

The pseudogap phase of the cuprate superconductors

University of Chicago
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JOHN TEMPLETON
FOUNDATION



Talk online: sachdev.physics.harvard.edu

Theorists at Harvard



Max Metlitski
(KITP, UCSB)



Andrea Allais



Matthias Punk
(Innsbruck)



Debanjan
Chowdhury



Alexandra
Thomson



Aavishkar Patel



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Jay Sau
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Cornell



Kazuhiro Fujita
Cornell/ BNL



Mohammad Hamidian
Cornell / BNL



Stephen Edkins
Cornell / St Andrews



Michael Lawler

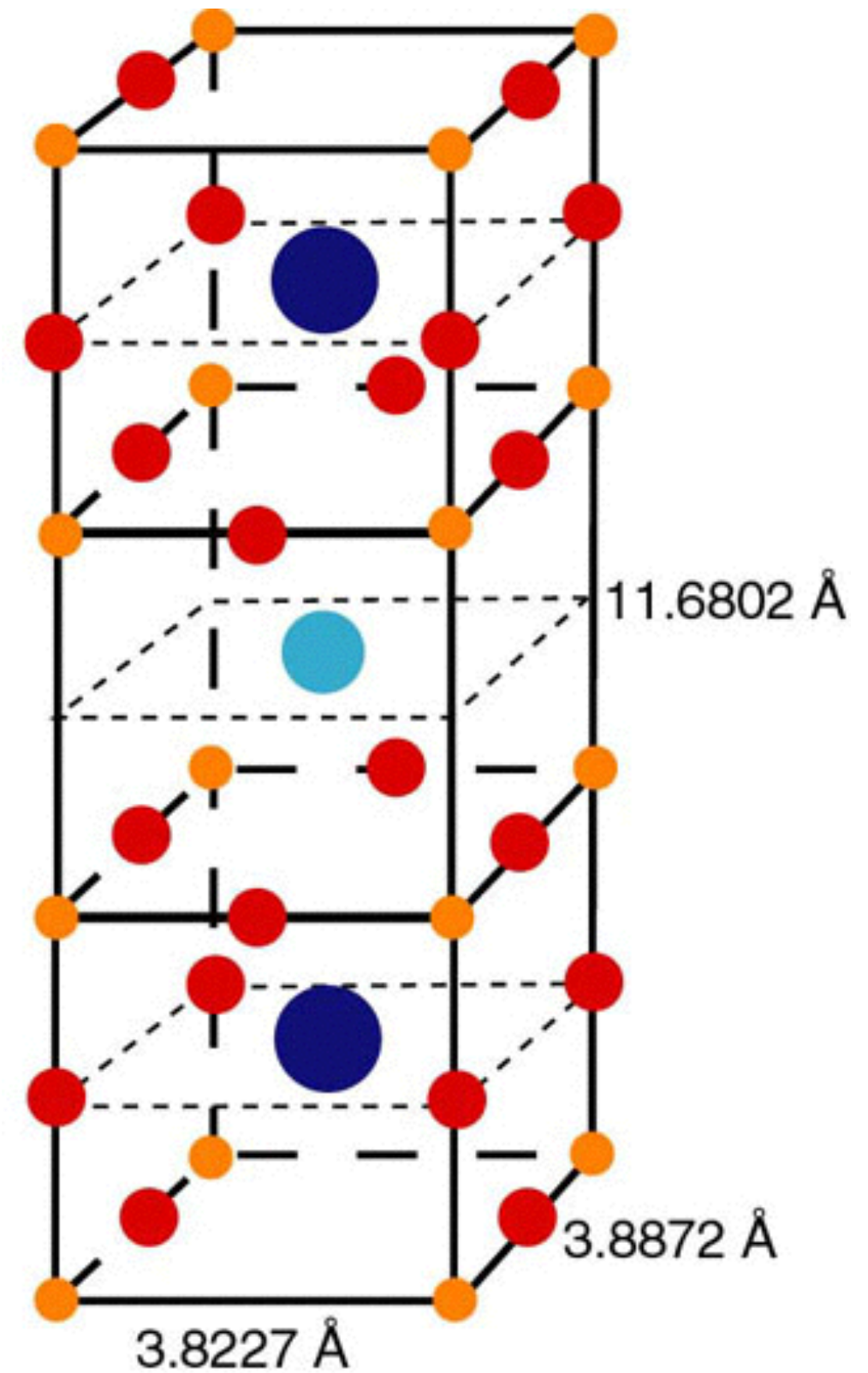
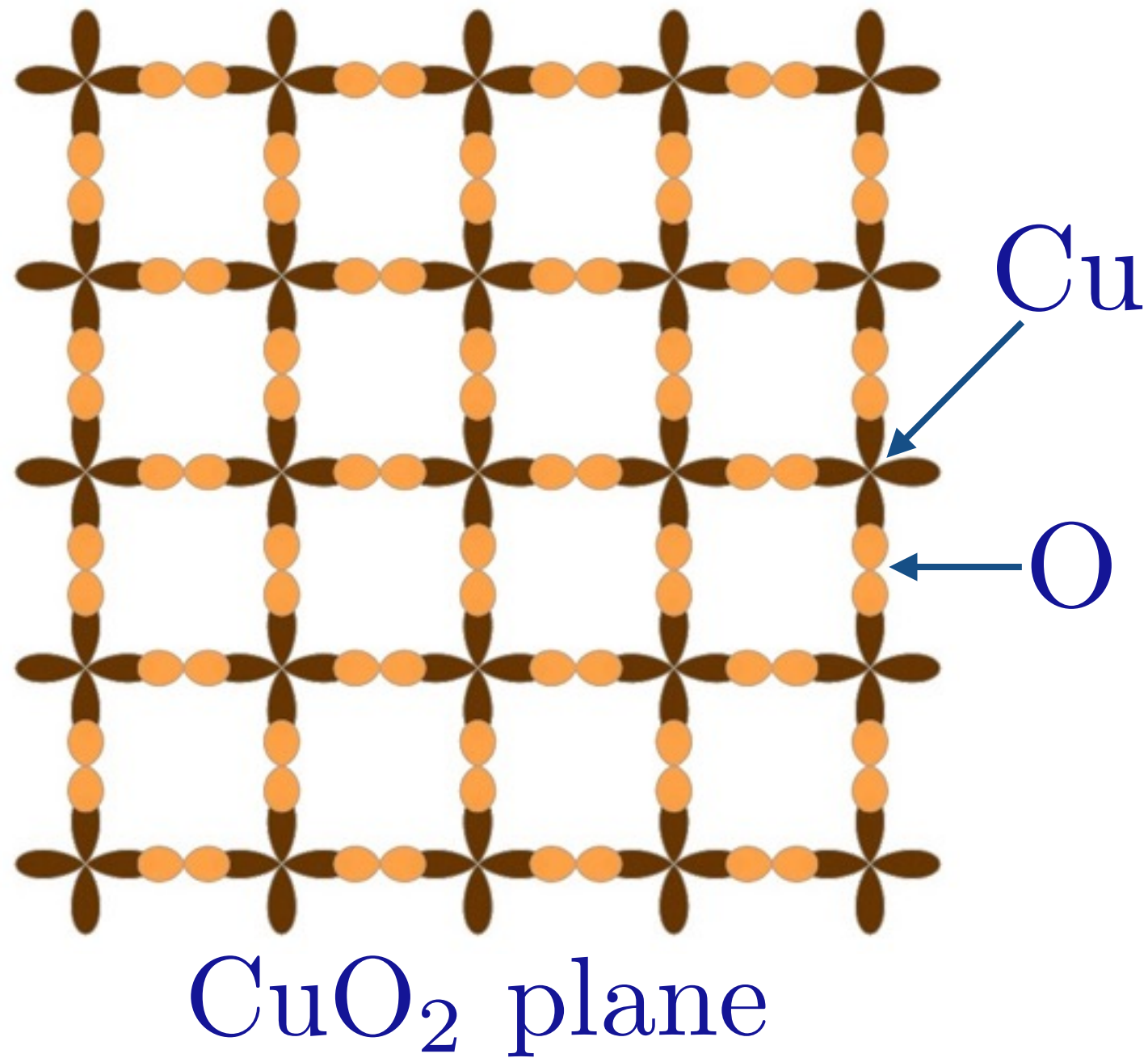


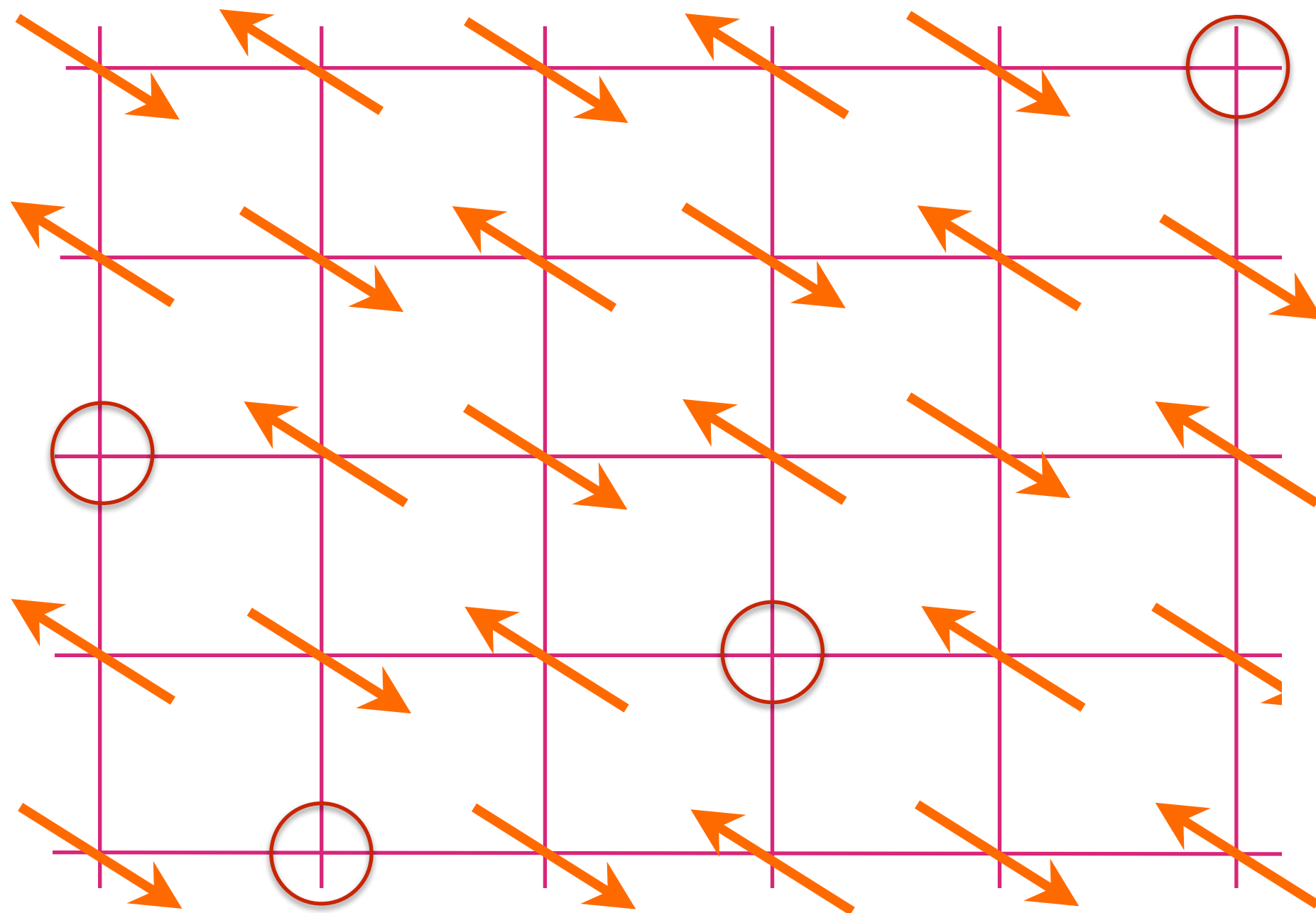
J. C. Seamus Davis



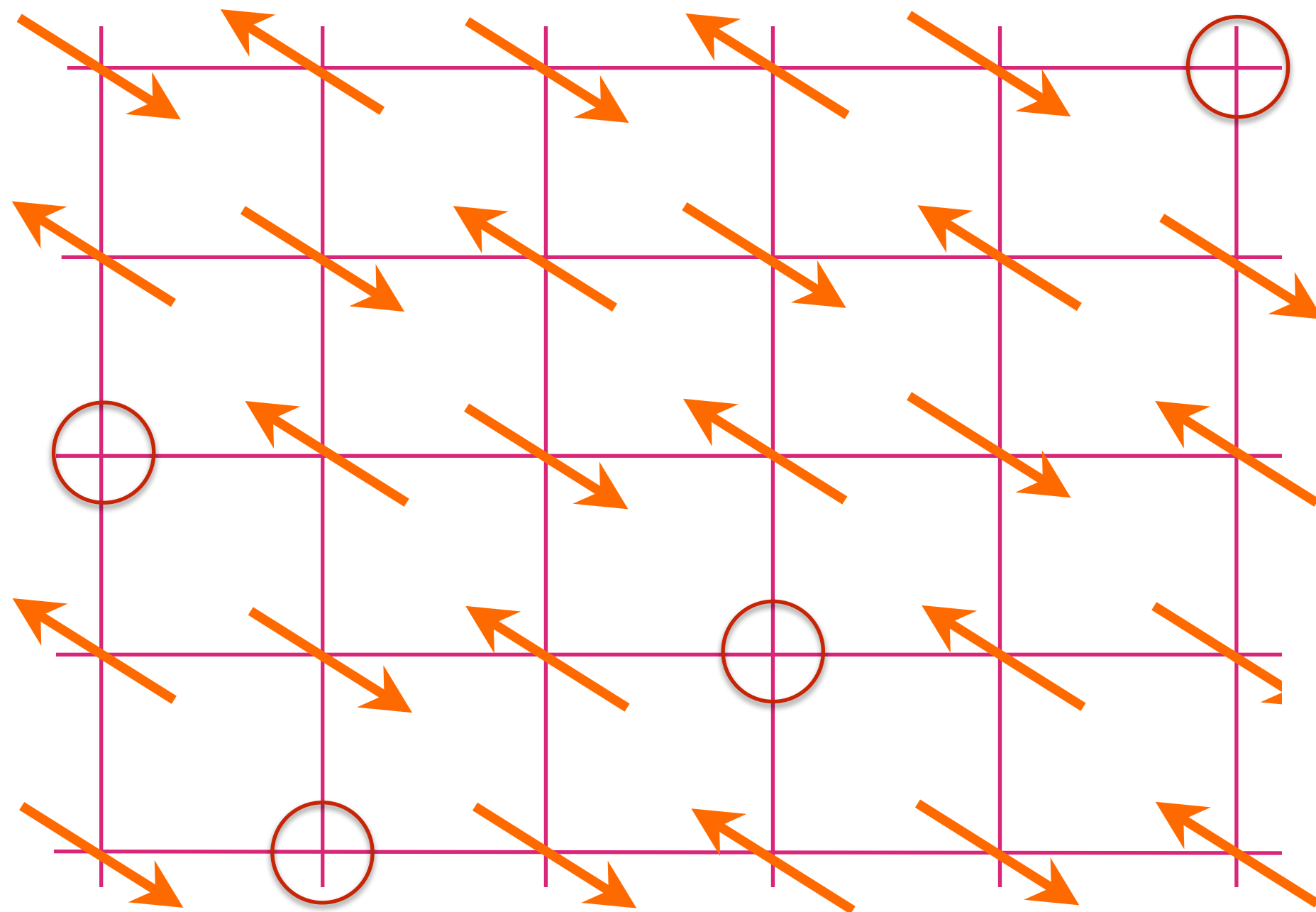
Eun-Ah Kim

High temperature superconductors



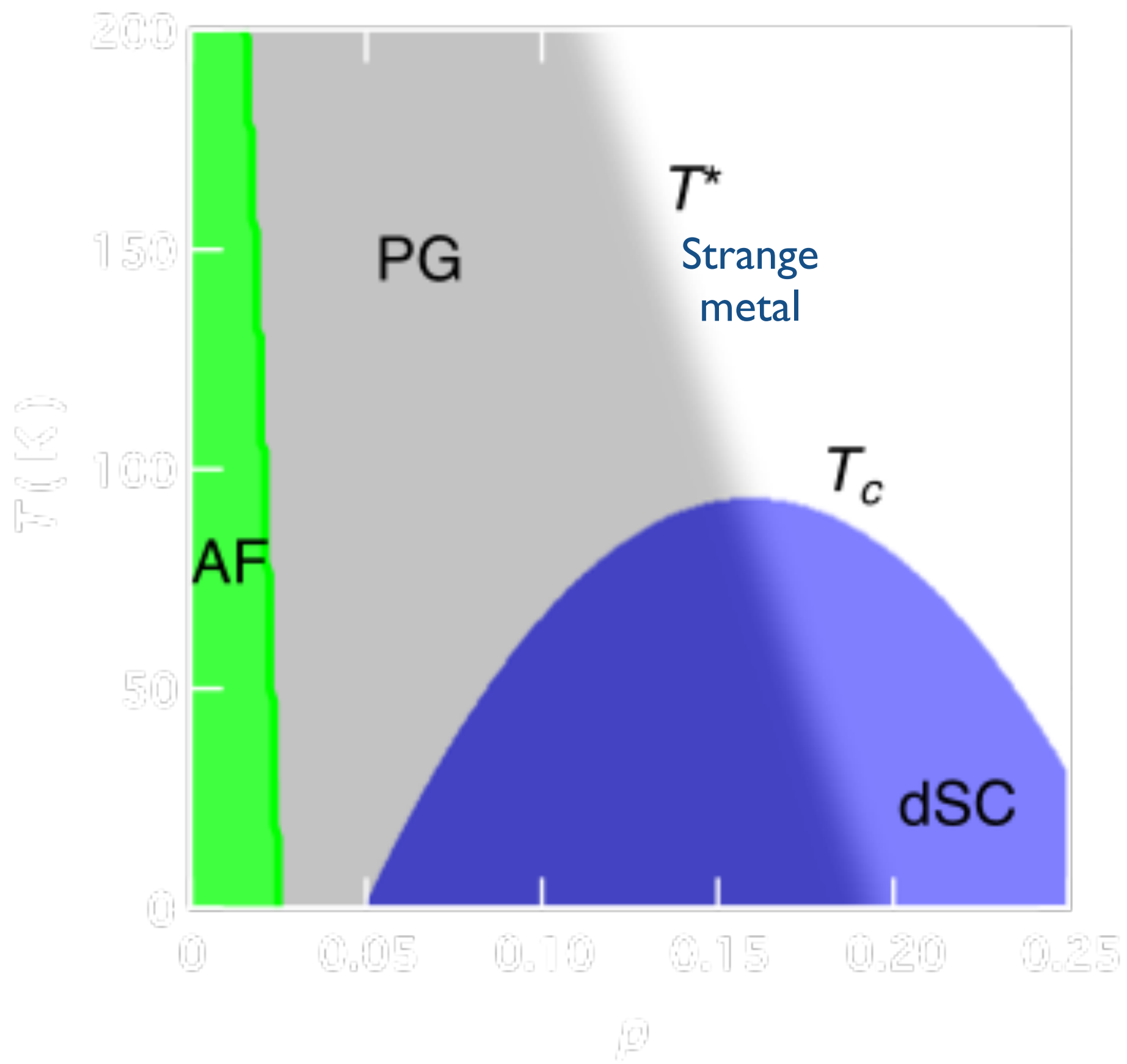


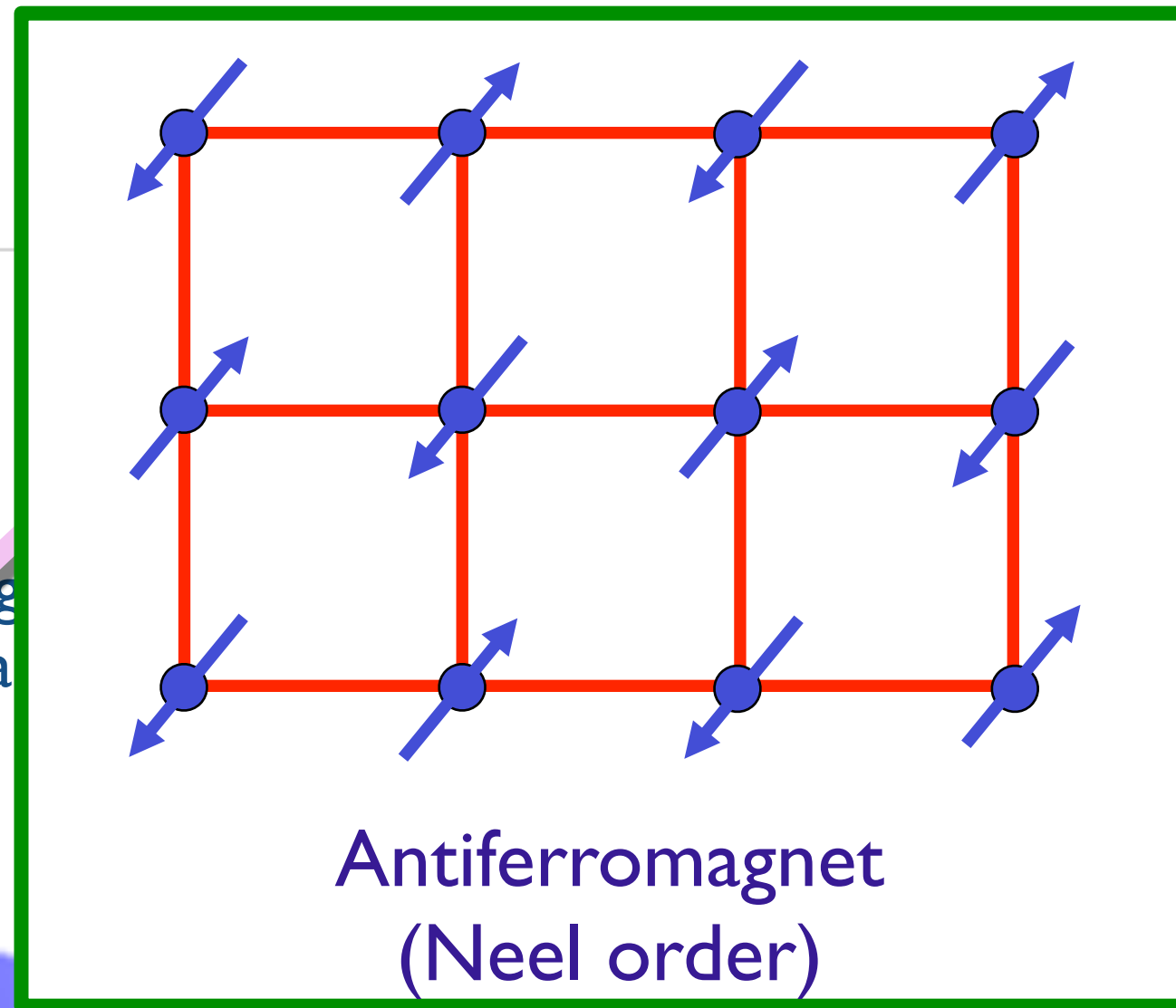
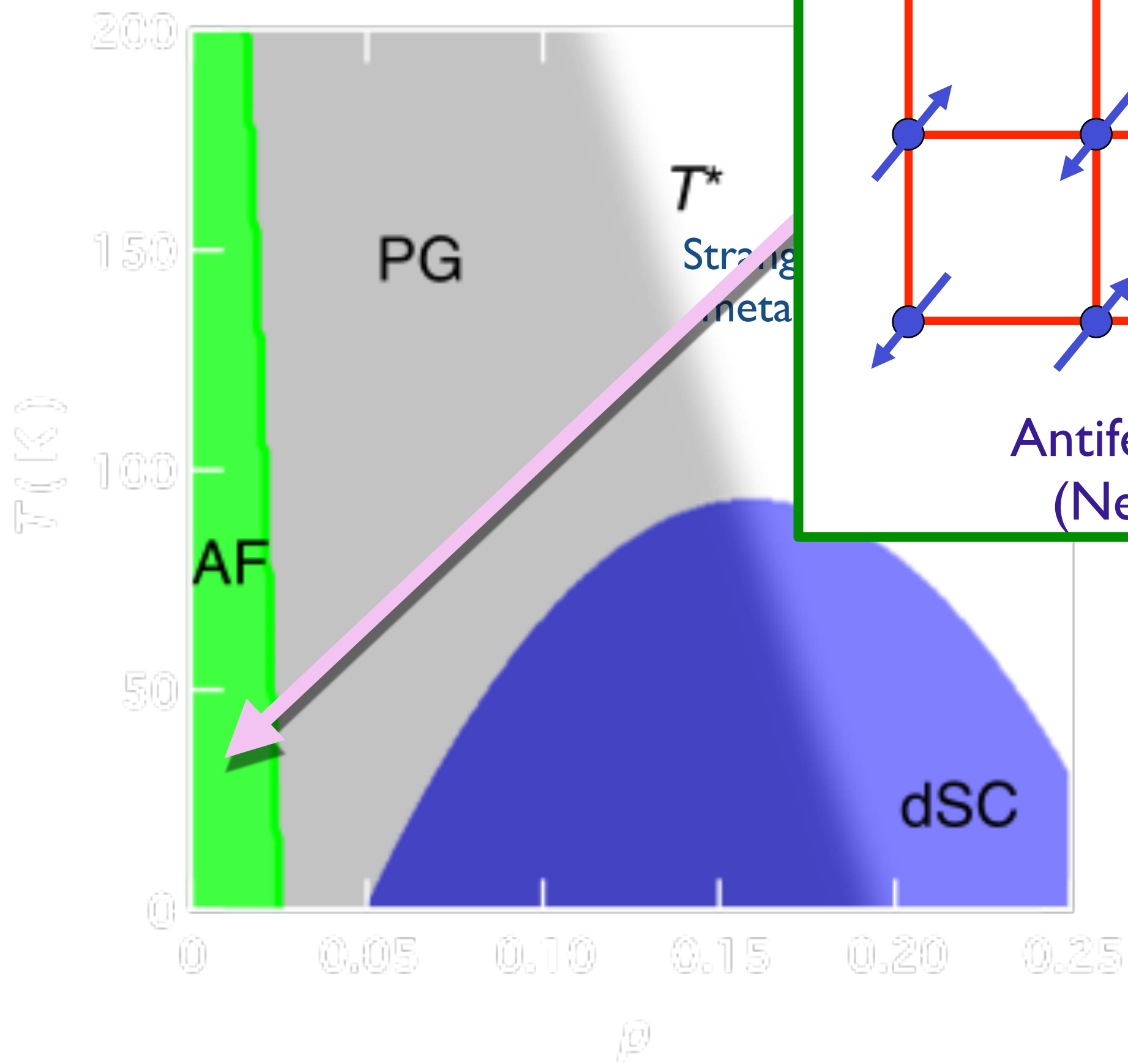
Anti-
ferromagnet
with p holes
per square

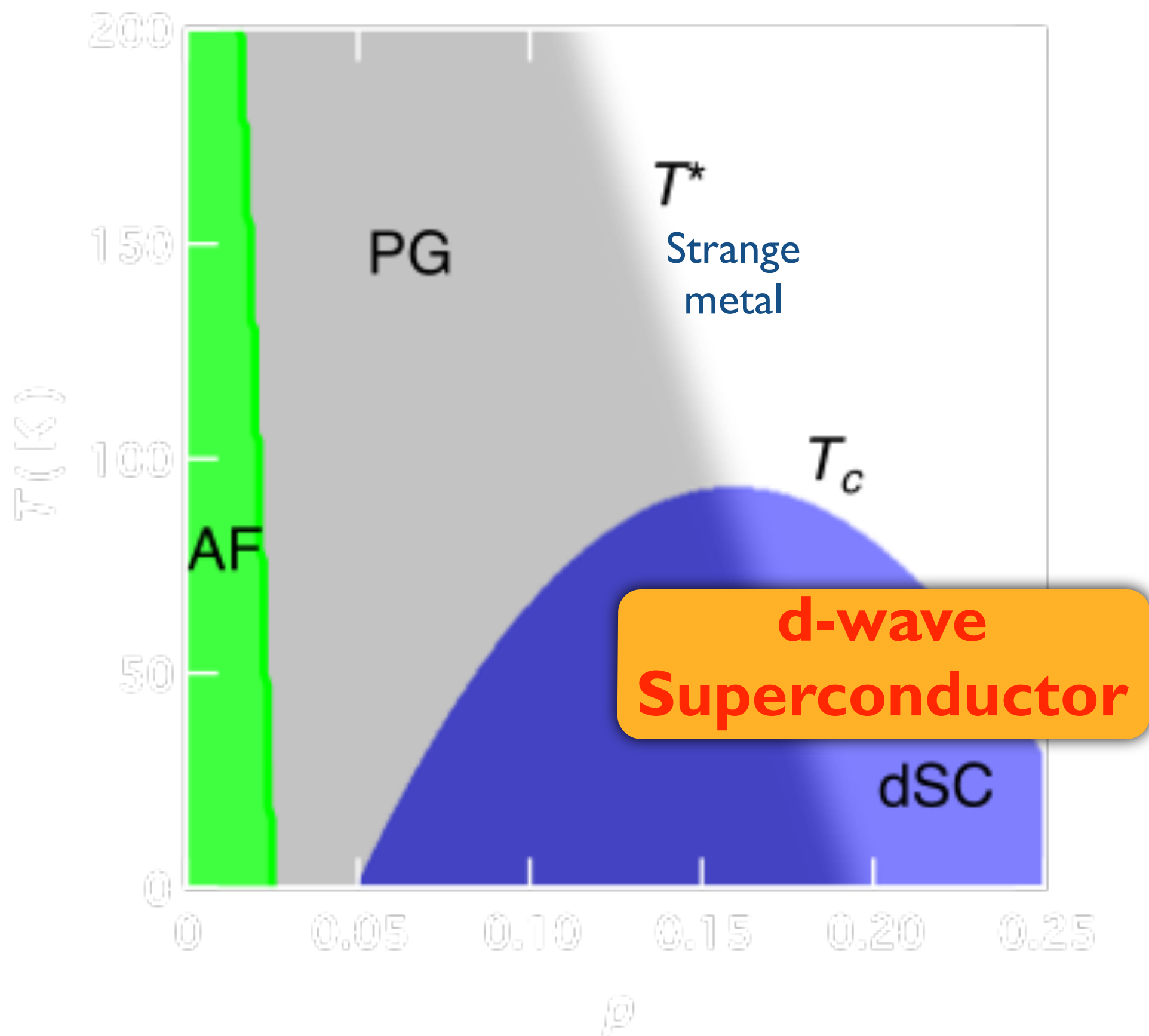


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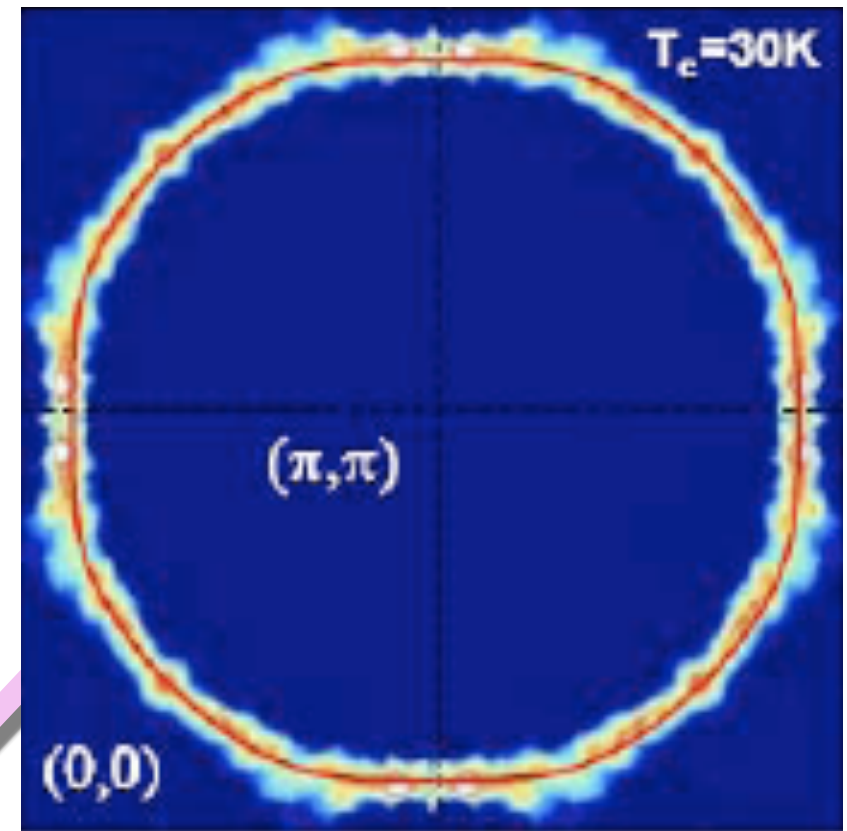
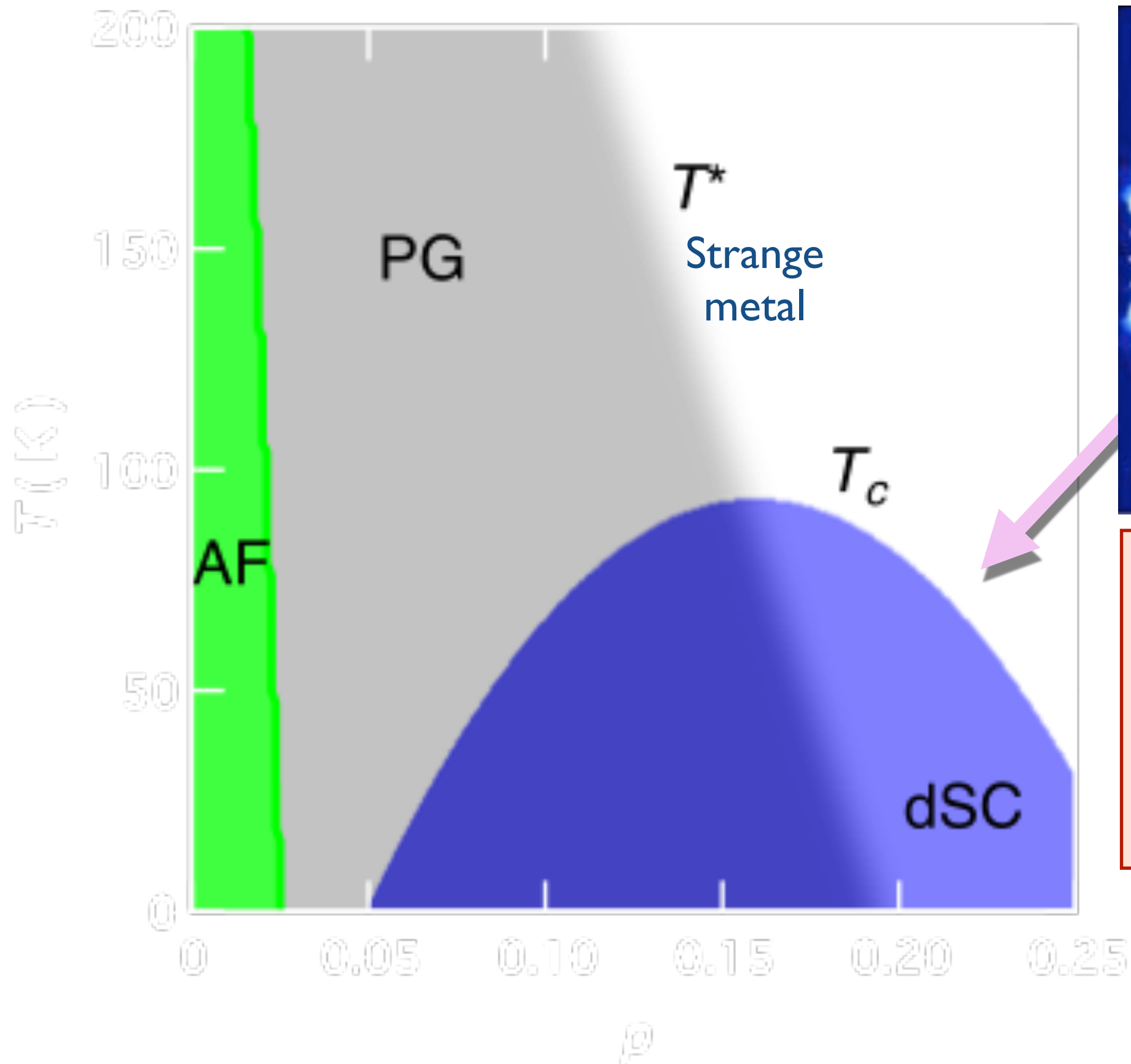
Note: relative to the fully-filled band insulator,
there are $1+p$ holes per square





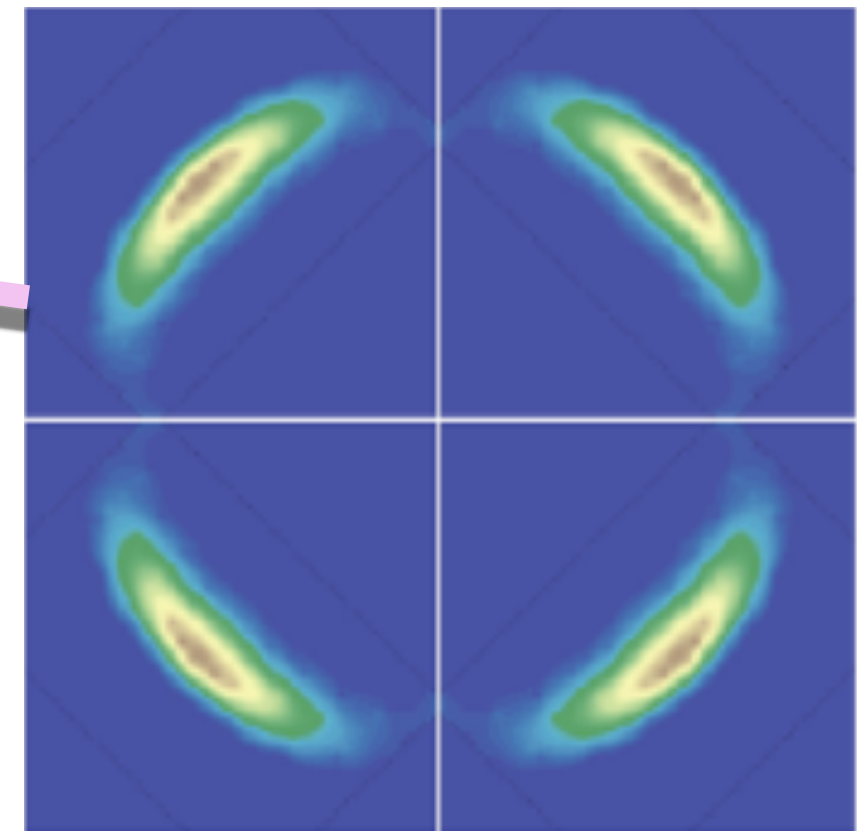
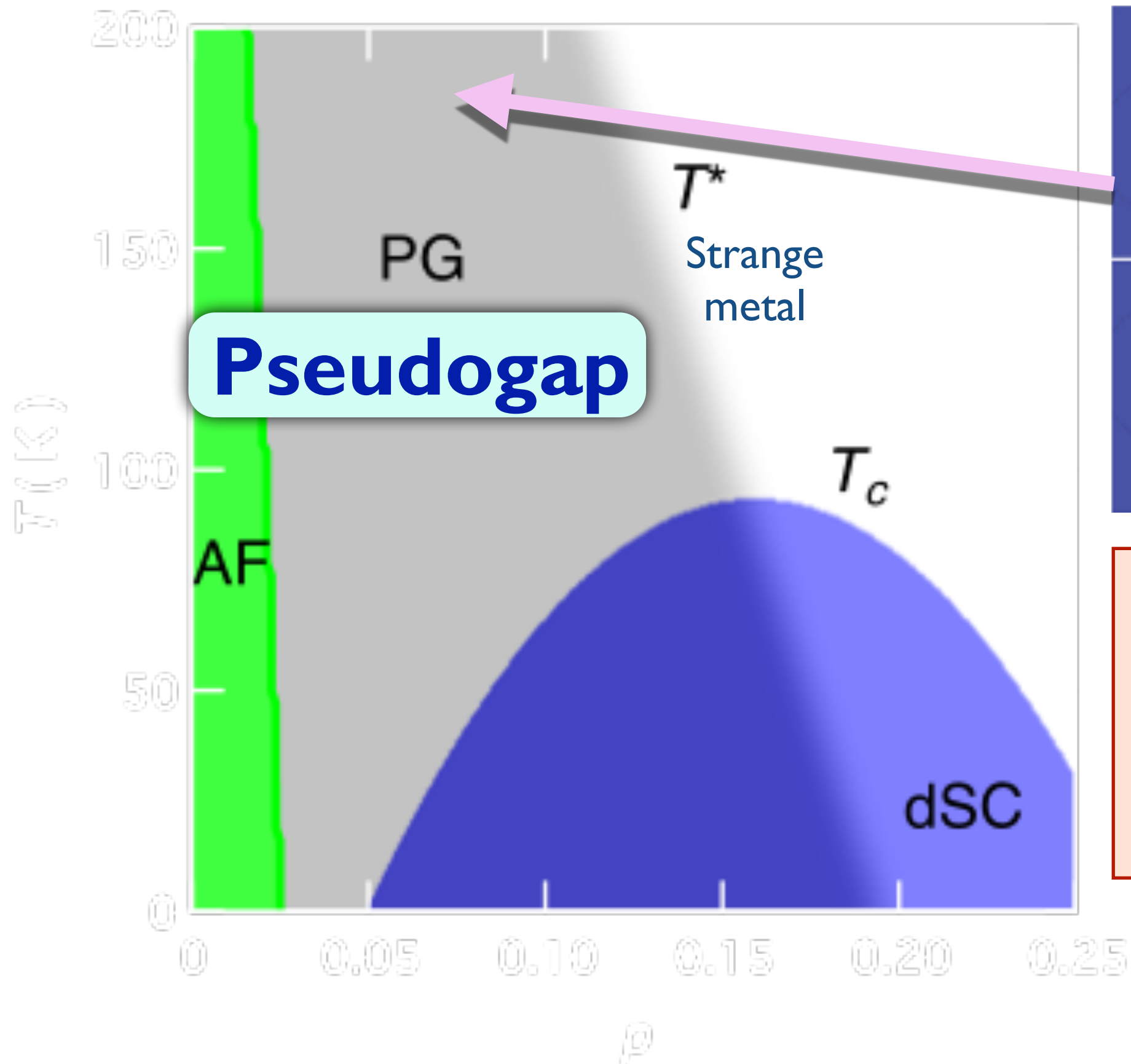


M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)

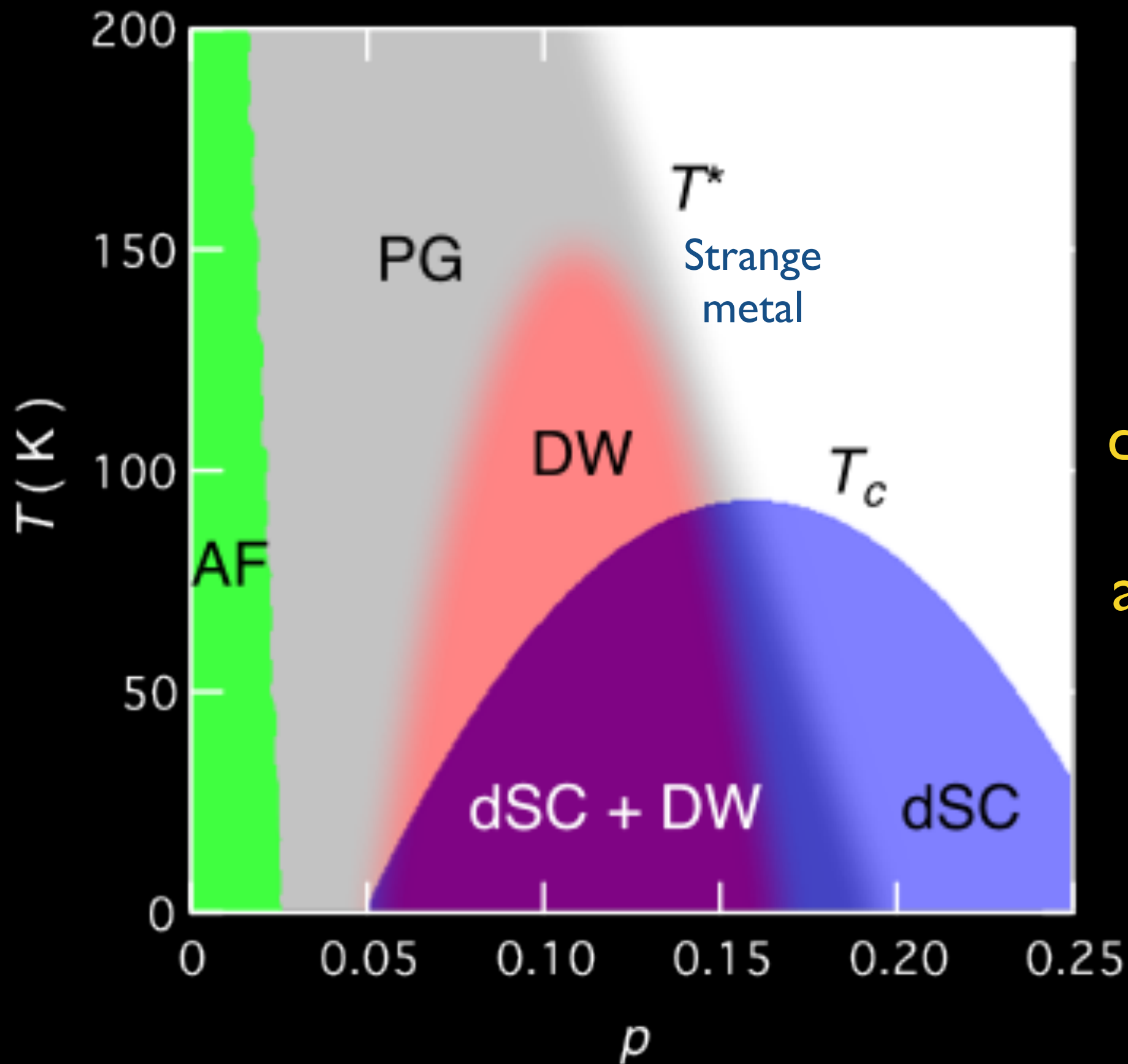


Fermi liquid:
Area enclosed
by Fermi surface
 $= | + p$

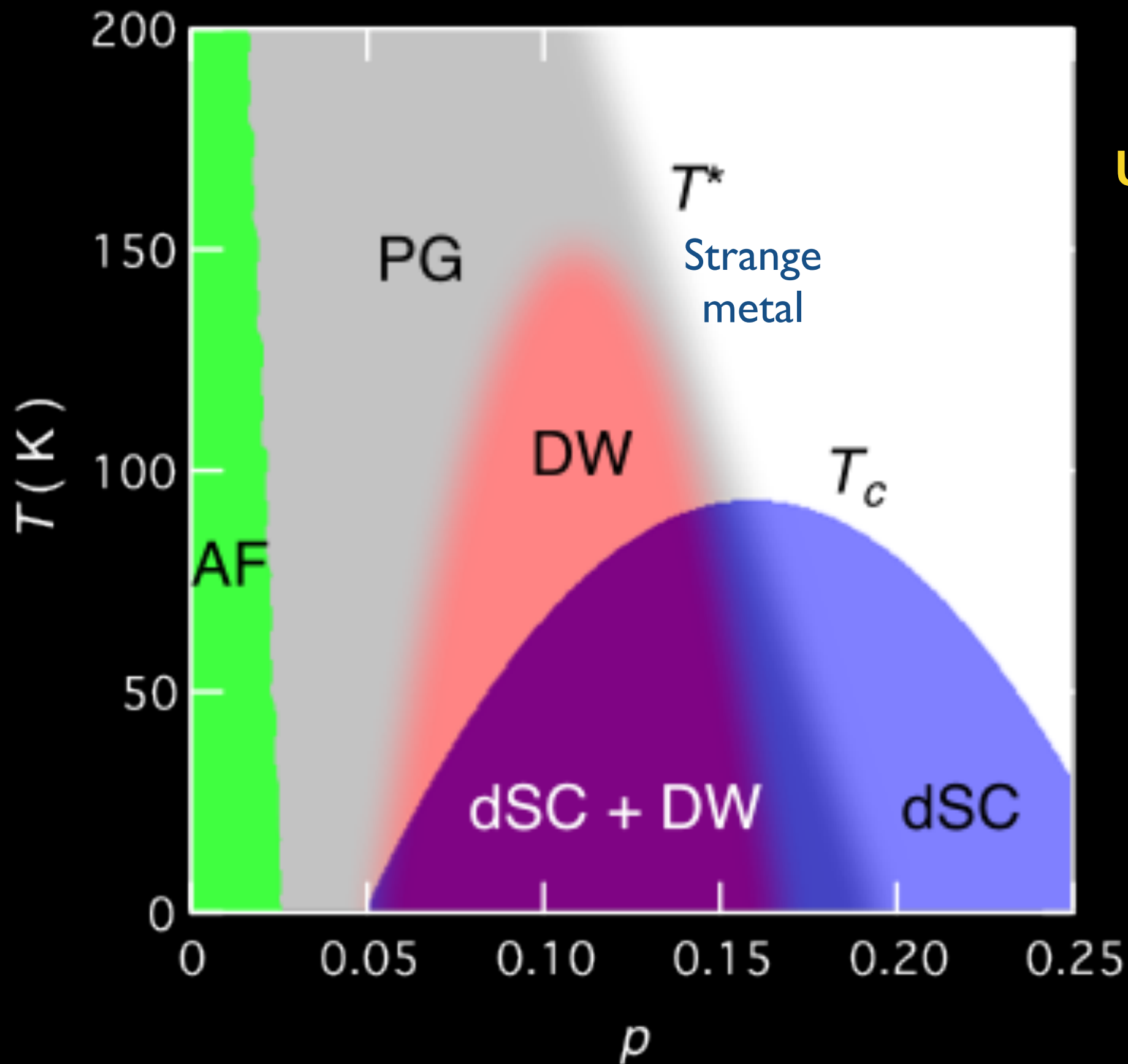
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)



“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
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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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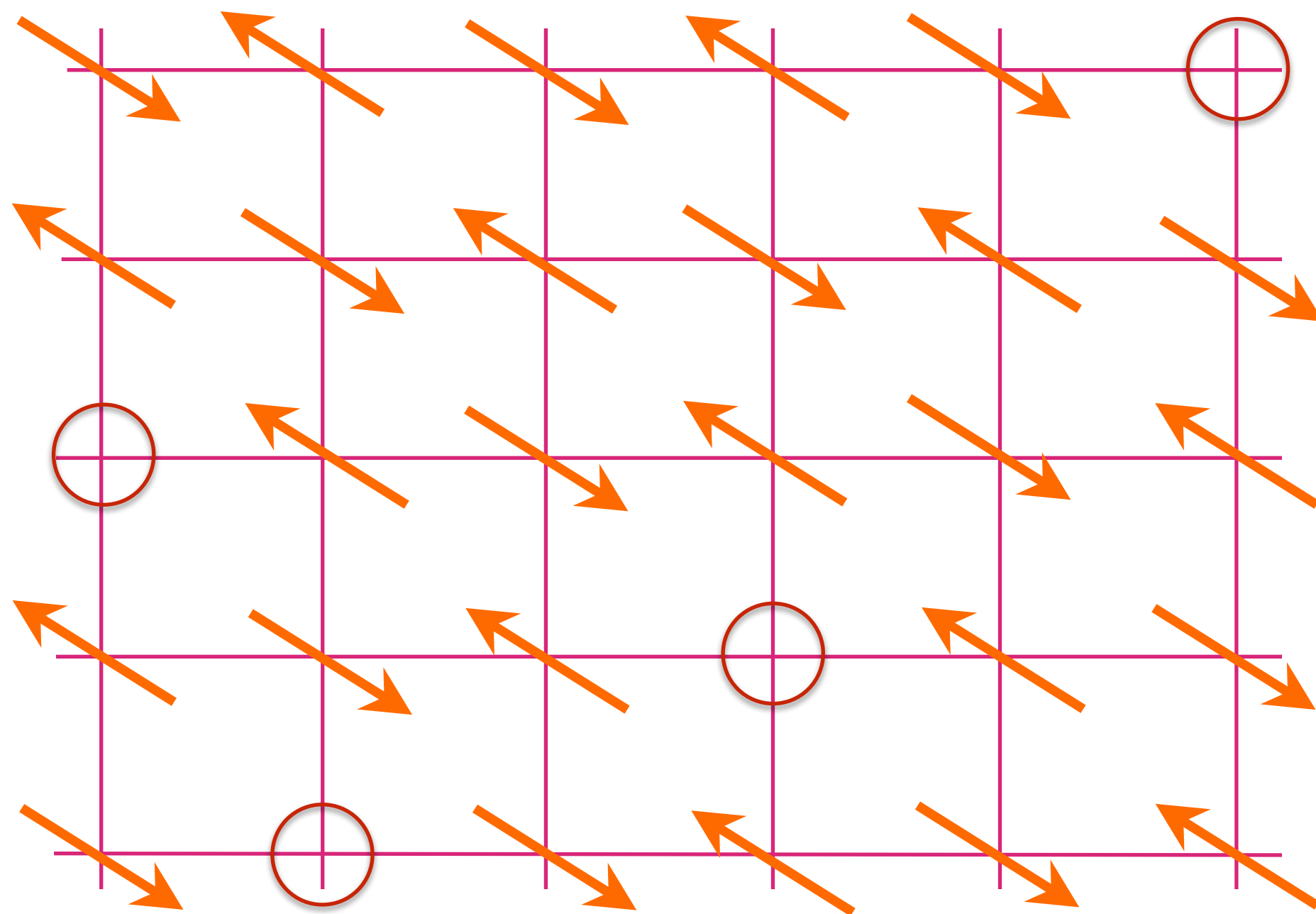
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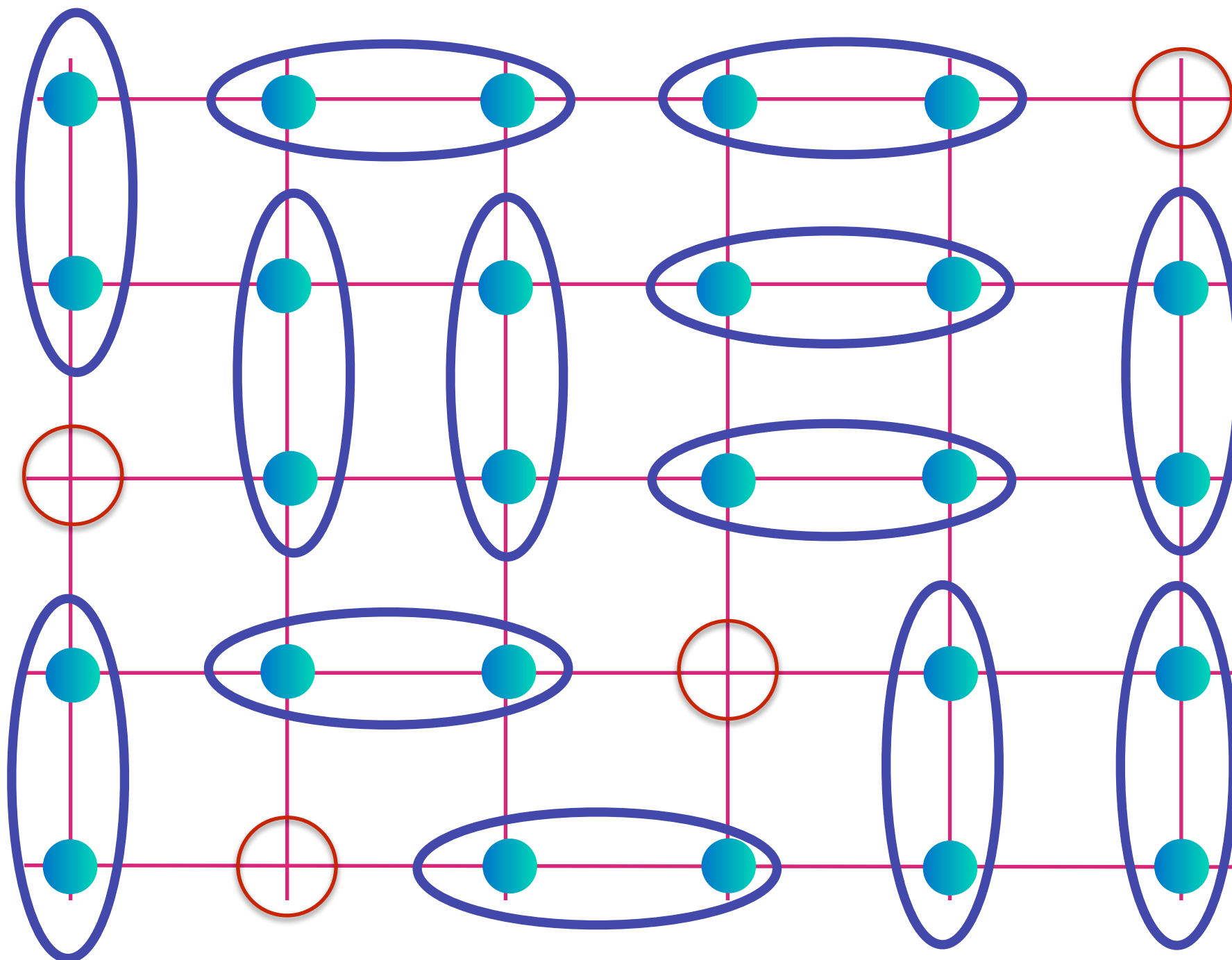
4. Quantum critical point near optimal p :

A Higgs critical point



Anti-
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with p holes
per square

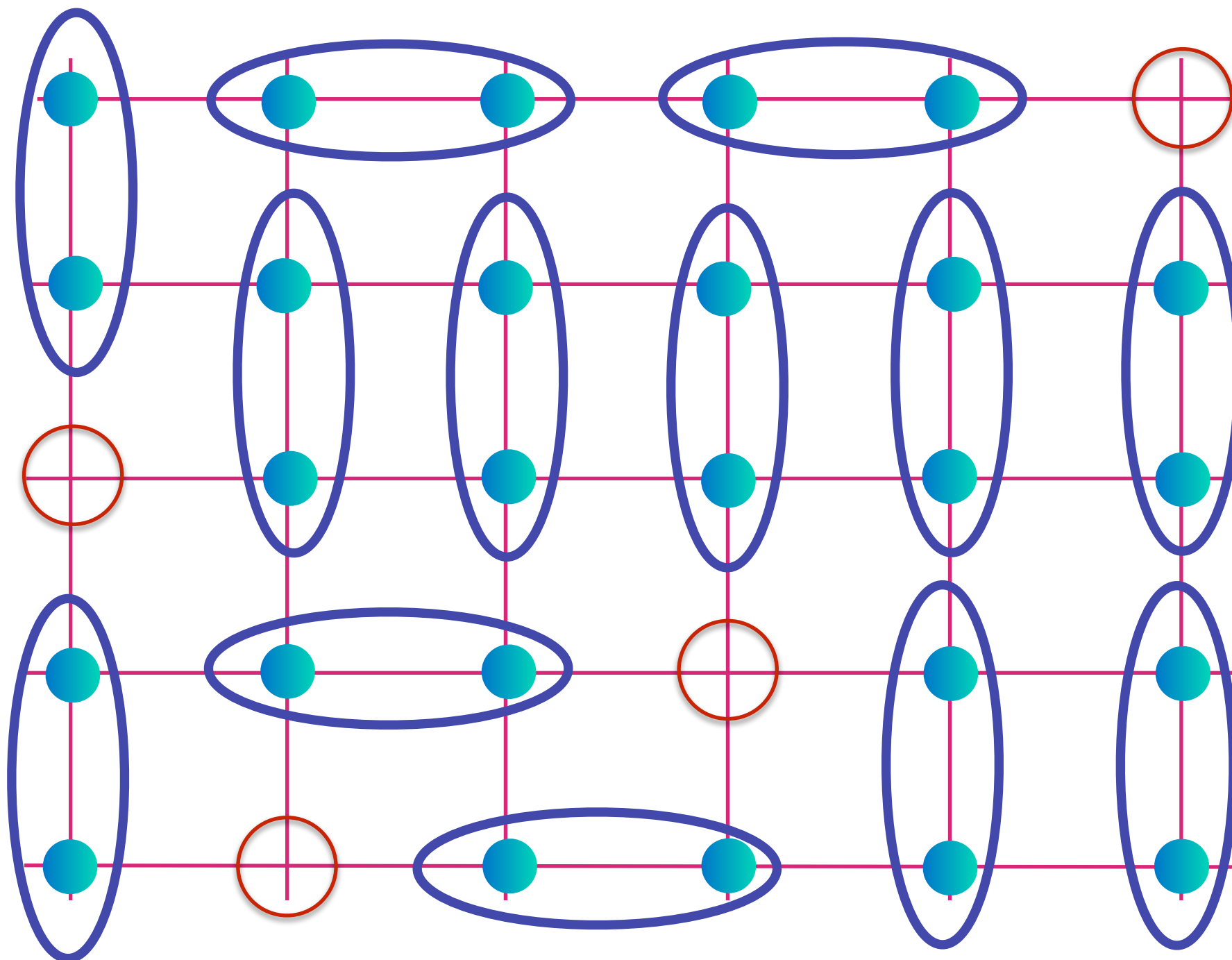
Note: relative to the fully-filled band insulator,
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Spin liquid
with emergent
gauge field
and
 p “holons”
(gauge-charged,
spinless,
charge $+e$
quasiparticles)
per square

$$\text{[Pair of sites in a blue oval]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

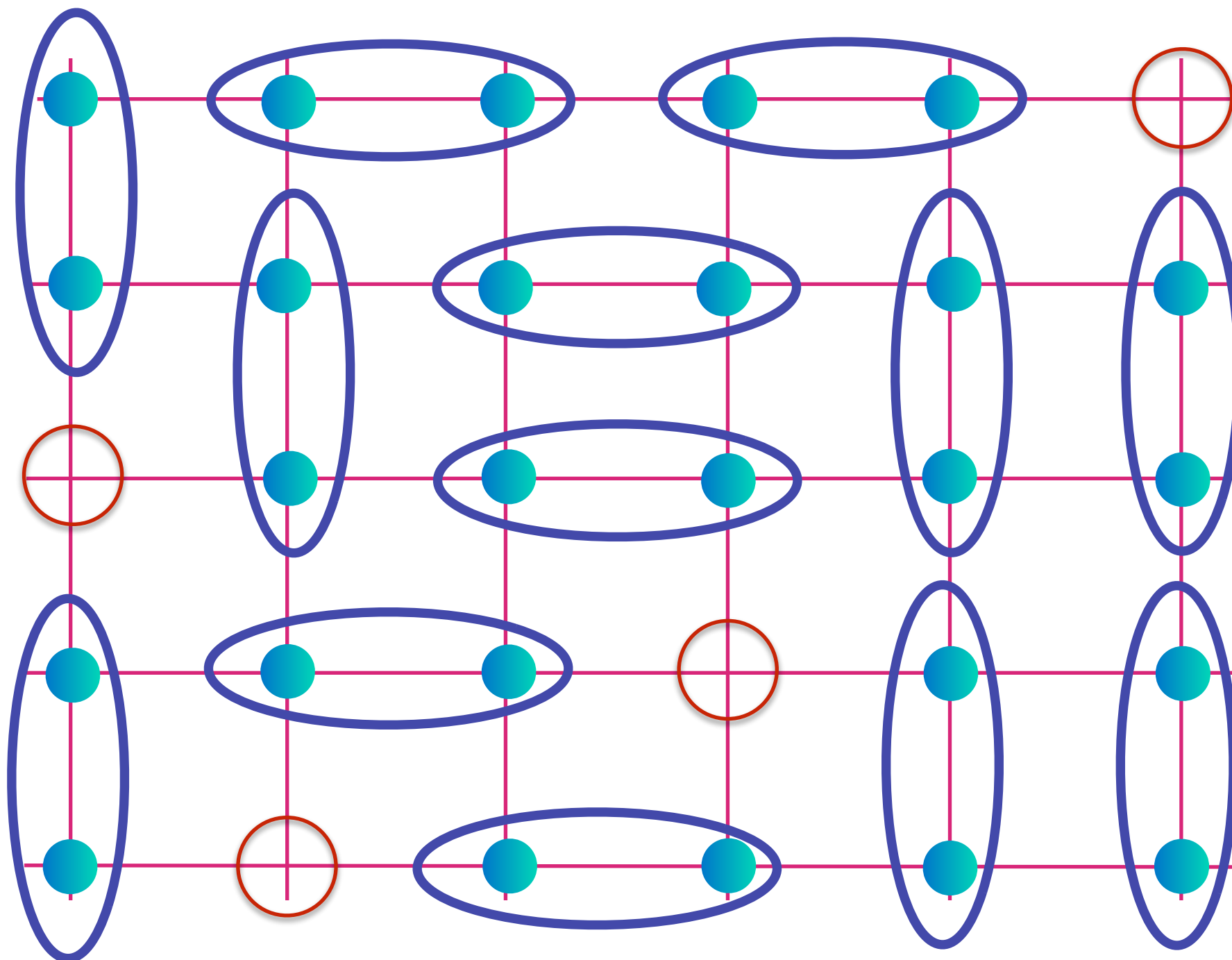
Baskaran, Zou, Anderson, Fradkin, Kivelson...



Spin liquid
with emergent
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per square

$$\text{[Blue oval with two cyan dots]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

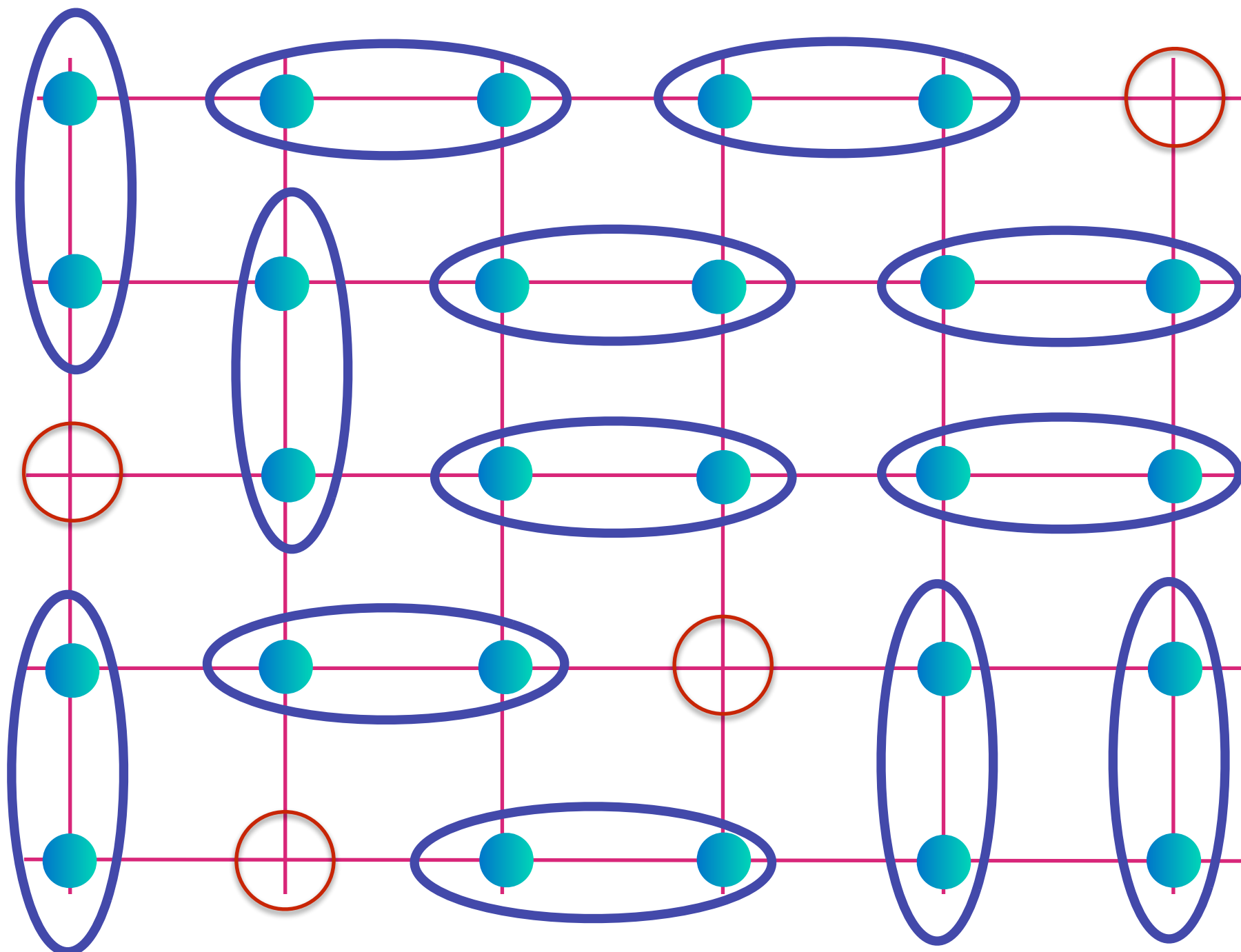
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$$\text{[Blue oval with two teal dots]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

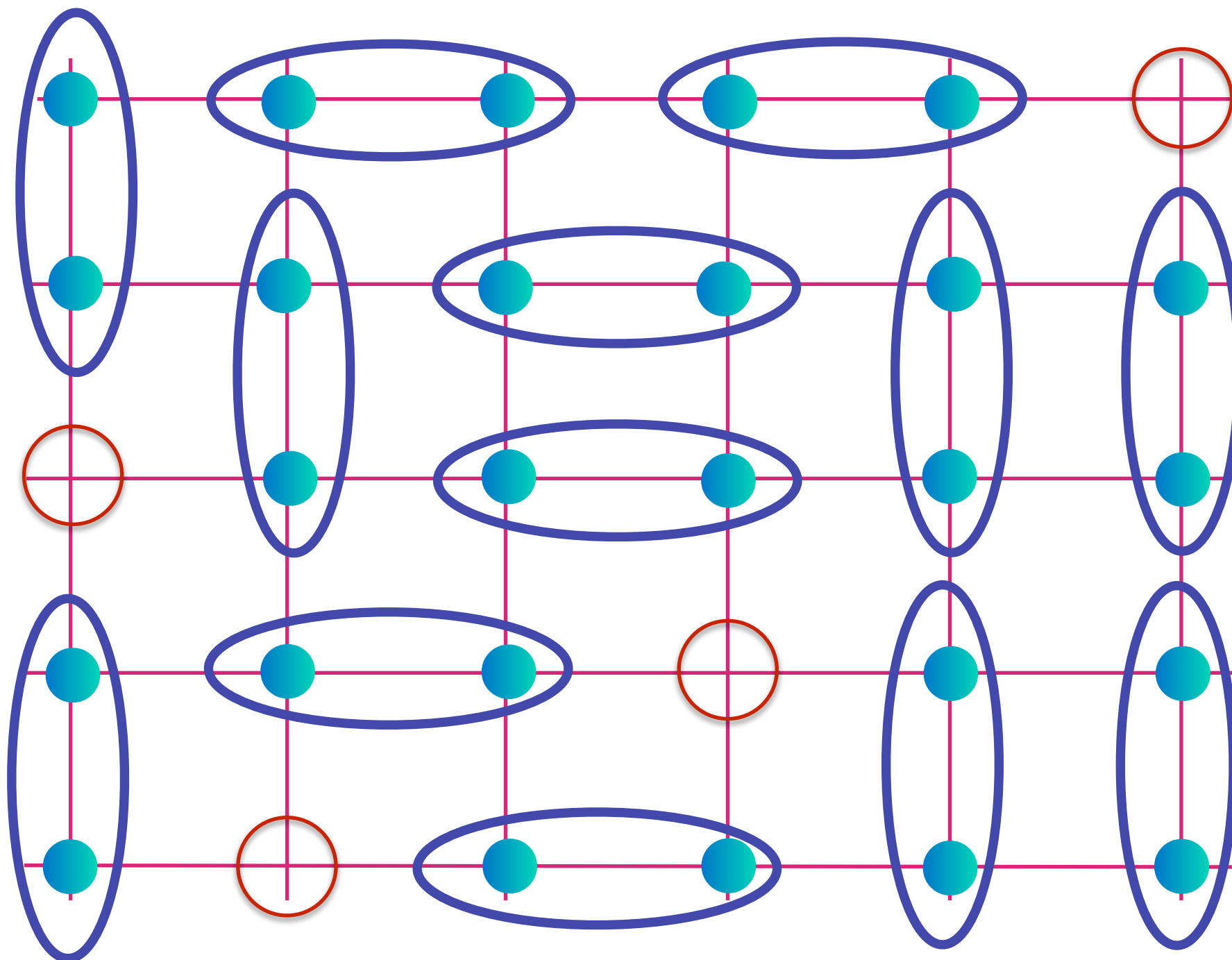
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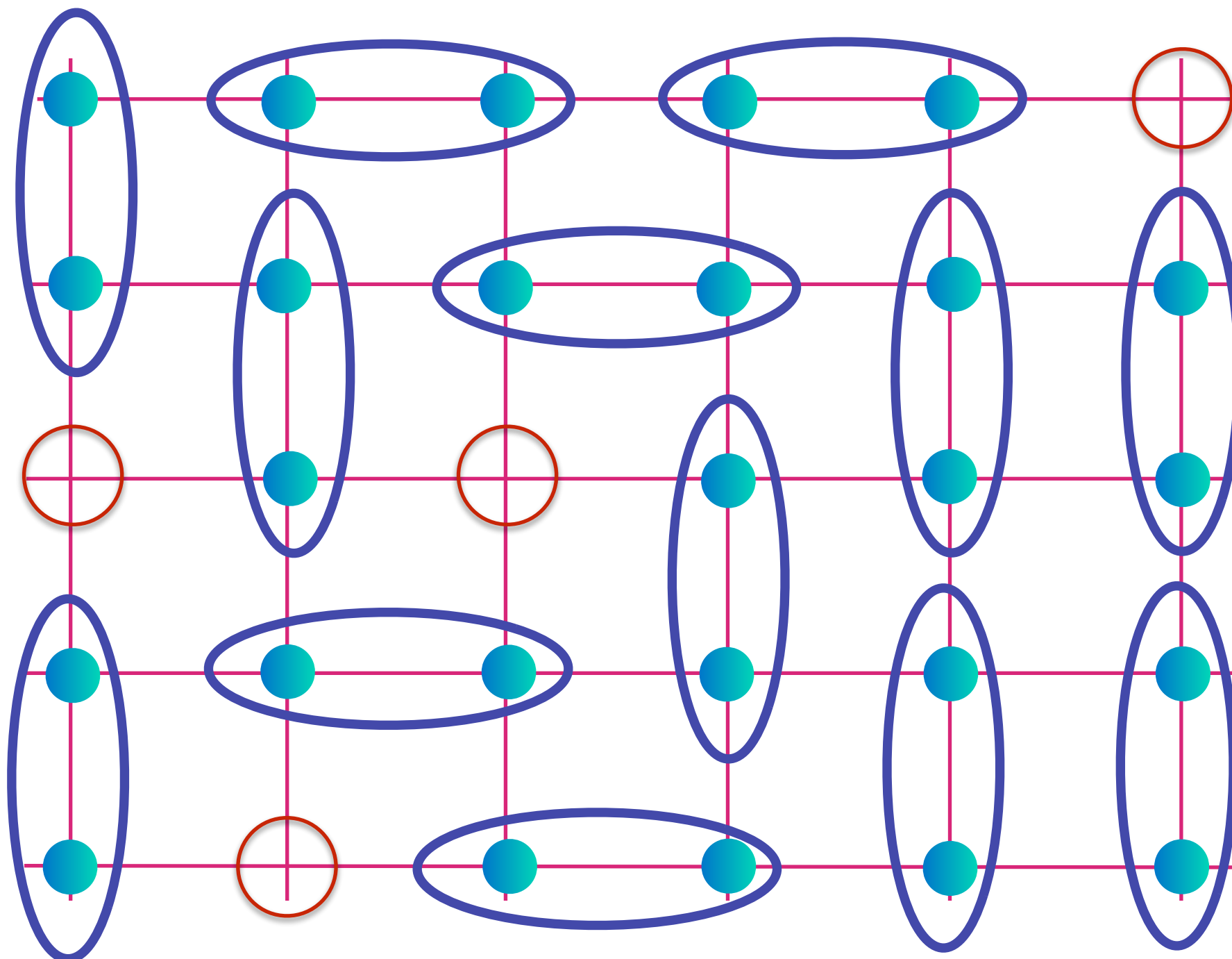
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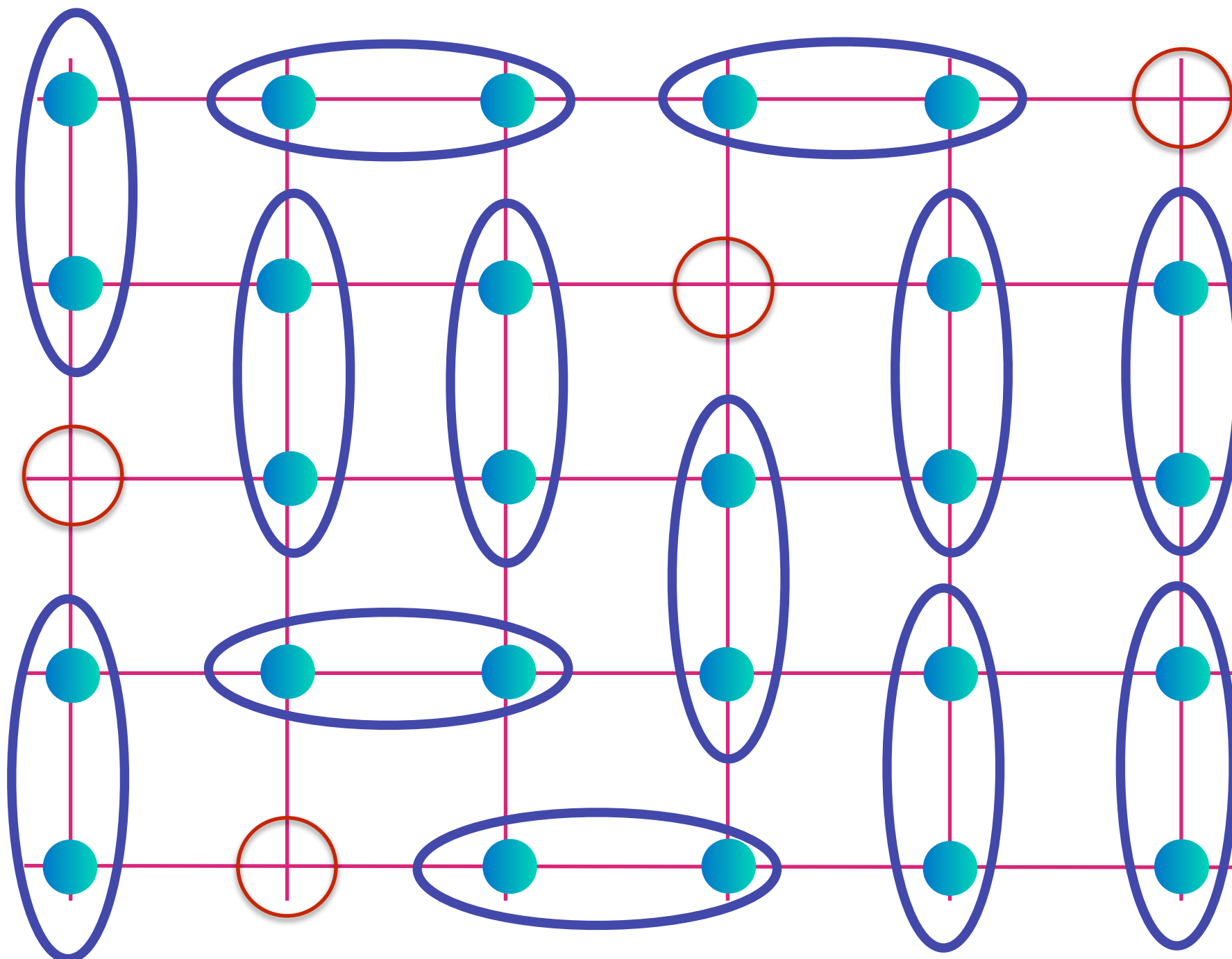
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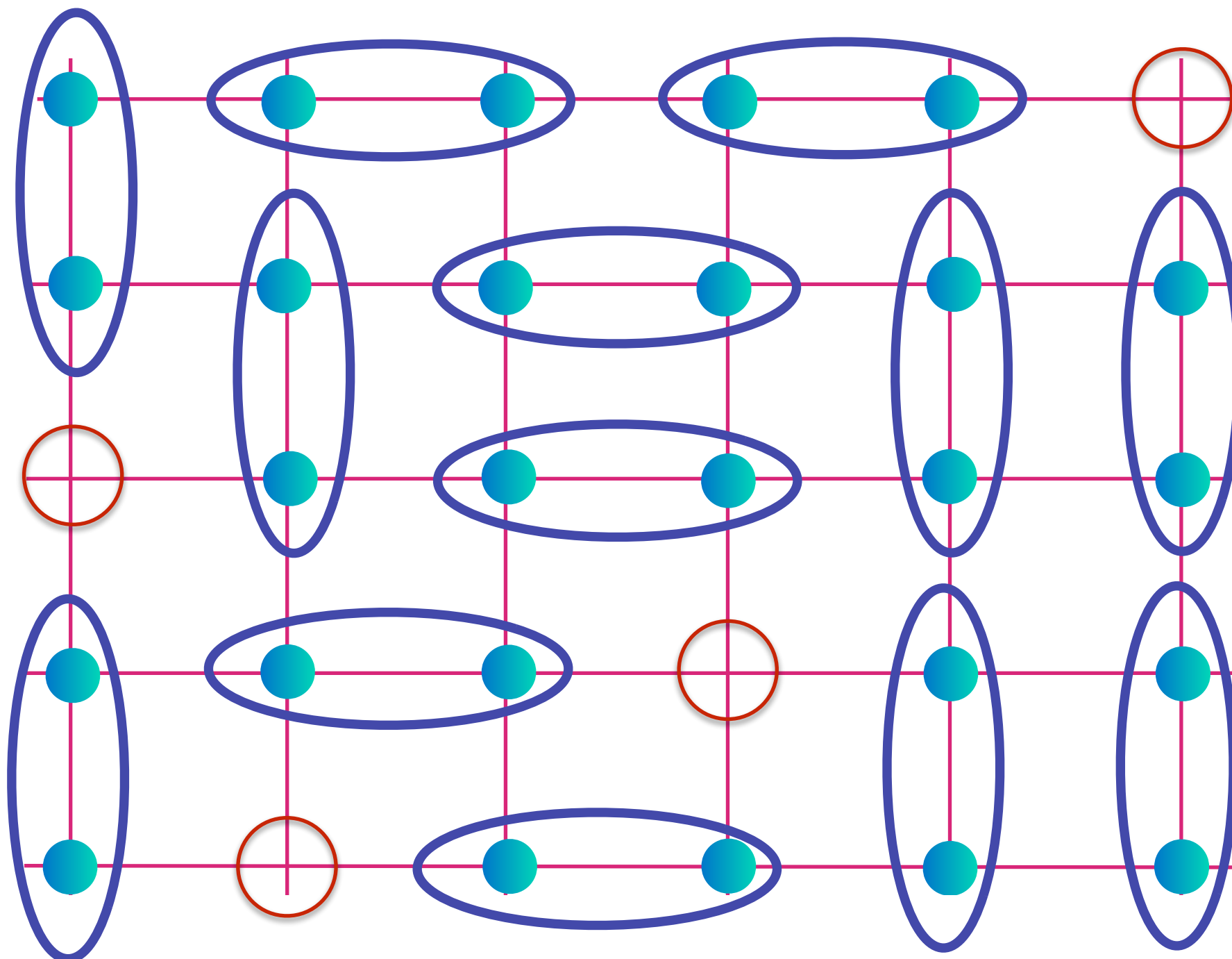
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Baskaran, Zou, Anderson, Fradkin, Kivelson...

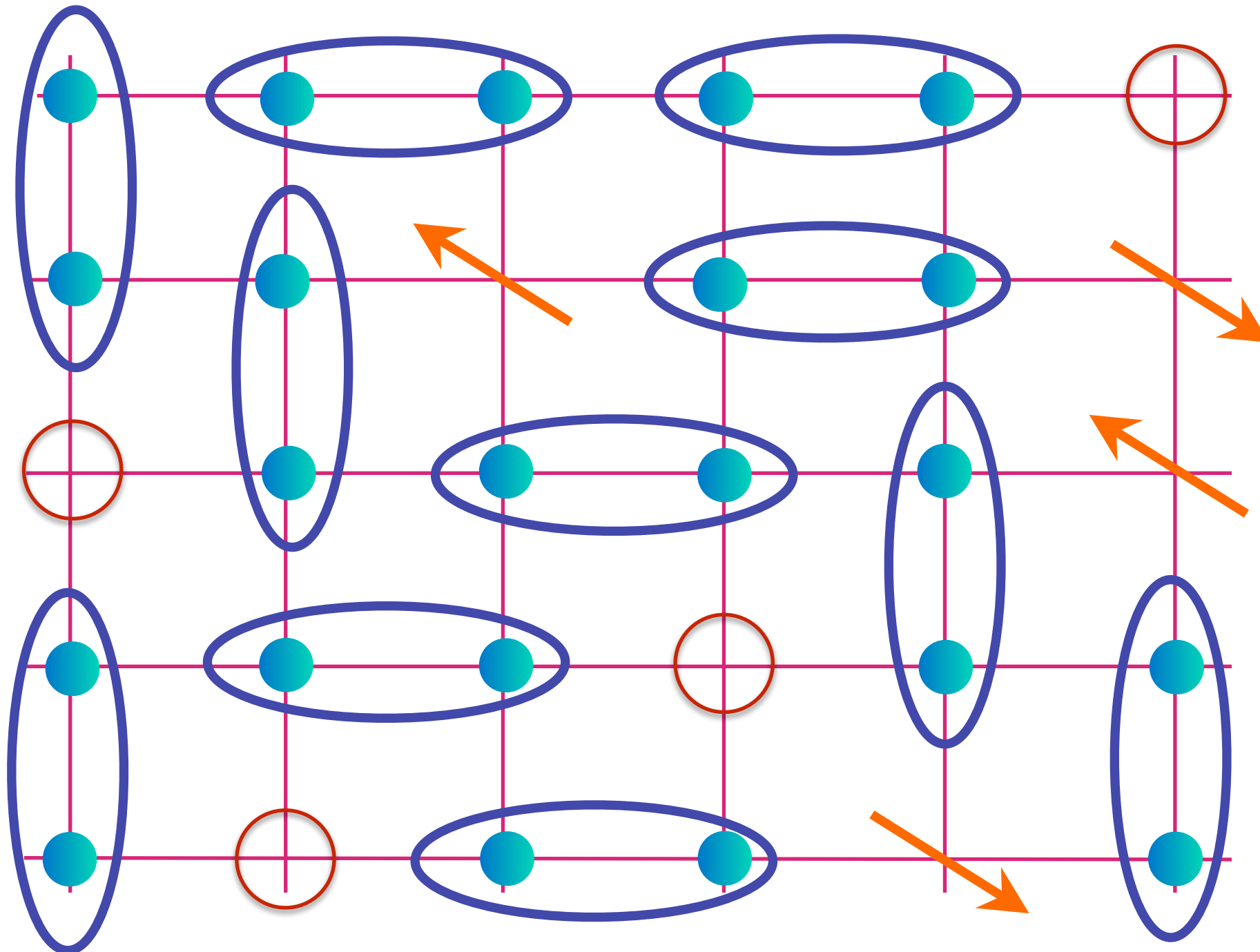


Spin liquid
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gauge field
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(gauge-charged,
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quasiparticles)
per square

$$\text{blue oval with two dots} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Baskaran, Zou, Anderson, Fradkin, Kivelson...

Gauge-charged, spin $S=1/2$, neutral “spinon” excitations

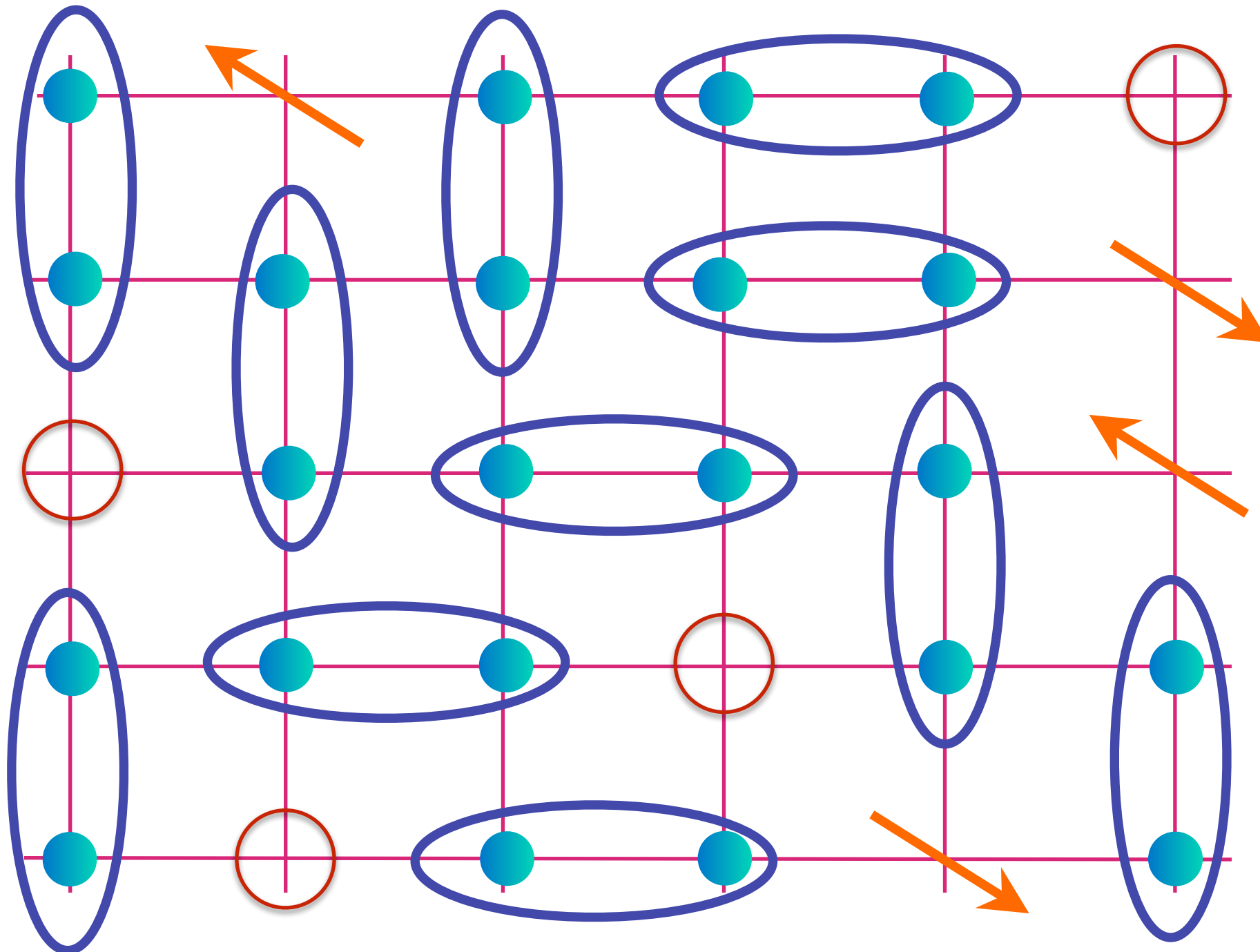


Spin liquid
with emergent
gauge field
and
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spinless,
charge $+e$
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per square

$$\text{[Blue oval with two cyan dots]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Baskaran, Zou, Anderson, Fradkin, Kivelson...

Gauge-charged, spin $S=1/2$, neutral “spinon” excitations

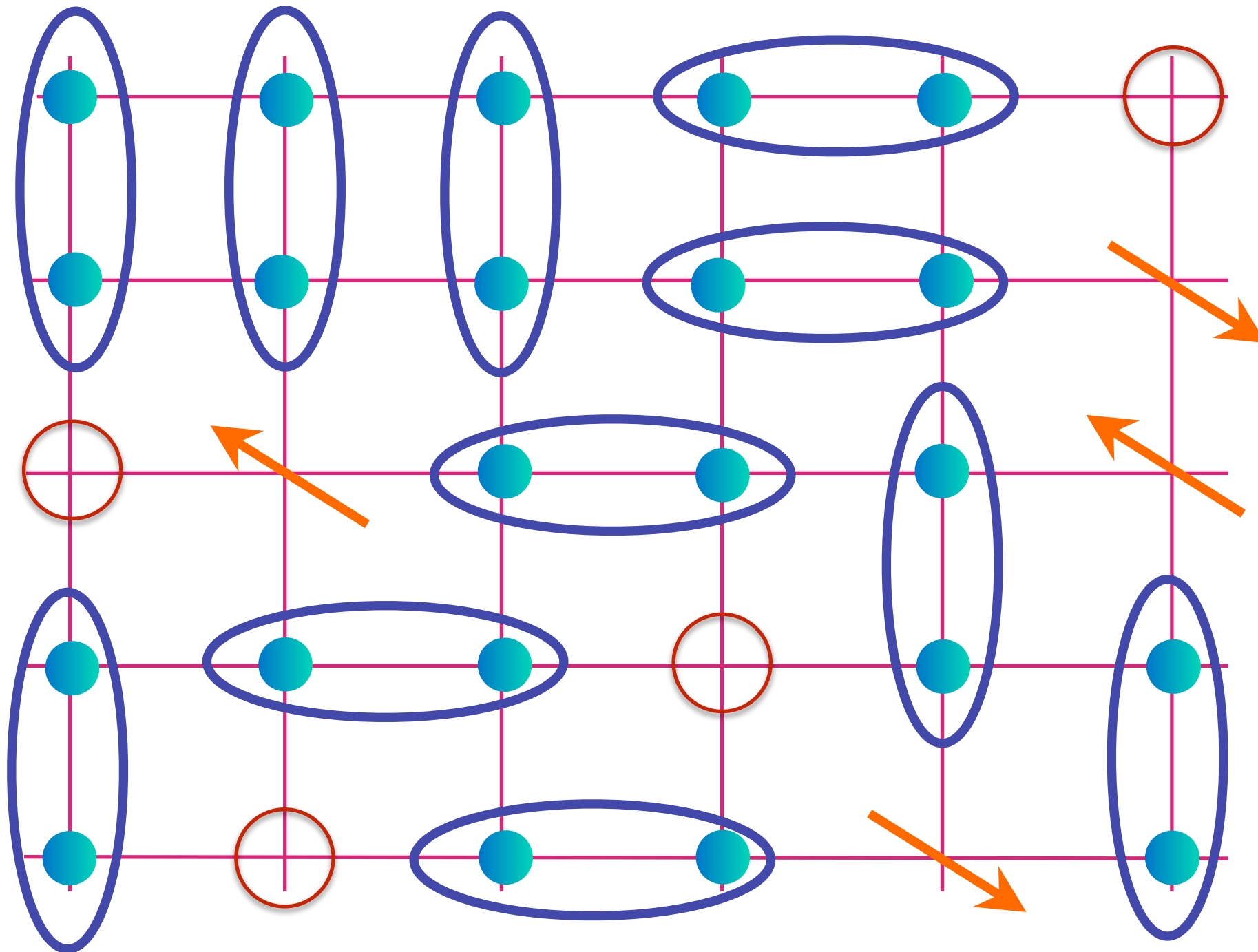


Spin liquid
with emergent
gauge field
and
 p “holons”
(gauge-charged,
spinless,
charge $+e$
quasiparticles)
per square

$$\text{blue oval with two red dots} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Baskaran, Zou, Anderson, Fradkin, Kivelson...

Gauge-charged, spin $S=1/2$, neutral “spinon” excitations

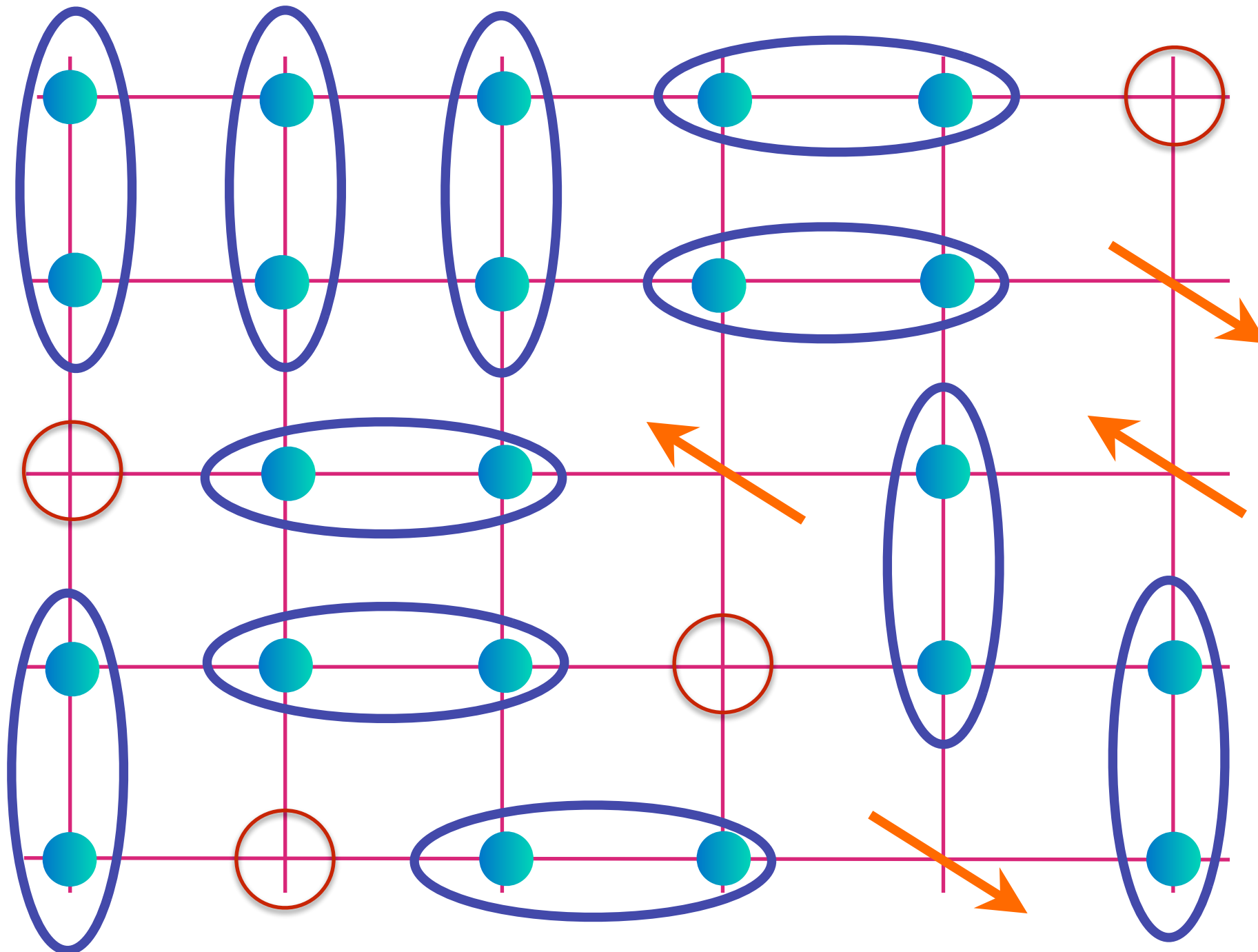


Spin liquid
with emergent
gauge field
and
 p “holons”
(gauge-charged,
spinless,
charge $+e$
quasiparticles)
per square

$$\text{[Two teal dots in a blue oval]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Baskaran, Zou, Anderson, Fradkin, Kivelson...

Gauge-charged, spin $S=1/2$, neutral “spinon” excitations

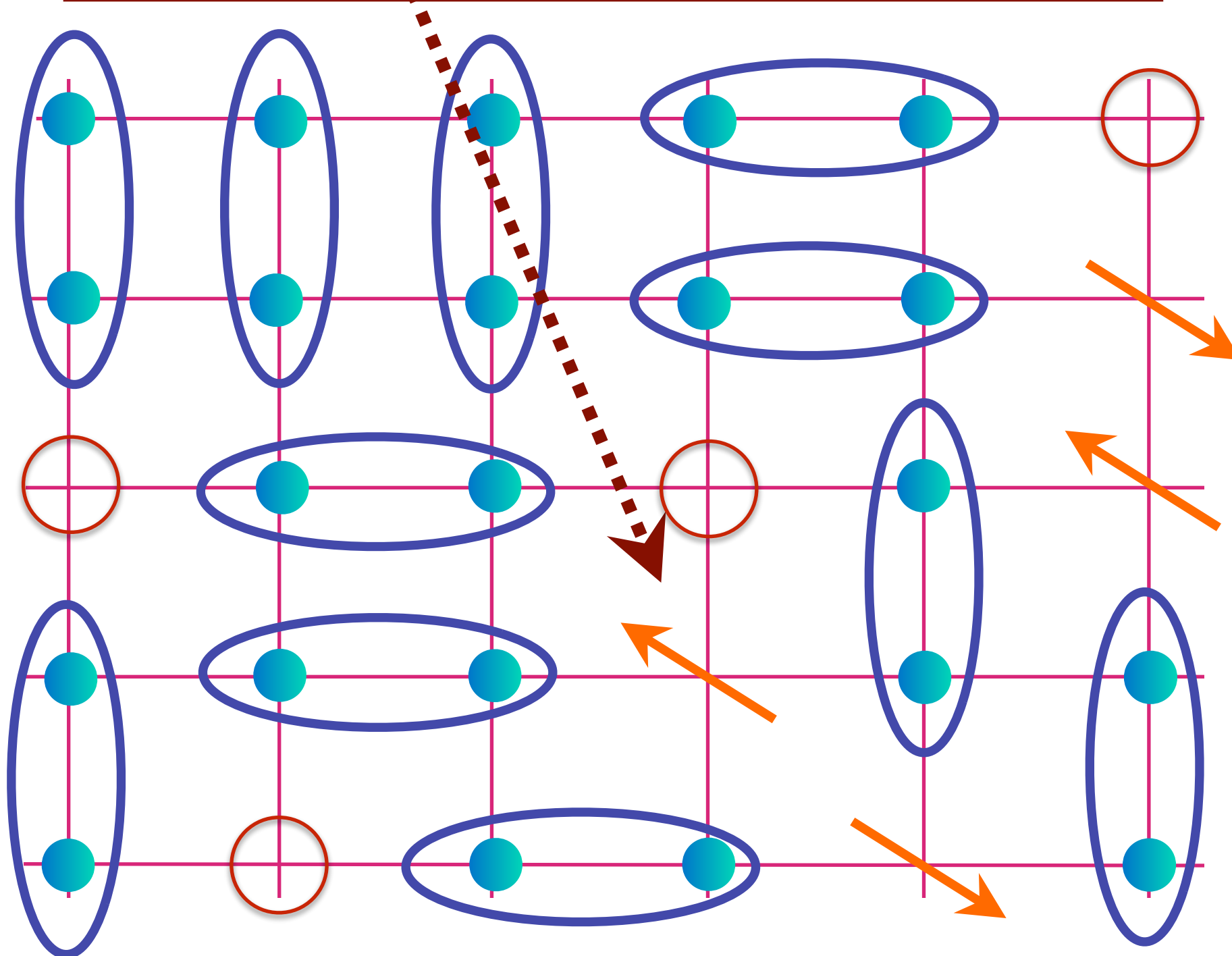


Spin liquid
with emergent
gauge field
and
 p “holons”
(gauge-charged,
spinless,
charge $+e$
quasiparticles)
per square

$$\text{blue oval with 2 dots} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Baskaran, Zou, Anderson, Fradkin, Kivelson...

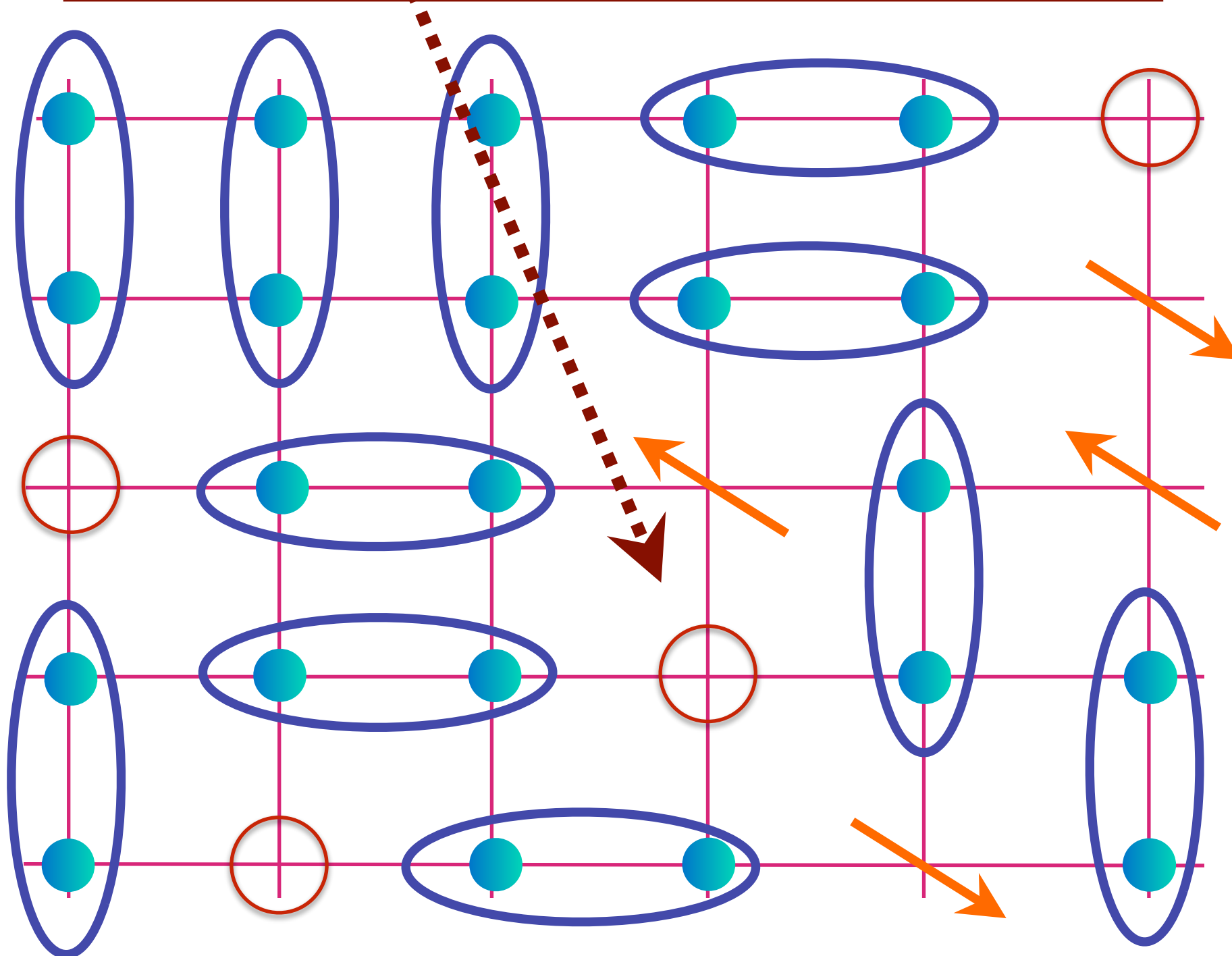
Nearest-neighbor hopping leads to attraction between holon and spinon, which can pay for the energy needed to create the spinon



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

$$\text{[Blue oval with two teal dots]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

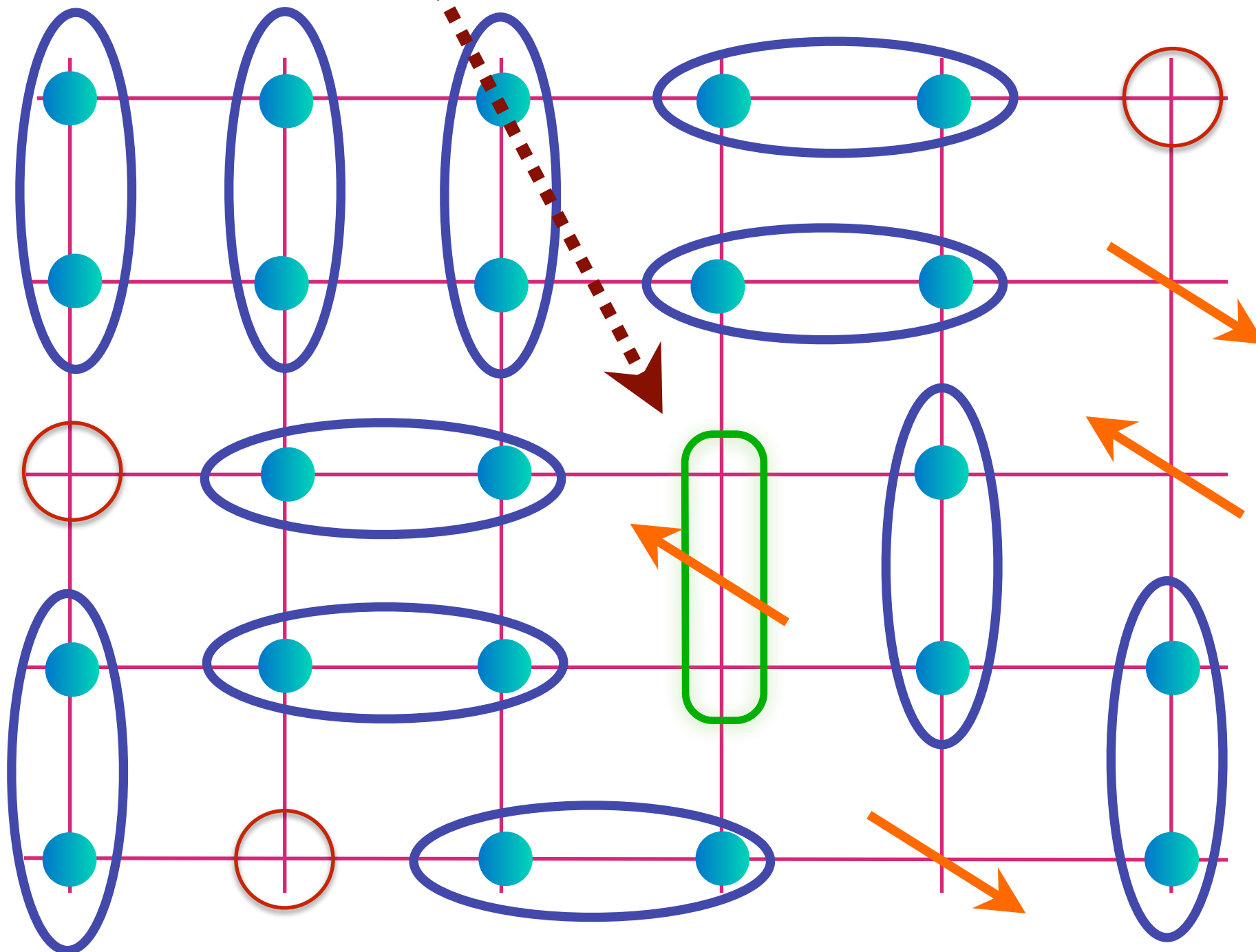
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Spin liquid
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quasiparticles)
per square

$$\text{[Blue oval with two teal dots]} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

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

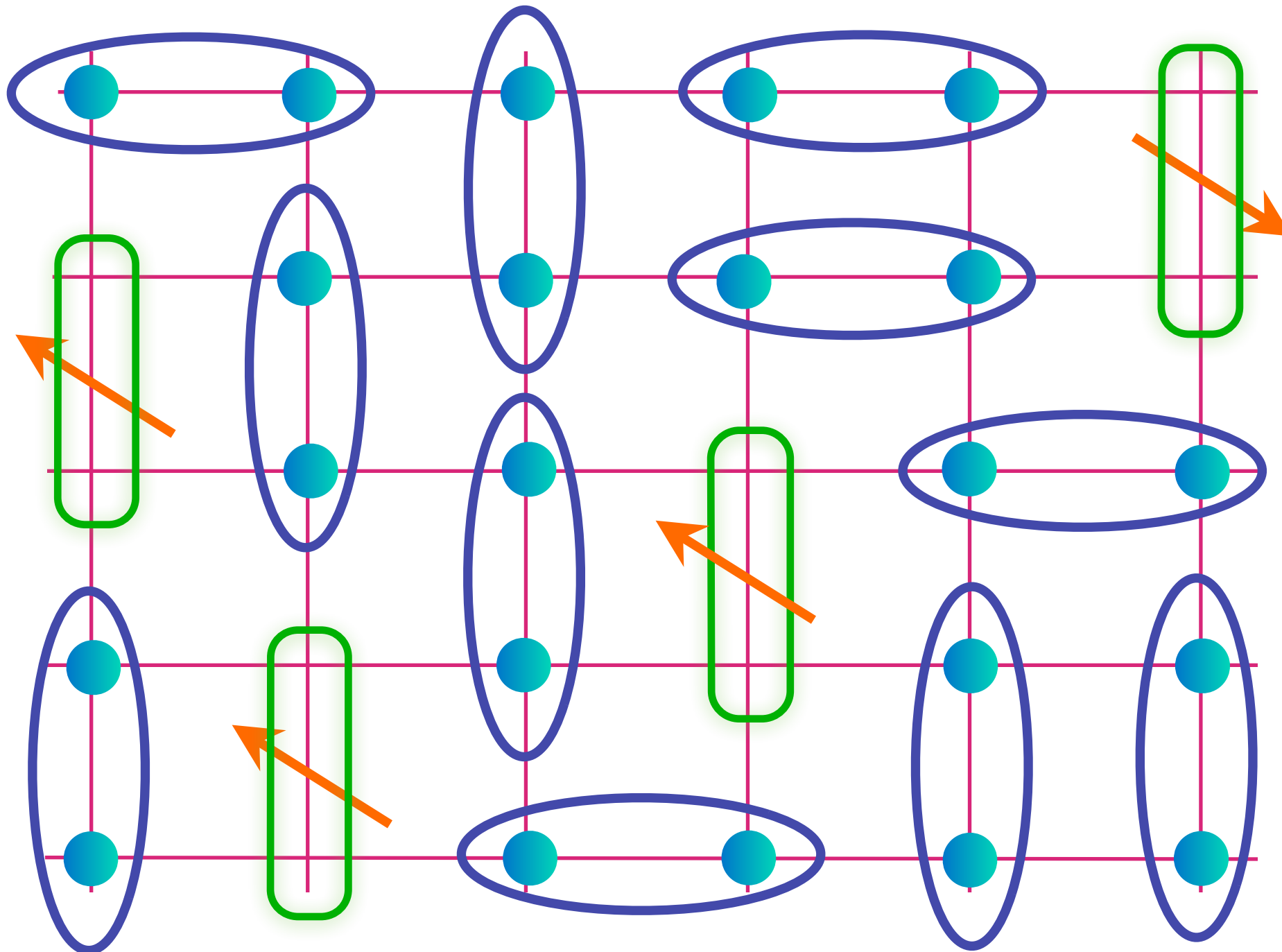


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per square

$$\text{Bond state} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

Fractionalized Fermi liquid (FL*)

$$\text{blue oval with two dots} = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$



Emergent
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and
gauge-neutral,
spin $S=1/2$,
charge $+e$
fermions
of density p

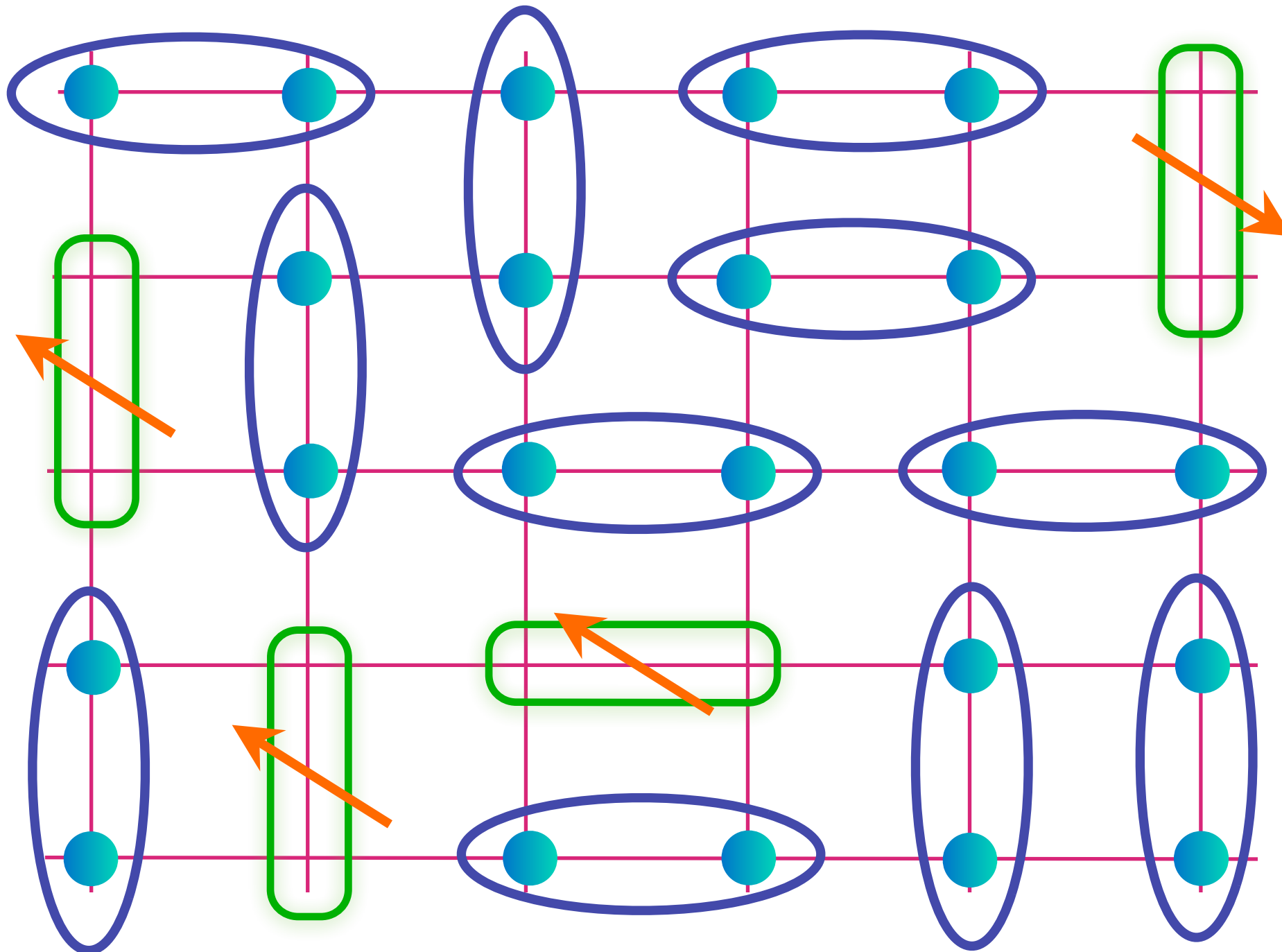
T. Senthil, S. S., M. Vojta *Phys. Rev. Lett.* **90**, 216403 (2003)

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

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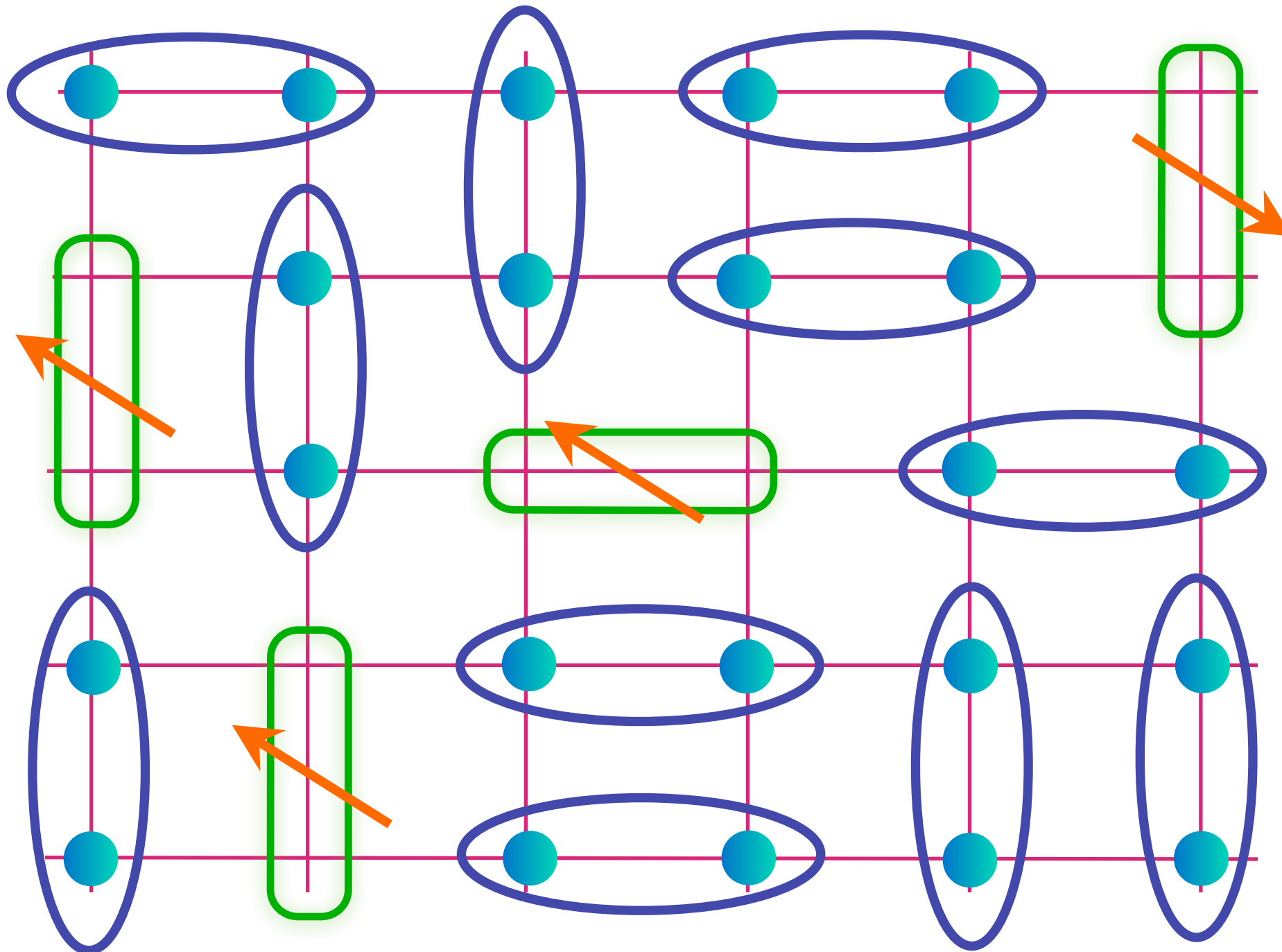
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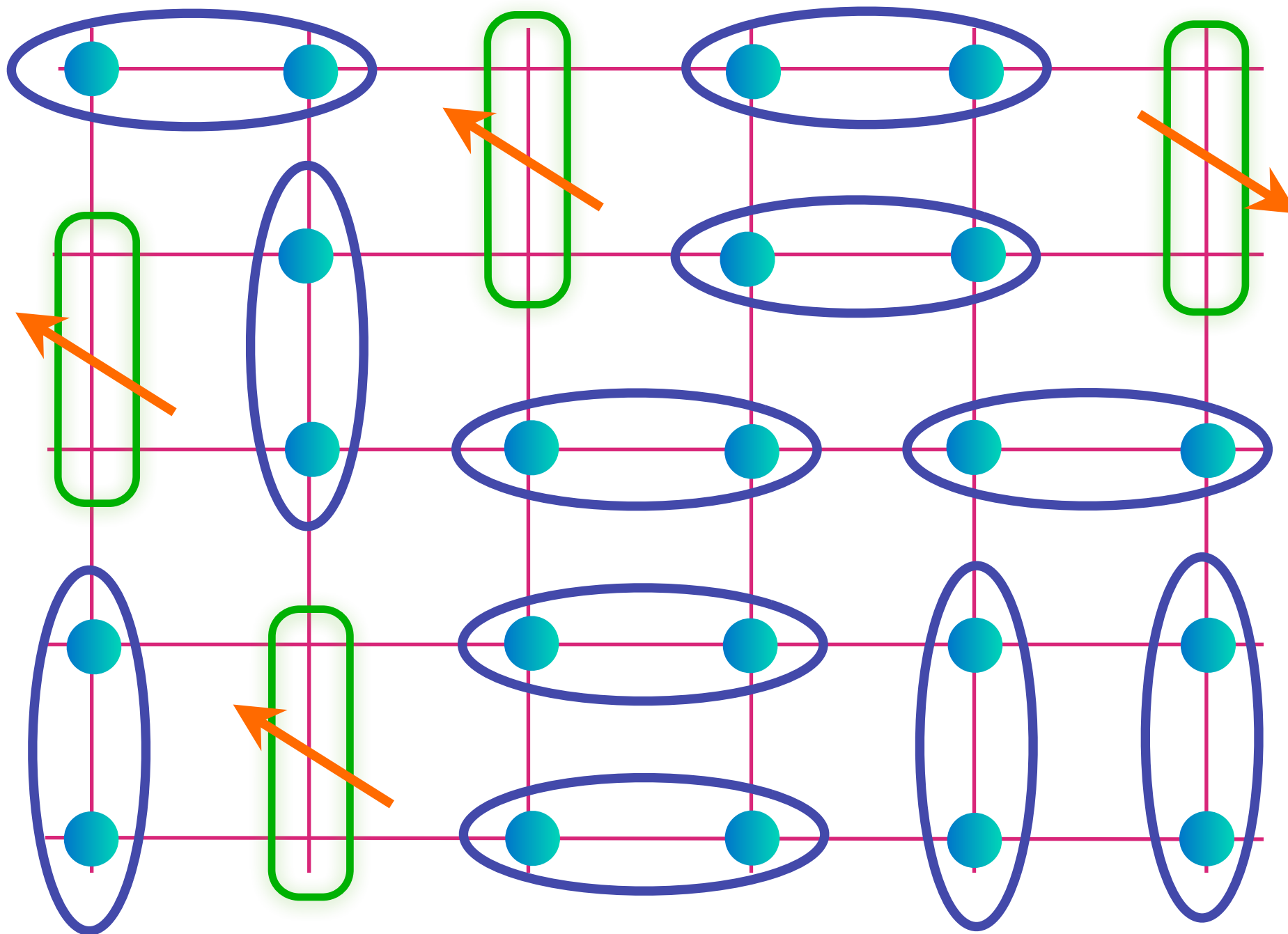
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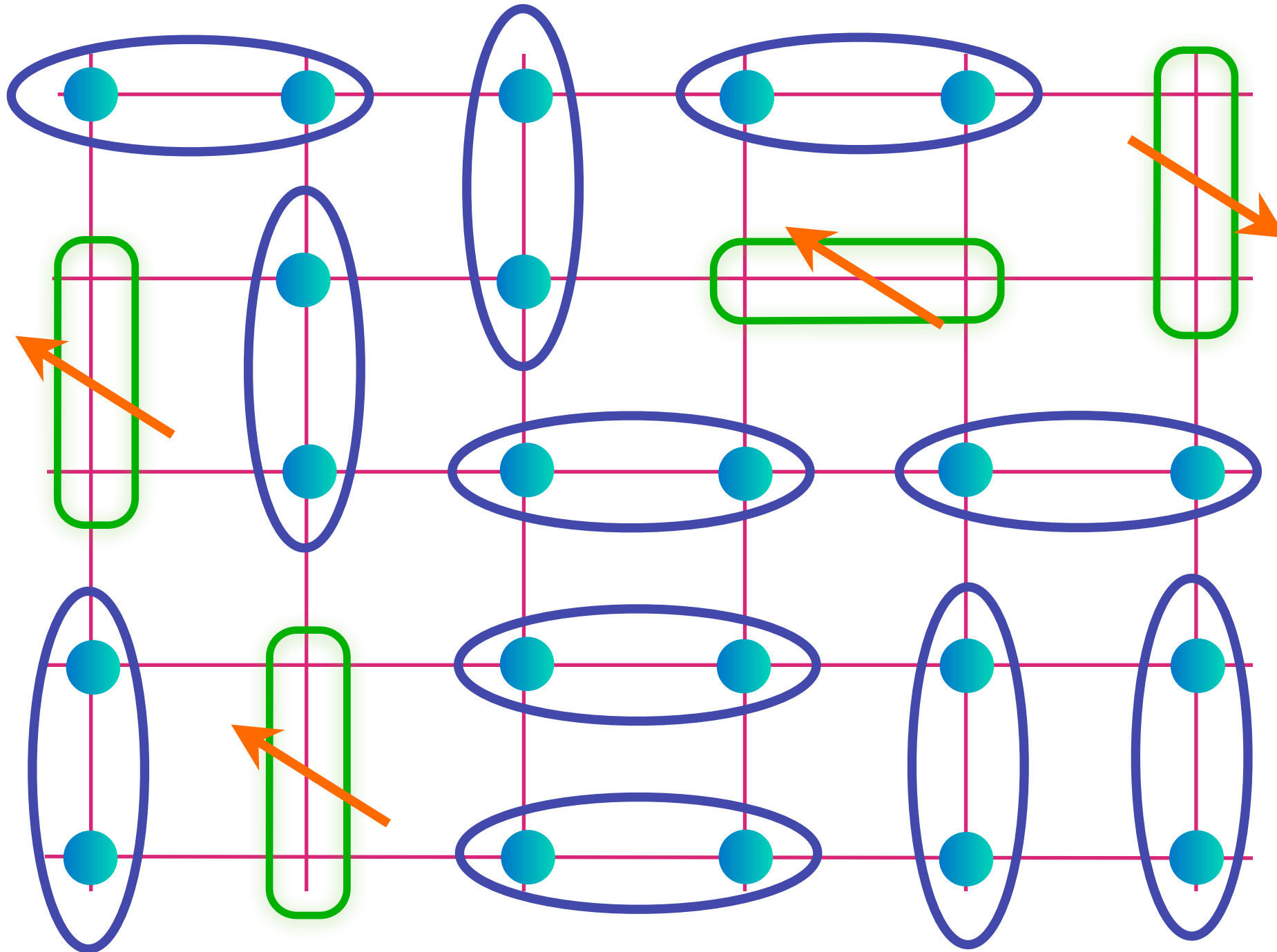
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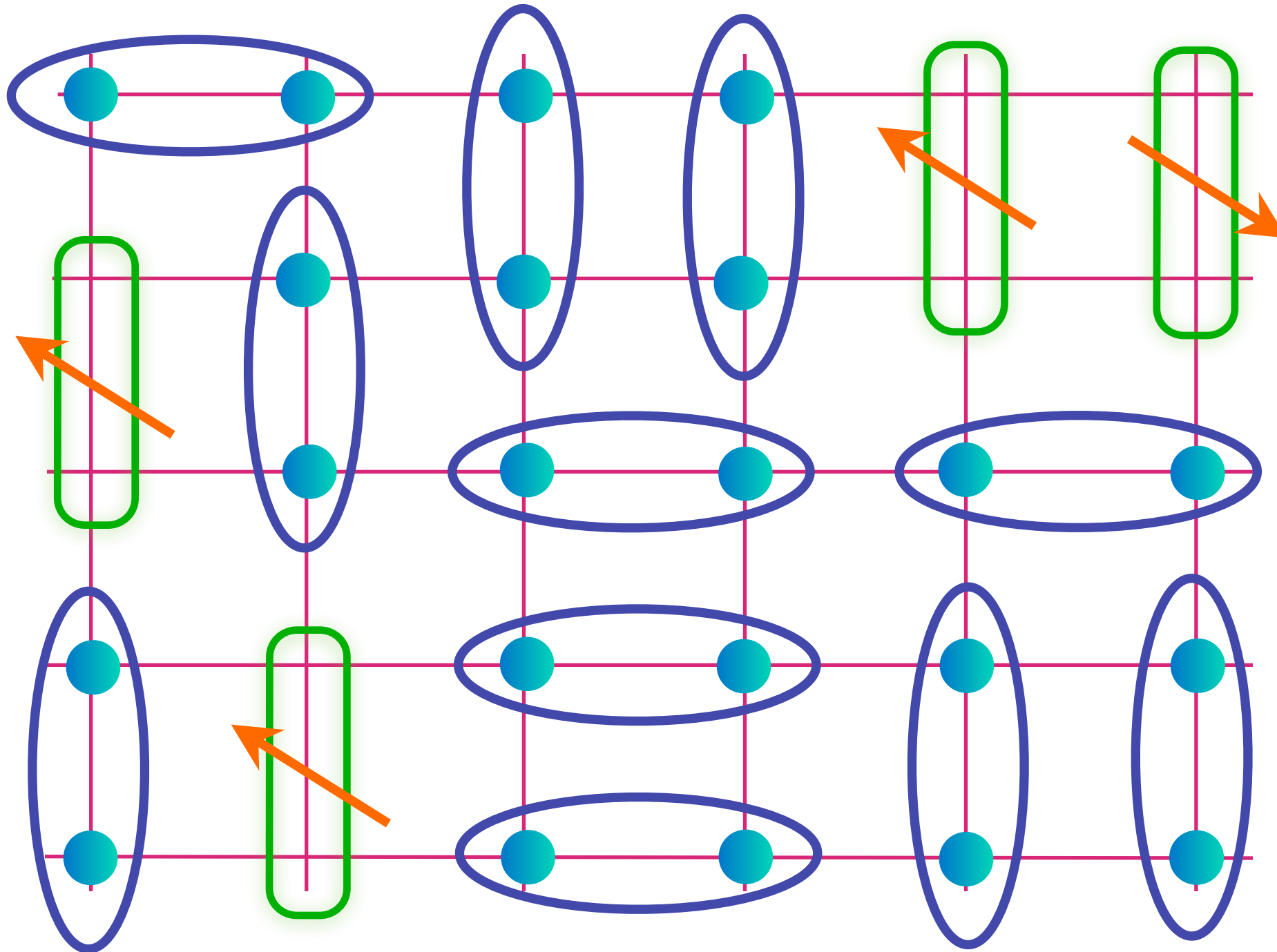
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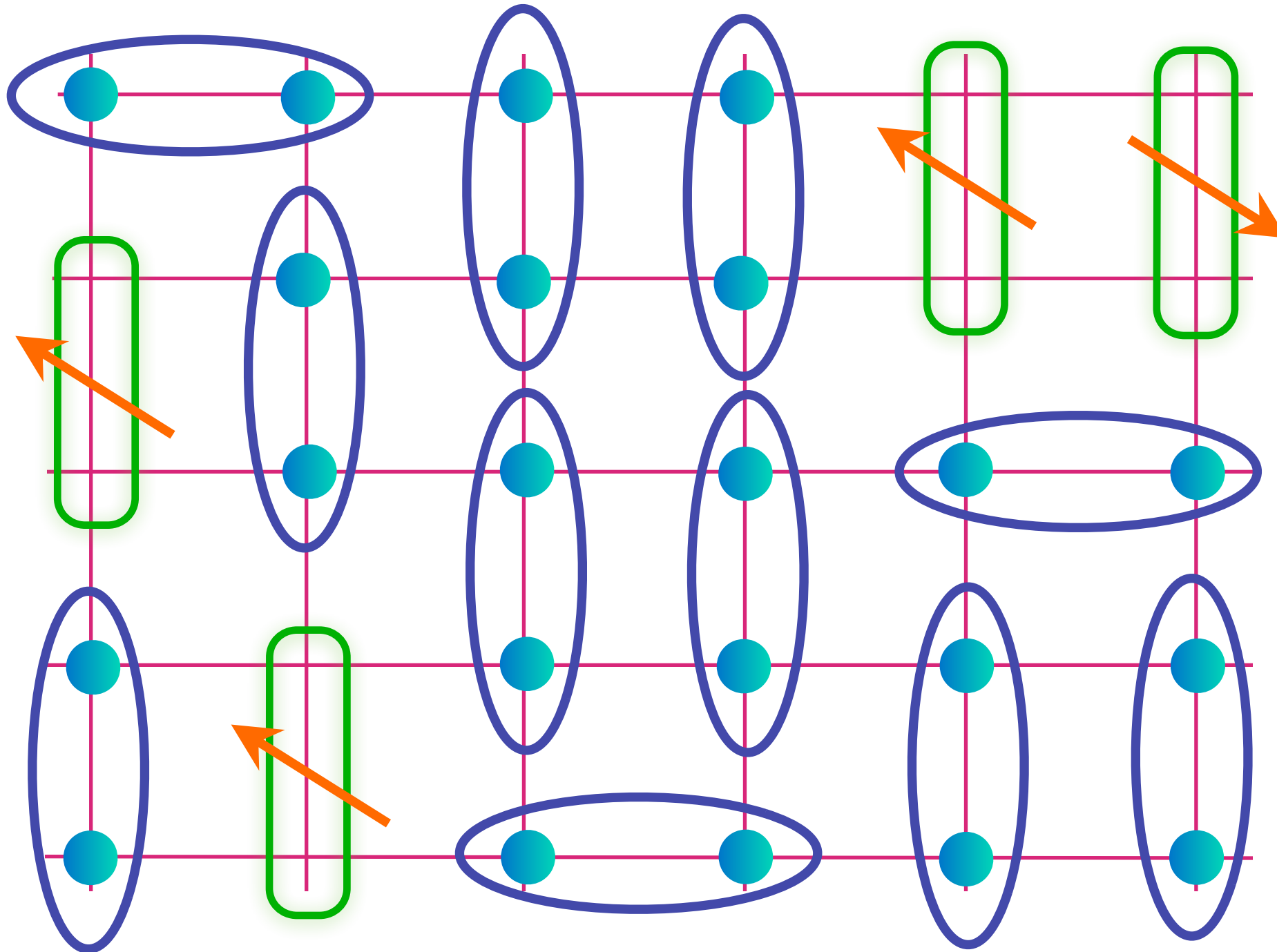
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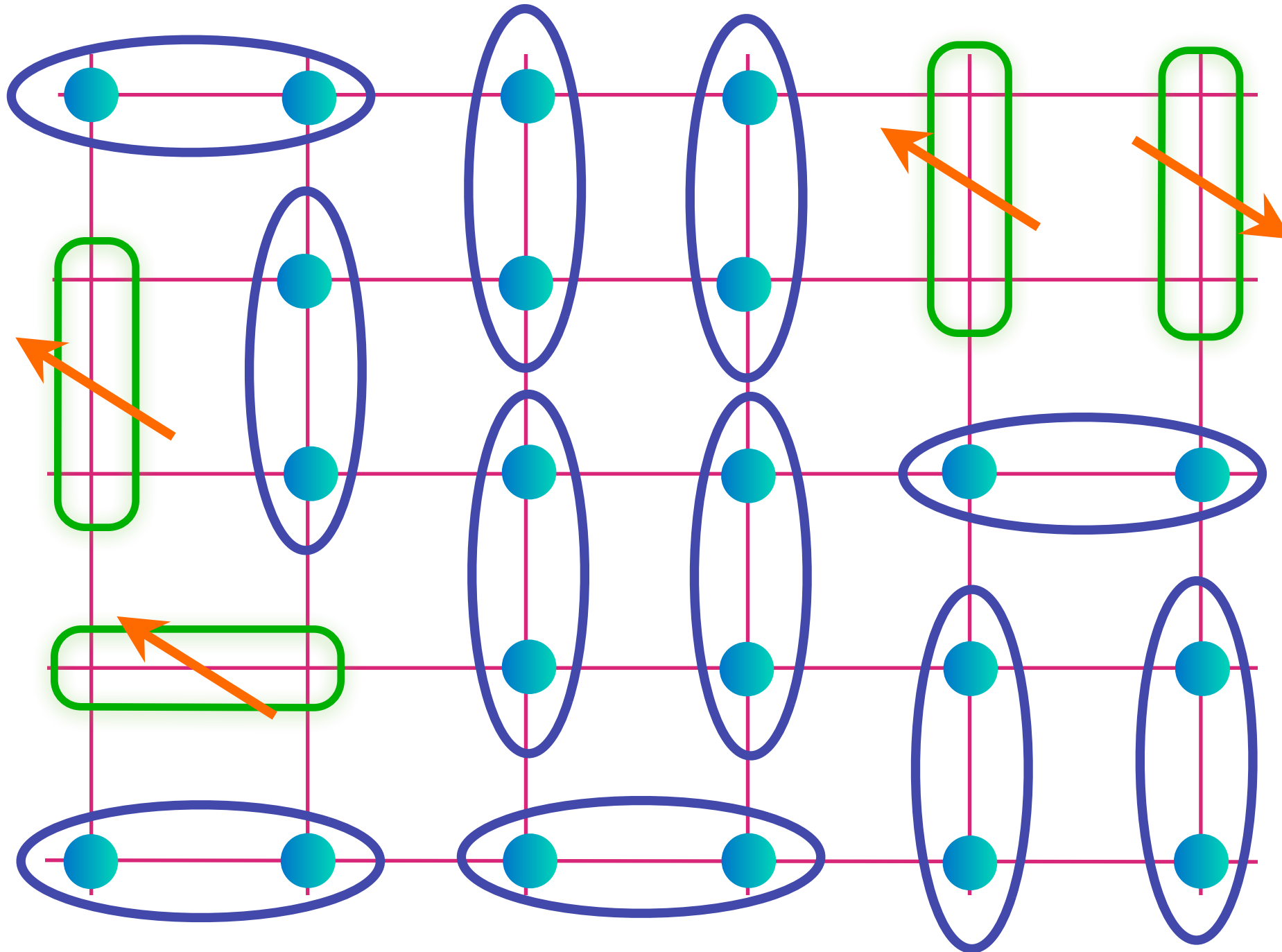
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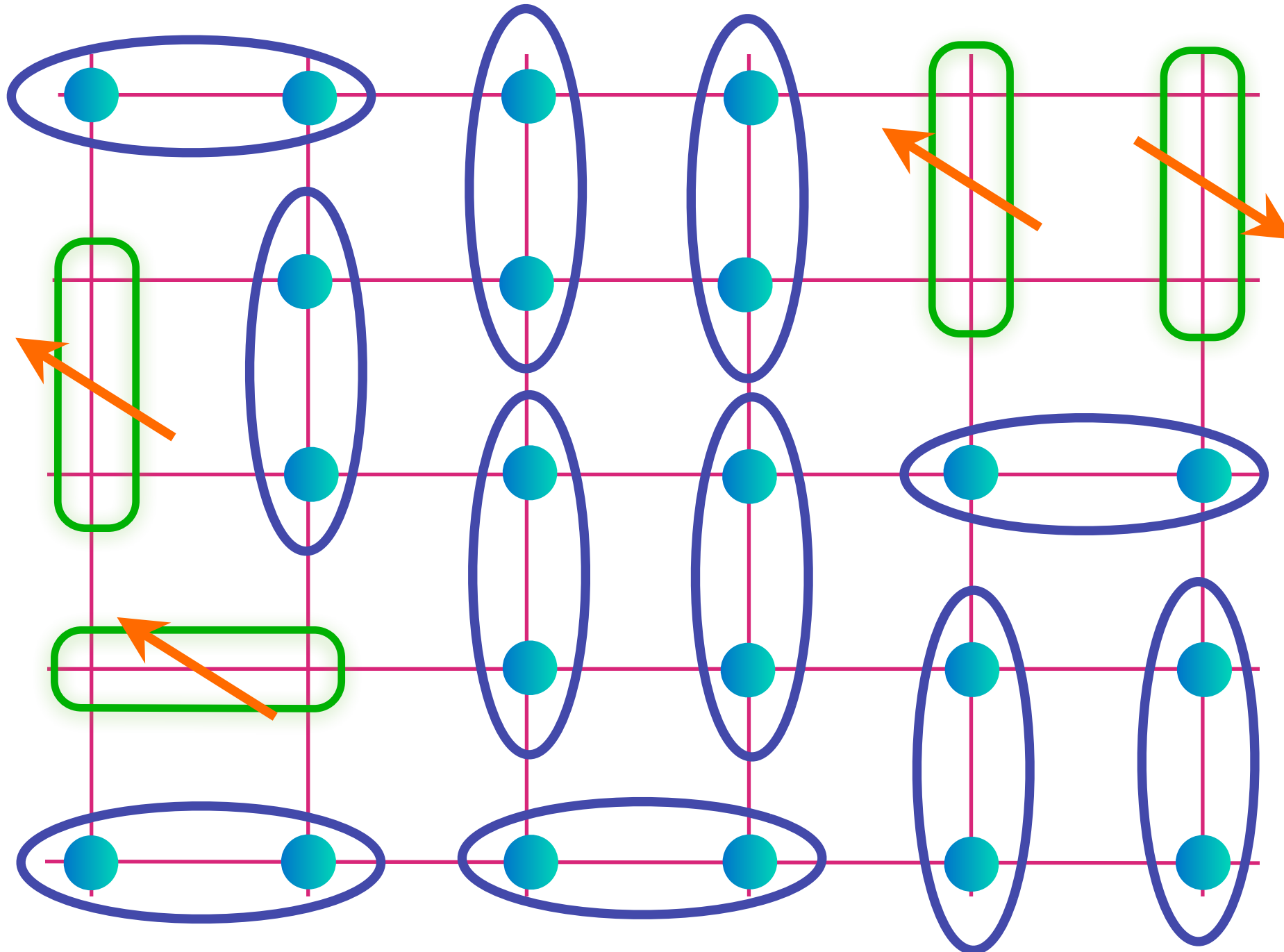
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Note:
electron-like
quasiparticle
can only be a
dimer because
of spin-liquid
background; it
is not possible
to have it on a
single site

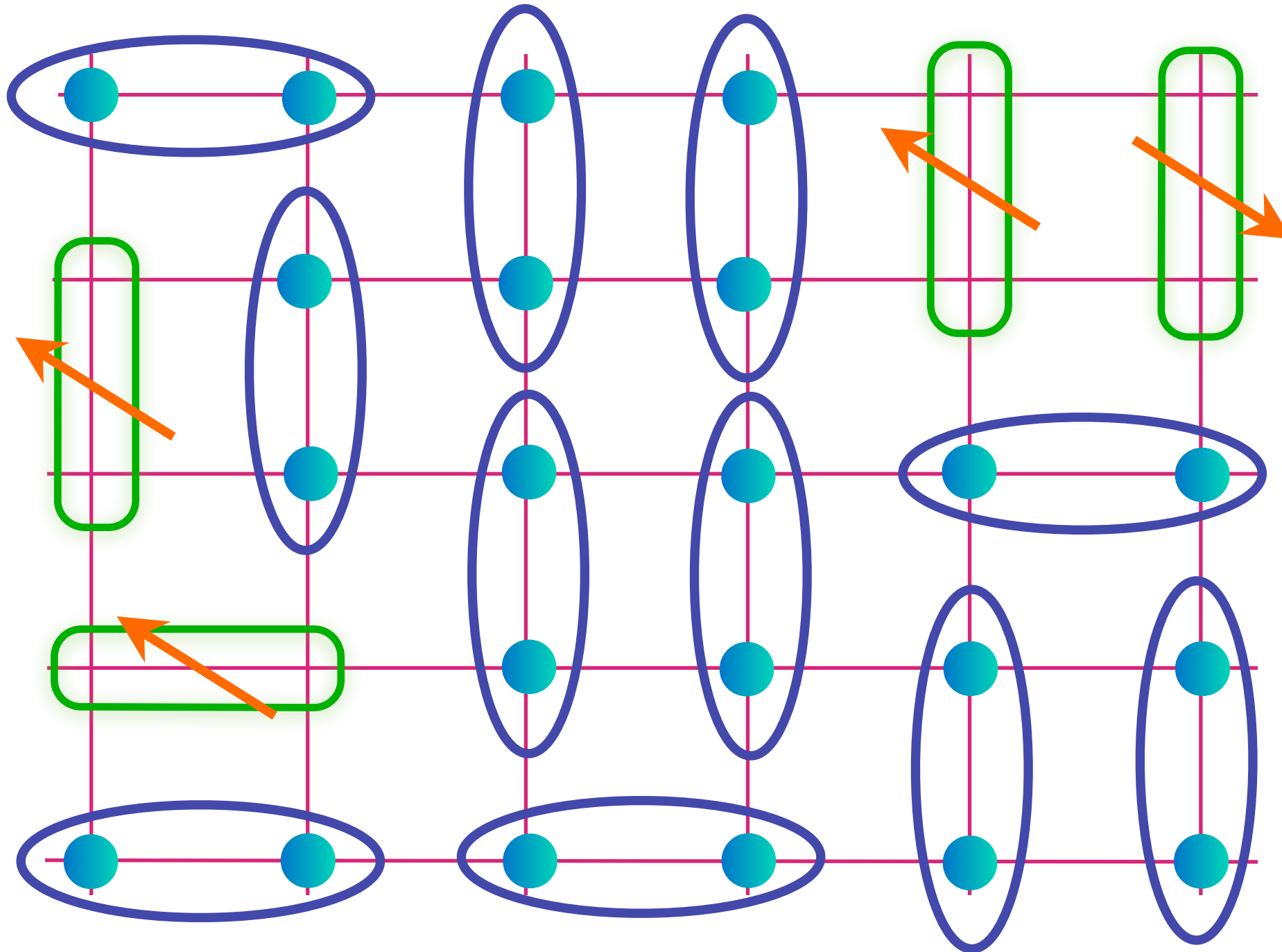
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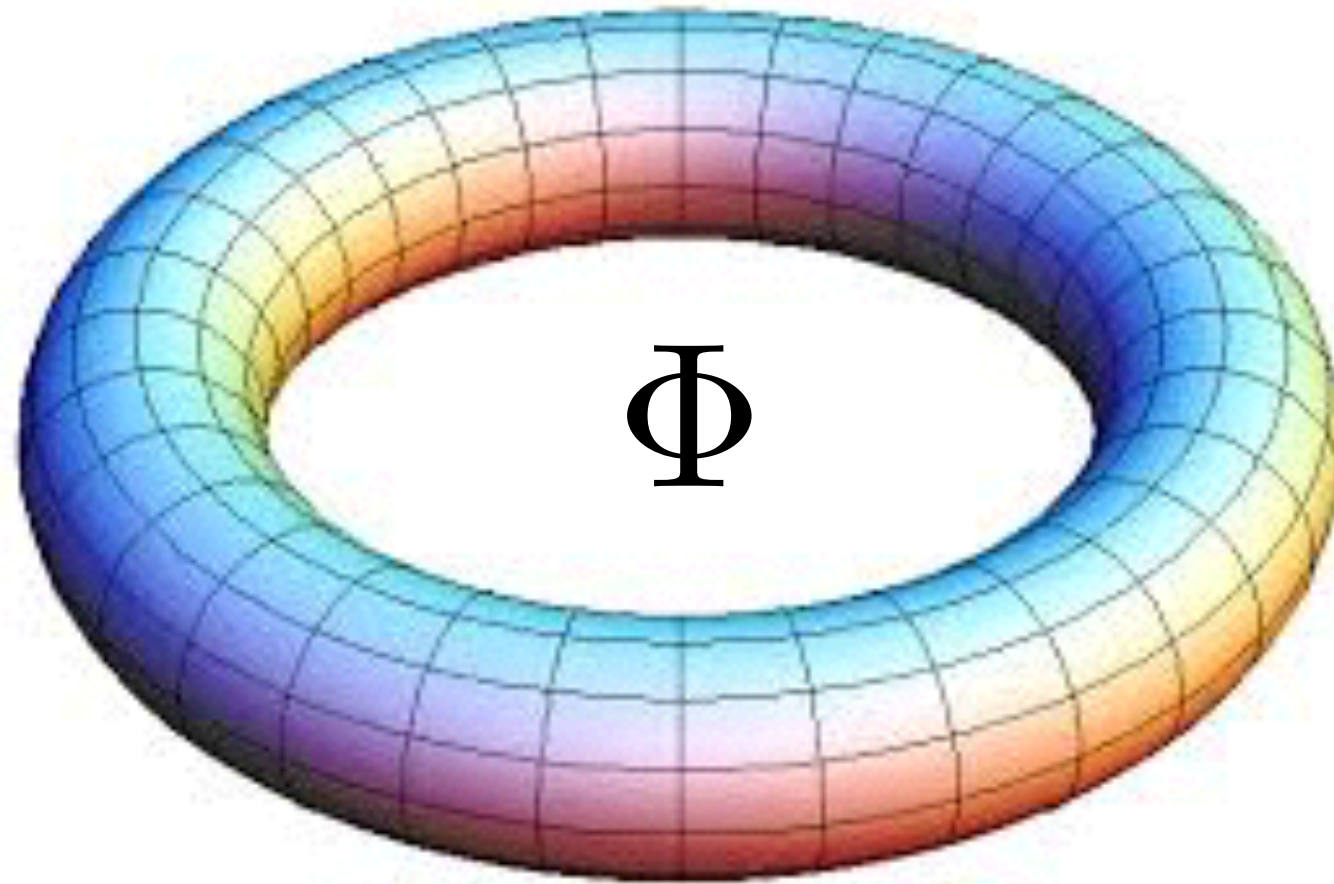
Realizes a
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Topological argument



Put metal on a torus, adiabatically insert flux $\Phi = h/e$ through hole, and measure change in momentum. In a FL, we can assume the only low energy excitations are quasiparticles near the Fermi surface, and this leads to a non-perturbative proof of the Luttinger relation on the area enclosed by the Fermi surface. Violations of the Luttinger relation are possible in the FL* because there are “topological” low energy excitations associated with a flux of the emergent gauge field in the hole of the torus.

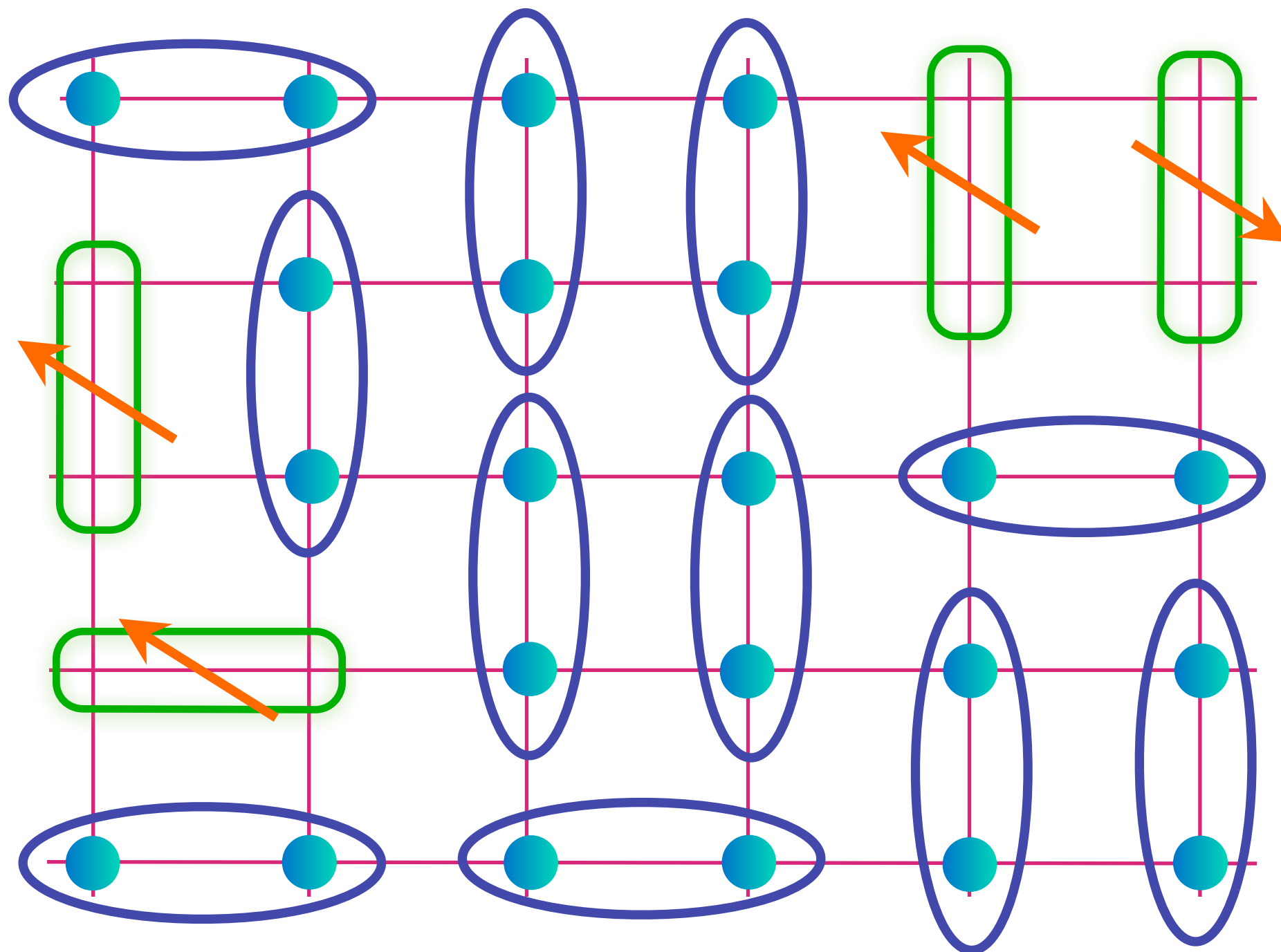
M. Oshikawa, *Phys. Rev. Lett.* **84**, 3370 (2000)

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

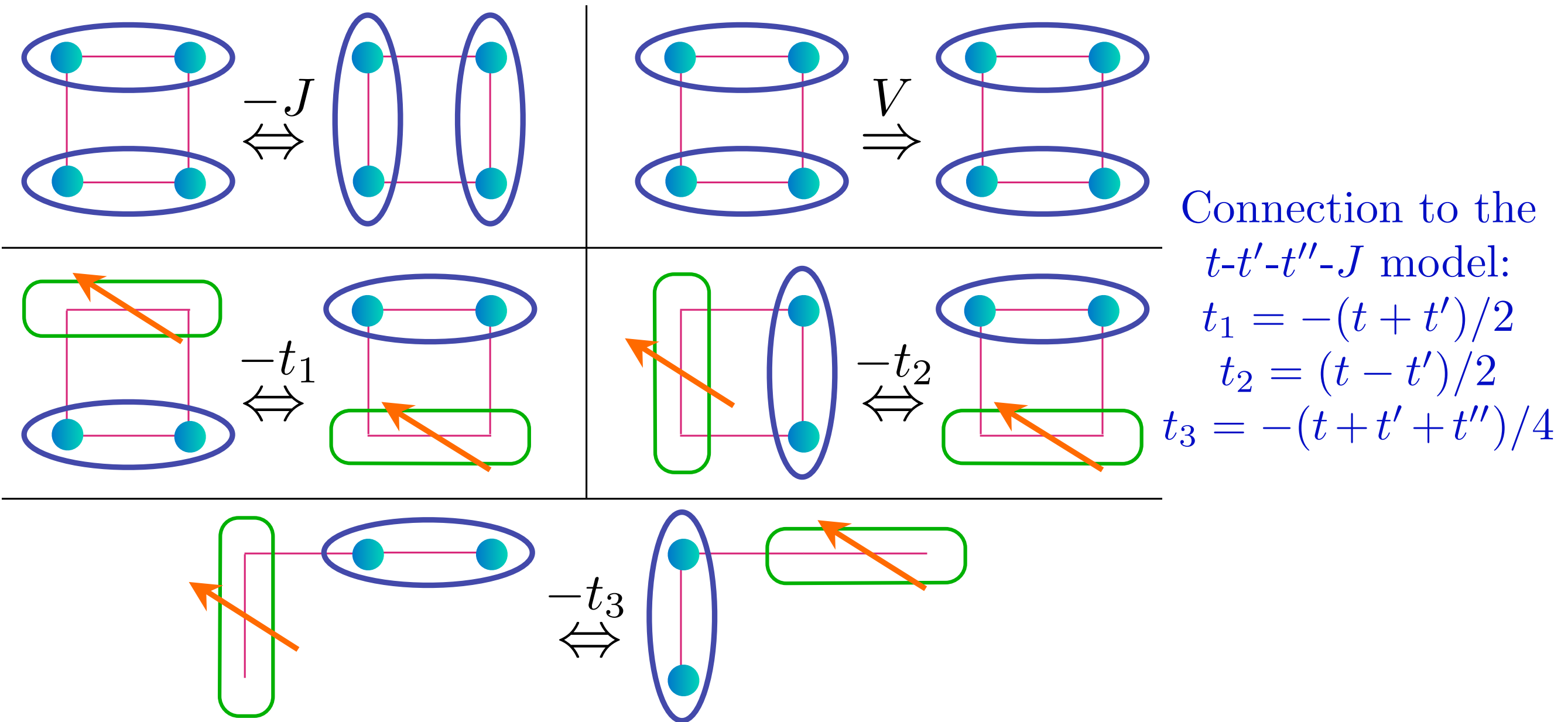
Characteristics of FL*

- 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.

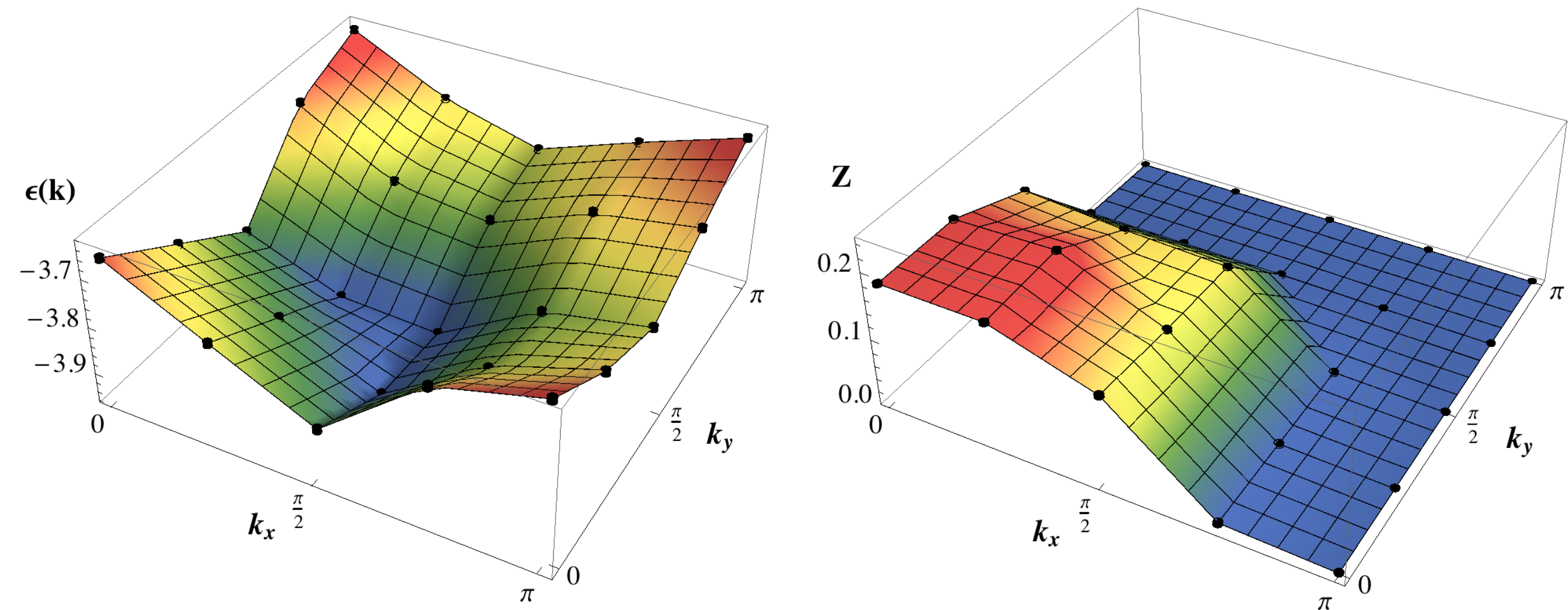
Quantum dimer model with bosonic and fermionic dimers



Quantum dimer model with bosonic and fermionic dimers

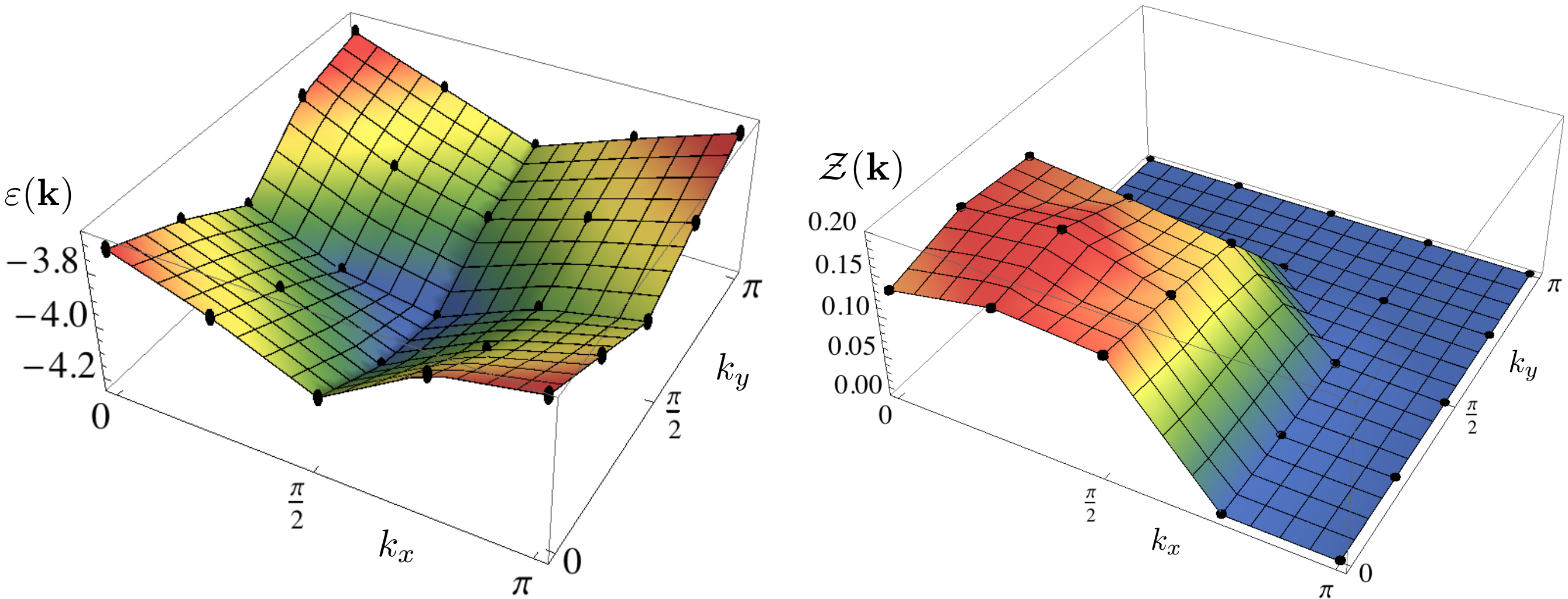


Quantum dimer model with bosonic and fermionic dimers

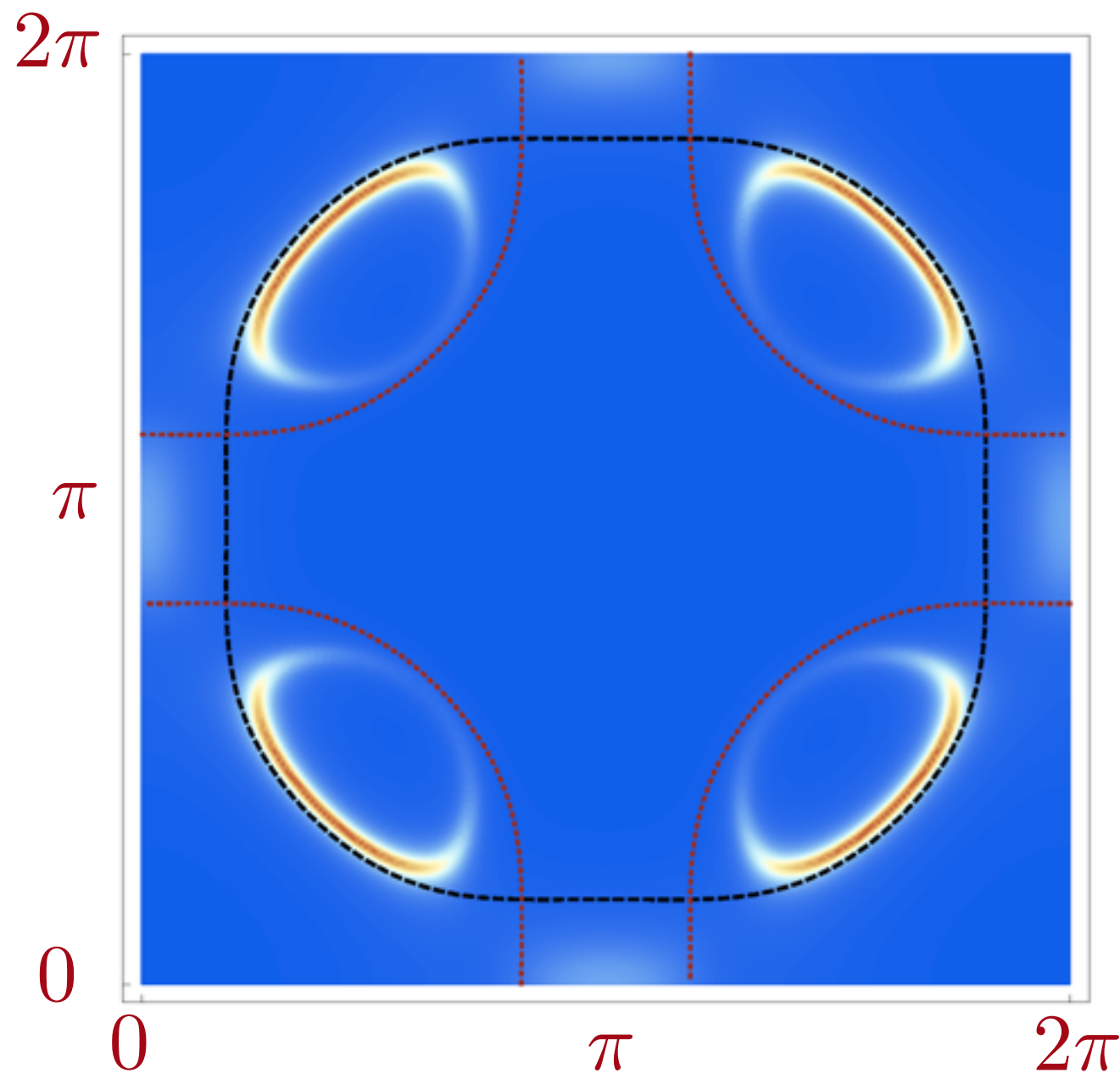


Dispersion and quasiparticle residue for $J = V = 1$, and hopping parameters obtained from the t - J model for the cuprates, $t_1 = -1.05$, $t_2 = 1.95$ and $t_3 = -0.6$, on a 8×8 lattice.

Quantum dimer model with bosonic and fermionic dimers



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.

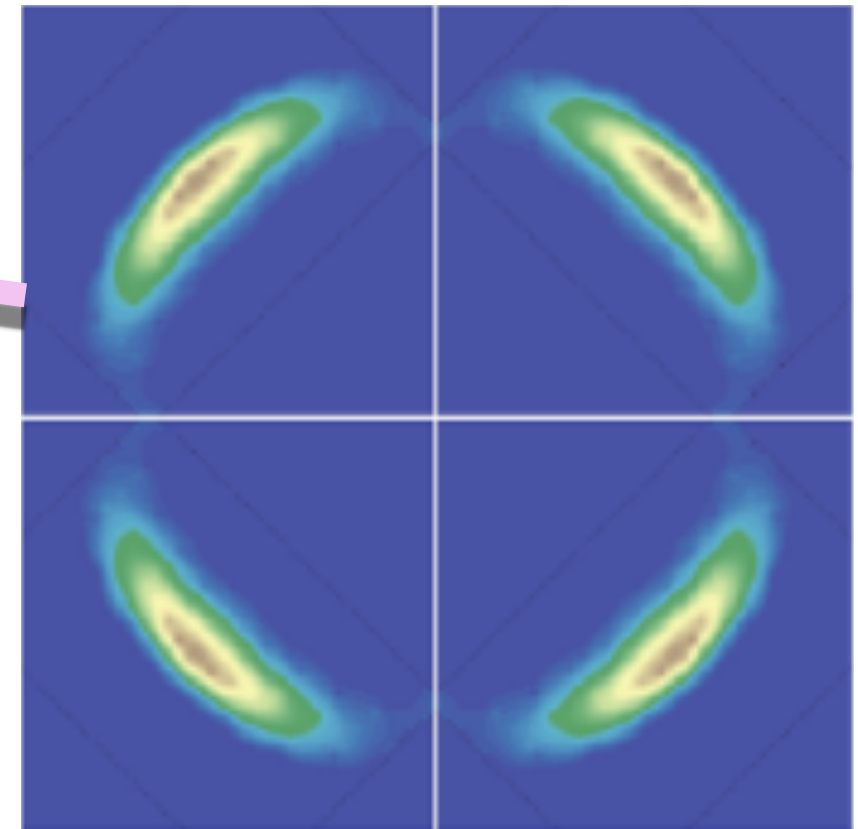
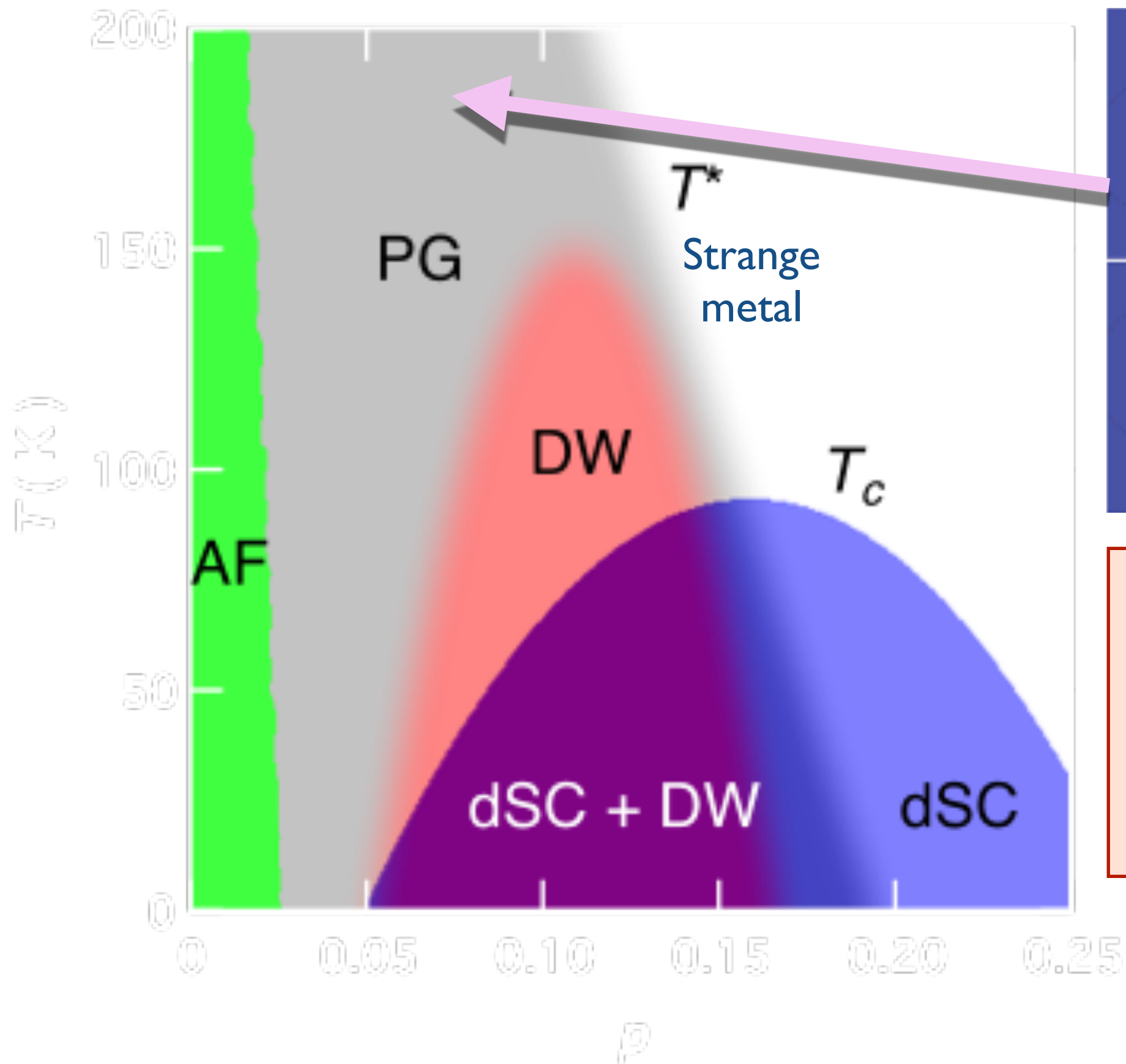


Electron spectral
function of FL*

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

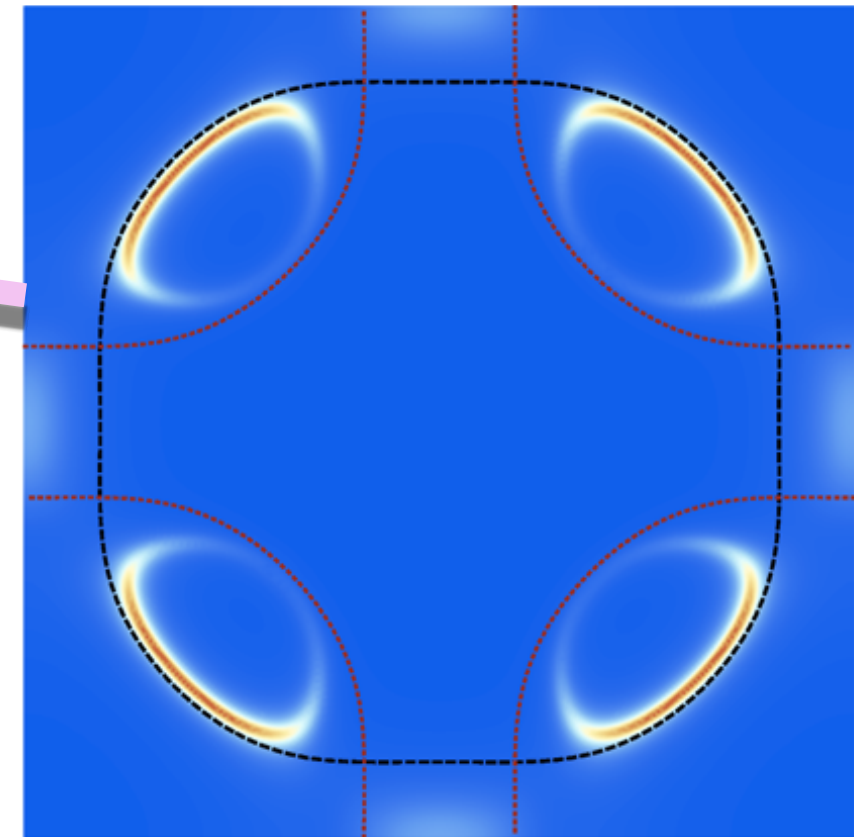
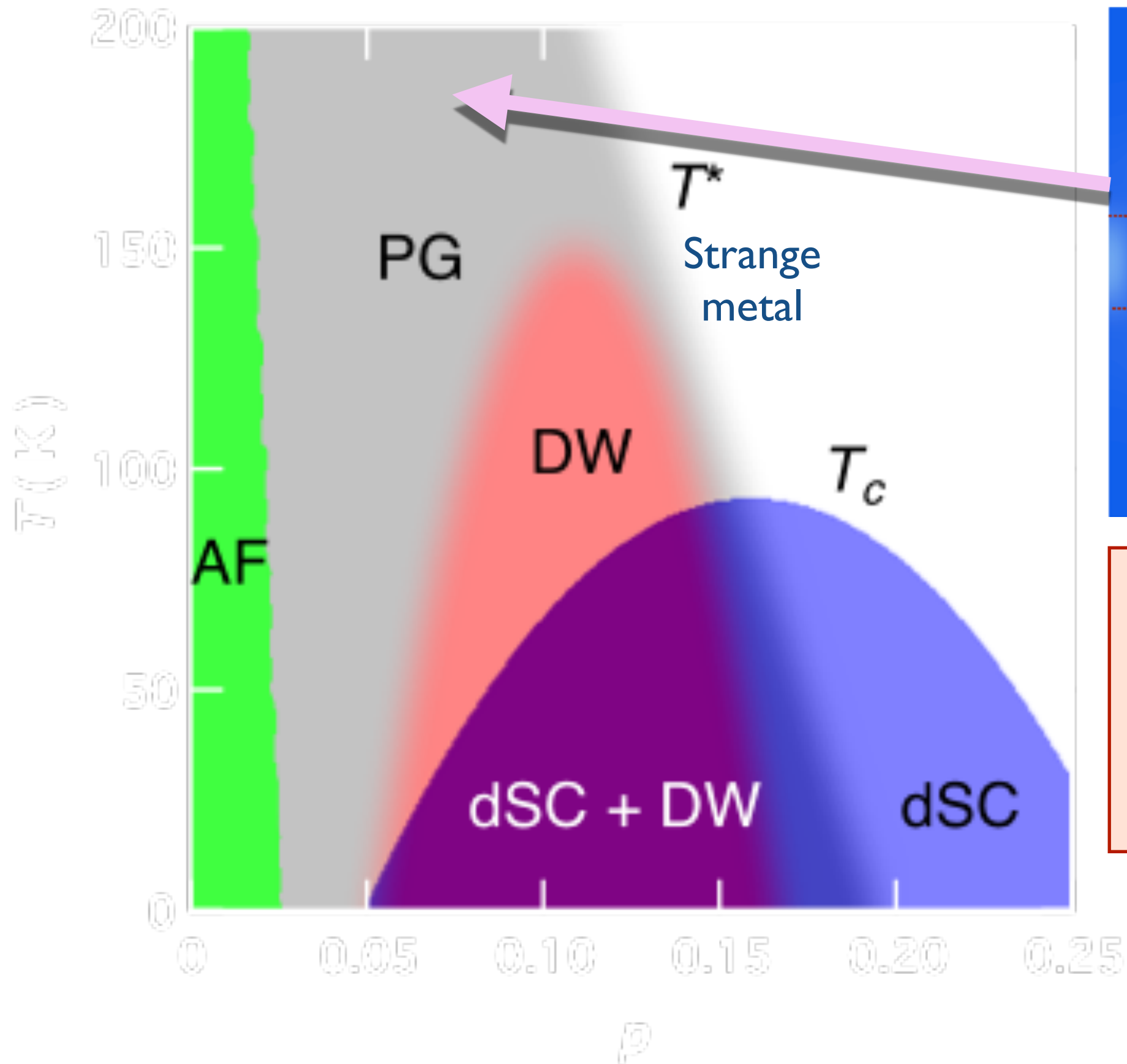
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)



“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:

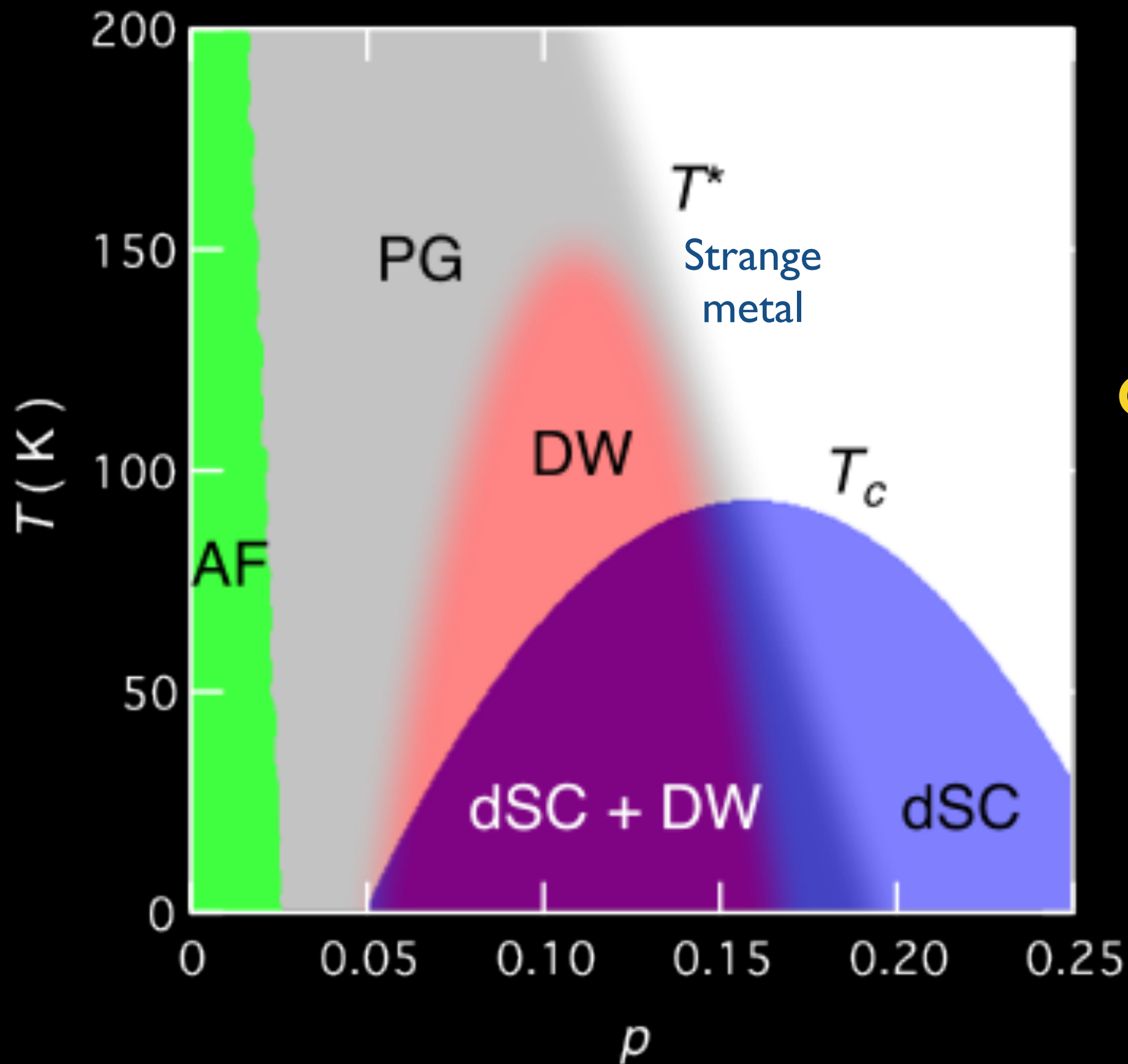
STM observation of predicted d -form factor density wave

3. Connecting high and low T :

Density wave instabilities

4. Quantum critical point near optimal p :

A Higgs critical point



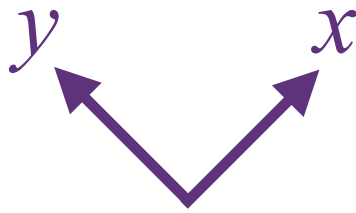
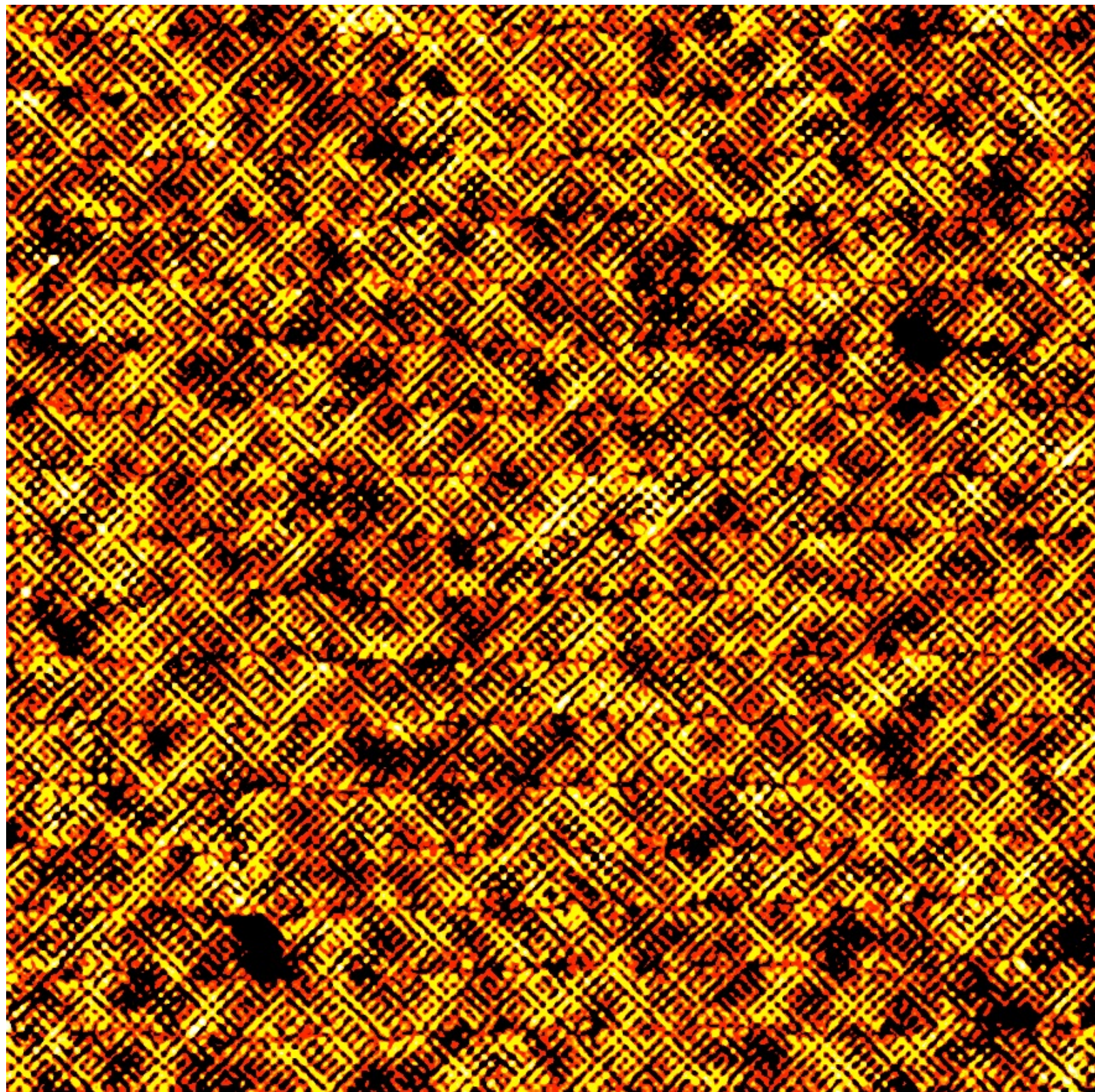
STM
of DW order
in non-La
materials

See also

C. Howald, H. Eisaki,
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Phys. Rev. B **67**,
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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.

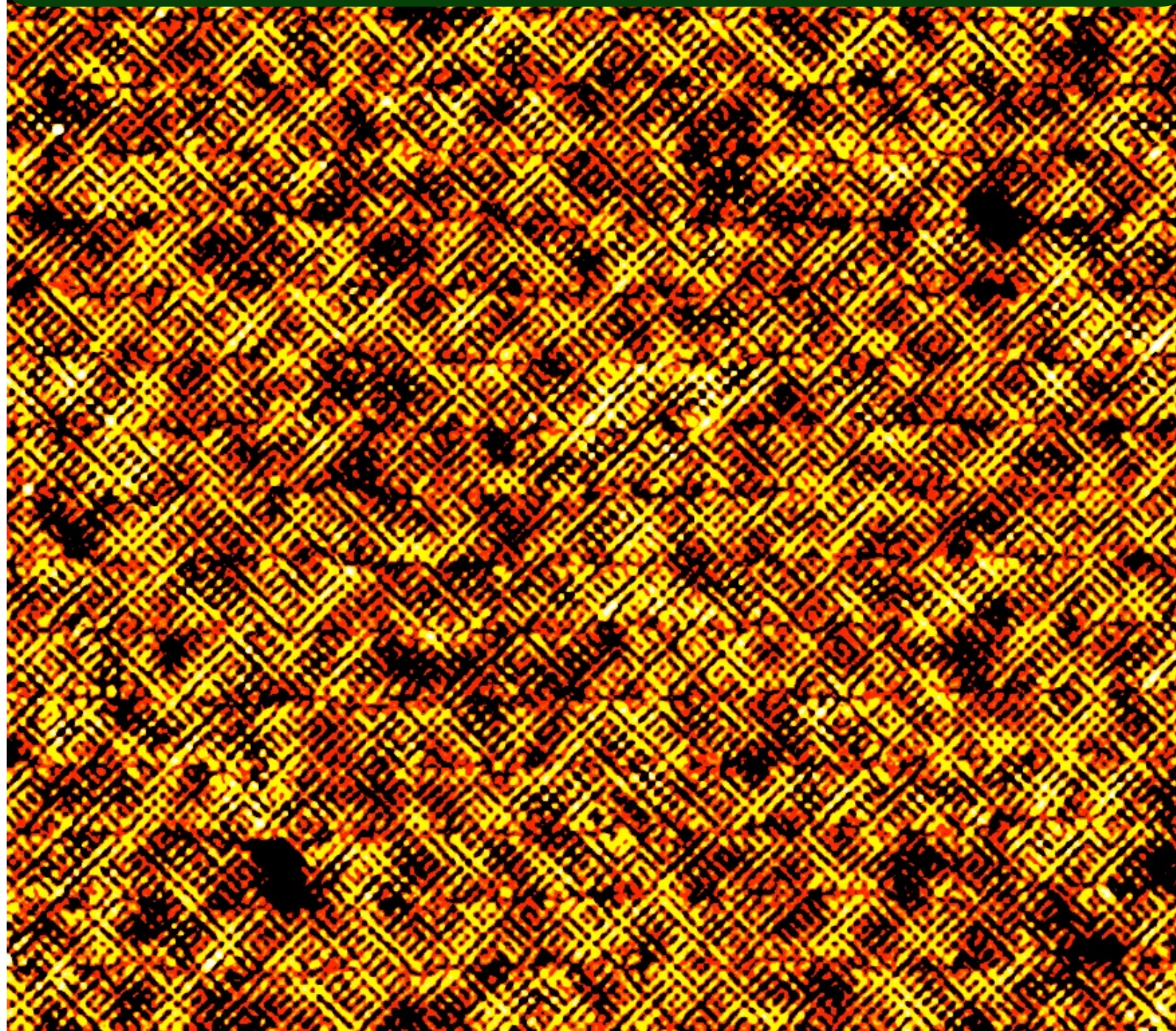
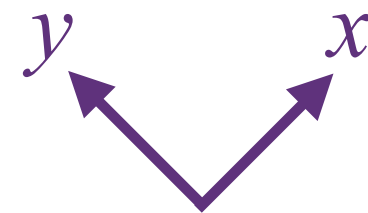
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Disordered uni-directional charge density waves
("stripes") with wavelength ≈ 4 lattice sites ?



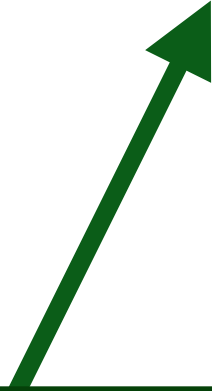
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Unconventional density wave (DW) :
Bose condensation of particle-hole pairs

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

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

Unconventional density wave (DW) :
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$$\langle c_{\alpha}^{\dagger}(\mathbf{r}_1) c_{\alpha}(\mathbf{r}_2) \rangle \\ = \left[\mathcal{P}(\mathbf{r}_1 - \mathbf{r}_2) \right] \times \Psi_{DW} \left(\frac{\mathbf{r}_1 + \mathbf{r}_2}{2} \right) e^{i\mathbf{Q} \cdot (\mathbf{r}_1 + \mathbf{r}_2)/2}$$

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

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

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

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

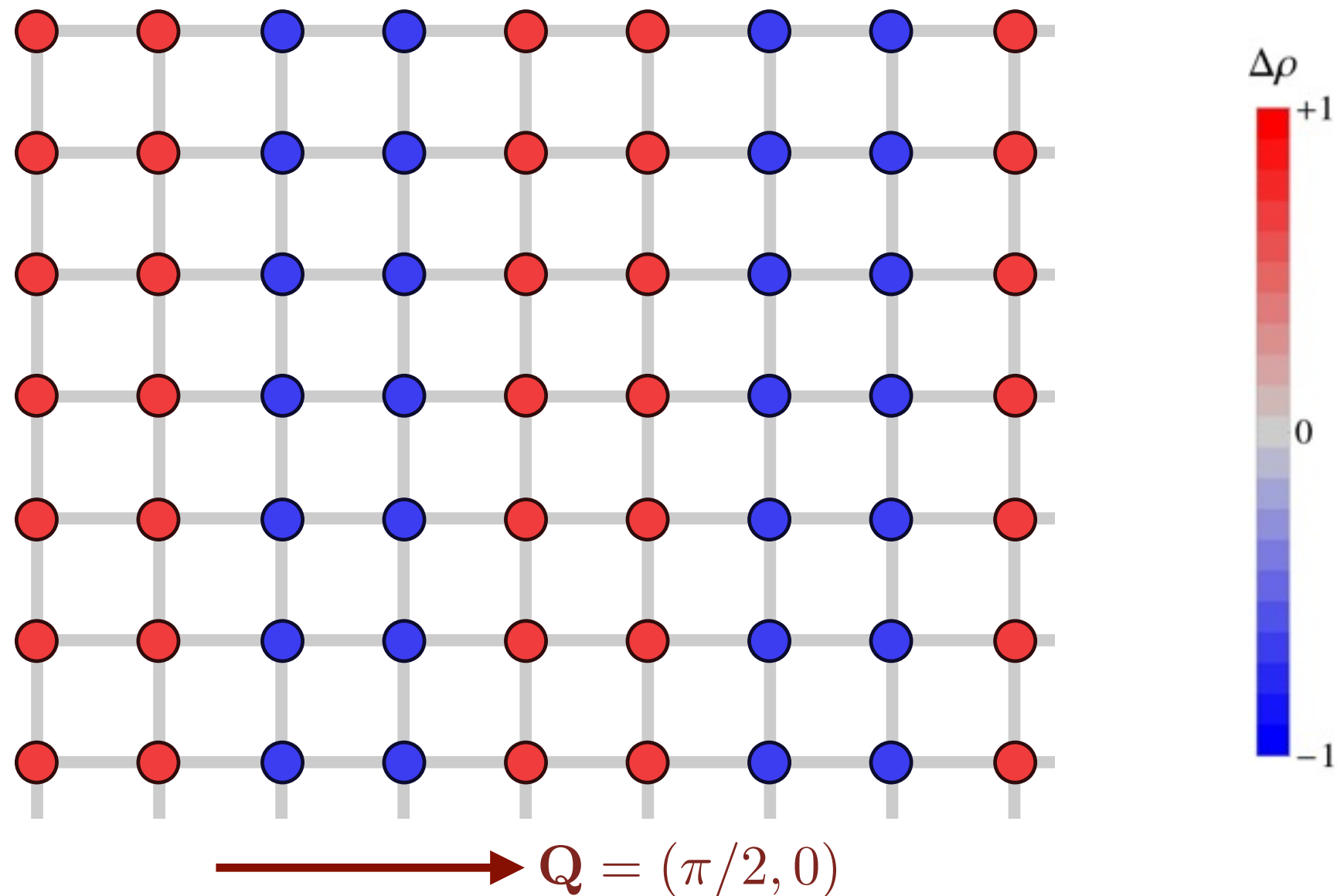
$$\mathcal{P}(\mathbf{k}) = \mathcal{P}_s + \mathcal{P}_{s'}(\cos k_x + \cos k_y) + \mathcal{P}_d(\cos k_x - \cos k_y)$$

Conventional CDW order: s-form factor

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

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

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

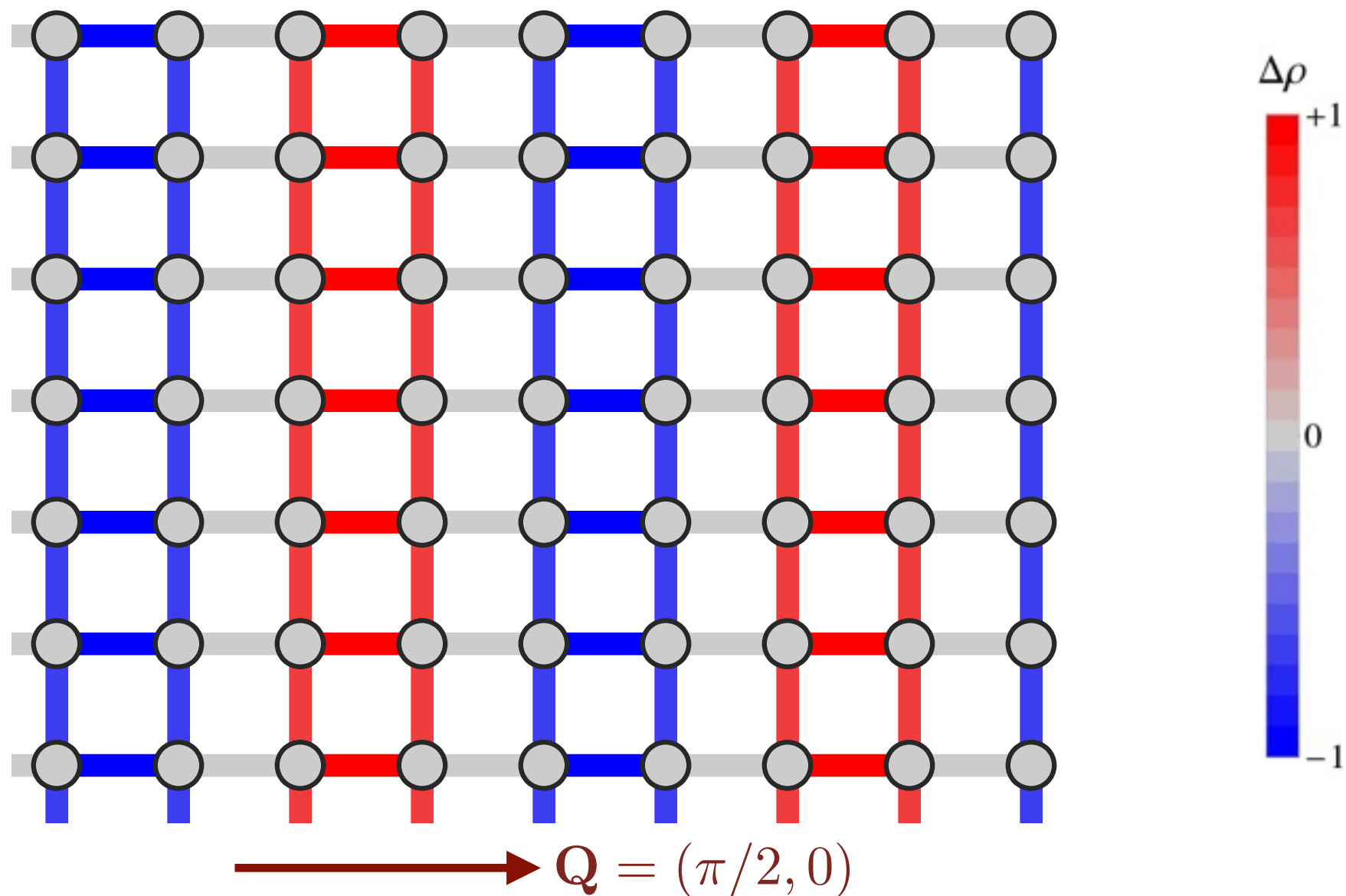


Unconventional DW order: s' -form factor

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

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

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

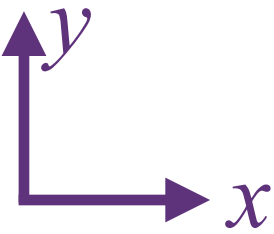


Unconventional DW order: $s + s'$ -form factor

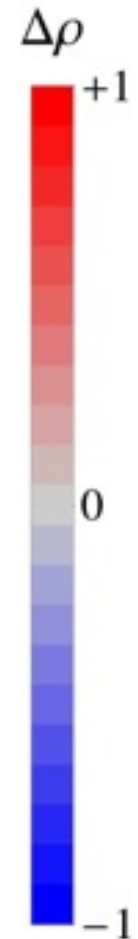
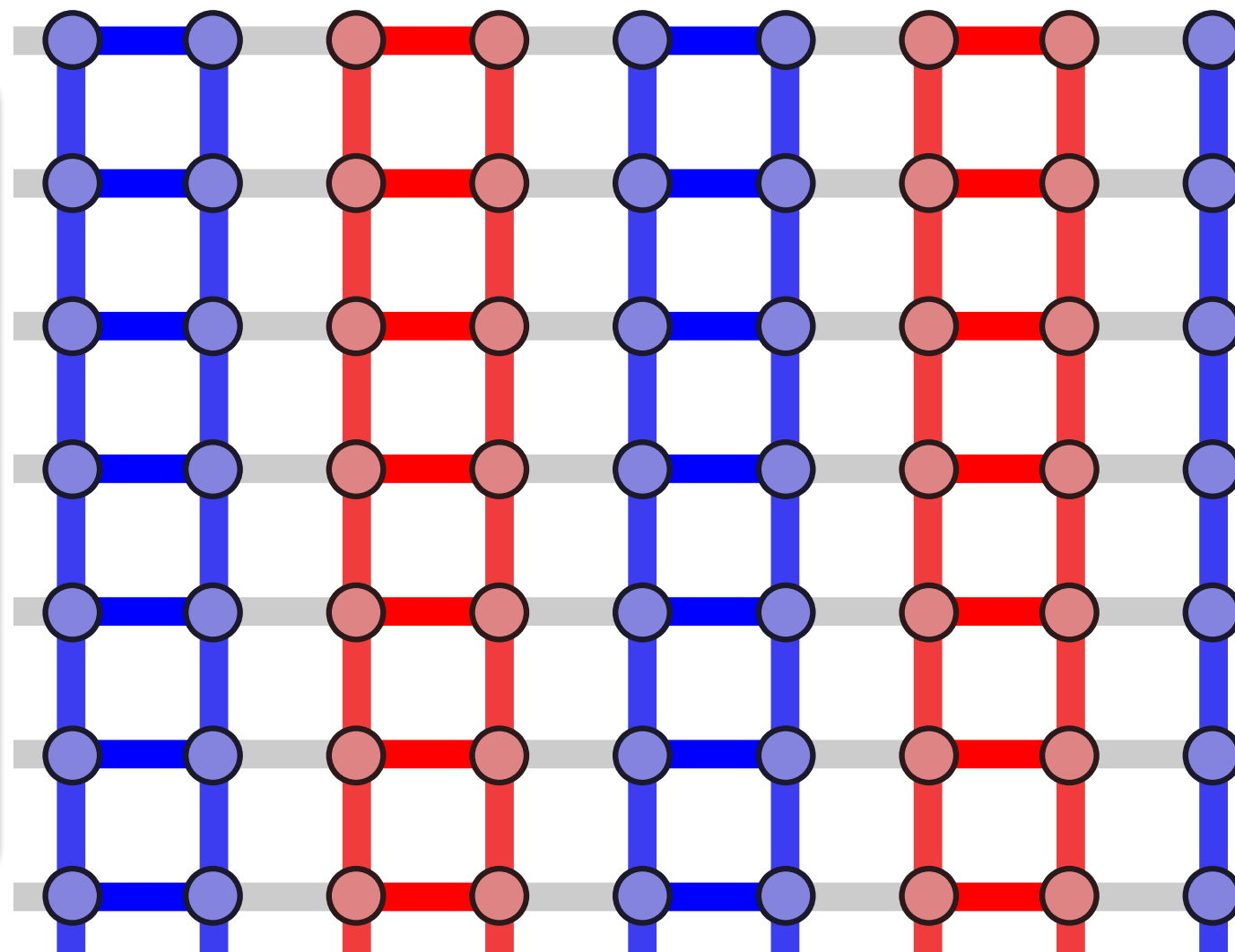
Plot of $P_{ij} = \langle c_{i\alpha}^\dagger c_{j\alpha} \rangle$ for $i = j$, and i, j nearest neighbors.

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

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

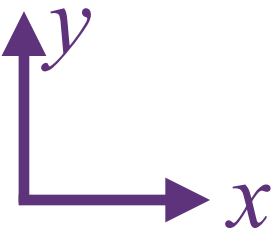


The pattern of charge densities and bond energies in the “stripe” model yields a combination of s and s' components



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

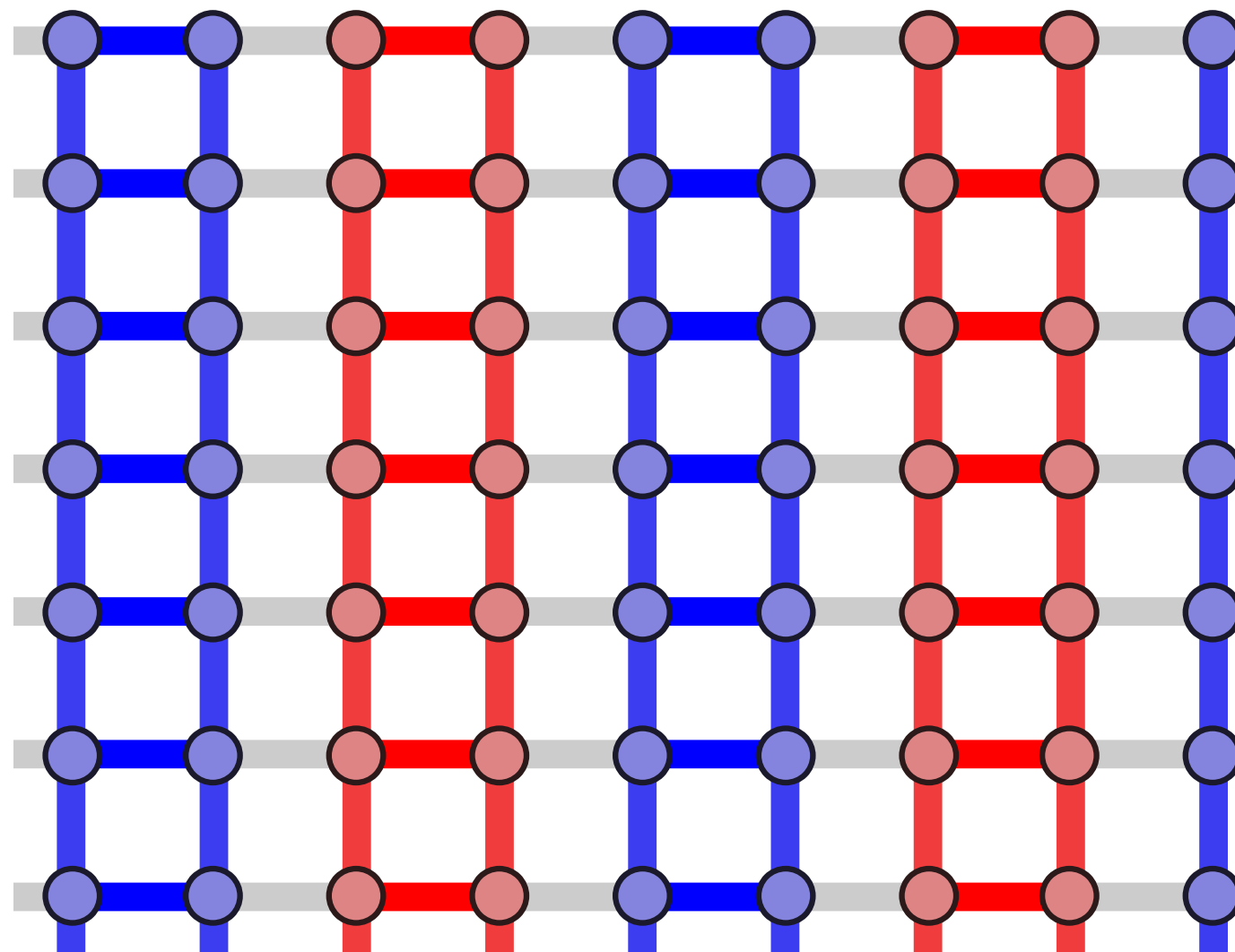
Unconventional DW order: $s + s'$ -form factor



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



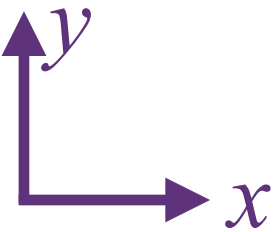
David
Hawthorn,
Waterloo

Unconventional DW order: d -form factor

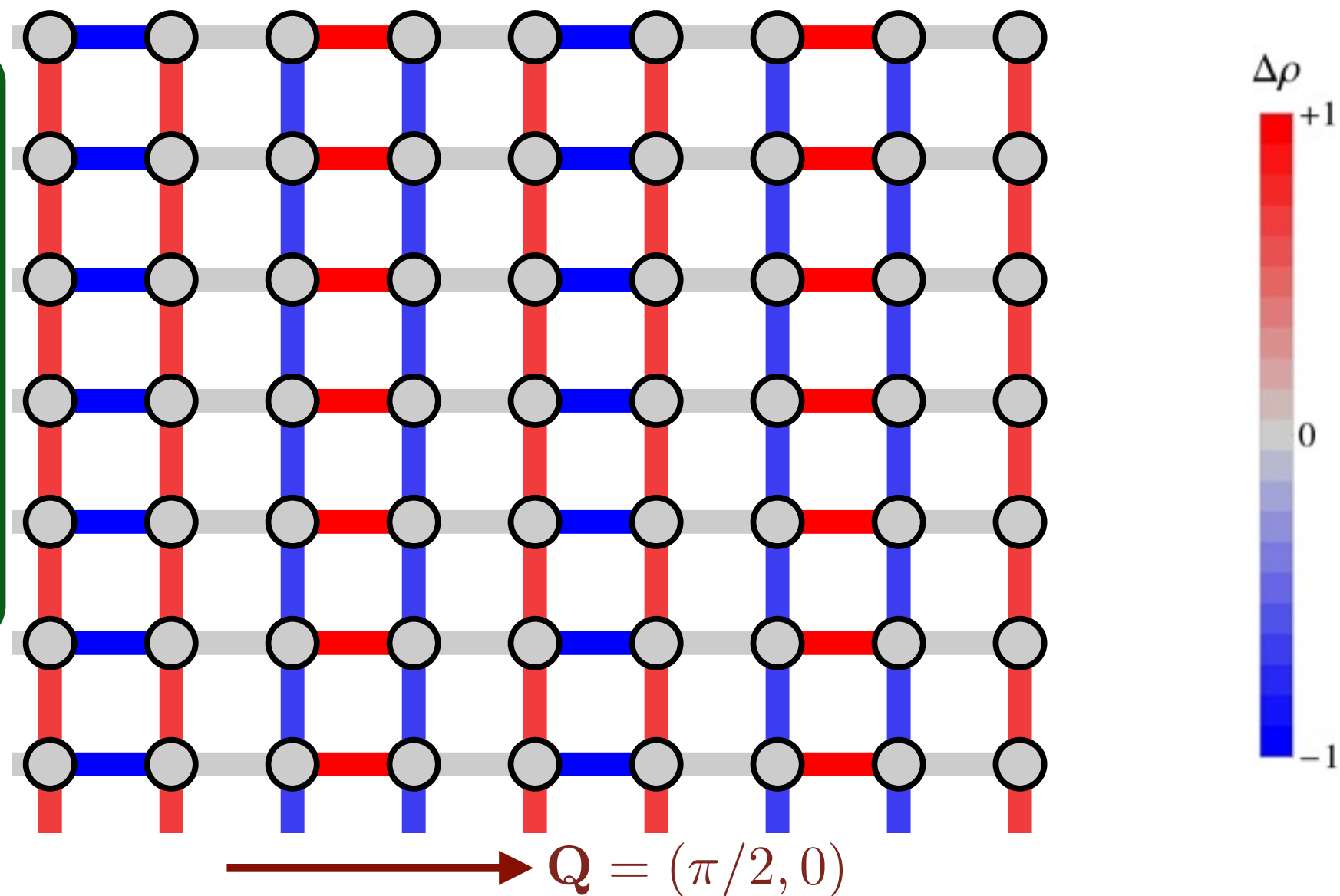
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$$\mathcal{P}(\mathbf{k}) = e^{i\phi} [\cos(k_x) - \cos(k_y)] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$



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



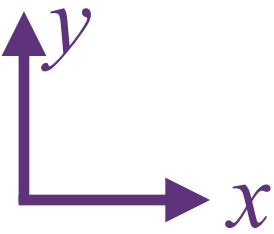
M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075128 (2010).
S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).

Unconventional DW order: d -form factor

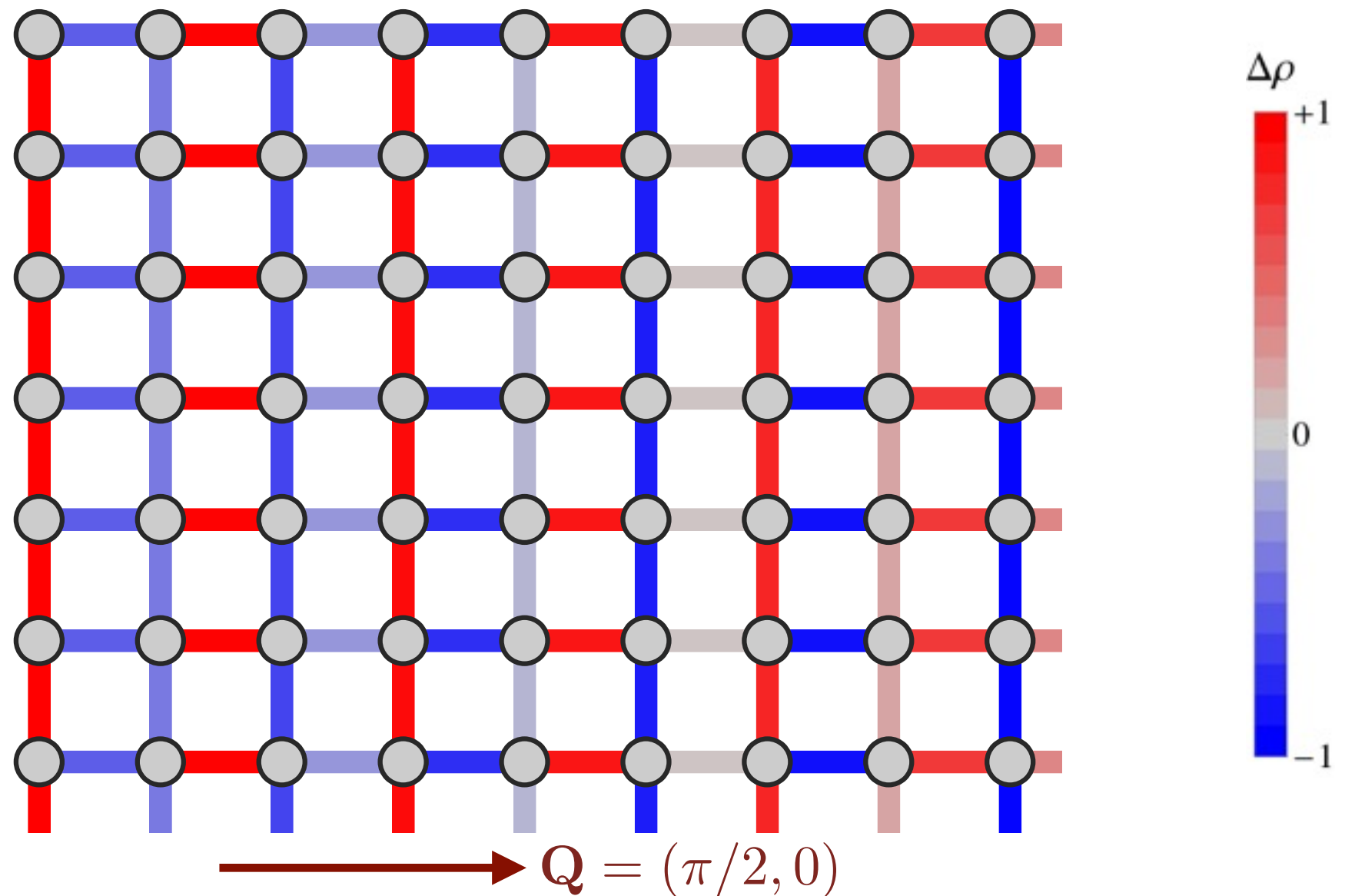
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$$\mathcal{P}(\mathbf{k}) = e^{i\phi} [\cos(k_x) - \cos(k_y)] \quad \text{and} \quad \mathbf{Q} = 2\pi(0.317, 0)$$



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

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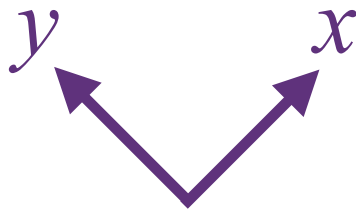
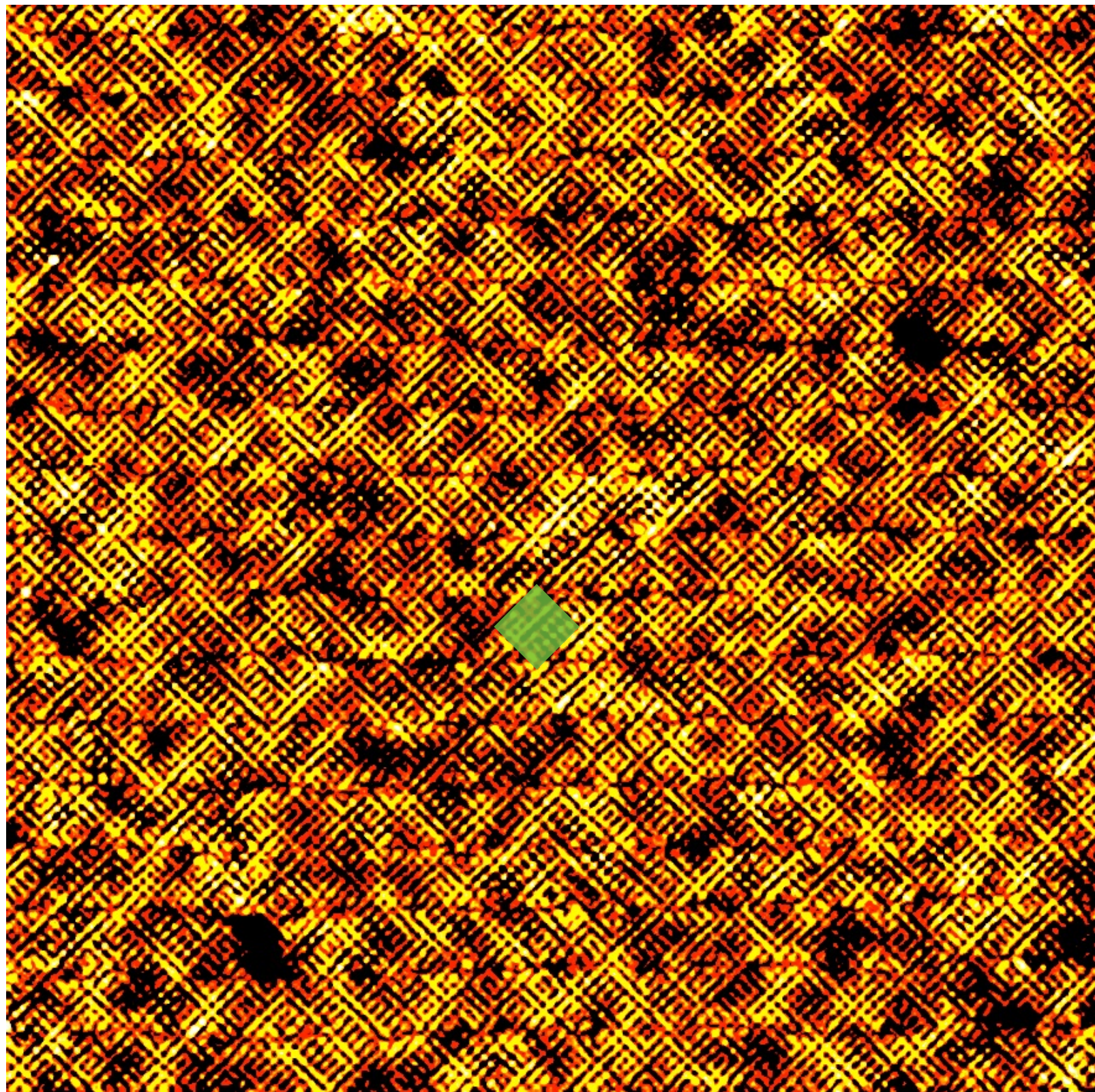
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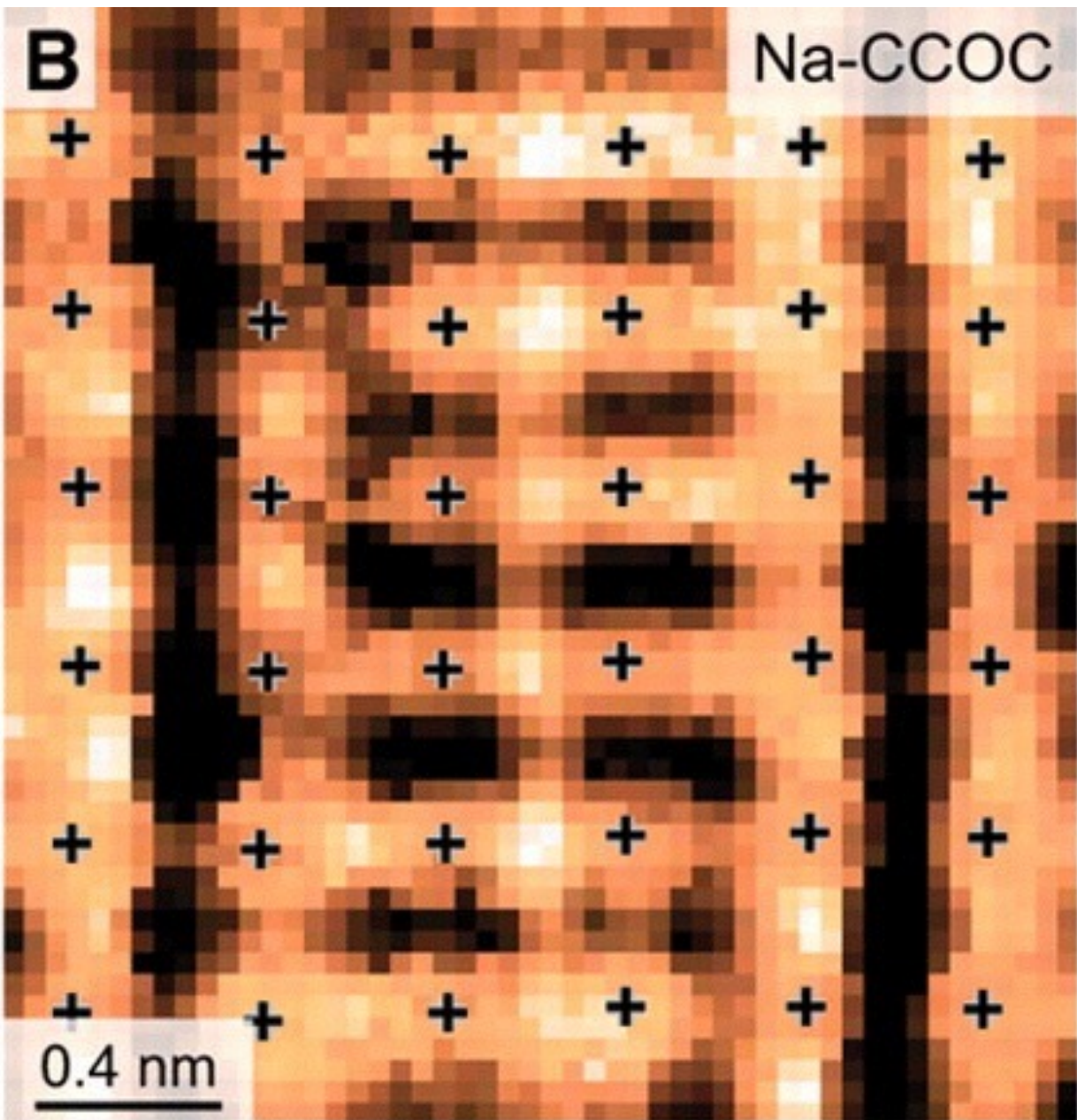
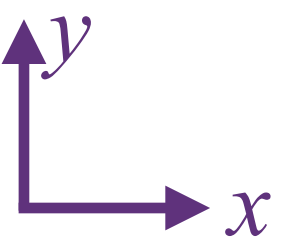
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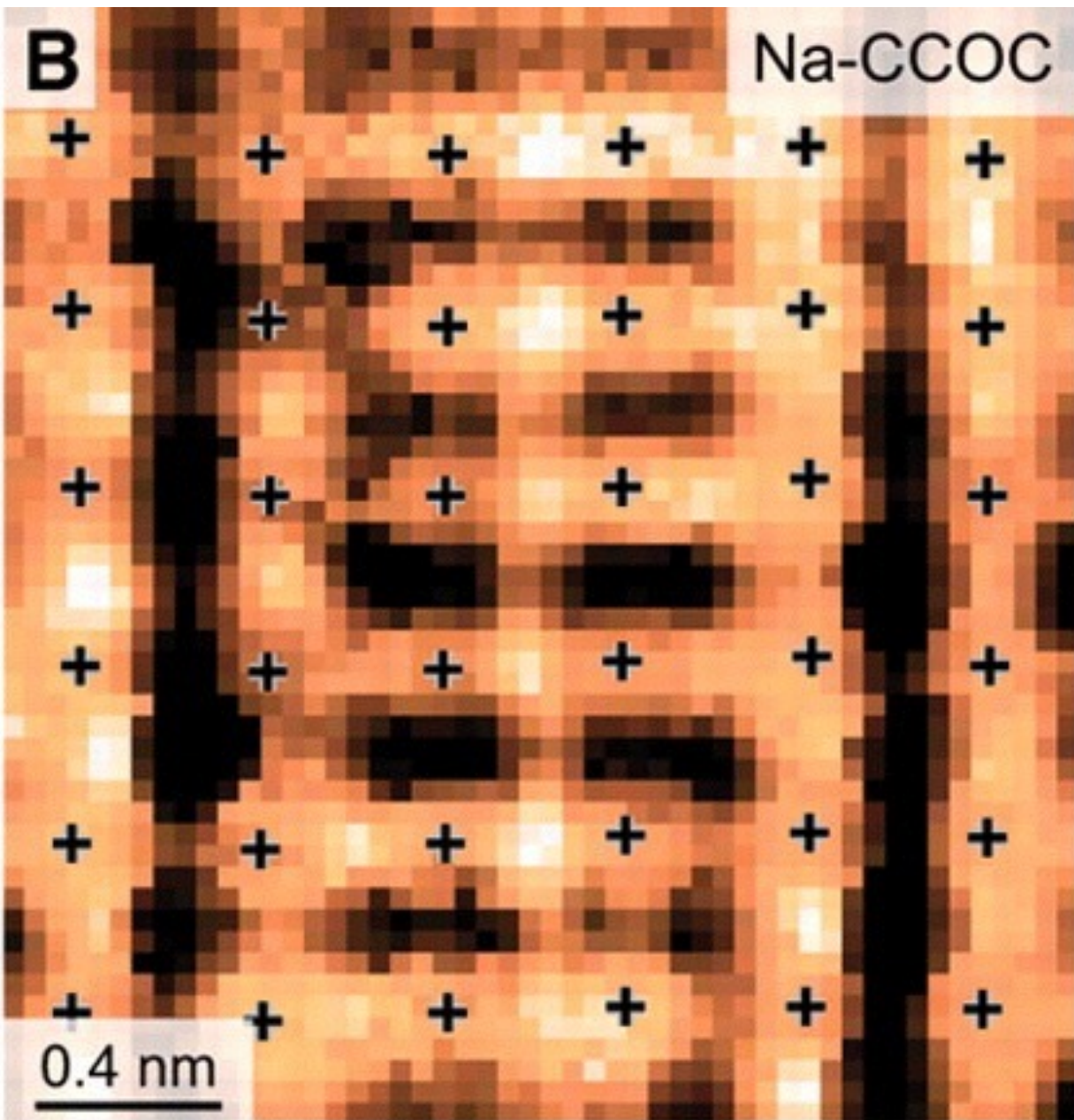
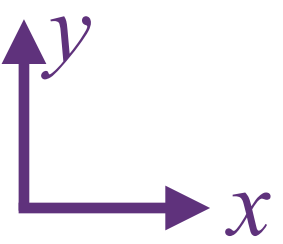
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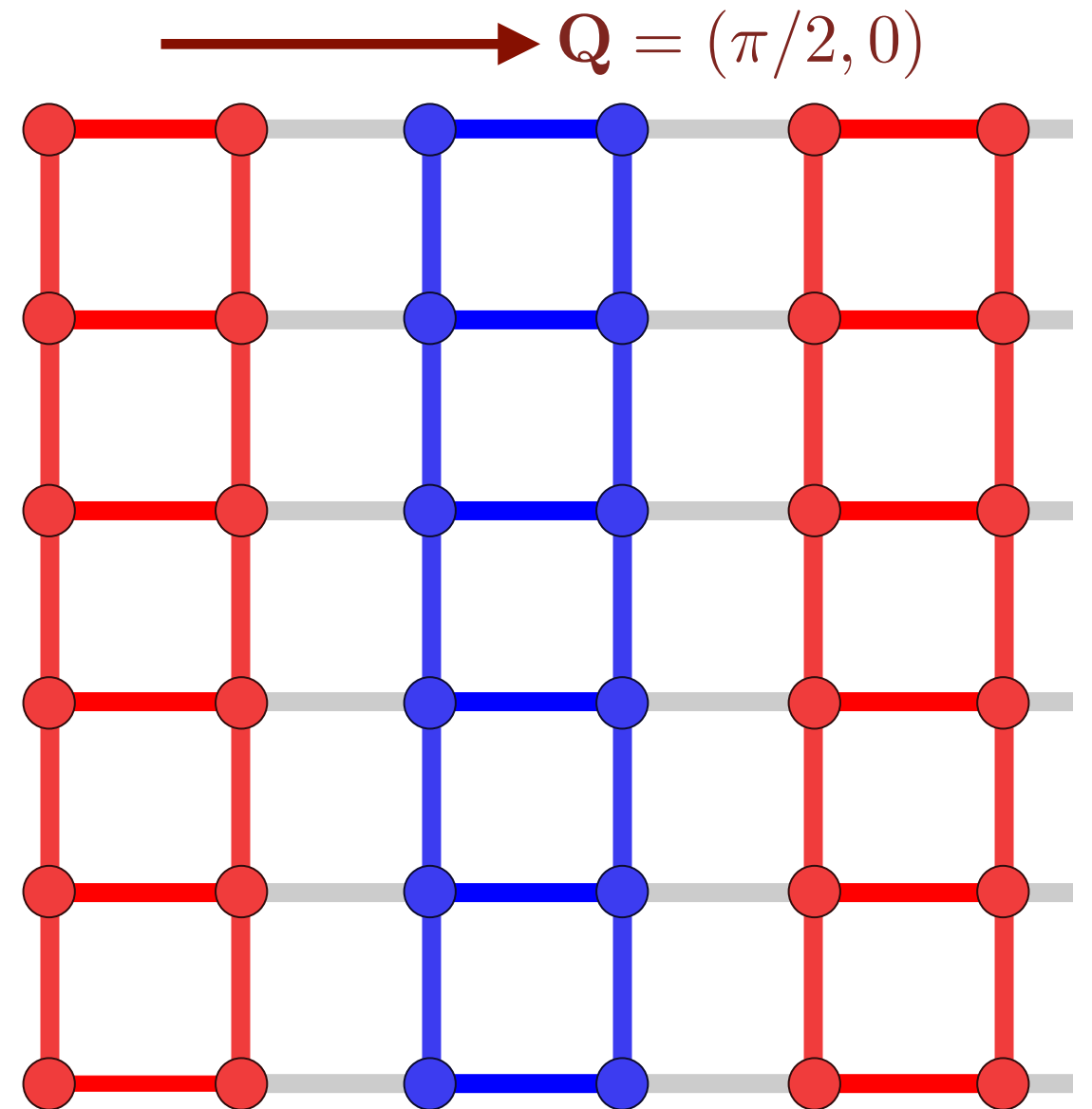
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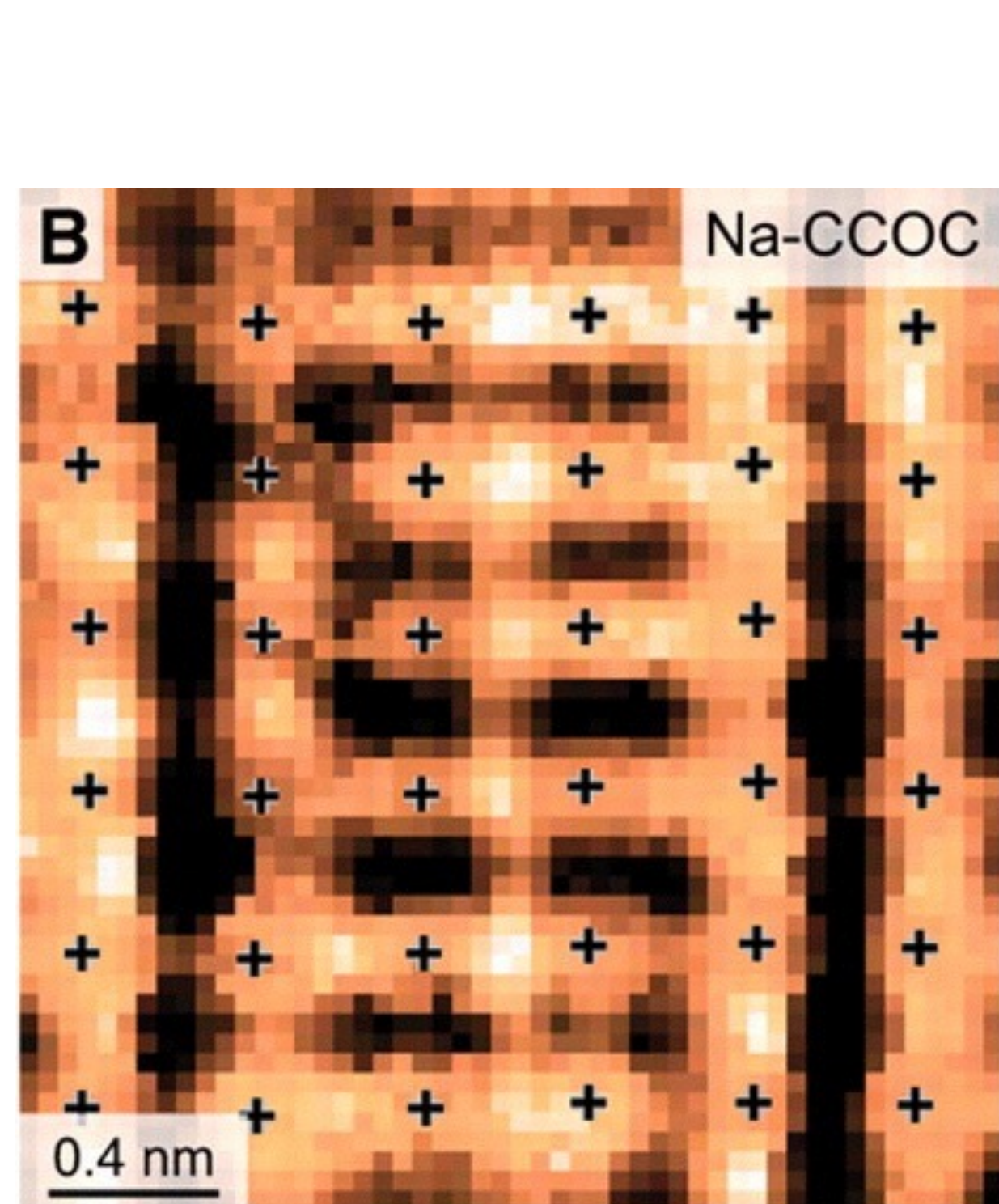


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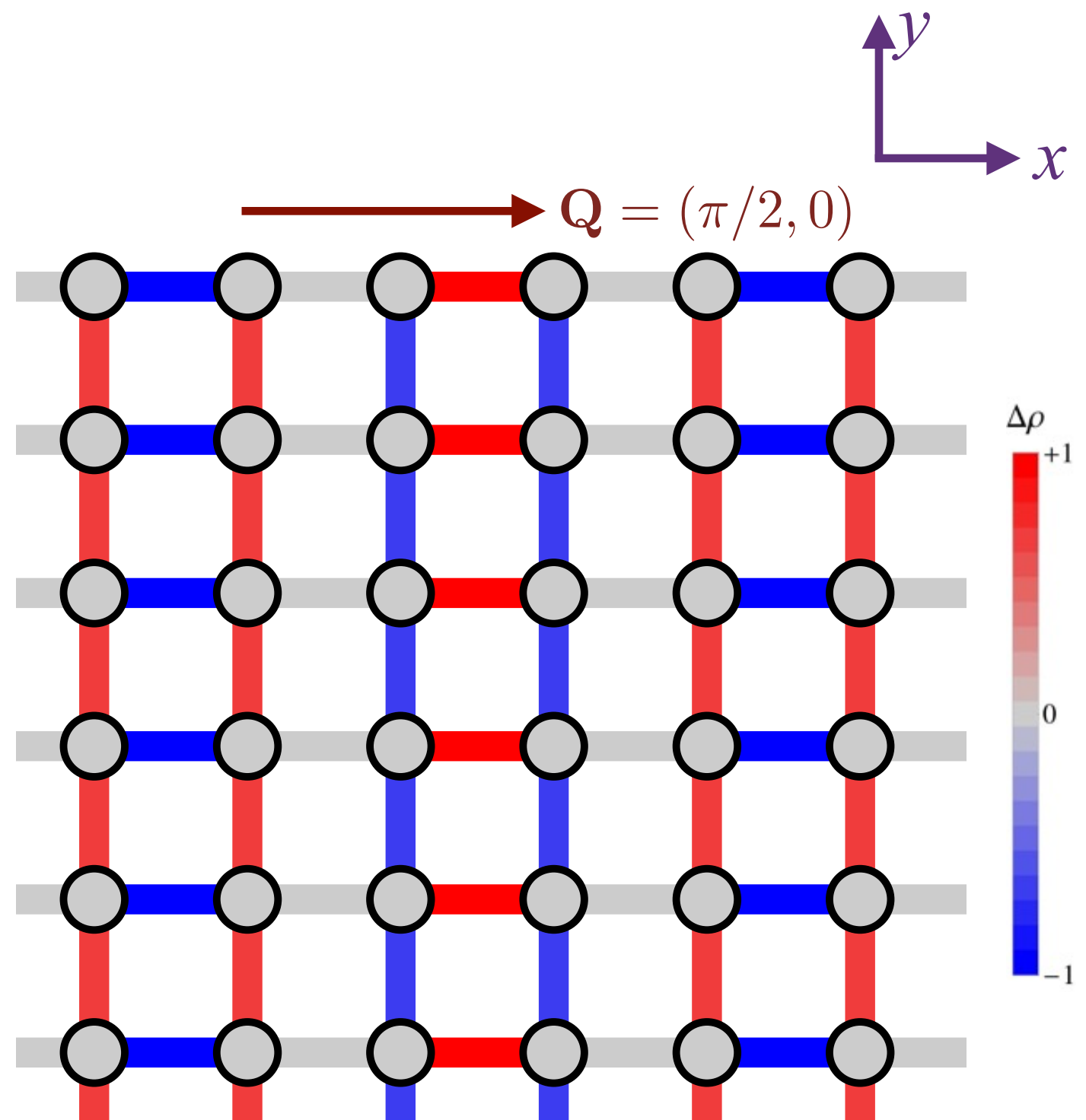


$s + s'$ -form factor density wave

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

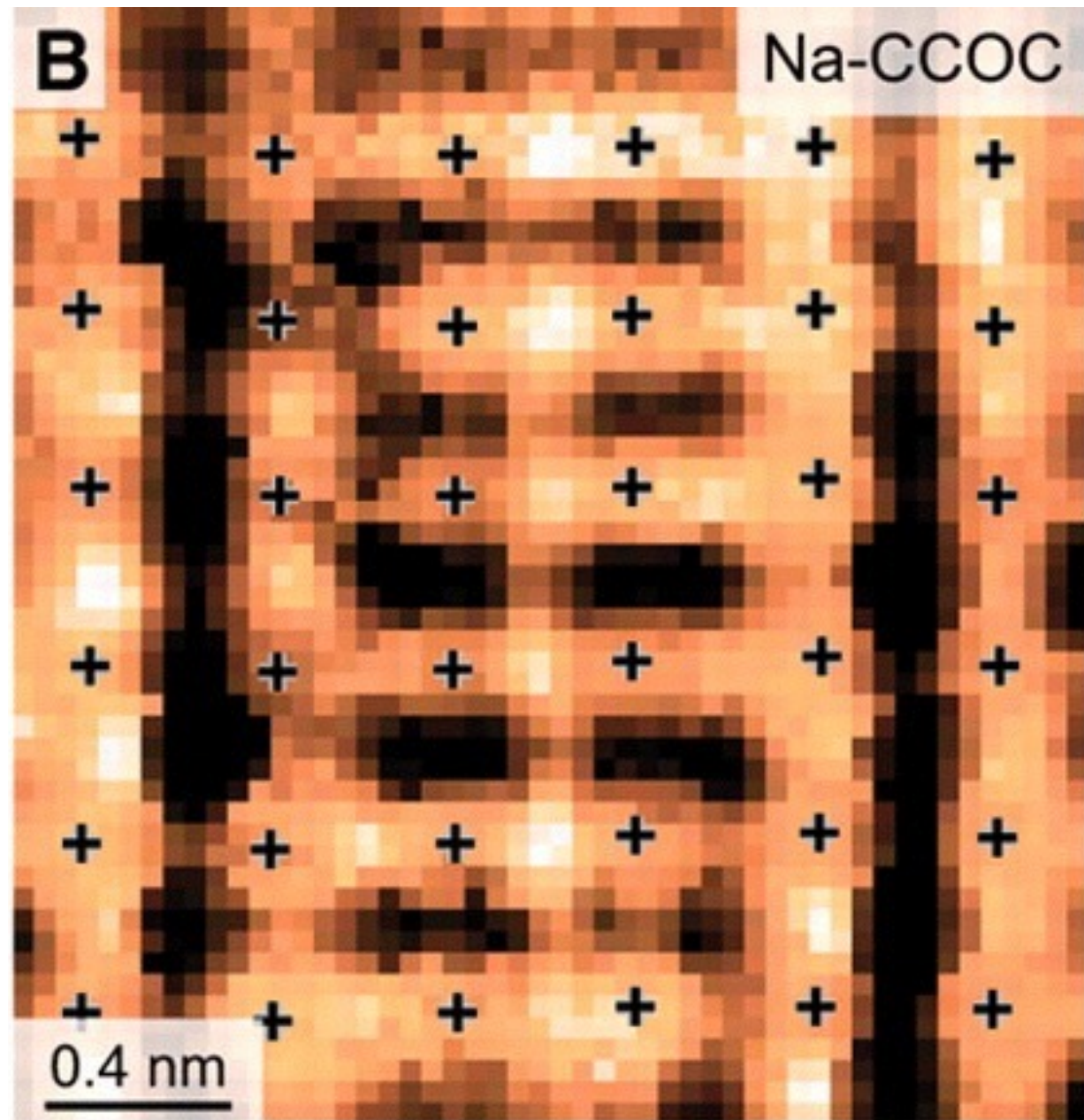
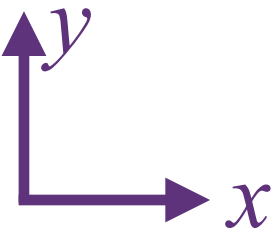


Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)

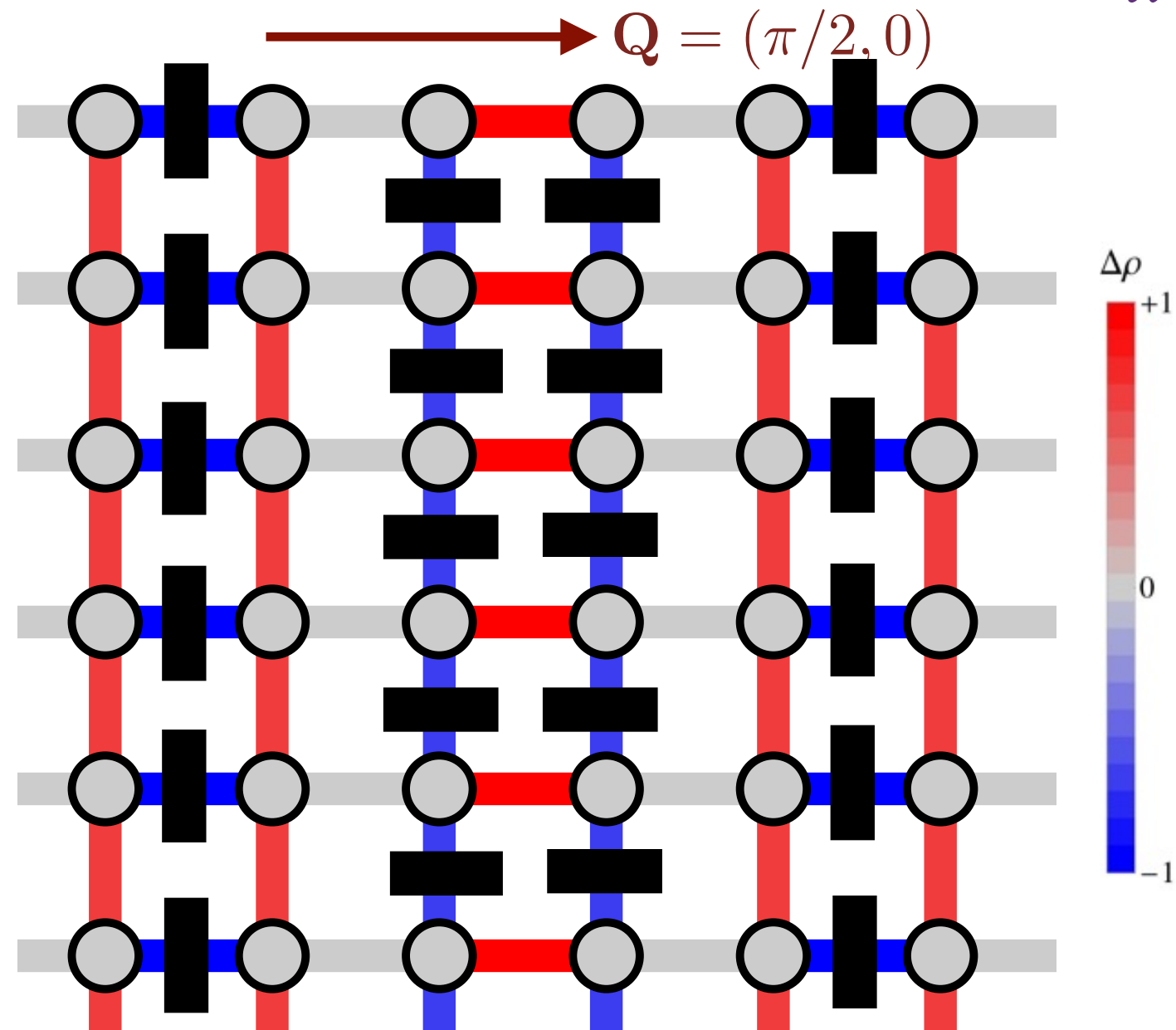


d-form factor density wave order

M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075128 (2010).
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Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)



d-form factor density wave order

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}

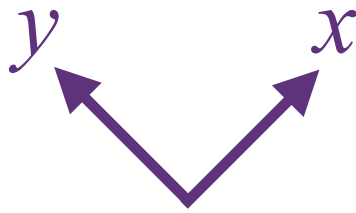
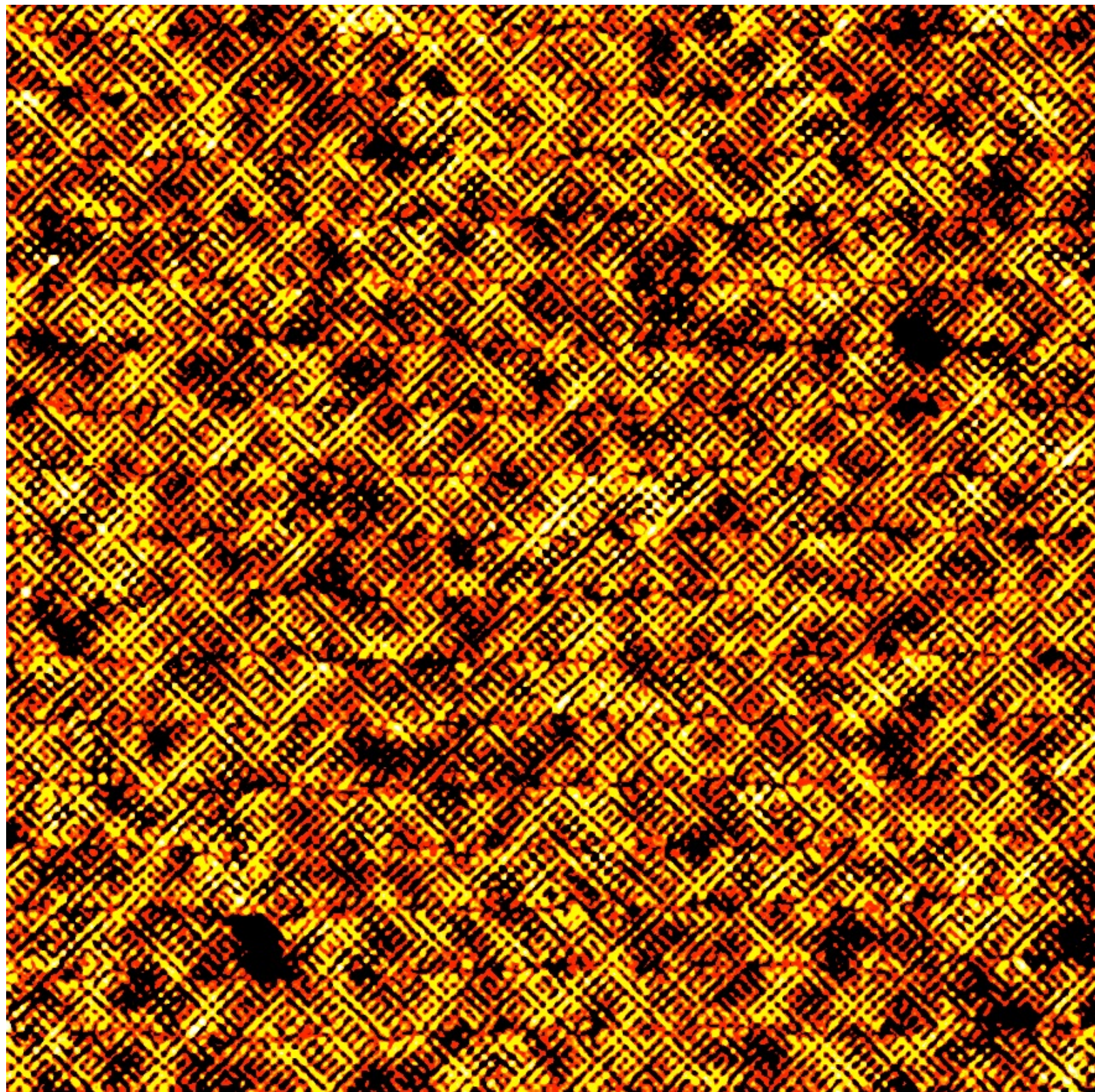
The identity of the fundamental broken symmetry (if any) in the underdoped cuprates is unresolved. However, evidence has been accumulating that this state may be an unconventional density wave. Here we carry out site-specific measurements within each CuO_2 unit cell, segregating the results into three separate electronic structure images containing only the Cu sites [$\text{Cu}(r)$] and only the x/y axis O sites [$\text{O}_x(r)$ and $\text{O}_y(r)$]. Phase-resolved Fourier analysis reveals directly that the modulations in the $\text{O}_x(r)$ and $\text{O}_y(r)$ 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.

See also

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A. Yazdani, Science
303, 1995 (2004).

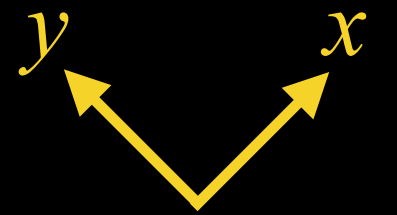
W. D. Wise, M. C. Boyer,
K. Chatterjee, T. Kondo,
T. Takeuchi, H. Ikuta,
Y. Wang, and
E. W. Hudson,
Nature Phys. **4**, 696
(2008).



“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.

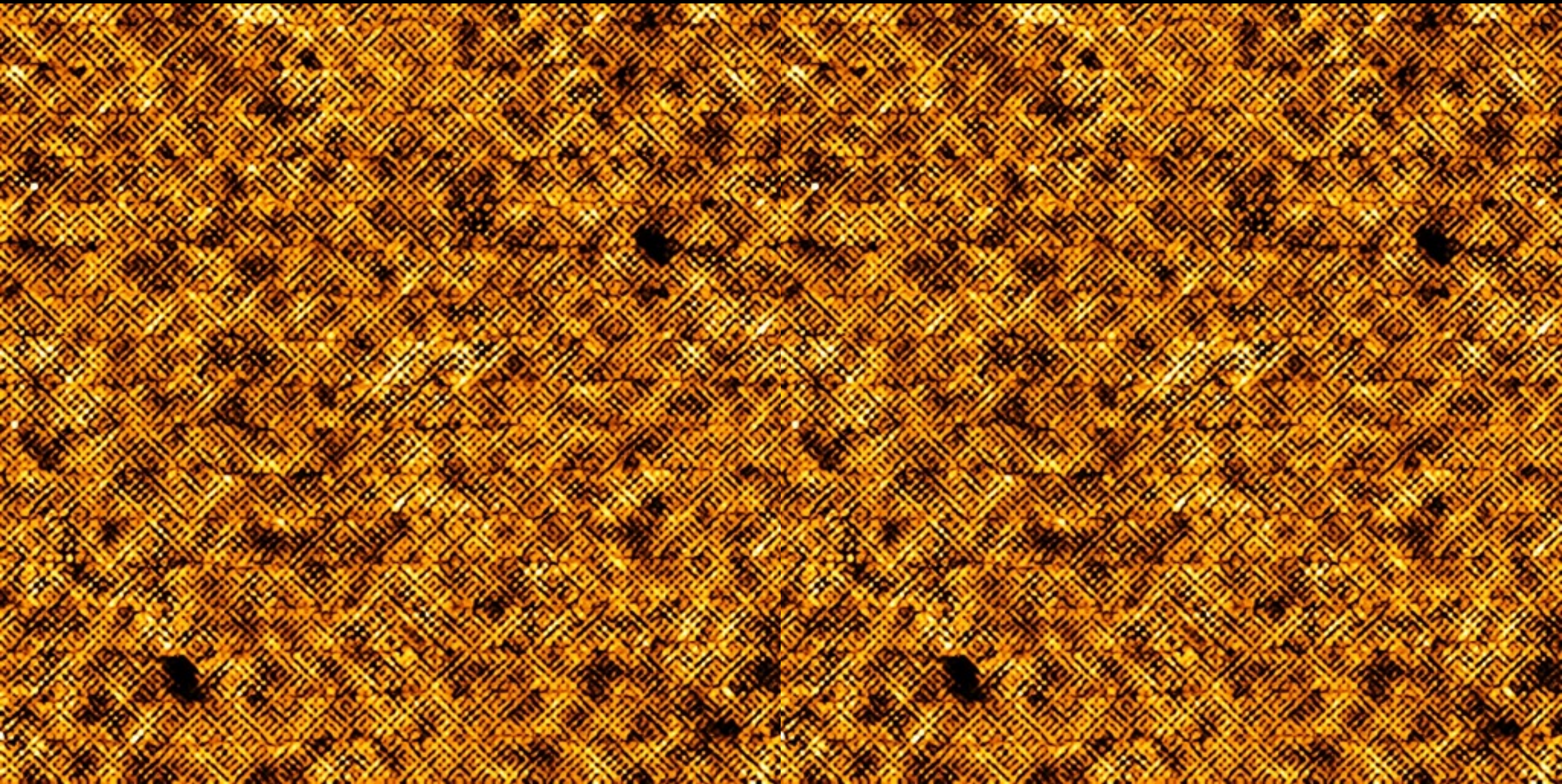
UD45K
BSCCO

$R(r, 150\text{mV})$



$R(r, 150\text{mV})$

$R(r, 150\text{mV})$



Note that these are identical images.

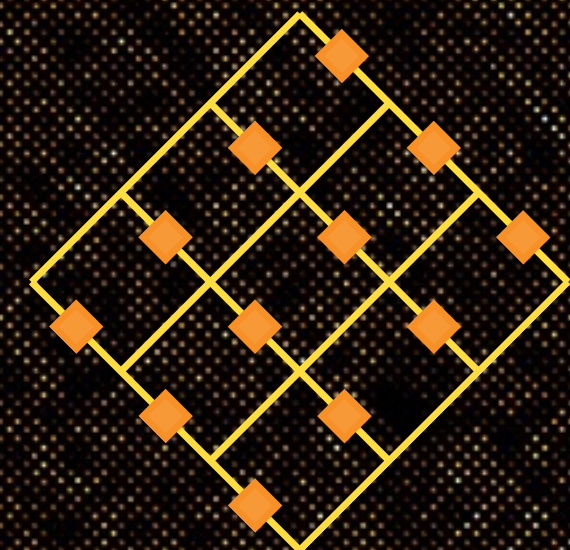
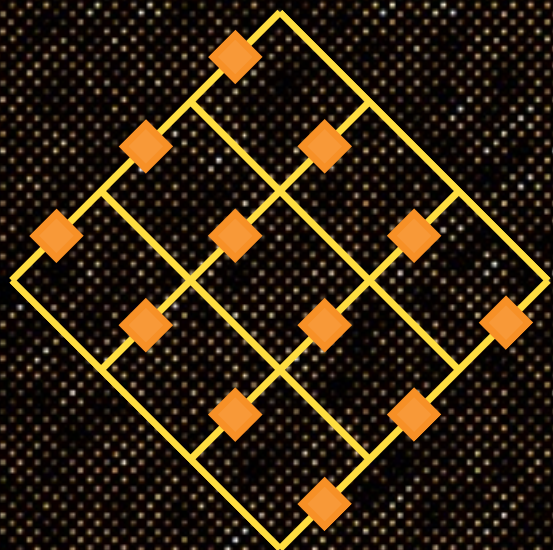
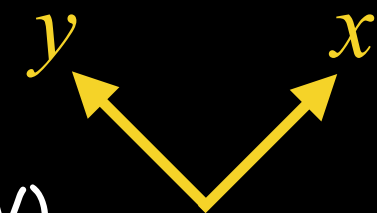
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

UD45K

$R(r=0, 150\text{mV})$

$R(r=O_x, 150\text{mV})$

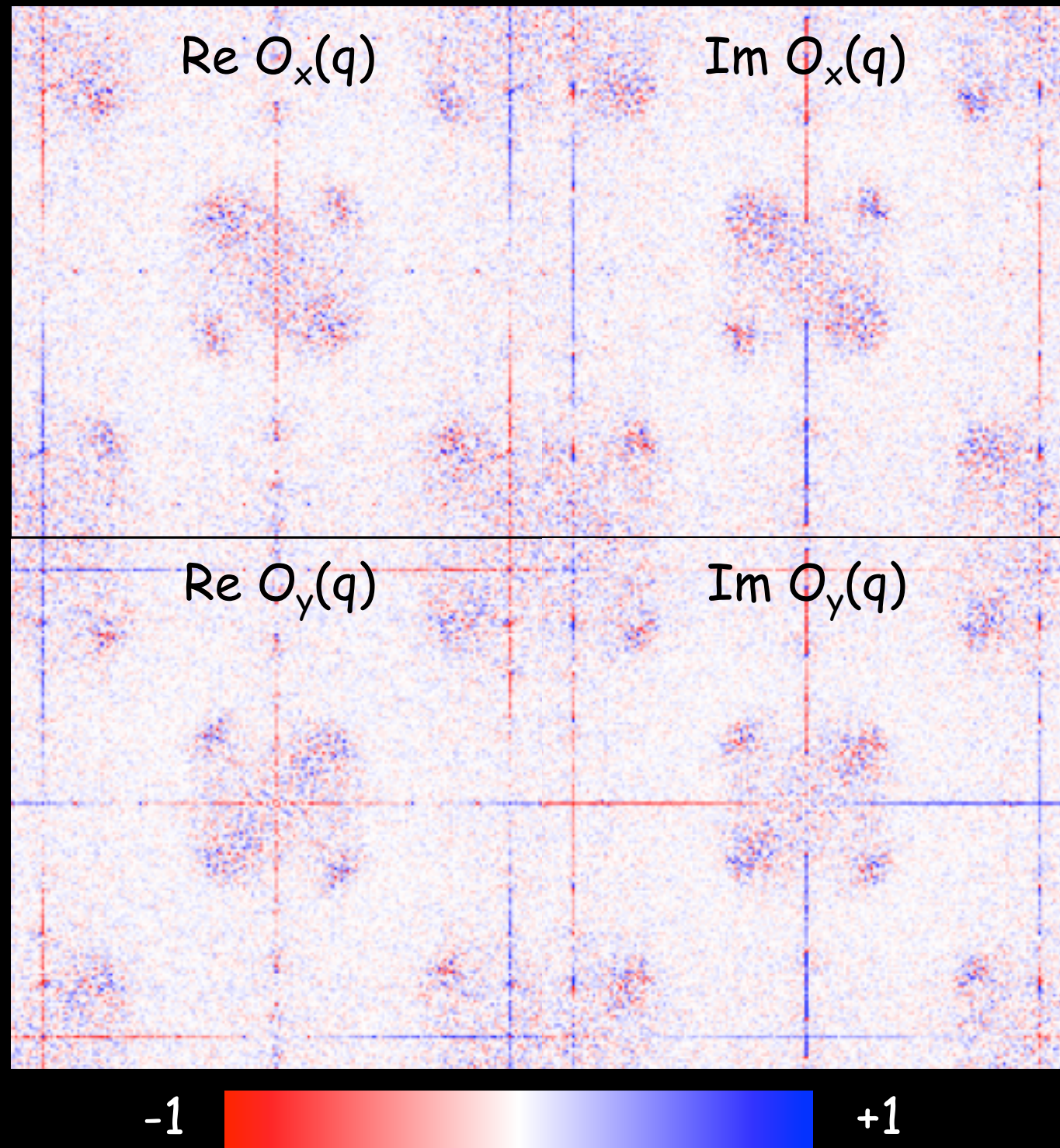
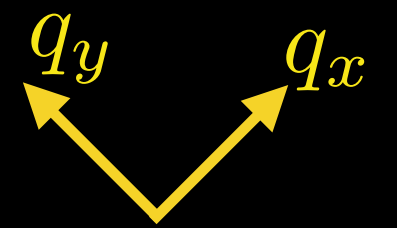
$R(r=O_y, 150\text{mV})$



0.6 1.5

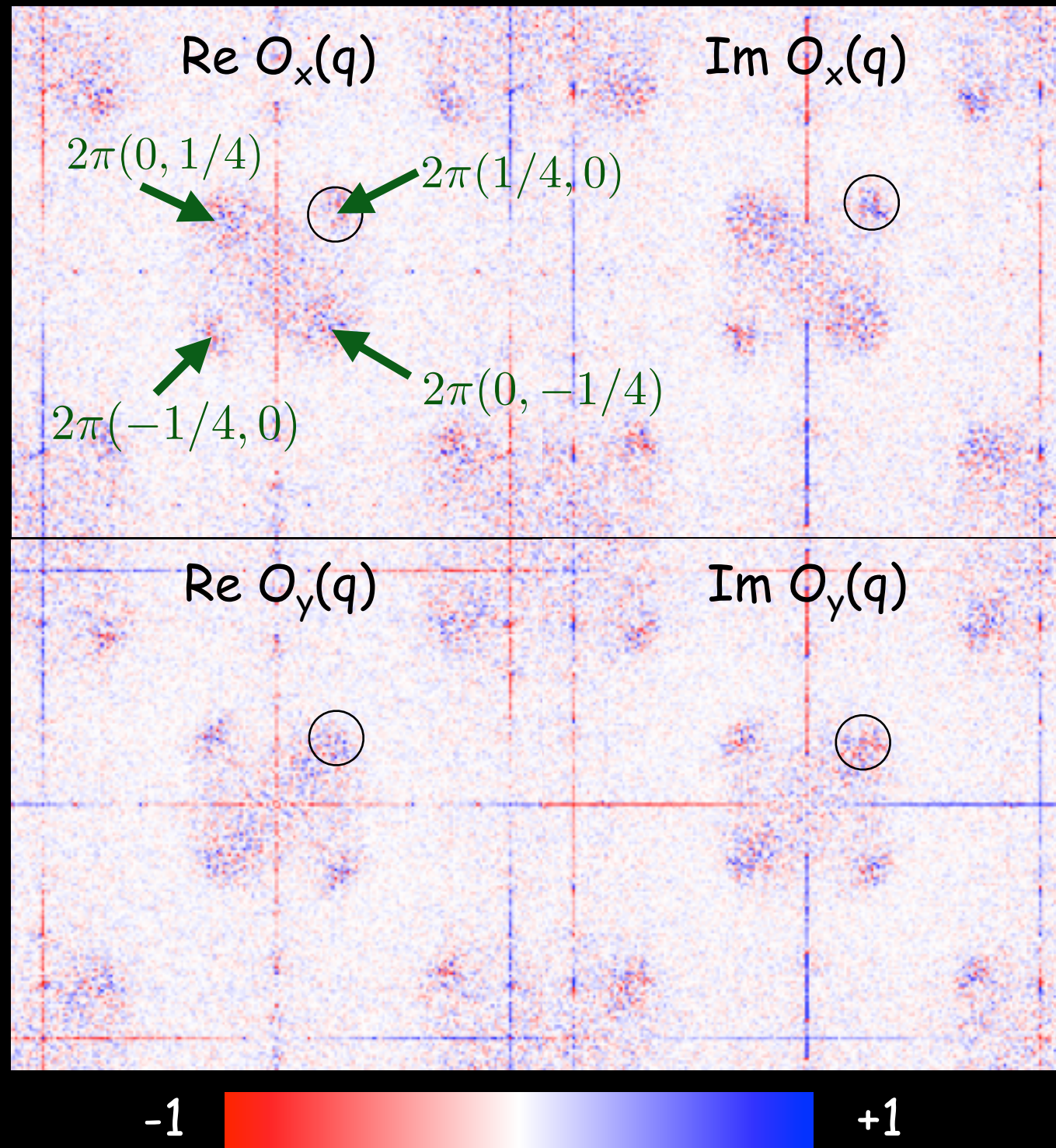
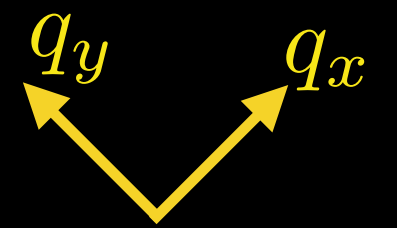
UD45K

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



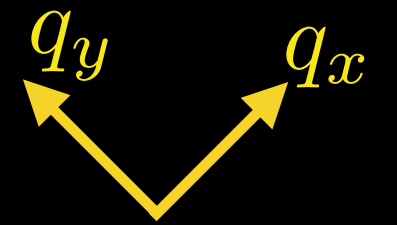
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

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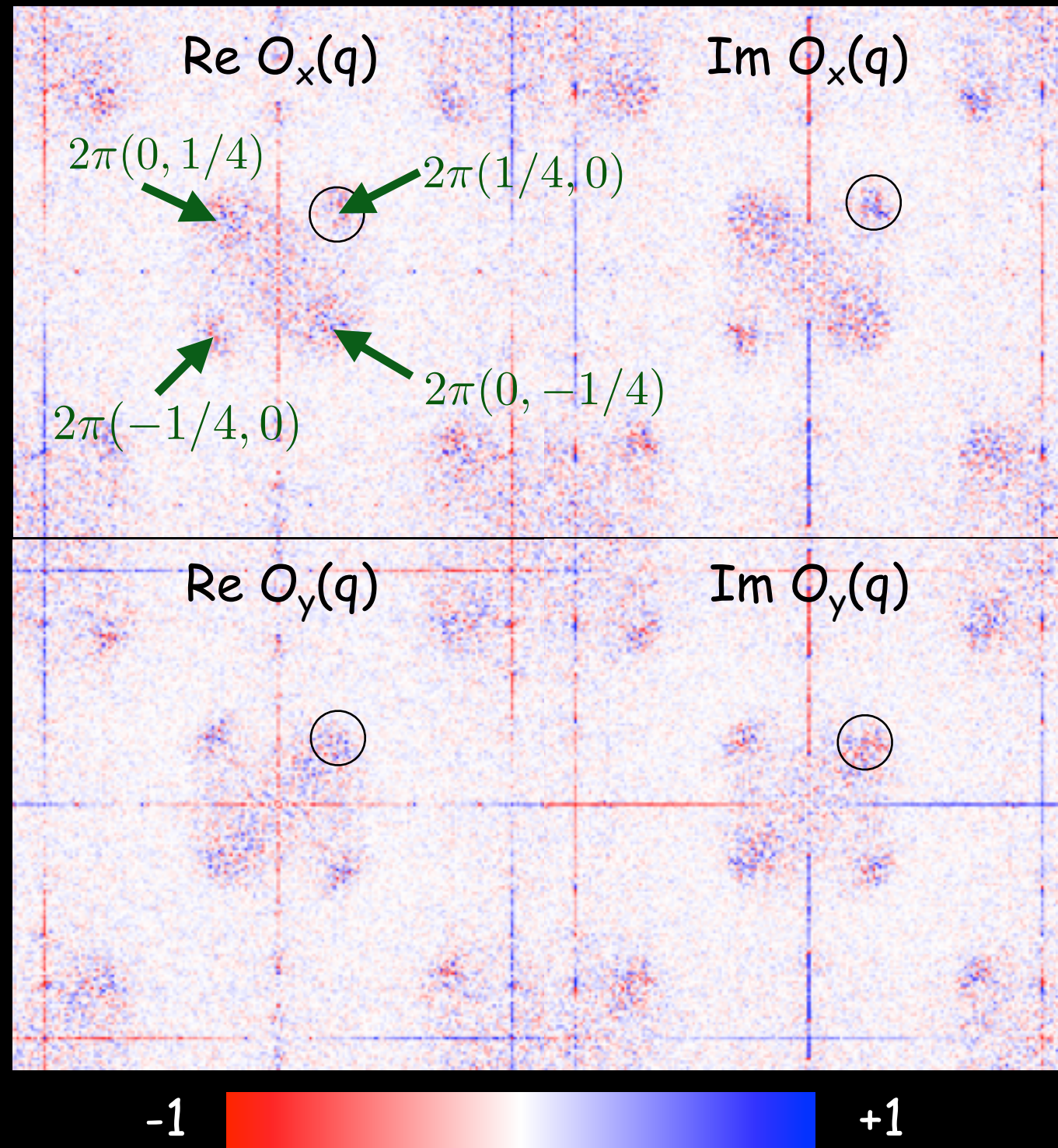


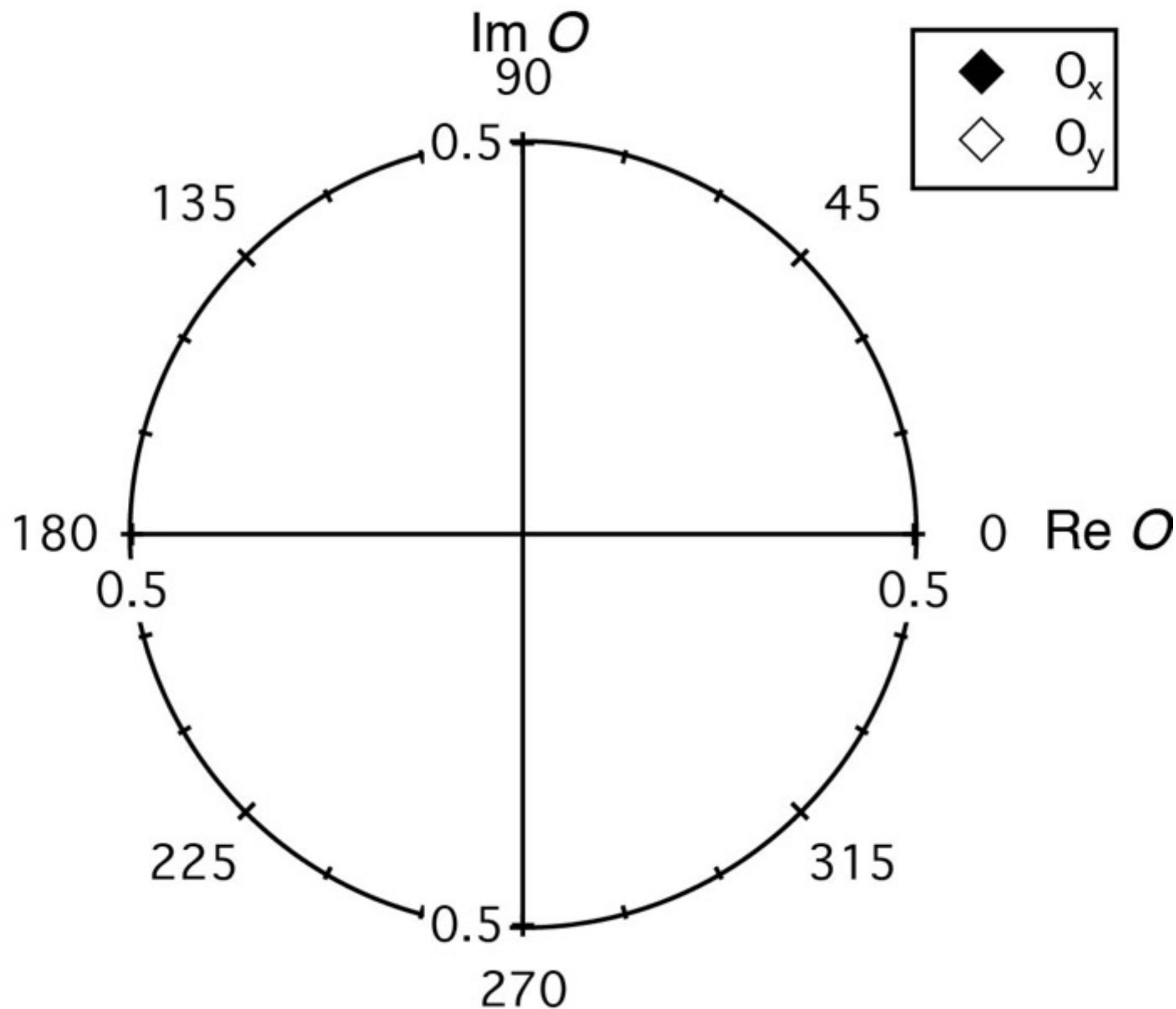
UD45K

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

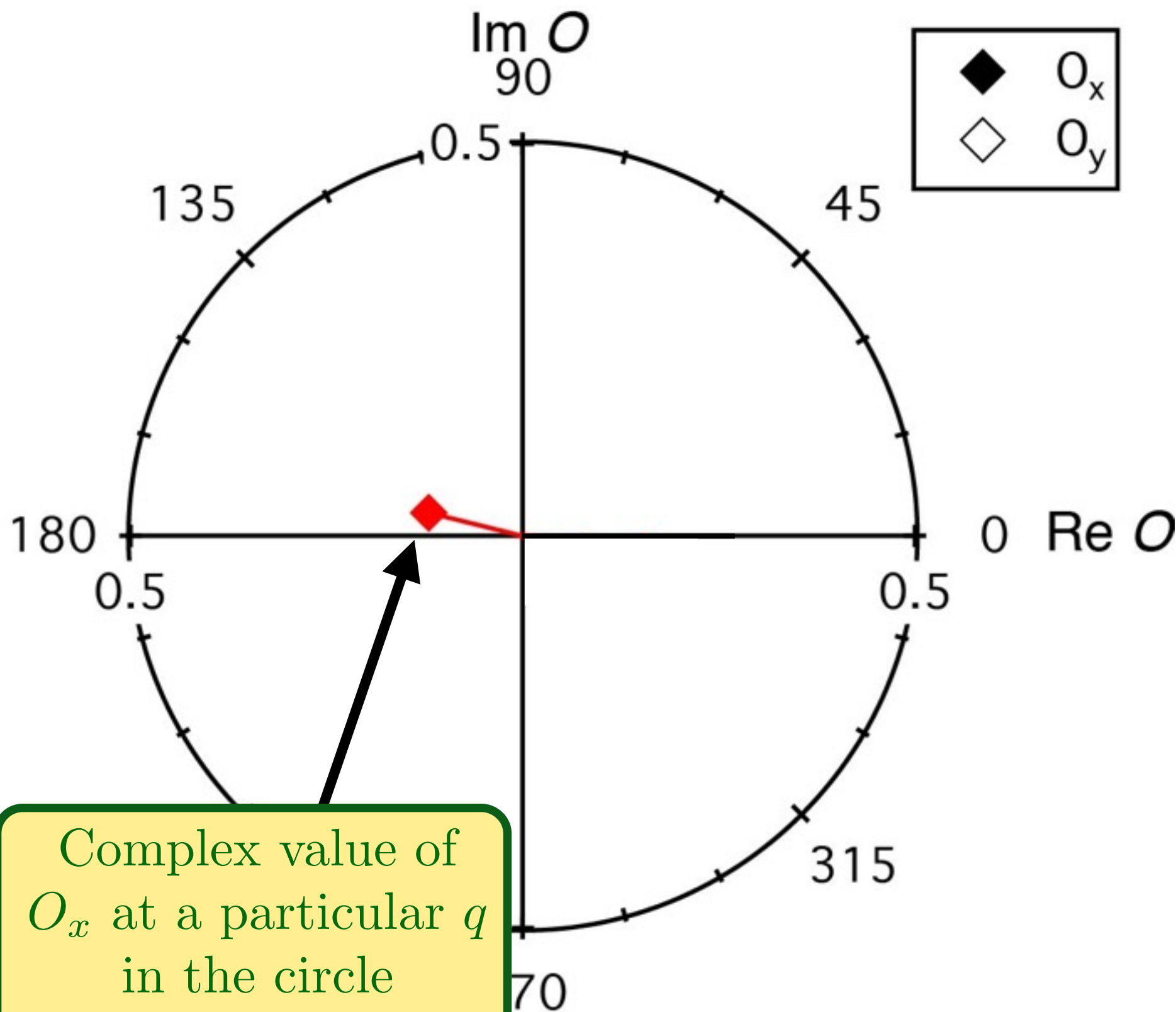


For each pixel in the circles, we obtain 2 complex numbers, $O_x(q)$ and $O_y(q)$.



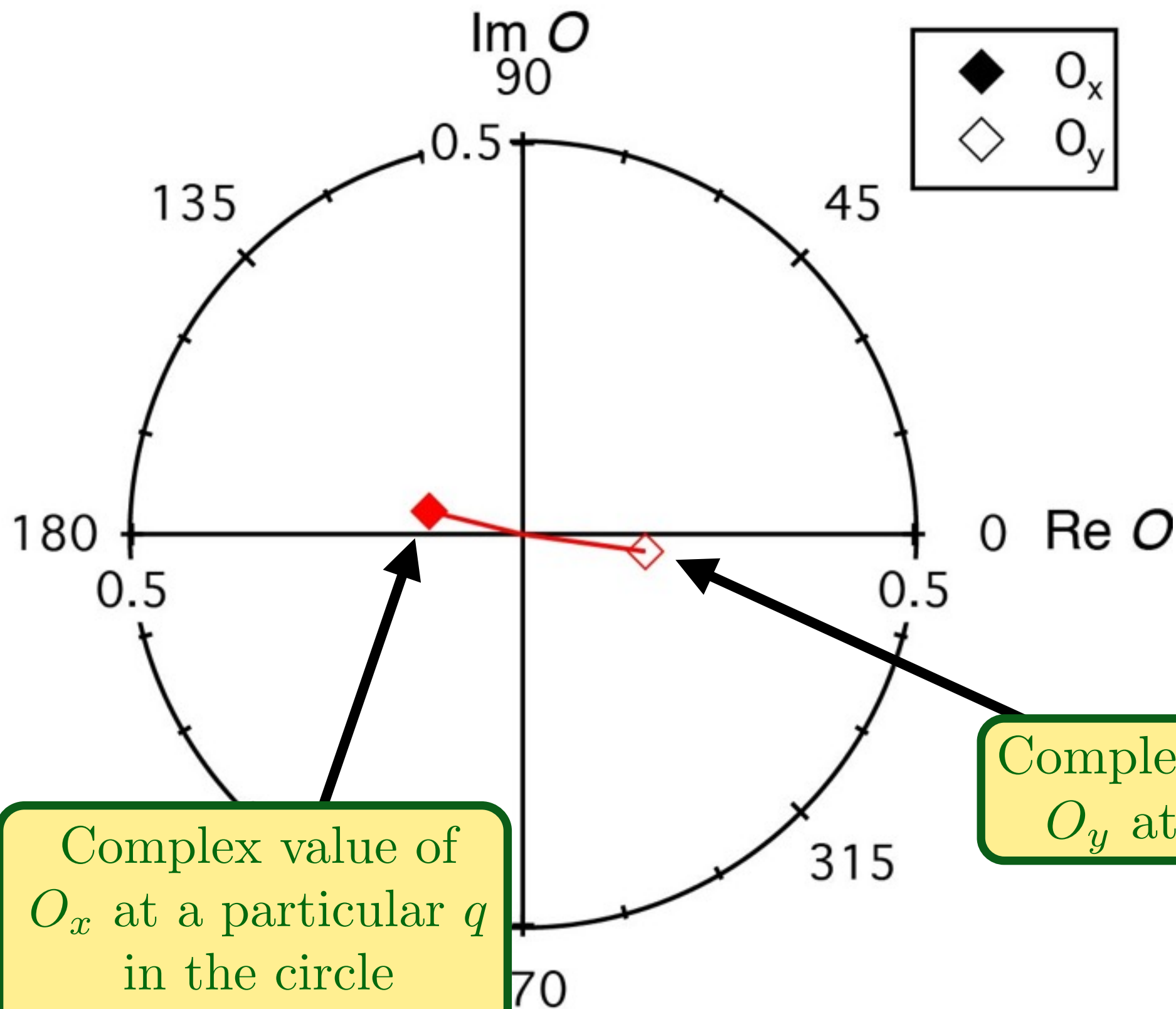


**Phase-sensitive
measurement of
the d -form factor
of density wave
order**



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

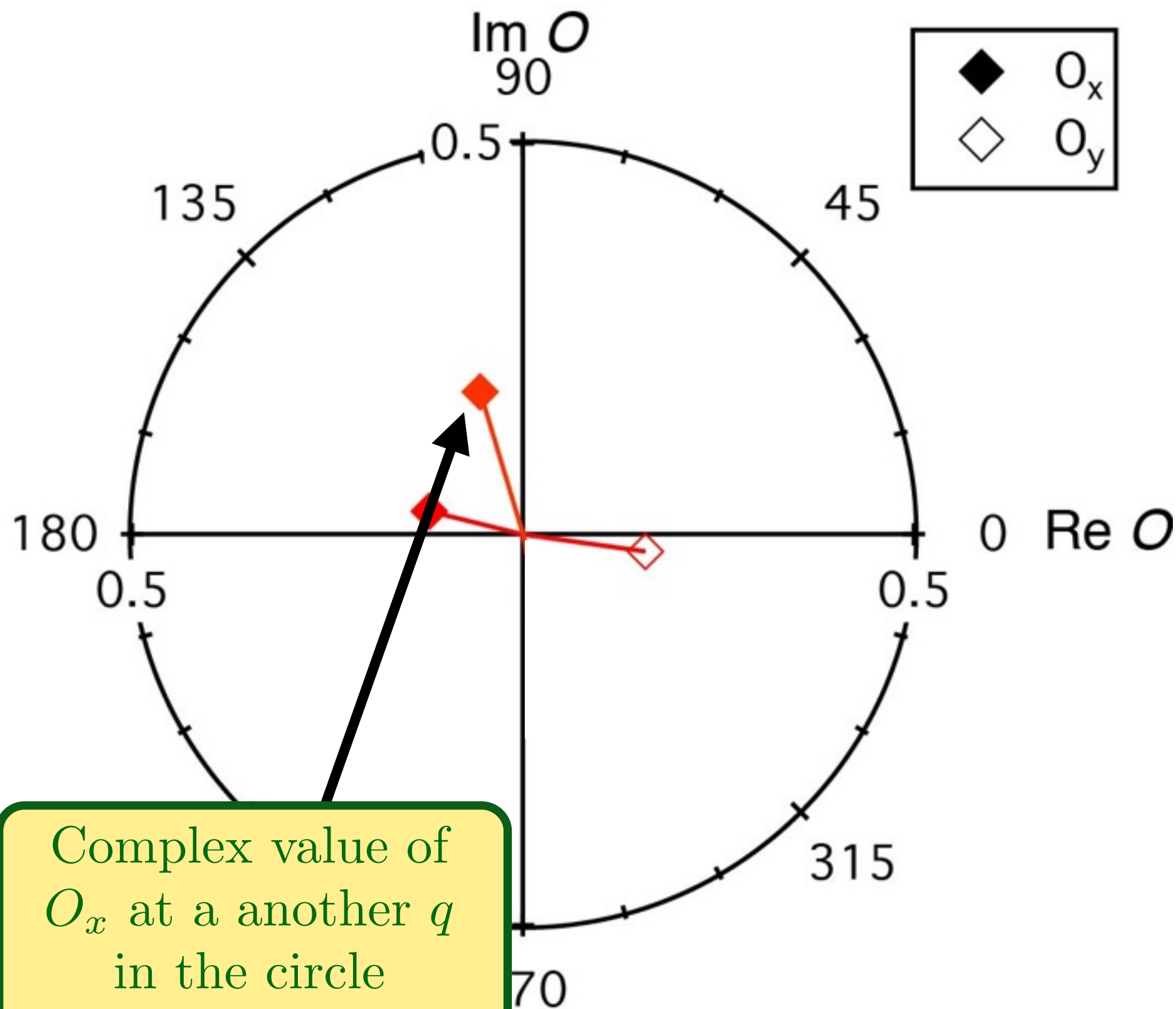
Complex value of
 O_x at a particular q
in the circle
around $2\pi(1/4, 0)$.



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

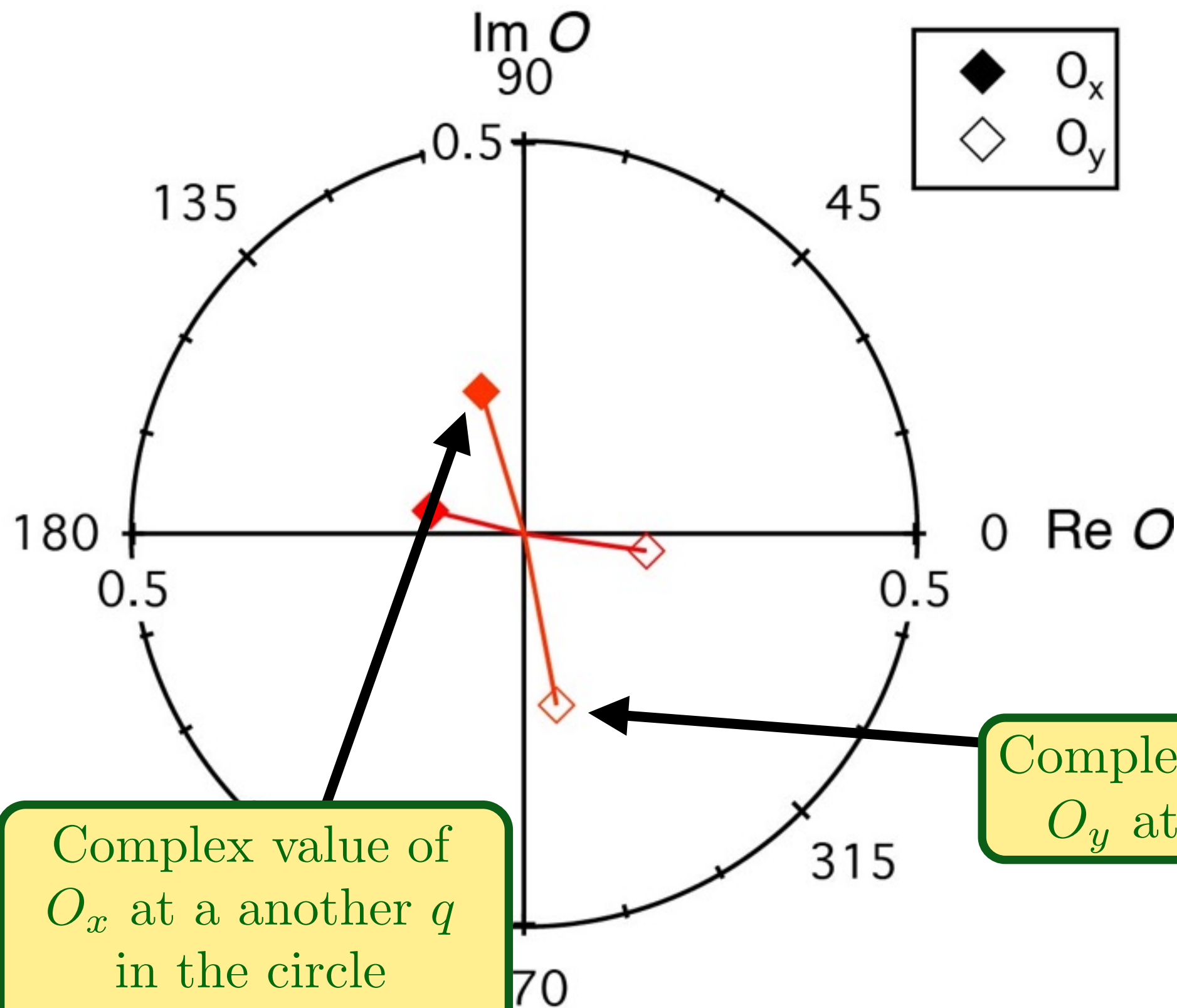
Complex value of
 O_x at a particular q
in the circle
around $2\pi(1/4, 0)$.

Complex value of
 O_y at same q



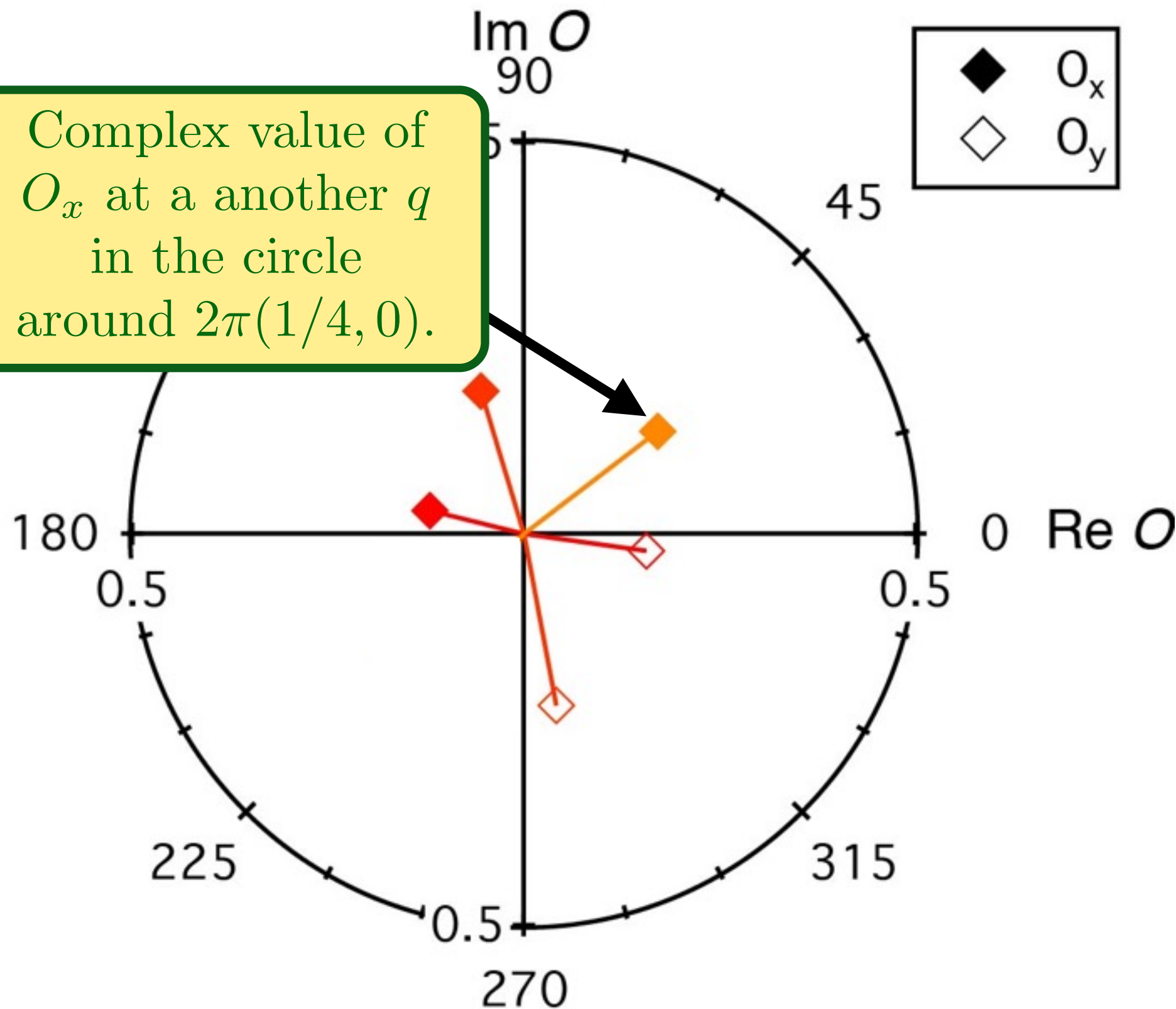
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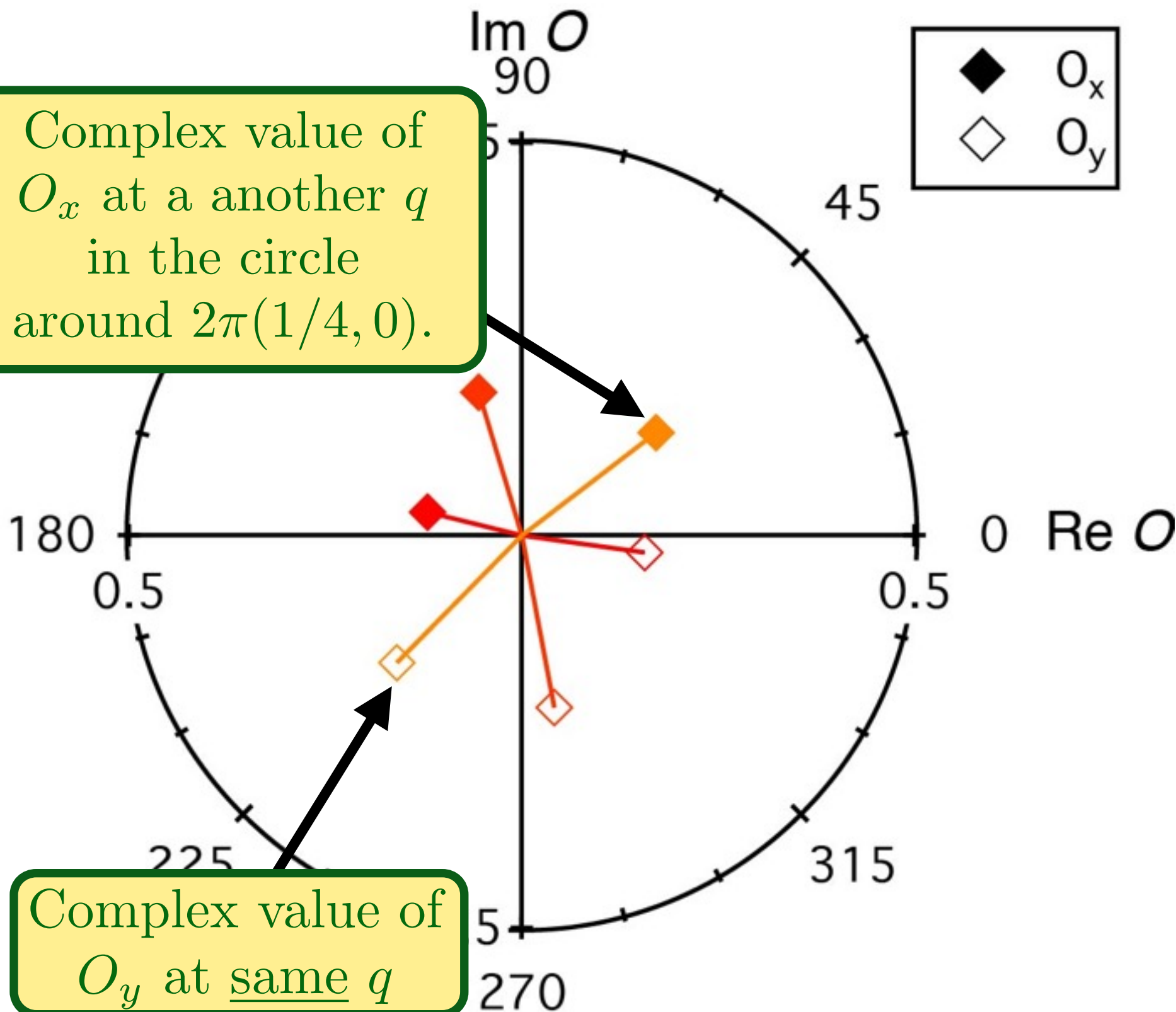
Complex value of O_x at a another q in the circle around $2\pi(1/4, 0)$.



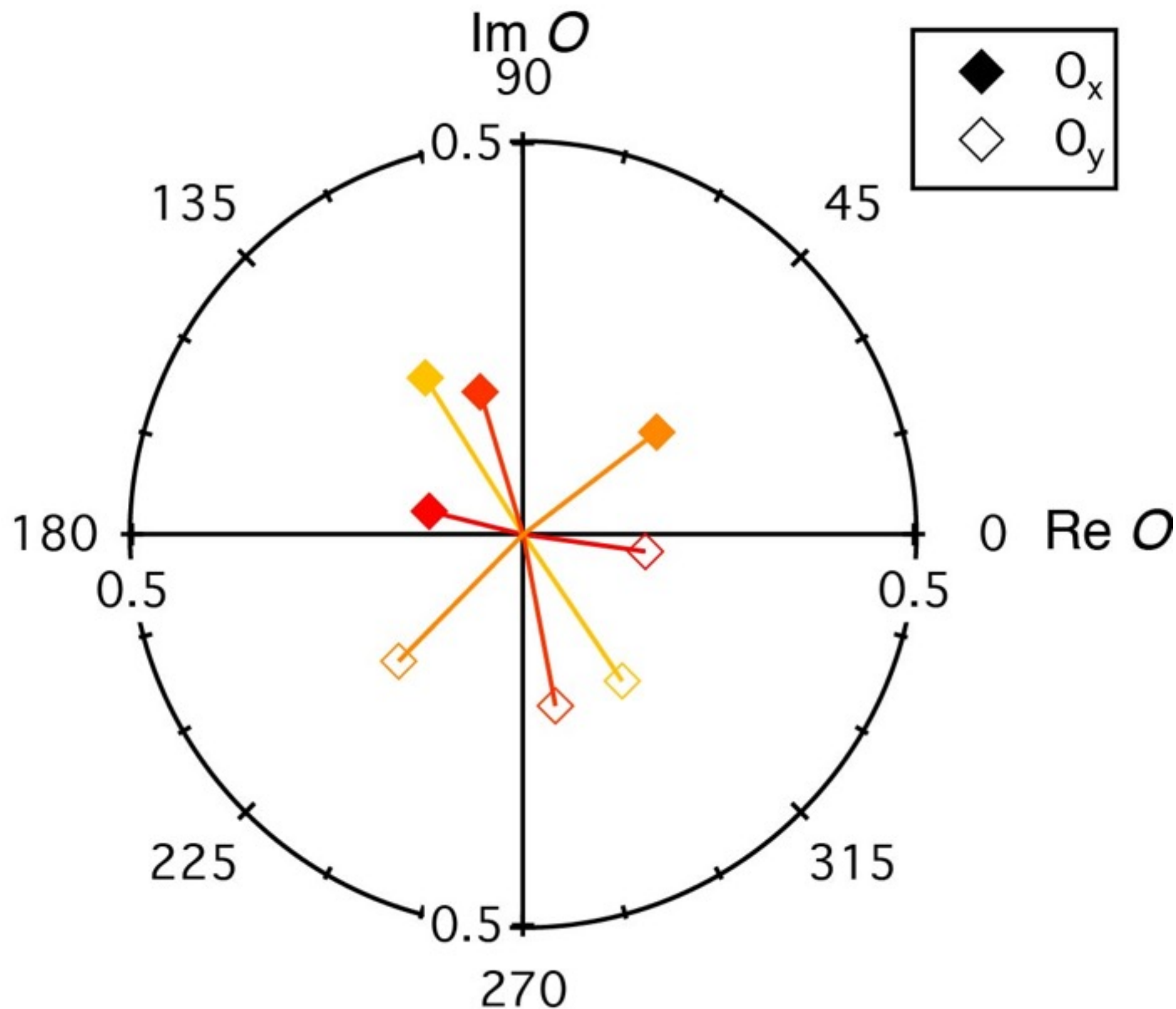
Phase-sensitive measurement of the d -form factor of density wave order

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

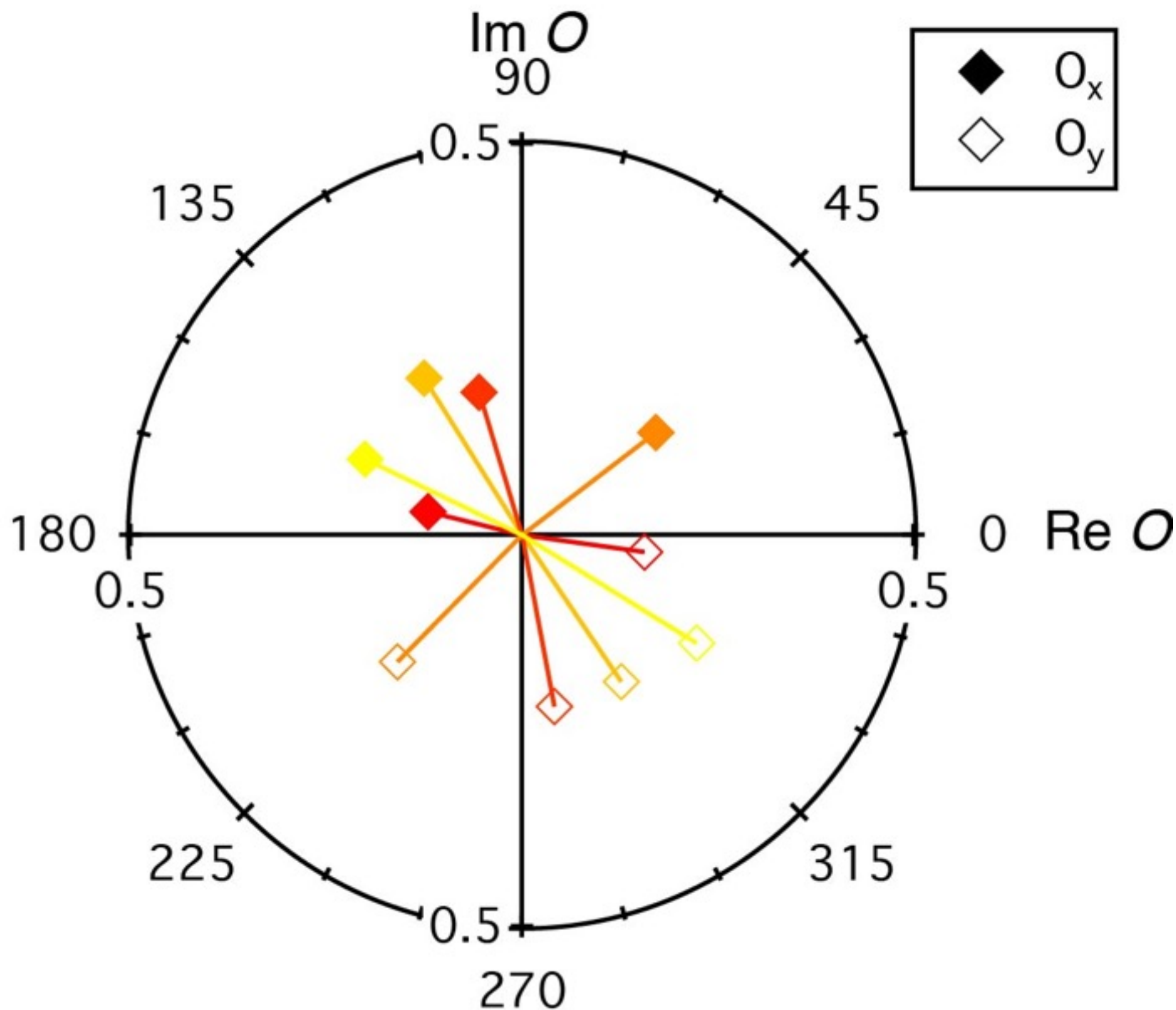
Complex value of O_y at same q



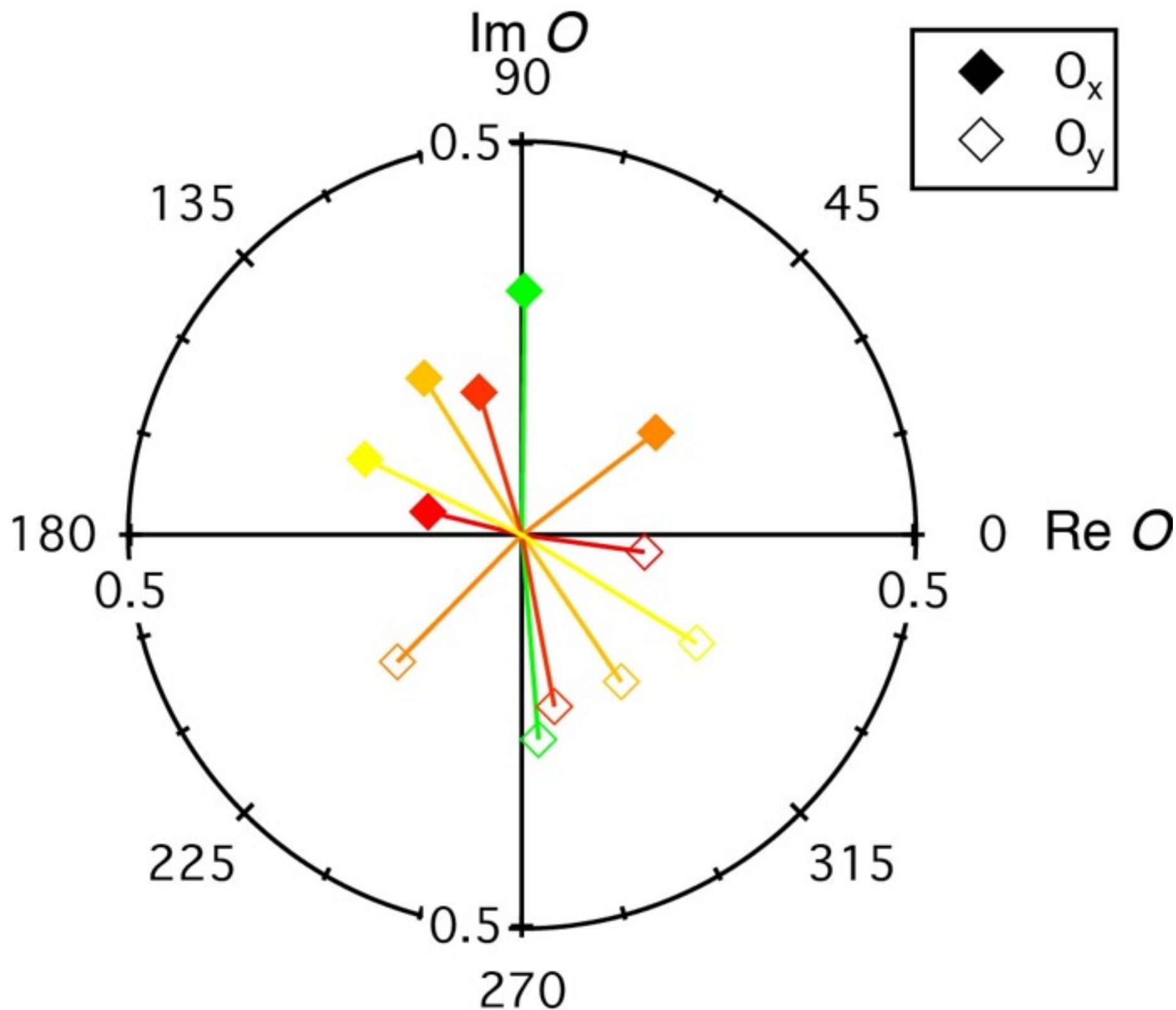
Phase-sensitive measurement of the d -form factor of density wave order



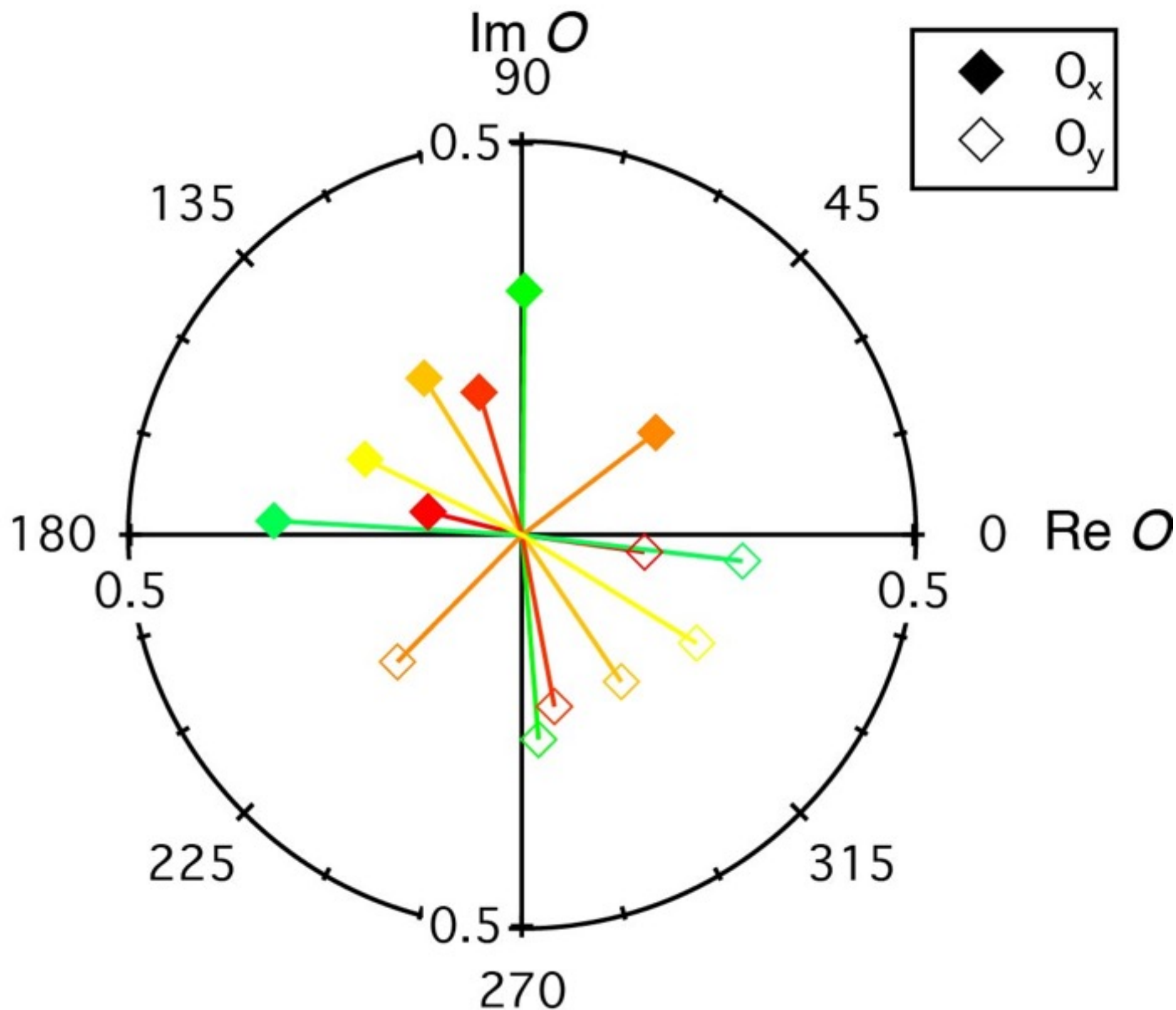
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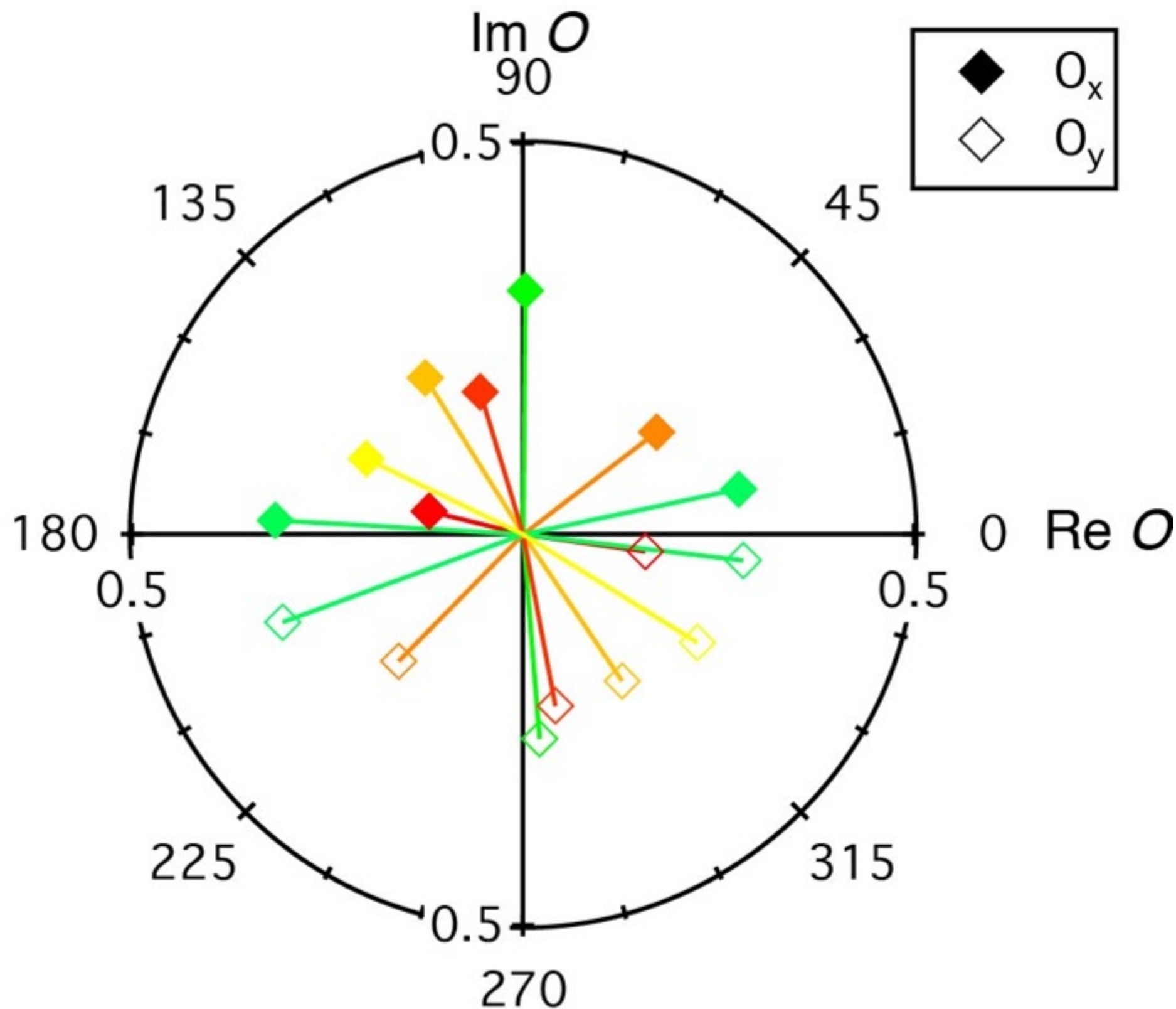
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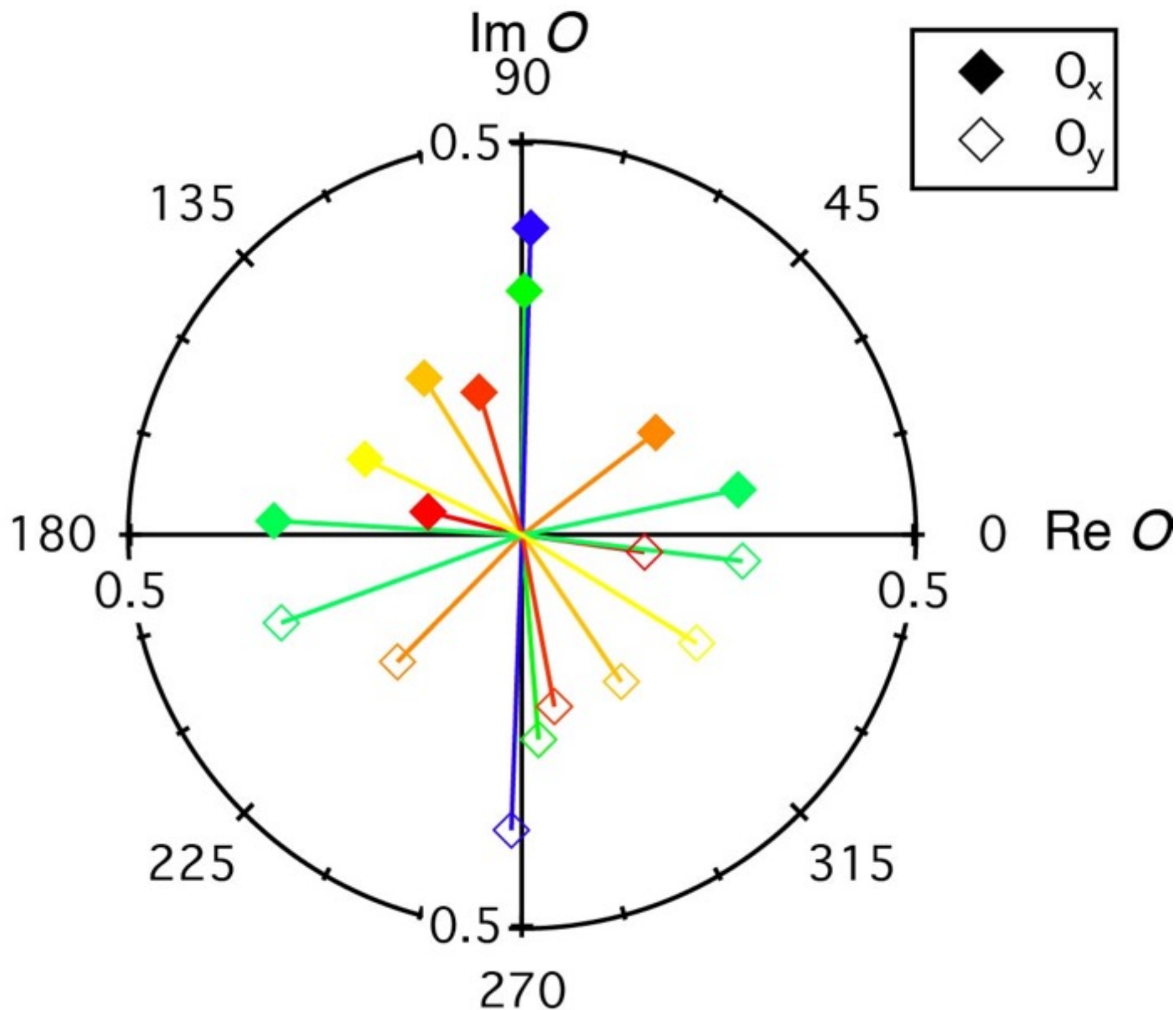
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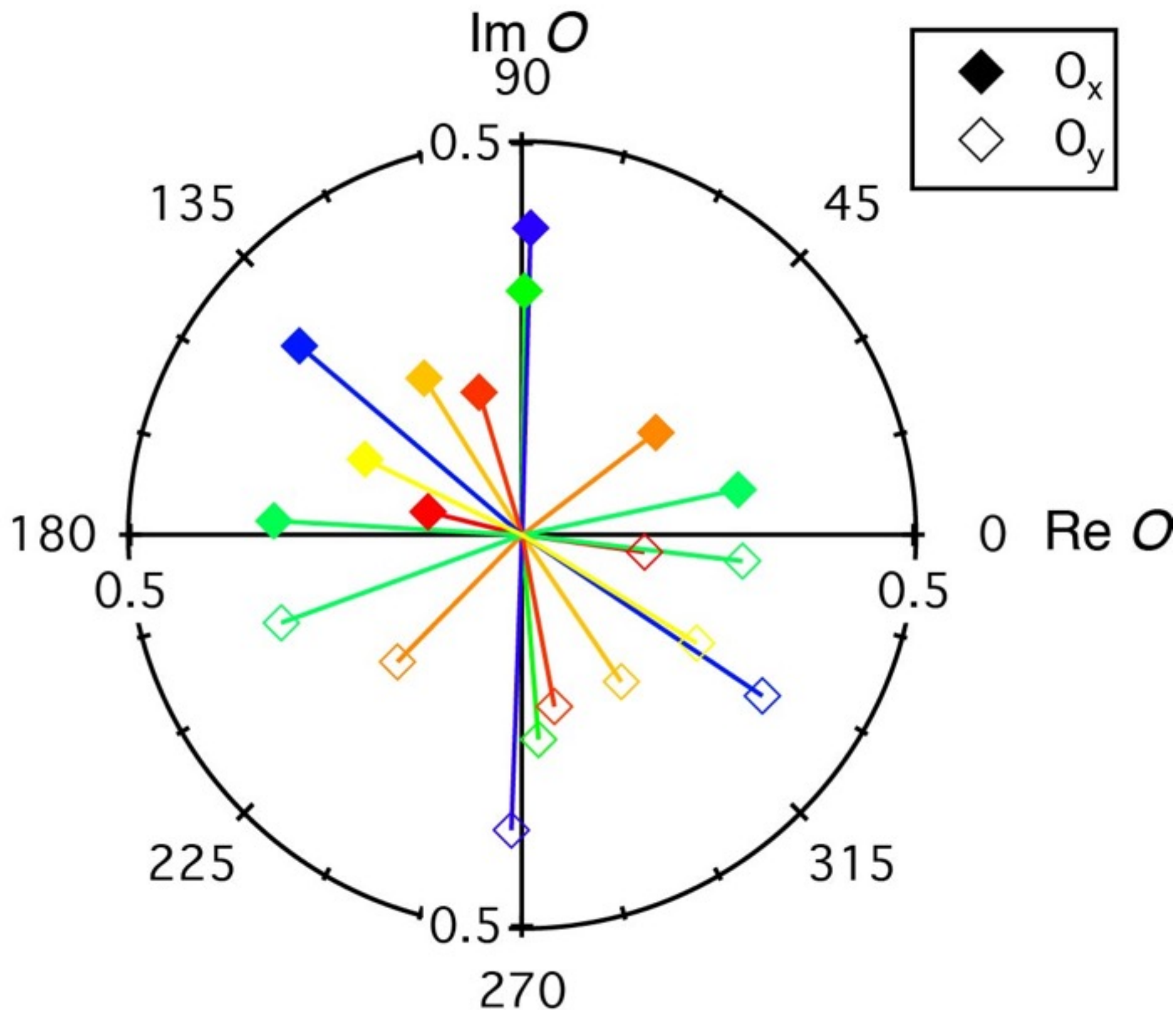
**Phase-sensitive
measurement of
the *d*-form factor
of density wave
order**



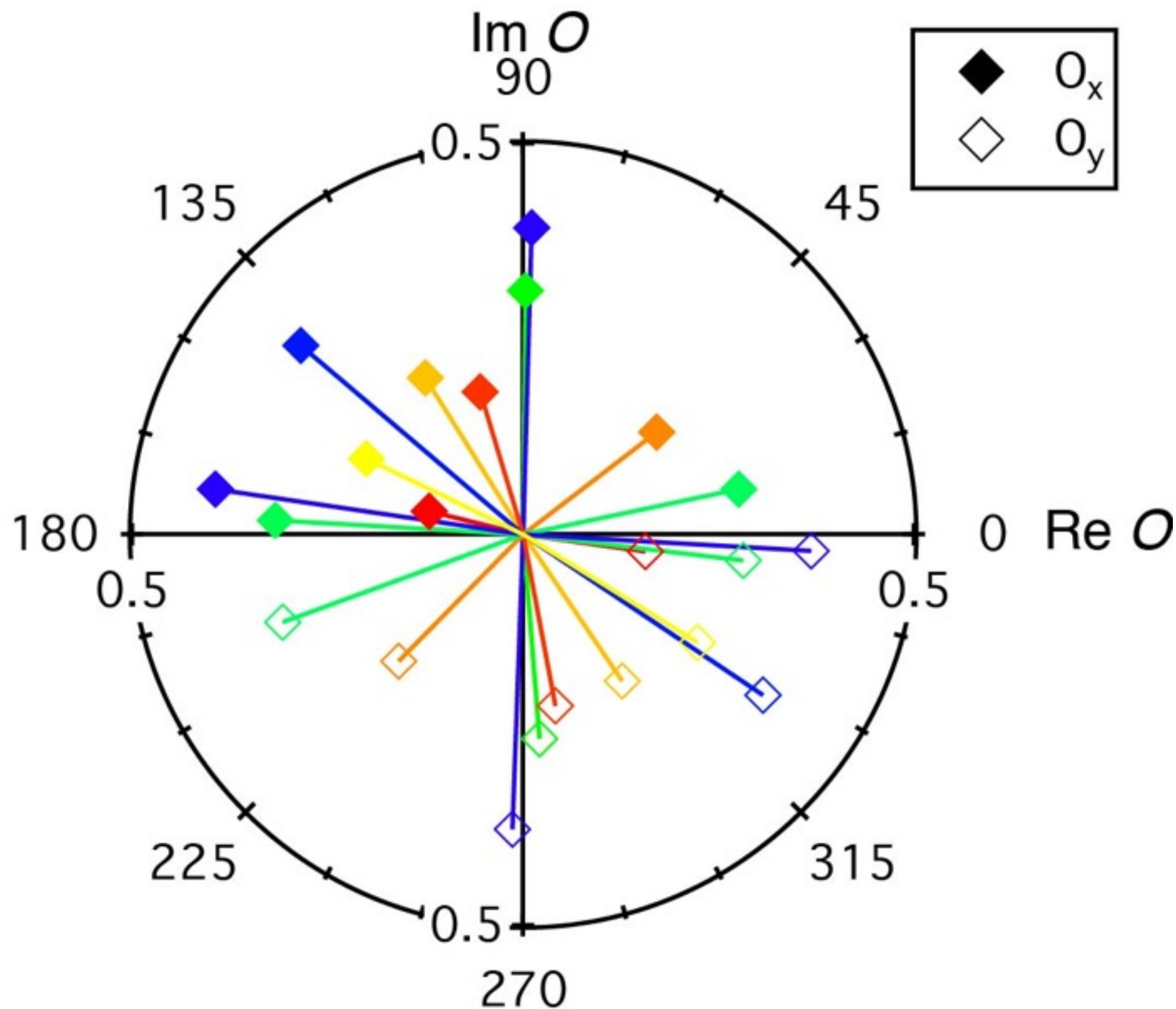
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of density wave
order**



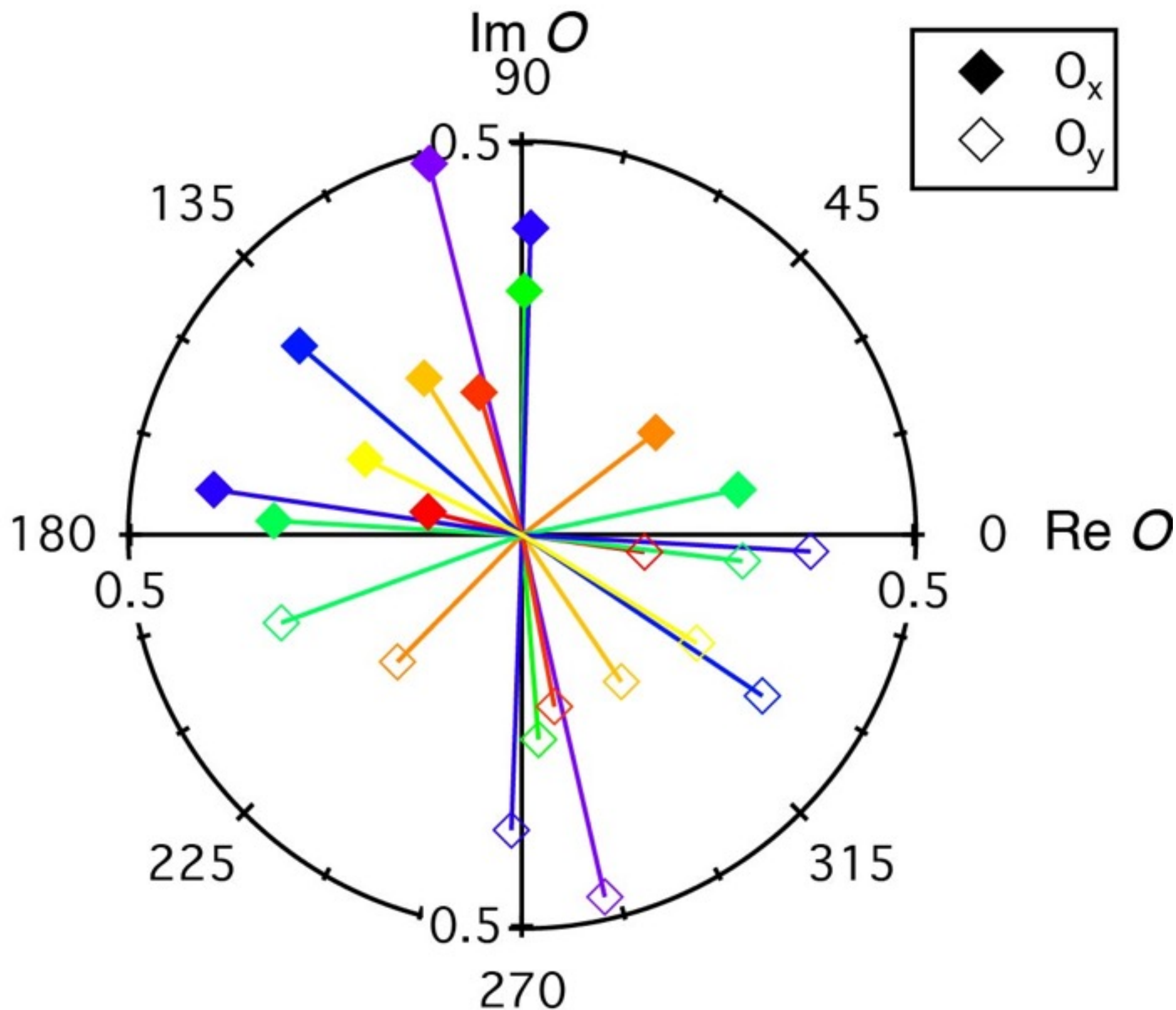
**Phase-sensitive
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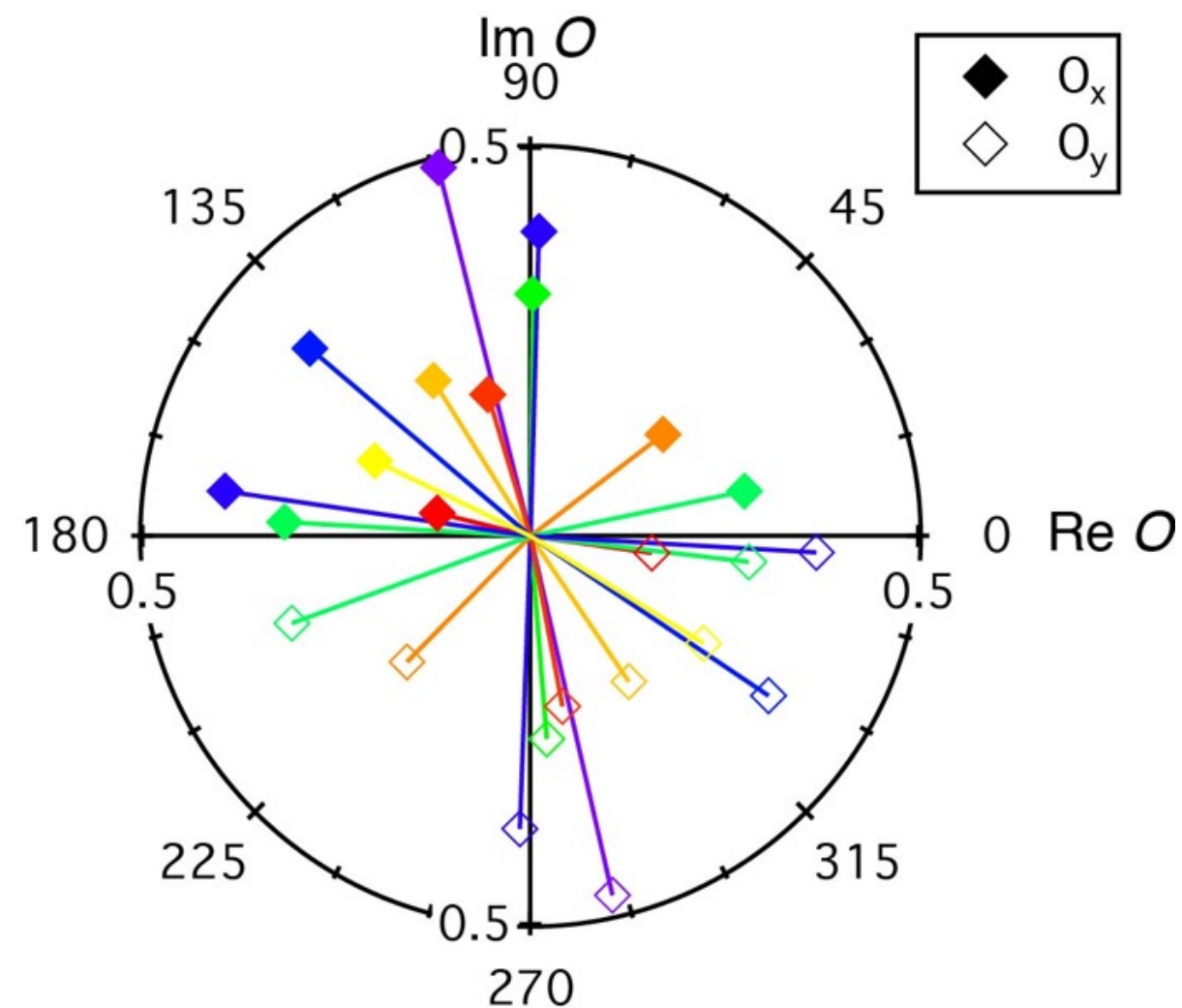
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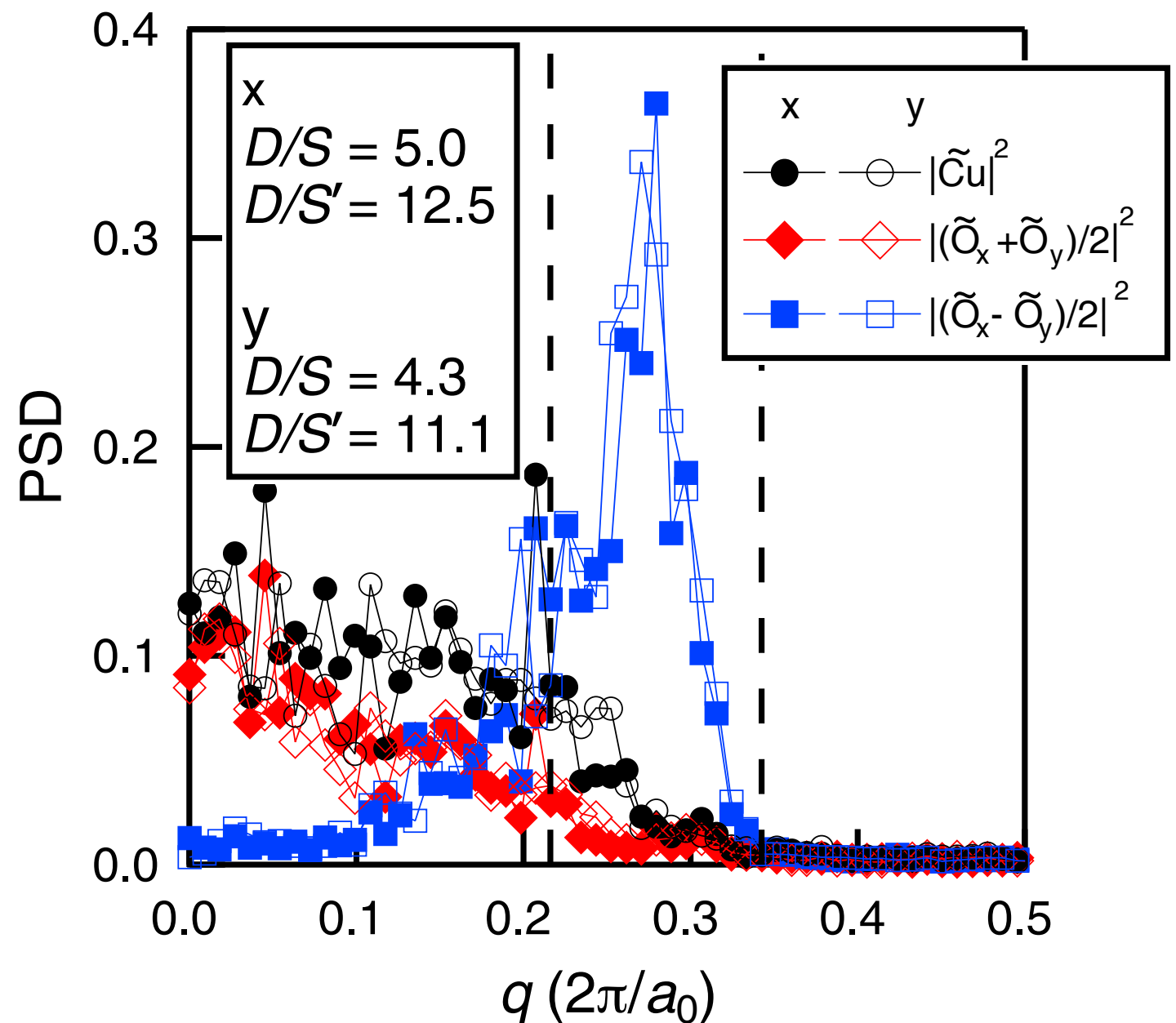
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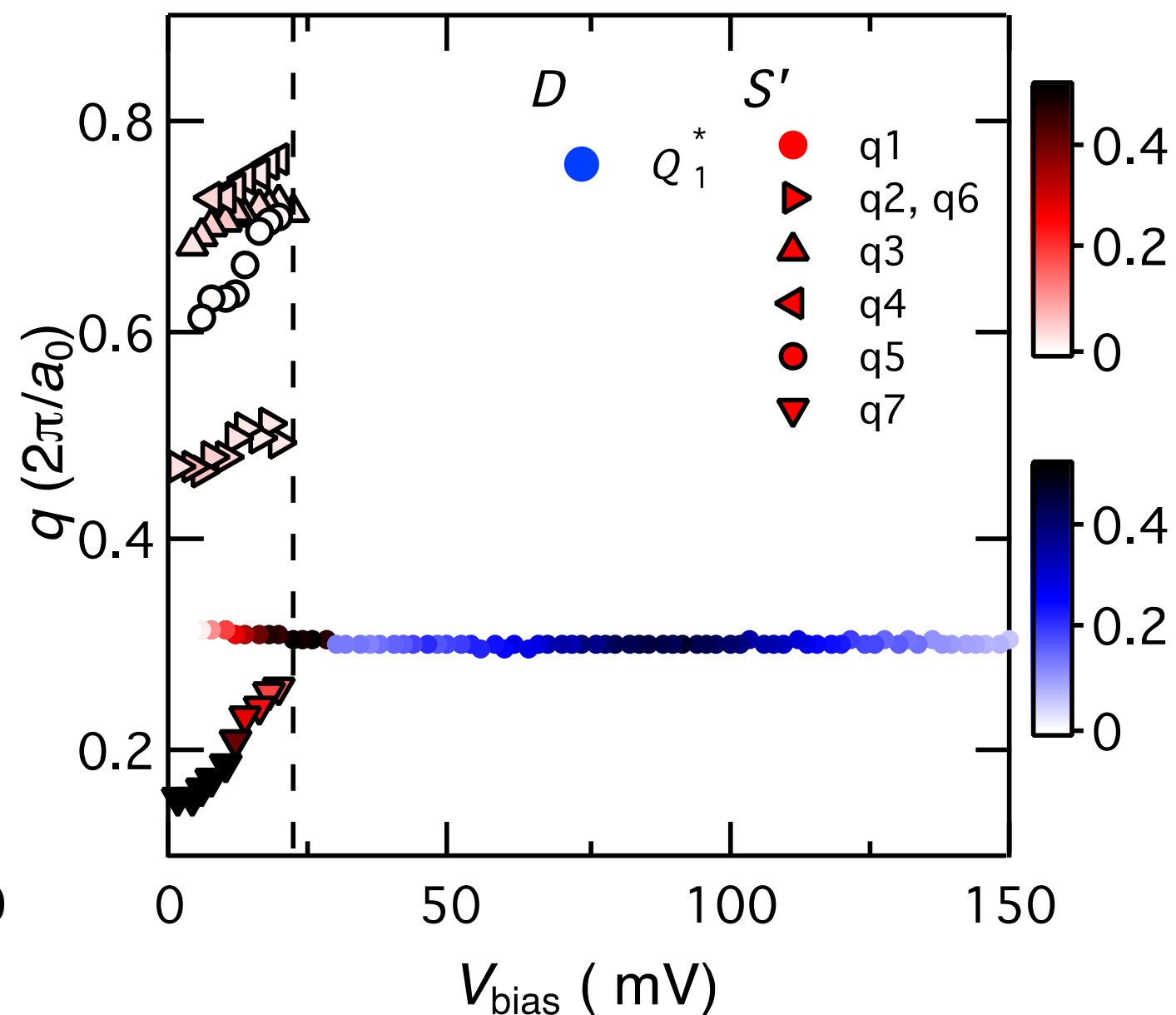
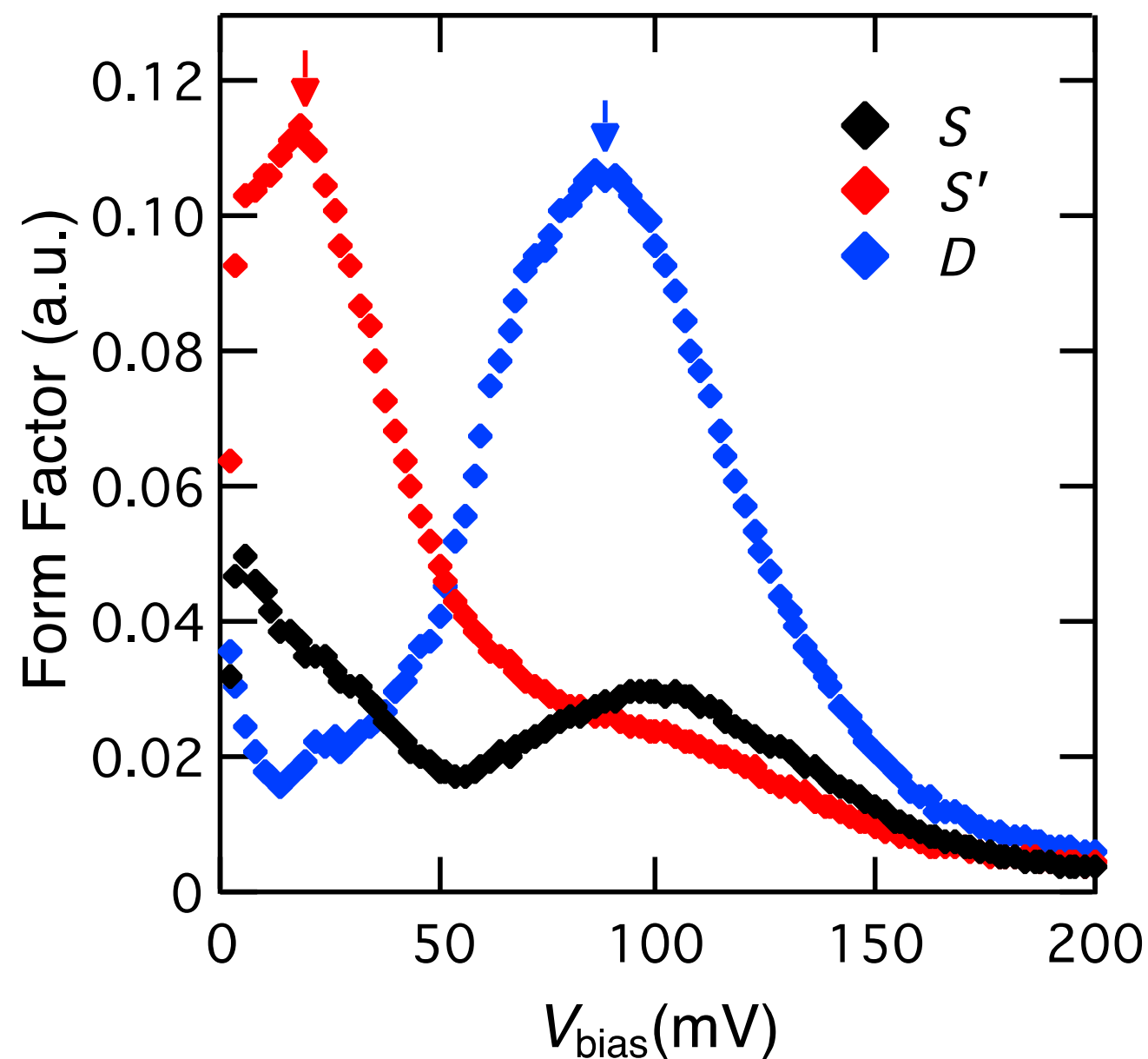
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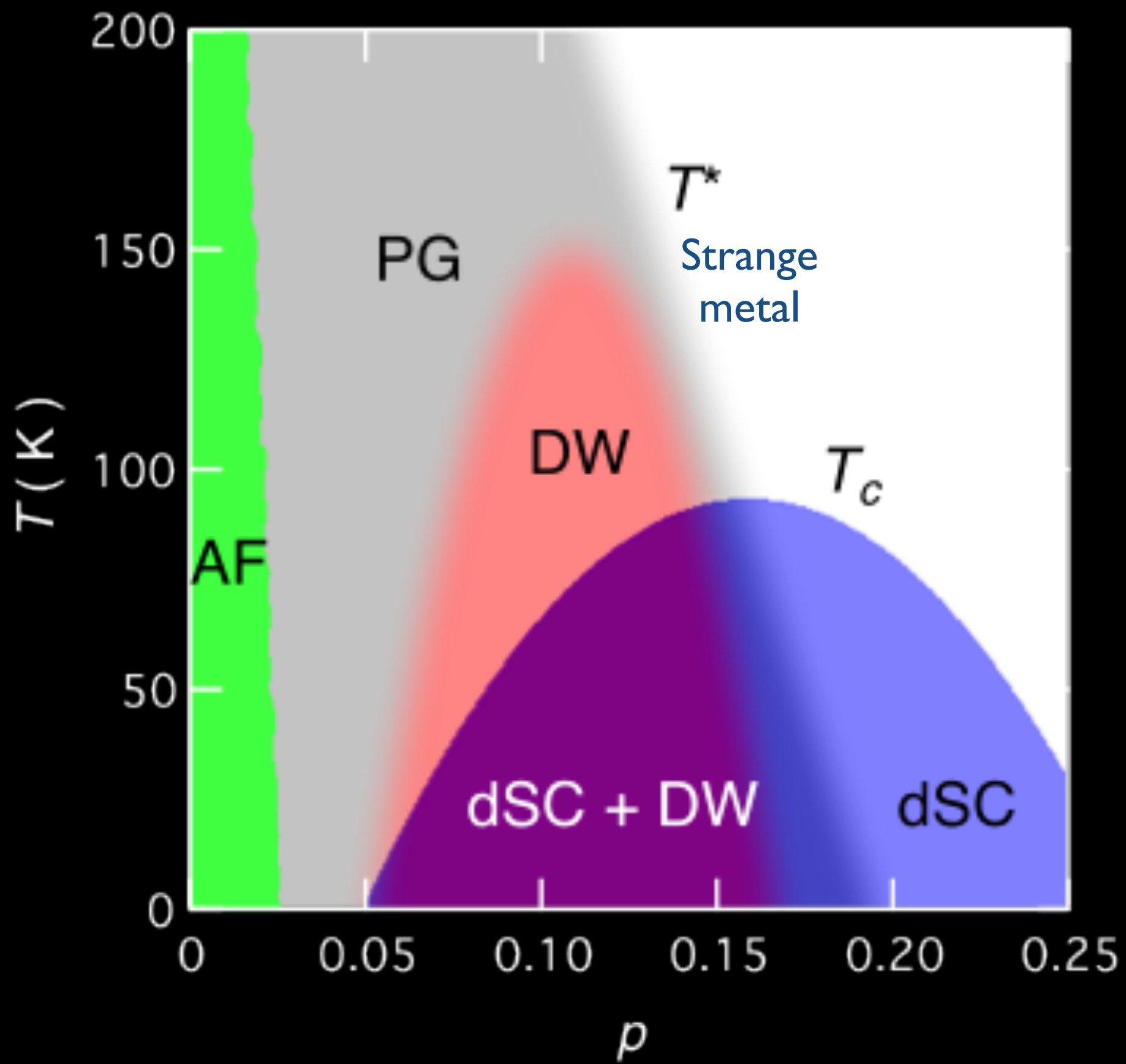
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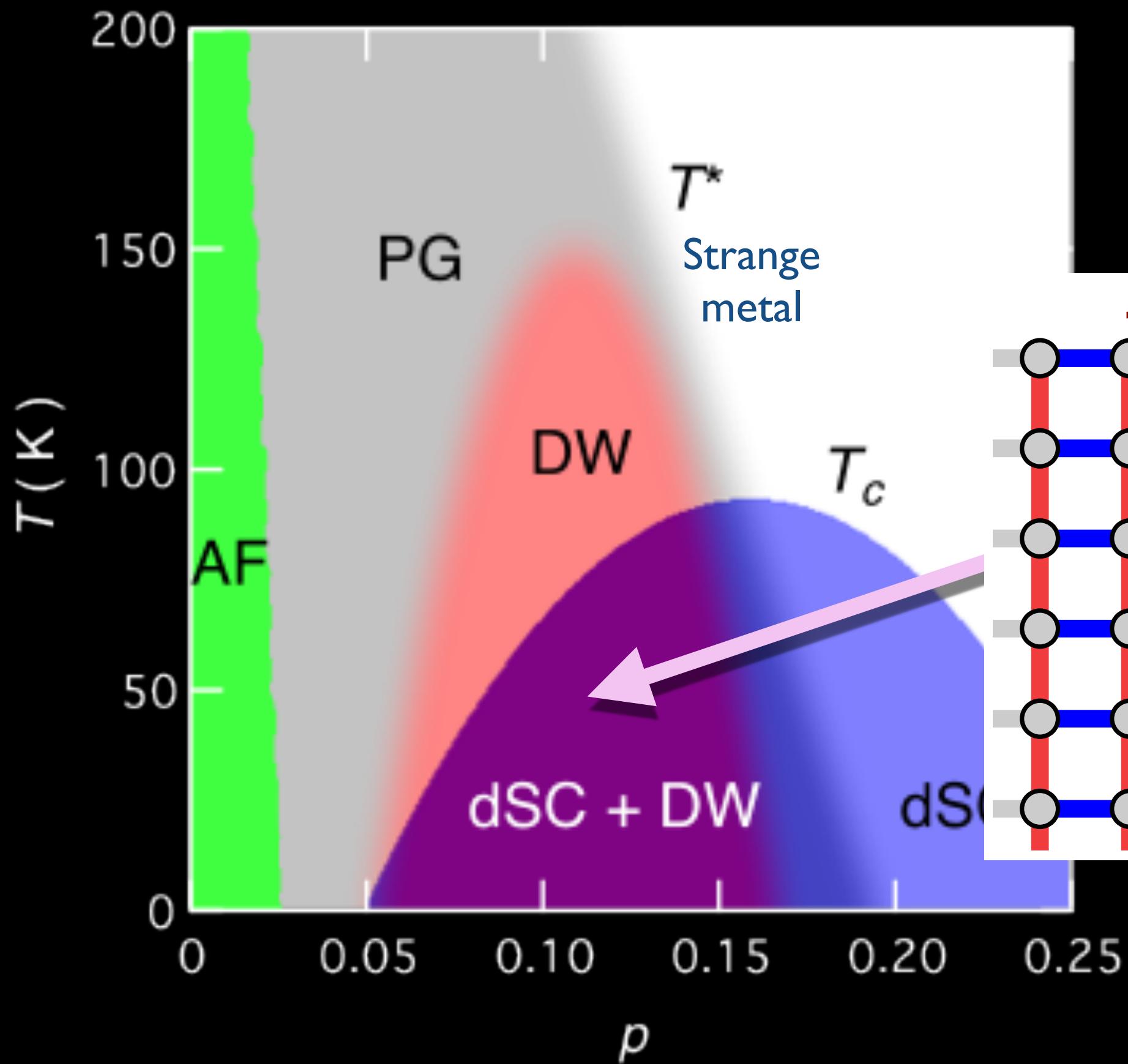


d -form factor is peaked at the pseudogap energy, and does not disperse as a function of wavevector

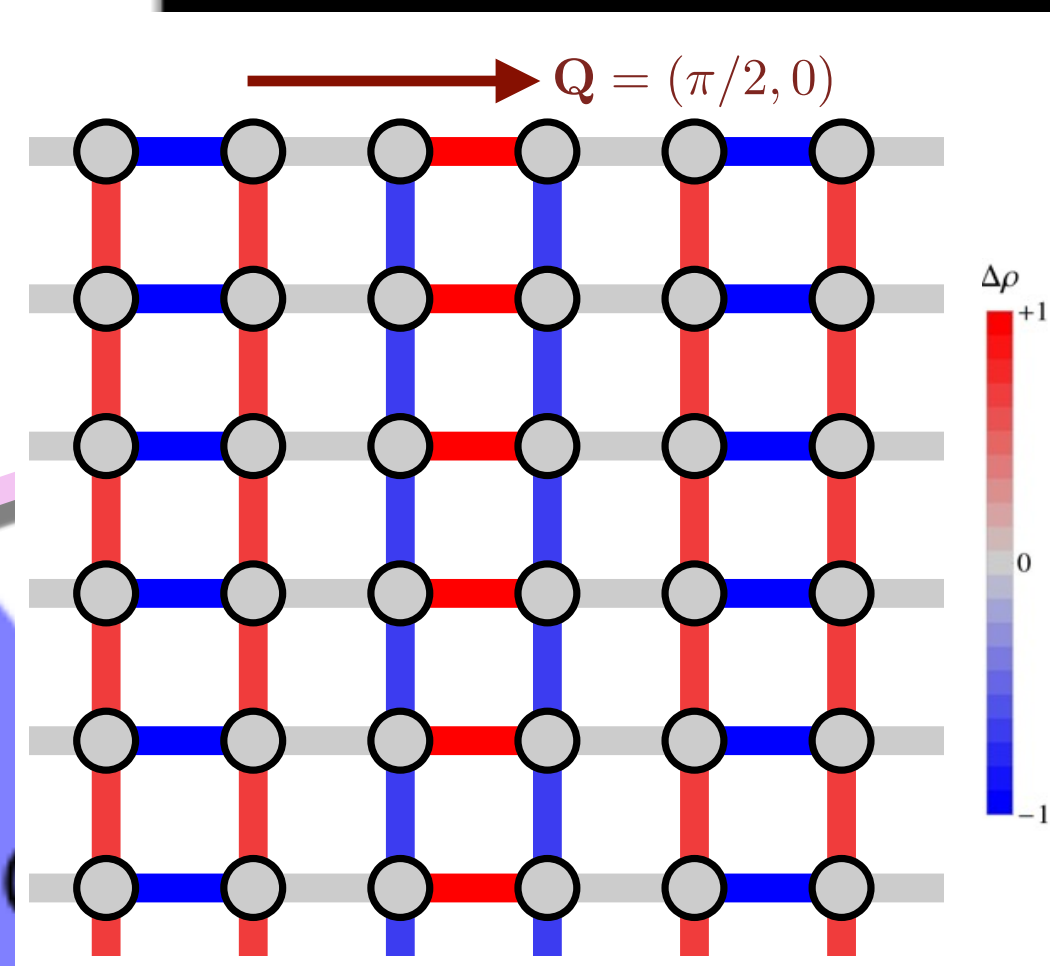


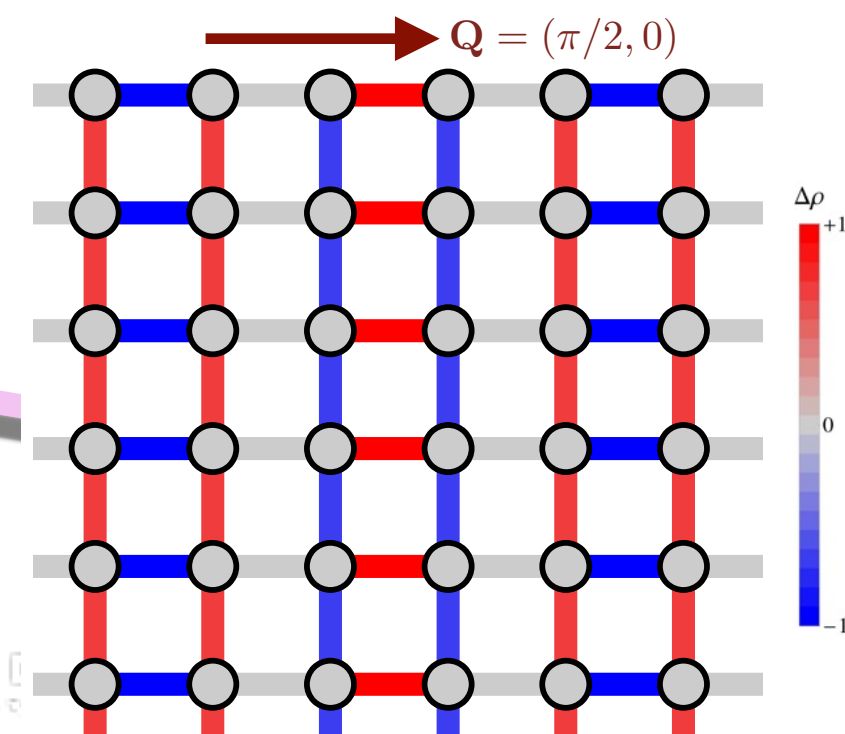
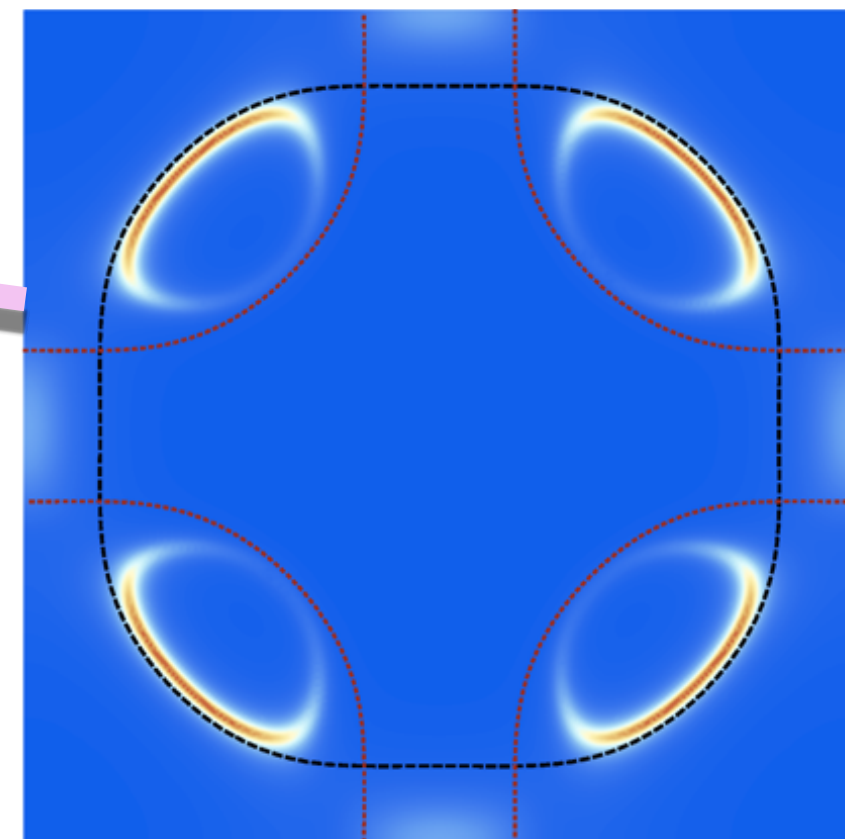
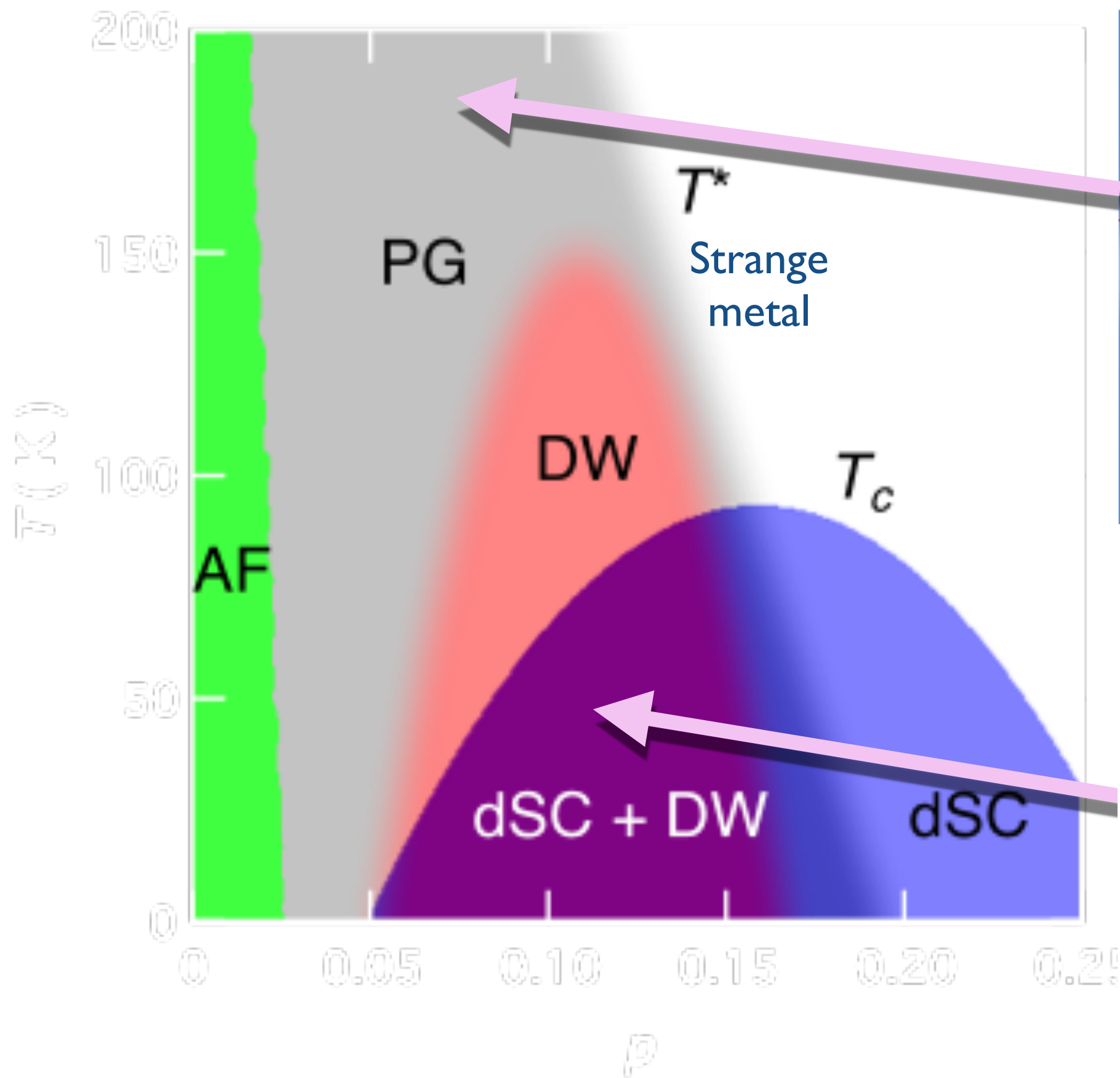
K. Fujita, M. H. Hamidian, S. D. Edkins, Chung Koo Kim, A. P. MacKenzie, H. Eisaki, S. Uchida, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, to appear





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





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1. The high T pseudogap:

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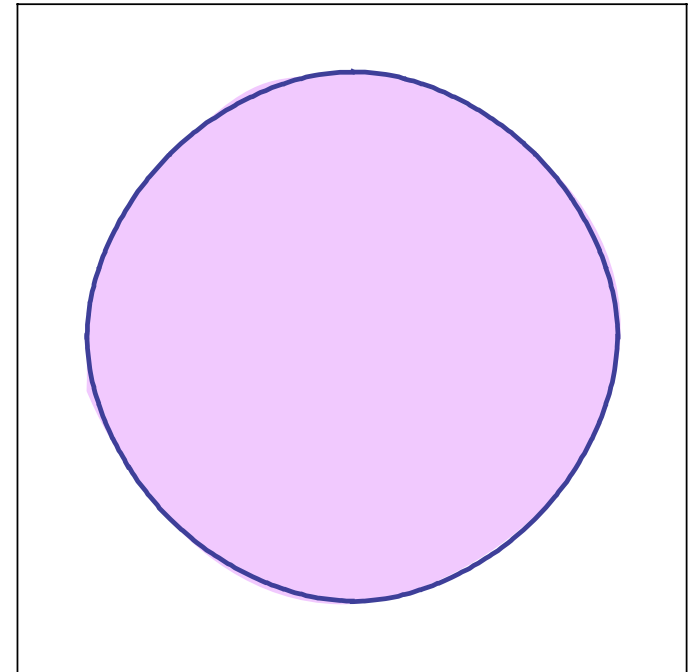
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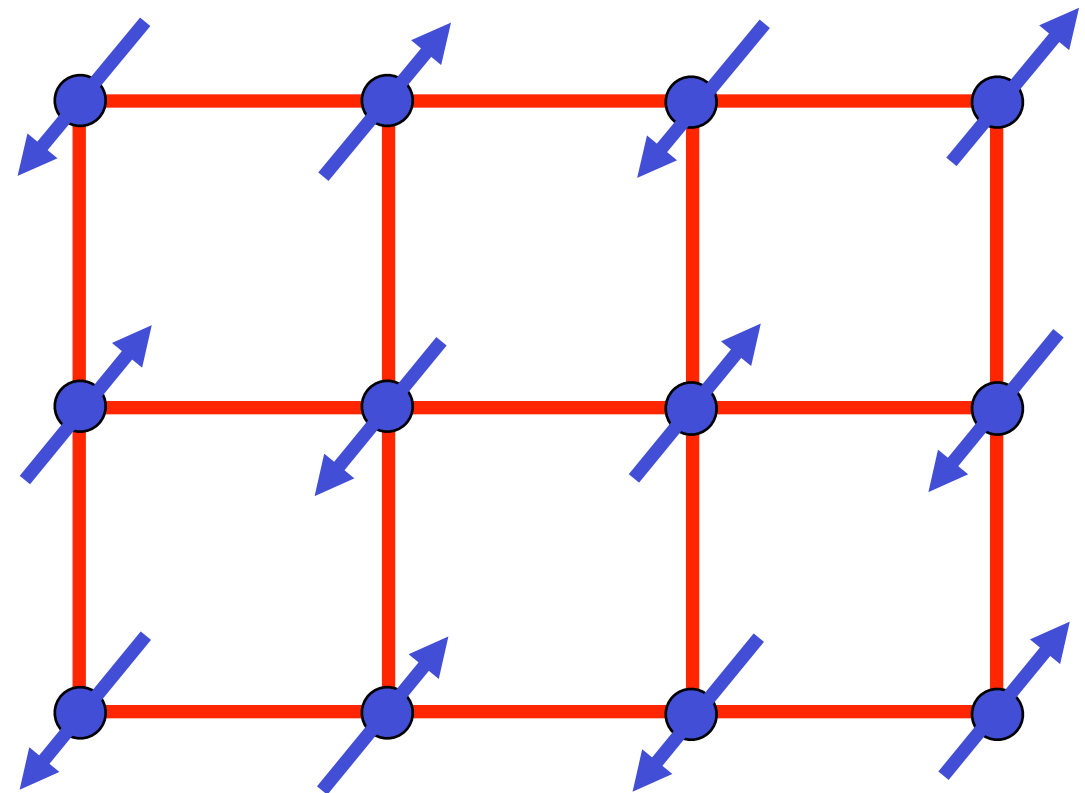


+

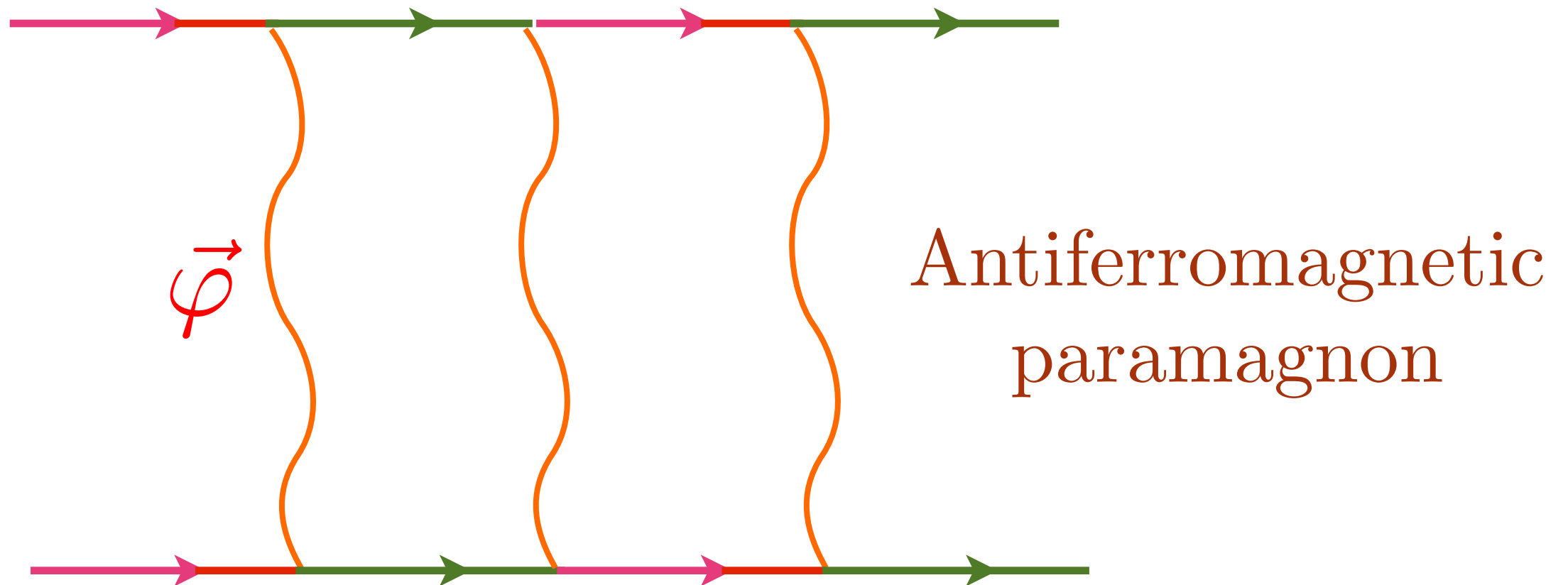
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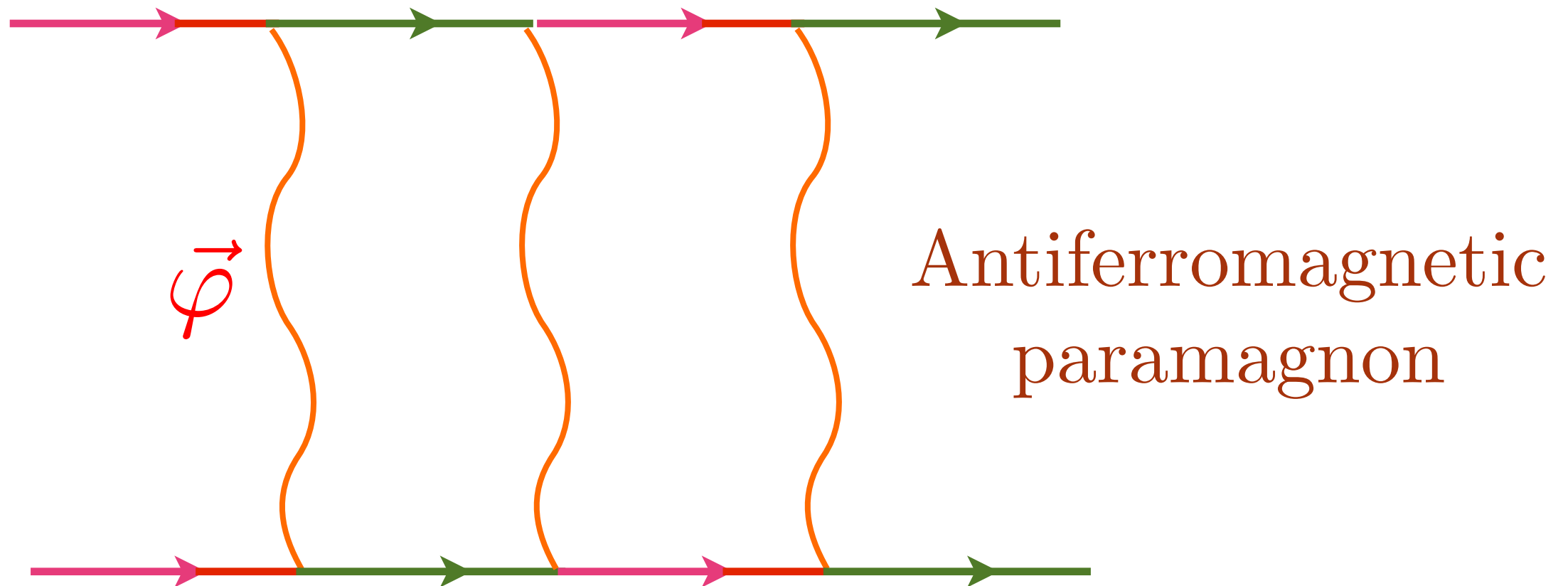


Pairing “glue” for d-wave superconductivity from antiferromagnetic fluctuations



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)

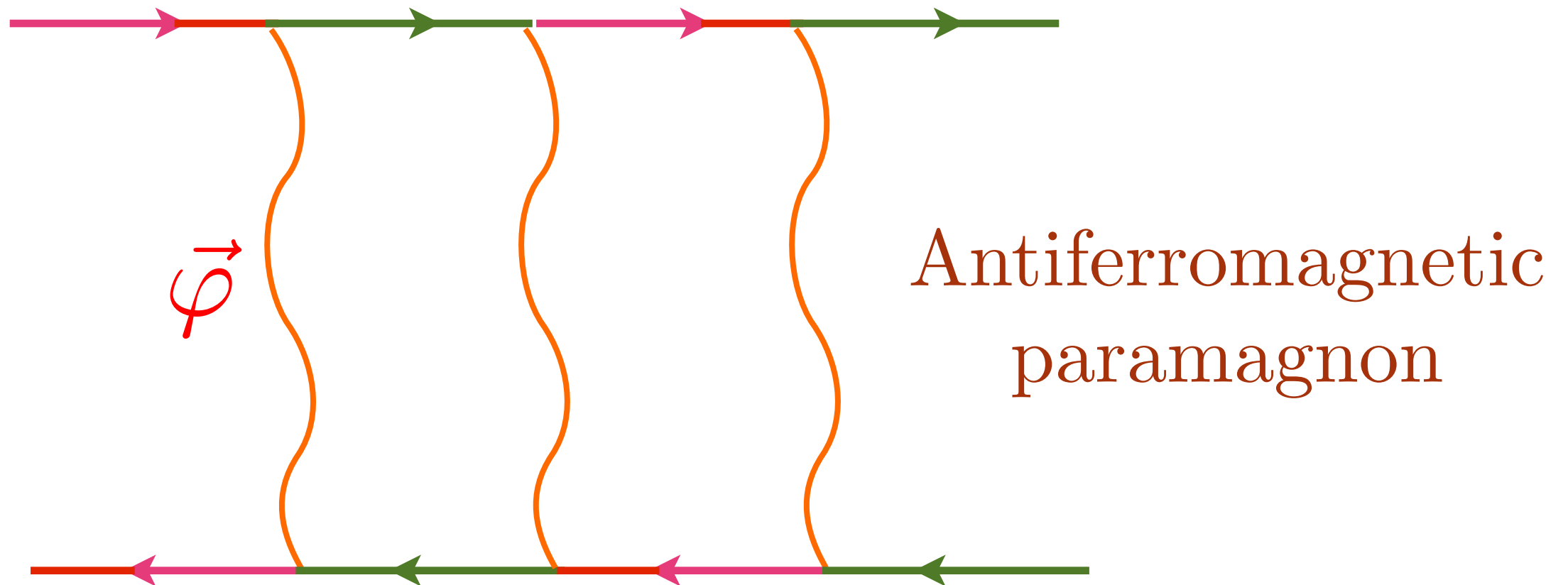
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Leads to $\langle c_{\mathbf{k}\alpha}^\dagger c_{-\mathbf{k}\beta}^\dagger \rangle = \varepsilon_{\alpha\beta} \Delta (\cos k_x - \cos k_y)$

- V. J. Emery, *J. Phys. (Paris) Colloq.* **44**, C3-977 (1983)
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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)

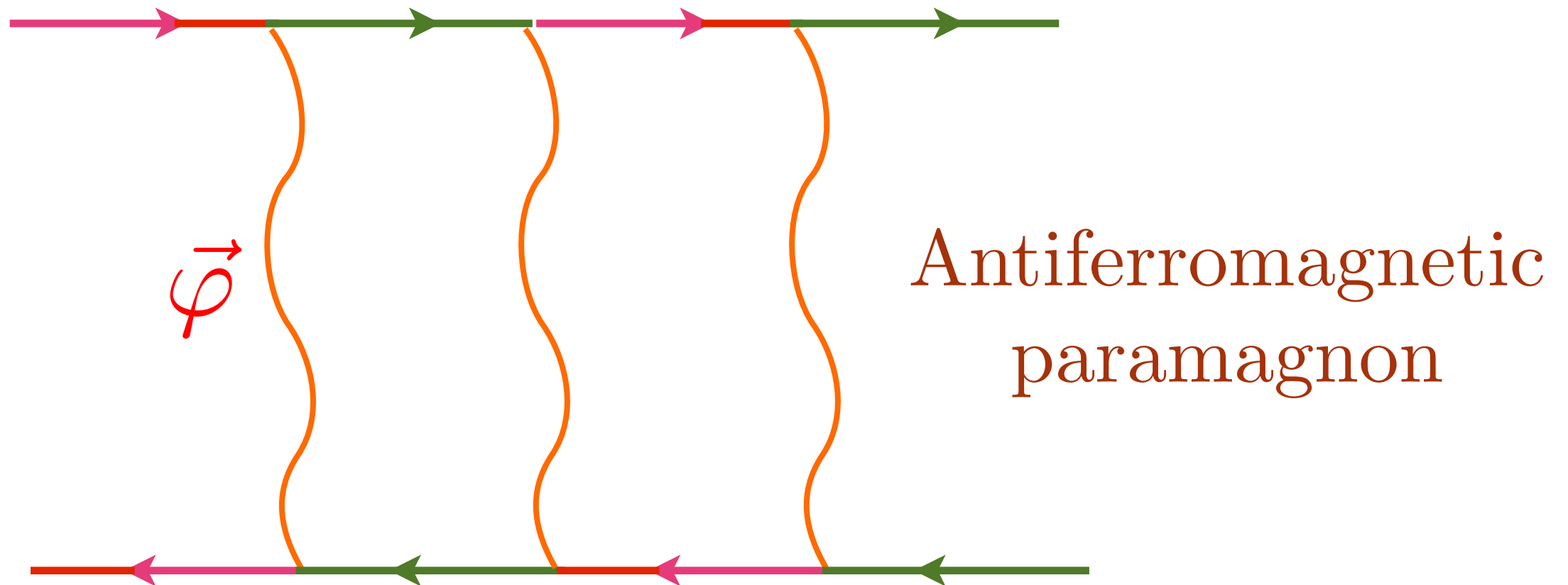
S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013)

K. B. Efetov, H. Meier, and C. Pépin, Nat. Phys. **9**, 442 (2013)

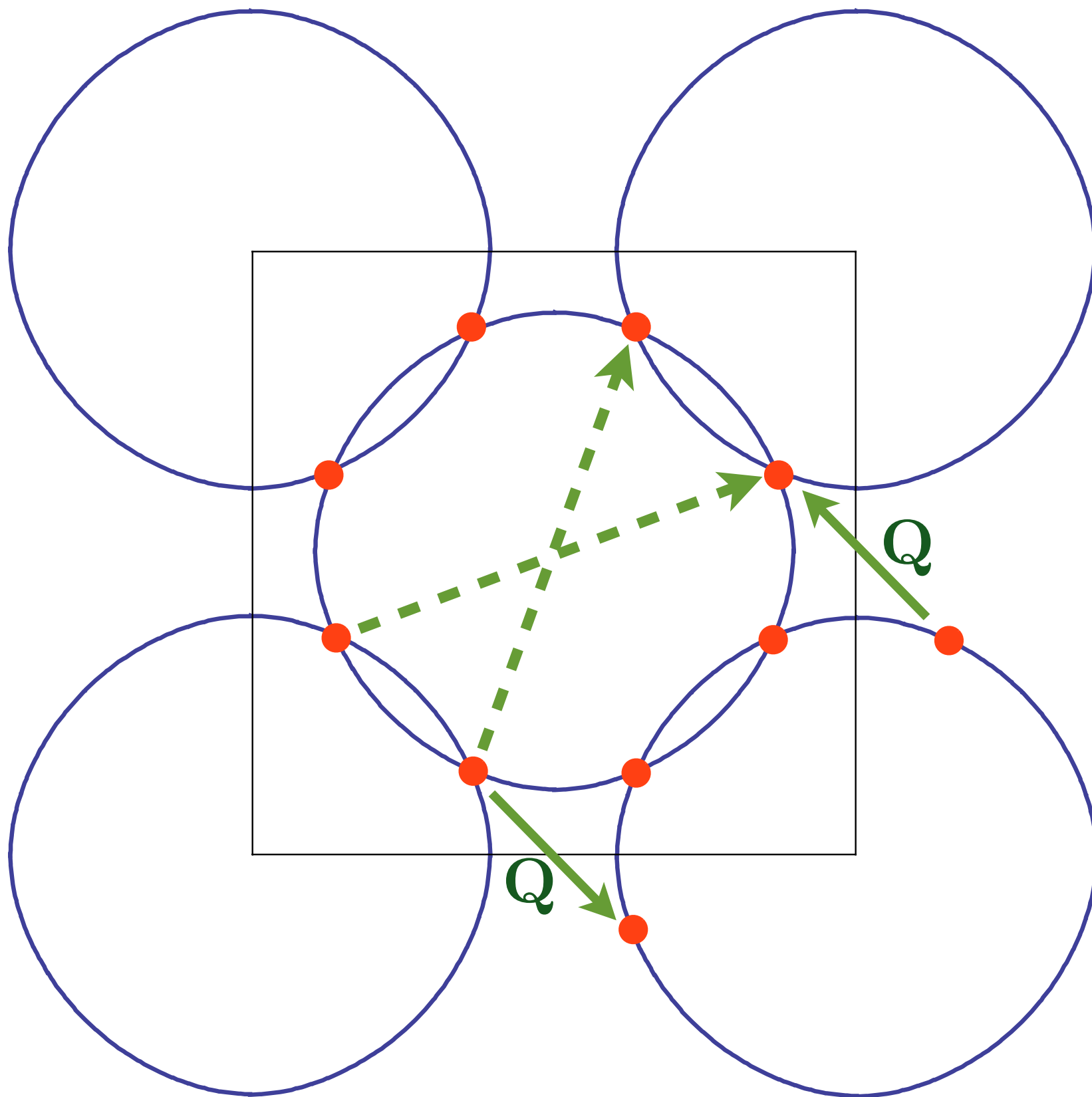
J. D. Sau and S. Sachdev, Phys. Rev. B **89**, 075129 (2014)

Y. Wang and A. V. Chubukov, Phys. Rev. B **90**, 035149 (2014)

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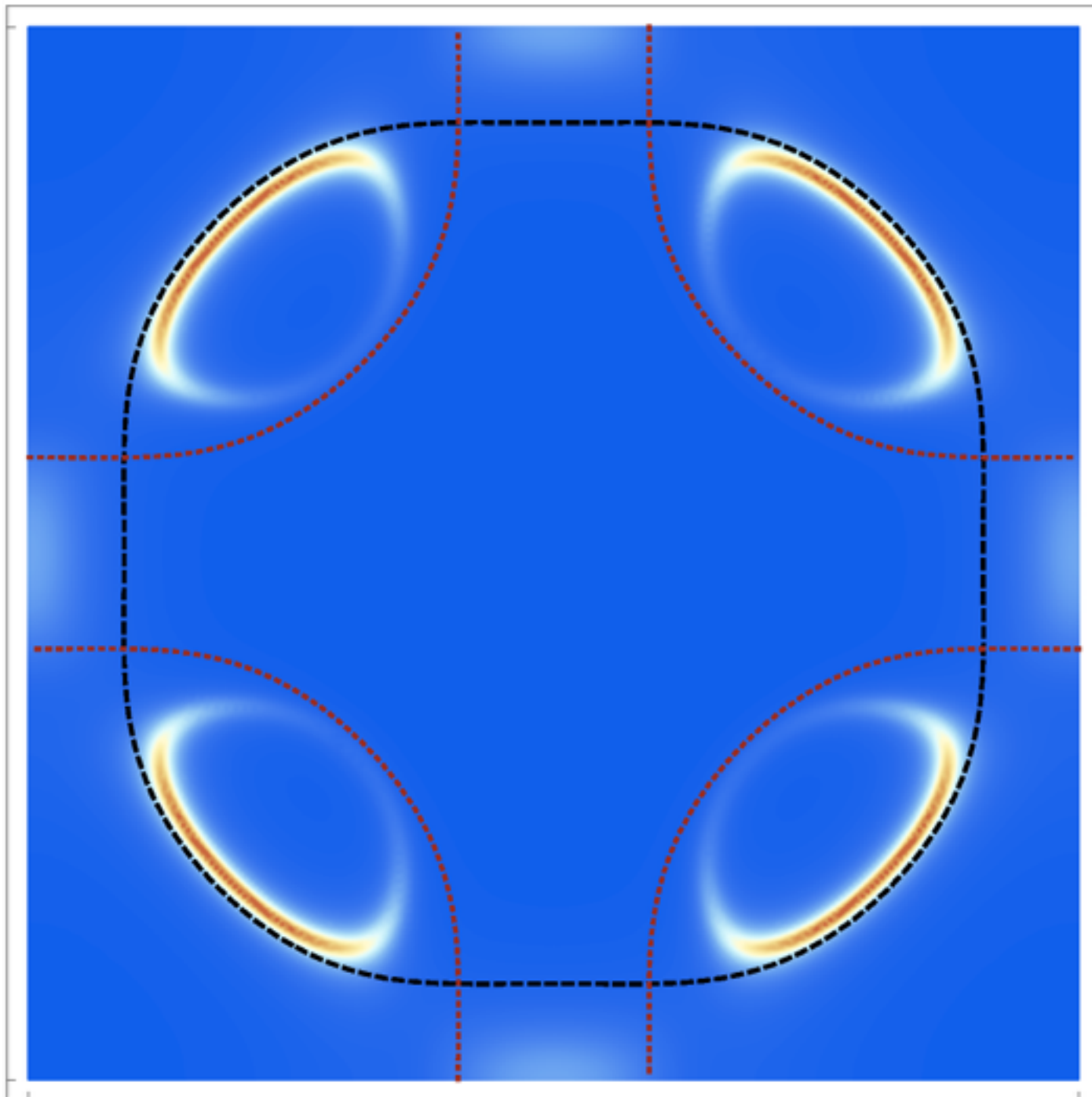


Leads to $\left\langle c_{\mathbf{k}+\mathbf{Q}/2,\alpha}^\dagger c_{\mathbf{k}-\mathbf{Q}/2,\alpha} \right\rangle =$
 $\mathcal{P}_s + \mathcal{P}_{s'}(\cos k_x + \cos k_y) + \mathcal{P}_d(\cos k_x - \cos k_y)$
with $\mathcal{P}_d$ dominant.



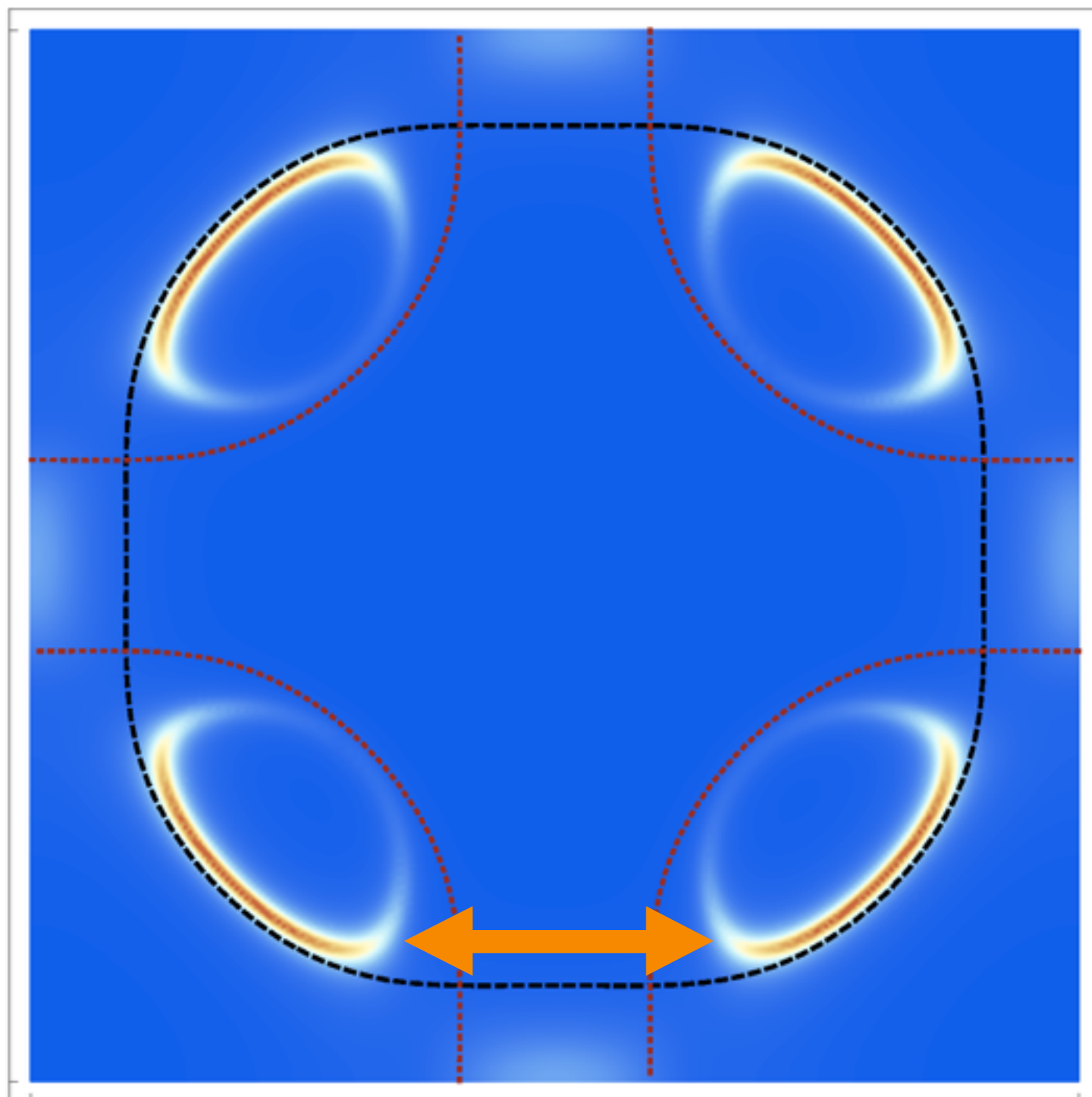
Density wave
instability of large
Fermi surface
leads to an
incorrect
“diagonal”
wavevector

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

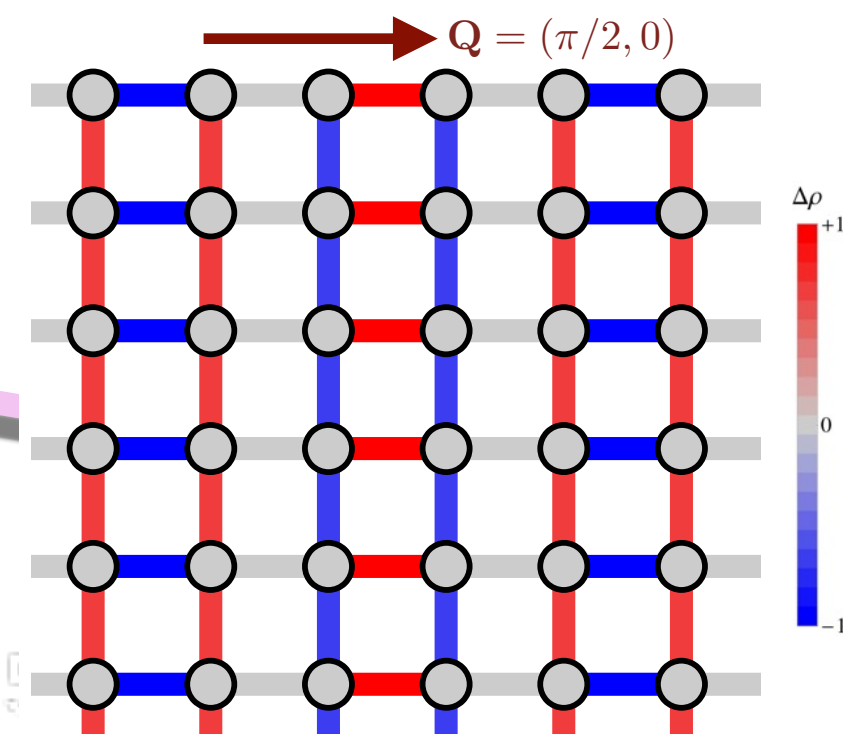
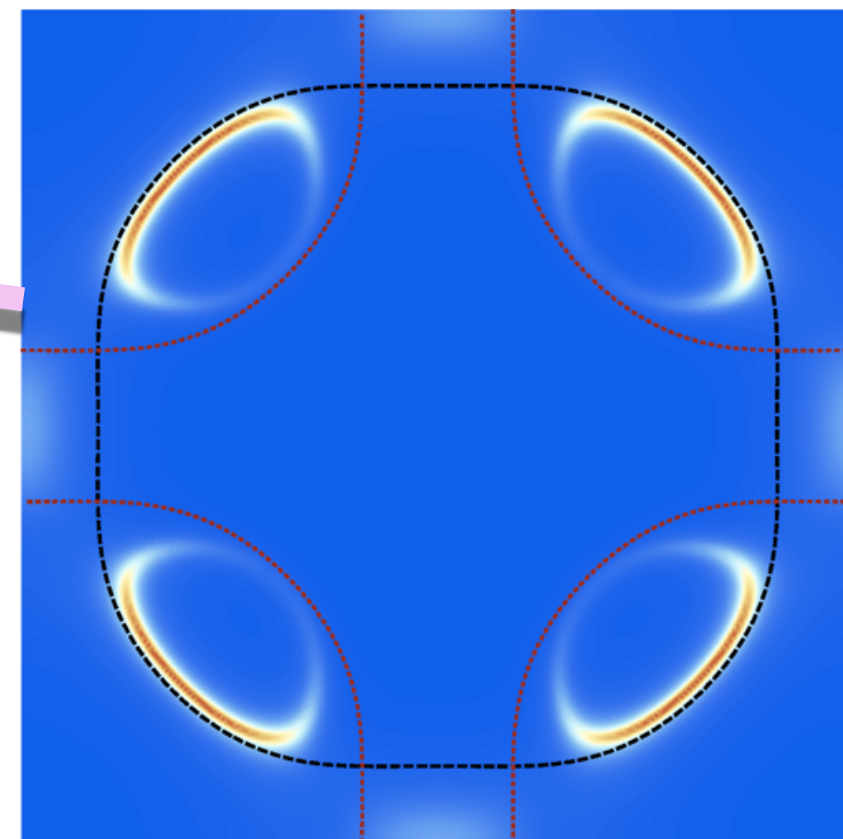
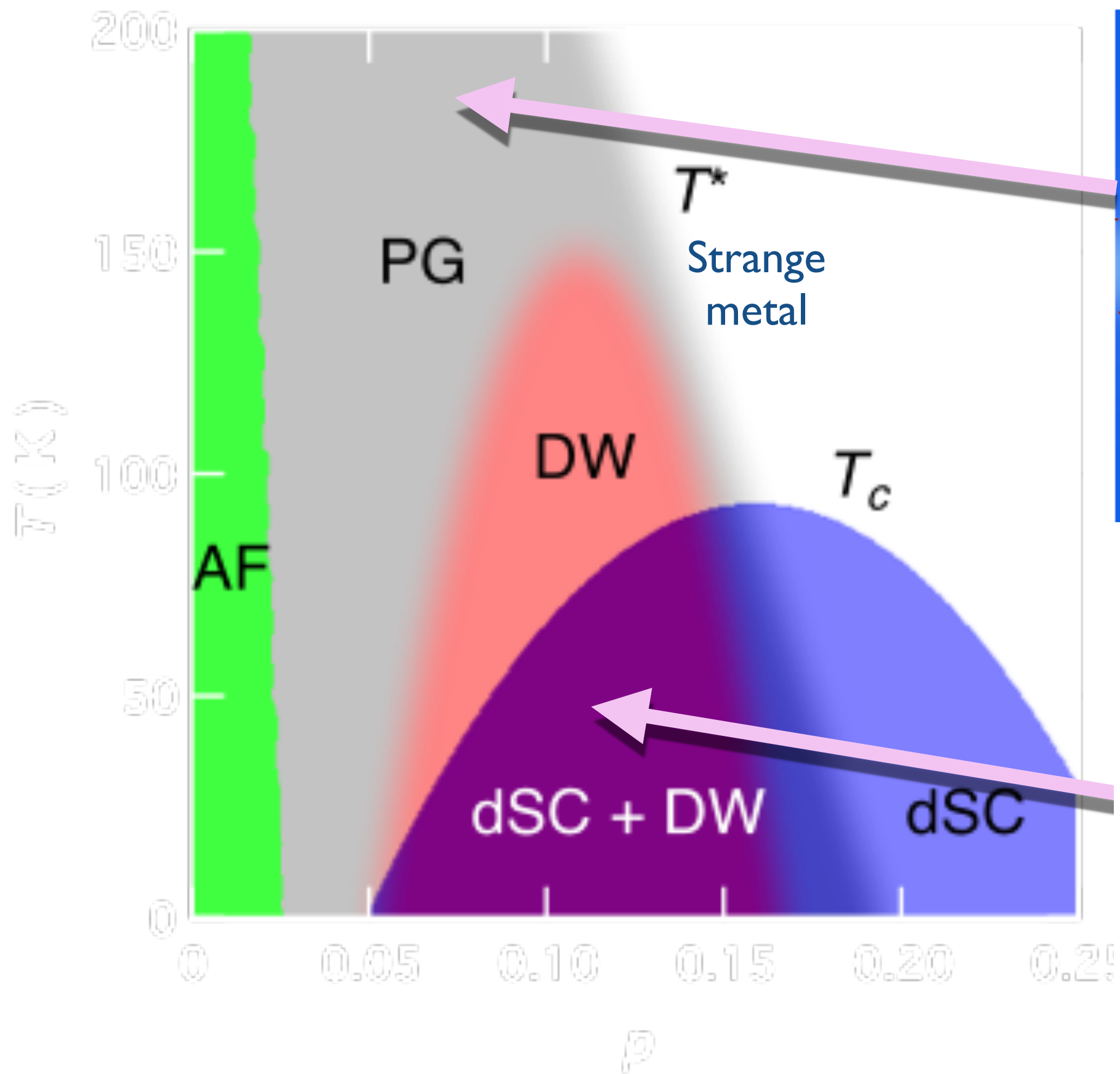


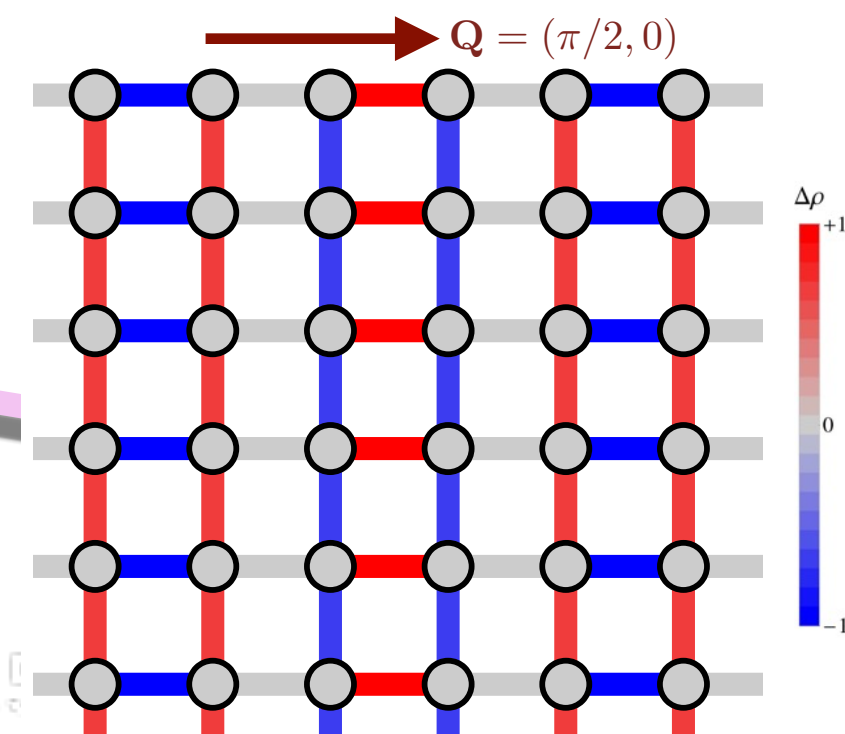
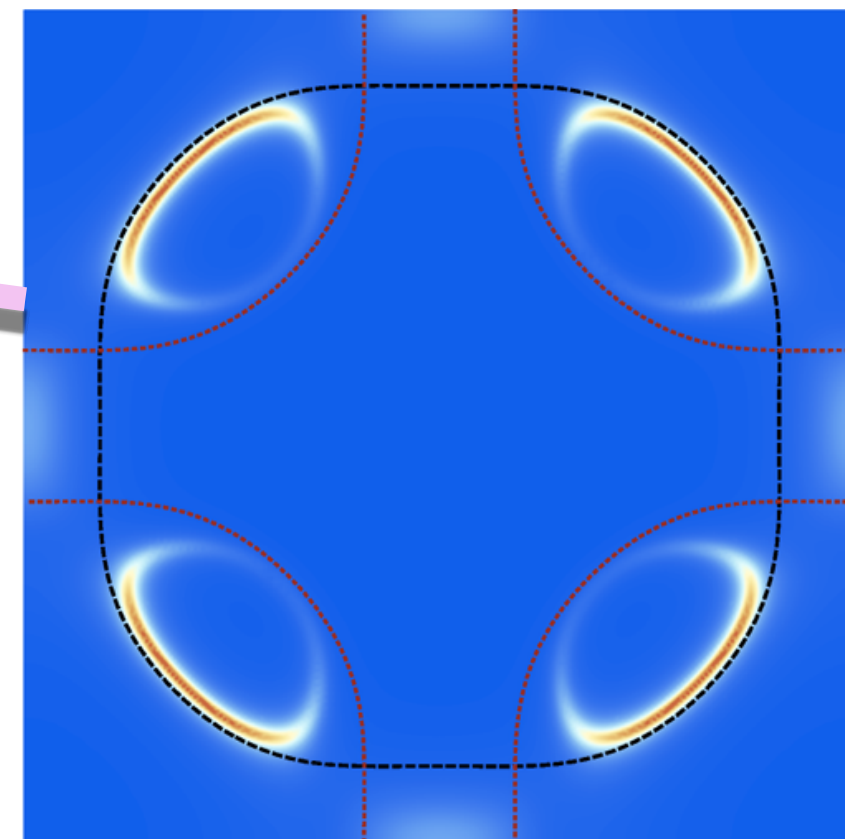
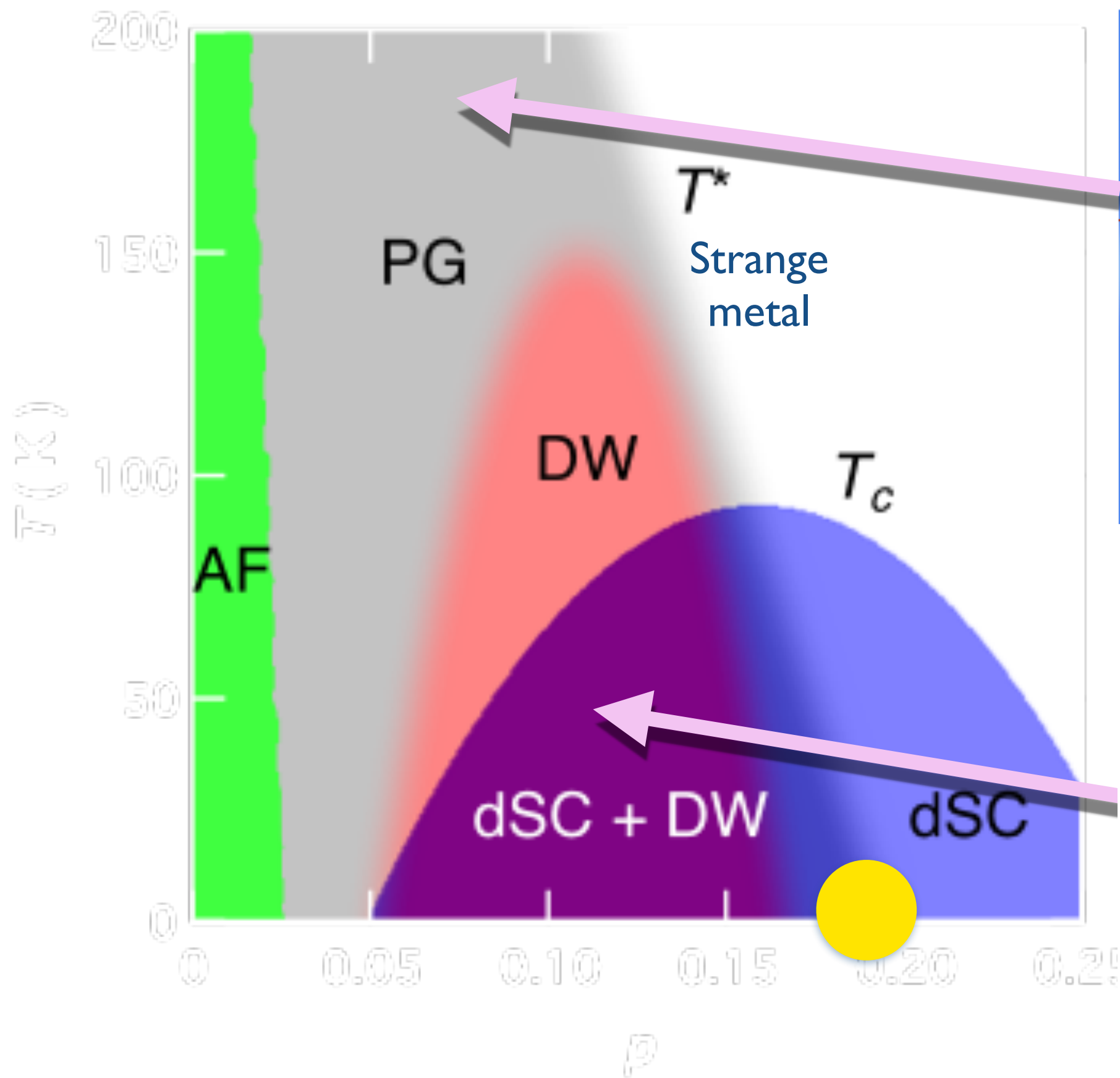
Fermi
surface
of FL*

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



Density wave
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and form-factor





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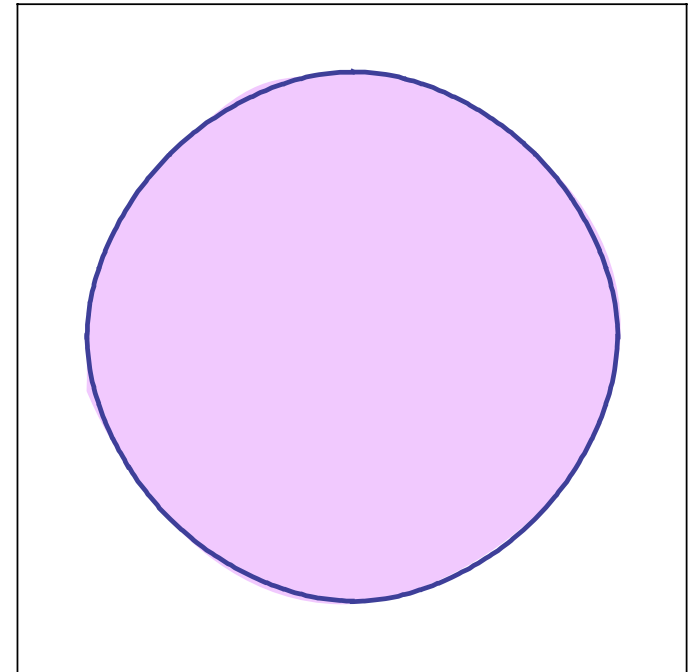
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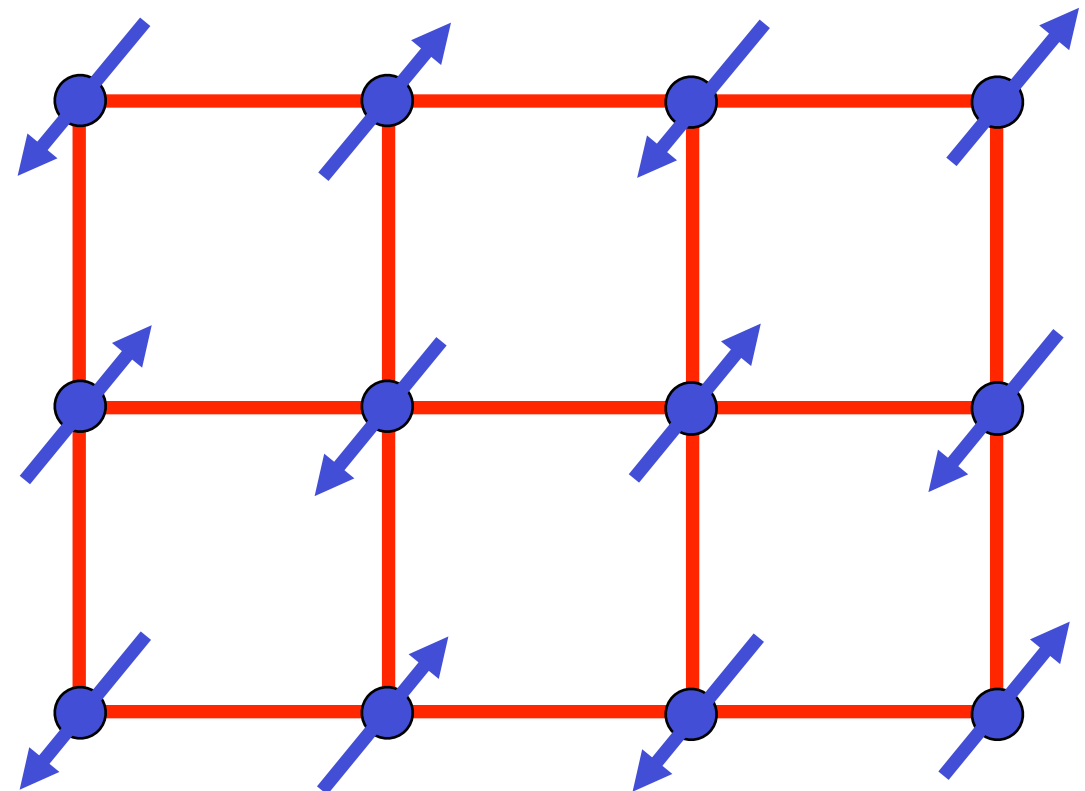


+

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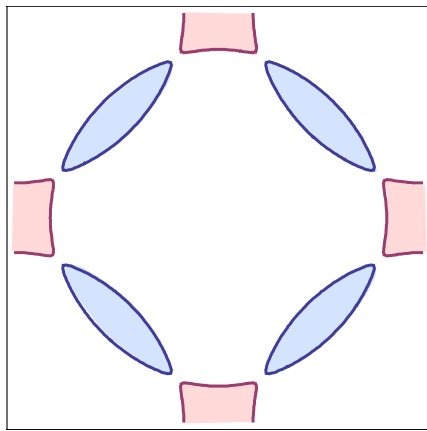
where $\mathbf{K} = (\pi, \pi)$ is the ordering
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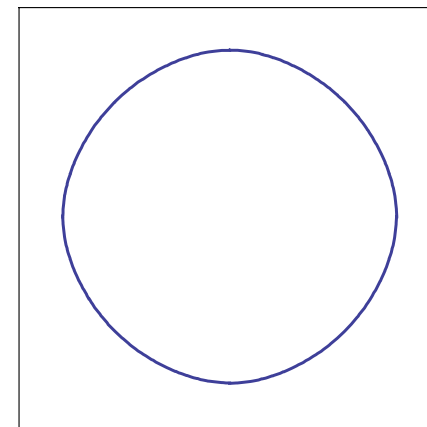
Conventional
Fermi liquids

$1/g$

(A) AFM order with
small Fermi pockets



(B) Fermi liquid with
large Fermi surface

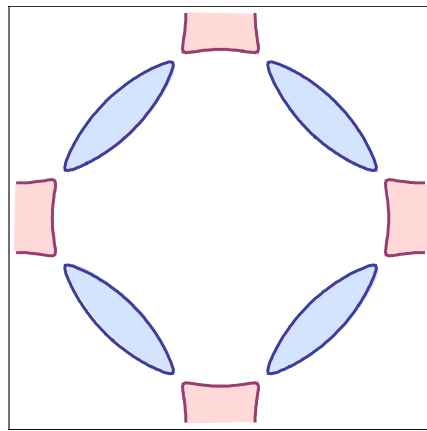


s

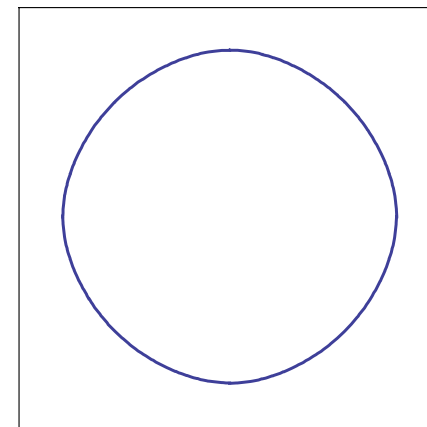
Hertz-Millis
criticality
of AFM order

Conventional
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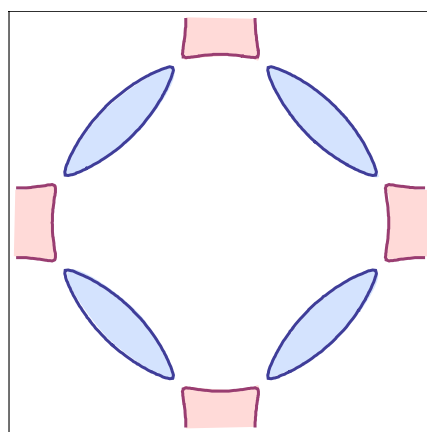
$1/g$

s

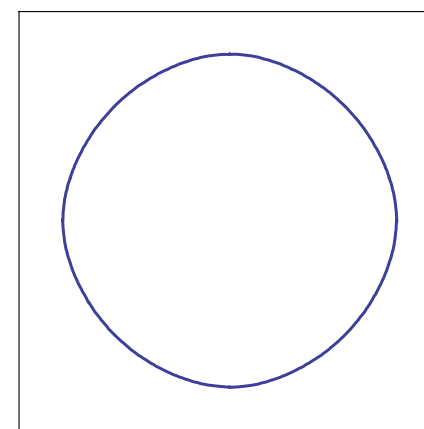
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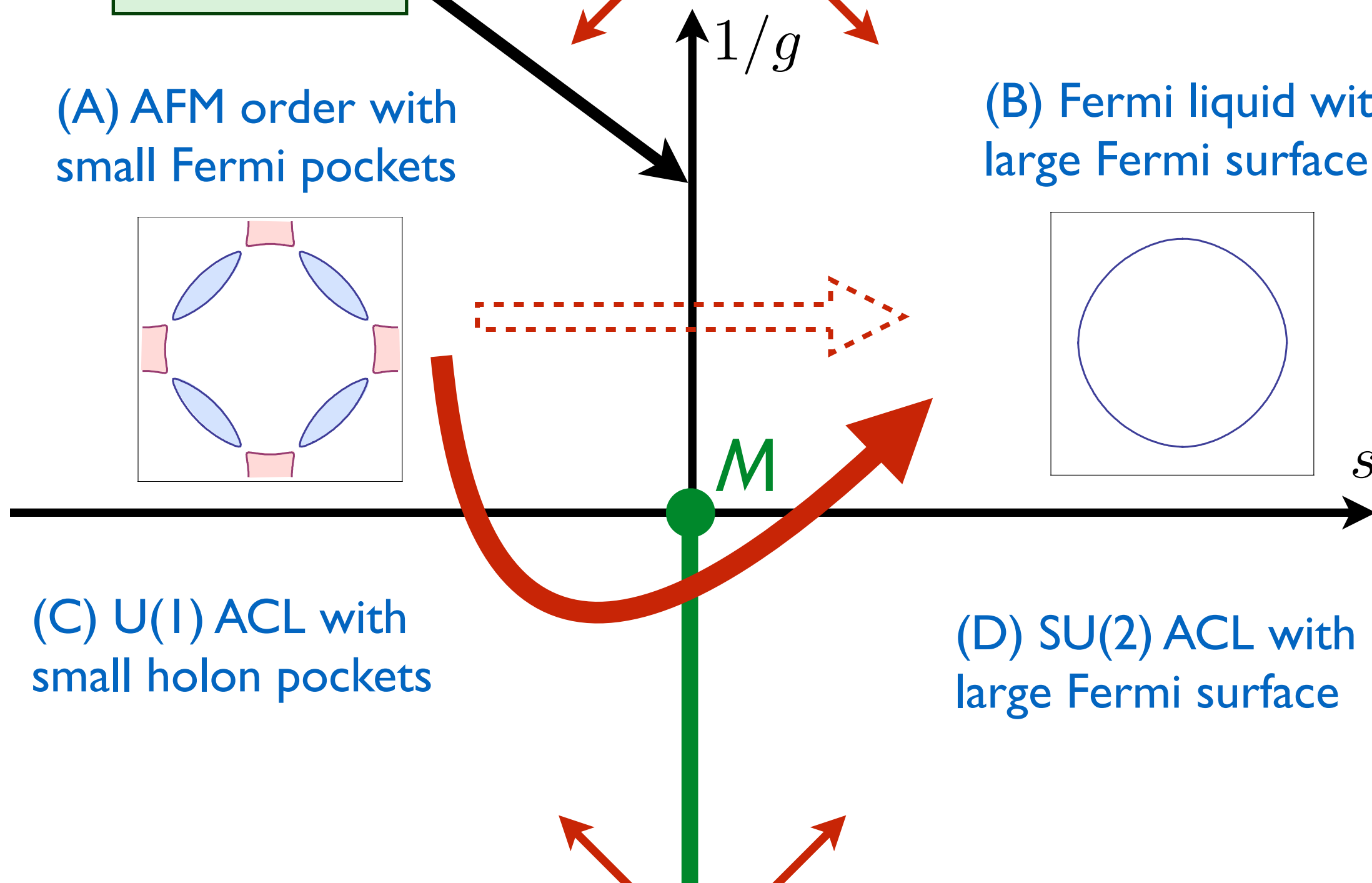


(C) U(1) ACL with
small holon pockets

(D) SU(2) ACL with
large Fermi surface

Non-Fermi
liquids

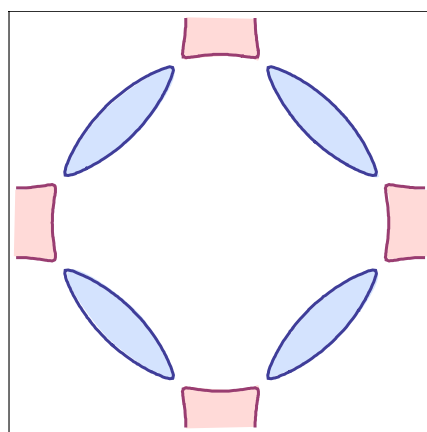
S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu,
Phys. Rev. B **80**, 155129 (2009)
D. Chowdhury and S. Sachdev, arXiv:1412.1086



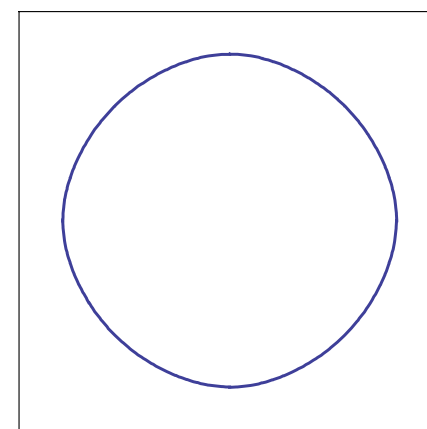
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(B) Fermi liquid with
large Fermi surface



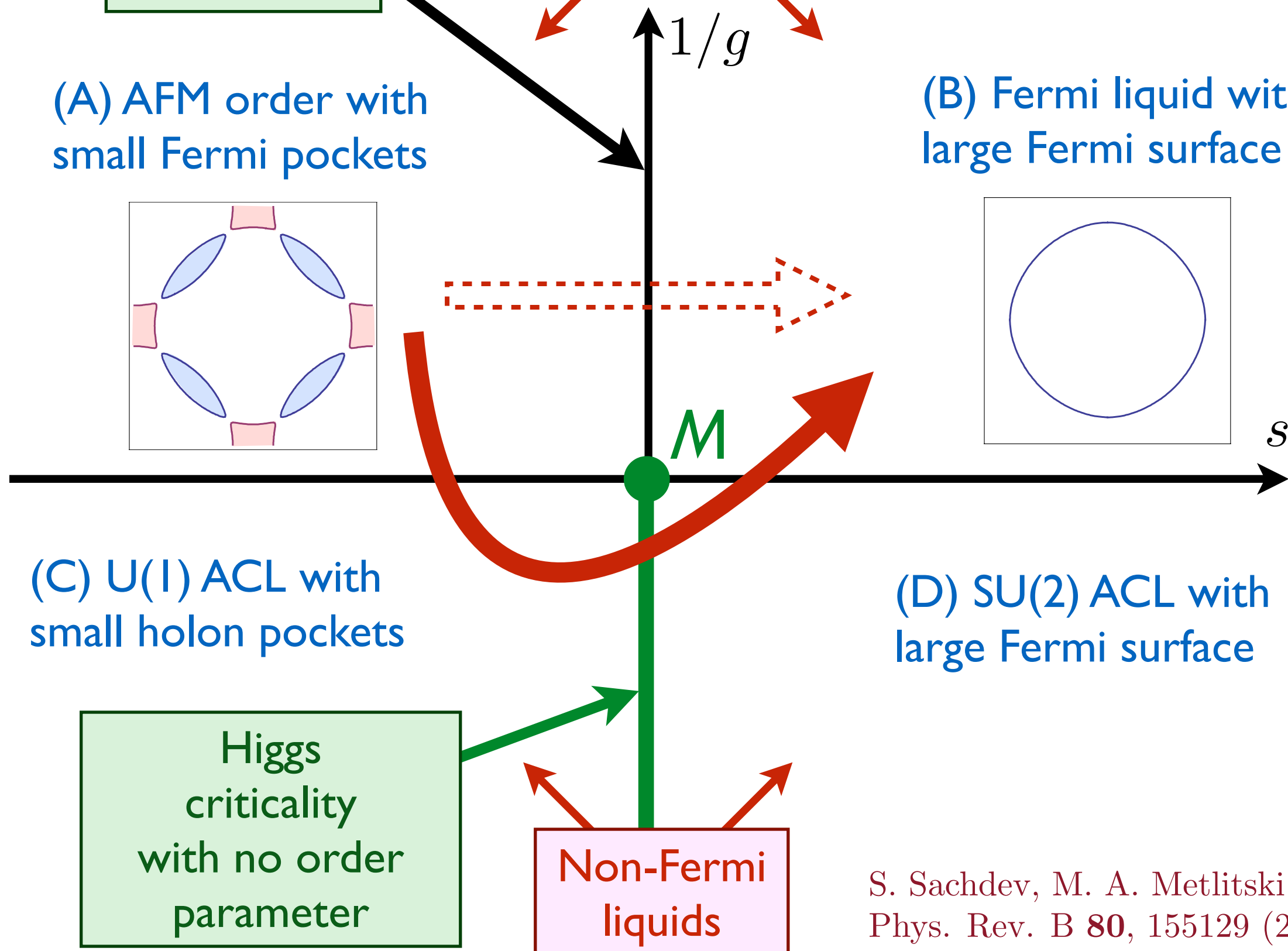
(C) U(1) ACL with
small holon pockets

Higgs
criticality
with no order
parameter

Non-Fermi
liquids

(D) SU(2) ACL with
large 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

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

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

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

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

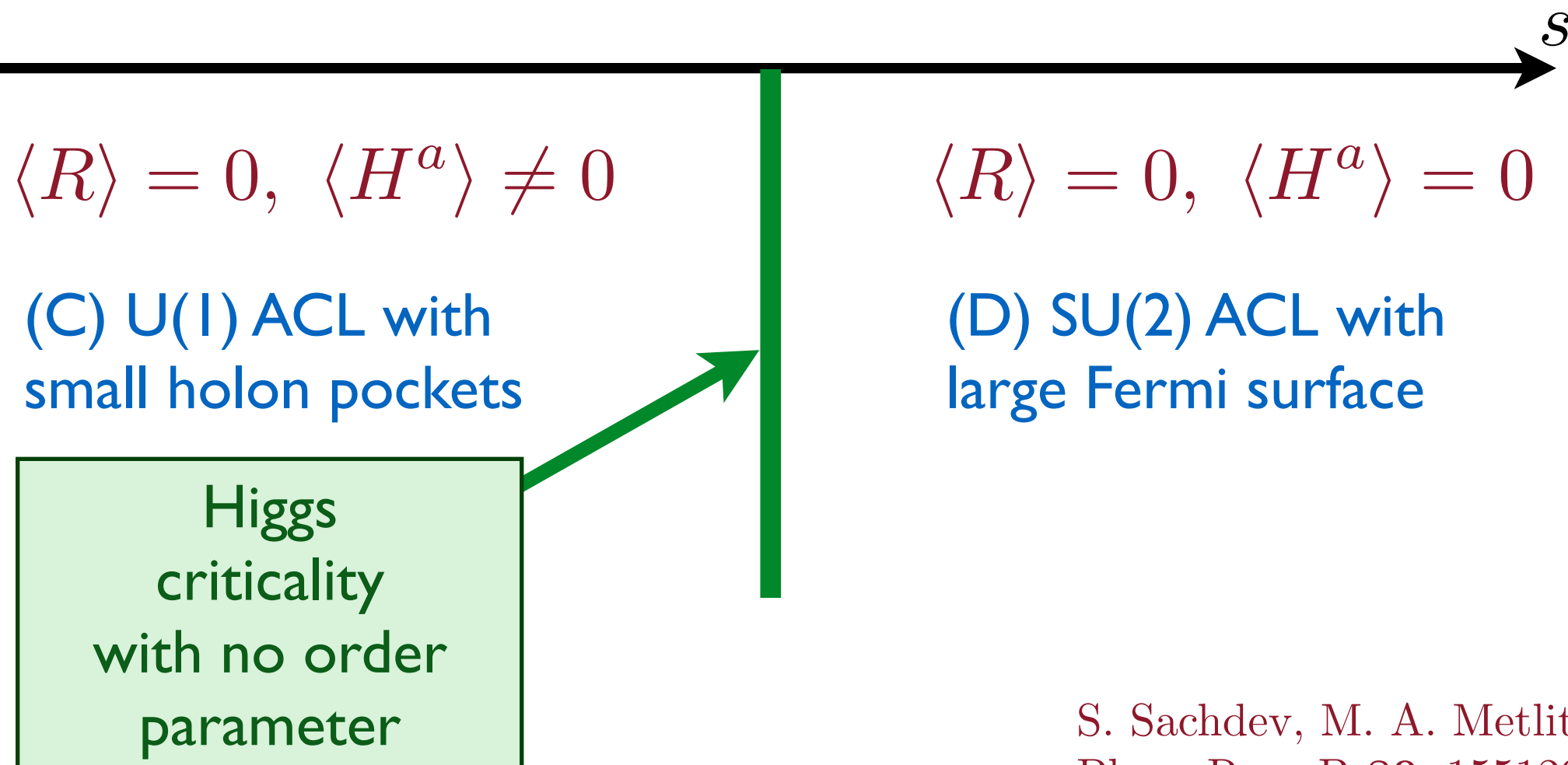
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- A real Higgs field, H , transforming as a gauge SU(2) adjoint, carrying lattice momentum (π, π) . Condensation of the Higgs breaks $SU(2) \rightarrow U(1)$, and transforms the large Fermi surface to a small Fermi surface.

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.



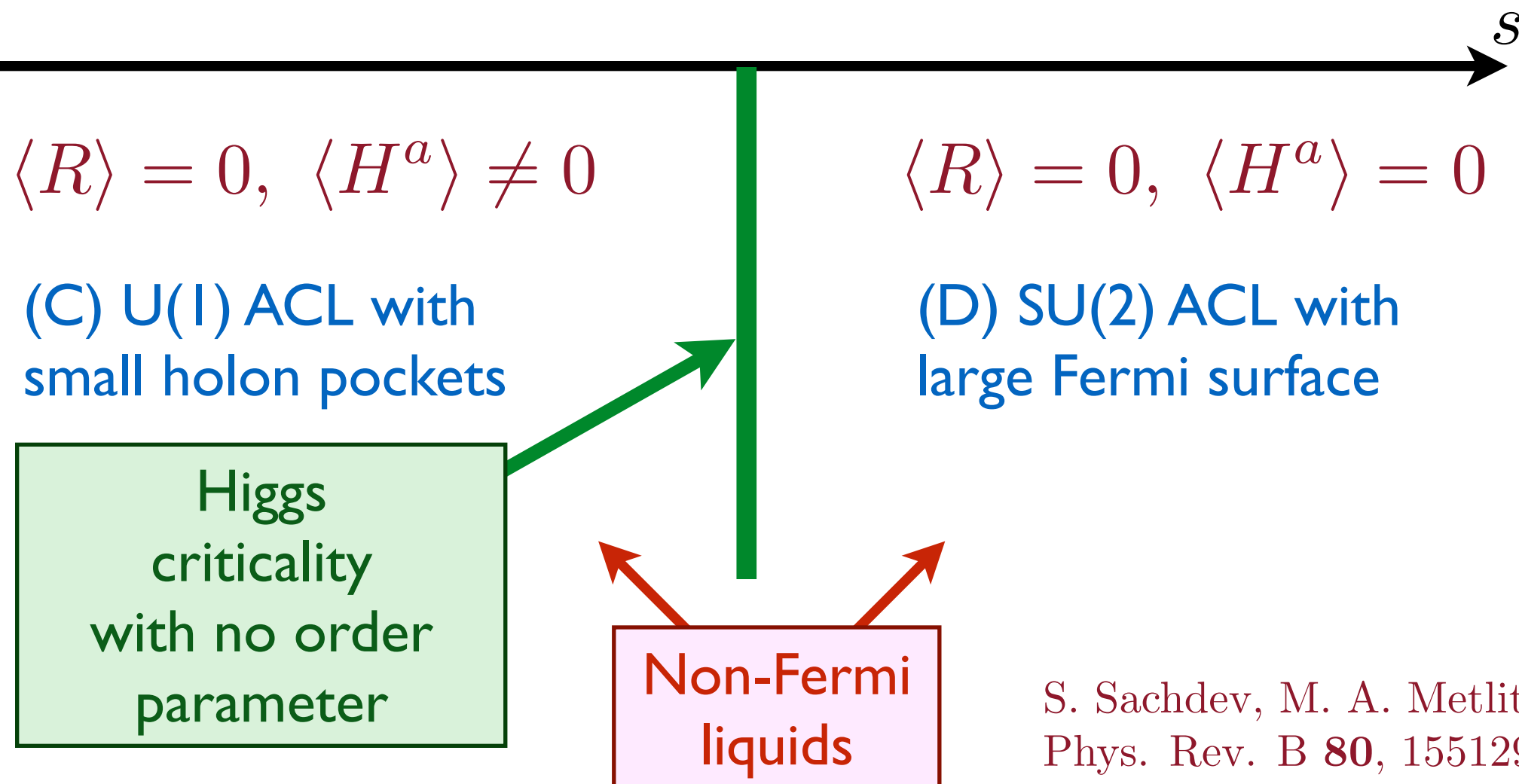
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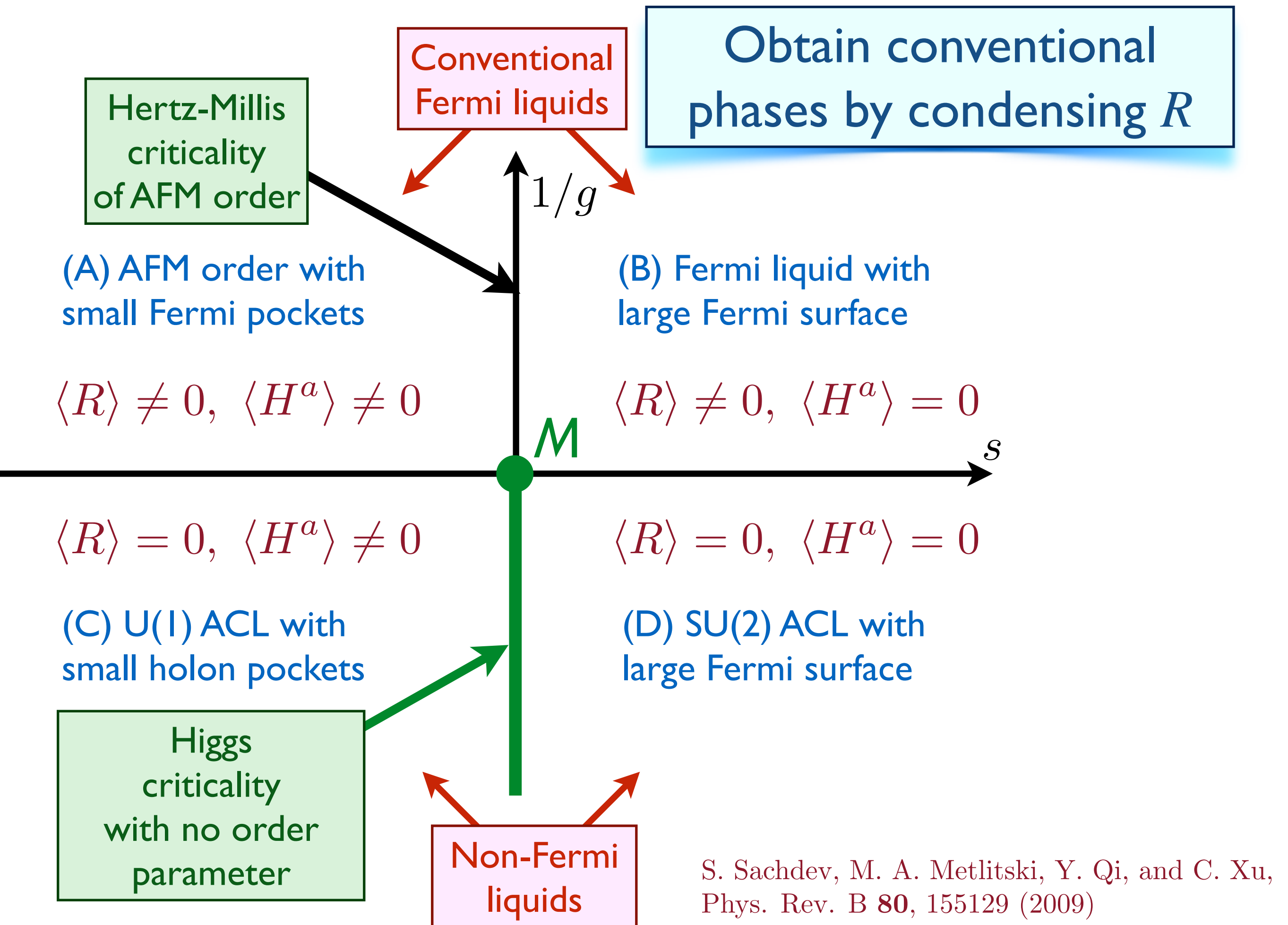
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- The Higgs condensation does not give the fermions a “mass”; instead it reconstructs the Fermi surface from *large* to *small*.
- The quantum phase transition has no gauge-invariant “order parameter”, and it does not break any global symmetries.

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



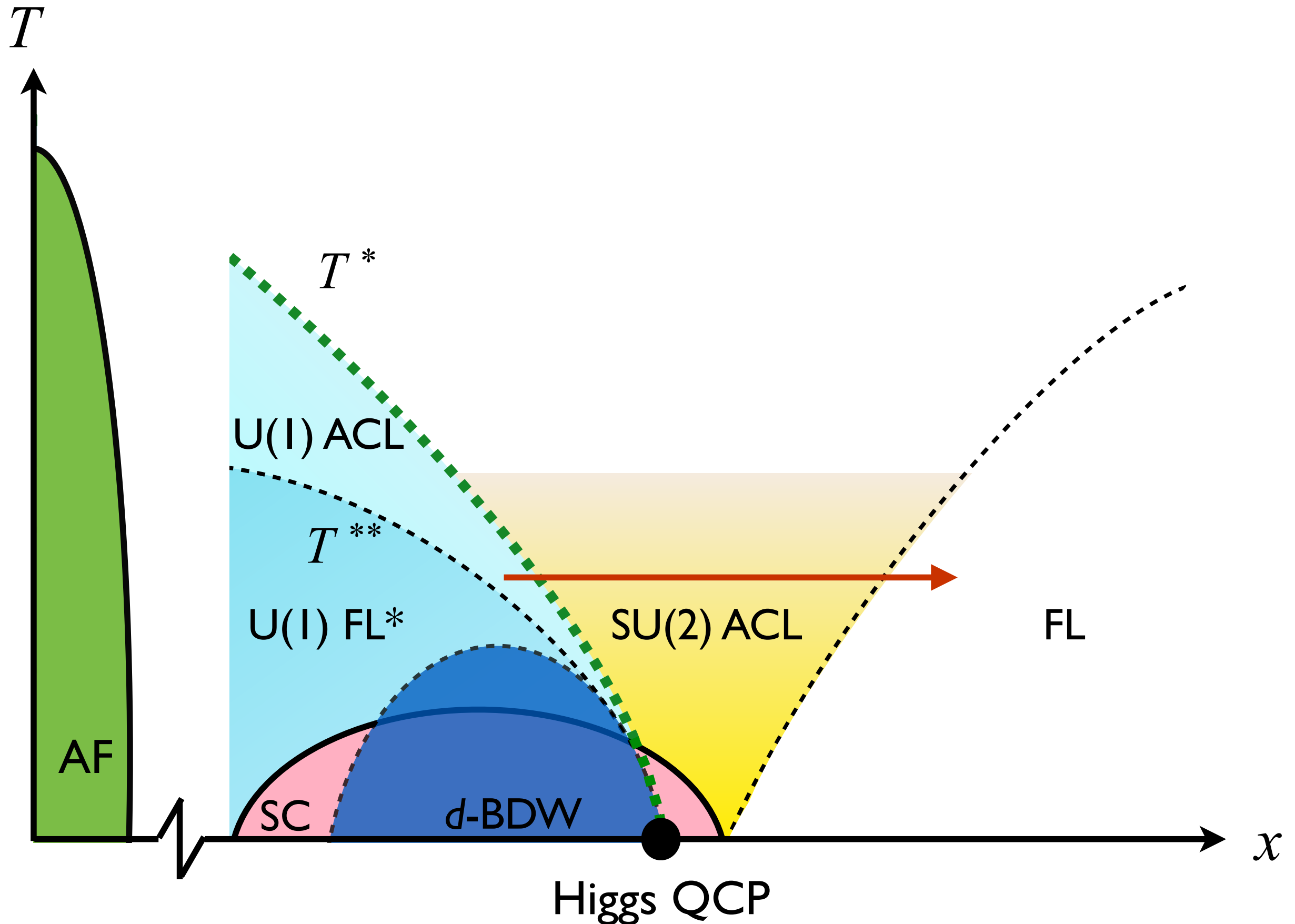
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SU(2) gauge theory for underlying quantum critical point



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.

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 $\mathcal{O} \sim H^2$.

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.

