The pseudogap phase of the cuprate superconductors

University of Maryland
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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

Jay Sau
(Maryland)

Cornell

Kazuhiro Fujita
Cornell/ BNL

Mohammad Hamidian
Cornell / BNL

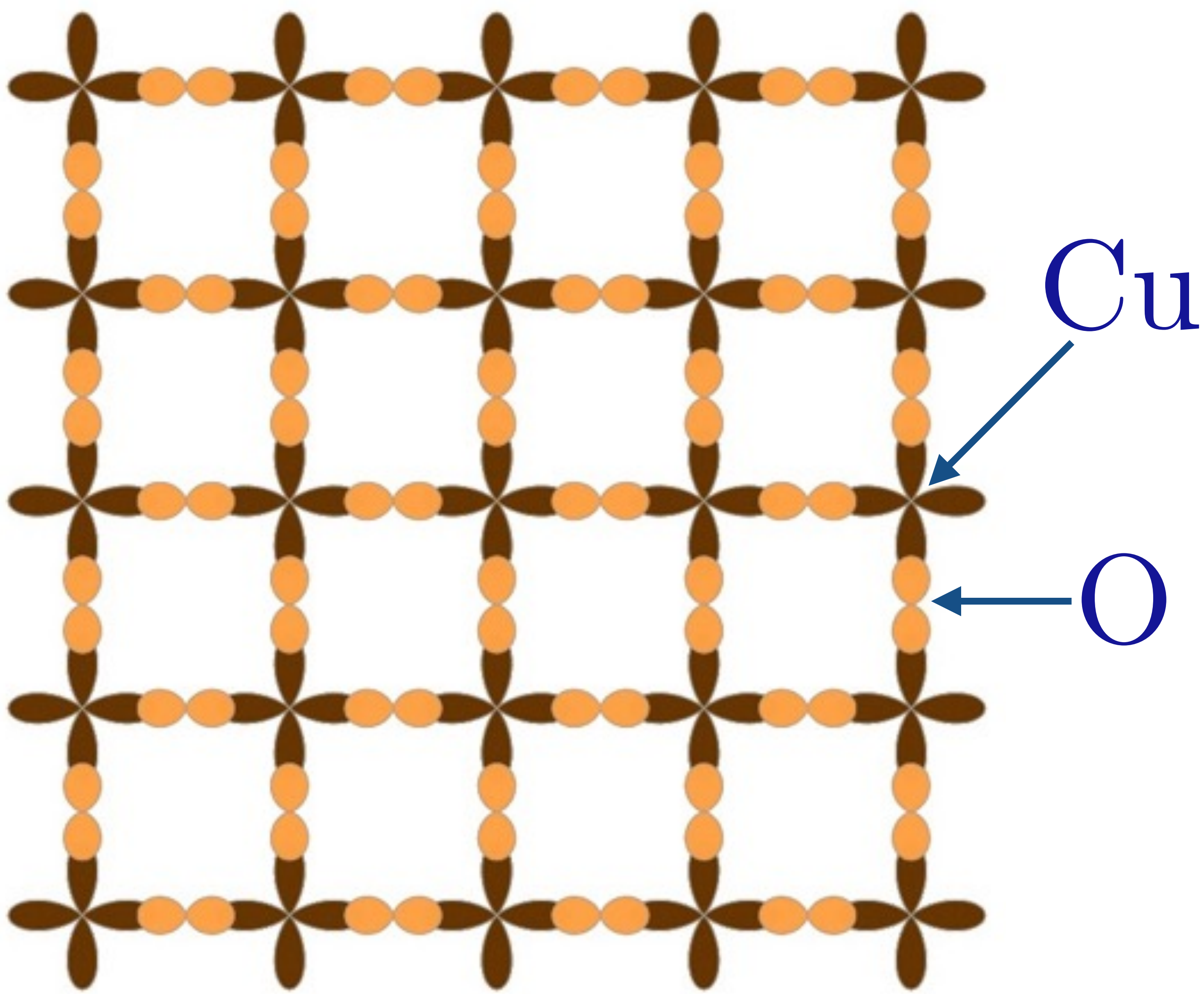
Stephen Edkins
Cornell / St Andrews

Michael Lawler

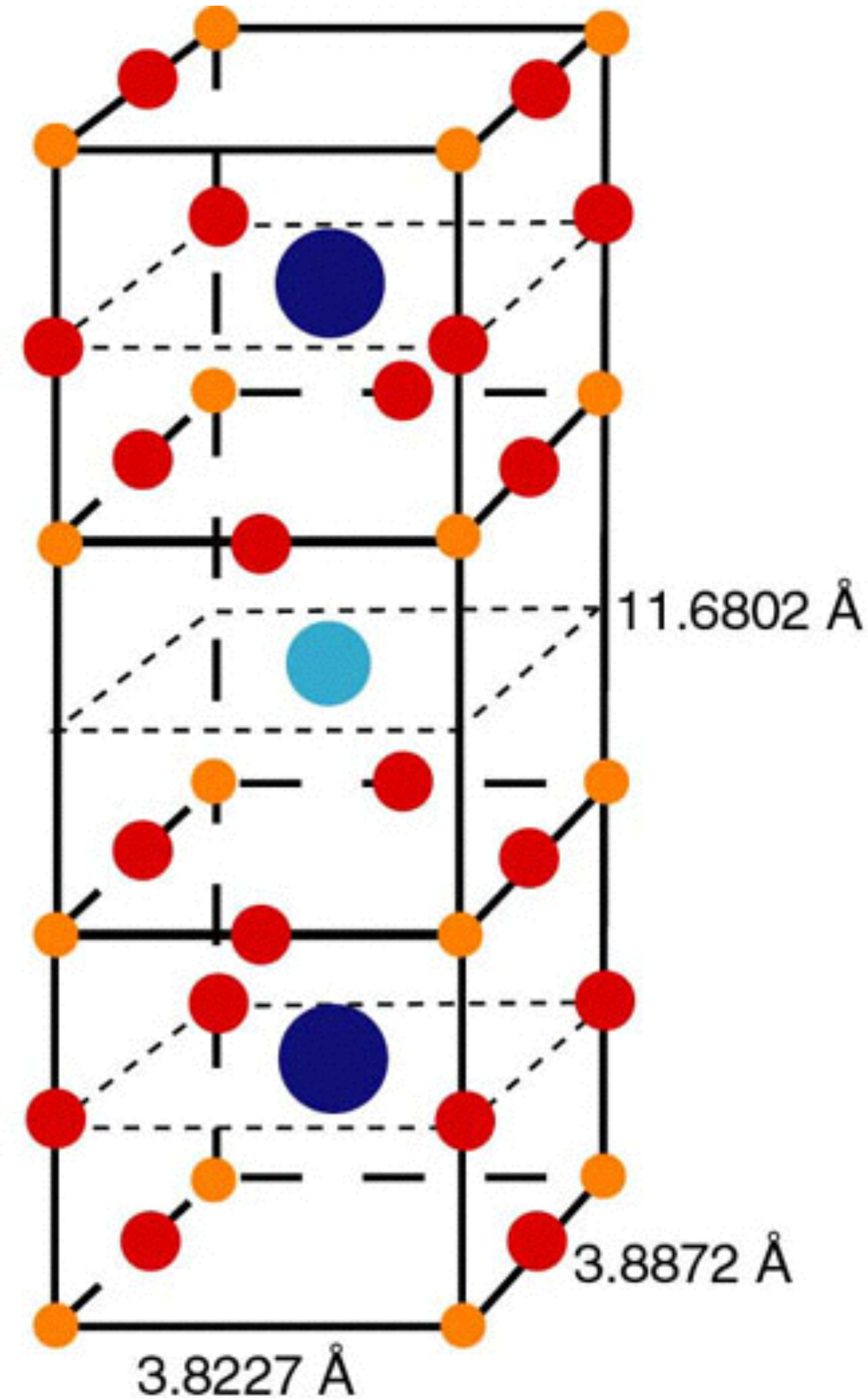
J. C. Seamus Davis

Eun-Ah Kim

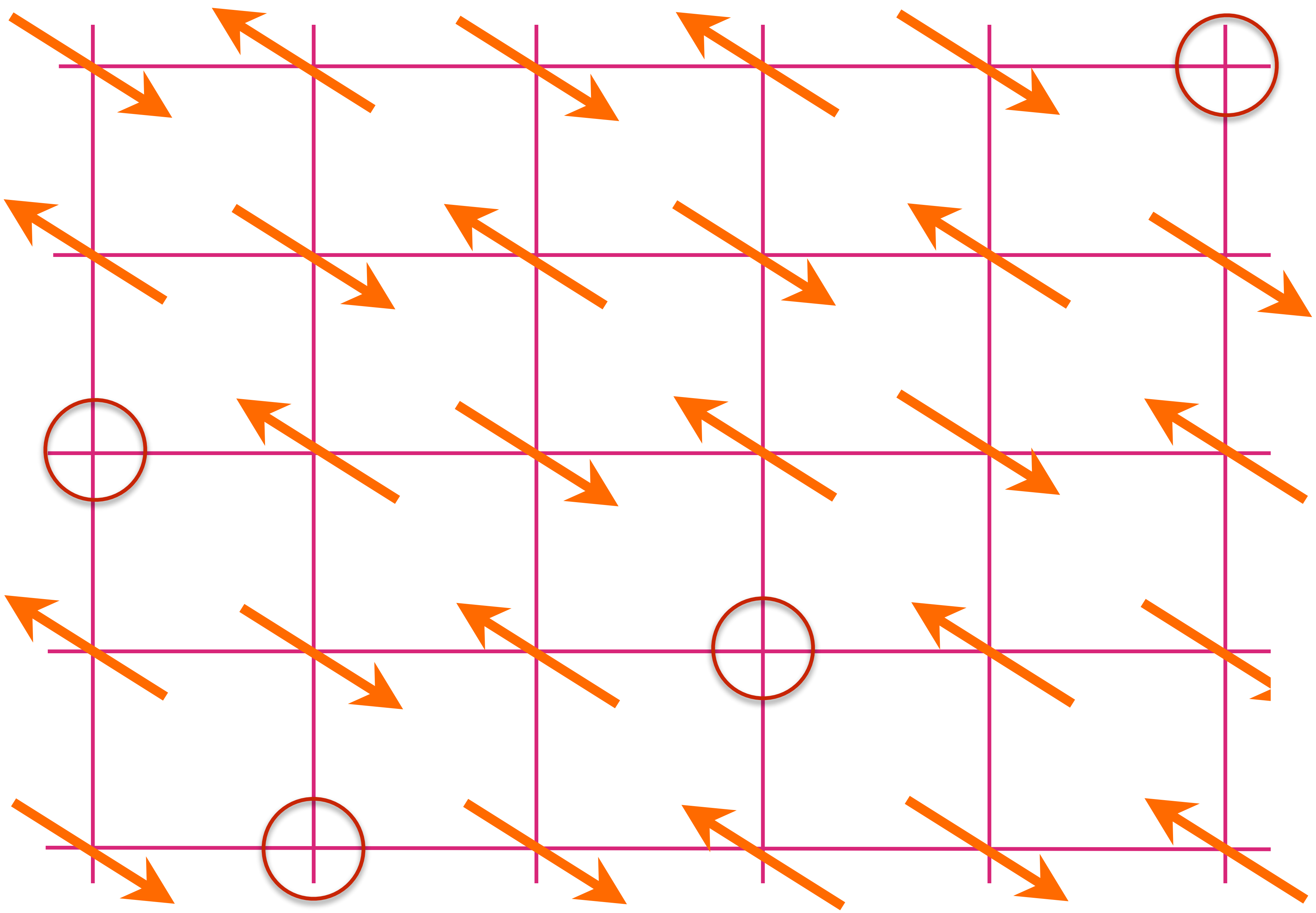
High temperature superconductors



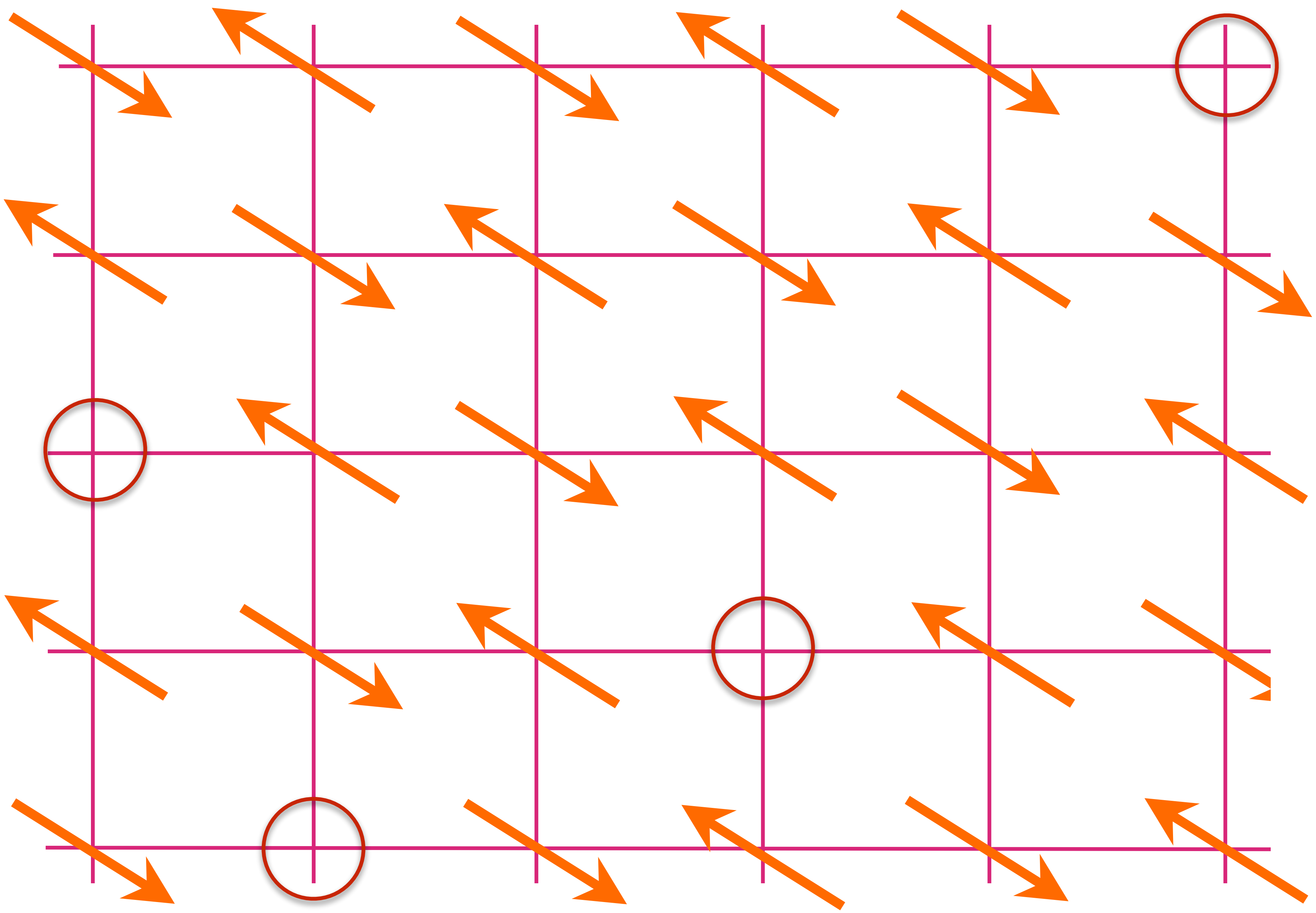
CuO_2 plane



$YBa_2Cu_3O_{6+x}$

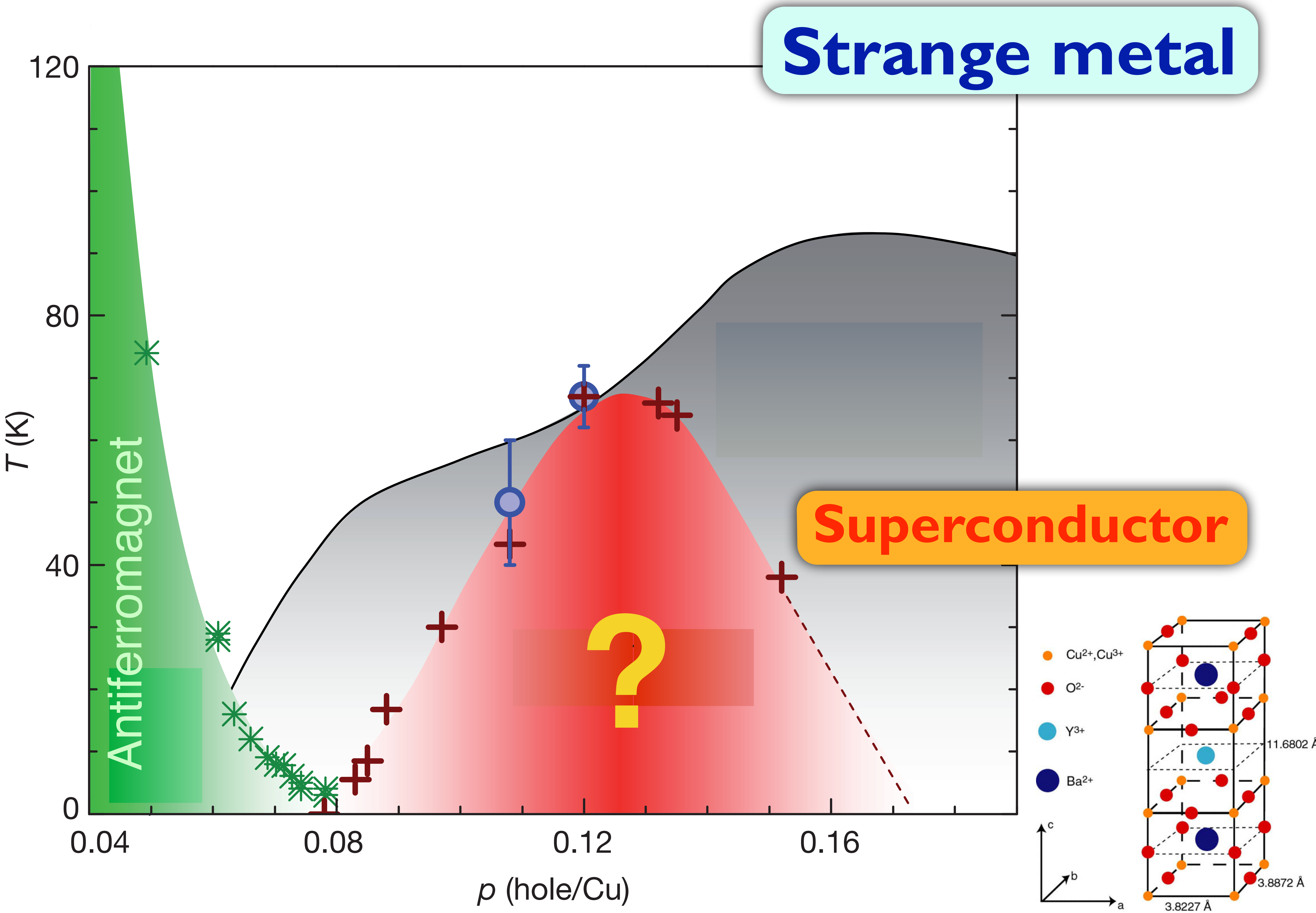


Anti-ferromagnet with p holes per square



Anti-ferromagnet with p holes per square

Note: relative to the fully-filled band insulator, there are $1+p$ holes per square



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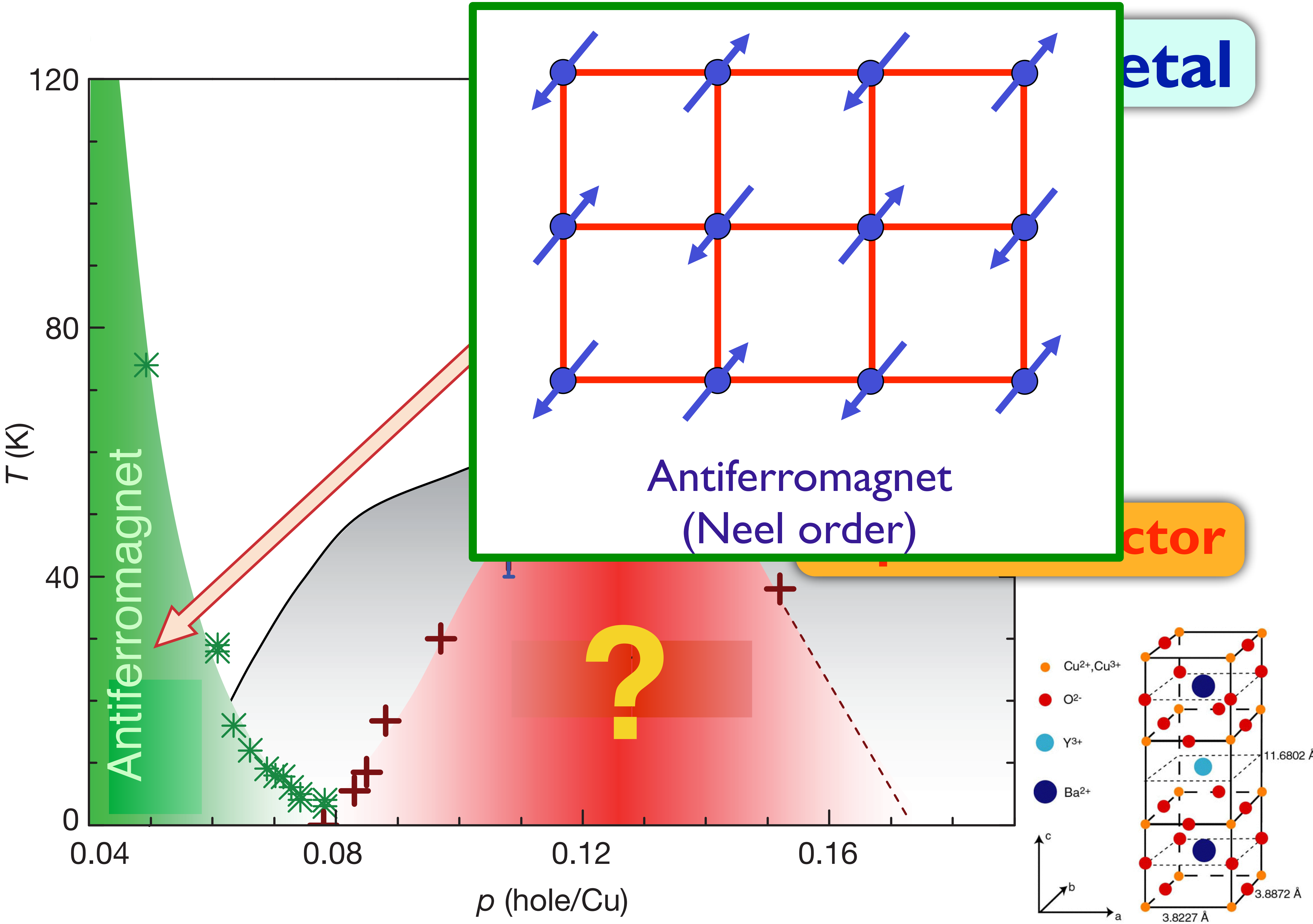

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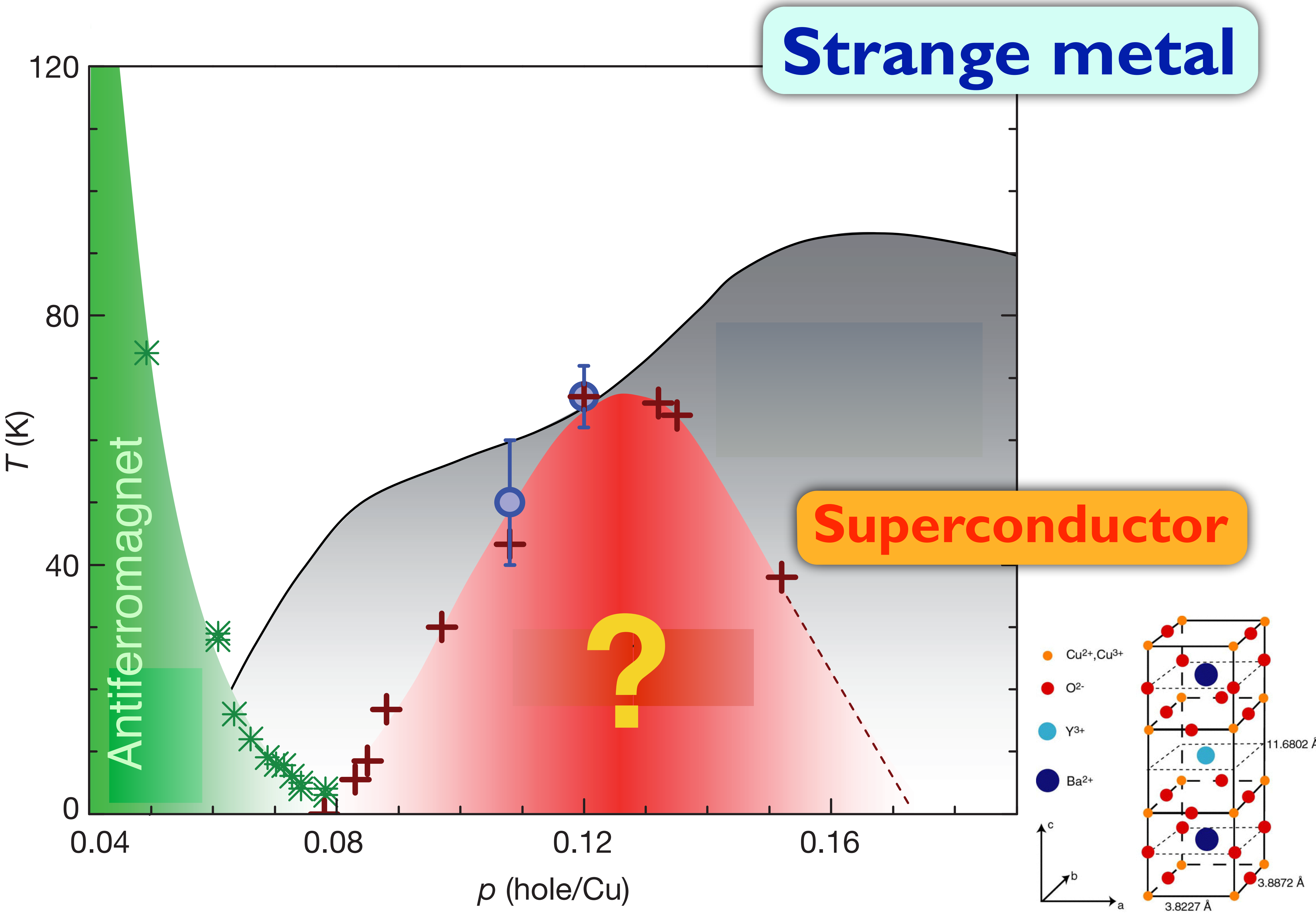

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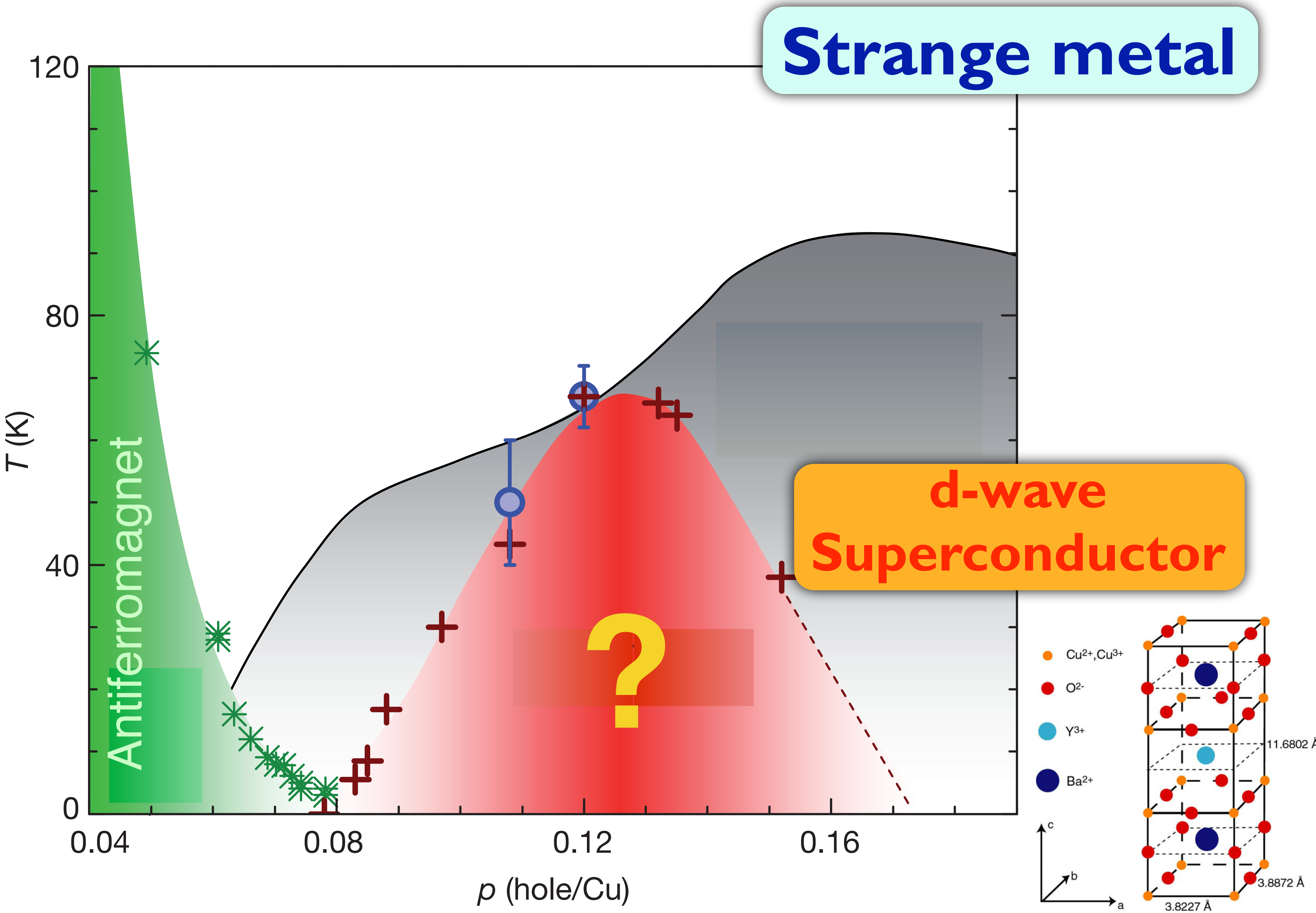

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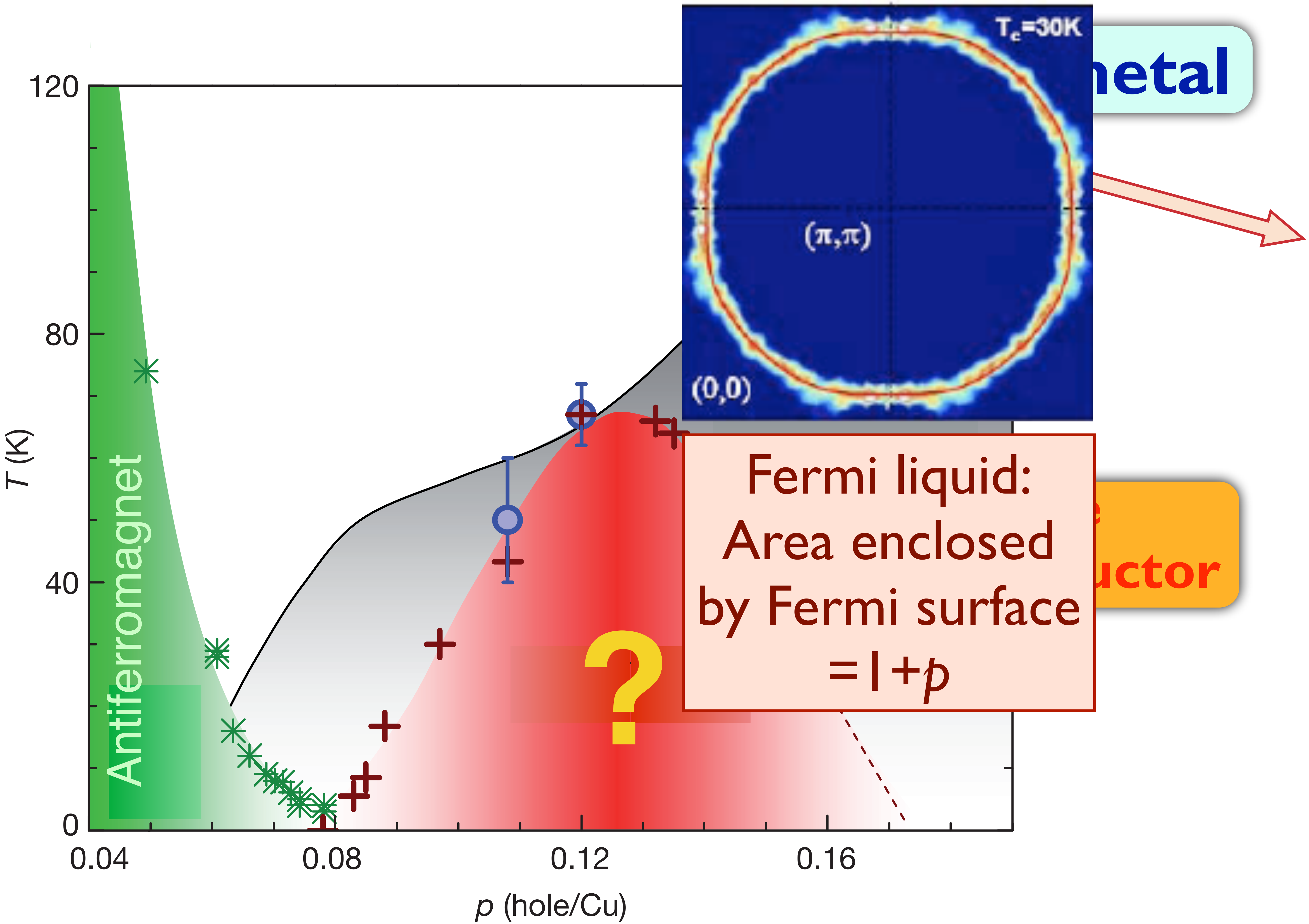
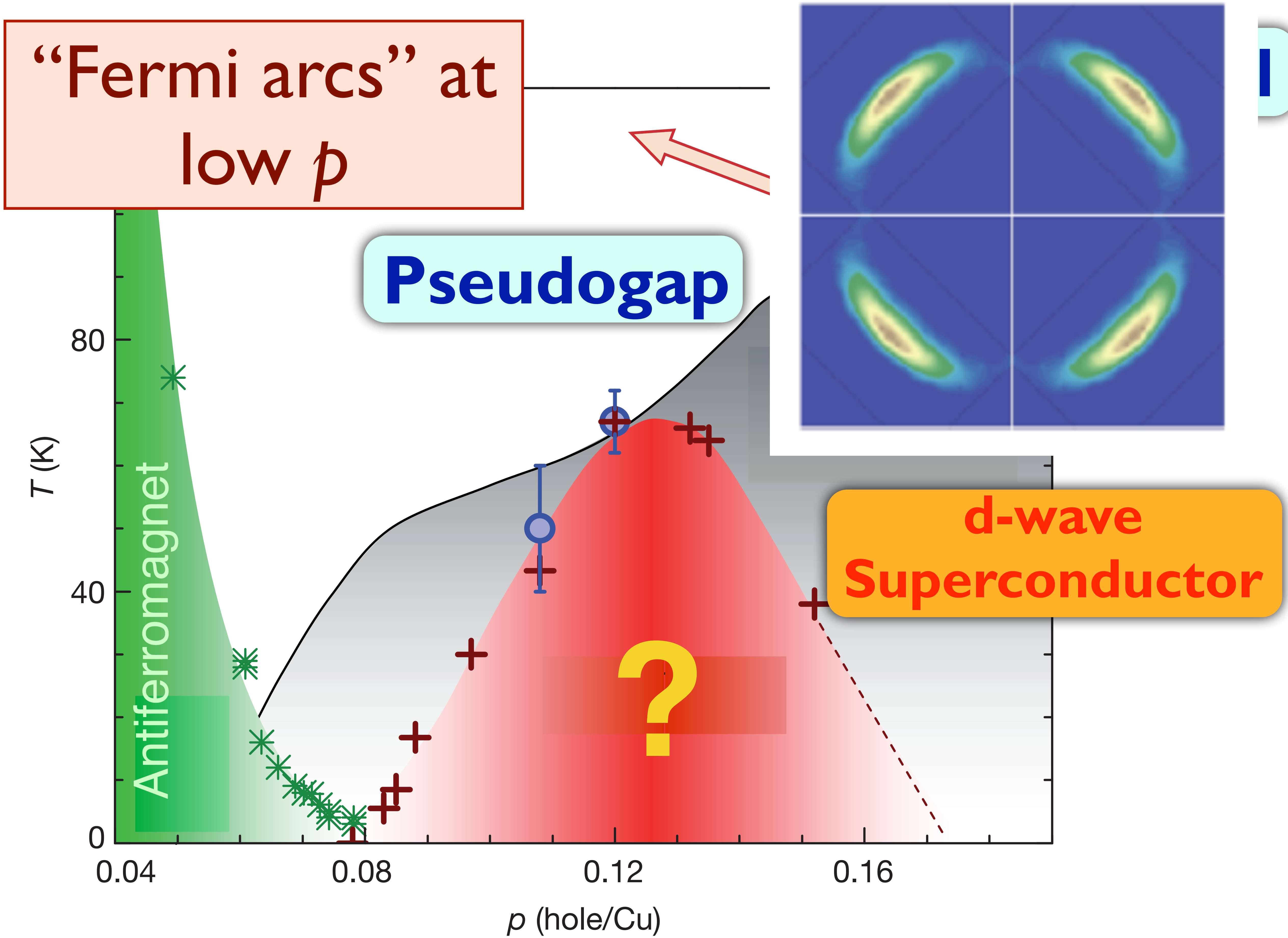


M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)



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)

Key question

At low temperatures in the pseudogap regime, there is a broken symmetry at low temperatures associated with a charge density wave (to be described in more detail shortly).

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Is the higher temperature pseudogap (with ``Fermi arc'' spectra) described by

(A) Thermal fluctuations of the low temperature orders (superconductivity, charge density wave, antiferromagnetism…)

OR

(B) A new type of metal with "topological order", which can be stable (in principle) as a quantum ground state

Outline

1. The low T pseudogap:
   STM observation of predicted
   d-form factor density wave

2. The high T pseudogap:
   A metal with topological order:
   *the Fractionalized Fermi liquid: FL**

3. Connecting high and low T:
   Density wave instabilities

4. Quantum critical point near optimal p:
   A Higgs critical point

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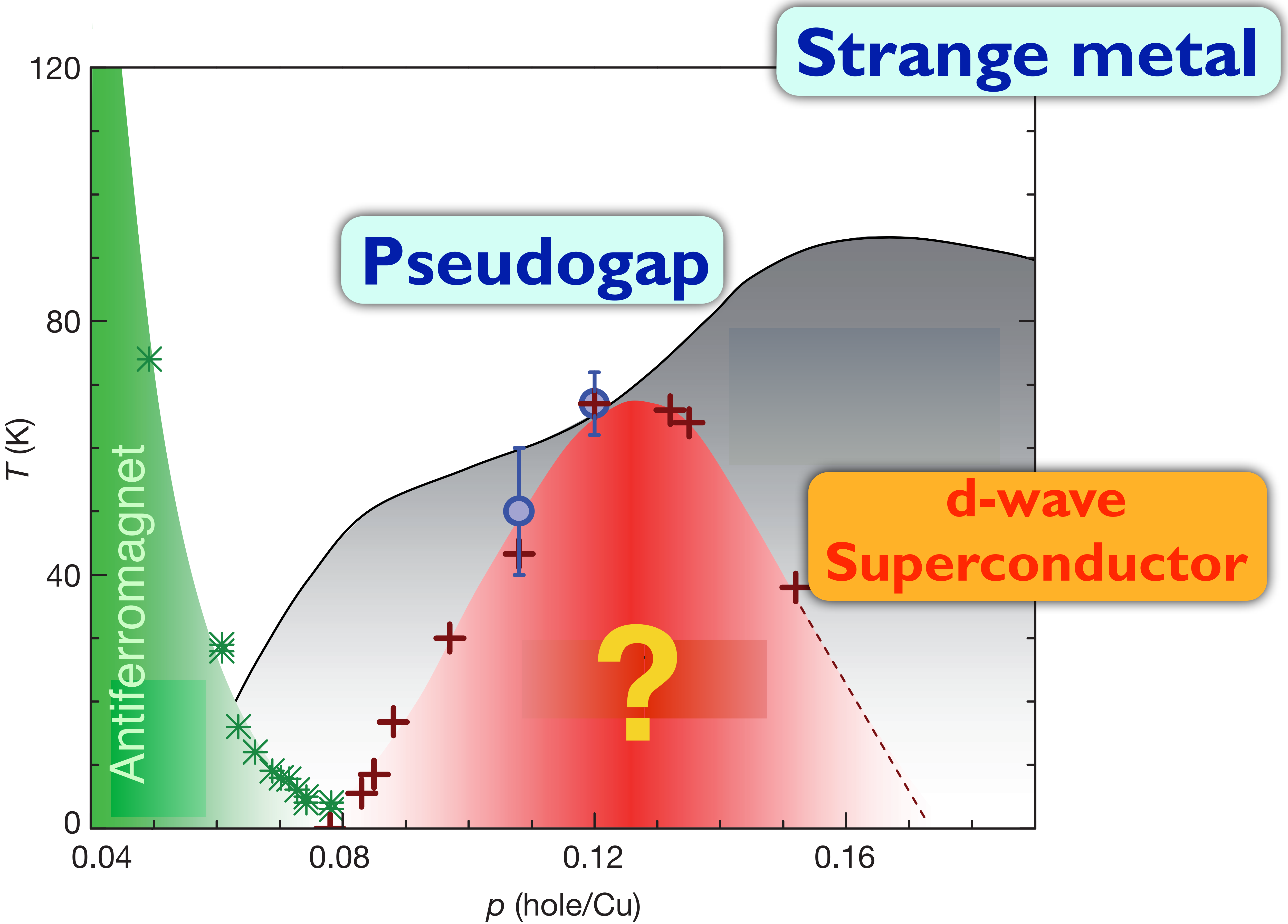

Strange metal
Pseudogap
d-wave
Superconductor
Antiferromagnet
?
120
80
40
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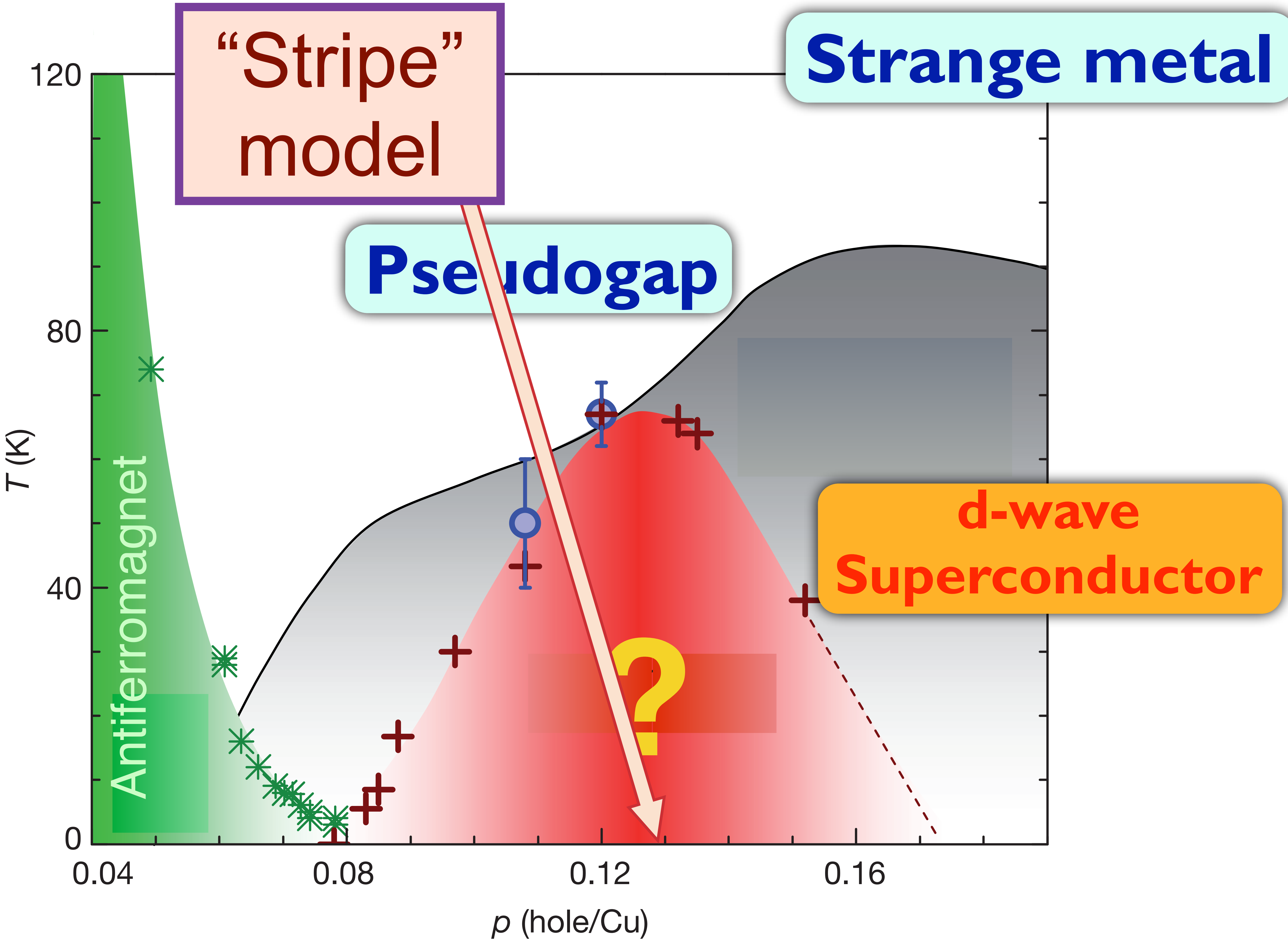
T (K)
0.04
0.08
0.12
0.16
p (hole/Cu)



"Stripe" model
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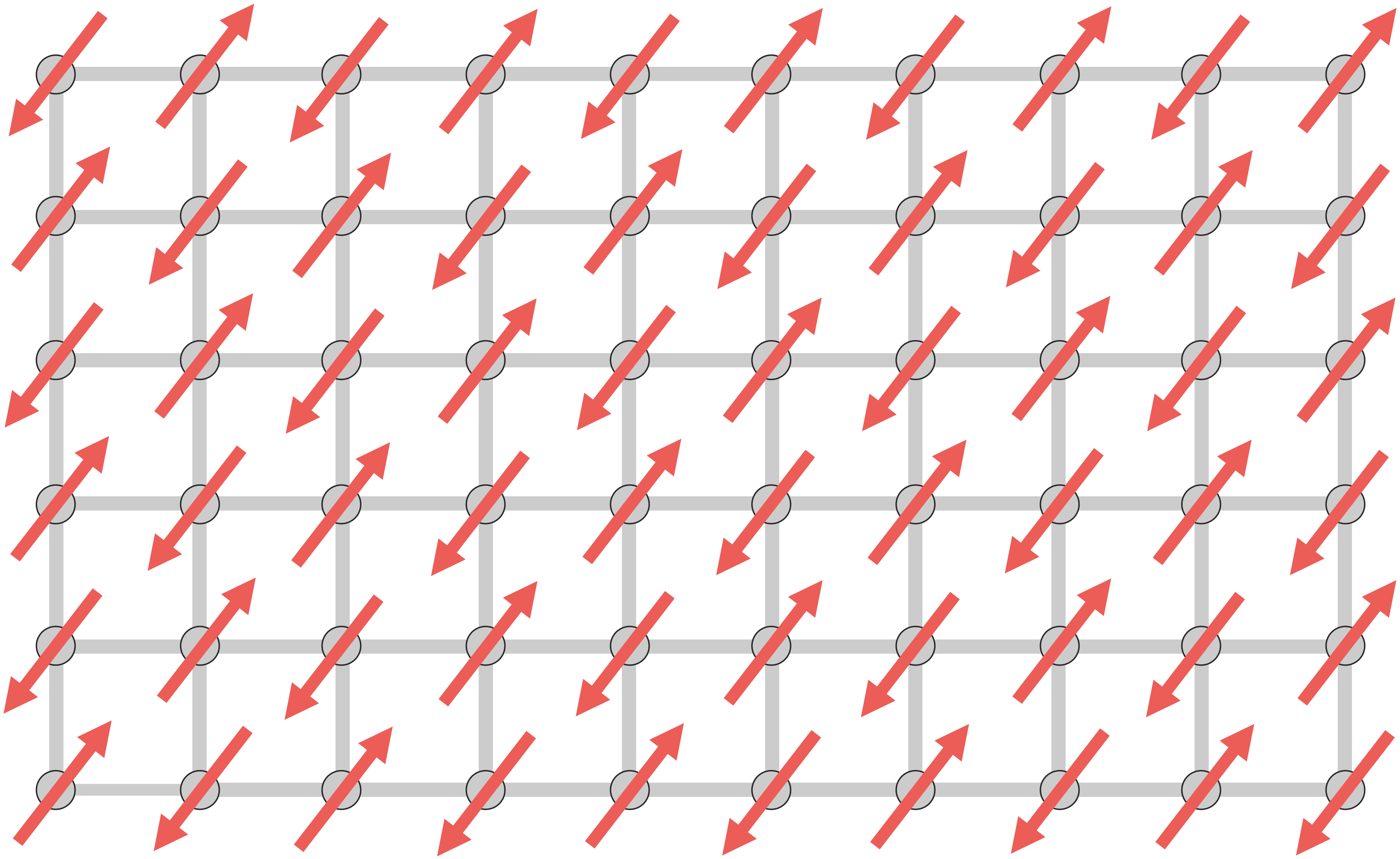
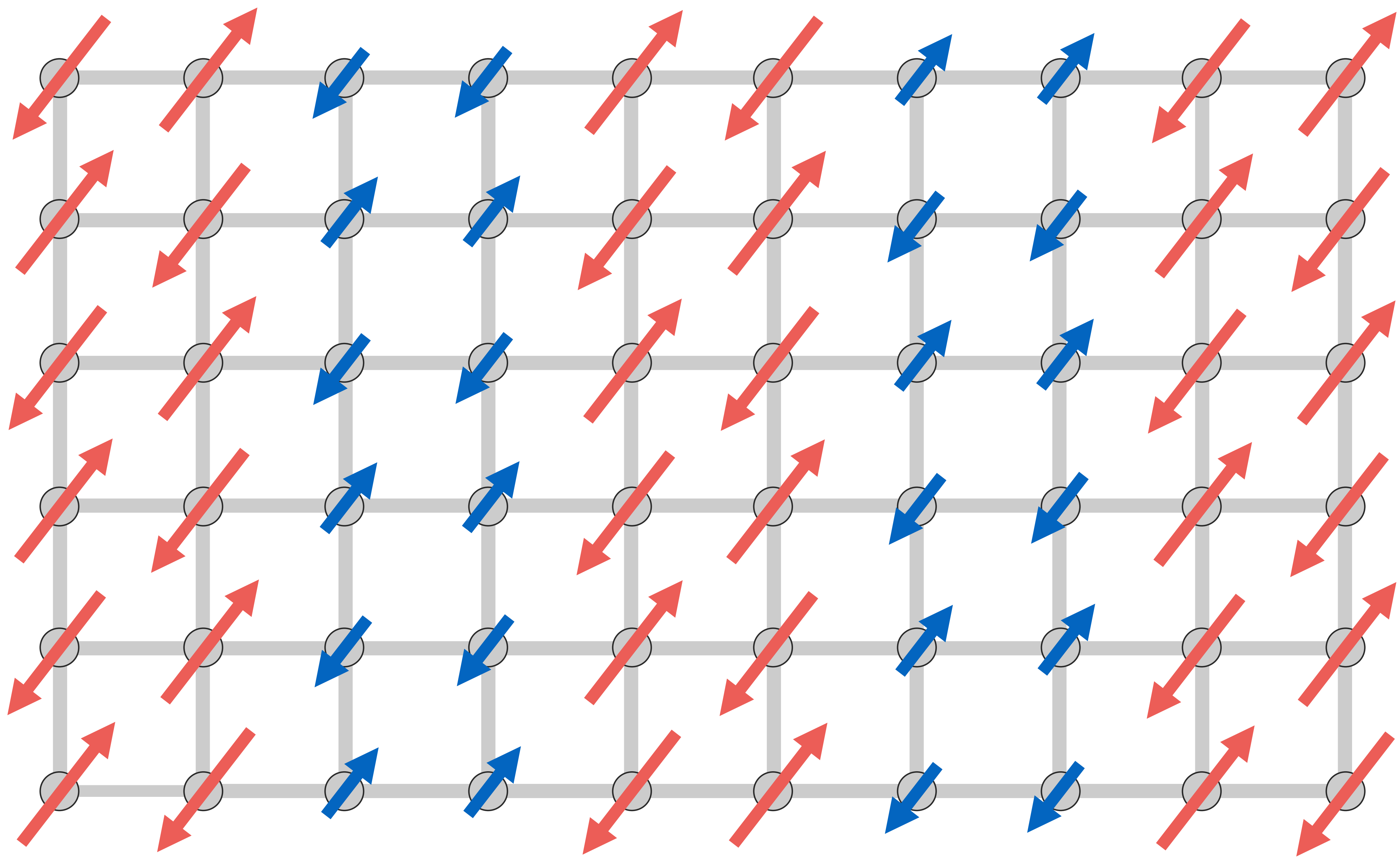


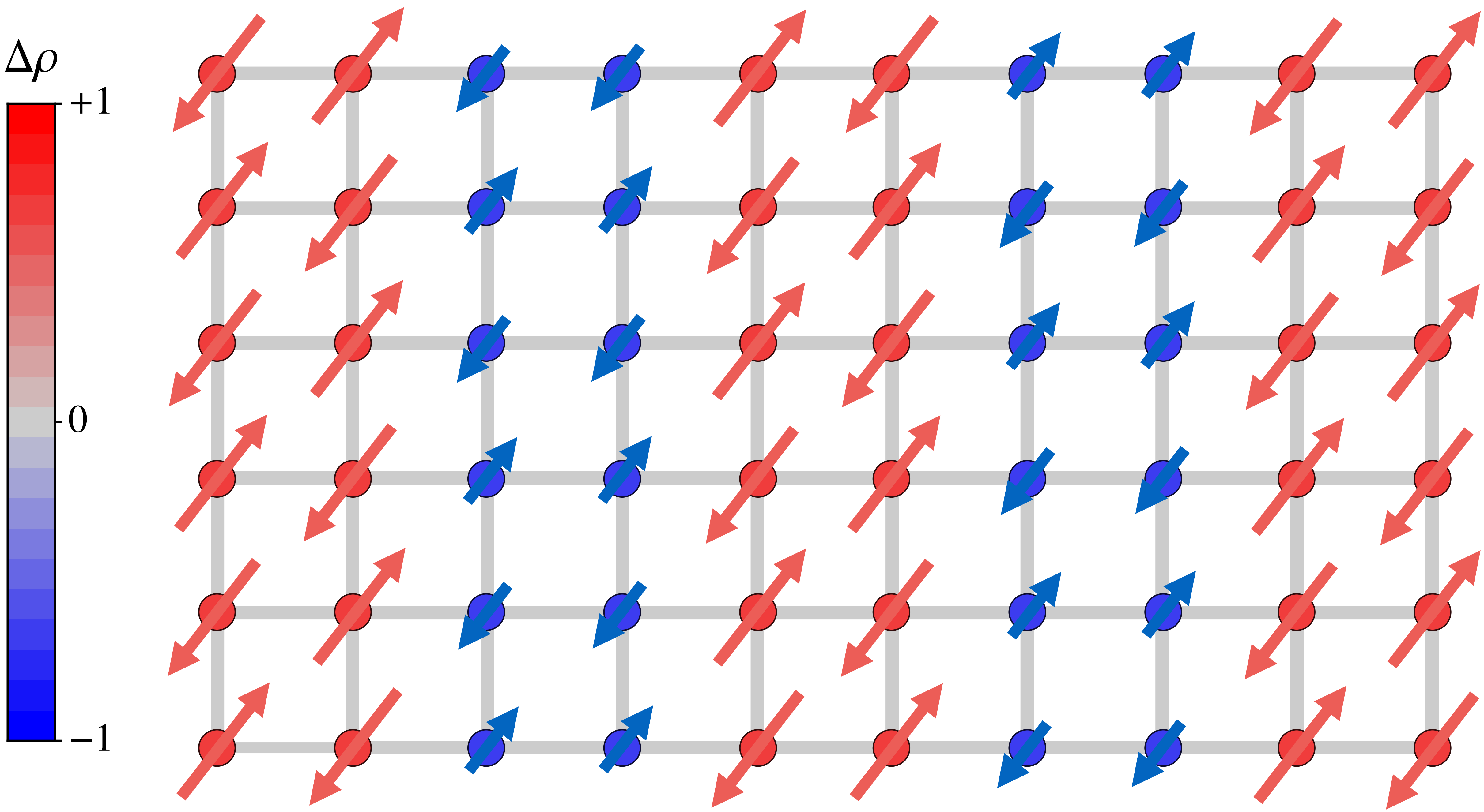
Start with an antiferromagnet

“Stripe” model



Domain walls 4 lattice spacings apart

“Stripe” model

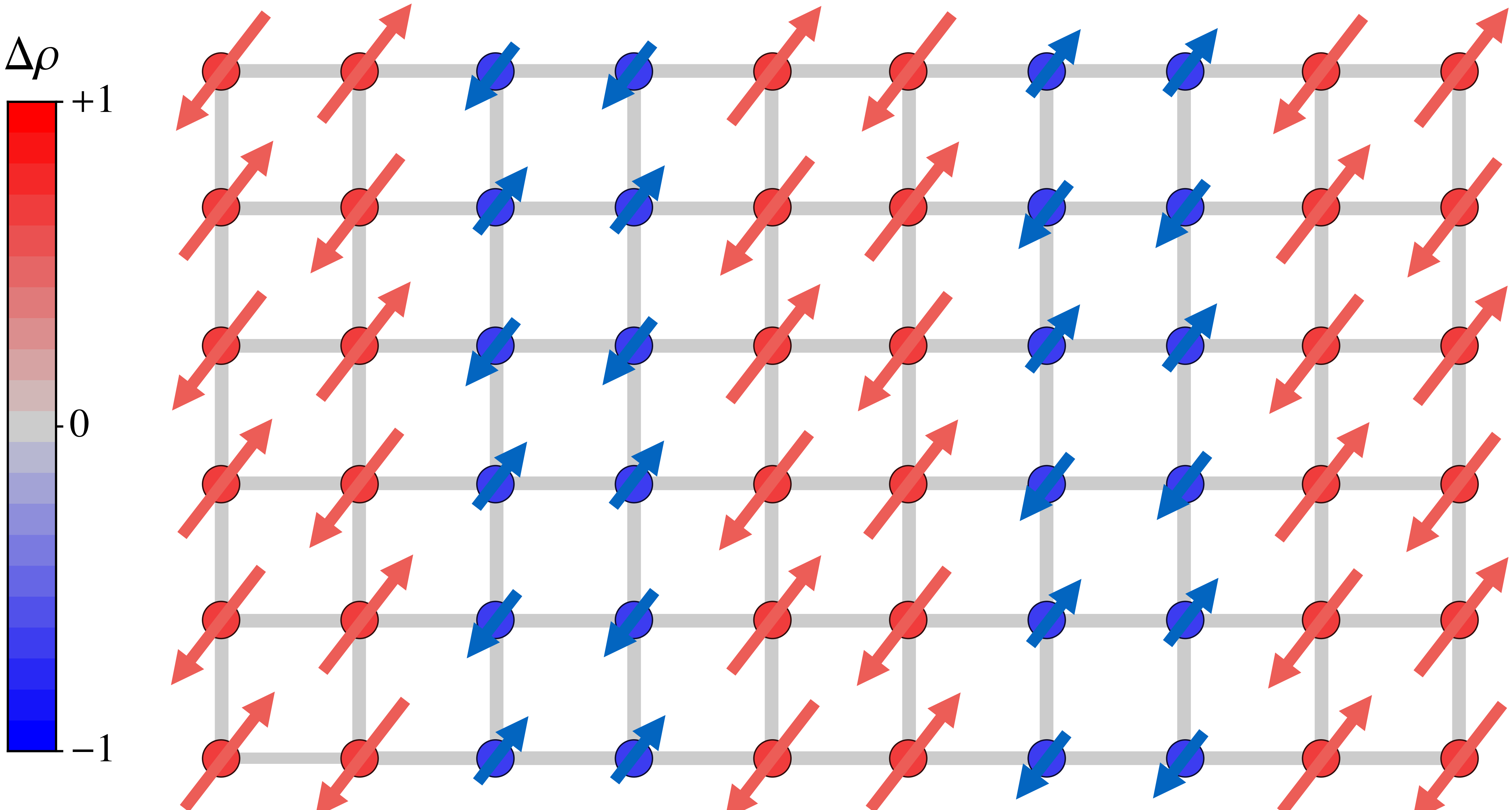


Put the holes in the domain walls

Observed in La-based compounds (Tranquada..)

Theory: Zaanen, Kivelson, Fradkin….

"Stripe" model



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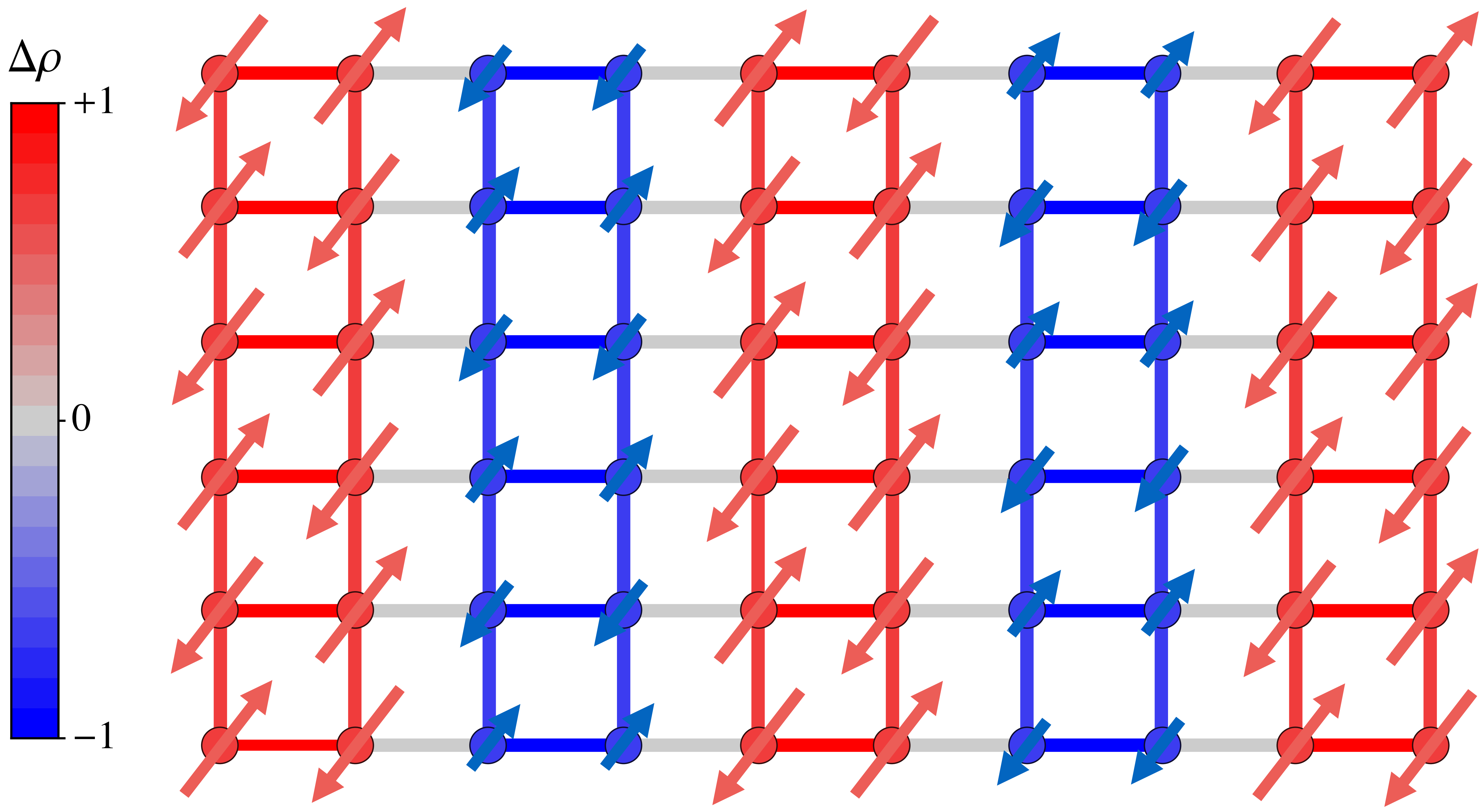
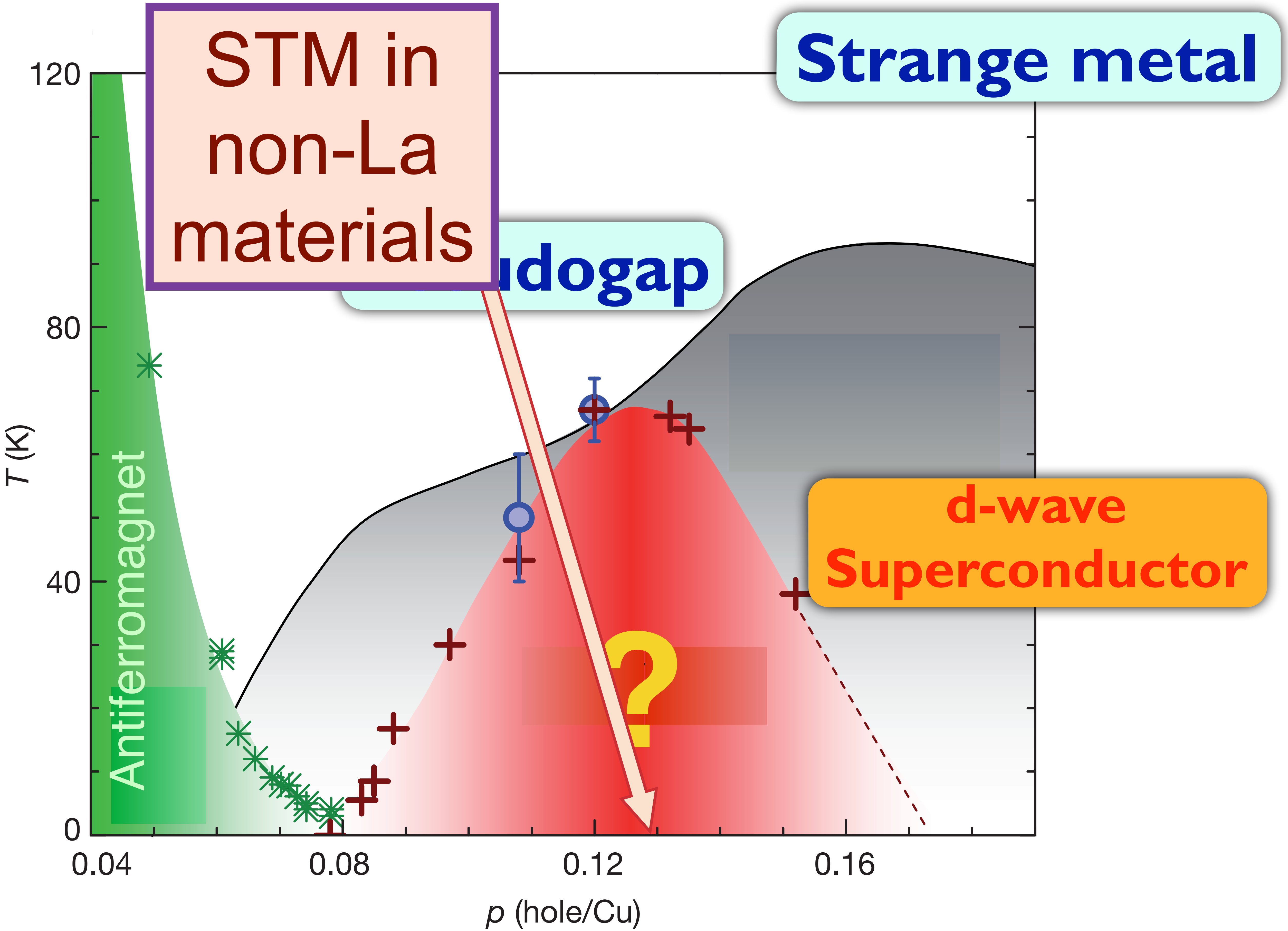


Colors on the bonds map the local exchange energy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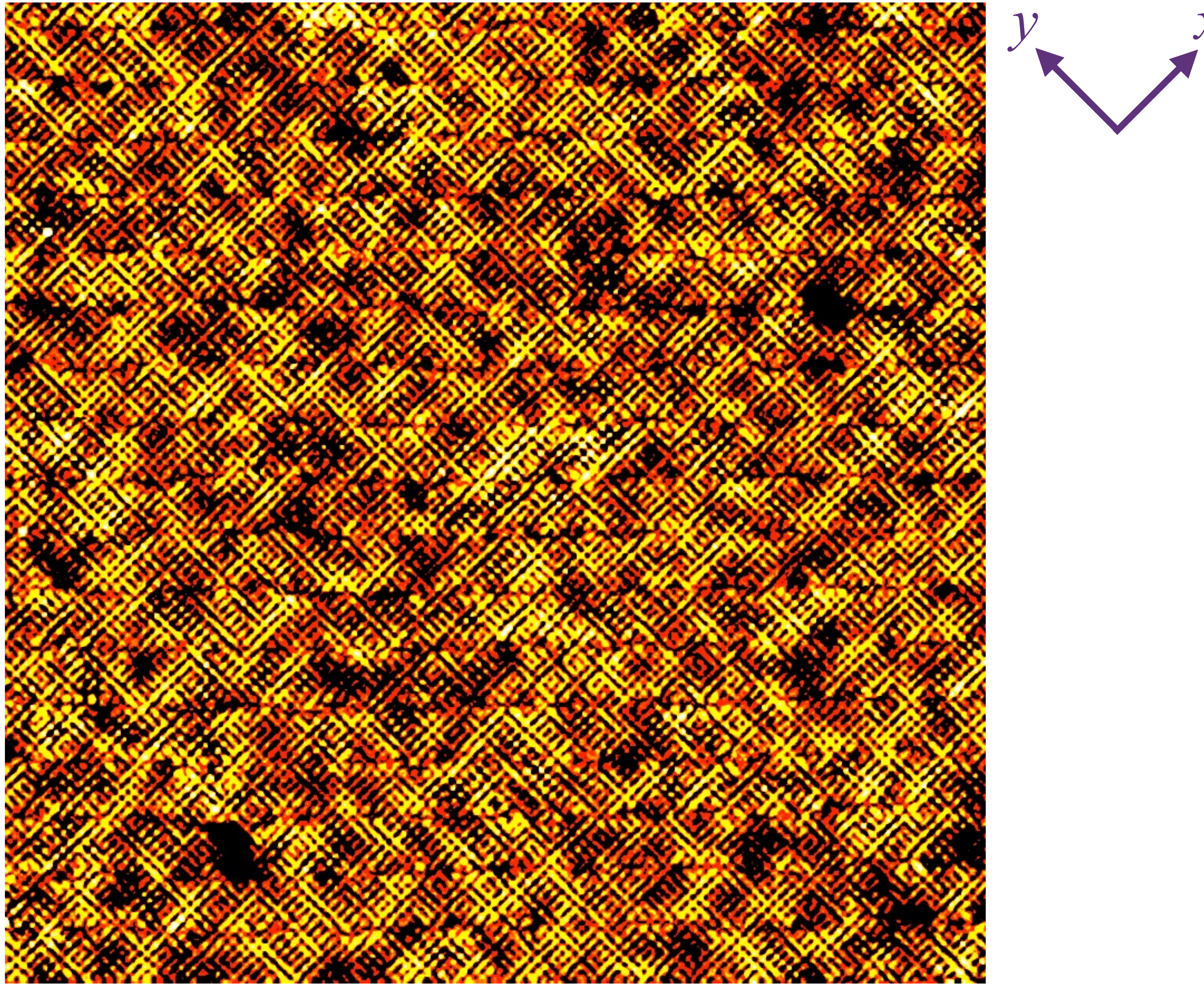

"R-map" of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007). Davis group has sub-angstrom resolution capabilities, with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

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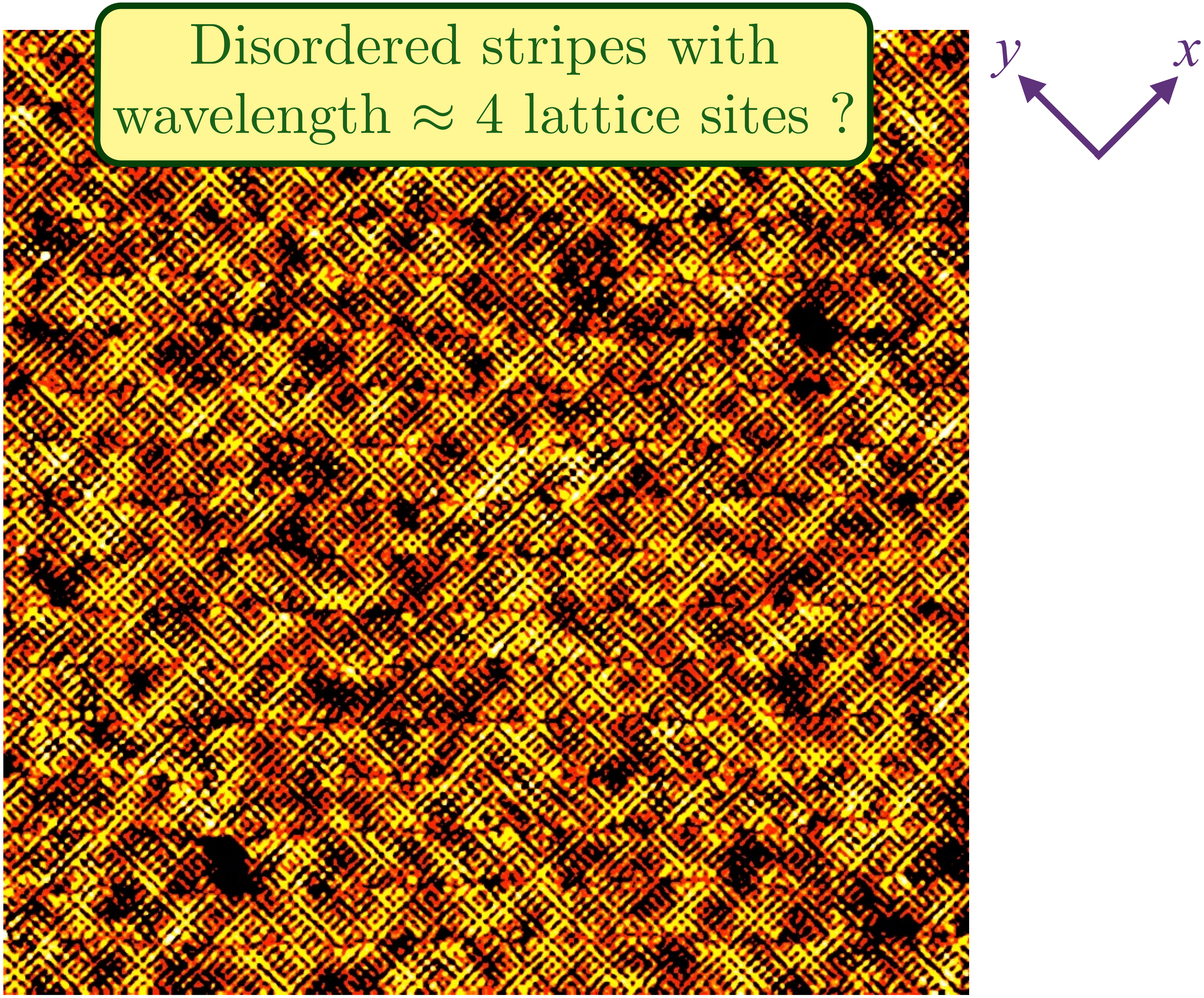

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Unconventional density wave (DW) : Bose condensation of particle-hole pairs

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

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

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)

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

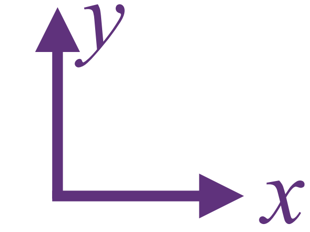
Time-reversal symmetry requires $\mathcal{P}(\mathbf{k}) = \mathcal{P}(-\mathbf{k})$.

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)

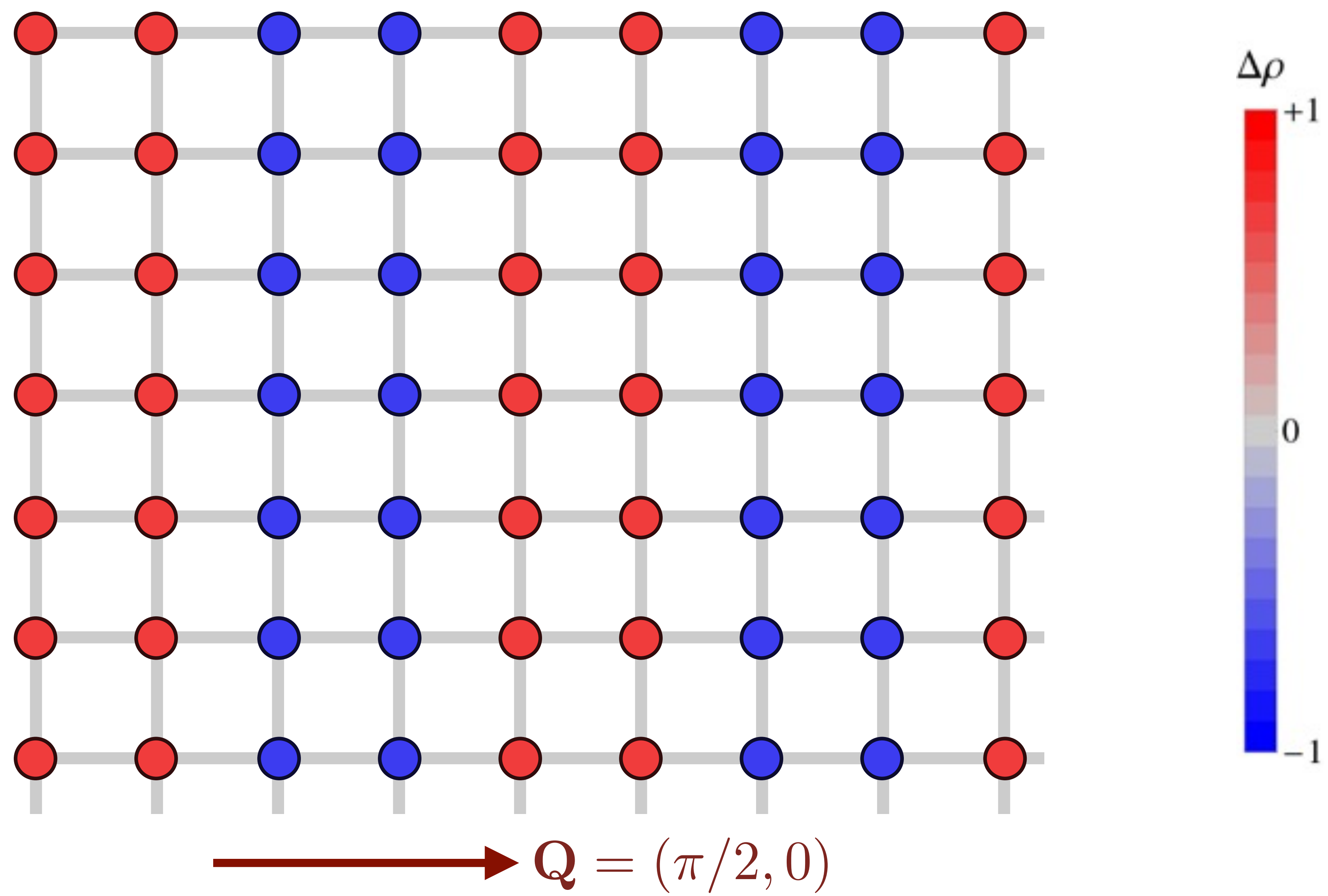
Conventional CDW order: s-form factor



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

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

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



Unconventional DW order: s'-form factor

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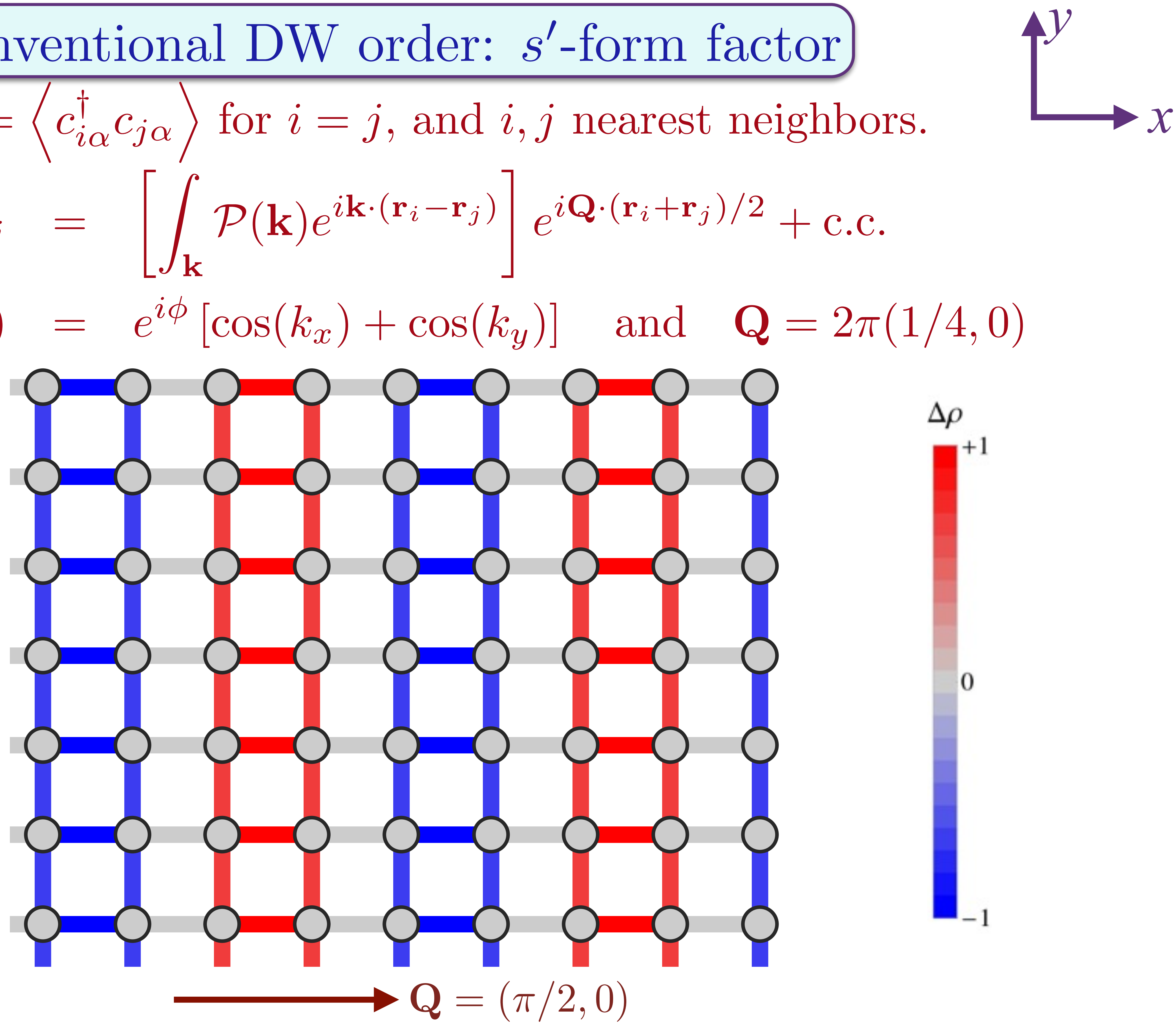
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) + \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$



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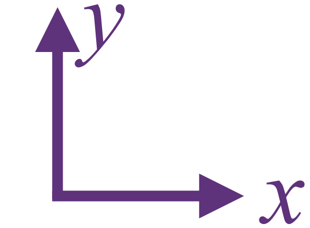

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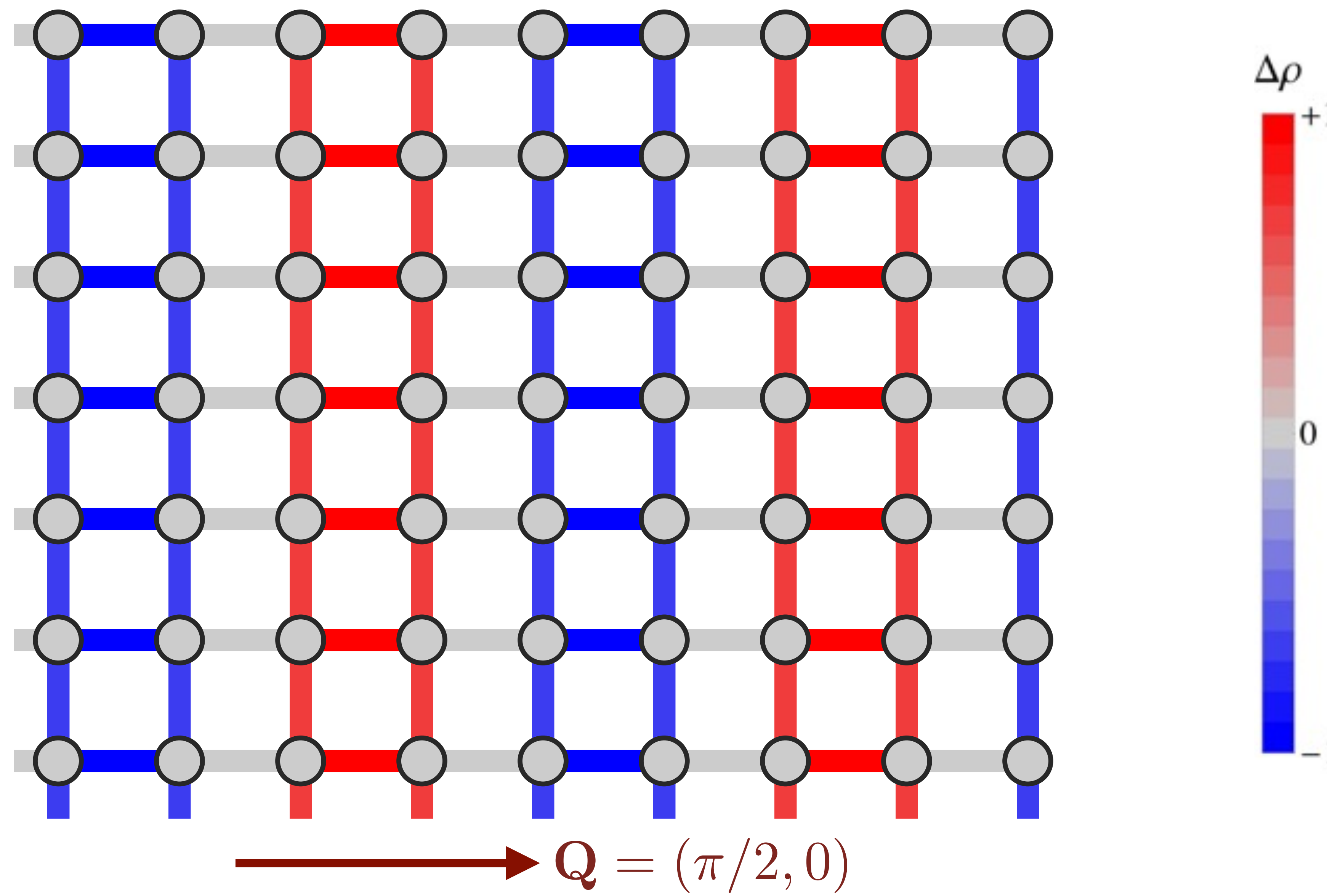
"Stripe" model



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

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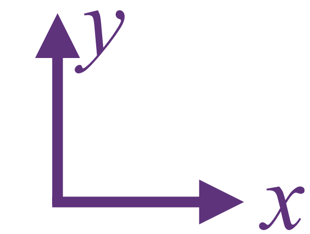

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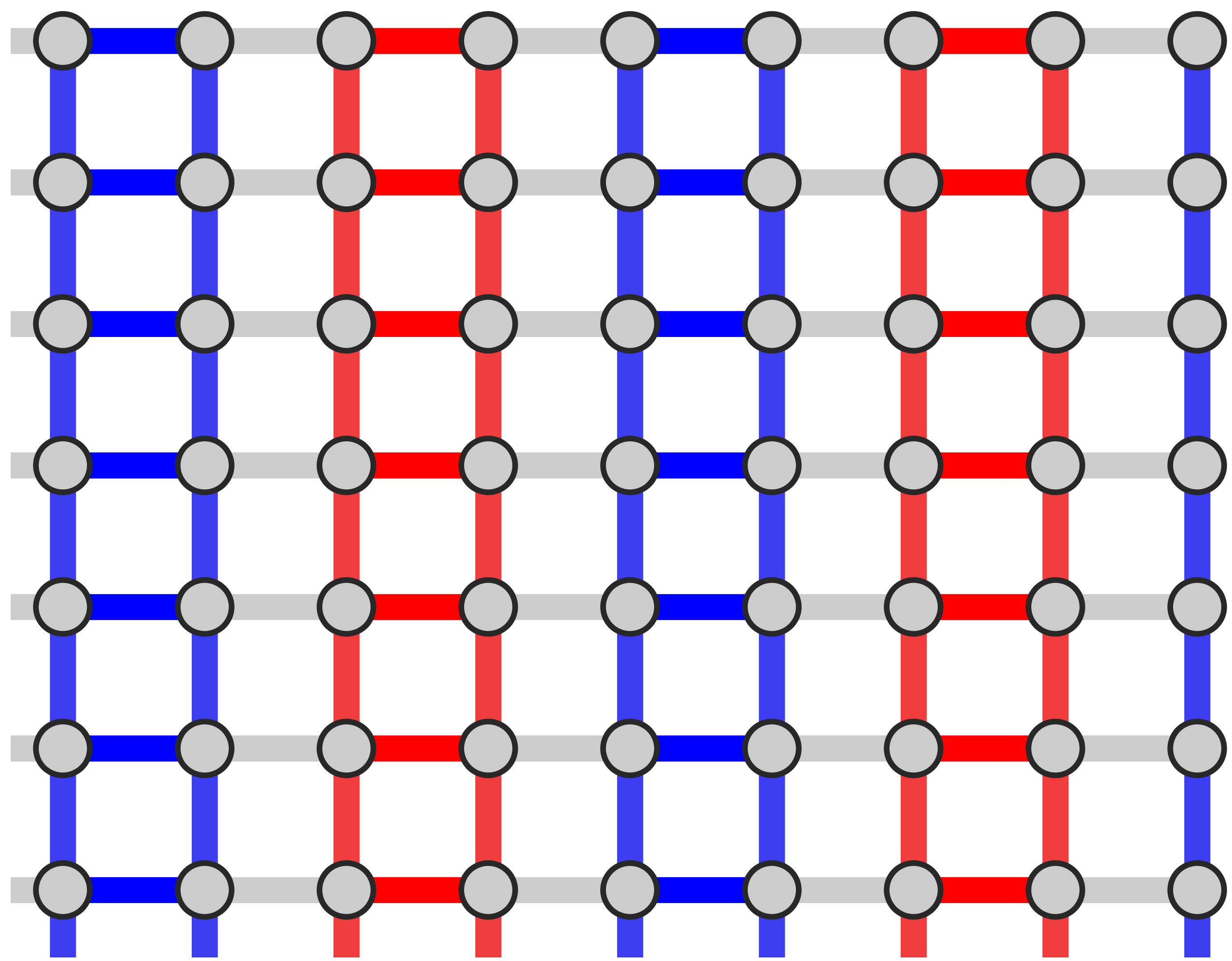
"Stripe" model

X-ray observations indicate strong s' component in LBCO

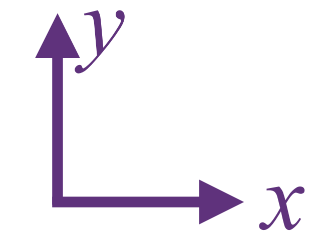


$\mathbf{Q} = (\pi/2, 0)$

David Hawthorn, Waterloo

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

Unconventional DW order: d-form factor



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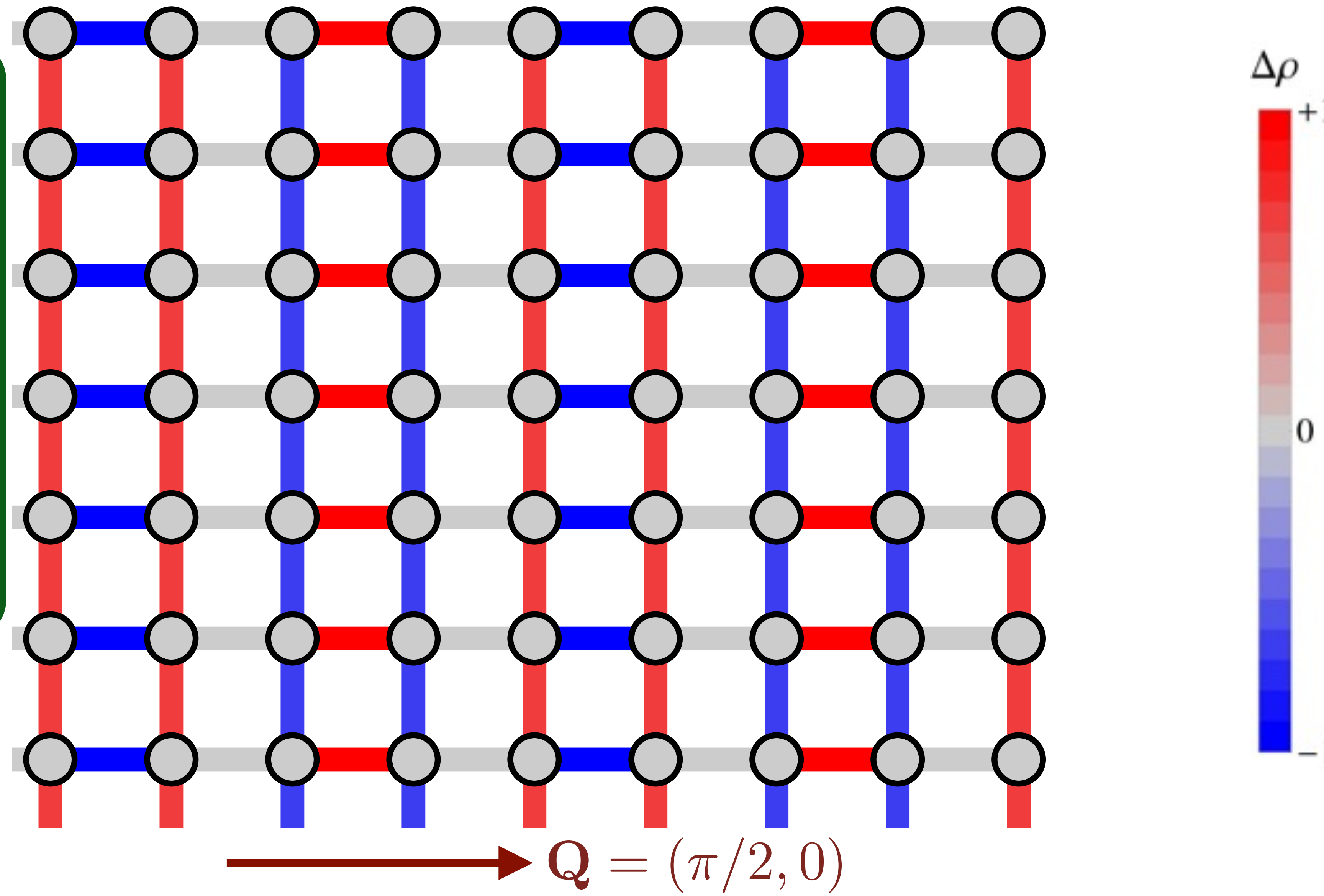
Our prediction:

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



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

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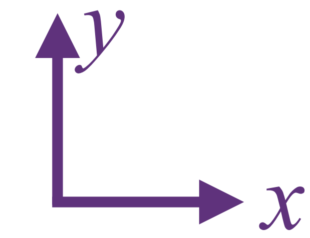

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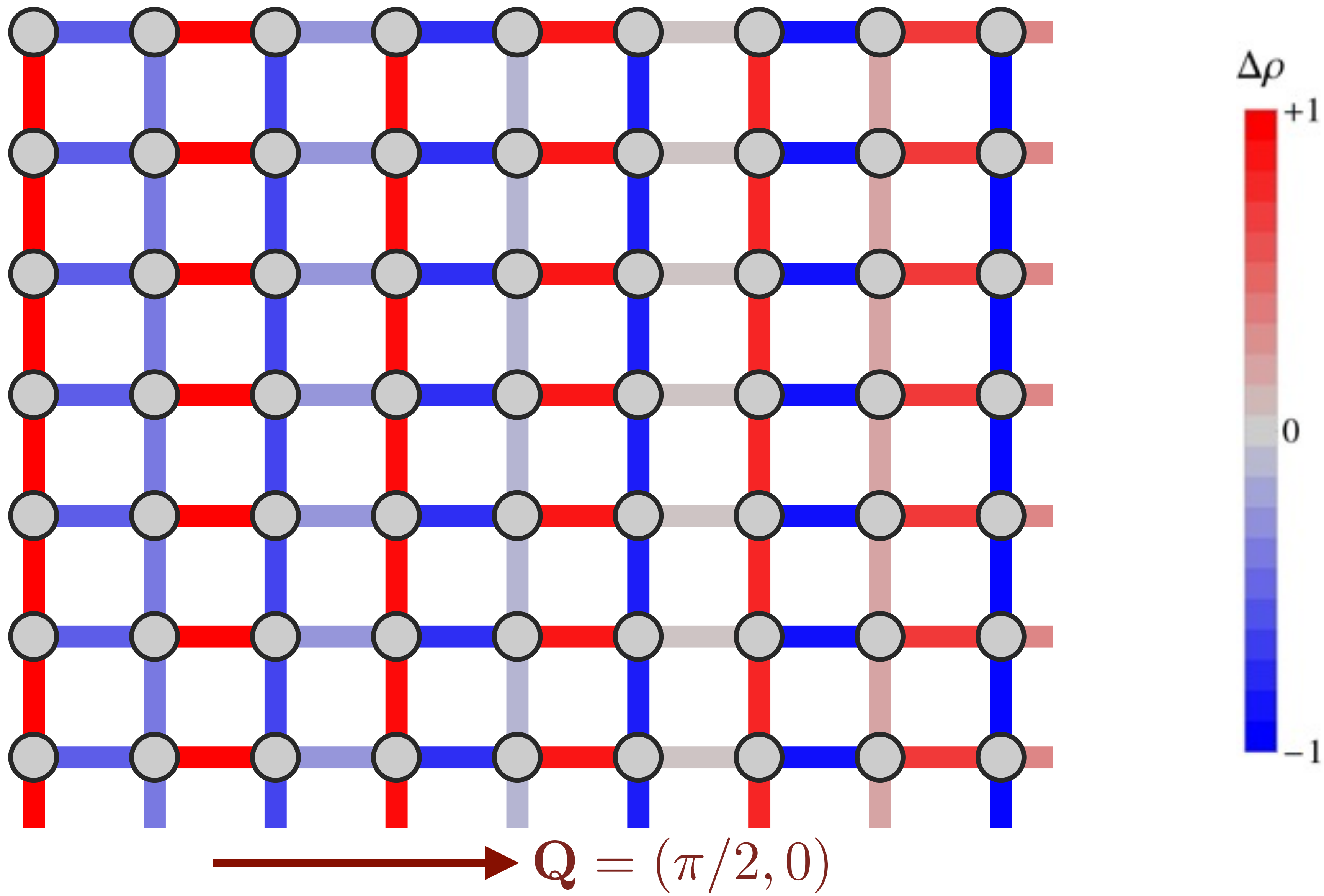

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Direct phase-sensitive identification of a *d*-form factor density wave in underdoped cuprates

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
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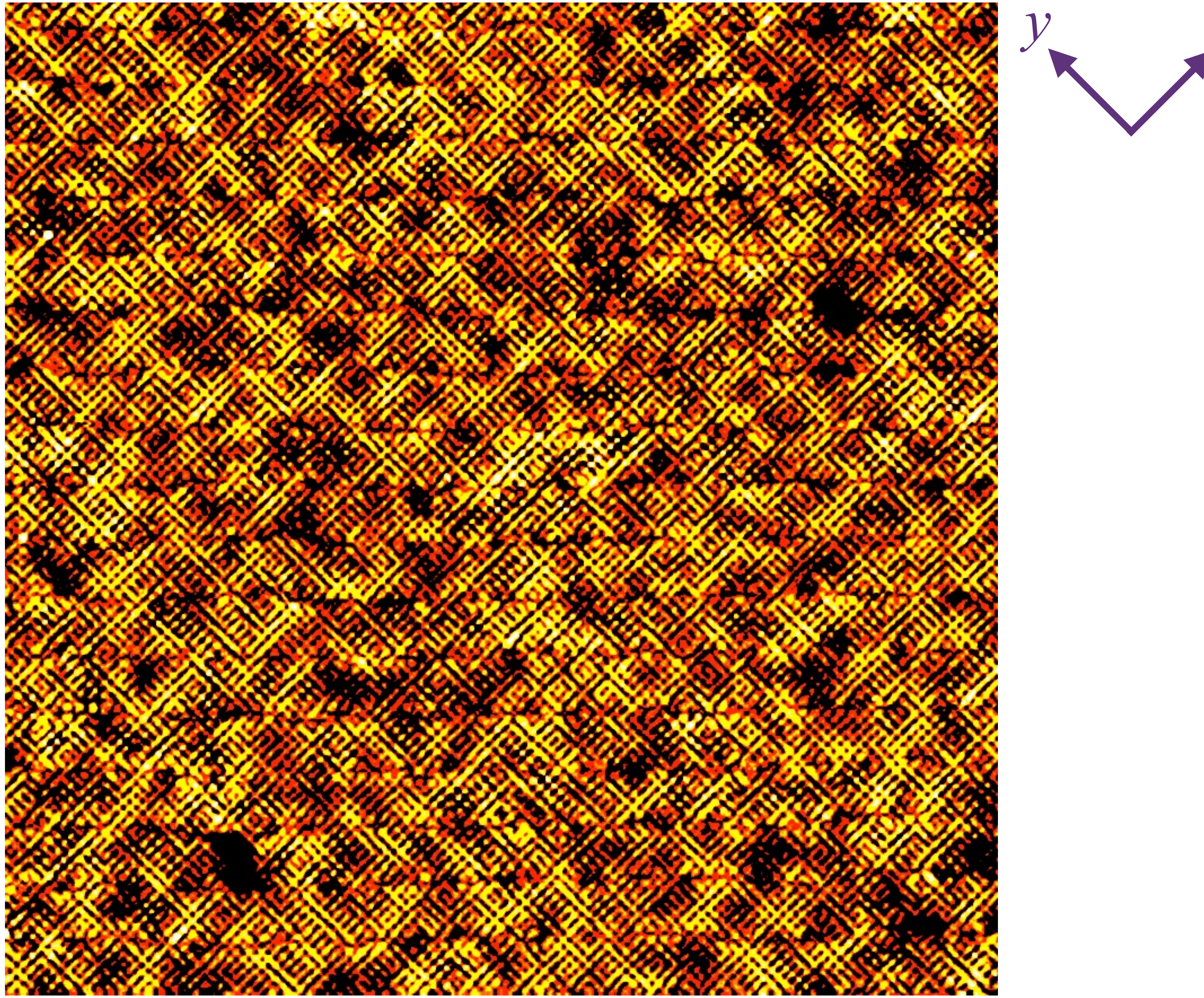

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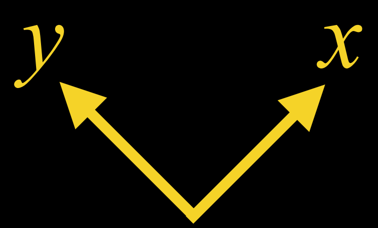
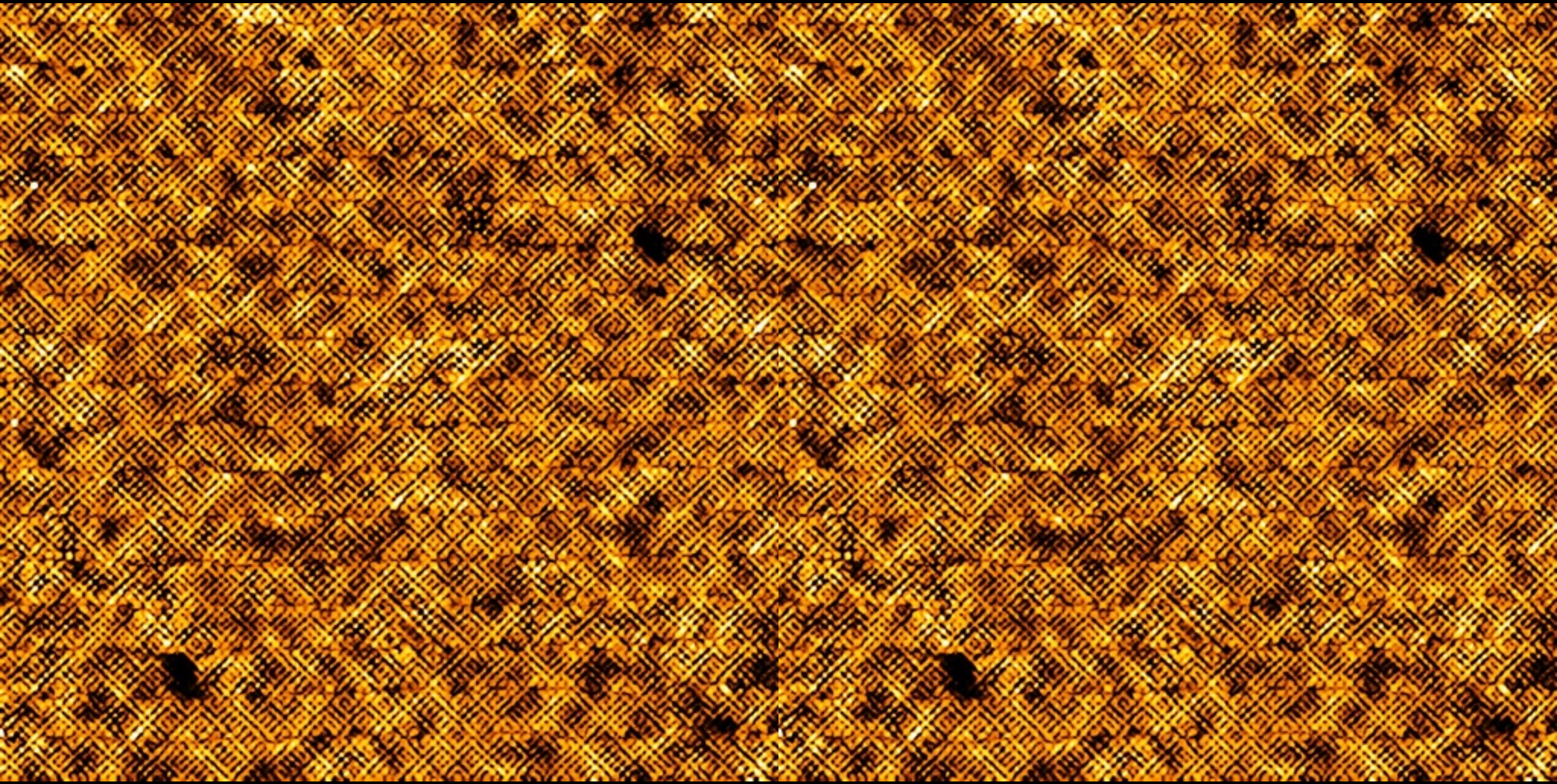
UD45K
BSCCO

R(r,150mV)

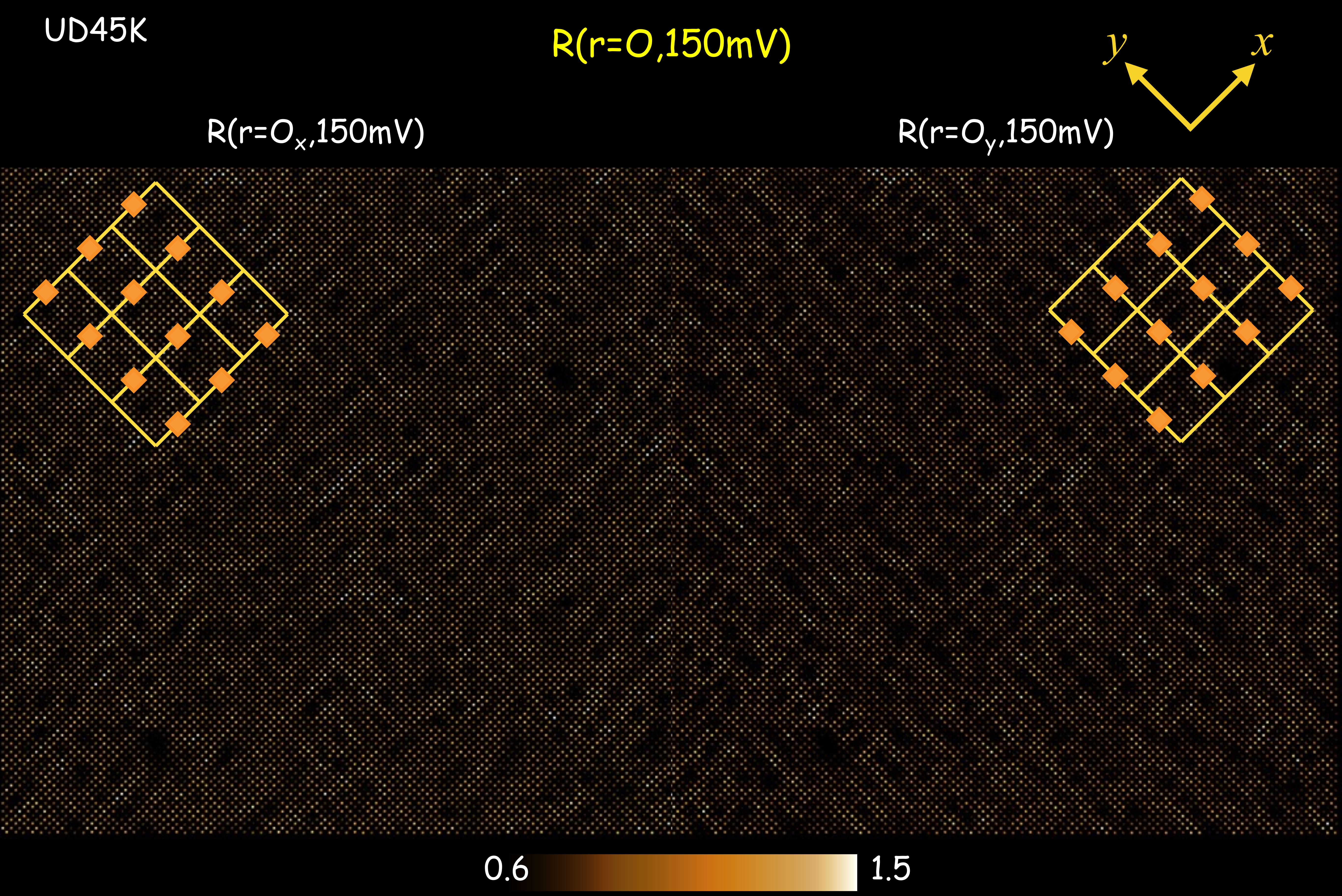


R(r,150mV) R(r,150mV)



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)



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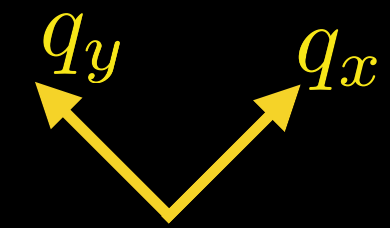
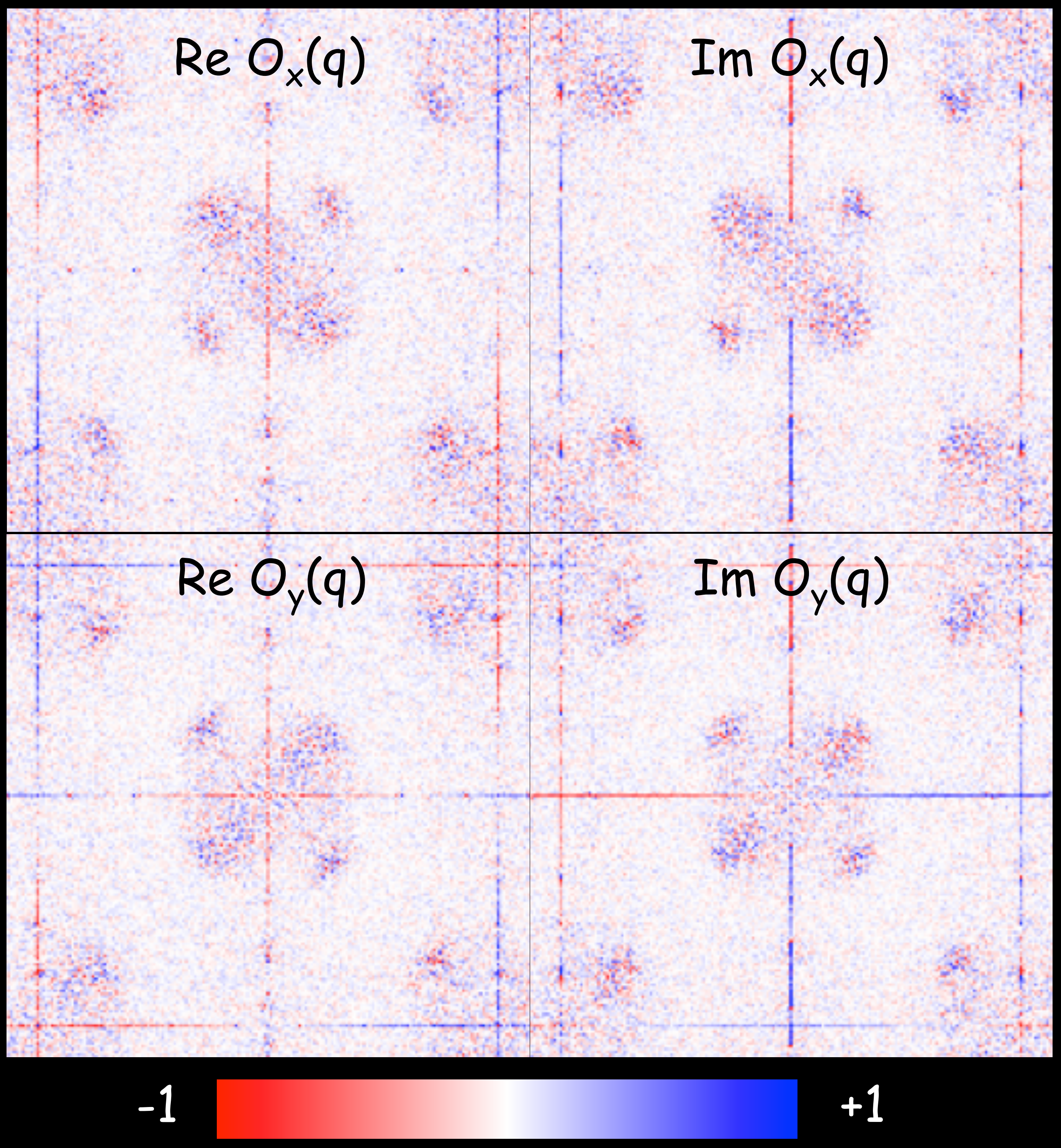
UD45K

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





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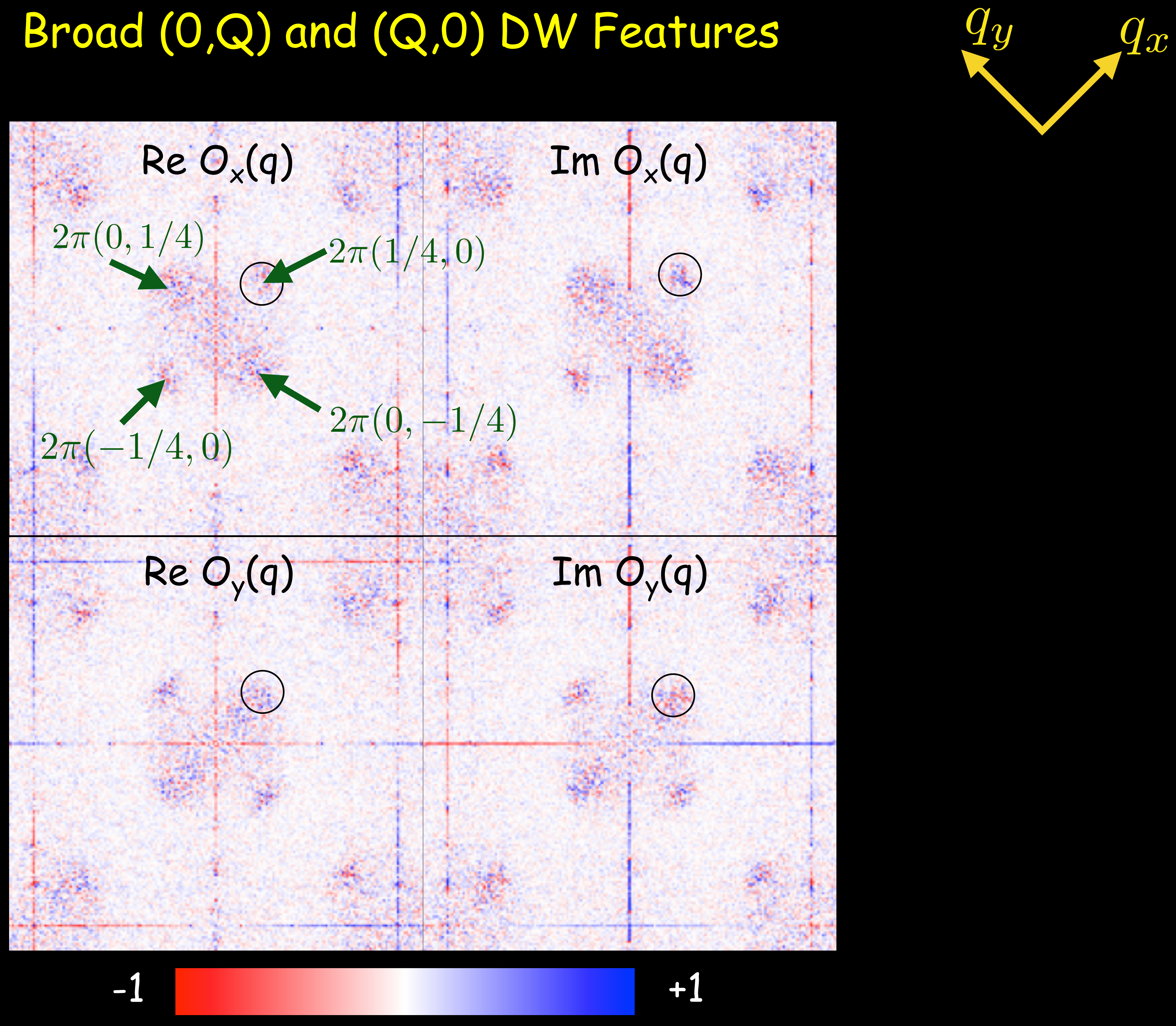

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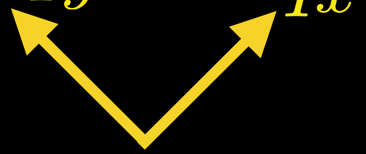
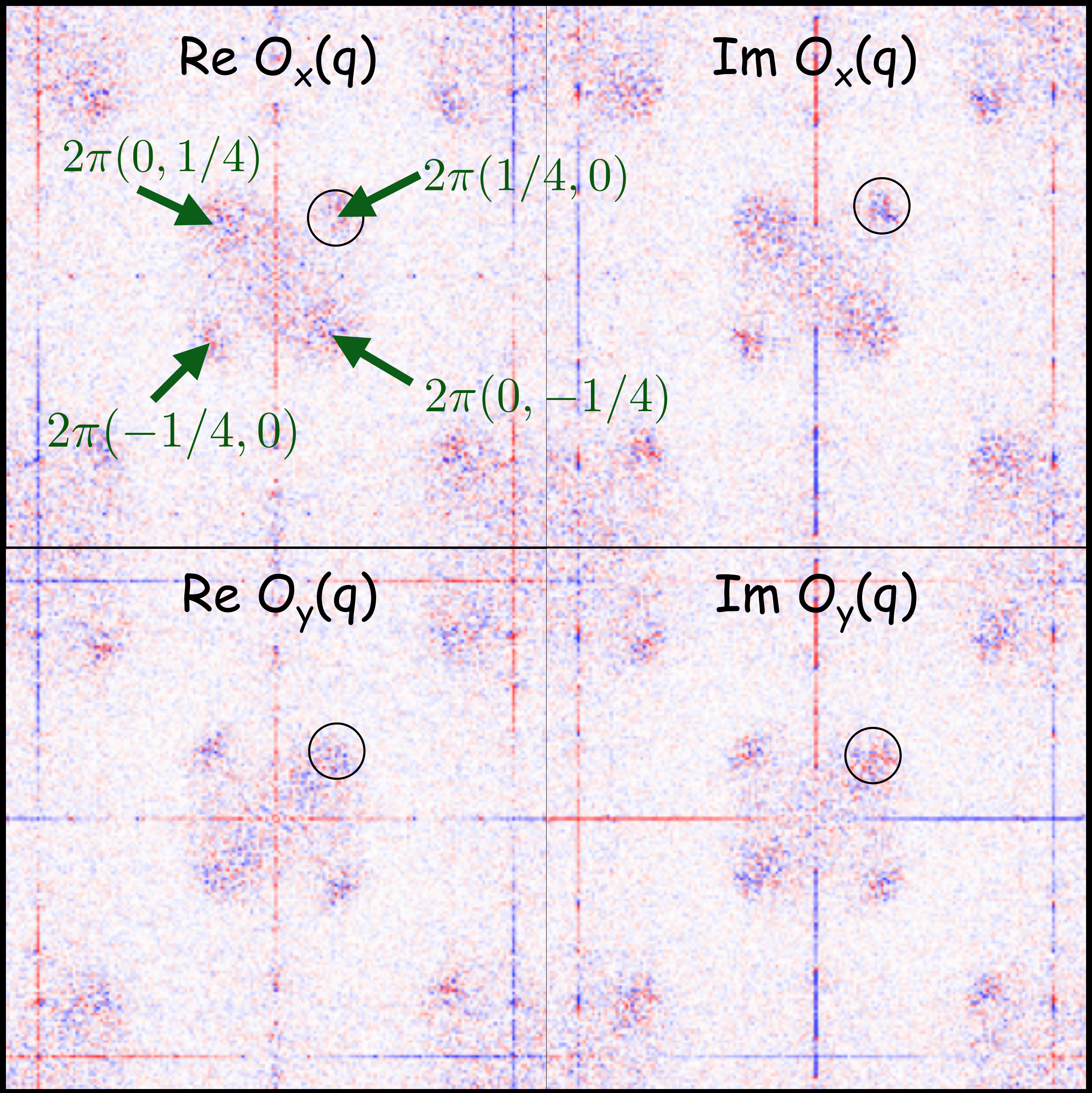
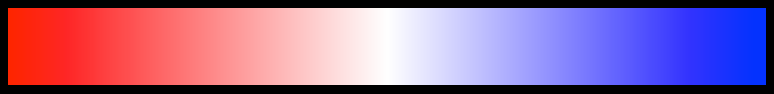


For each pixel in the circles, we obtain 2 complex numbers, $O_x(q)$ and $O_y(q)$.





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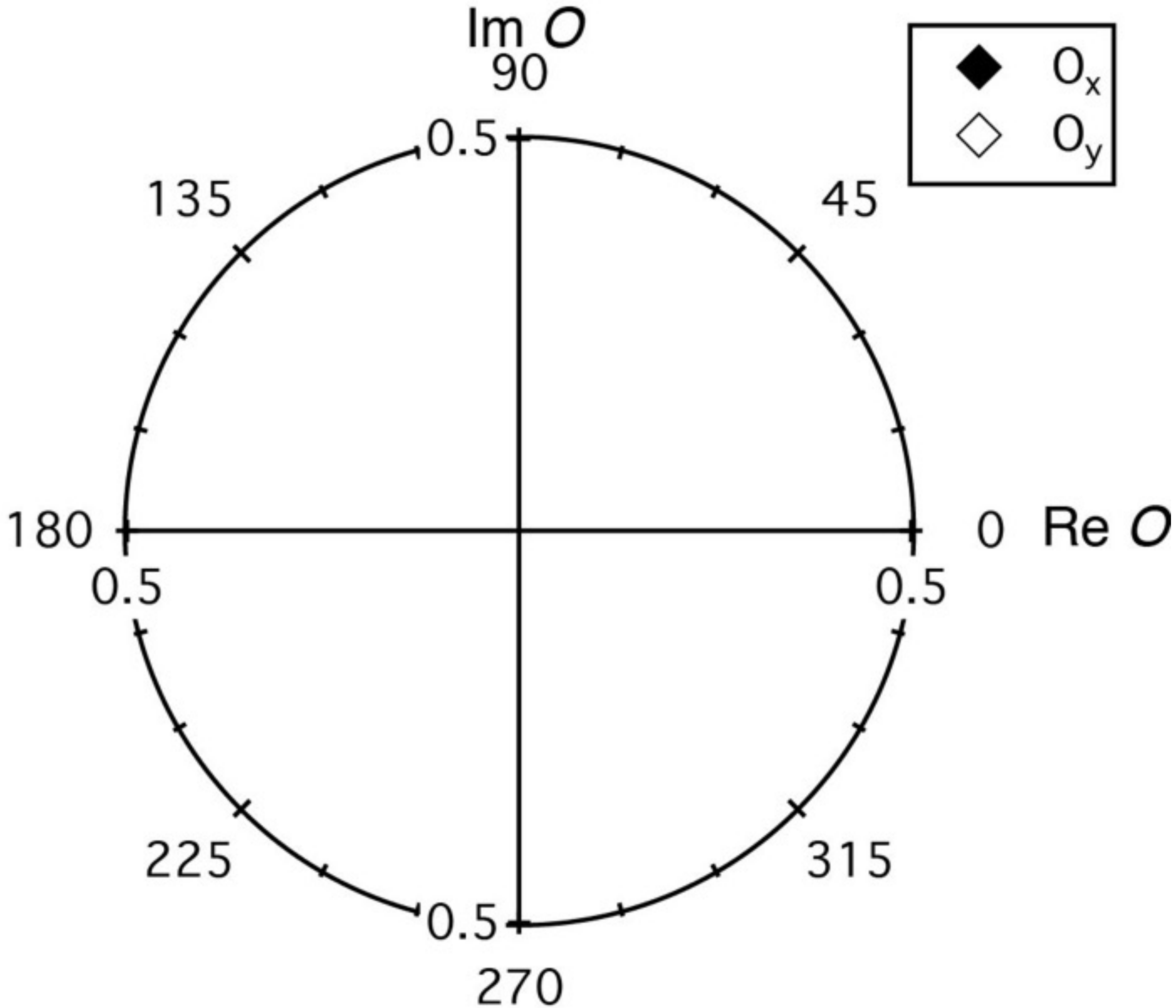

Phase-sensitive measurement of the *d*-form factor of density wave order

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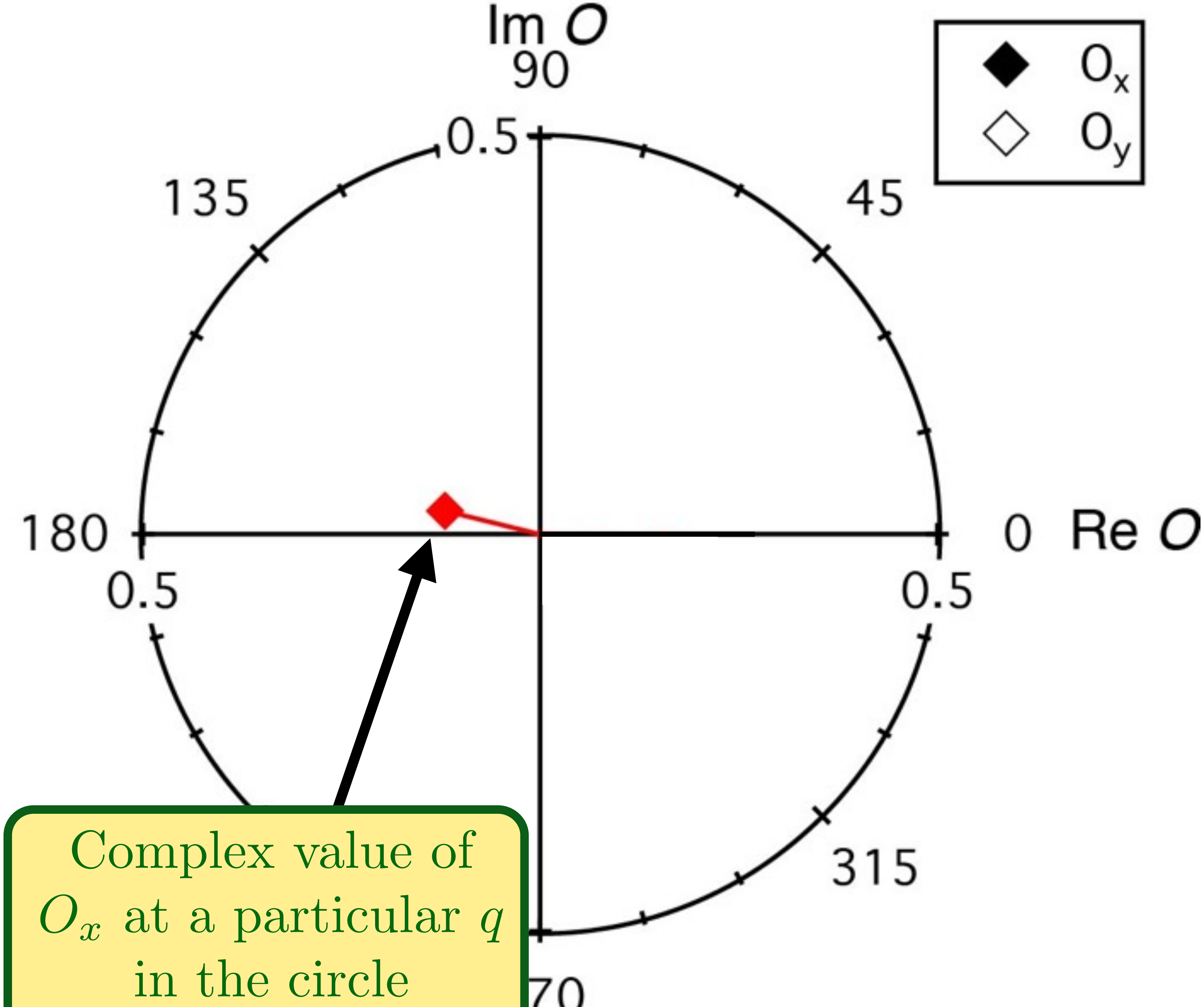

Complex value of O_x at a particular q in the circle around $2\pi(1/4, 0)$.

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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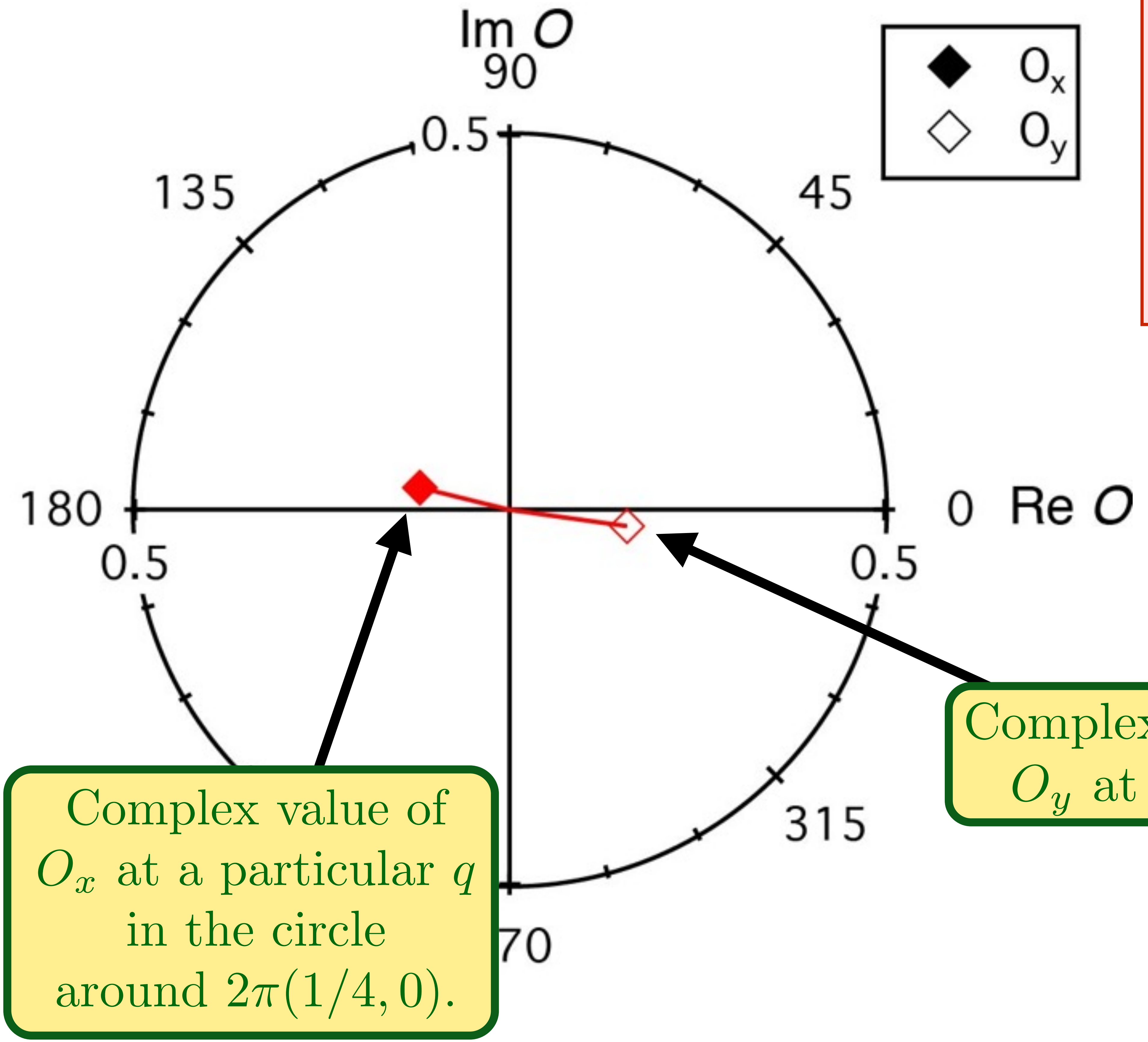

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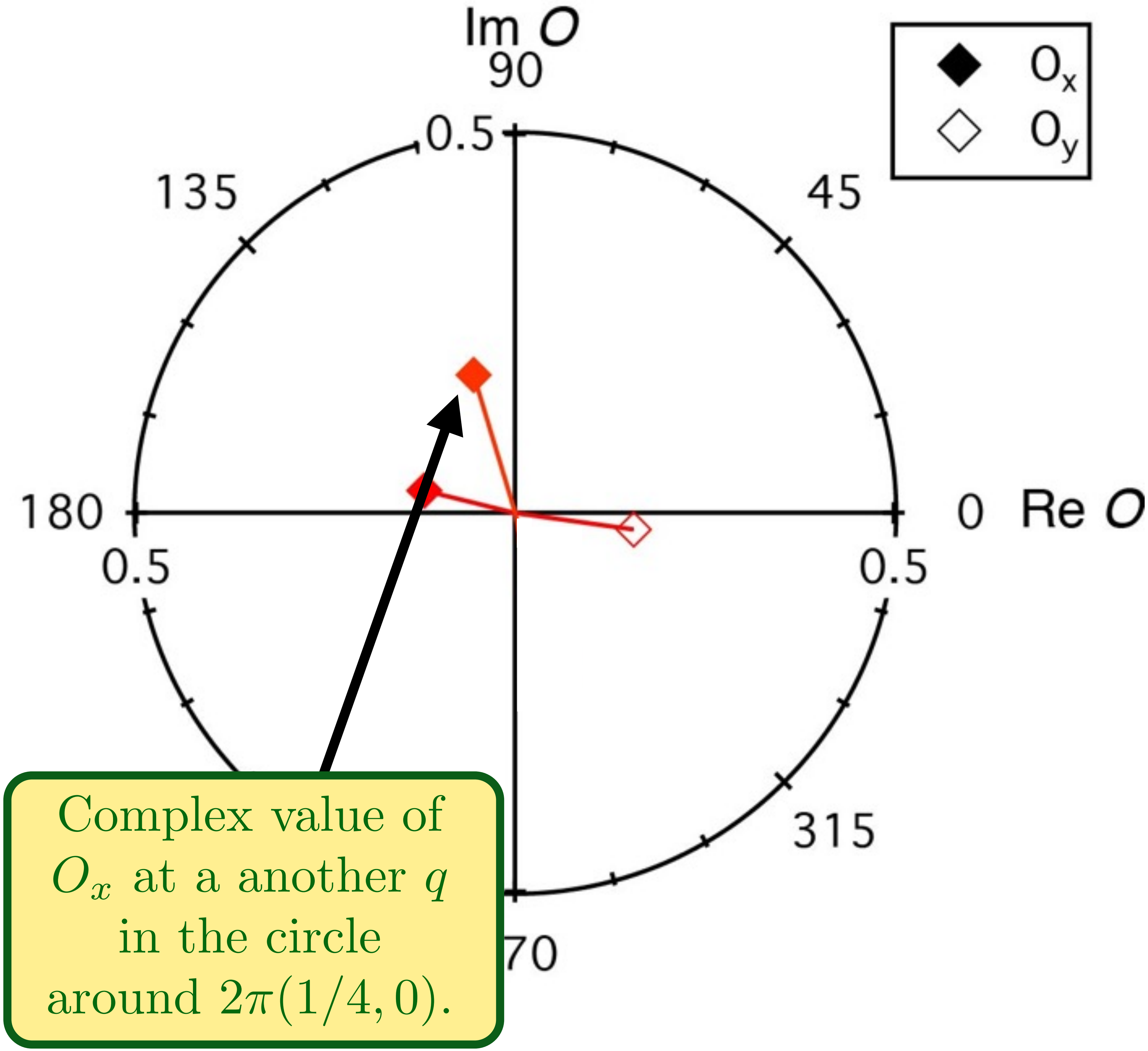

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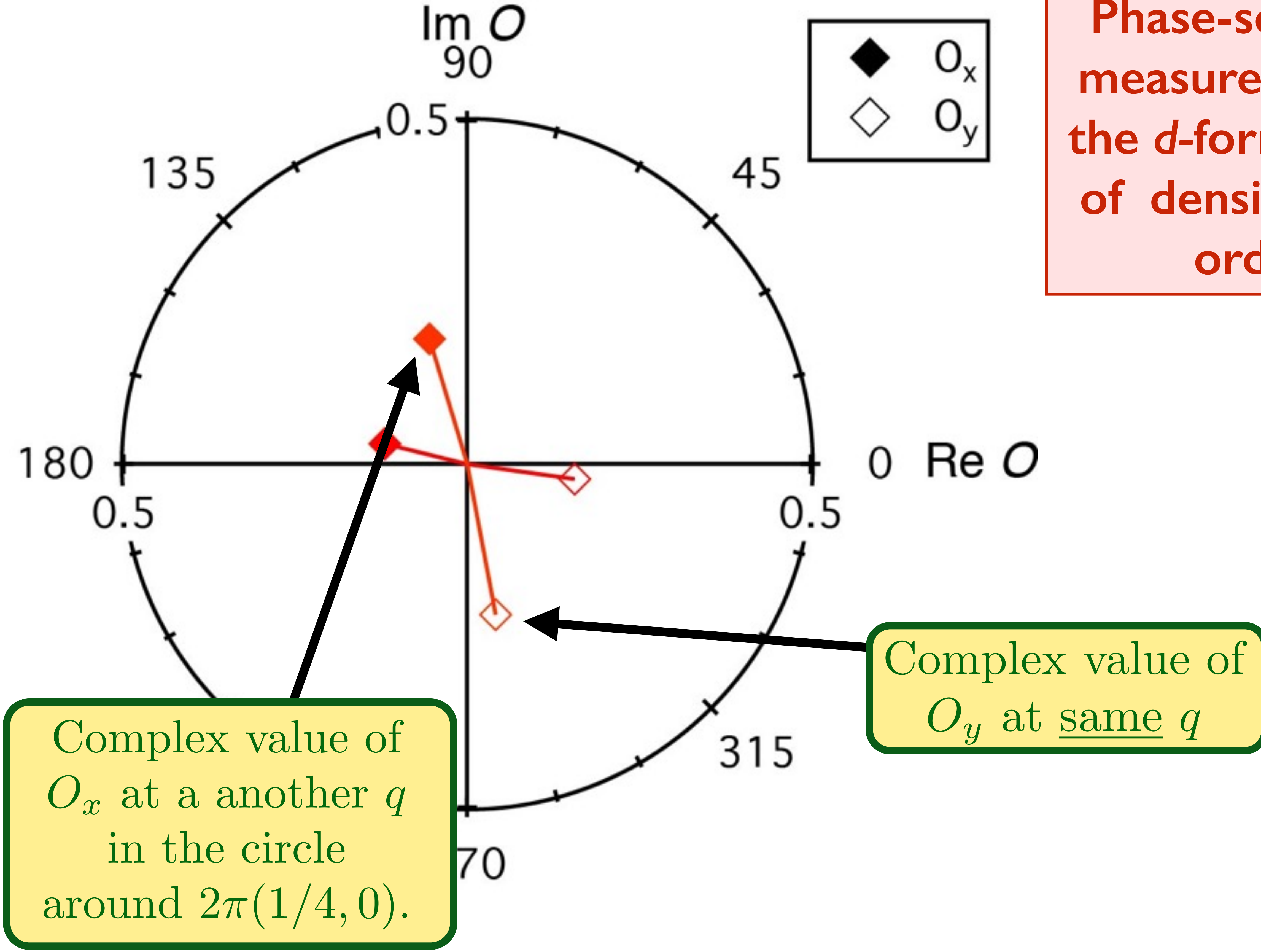

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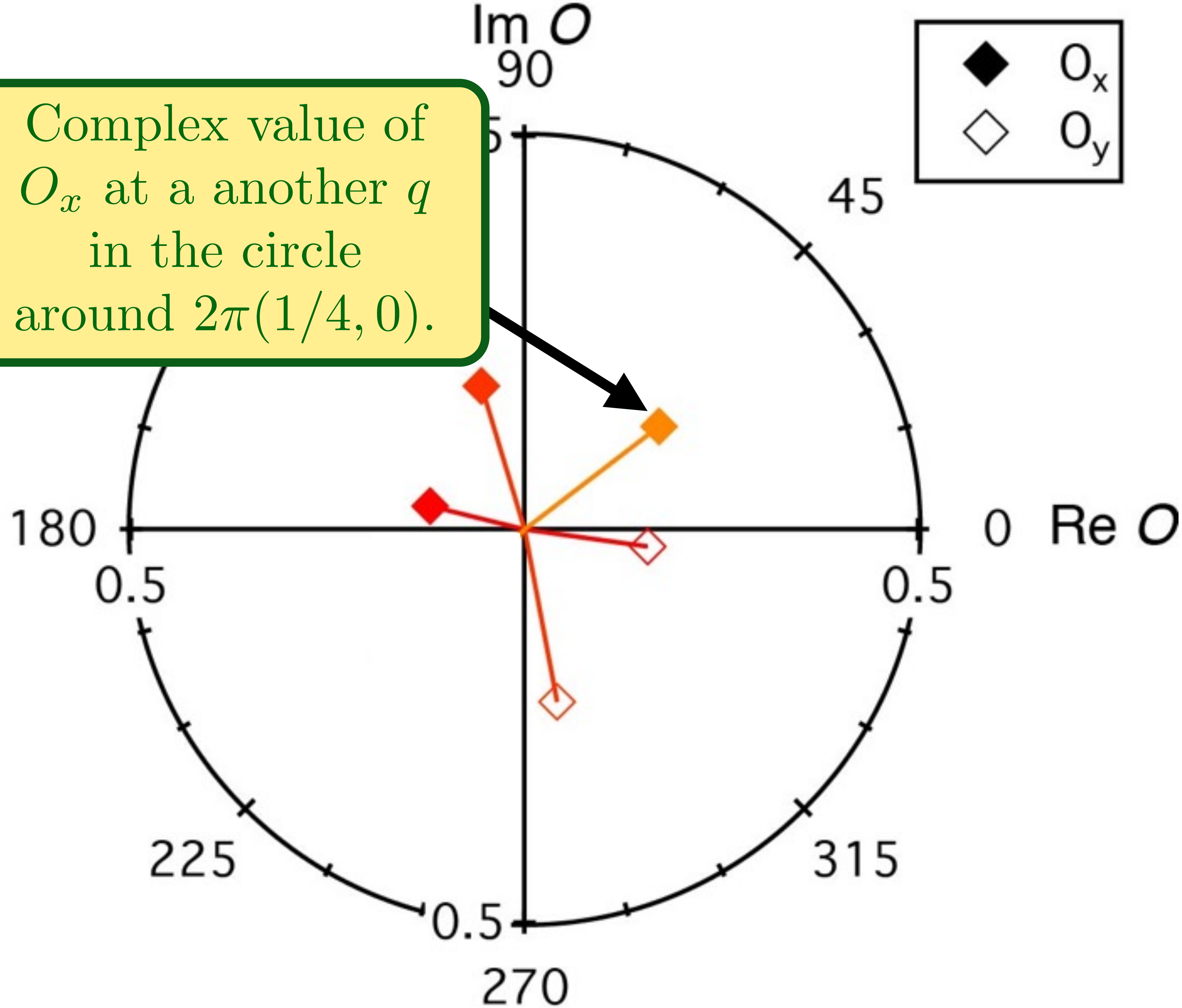
Phase-sensitive measurement of the *d*-form factor of density wave order

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



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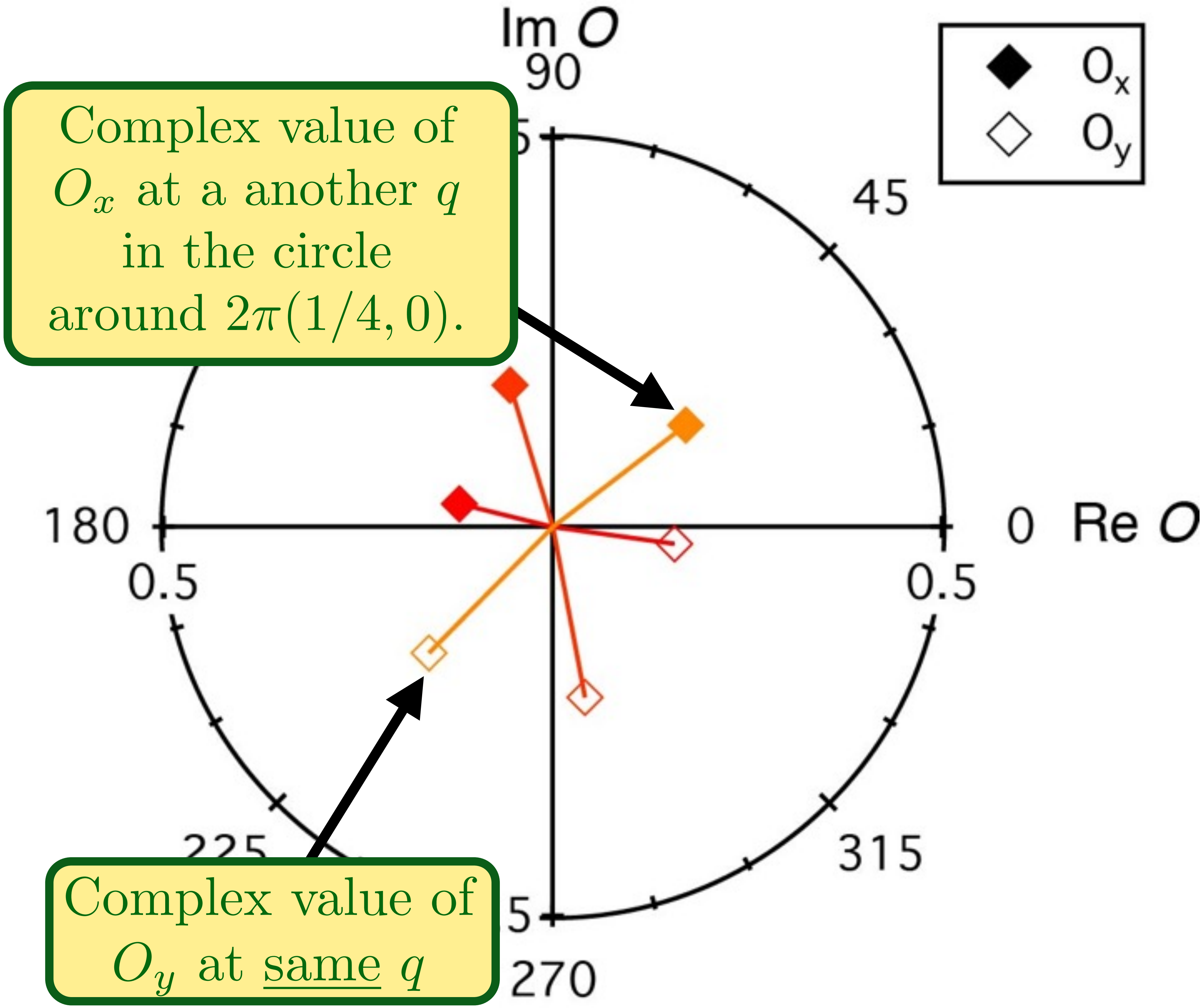

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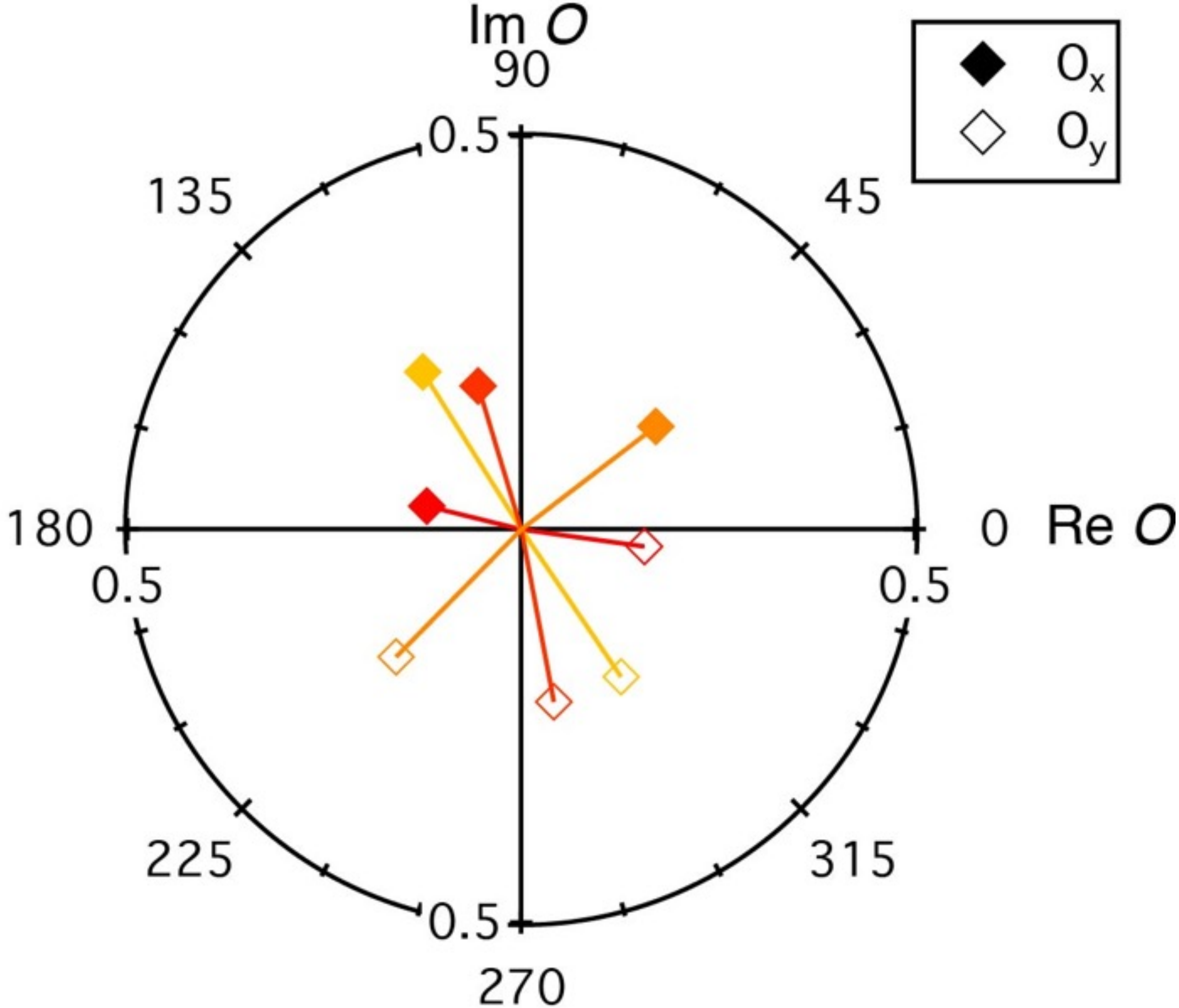

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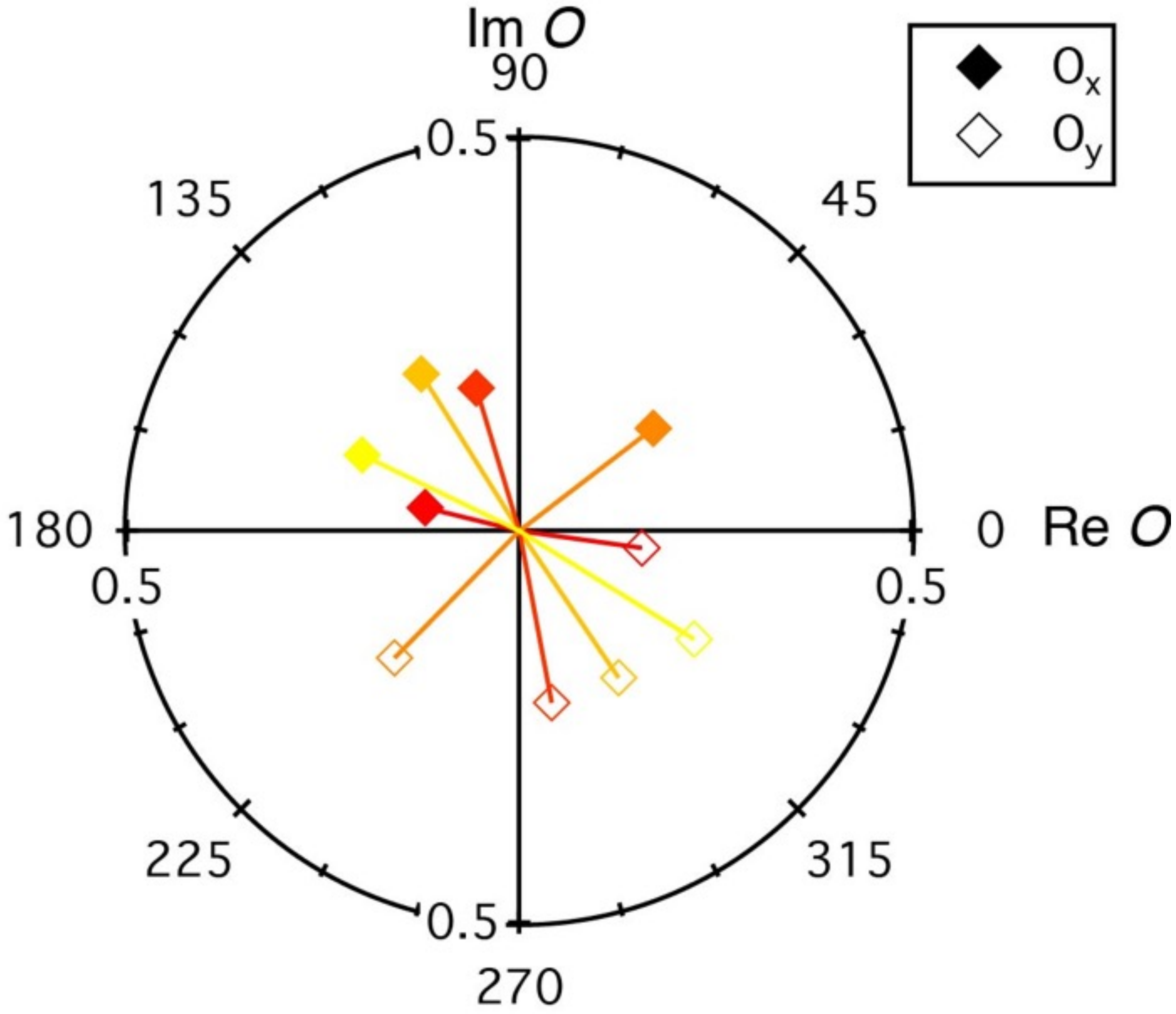

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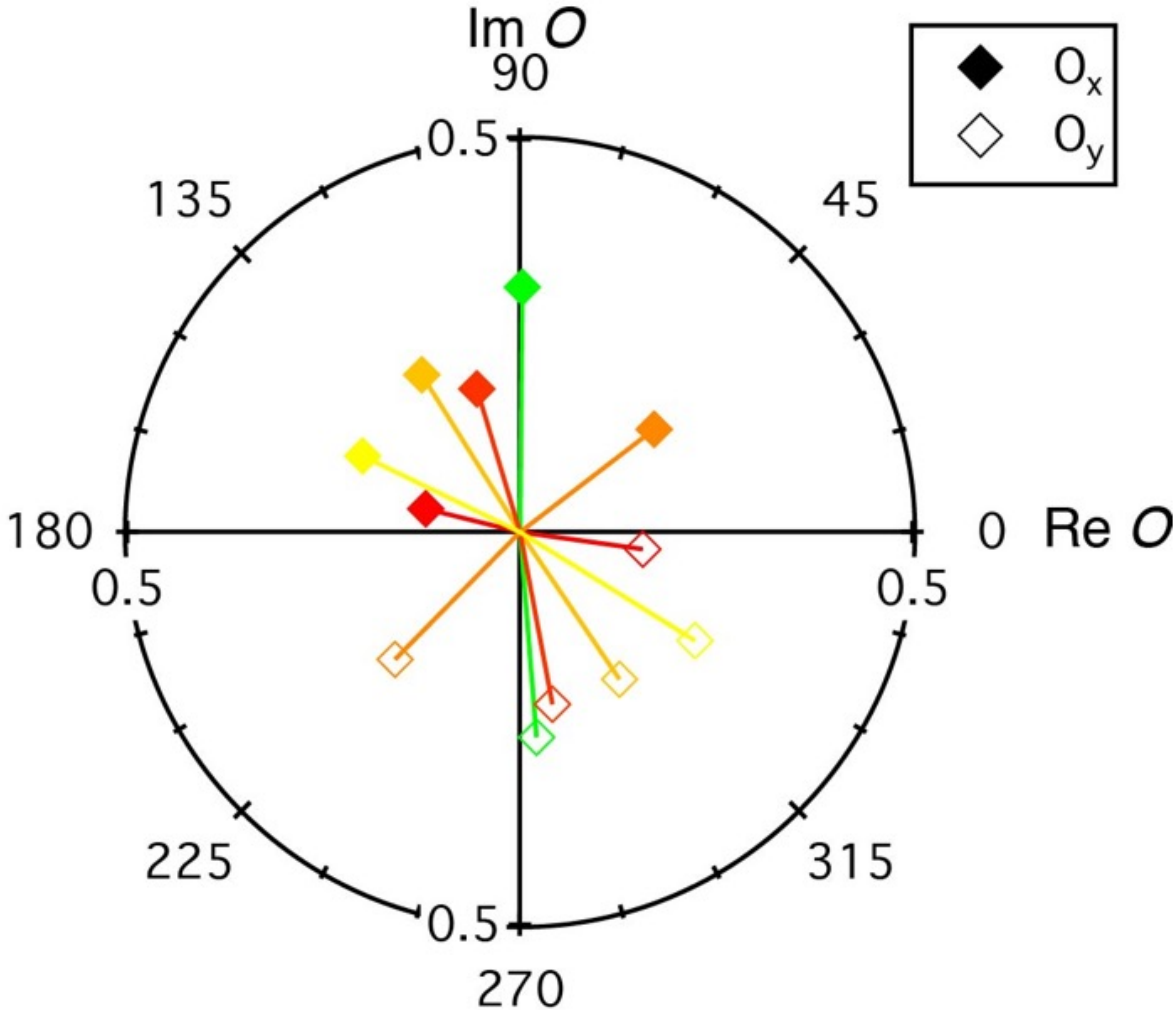

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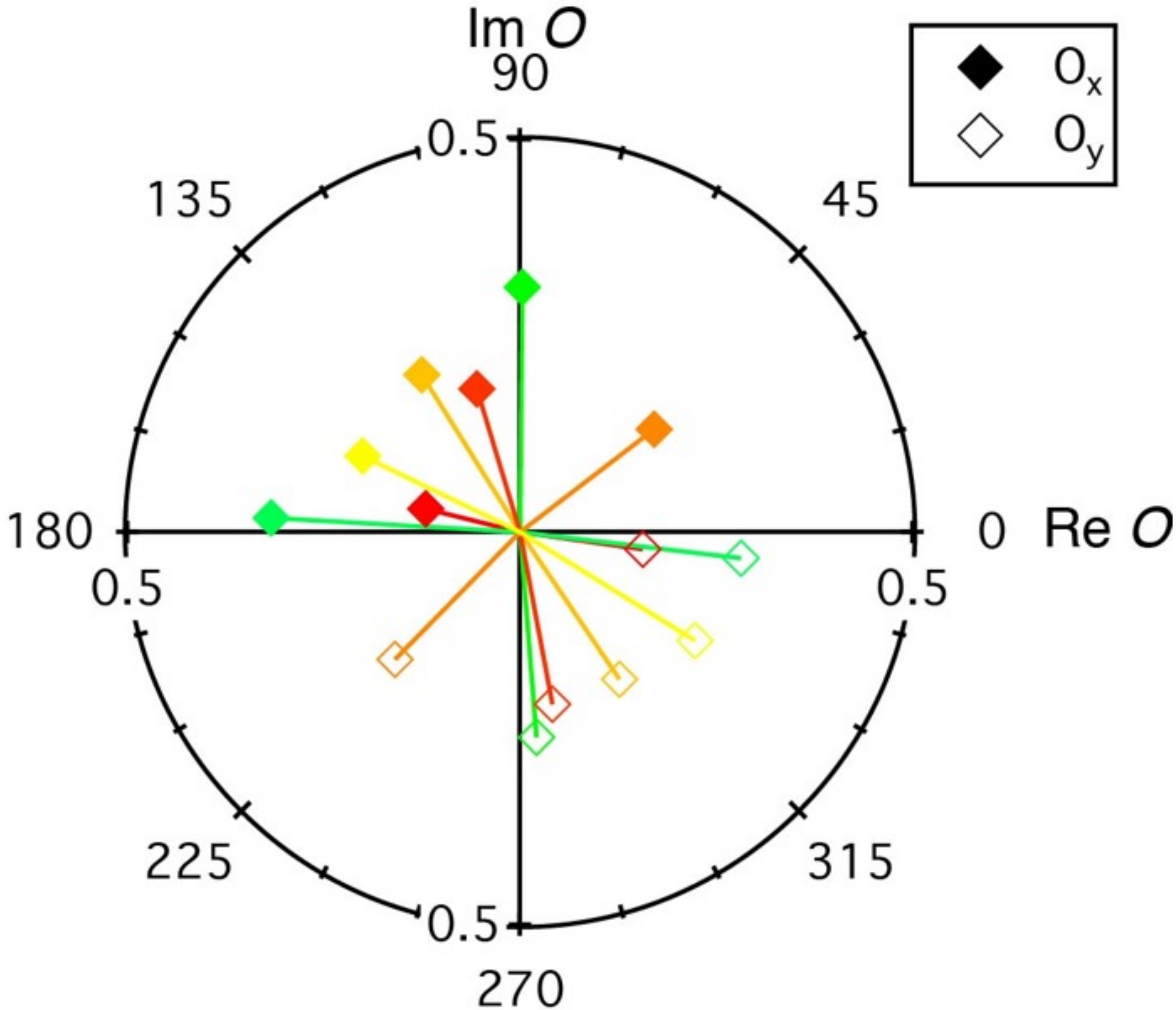

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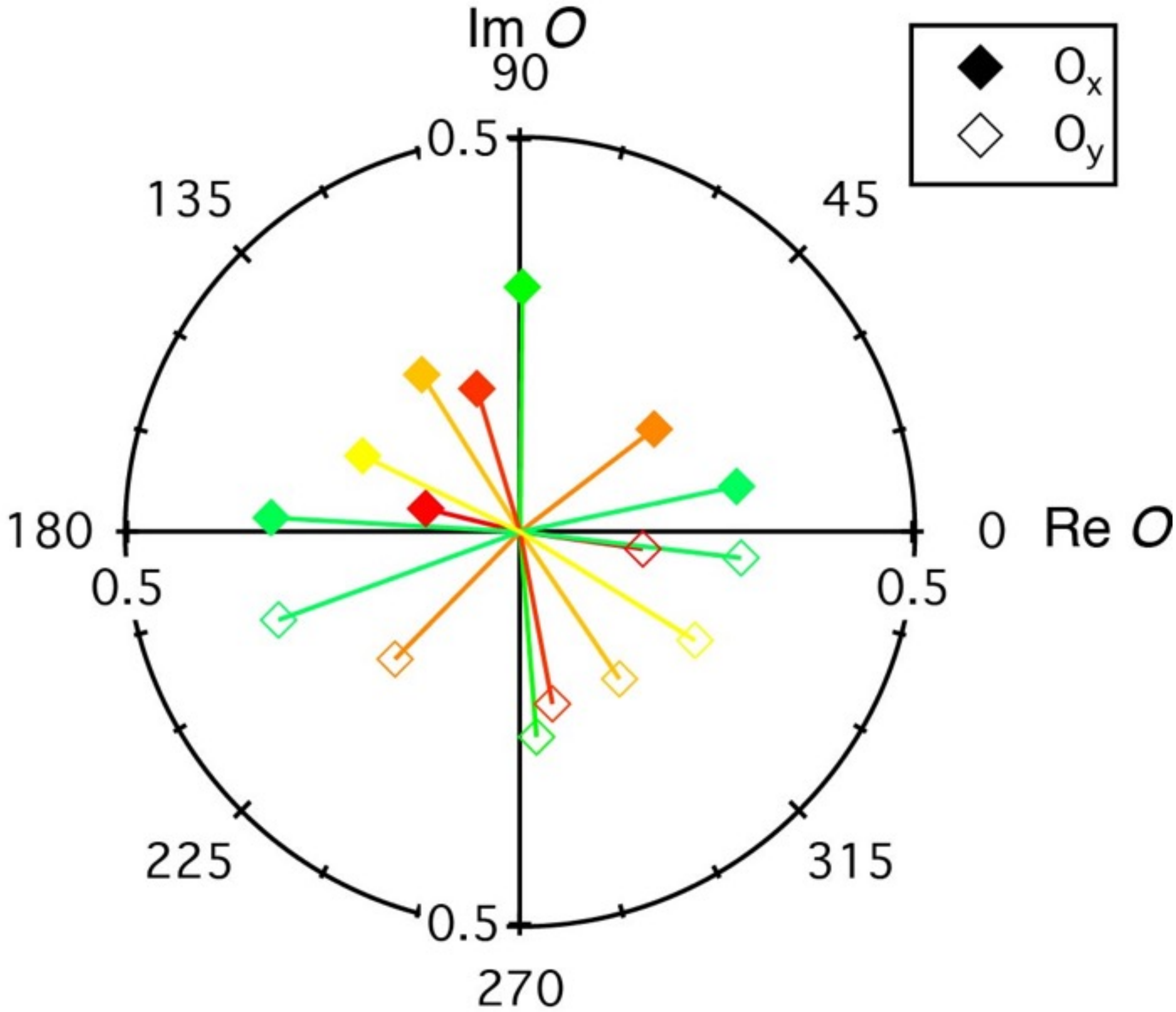

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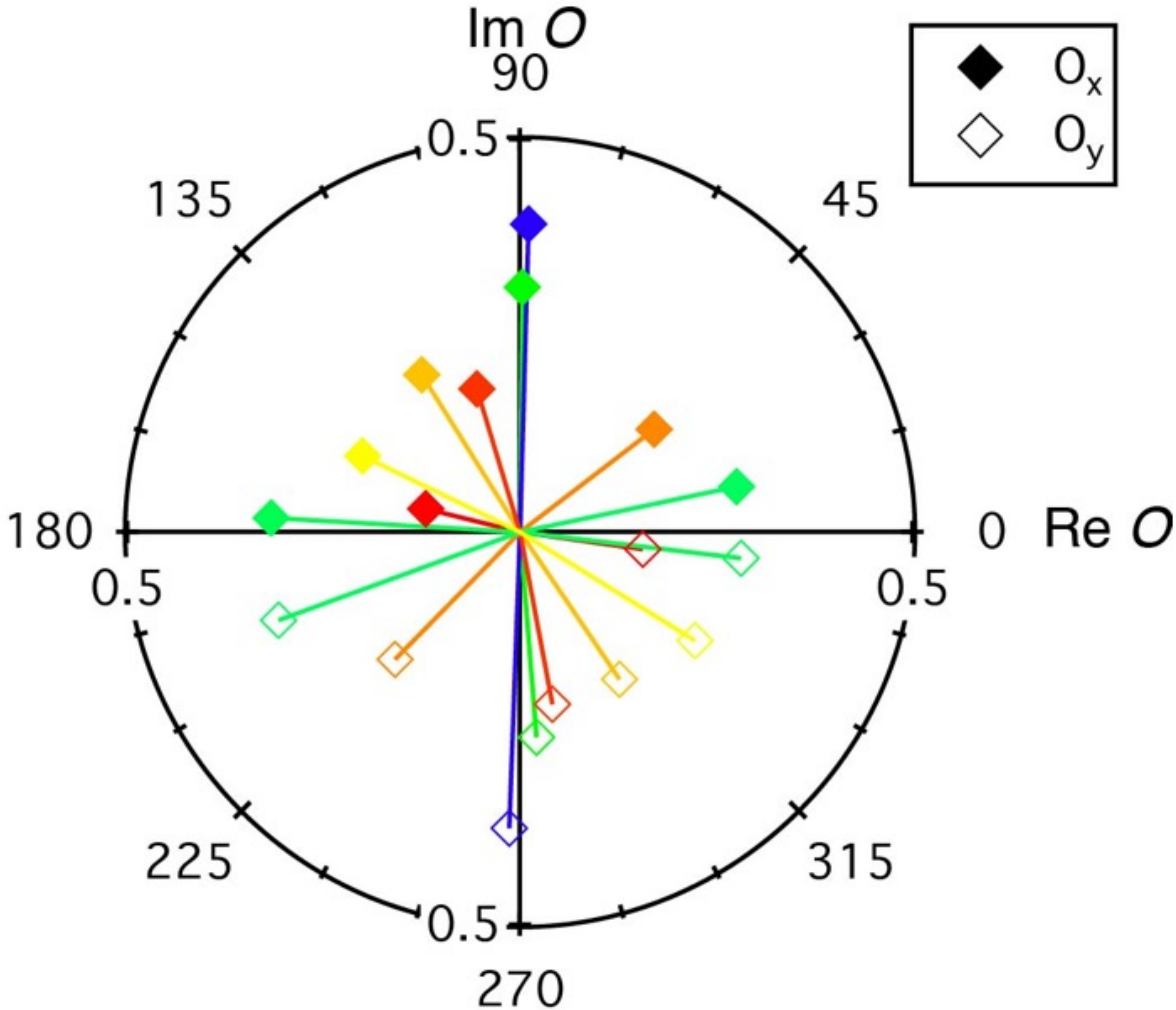

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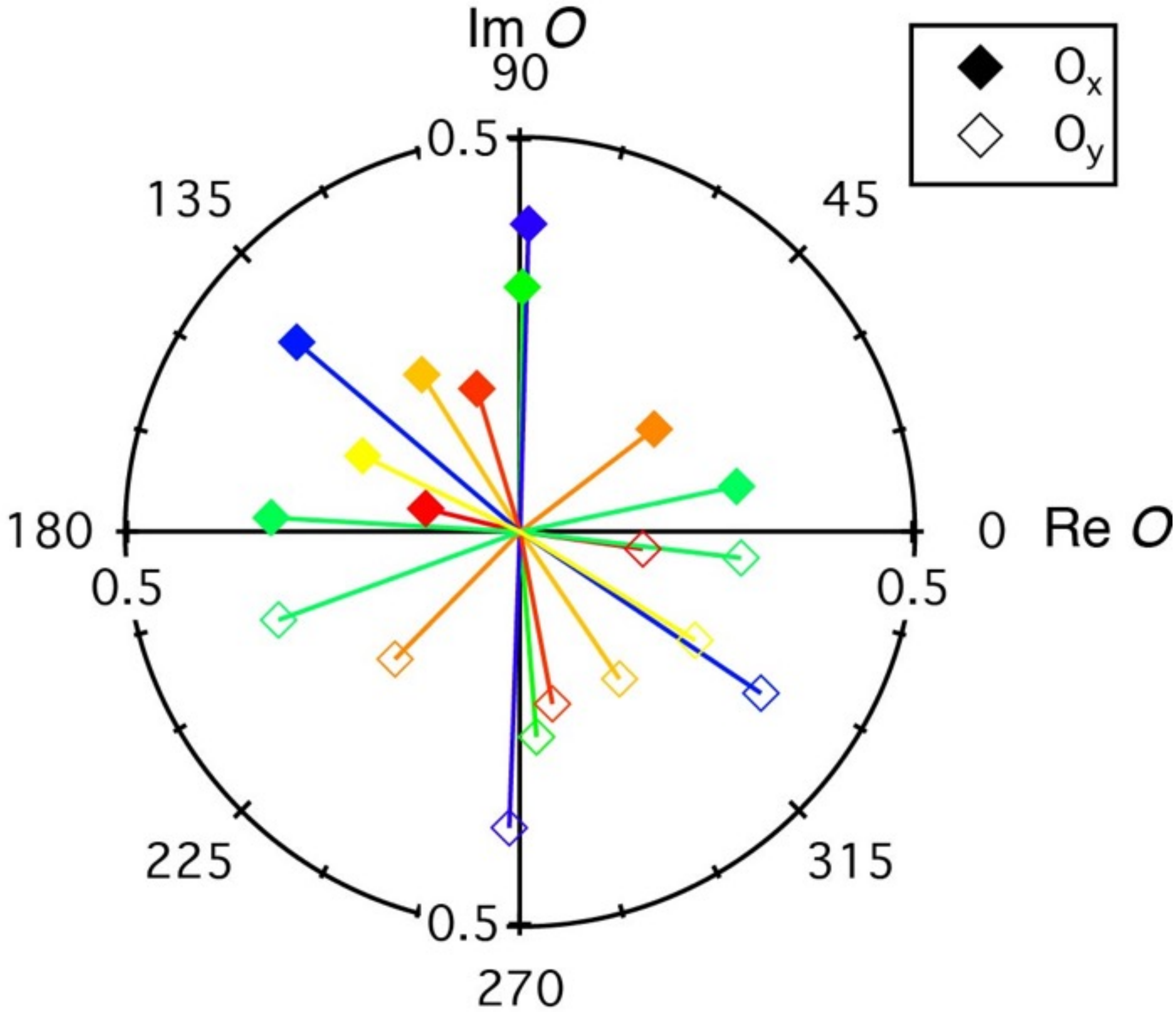

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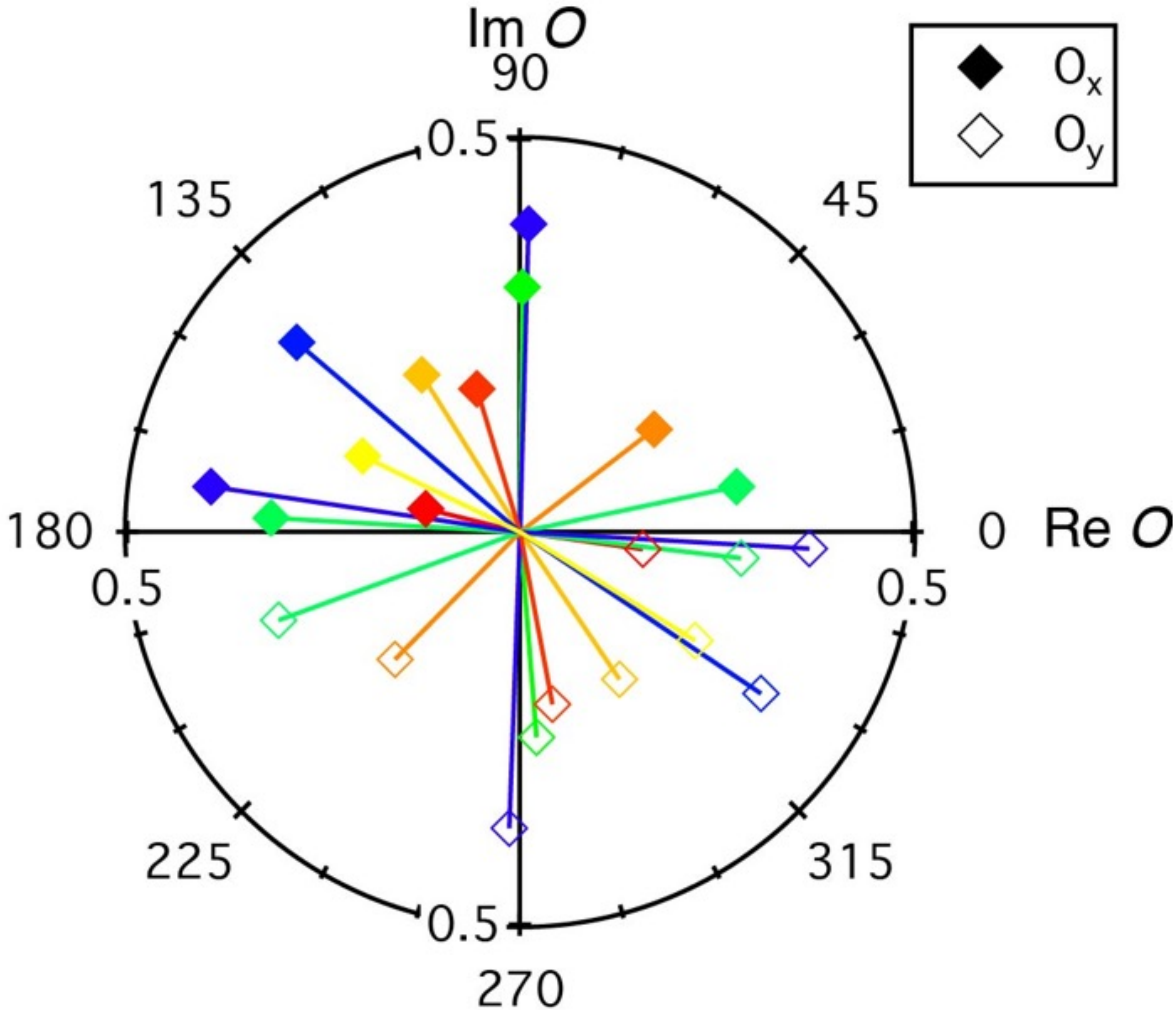

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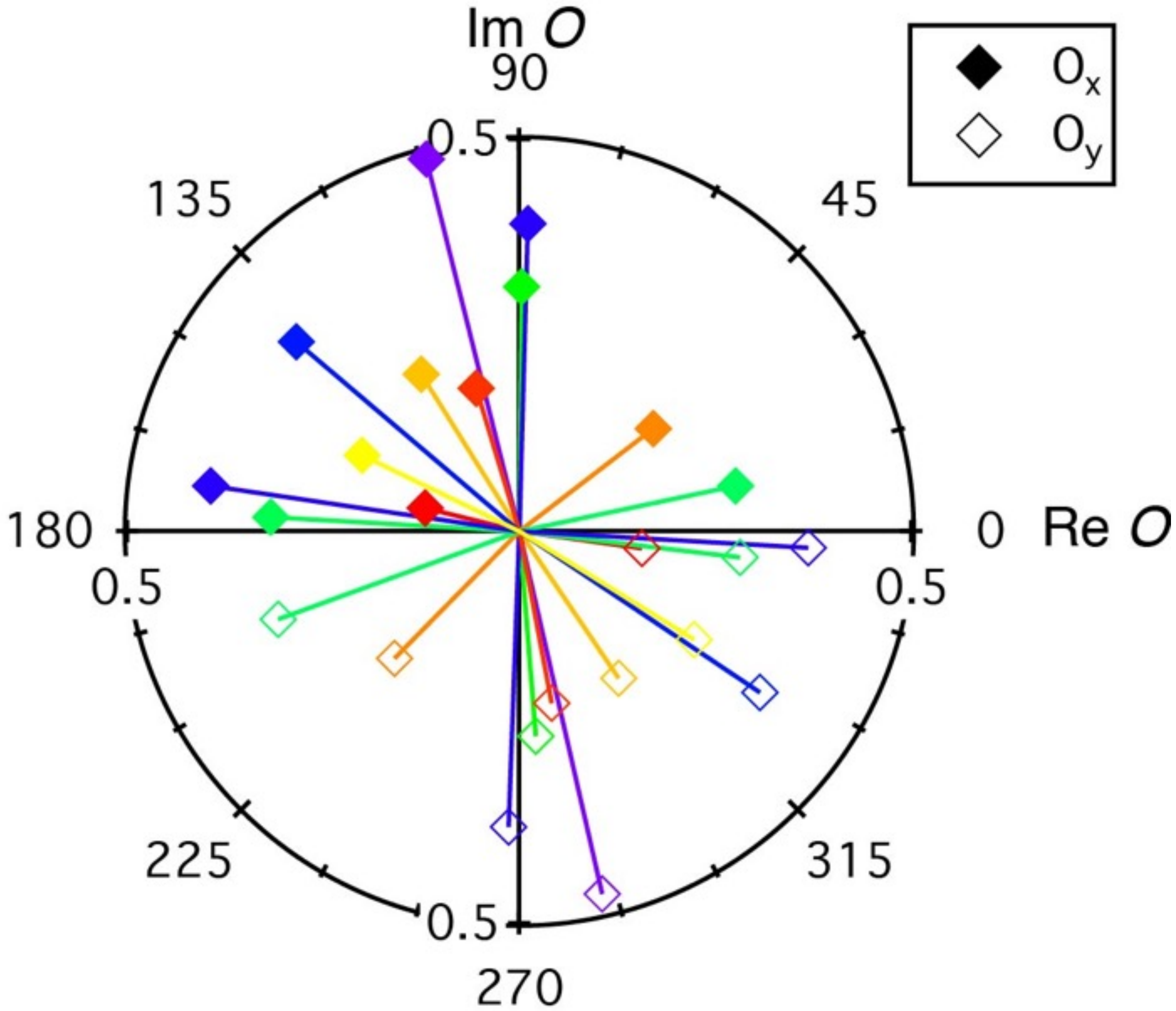

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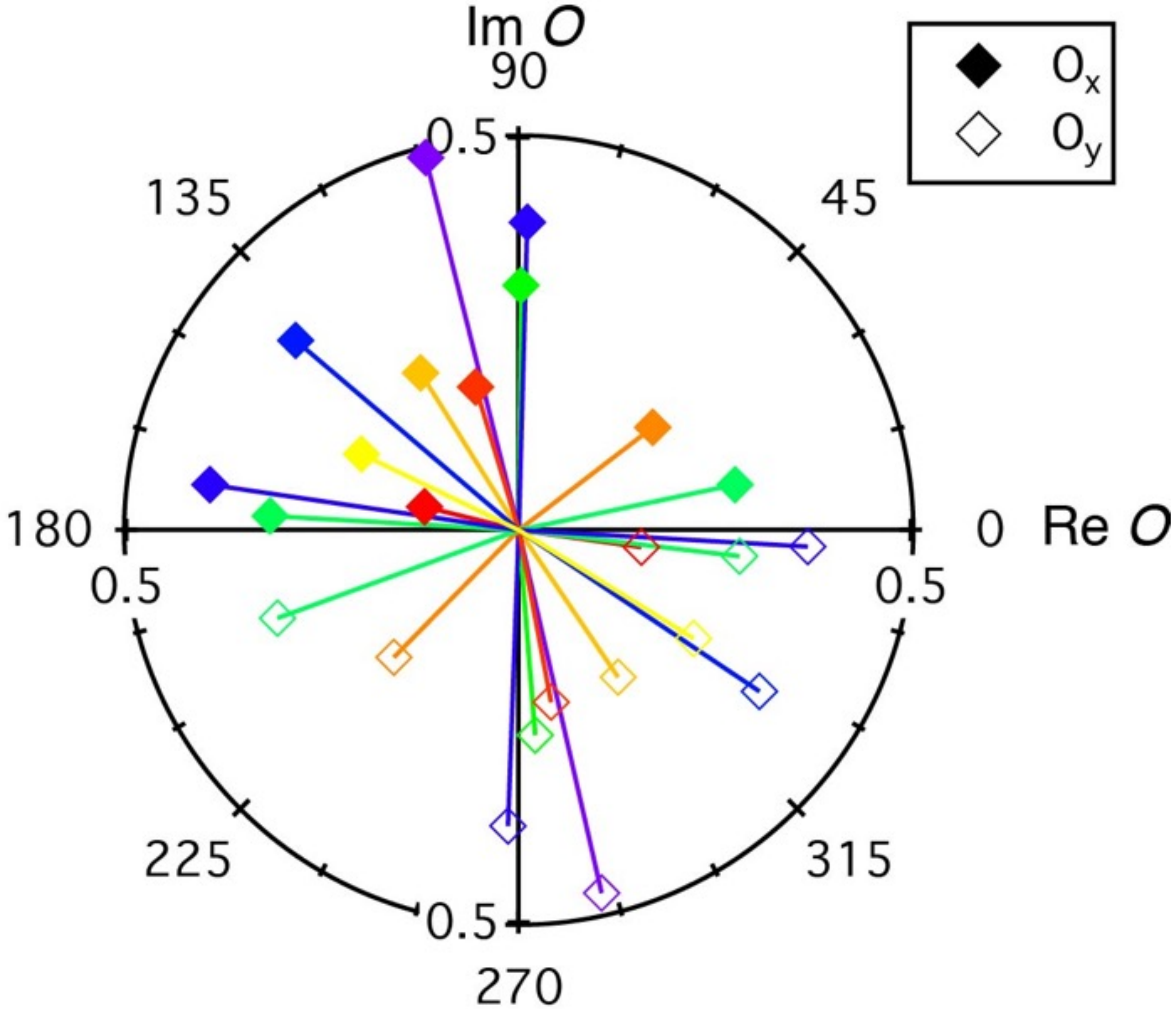

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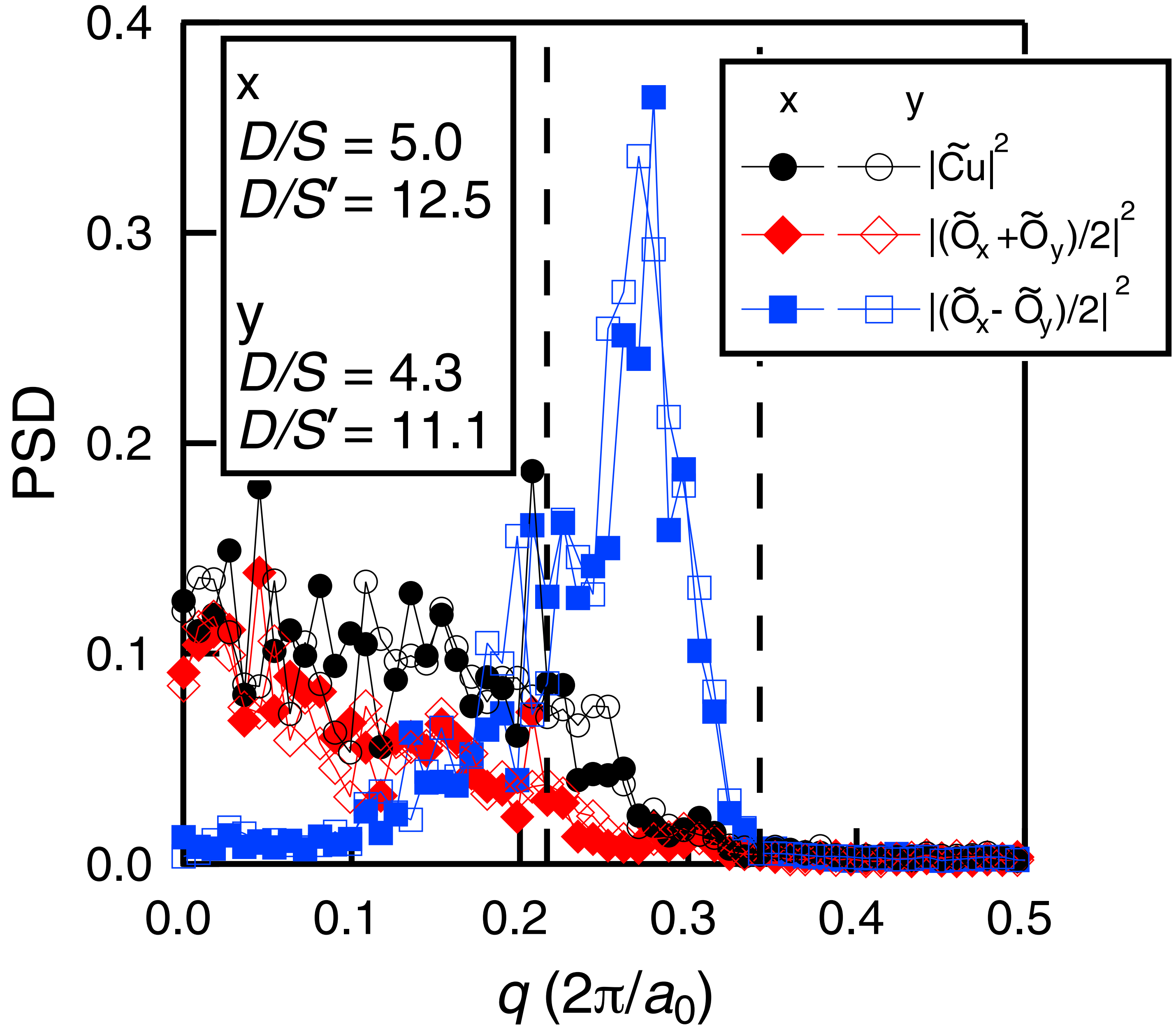

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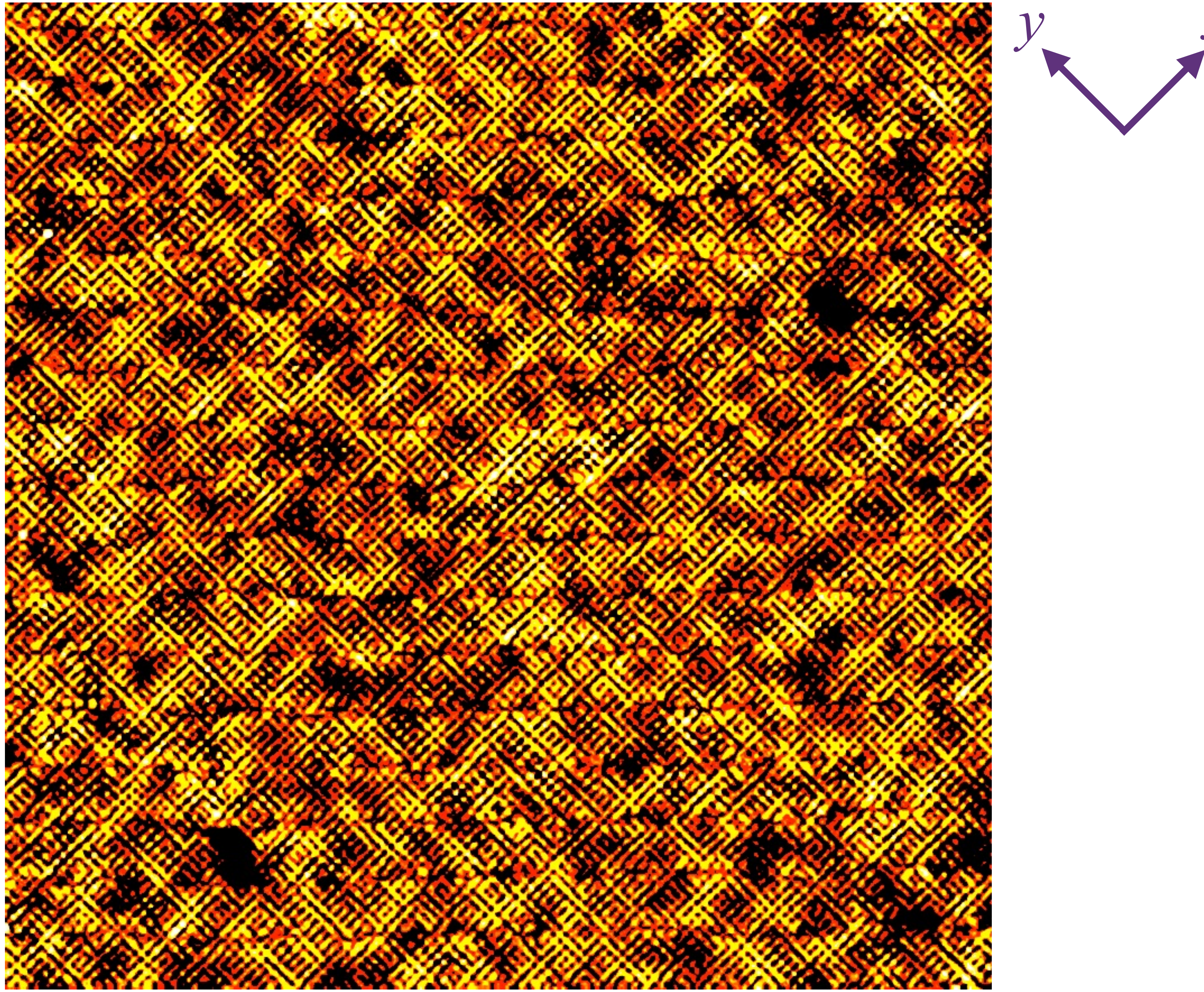

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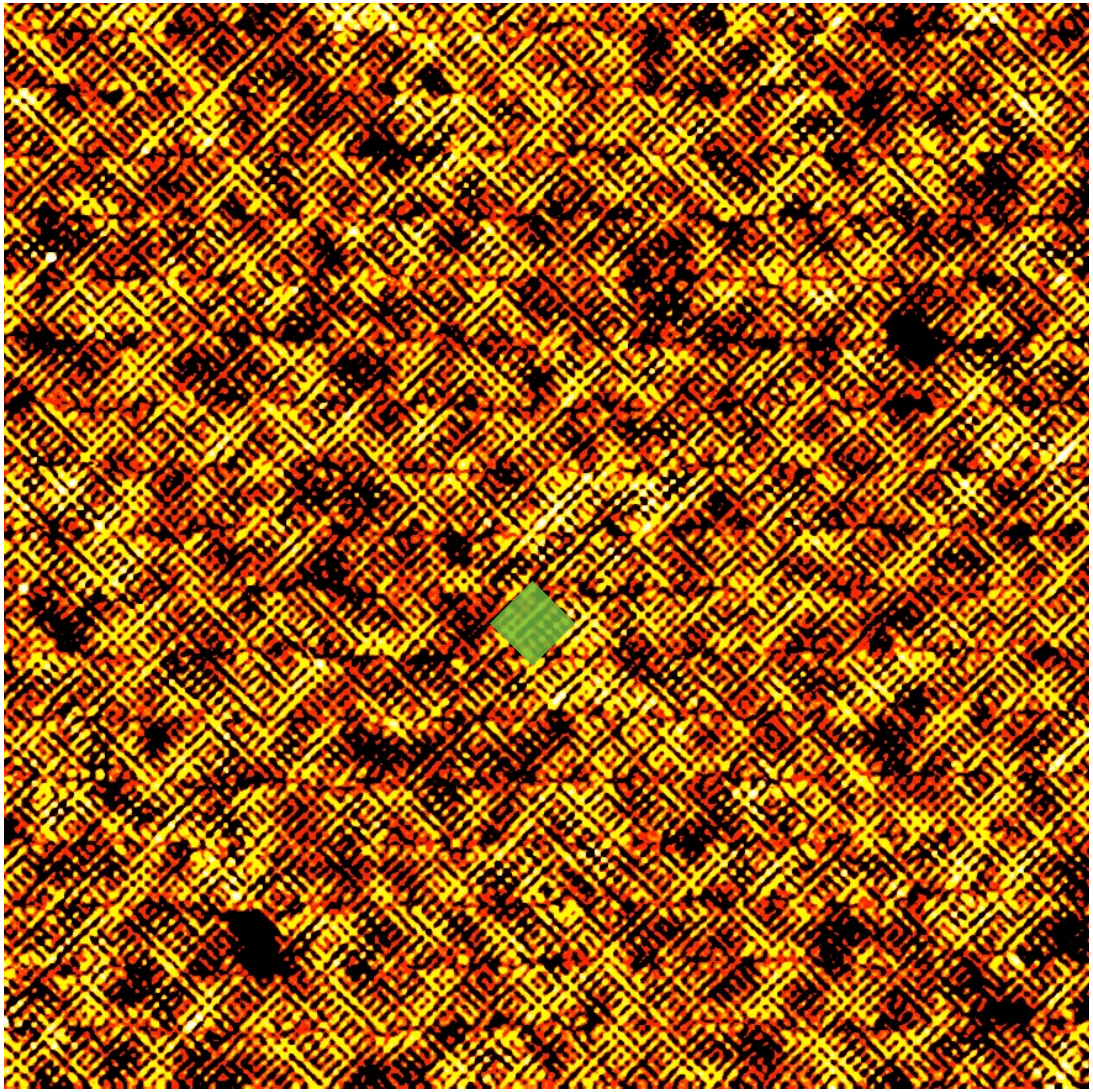

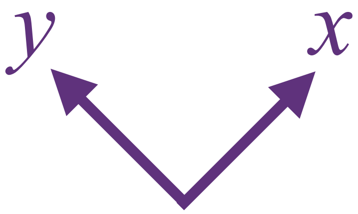

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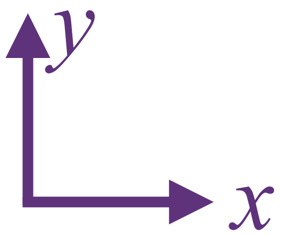

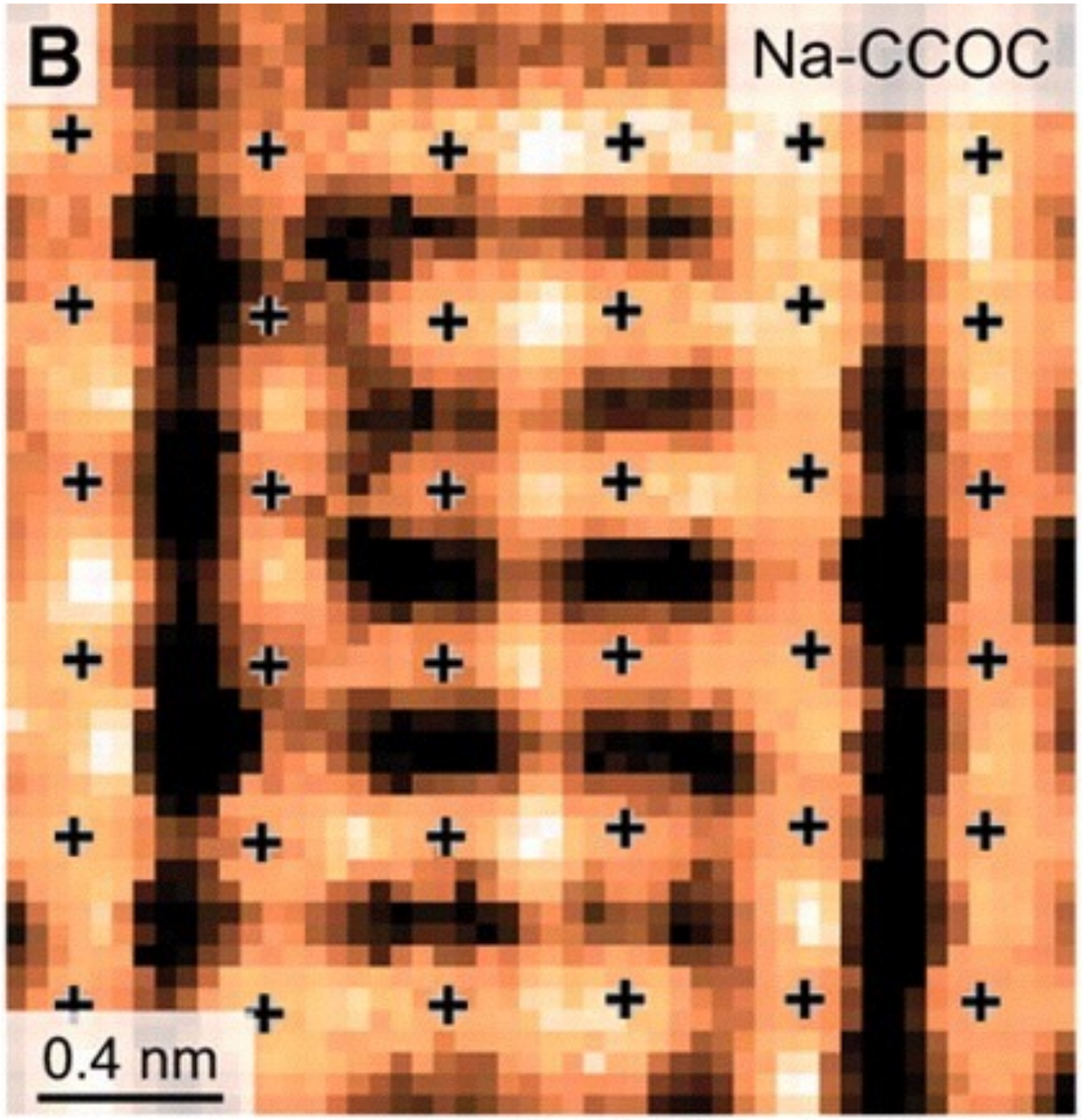

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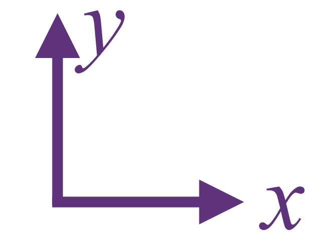

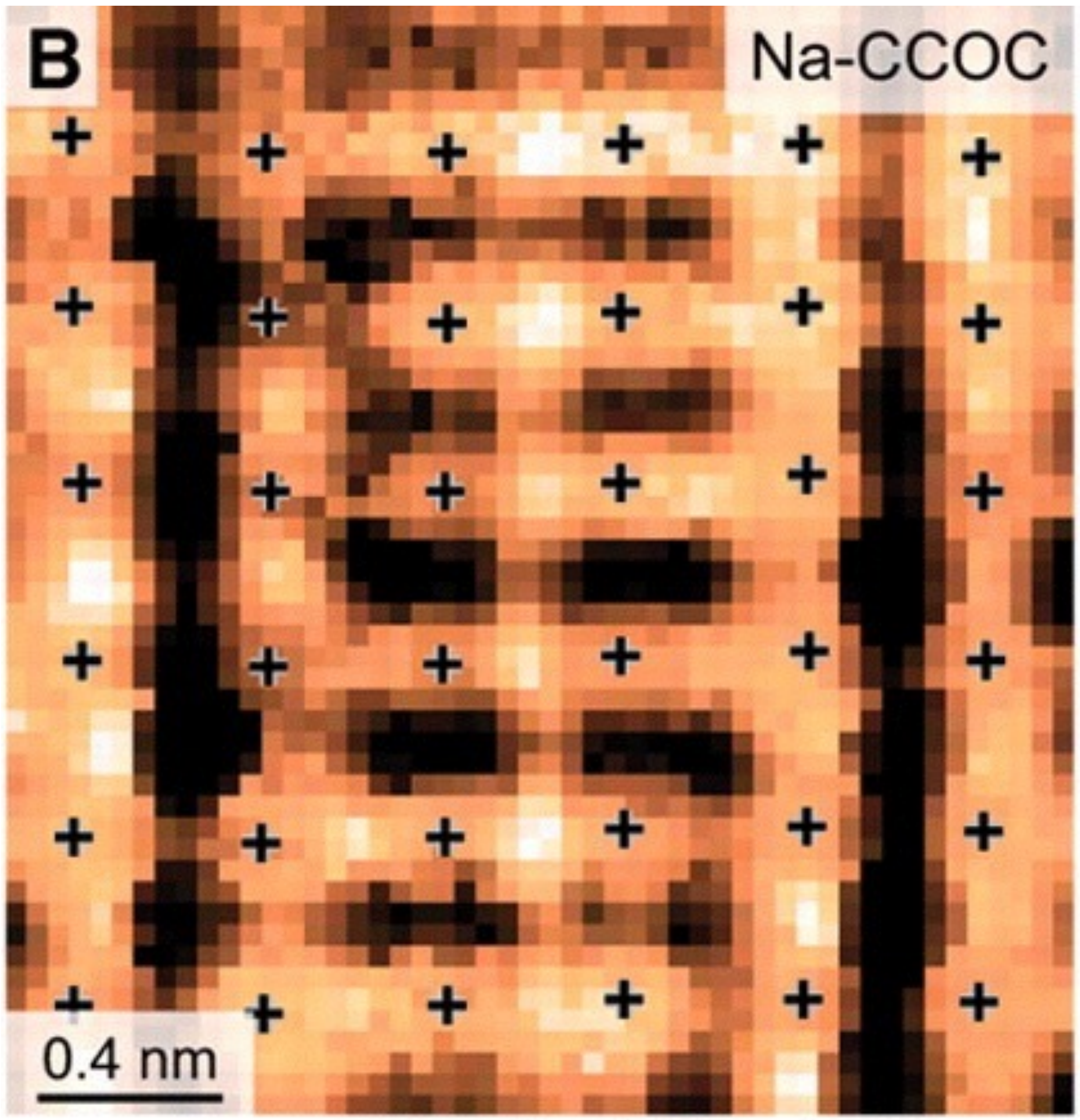

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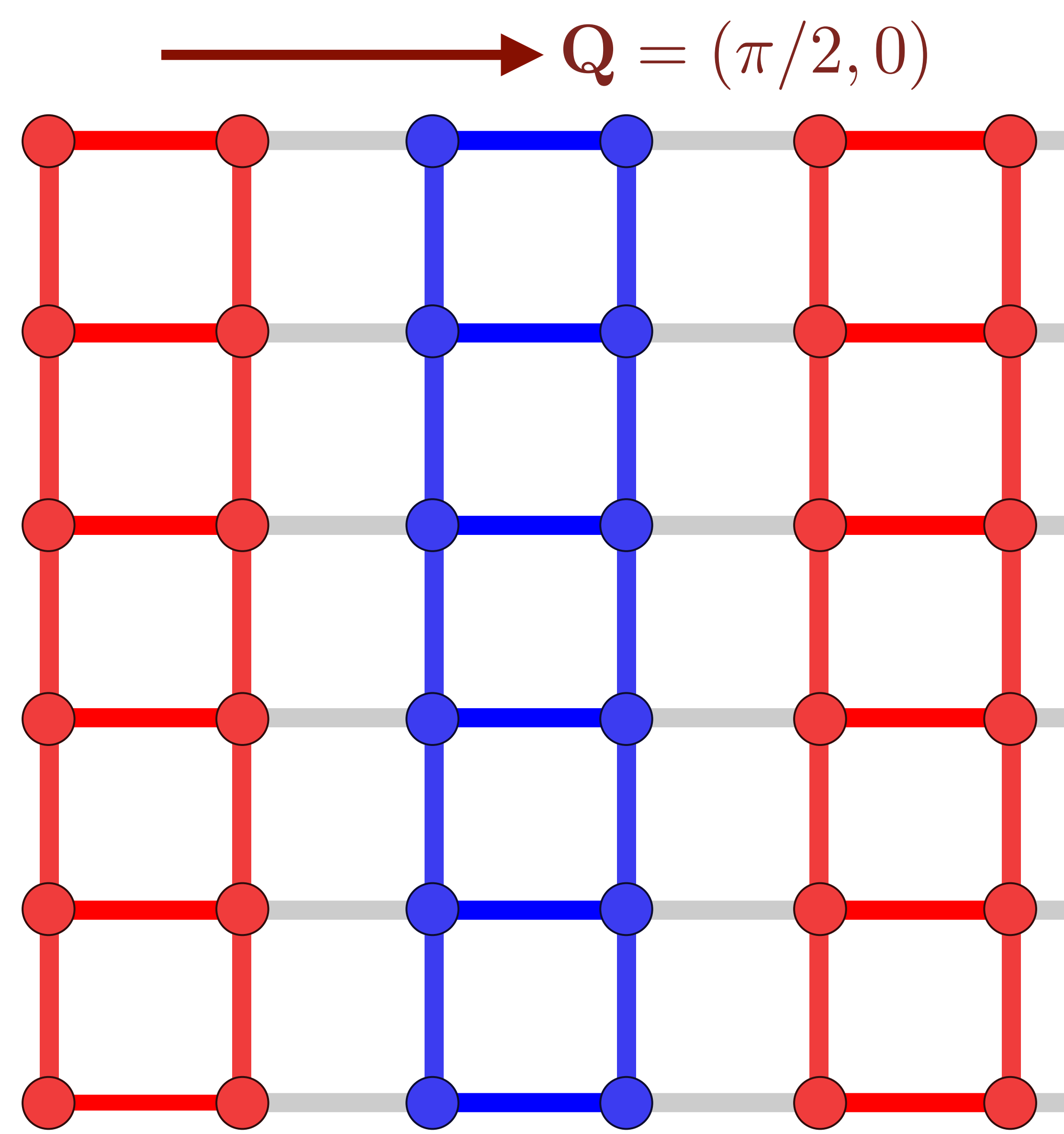
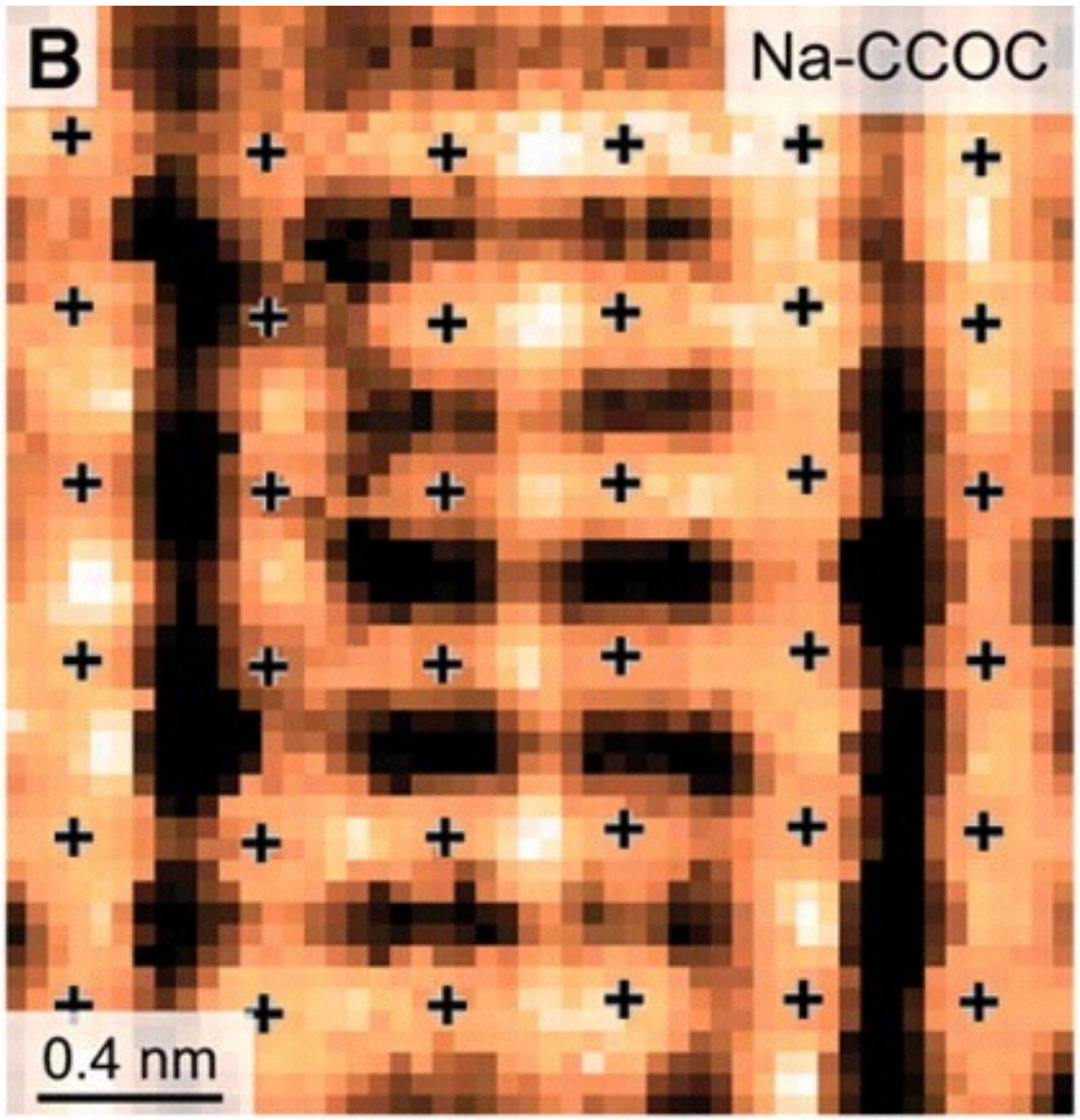
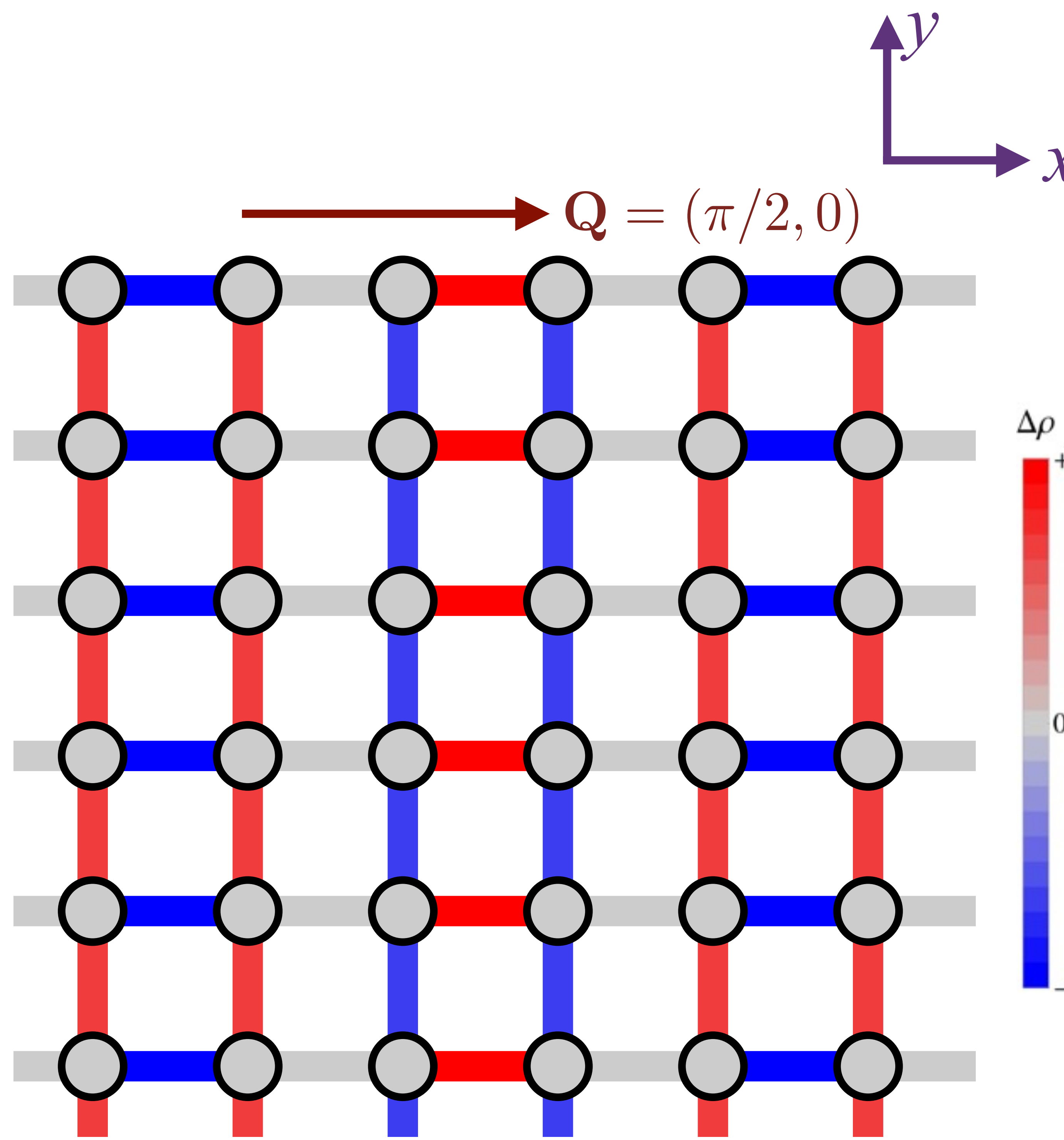


$s + s'$-form factor density wave

$s + s'$ form factor (stripe model) does **<u>not</u>** match STM measurements on BSCCO, Na-CCOC.

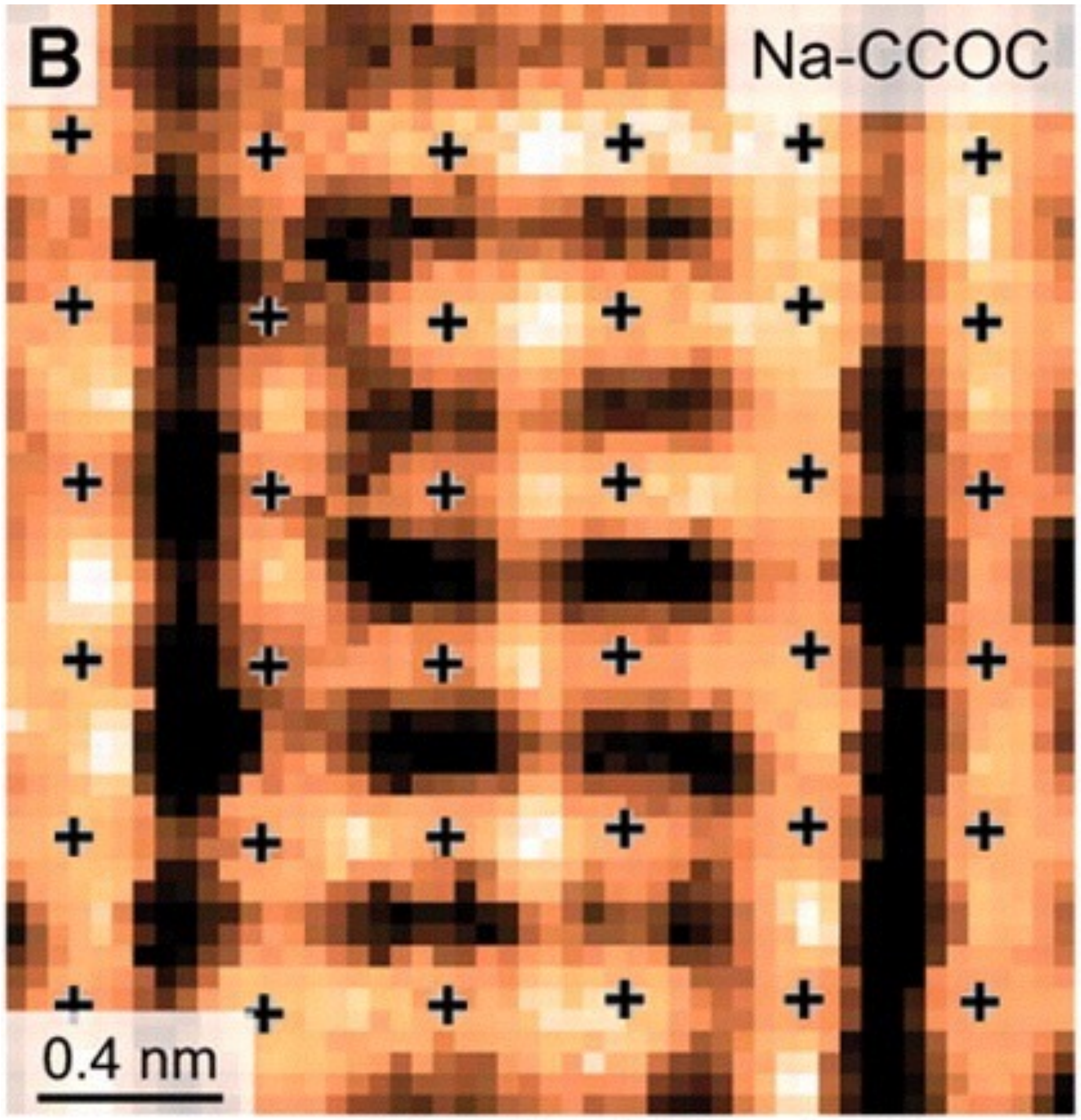


Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)



d-form factor density wave order

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



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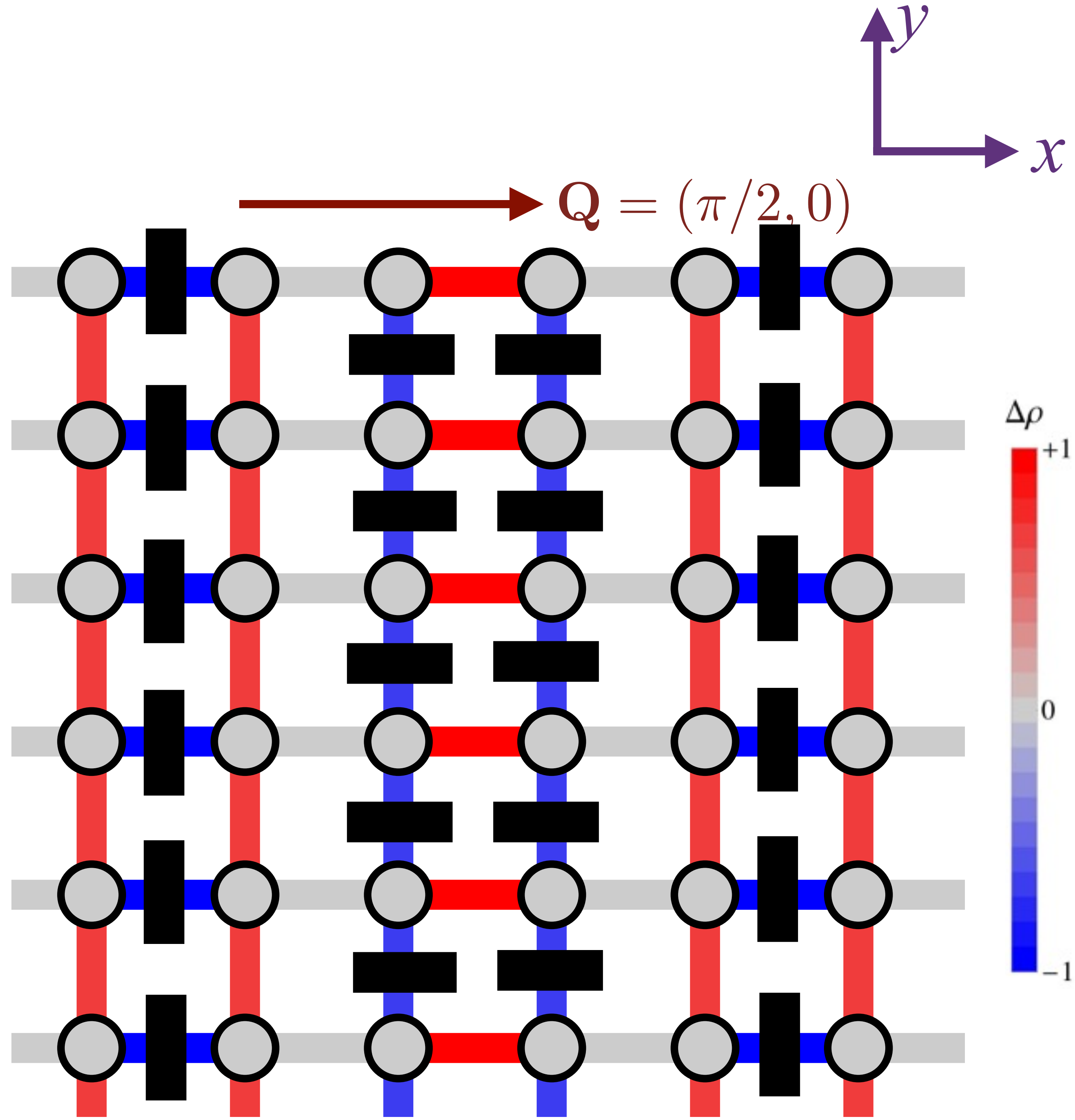

d-form factor density wave order

Predicted *d* form factor observed
in STM measurements on BSCCO, Na-CCOC !

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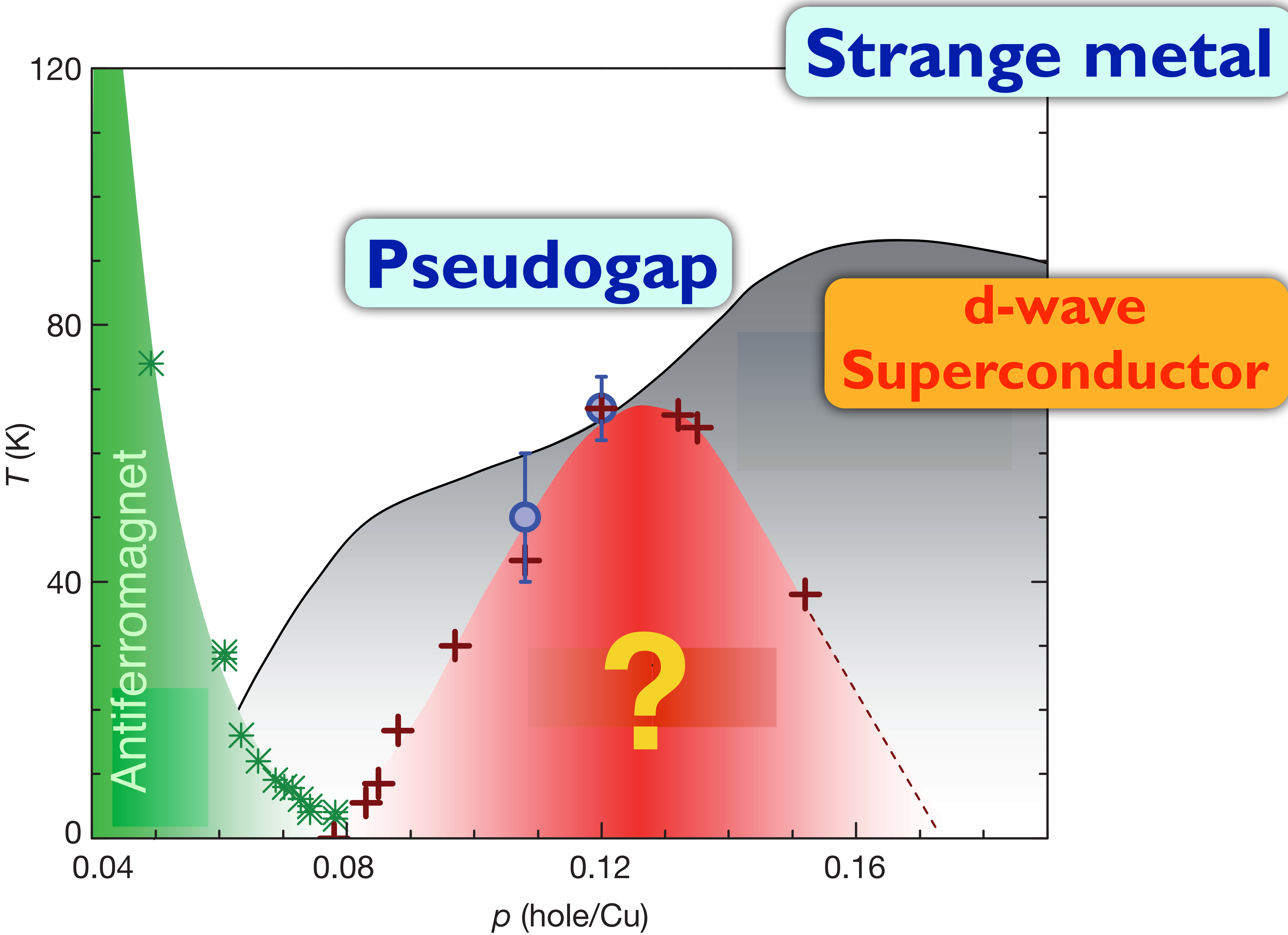
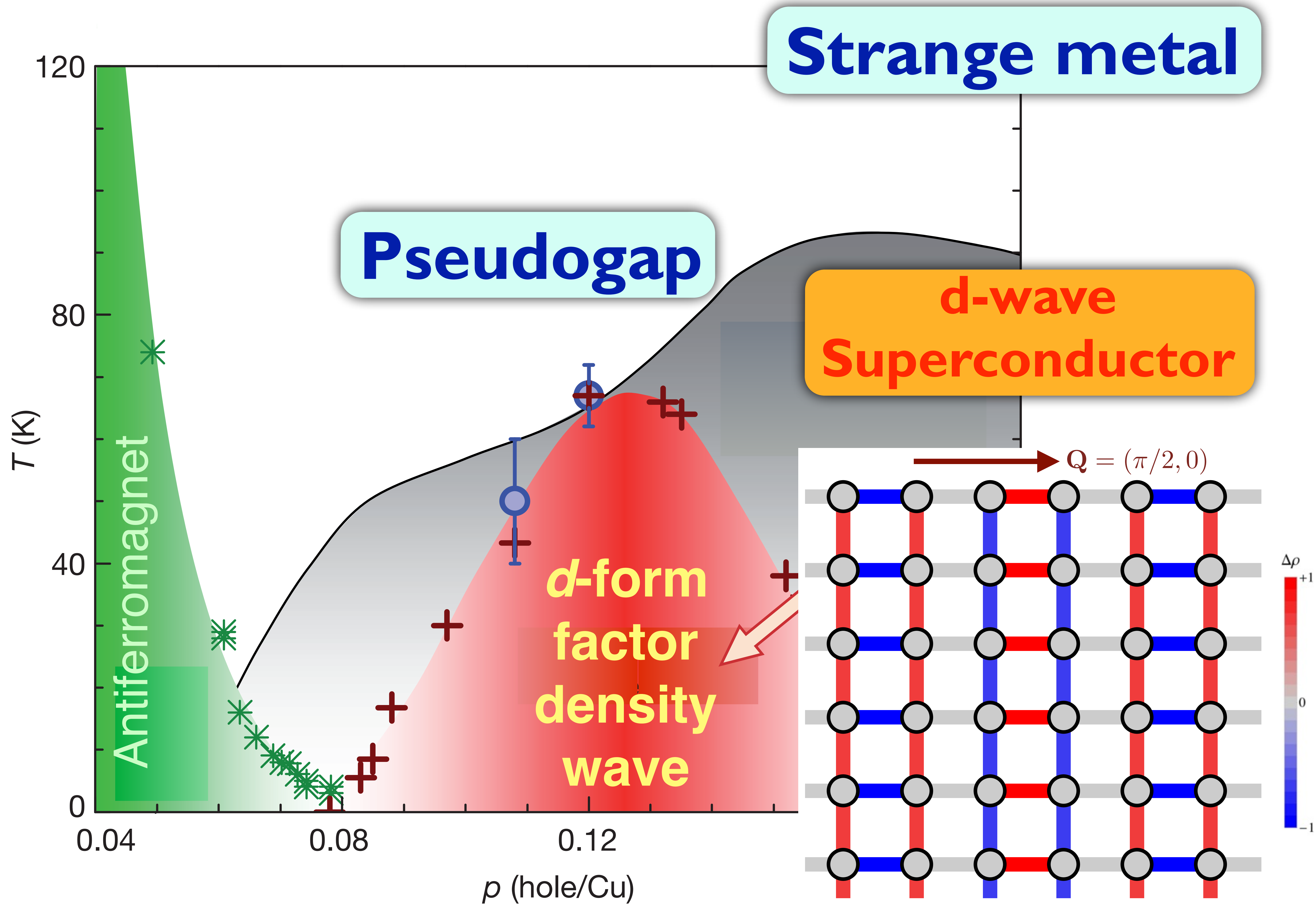


Strange metal
Pseudogap
d-wave
Superconductor
Antiferromagnet
?
120
80
40
0
T (K)
0.04
0.08
0.12
0.16
p (hole/Cu)



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)

Outline

1. The low T pseudogap:
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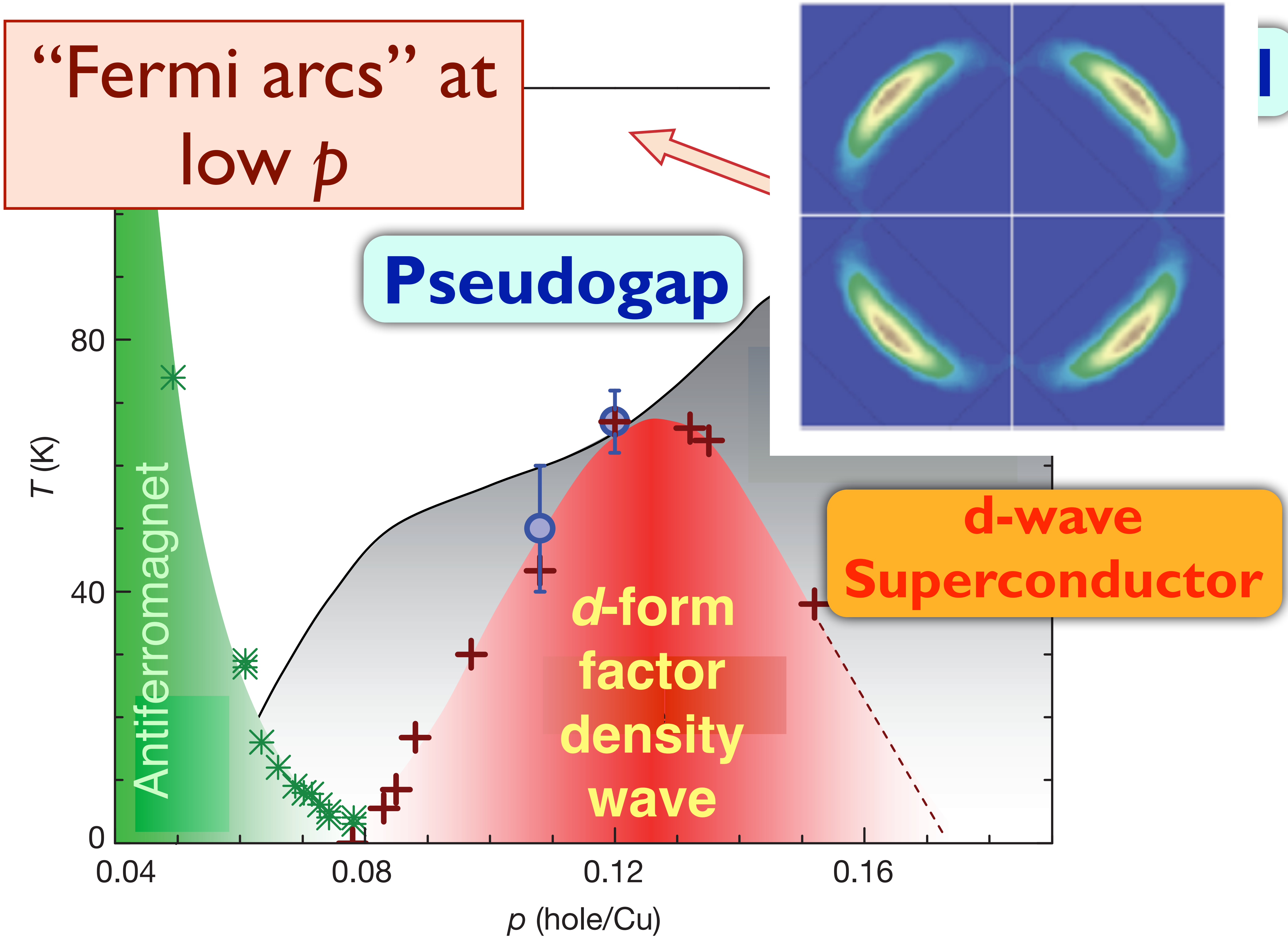
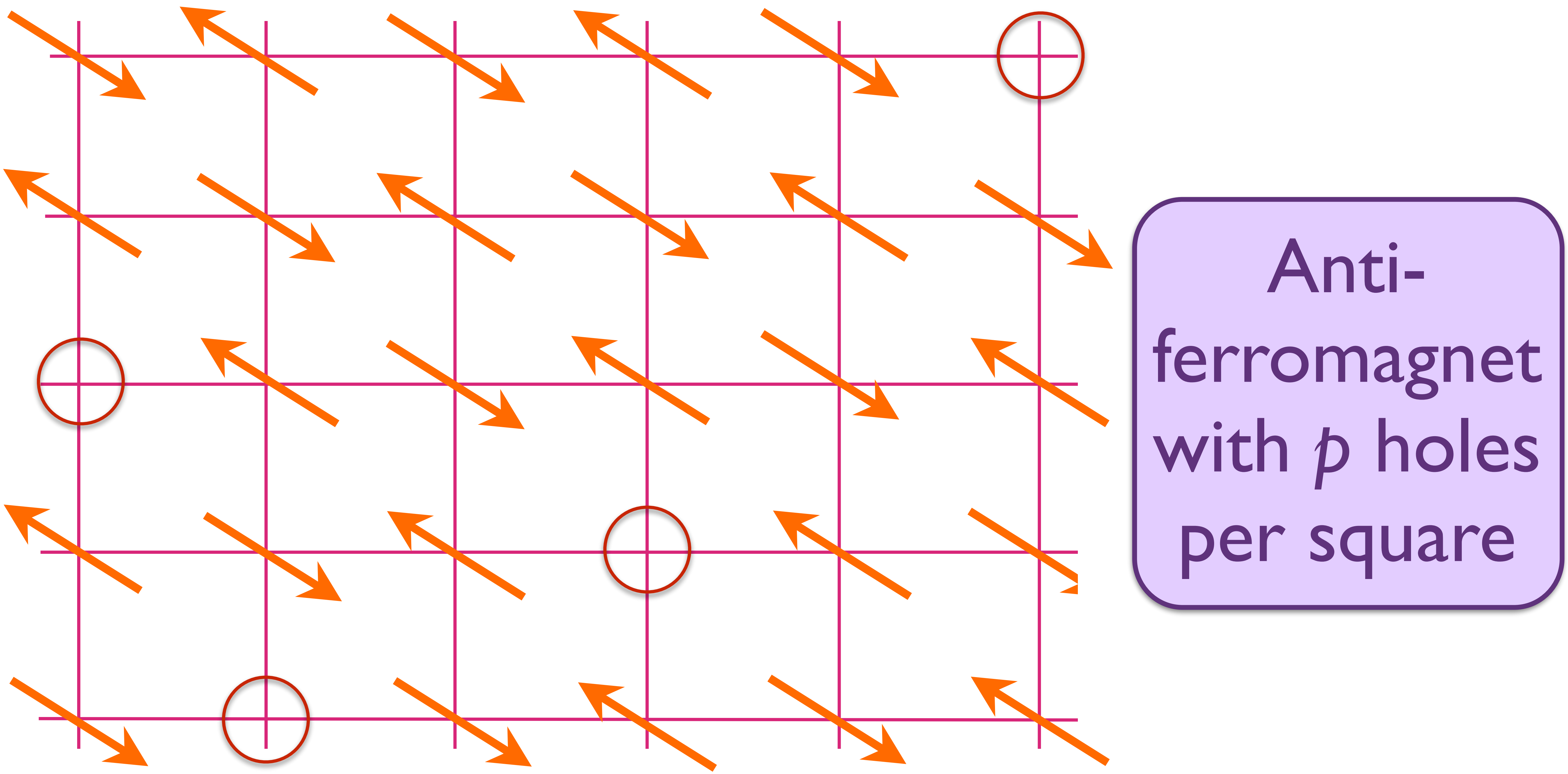
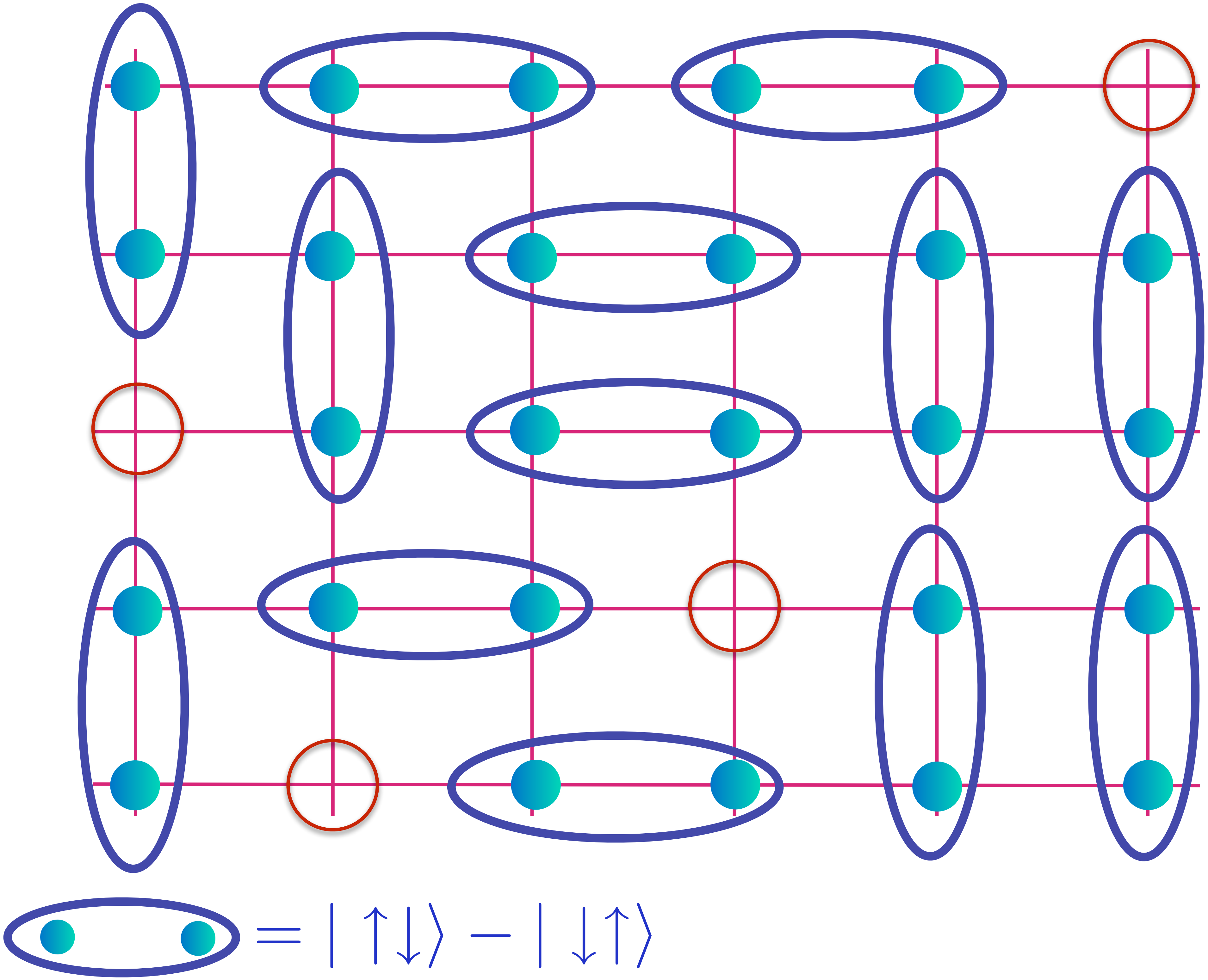


Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)



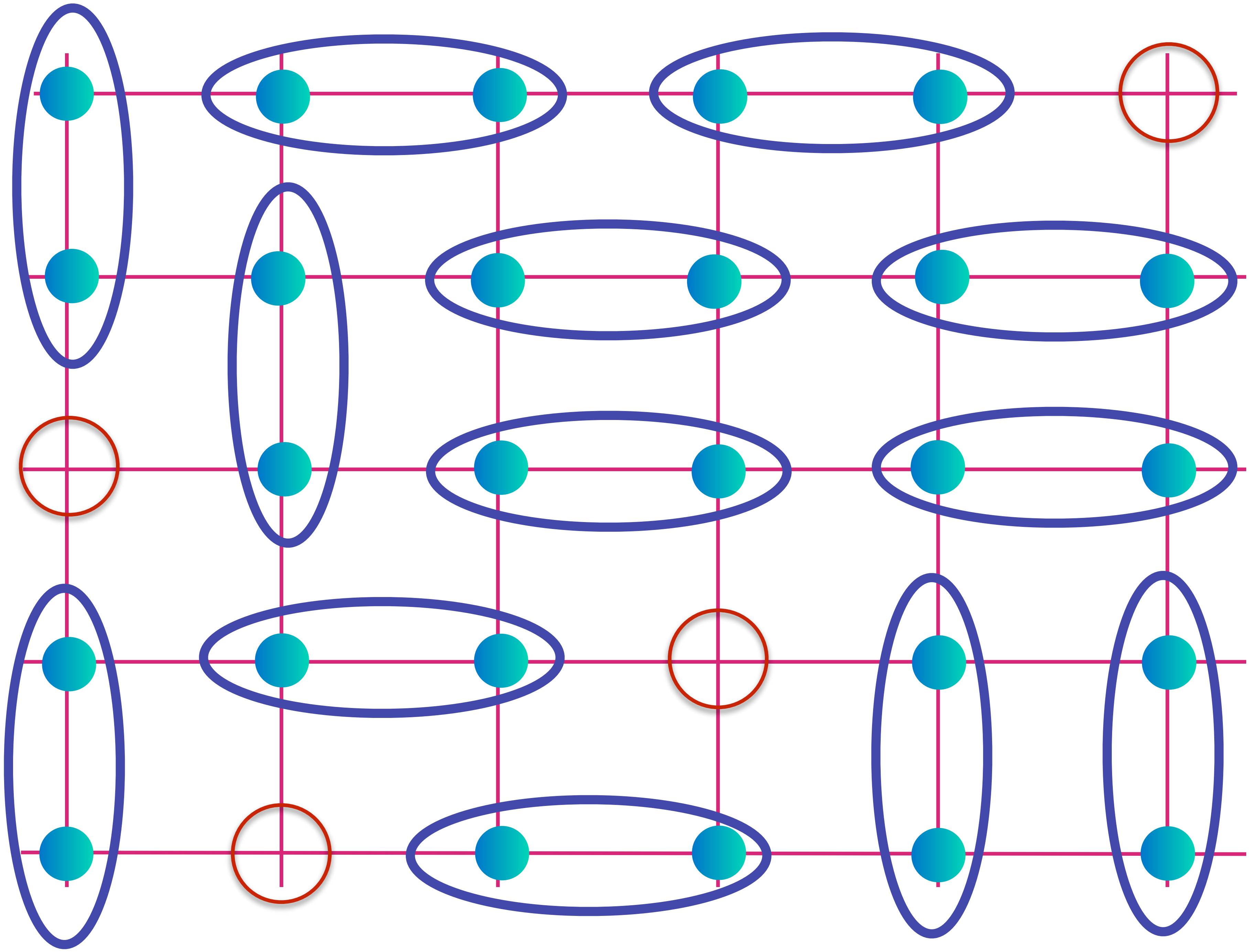
Note: relative to the fully-filled band insulator, there are $1+p$ holes per square

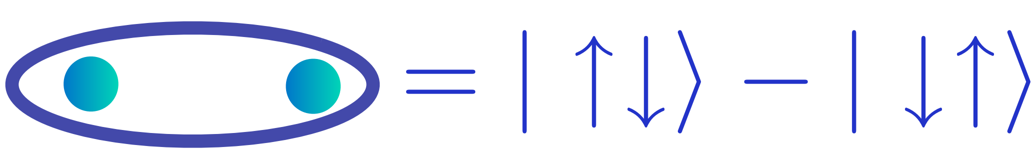


$$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Spin liquid
with
p "holons"
(spinless,
charge +e
quasiparticles)
per square

Baskaran, Zou, Anderson, Fradkin, Kivelson…





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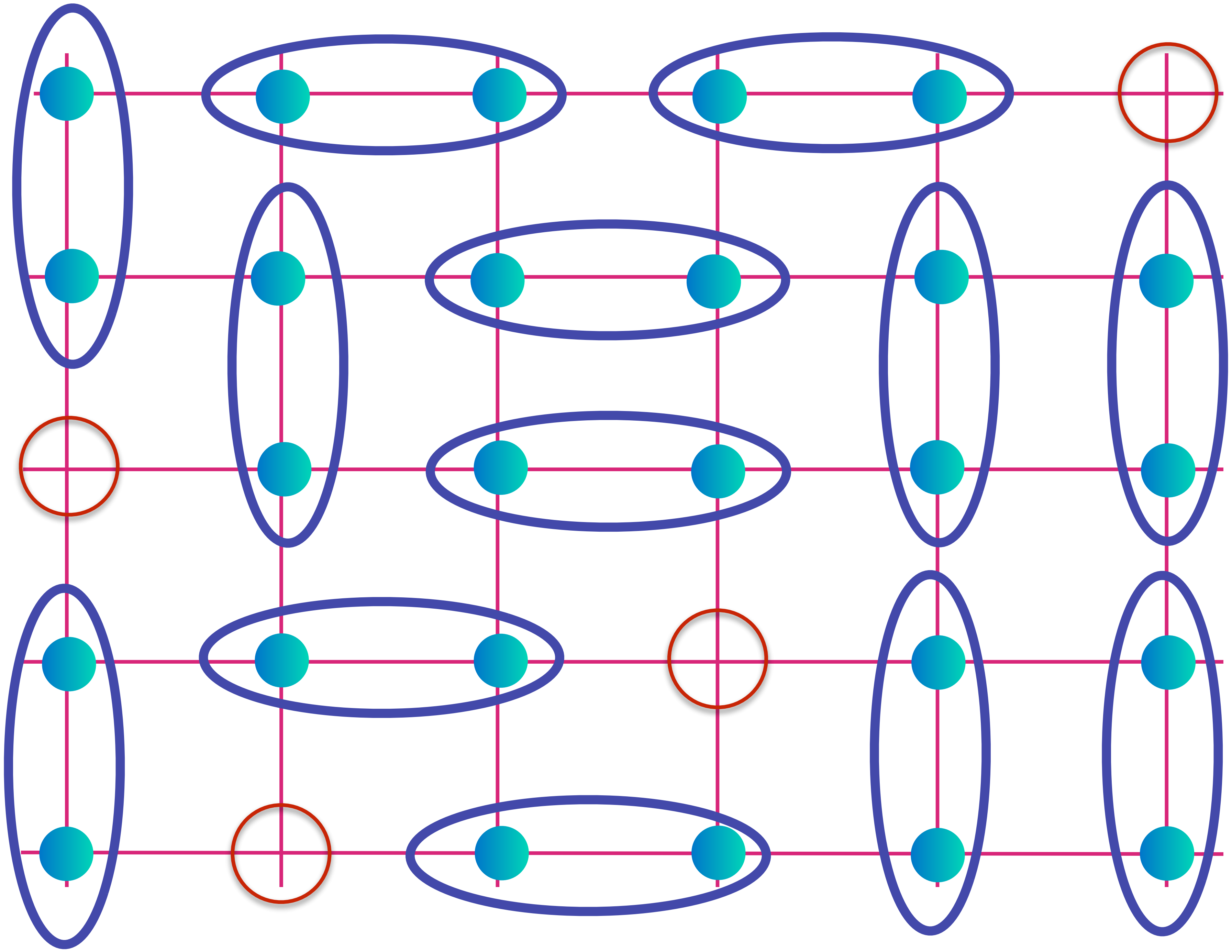

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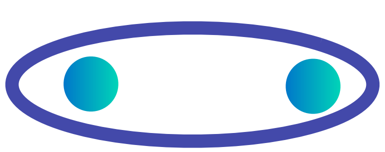
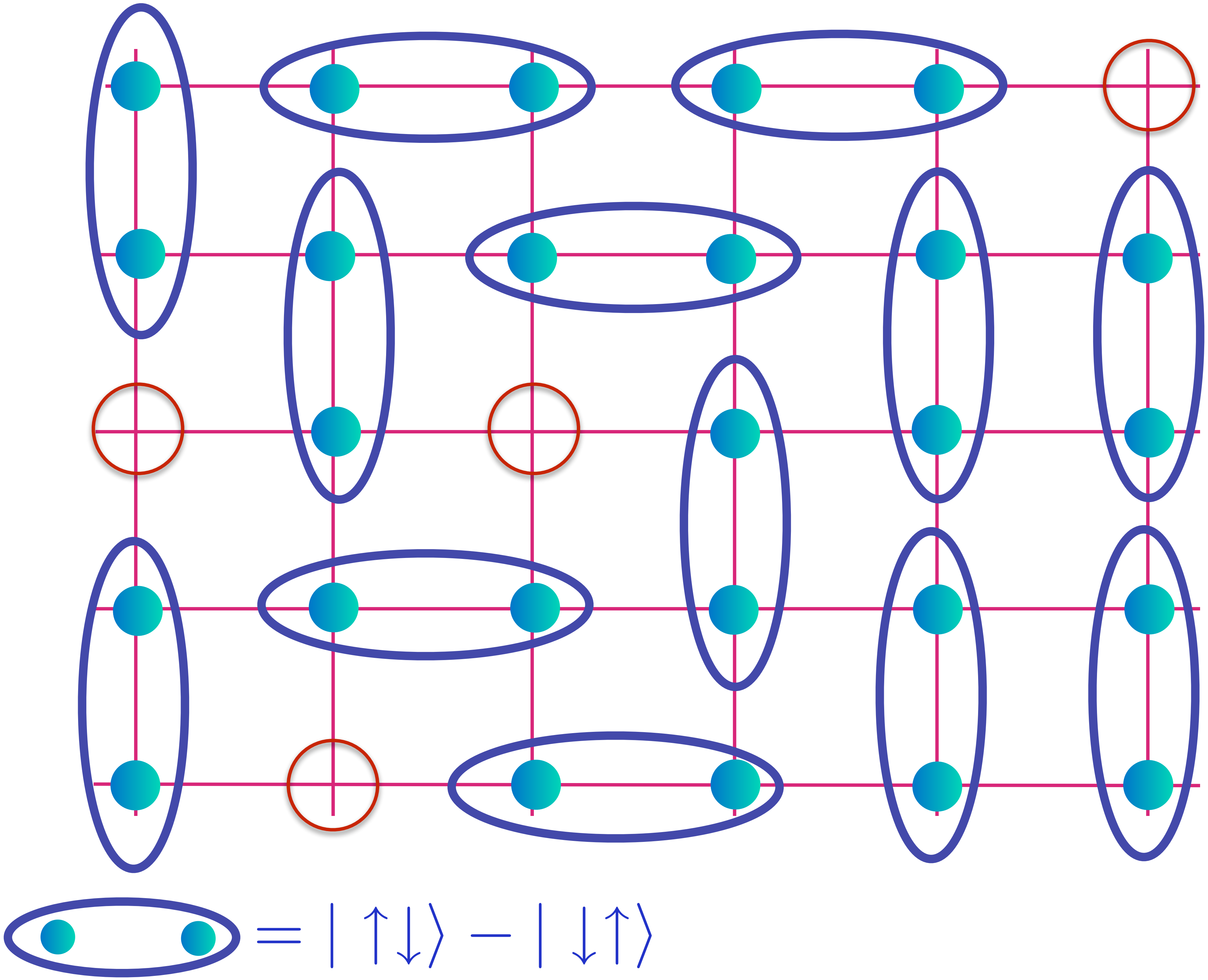
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Baskaran, Zou, Anderson, Fradkin, Kivelson…



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

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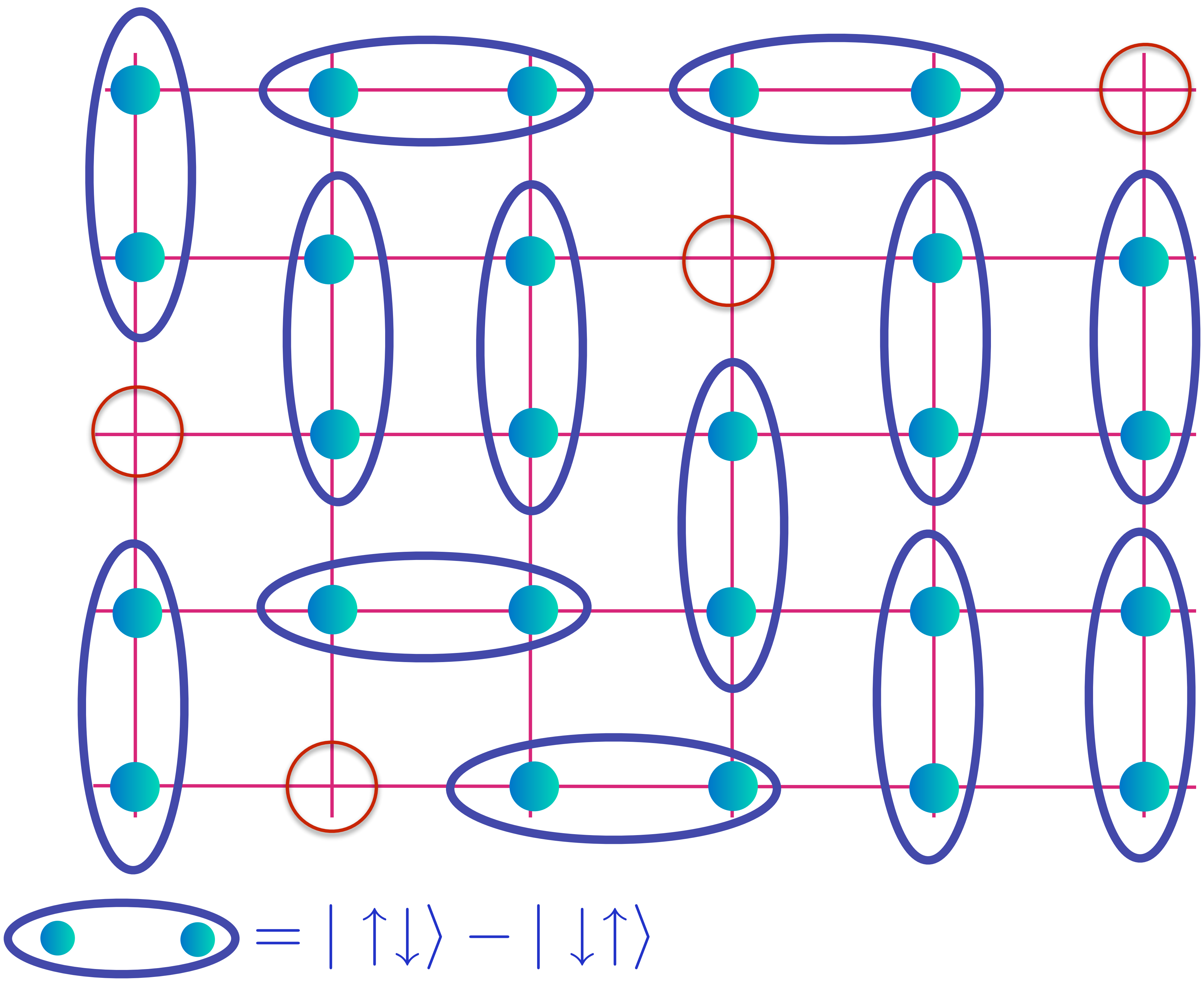
Baskaran, Zou, Anderson, Fradkin, Kivelson…



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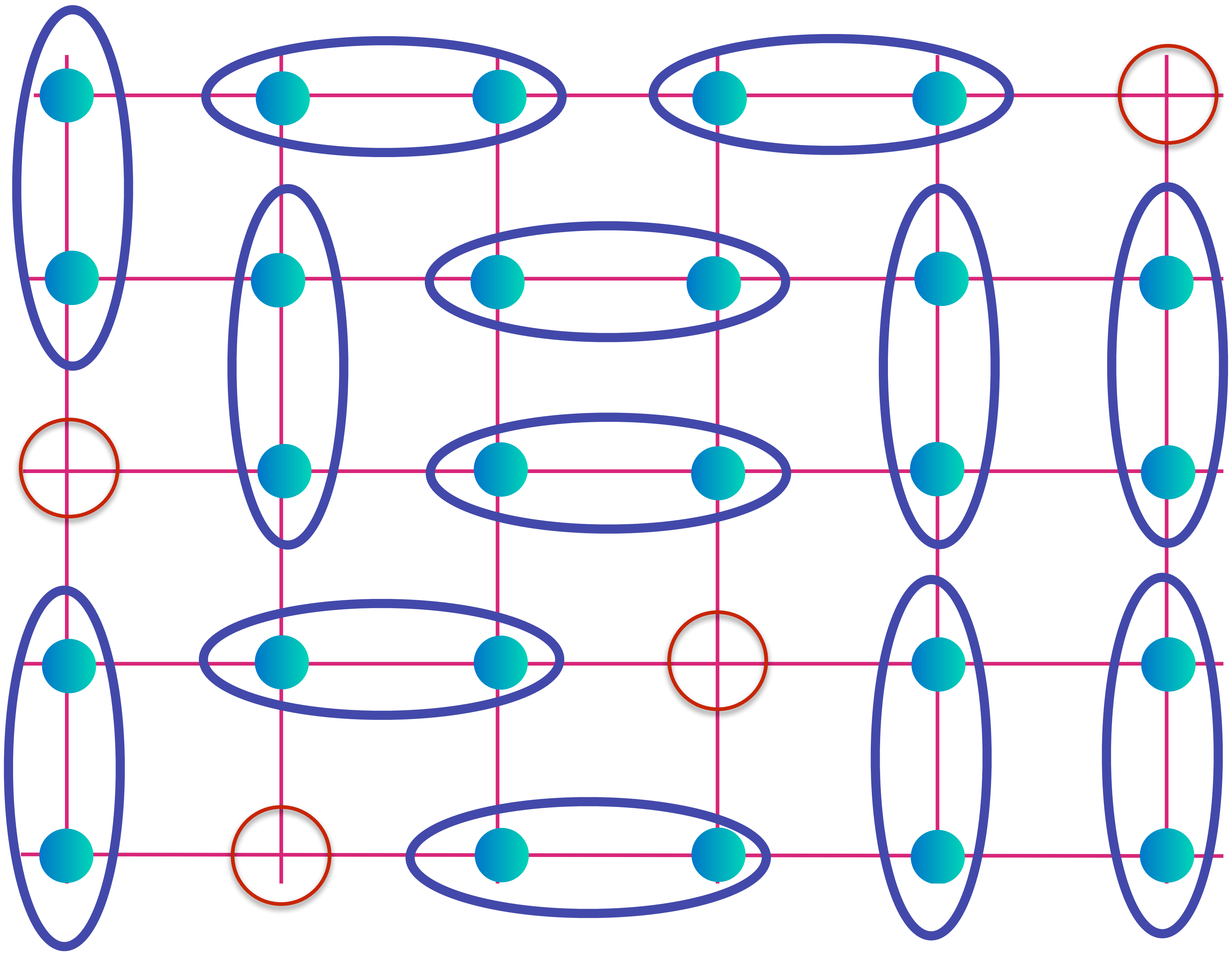

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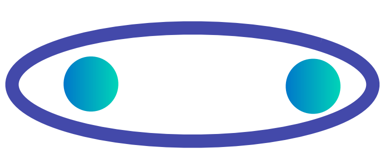
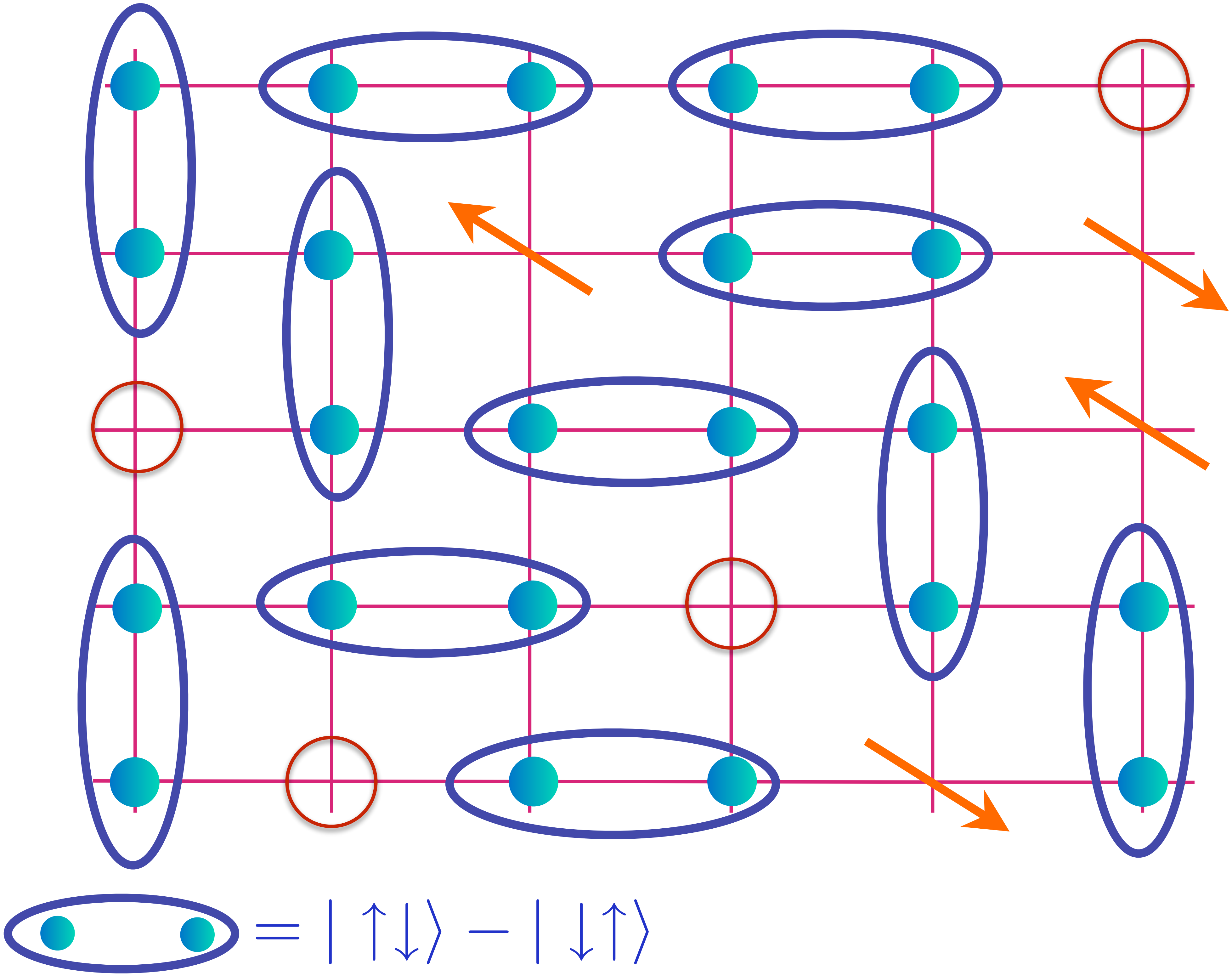
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Baskaran, Zou, Anderson, Fradkin, Kivelson…

Neutral spin S=1/2 "spinon" excitations



Spin liquid
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Baskaran, Zou, Anderson, Fradkin, Kivelson…

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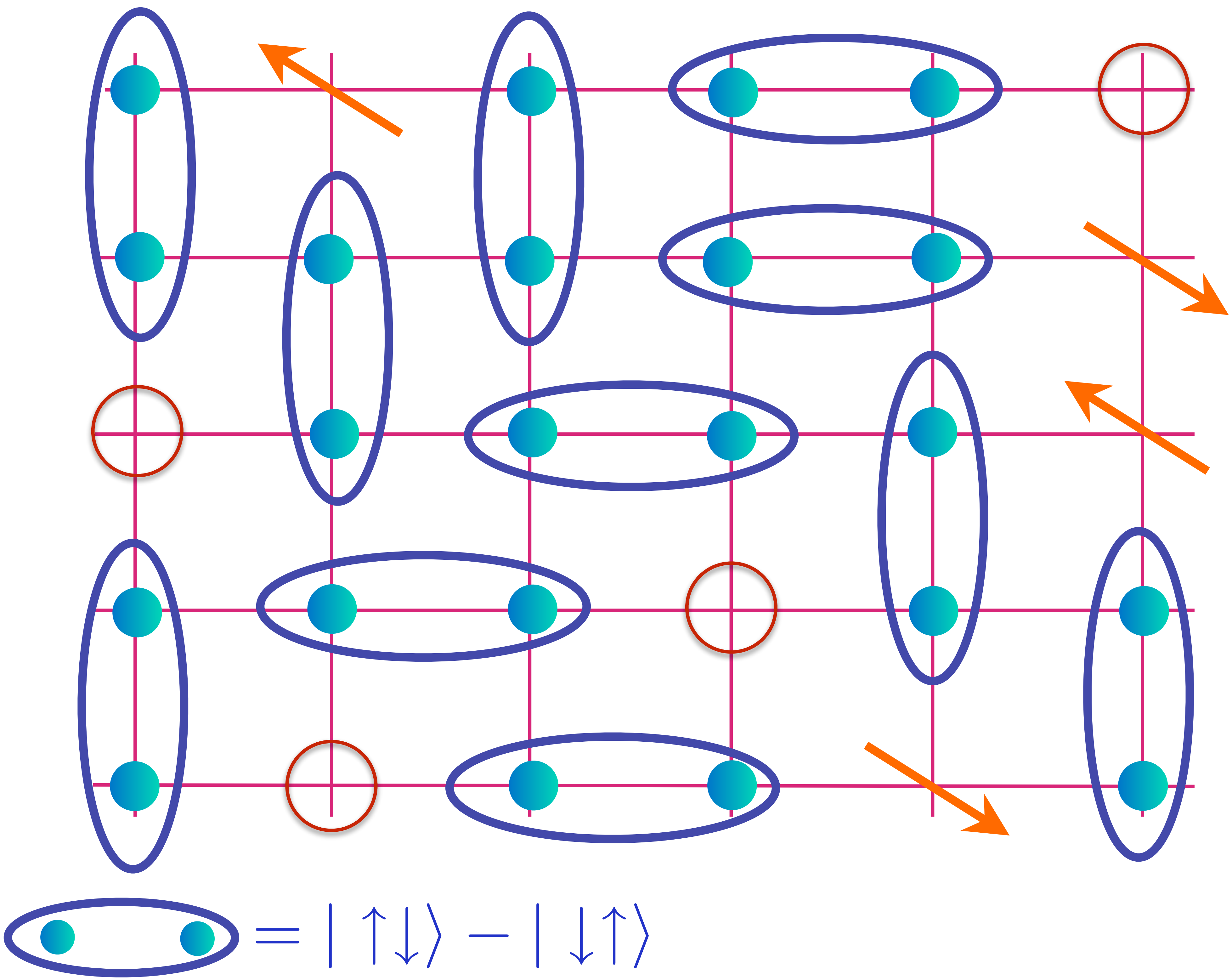

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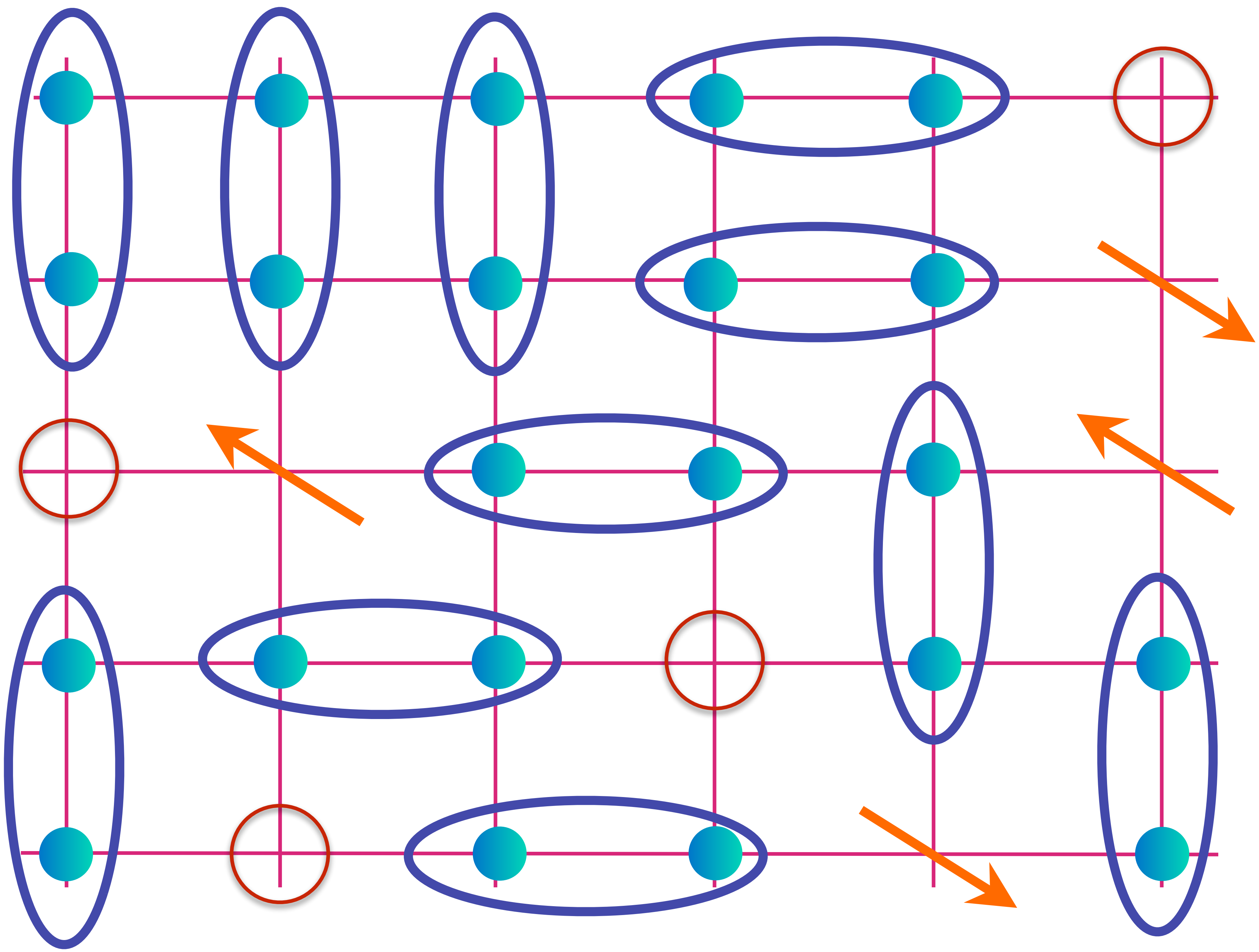
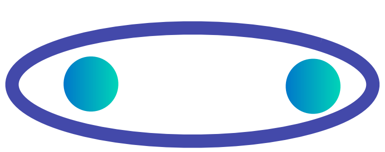


Spin liquid with p "holons" (spinless, charge +e quasiparticles) per square

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

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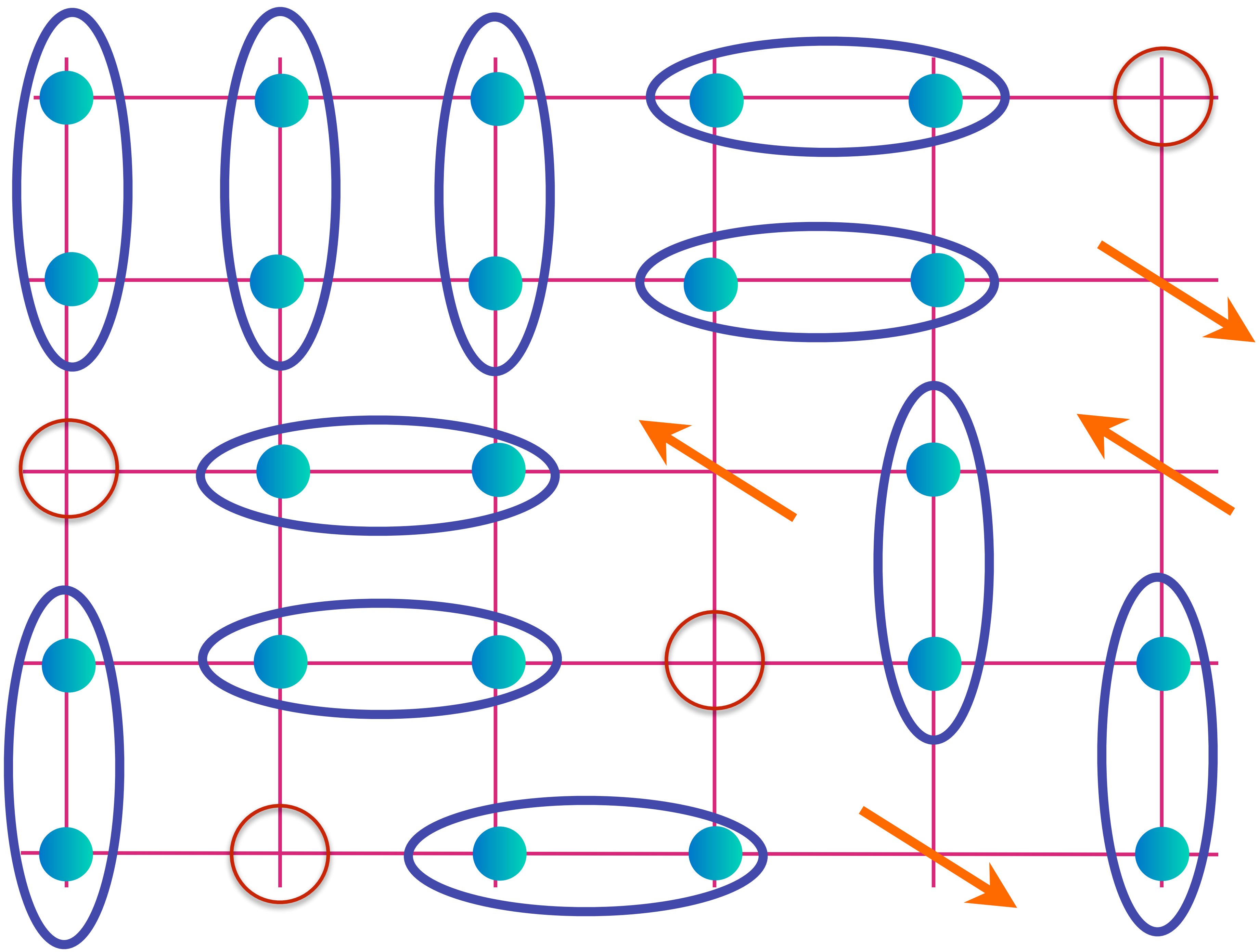

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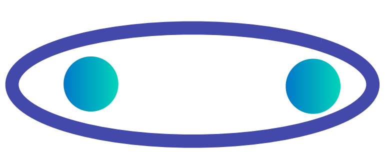 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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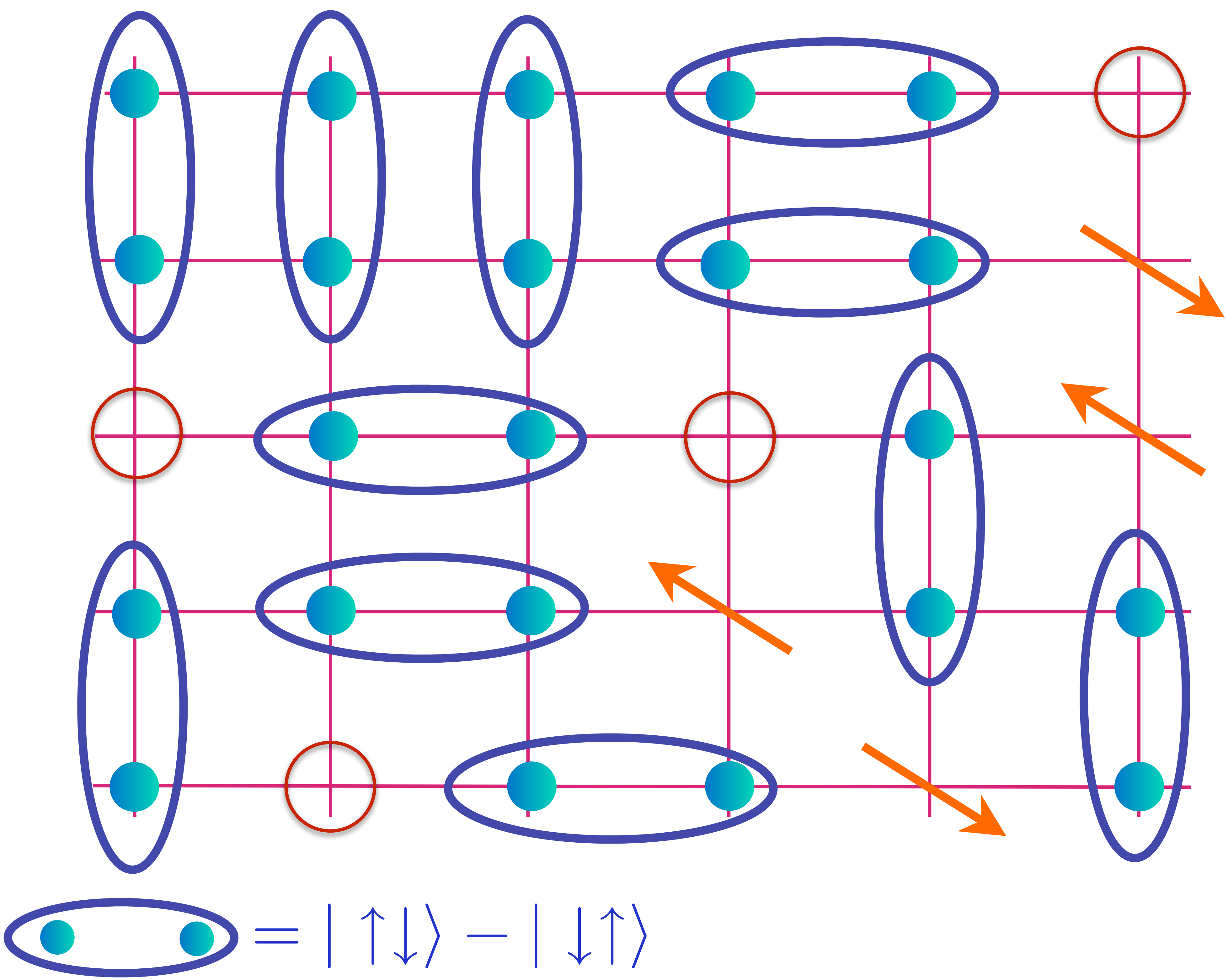

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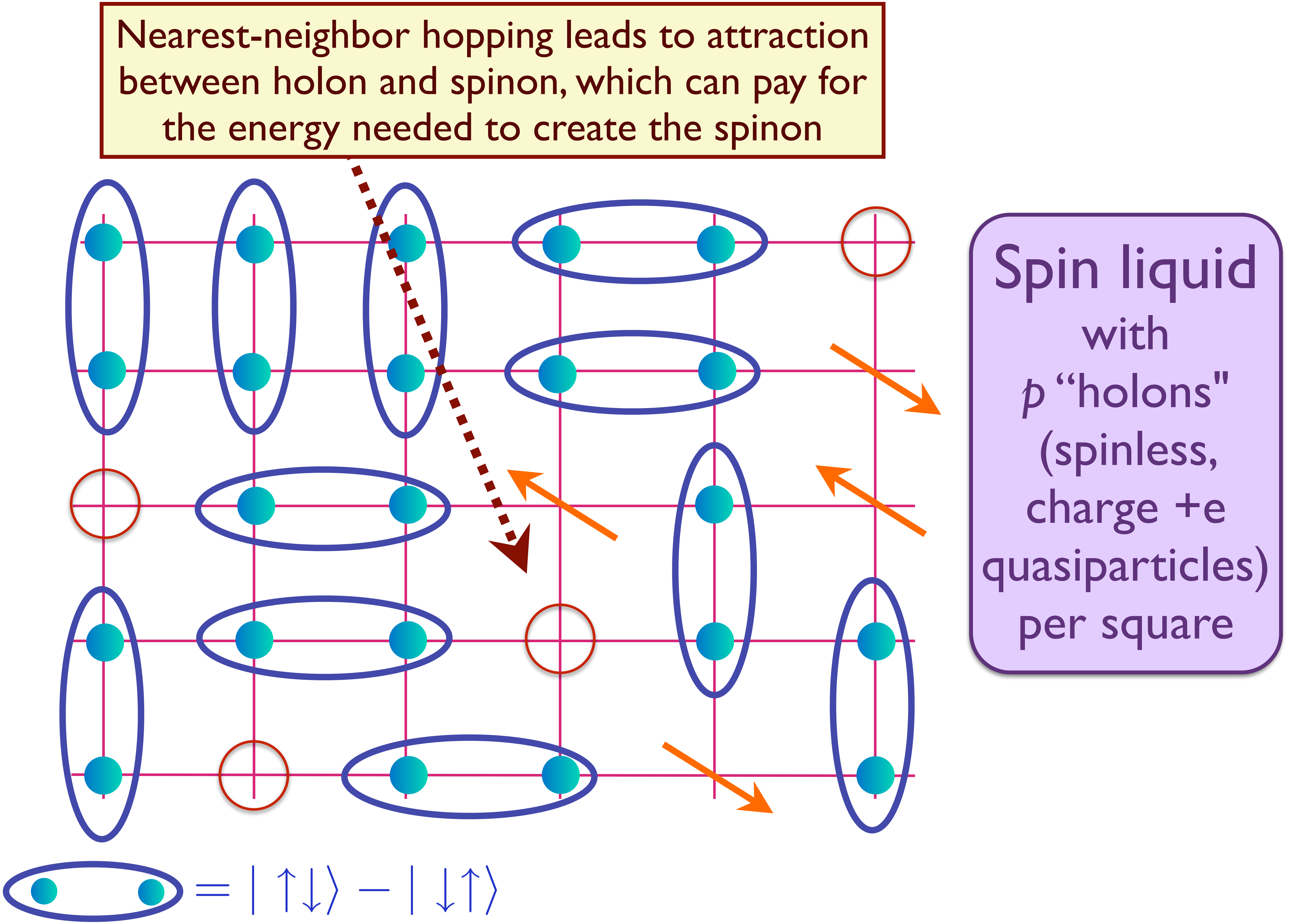
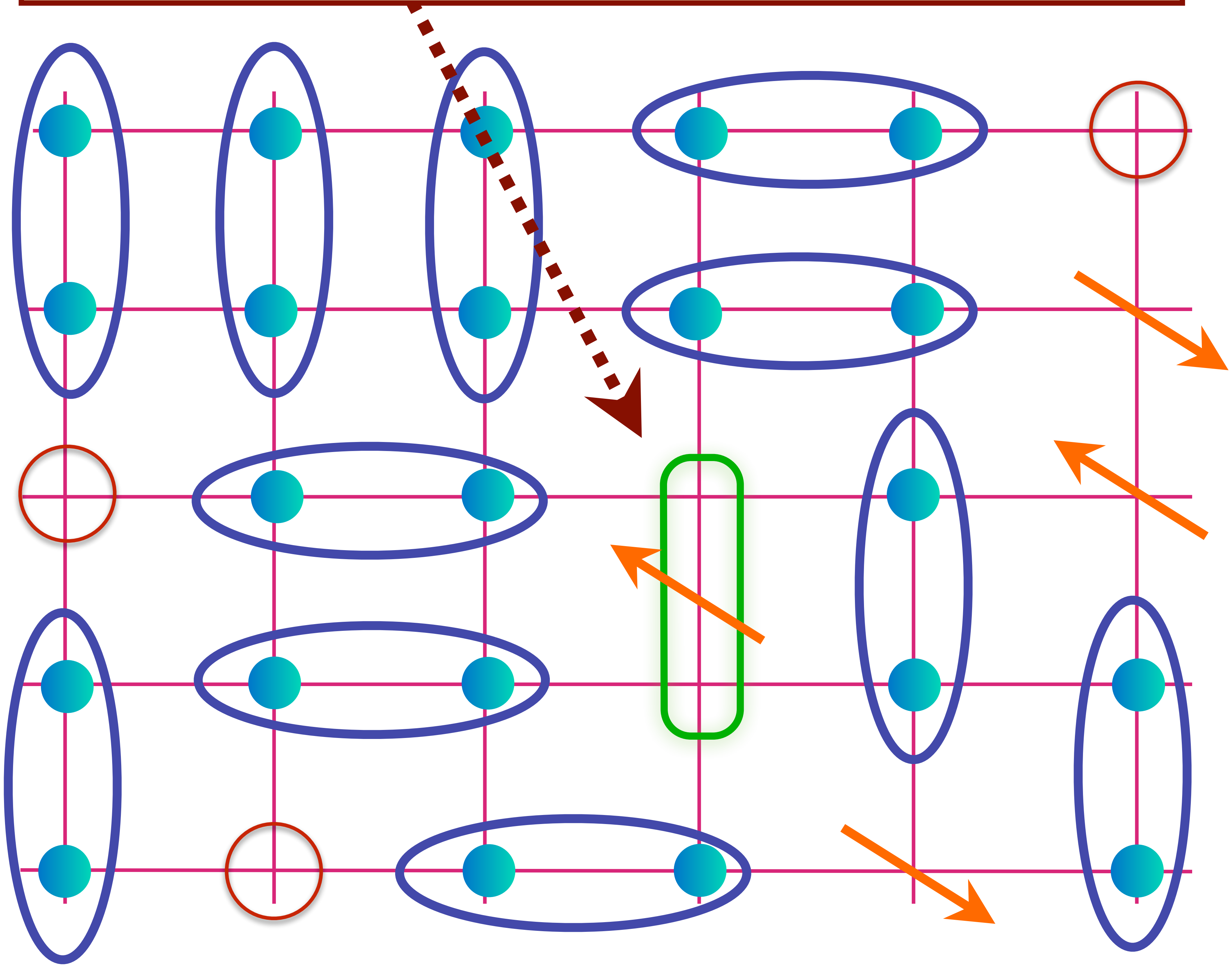
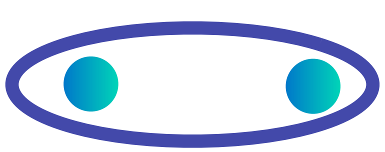


R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, *Phys. Rev. B* **75**, 235122 (2007)

Electron (or hole) resides on a "bonding" orbital between two sites



Spin liquid with p "holons" (spinless, charge +e quasiparticles) per square



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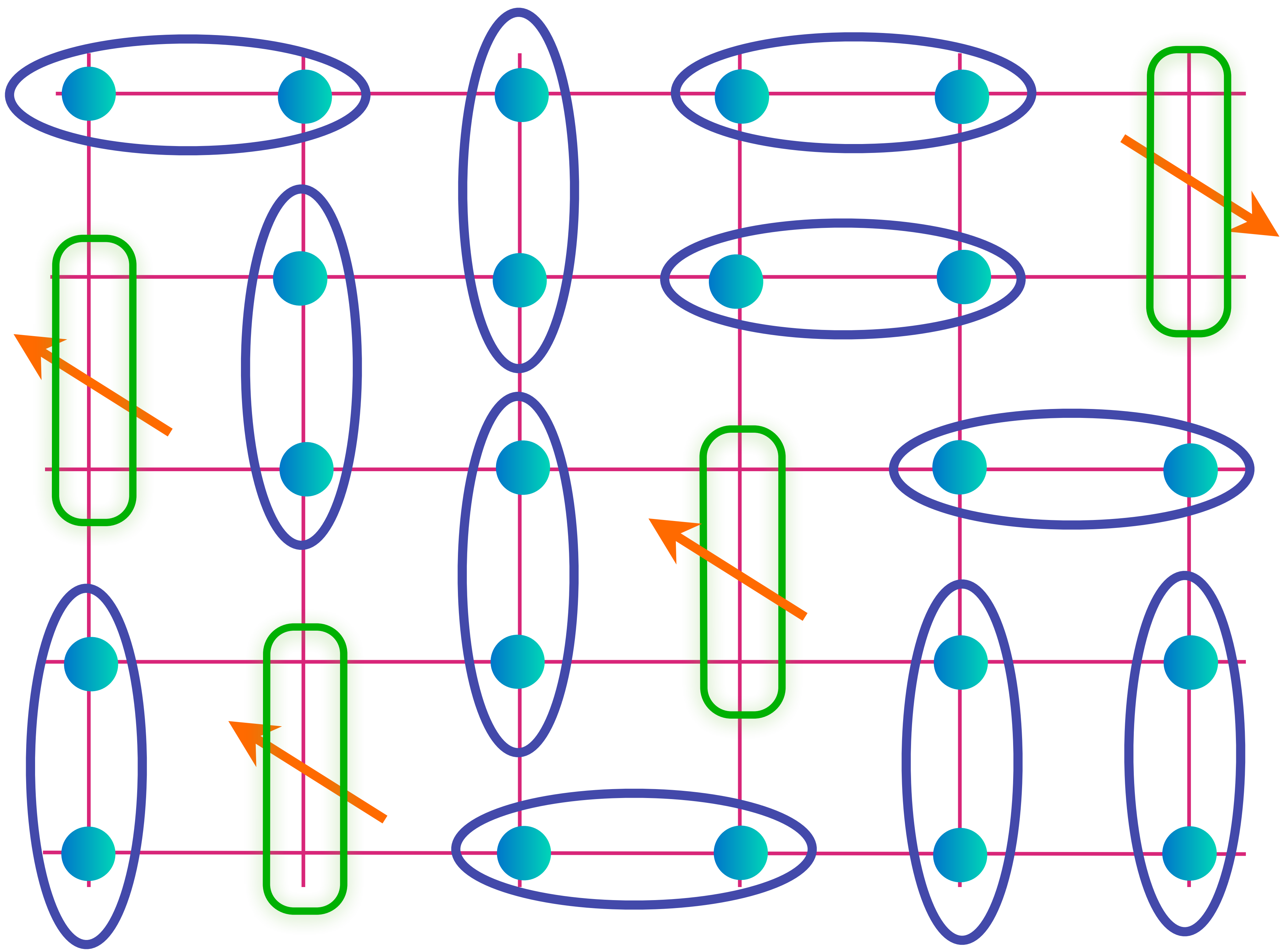
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, *Phys. Rev. B* **75**, 235122 (2007)

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



FL* !

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

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

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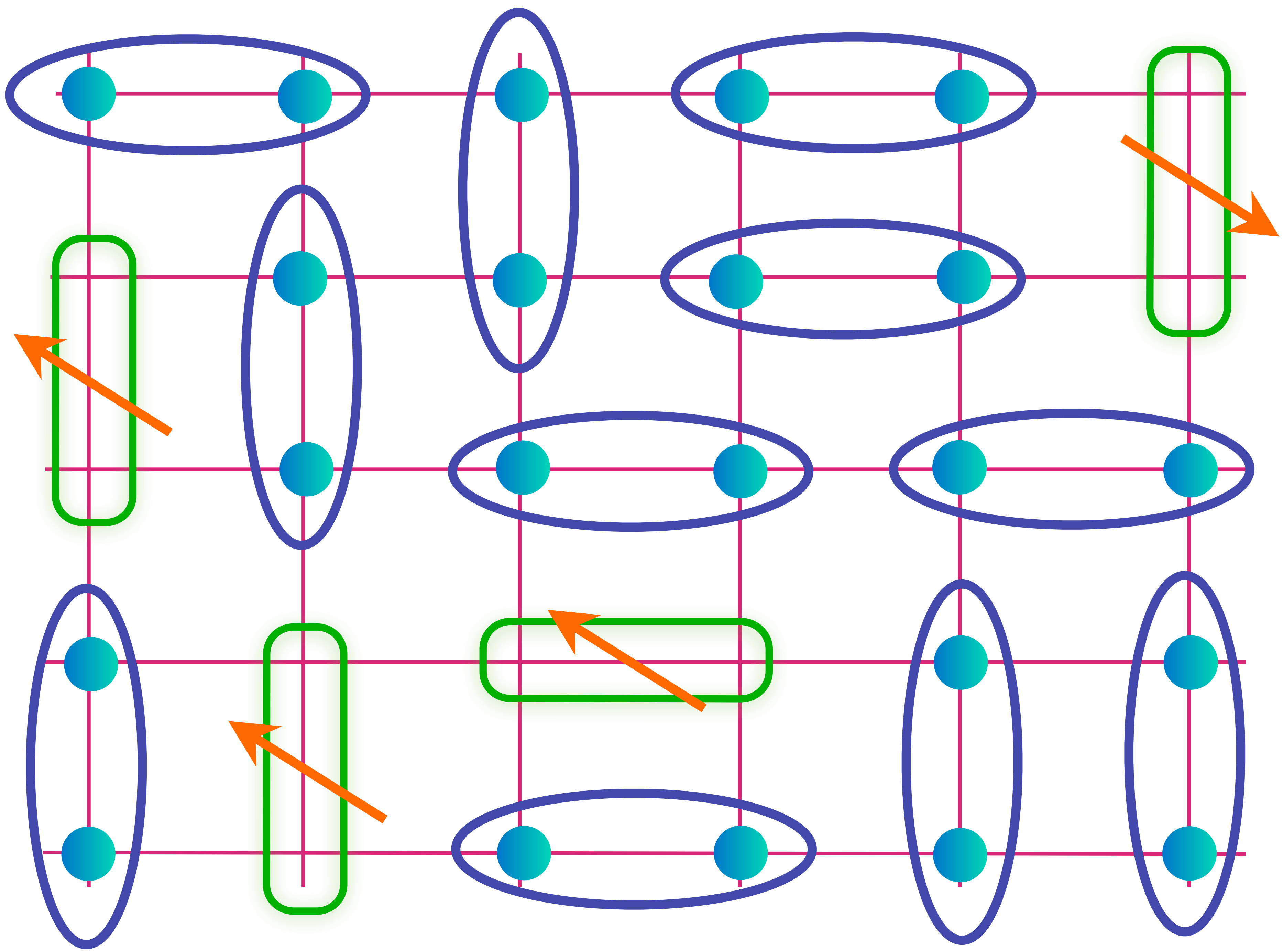

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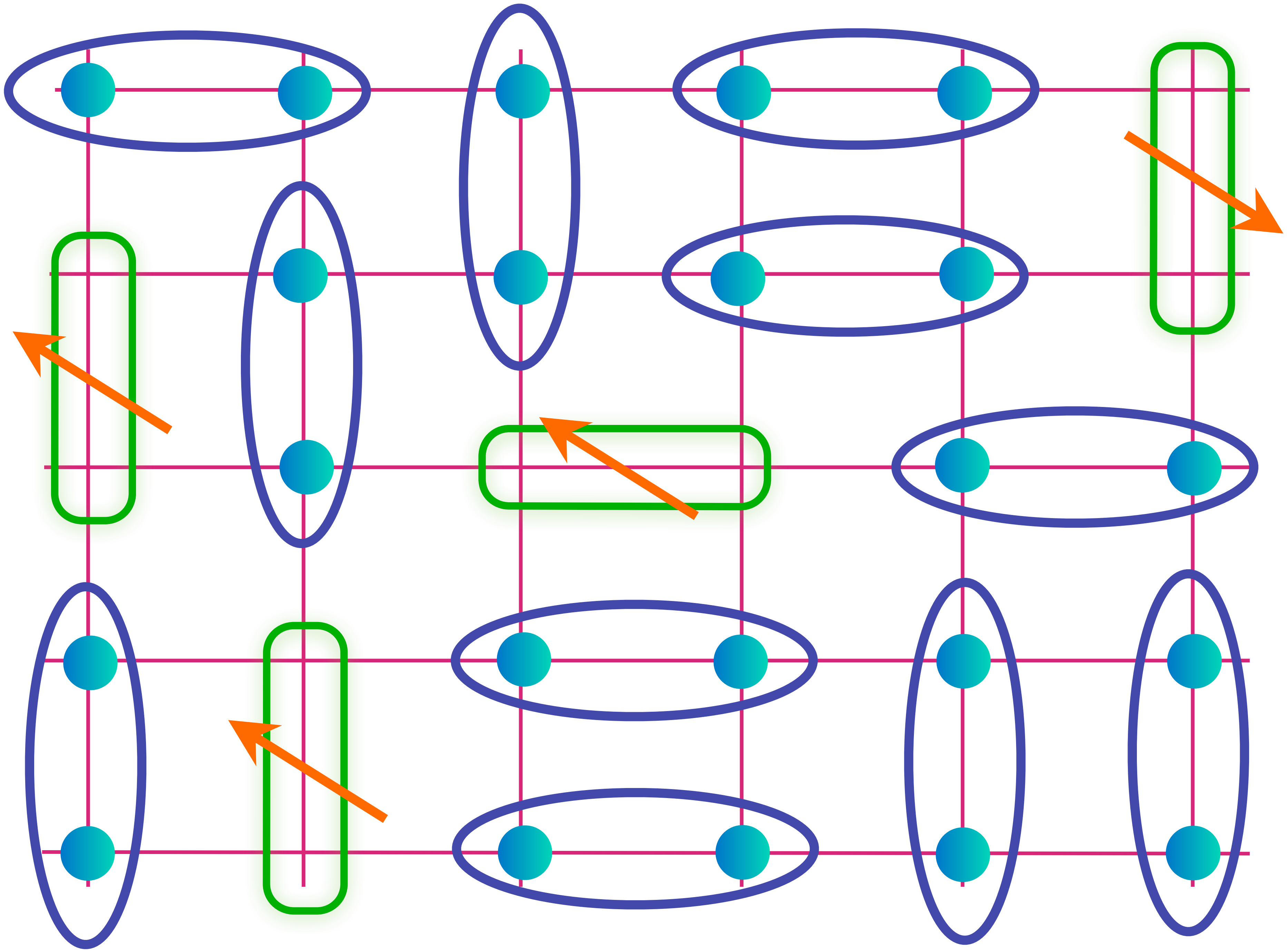

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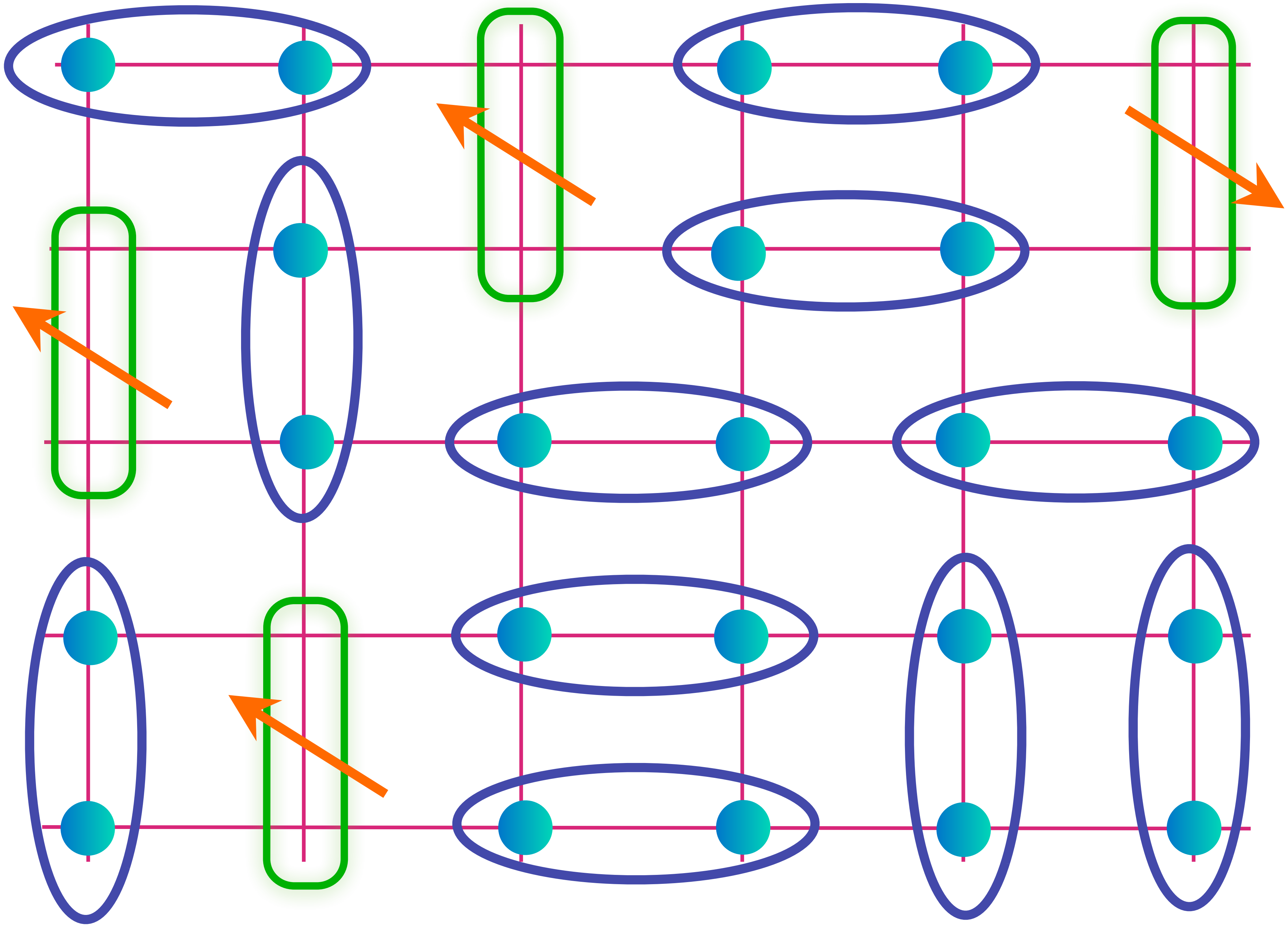

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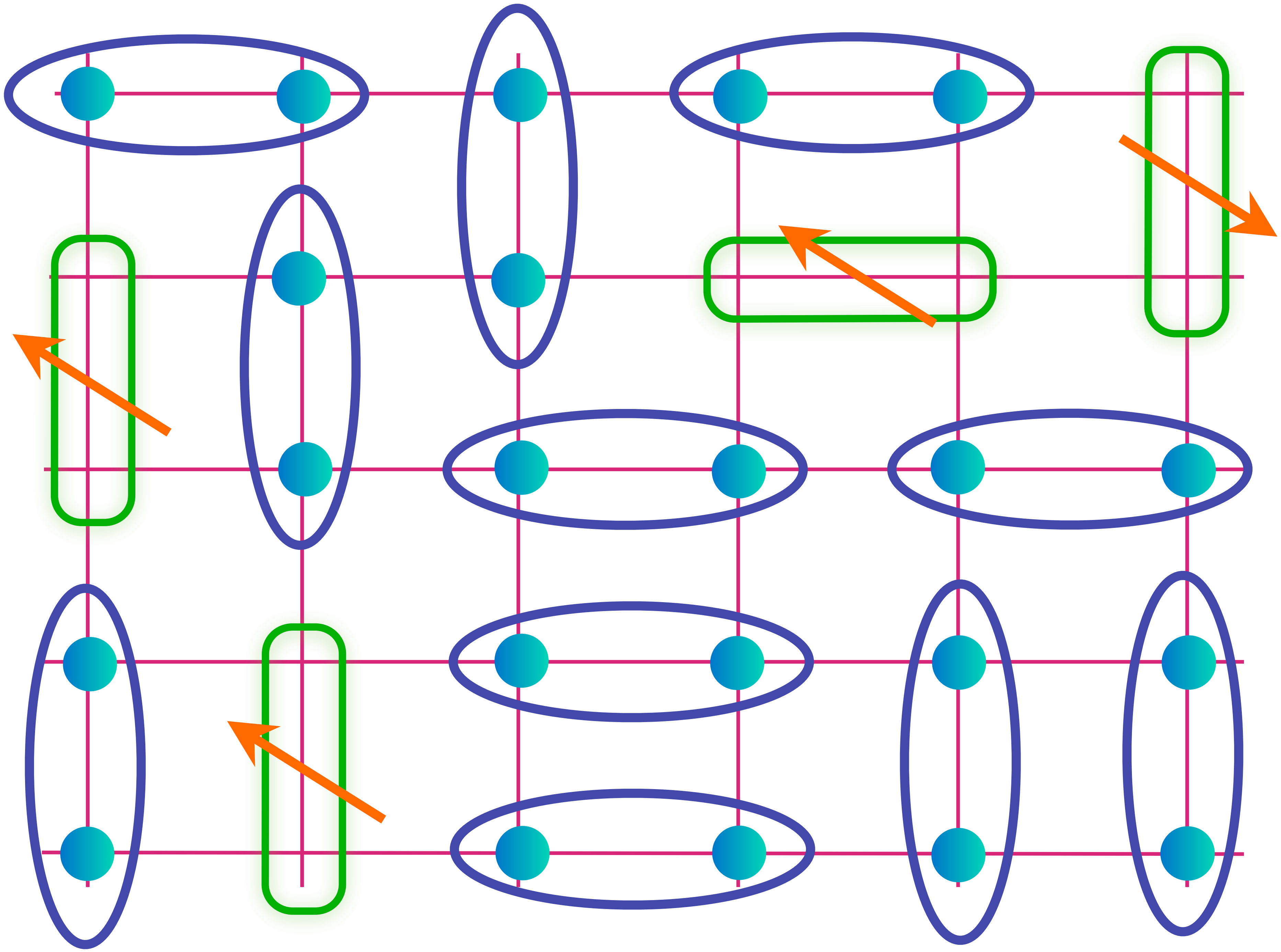

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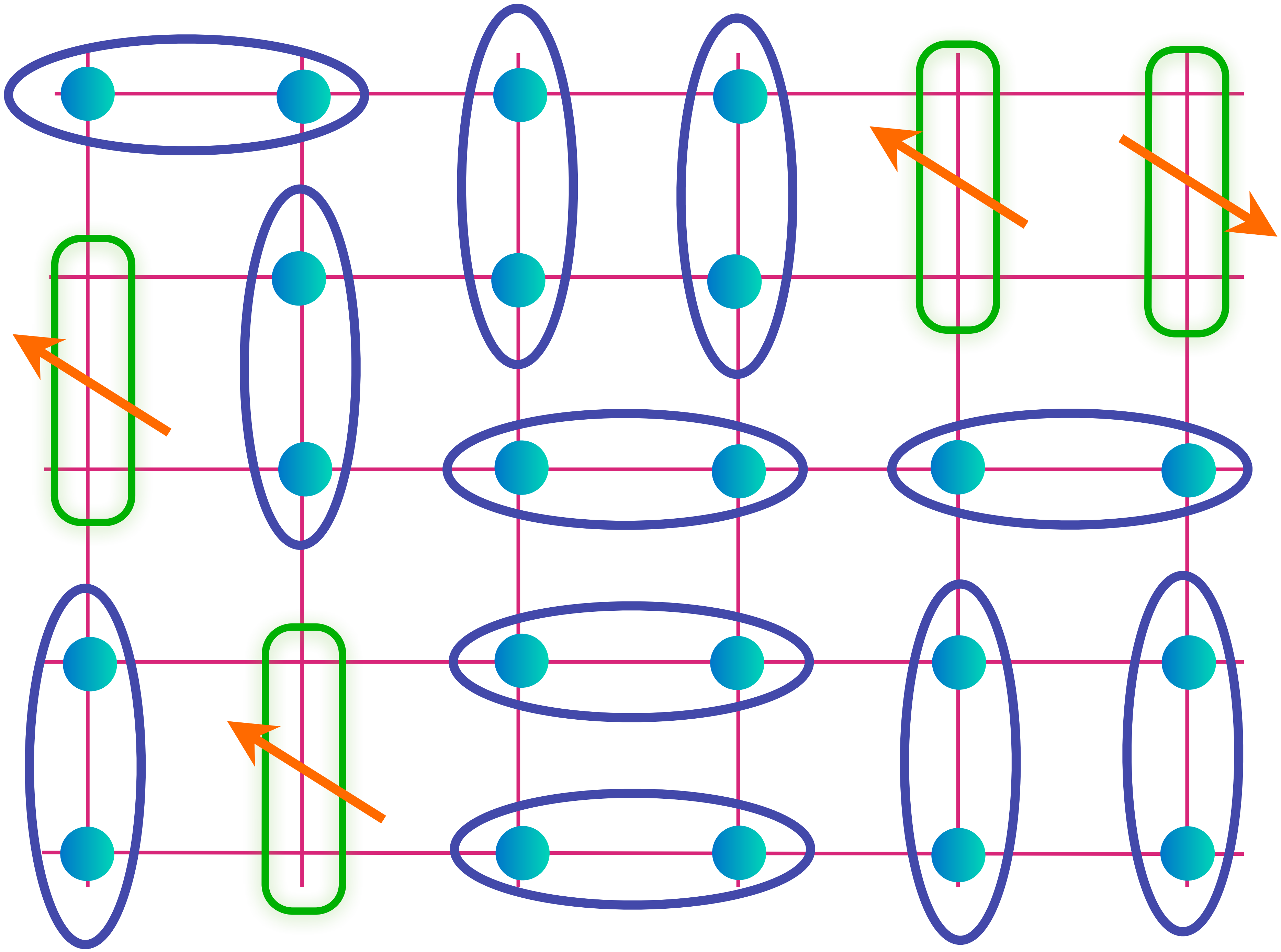

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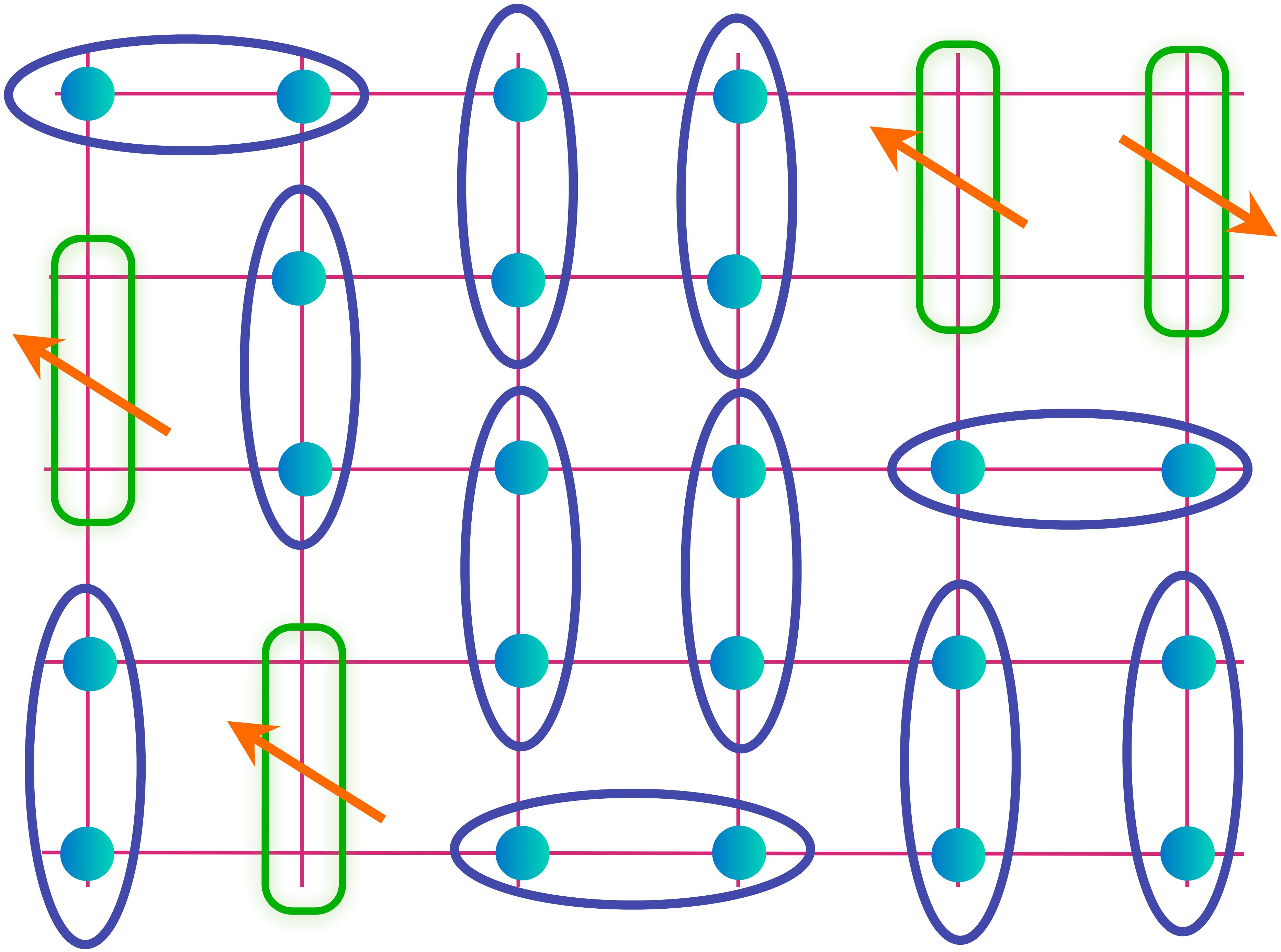

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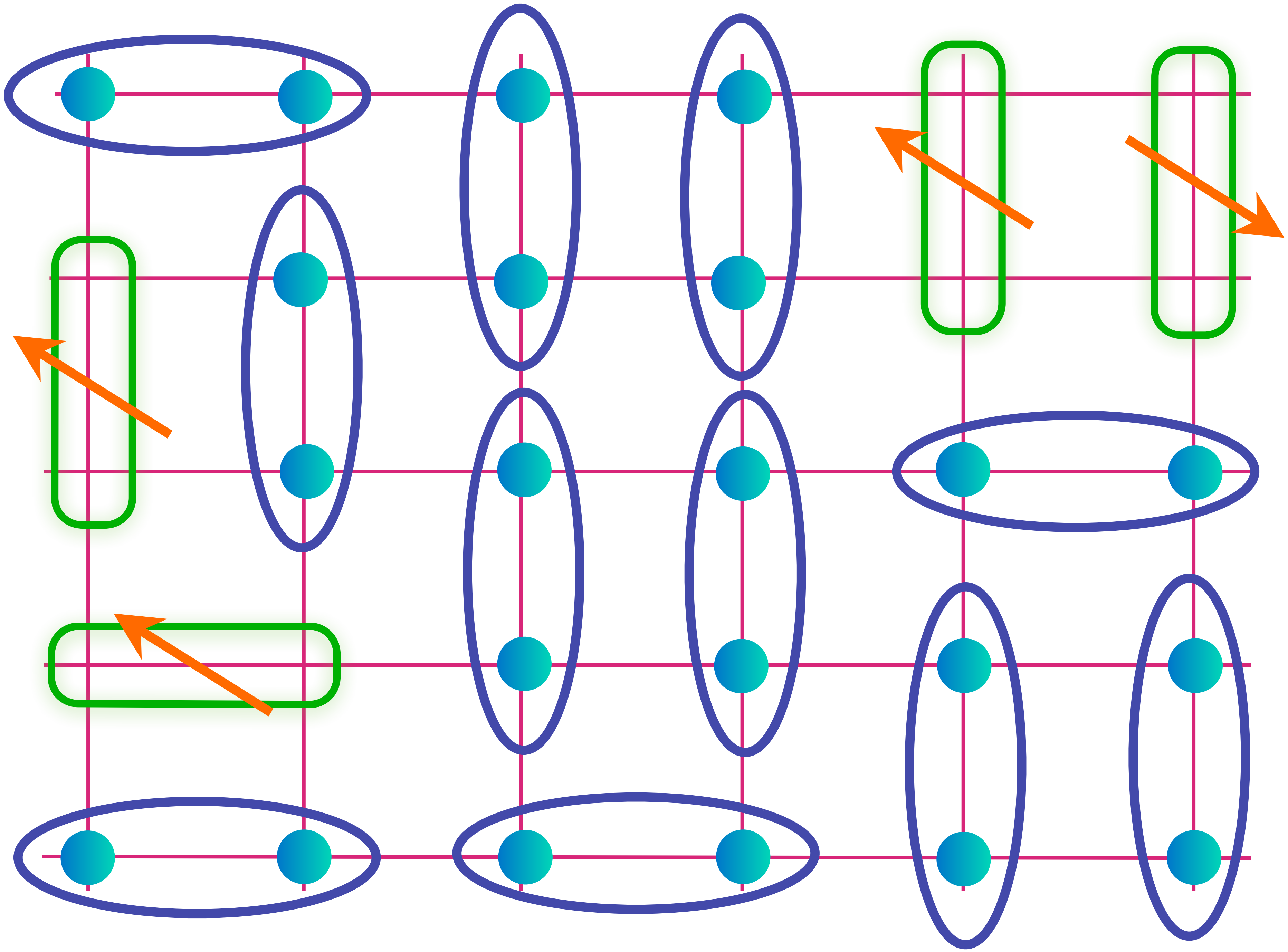

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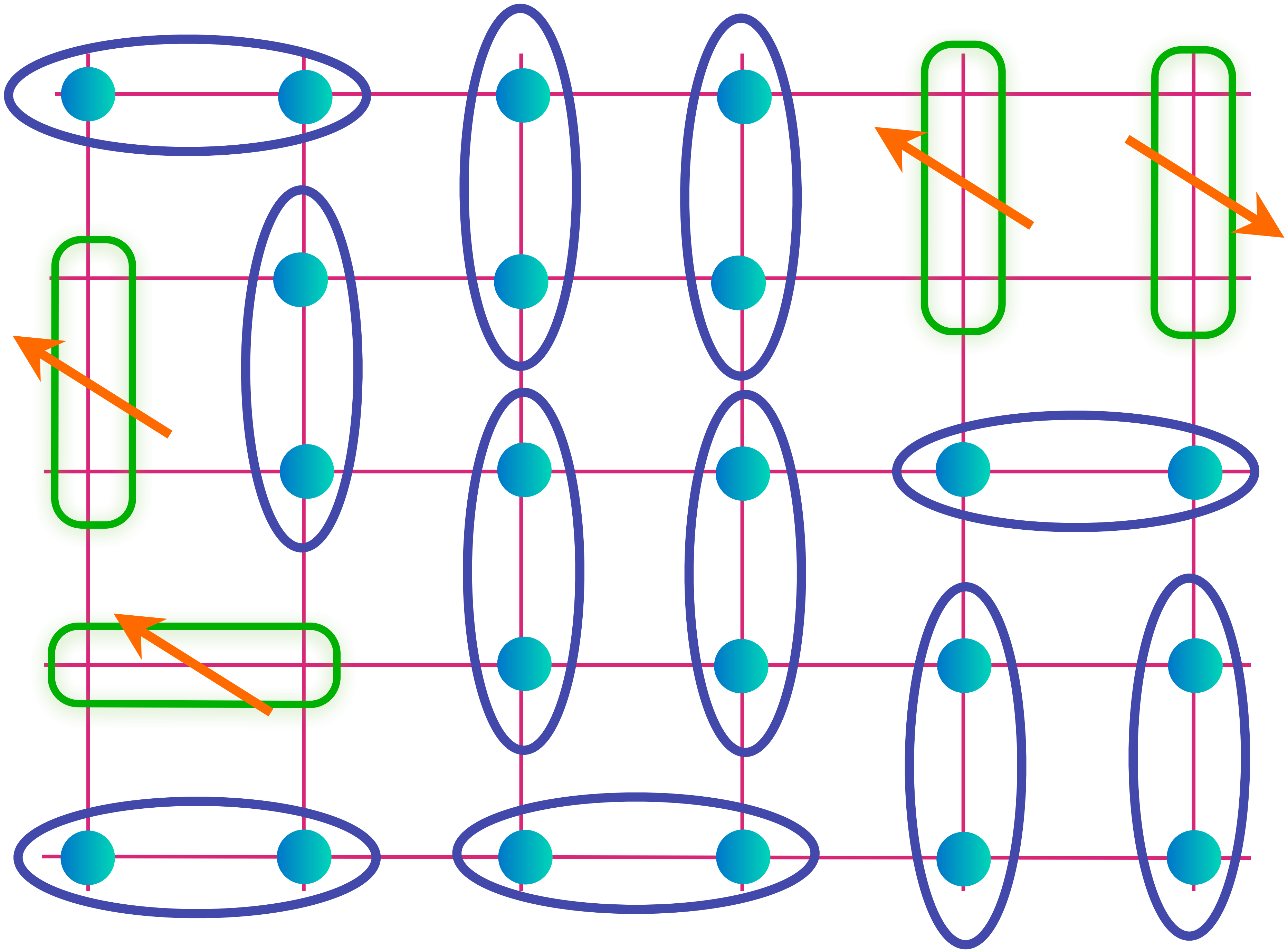

FL* !

Described by a quantum dimer model with bosonic and fermionic dimers

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

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

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- The emergent gauge excitations are needed to account for the breakdown of the Luttinger theorem.

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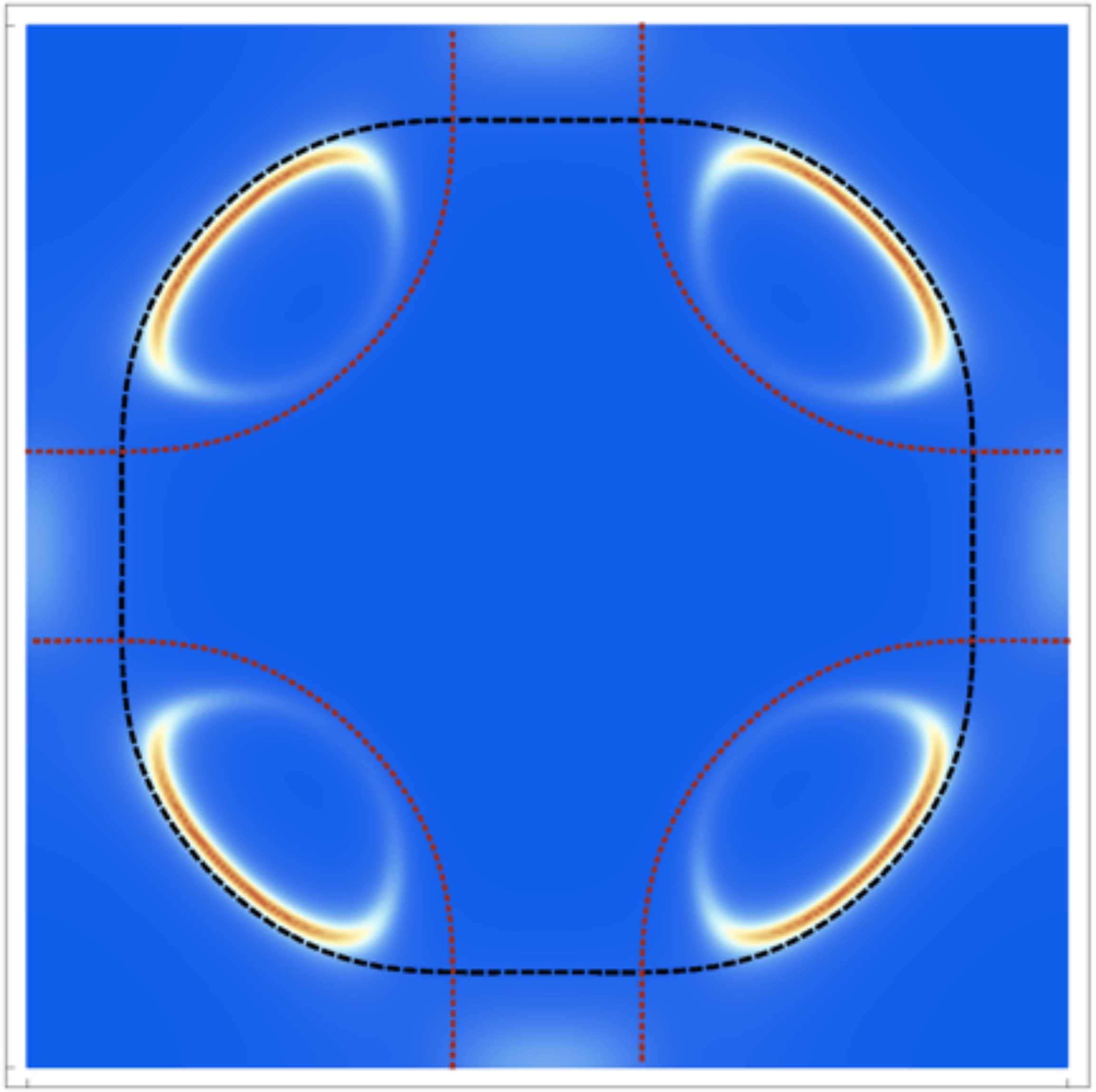
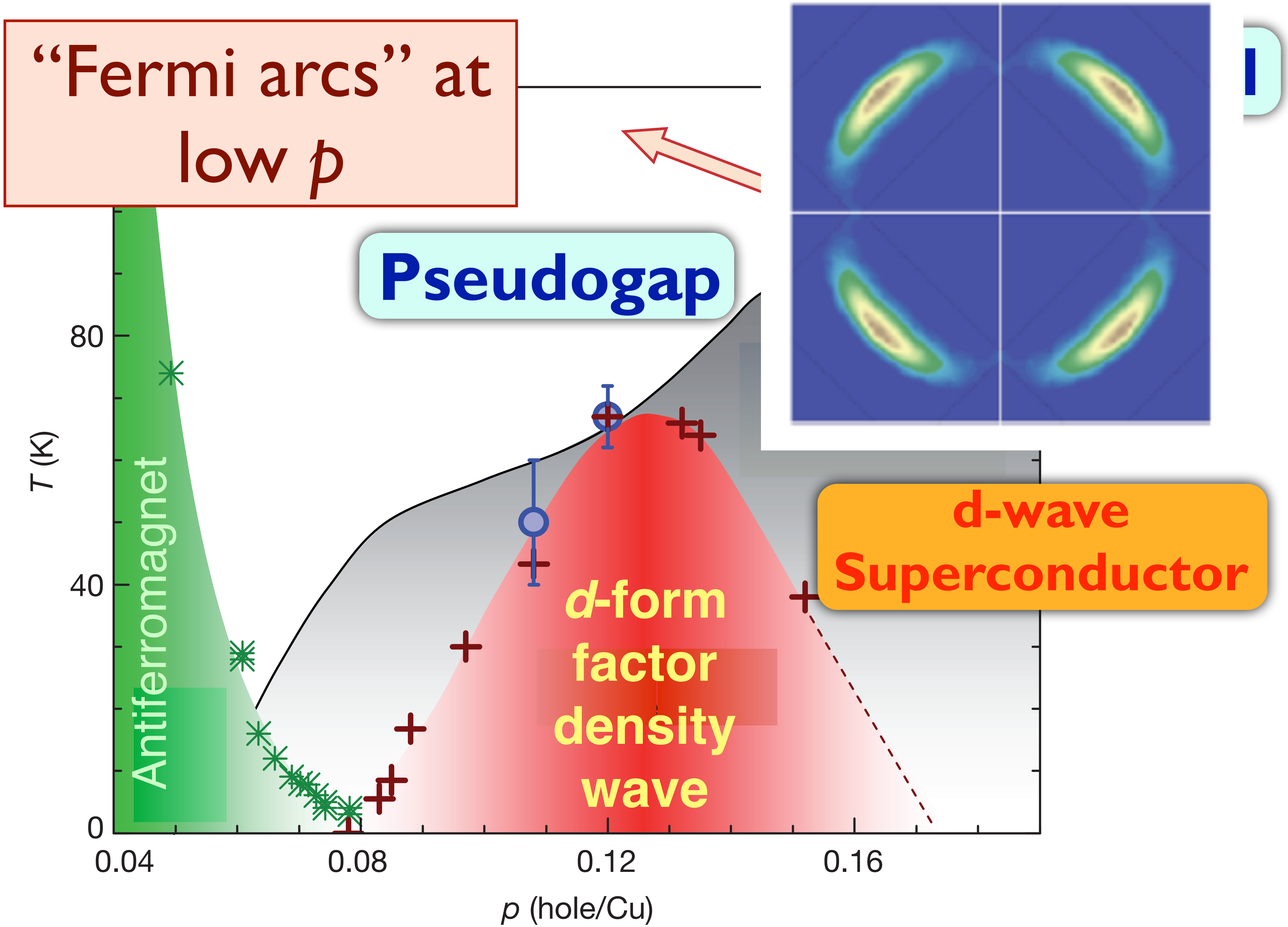


Electron spectral function of FL*

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

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



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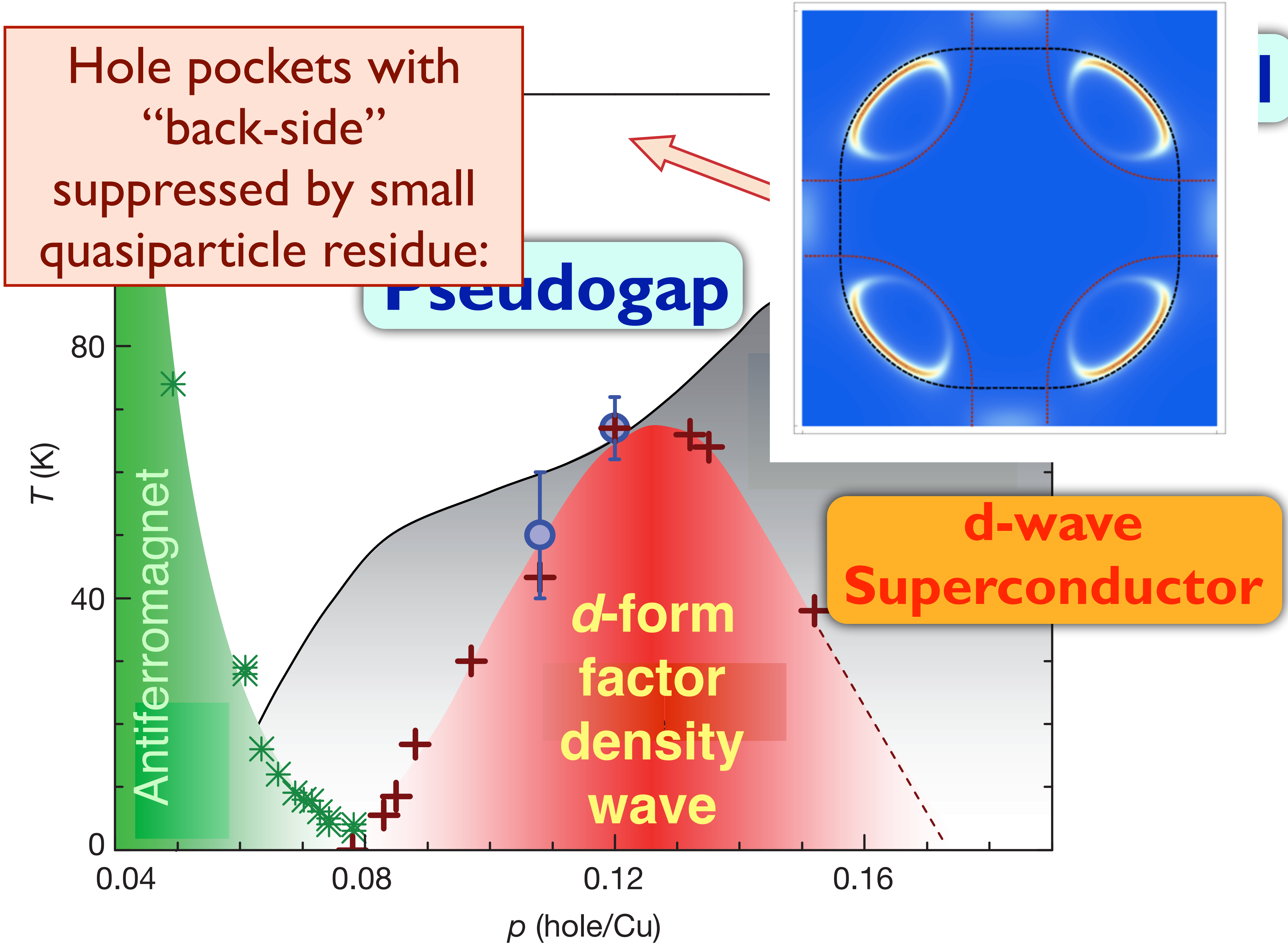

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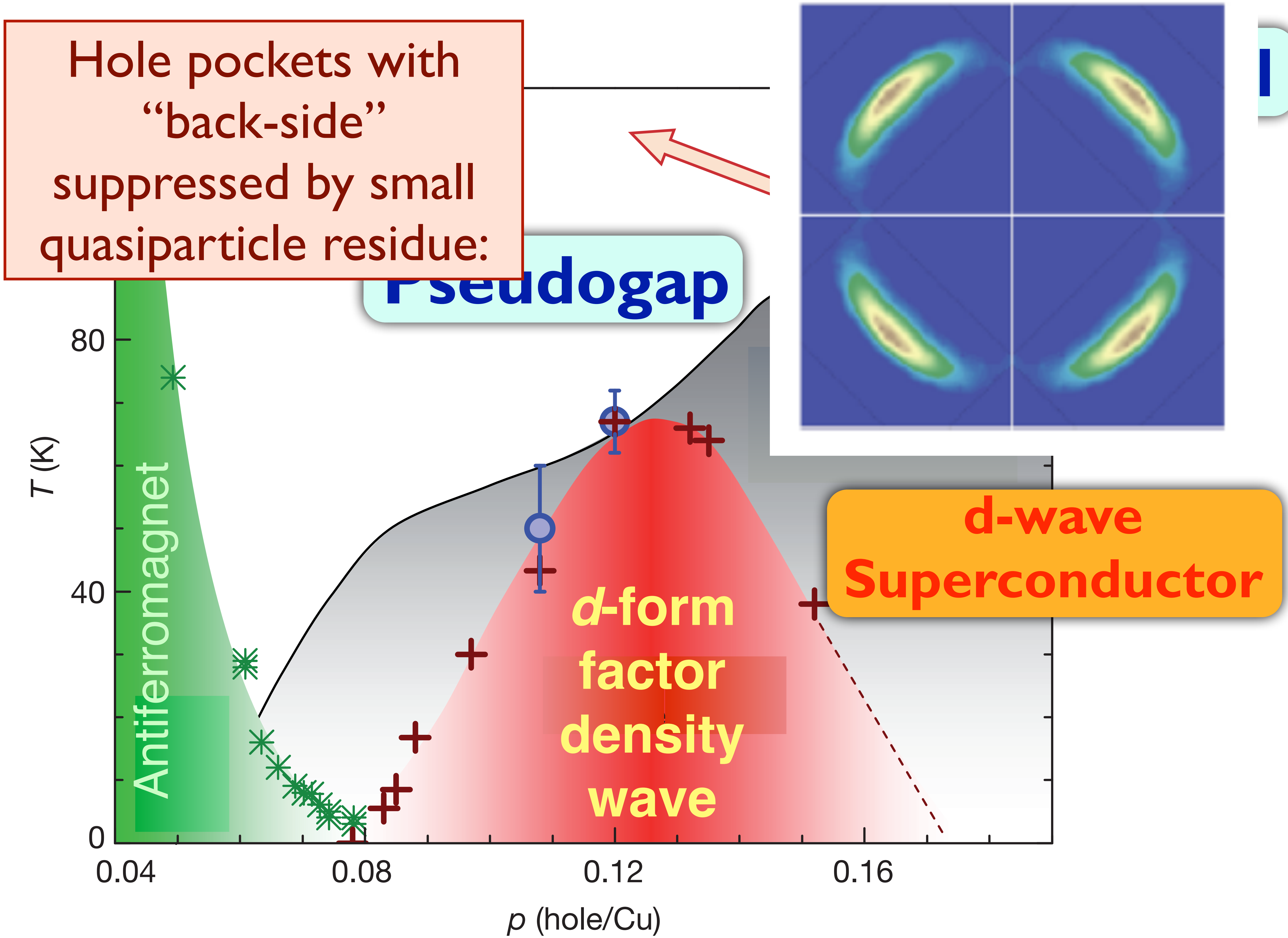
D. Chowdhury and S. Sachdev, arXiv:1409.5430



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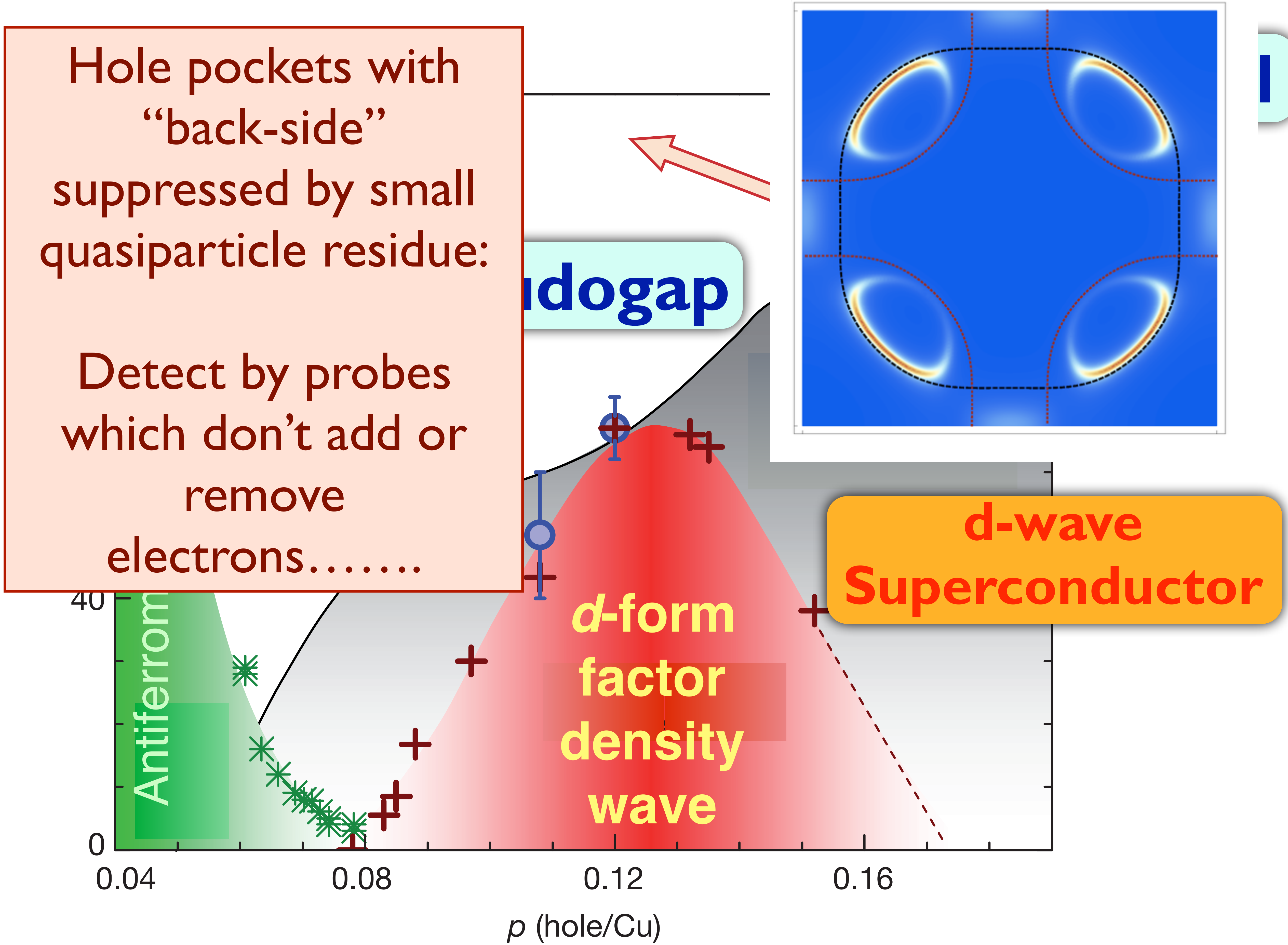

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Outline

1. The low *T* pseudogap:
   STM observation of predicted
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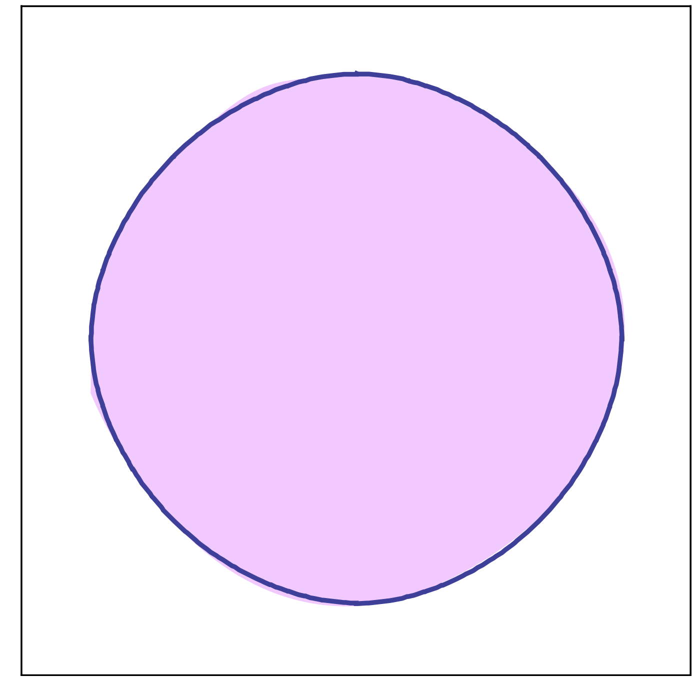
2. The high *T* pseudogap:
   A metal with topological order:
   *the Fractionalized Fermi liquid: FL**

3. Connecting high and low *T*:
   Density wave instabilities

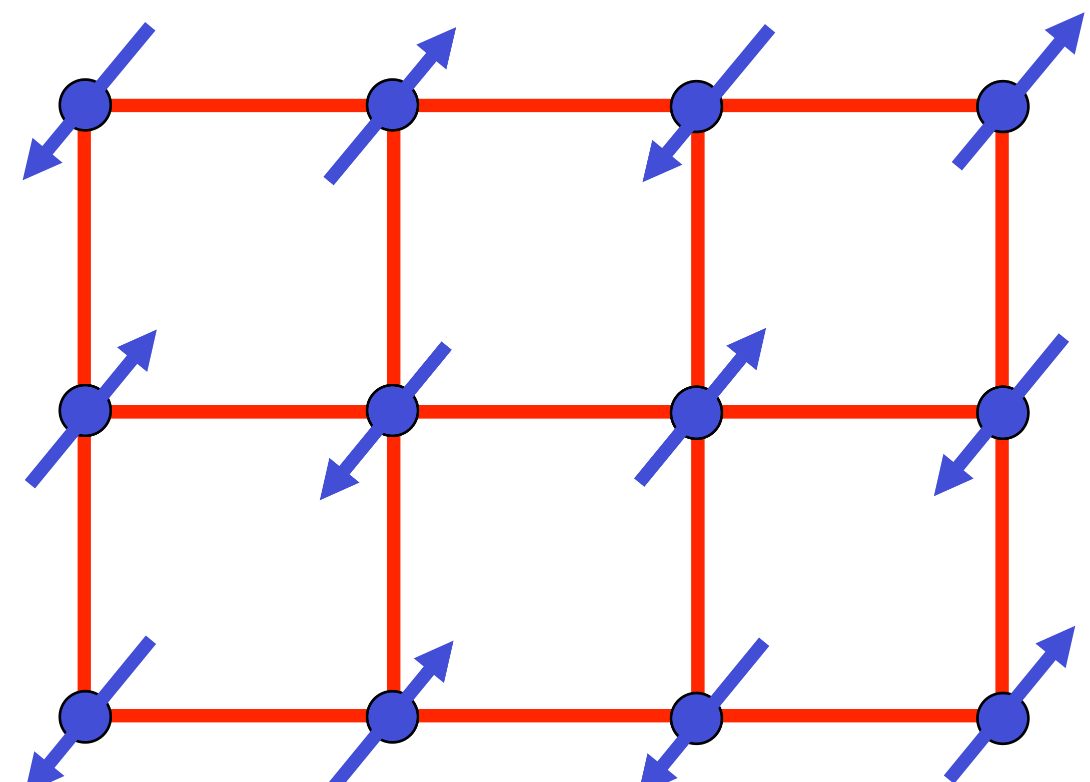
4. Quantum critical point near optimal *p*:
   A Higgs critical point

Fermi surface+antiferromagnetism

Metal with "large"
Fermi surface



+

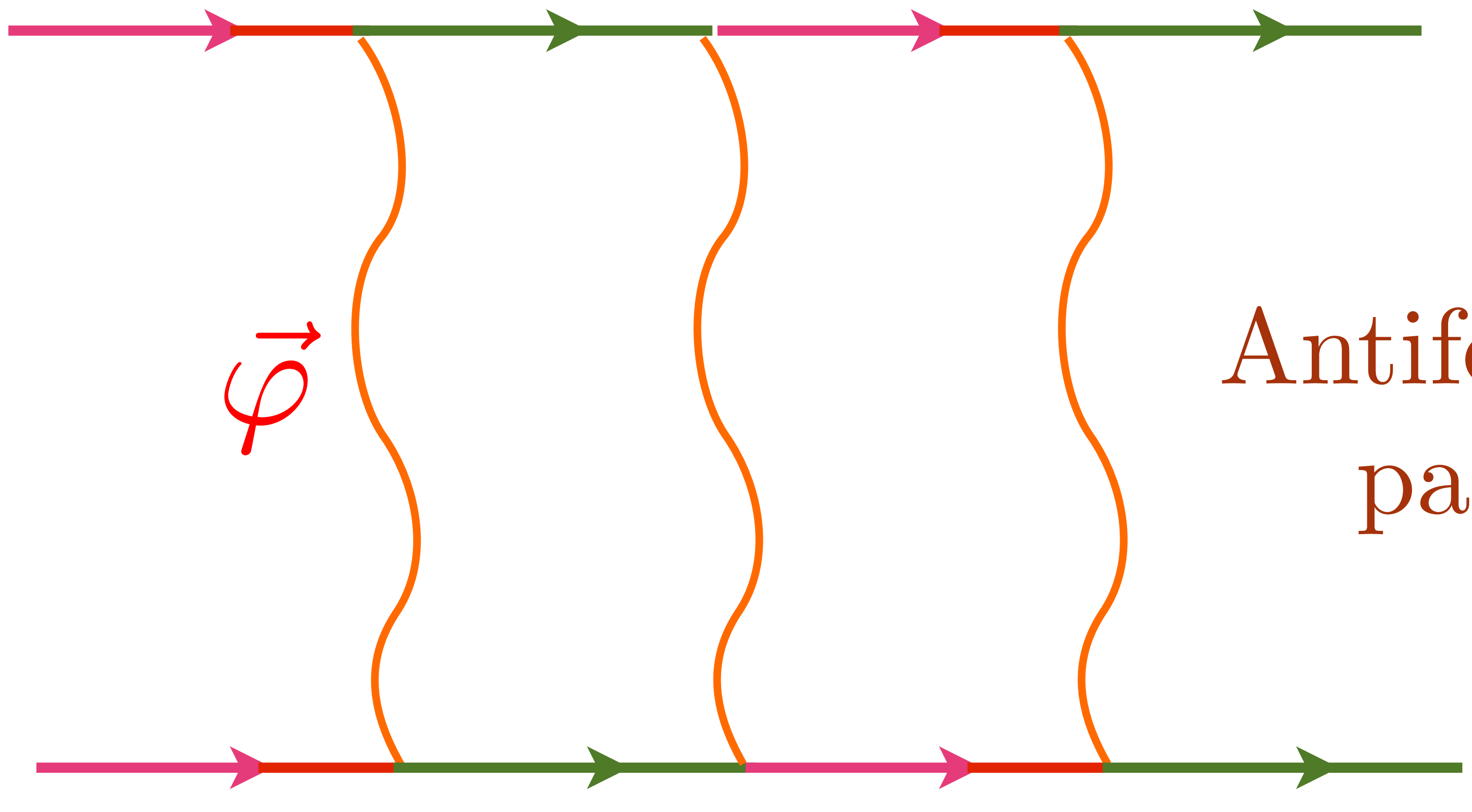


The electron spin polarization obeys

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

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

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



Antiferromagnetic paramagnon

V. J. Emery, *J. Phys. (Paris) Colloq.* **44**, C3-977 (1983)
D.J. Scalapino, E. Loh, and J.E. Hirsch, *Phys. Rev. B* **34**, 8190 (1986)
K. Miyake, S. Schmitt-Rink, and C. M.Varma, *Phys. Rev. B* **34**, 6554 (1986)
P. Monthoux, A.V. Balatsky, and D. Pines, *Phys. Rev. Lett.* **67**, 3448 (1991)

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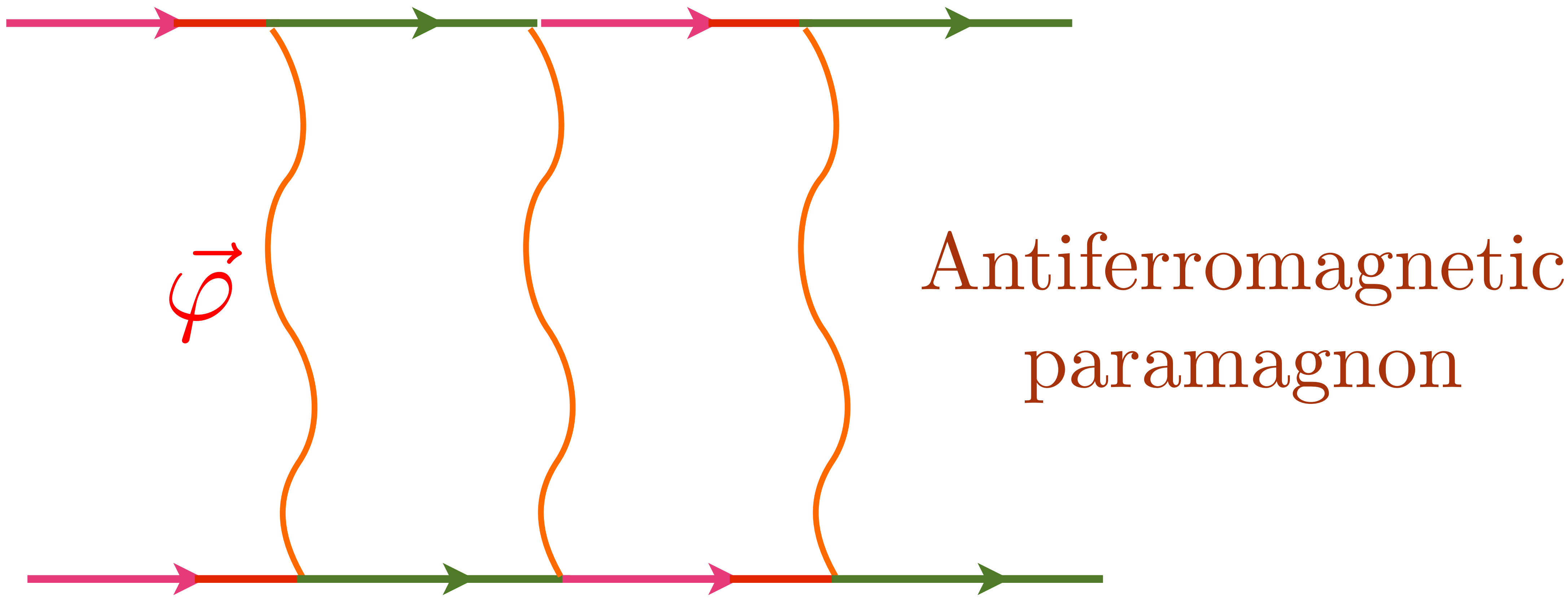

$$\text{Leads to } \left\langle c^\dagger_{\mathbf{k}\alpha} c^\dagger_{-\mathbf{k}\beta} \right\rangle = \varepsilon_{\alpha\beta} \Delta (\cos k_x - \cos k_y)$$

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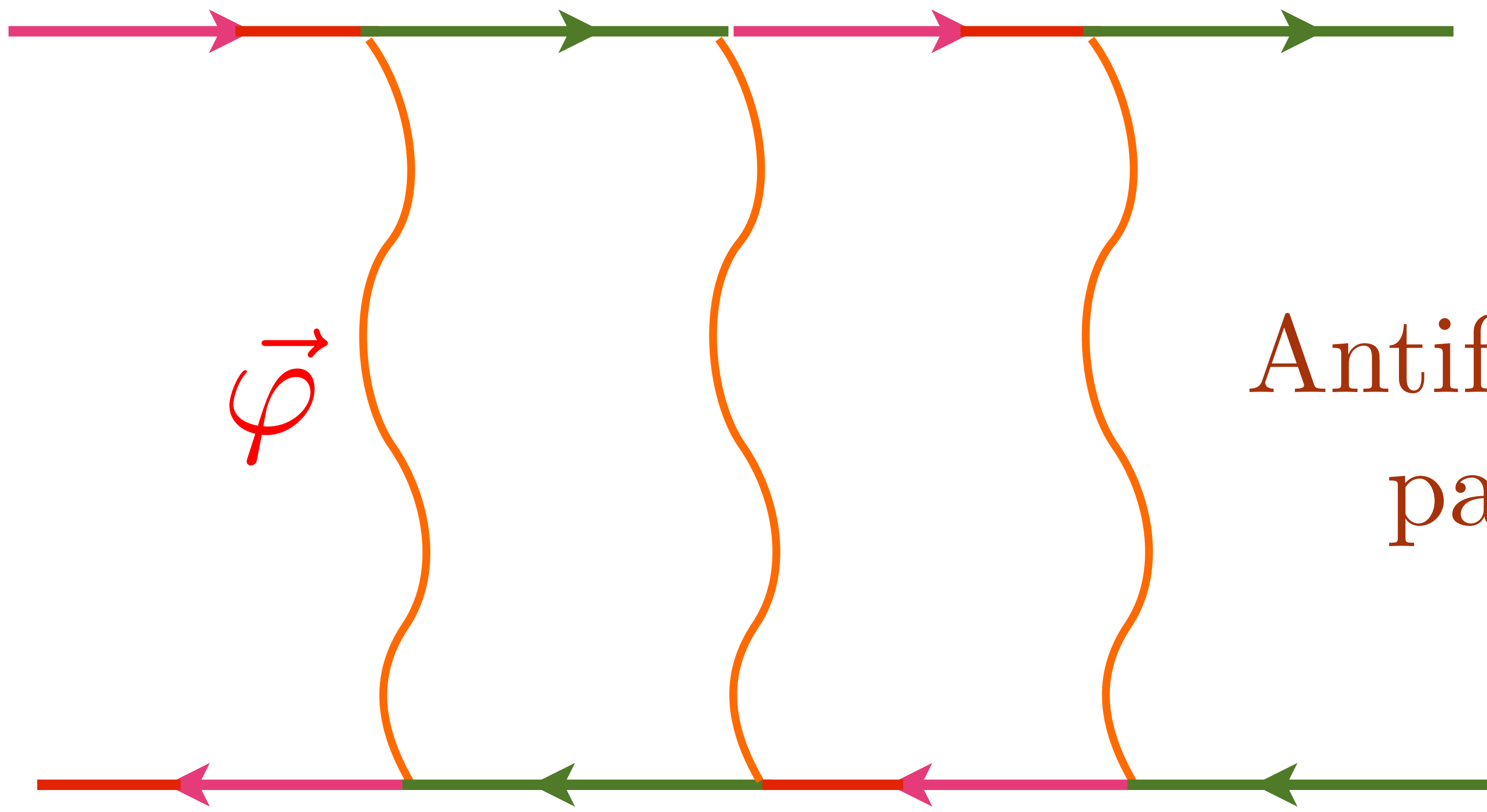
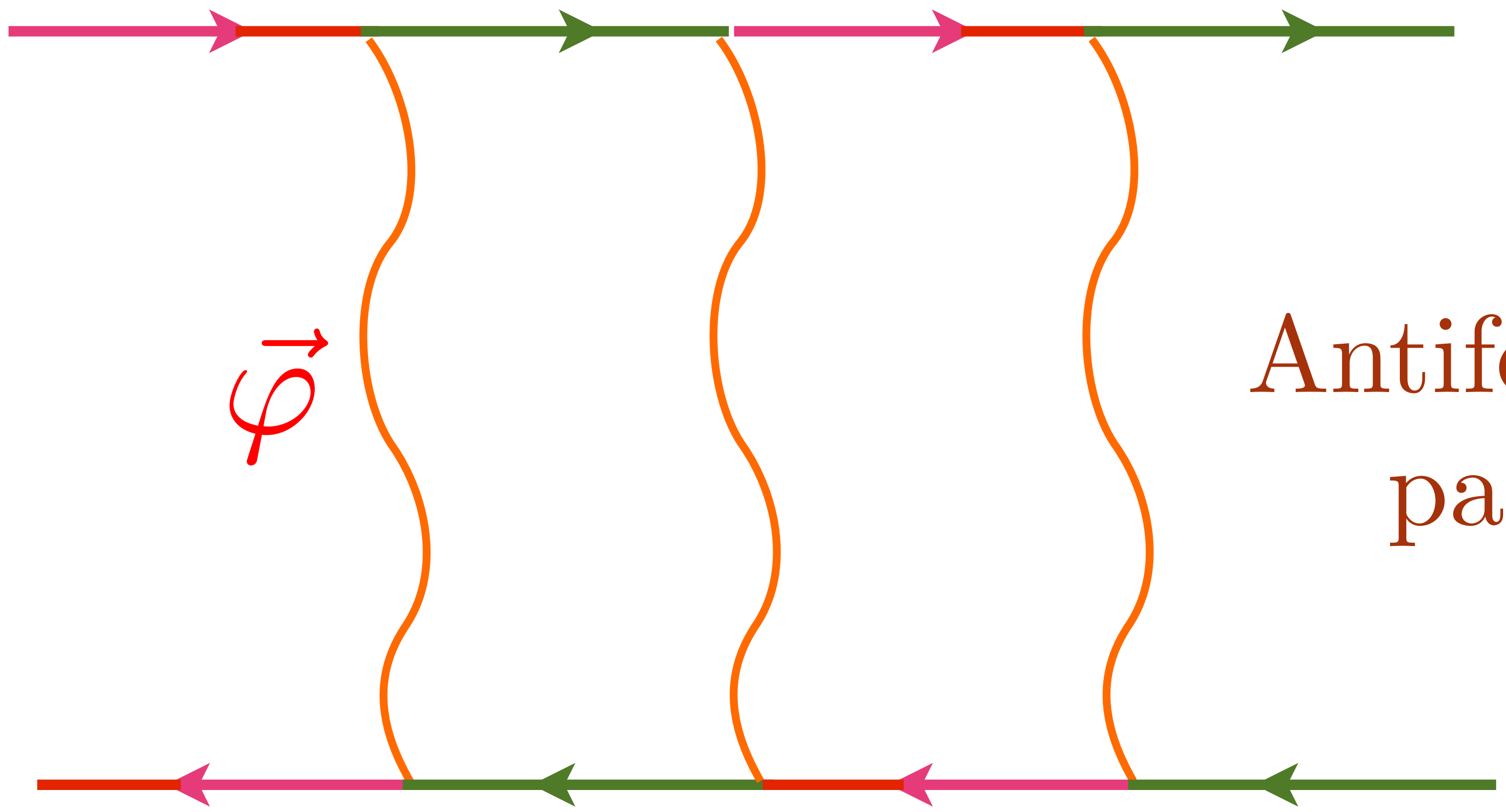
Same glue can lead to "d-wave" particle-hole pairing !



Antiferromagnetic paramagnon

M. A. Metlitski and S. Sachdev, Phys. Rev. B **85**, 075127 (2010)
T. Holder and W. Metzner, Phys. Rev. B **85**, 165130 (2012)
M. Bejas, A. Greco, and H. Yamase, Phys. Rev. B **86**, 224509 (2012)
S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013)
K. B. Efetov, H. Meier, and C. Pépin, Nat. Phys. **9**, 442 (2013)
J. D. Sau and S. Sachdev, Phys. Rev. B **89**, 075129 (2014)
Y. Wang and A. V. Chubukov, Phys. Rev. B **90**, 035149 (2014)

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



Leads to $\left\langle c^{\dagger}_{\mathbf{k}+\mathbf{Q}/2,\alpha} c_{\mathbf{k}-\mathbf{Q}/2,\alpha} \right\rangle =$
$\mathcal{P}_s + \mathcal{P}_{s'}(\cos k_x + \cos k_y) + \mathcal{P}_d(\cos k_x - \cos k_y)$
with $\mathcal{P}_d$ dominant.

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

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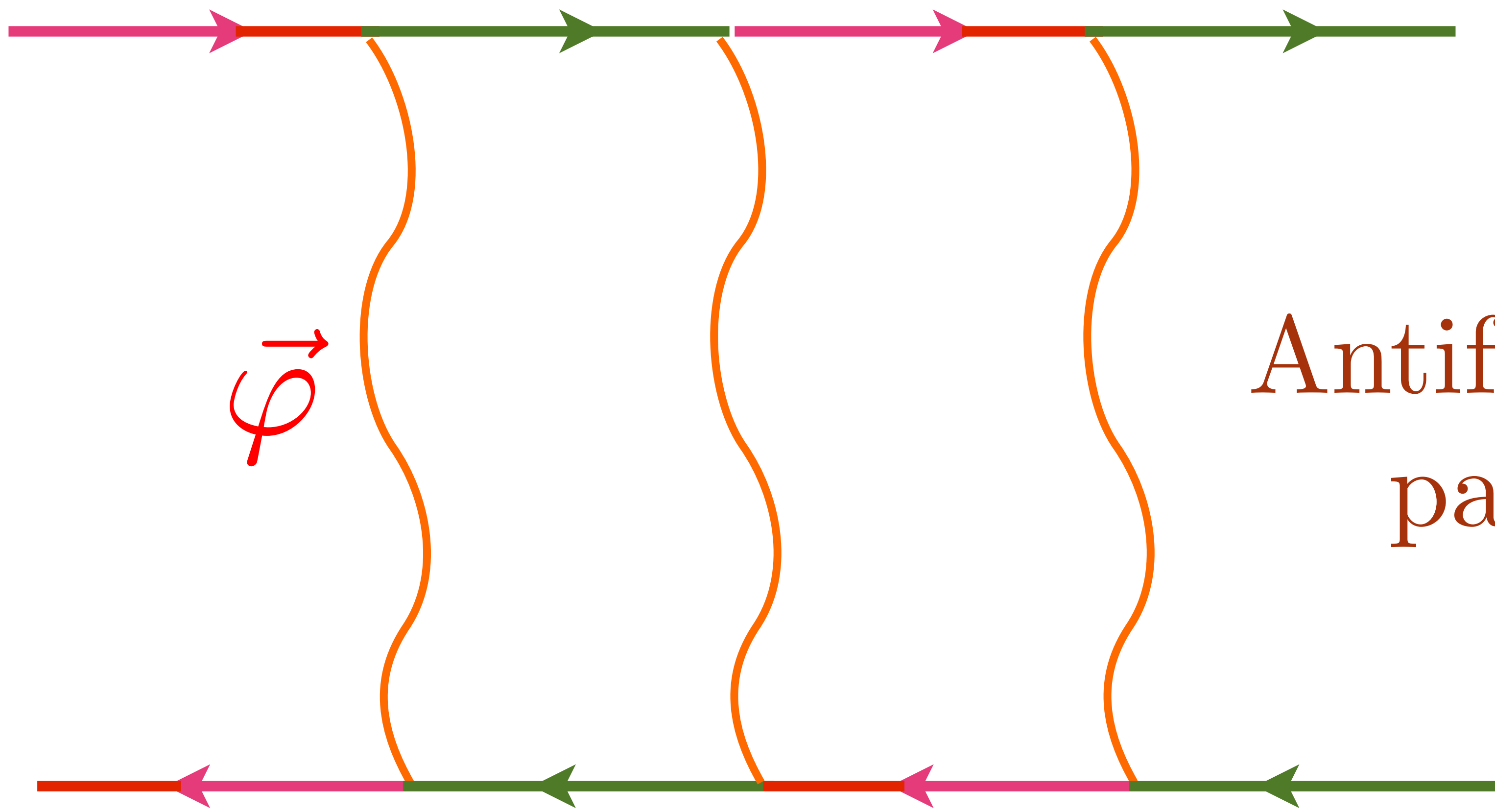

Antiferromagnetic paramagnon

Note: previous work on density waves with non-zero angular momentum used $\left\langle c^\dagger_{\mathbf{k}+\mathbf{Q},\alpha} c_{\mathbf{k},\alpha} \right\rangle \sim (\cos k_x - \cos k_y)$;
this is a *different* state which has components both even and odd under time-reversal.

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

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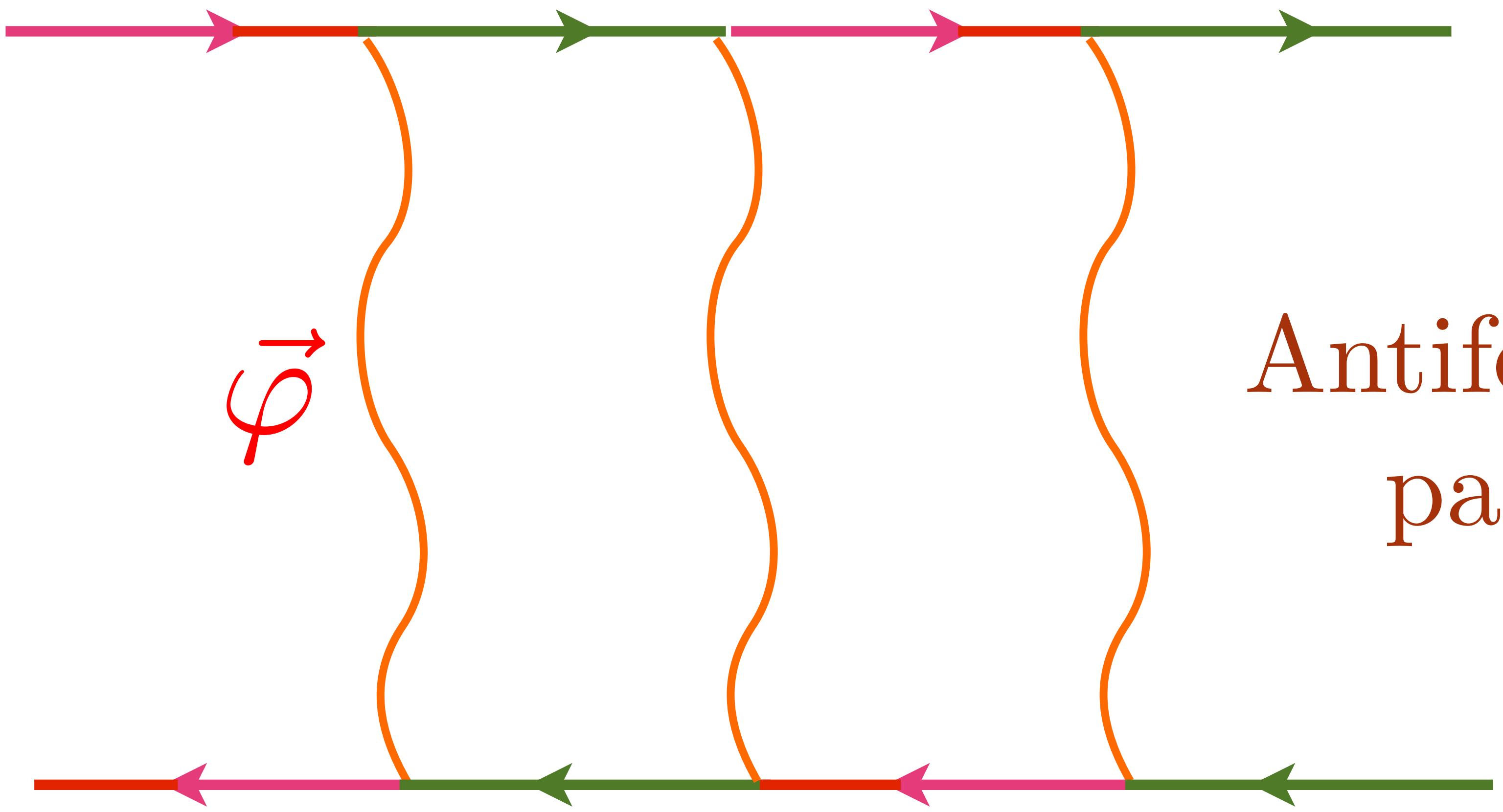

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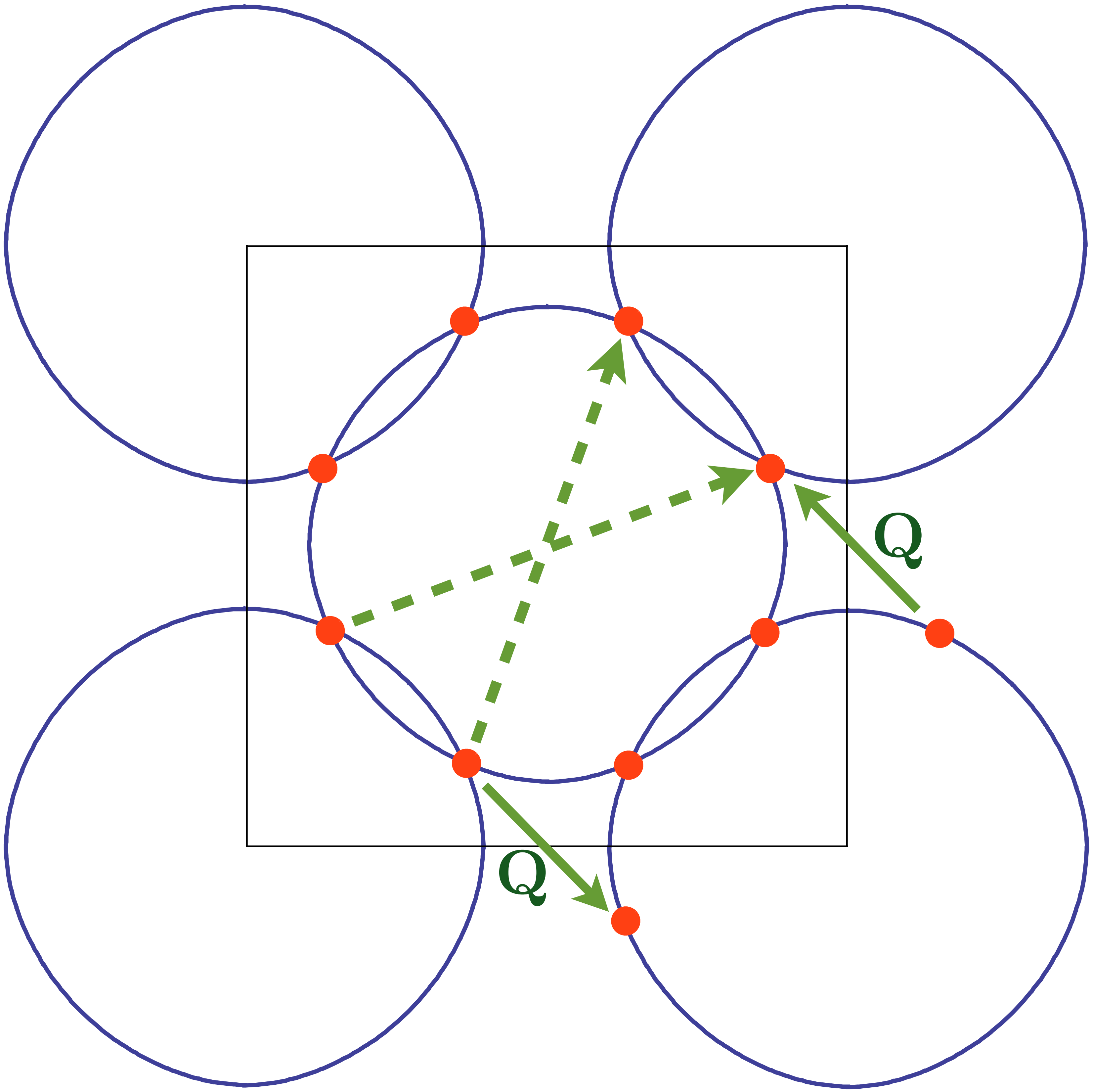
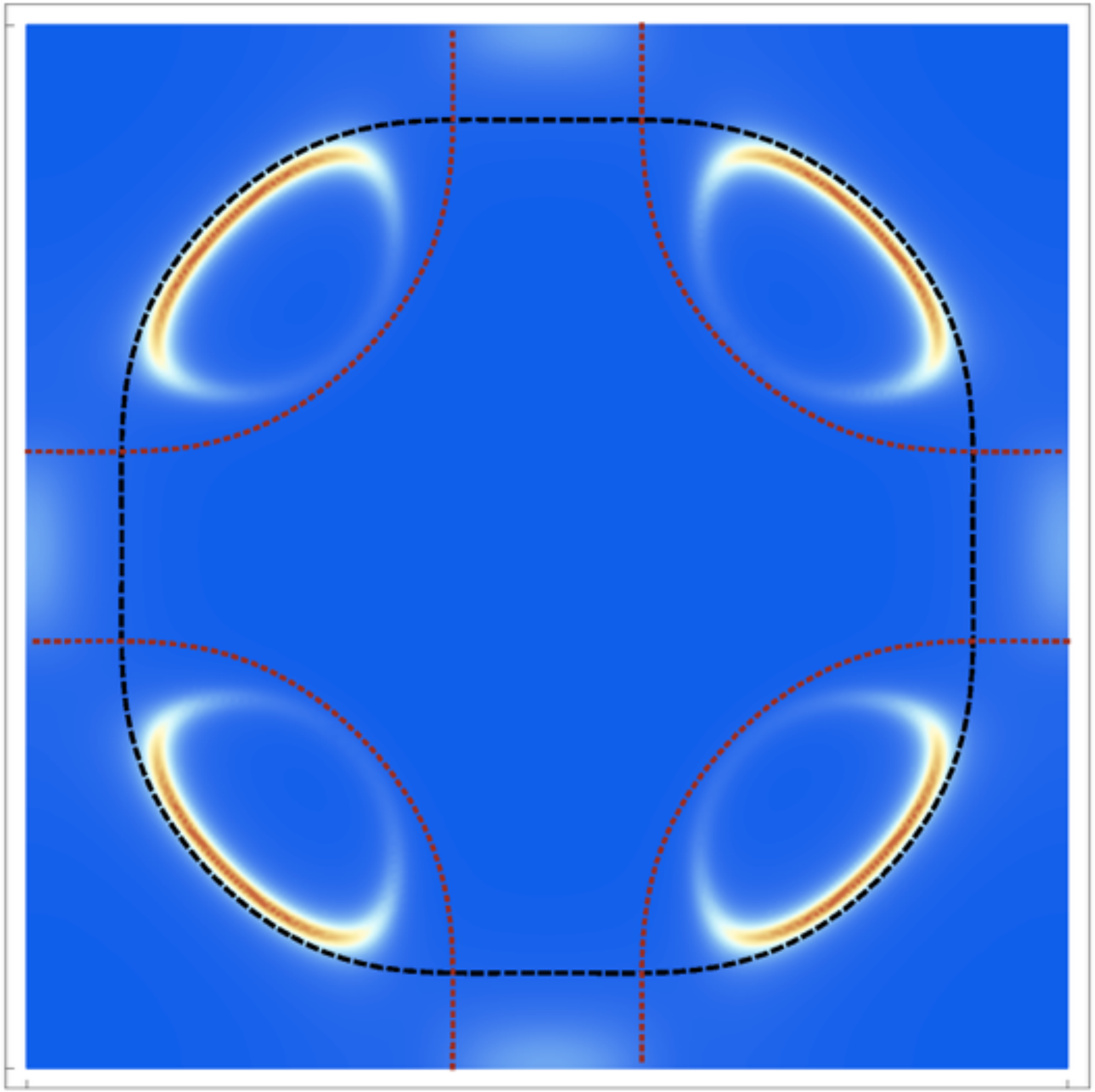


Density wave instability of large Fermi surface leads to an incorrect "diagonal" wavevector

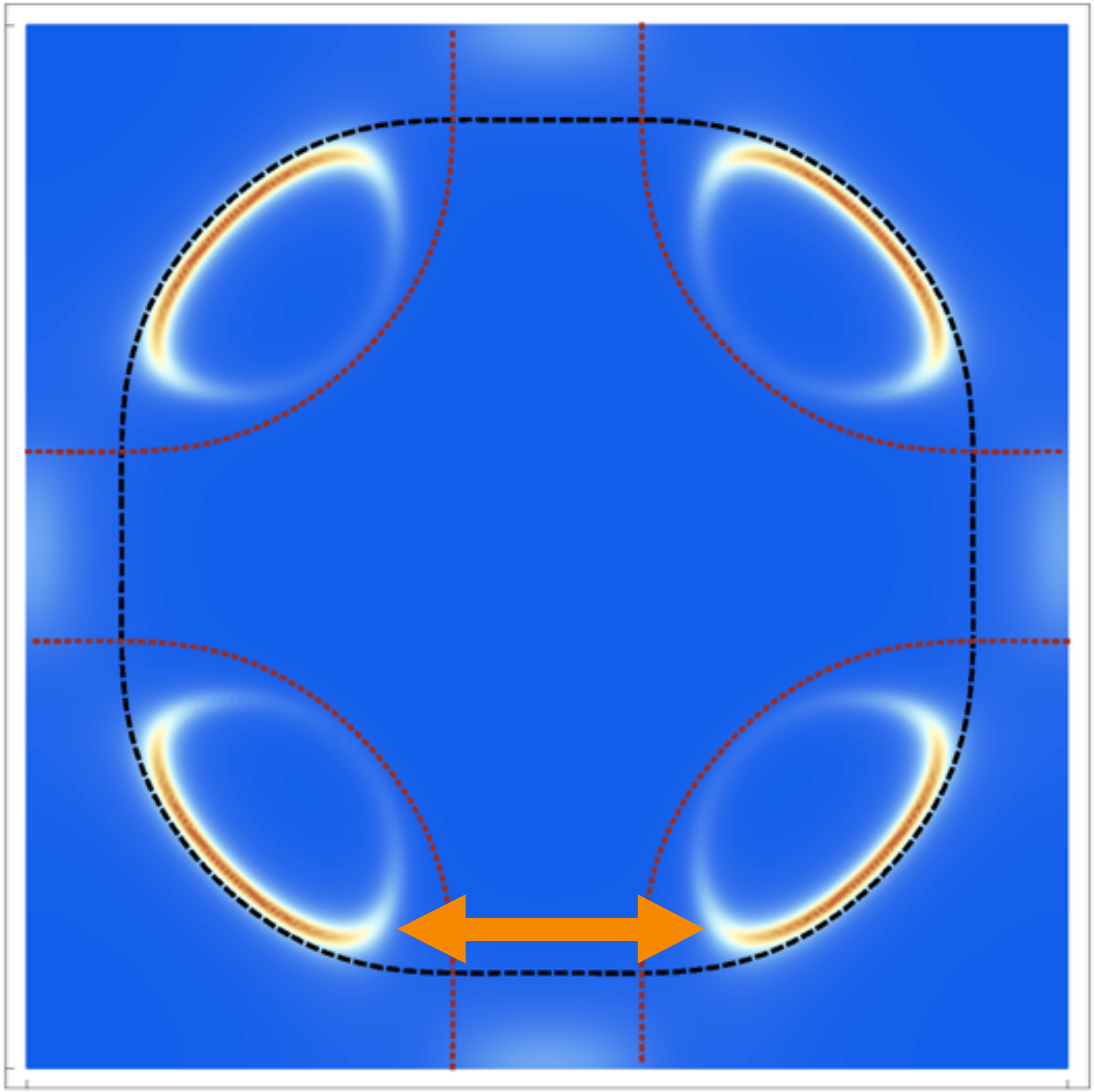
$$\left\langle c^\dagger_{\mathbf{k}-\mathbf{Q}/2,\alpha} c_{\mathbf{k}+\mathbf{Q}/2,\alpha} \right\rangle = \mathcal{P}_d (\cos k_x - \cos k_y)$$

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



Fermi surface of FL*

Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)



Density wave instability of FL* leads to the observed wavevector and form-factor

D. Chowdhury and S. Sachdev, arXiv:1409.5430

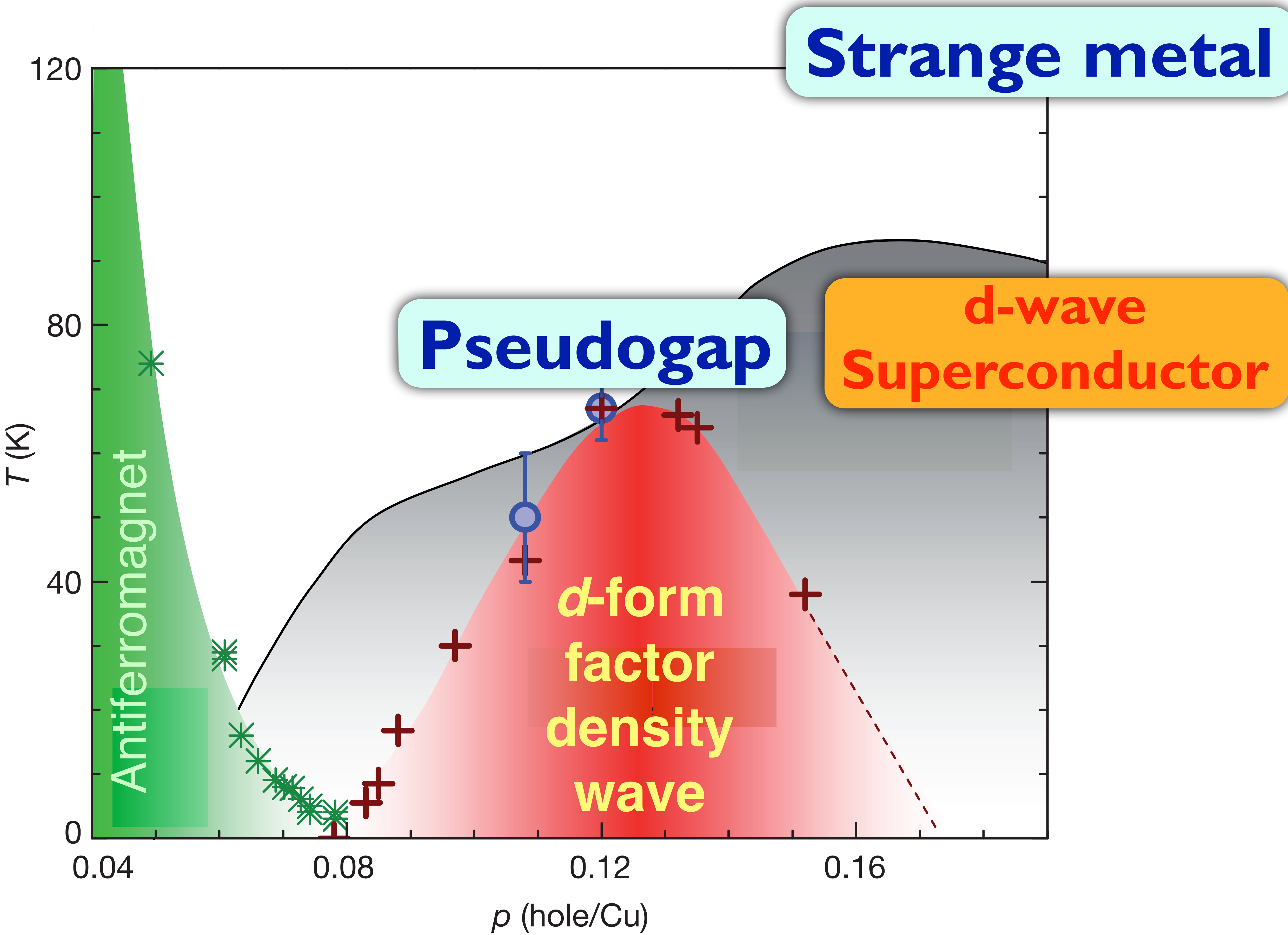
Outline

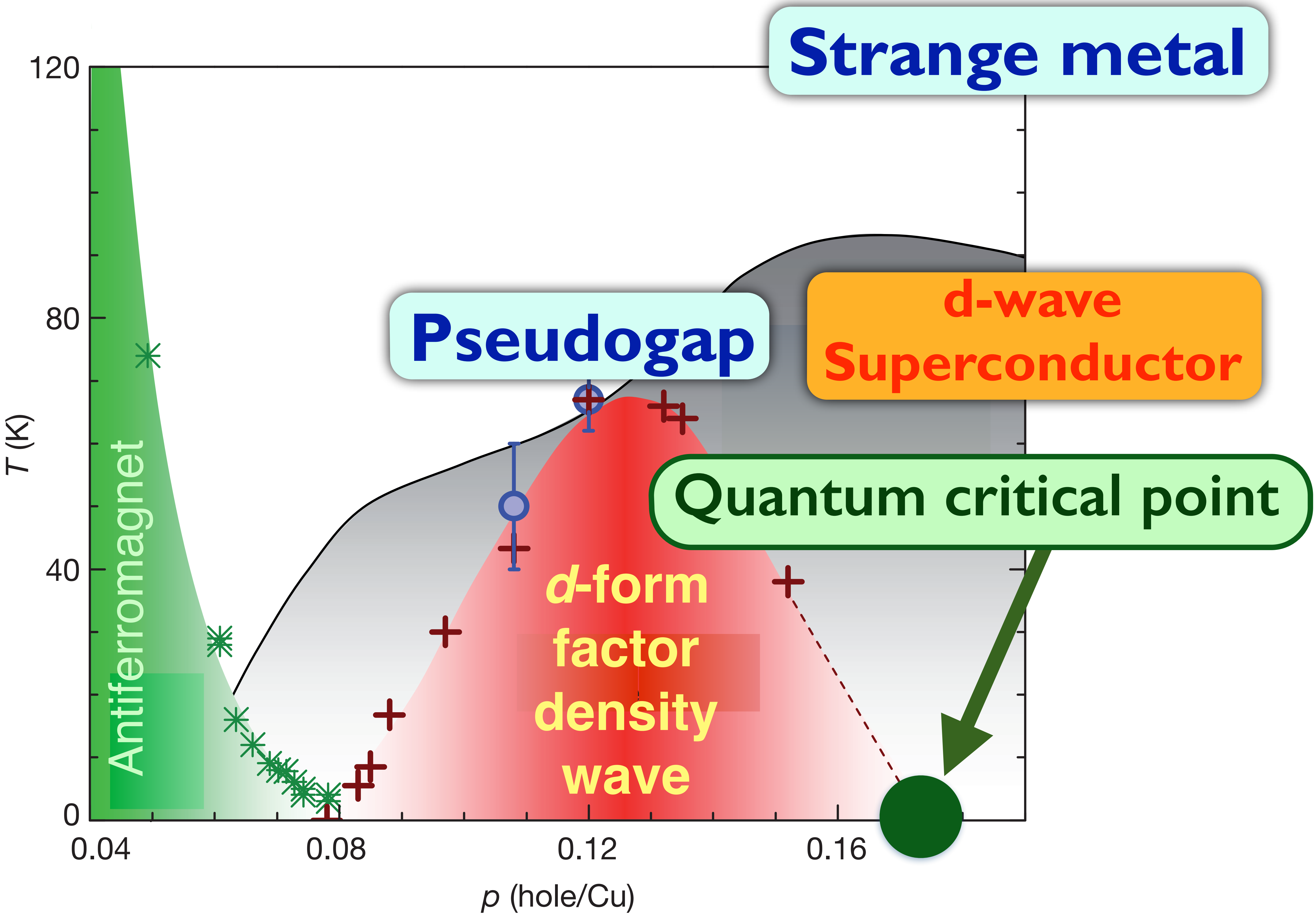
1. The low T pseudogap:
   STM observation of predicted d-form factor density wave

2. The high T pseudogap:
   *A metal with topological order: the Fractionalized Fermi liquid: FL**

3. Connecting high and low T:
   Density wave instabilities

4. Quantum critical point near optimal p:
   A Higgs critical point


Strange metal
120
80
40
0
T (K)
Antiferromagnet
Pseudogap
d-wave
Superconductor
d-form
factor
density
wave
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)

SU(2) gauge theory for underlying quantum critical point

Write the electron operator c_α ($\alpha = \uparrow, \downarrow$ are spin indices) as

$$\left(\begin{array}{c} c_\uparrow \\ c_\downarrow \end{array} \right) = R \left(\begin{array}{c} \psi_+ \\ \psi_- \end{array} \right)$$

where R is a SU(2) matrix which determines the orientation of the local antiferromagnetic order, and $\psi_\pm$ are spinless fermions which carry the global electron U(1) charge.

This parameterization is invariant under a SU(2) *gauge* transformation

$$\left(\begin{array}{c} \psi_+ \\ \psi_- \end{array} \right) \rightarrow U \left(\begin{array}{c} \psi_+ \\ \psi_- \end{array} \right) \quad ; \quad R \rightarrow R U^\dagger$$

S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, Phys. Rev. B **80**, 155129 (2009)
D. Chowdhury and S. Sachdev, arXiv:1412.1086

SU(2) gauge theory for underlying quantum critical point

Assume field R is non-critical.

- Fermion ψ, transforming as a gauge SU(2) fundamental, with dispersion $\varepsilon_{\mathbf{k}}$ from the band structure, at a non-zero chemical potential: has a "large" Fermi surface.

- A SU(2) gauge boson.

- A real Higgs field, H, transforming as a gauge SU(2) adjoint, carrying lattice momentum (π, π). Condensation of the Higgs breaks SU(2) $\rightarrow$ U(1), and transforms the large Fermi surface to a small Fermi surface.

S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, Phys. Rev. B **80**, 155129 (2009)
D. Chowdhury and S. Sachdev, arXiv:1412.1086

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- The quantum critical theory is the Higgs transition where the gauge "symmetry" breaks from SU(2) down to U(1), in the presence of a Fermi surface of fermions carrying fundamental SU(2) charges.

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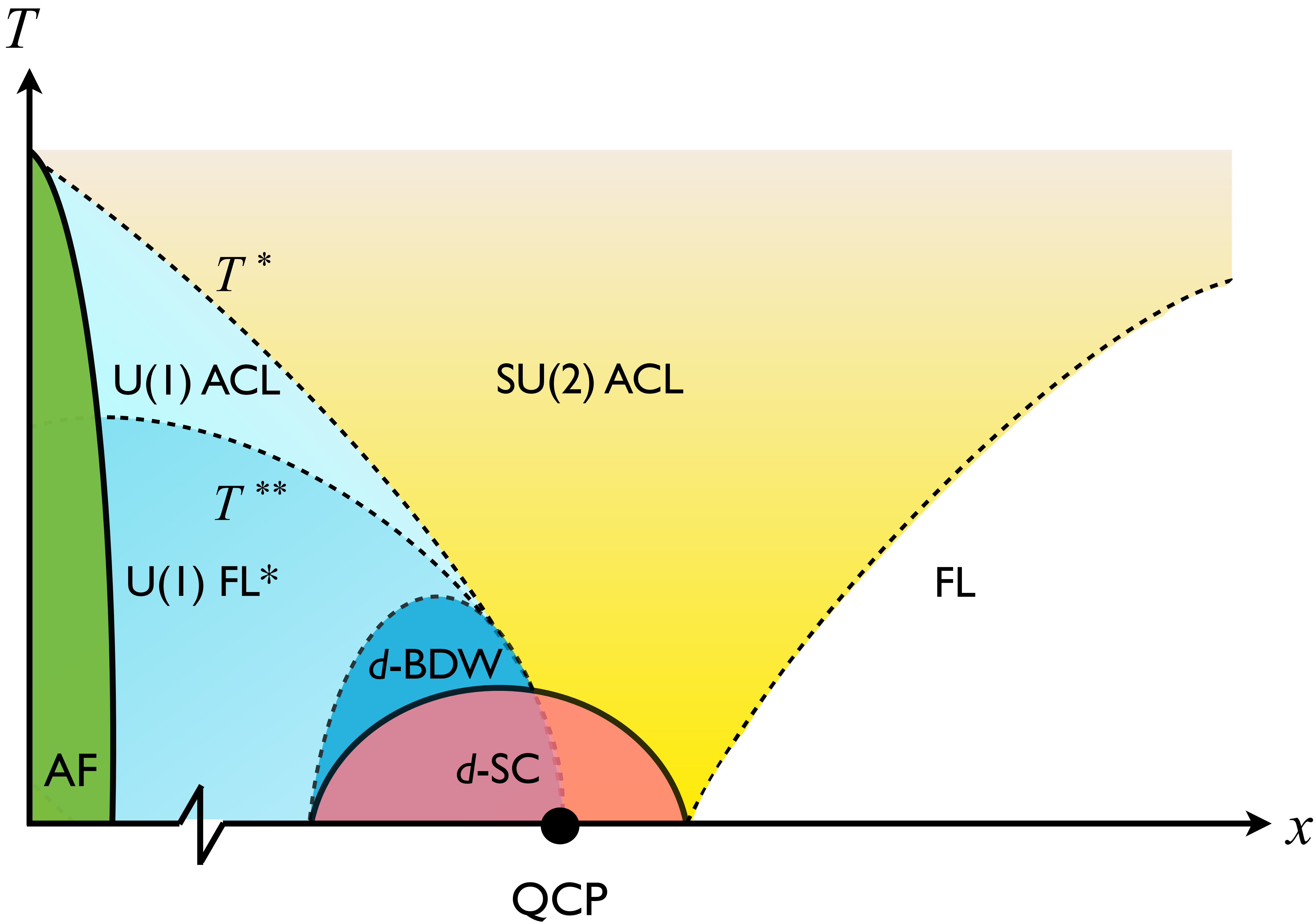

D. Chowdhury and S. Sachdev, arXiv:1412.1086

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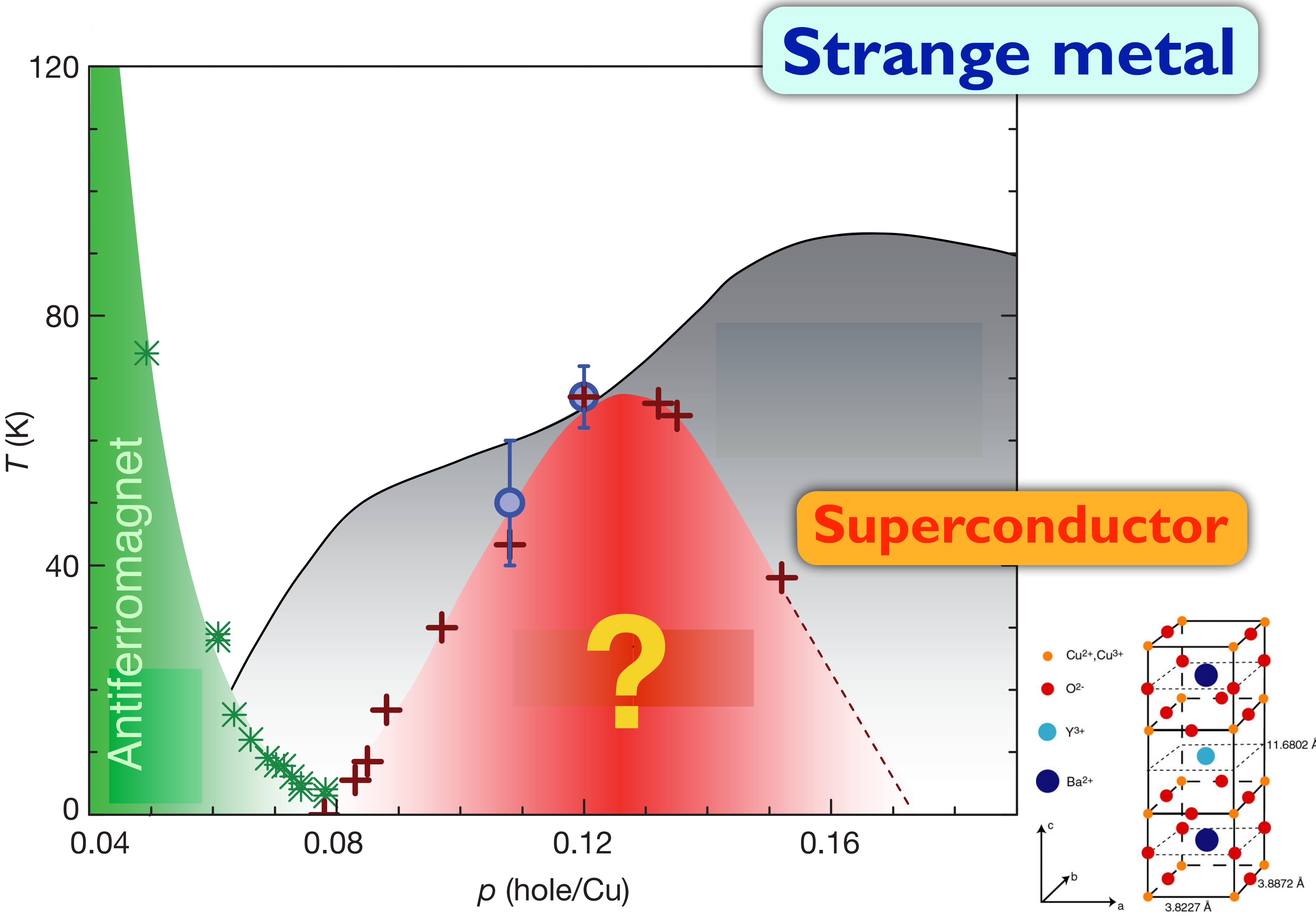
- The quantum phase transition has no gauge-invariant "order parameter", and it does not break any global symmetries.

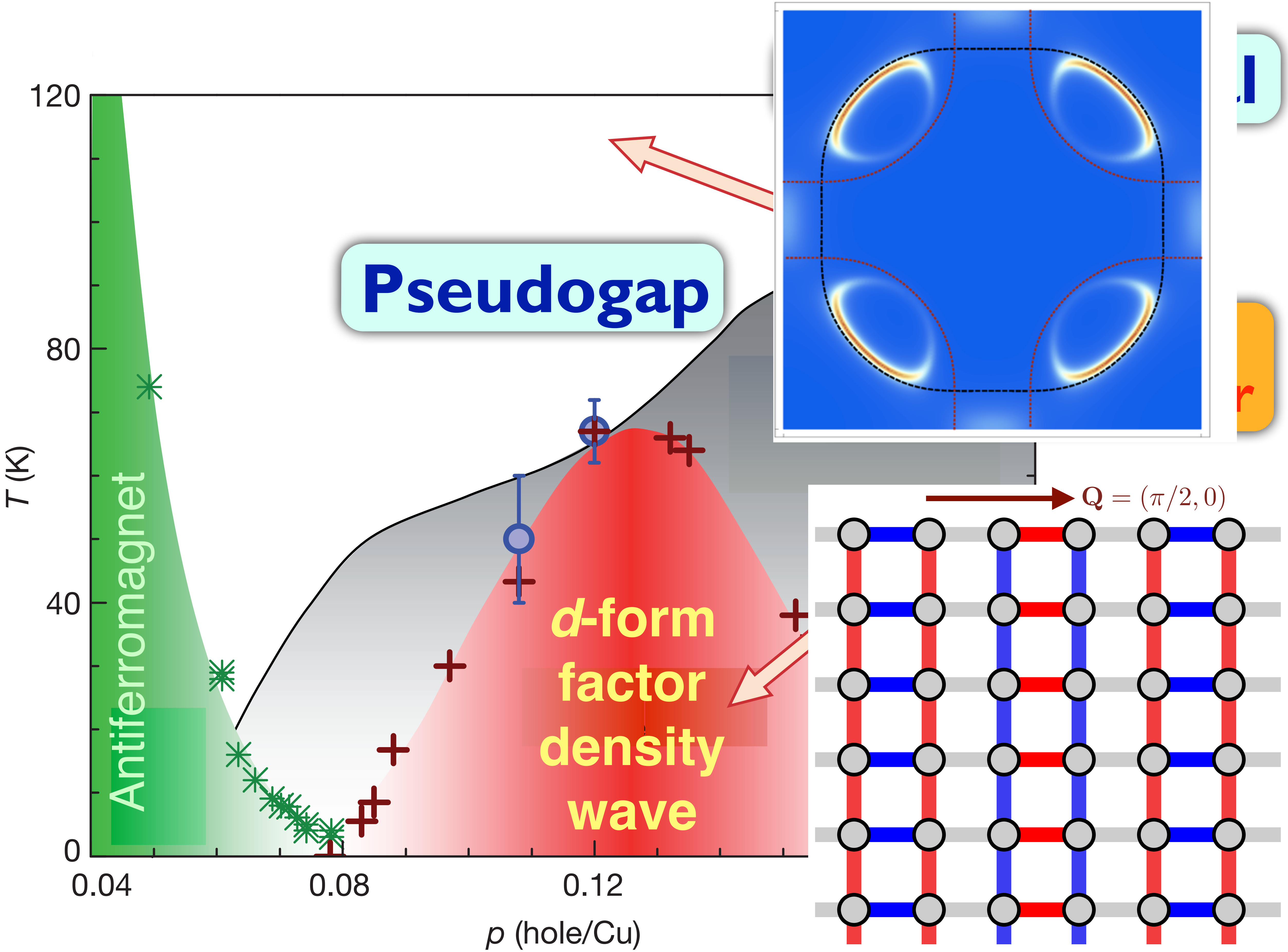
S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, Phys. Rev. B **80**, 155129 (2009)
D. Chowdhury and S. Sachdev, arXiv:1412.1086

Conclusions

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

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


Strange metal
Superconductor
Antiferromagnet
?
120
80
40
0
T (K)
0.04
0.08
0.12
0.16
p (hole/Cu)
Cu2+,Cu3+
O2-
Y3+
Ba2+
c
b
a
3.8227 Å
3.8872 Å



Pseudogap
Antiferromagnet
d-form factor density wave
T (K)
p (hole/Cu)
120
80
40
0
0.04
0.08
0.12
$\mathbf{Q} = (\pi/2, 0)$
$\Delta\rho$
+1
0
−1