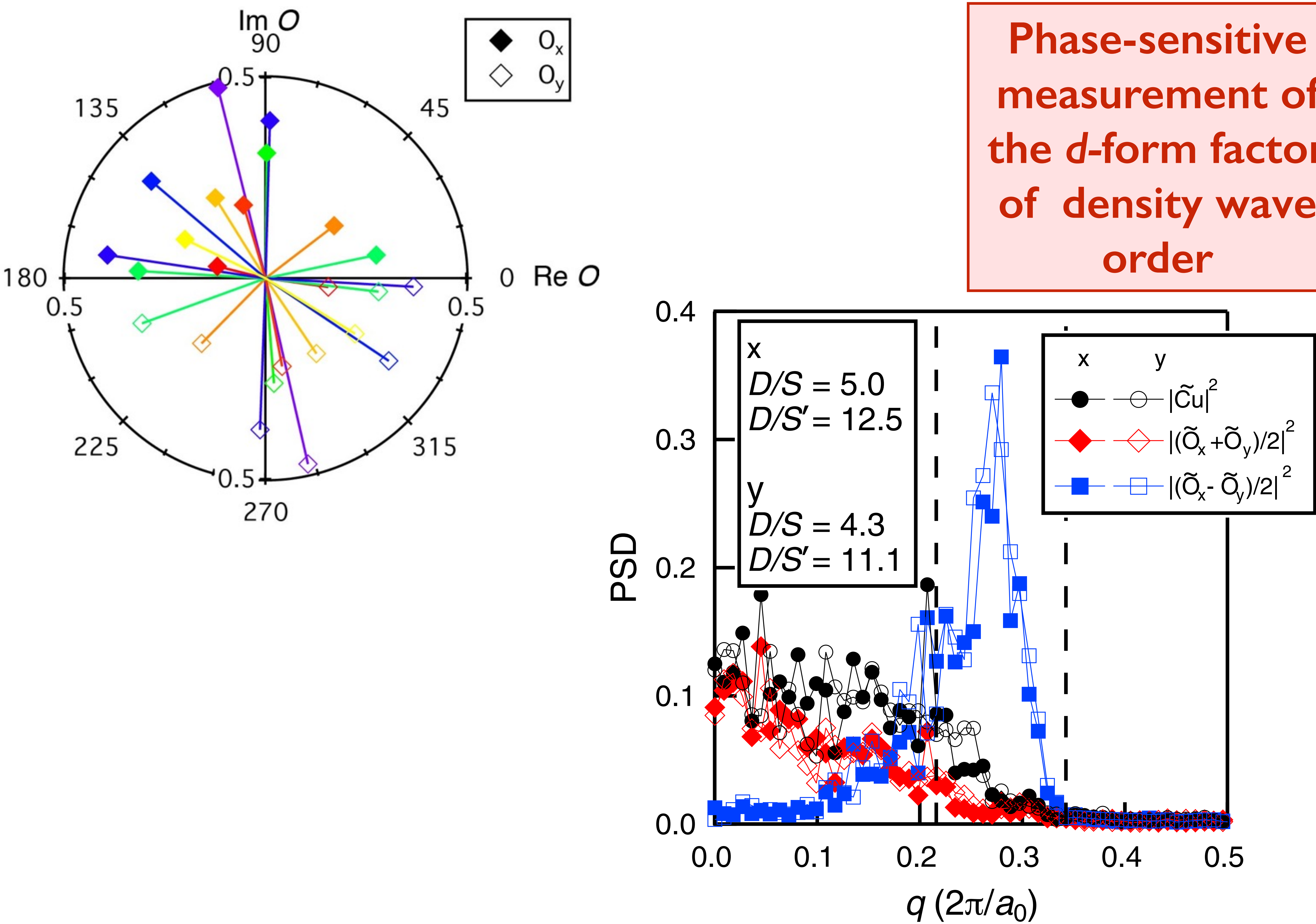

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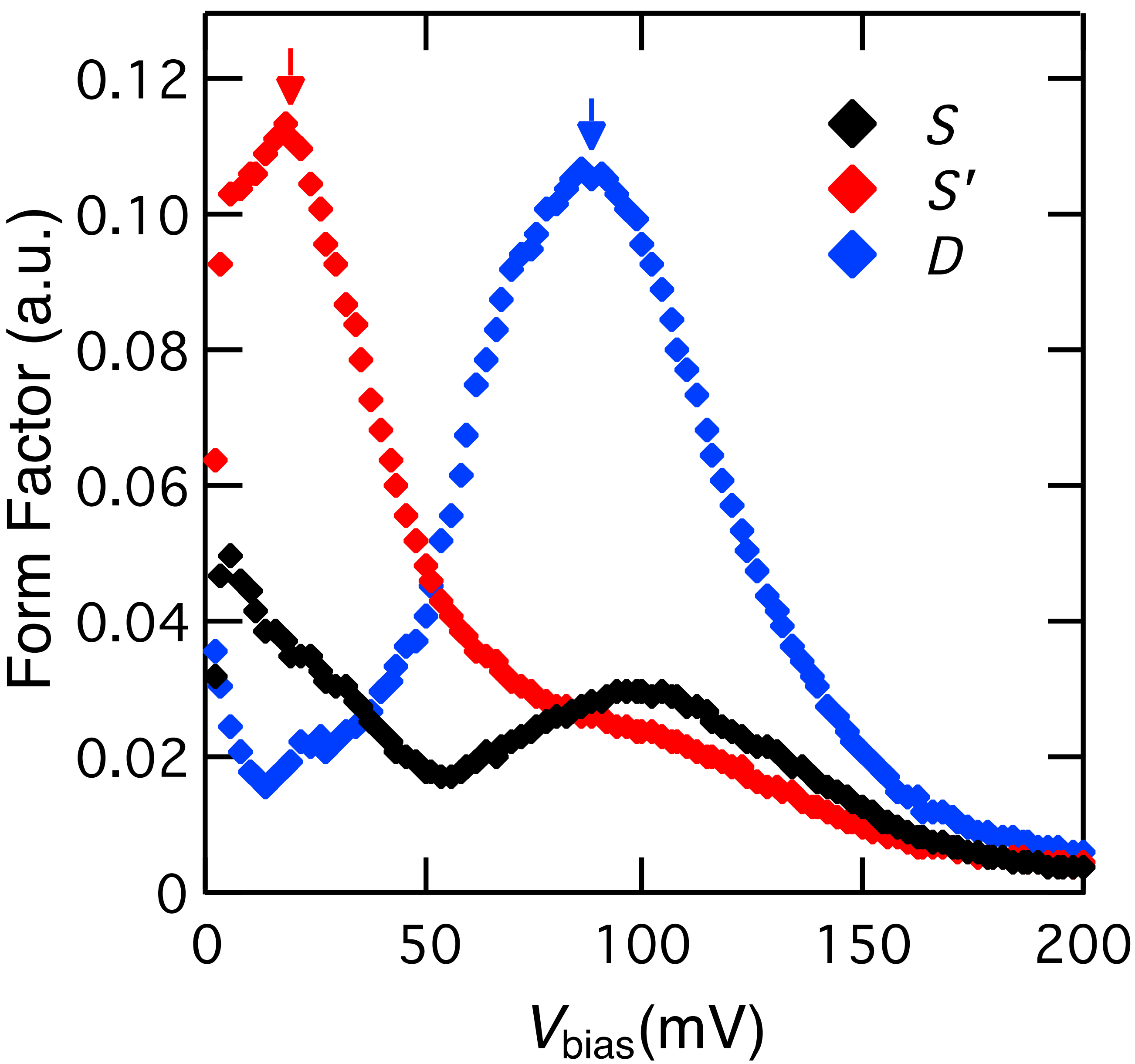
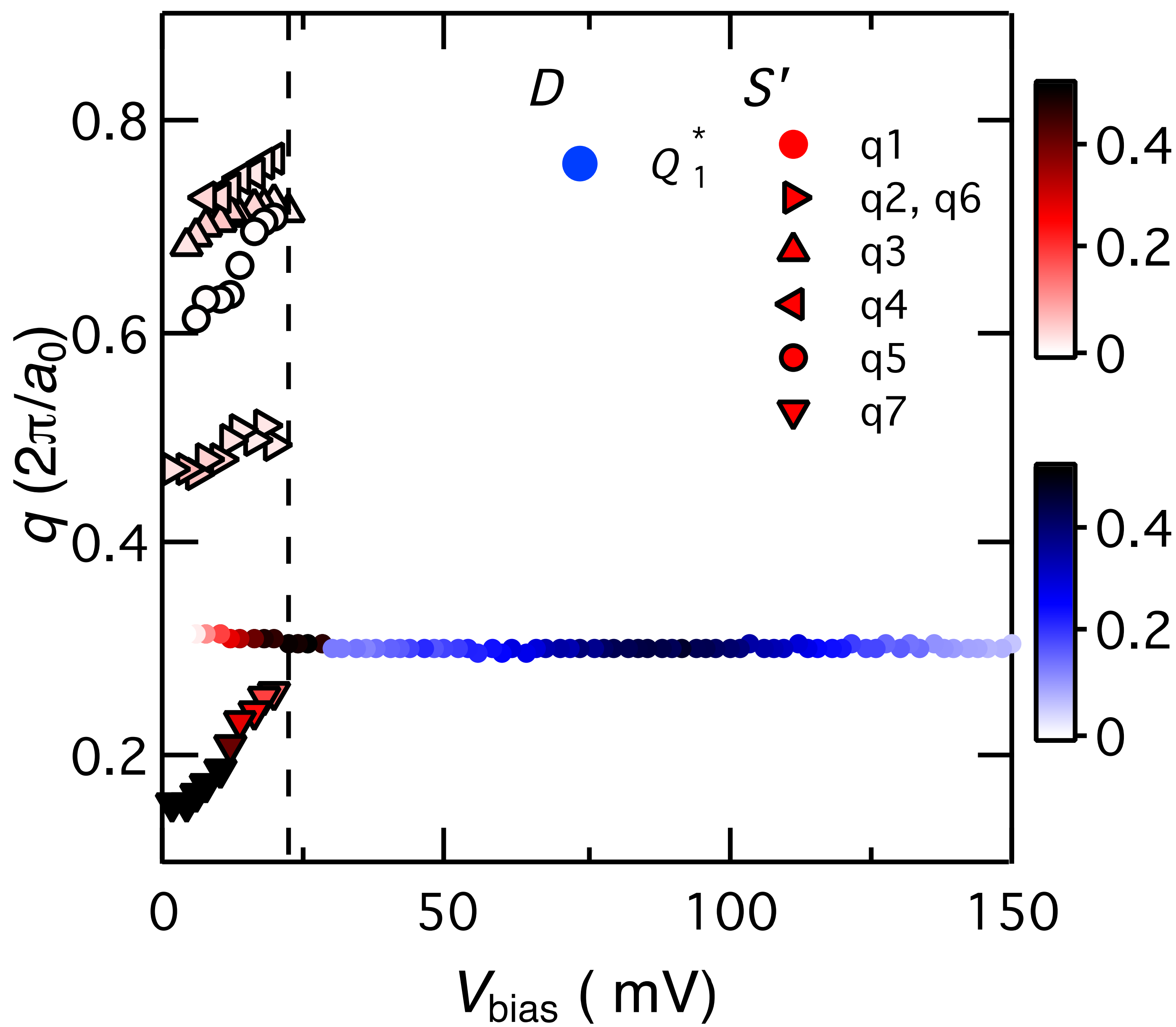
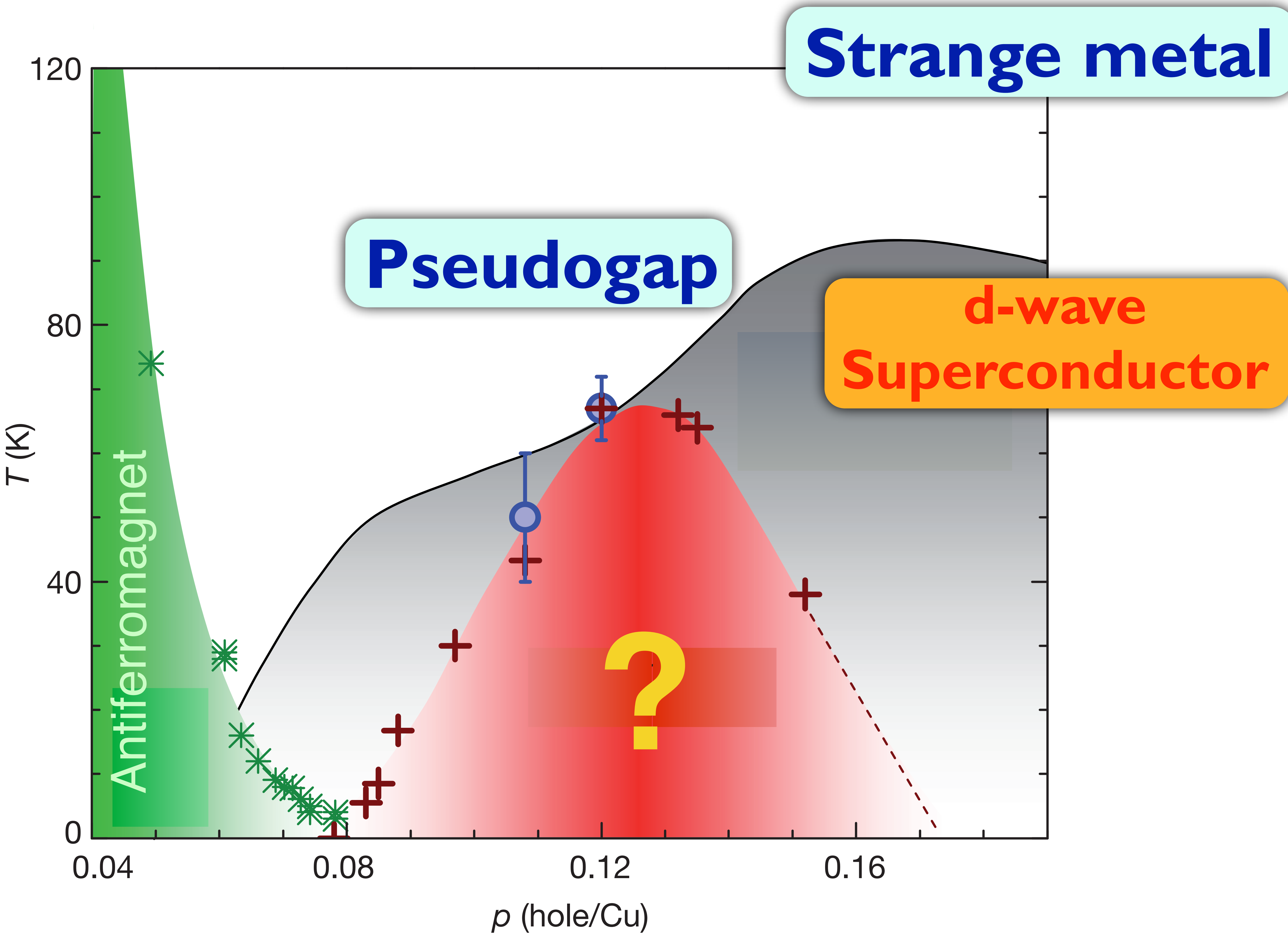
d-form factor is peaked at the pseudogap energy, and does not disperse as a function of wavevector

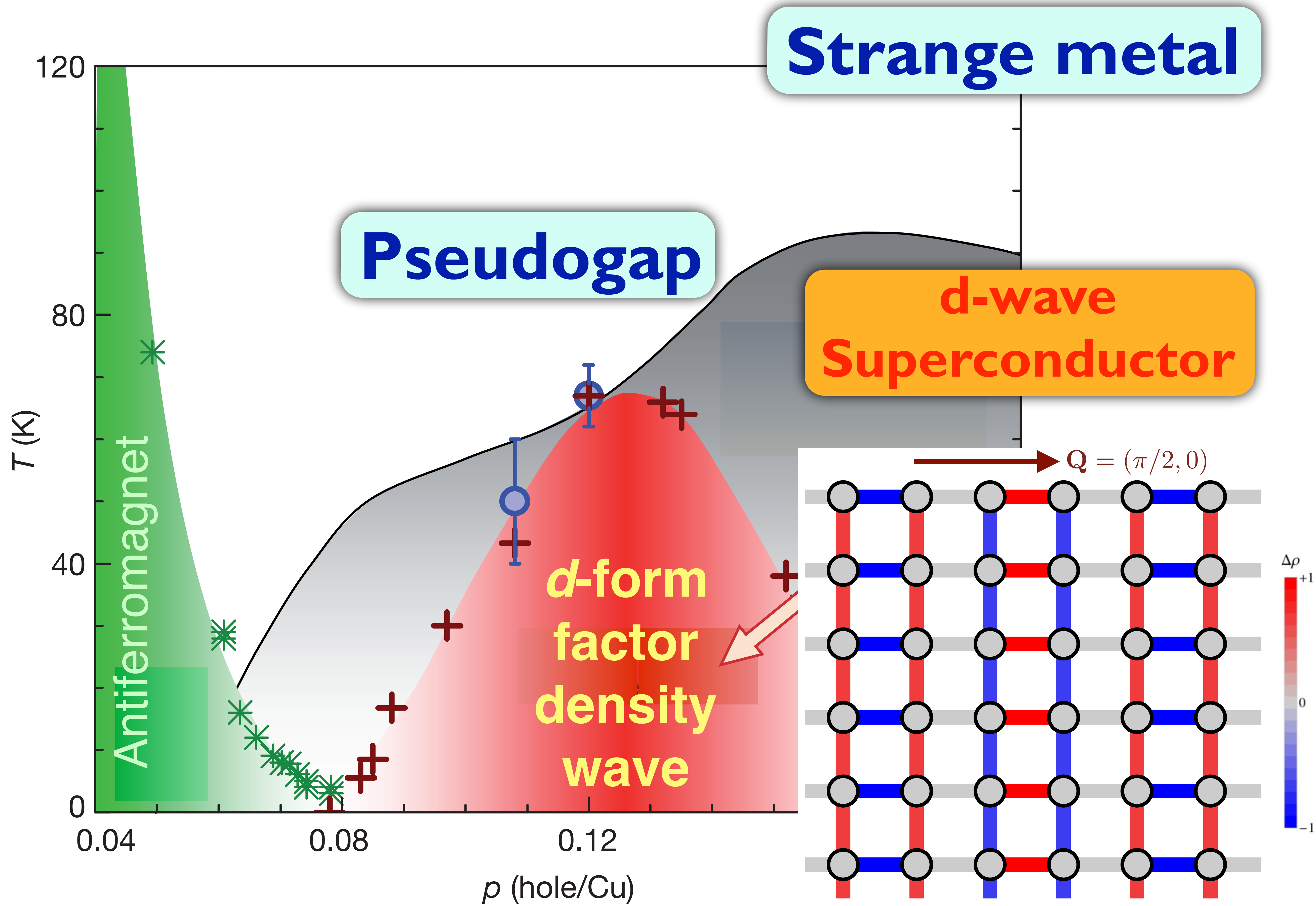




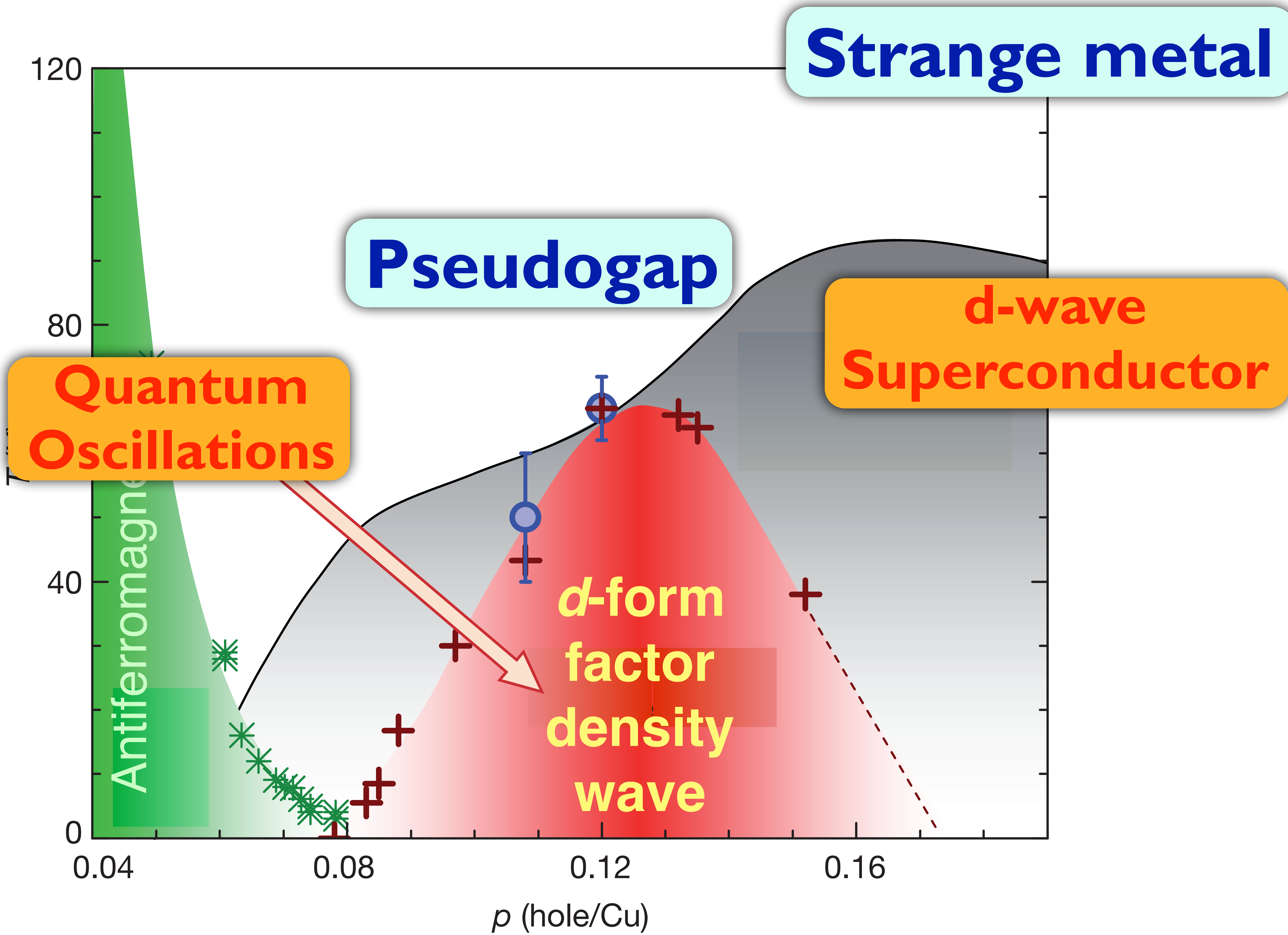
K. Fujita, M. H. Hamidian, S. D. Edkins, Chung Koo Kim, A. P. MacKenzie,
H. Eisaki, S. Uchida, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, to appear



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



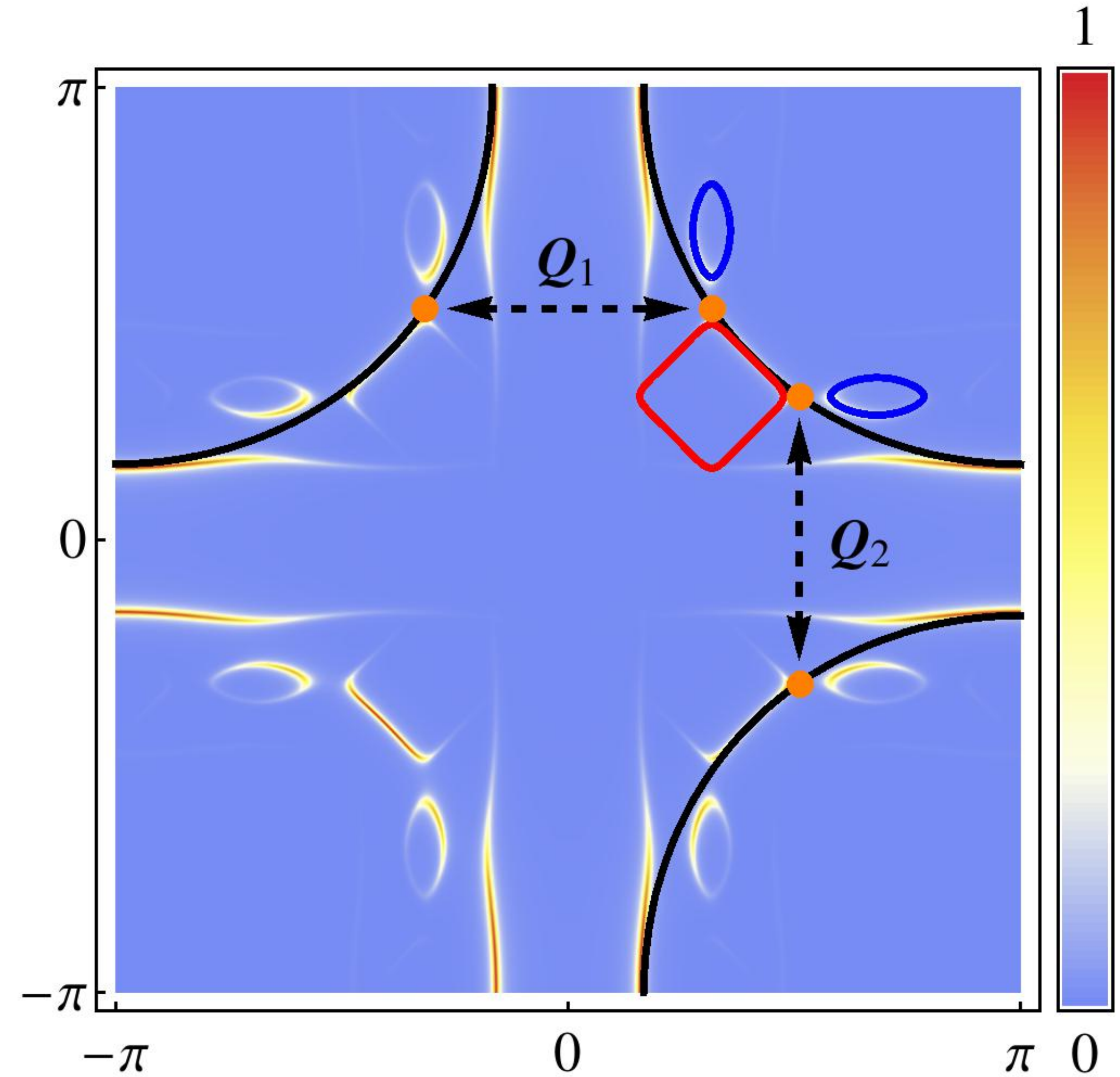
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)



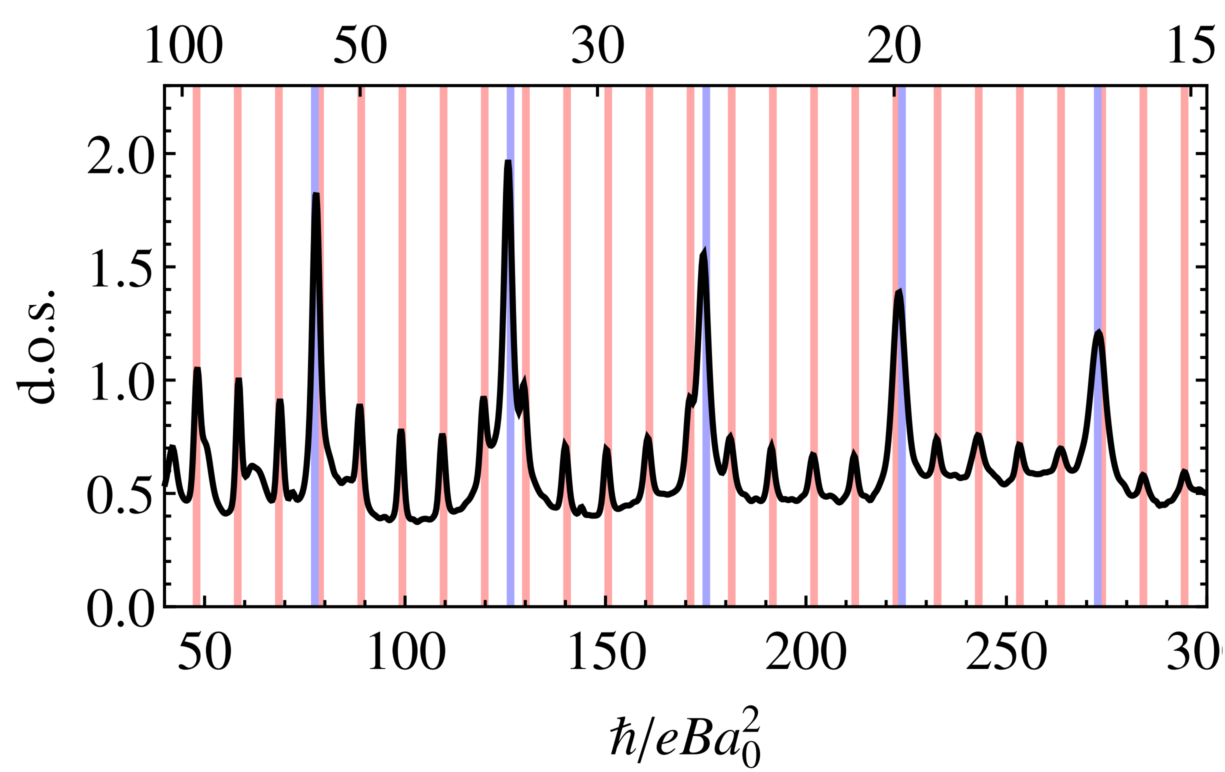
Strange metal
Pseudogap
d-wave
Superconductor
Quantum
Oscillations
Antiferromagnet
d-form
factor
density
wave
120
80
40
0
0.04
0.08
0.12
0.16
p (hole/Cu)

Andrea Allais
(see poster)

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

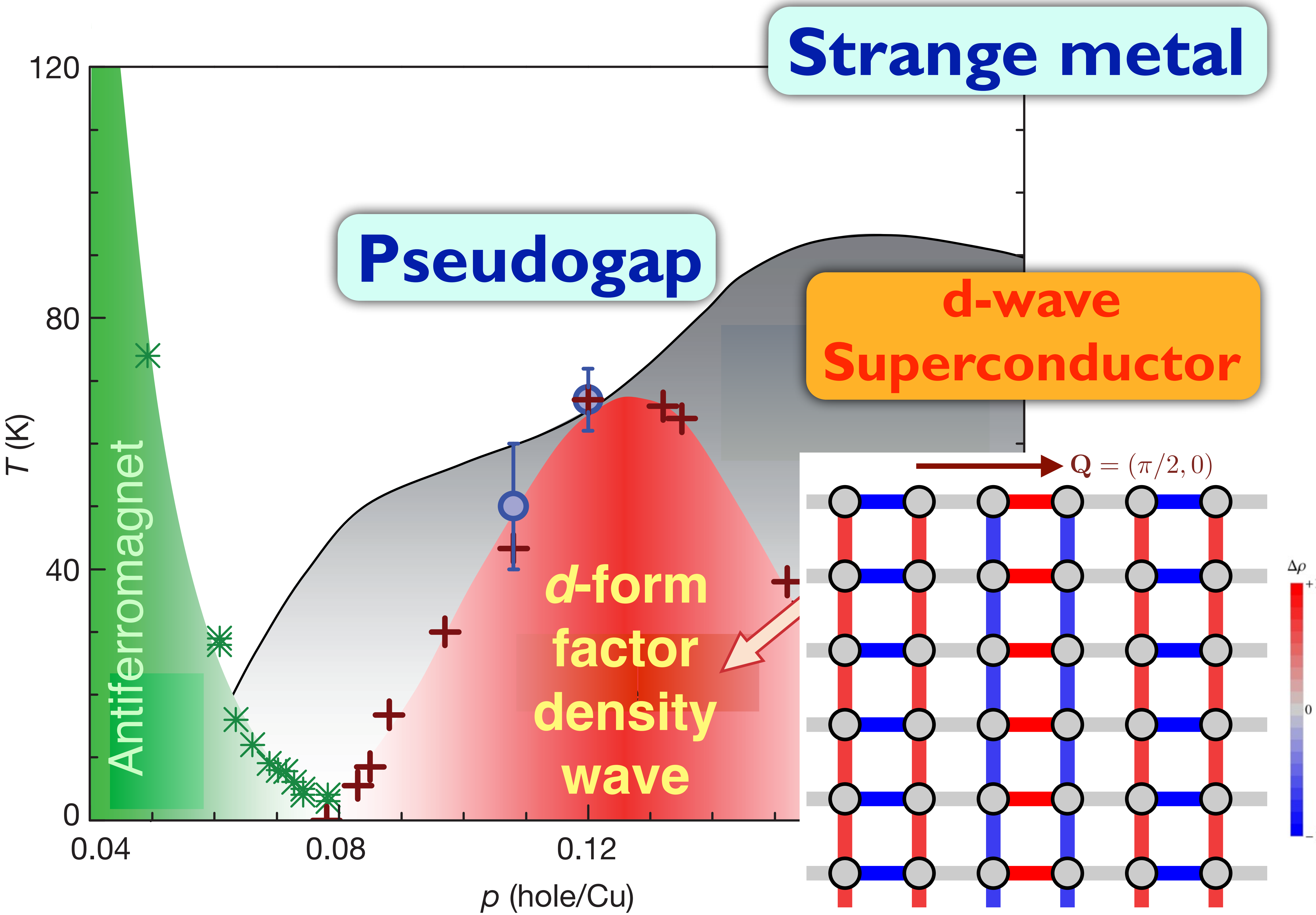


Electron pocket: 432 Tesla
Hole pocket: 90.9 Tesla



Andrea Allais,
Debanjan Chowdhury,
and Subir Sachdev,

arXiv:1406.0503



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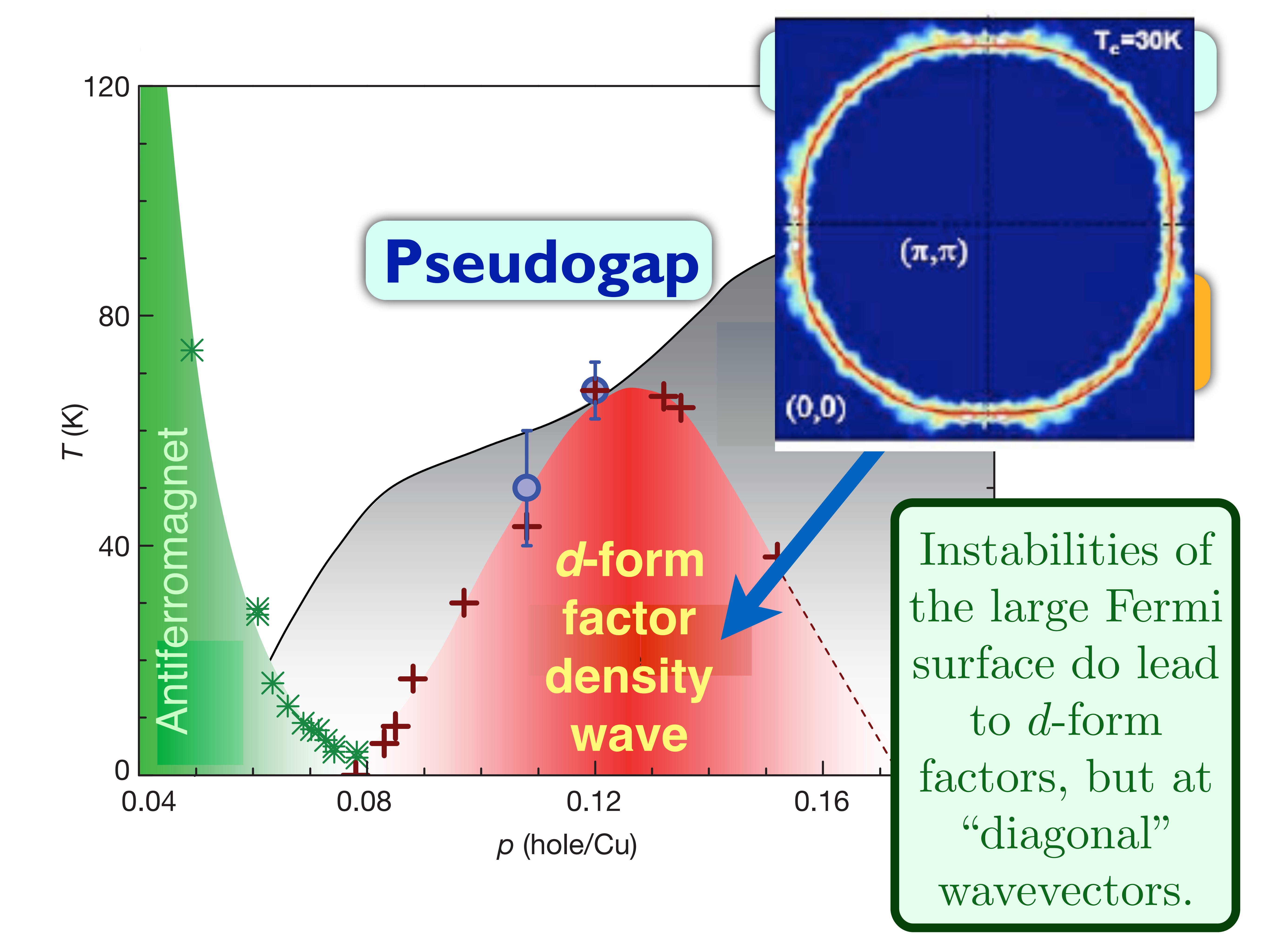
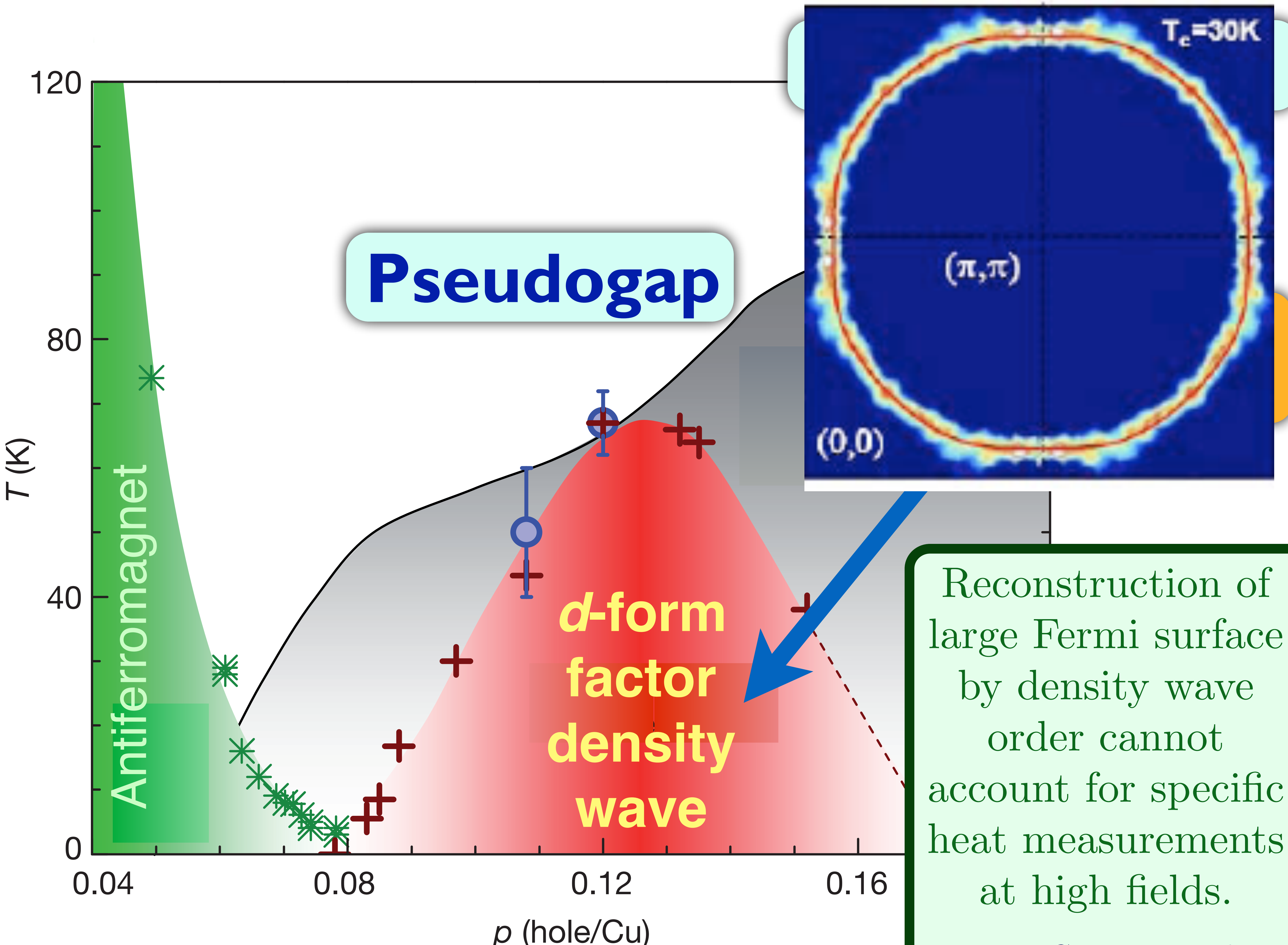


120
80
40
0
T (K)
0.04
0.08
0.12
0.16
p (hole/Cu)
Antiferromagnet
Pseudogap
d-form factor density wave
T_c=30K
(π,π)
(0,0)
Instabilities of the large Fermi surface do lead to d-form factors, but at "diagonal" wavevectors.



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).

Adventures with the spin-fermion model, and beyond

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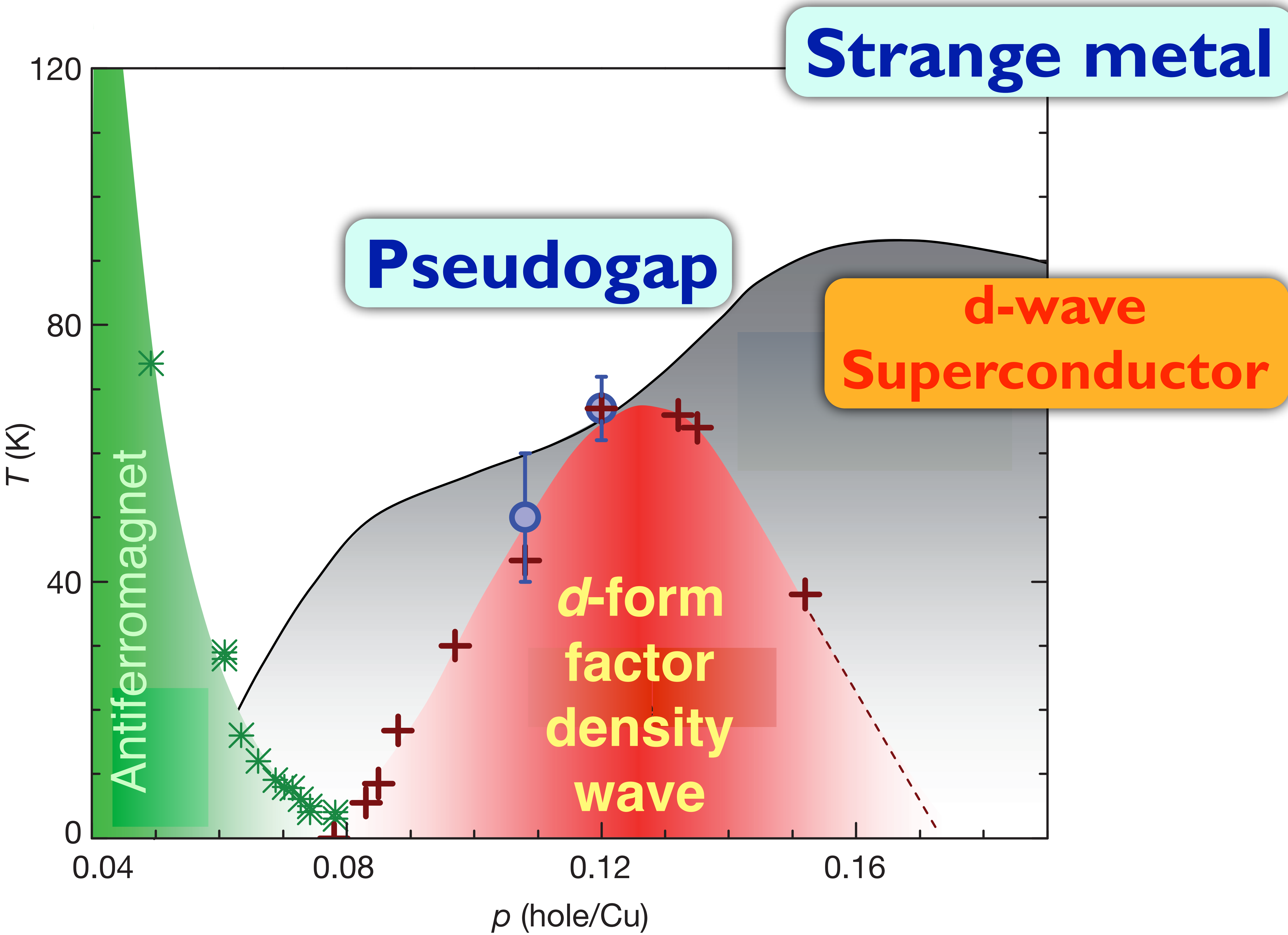
Debanjan Chowdhury

Alexandra Thomson



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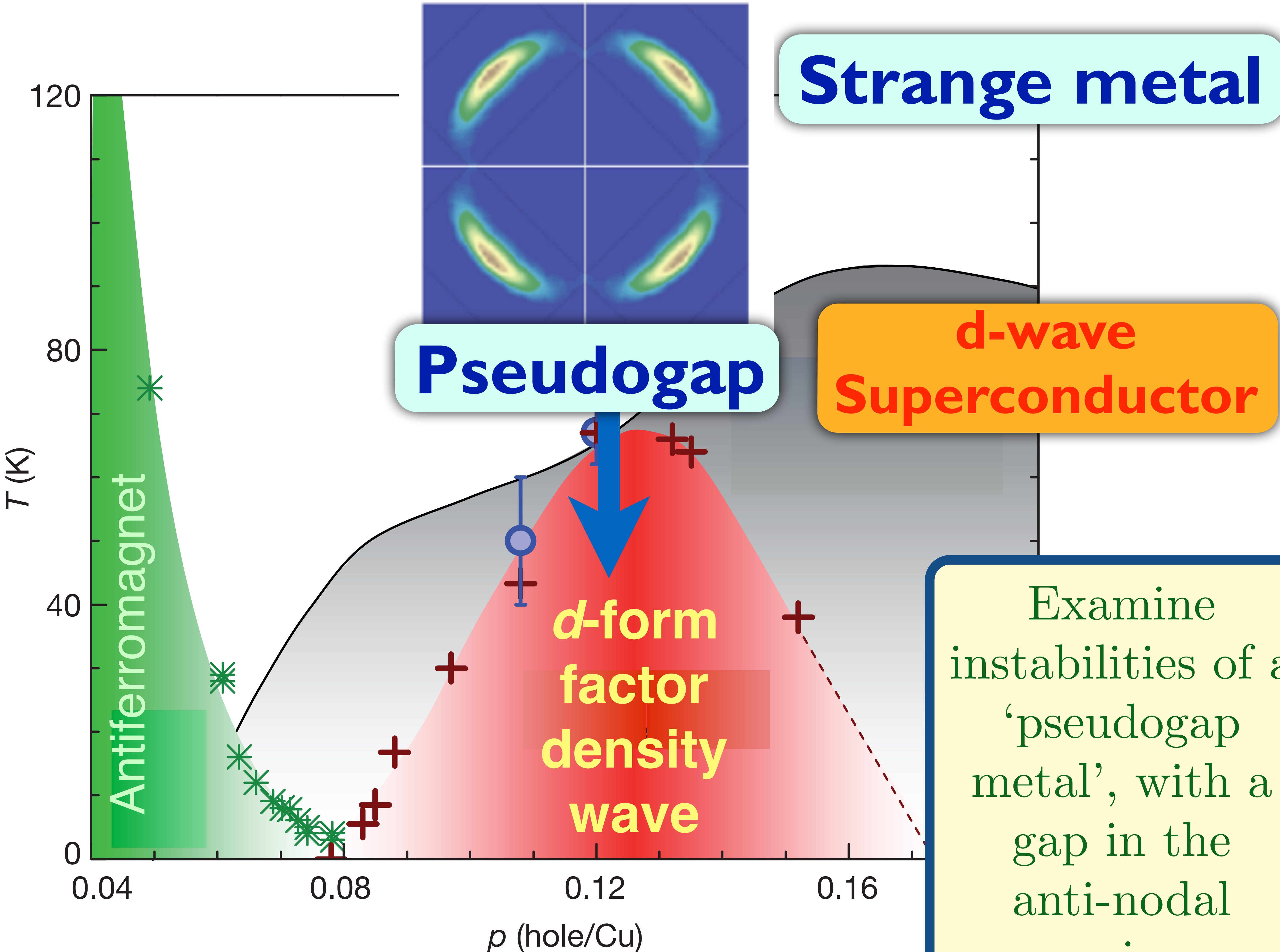
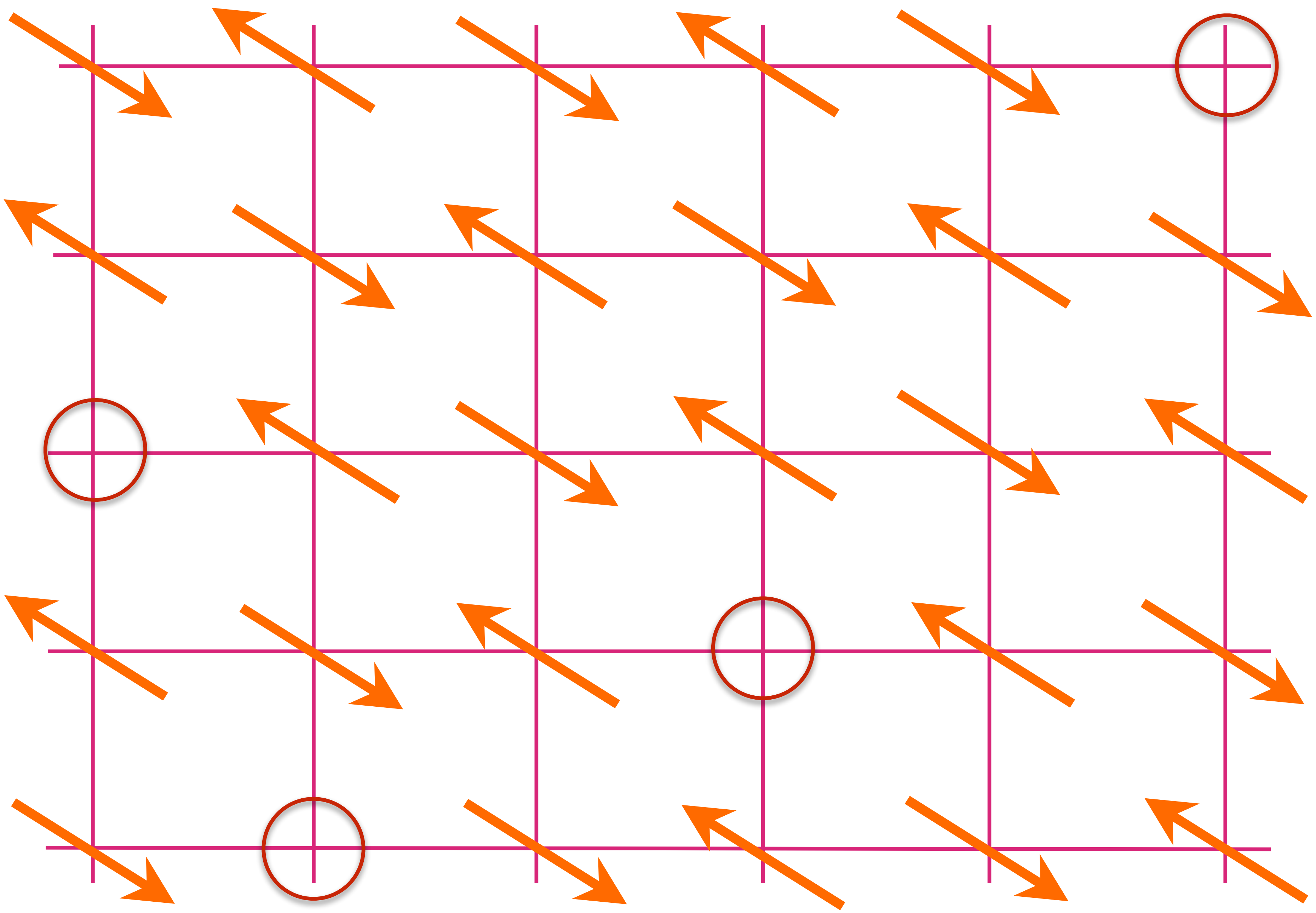


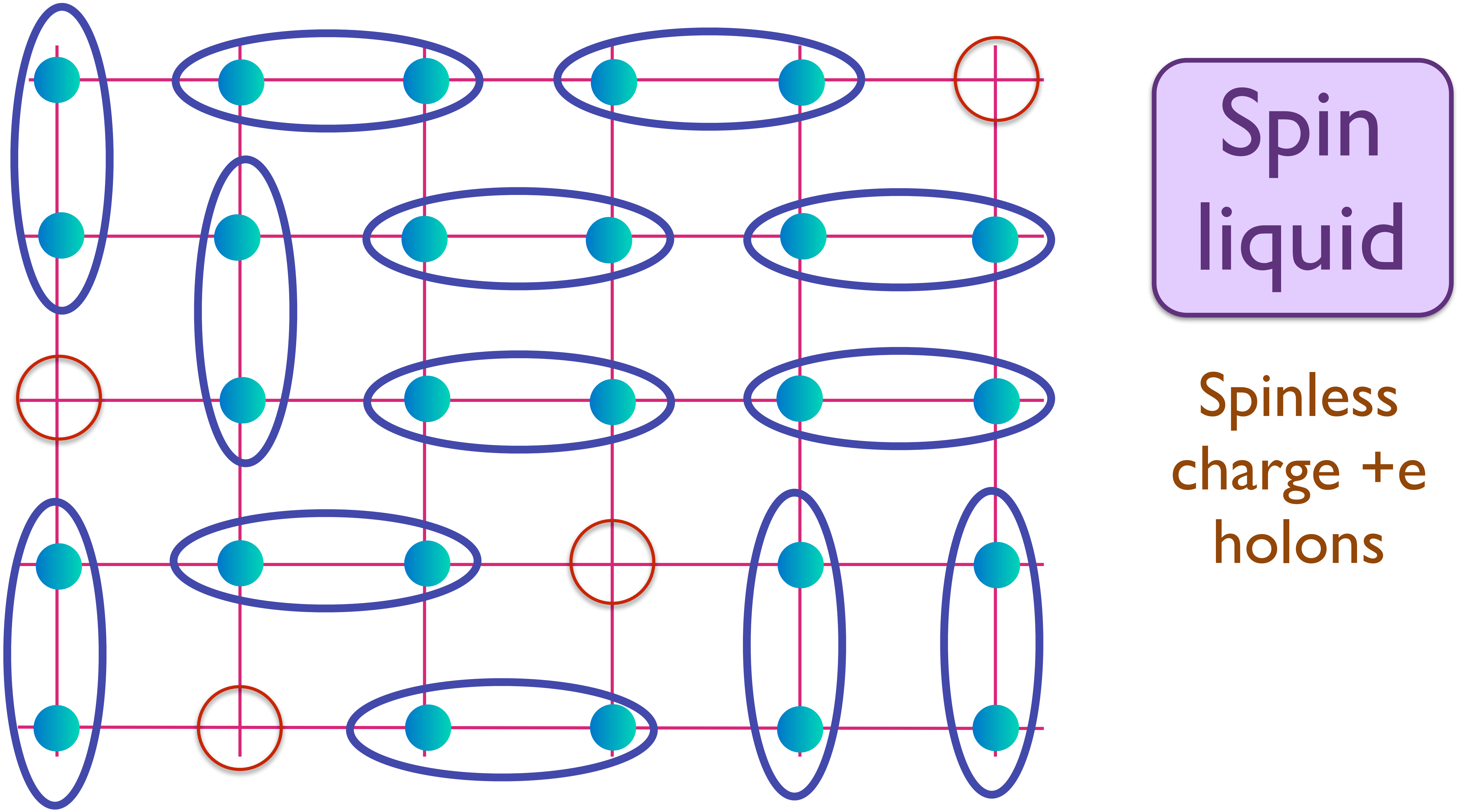
Examine instabilities of a 'pseudogap metal', with a gap in the anti-nodal region

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



Doped anti-ferromagnet

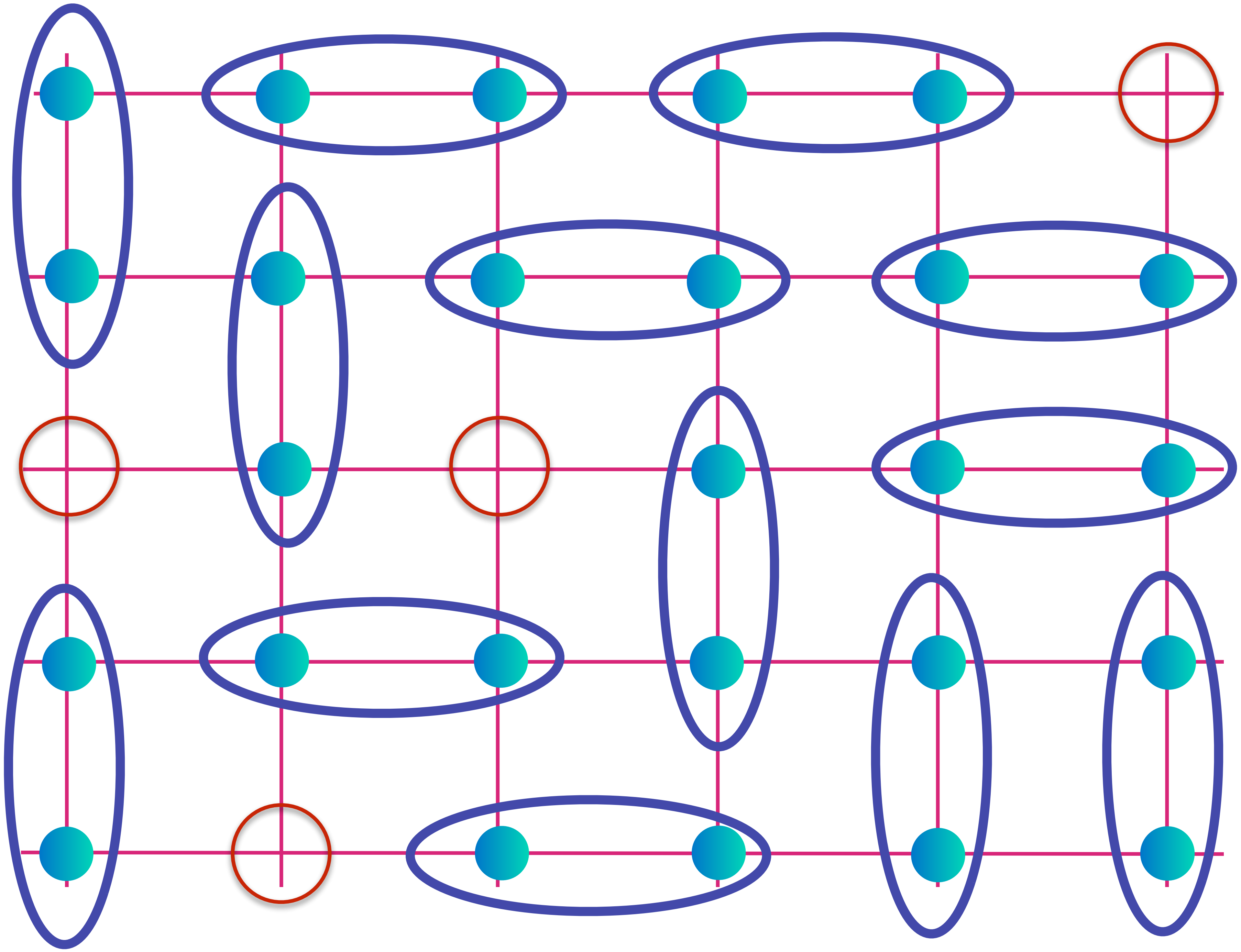
Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)



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

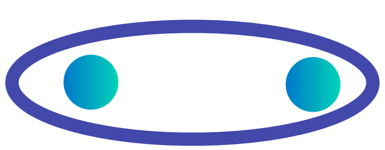
Baskaran, Zou, Anderson, Fradkin, Kivelson…

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



Spin liquid

Spinless charge +e holons



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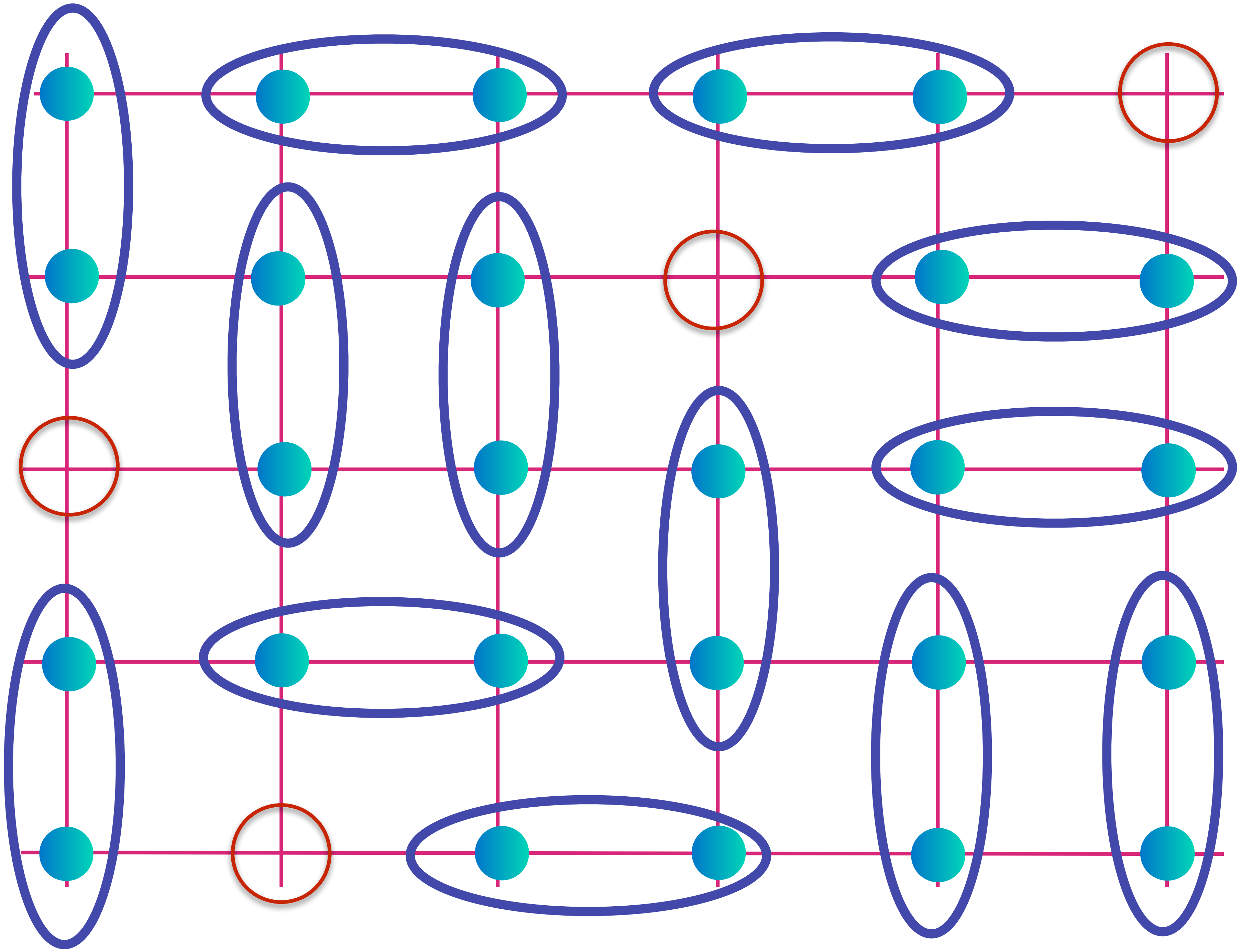

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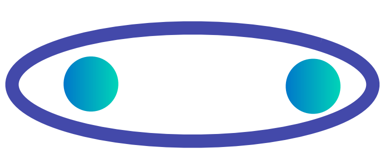 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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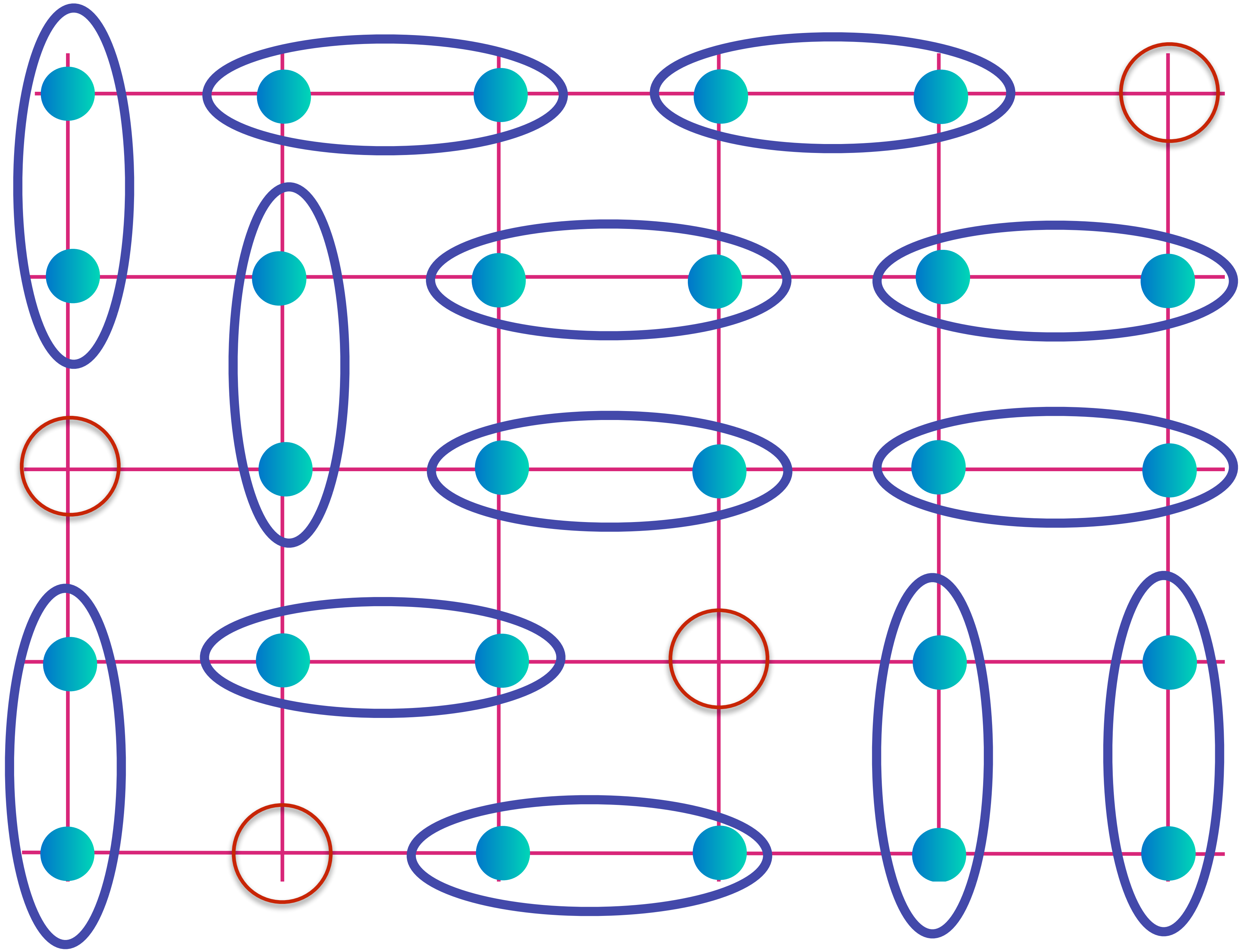

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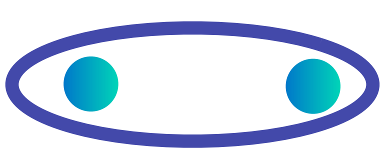
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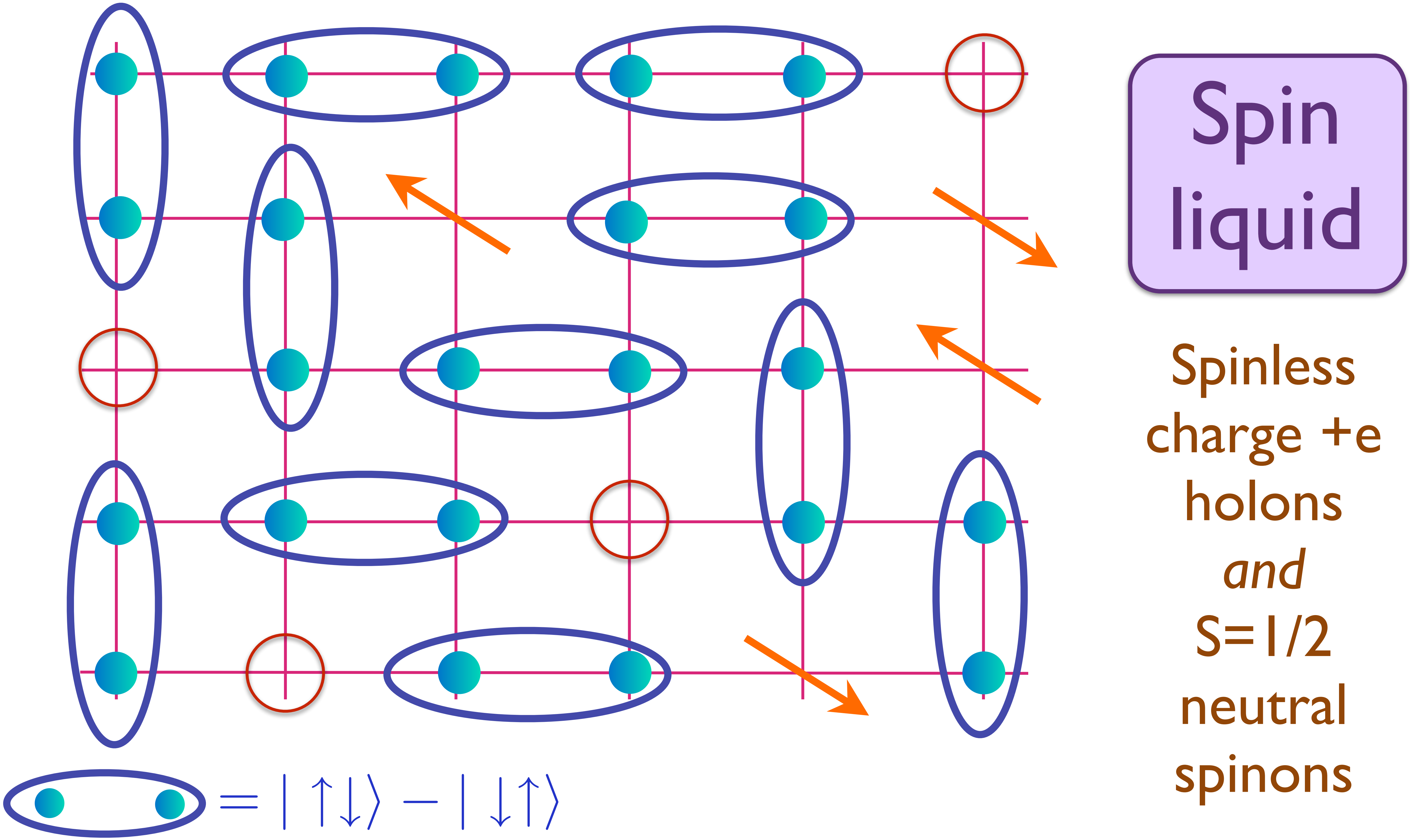

Spinless charge +e holons *and* S=1/2 neutral spinons

Baskaran, Zou, Anderson, Fradkin, Kivelson…

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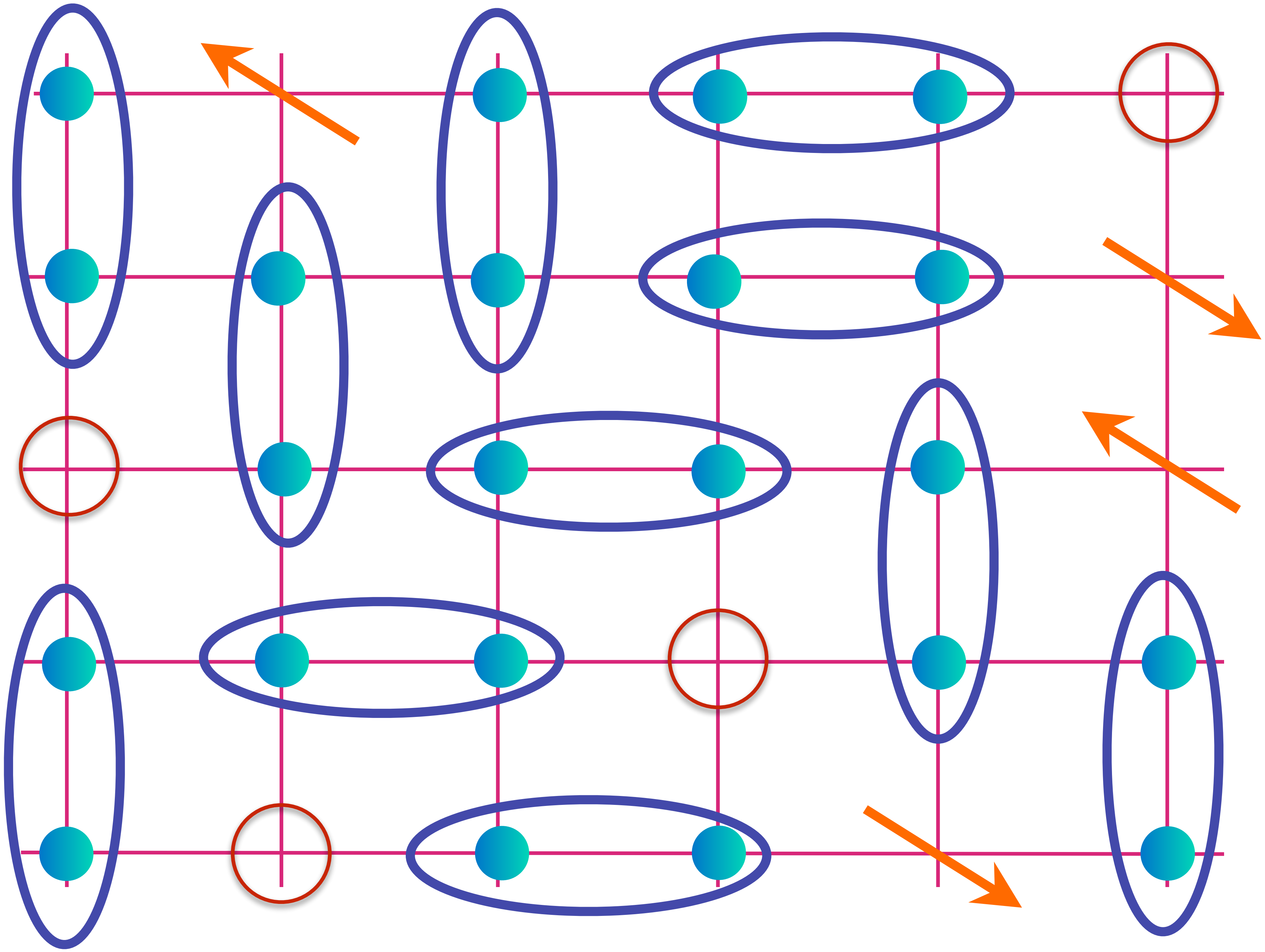

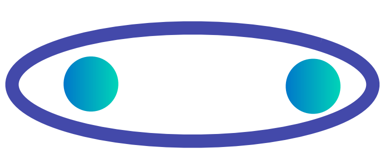 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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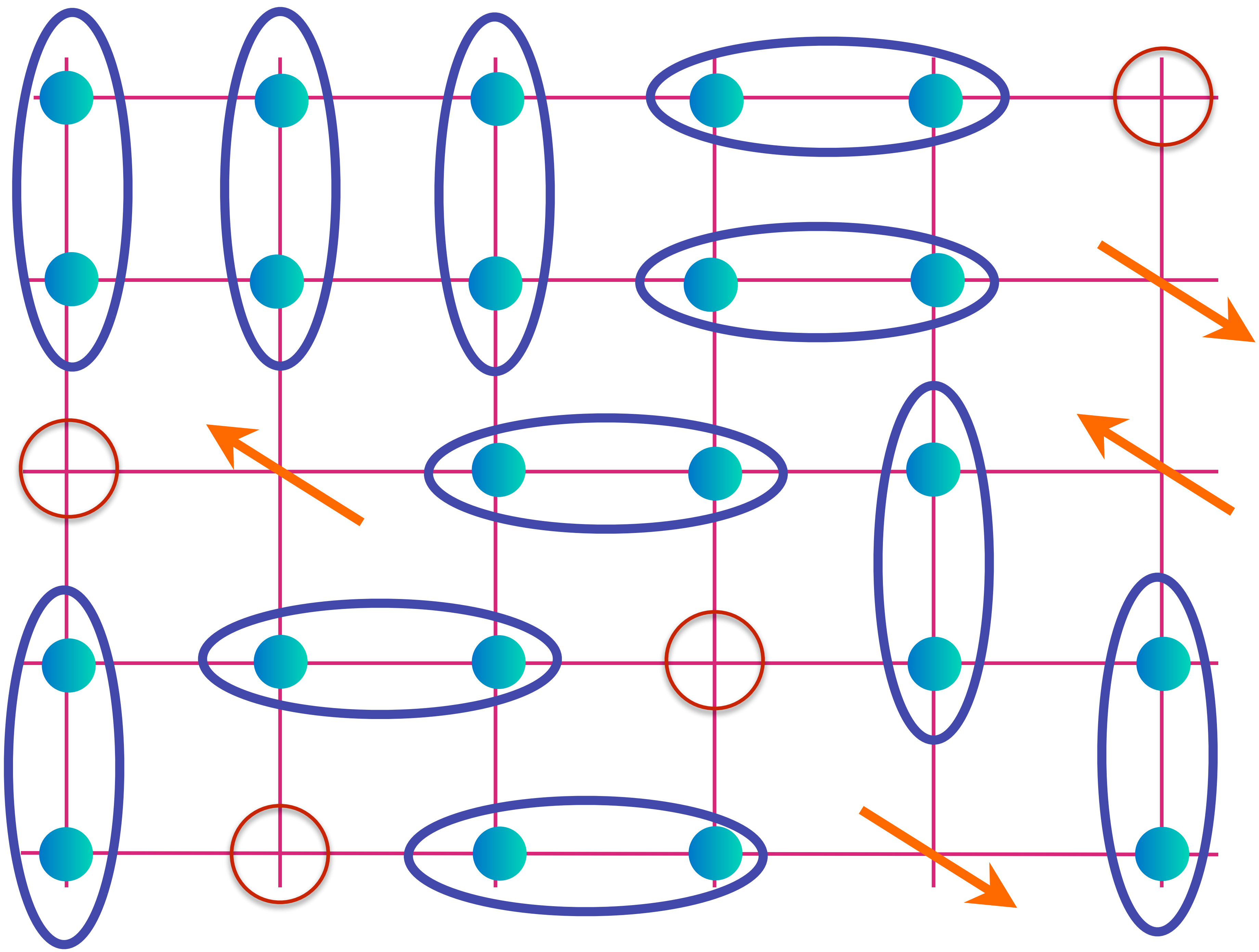

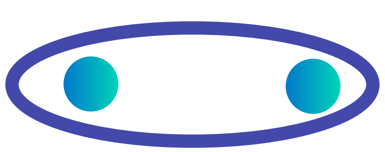 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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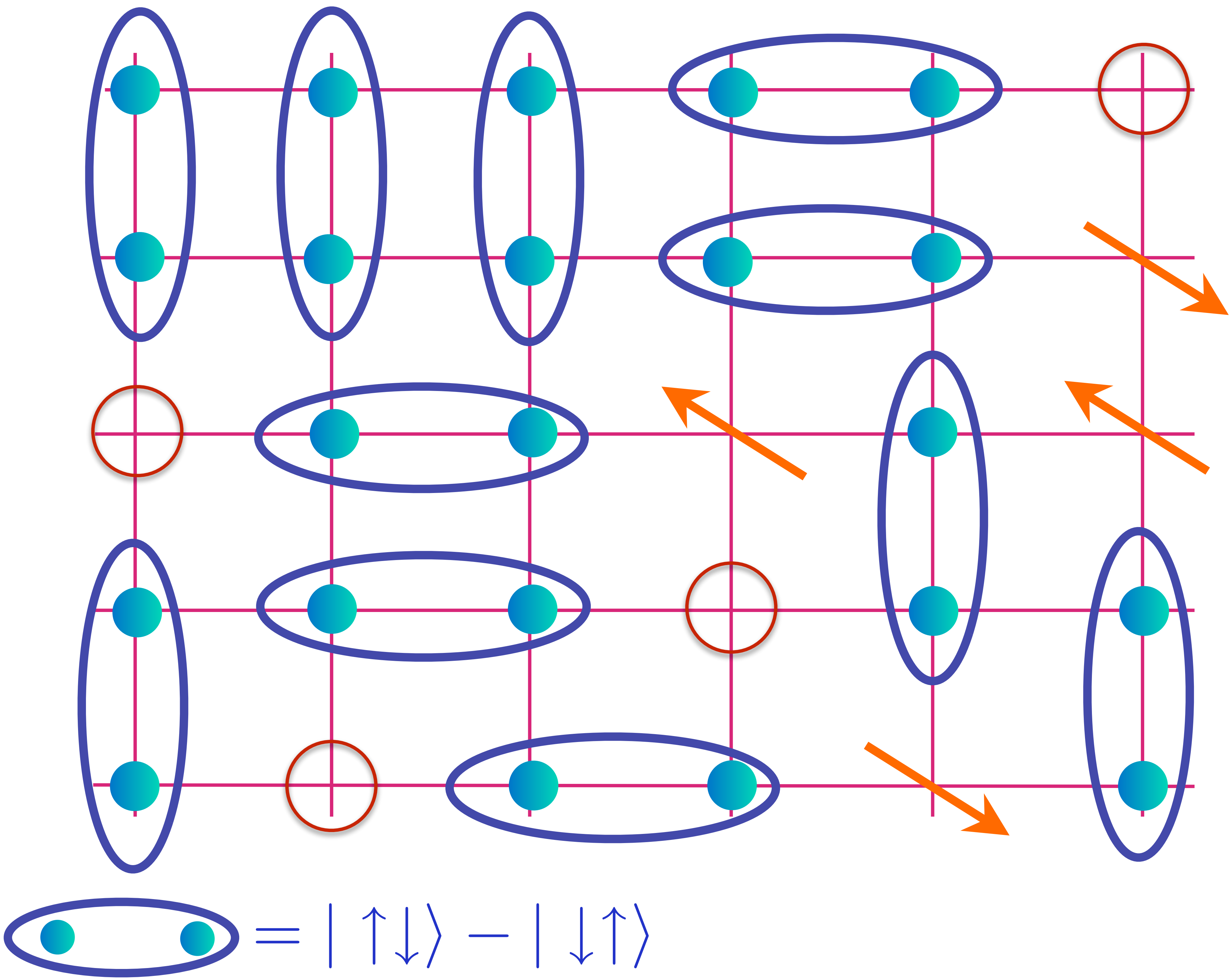

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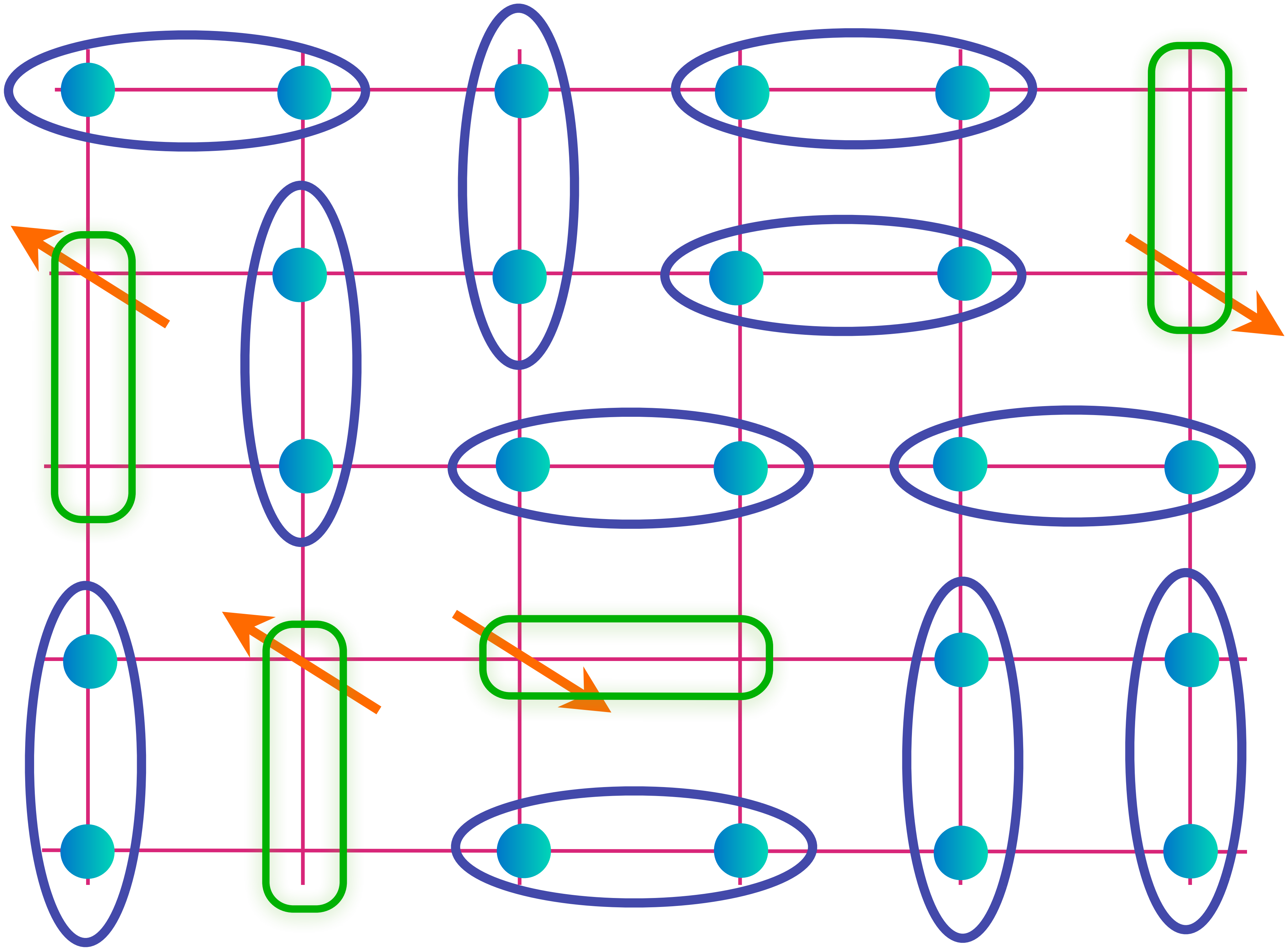

FL* !

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

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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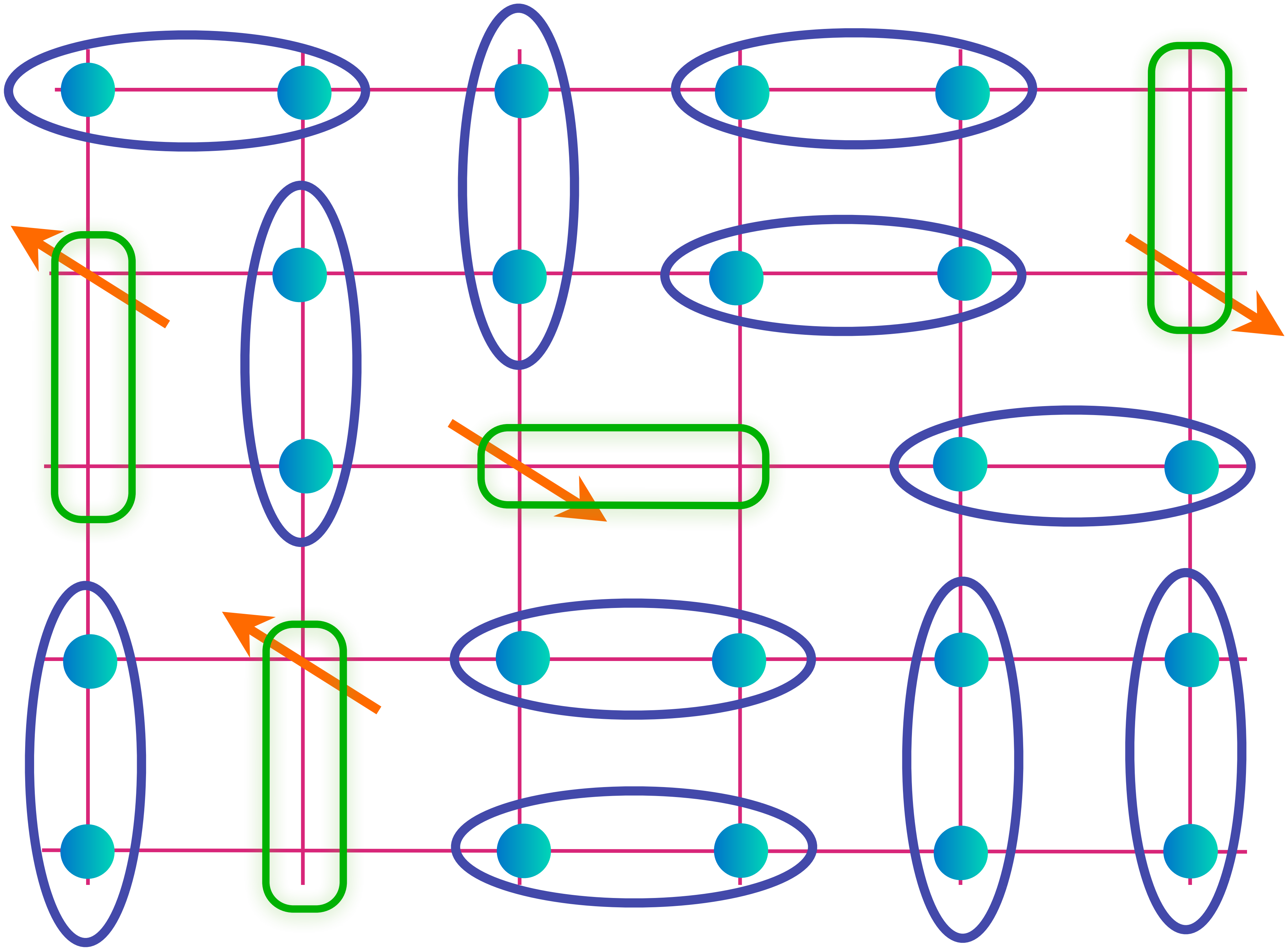

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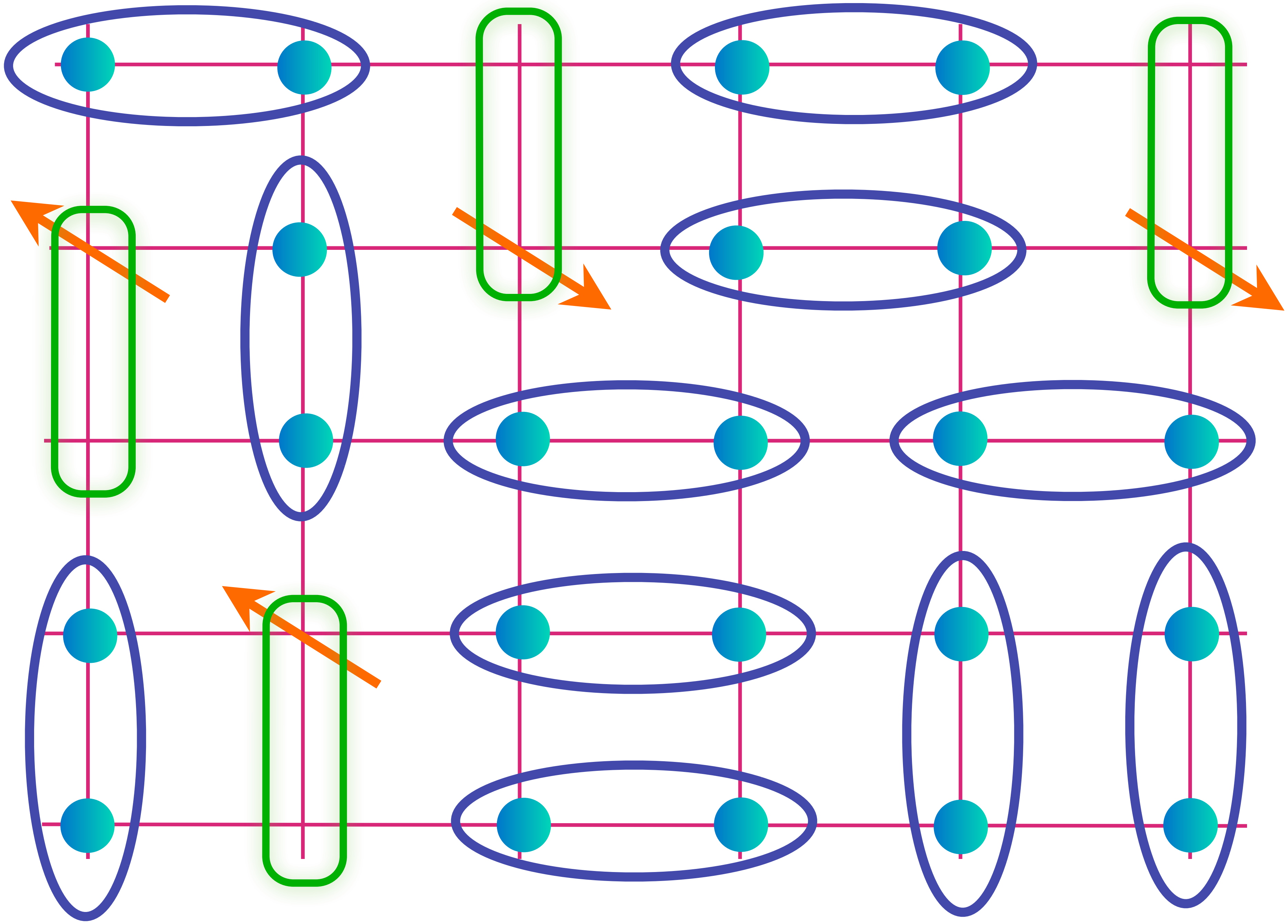

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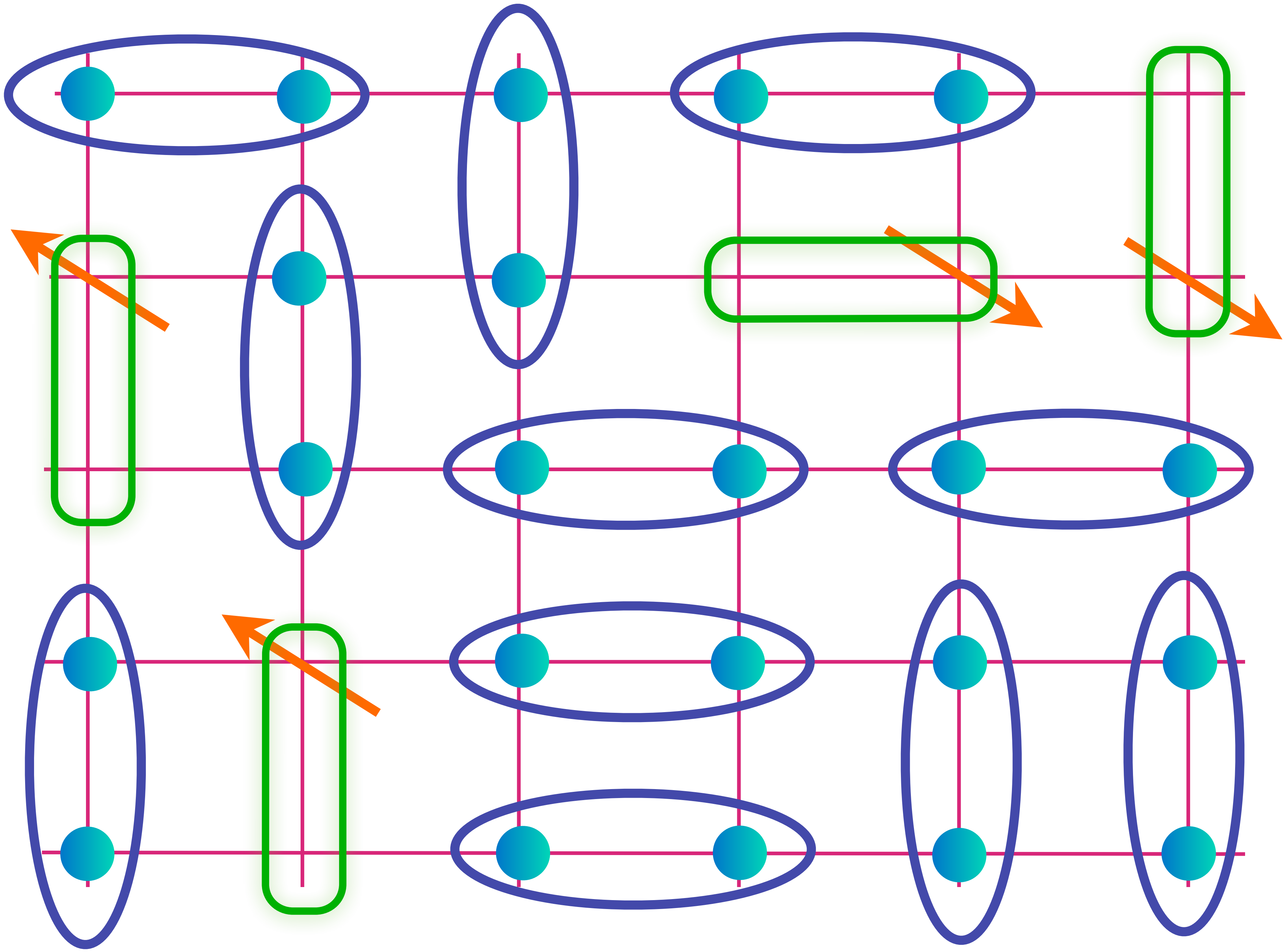

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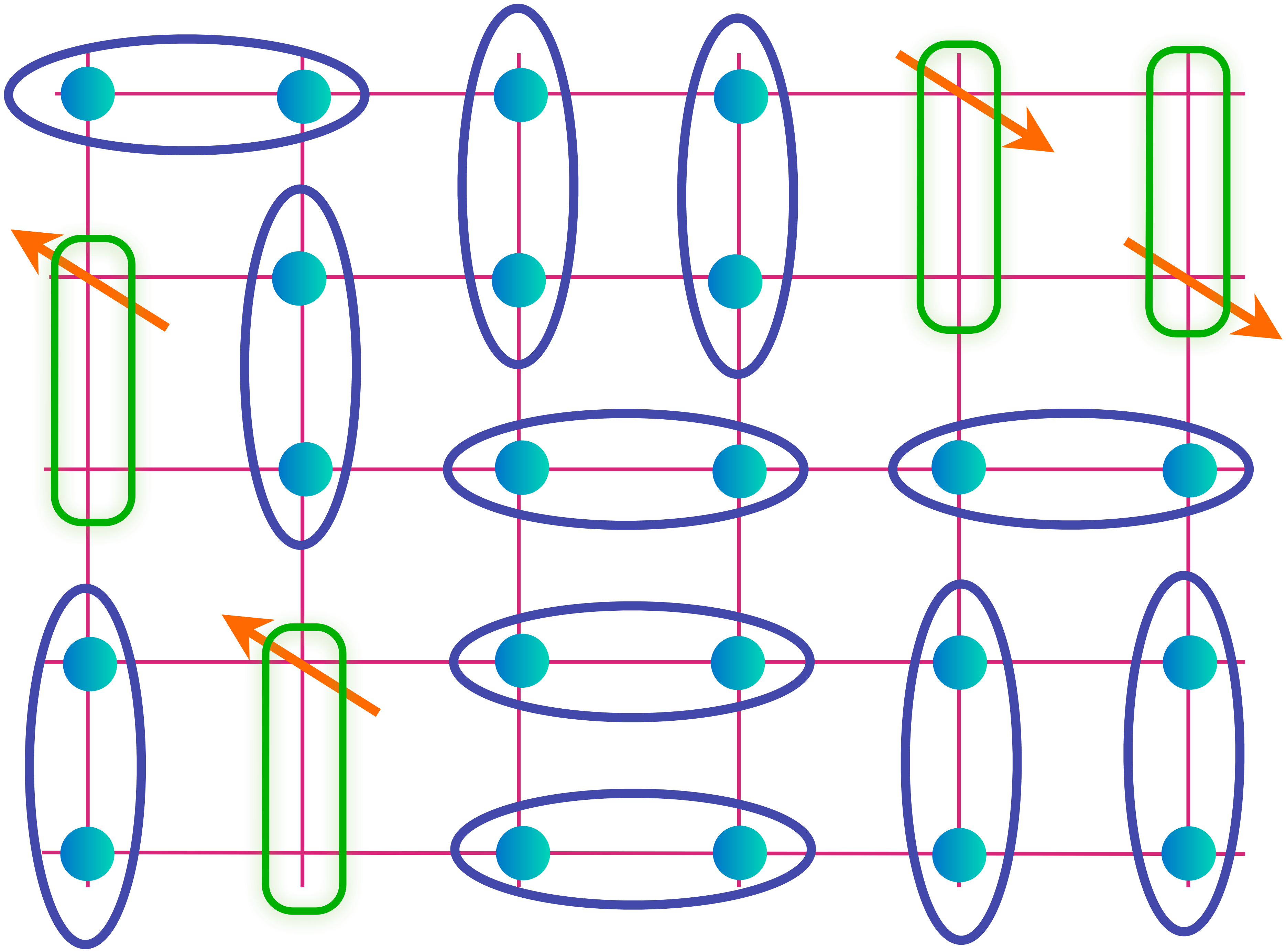

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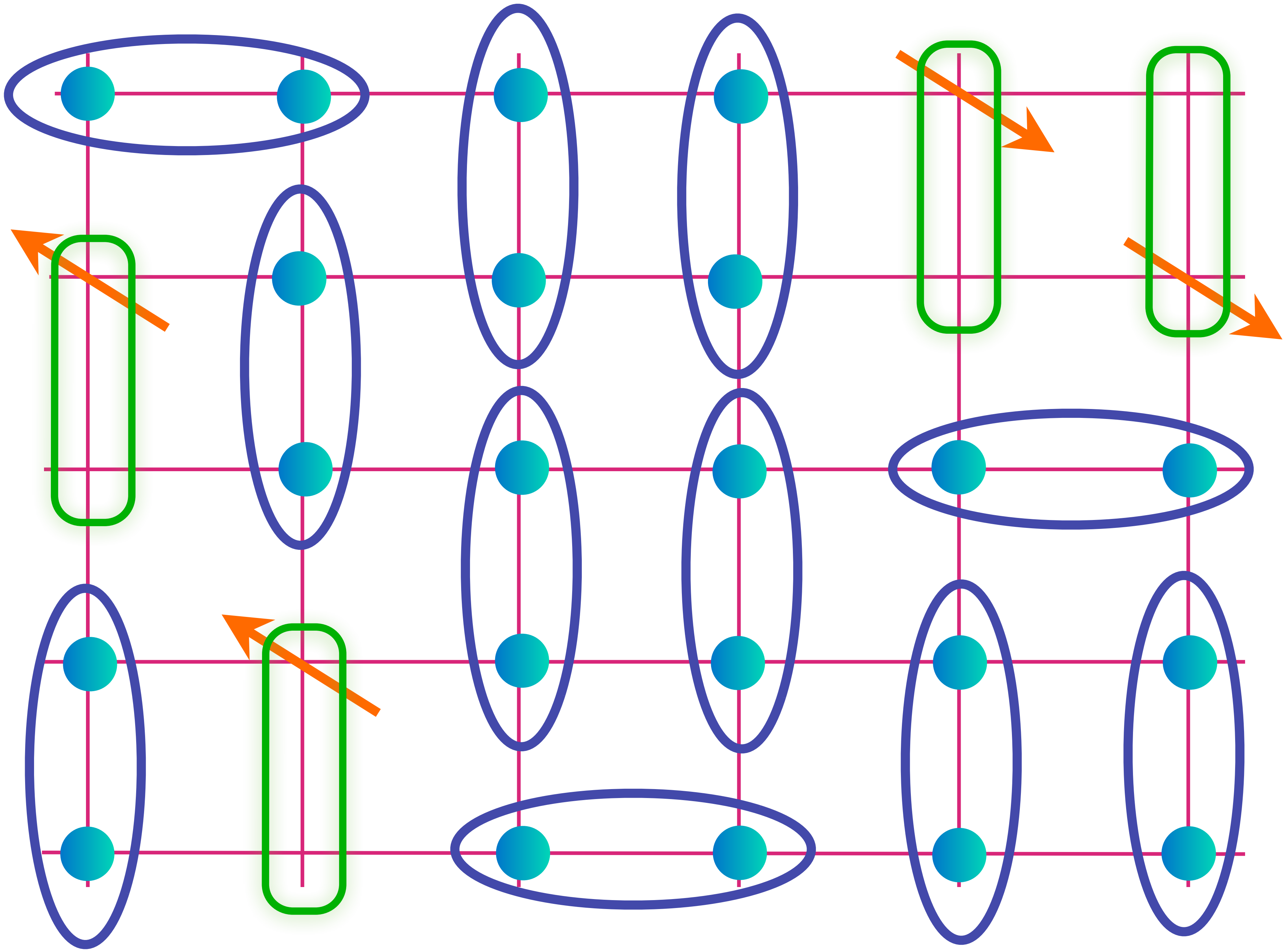

FL* !

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and
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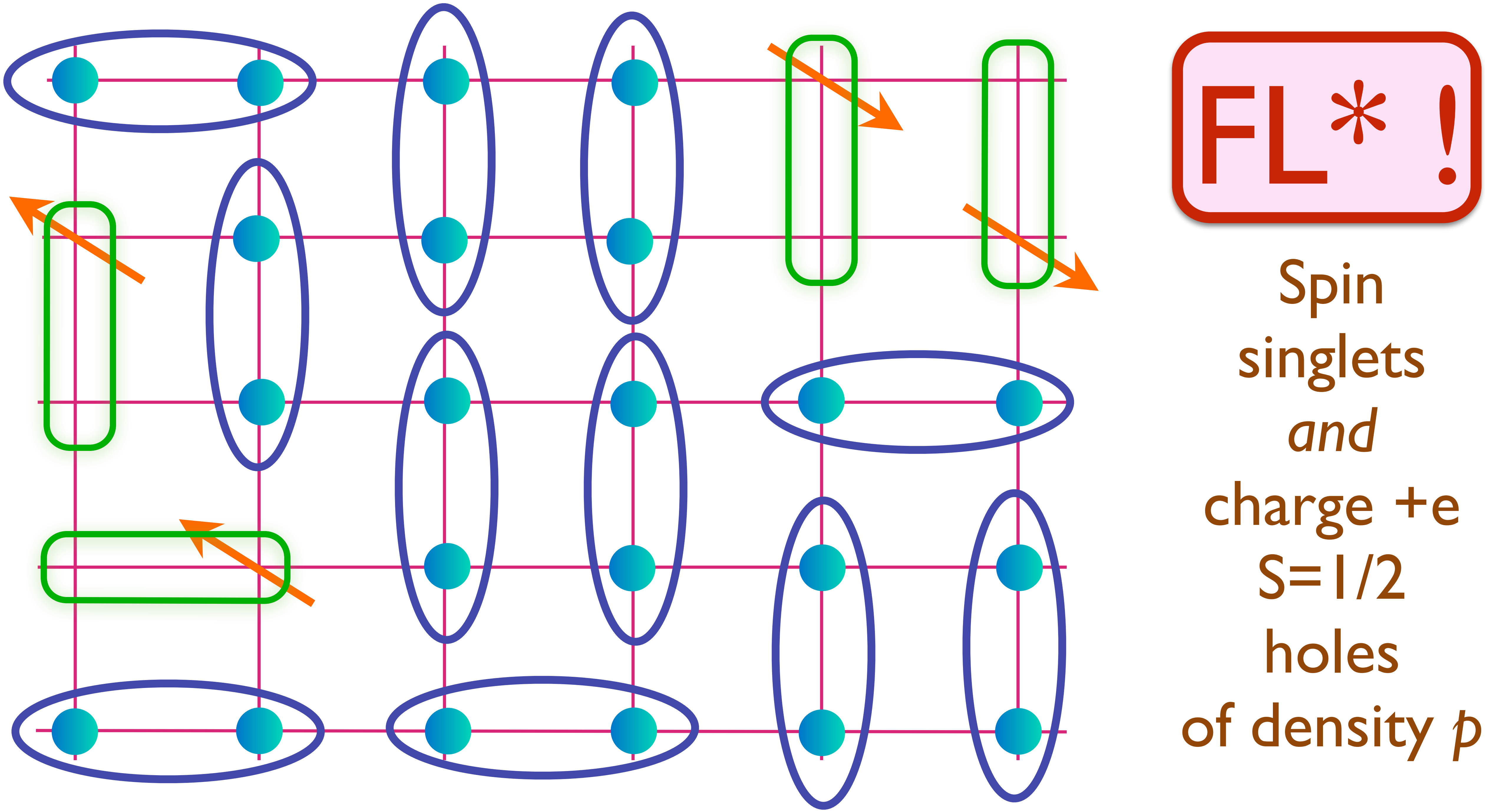

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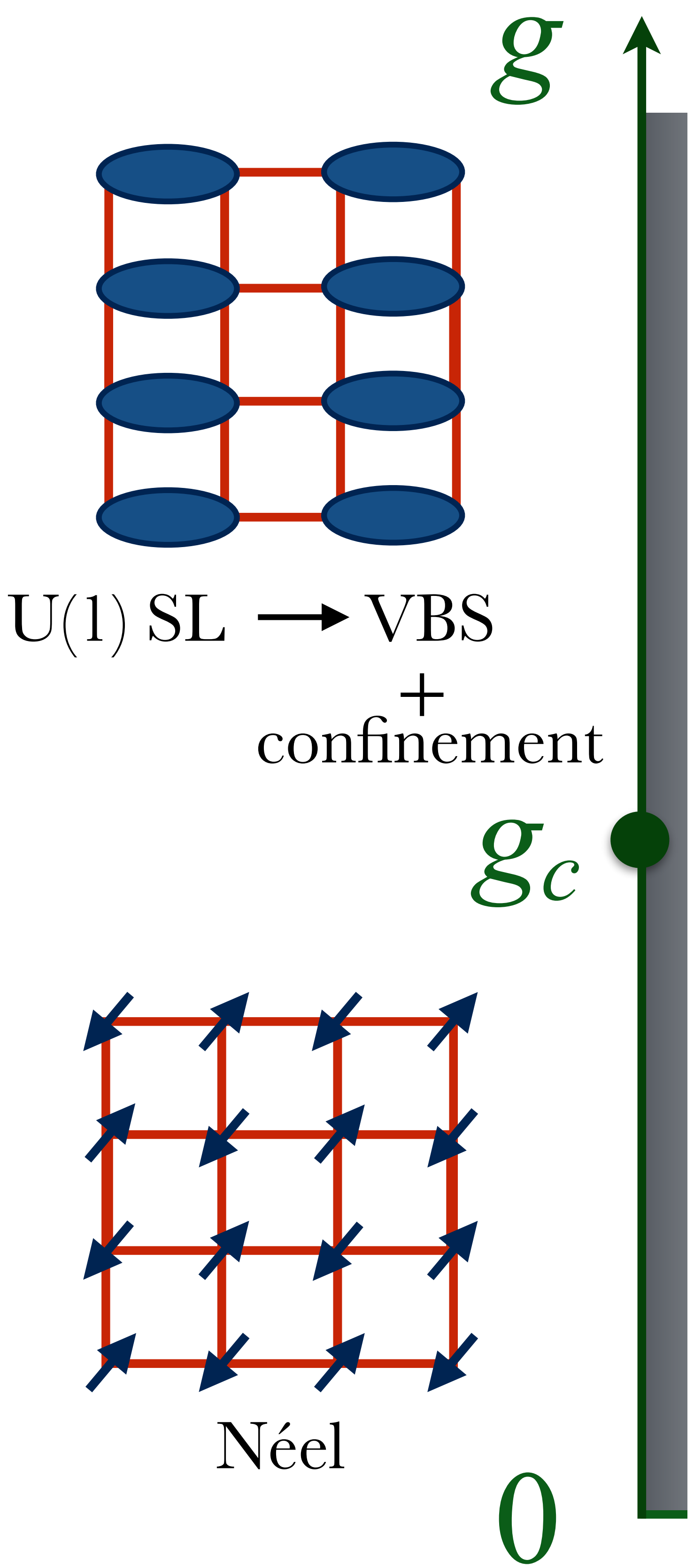
M. Punk and S. Sachdev, *Phys. Rev. B* **85**, 195123 (2012)

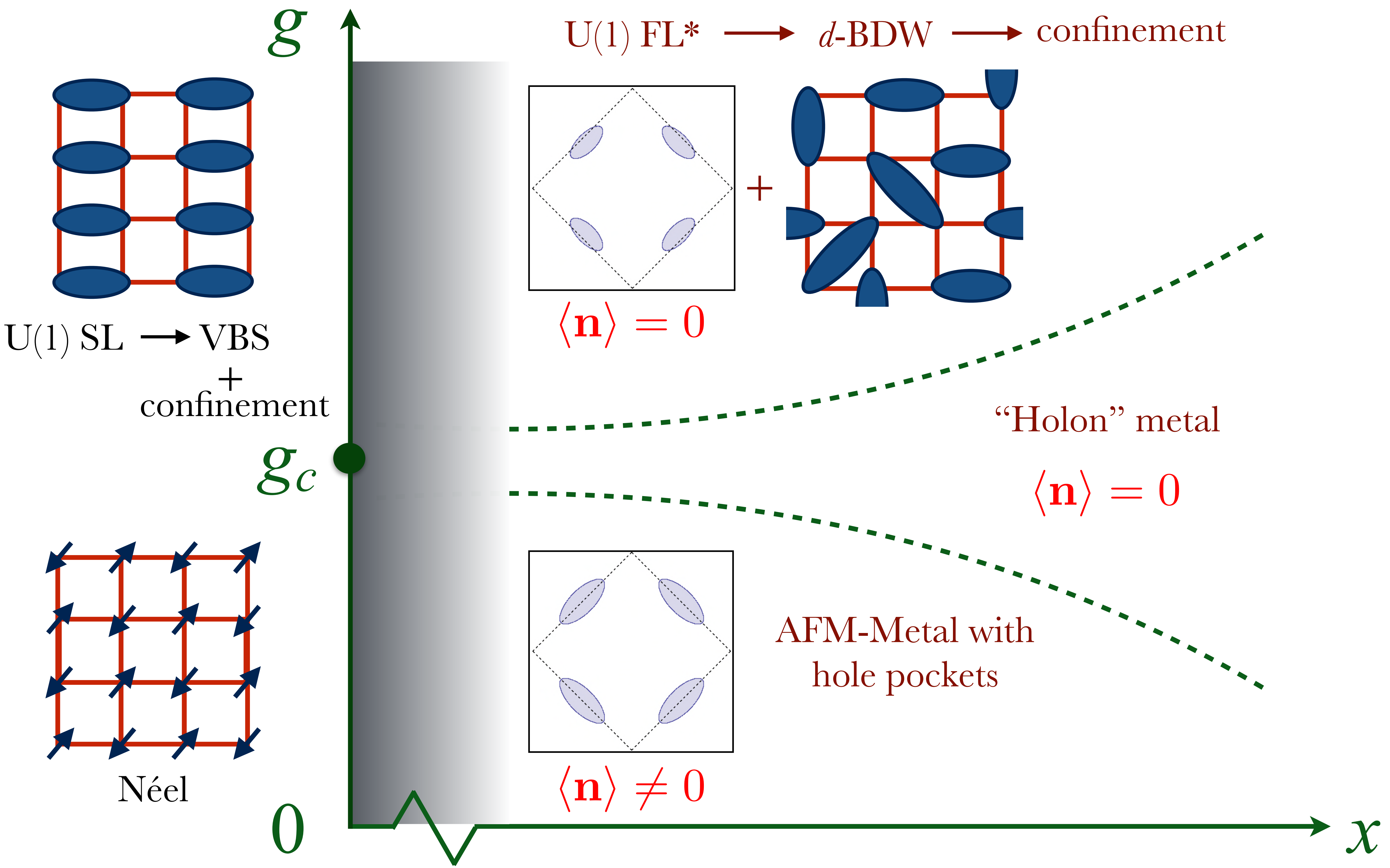
Characteristics of FL* phase

- 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.

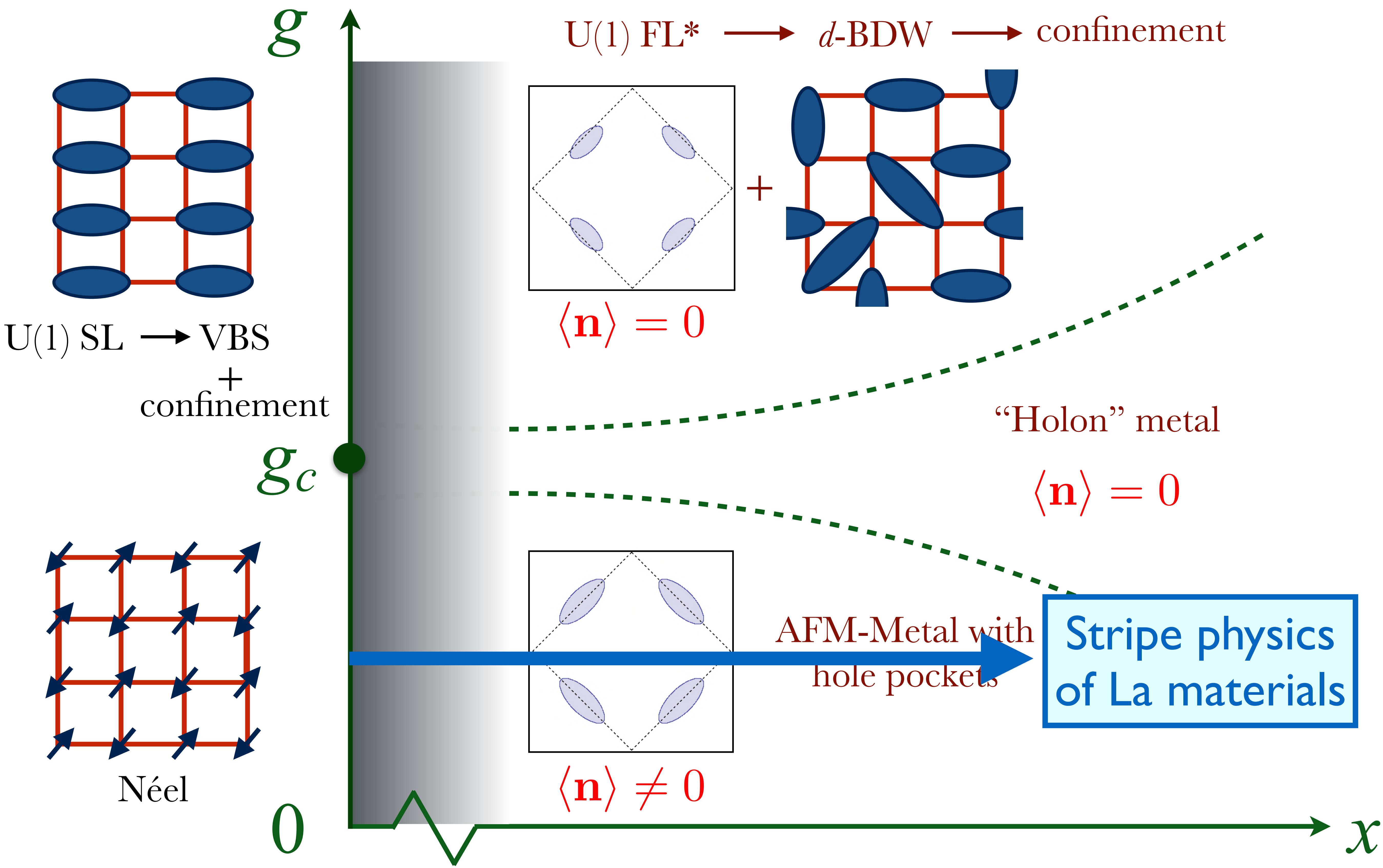
T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)



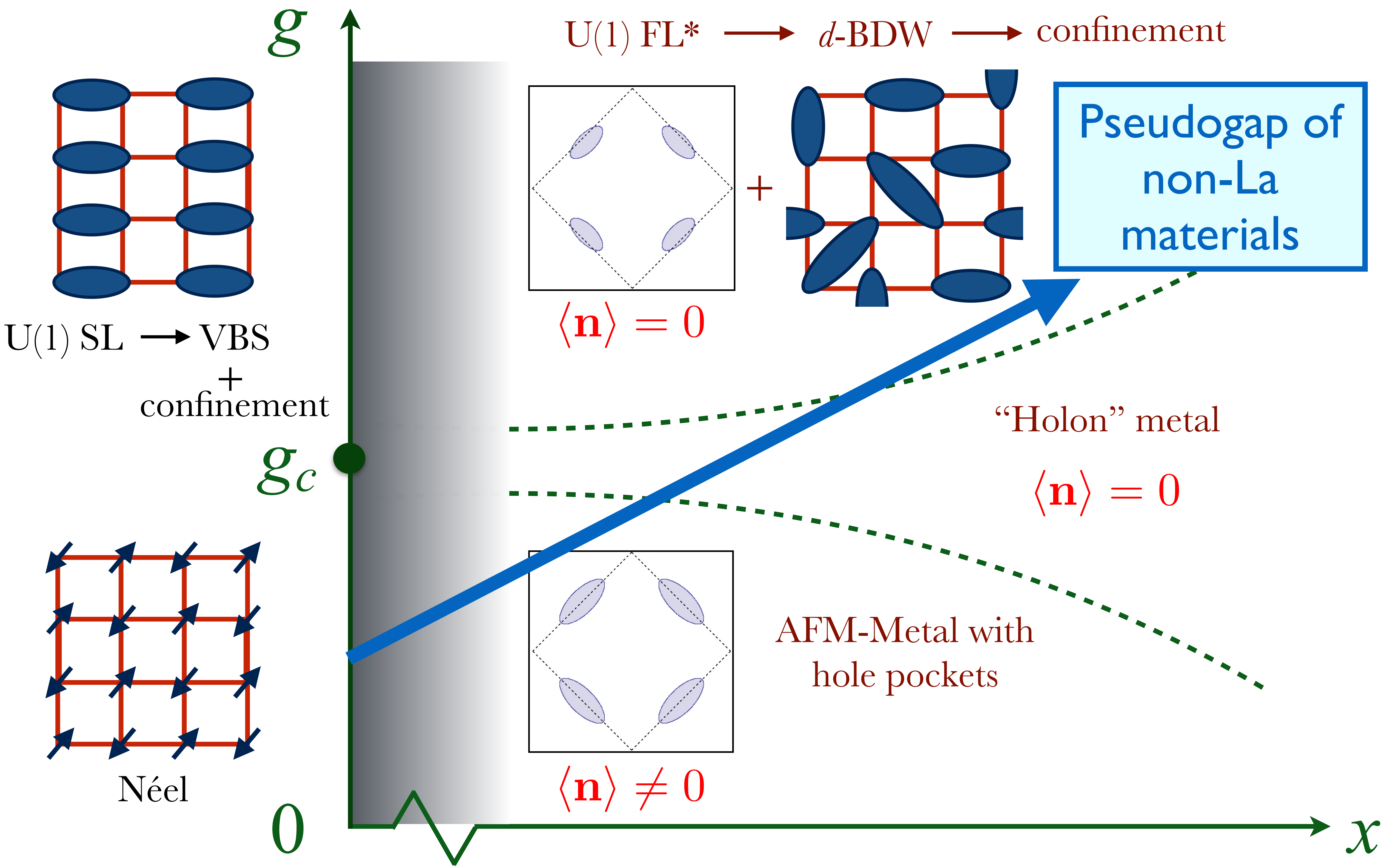
g
U(1) SL ⟶ VBS
+
confinement
g_c
Néel
0



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



D. Chowdhury and S. Sachdev, arXiv:1409.5430
A. Thomson and S. Sachdev, arXiv:1410.3483



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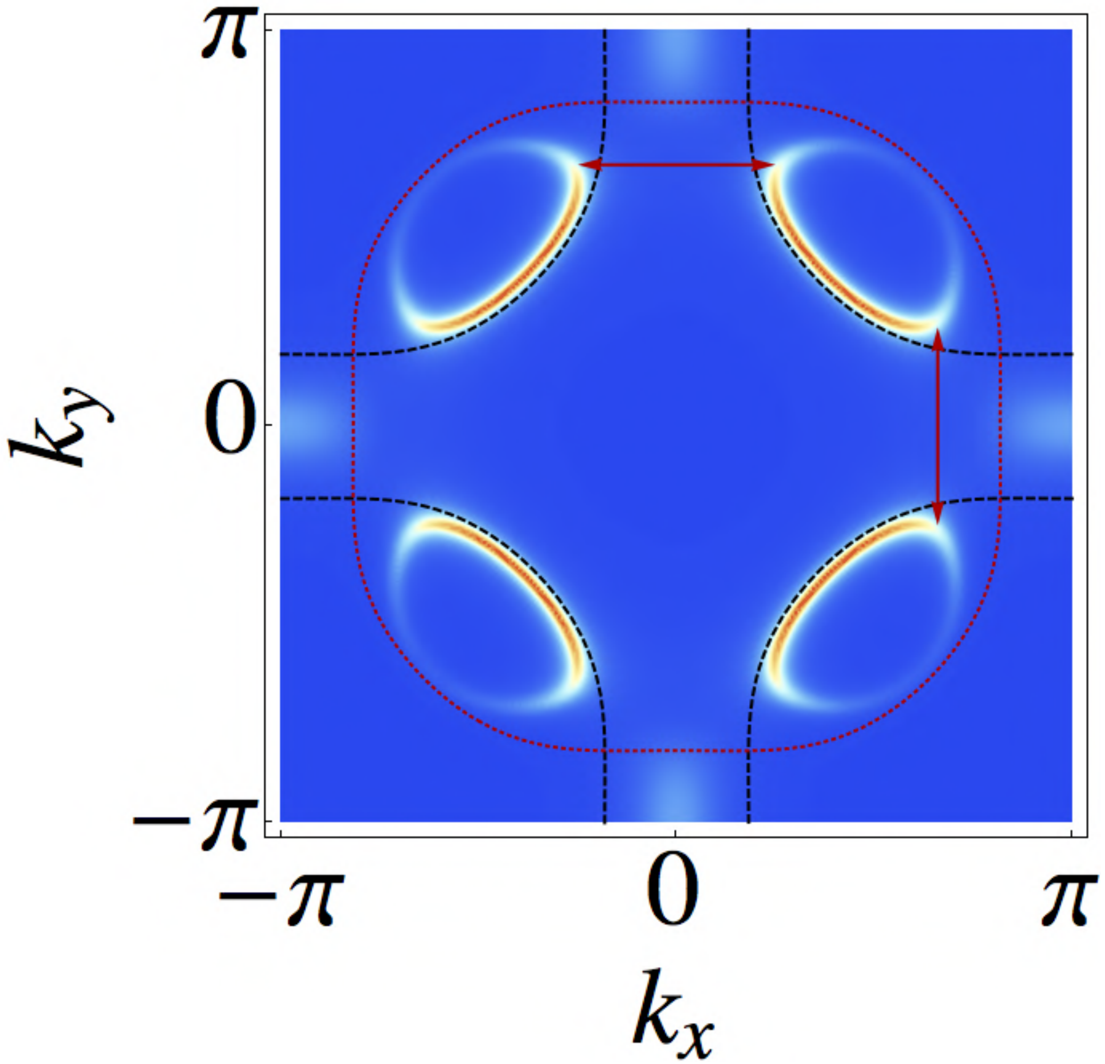
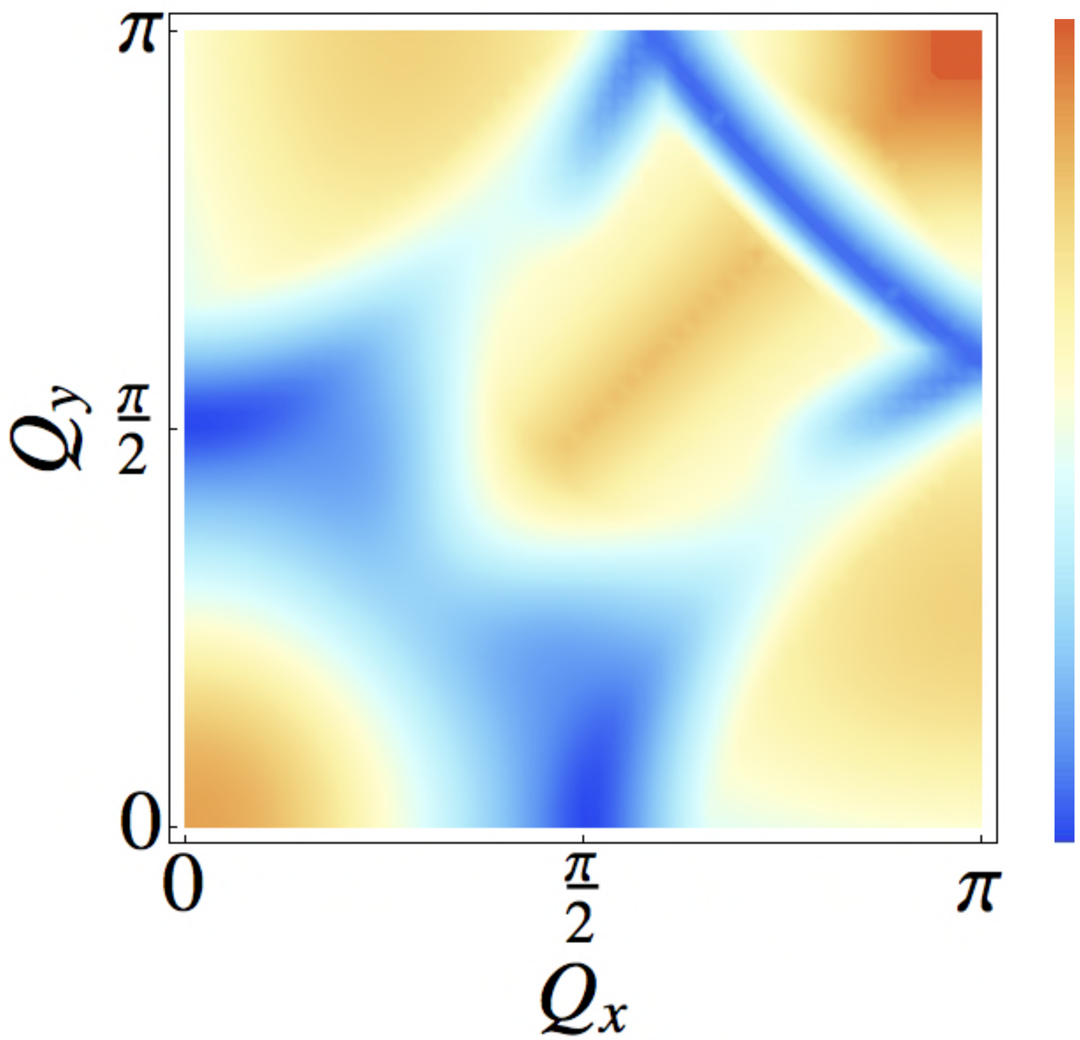


Electron spectral function of FL*

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



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

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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.

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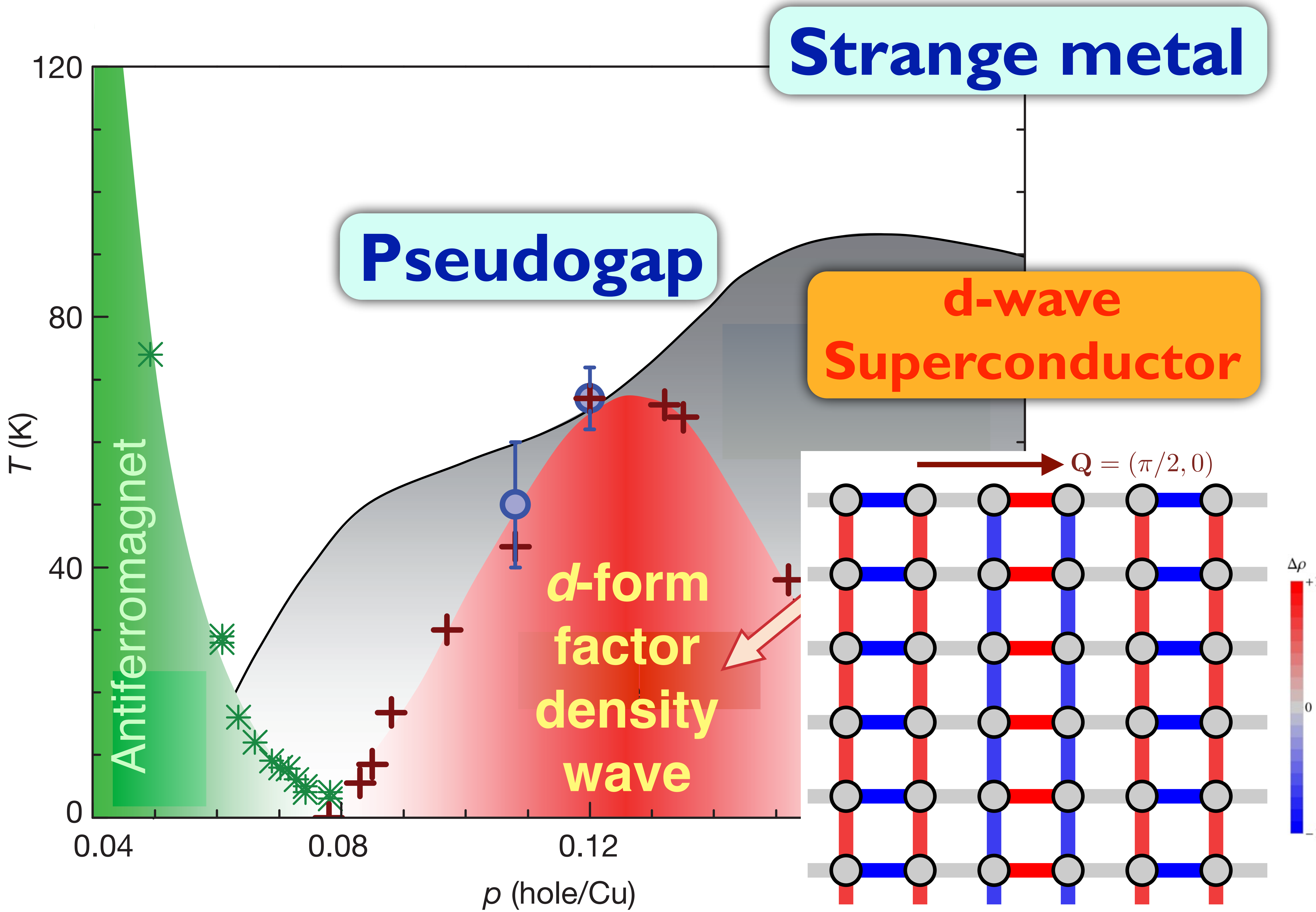
3. The *d*-form factor is an unexpected window into the electronic structure of the pseudogap, with evidence for a fractionalized Fermi liquid (FL*) model.



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