The pseudogap phase of the cuprate superconductors

University of Colorado, Boulder
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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

NSF

JOHN TEMPLETON FOUNDATION

PHYSICS HARVARD

Talk online: sachdev.physics.harvard.edu

Theorists at Harvard

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(KITP, UCSB)

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Cornell

Kazuhiro Fujita
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Stephen Edkins
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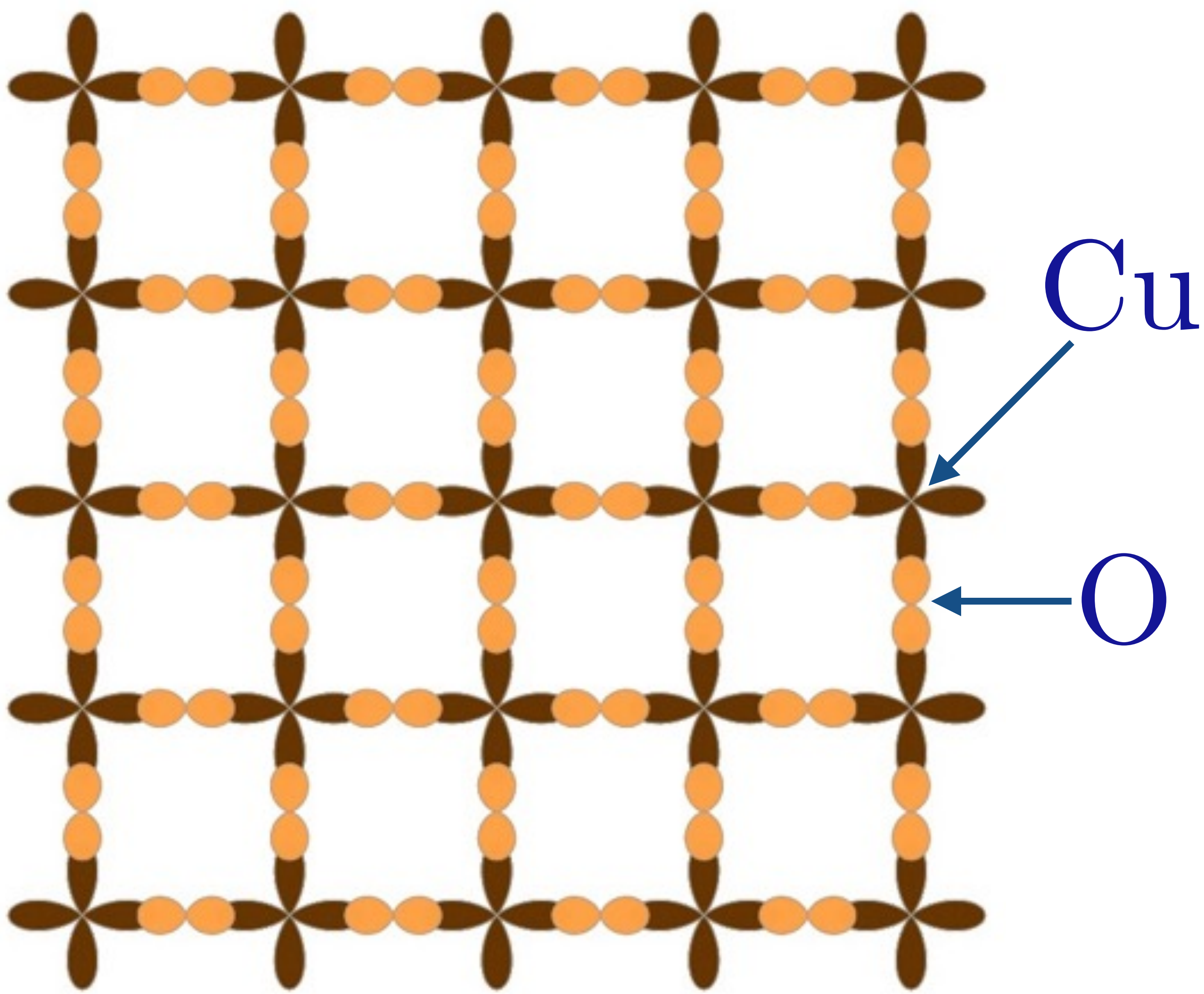
Michael Lawler

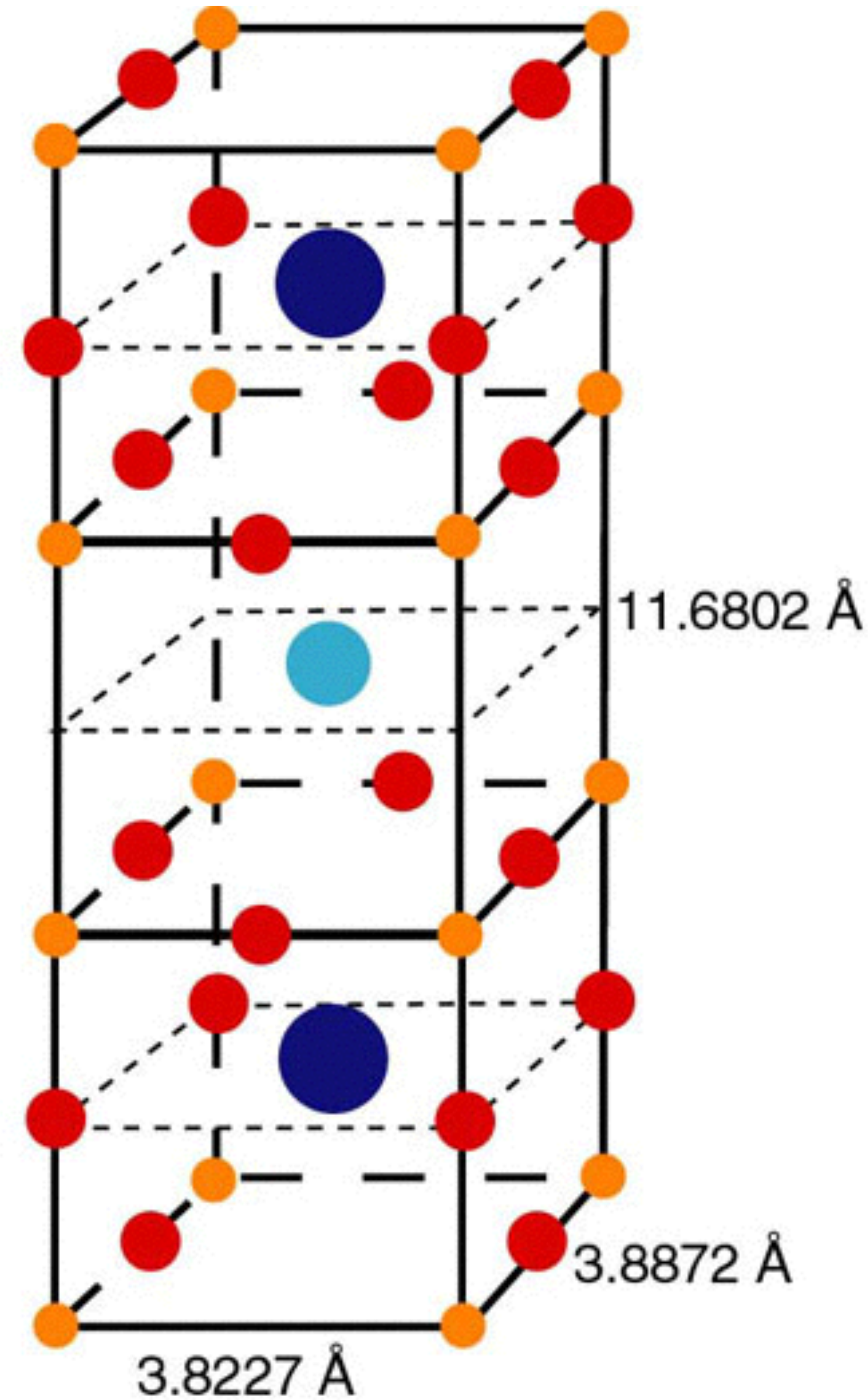
J. C. Seamus Davis

Eun-Ah Kim

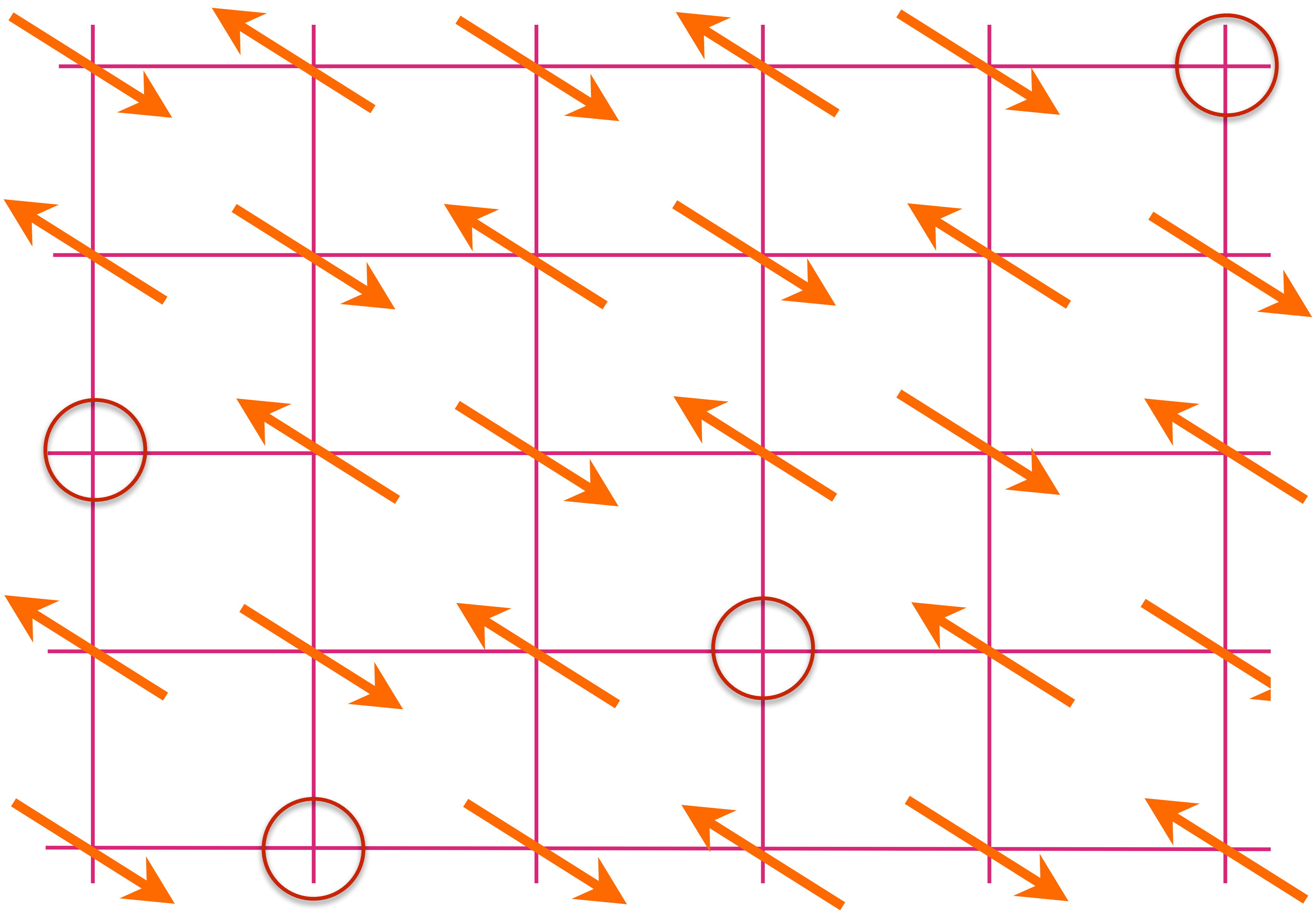
High temperature superconductors



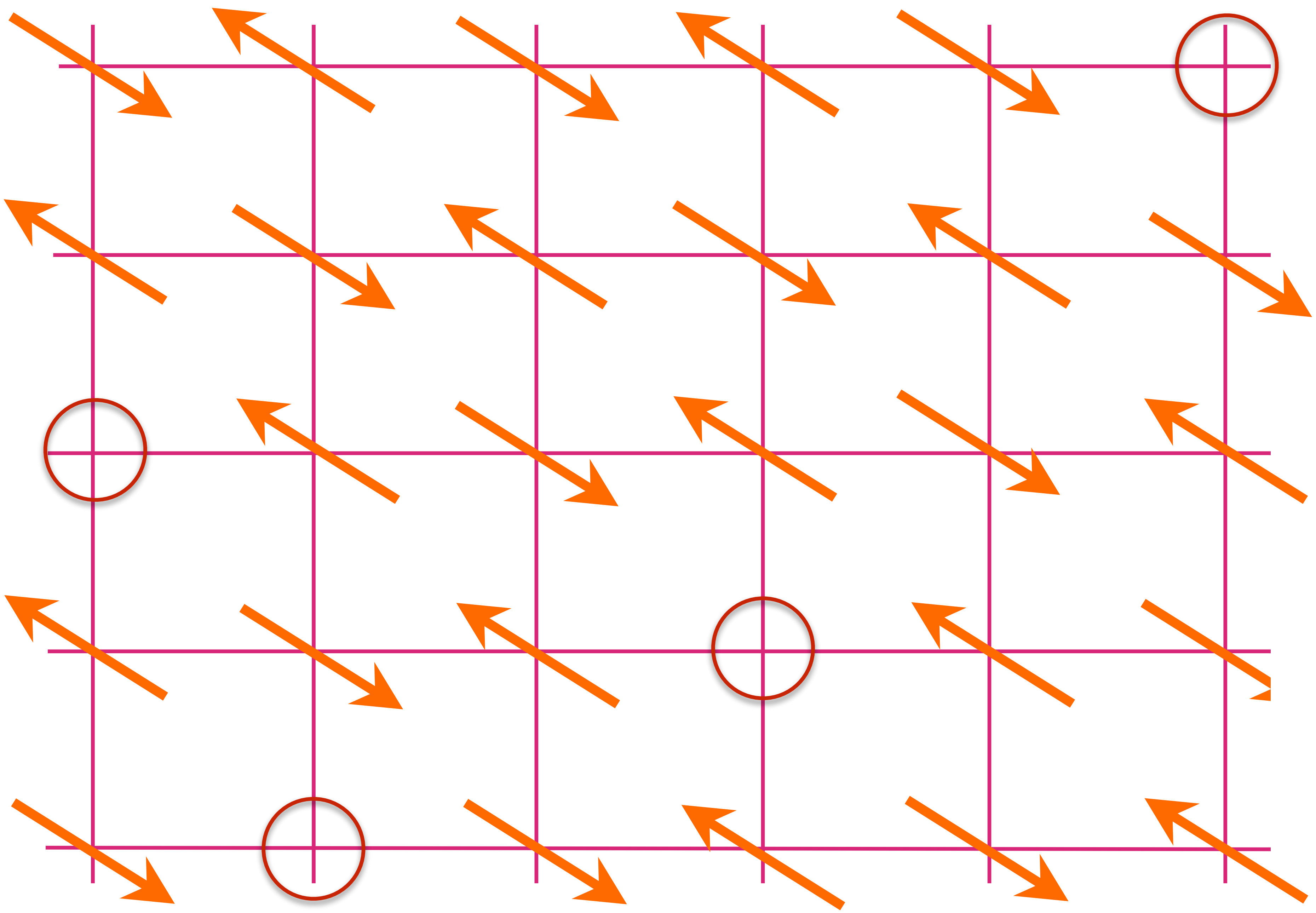
CuO_2 plane



$YBa_2Cu_3O_{6+x}$

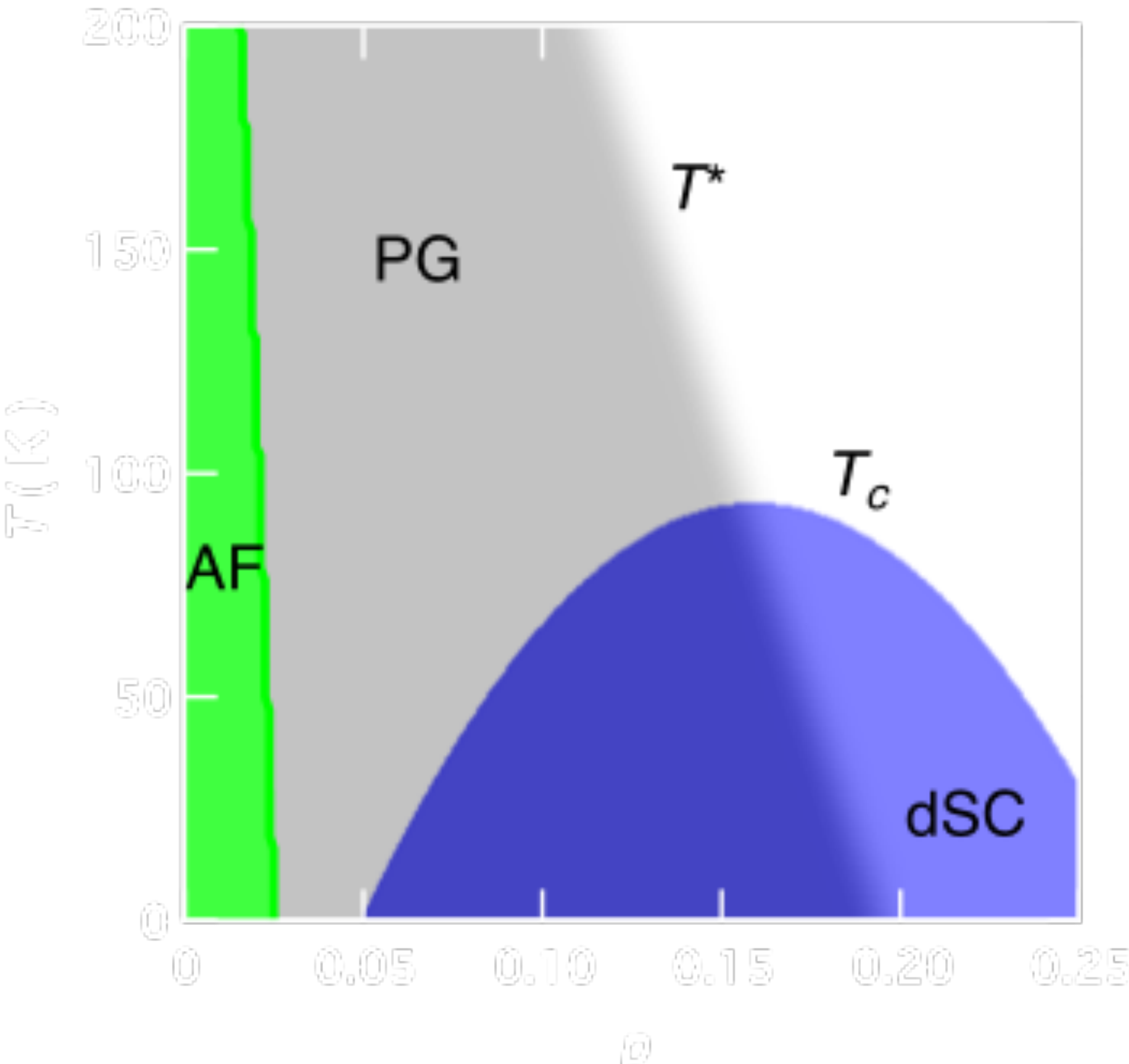


Anti-ferromagnet with p holes per square

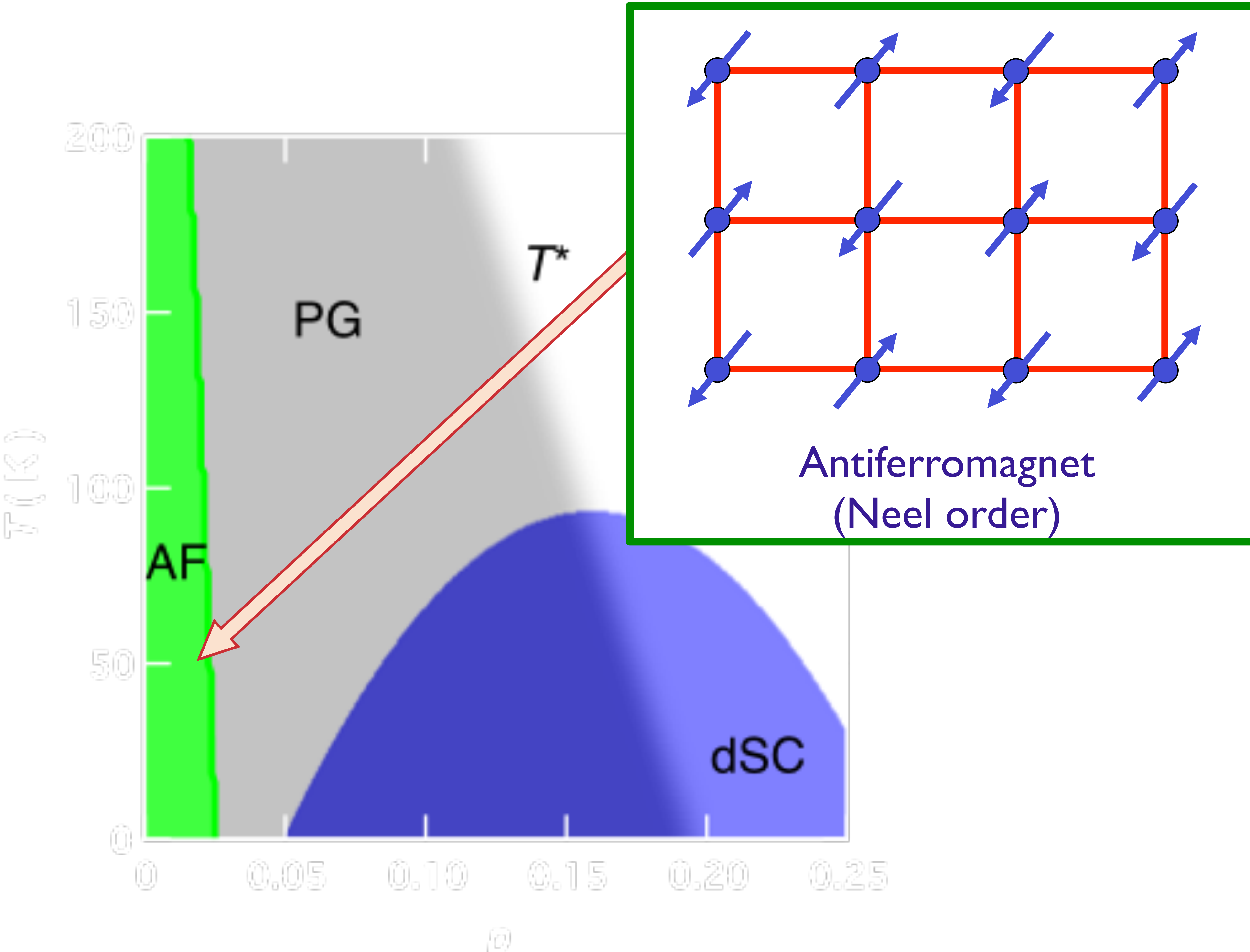


Anti-ferromagnet with p holes per square

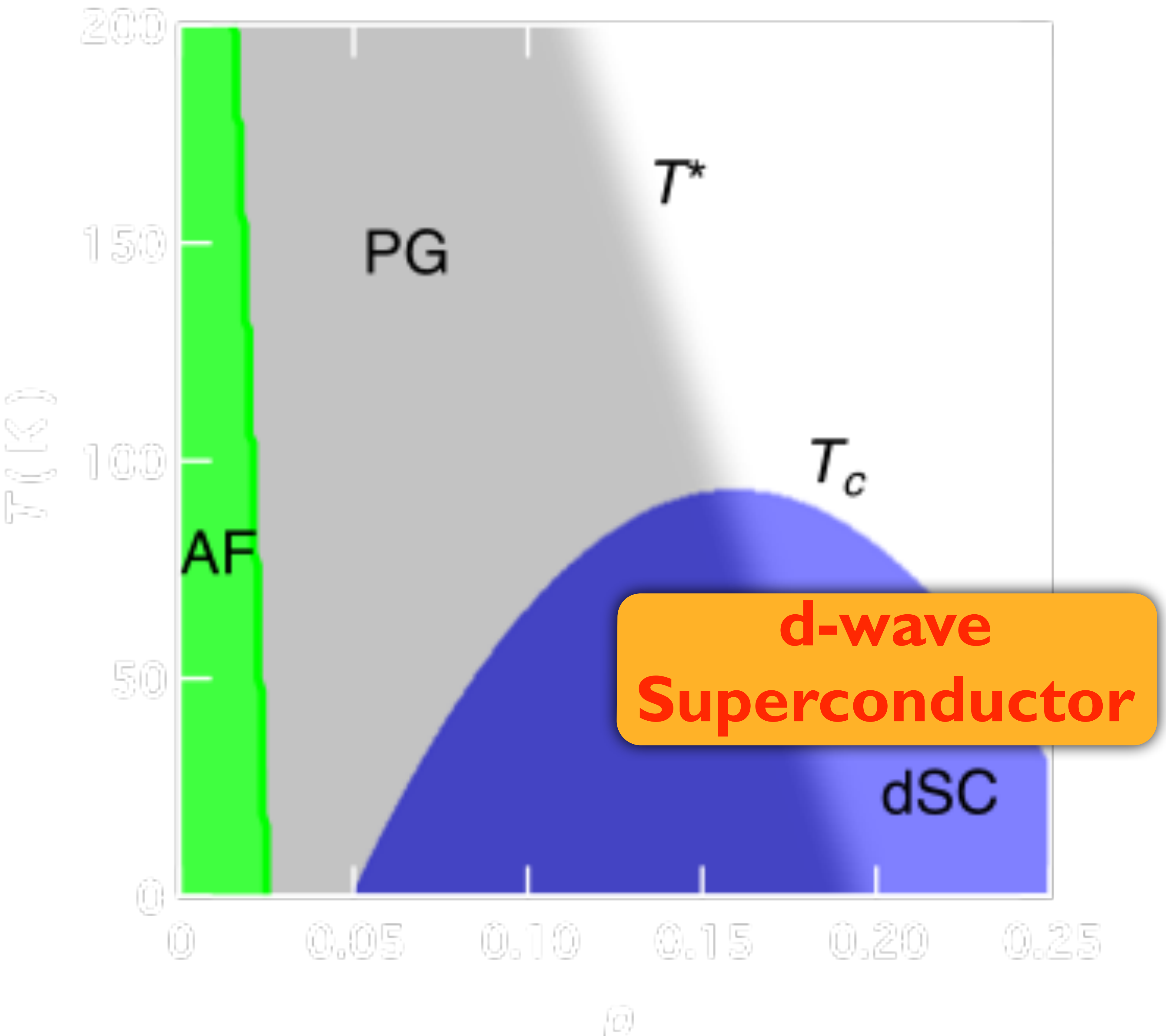
Note: relative to the fully-filled band insulator, there are $1+p$ holes per square



T*
PG
T_c
AF
dSC
200
150
100
50
0
T (K)
0
0.05
0.10
0.15
0.20
0.25
p



200
150
100
50
0
T (K)
0
0.05
0.10
0.15
0.20
0.25
p
AF
PG
T*
dSC
Antiferromagnet
(Neel order)



T (K)
200
150
100
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0
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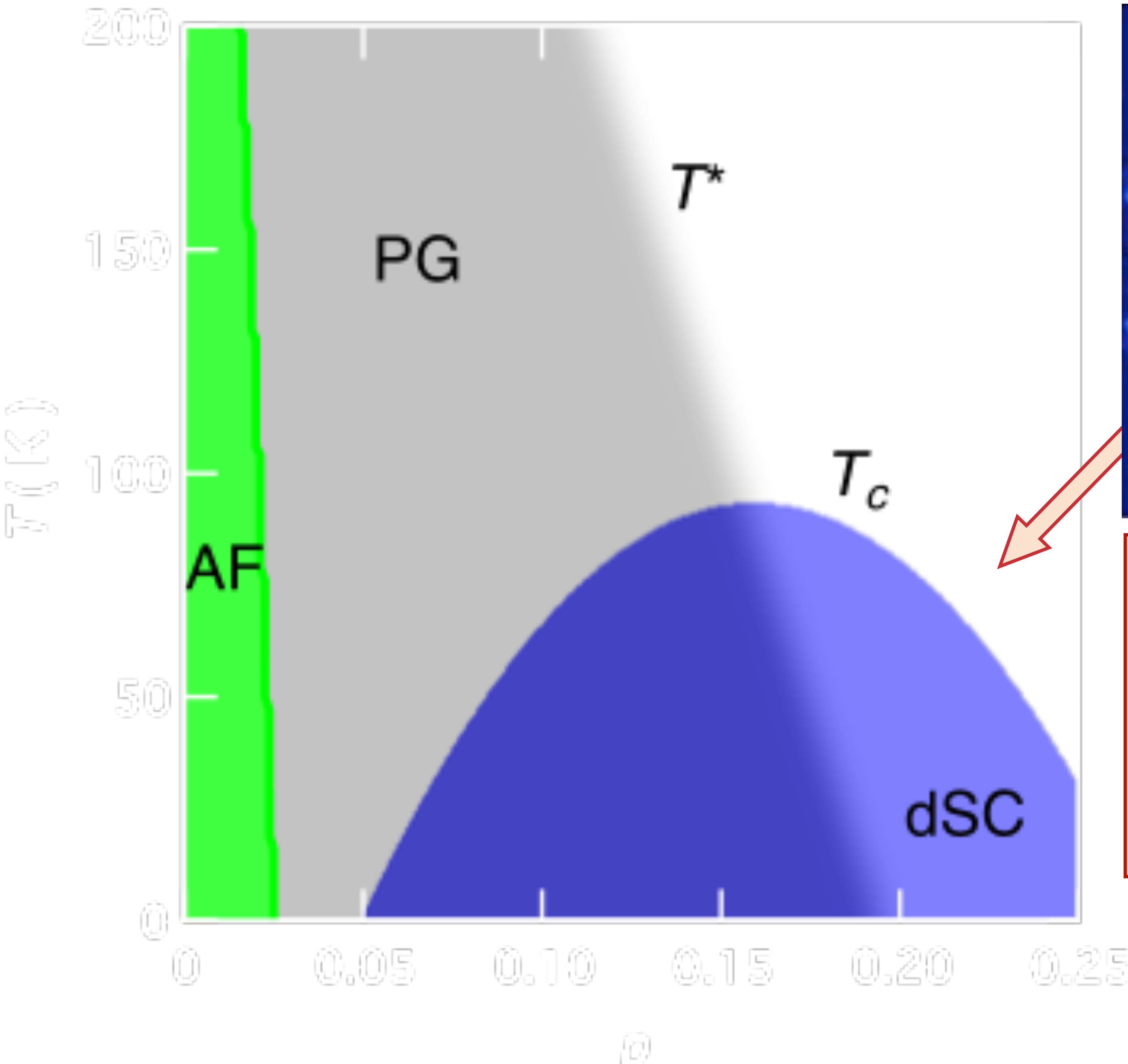
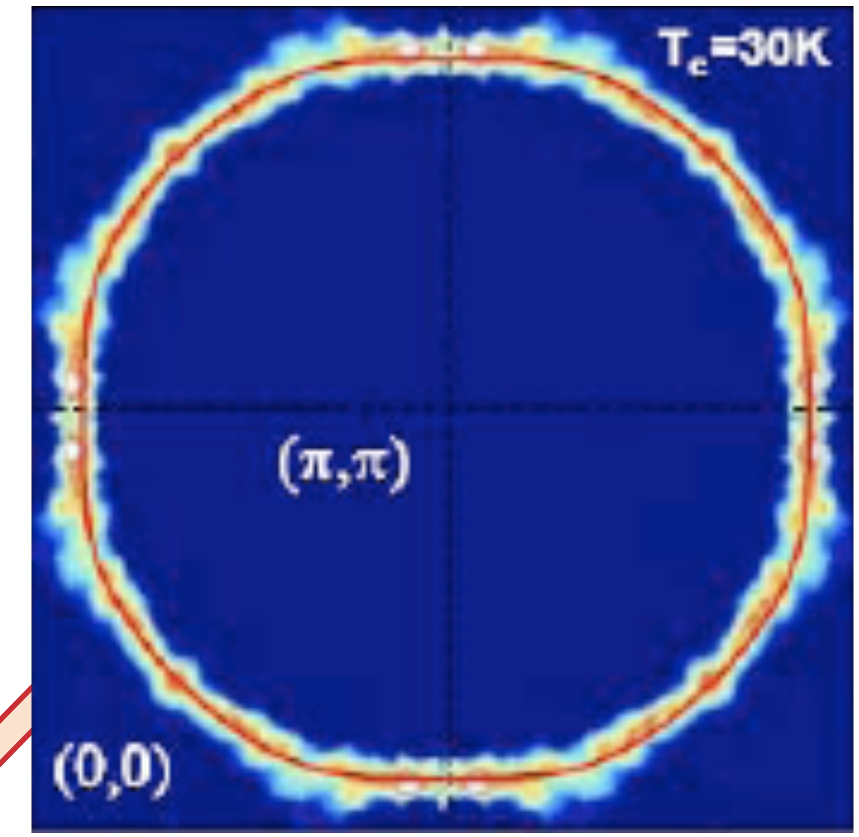
0.05
0.10
0.15
0.20
0.25
p
AF
PG
T*
Tc
dSC
d-wave
Superconductor

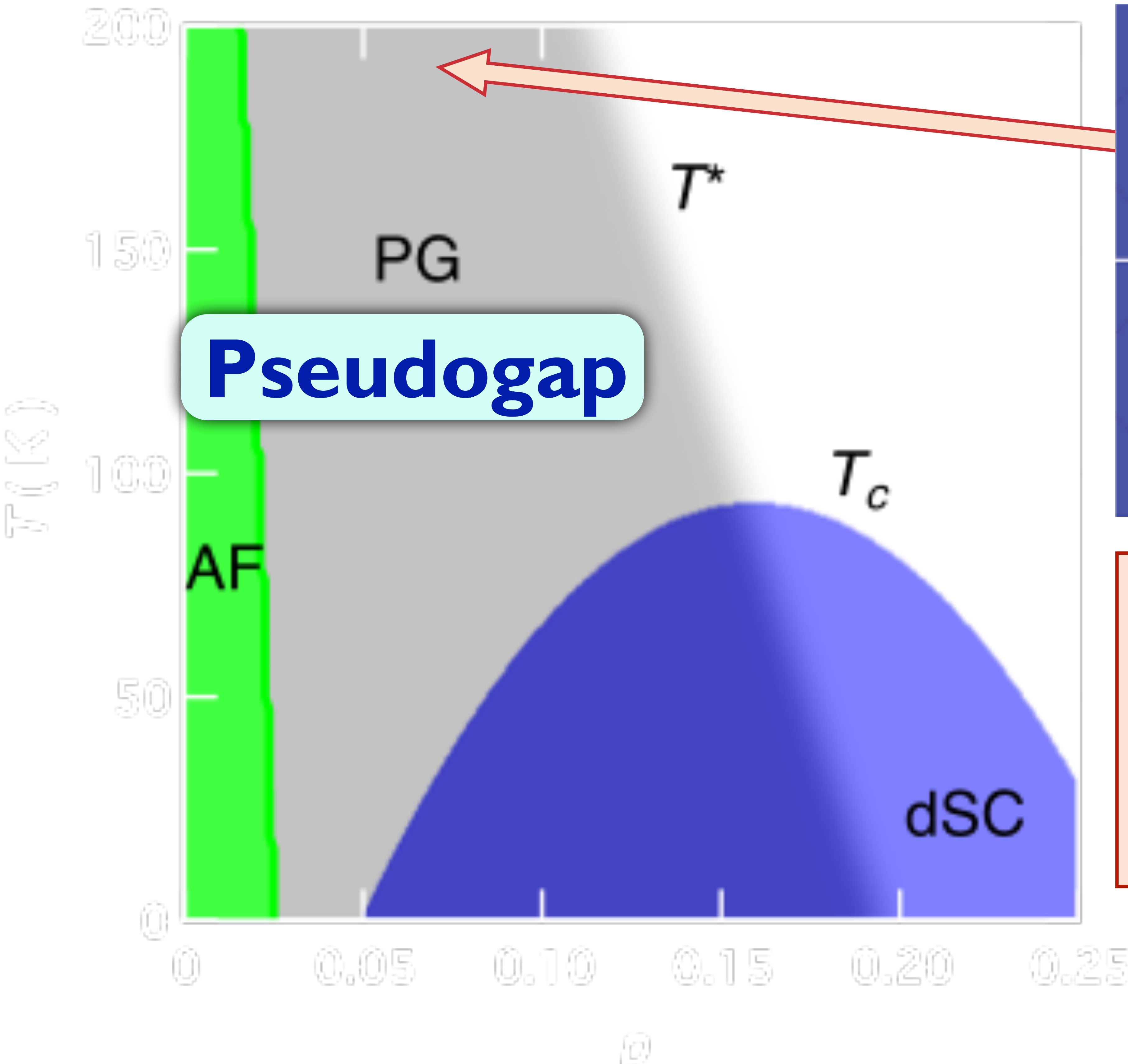
M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)

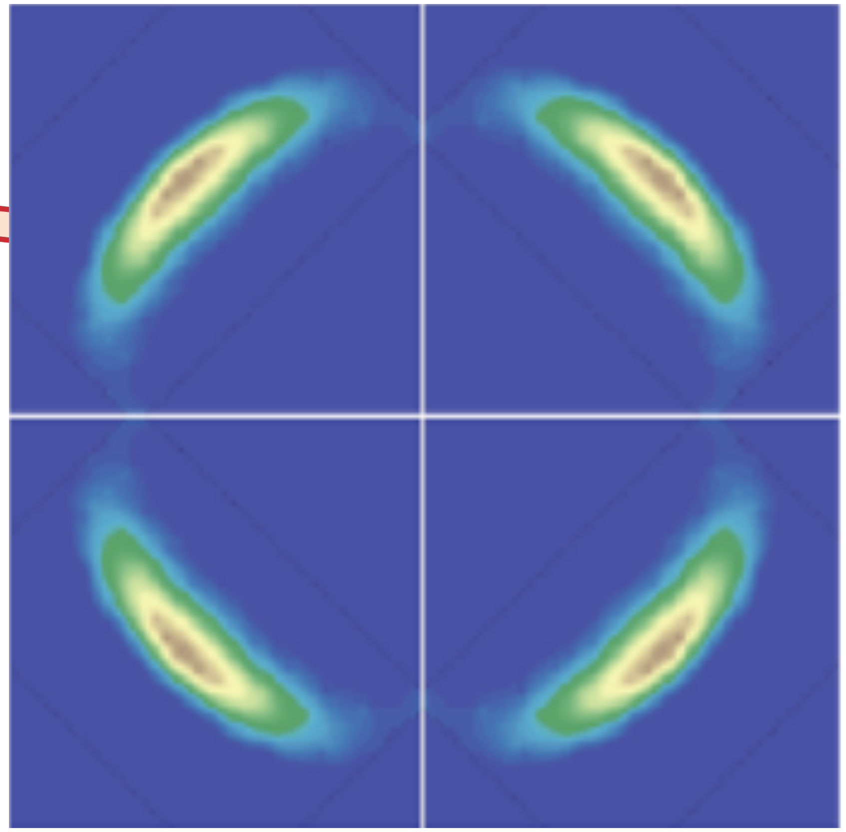




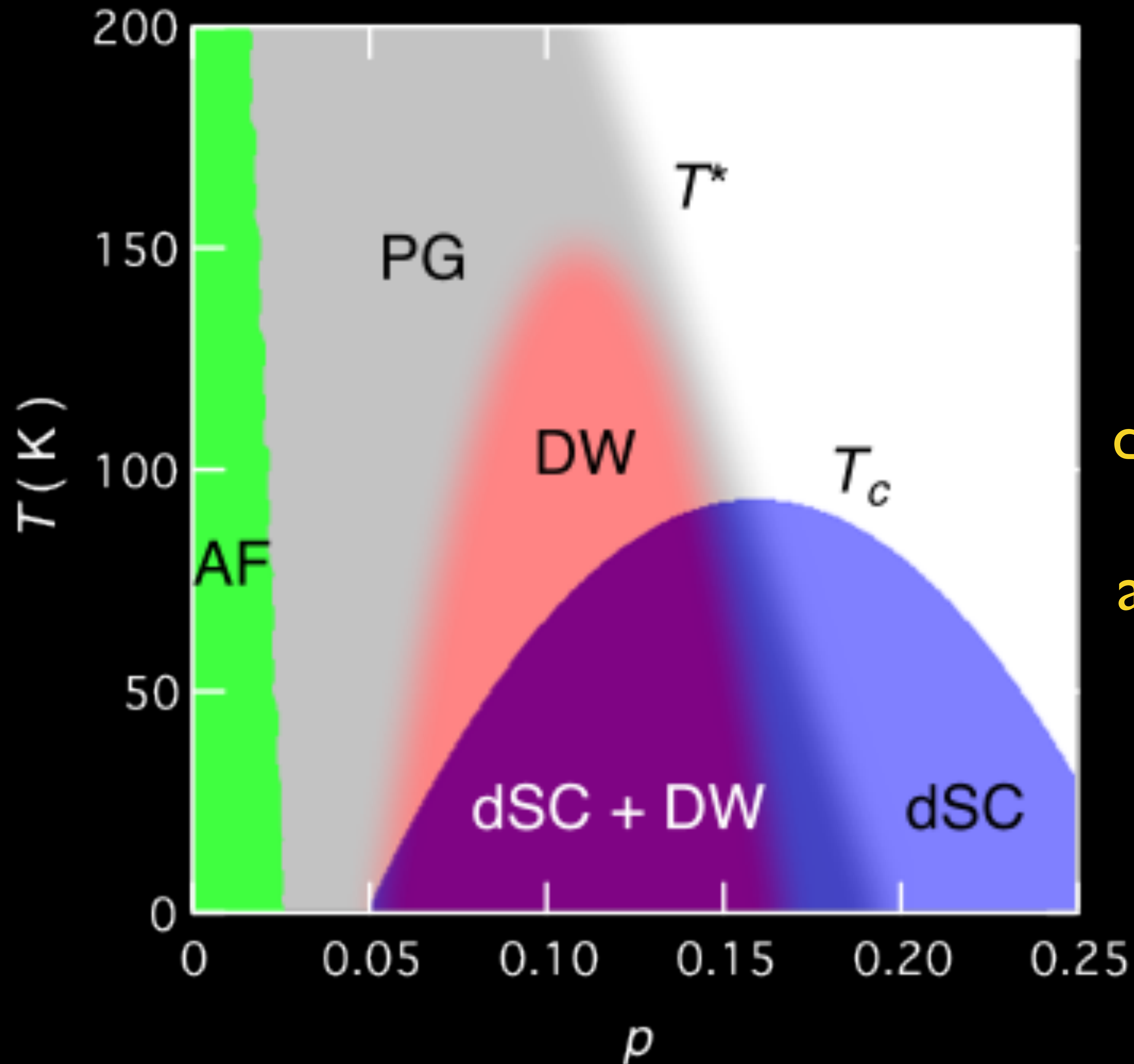
Fermi liquid:
Area enclosed
by Fermi surface
$=1+p$

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)

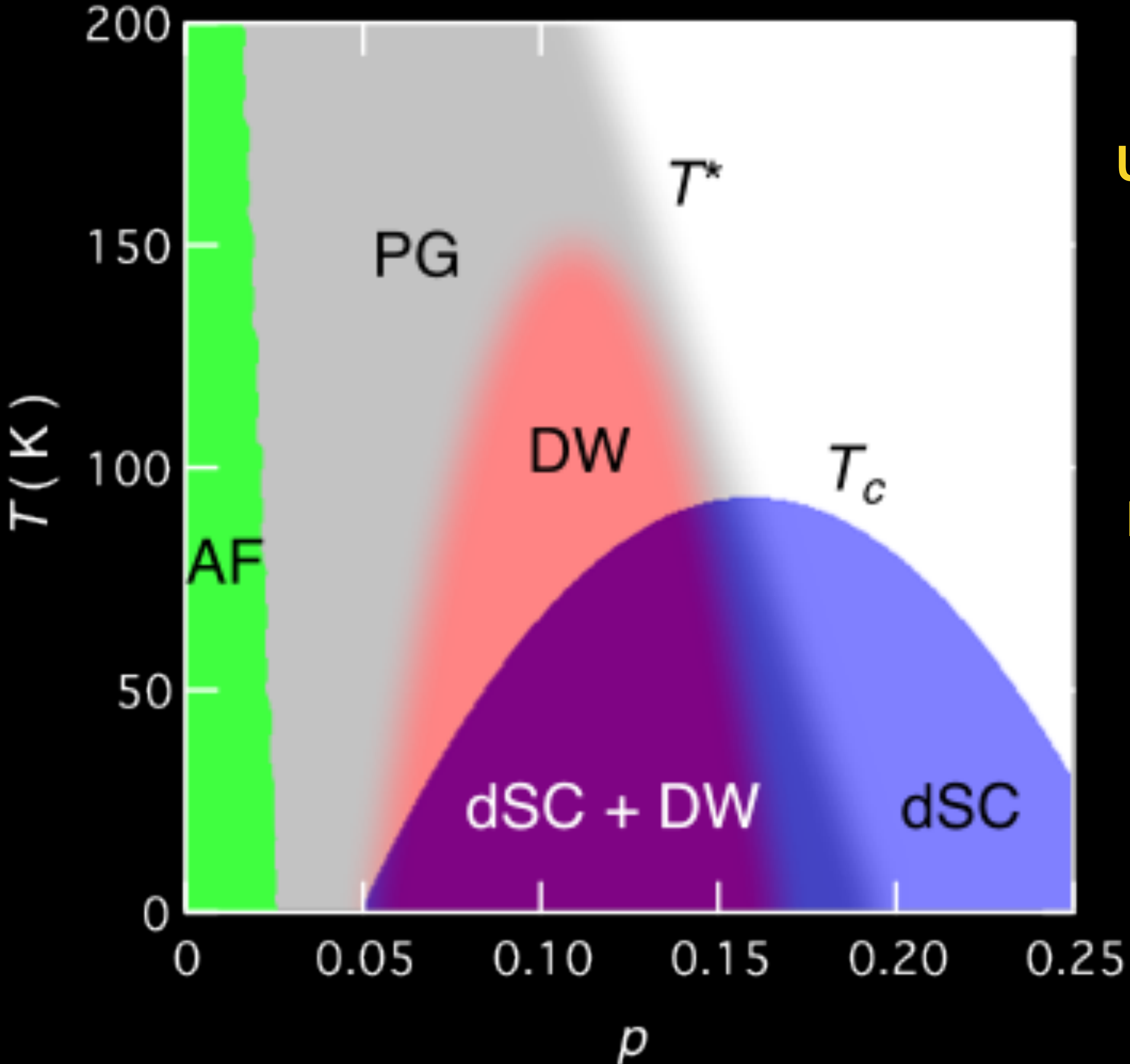




"Fermi arcs" at low p



Numerous recent experiments indicating density wave (DW) order at low T in all the underdoped cuprates



How do we understand the Fermi arc spectrum, and what is its relationship to the density wave (DW) order at lower *T* ?

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

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

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(A) Thermal fluctuations of the low temperature orders (superconductivity, 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 high T pseudogap:
   A quantum dimer model for a metal with topological order

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

3. Connecting high and low T:
   Density wave instabilities

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

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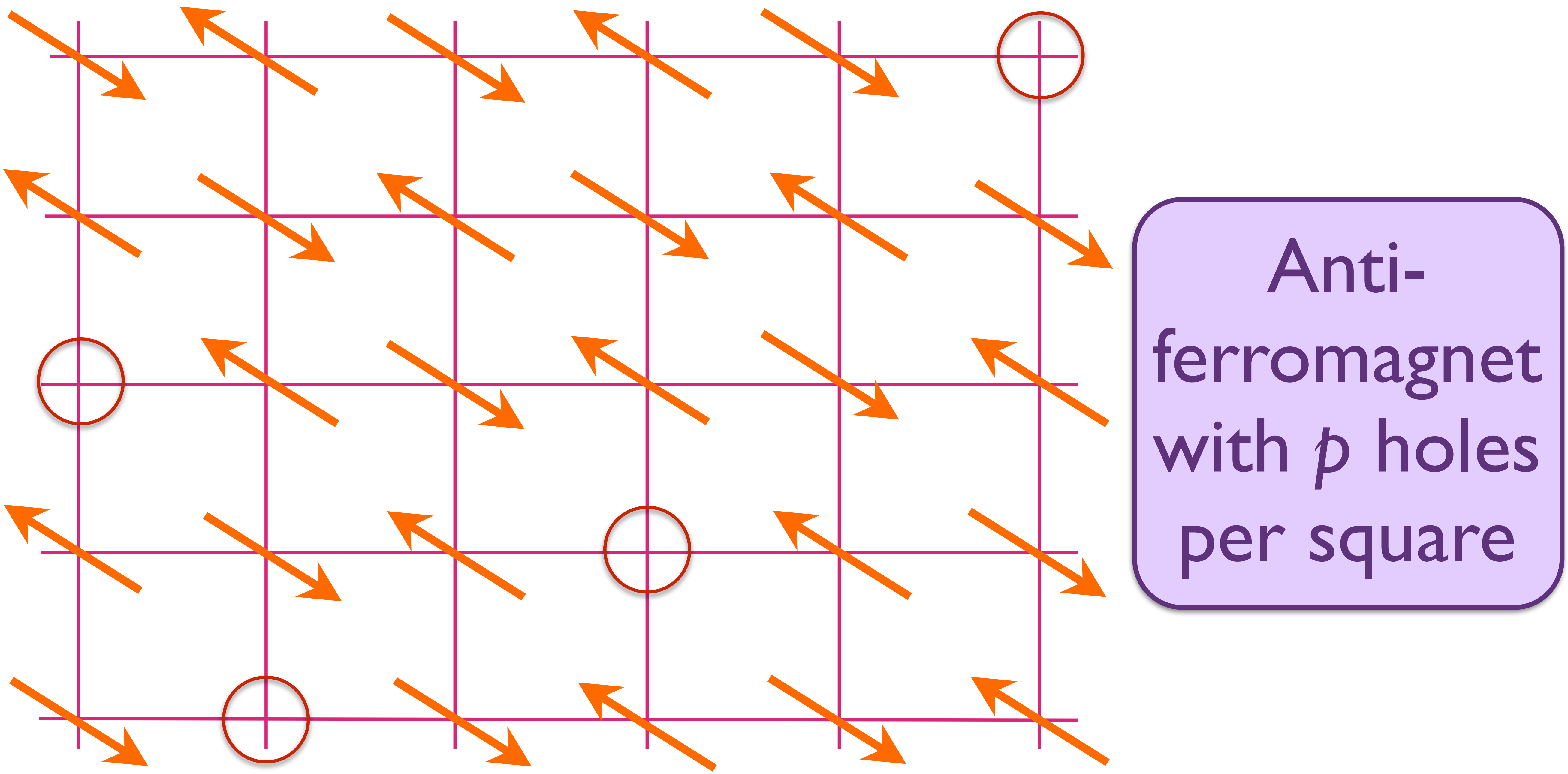

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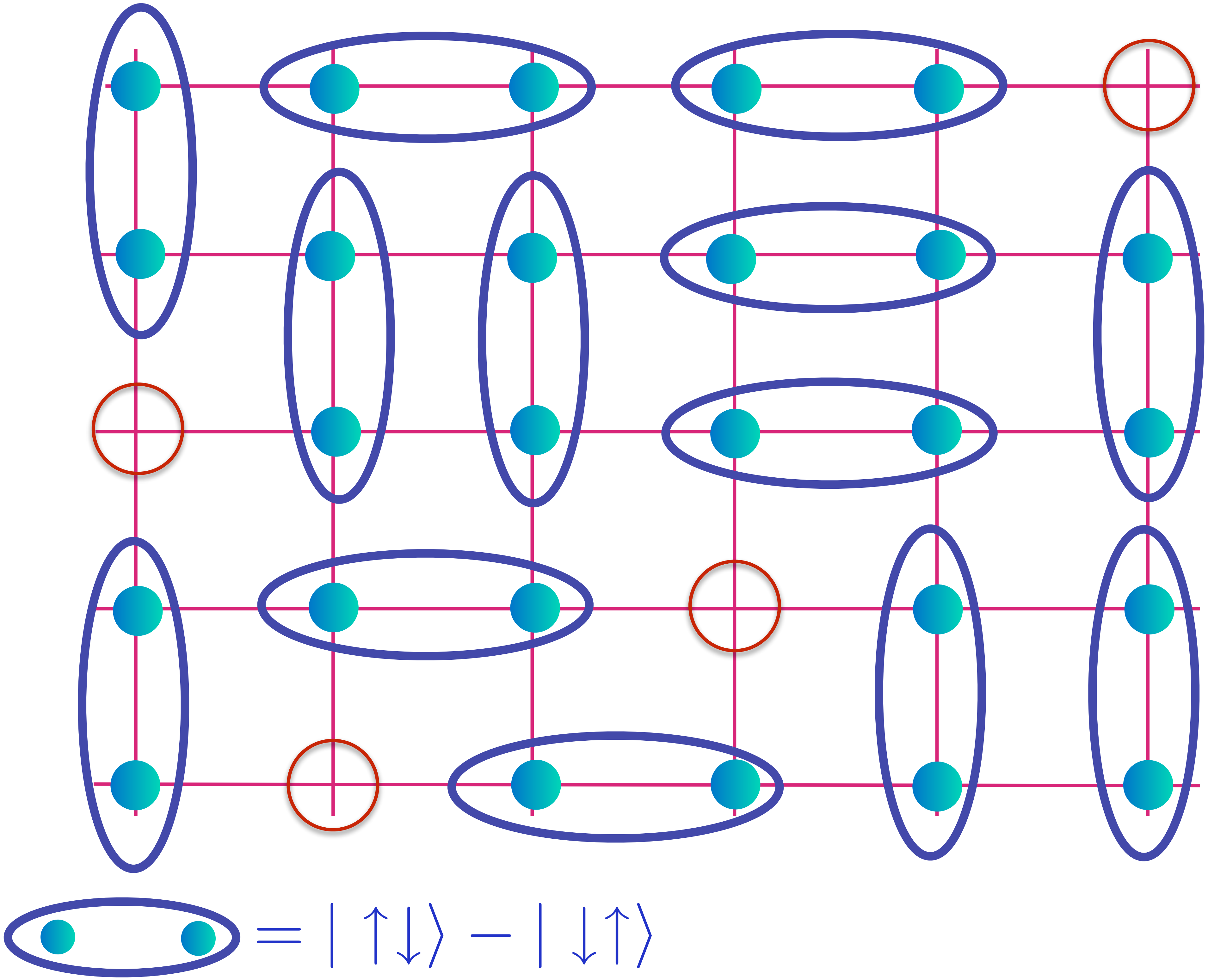
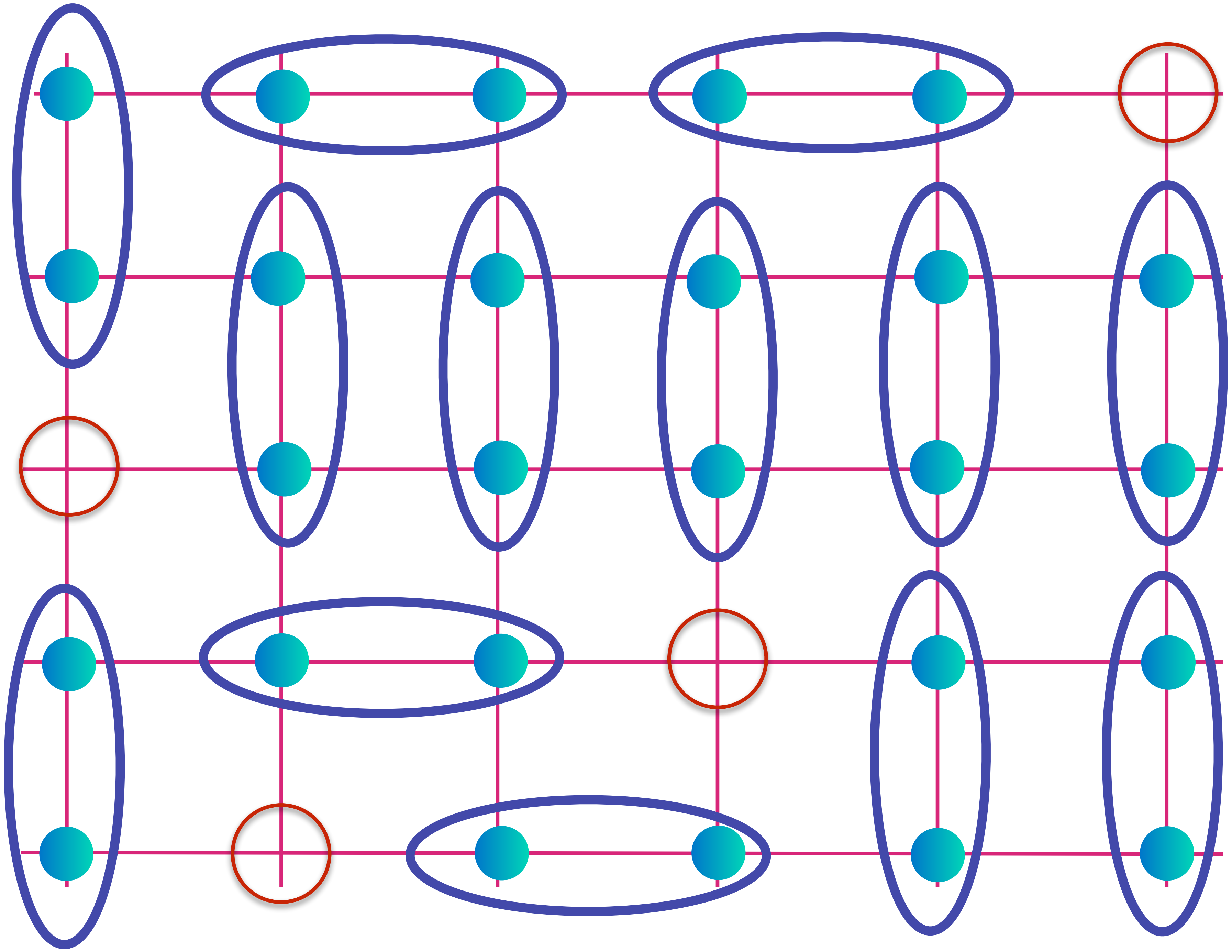


$$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Spin liquid
with emergent
gauge field
and
p “holons"
(gauge-charged,
spinless,
charge +e
quasiparticles)
per square

Baskaran, Zou, Anderson, Fradkin, Kivelson…



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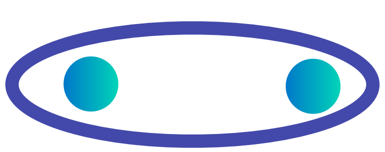 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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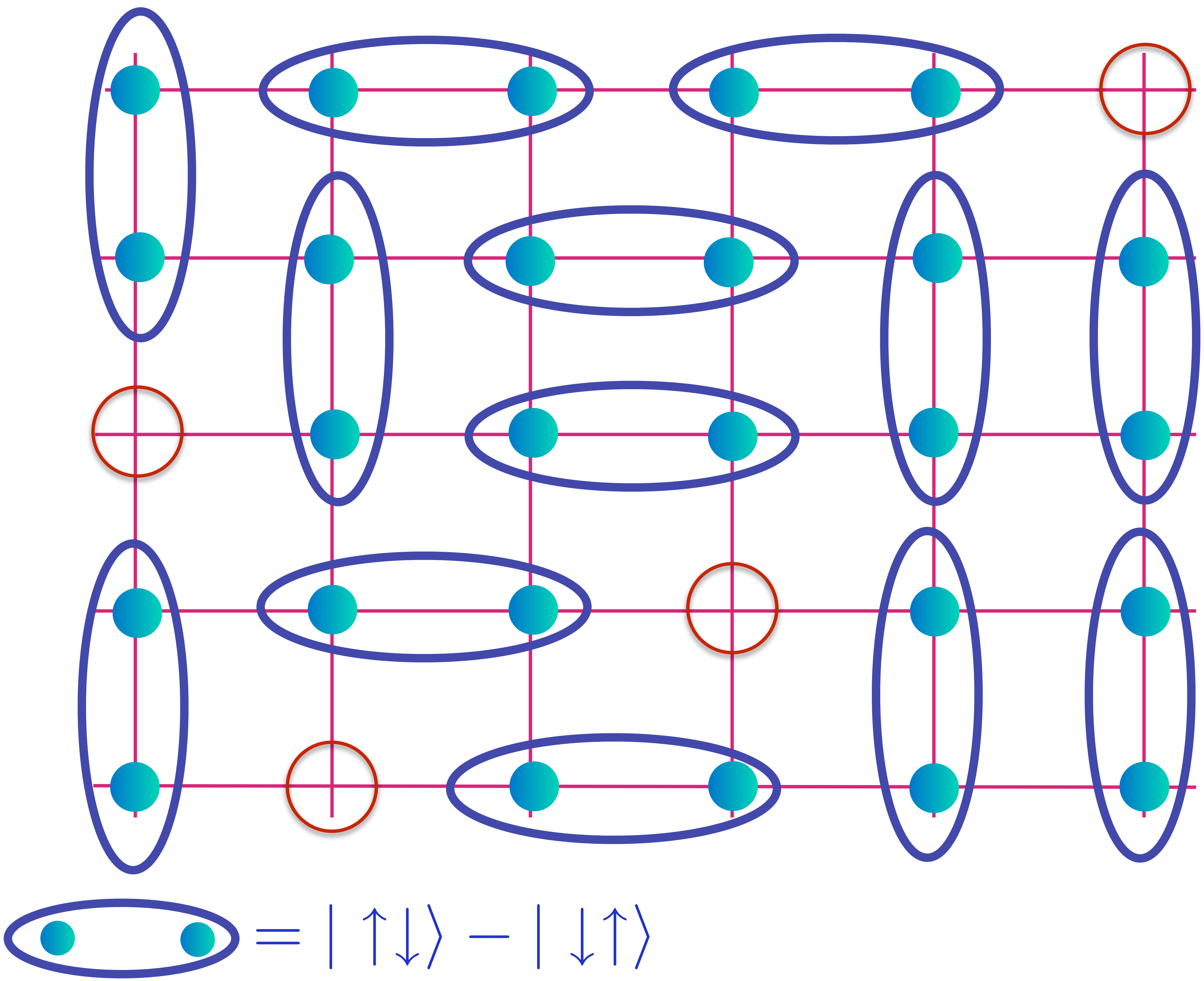

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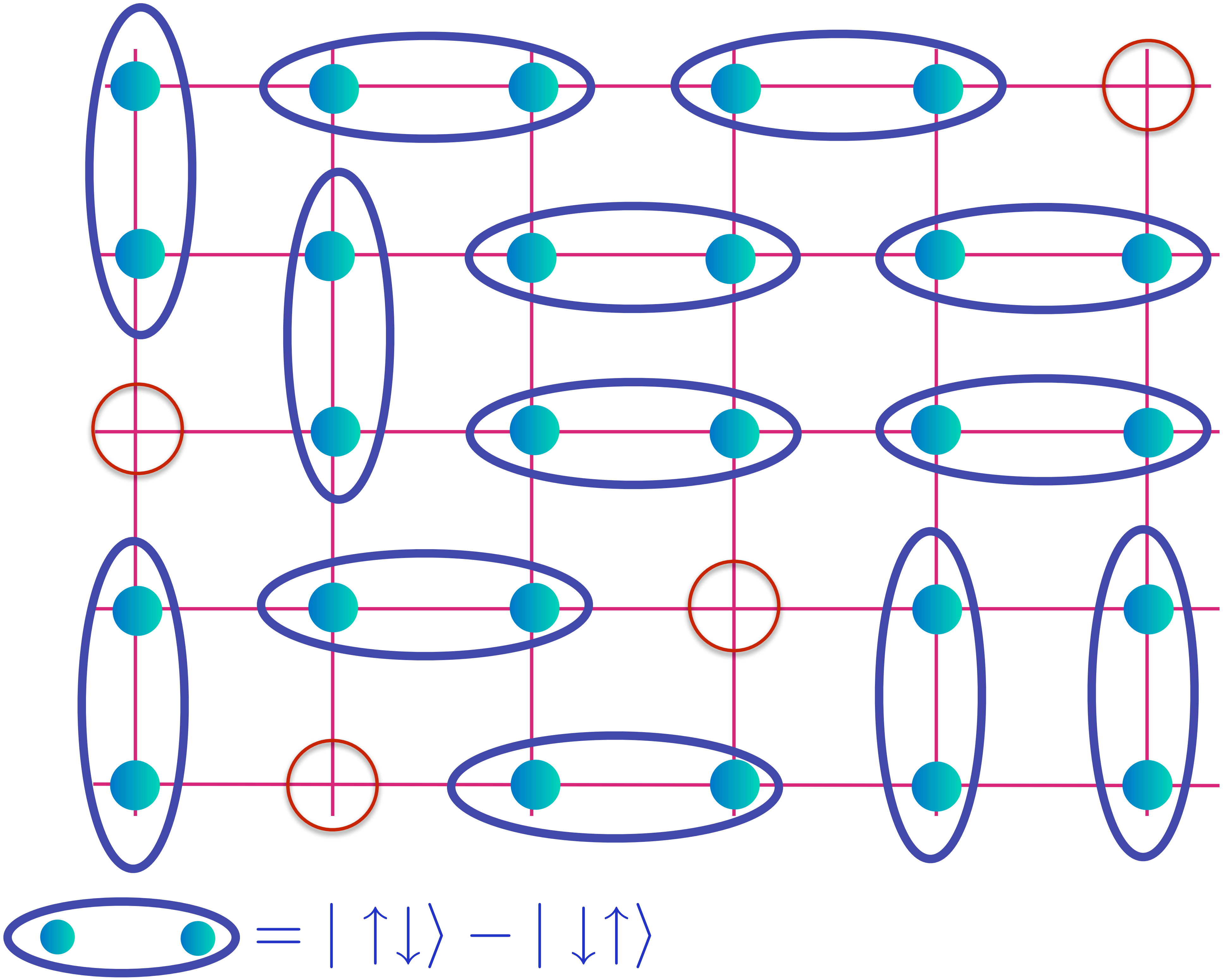

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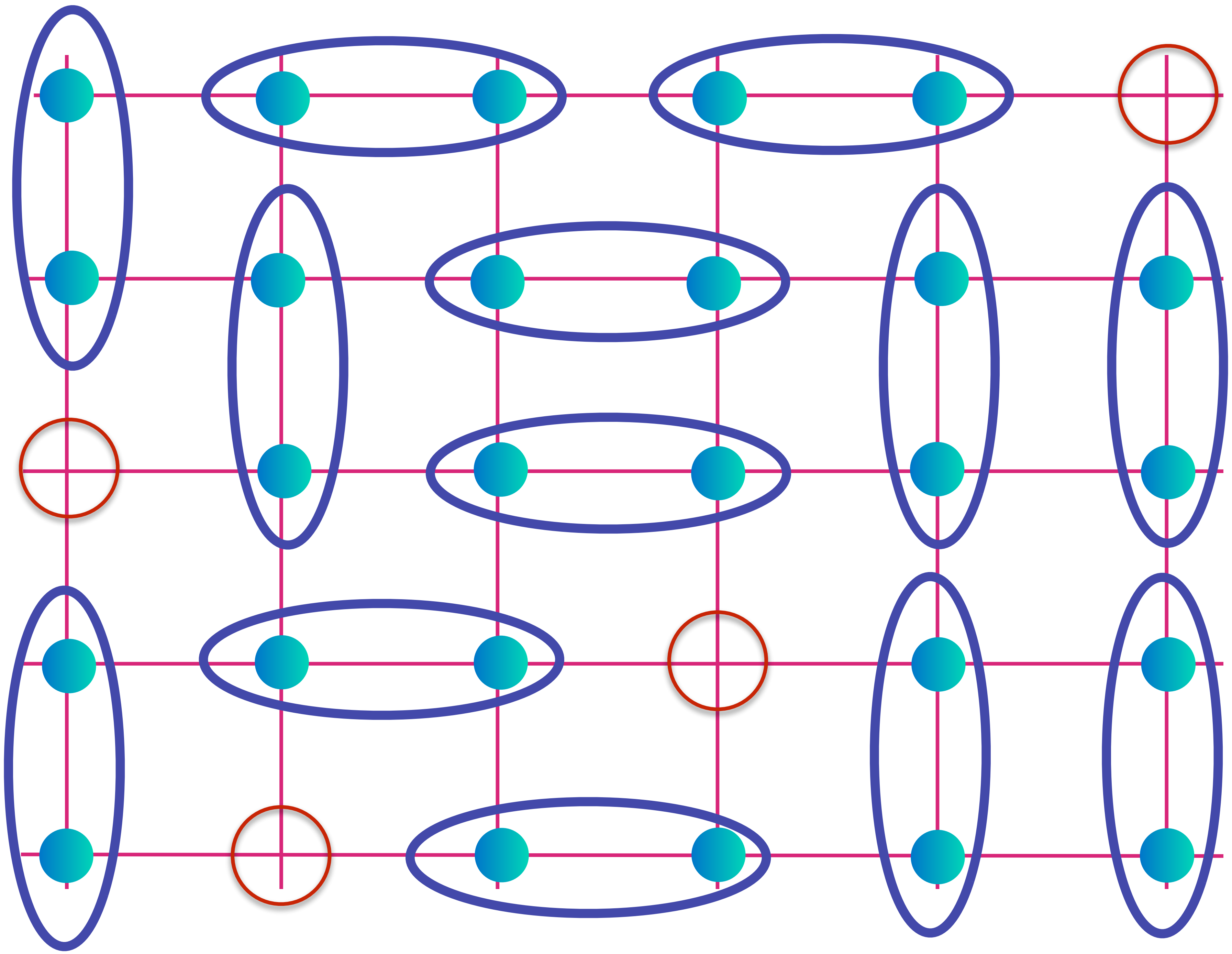

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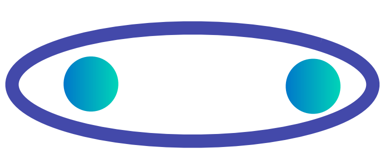 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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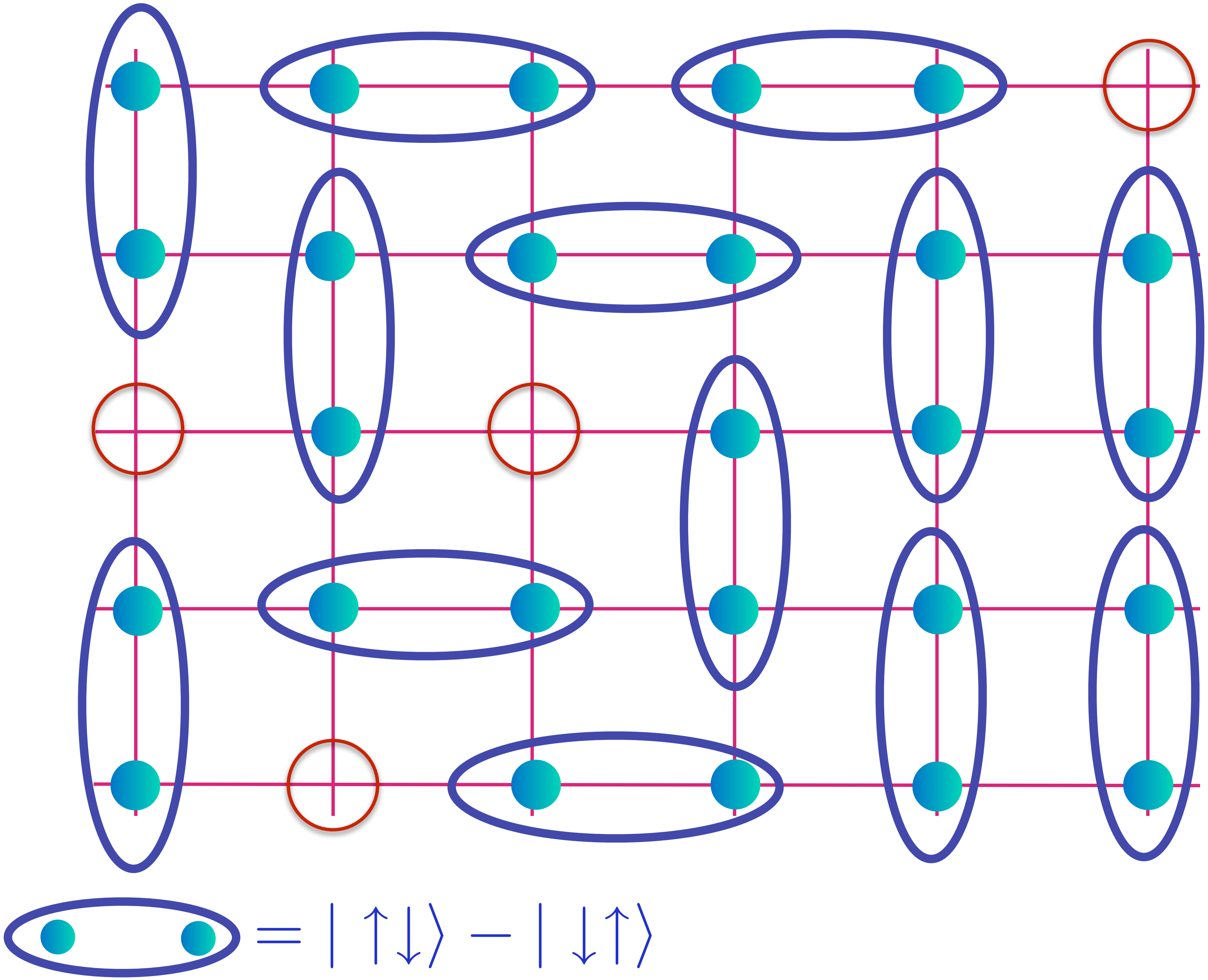

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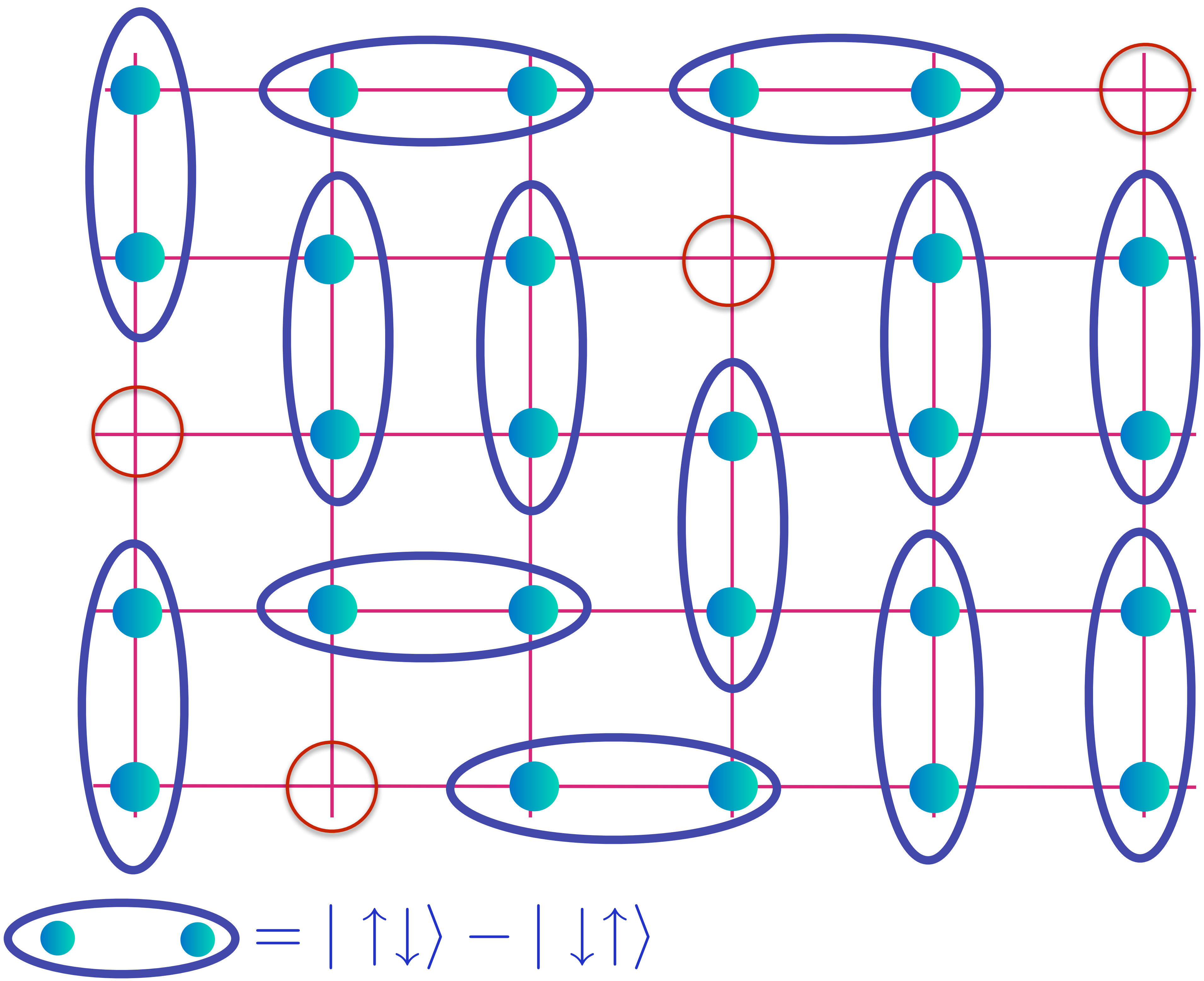

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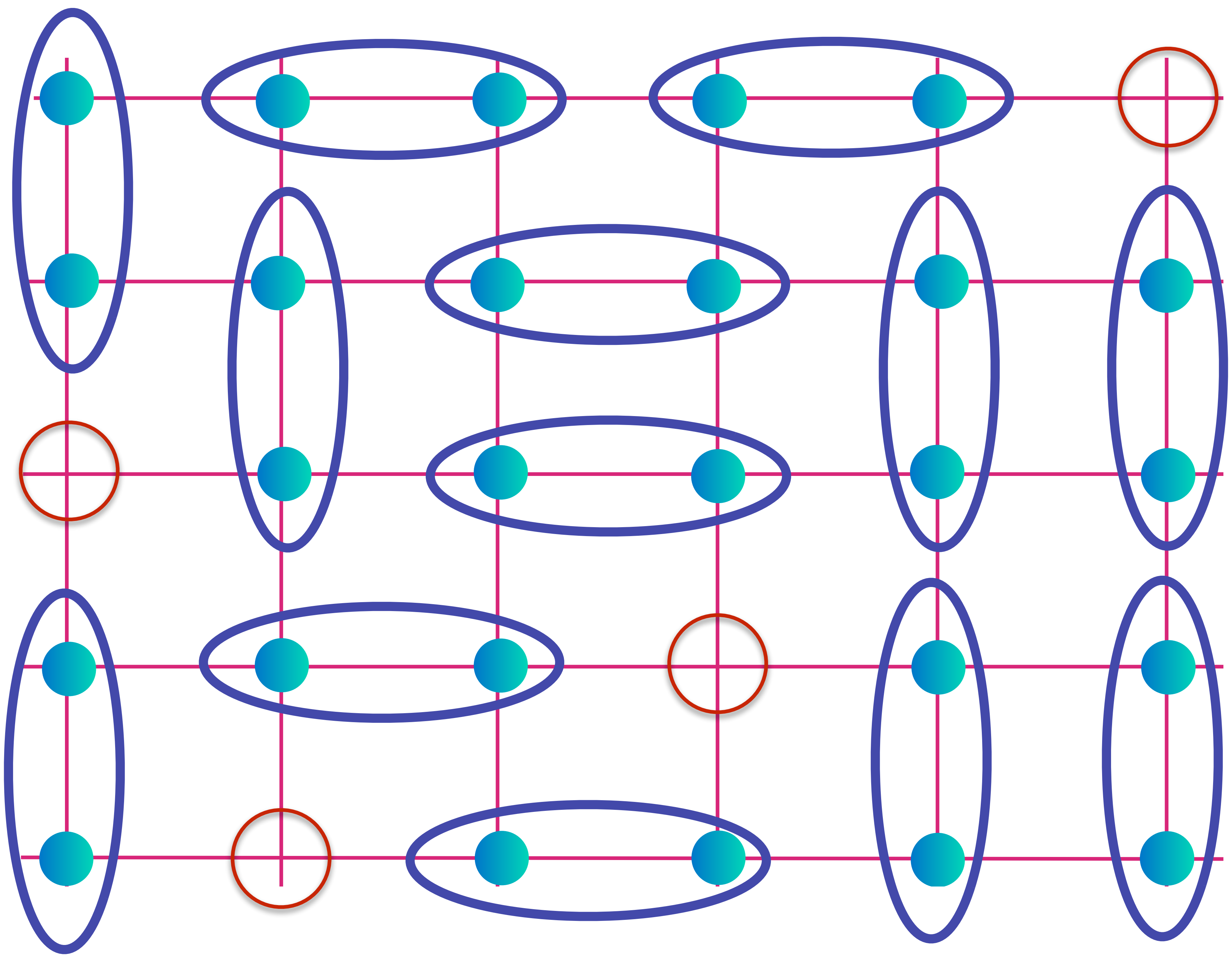

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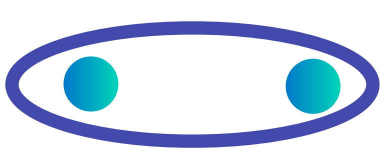 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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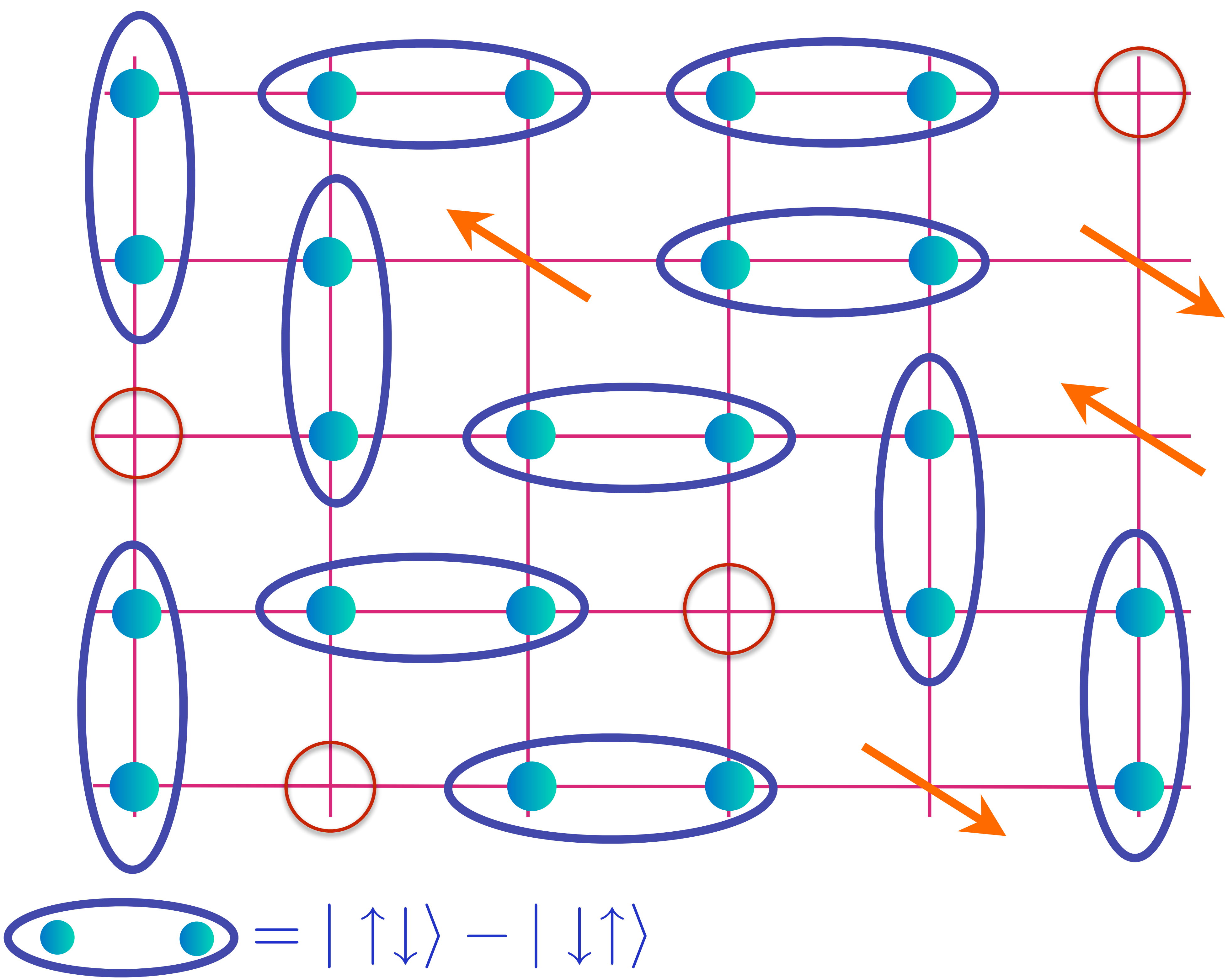
Gauge-charged, spin S=1/2, neutral "spinon" excitations



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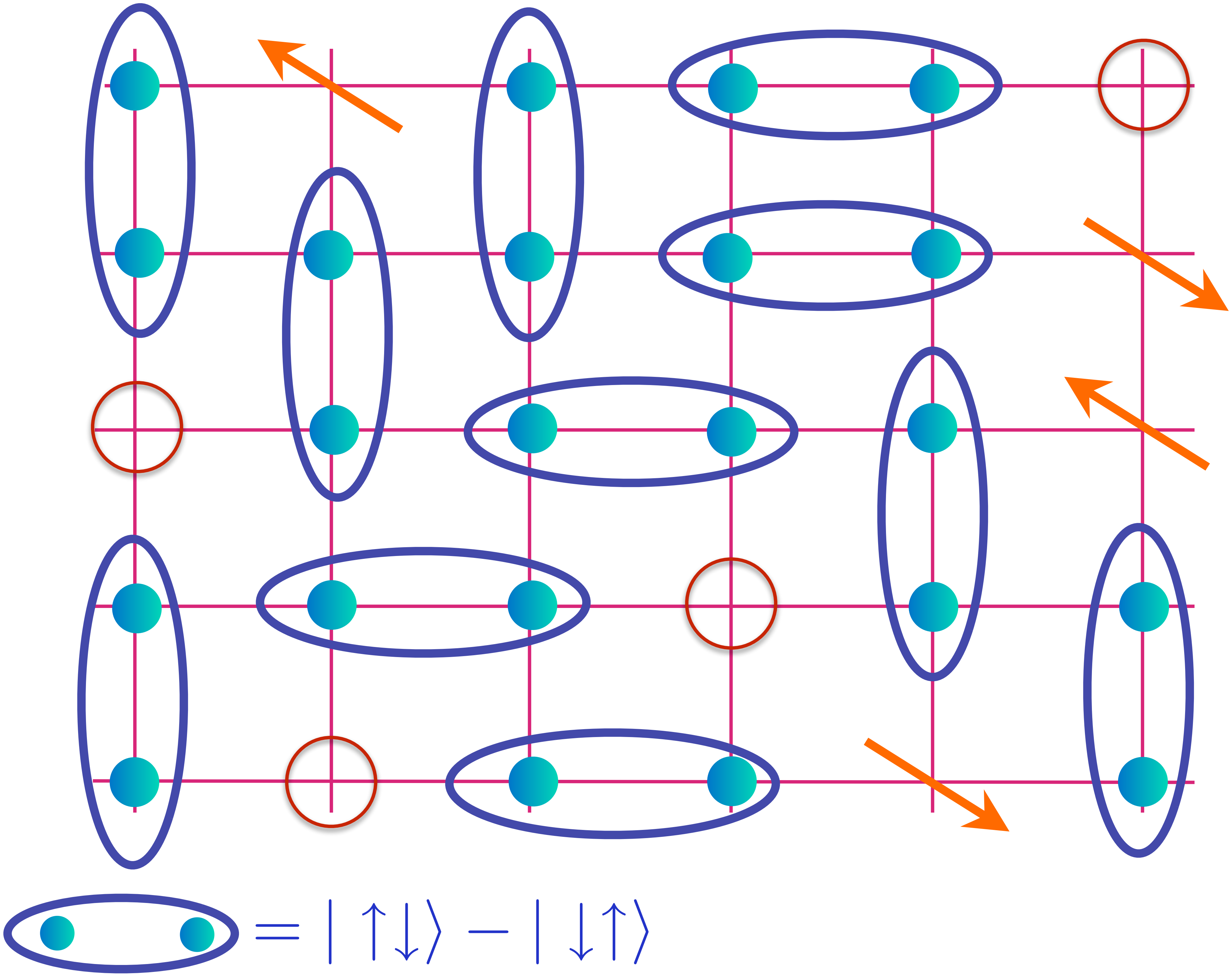

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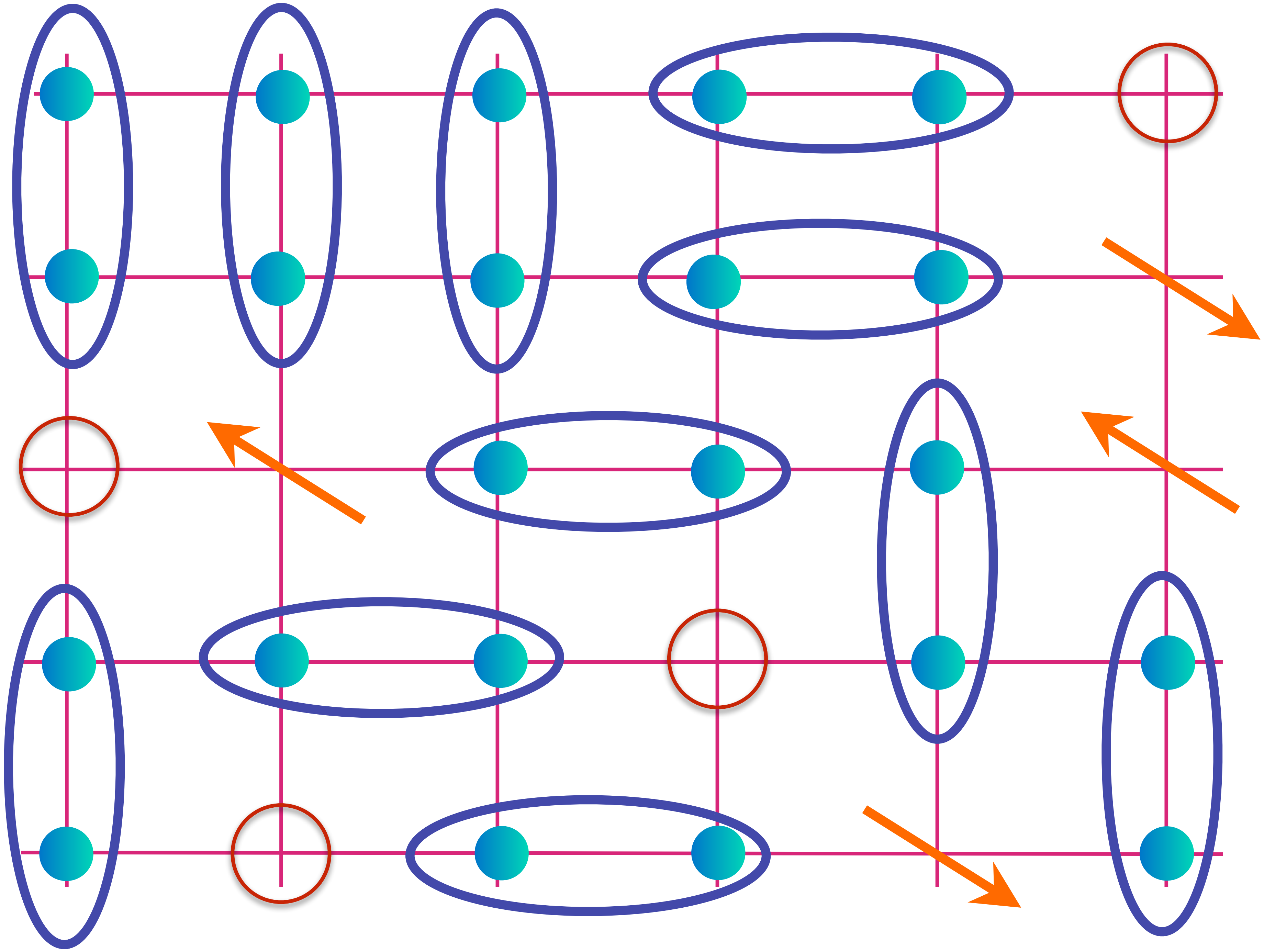

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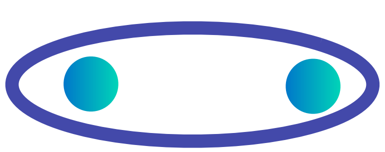
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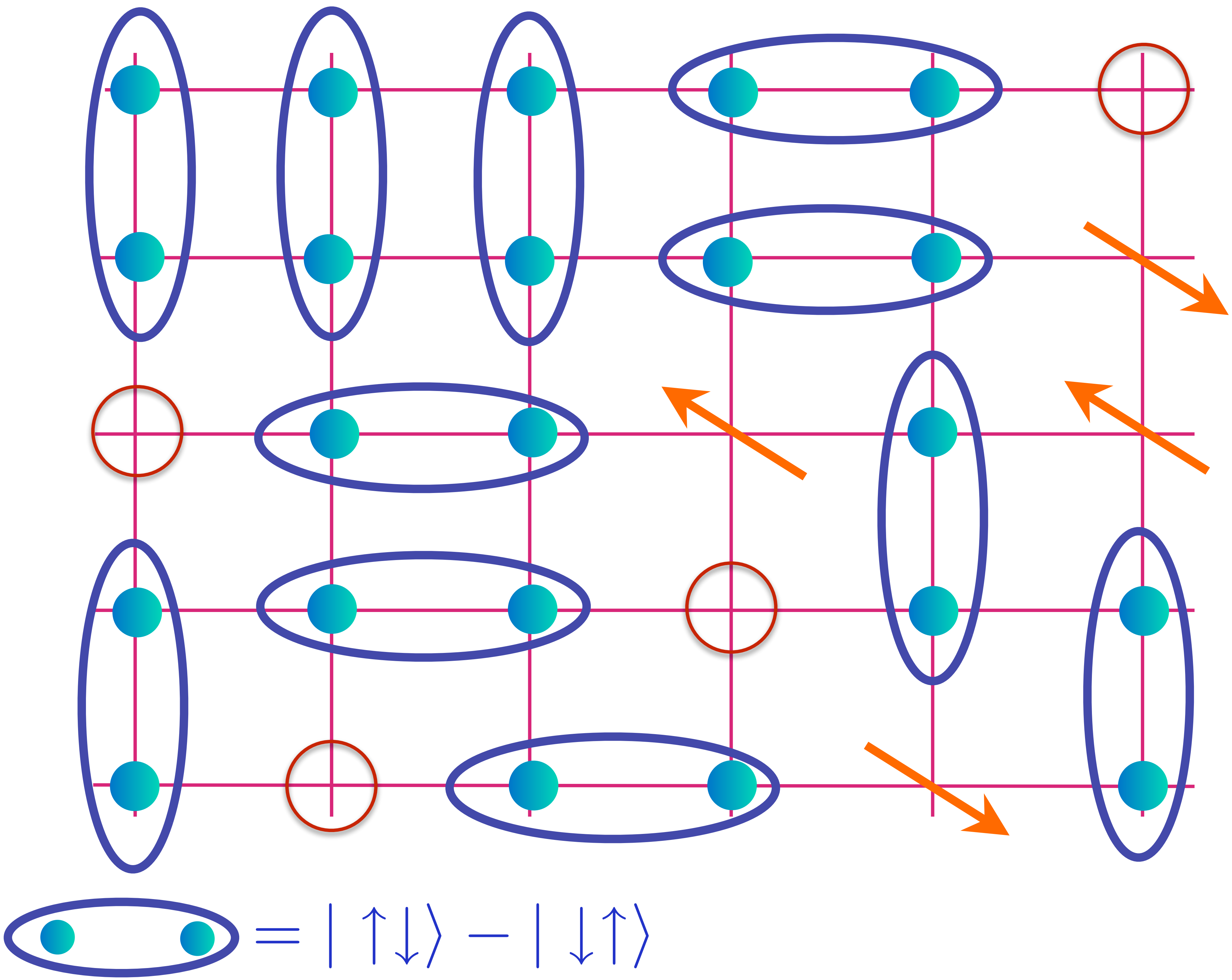

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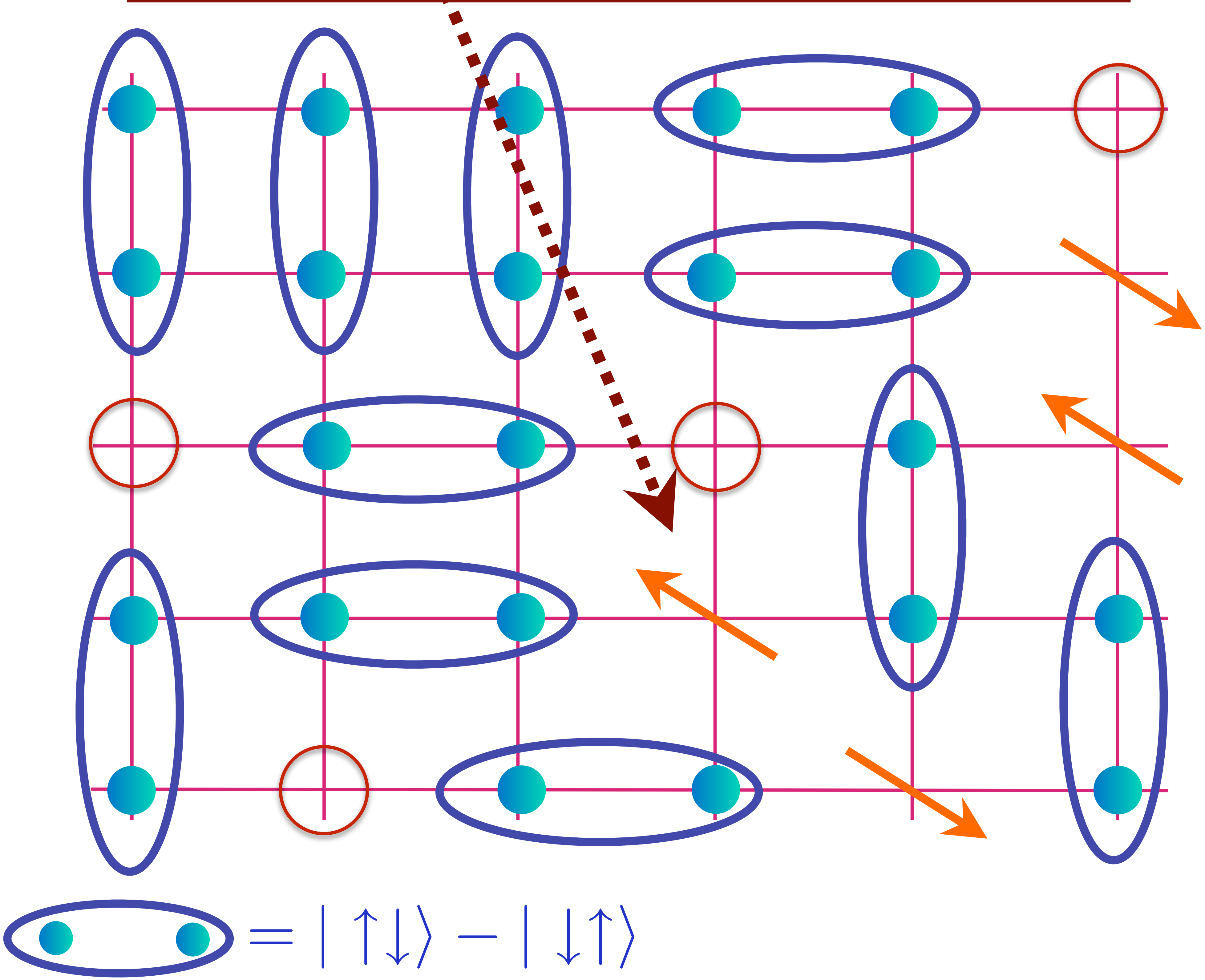
Nearest-neighbor hopping leads to attraction between holon and spinon, which can pay for the energy needed to create the spinon



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

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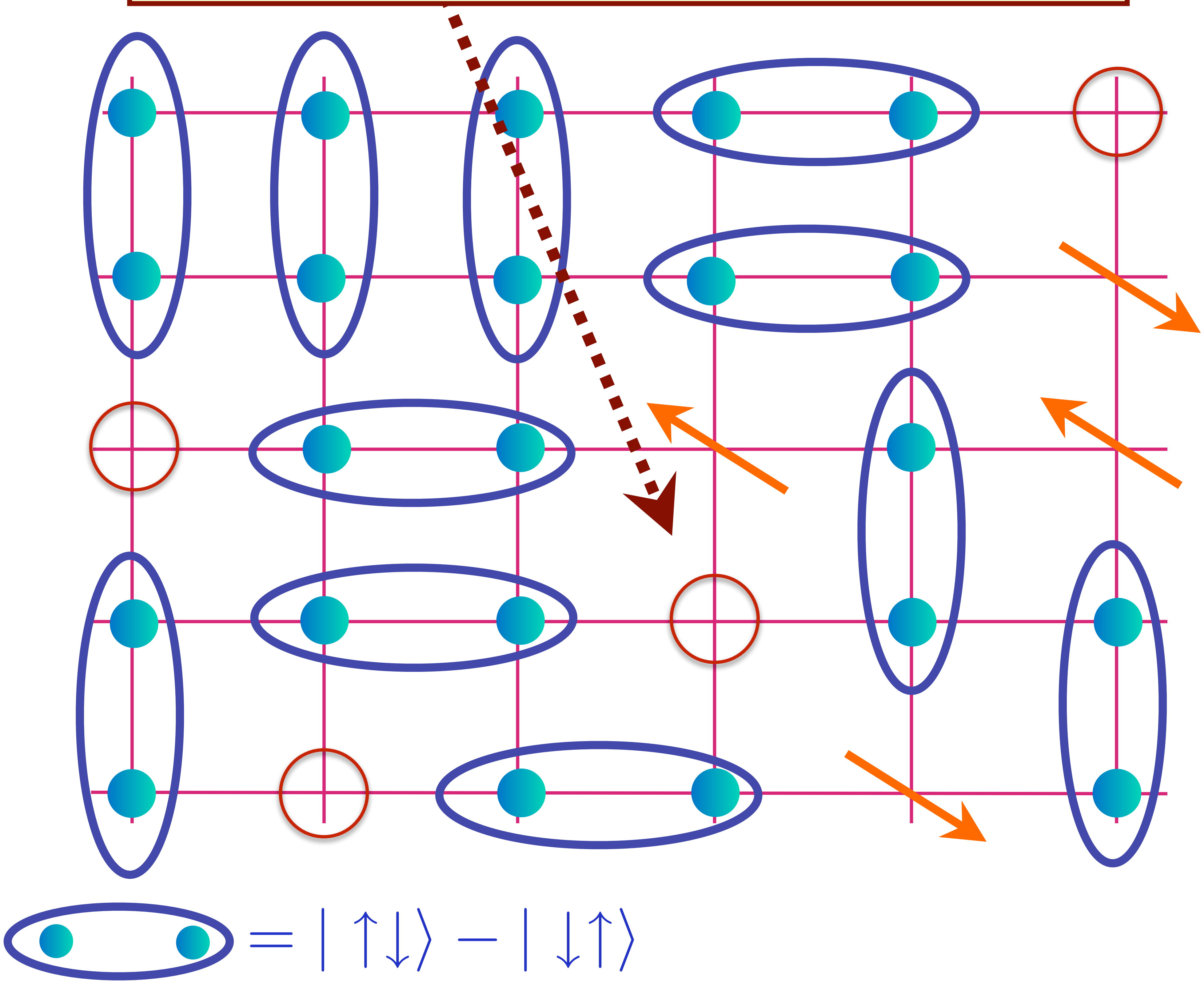

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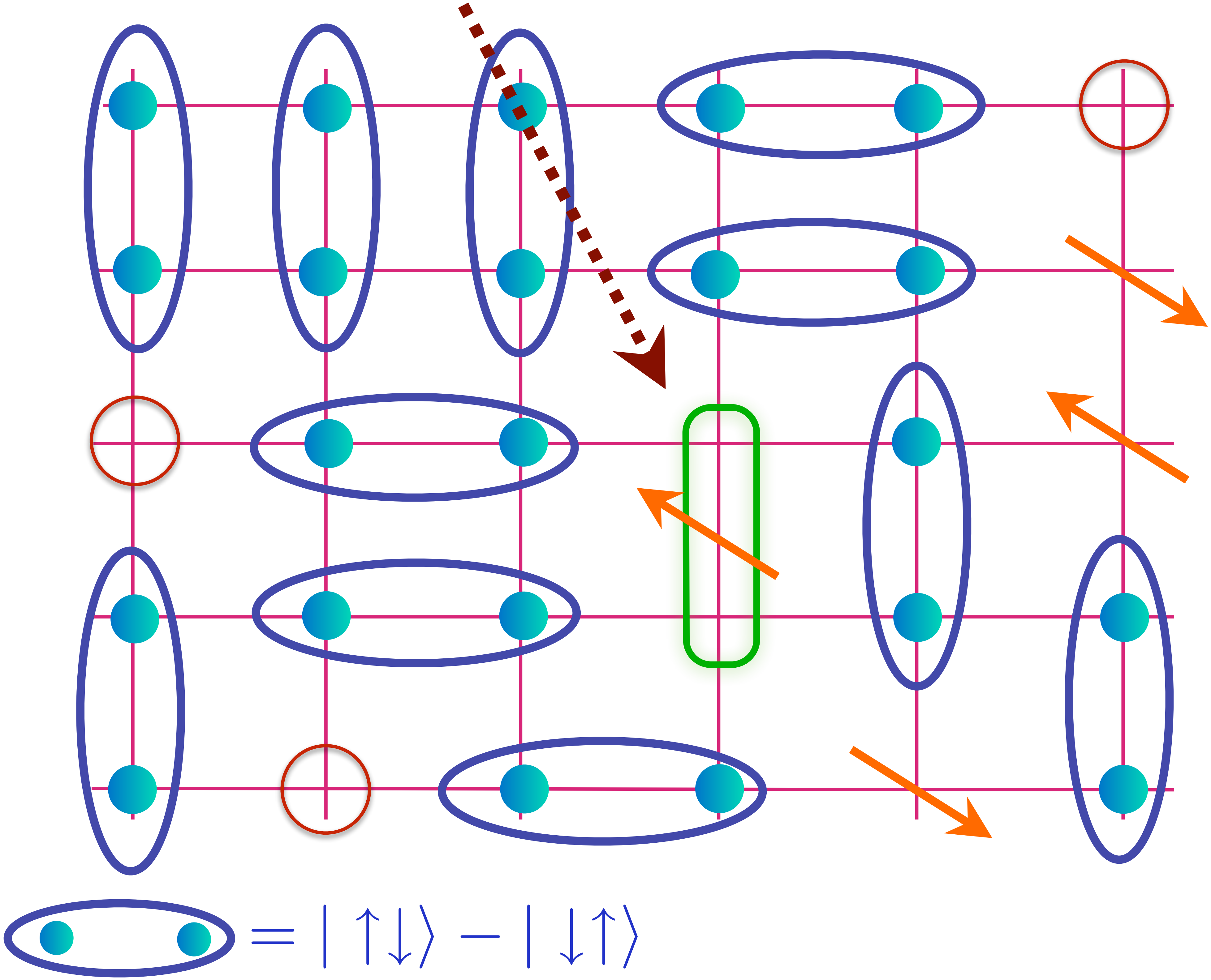
Spinon-holon bound state resides on a "bonding" orbital between two sites



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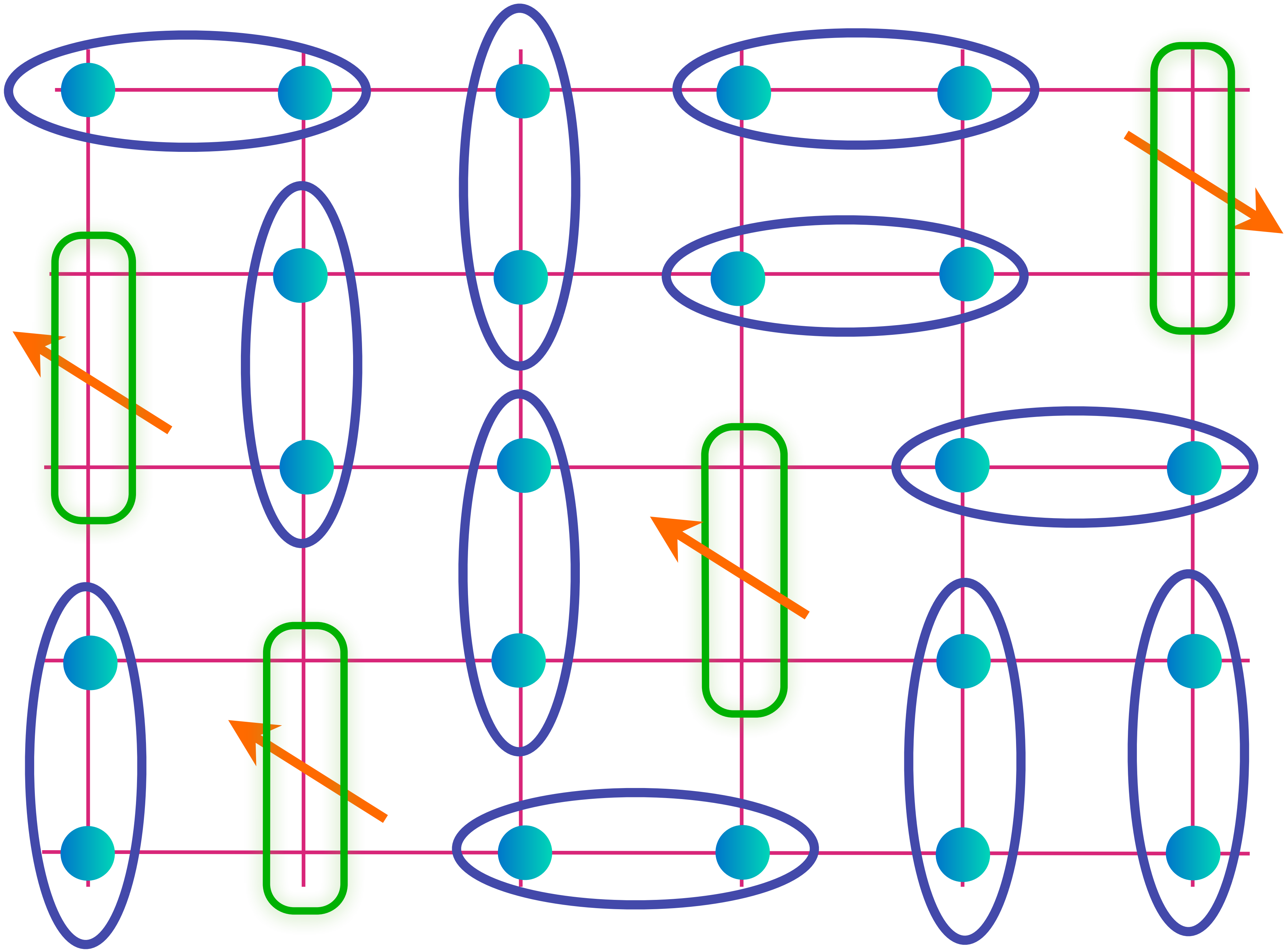
Fractionalized Fermi liquid (FL*)



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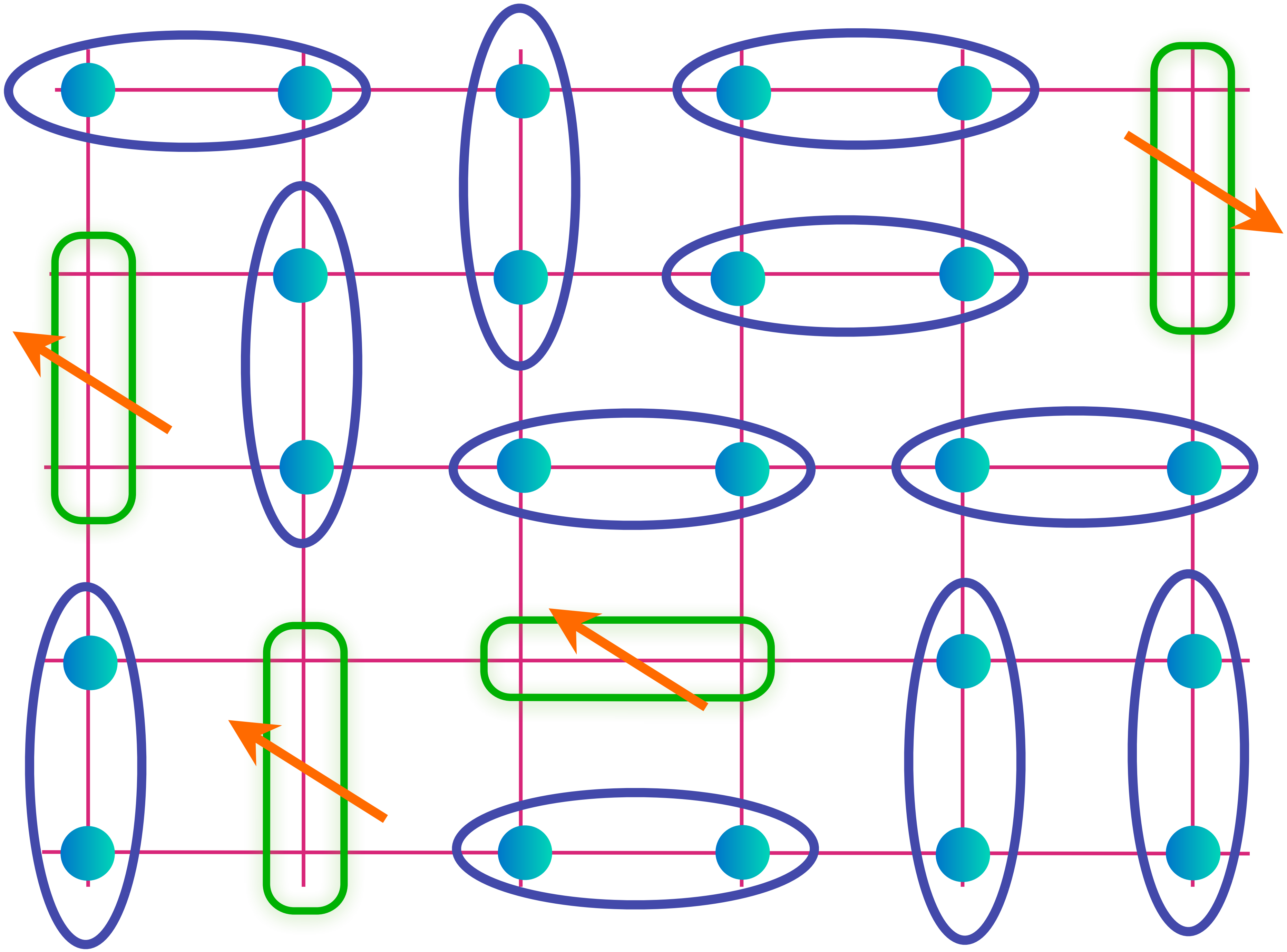

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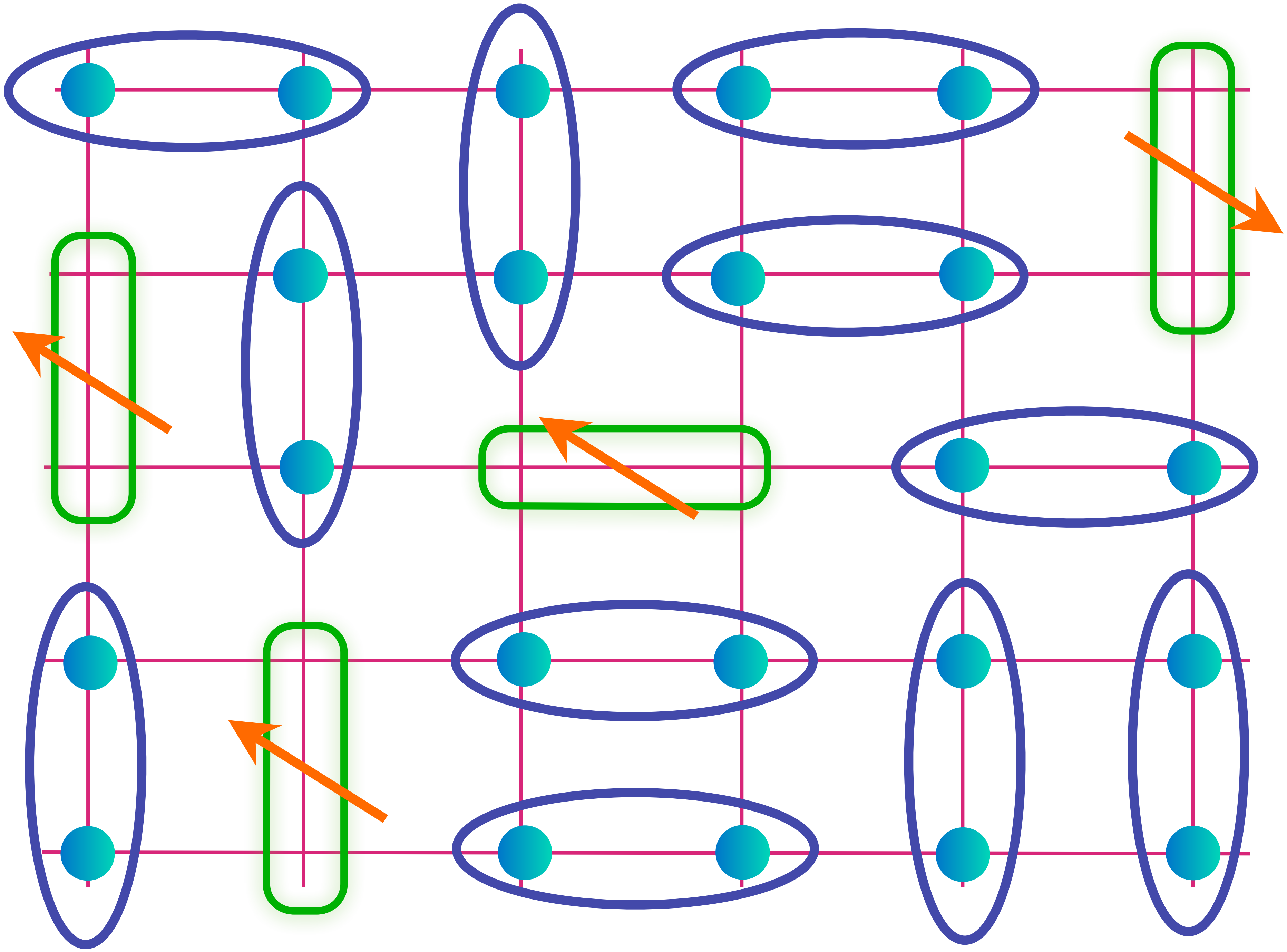

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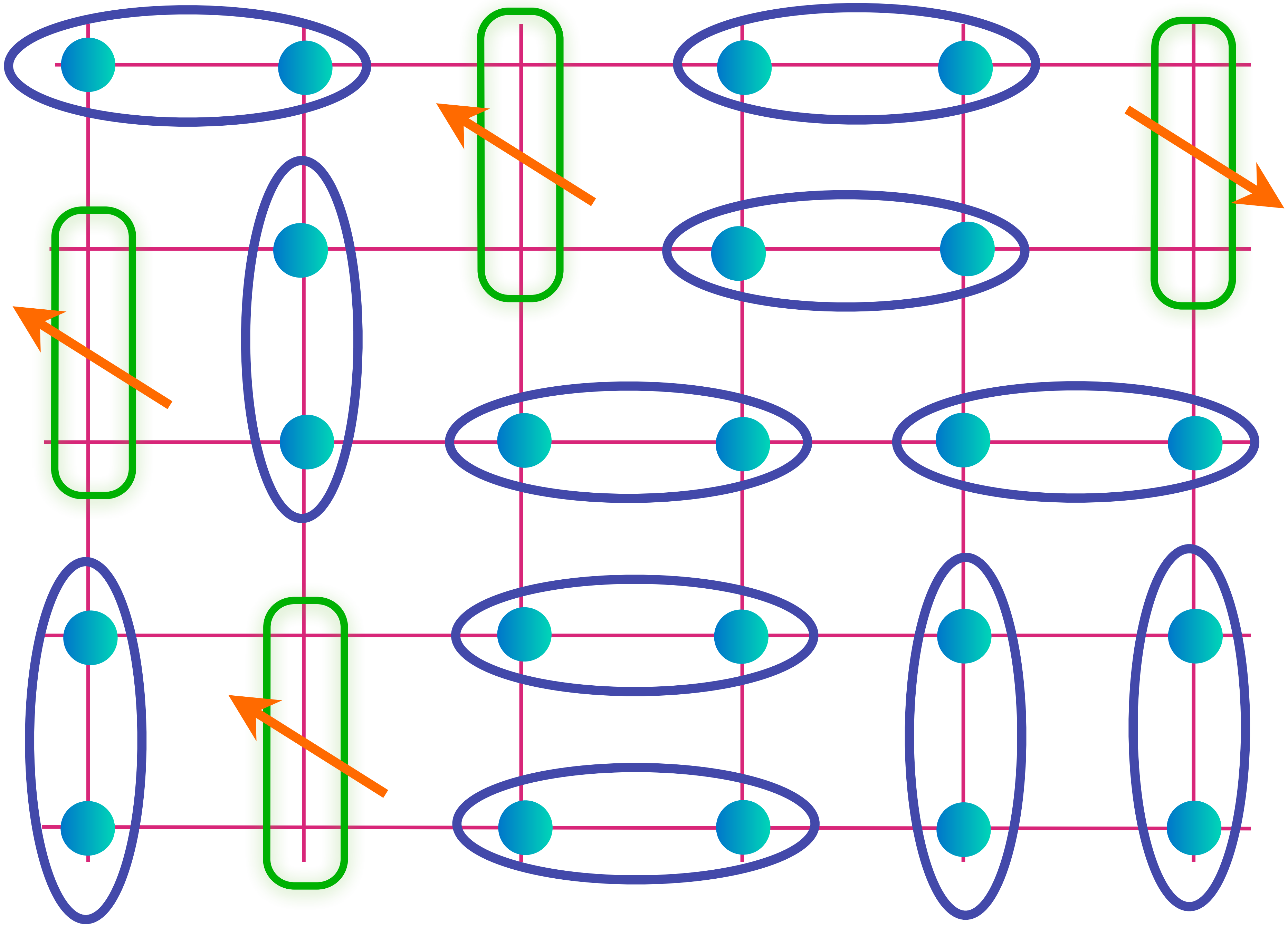

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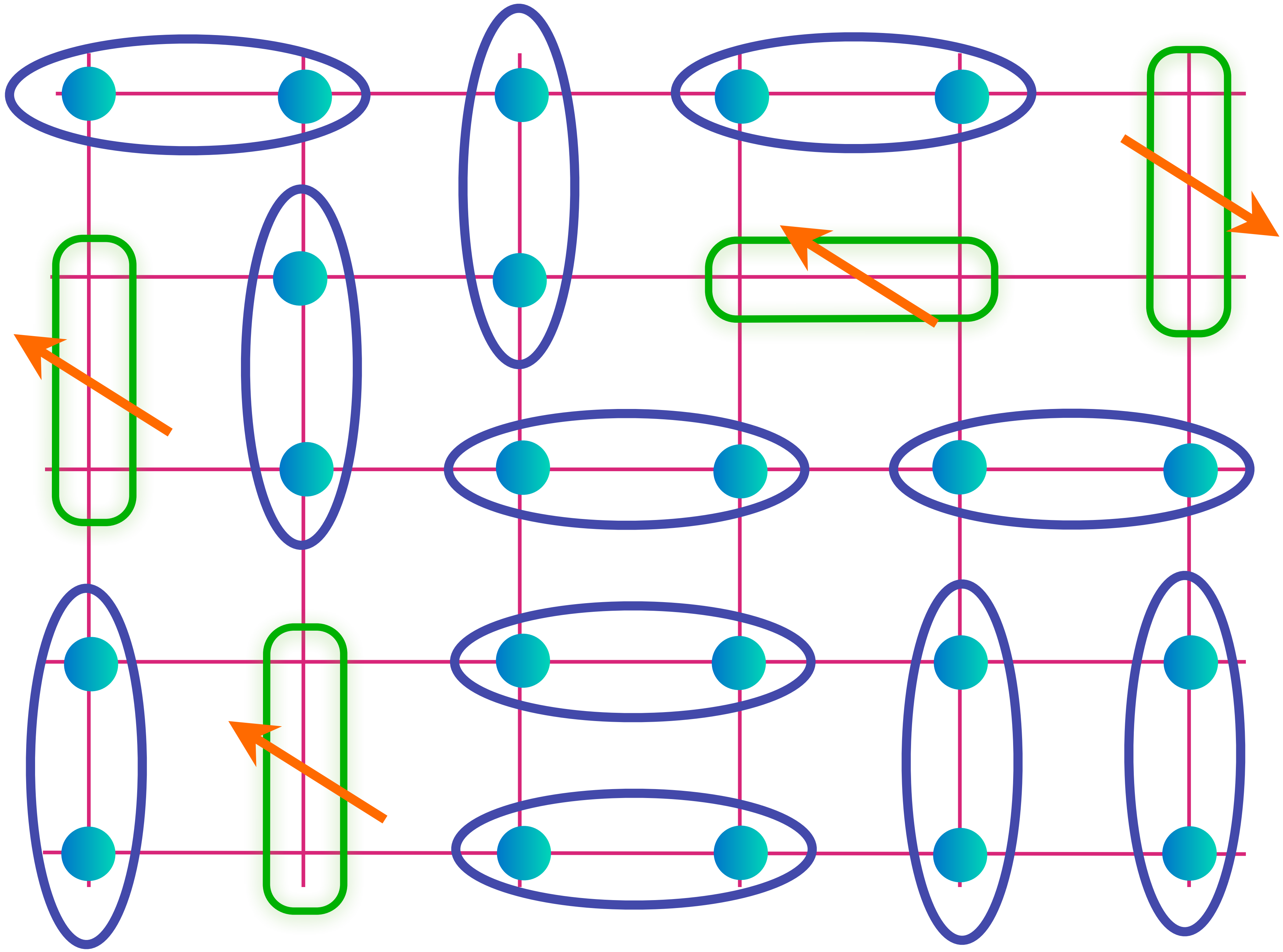

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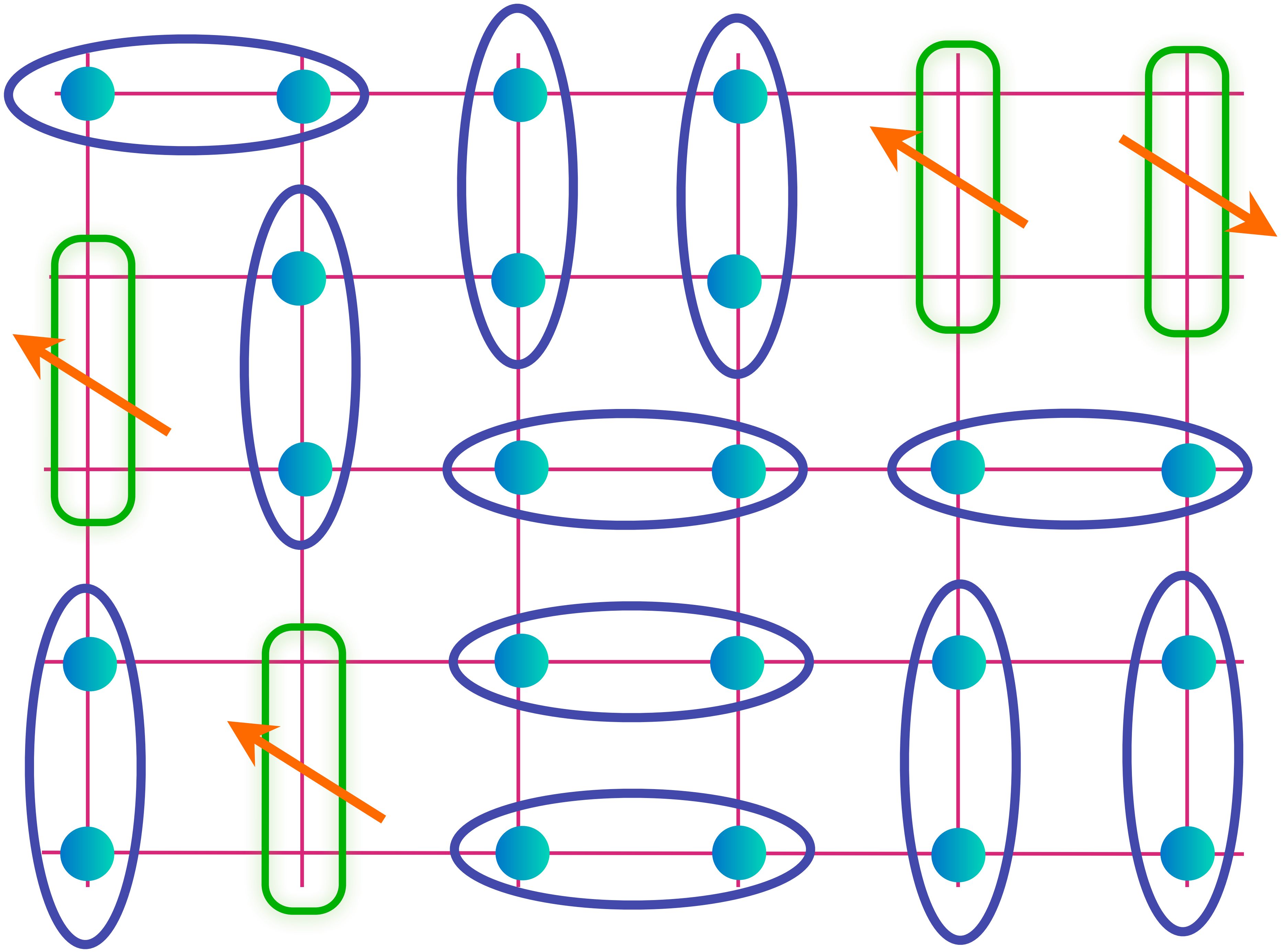

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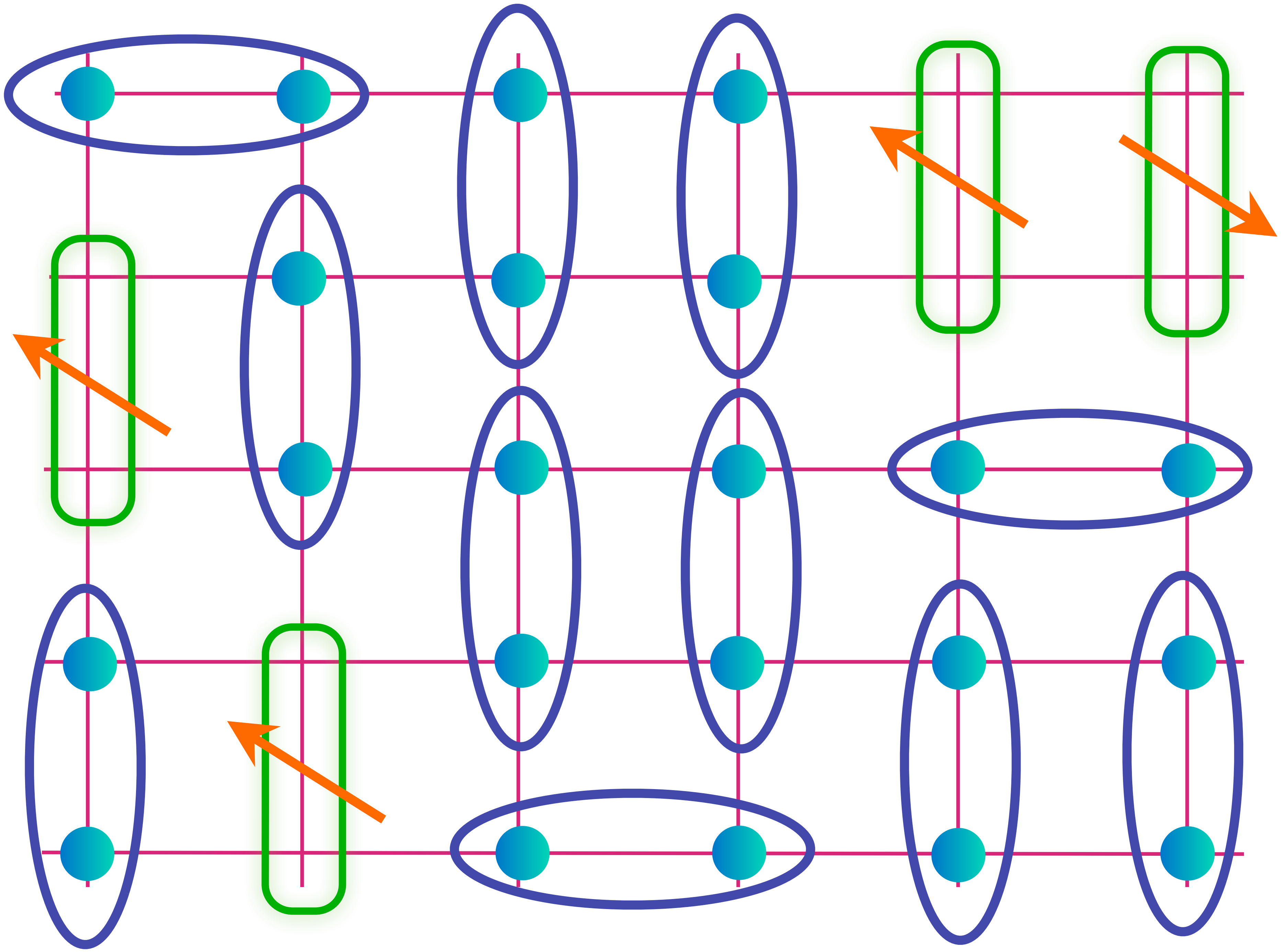

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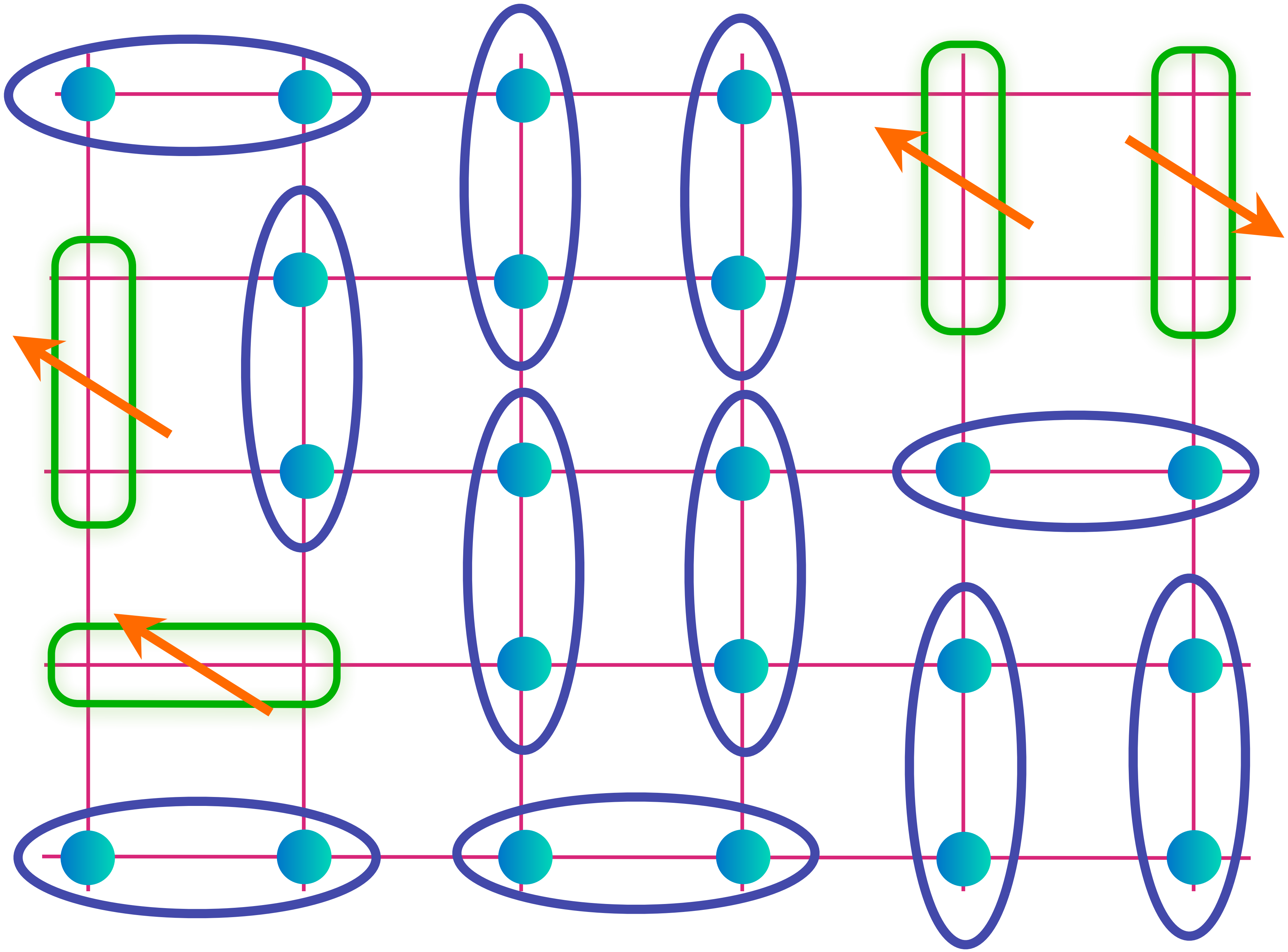

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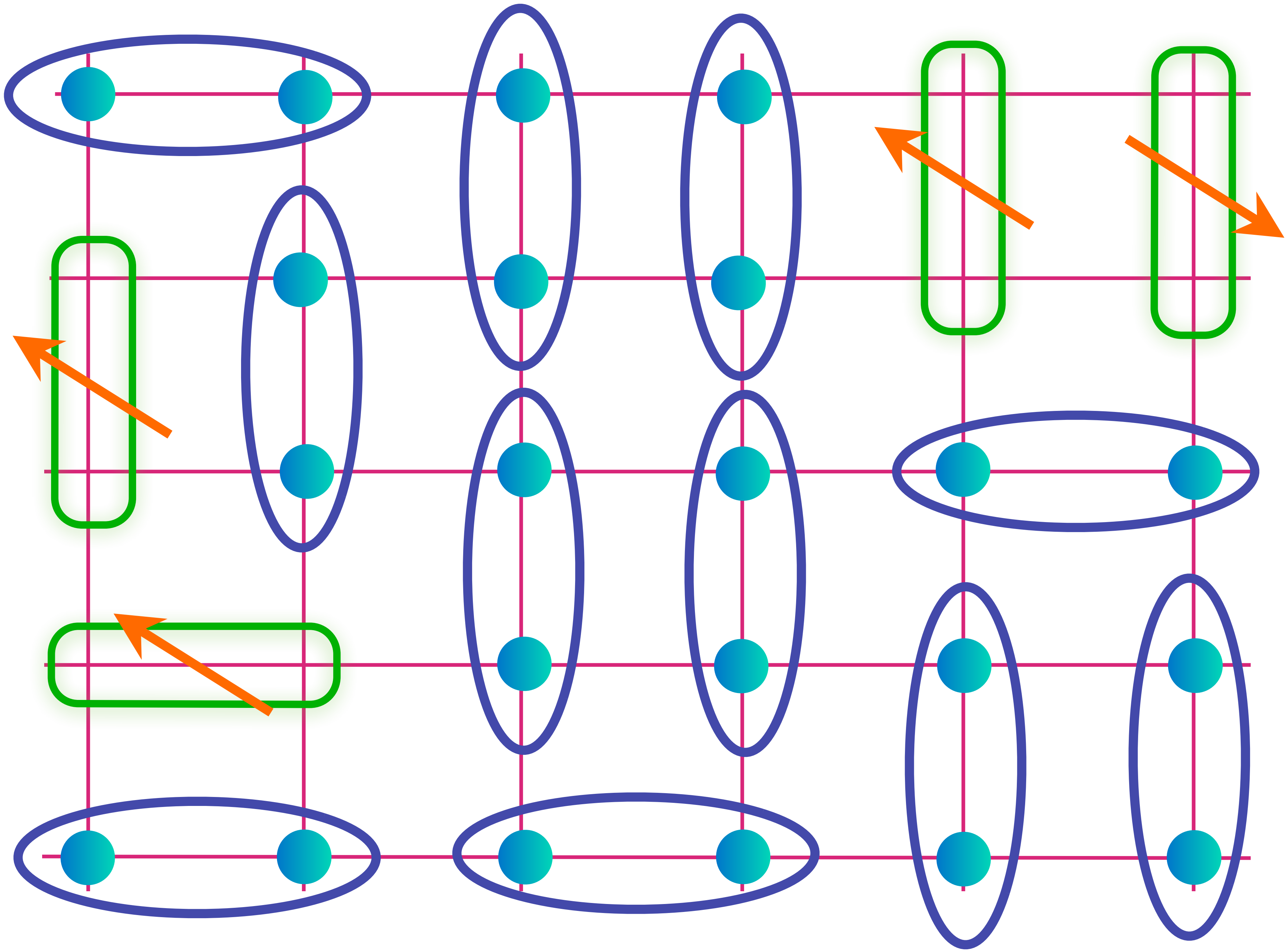


Realizes a metal with a Fermi surface of area *p*, *and* "topological order"

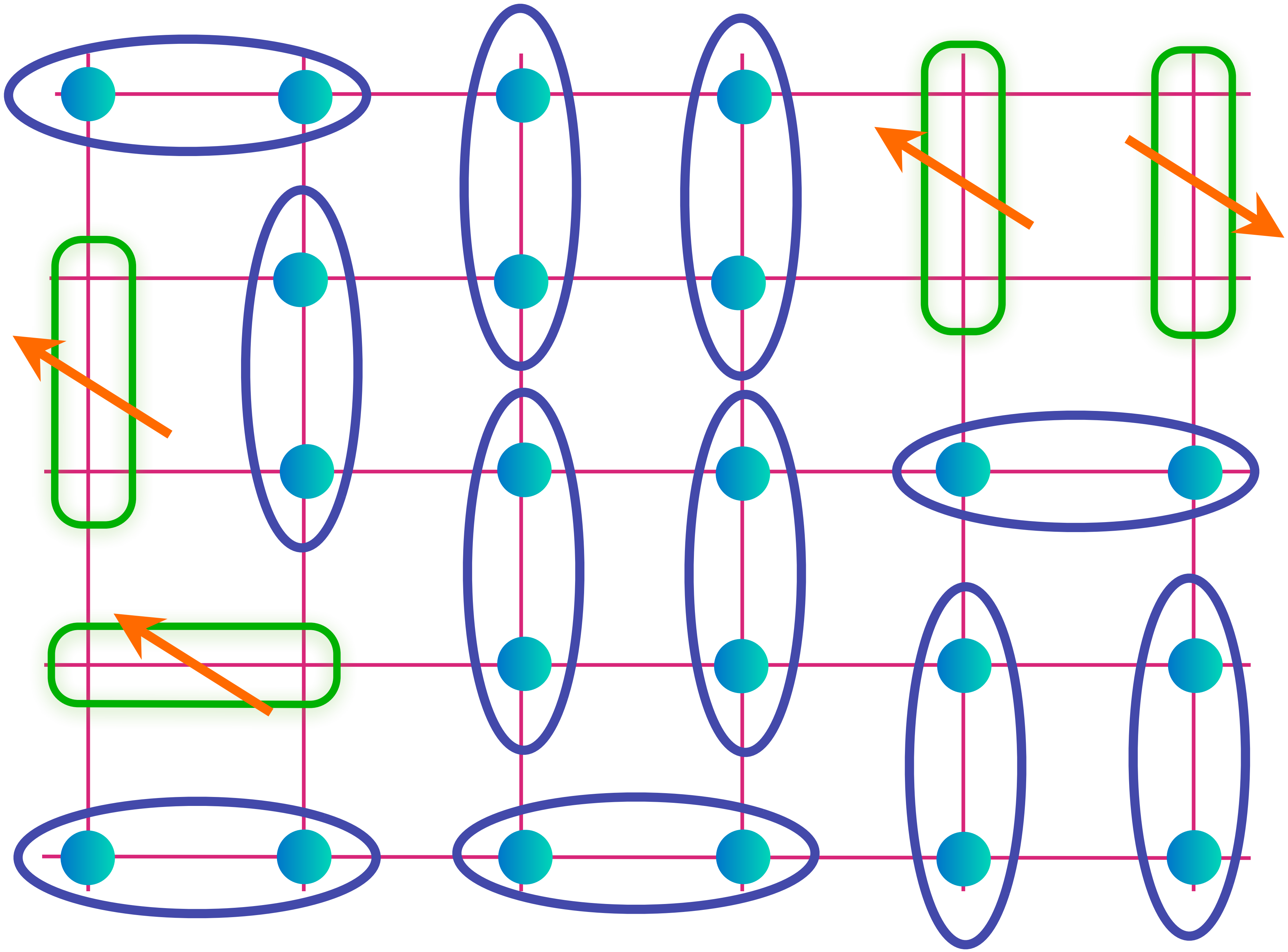
T. Senthil, S. Sachdev, M. Vojta *Phys. Rev. Lett.* **90**, 216403 (2003)
M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978.

Characteristics of FL*

- 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 Oshikawa’s proof of the Luttinger theorem.

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

Quantum dimer model with bosonic and fermionic dimers



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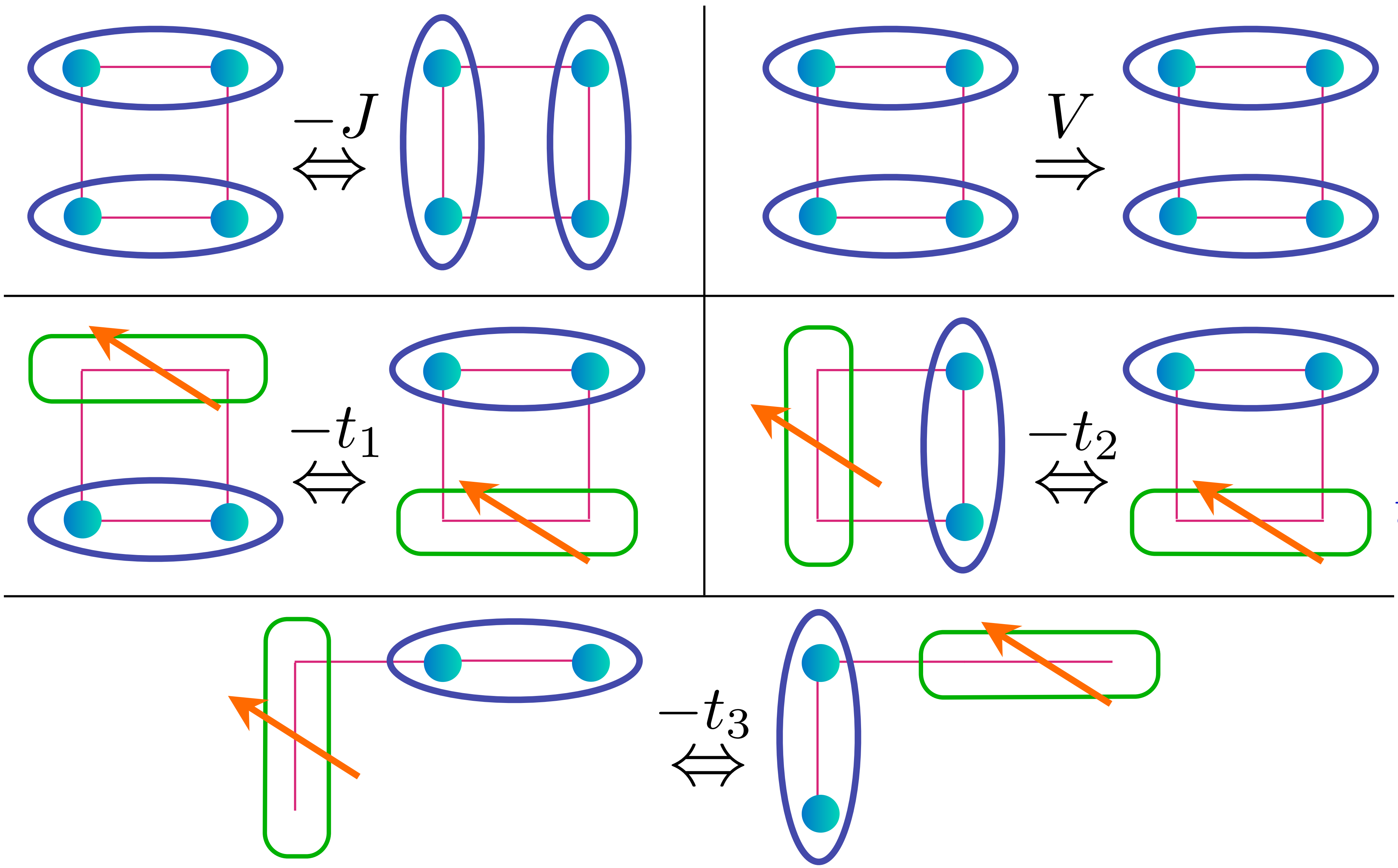
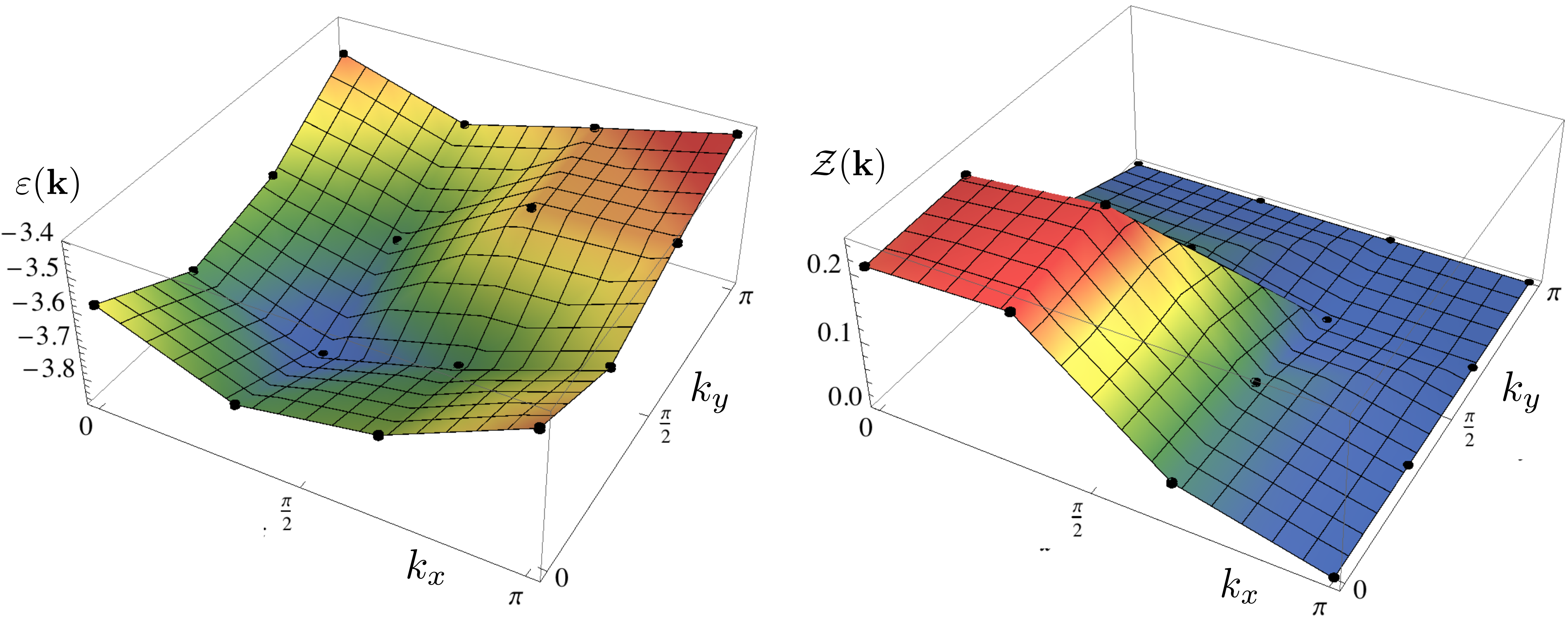


Connection to the t-t'-t''-J model:

$$t_1 = -(t + t')/2$$
$$t_2 = (t - t')/2$$
$$t_3 = -(t + t' + t'')/4$$

M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978

Quantum dimer model with bosonic and fermionic dimers



Dispersion and quasiparticle residue for $J = V = 1$, and hopping parameters obtained from the t-J model for the cuprates, $t_1 = -1.05$, $t_2 = 1.95$ and $t_3 = -0.6$, on a 6×6 lattice.

M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978

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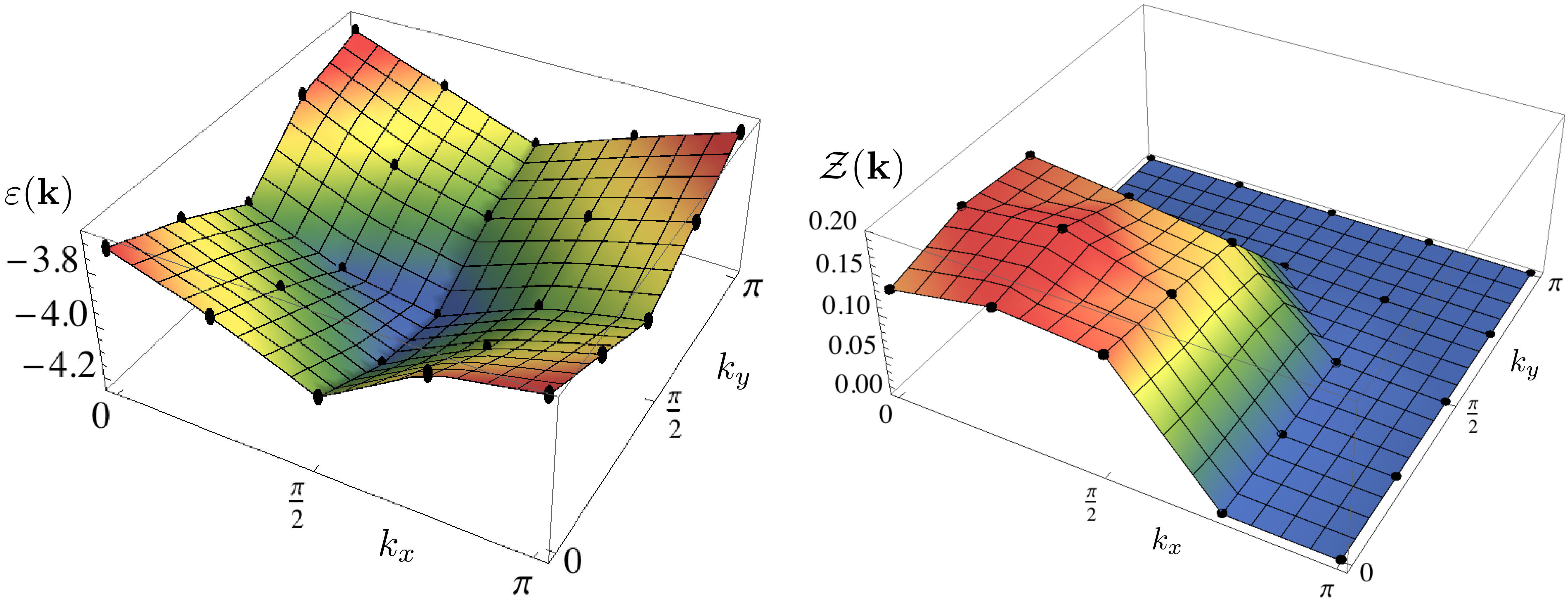
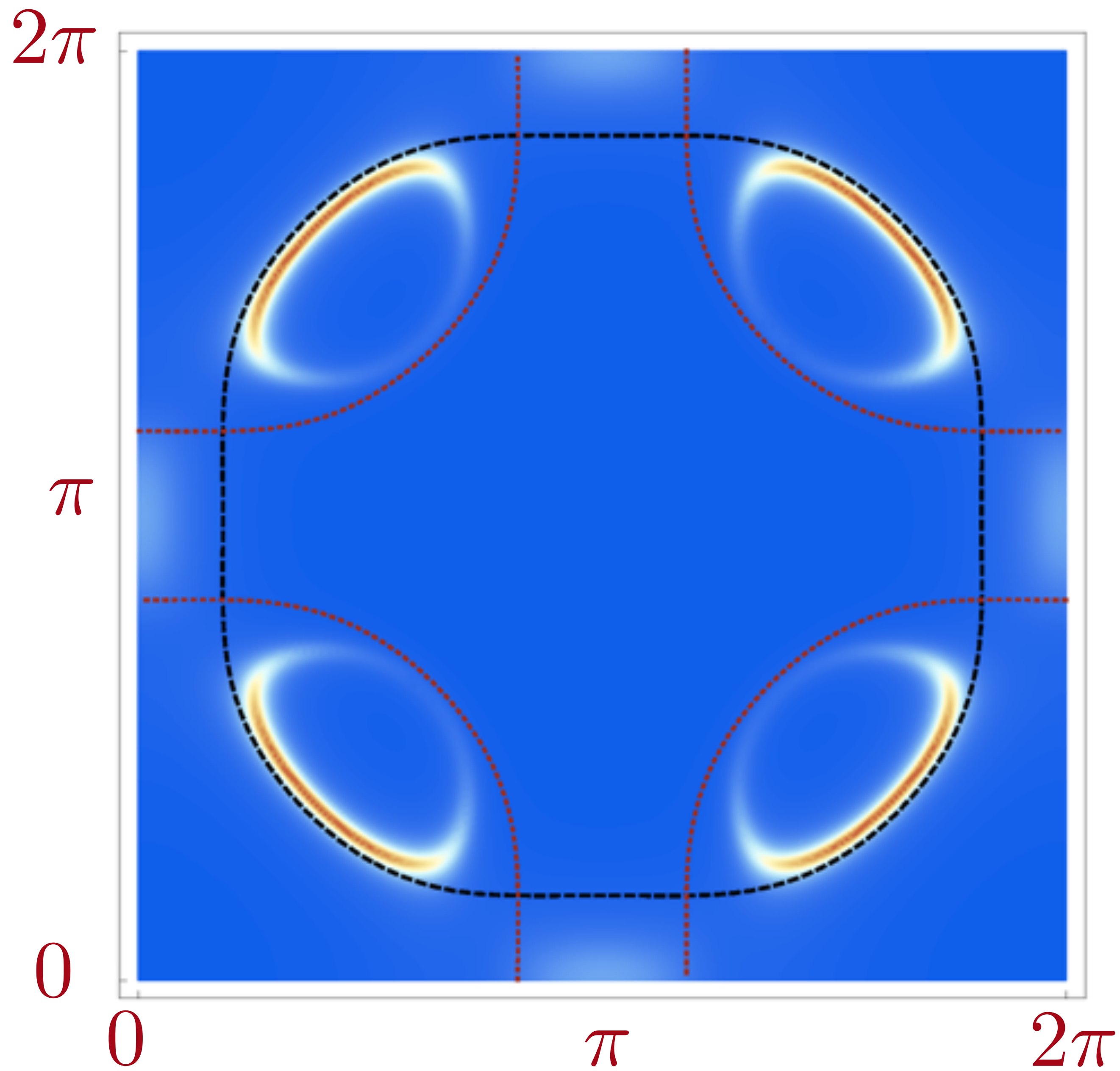


Dispersion and quasiparticle residue for $J = V = 1$, and hopping parameters $t_1 = 1$, $t_2 = 1$ and $t_3 = -1$, on a 8×8 lattice.

M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978

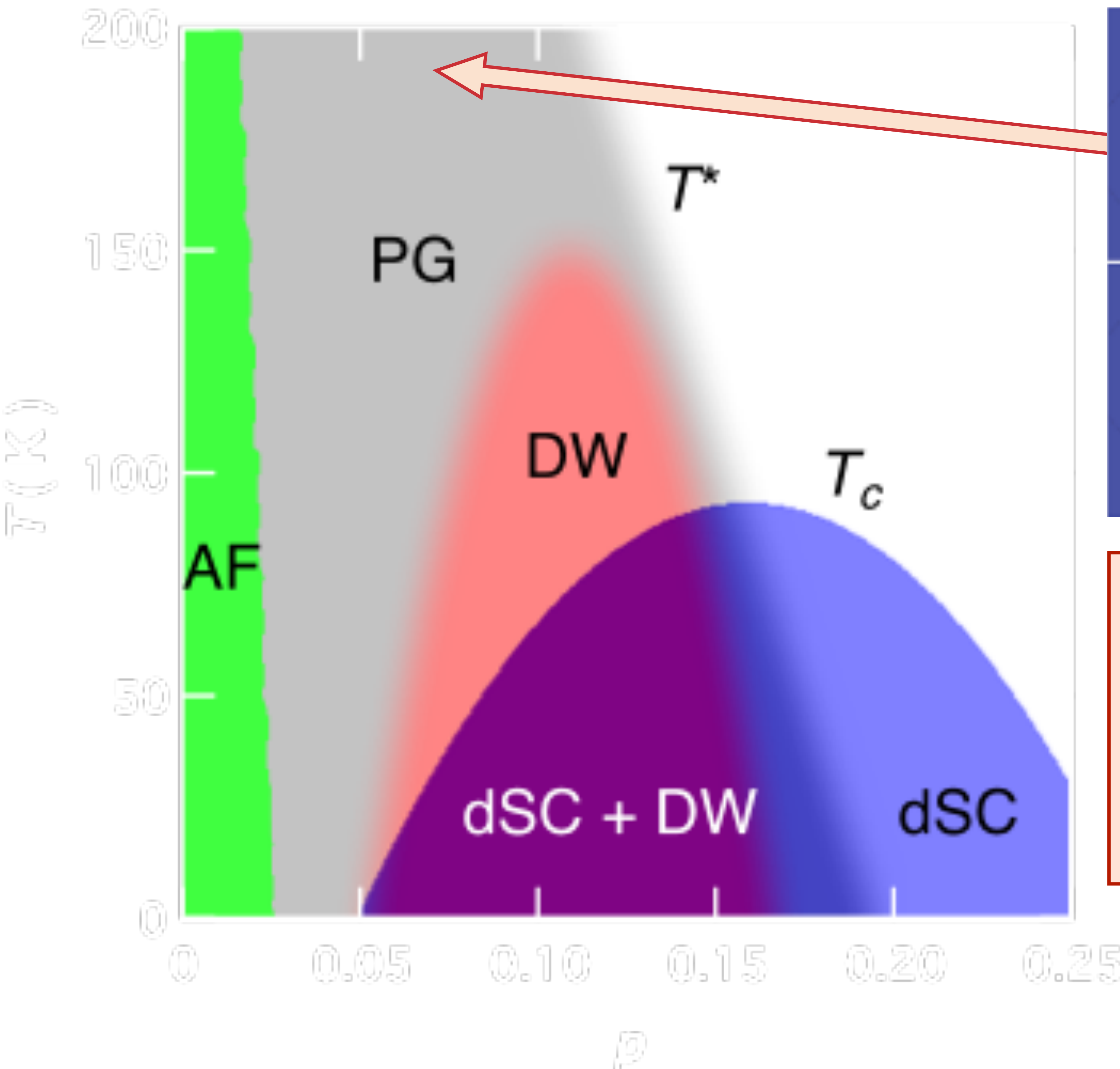


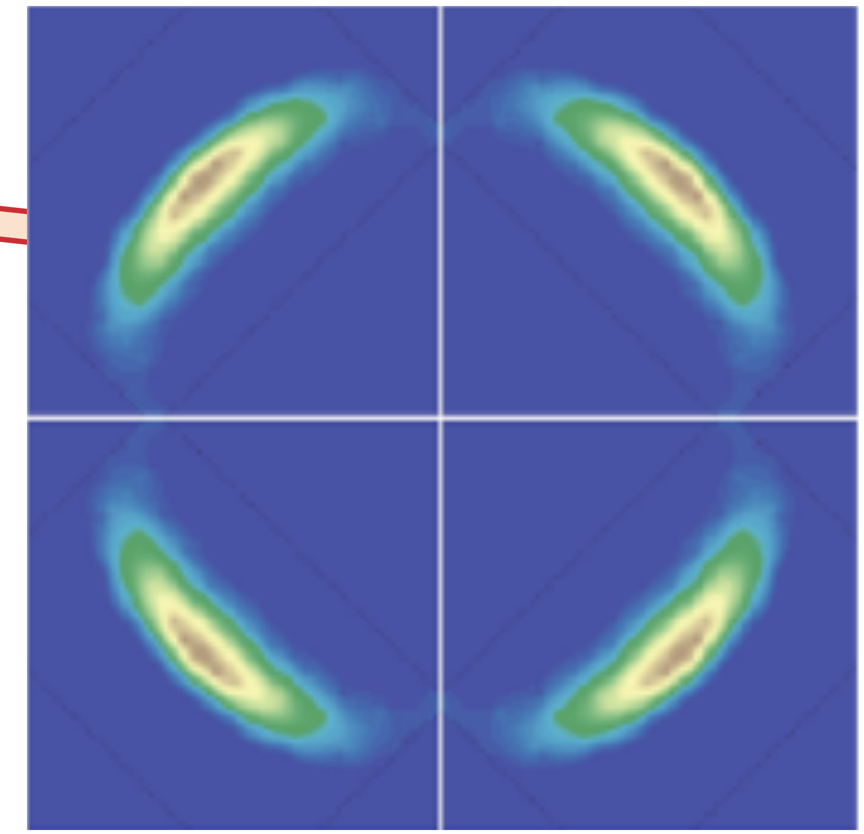
Electron spectral function of FL*

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, A. Allais, and S. Sachdev, arXiv:1501.00978

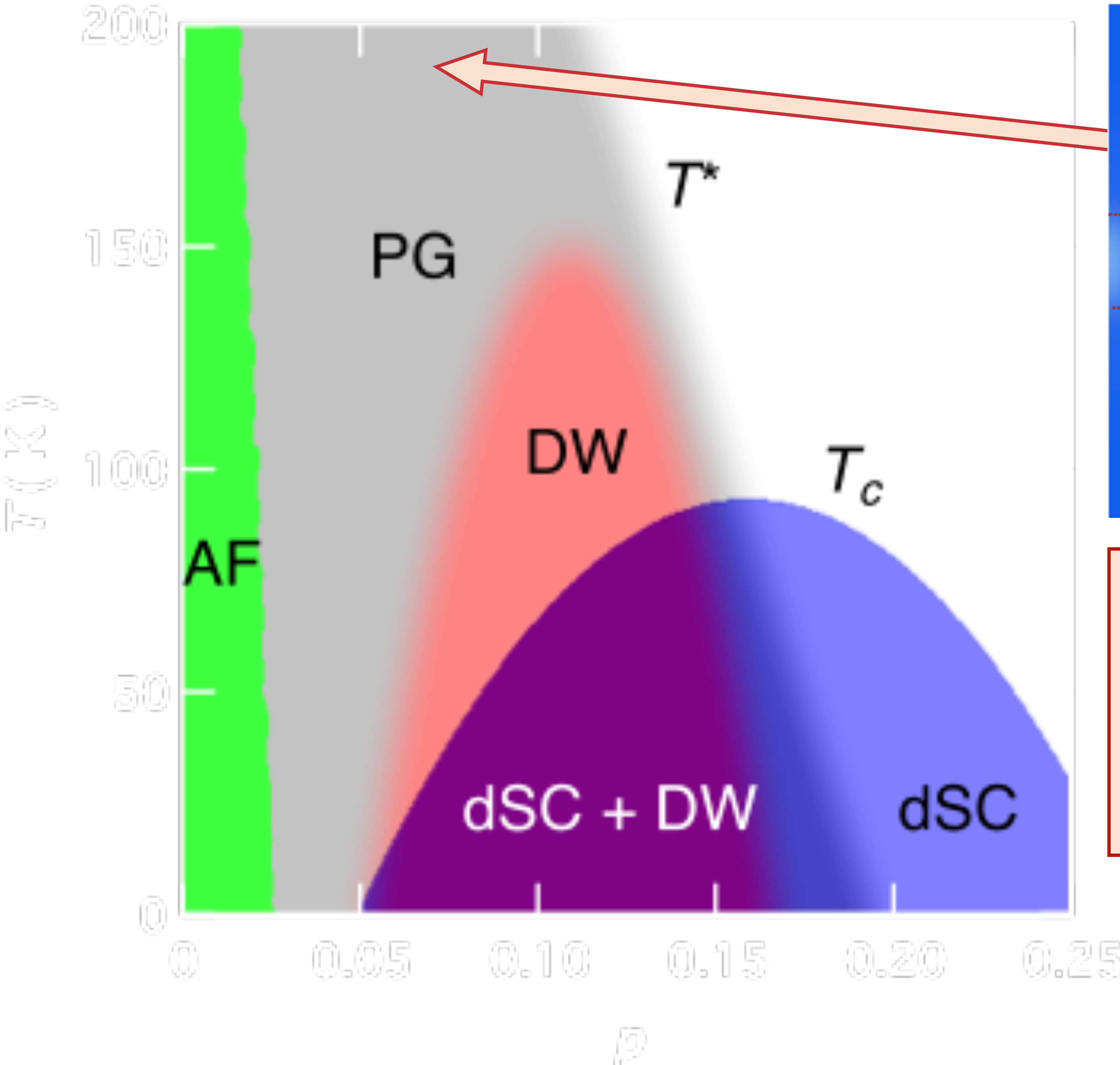
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)

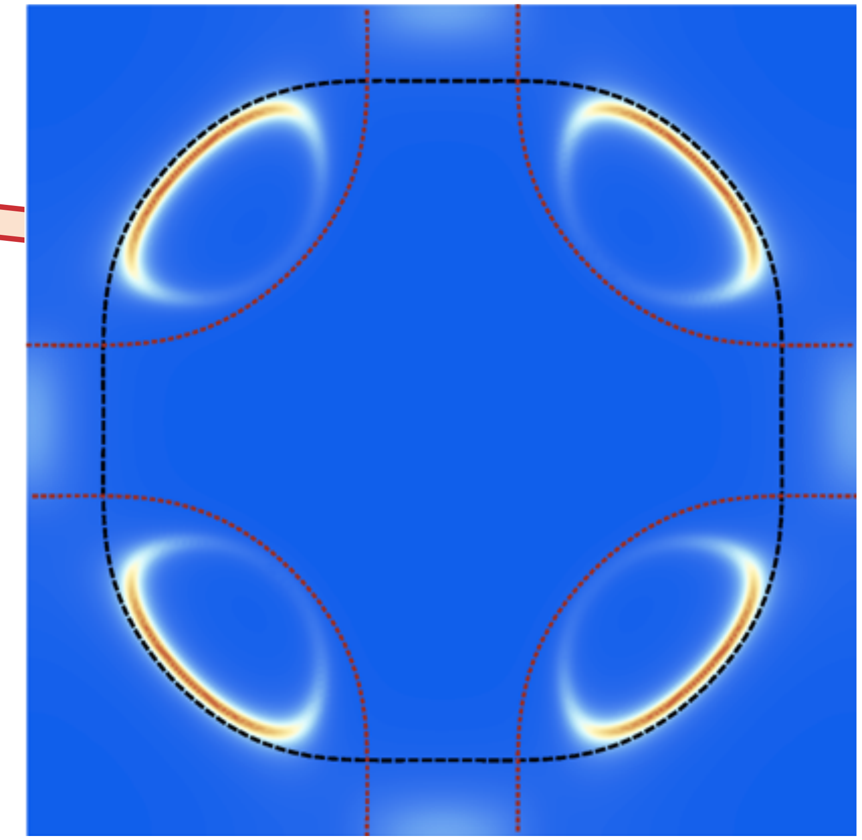




“Fermi arcs” at low p

Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978





FL* described by a quantum dimer model

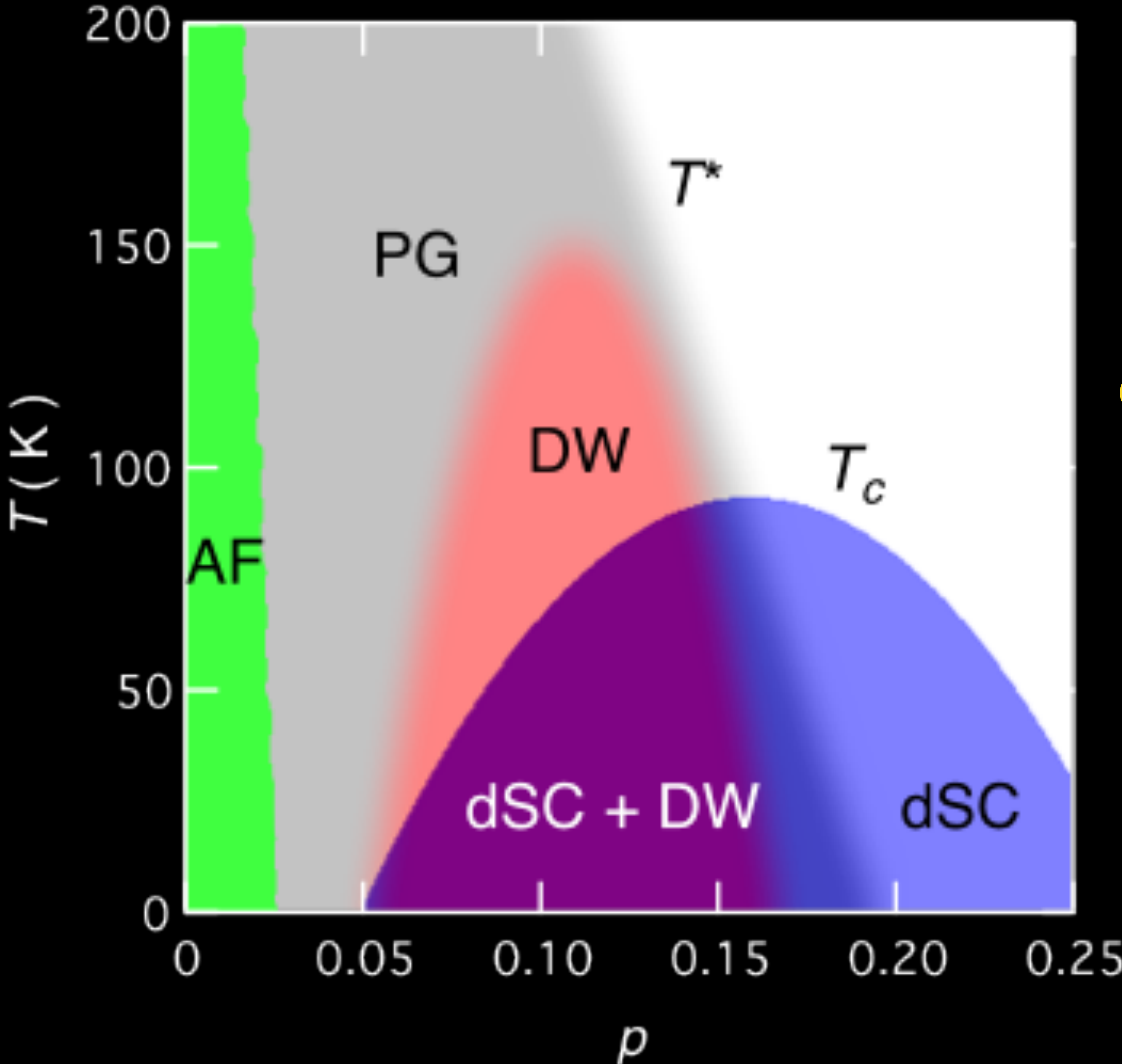
Outline

1. The high *T* pseudogap:
   A quantum dimer model for a metal with topological order

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

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

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



STM
of DW order
in non-La
materials

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

M. Vershinin, S. Misra, S. Ono, Y. Abe, Yoichi Ando, and A. Yazdani, Science **303**, 1995 (2004).

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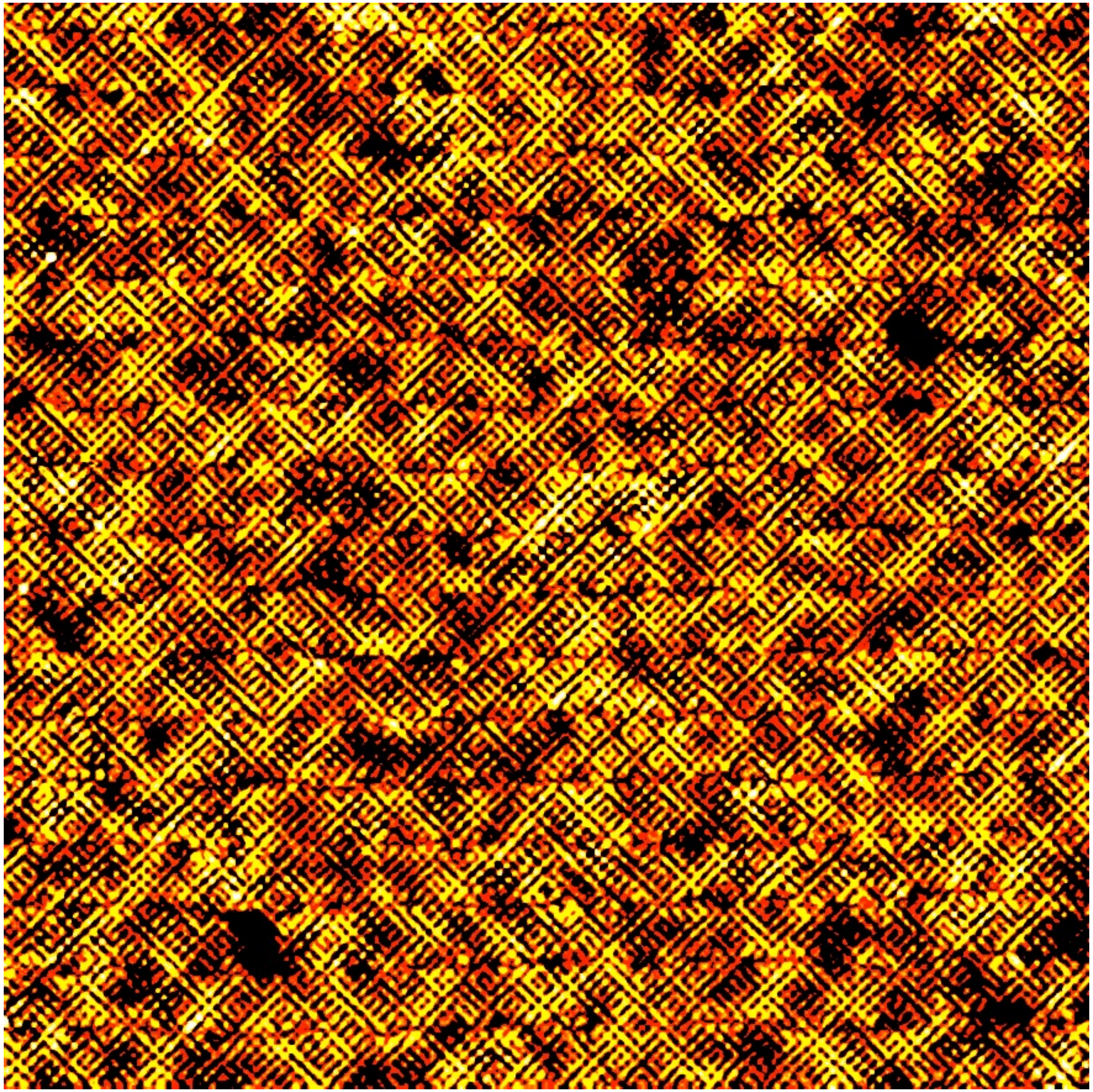

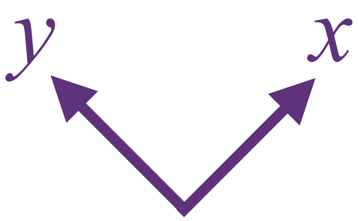

"R-map" of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007). Davis group has sub-angstrom resolution capabilities, with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

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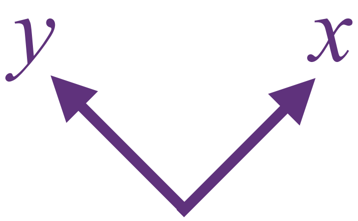
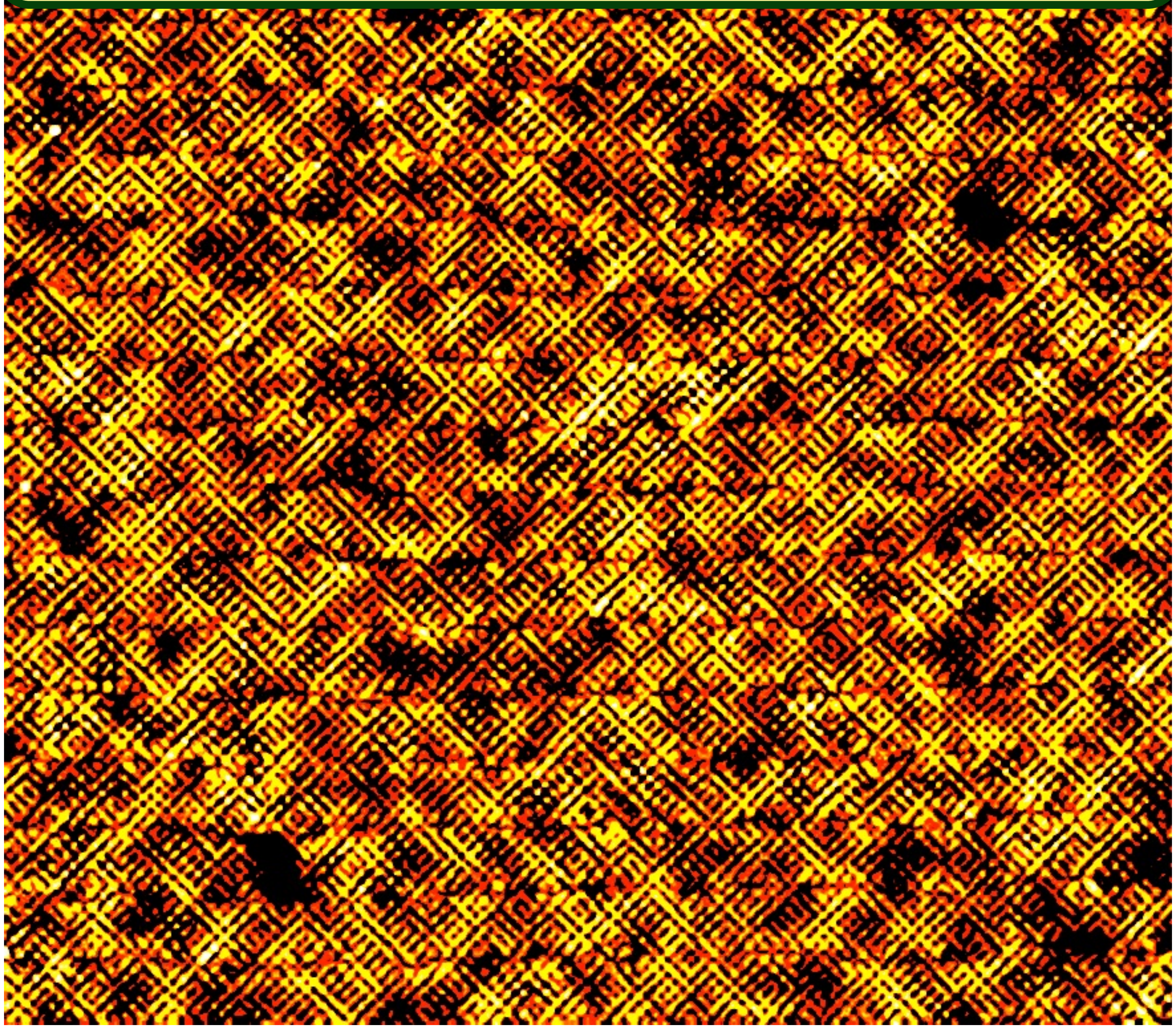
W. D. Wise, M. C. Boyer, K. Chatterjee, T. Kondo, T. Takeuchi, H. Ikuta, Y. Wang, and E. W. Hudson, Nature Phys. **4**, 696 (2008).

Disordered uni-directional charge density waves ("stripes") with wavelength ≈ 4 lattice sites ?





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

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

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

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

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

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

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

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

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

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

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

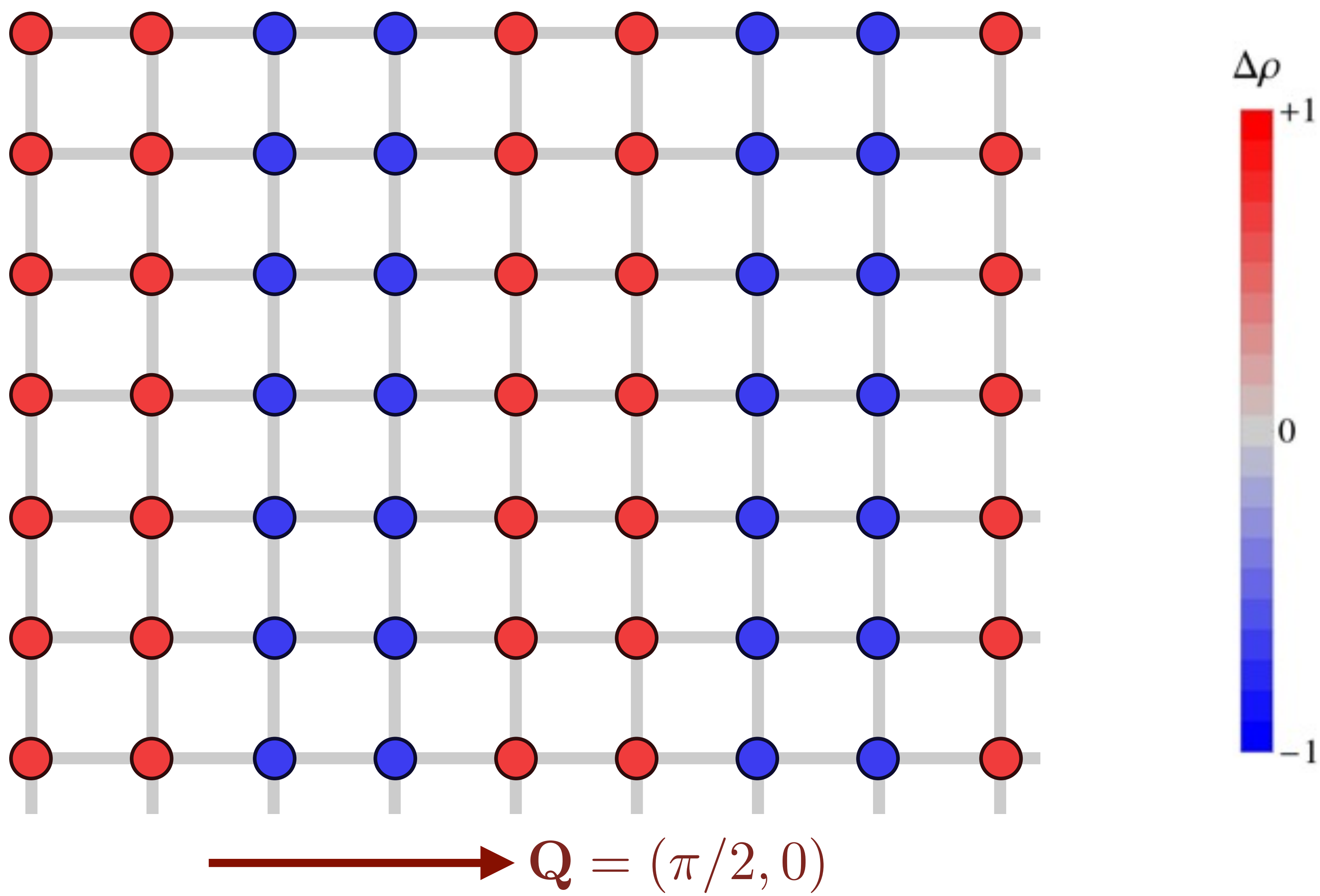
M.A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)

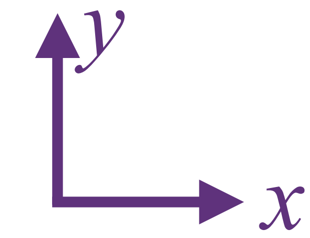
Conventional CDW order: s-form factor

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

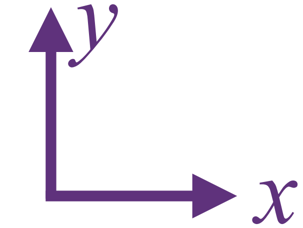
$$P_{ij} = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}\cdot(\mathbf{r}_i + \mathbf{r}_j)/2} + \text{c.c.}$$

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





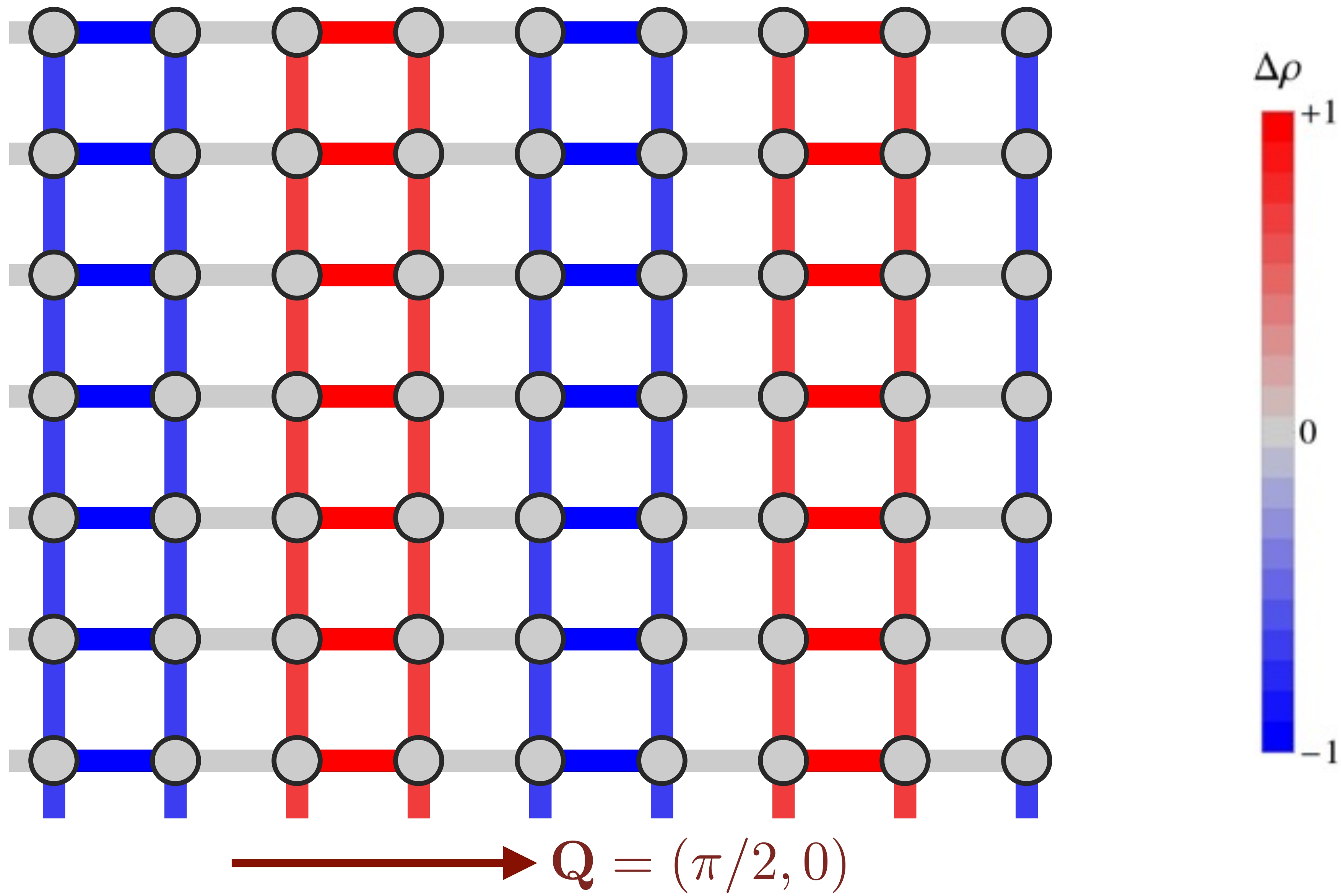
Unconventional DW order: s'-form factor



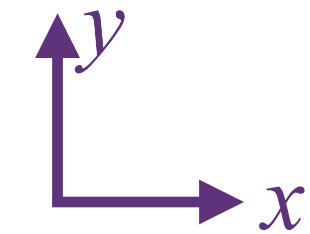
Plot of $P_{ij} = \left\langle c^\dagger_{i\alpha} c_{j\alpha} \right\rangle$ for $i = j$, and i, j nearest neighbors.

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

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



Unconventional DW order: $s + s'$-form factor



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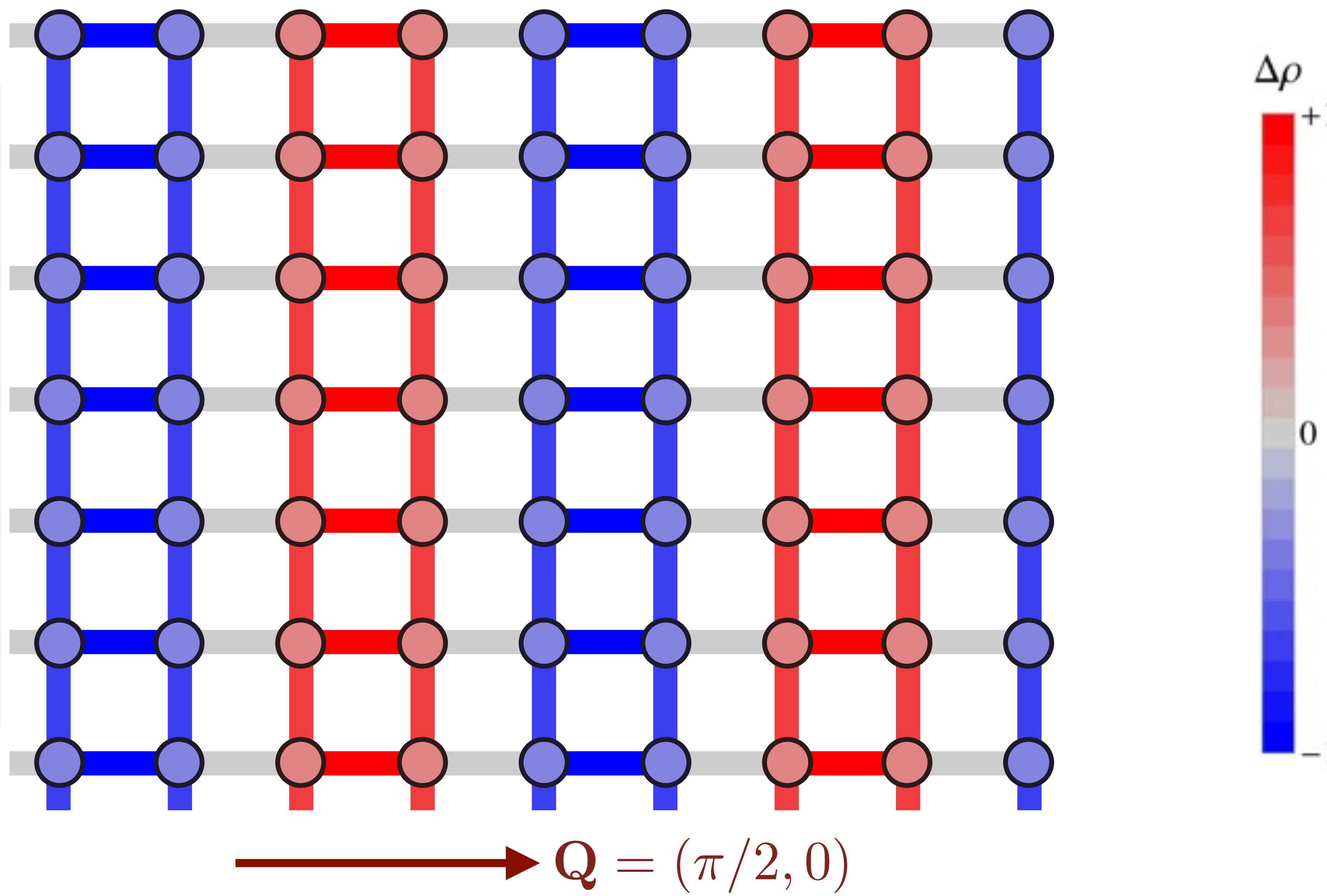
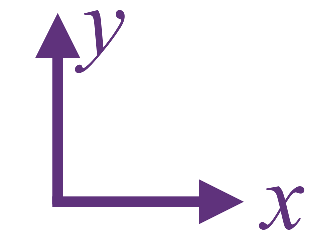
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[1/2 + \cos(k_x) + \cos(k_y)\right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$

The pattern of charge densities and bond energies in the "stripe" model yields a combination of s and s' components



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

Unconventional DW order: $s + s'$-form factor



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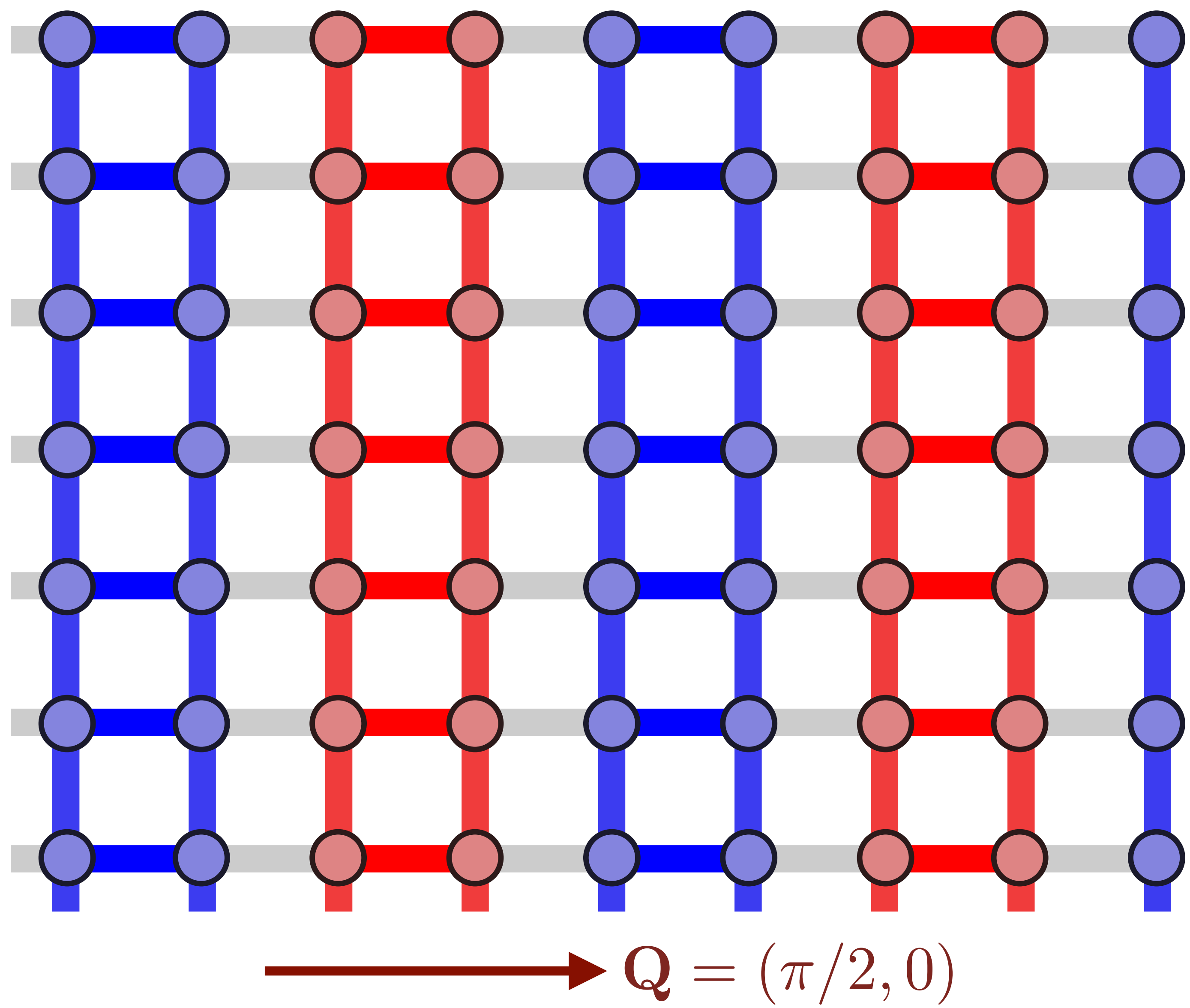
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[1/2 + \cos(k_x) + \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$

X-ray observations indicate strong s' component in LBCO

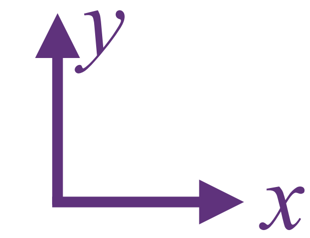


$\mathbf{Q} = (\pi/2, 0)$

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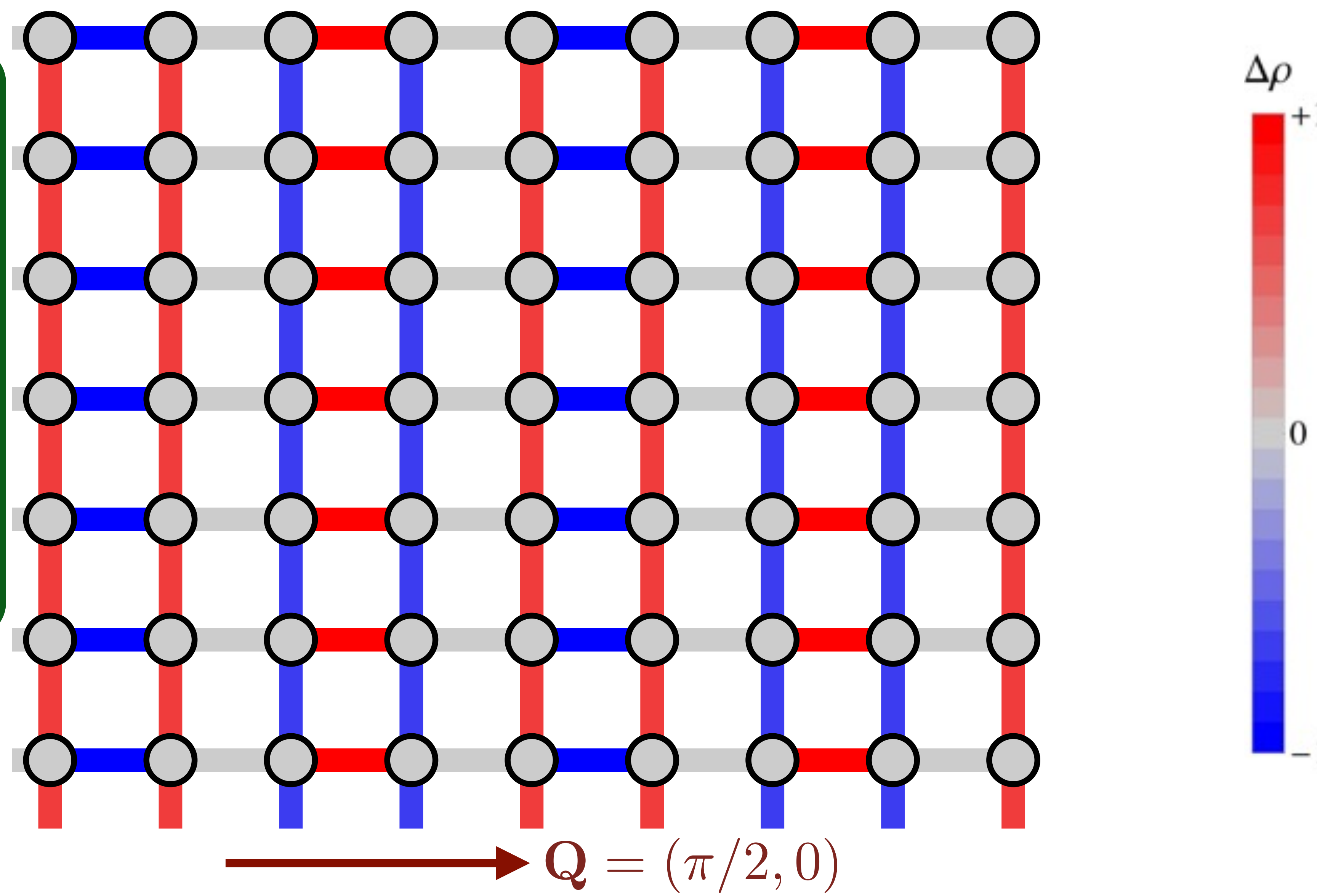
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) - \cos(k_y)\right] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$

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



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

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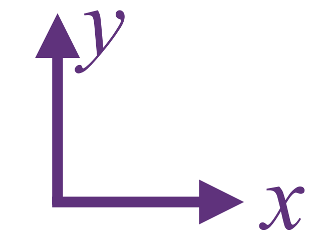

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$$\mathcal{P}(\mathbf{k}) = e^{i\phi} \left[\cos(k_x) - \cos(k_y) \right] \quad \text{and} \quad \mathbf{Q} = 2\pi(0.317, 0)$$

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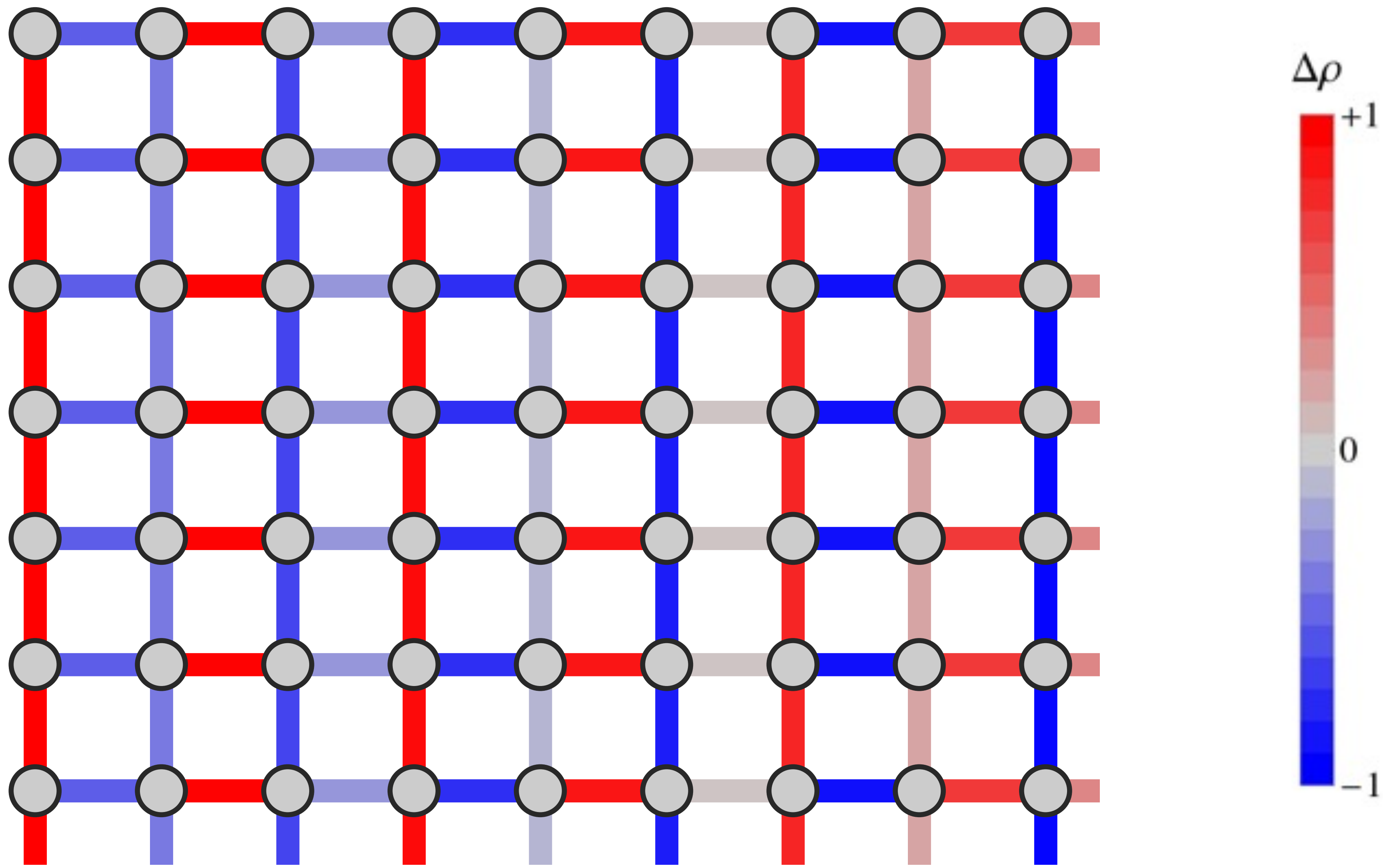

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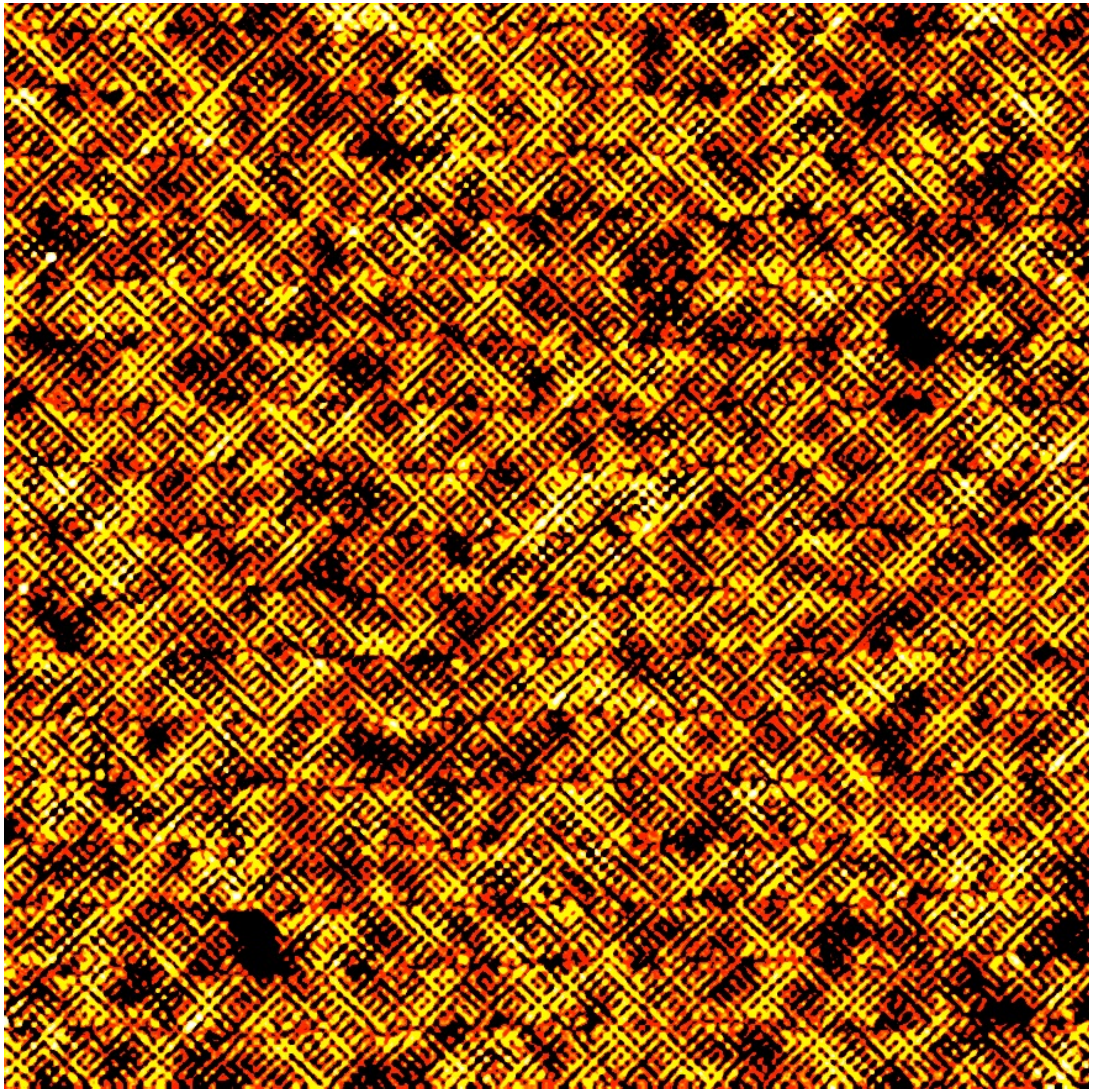

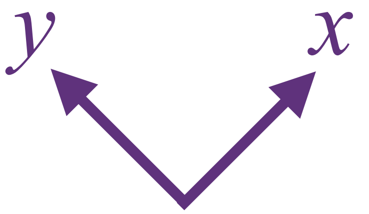

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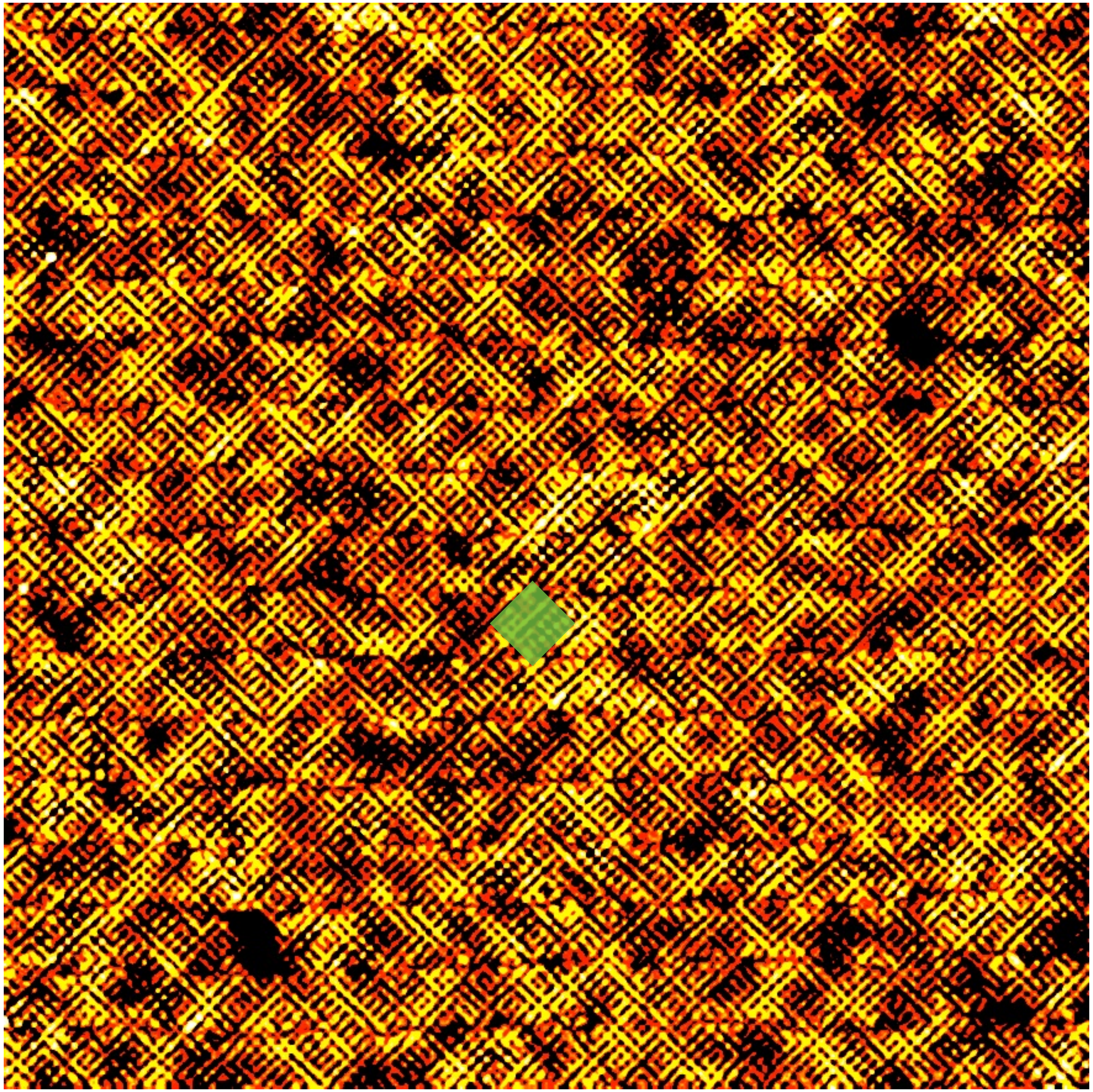

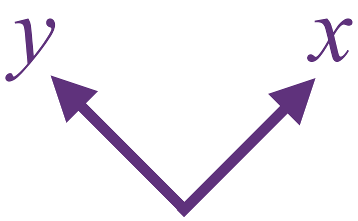

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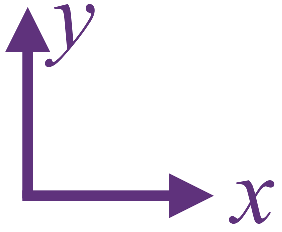

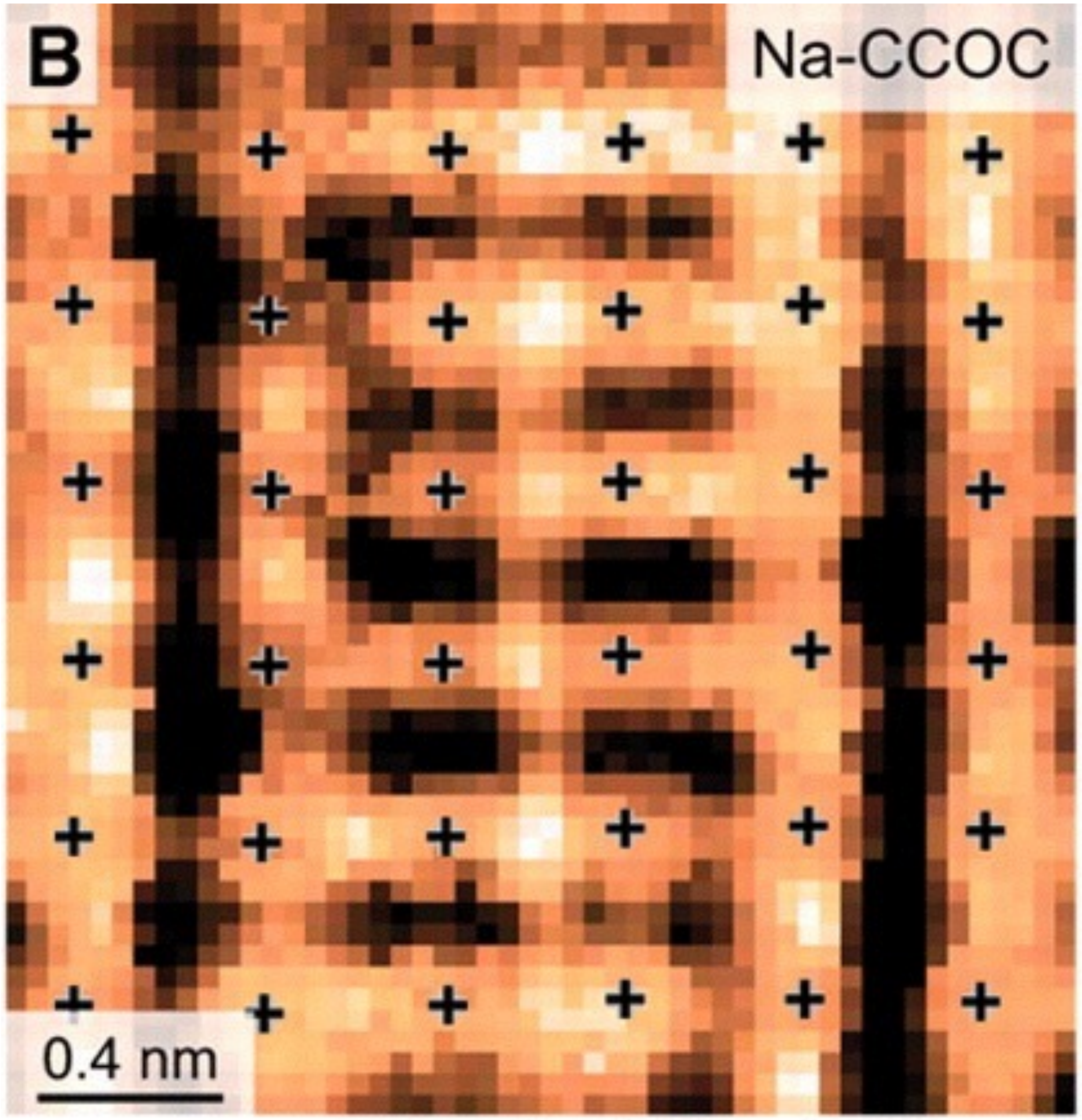

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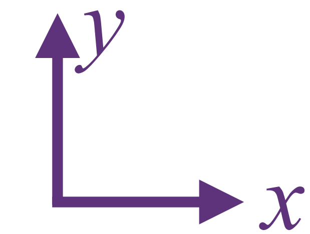

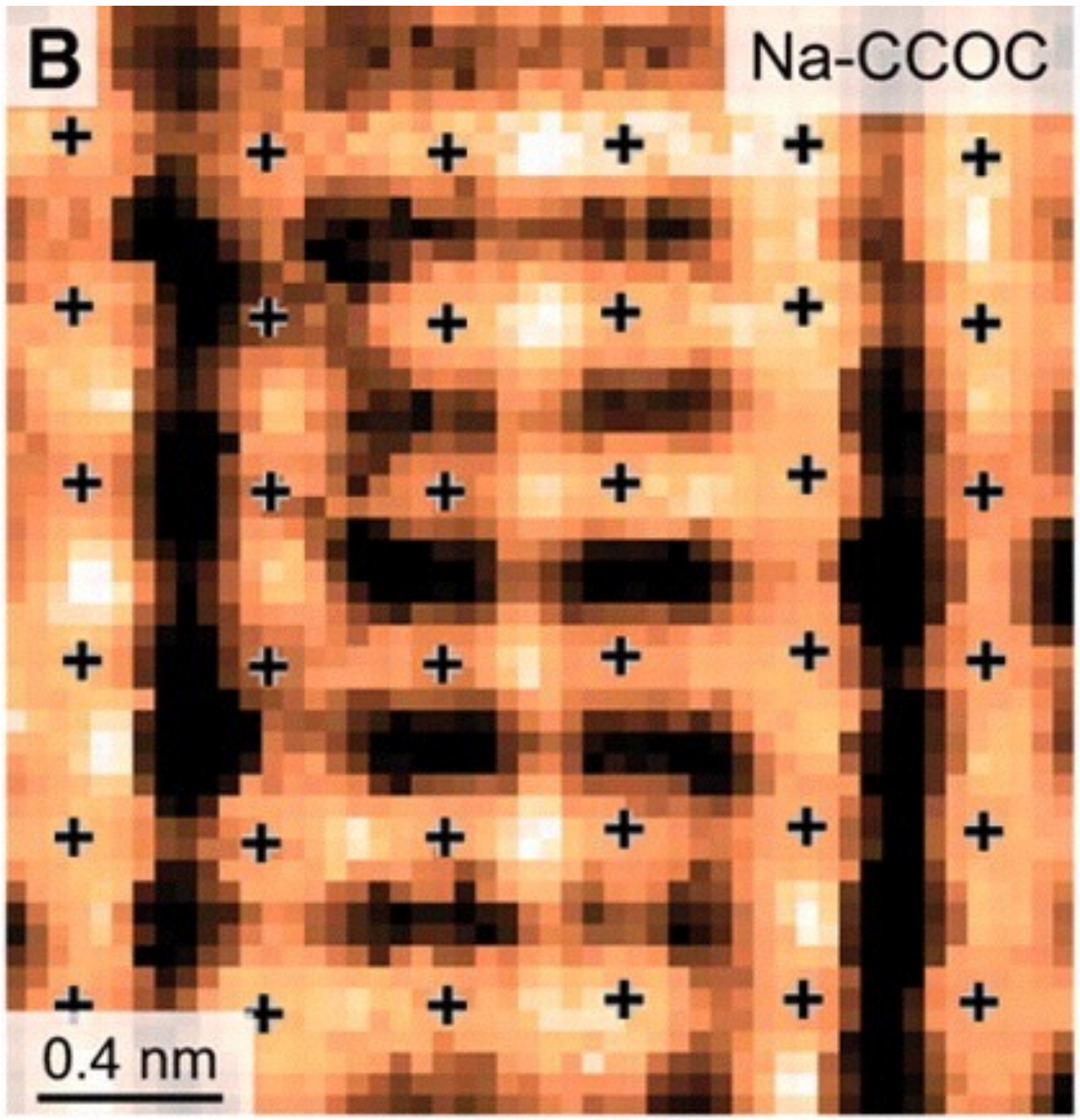

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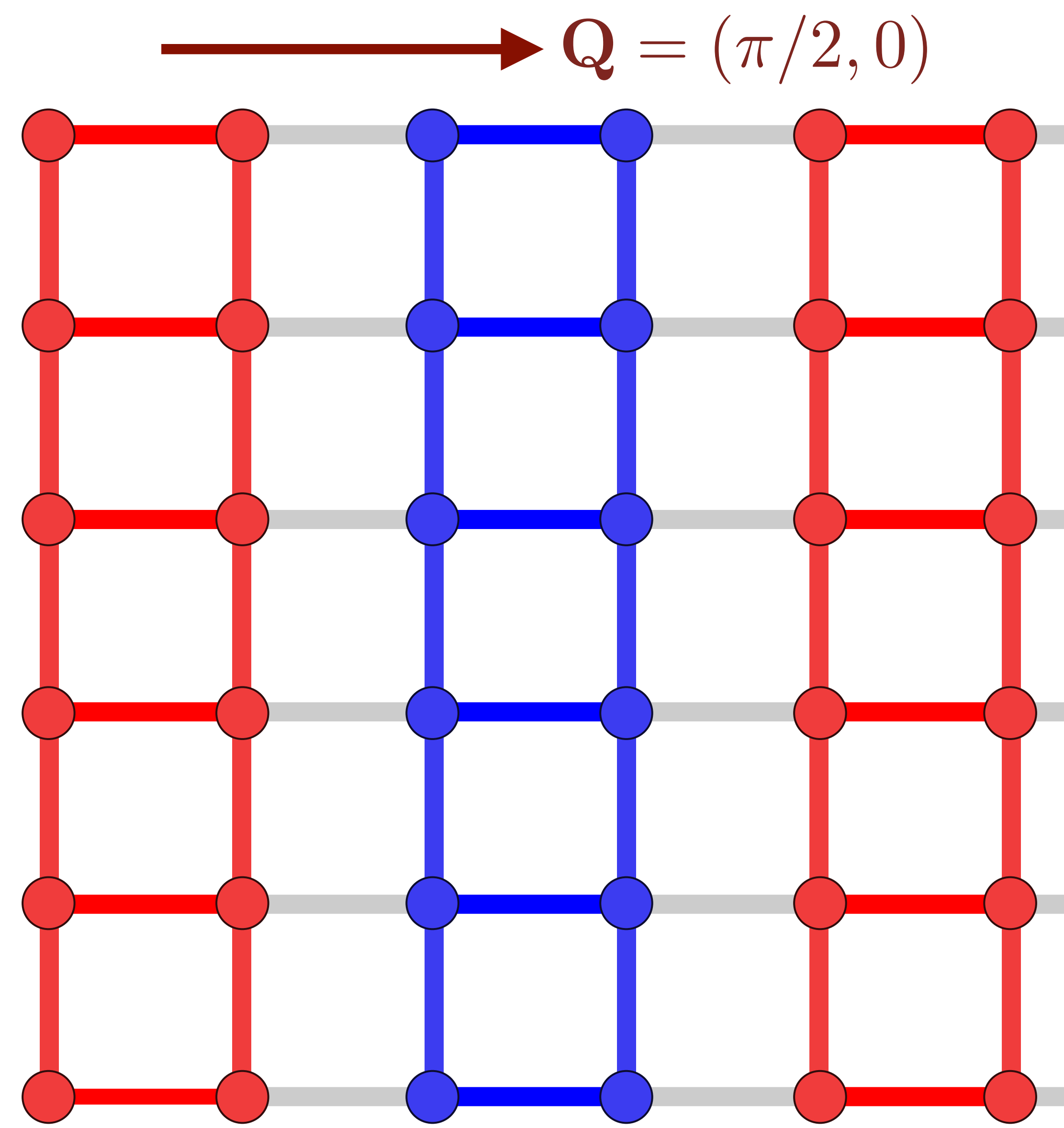
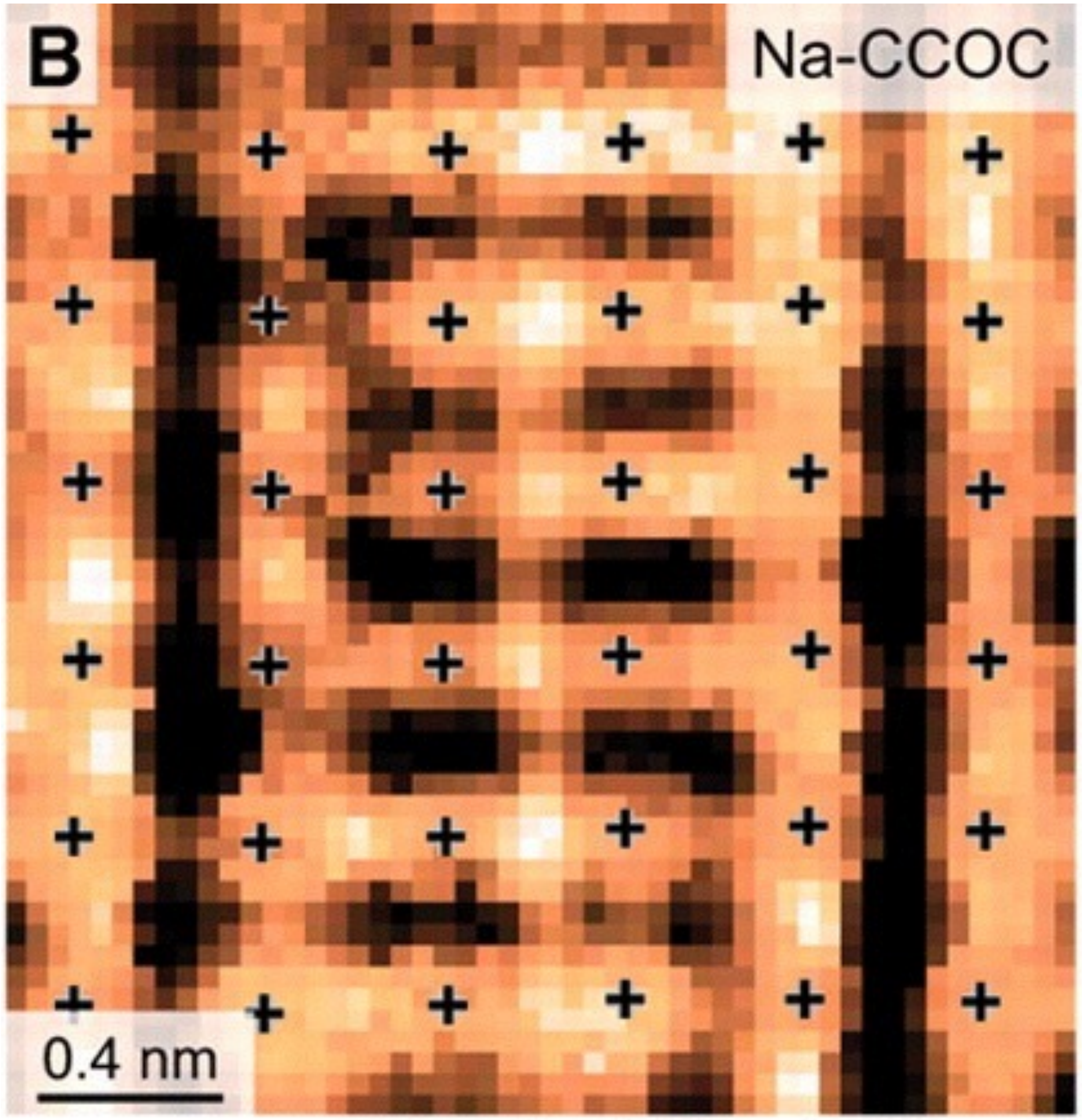
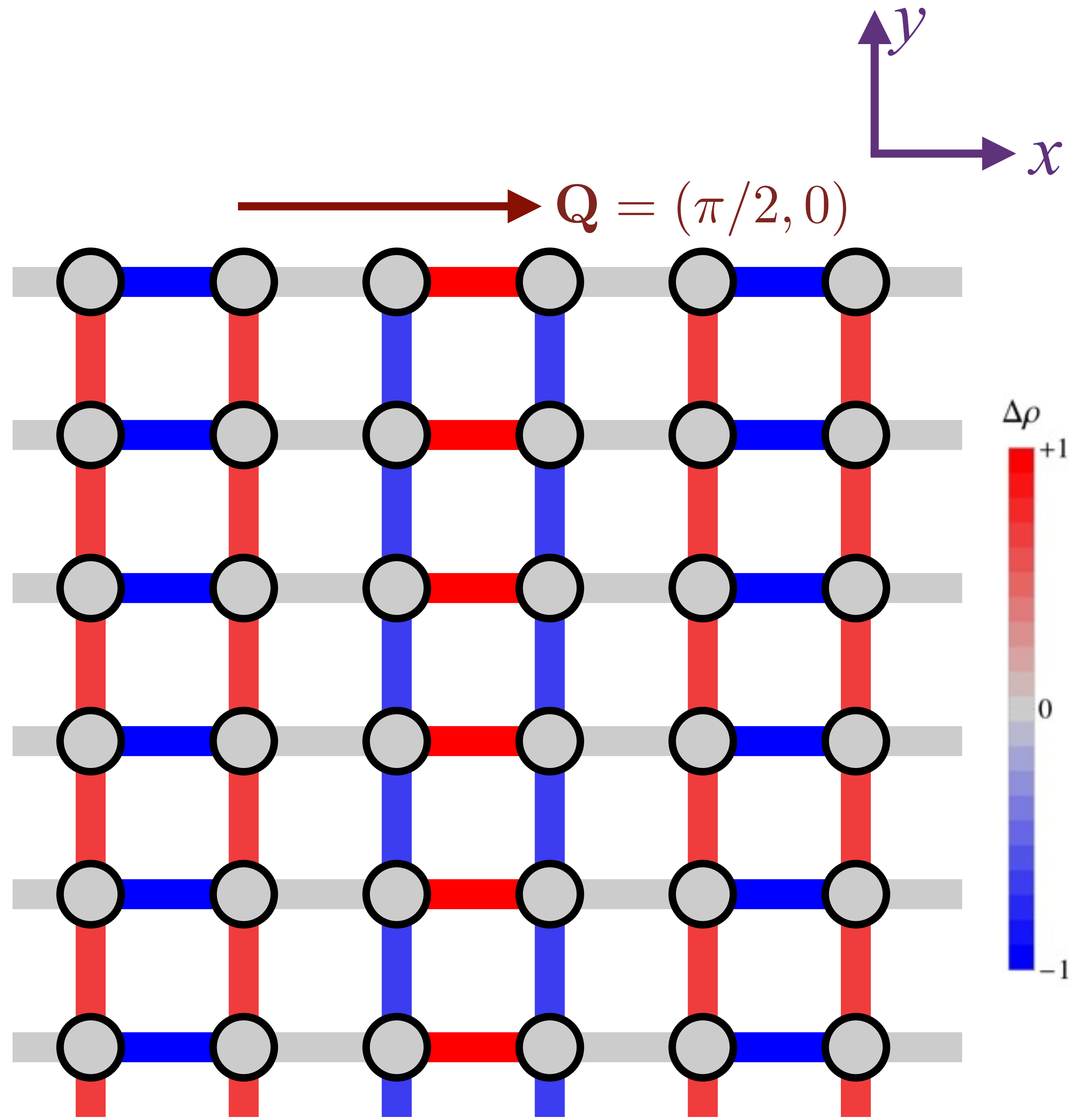


$s + s'$-form factor density wave

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



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



d-form factor density wave order

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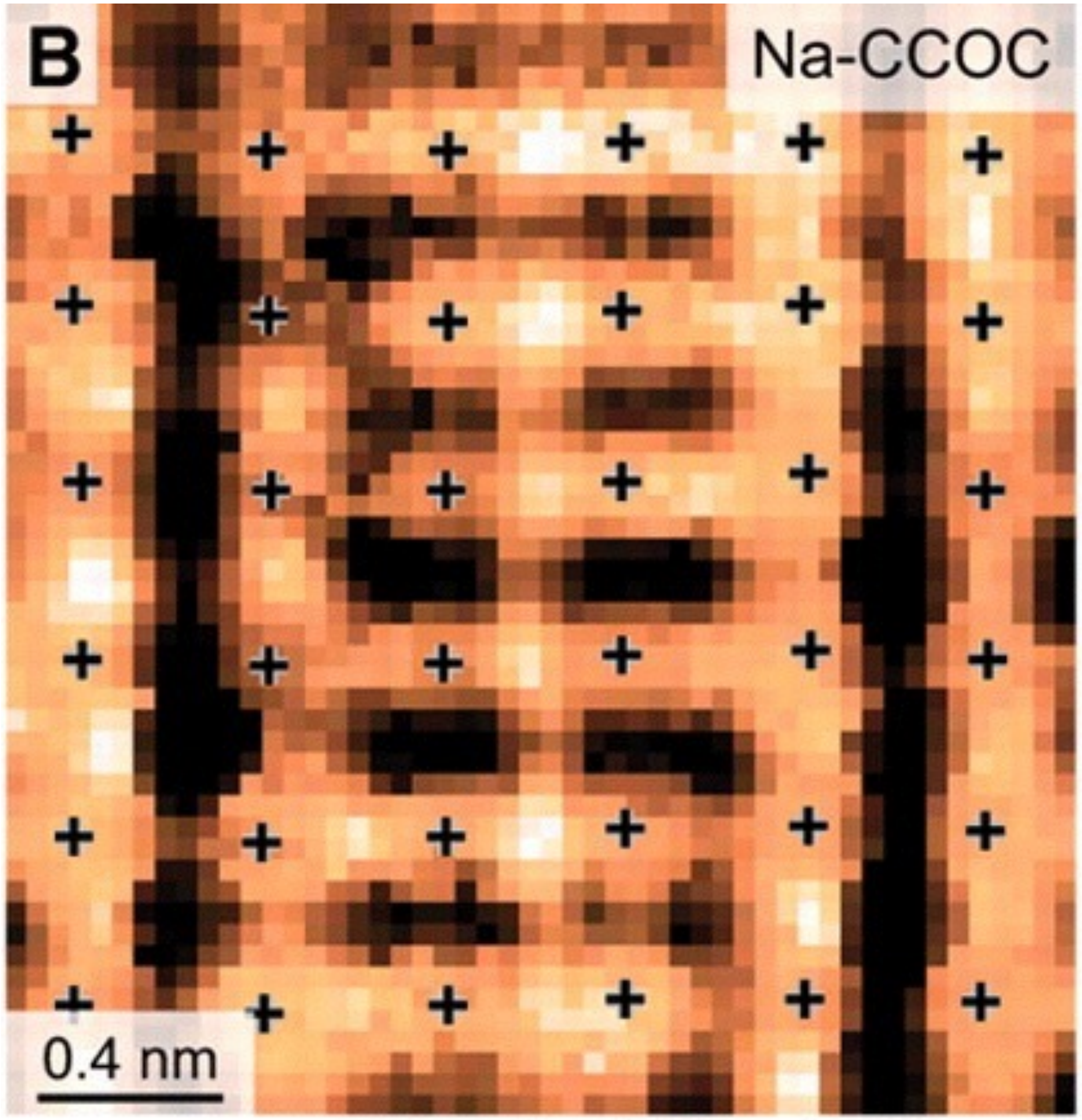

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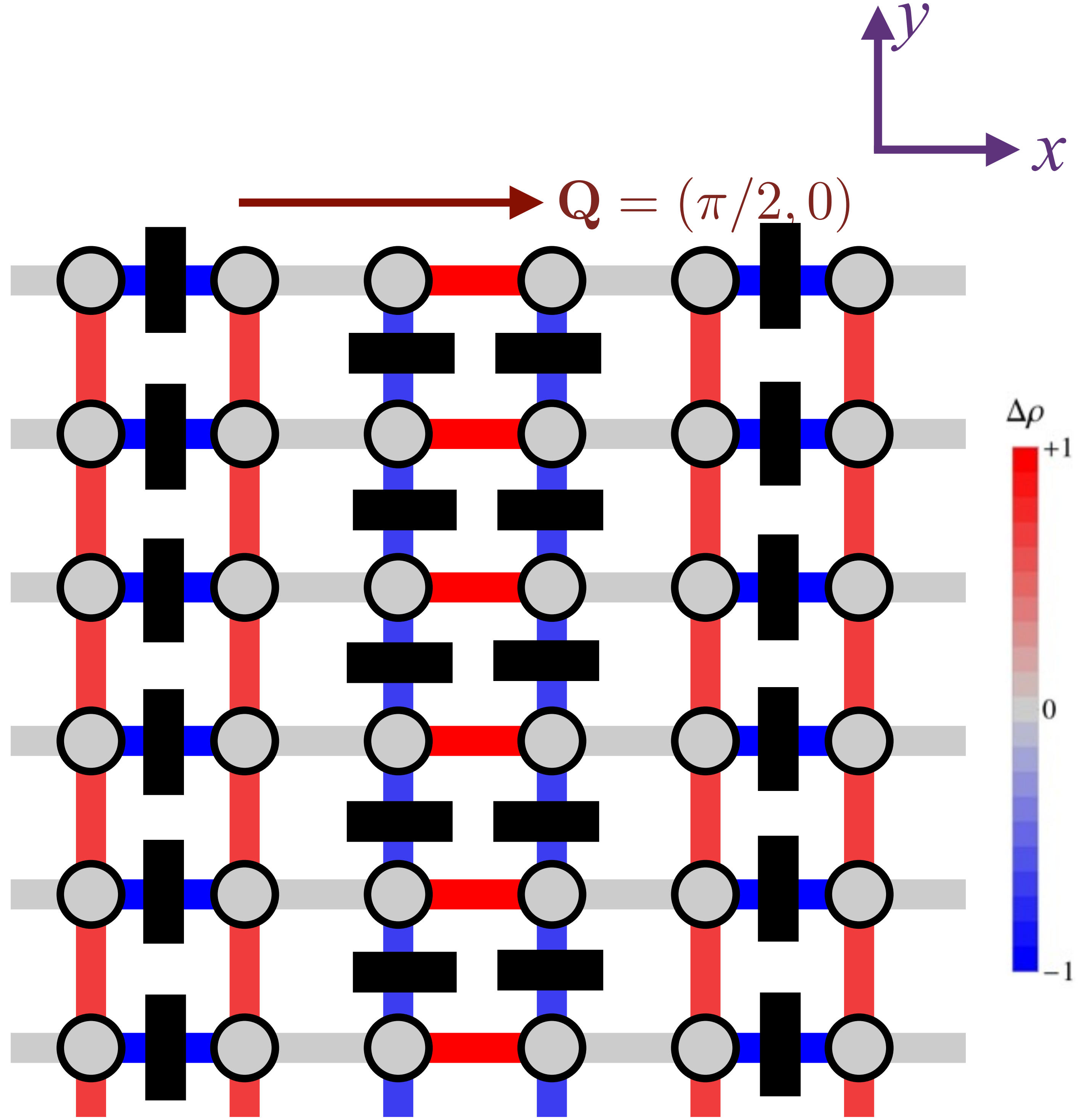


d-form factor density wave order

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

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

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]

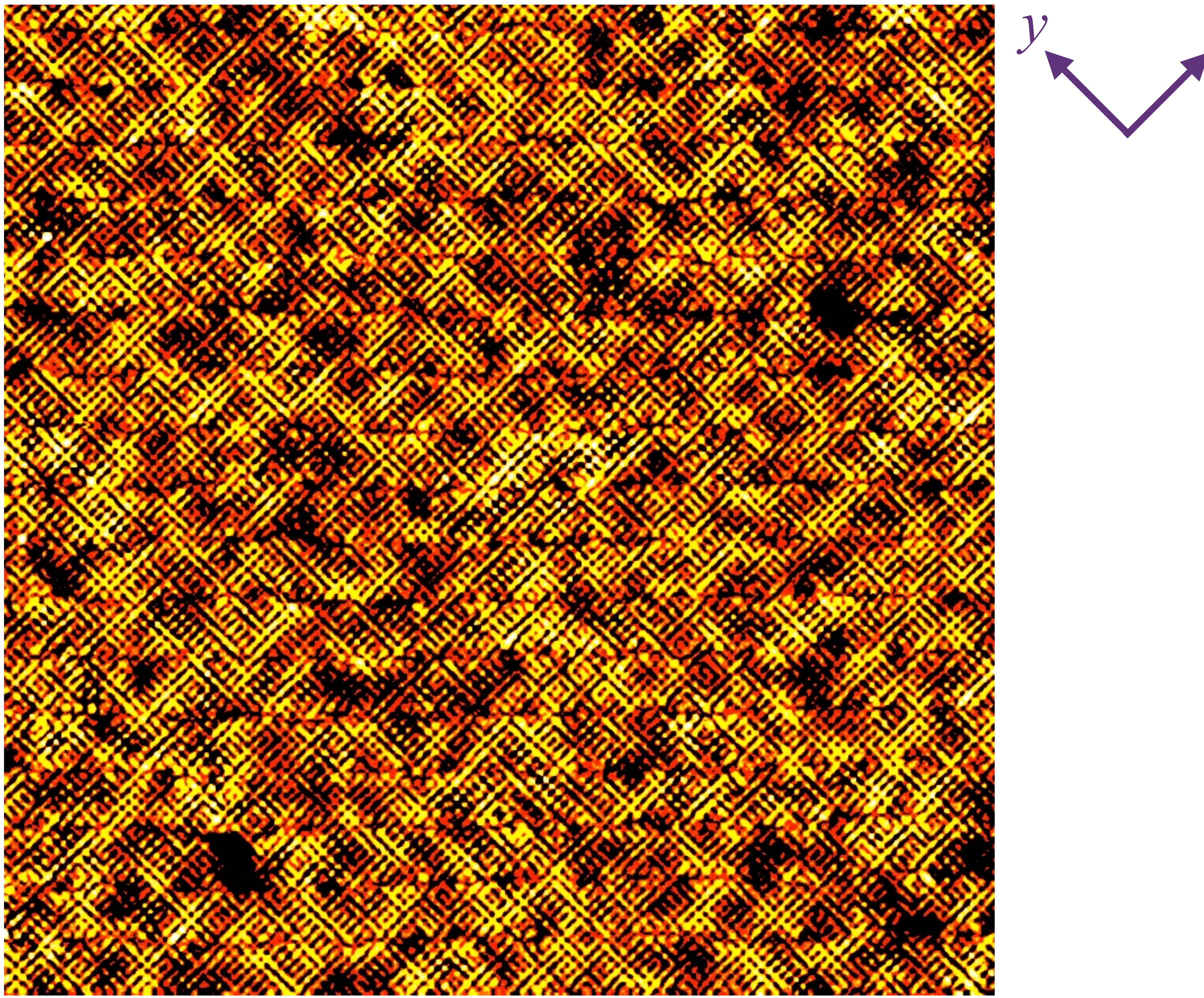
The identity of the fundamental broken symmetry (if any) in the underdoped cuprates is unresolved. However, evidence has been accumulating that this state may be an unconventional density wave. Here we carry out site-specific measurements within each CuO_2 unit cell, segregating the results into three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

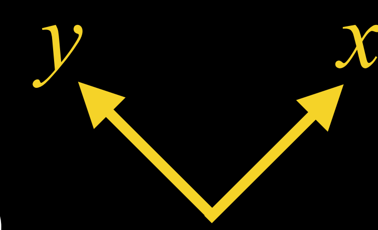
W. D. Wise, M. C. Boyer, K. Chatterjee, T. Kondo, T. Takeuchi, H. Ikuta, Y. Wang, and E. W. Hudson, Nature Phys. **4**, 696 (2008).



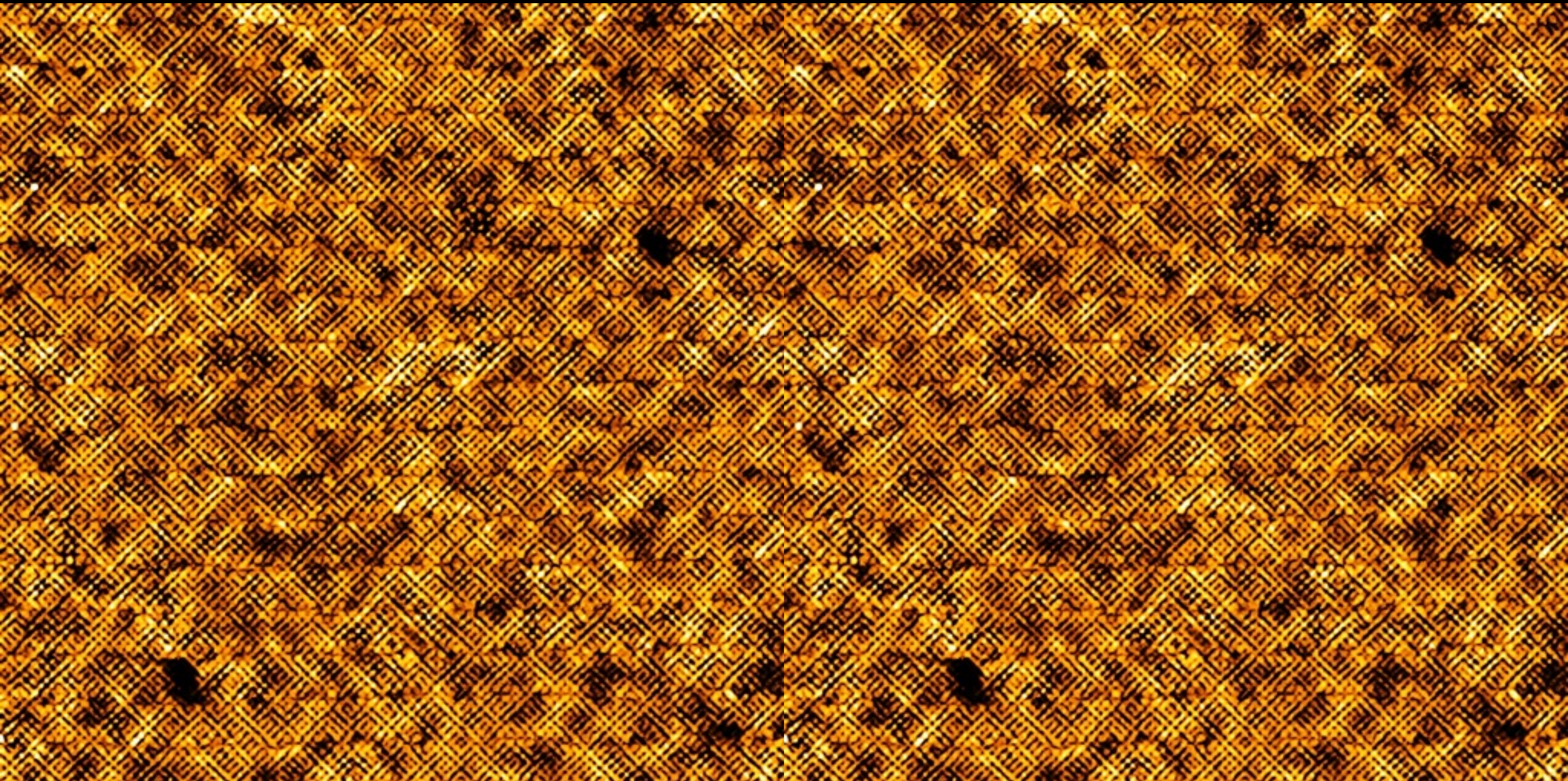
"R-map" of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007). Davis group has sub-angstrom resolution capabilities, with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

UD45K
BSCCO

R(r,150mV)

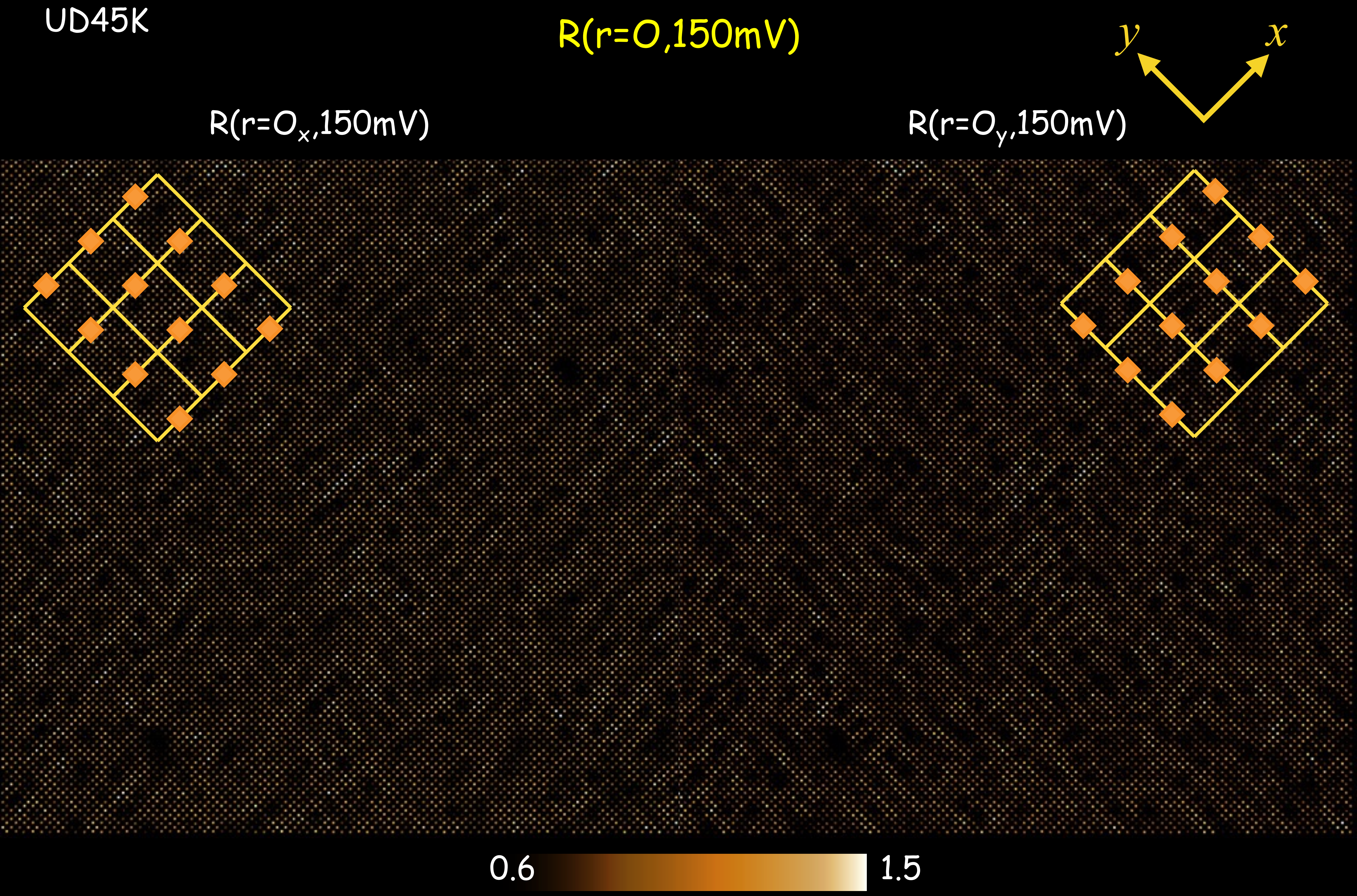


R(r,150mV) R(r,150mV)



Note that these are identical images.

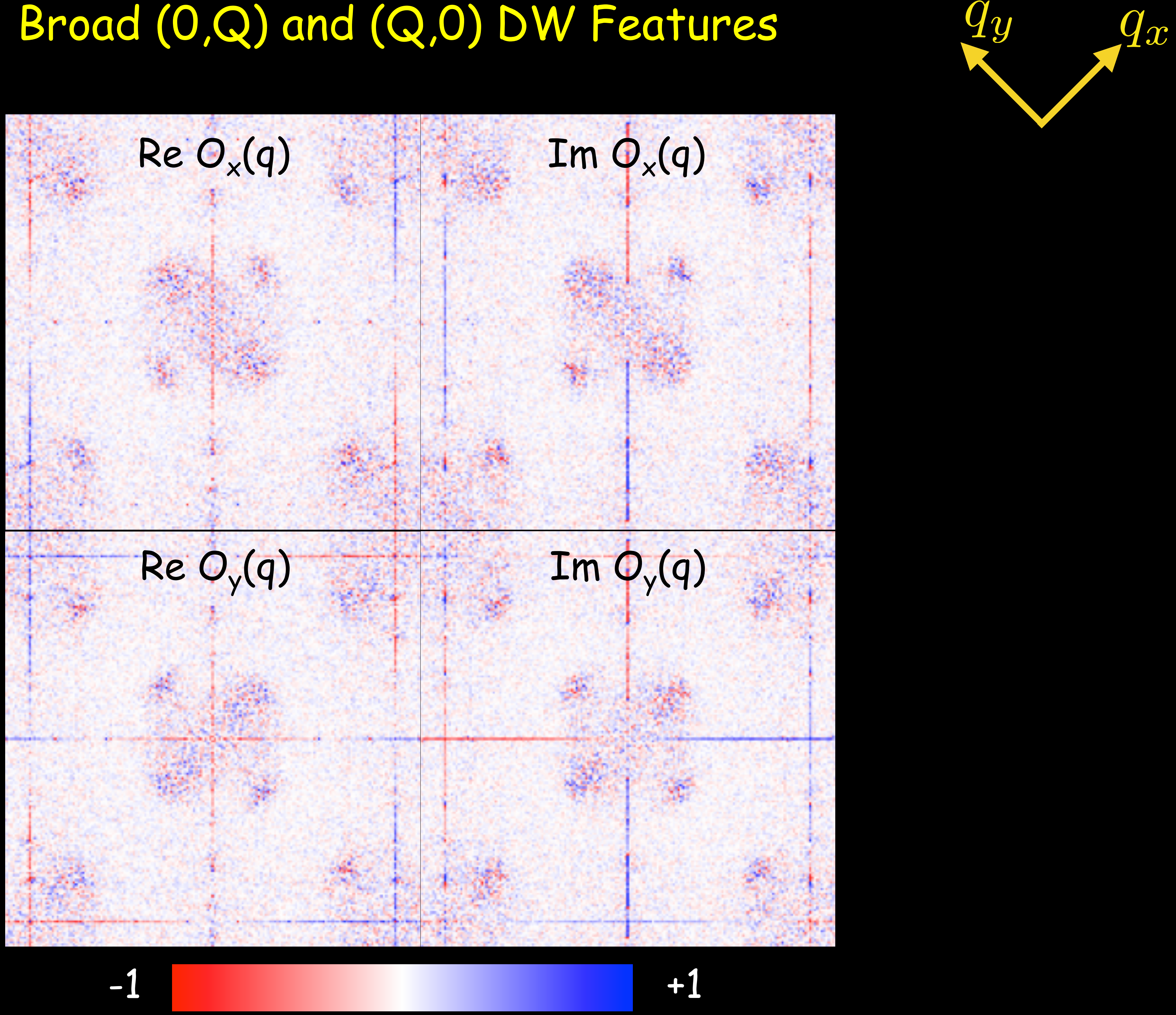
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)



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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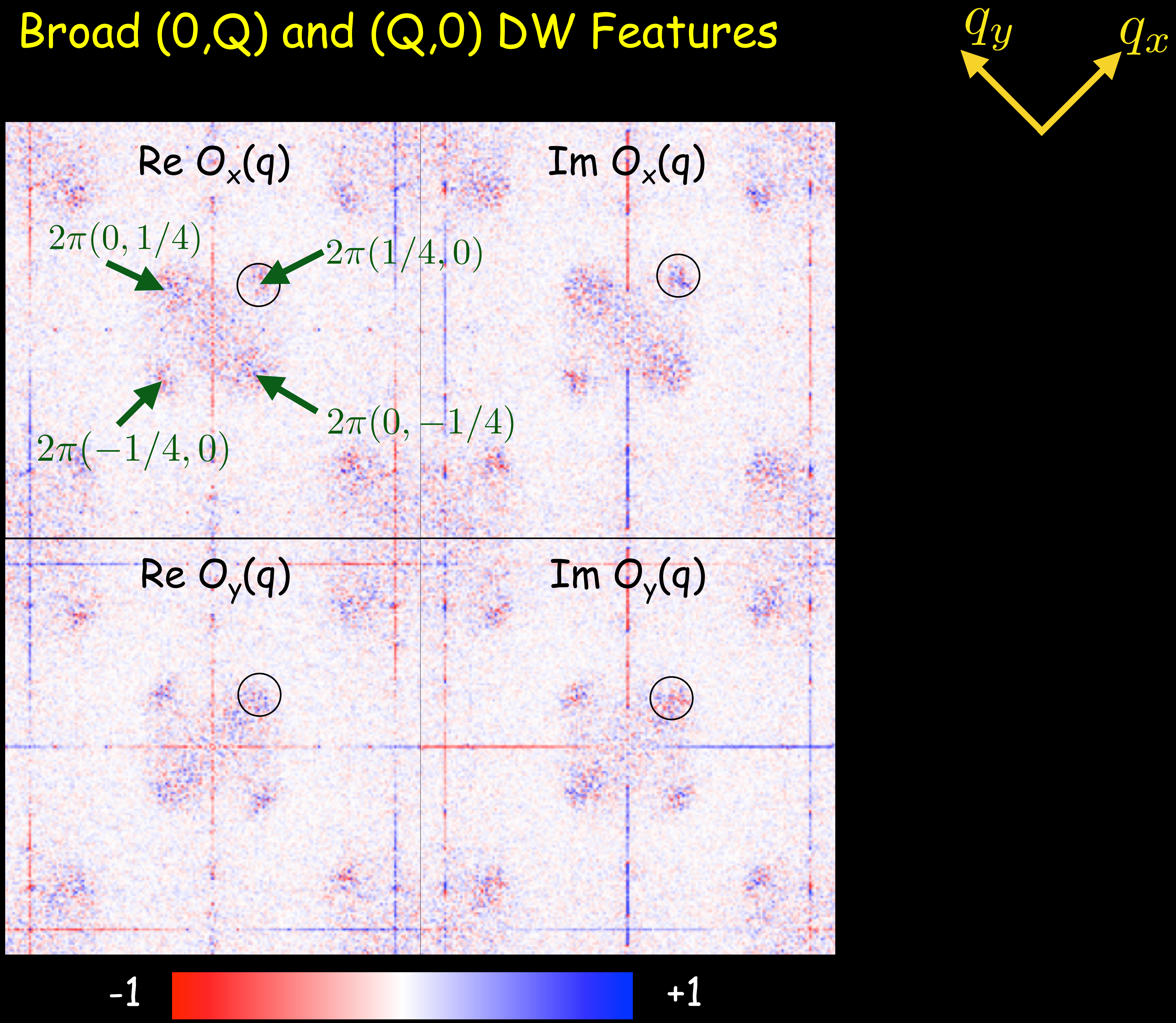

K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

UD45K

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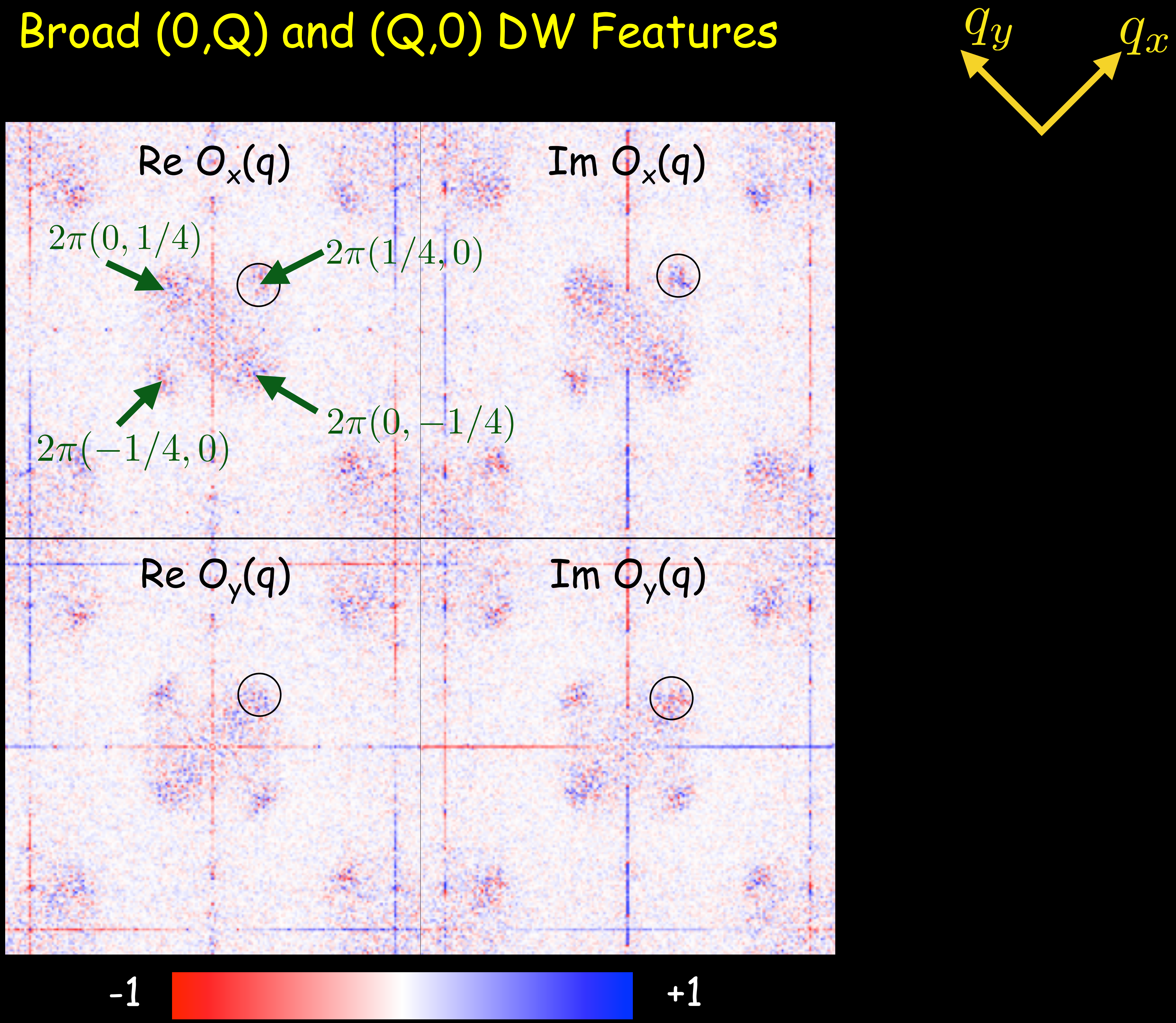
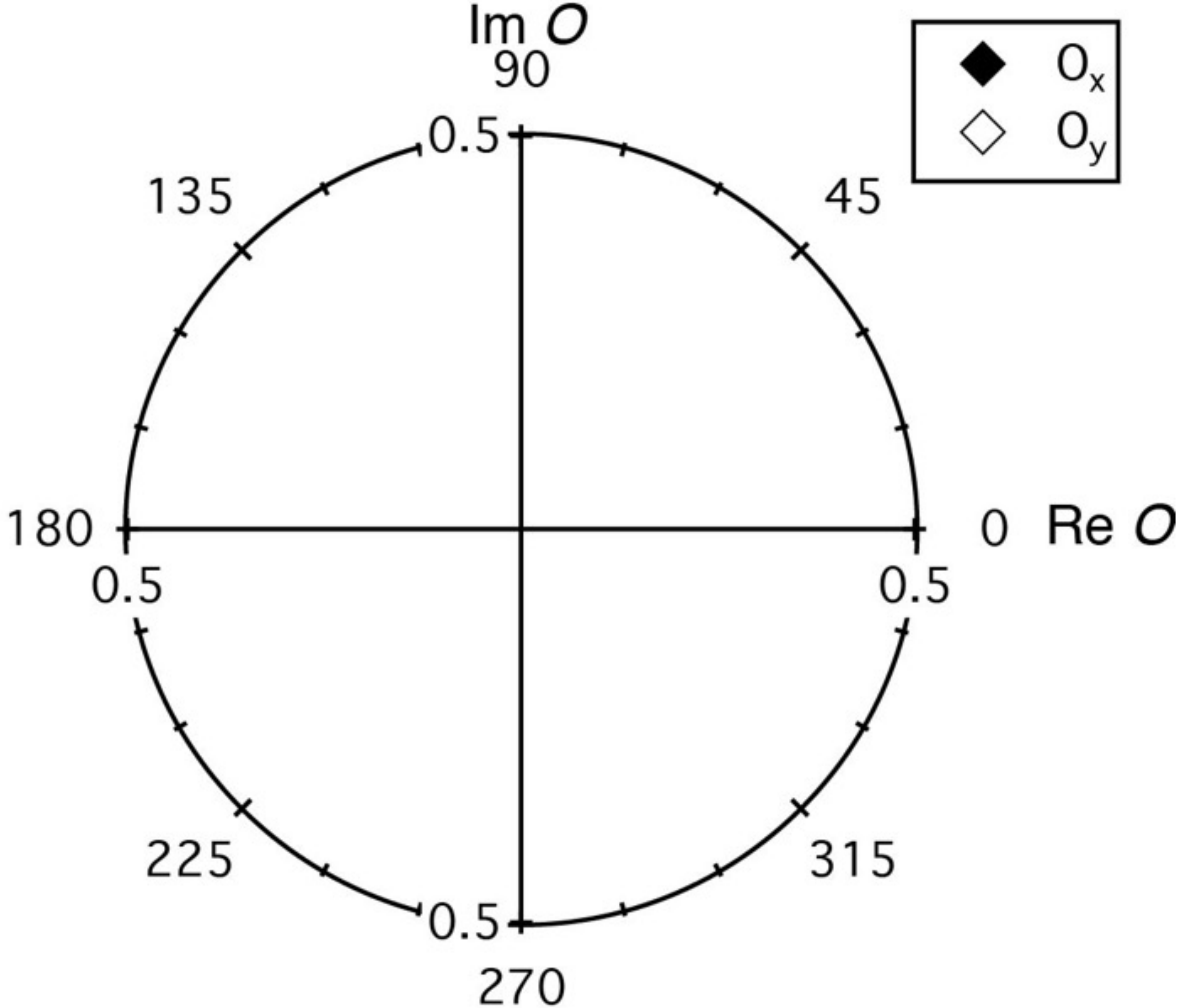


For each pixel in the circles, we obtain 2 complex numbers, $O_x(q)$ and $O_y(q)$.

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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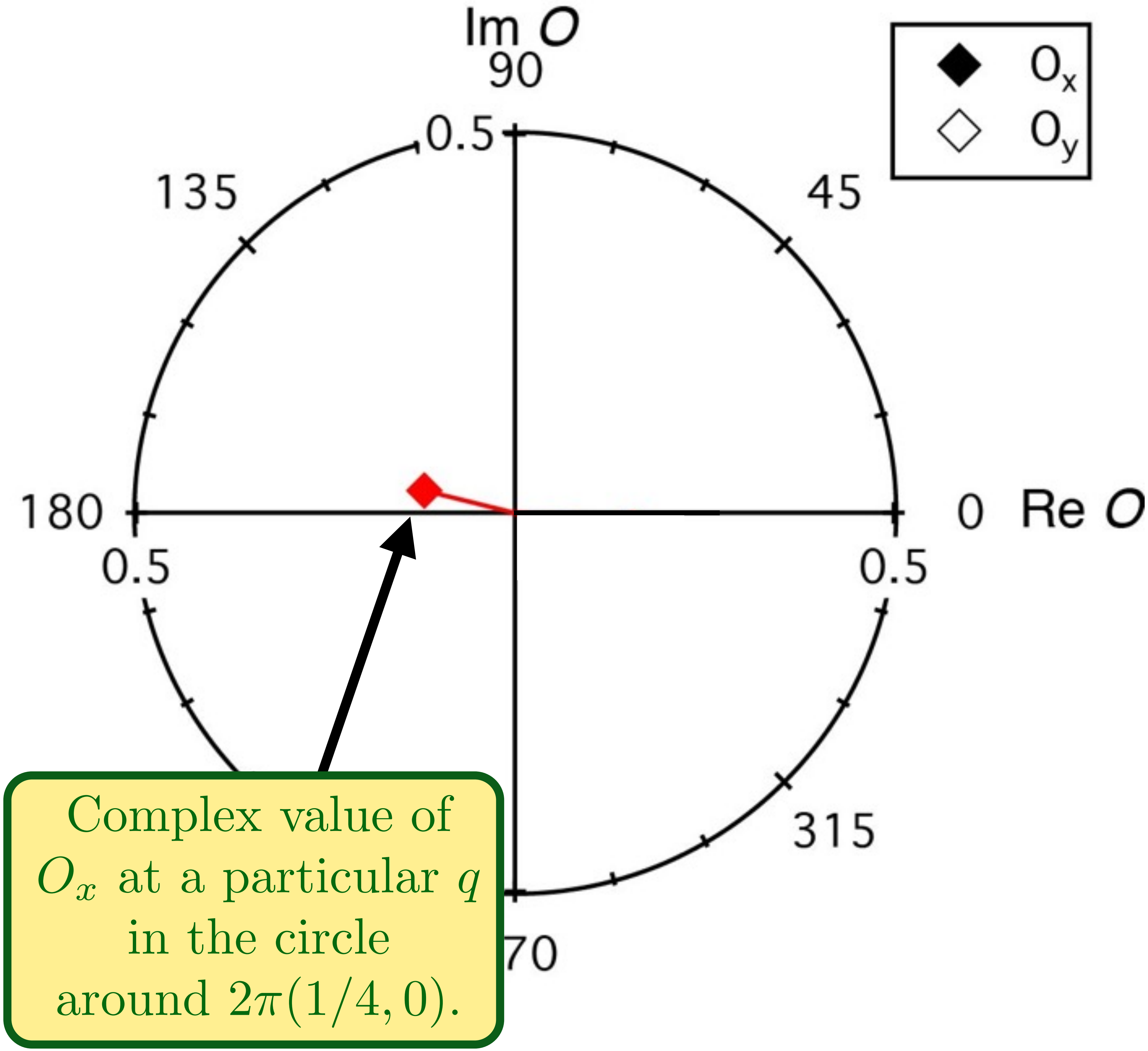

K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

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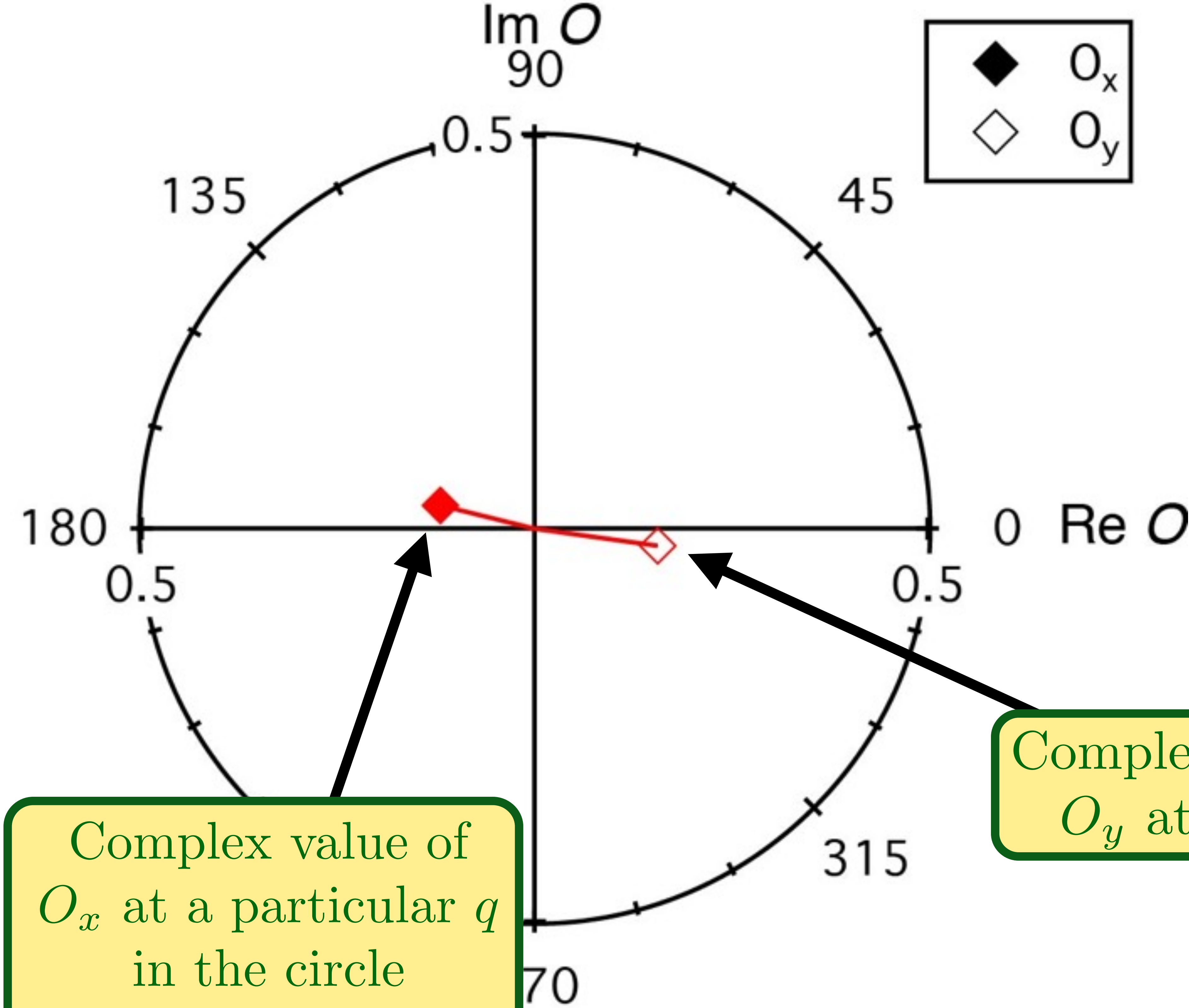

Complex value of O_x at a particular q in the circle around $2\pi(1/4, 0)$.

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

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

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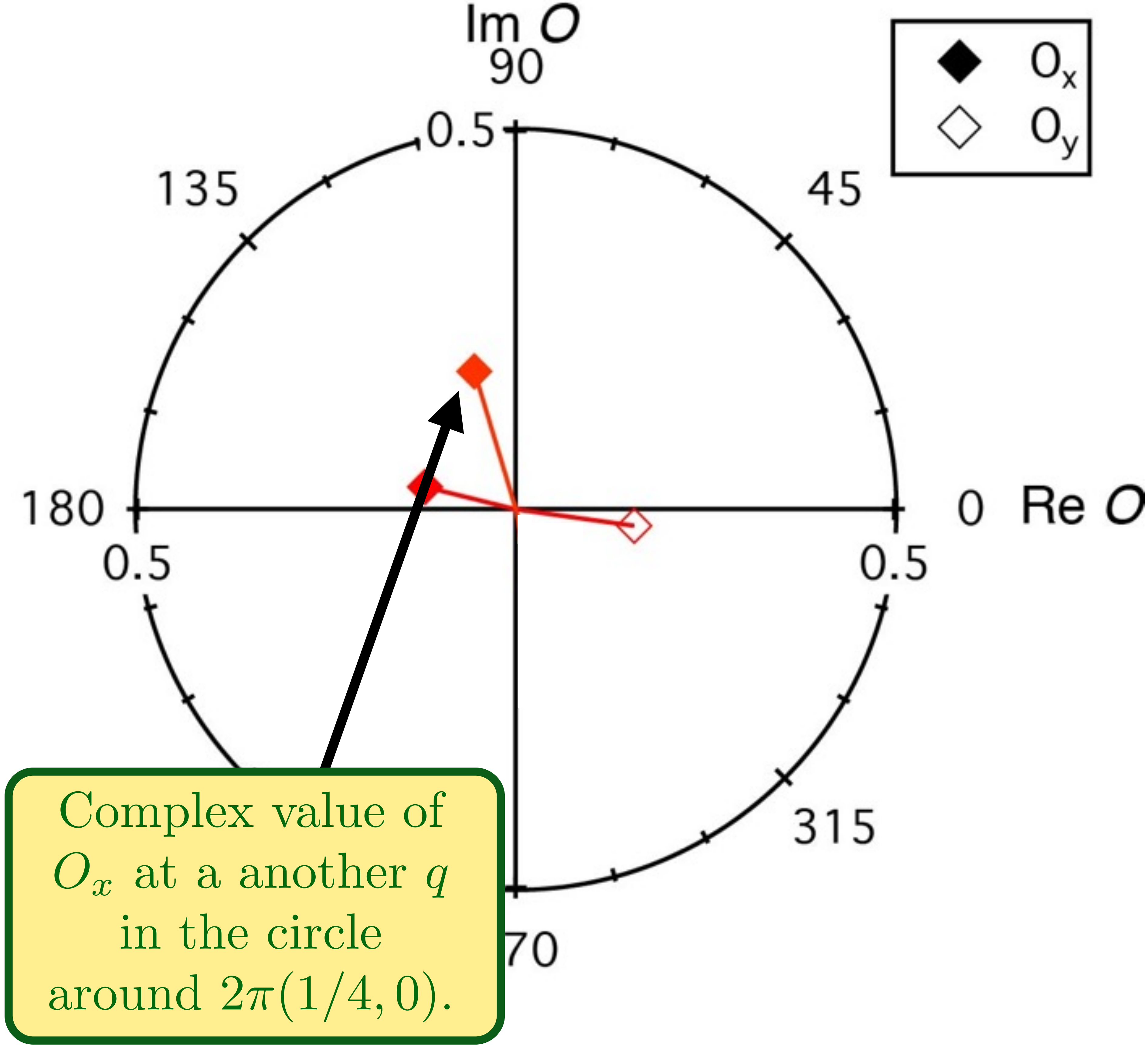

K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

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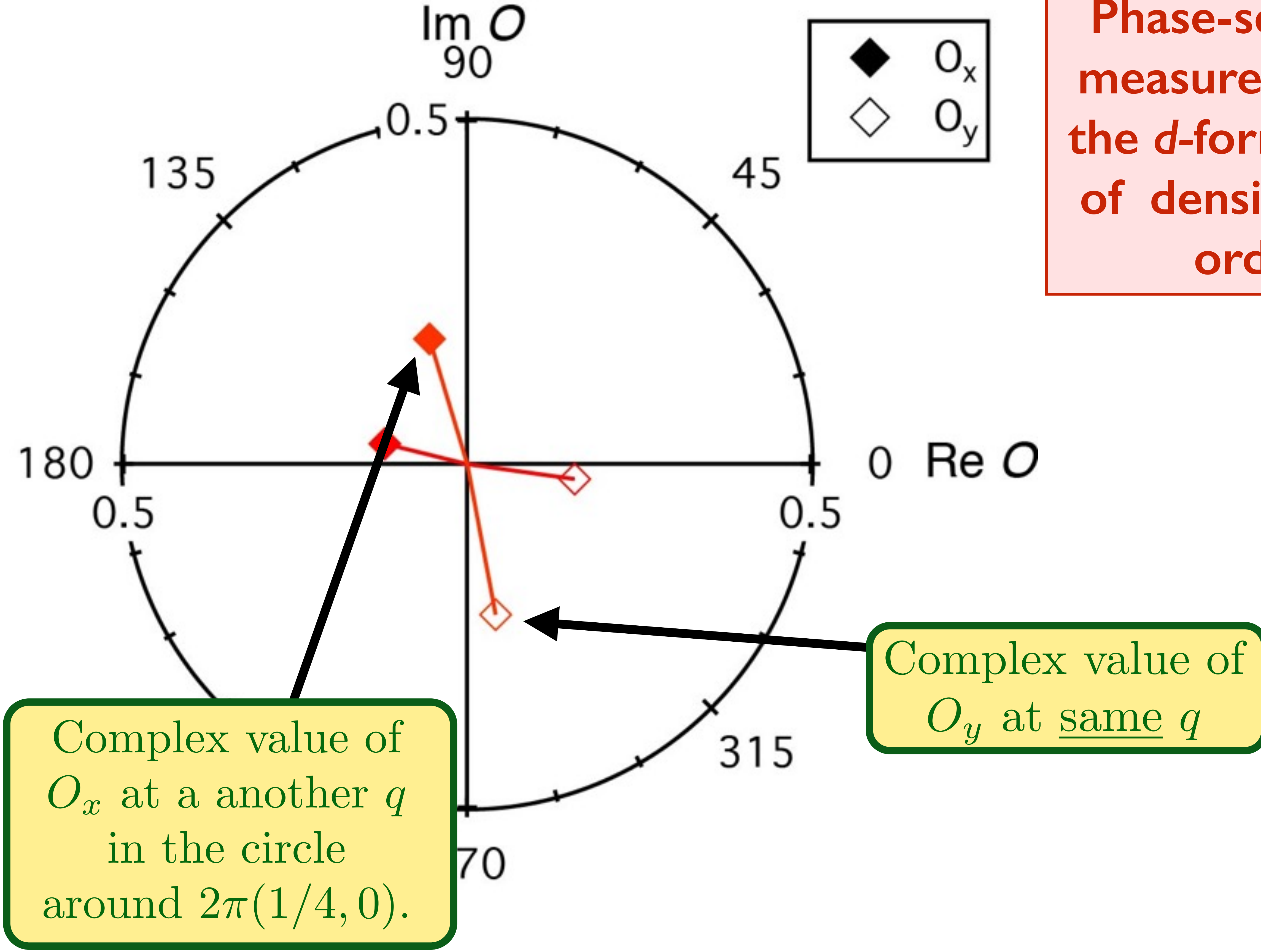

K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

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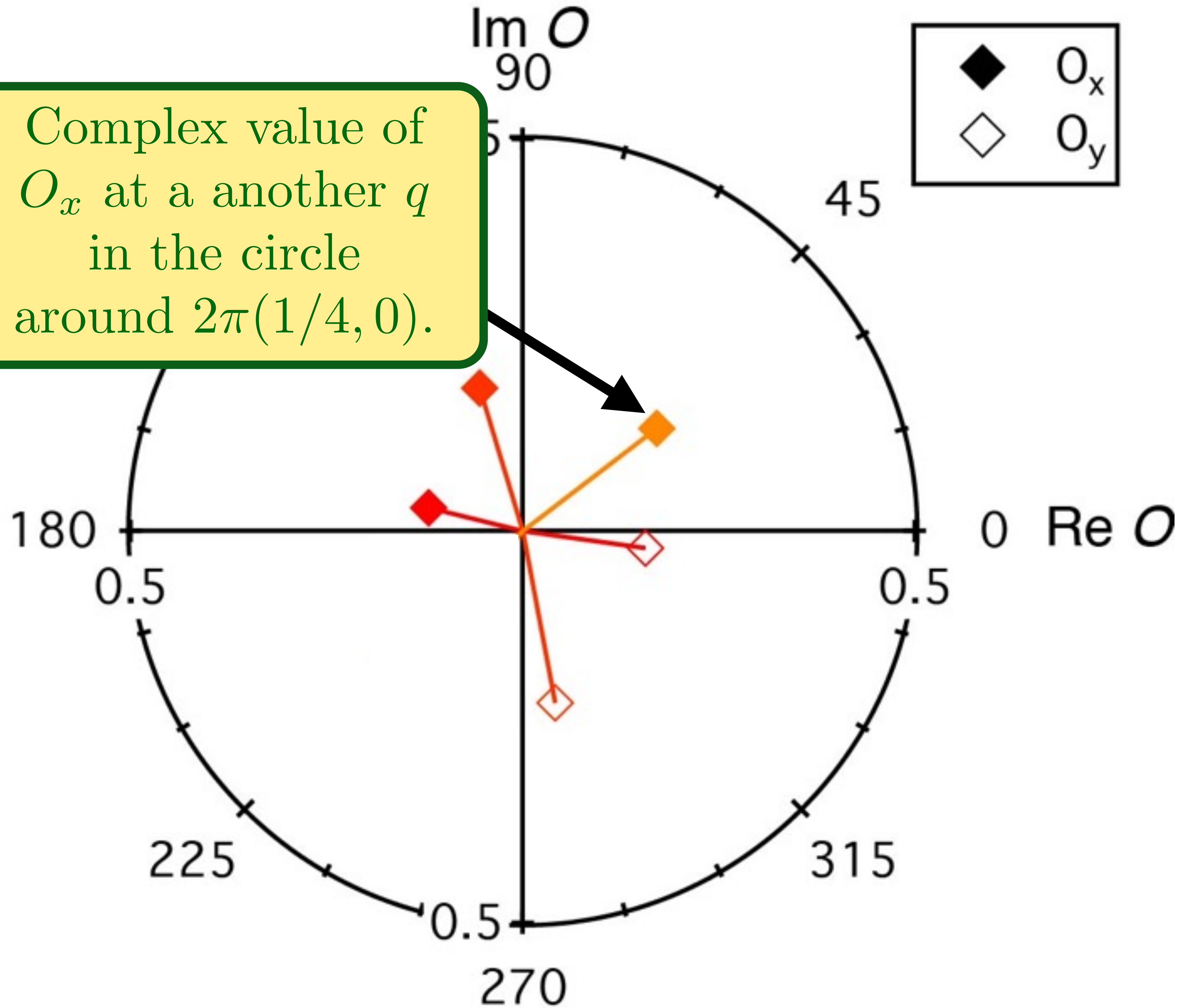

Complex value of O_x at a another q in the circle around $2\pi(1/4, 0)$.

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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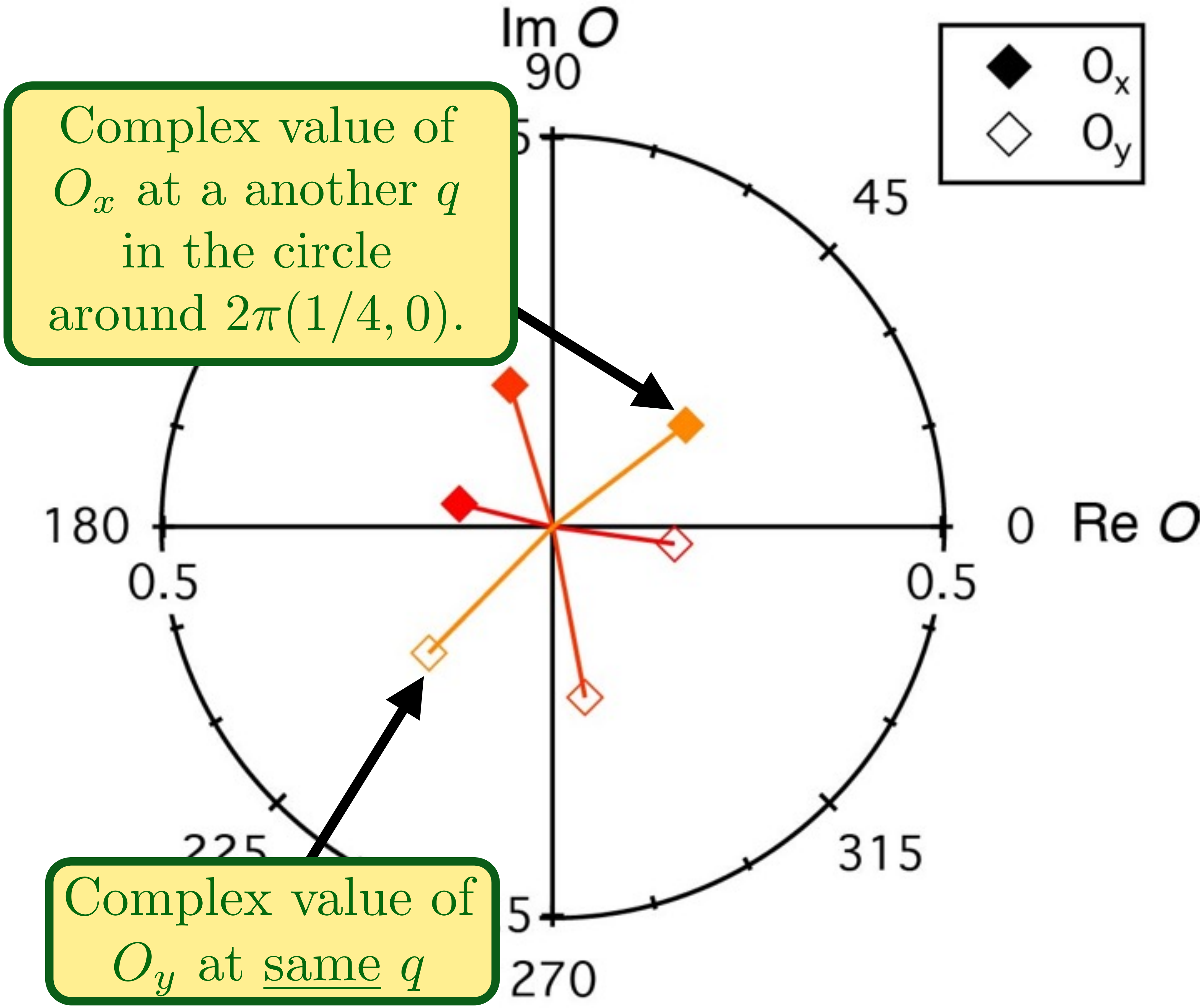
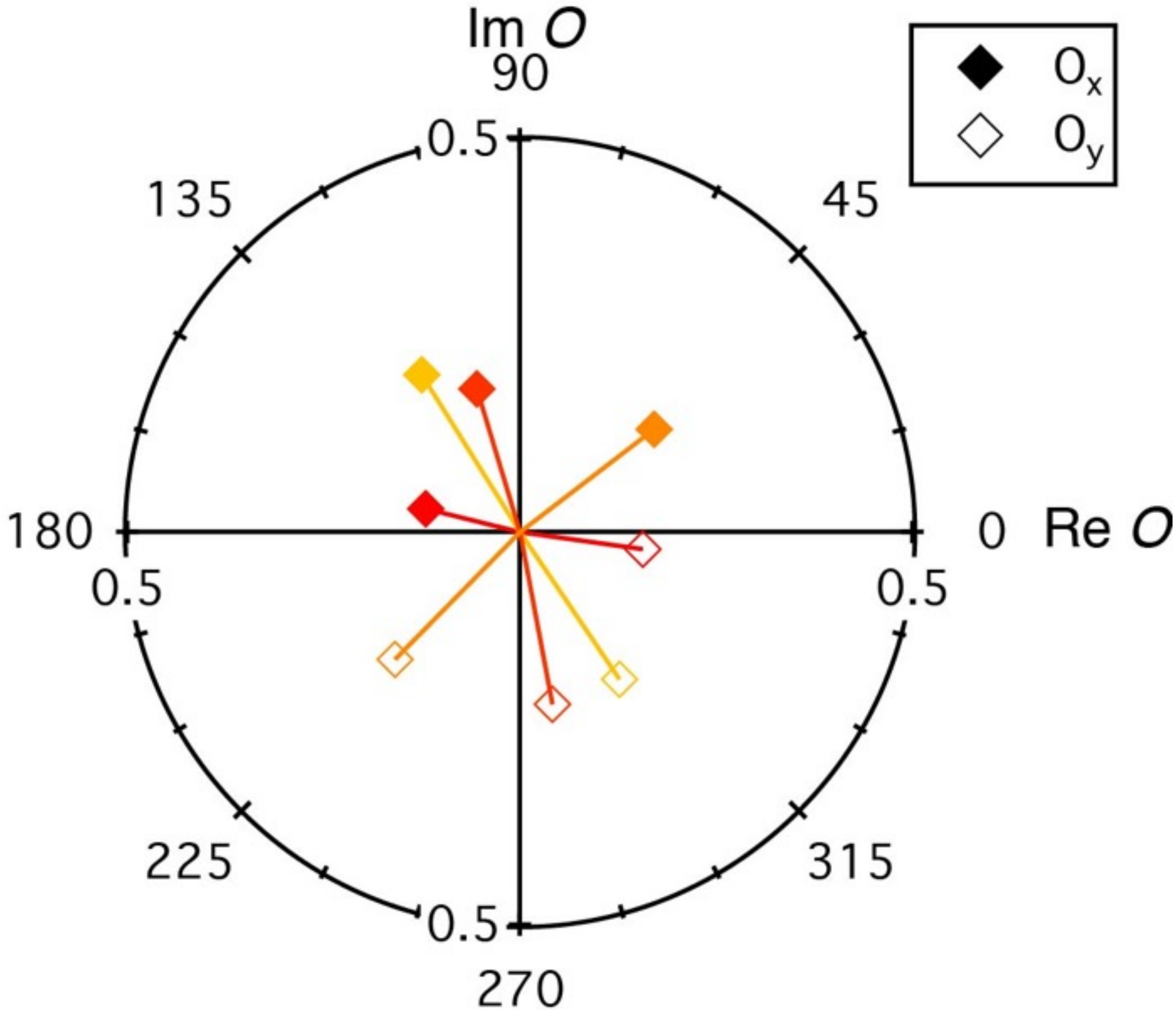


K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)



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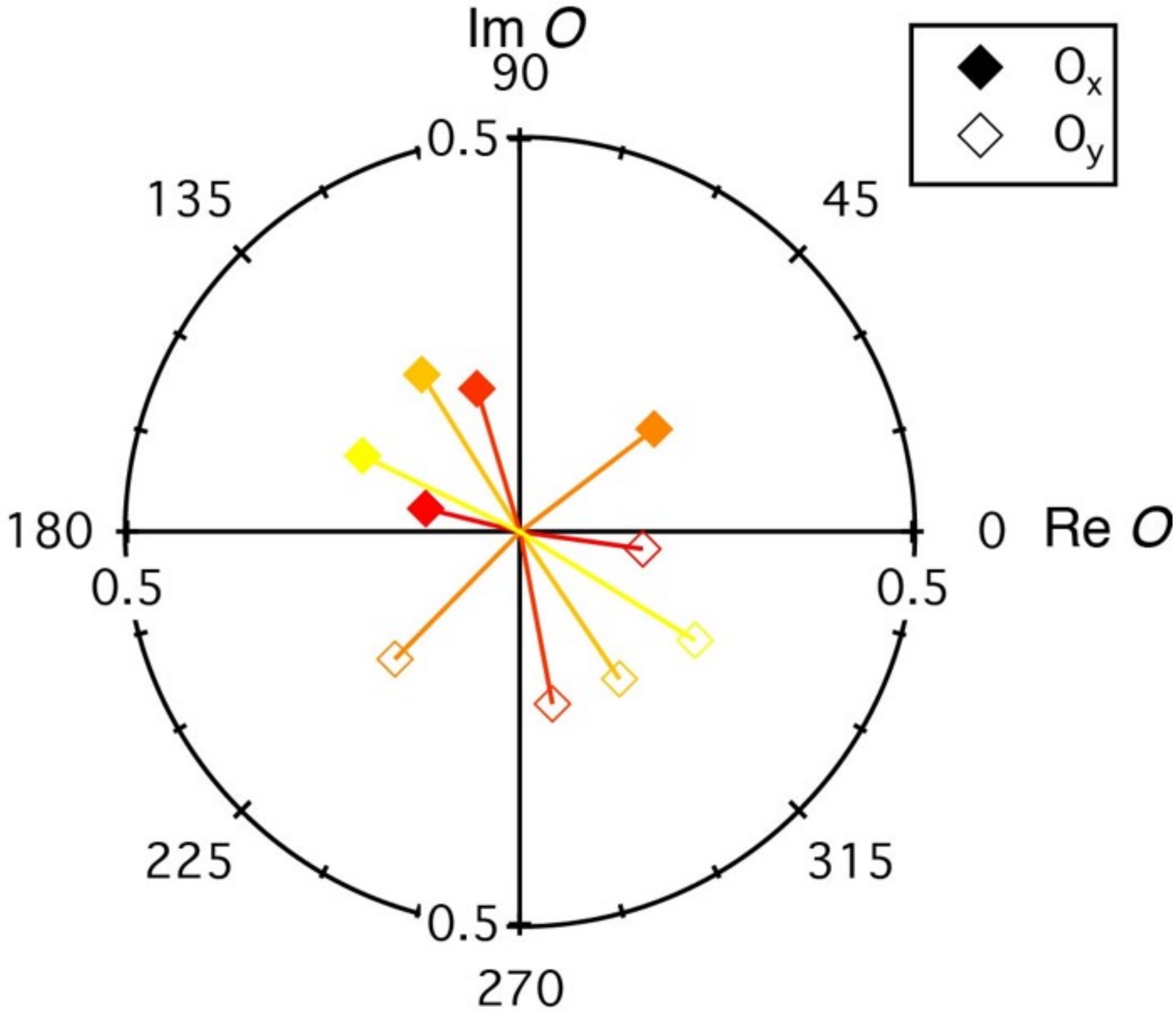

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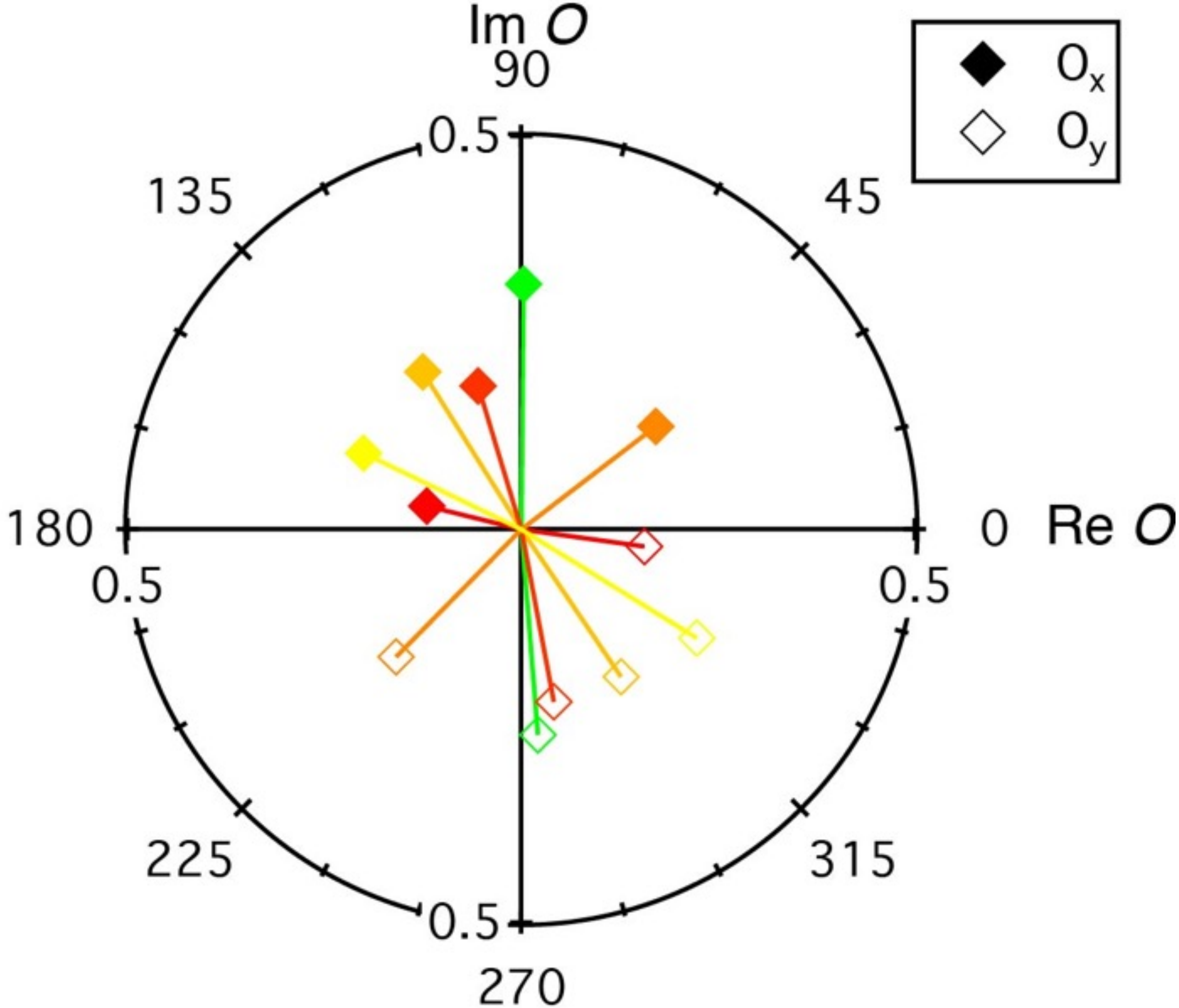

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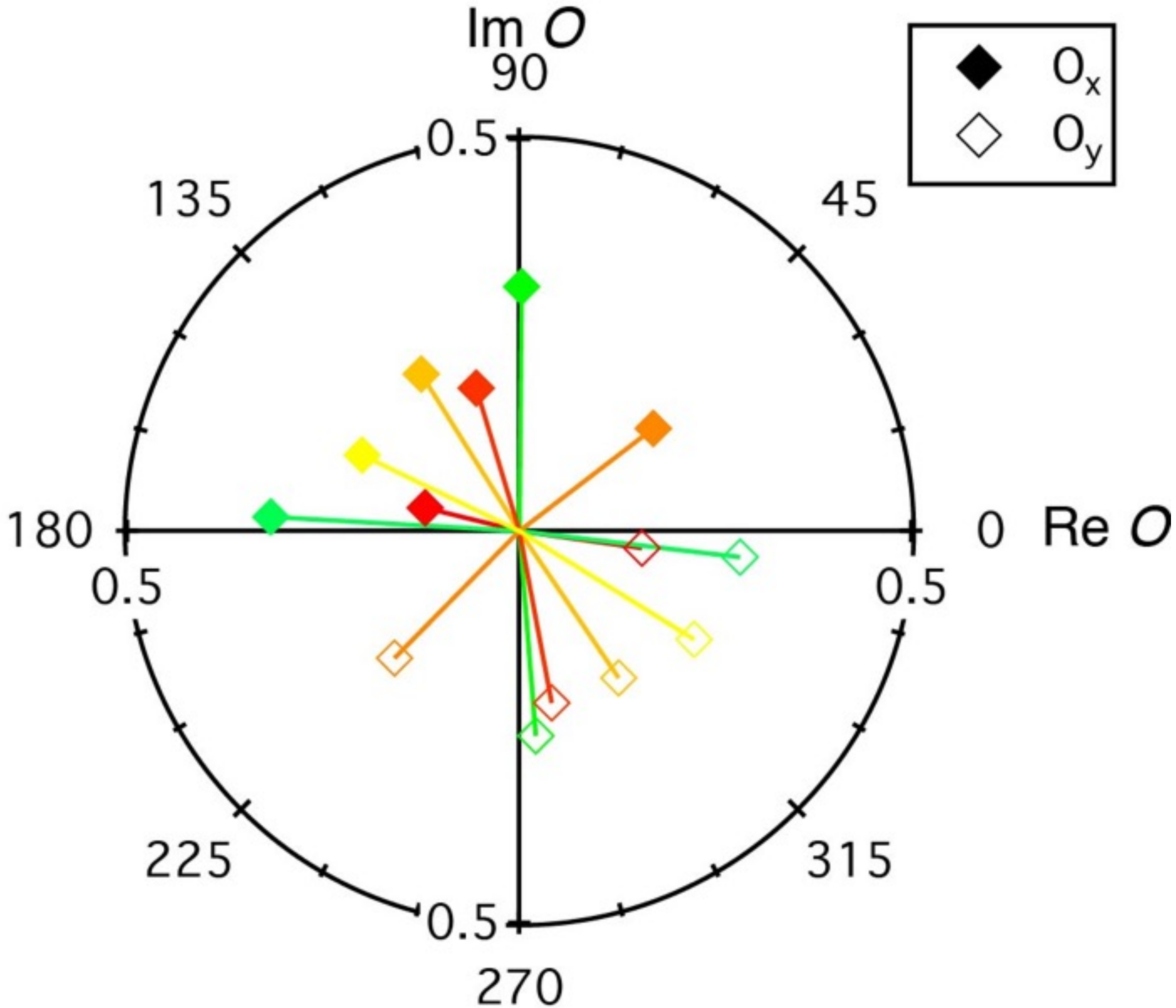

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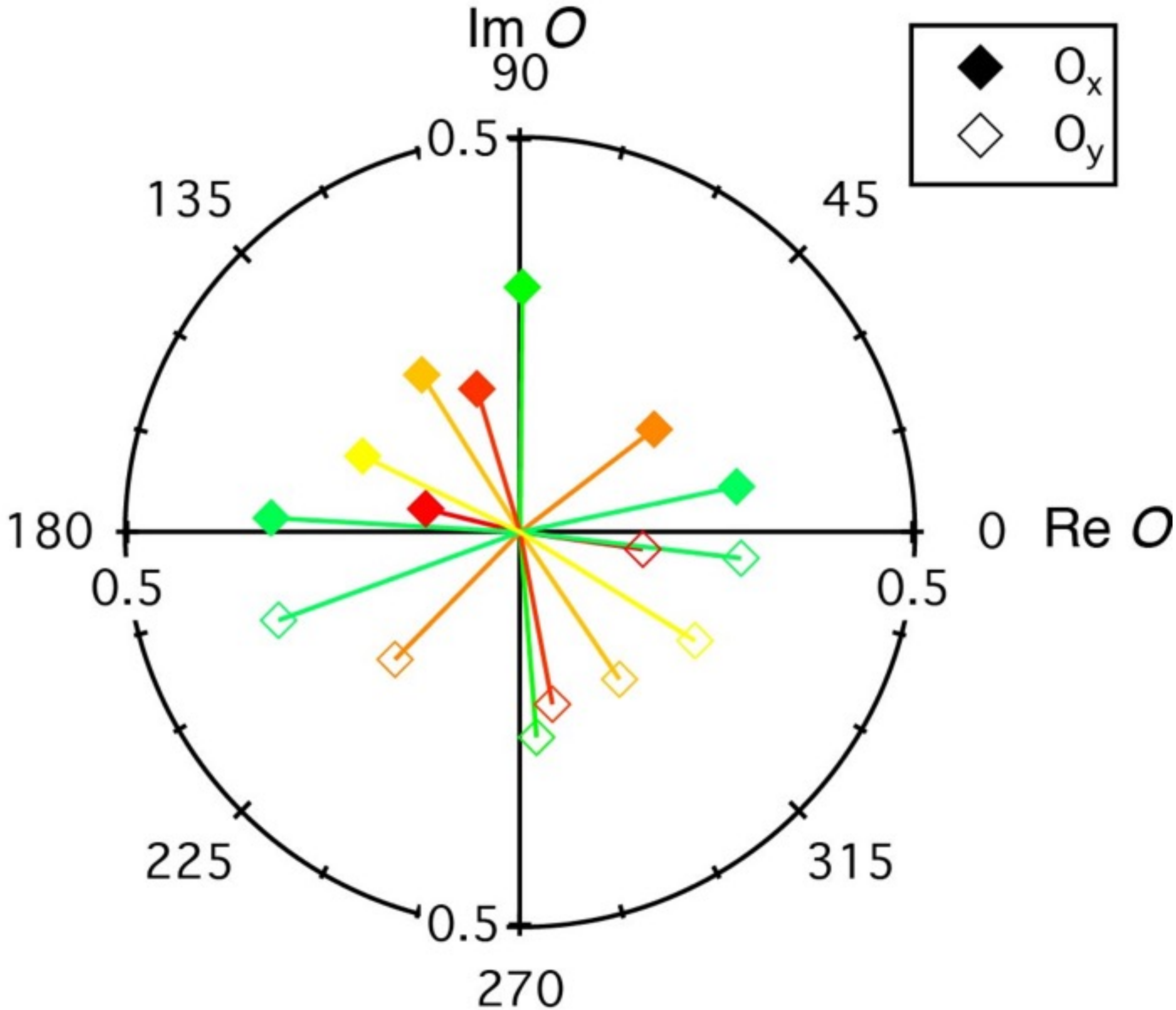

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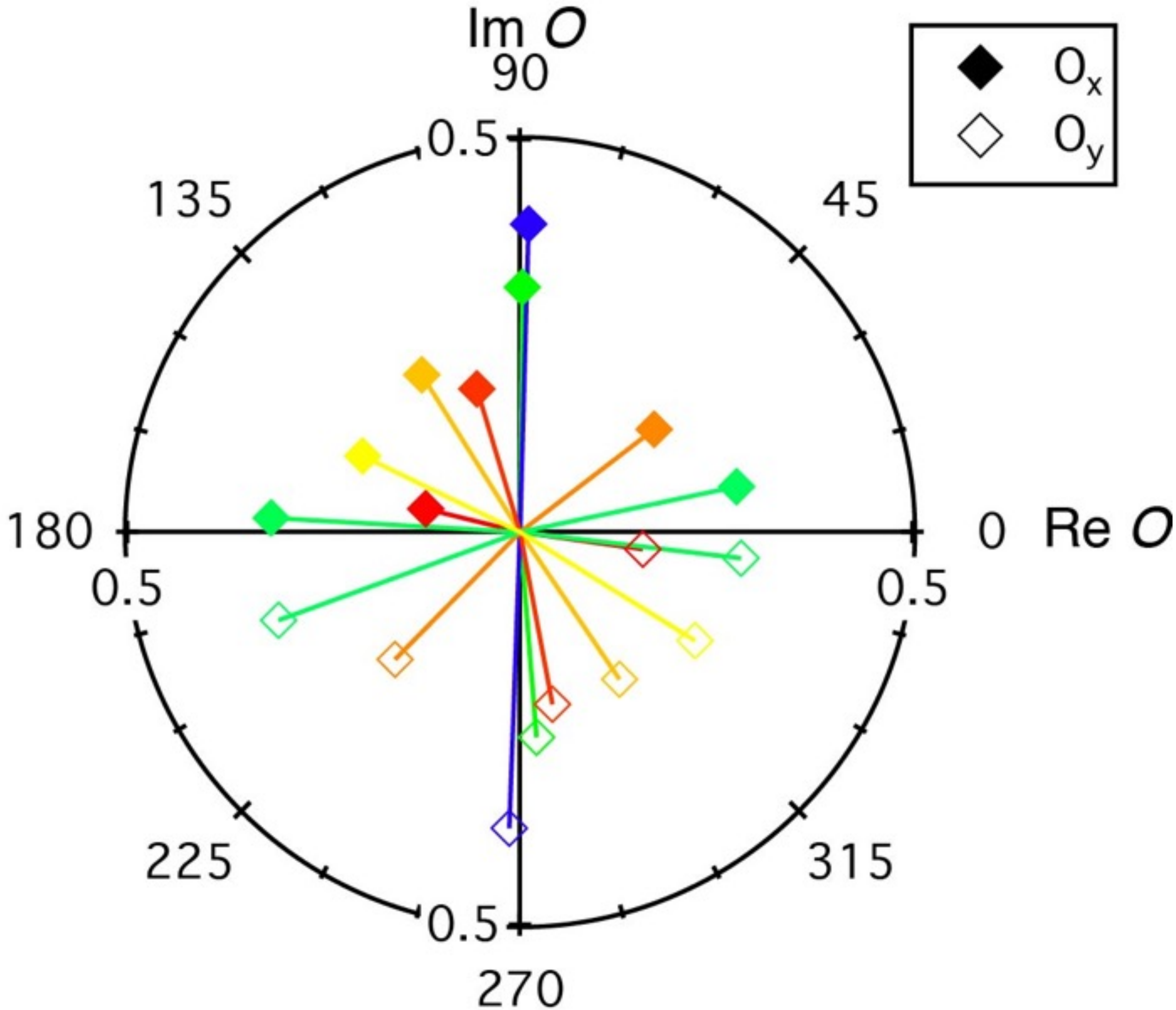

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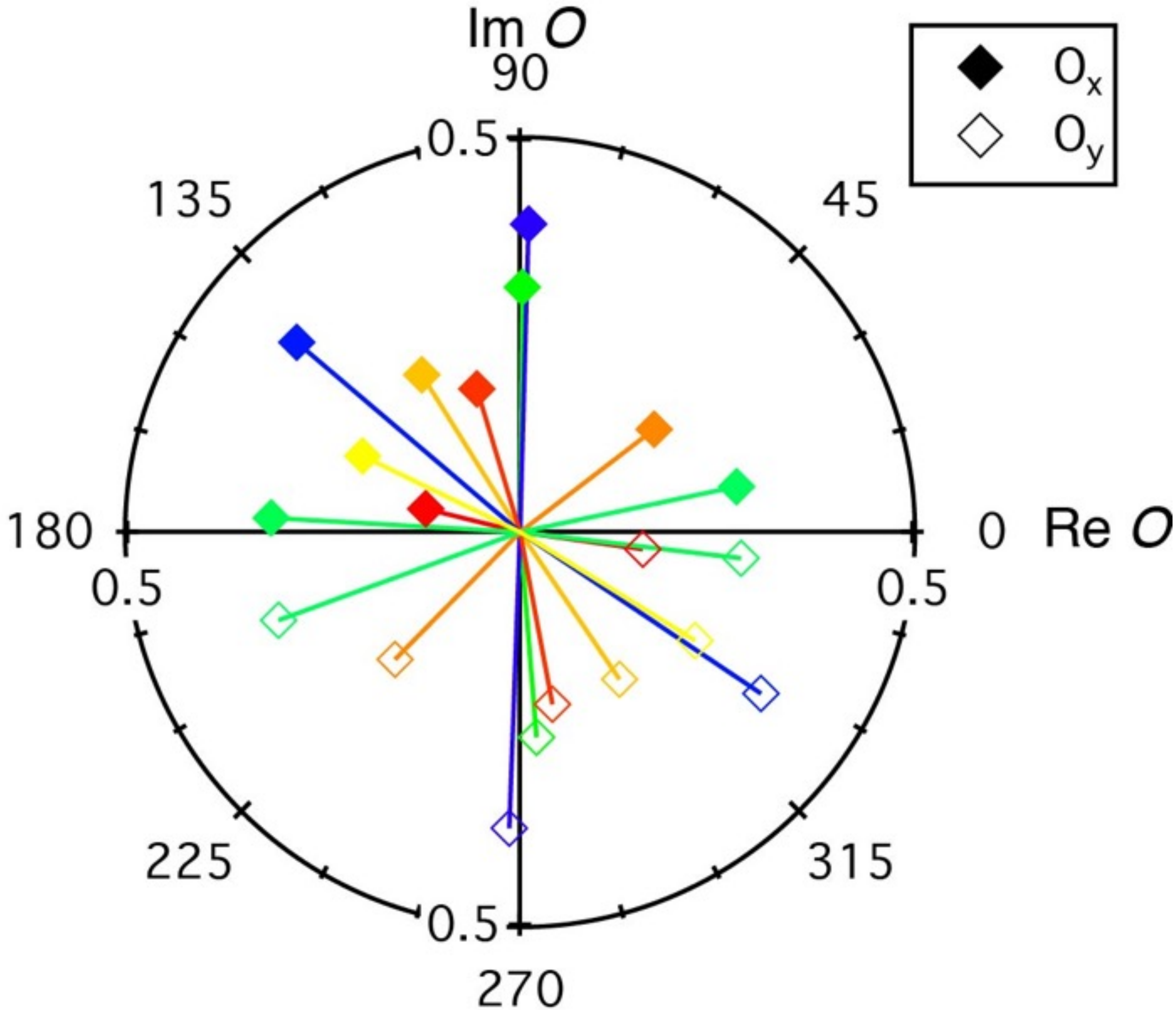

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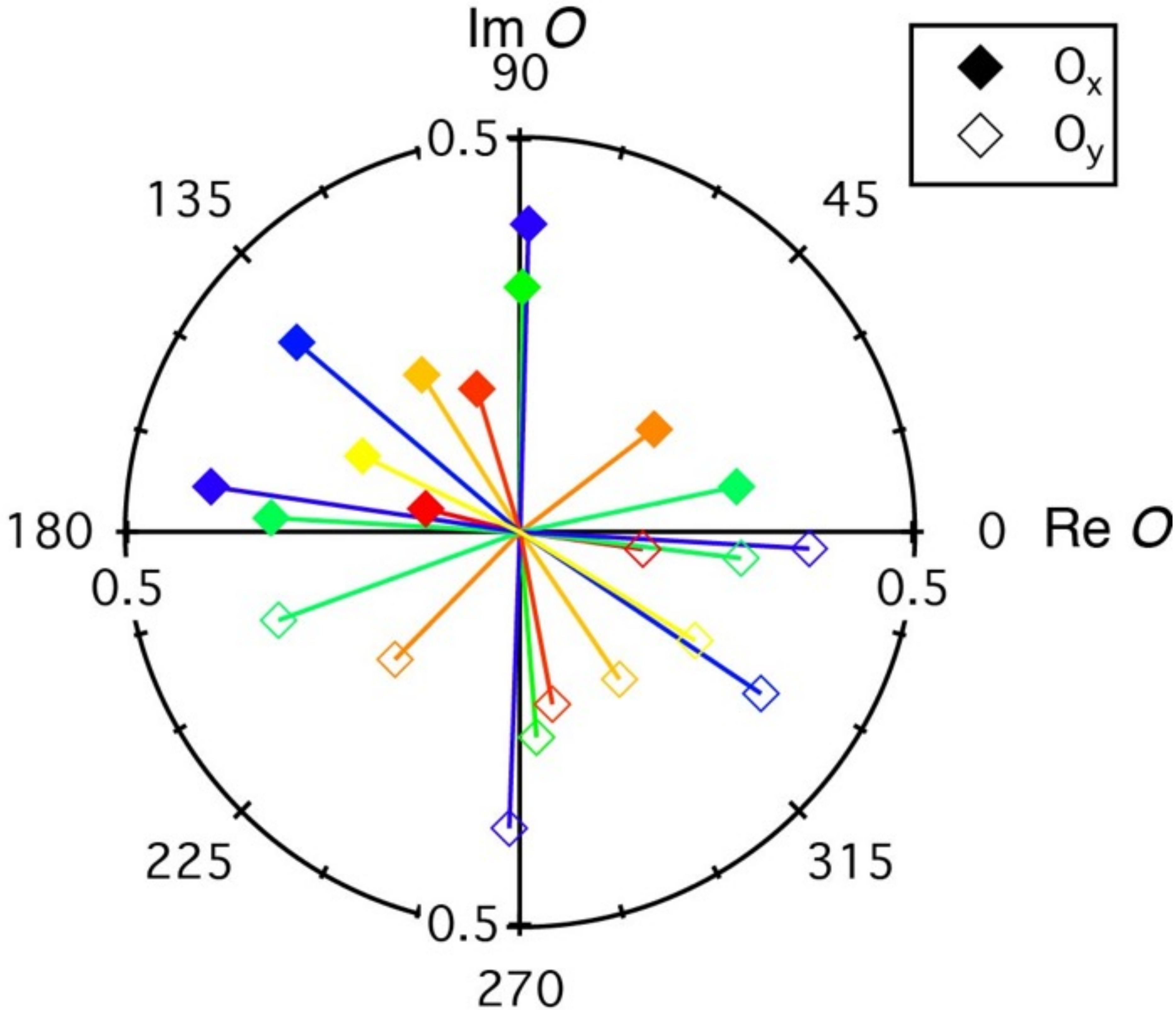

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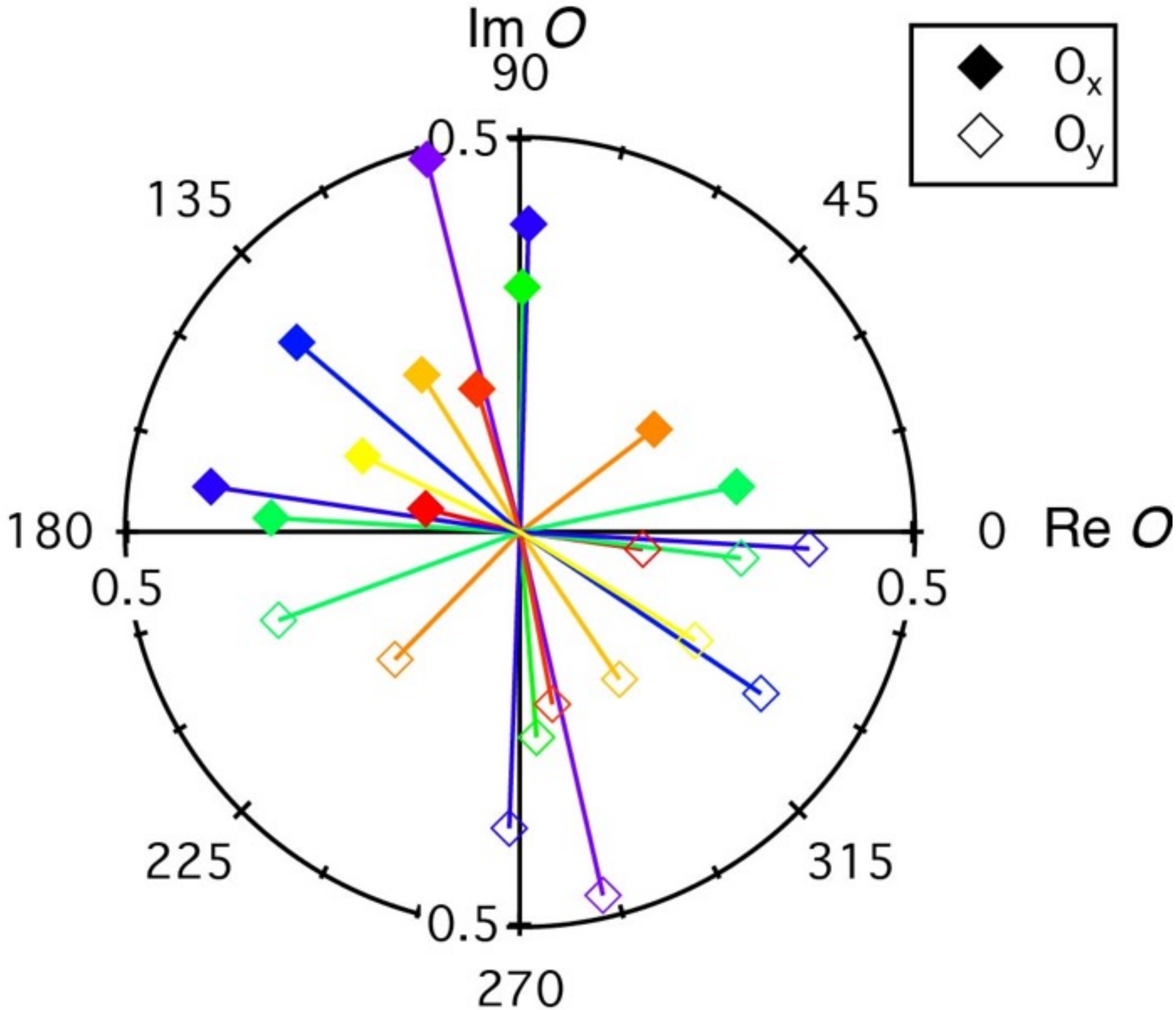

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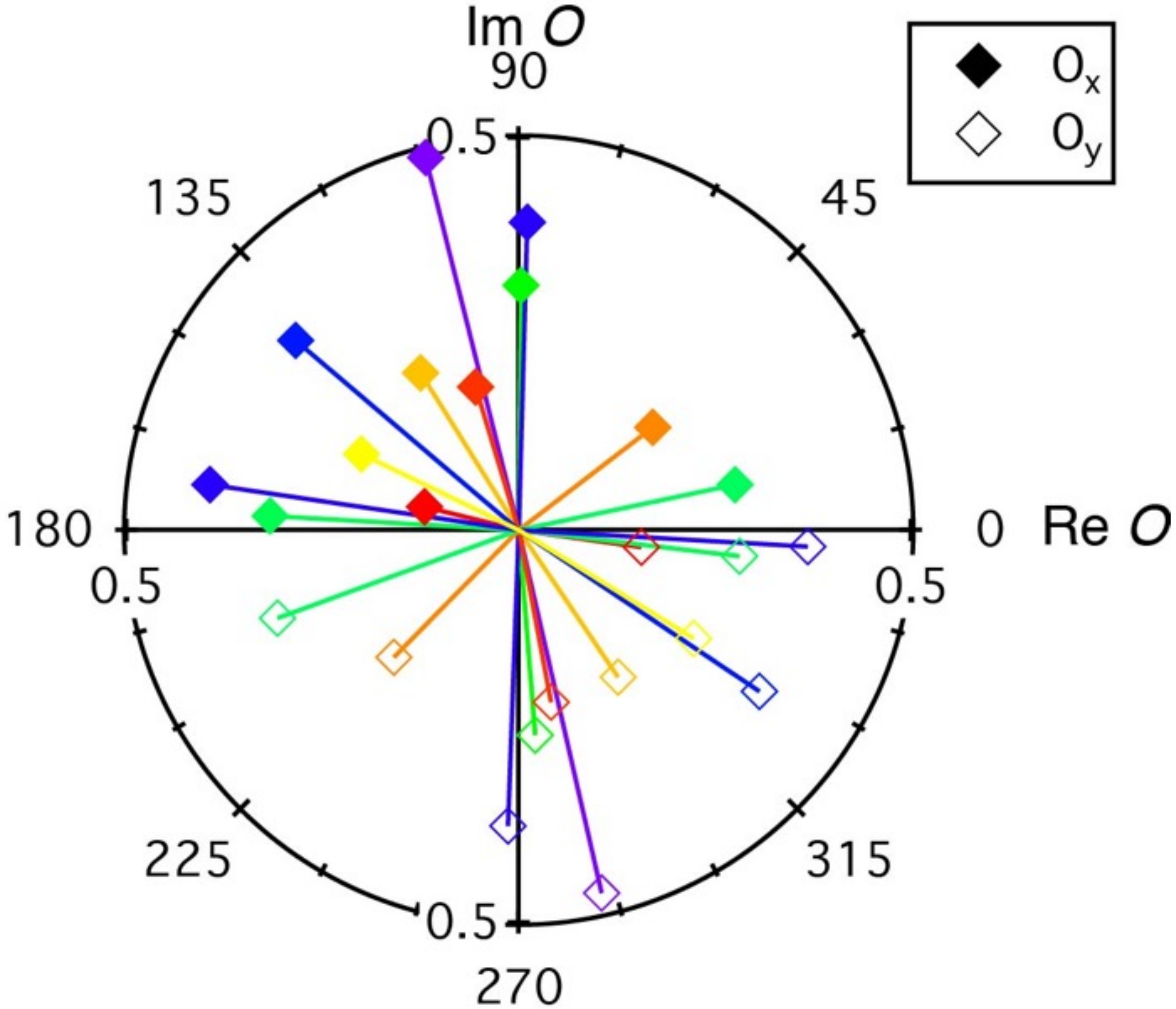

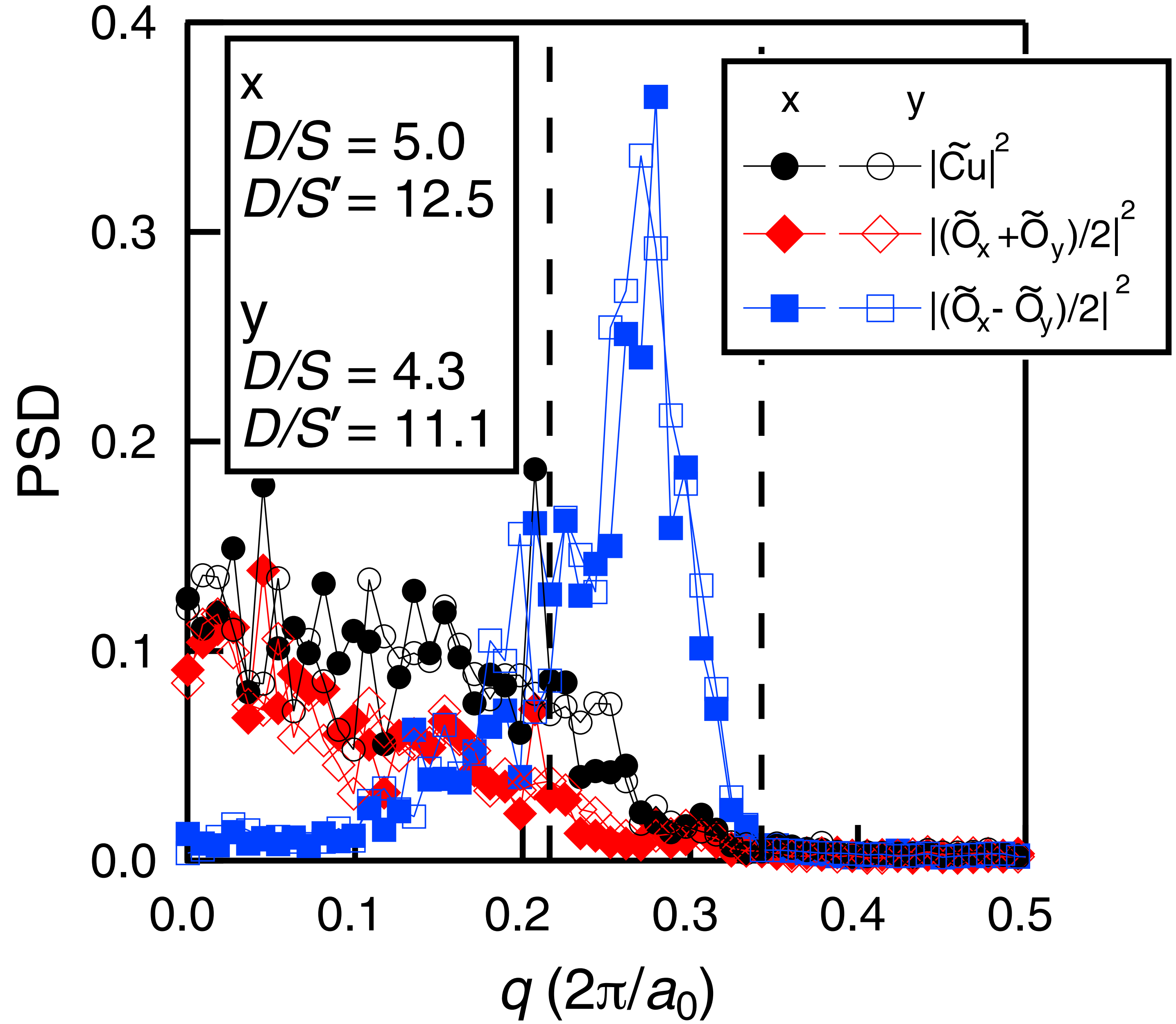

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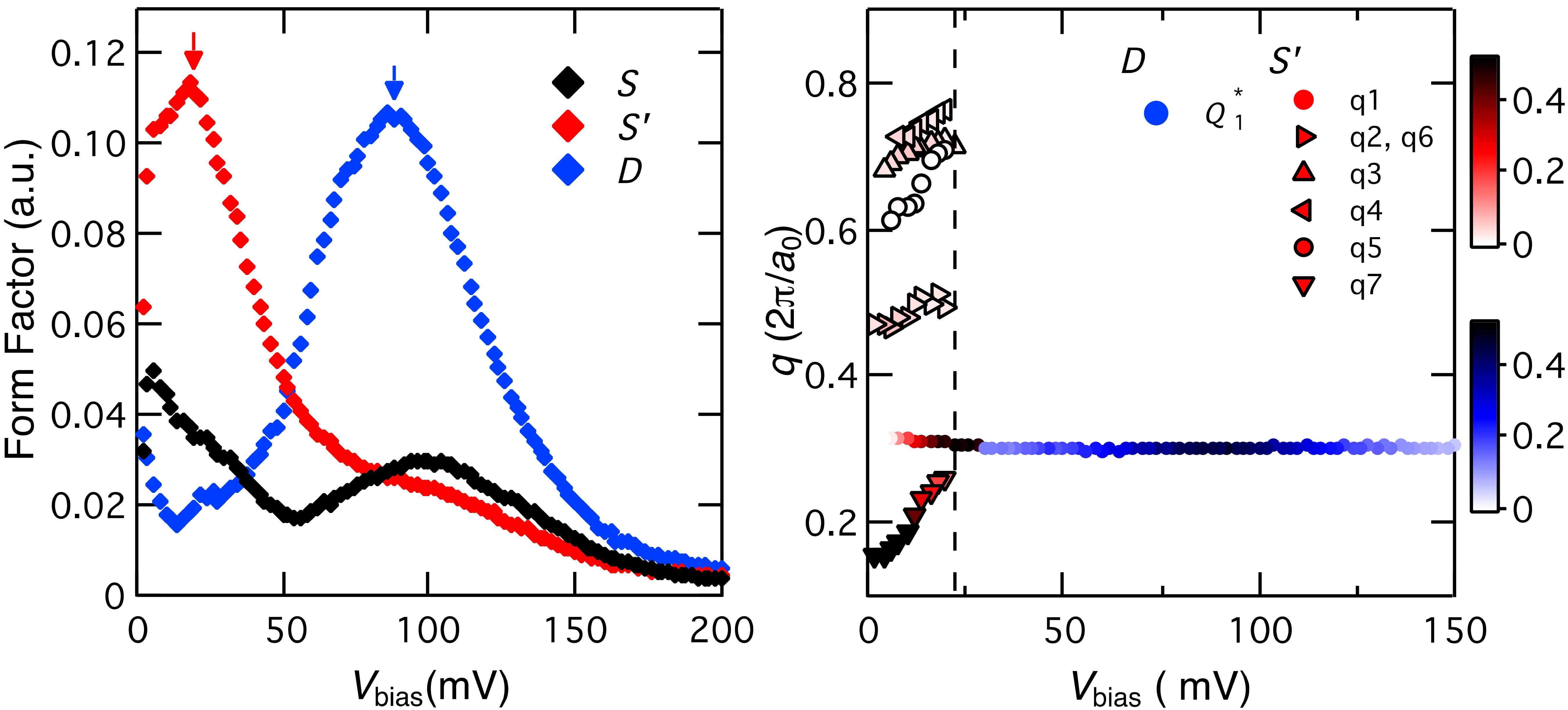
d-form factor is peaked at the pseudogap energy, and does not disperse as a function of wavevector



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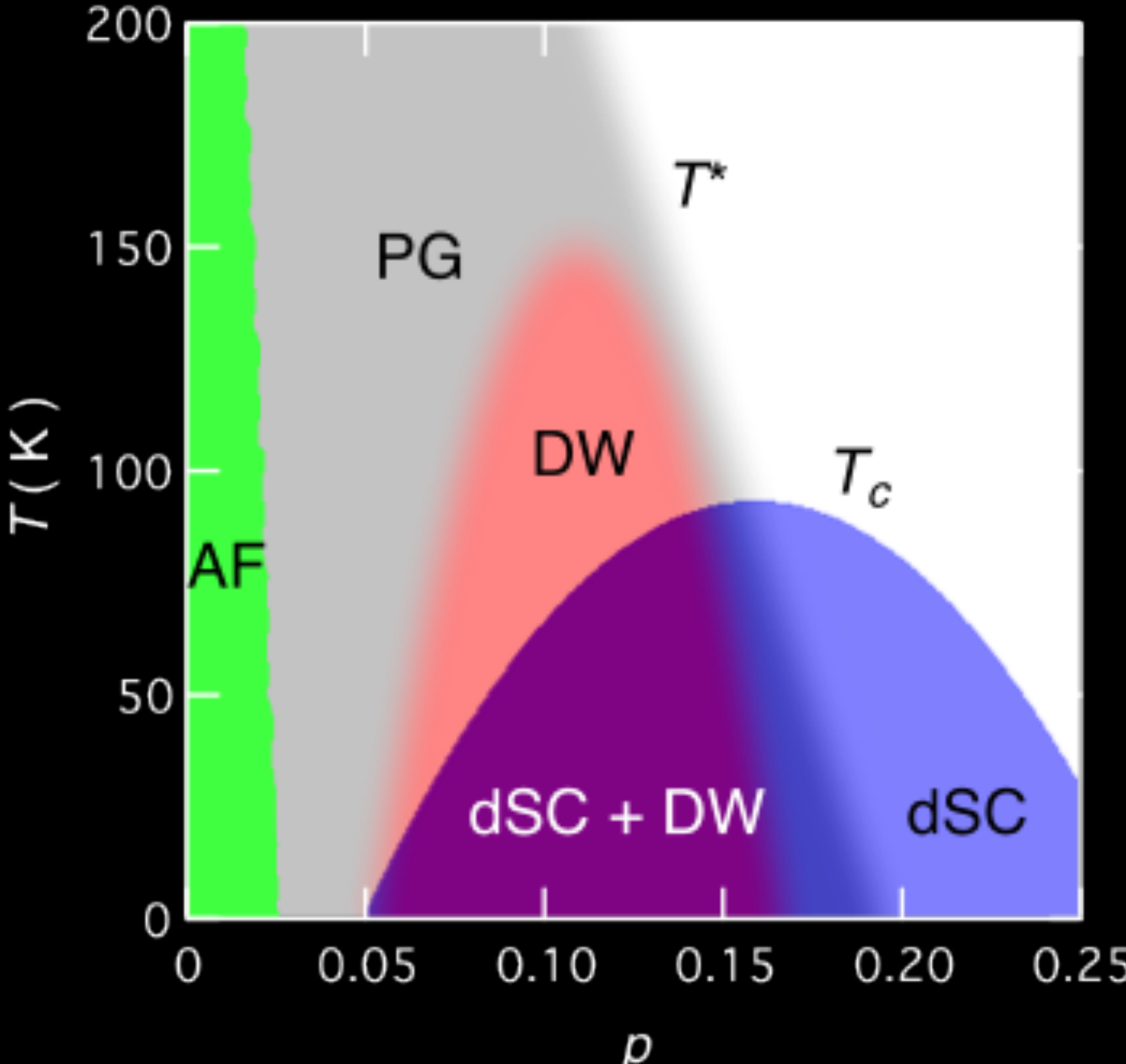
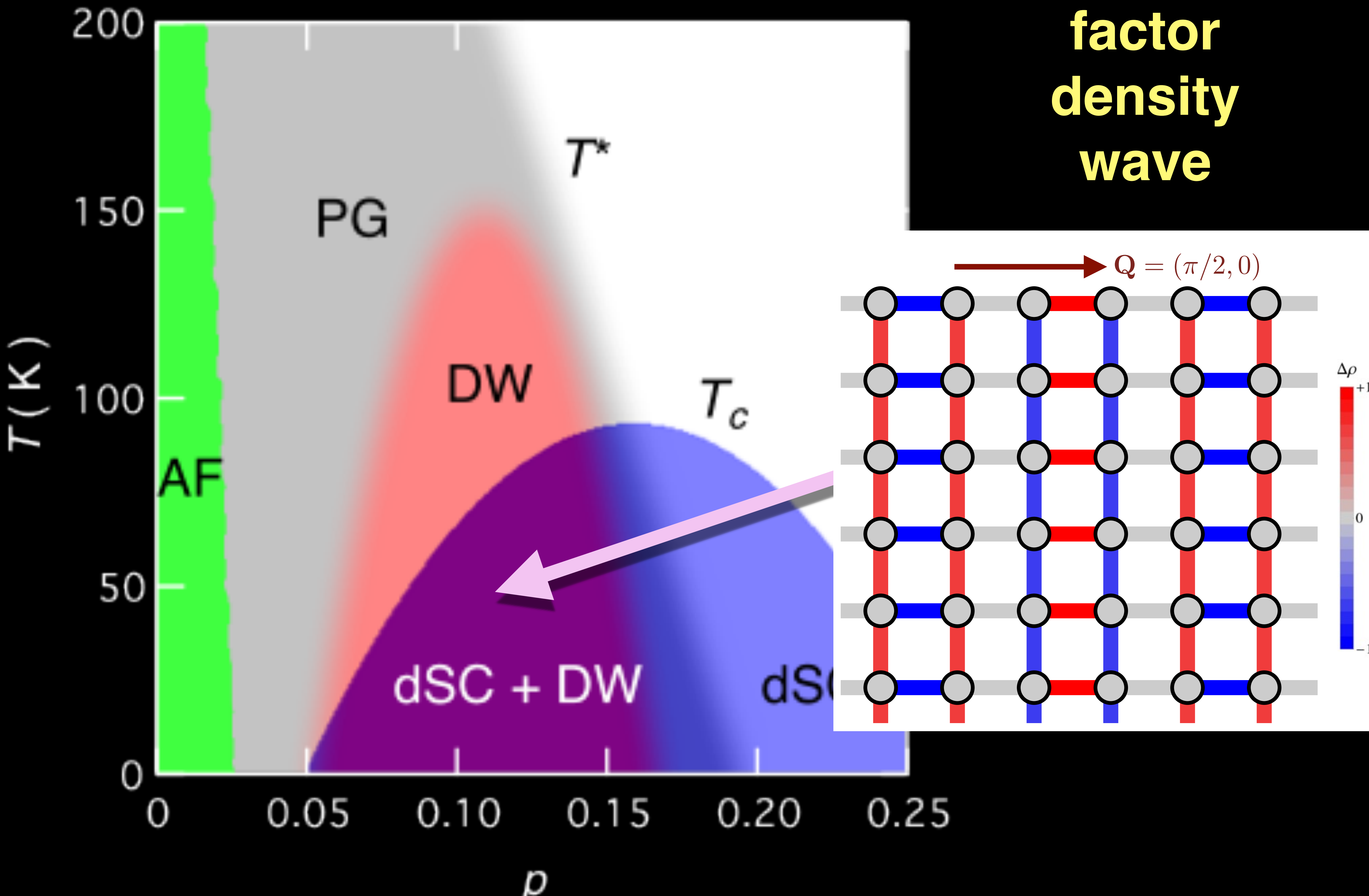
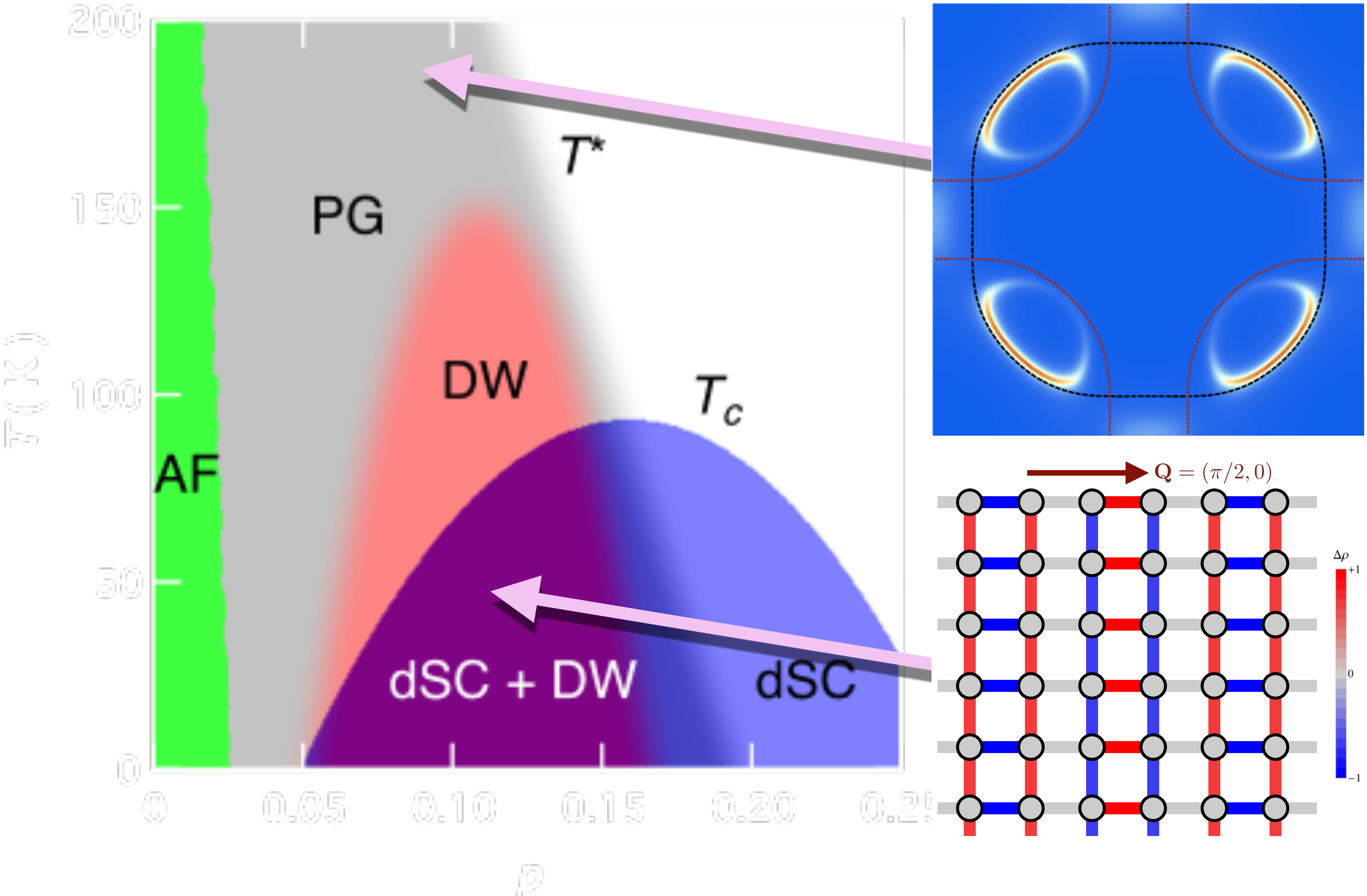


200
150
100
50
0
T (K)
0
0.05
0.10
0.15
0.20
0.25
p
AF
PG
T*
DW
Tc
dSC + DW
dSC

d-form factor density wave





200
150
100
50
0
0
0.05
0.10
0.15
0.20
T (K)
p
AF
PG
T*
DW
T_c
dSC + DW
dSC
$\mathbf{Q} = (\pi/2, 0)$
$\Delta\rho$
+1
0
−1

Outline

1. The high *T* pseudogap:
   A quantum dimer model for a metal with topological order

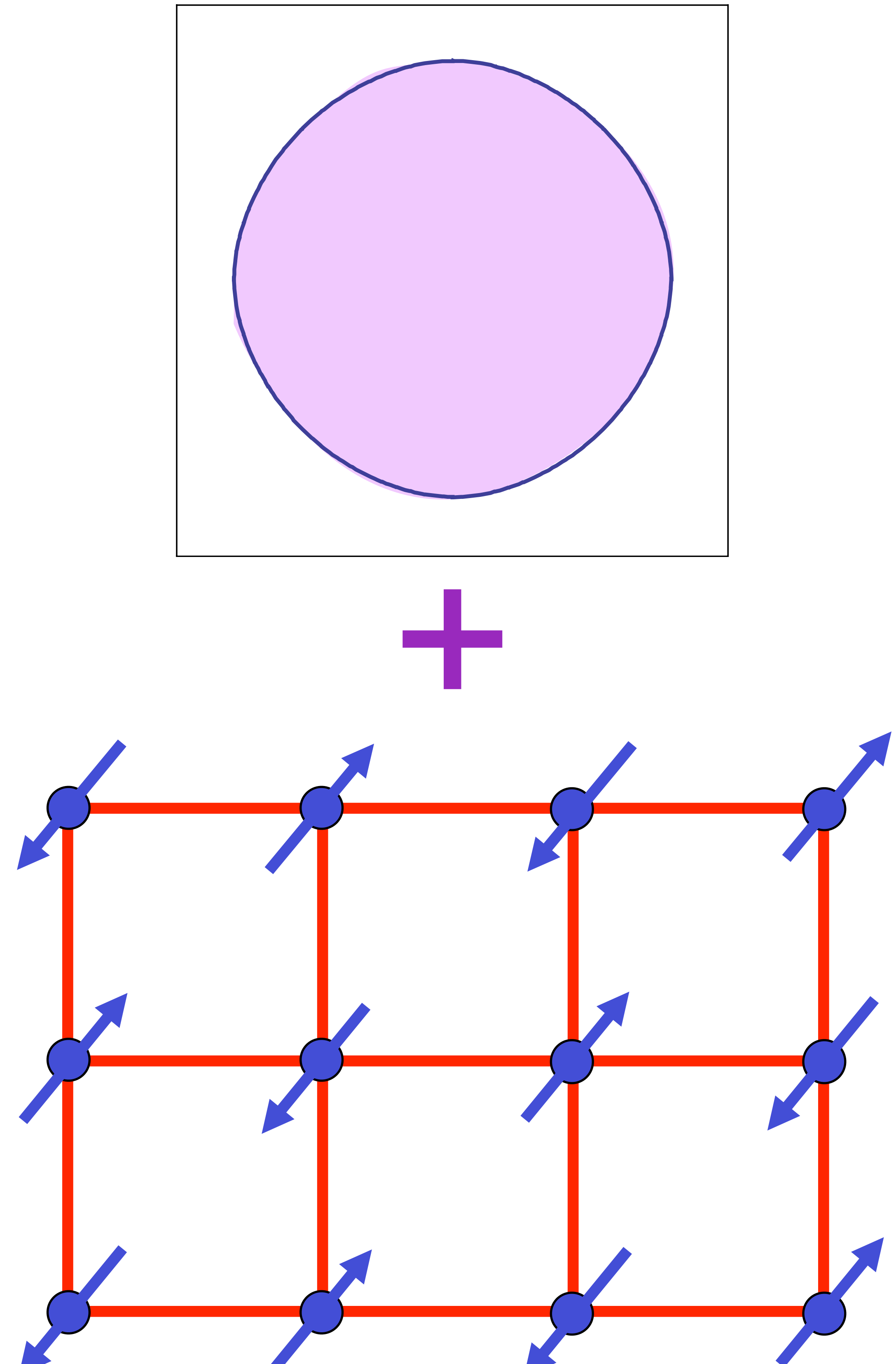
2. The low *T* pseudogap:
   STM observation of predicted d-form factor density wave

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

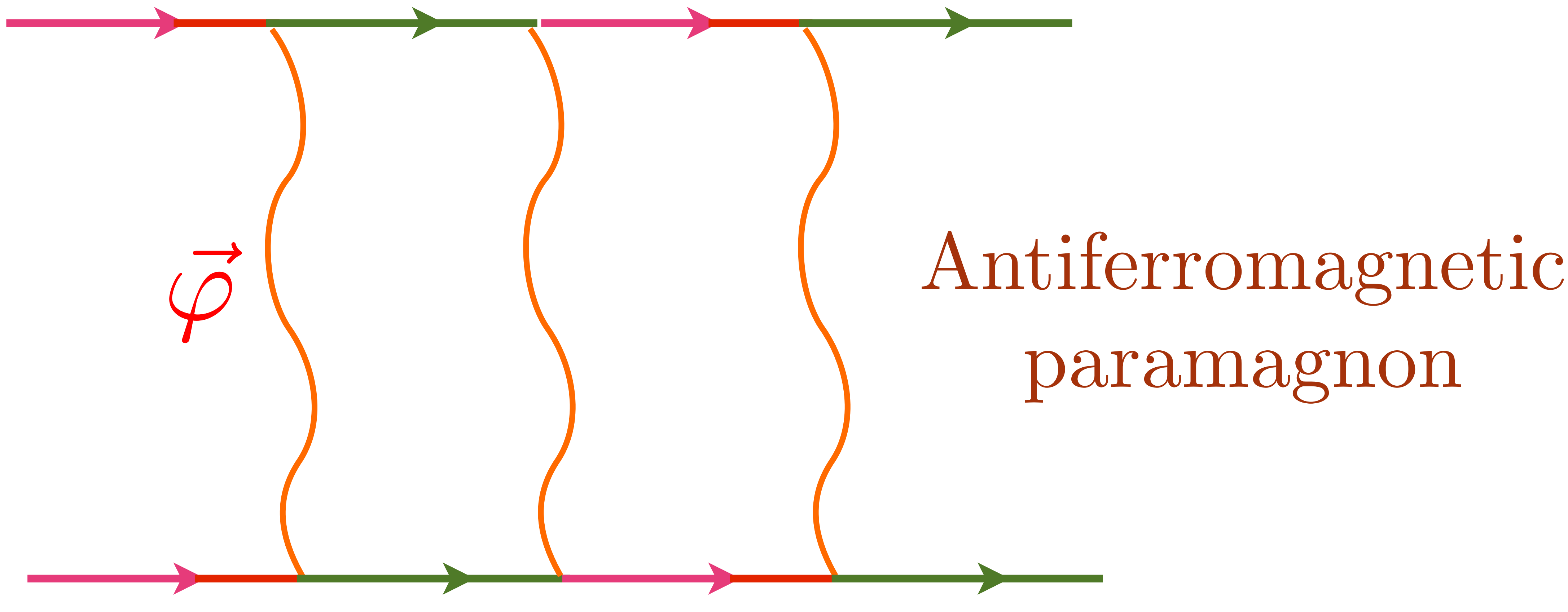


The electron spin polarization obeys

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

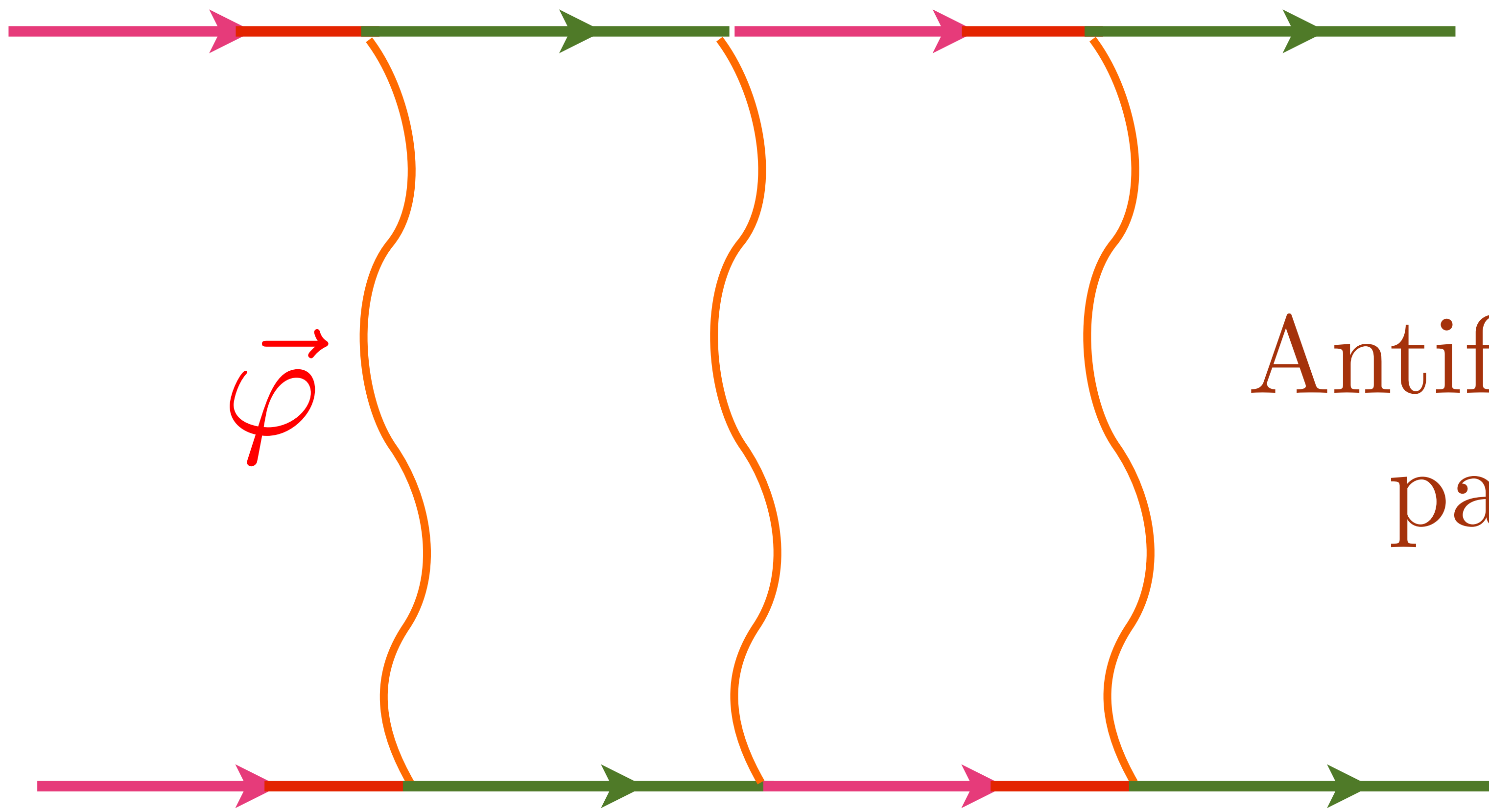
where $\mathbf{K} = (\pi,\pi)$ is the ordering wavevector.

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



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)

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



Antiferromagnetic paramagnon

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

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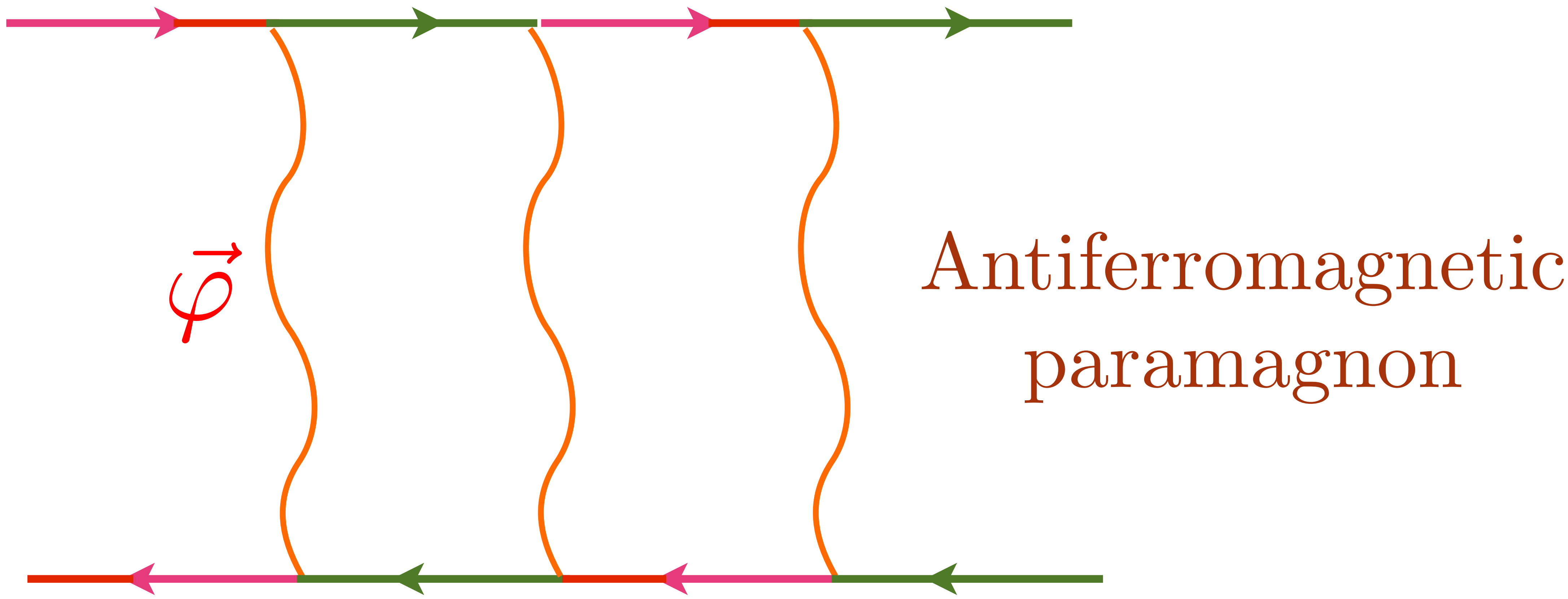
Same glue can lead to "d-wave" particle-hole pairing



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)

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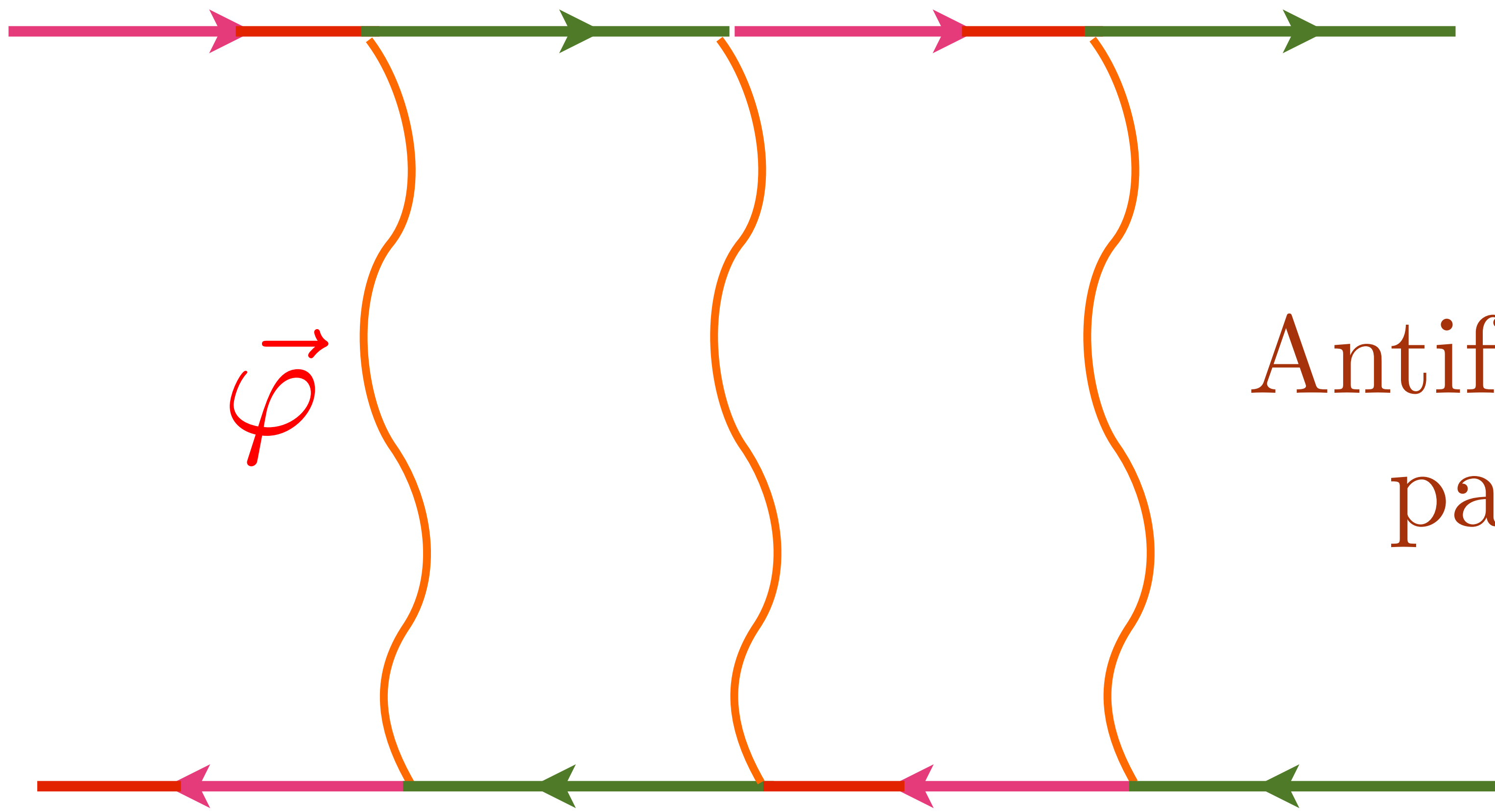
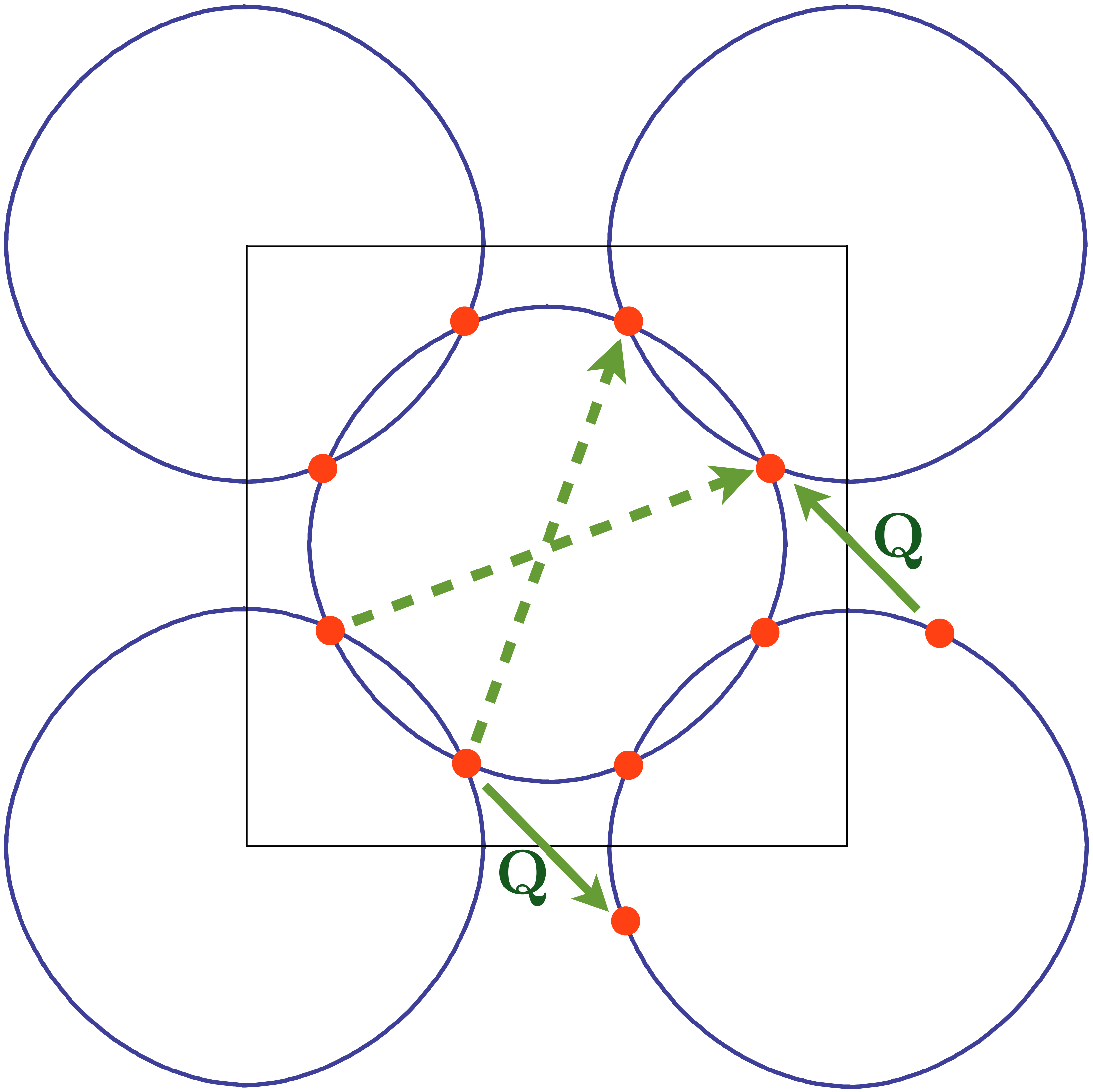


Leads to $\left\langle c^{\dagger}_{\mathbf{k}+\mathbf{Q}/2,\alpha} c_{\mathbf{k}-\mathbf{Q}/2,\alpha} \right\rangle =$

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

with $\mathcal{P}_d$ dominant.

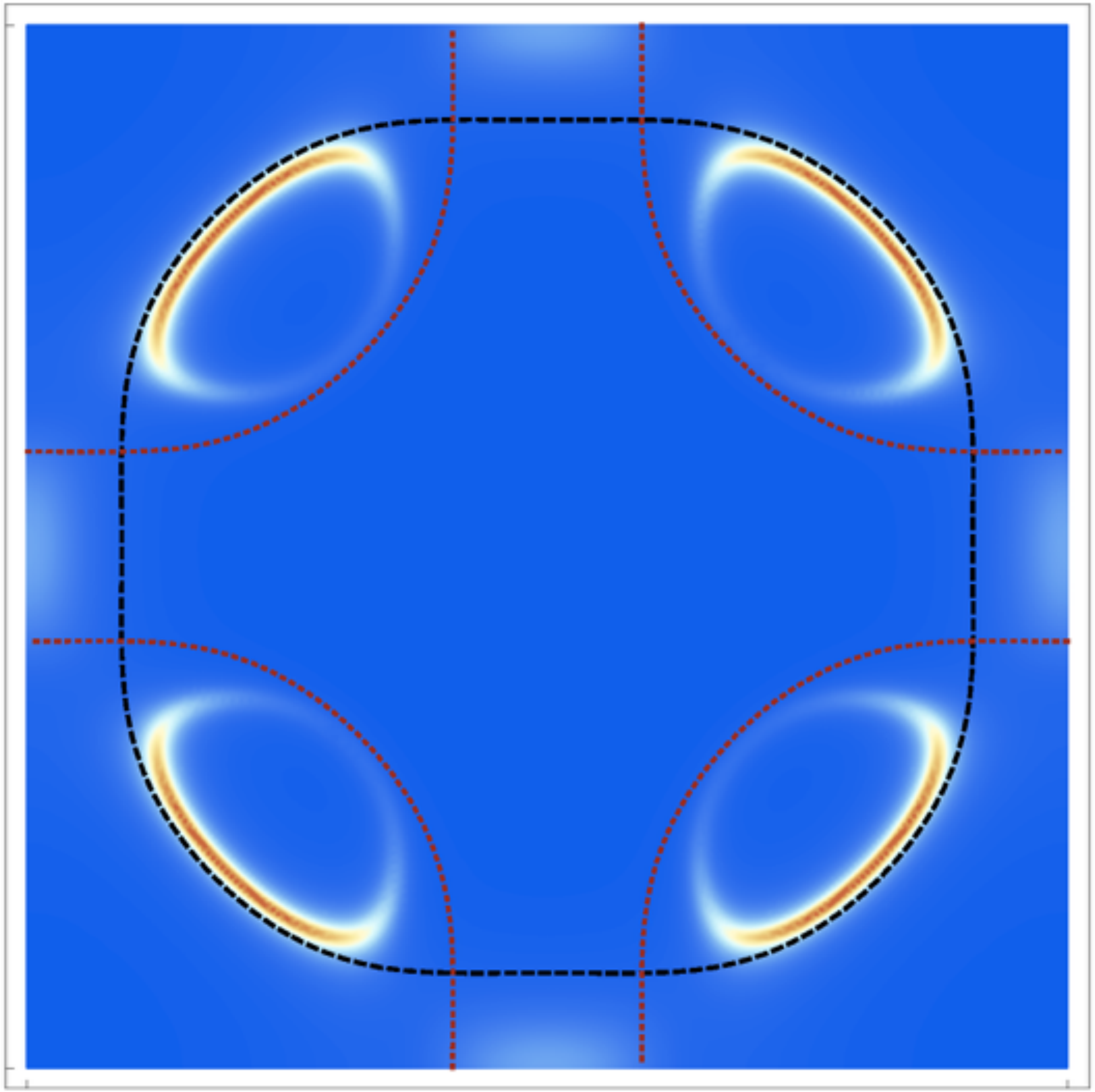
S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013)



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

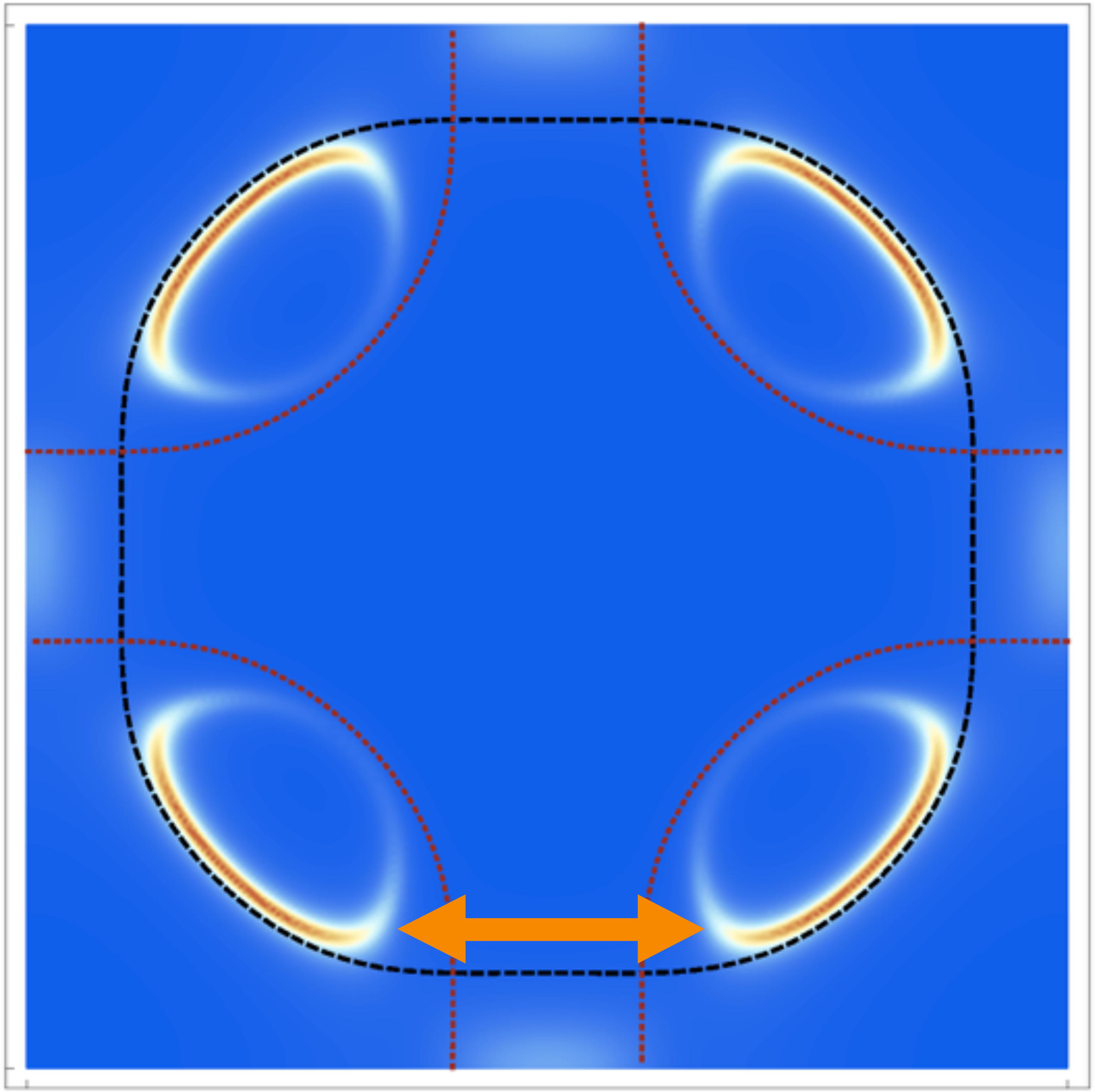
$$\left\langle c^{\dagger}_{\mathbf{k}-\mathbf{Q}/2,\alpha} c_{\mathbf{k}+\mathbf{Q}/2,\alpha} \right\rangle = \mathcal{P}_d(\cos k_x - \cos k_y)$$

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



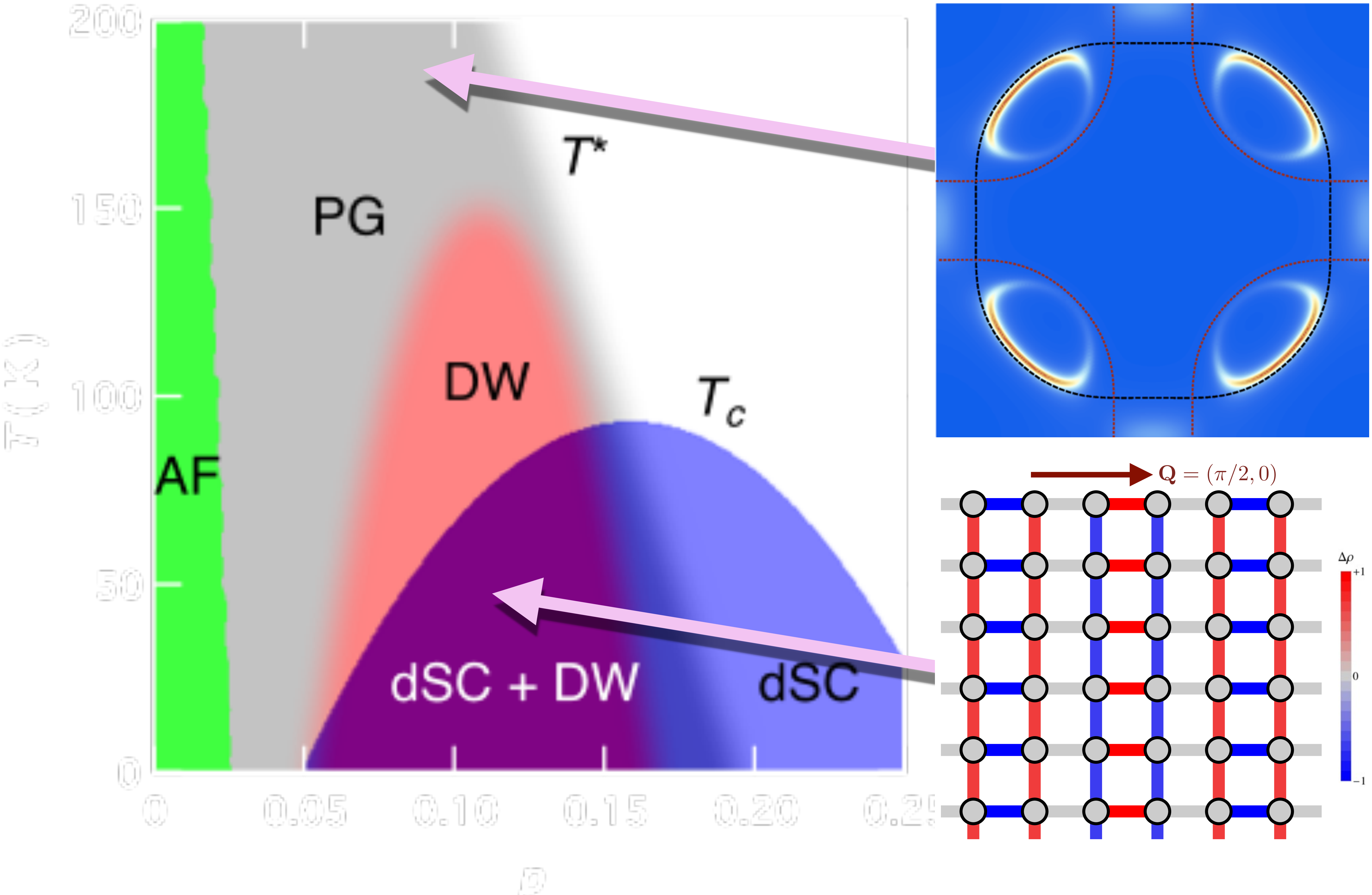
Fermi surface of FL*

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

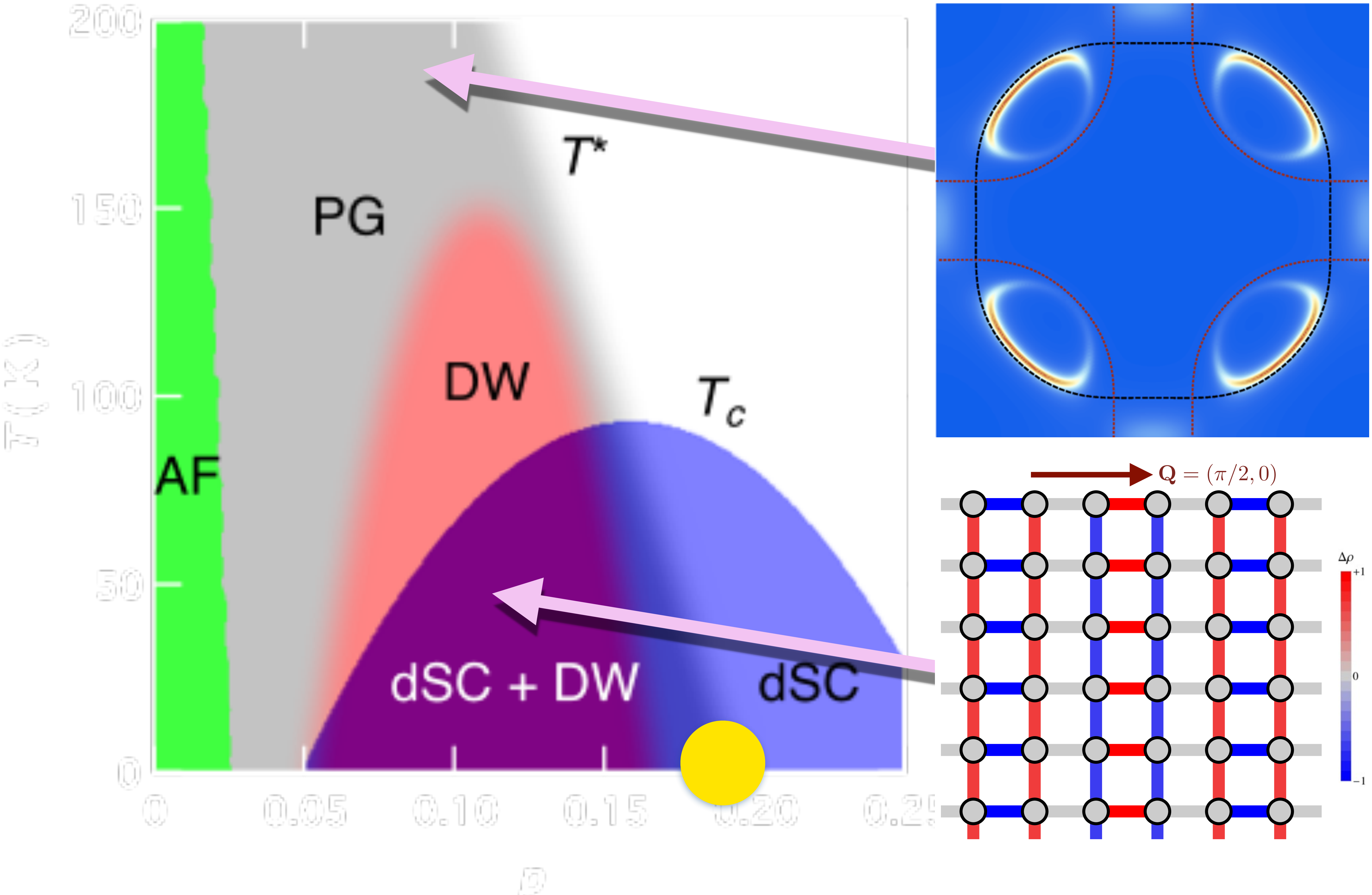


Density wave instability of FL* leads to the observed wavevector and form-factor

D. Chowdhury and S. Sachdev, Physical Review B **90**, 245136 (2014).



T*
PG
DW
Tc
AF
dSC + DW
dSC
200
150
100
50
0
T (K)
0
0.05
0.10
0.15
0.20
p
Q = (π/2, 0)
Δρ
+1
0
−1



200
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T (K)
0
0.05
0.10
0.15
0.20
p
PG
T*
DW
T_c
AF
dSC + DW
dSC
$\mathbf{Q} = (\pi/2, 0)$
$\Delta\rho$
+1
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Outline

1. The high T pseudogap:
   A quantum dimer model for a metal with topological order

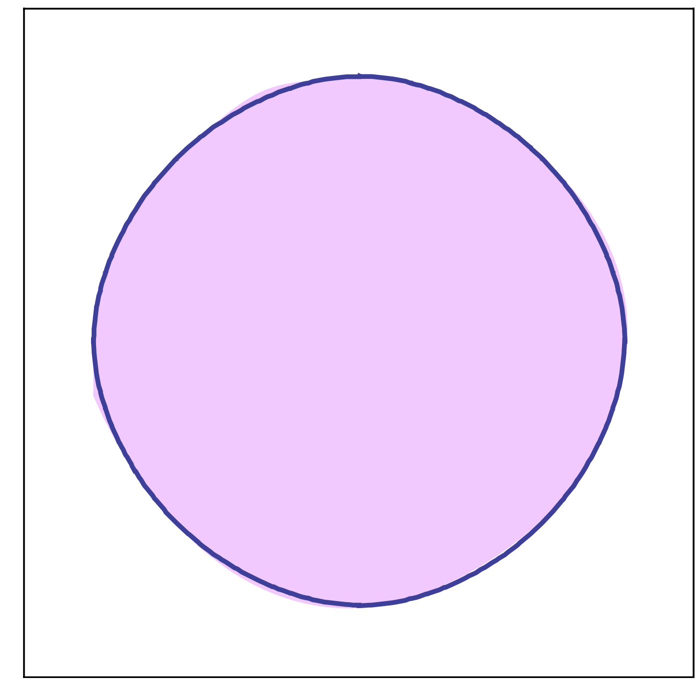
2. The low T pseudogap:
   STM observation of predicted d-form factor density wave

3. Connecting high and low T:
   Density wave instabilities

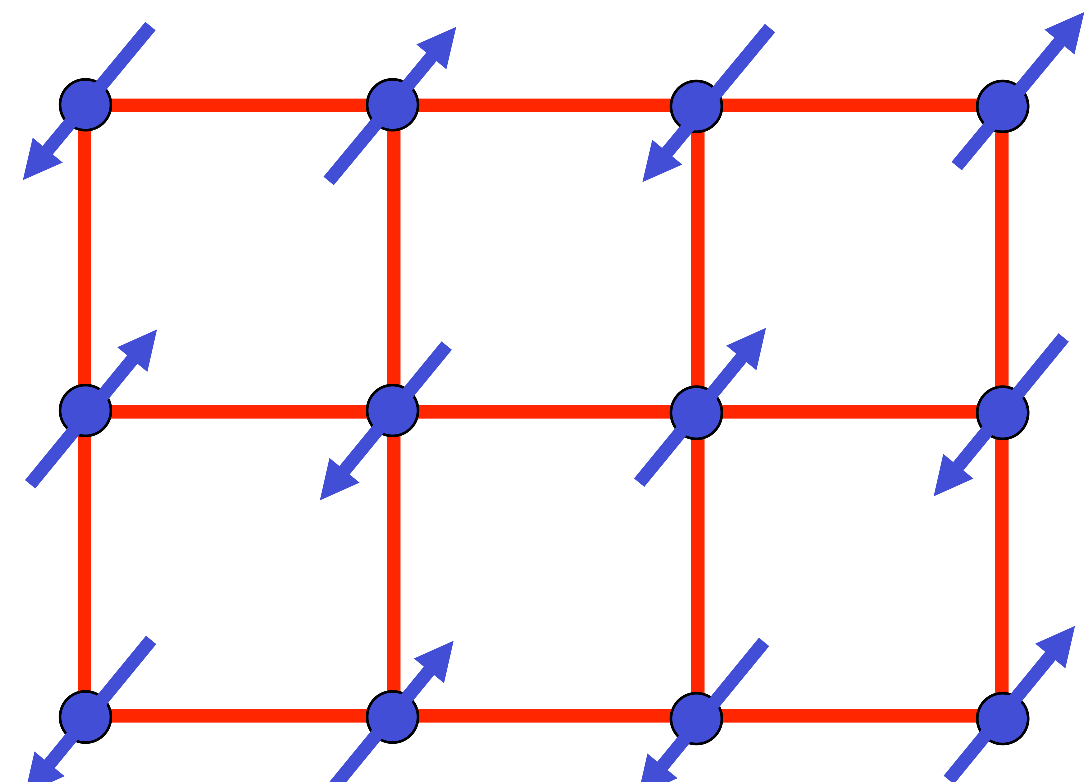
4. Quantum critical point near optimal p:
   A Higgs critical point

Fermi surface+antiferromagnetism

Metal with "large"
Fermi surface



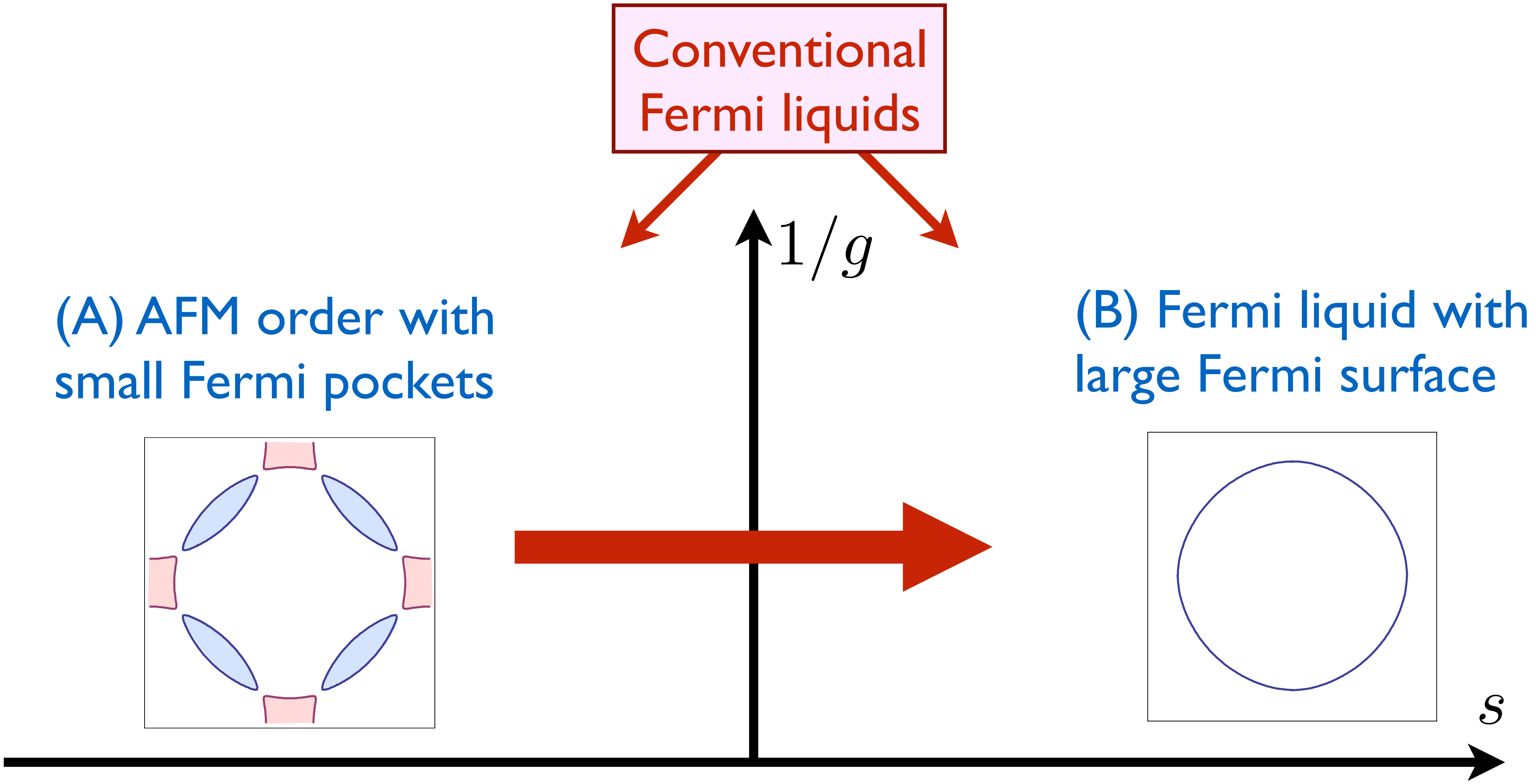
+



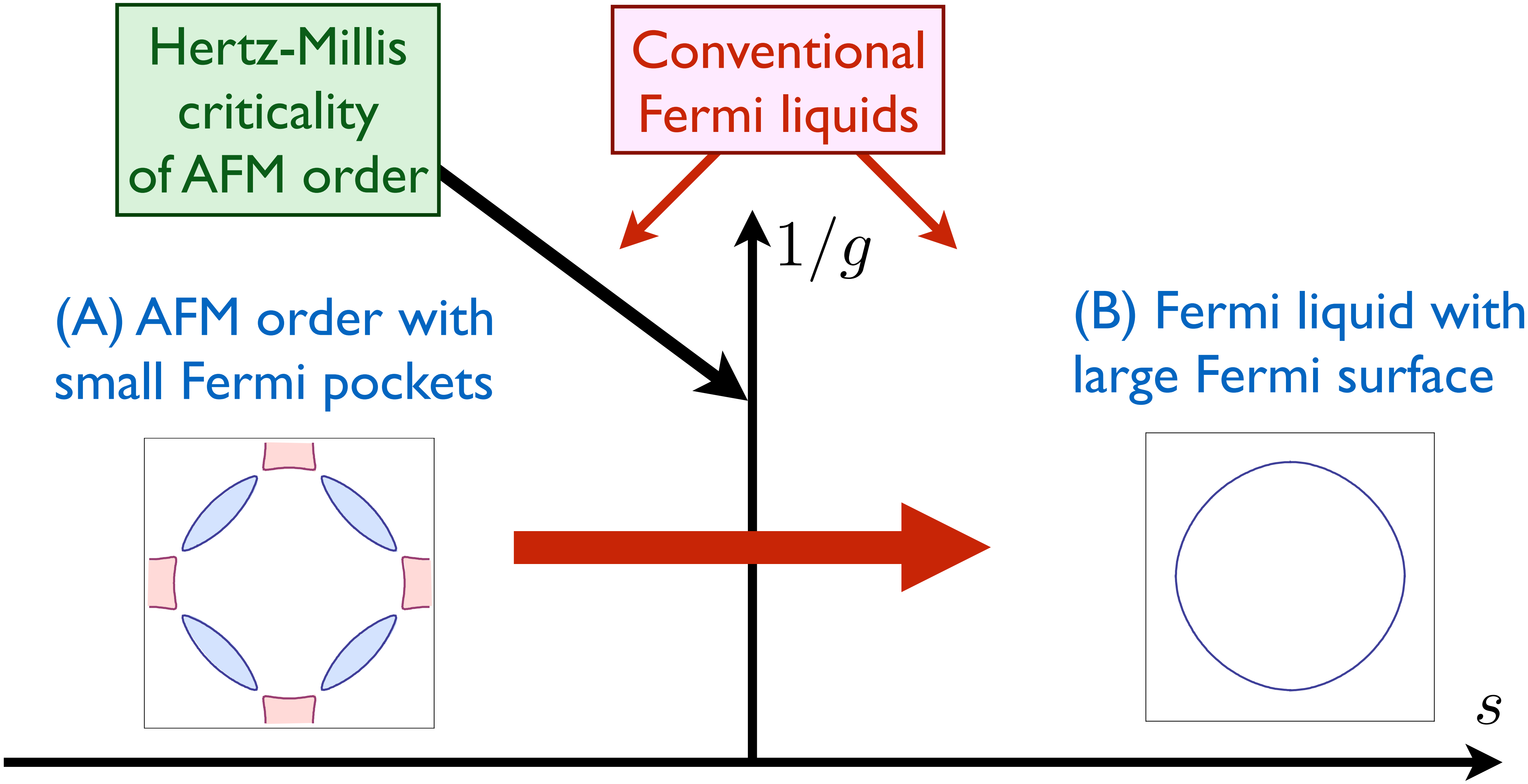
The electron spin polarization obeys

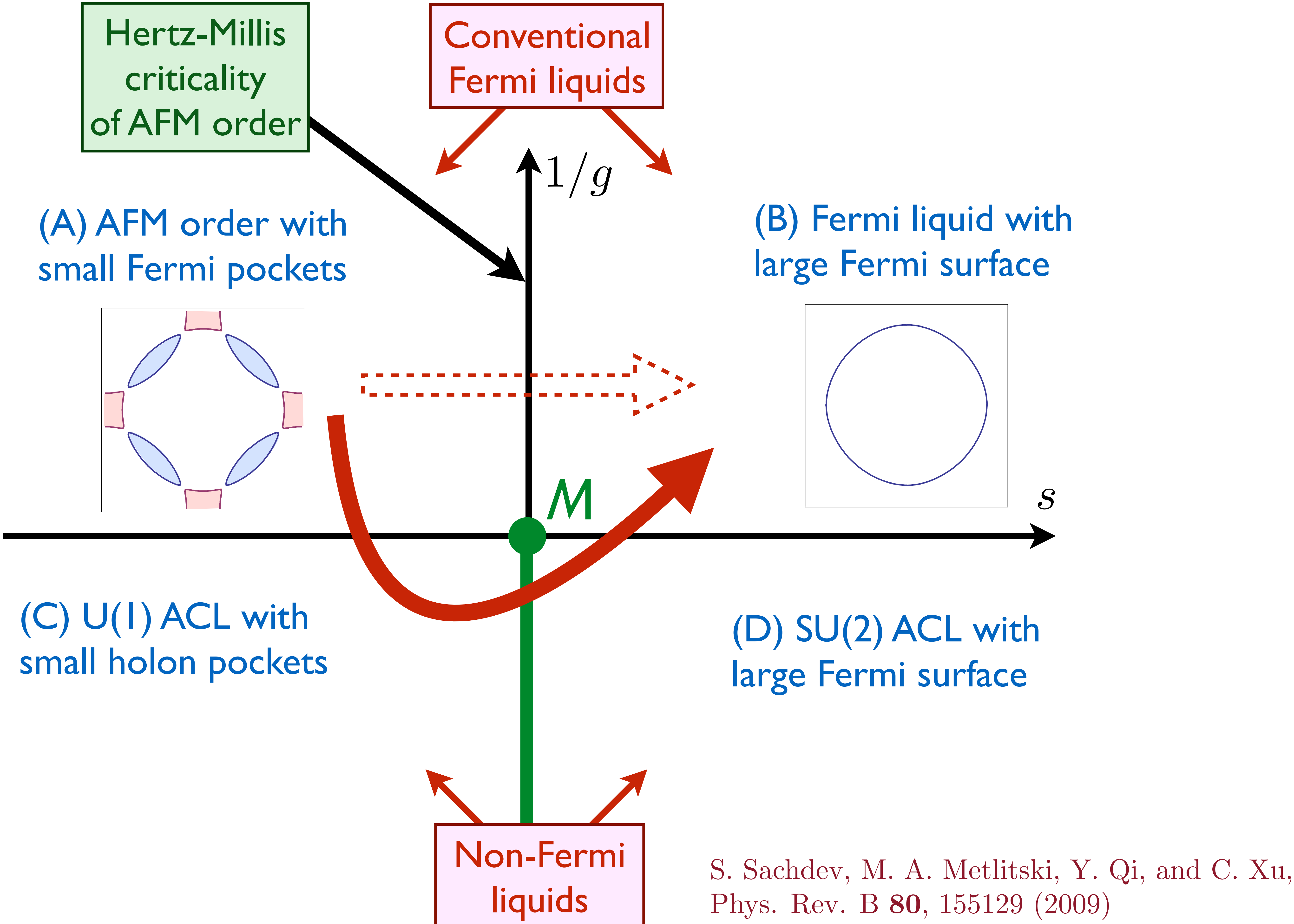
$$\left\langle \vec{S}(\mathbf{r},\tau) \right\rangle = \vec{\varphi}(\mathbf{r},\tau) e^{i\mathbf{K}\cdot\mathbf{r}}$$

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



Conventional
Fermi liquids
$1/g$
(A) AFM order with
small Fermi pockets
(B) Fermi liquid with
large Fermi surface
s


Hertz-Millis criticality of AFM order
Conventional Fermi liquids
$1/g$
(A) AFM order with small Fermi pockets
(B) Fermi liquid with large Fermi surface
s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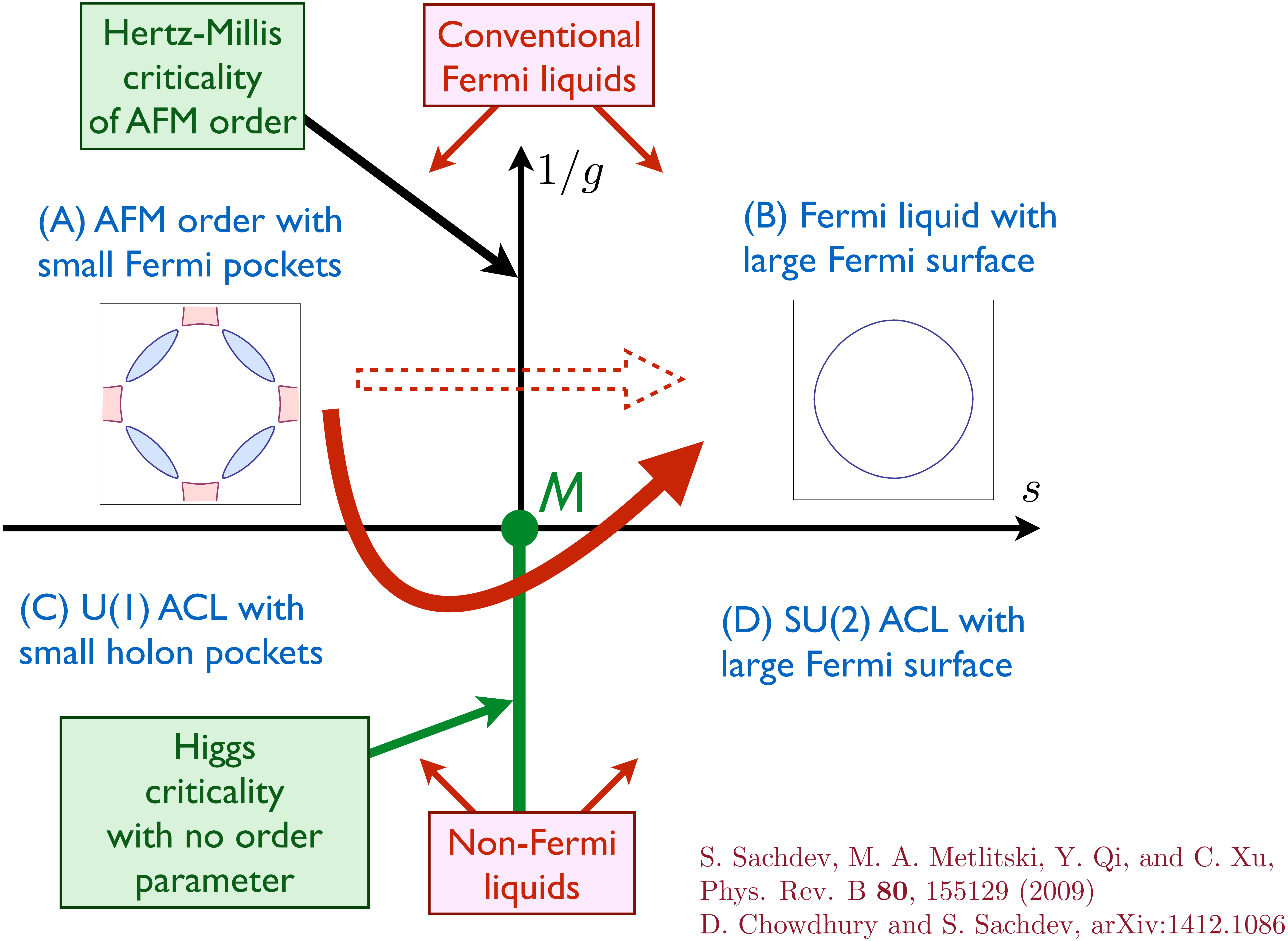
(C) U(1) ACL with small holon pockets
(D) SU(2) ACL with large Fermi surface
Non-Fermi liquids
S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, Phys. Rev. B **80**, 155129 (2009)
D. Chowdhury and S. Sachdev, arXiv:1412.1086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Higgs criticality with no order parameter
Non-Fermi liquids
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D. Chowdhury and S. Sachdev, arXiv:1412.1086

SU(2) gauge theory

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

$$\begin{pmatrix} c_\uparrow \\ c_\downarrow \end{pmatrix} = R \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix}$$

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

$$\begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix} \rightarrow U \begin{pmatrix} \psi_+ \\ \psi_- \end{pmatrix} \quad ; \quad R \rightarrow R U^\dagger$$

S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, Phys. Rev. B **80**, 155129 (2009)
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SU(2) gauge theory

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.

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The electrons, c_α move in the presence of local antiferromagnetic order $\vec{n}$. In the rotating reference frame, this is equivalent to a Yukawa coupling between the ψ fermions and a spin-singlet, gauge-SU(2) adjoint *Higgs field* H^a given by

$$H^a = \frac{1}{2} \text{Tr} \left[\sigma^\ell R \sigma^a R^\dagger \right] n_\ell$$

S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, Phys. Rev. B **80**, 155129 (2009)
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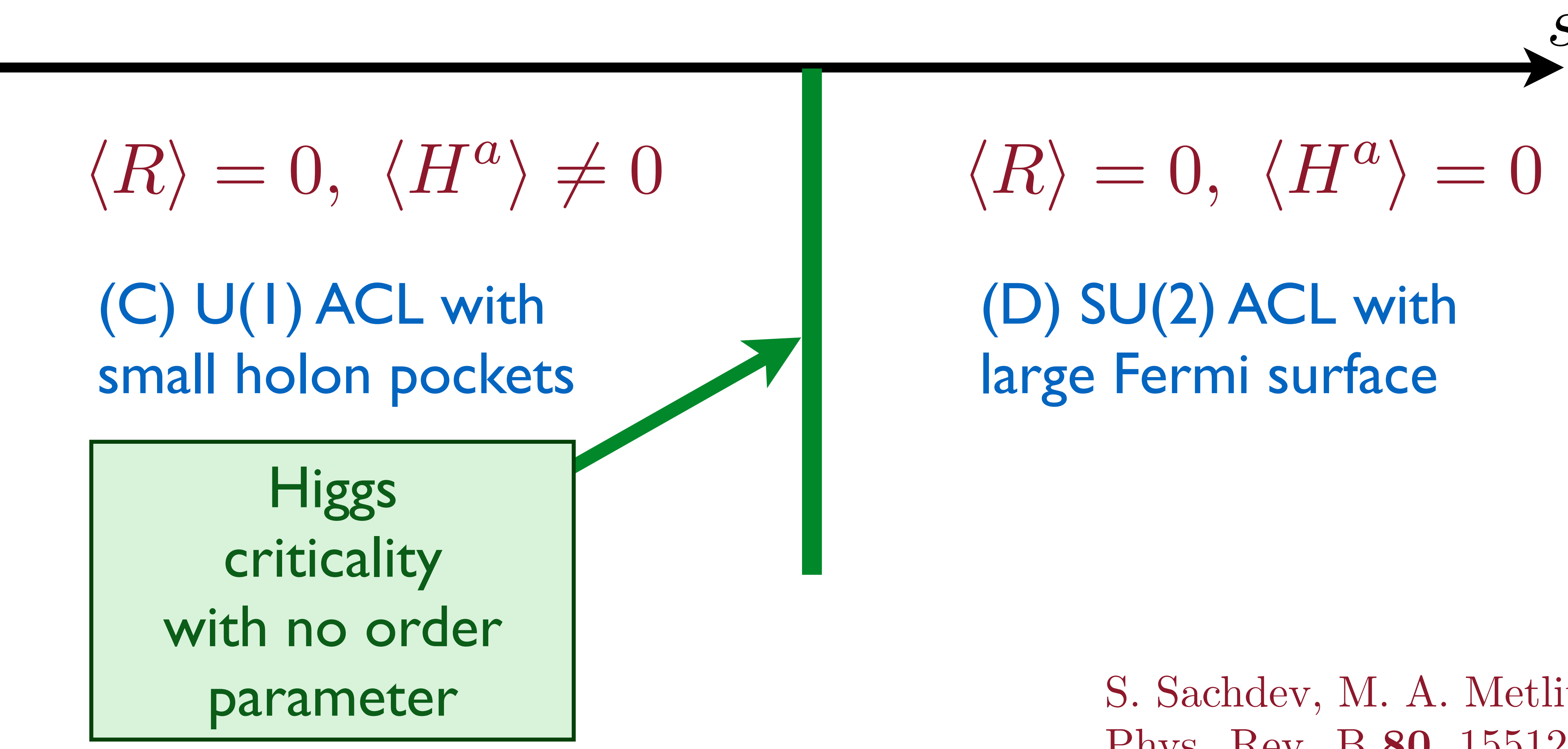
- A SU(2) gauge boson.

- 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

SU(2) gauge theory for underlying quantum critical point

- 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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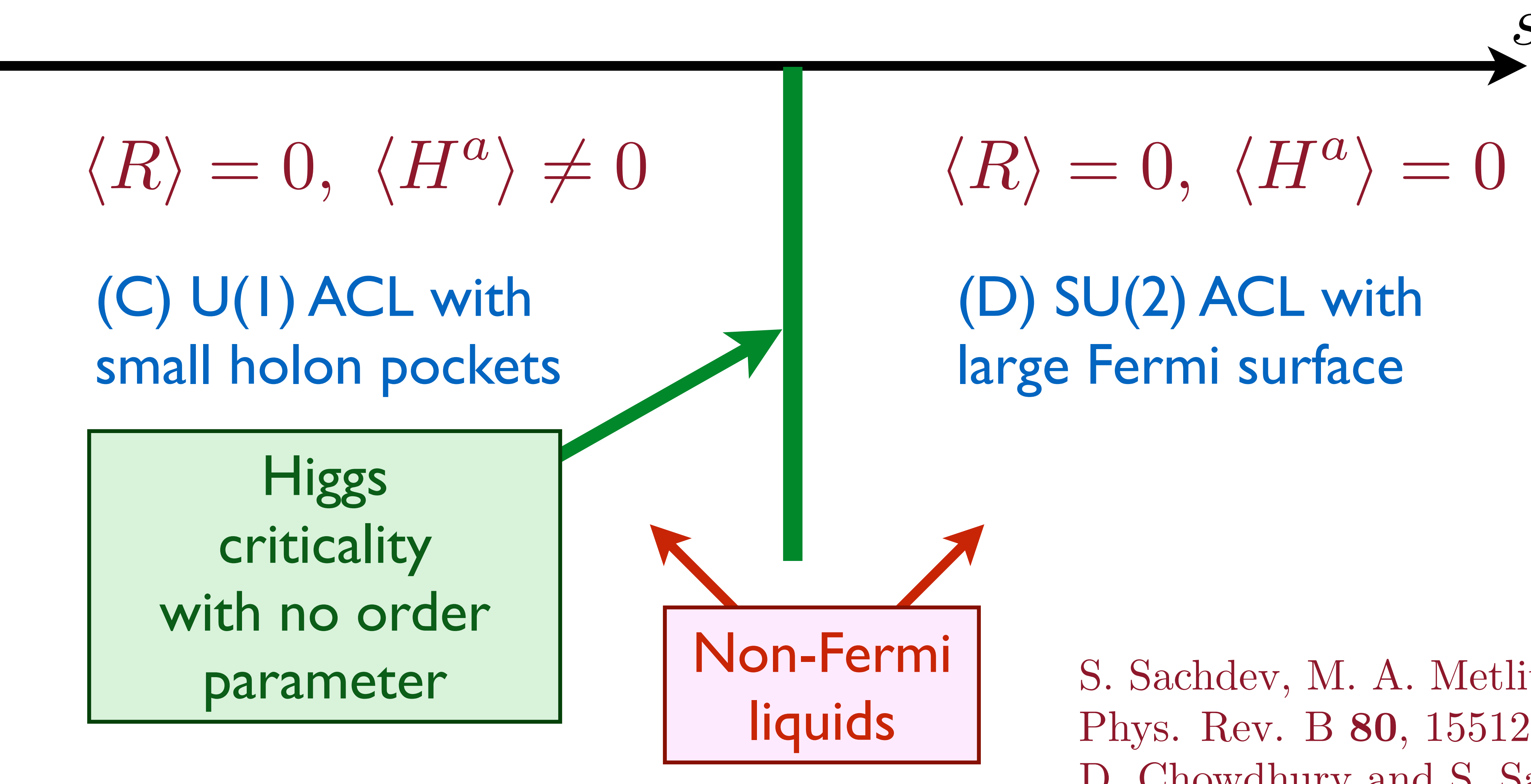
- The Higgs condensation does not give the fermions a "mass"; instead it reconstructs the Fermi surface from *large* to *small*.

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

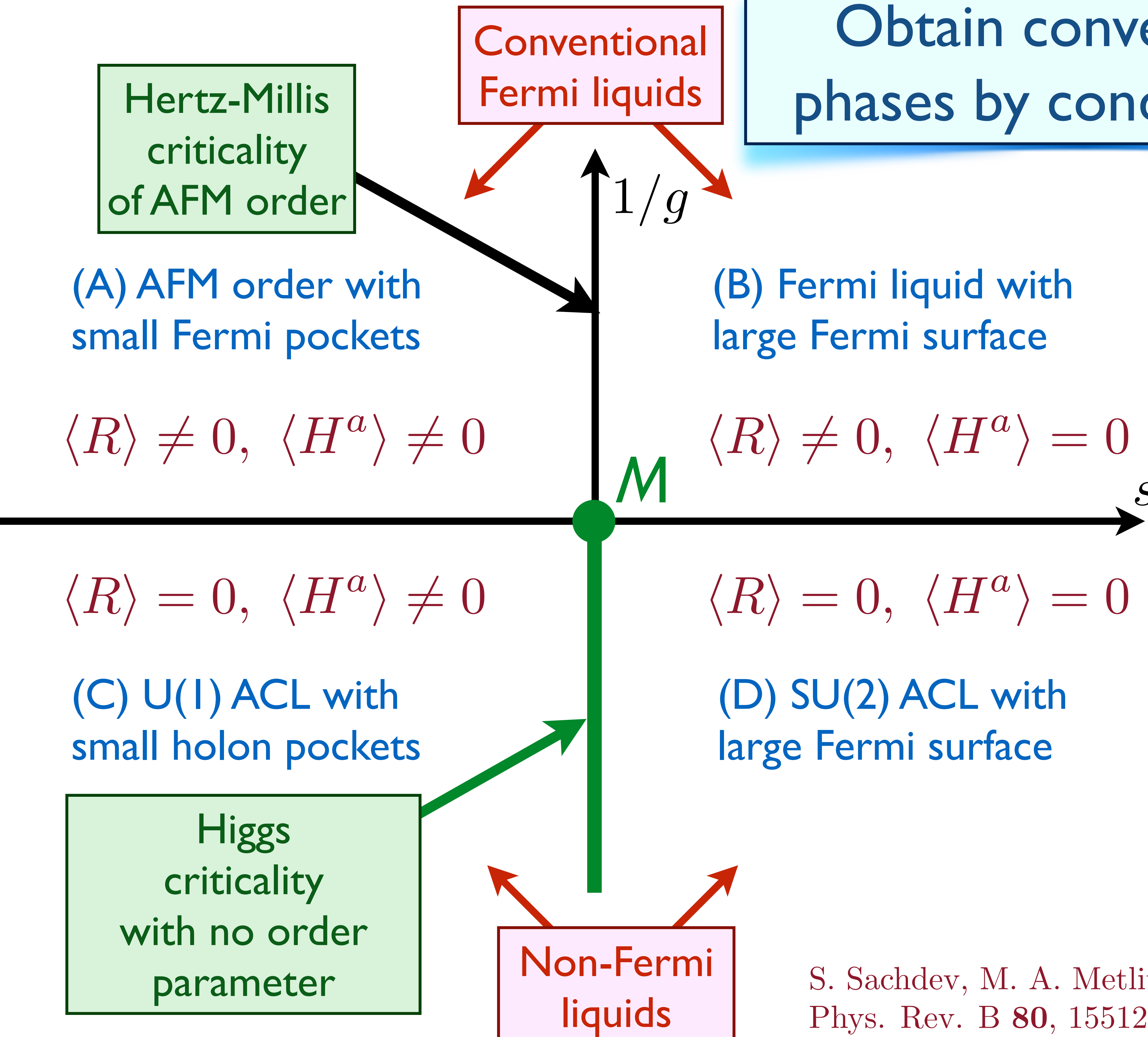
S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu, Phys. Rev. B **80**, 155129 (2009)
D. Chowdhury and S. Sachdev, arXiv:1412.1086

Higgs transition between non-Fermi liquid metals with large and small Fermi surfaces



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

Obtain conventional phases by condensing R



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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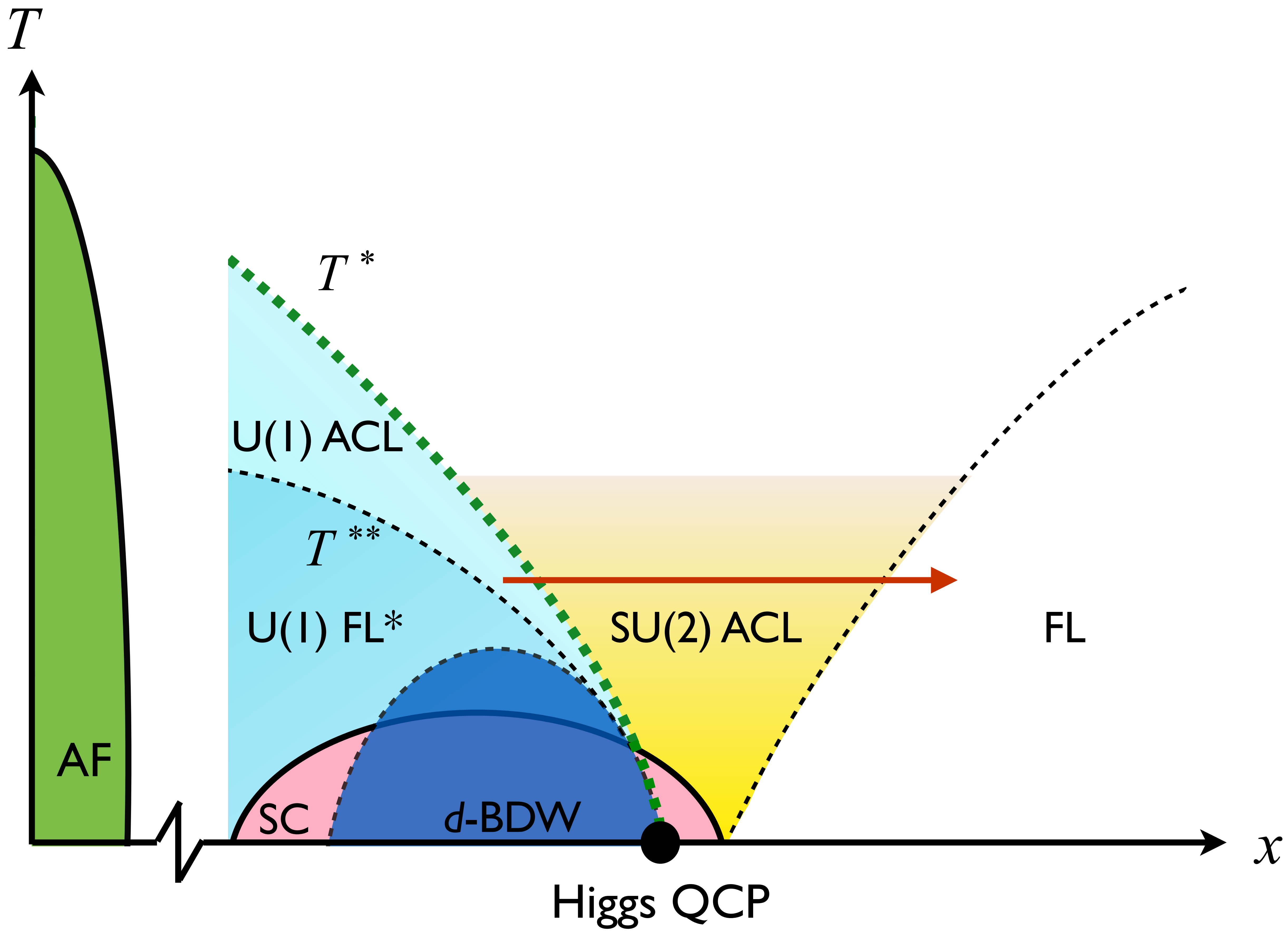


D. Chowdhury and S. Sachdev, arXiv:1412.1086

SU(2) gauge theory for underlying quantum critical point

Transport in QC regime:

All points on the Fermi surface have a rapid relaxation to local thermal equilibrium by processes which conserve a suitably defined momentum.

Relaxation of the momentum occurs at a slower rate.

S. A. Hartnoll, R. Mahajan, M. Punk and S. Sachdev, Phys. Rev. B **89**, 155130 (2014)
A. Patel and S. Sachdev, arXiv:1408.6549

SU(2) gauge theory for underlying quantum critical point

The resistivity of this strange metal is *not* determined by the scattering rate of charged excitations near the Fermi surface, but by the dominant rate of momentum loss by *any* excitation, whether neutral or charged, or fermionic or bosonic.

There is a dominant contribution $\rho(T) \sim T$ by the coupling of long-wavelength disorder to the gauge-invariant operator $\mathcal{O} \sim H^2$.

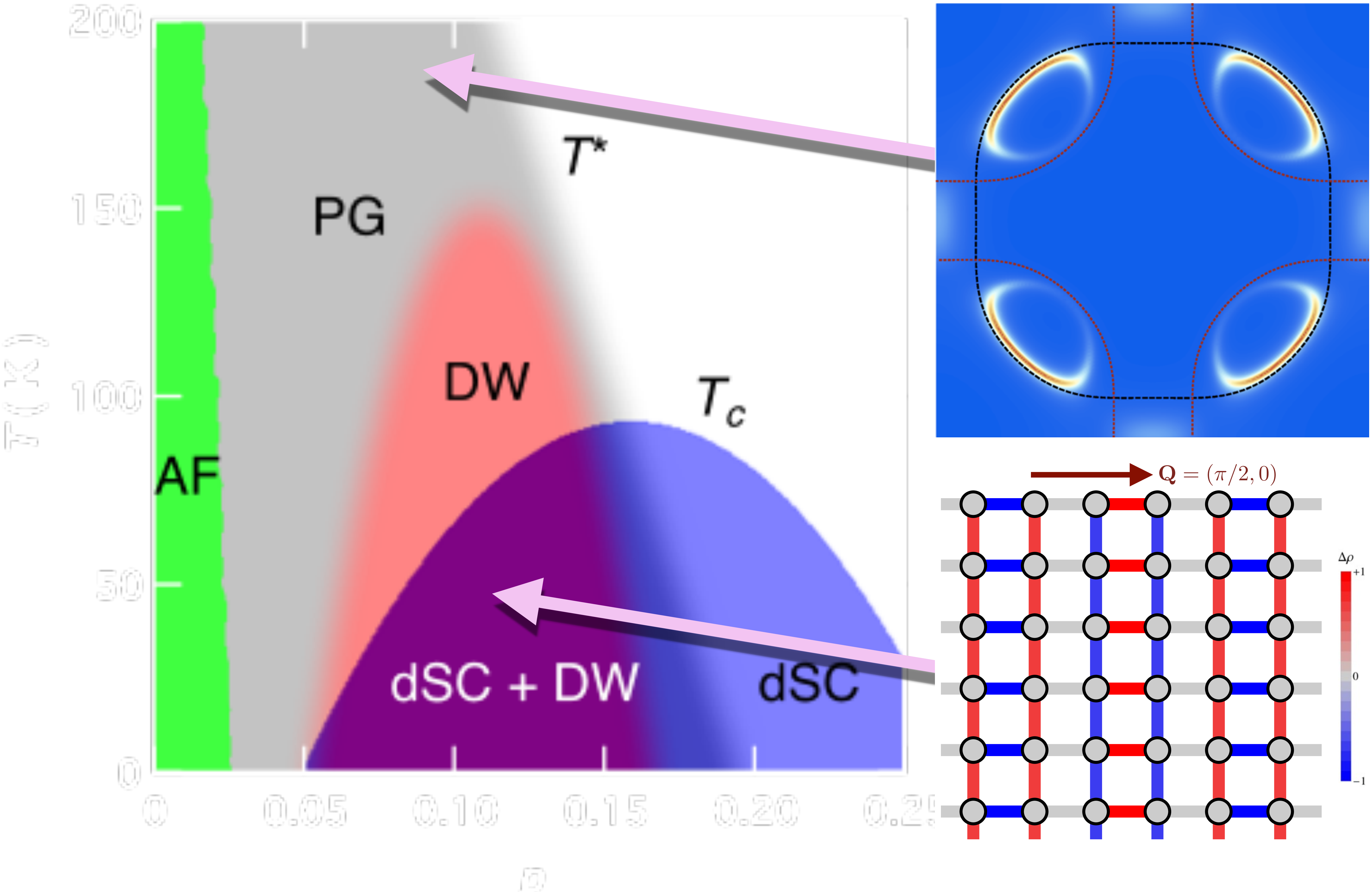
S. A. Hartnoll, R. Mahajan, M. Punk and S. Sachdev, Phys. Rev. B **89**, 155130 (2014)
A. Patel and S. Sachdev, arXiv:1408.6549

Conclusions

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

2. The "electron becomes a dimer" in the pseudogap metal: proposed a quantum dimer model.

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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