

Adventures with the spin-fermion model, and beyond

Pines@90, SCES@60

University of Illinois, Urbana
October 18, 2014

Subir Sachdev



Talk online: sachdev.physics.harvard.edu

Spin-fermion model @25

PHYSICAL REVIEW B

VOLUME 42, NUMBER 1

1 JULY 1990

Phenomenological model of nuclear relaxation in the normal state of $\text{YBa}_2\text{Cu}_3\text{O}_7$

A. J. Millis

AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

Hartmut Monien and David Pines

Physics Department, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801

(Received 27 November 1989; revised manuscript received 7 March 1990)

A phenomenological model of a system of antiferromagnetically correlated spins is shown to give a good quantitative description of NMR, nuclear-quadrupole-resonance, and Knight-shift measurements on yttrium, planar copper, and planar oxygen sites in $\text{YBa}_2\text{Cu}_3\text{O}_7$. The antiferromagnetic correlation length is estimated to be ~ 2.5 lattice constants at $T = 100$ K. The temperature dependence of the correlation length ceases at $T_x \simeq 100$ K. The enhancement of the observed relaxation rates over what is expected for weakly interacting electrons is calculated and shown to be large. Extension of the calculation to other cuprate superconductors is discussed.



Spin-fermion model @25

VOLUME 67, NUMBER 24

PHYSICAL REVIEW LETTERS

9 DECEMBER 1991

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

P. Monthoux,⁽¹⁾ A. V. Balatsky,^{(1),(2),(a)} and D. Pines⁽¹⁾

⁽¹⁾*Department of Physics, University of Illinois at Urbana-Champaign, 1110 West Green Street, Urbana, Illinois 61801*

⁽²⁾*Landau Institute for Theoretical Physics, Moscow, U.S.S.R.*

(Received 17 July 1991)

We show that the retarded interaction between quasiparticles on a 2D square lattice induced by the exchange of antiferromagnetic paramagnons leads uniquely to a transition to a superconducting state with $d_{x^2-y^2}$ symmetry. With a spin-excitation spectrum and a quasiparticle-paramagnon coupling determined by fits to normal-state experiments, we obtain high transition temperatures and energy-gap behaviors comparable to those measured for $\text{YBa}_2\text{Cu}_3\text{O}_7$, $\text{YBa}_2\text{Cu}_3\text{O}_{6.63}$, and $\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_4$.



Spin-fermion model @25

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



Spin-fermion model @25

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



Max Metlitski

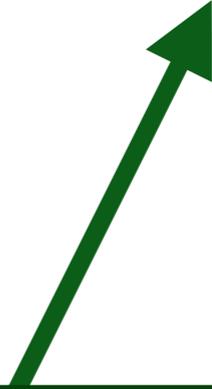
- M. A. Metlitski and S. Sachdev, Phys. Rev. B **85**, 075127 (2010)
T. Holder and W. Metzner, Phys. Rev. B **85**, 165130 (2012)
M. Bejas, A. Greco, and H. Yamase, Phys. Rev. B **86**, 224509 (2012)
S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013)
K. B. Efetov, H. Meier, and C. Pépin,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

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

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

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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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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)

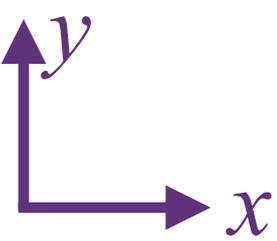
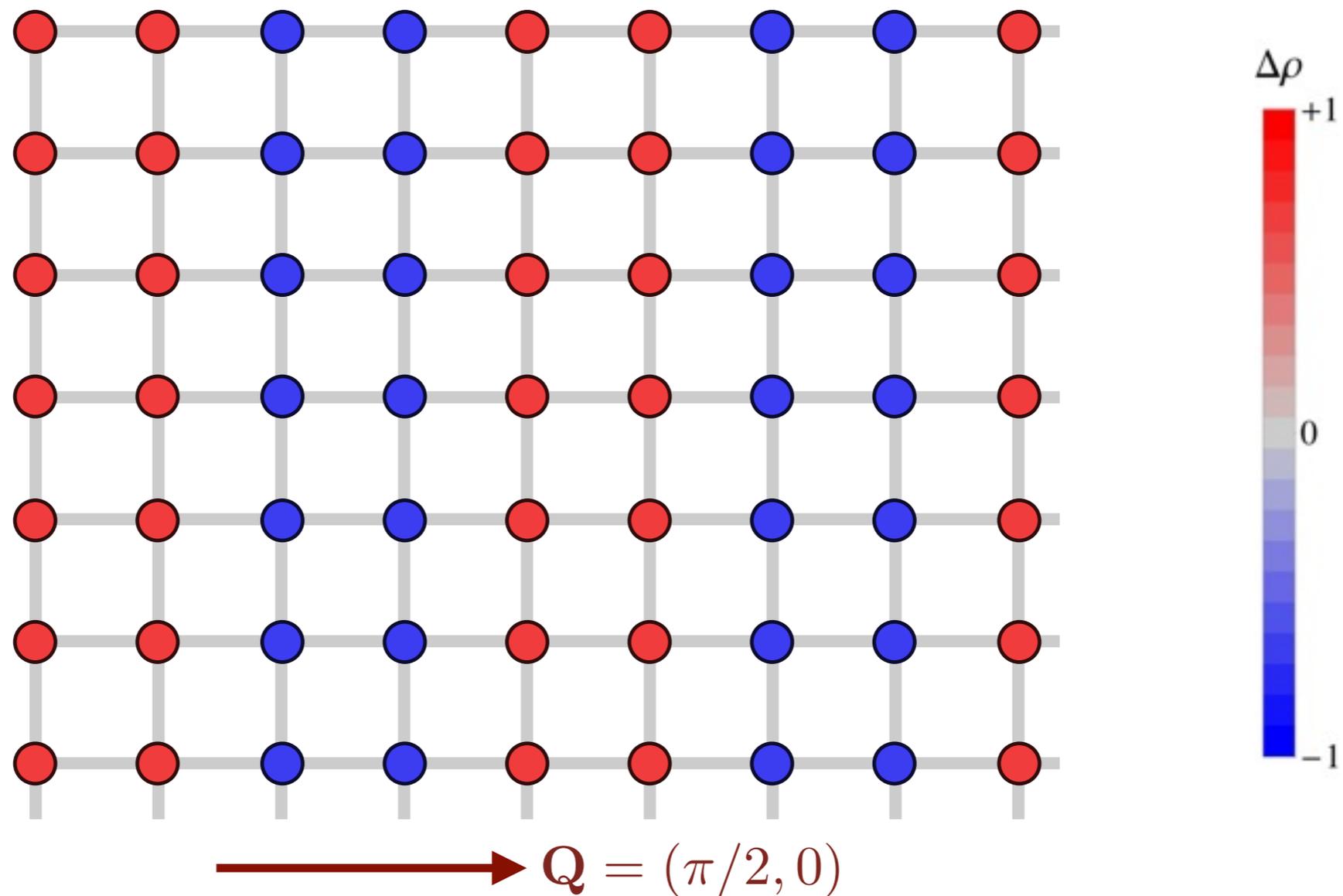
$$\mathcal{P}(\mathbf{k}) = \mathcal{P}_s + \mathcal{P}_{s'}(\cos k_x + \cos k_y) + \mathcal{P}_d(\cos k_x - \cos k_y)$$

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.

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

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

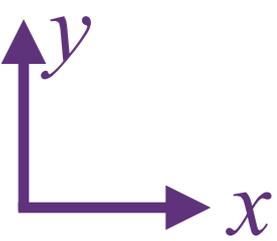
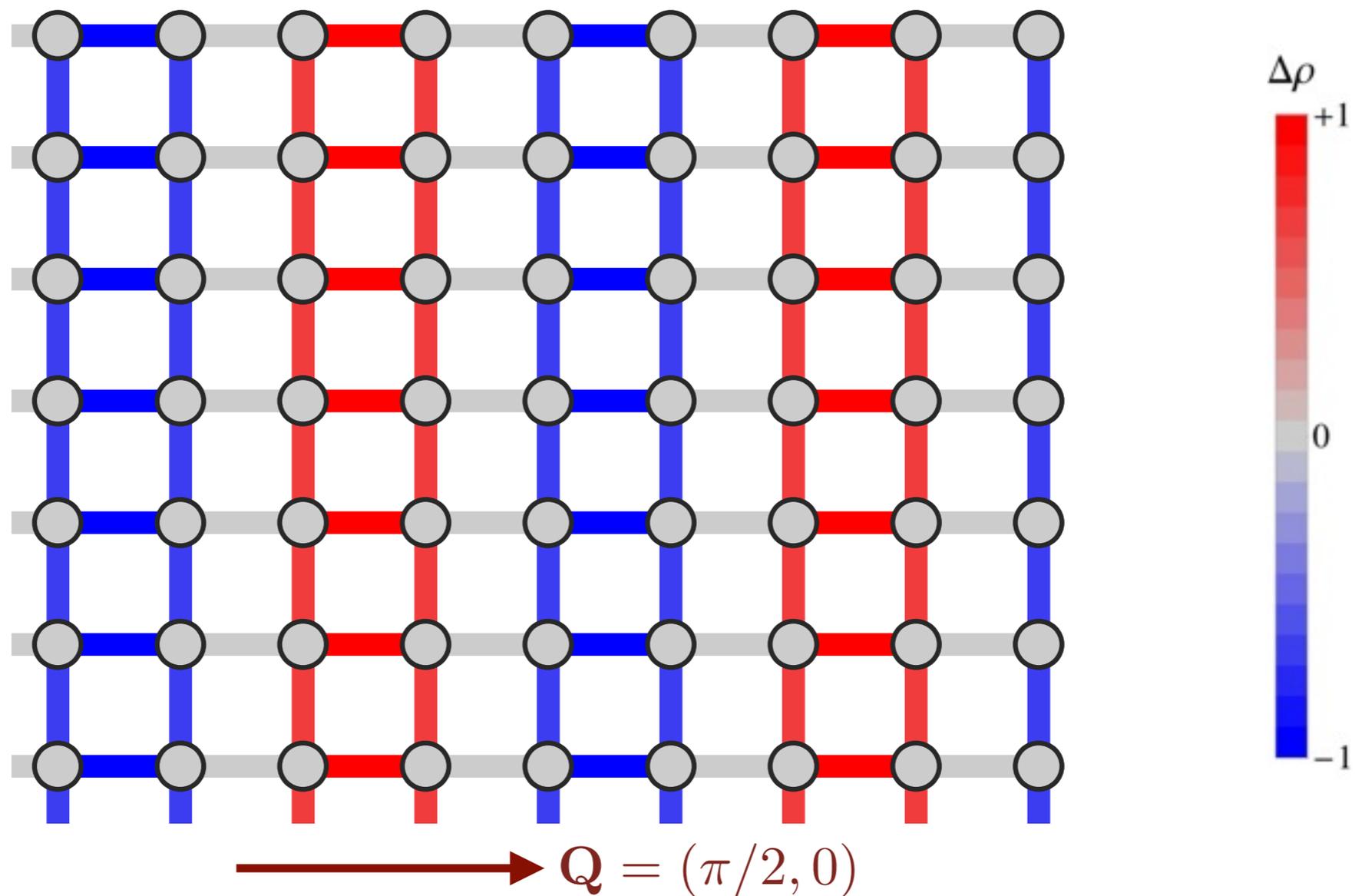


Unconventional DW order: s' -form factor

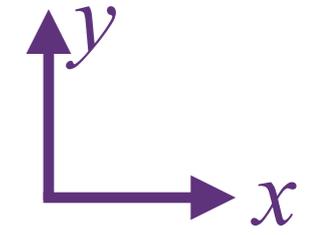
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$$\mathcal{P}(\mathbf{k}) = e^{i\phi} [\cos(k_x) + \cos(k_y)] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$



Unconventional DW order: s' -form factor

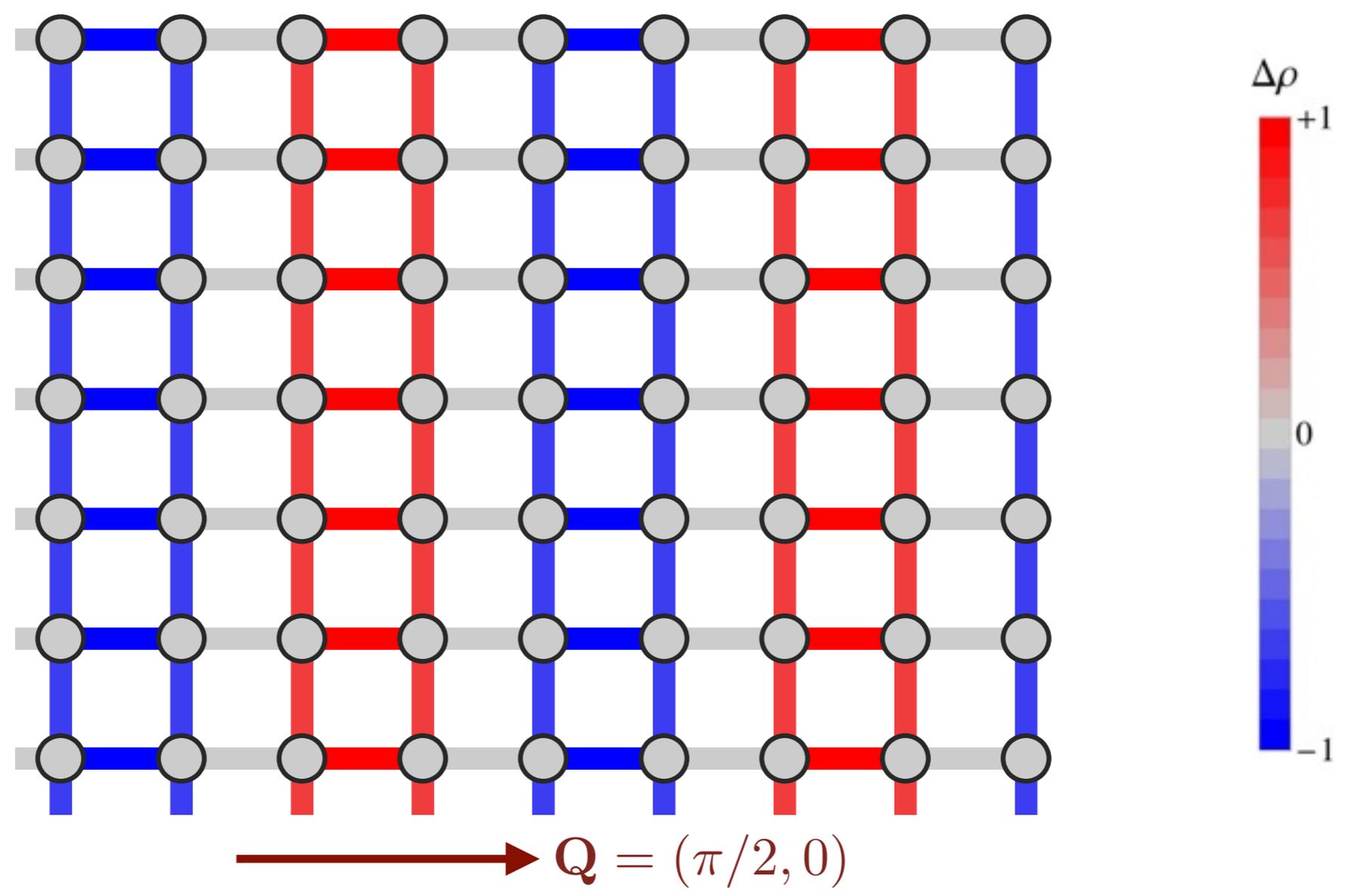


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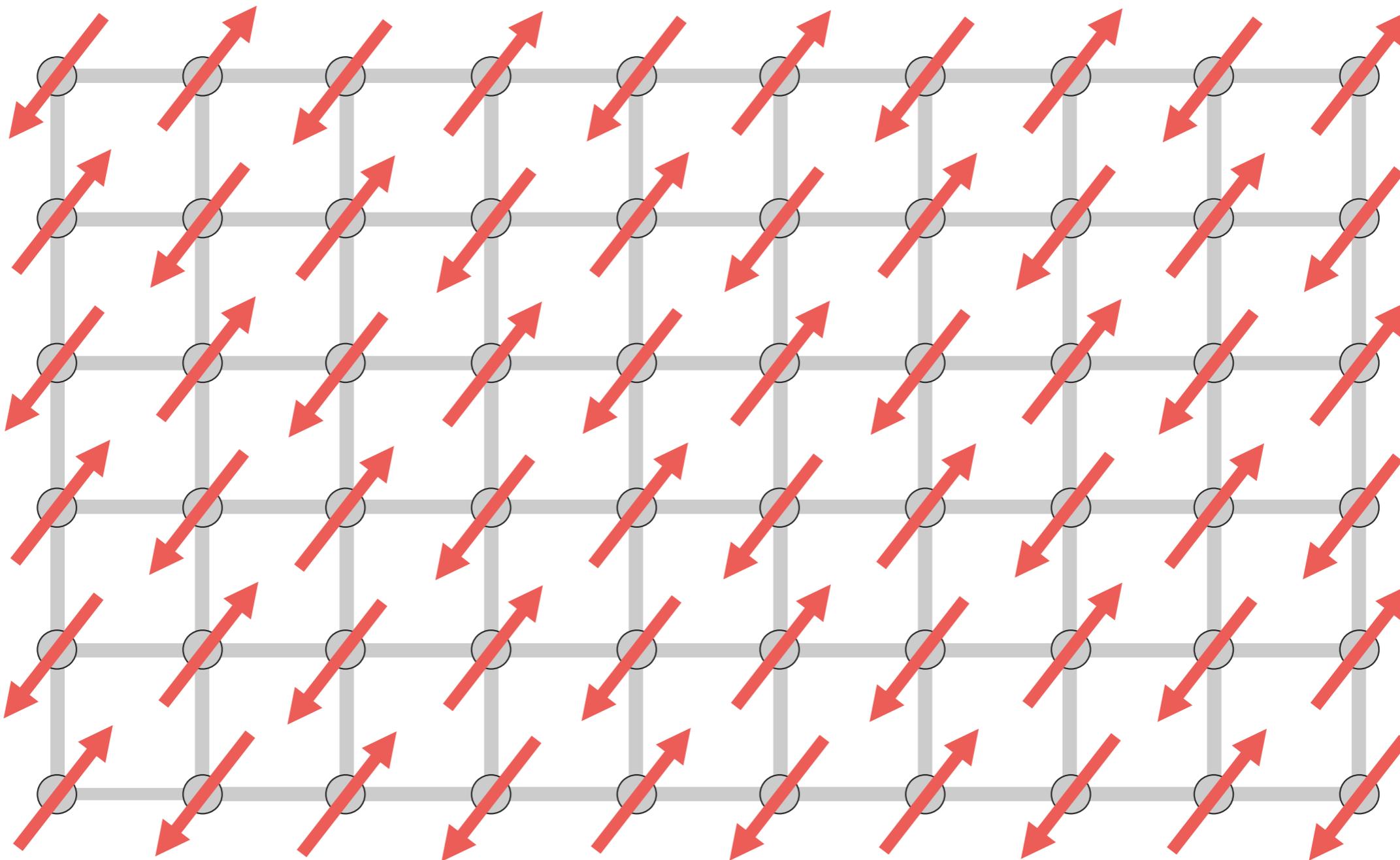
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$$\mathcal{P}(\mathbf{k}) = e^{i\phi} [\cos(k_x) + \cos(k_y)] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$

“Stripe”
model !

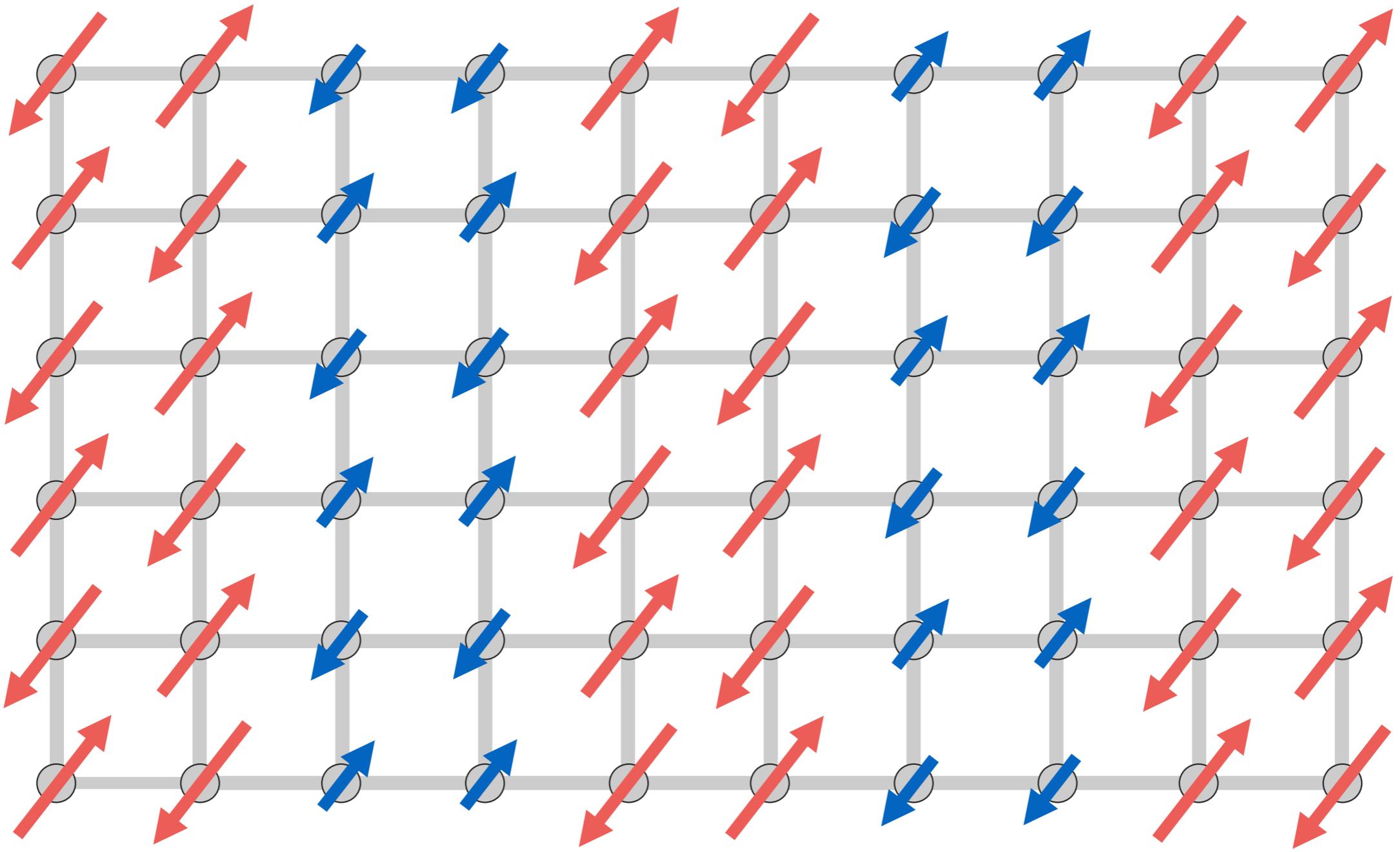


“Stripe” model



Start with an antiferromagnet

“Stripe” model

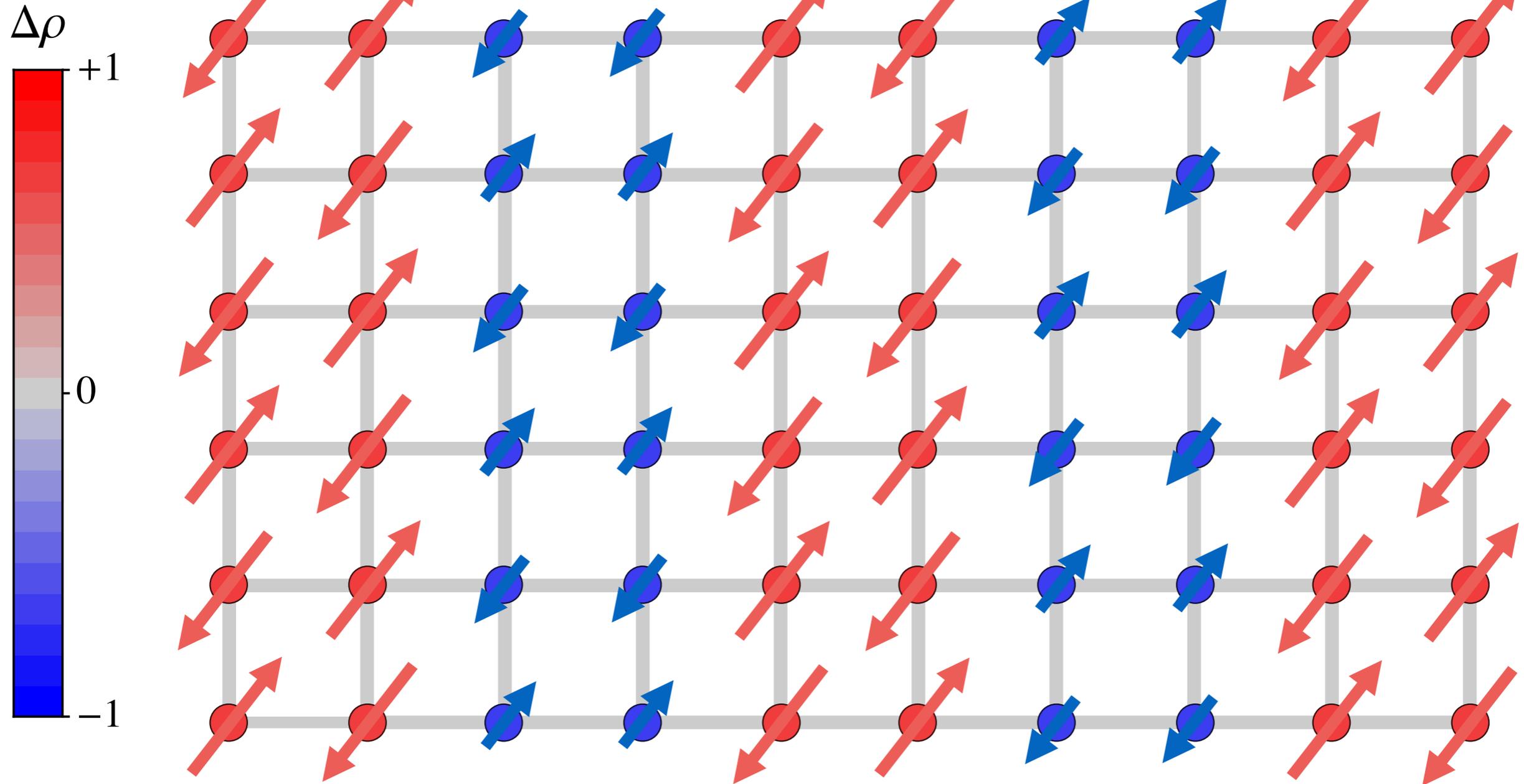


Domain walls 4 lattice spacings apart

“Stripe” model

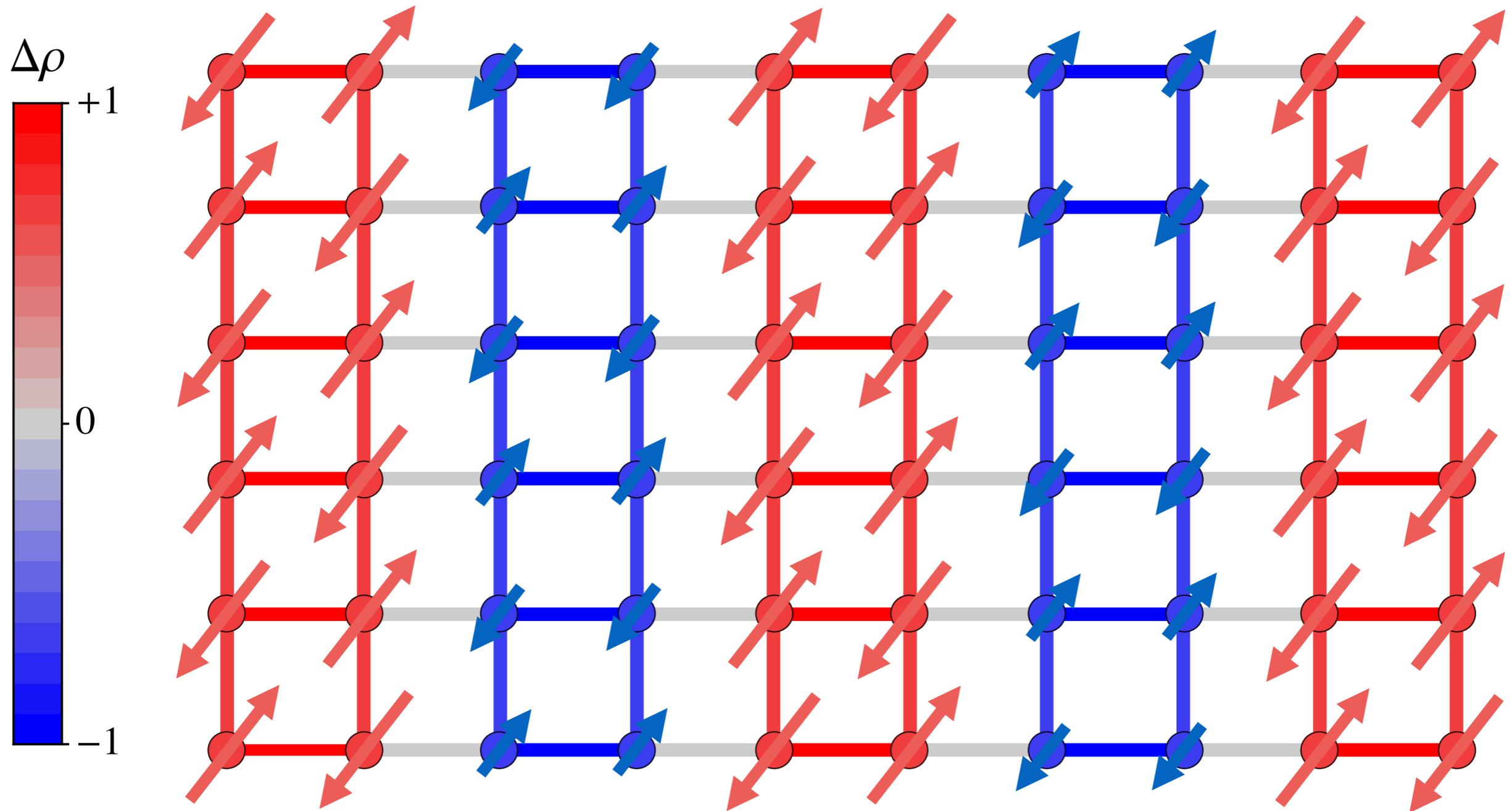
Observed in La-based
compounds (Tranquada..)

Theory: Zaanen, Kivelson, Fradkin....



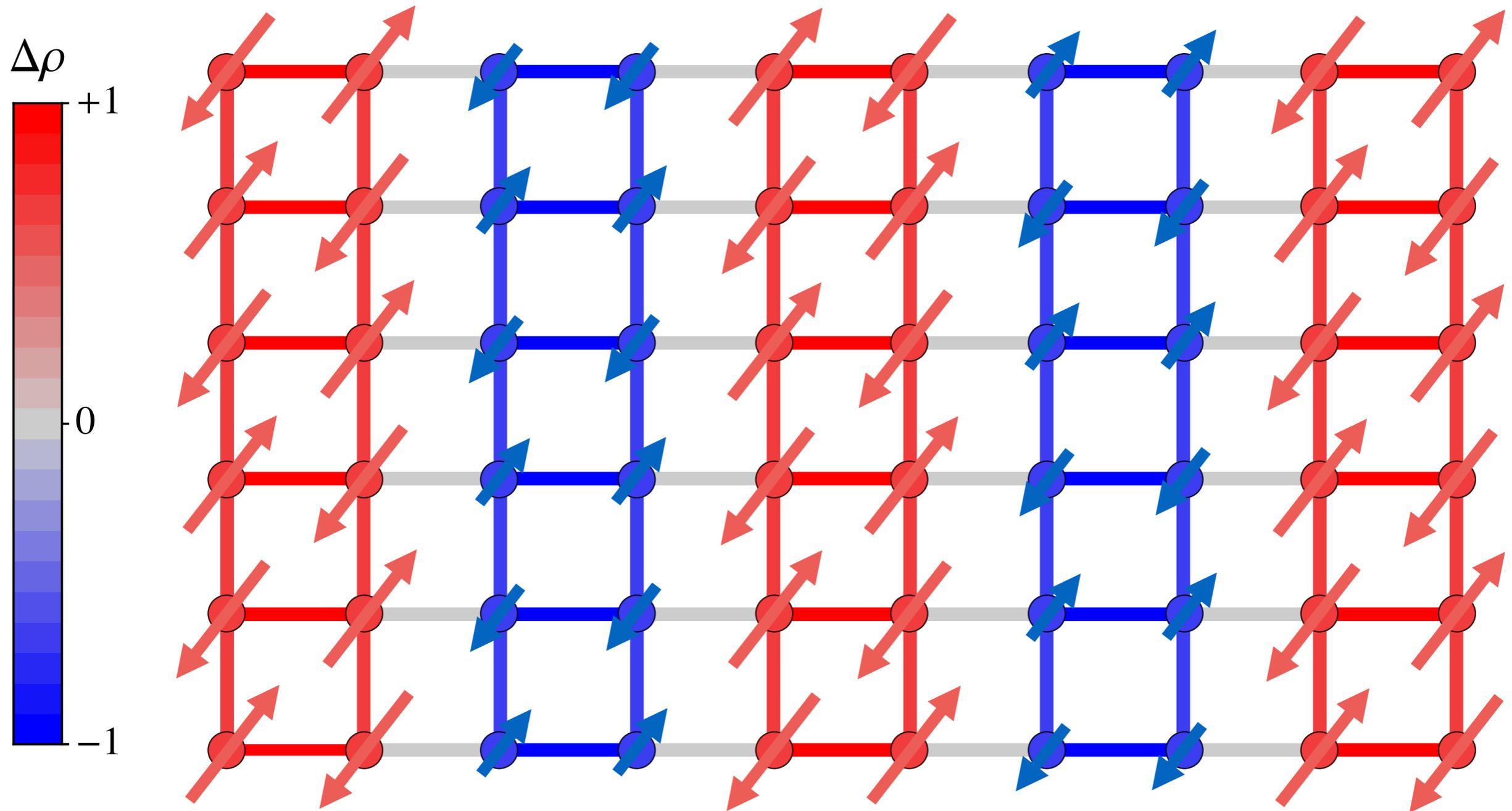
Put the holes in the domain walls

“Stripe”
model



Colors on the bonds map the local exchange energy

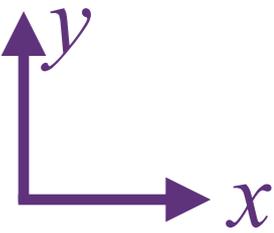
“Stripe”
model



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

Unconventional DW order: s' -form factor

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

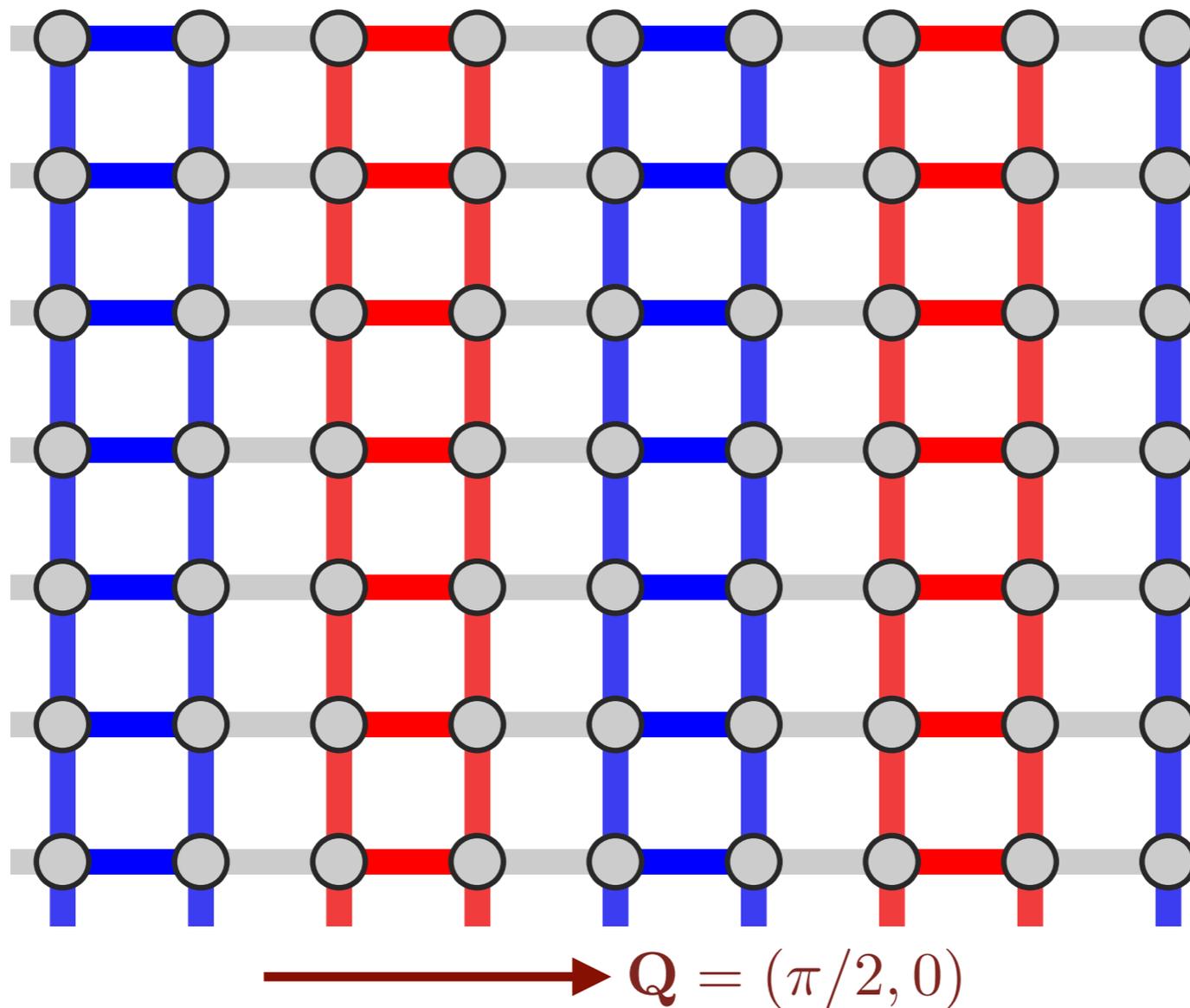


$$P_{ij} = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k} \cdot (\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q} \cdot (\mathbf{r}_i + \mathbf{r}_j)/2} + \text{c.c.}$$

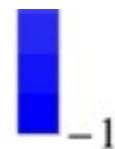
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} [\cos(k_x) + \cos(k_y)] \quad \text{and} \quad \mathbf{Q} = 2\pi(1/4, 0)$$

“Stripe”
model !

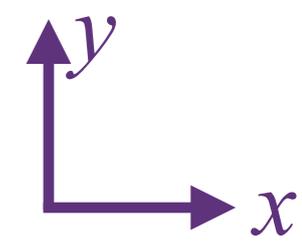
X-ray
observations
indicate
strong s'
component in
LBCO



David
Hawthorn



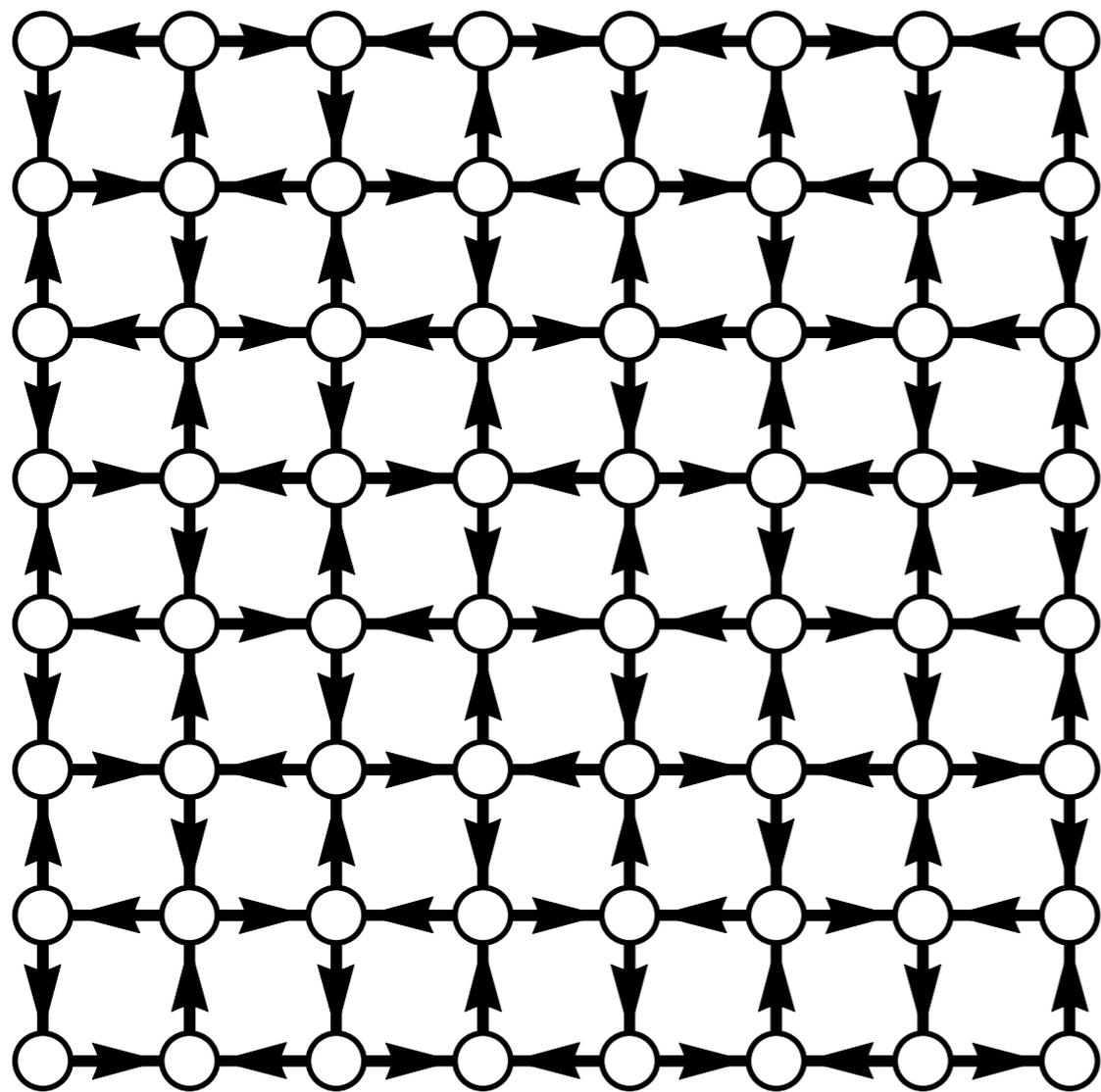
Current order: p -form factor



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

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

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



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

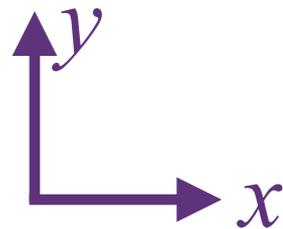
S. Chakravarty, R. B. Laughlin, D. K. Morr, and C. Nayak, Phys. Rev. B **63**, 094503 (2001).

P. A. Lee, N. Nagaosa, and X.-G. Wen, Rev. Mod. Phys. **78**, 17 (2006).

R. B. Laughlin, Phys. Rev. B **89**, 035134 (2014).

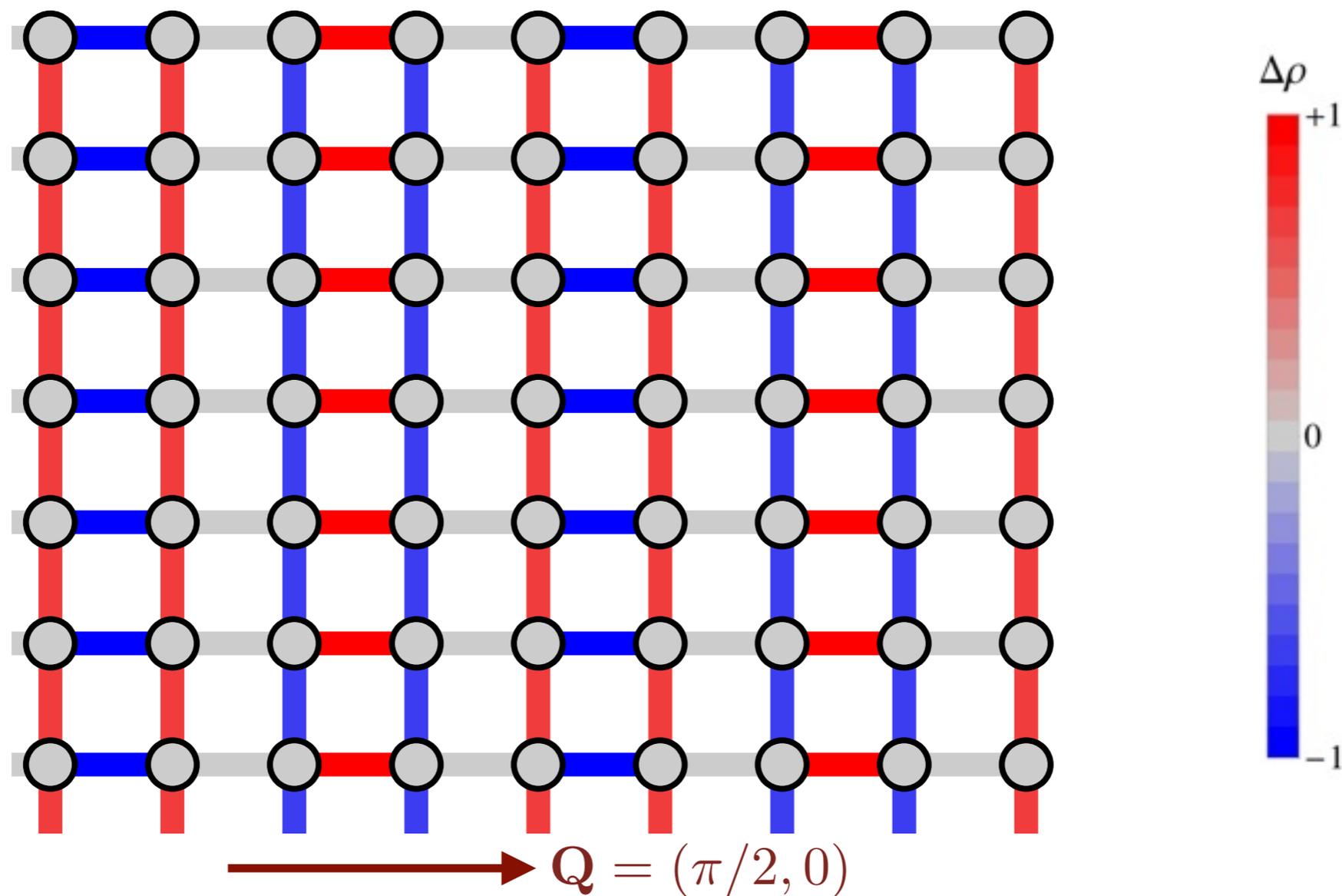
Unconventional DW order: d -form factor

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



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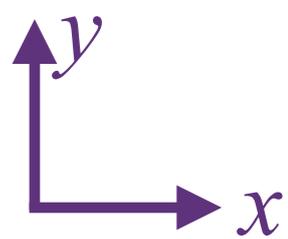
M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075128 (2010).
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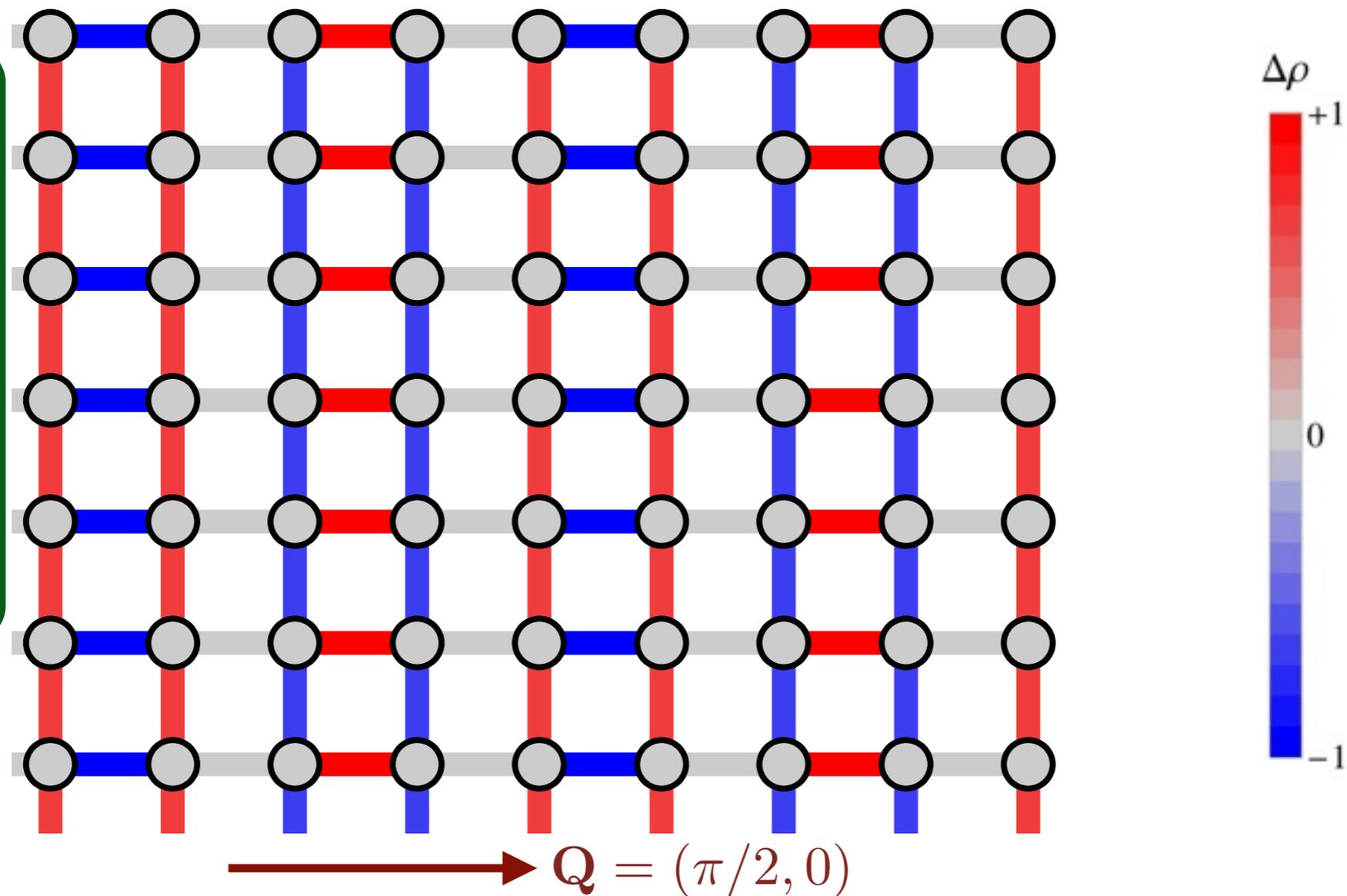
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Our prediction:
Density wave on
horizontal
bonds has a
phase-shift of π
relative to the
wave on vertical
bonds



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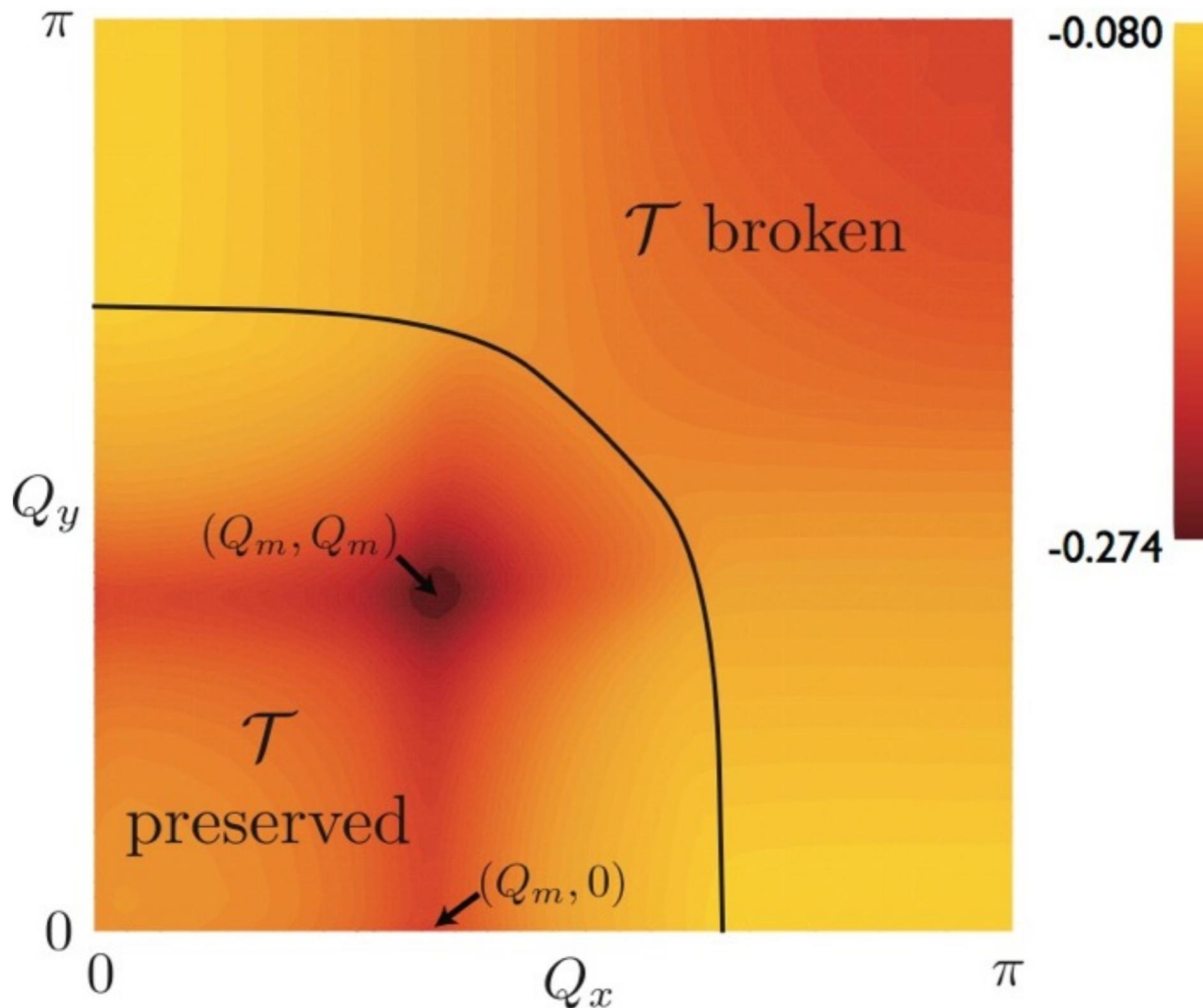
Spin-fermion model @25

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

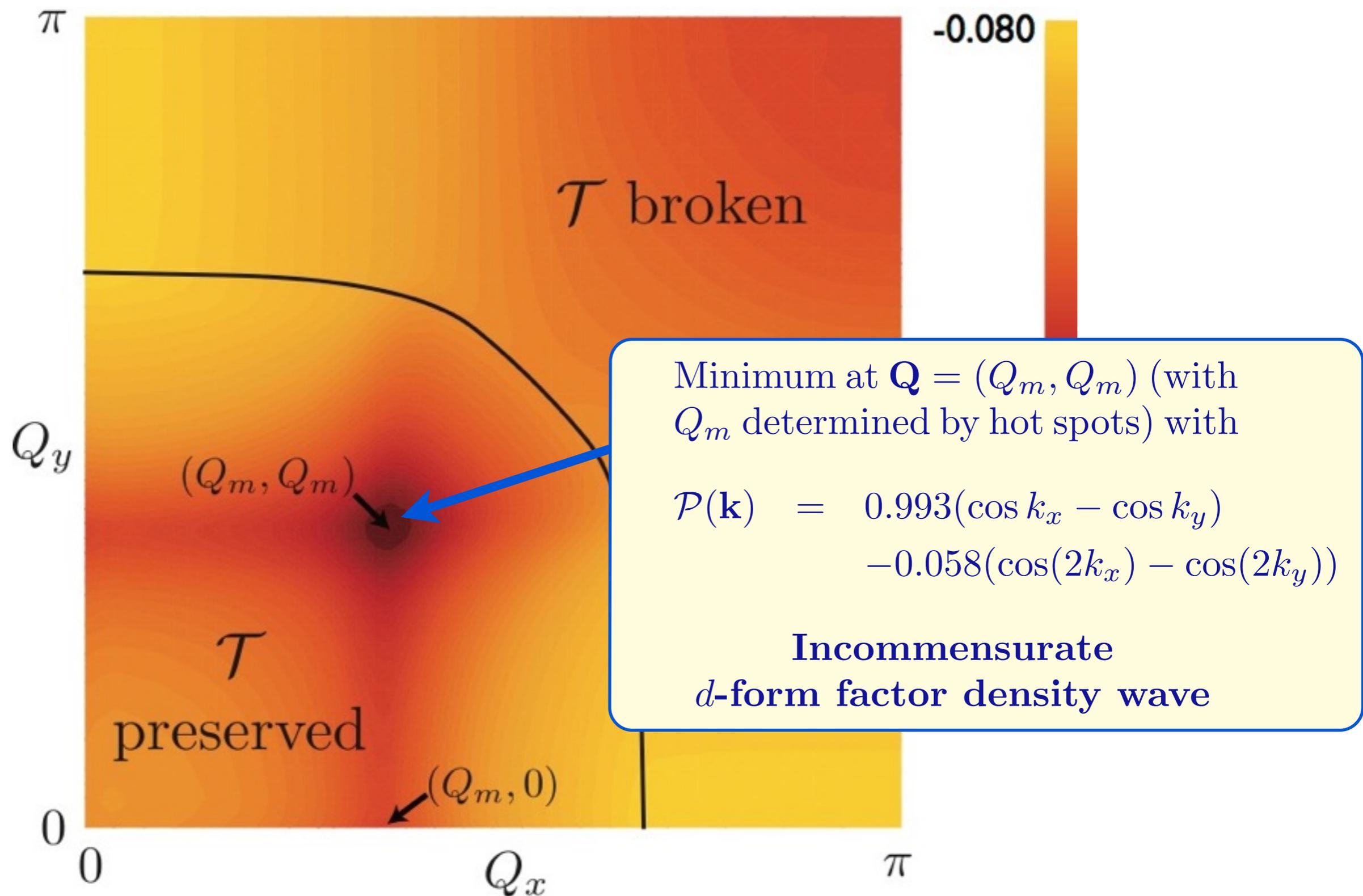


Compute eigenvalues, $\lambda(\mathbf{Q})$, of the spin-singlet, particle-hole propagator. The corresponding eigenvector is $\mathcal{P}(\mathbf{k})$ and this leads to the order

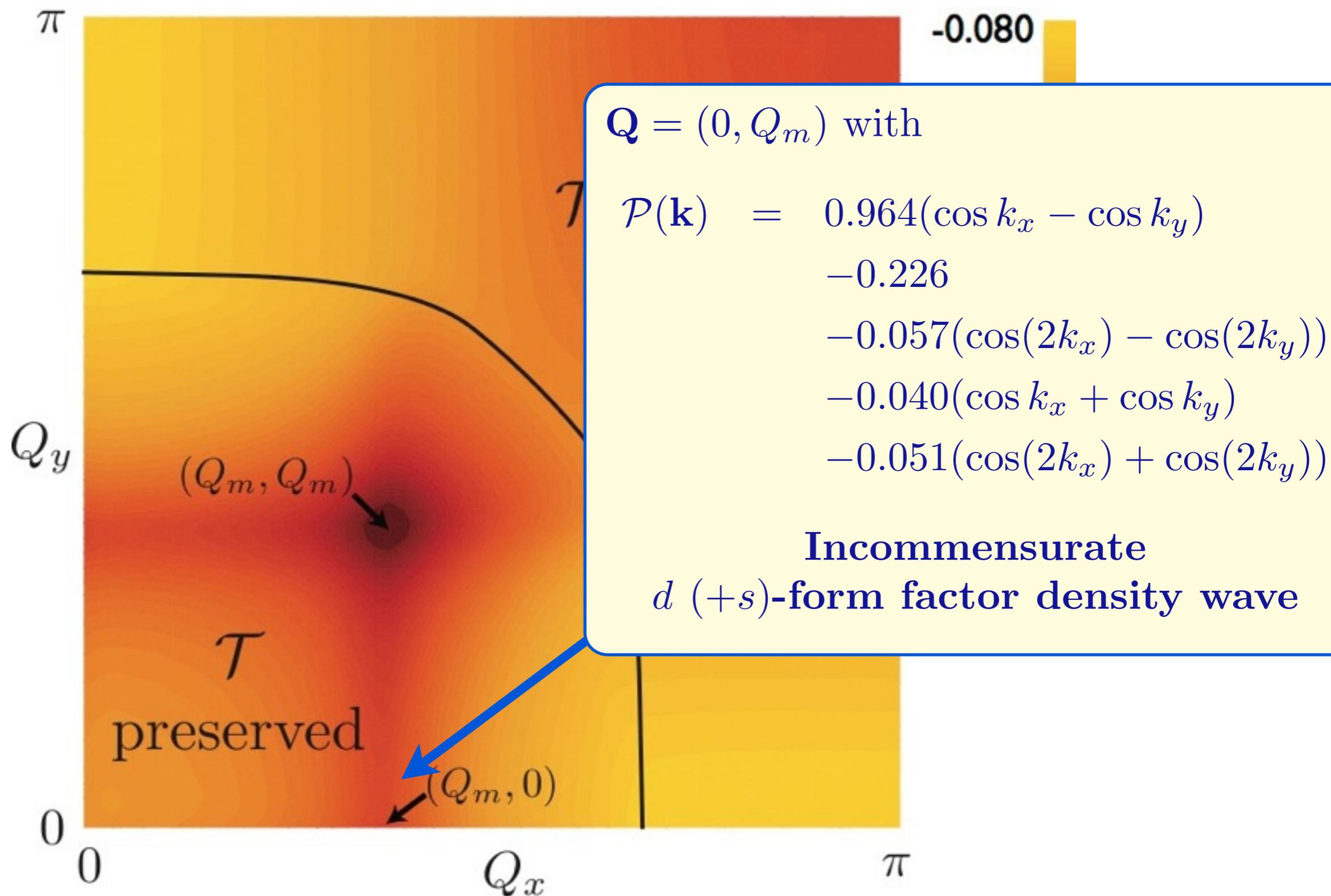
$$\langle c_{i\alpha}^\dagger c_{j\alpha} \rangle = \left[\int_{\mathbf{k}} \mathcal{P}(\mathbf{k}) e^{i\mathbf{k} \cdot (\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q} \cdot (\mathbf{r}_i + \mathbf{r}_j) / 2}$$



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



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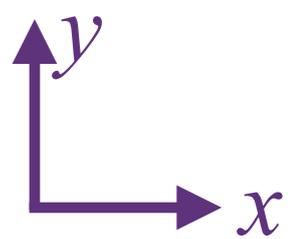
Eigenvalues, $\lambda(\mathbf{Q})$, of the spin-singlet, particle-hole propagator.
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Unconventional DW order: d -form factor

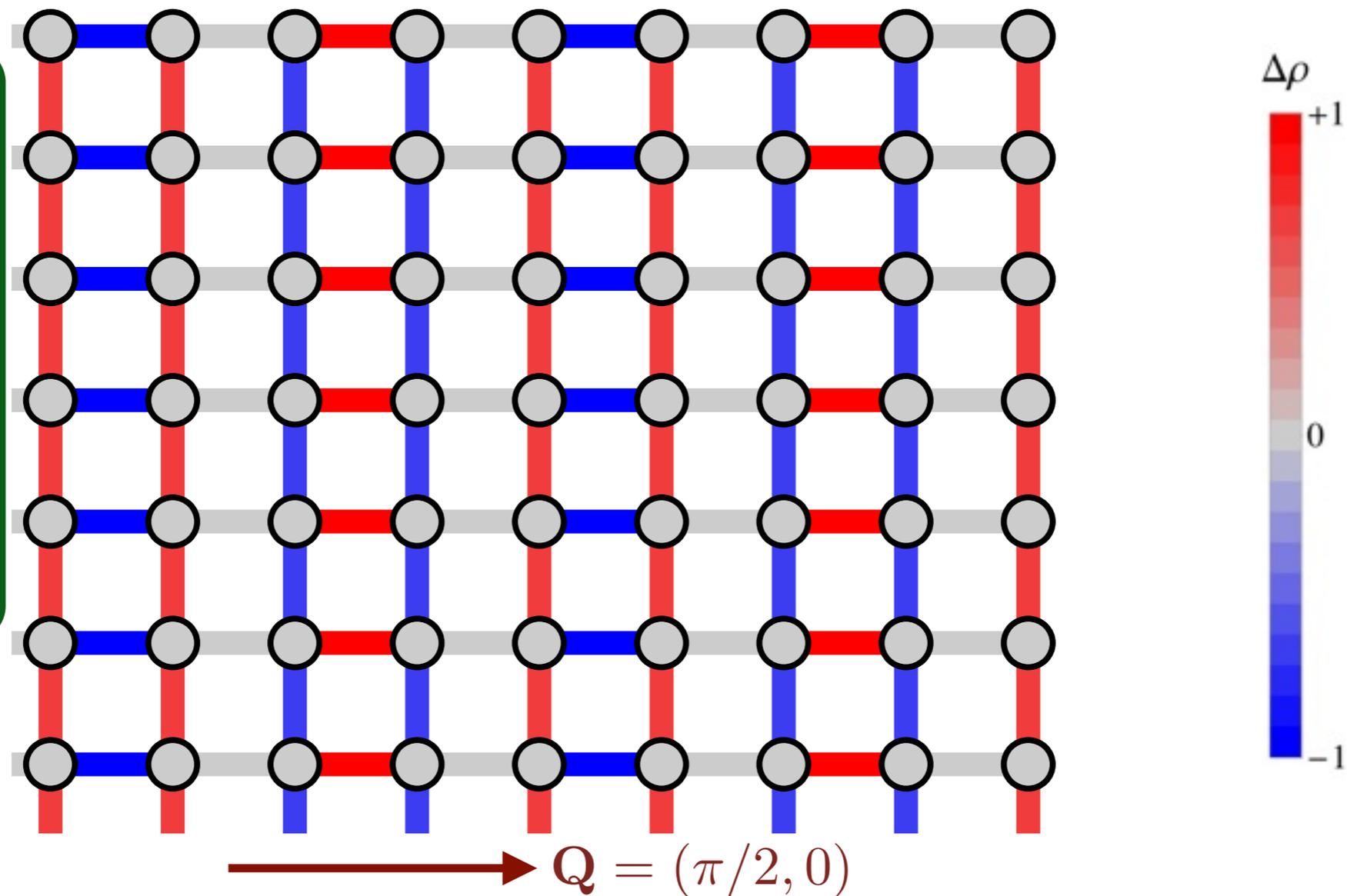
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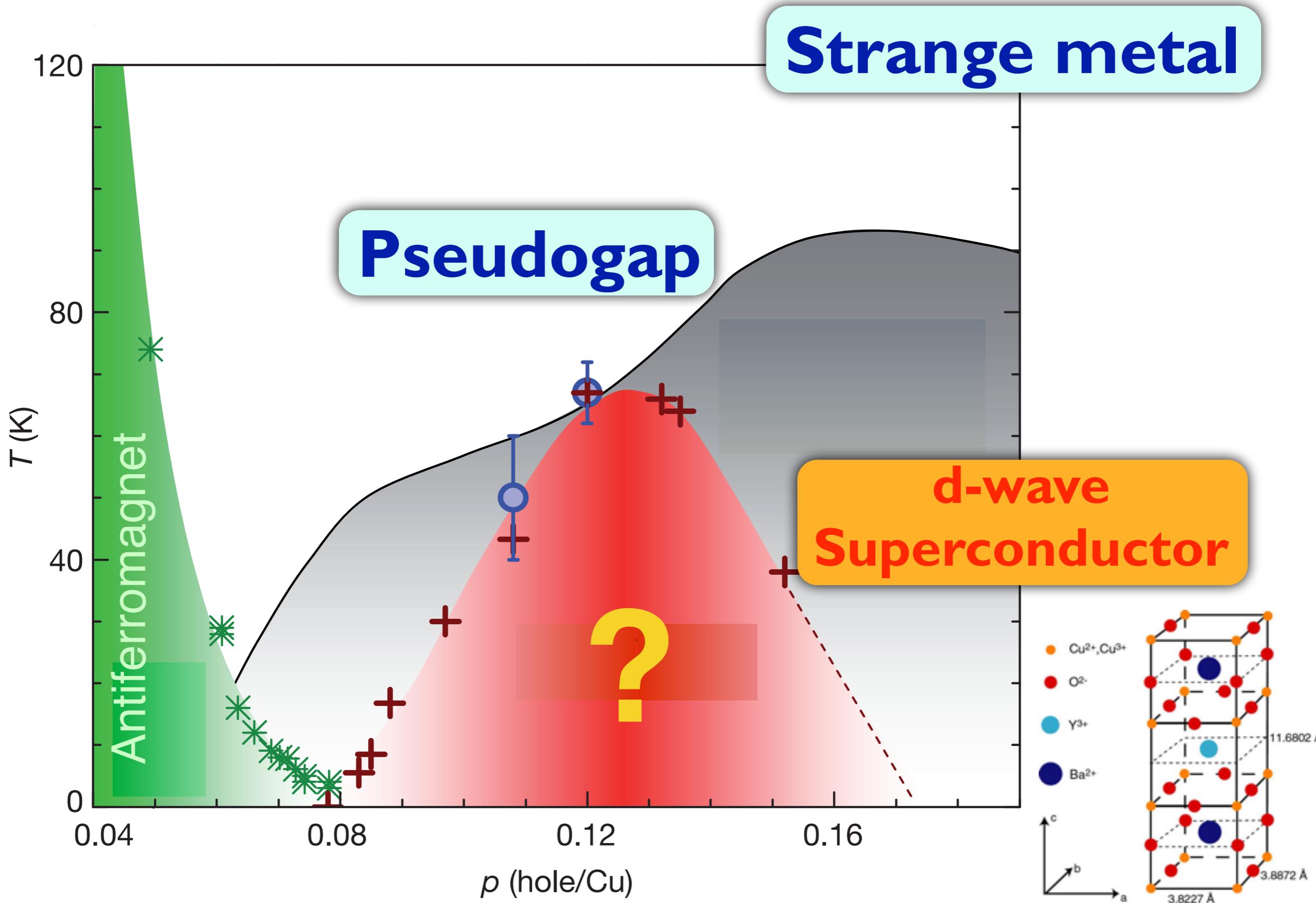
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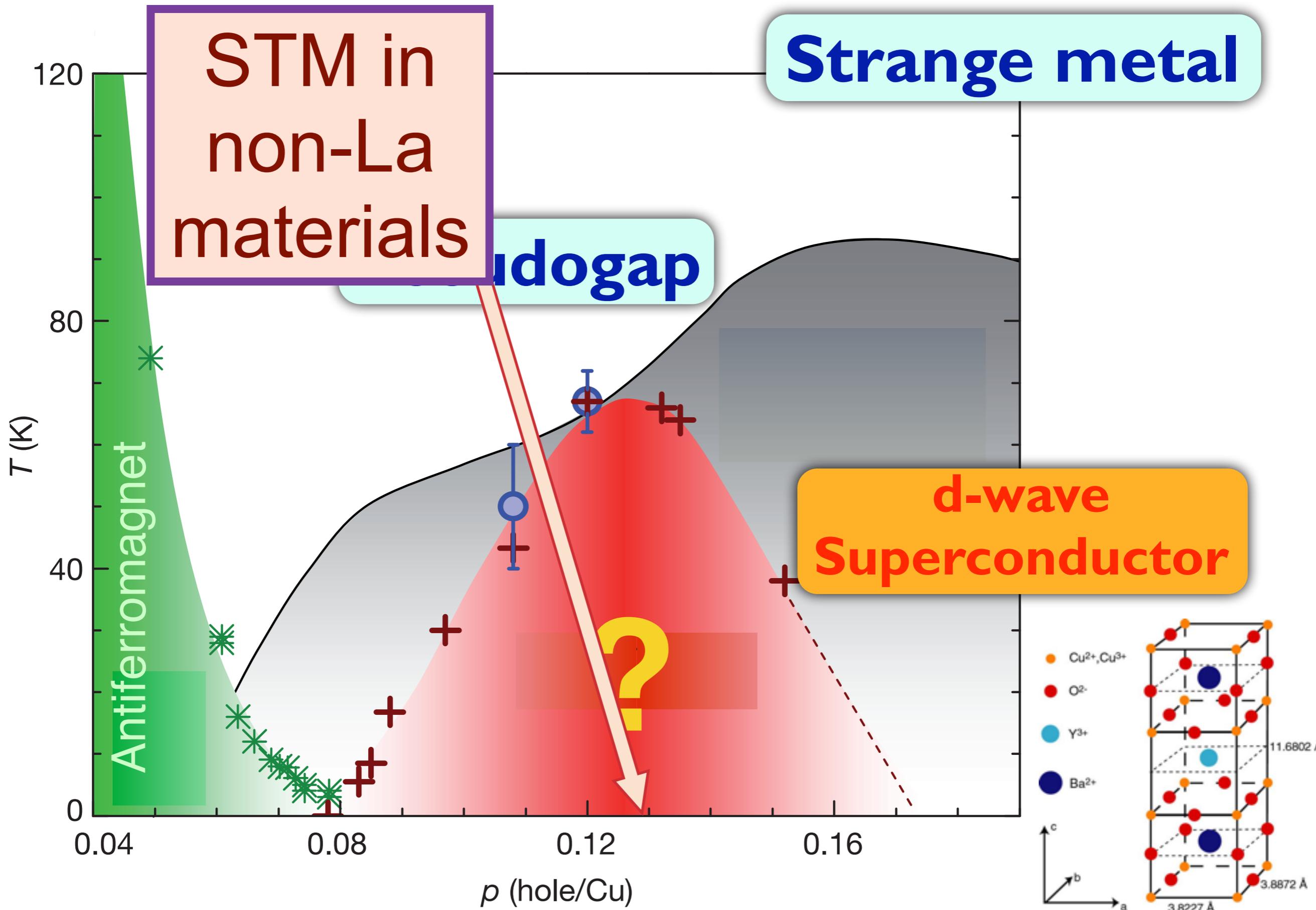
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T. Wu, H. Mayaffre, S. Kramer, M. Horvatic, C. Berthier, W.N. Hardy, R. Liang, D.A. Bonn, and M.-H. Julien, *Nature* **477**, 191 (2011).



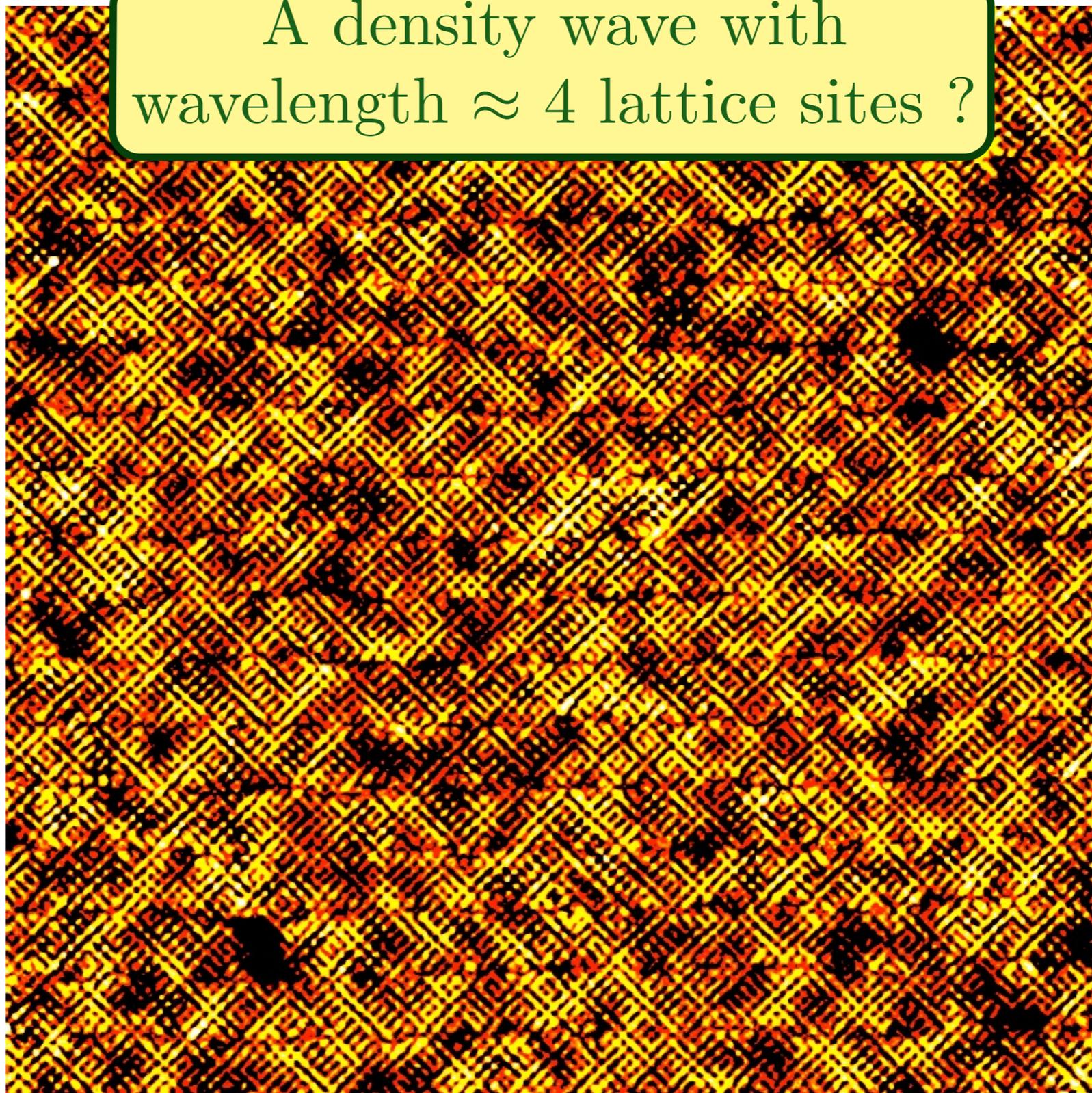
See also

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

M. Vershinin, S. Misra,
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303, 1995 (2004).

W. D. Wise, M. C. Boyer,
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Nature Phys. **4**, 696
(2008).

A density wave with
wavelength ≈ 4 lattice sites ?



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

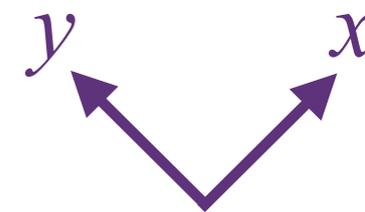
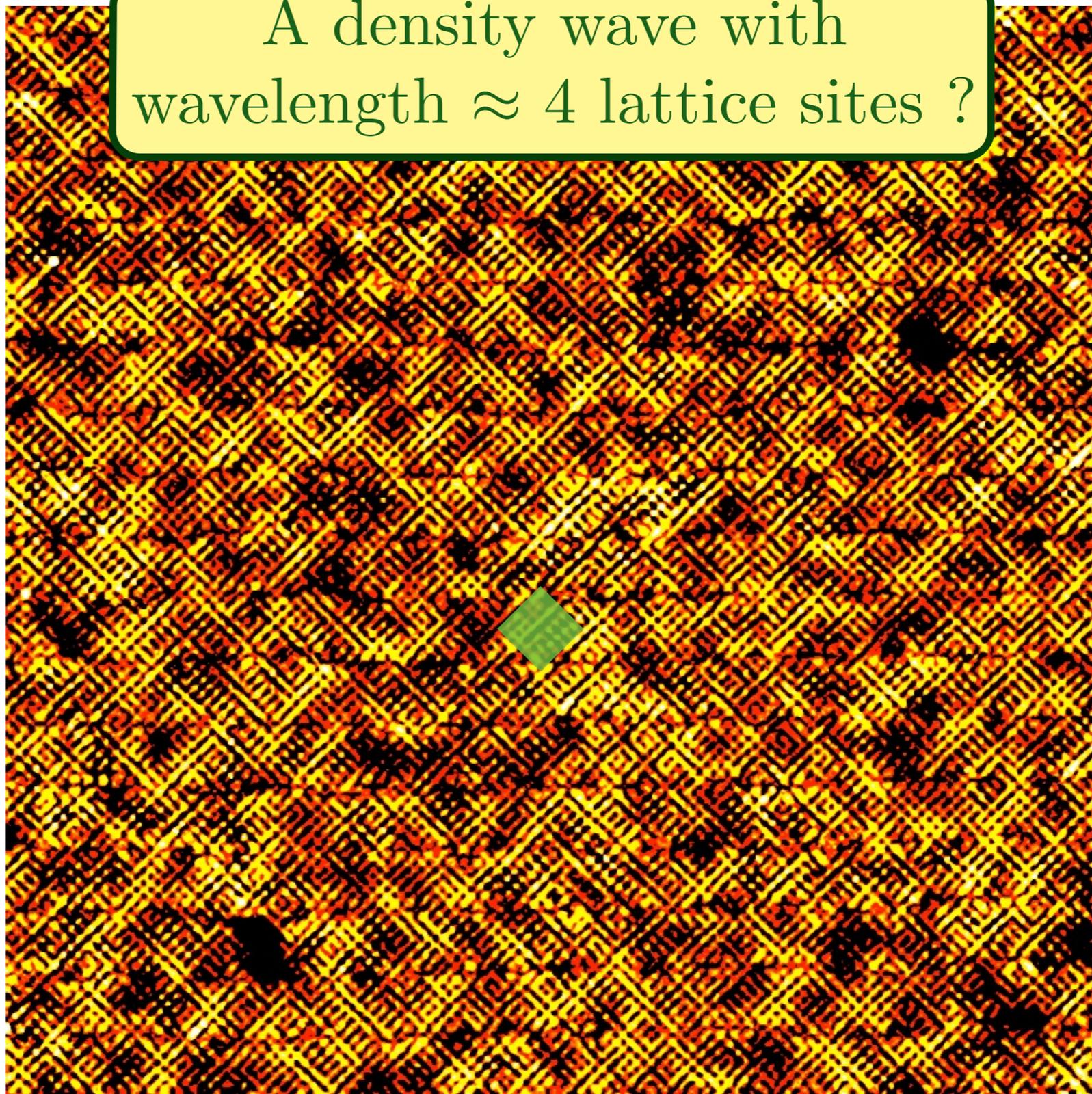
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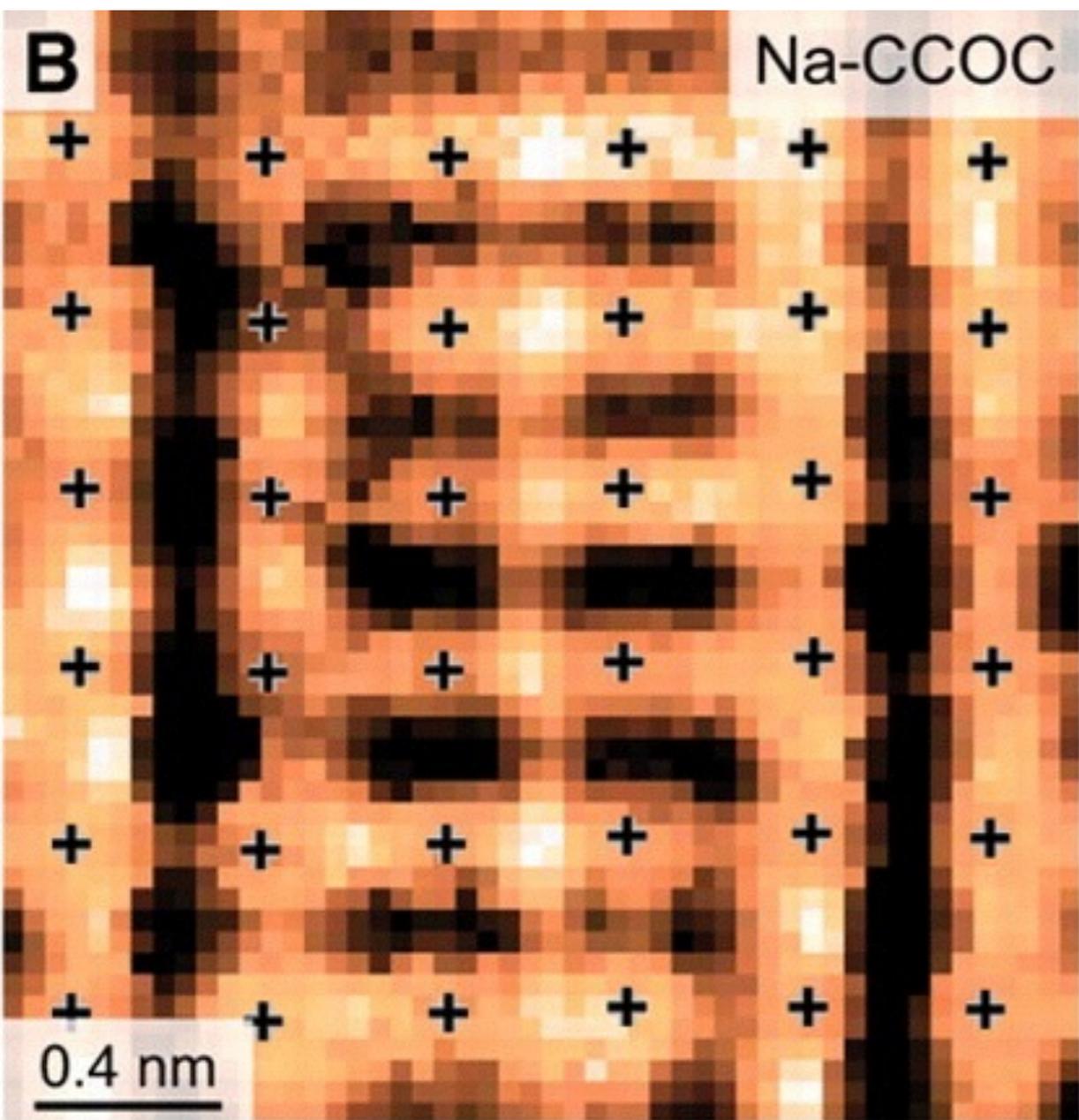
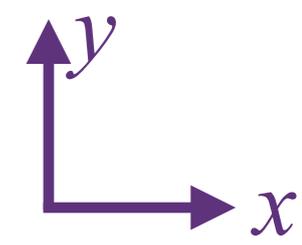
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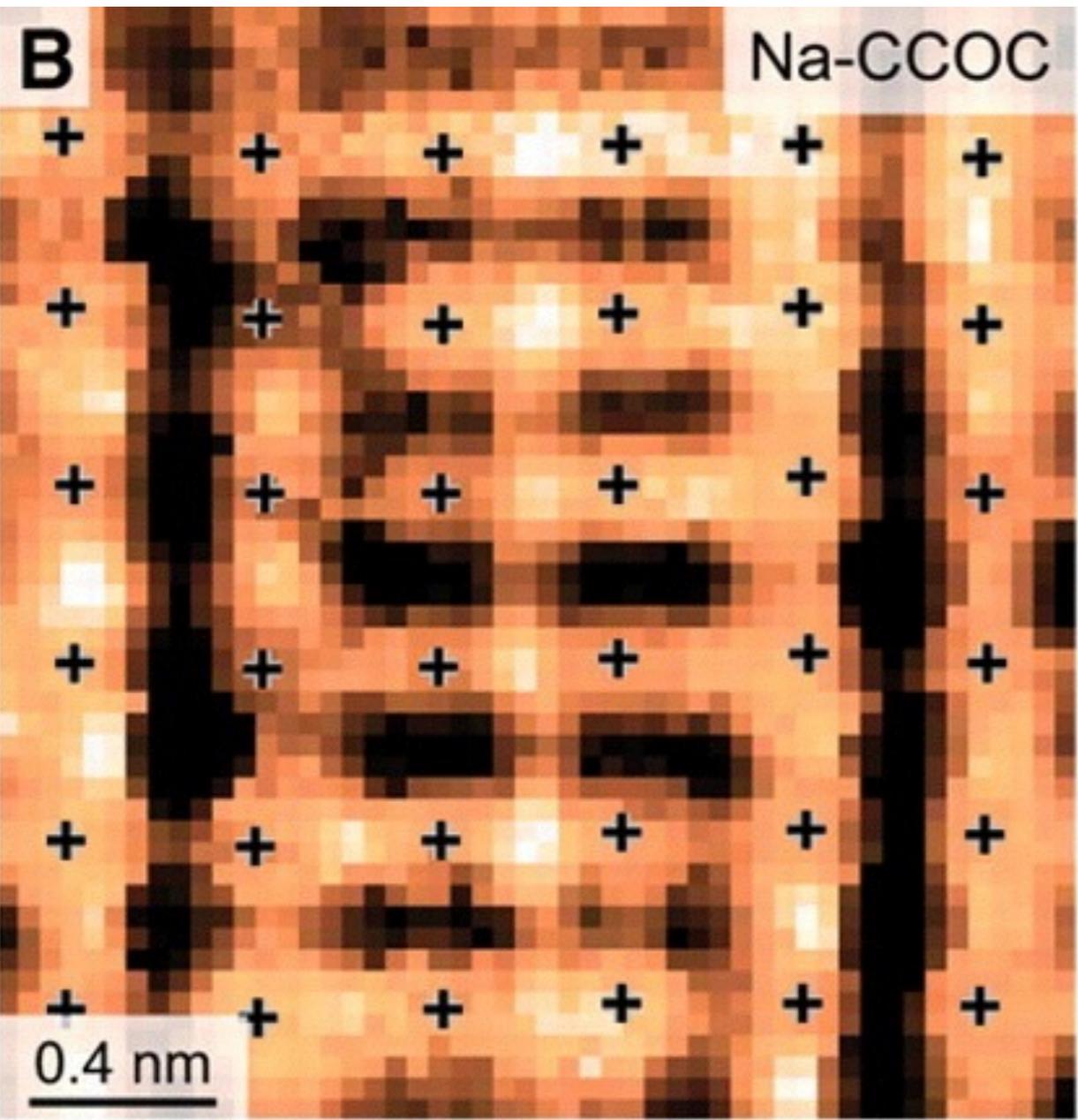
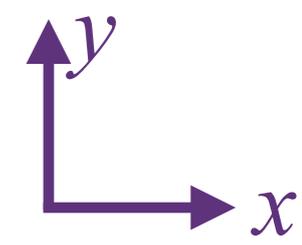
A density wave with
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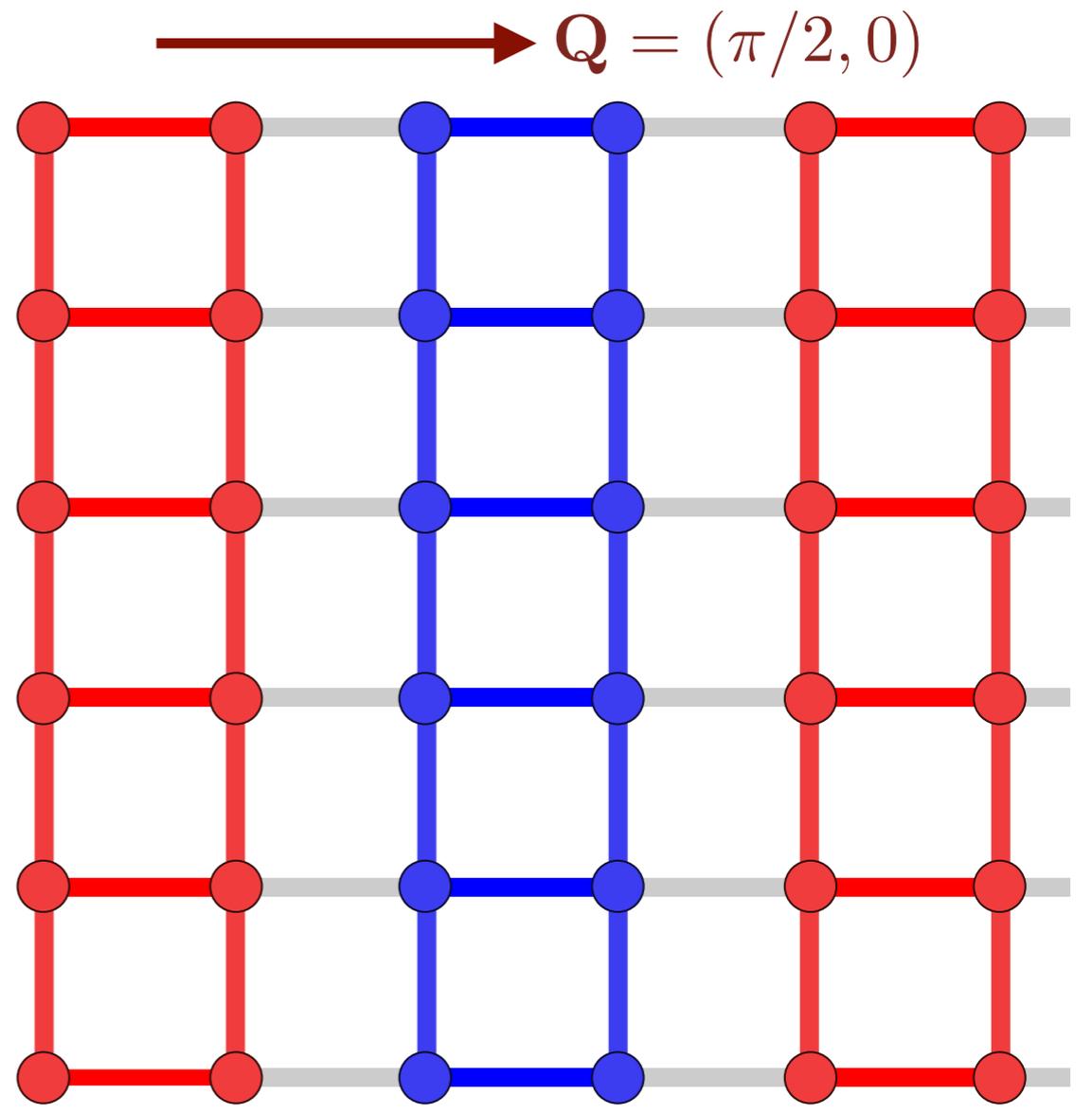
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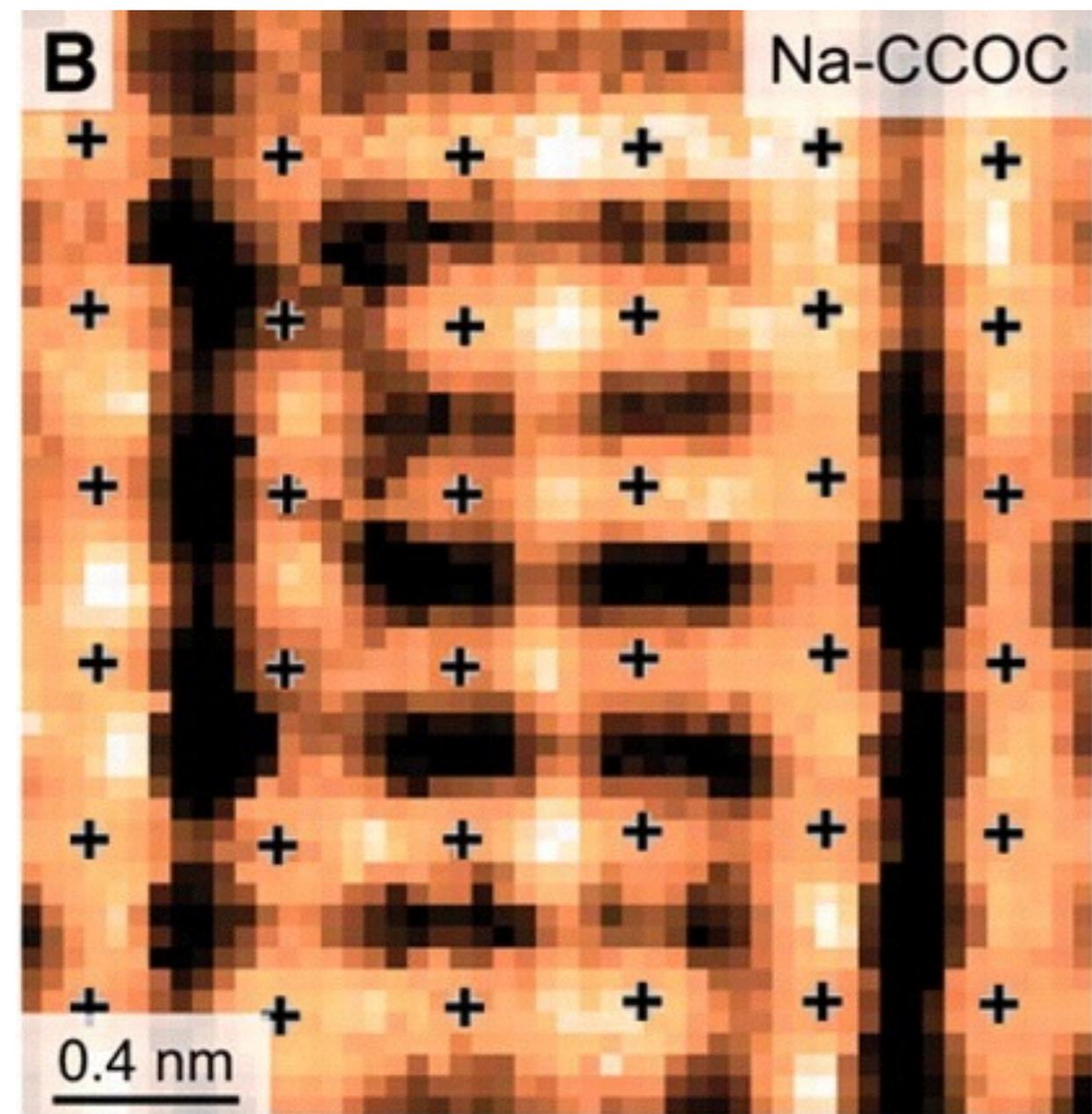


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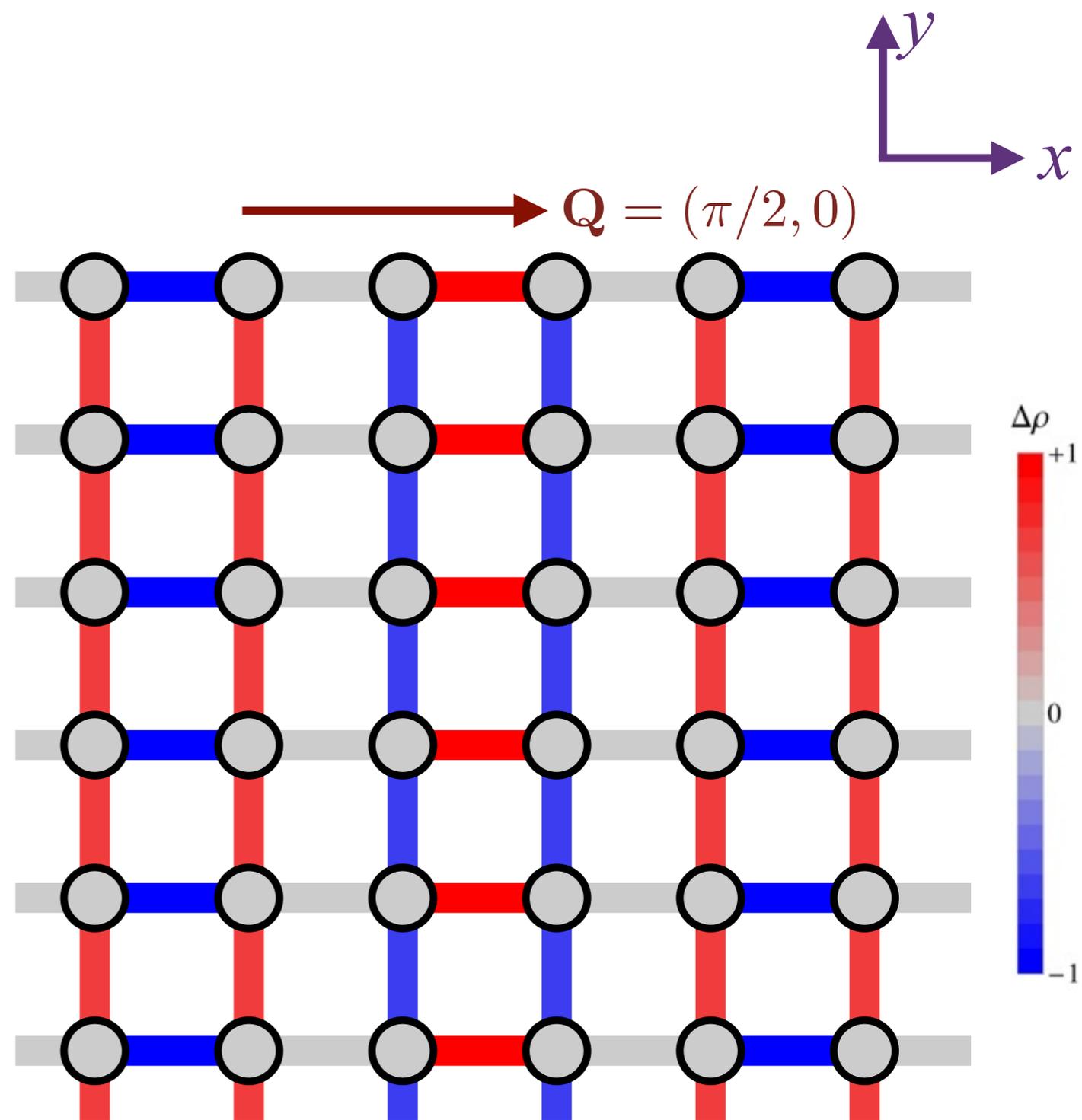


$s + s'$ -form factor density wave

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

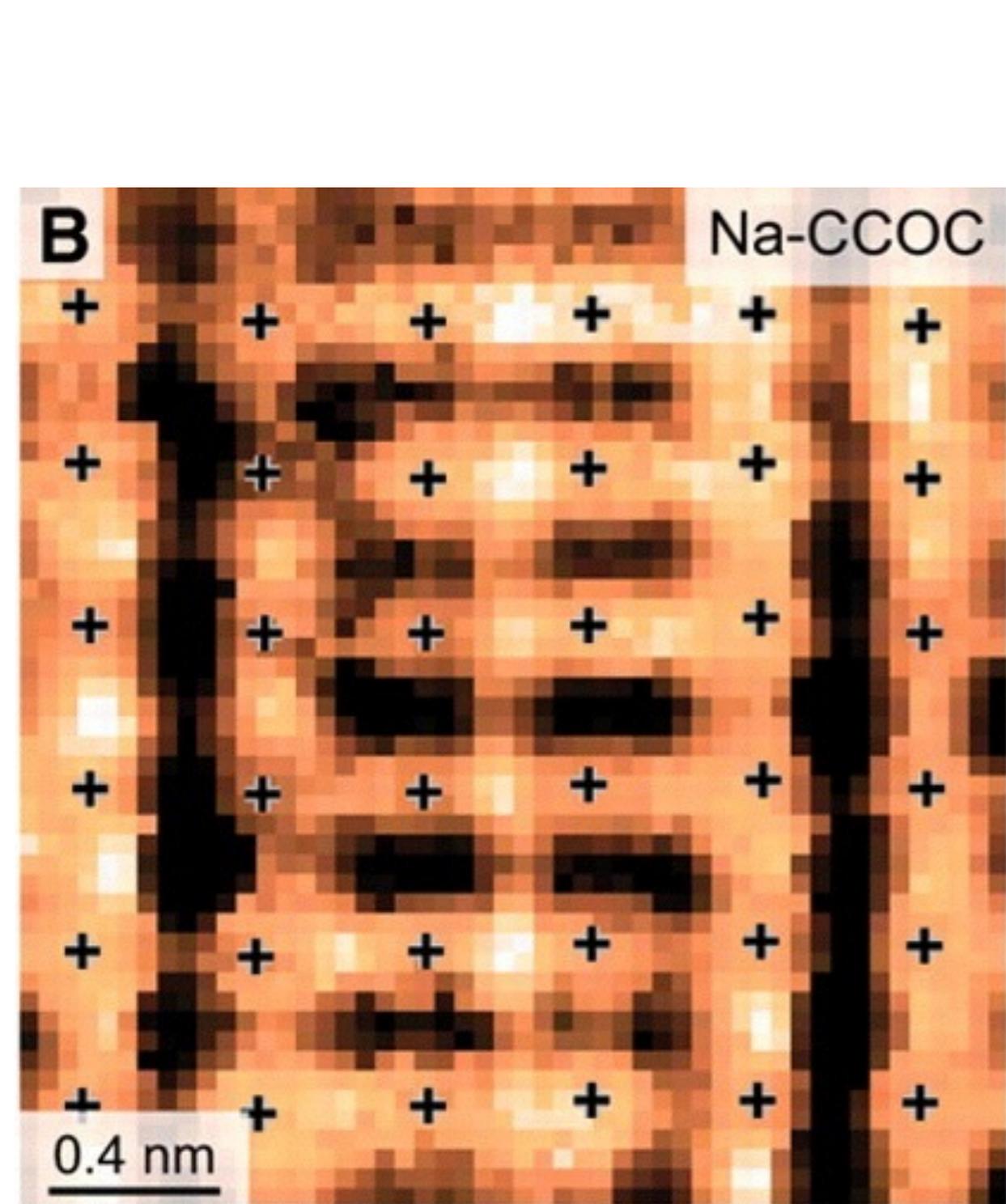


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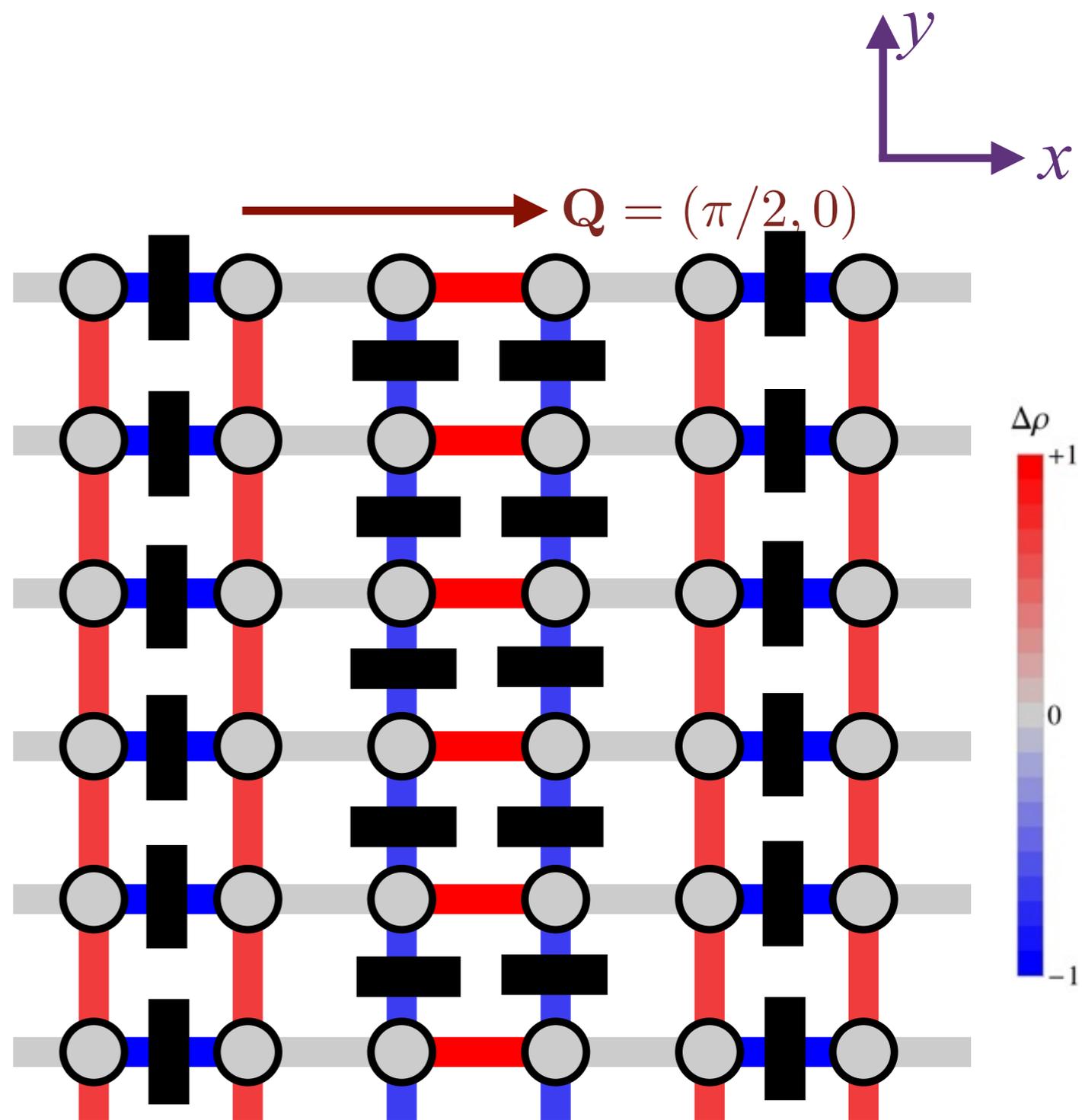


d-form factor density wave order

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



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



d-form factor density wave order

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

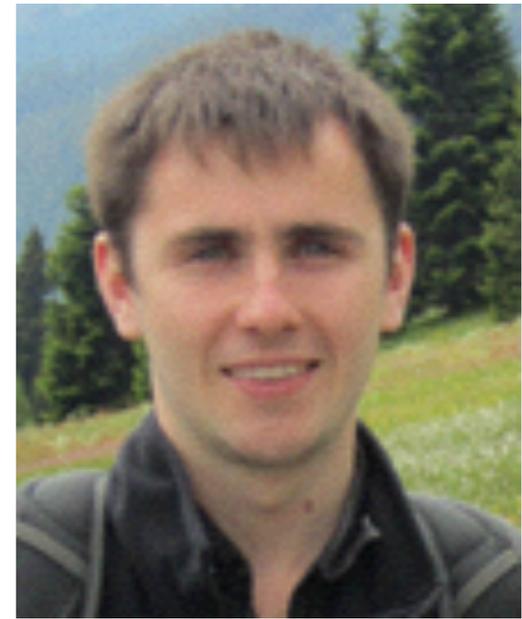
Cornell



Kazuhiro Fujita
Cornell/ BNL



Mohammad Hamidian
Cornell / BNL



Stephen Edkins
Cornell / St Andrews



Michael Lawler



J. C. Seamus Davis



Eun-Ah Kim

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

Kazuhiro Fujita^{a,b,c,1}, Mohammad H. Hamidian^{a,b,1}, Stephen D. Edkins^{b,d}, Chung Koo Kim^a, Yuhki Kohsaka^e, Masaki Azuma^f, Mikio Takano^g, Hidenori Takagi^{c,h,i}, Hiroshi Eisaki^j, Shin-ichi Uchida^c, Andrea Allais^k, Michael J. Lawler^{b,l}, Eun-Ah Kim^b, Subir Sachdev^{k,m}, and J. C. Séamus Davis^{a,b,d,2}

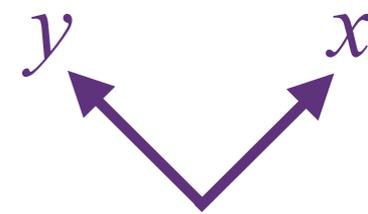
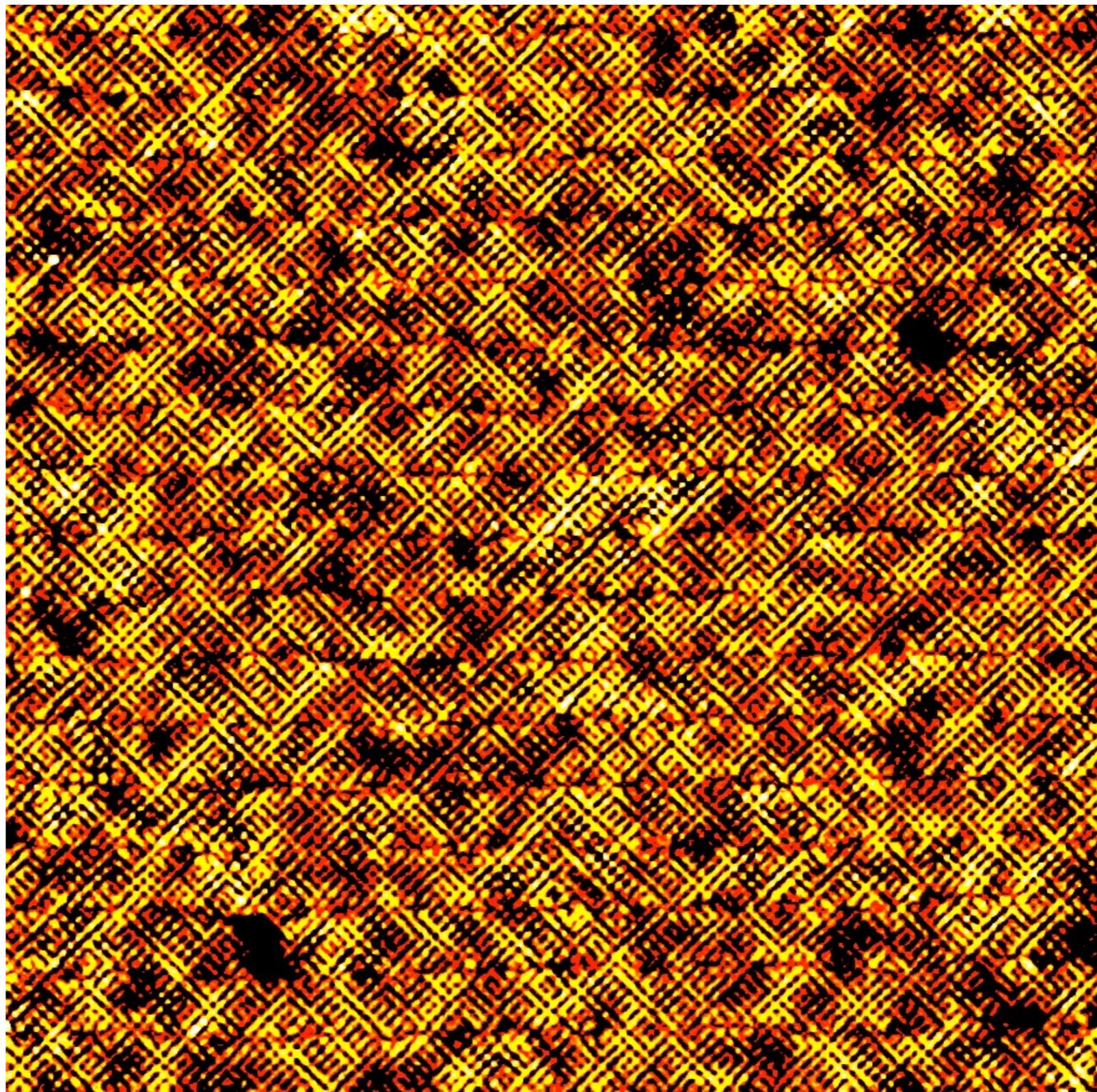
The identity of the fundamental broken symmetry (if any) in the underdoped cuprates is unresolved. However, evidence has been accumulating that this state may be an unconventional density wave. Here we carry out site-specific measurements within each CuO_2 unit cell, segregating the results into three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

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).

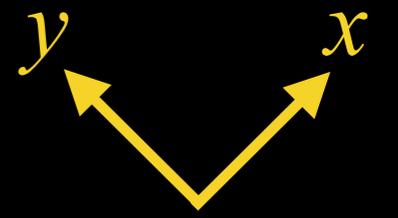
W. D. Wise, M. C. Boyer,
K. Chatterjee, T. Kondo,
T. Takeuchi, H. Ikuta,
Y. Wang, and
E. W. Hudson,
Nature Phys. **4**, 696
(2008).



“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.**

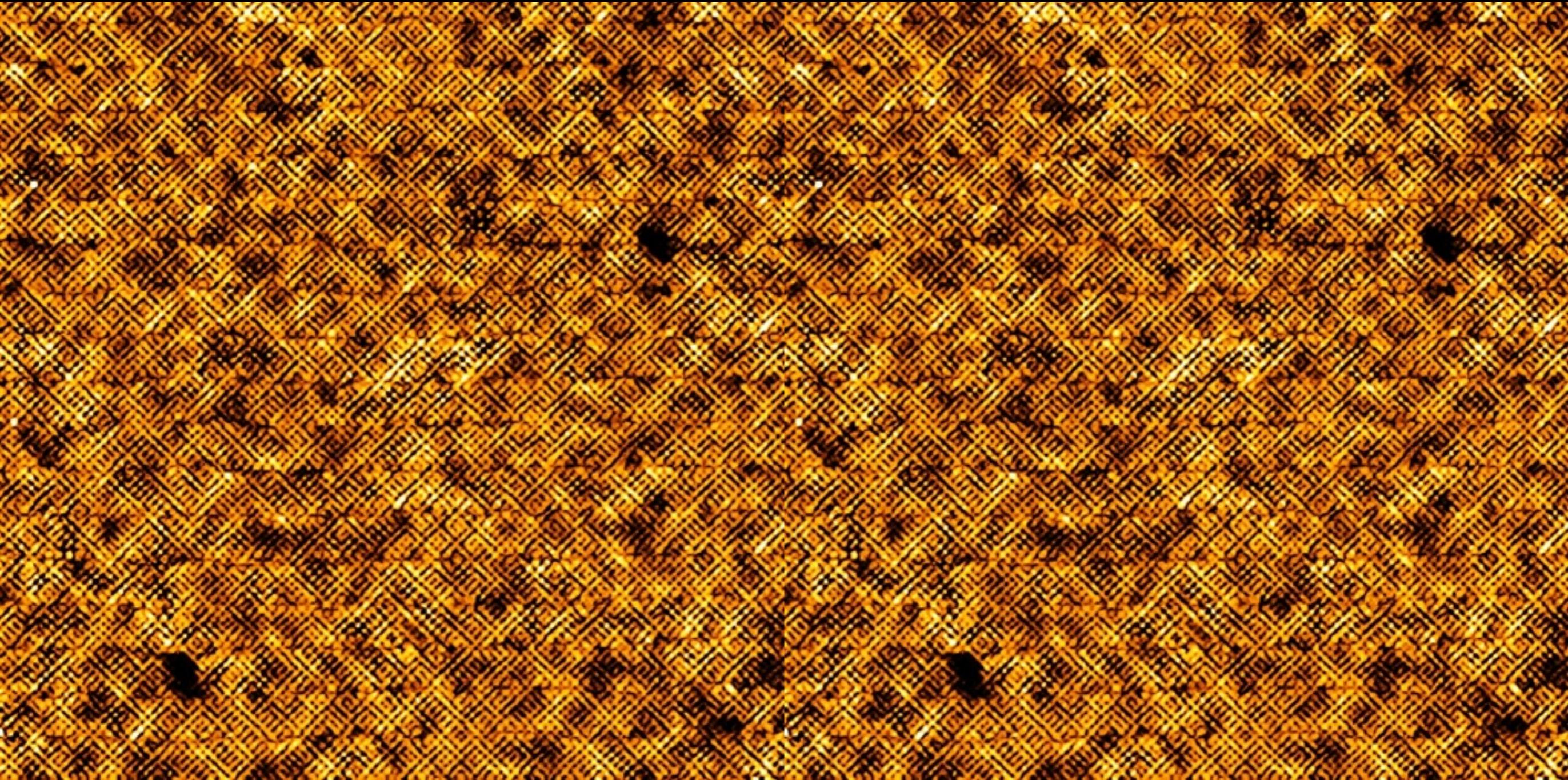
UD45K
BSCCO

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



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

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



Note that these are identical images.

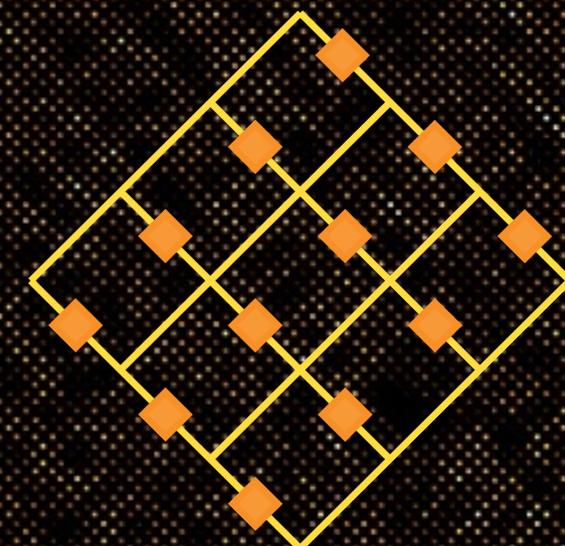
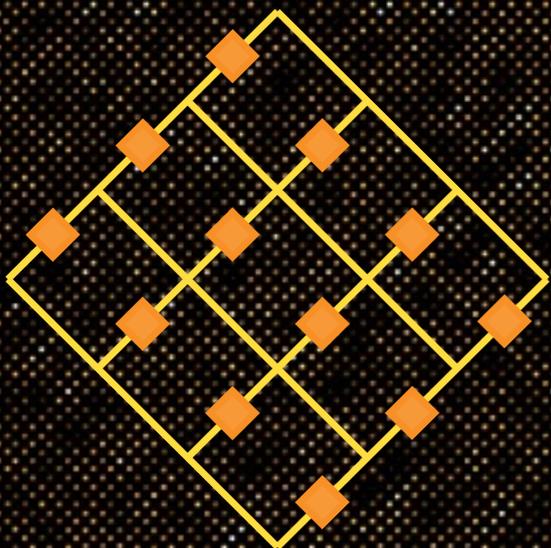
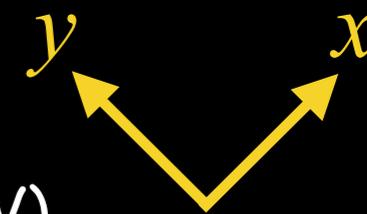
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)

UD45K

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

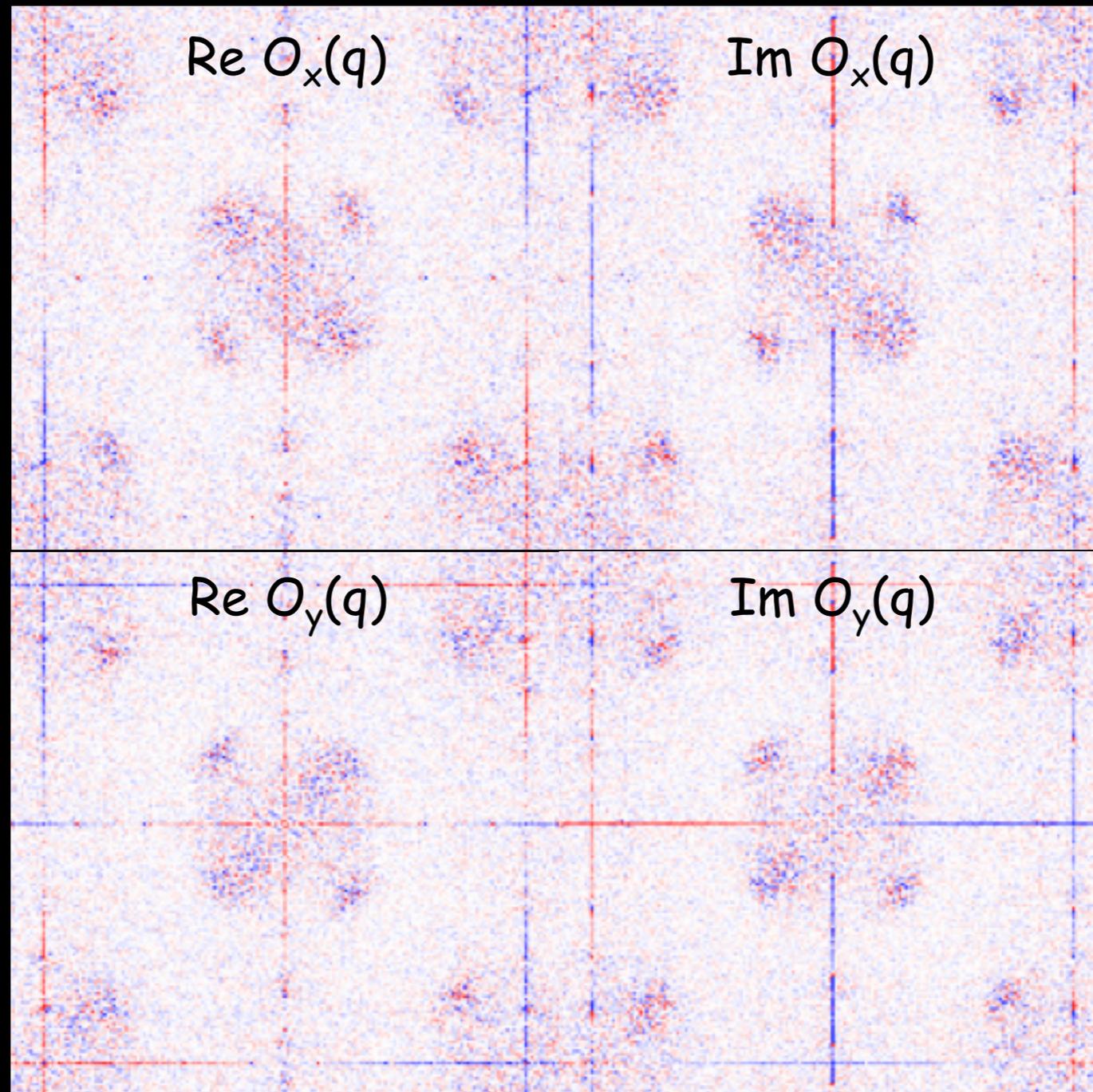
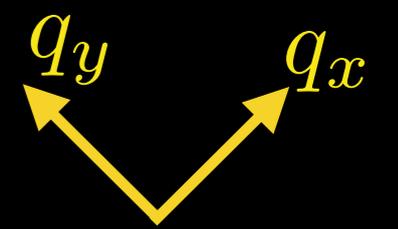
$R(r=O_x, 150\text{mV})$

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

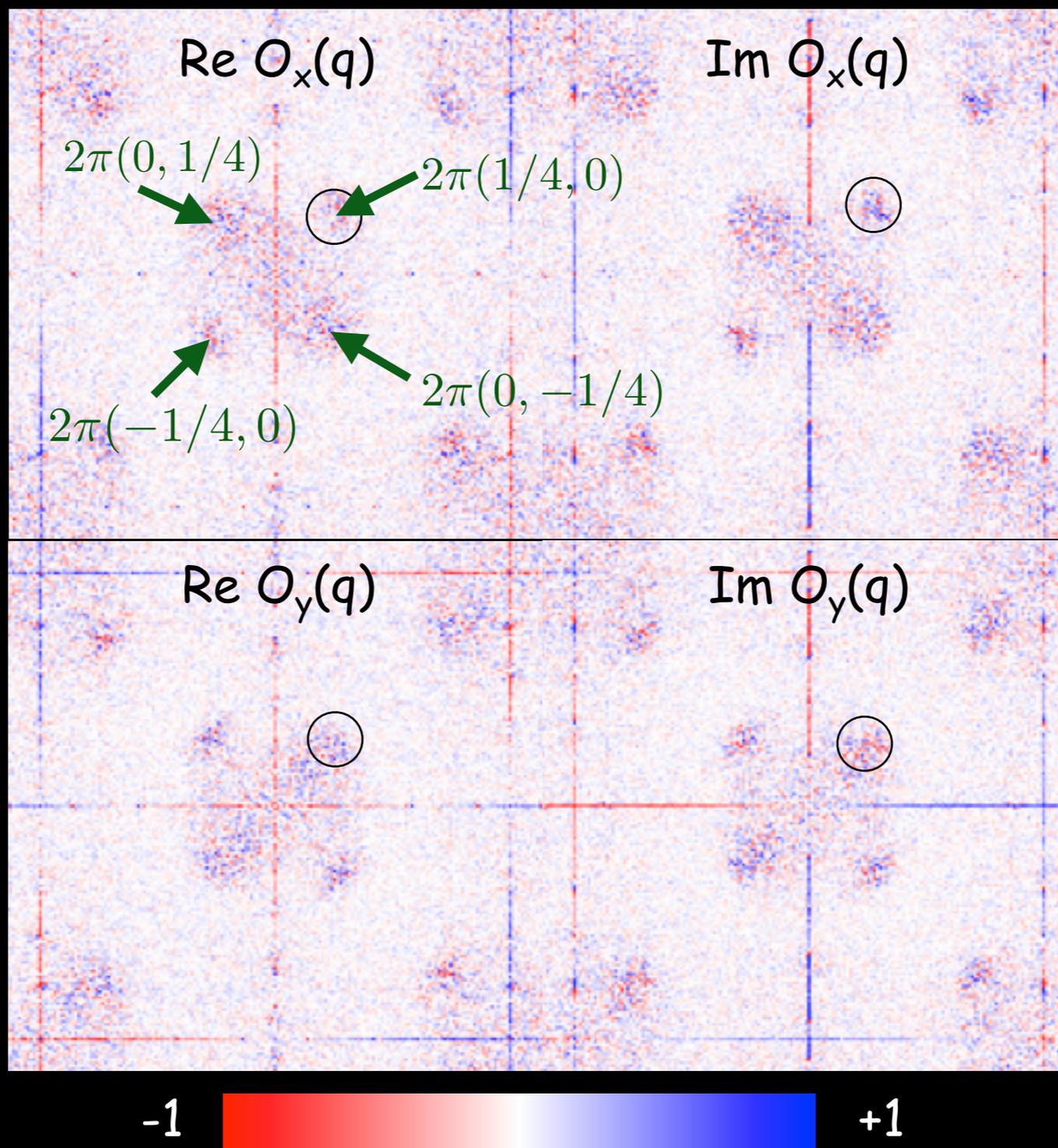
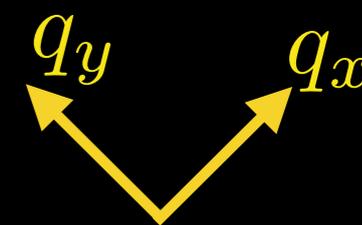


UD45K

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

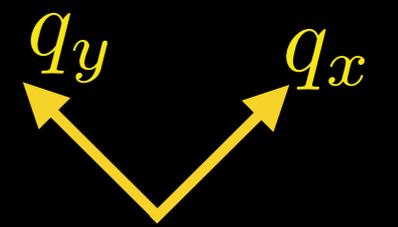


Broad (0,Q) and (Q,0) DW Features

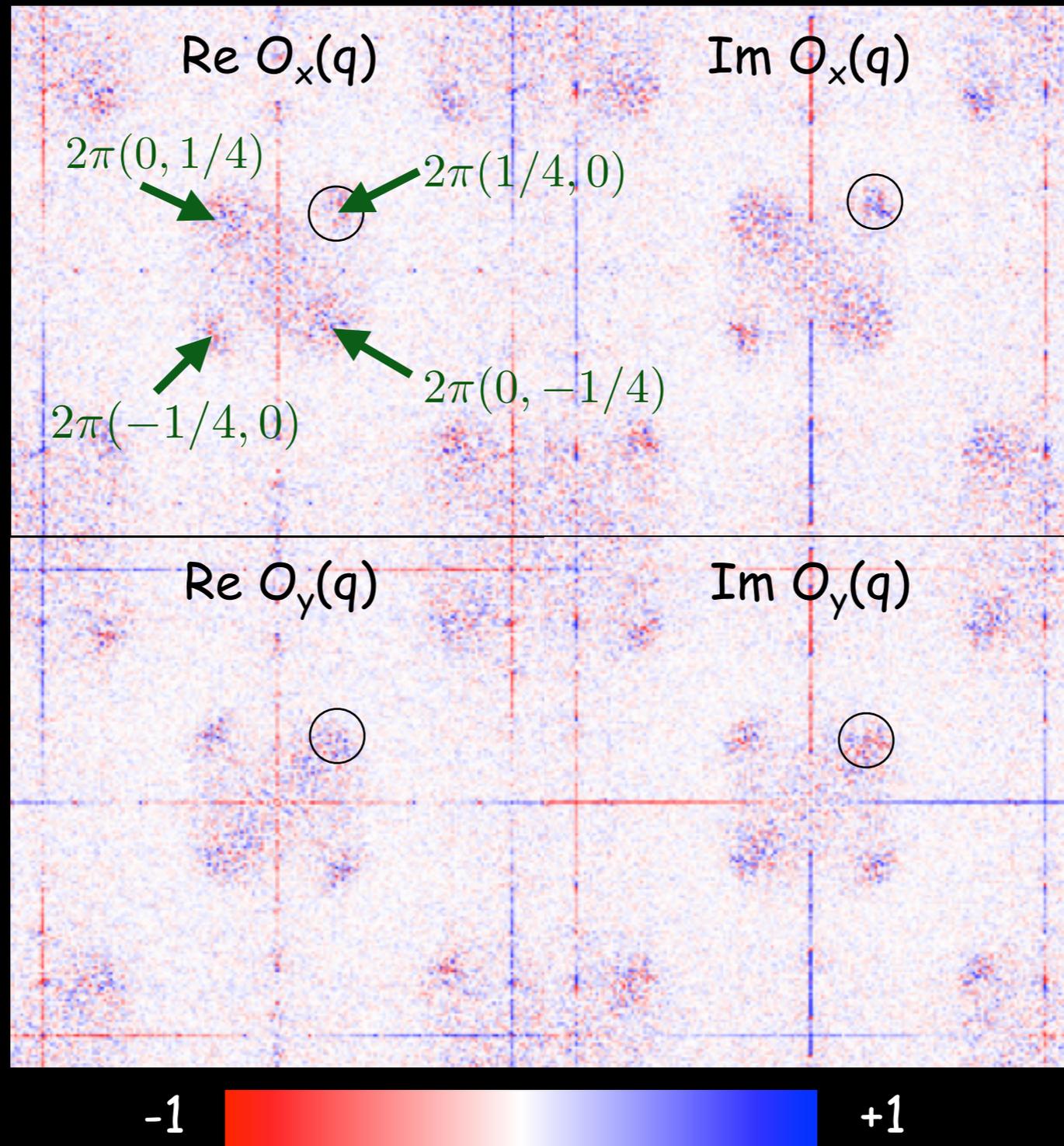


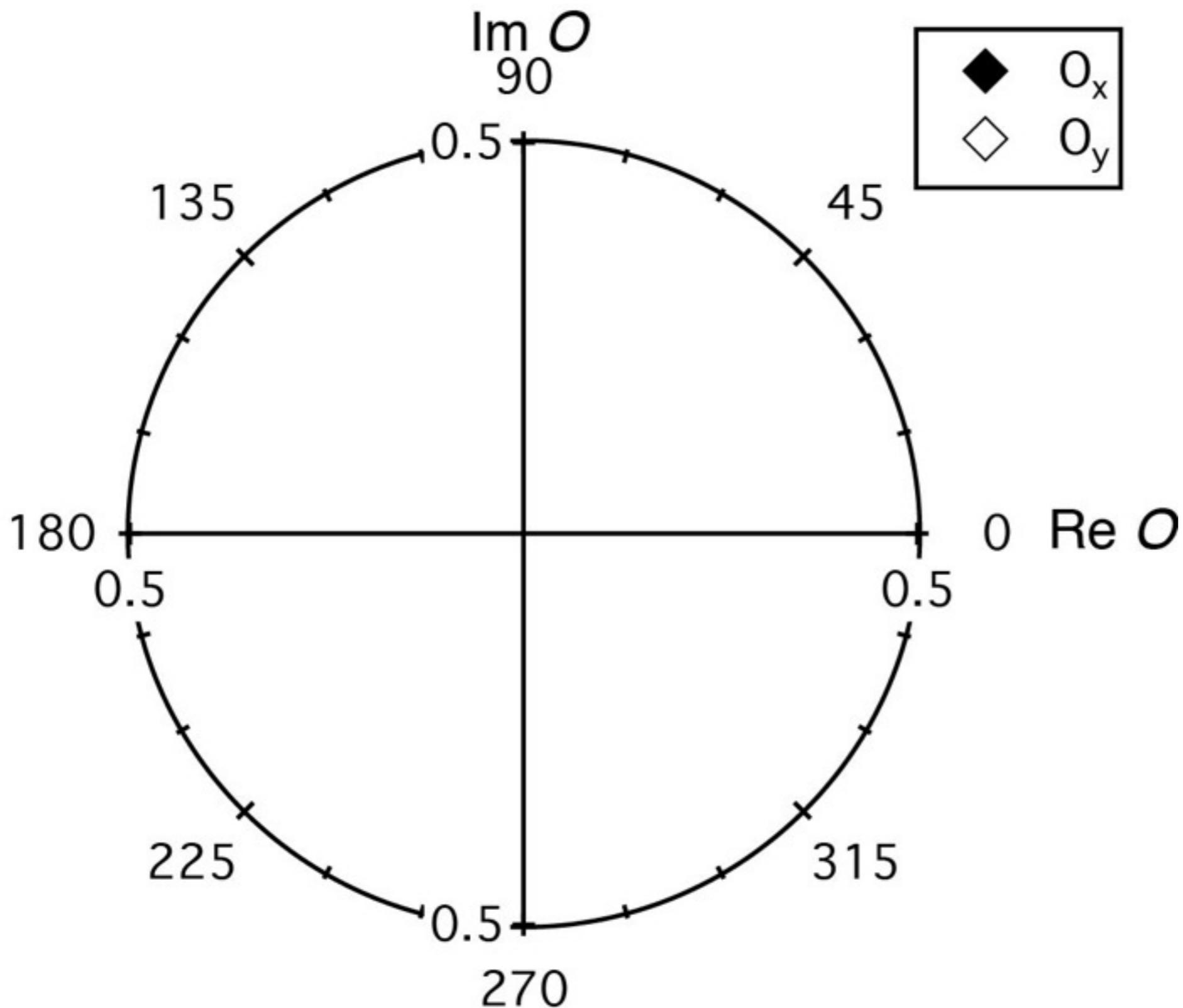
UD45K

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

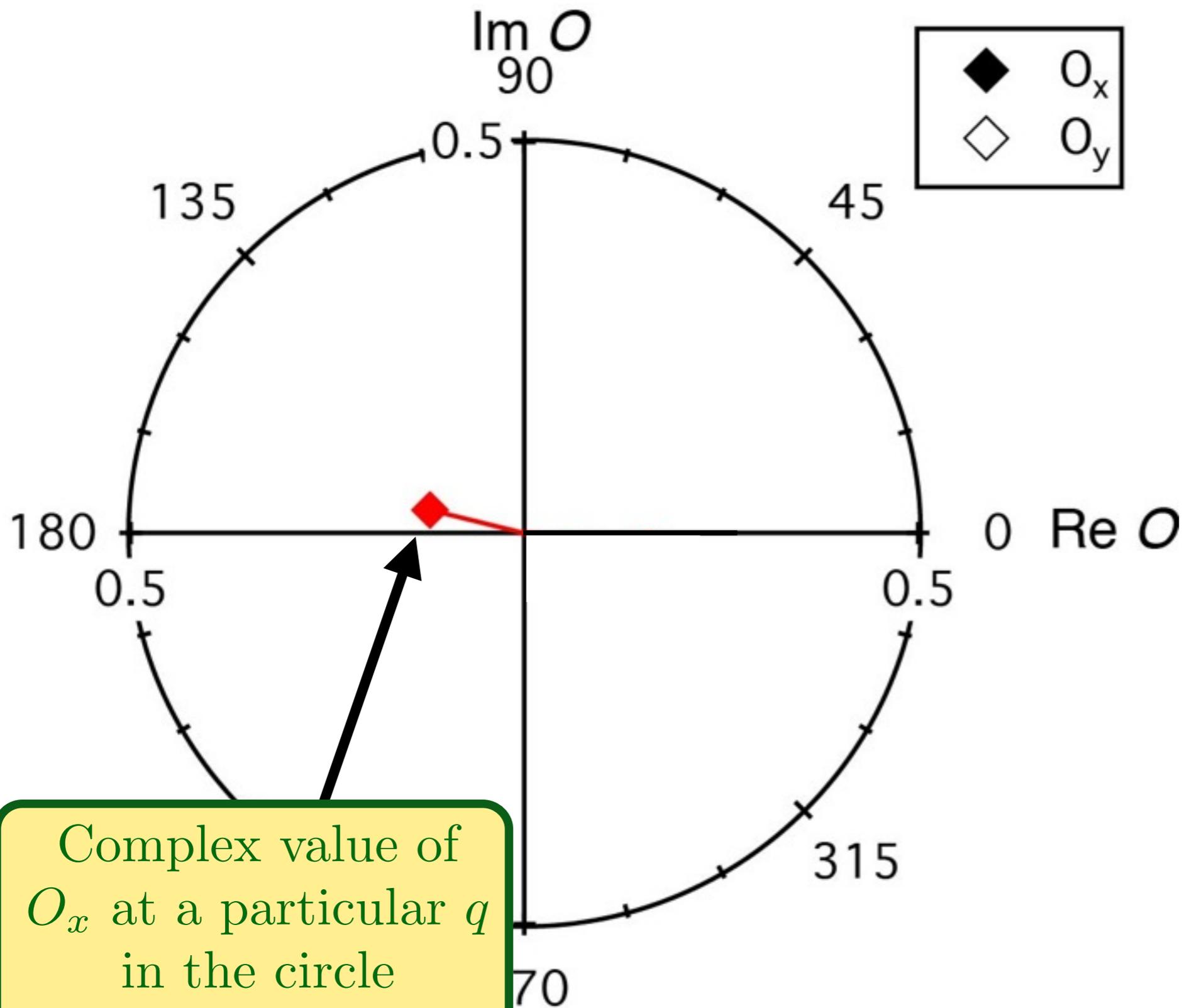


For each pixel in the circles, we obtain 2 complex numbers, $O_x(q)$ and $O_y(q)$.



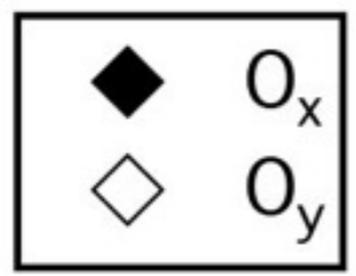
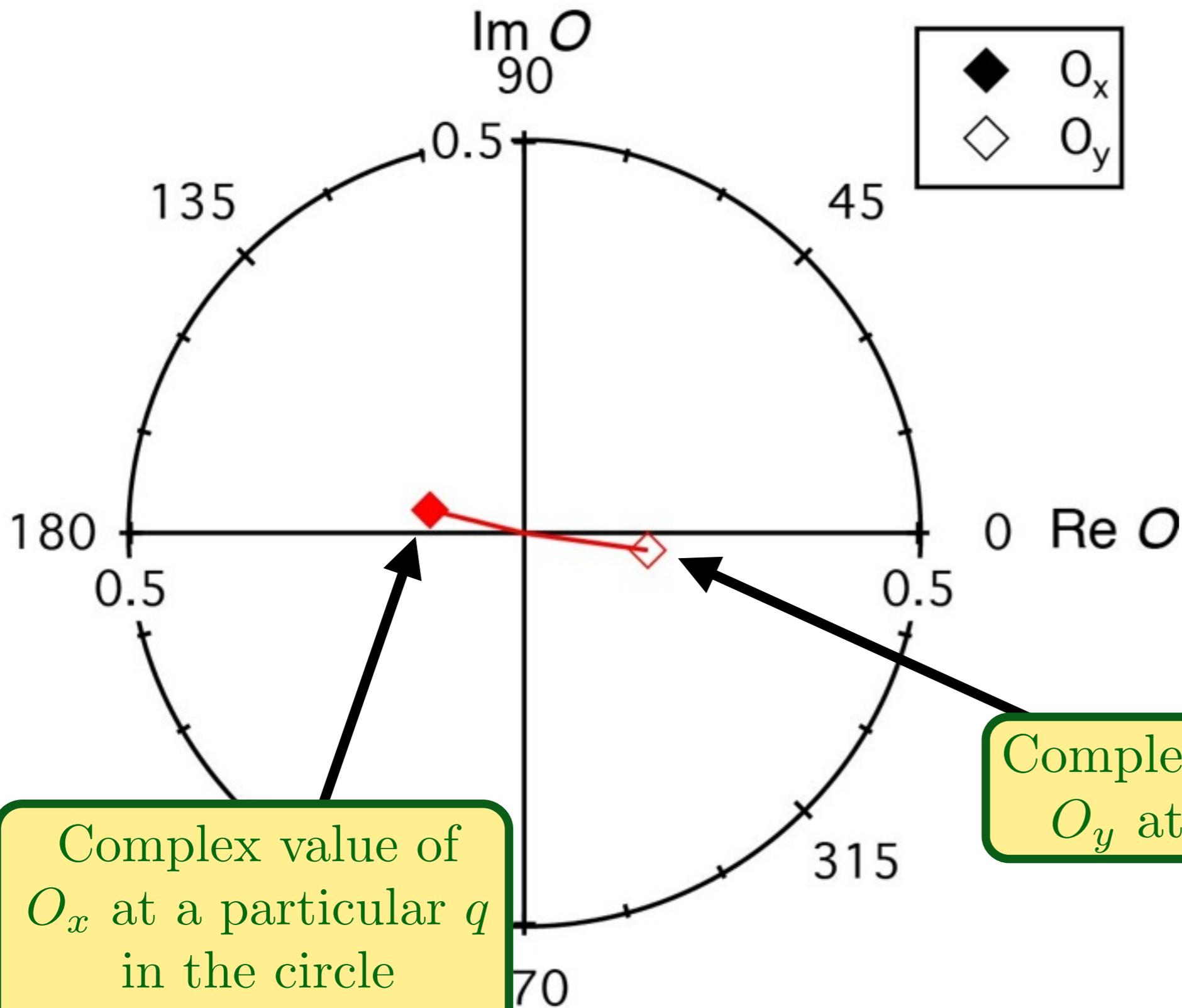


Phase-sensitive measurement of the d -form factor of density wave order



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

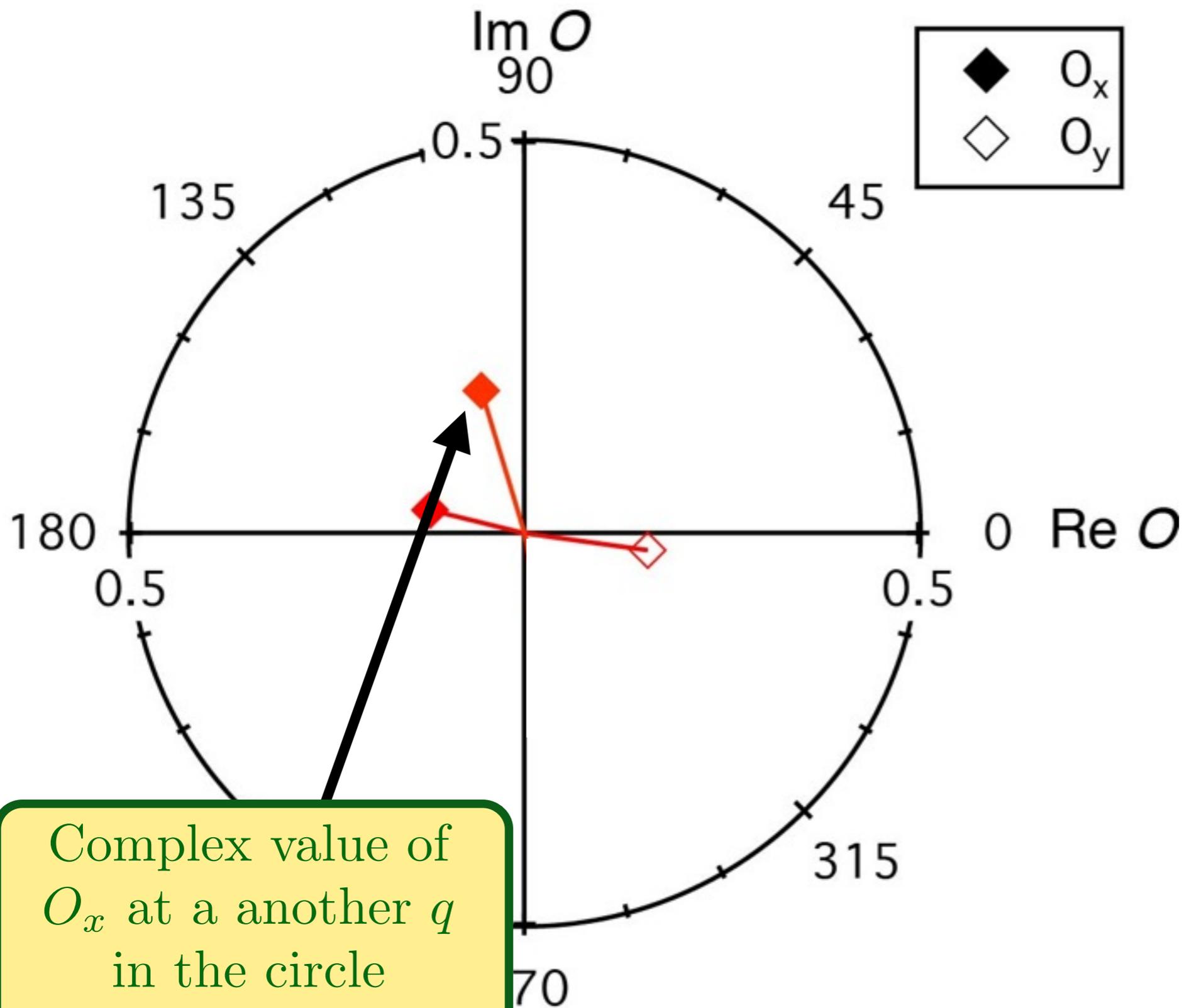
Complex value of O_x at a particular q in the circle around $2\pi(1/4, 0)$.



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

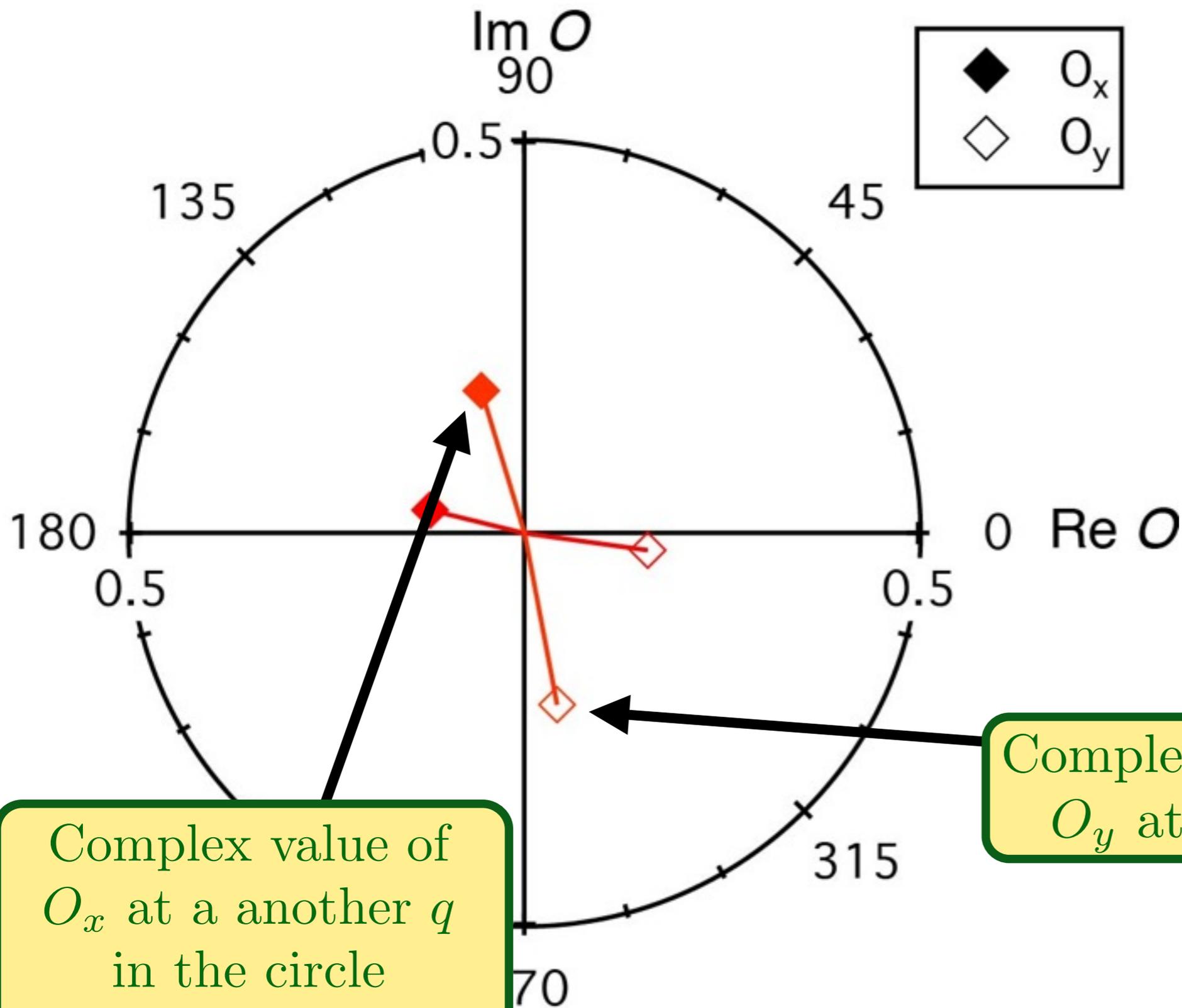
Complex value of O_x at a particular q in the circle around $2\pi(1/4, 0)$.

Complex value of O_y at same q



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 $2\pi(1/4, 0)$.

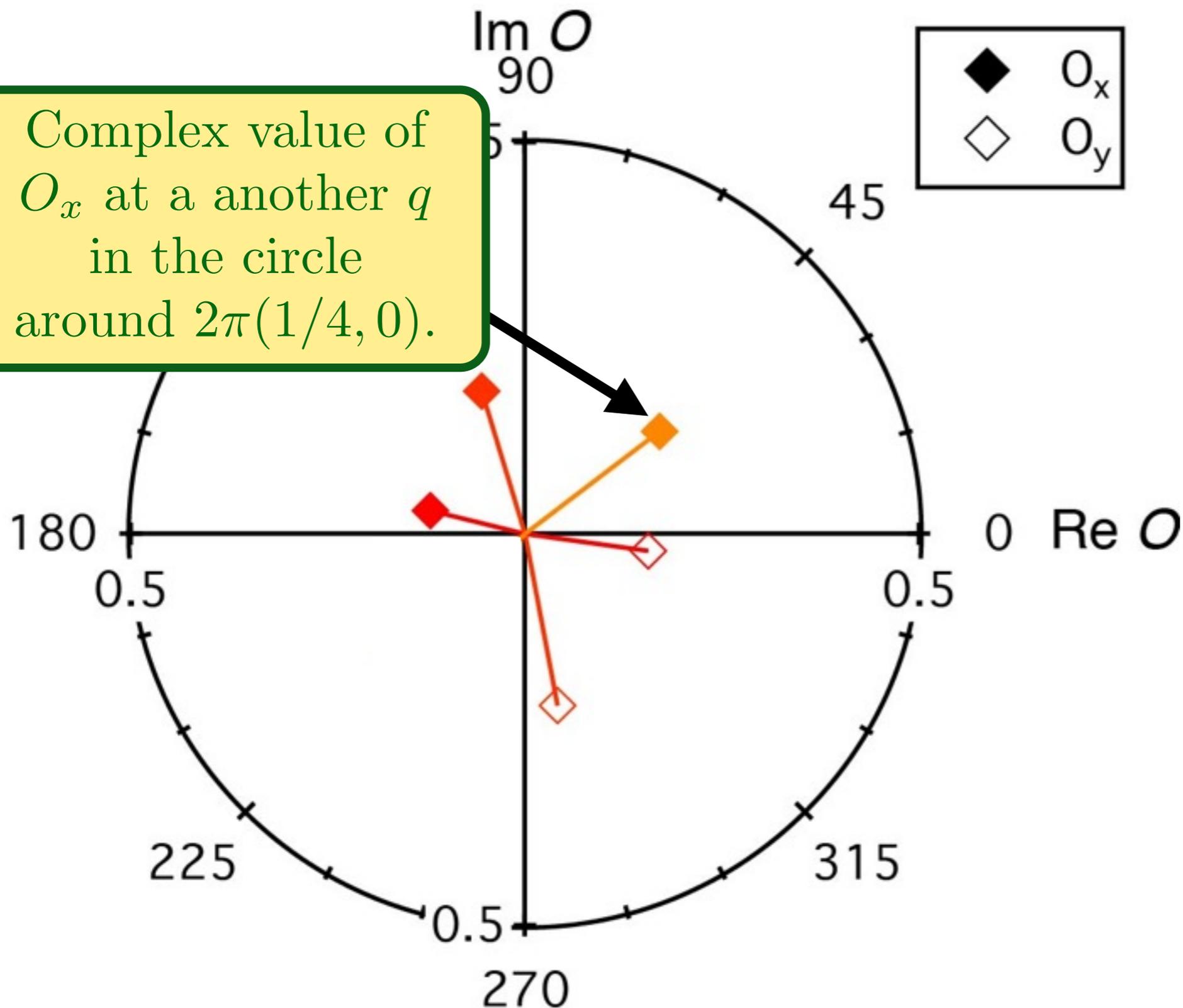


Phase-sensitive measurement of the d -form factor of density wave order

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

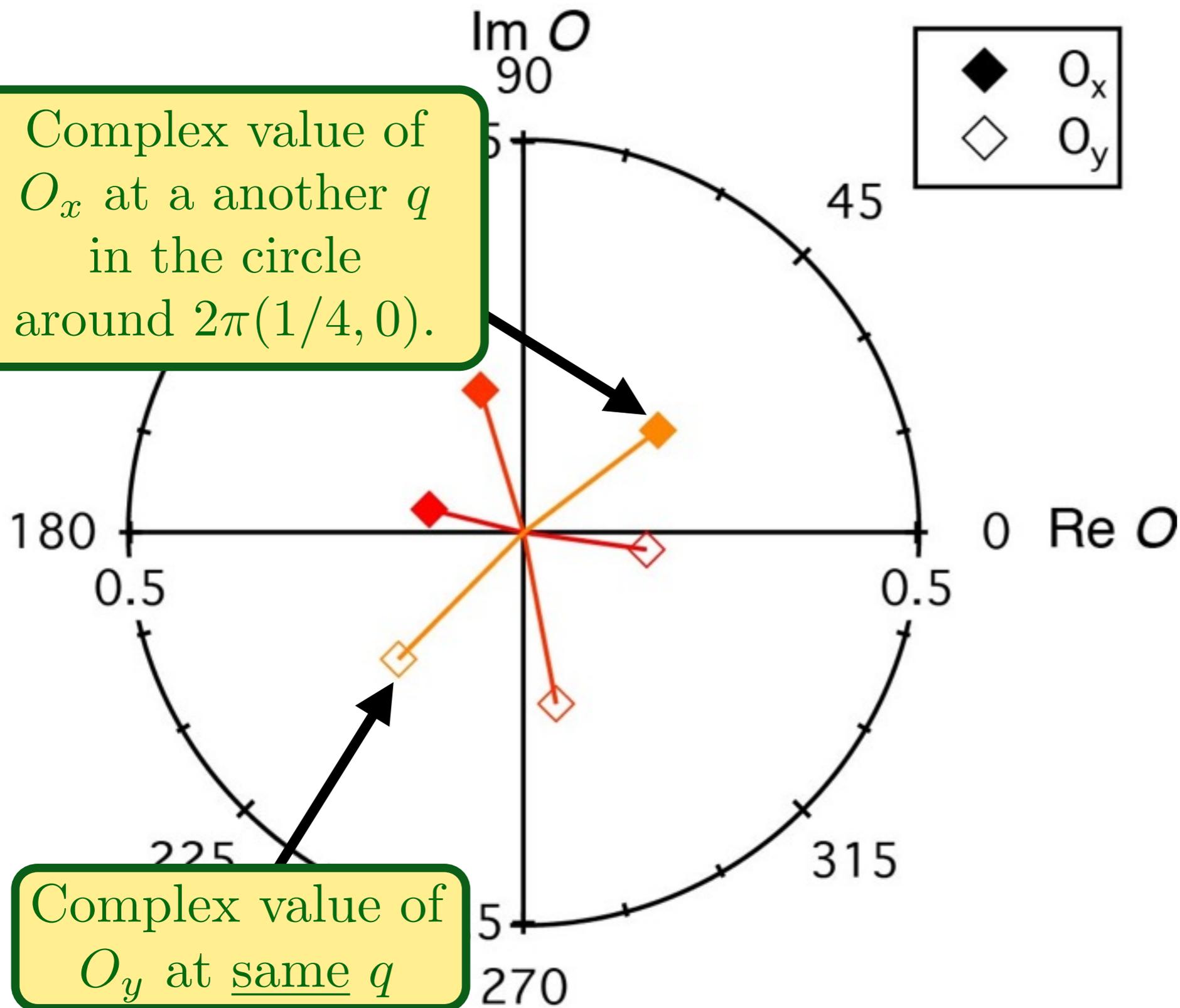
Complex value of O_y at same q

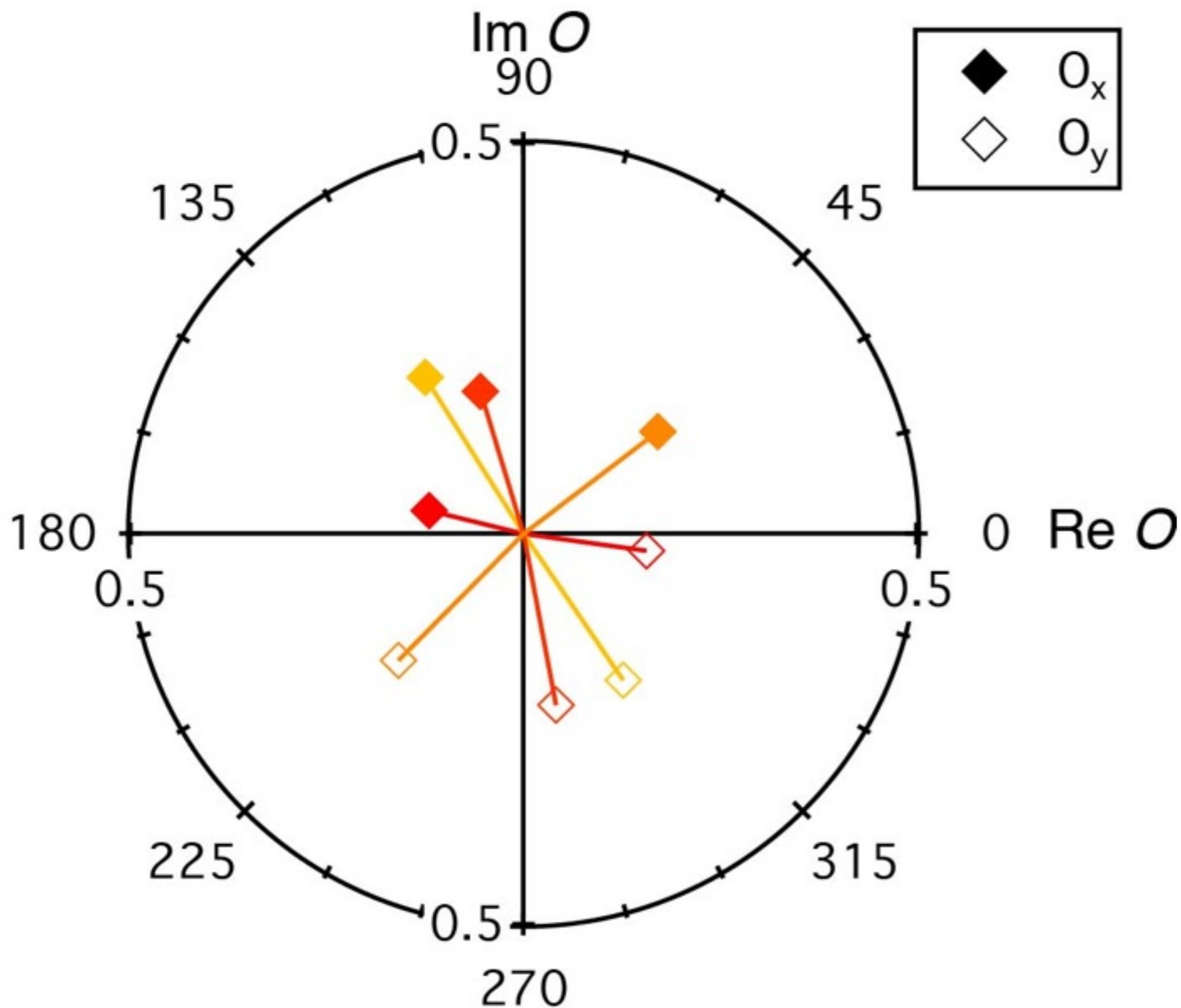
Complex value of O_x at a another q in the circle around $2\pi(1/4, 0)$.



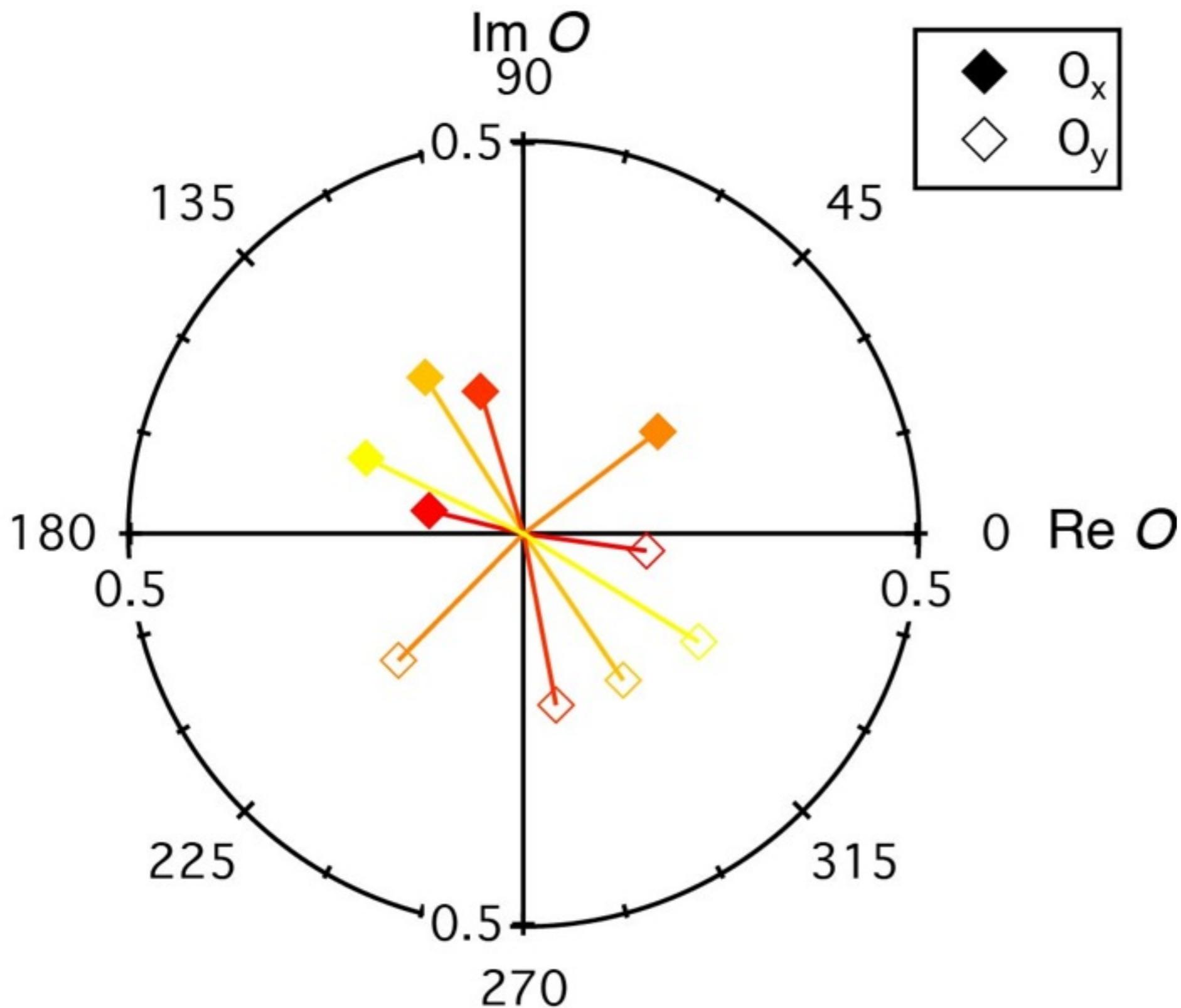
Phase-sensitive measurement of the d -form factor of density wave order

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

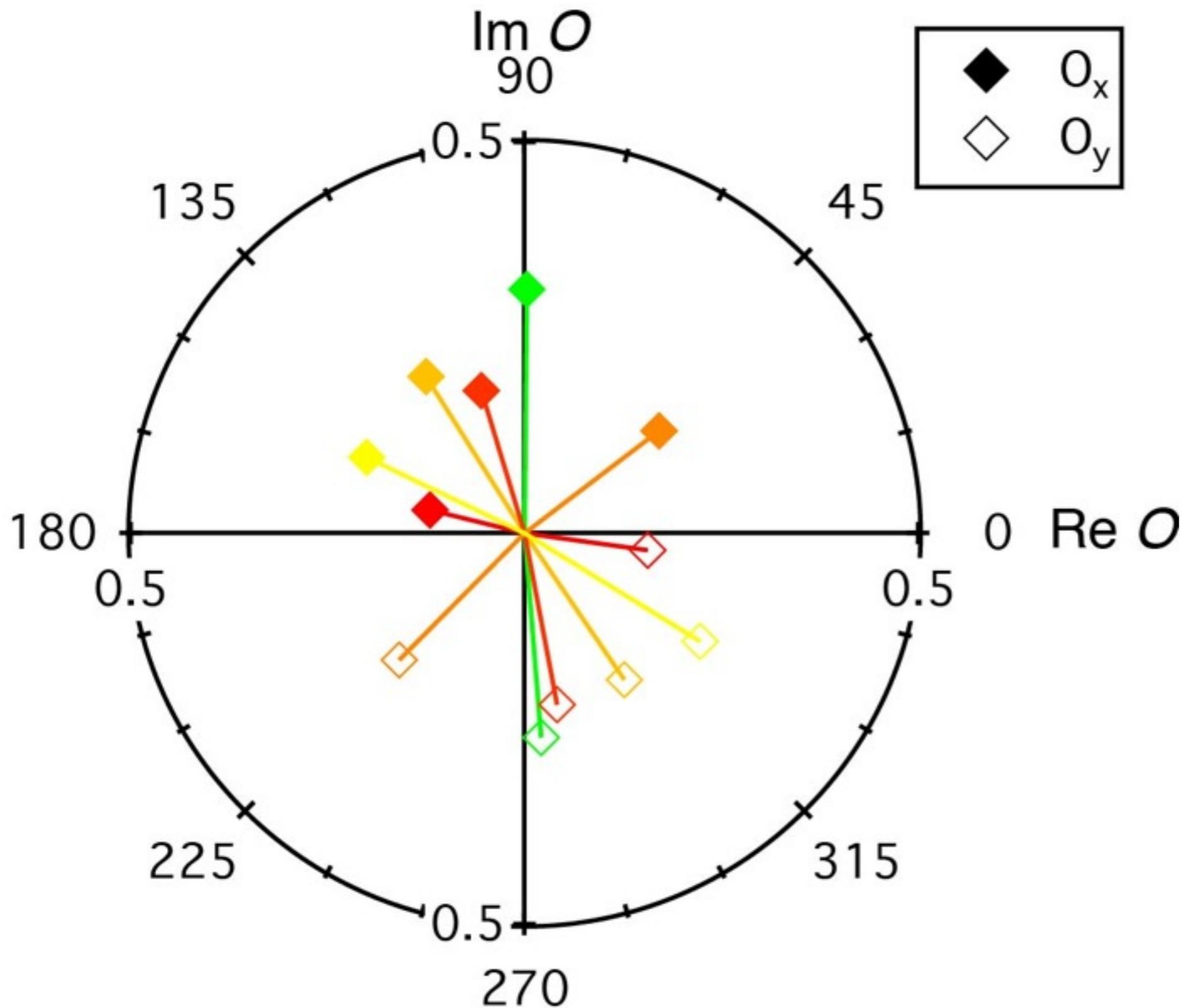




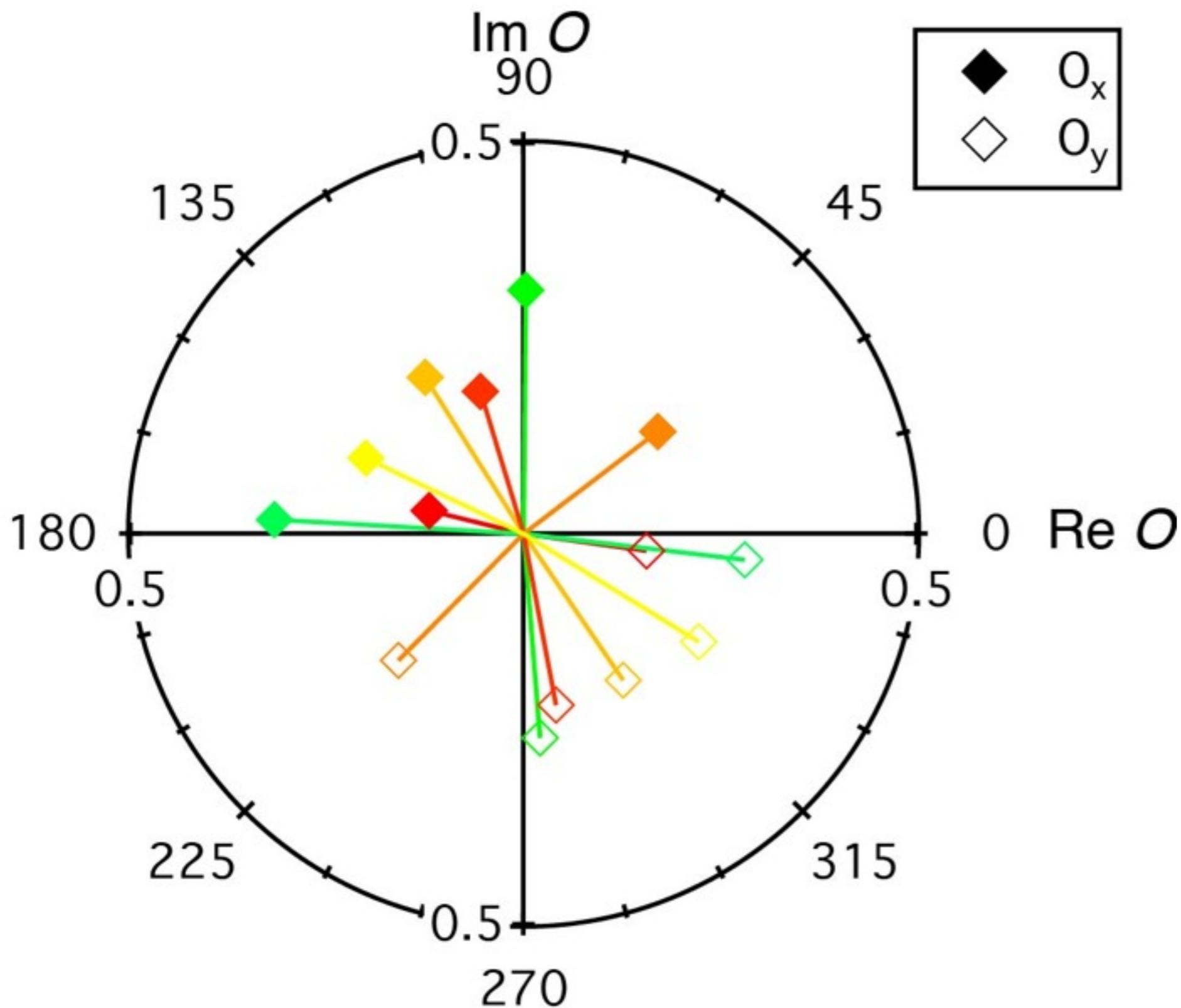
Phase-sensitive measurement of the d -form factor of density wave order



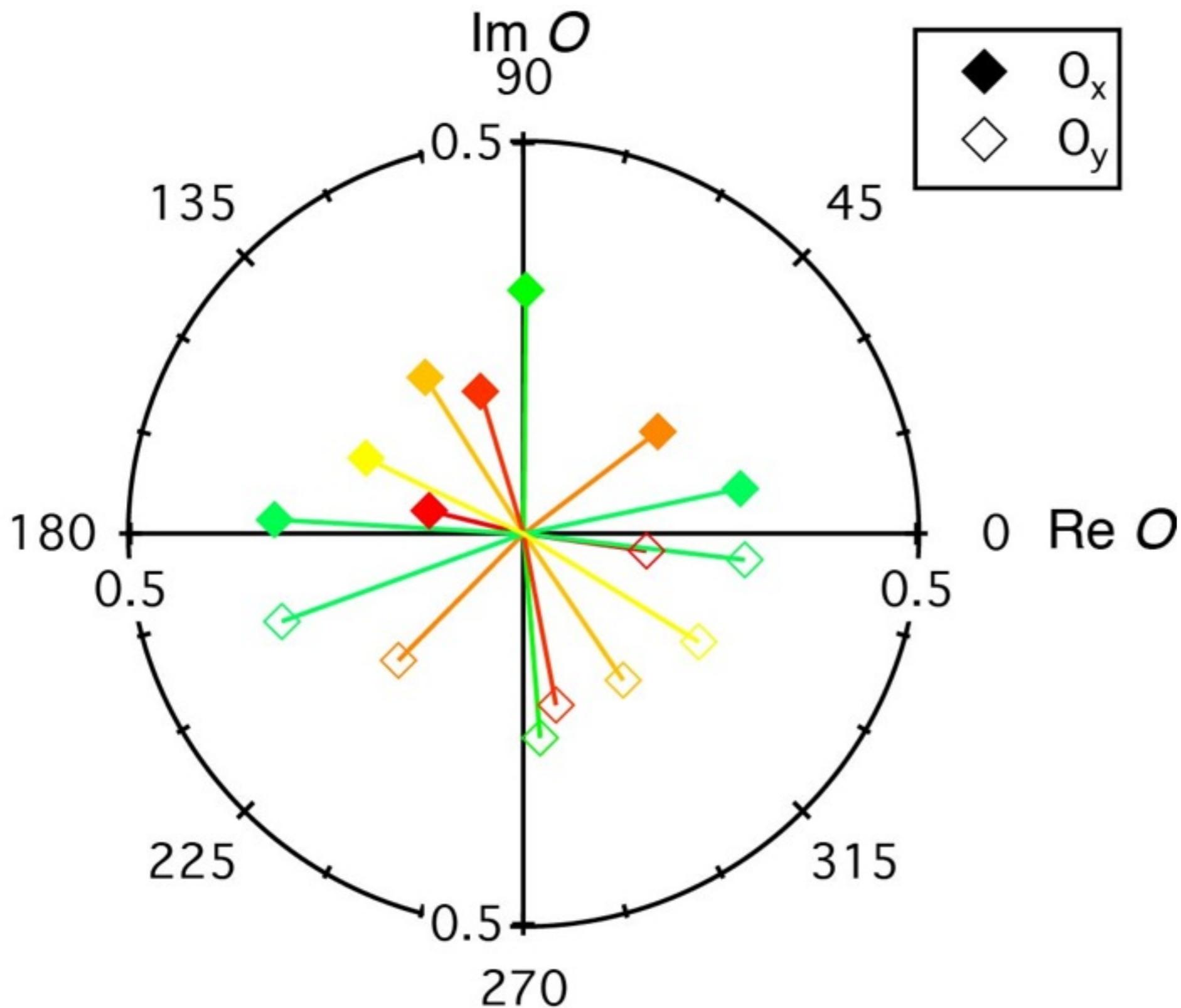
Phase-sensitive measurement of the d -form factor of density wave order



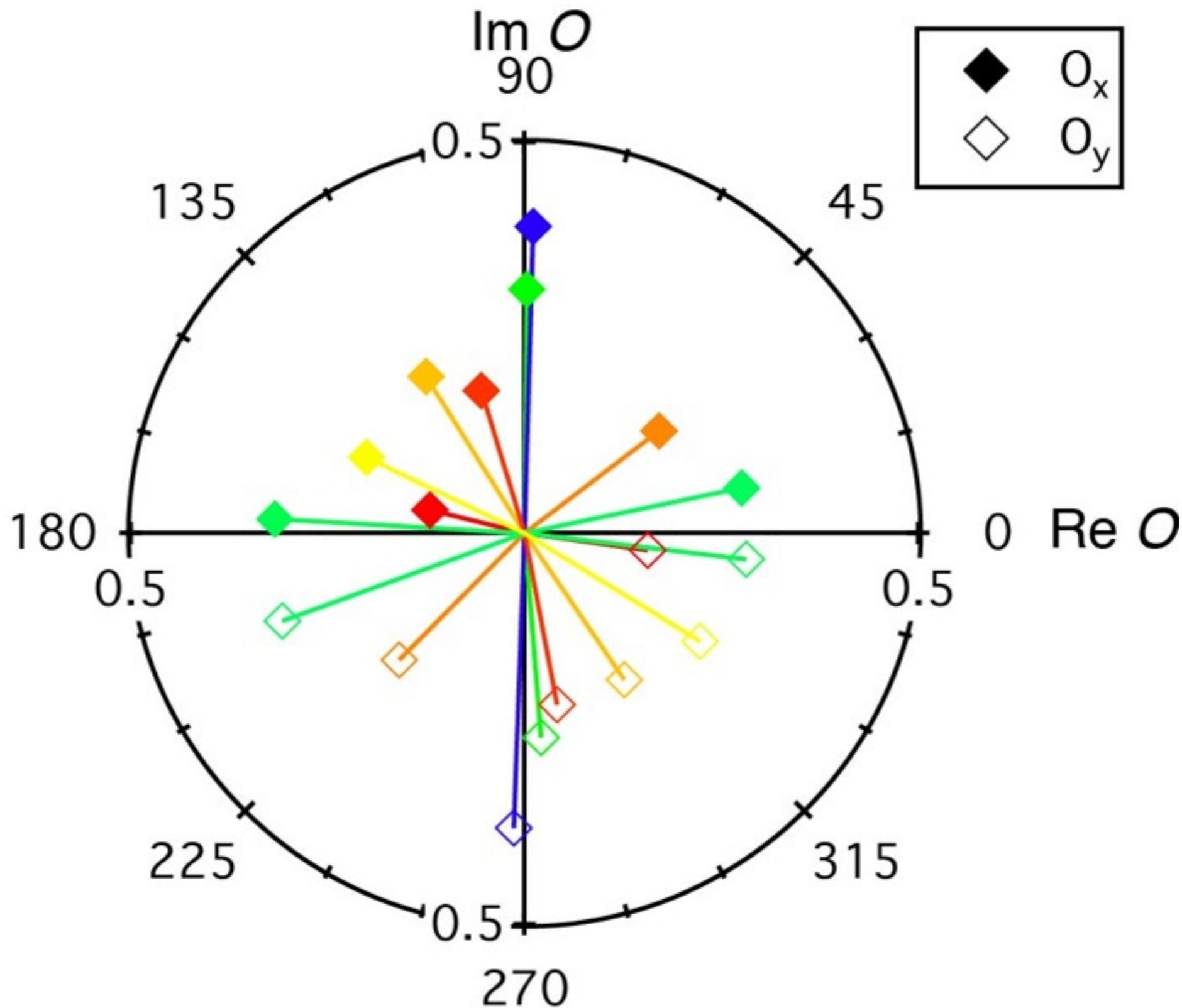
Phase-sensitive measurement of the d -form factor of density wave order



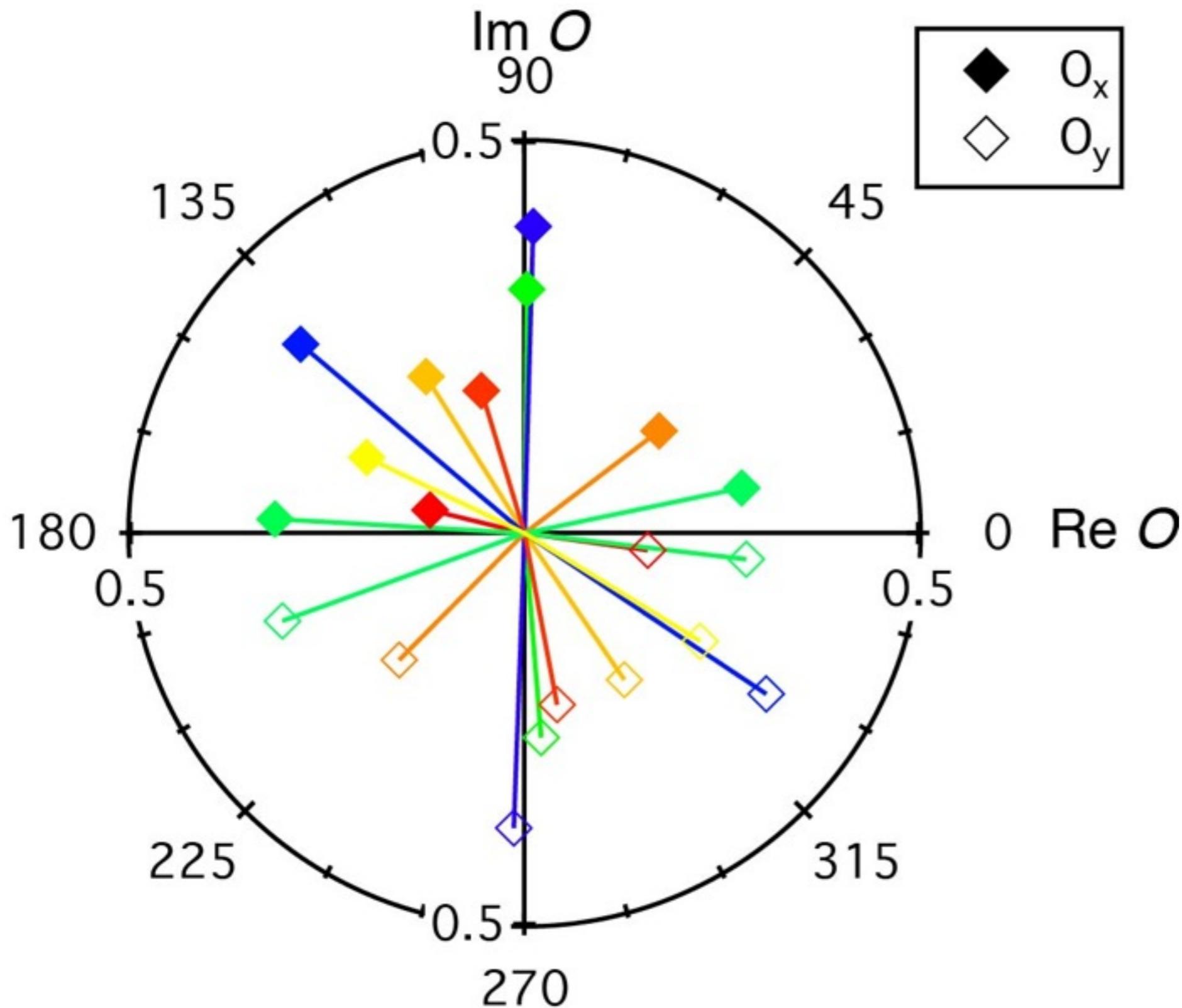
Phase-sensitive measurement of the d -form factor of density wave order



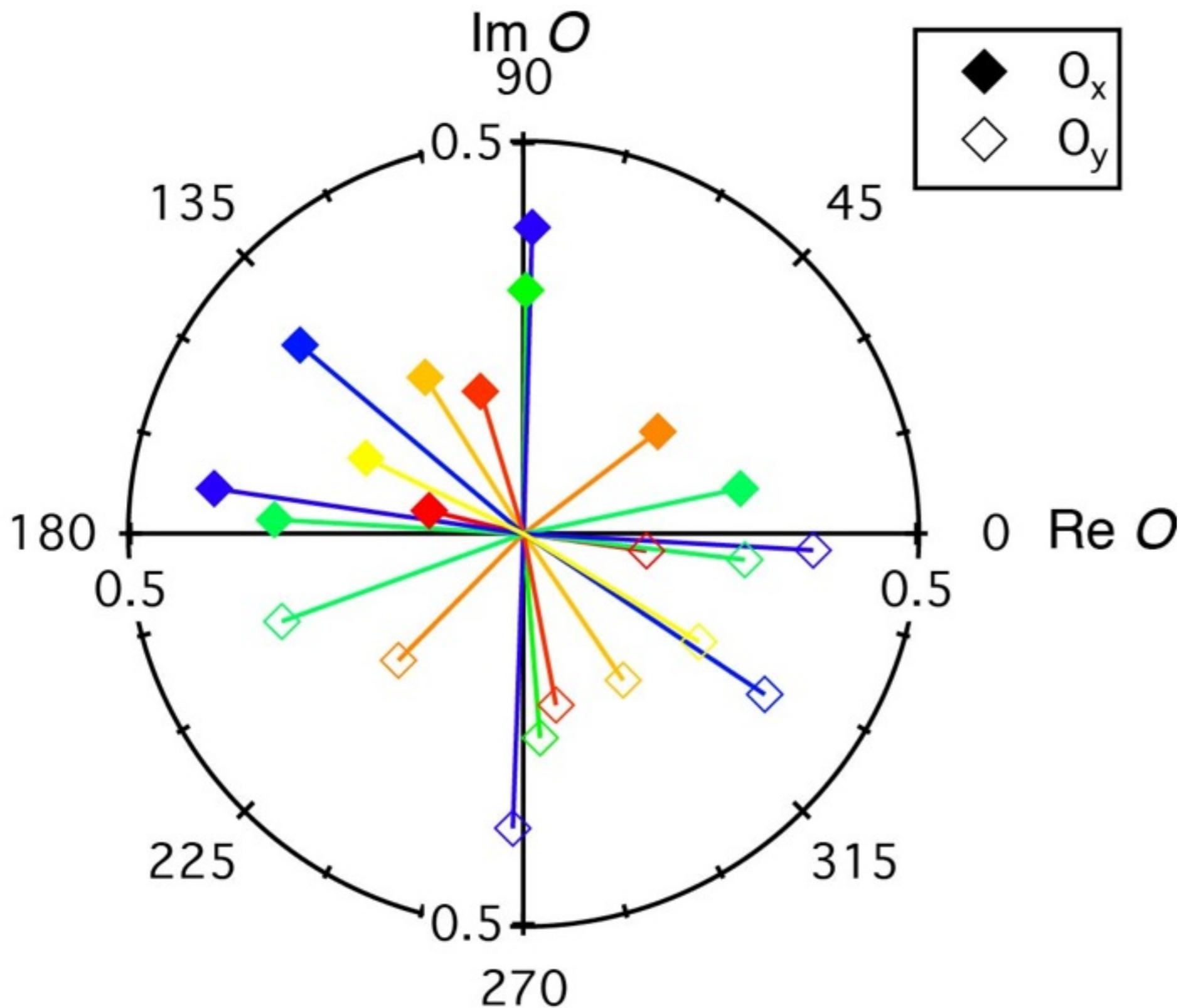
Phase-sensitive measurement of the *d*-form factor of density wave order



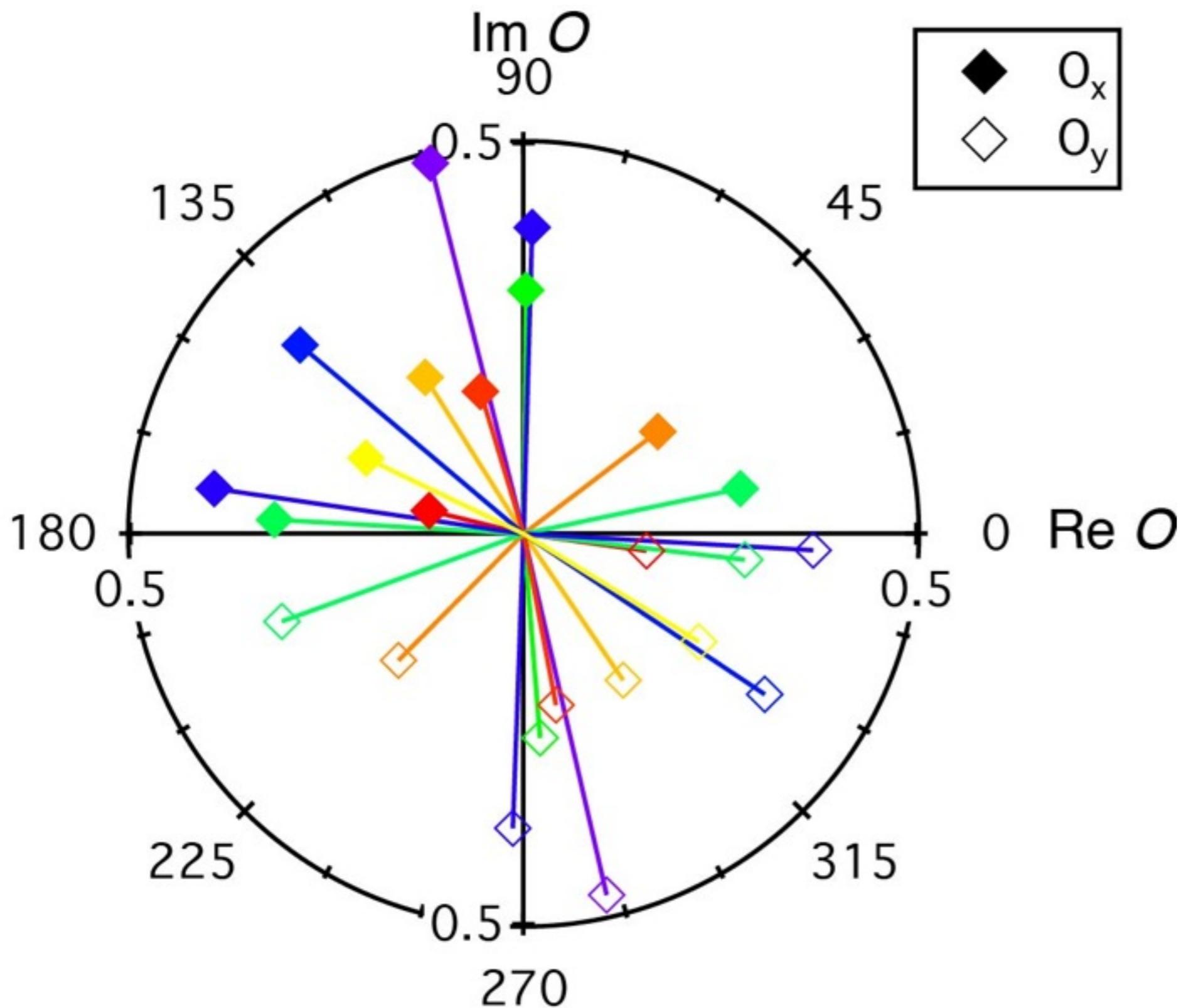
Phase-sensitive measurement of the d -form factor of density wave order



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

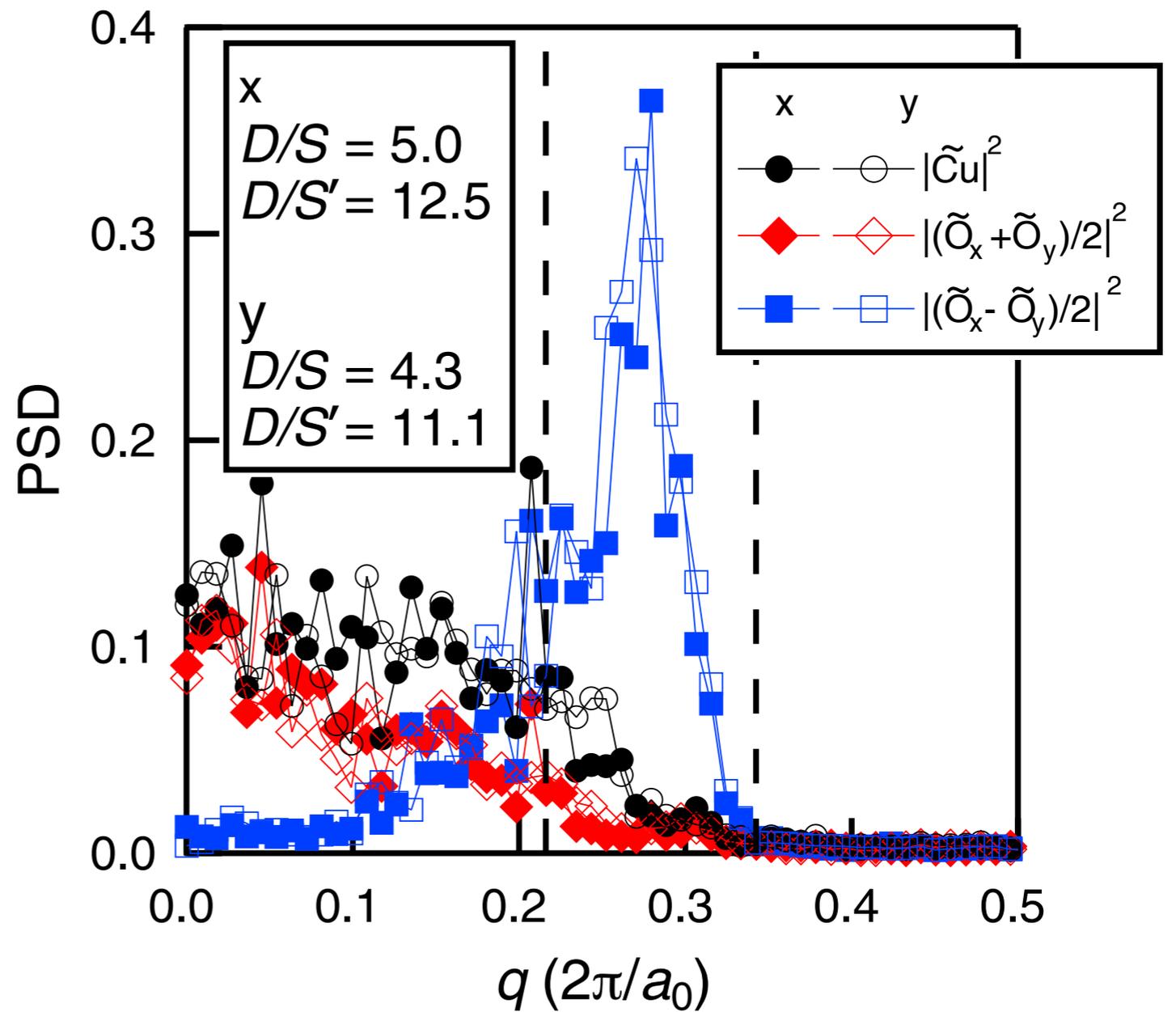
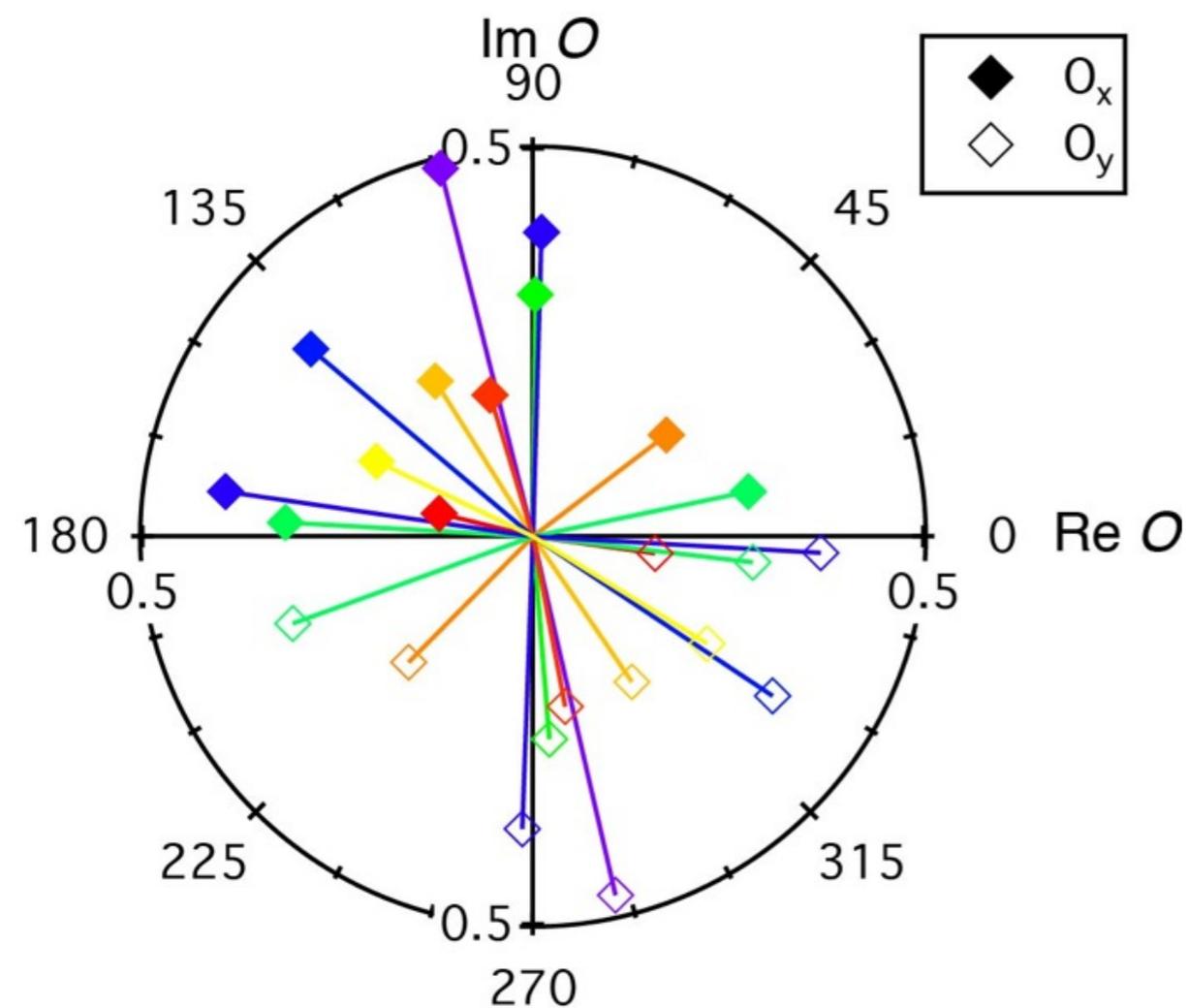


Phase-sensitive measurement of the *d*-form factor of density wave order

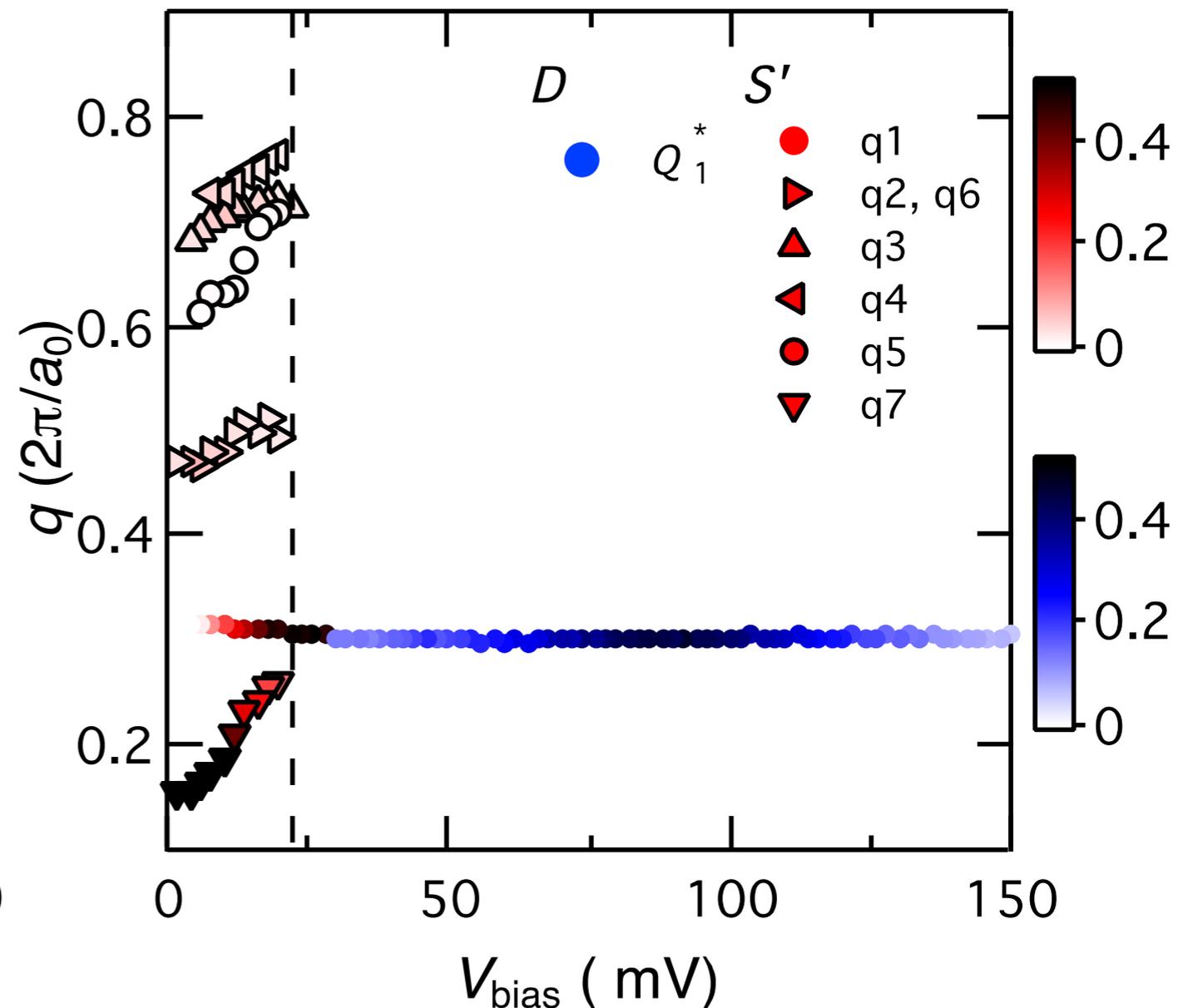
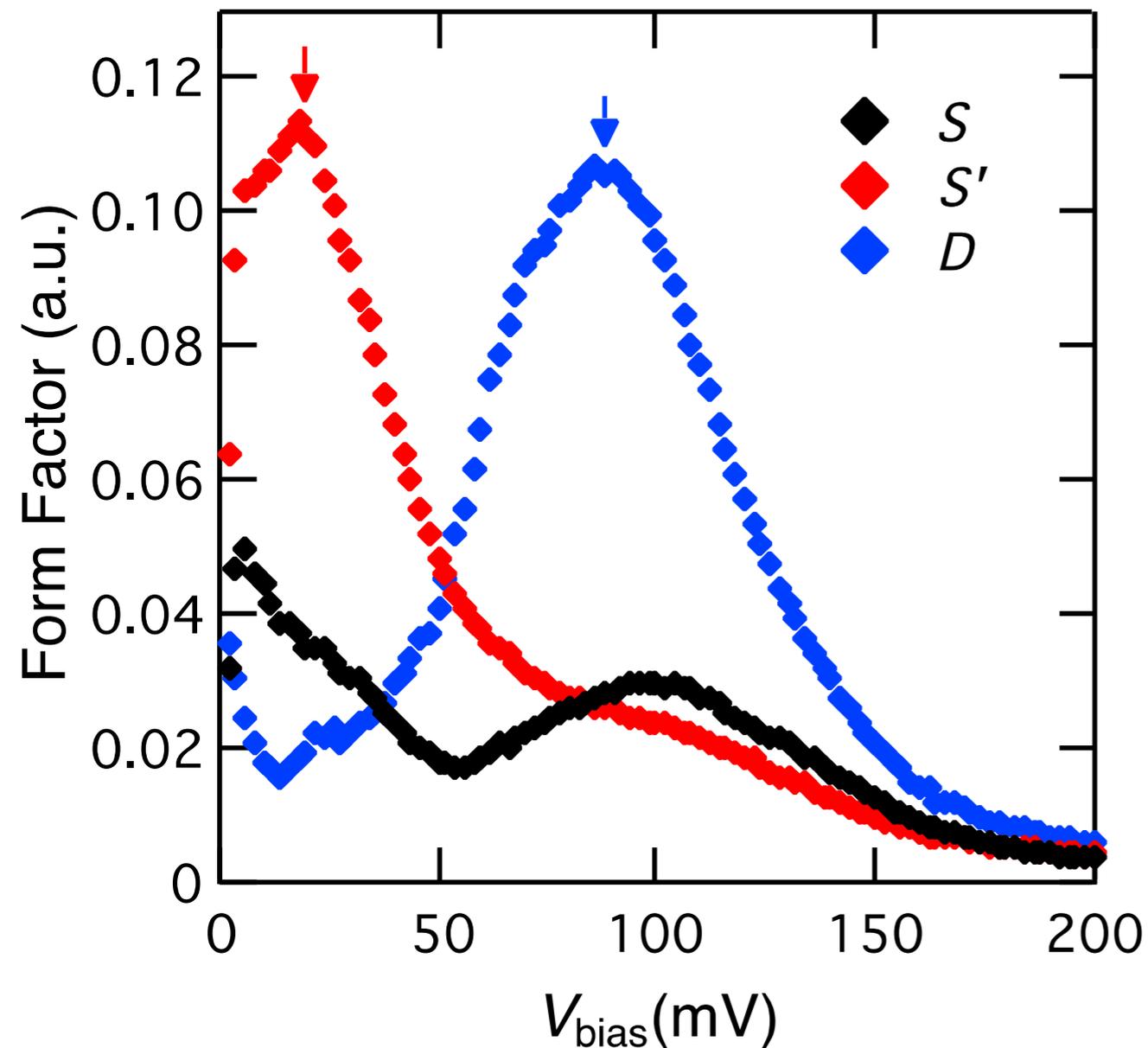


**Phase-sensitive
measurement of
the d -form factor
of density wave
order**

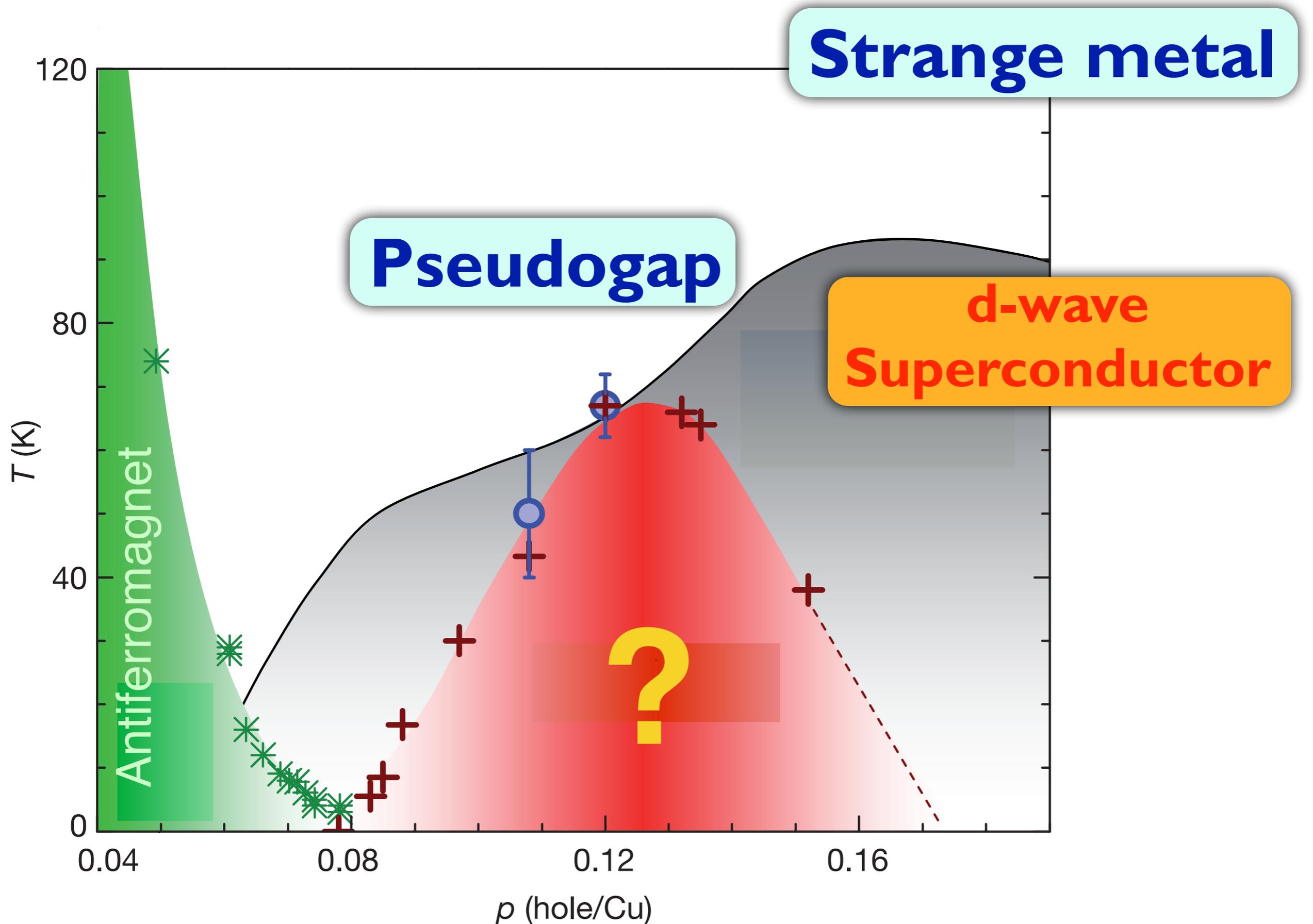
Phase-sensitive measurement of the d -form factor of density wave order



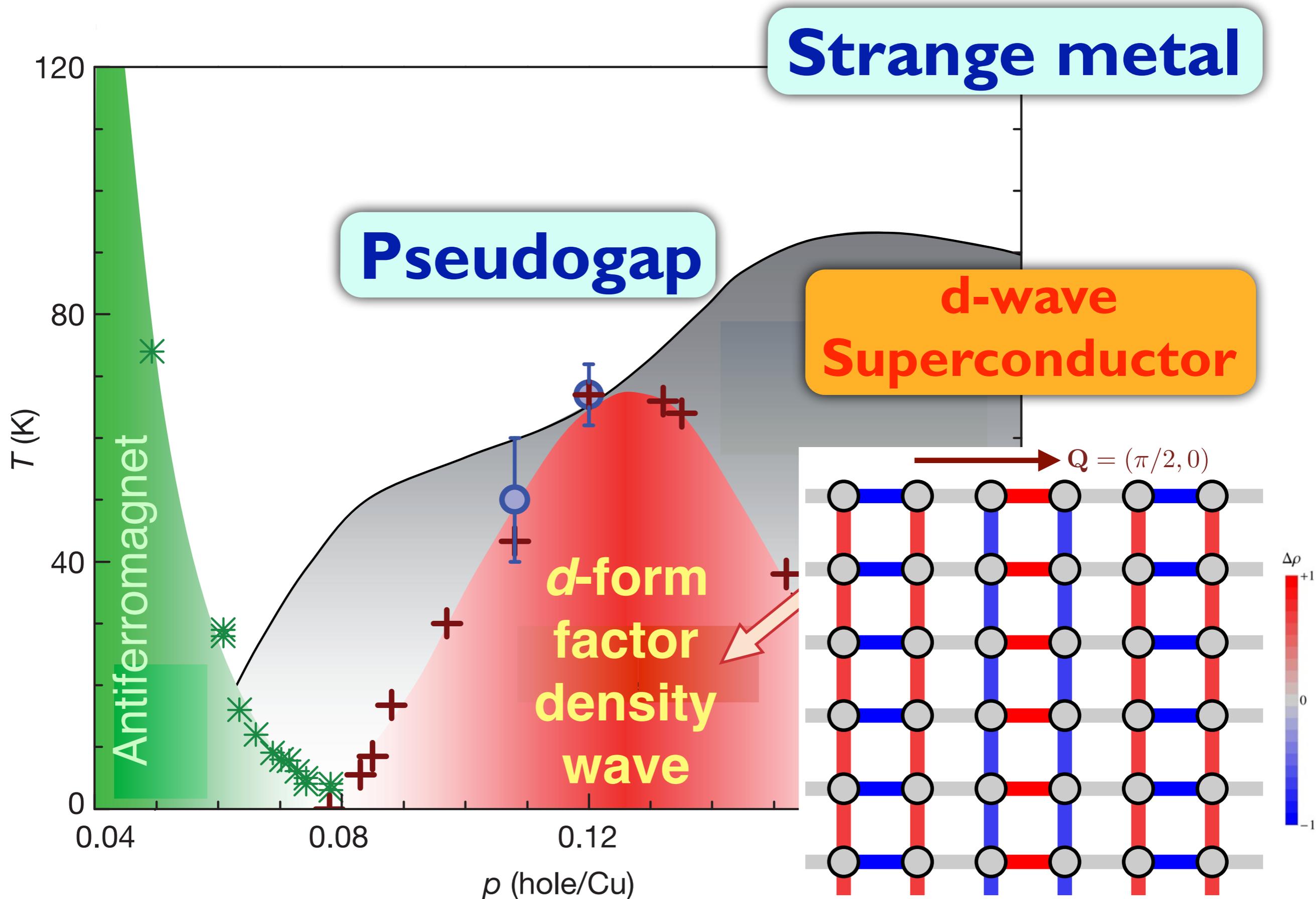
d -form factor is peaked at the pseudogap energy, and does not disperse as a function of wavevector



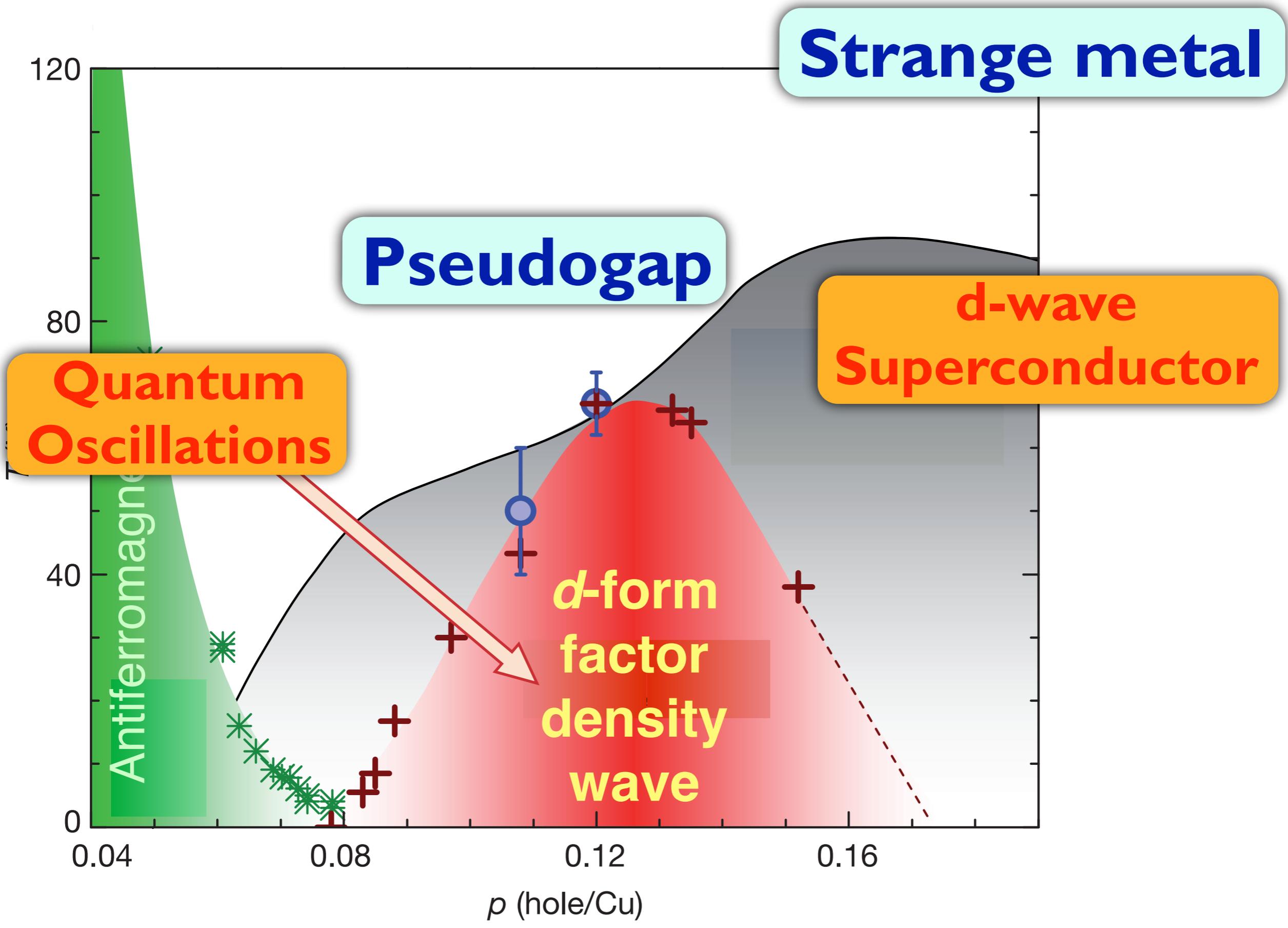
K. Fujita, M. H. Hamidian, S. D. Edkins, Chung Koo Kim, A. P. MacKenzie, H. Eisaki, S. Uchida, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, to appear



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



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



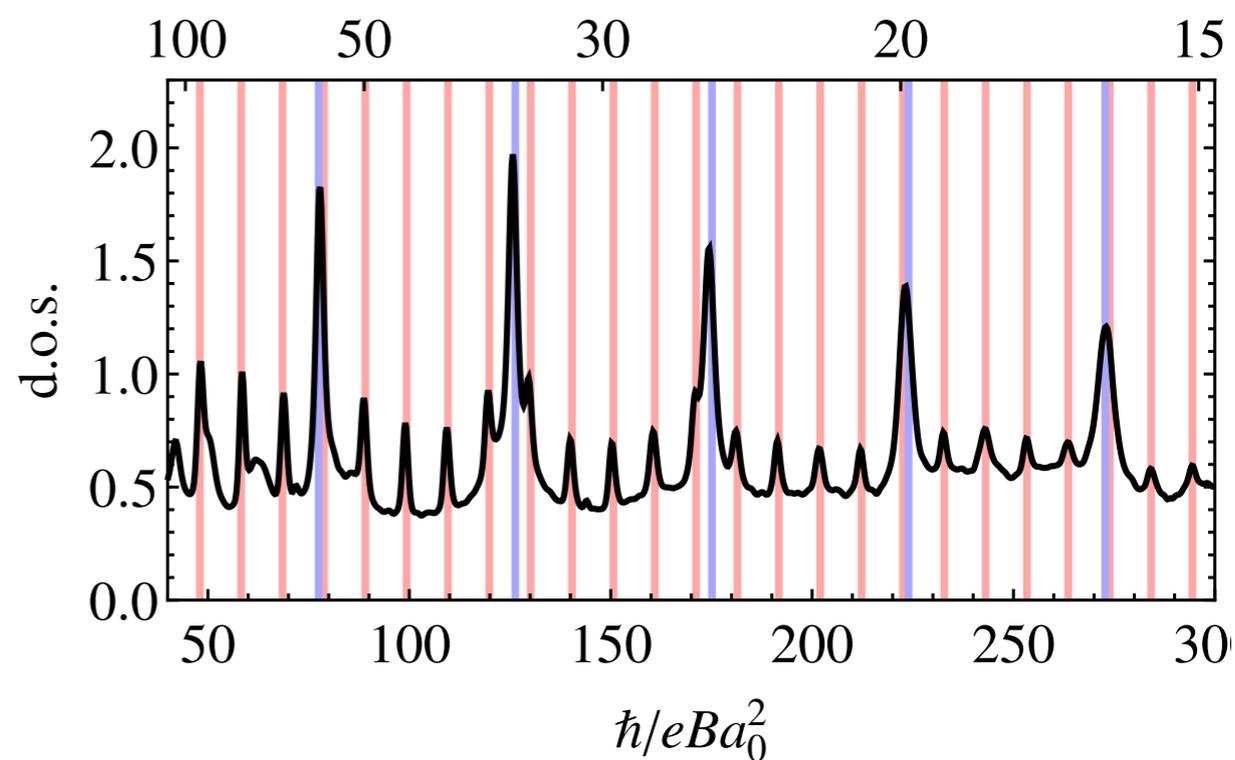
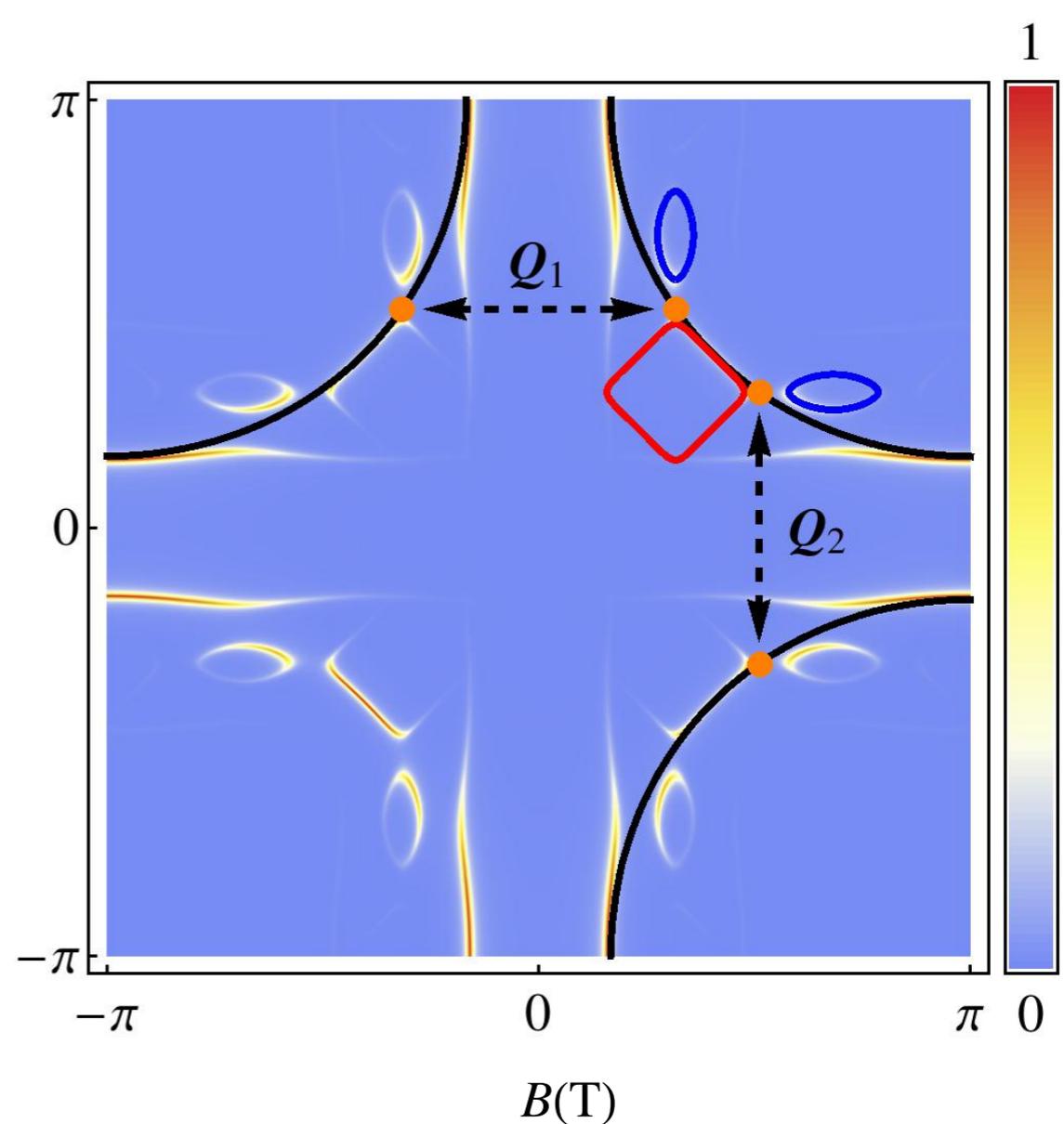


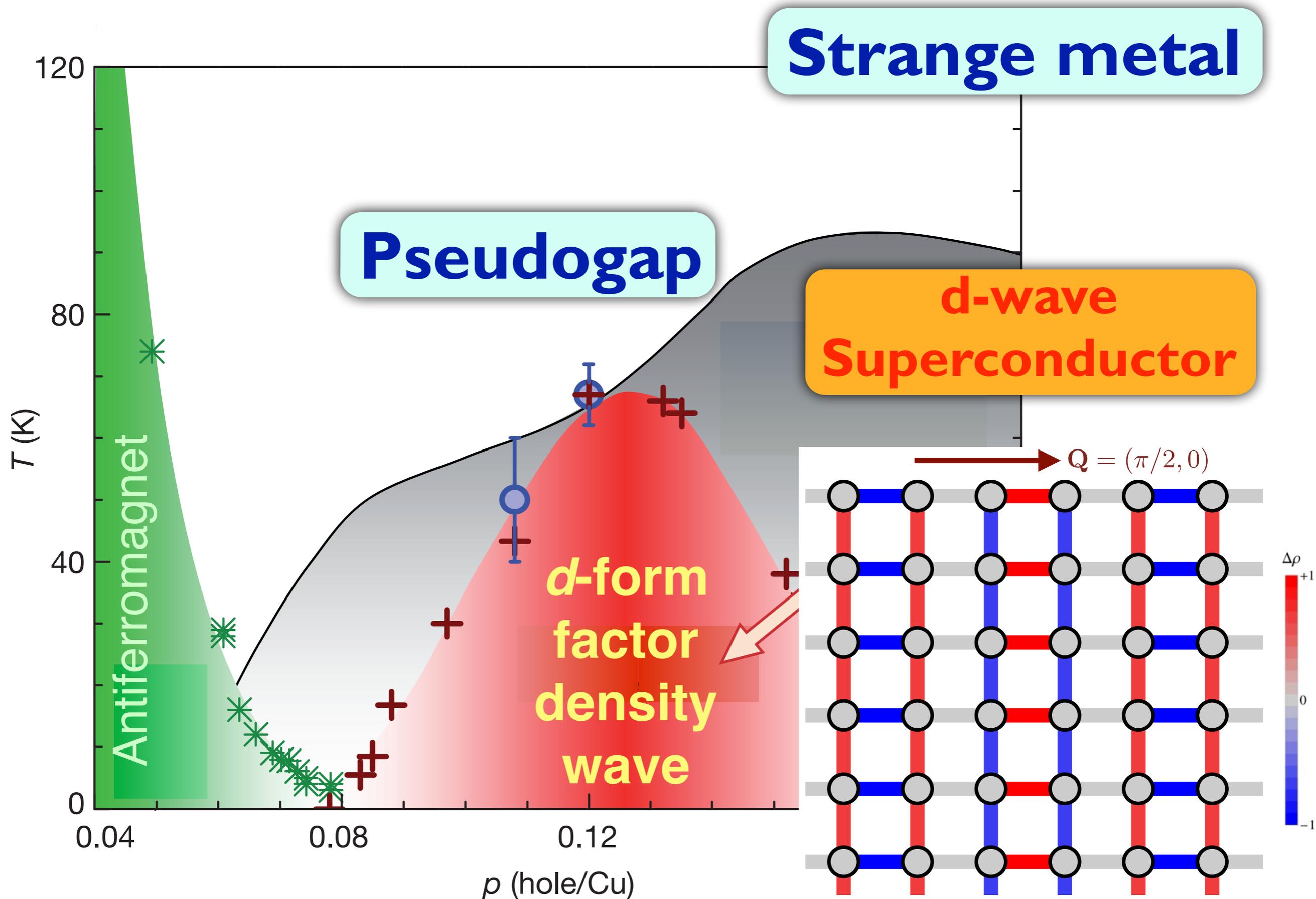
Andrea Allais
(see poster)

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

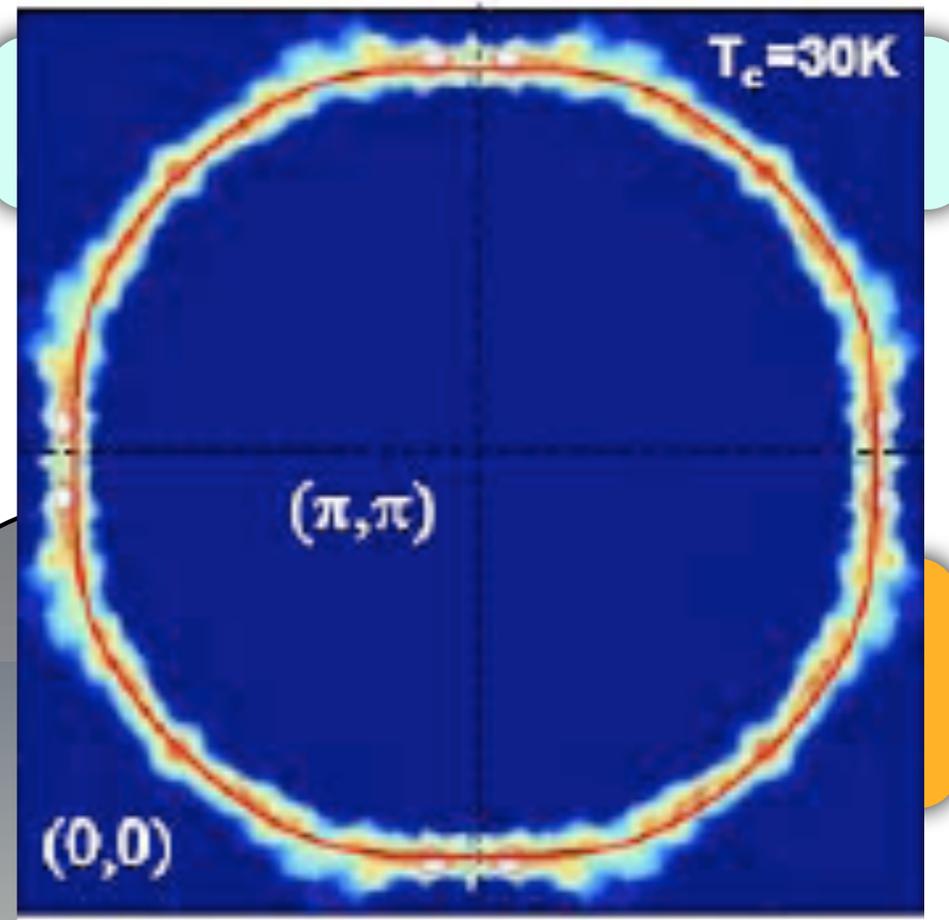
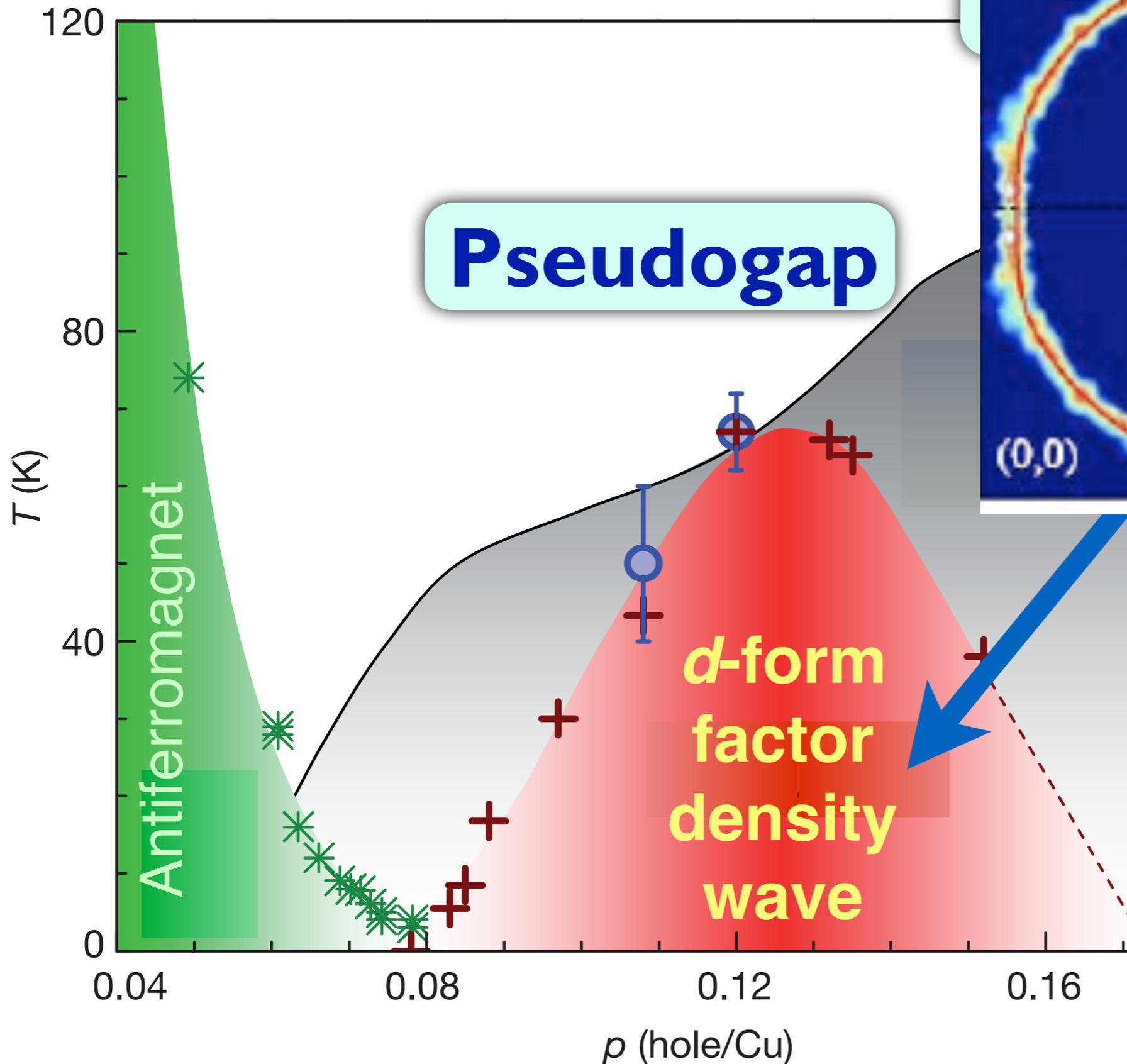
Electron pocket: 432 Tesla
Hole pocket: 90.9 Tesla

Andrea Allais,
Debanjan Chowdhury,
and Subir Sachdev,
arXiv:1406.0503

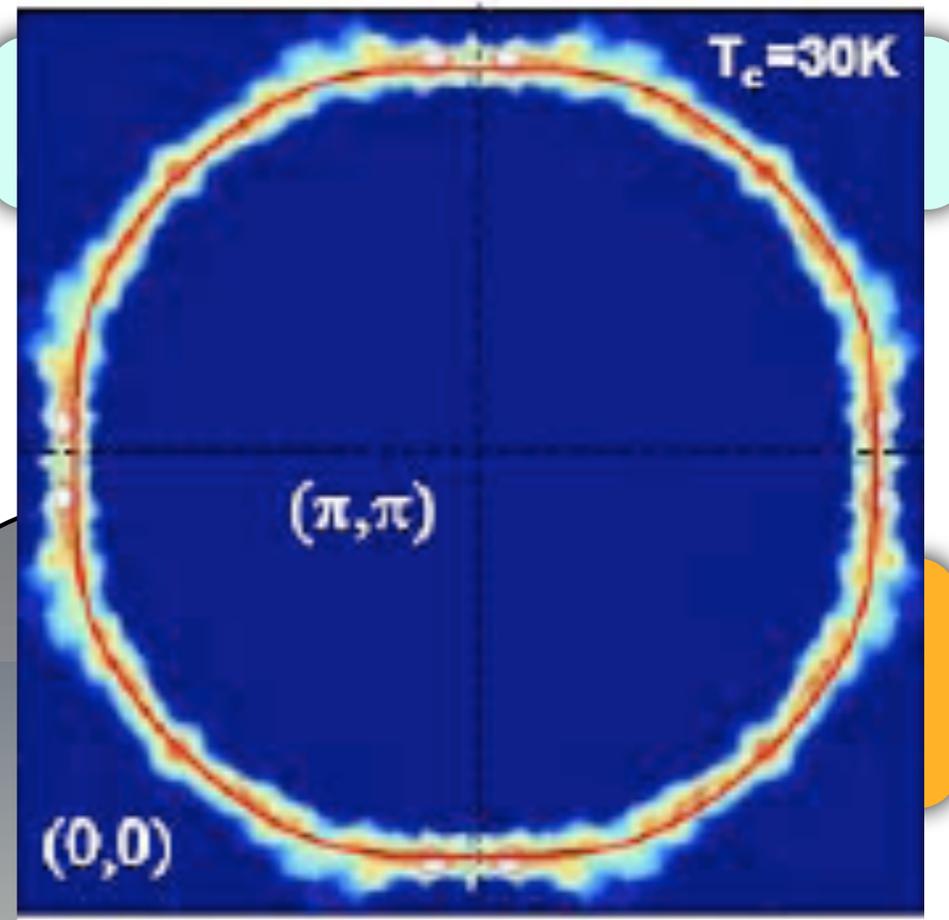
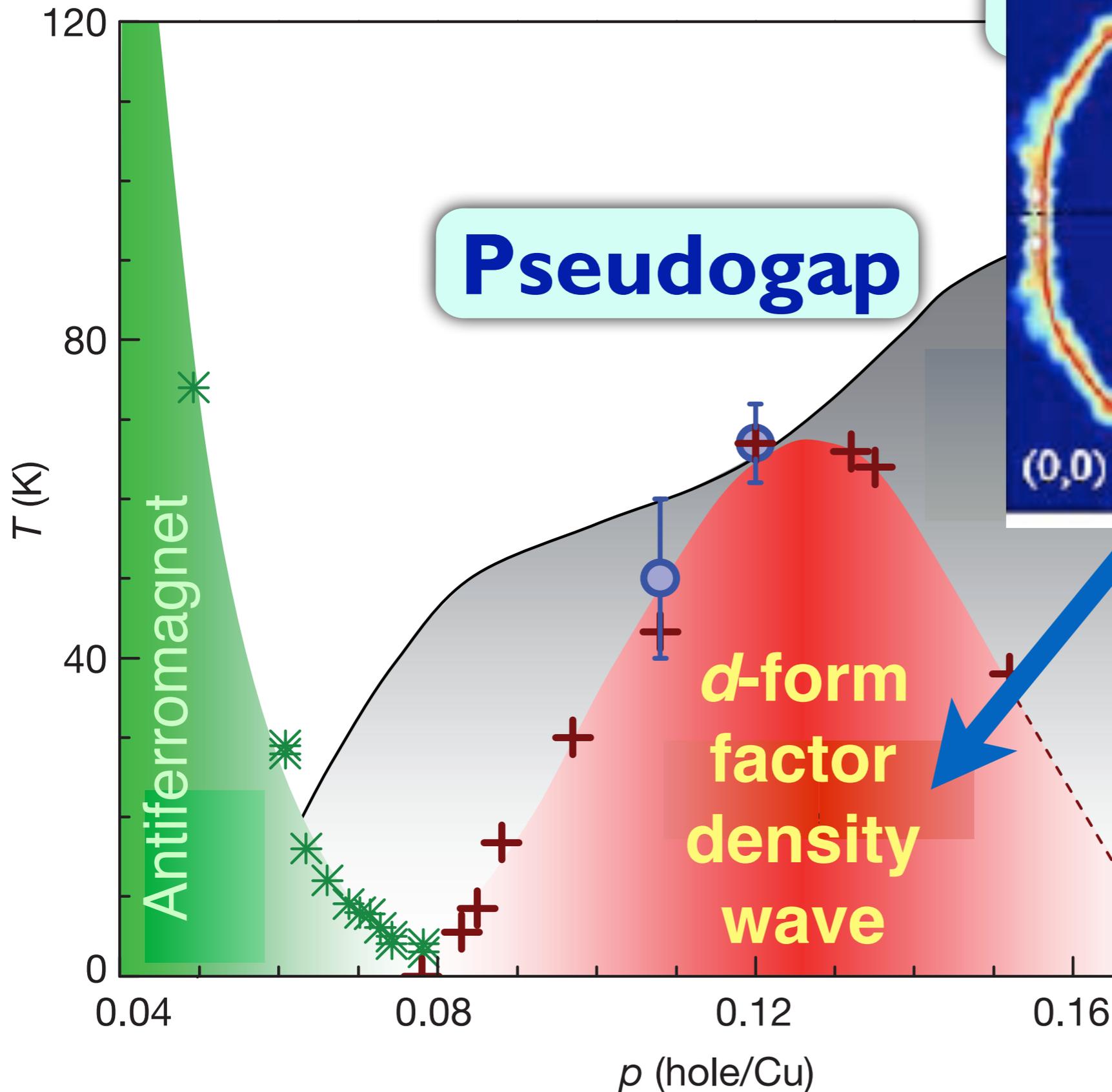




K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS 111, E3026 (2014)



Instabilities of the large Fermi surface do lead to *d*-form factors, but at “diagonal” wavevectors.



Reconstruction of large Fermi surface by density wave order cannot account for specific heat measurements at high fields.

R. C. Riggs *et al.*,
Nature Physics **7**, 332 (2011).

Adventures with the spin-fermion model, and beyond

Adventures with the spin-fermion model,

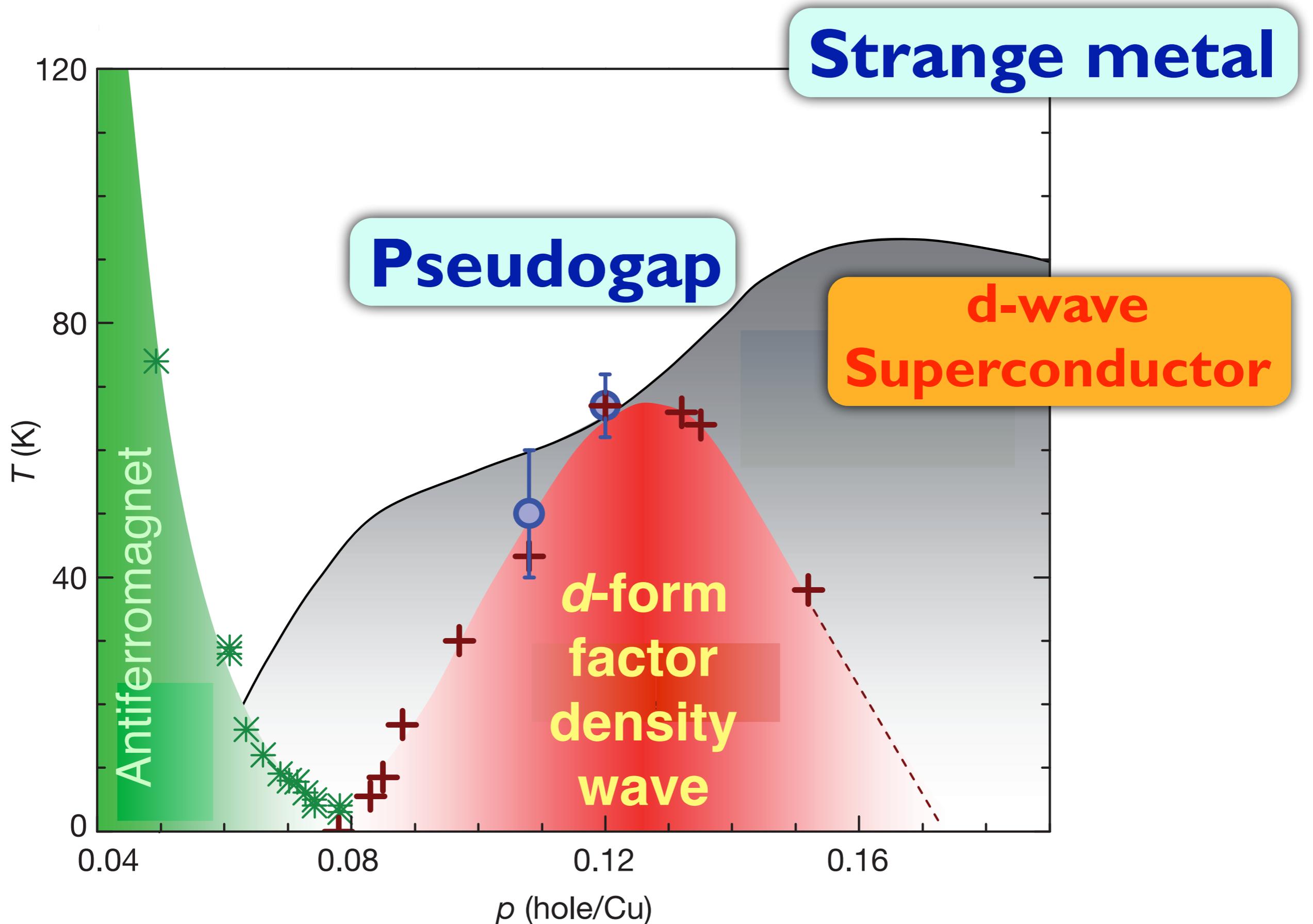
and beyond

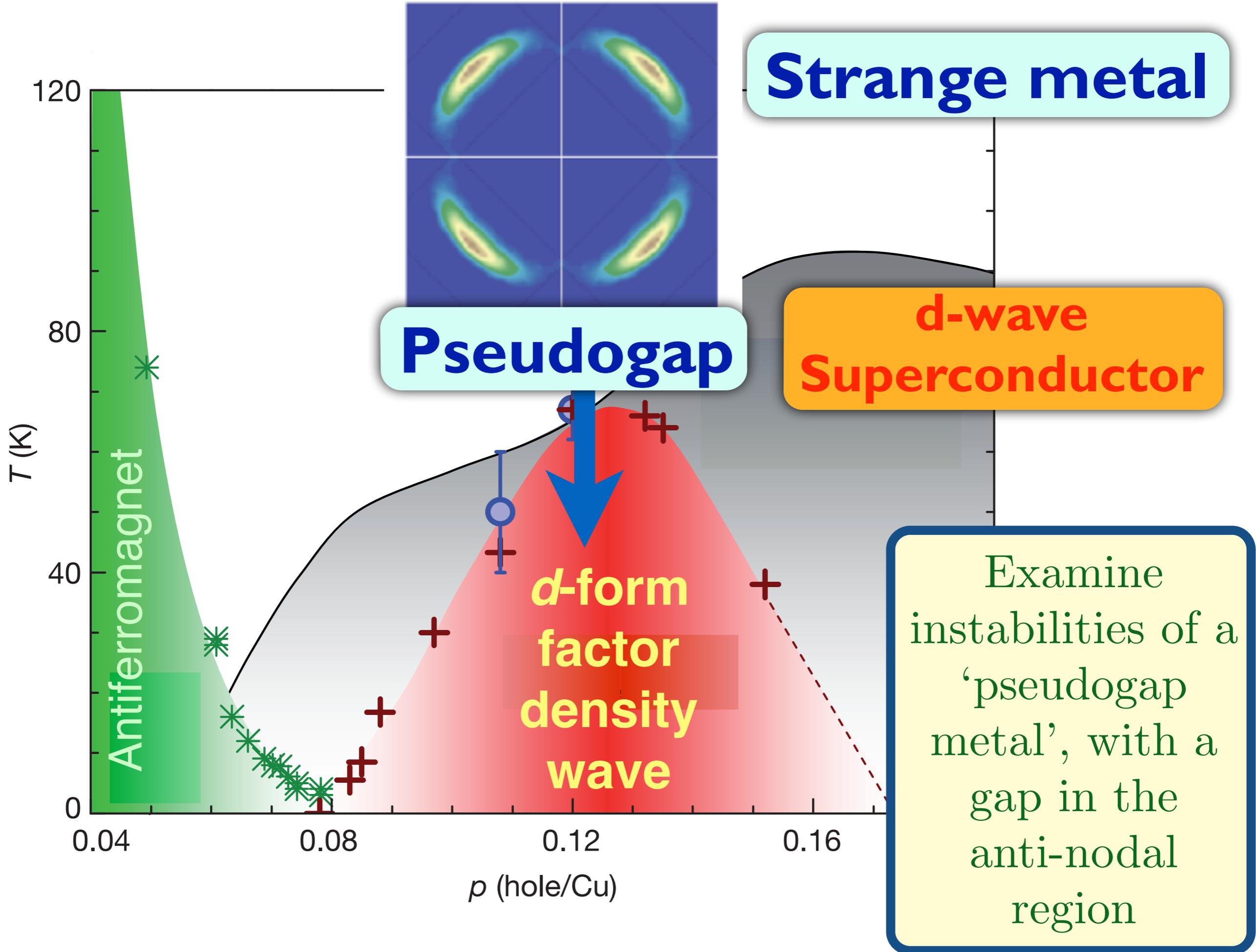


Debanjan
Chowdhury

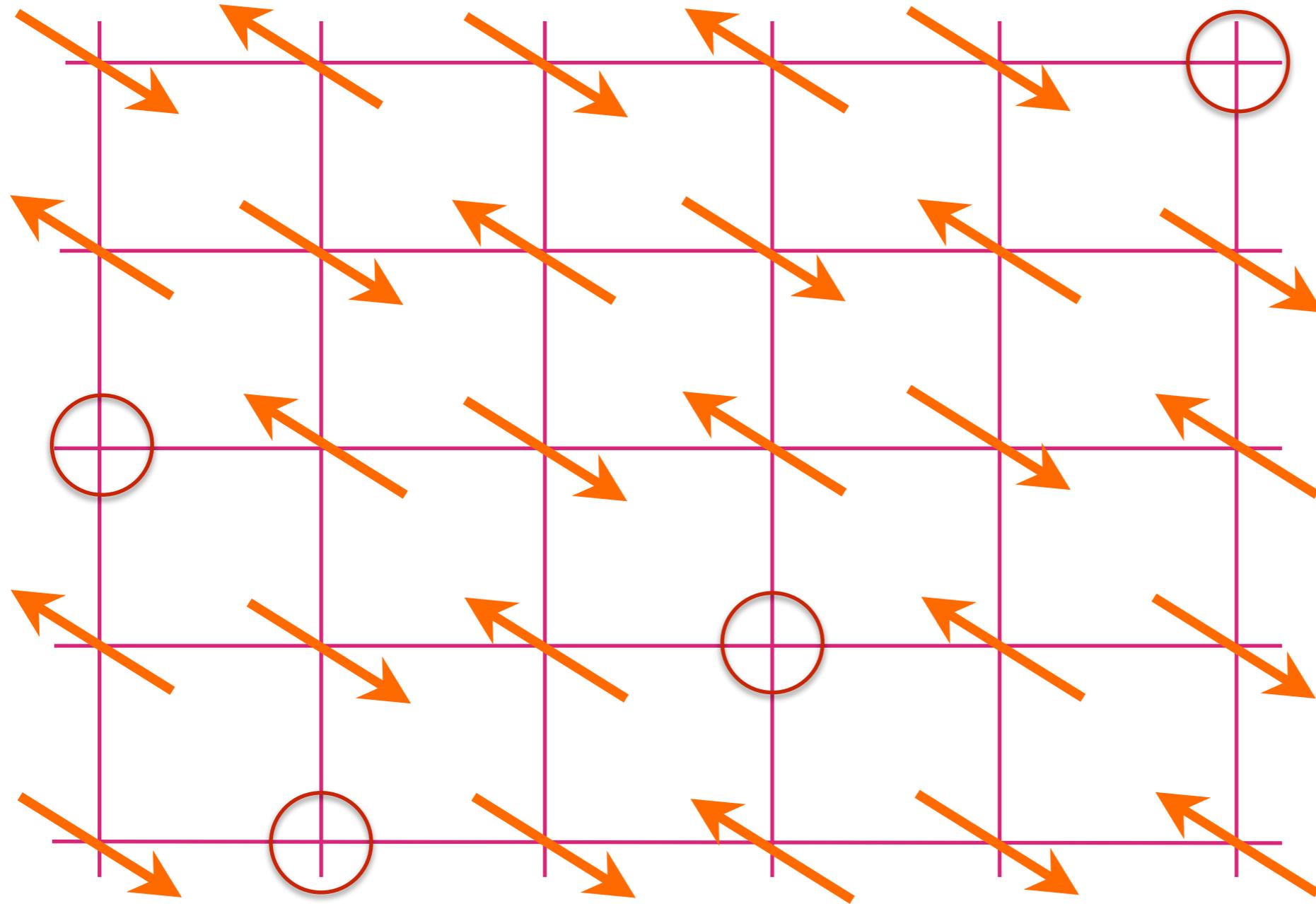


Alexandra
Thomson



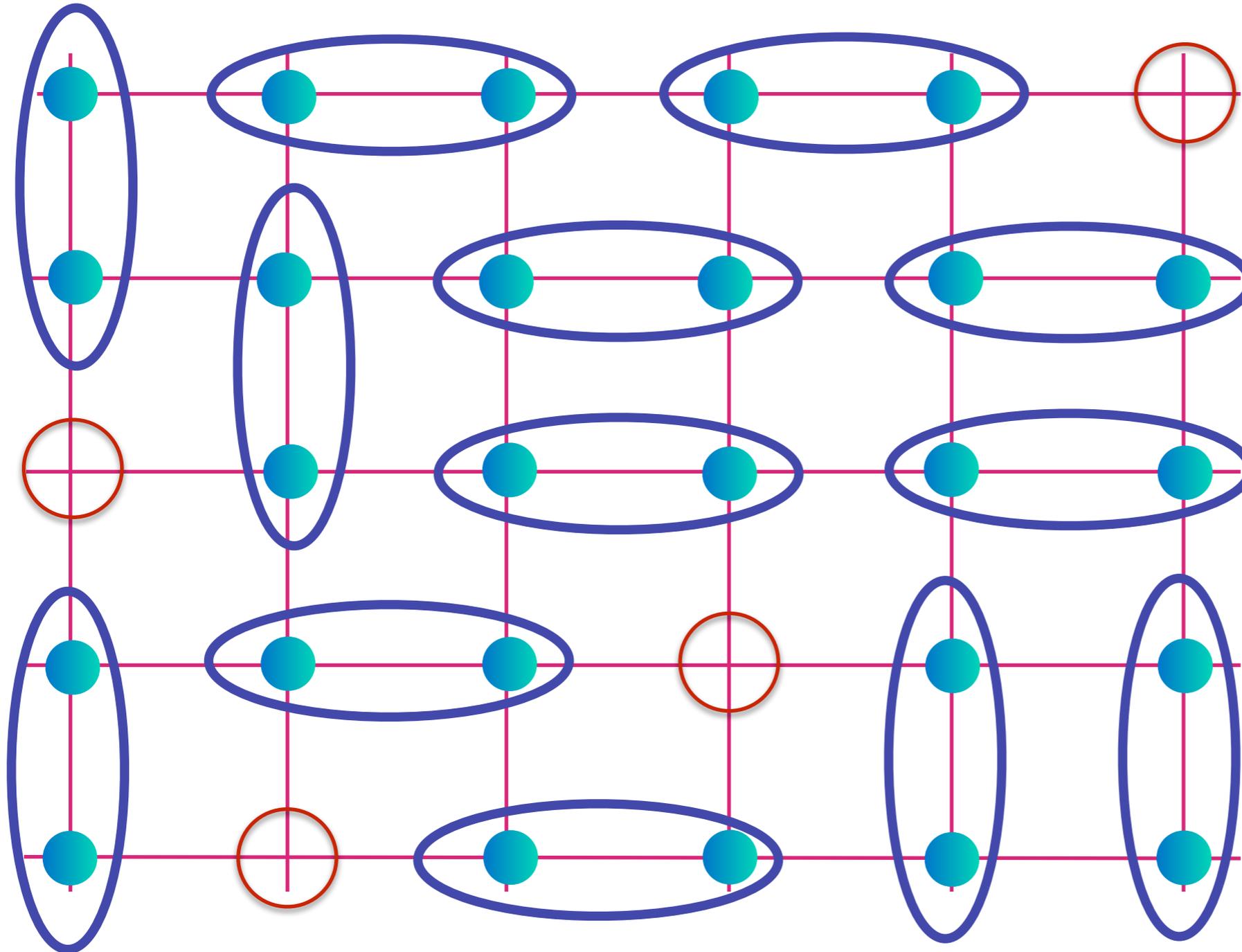


Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)



Doped
anti-
ferromagnet

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



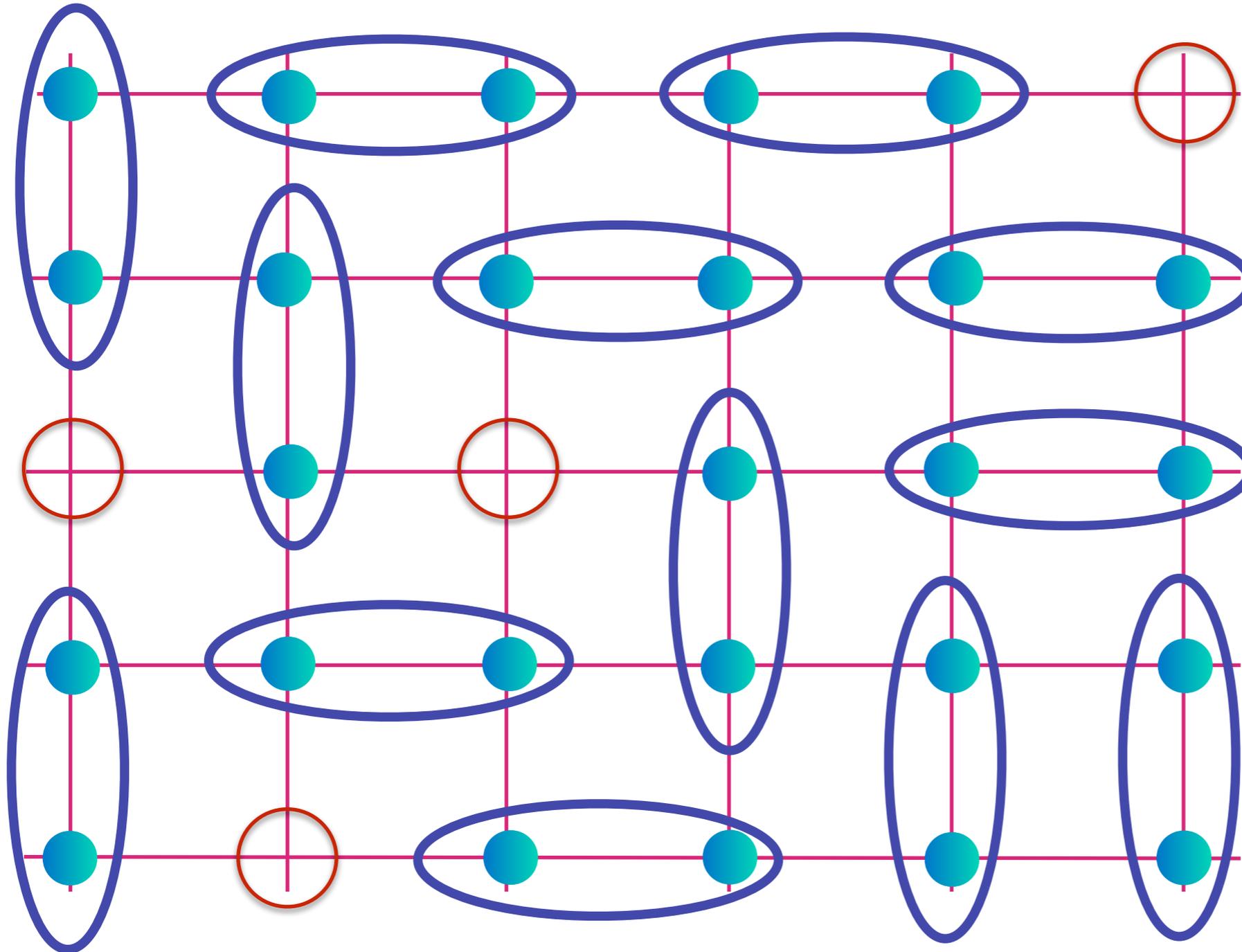
Spin
liquid

Spinless
charge $+e$
holons

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

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

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



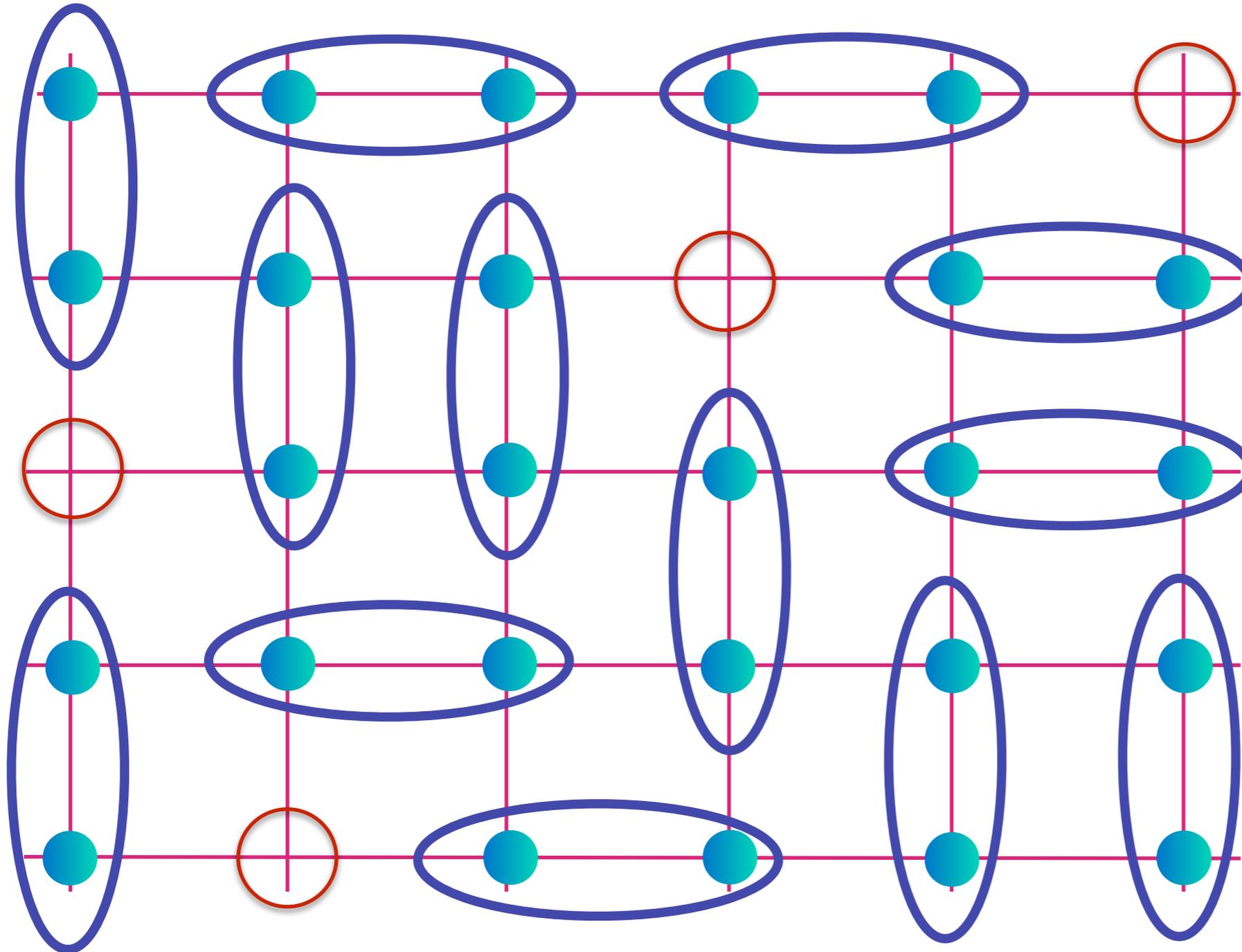
Spin
liquid

Spinless
charge $+e$
holons

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

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

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



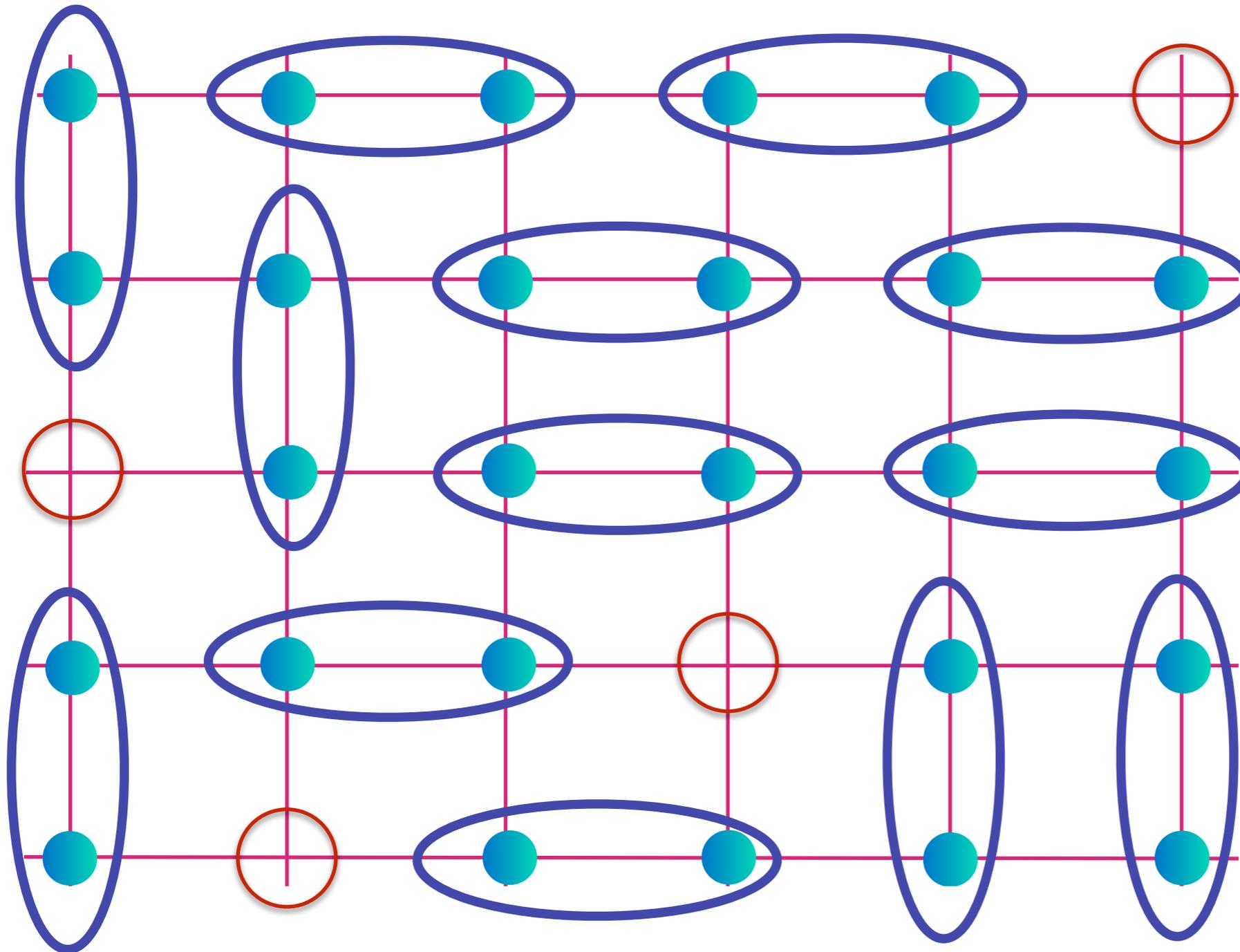
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Baskaran, Zou, Anderson, Fradkin, Kivelson...

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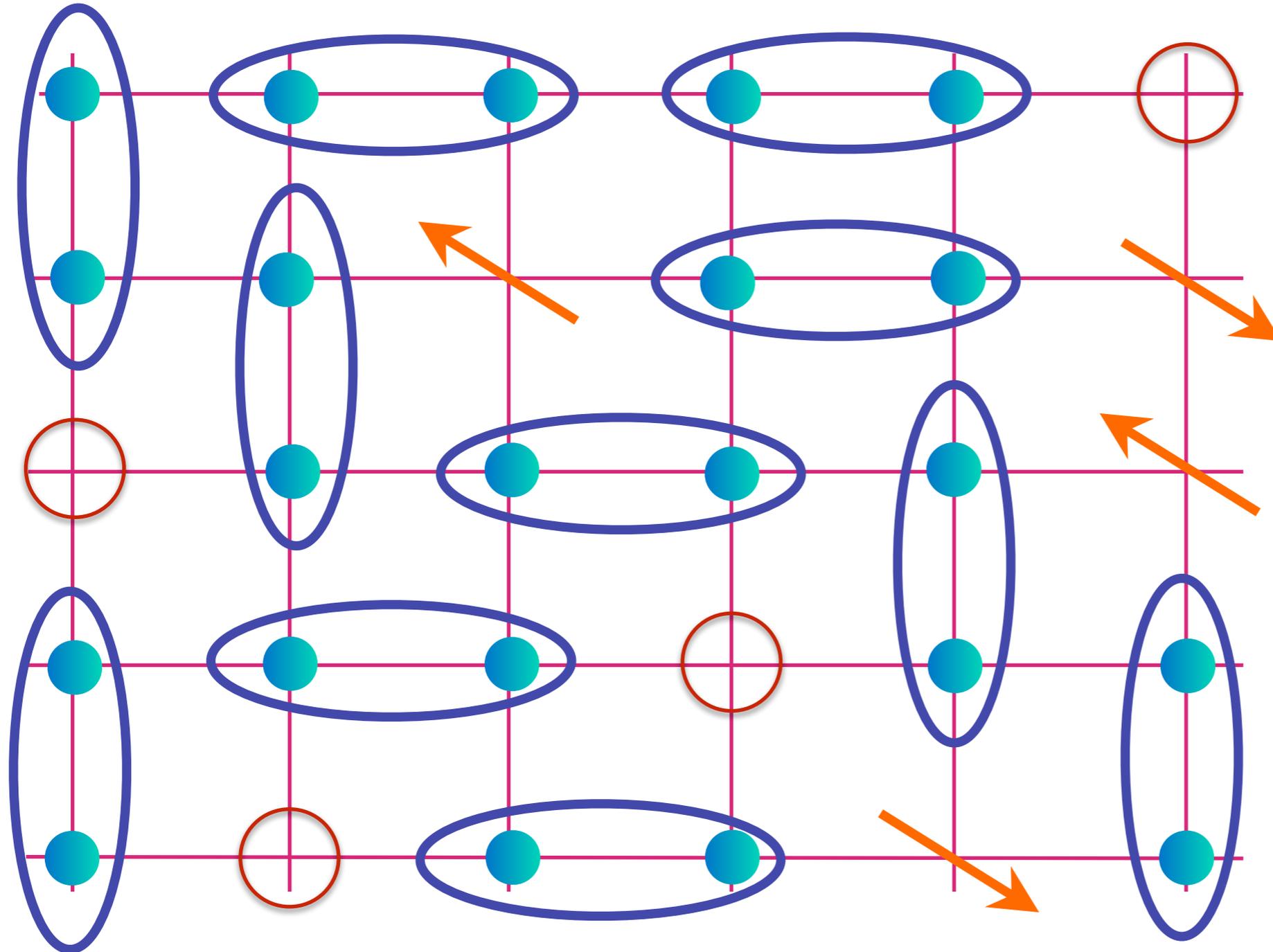
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liquid

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

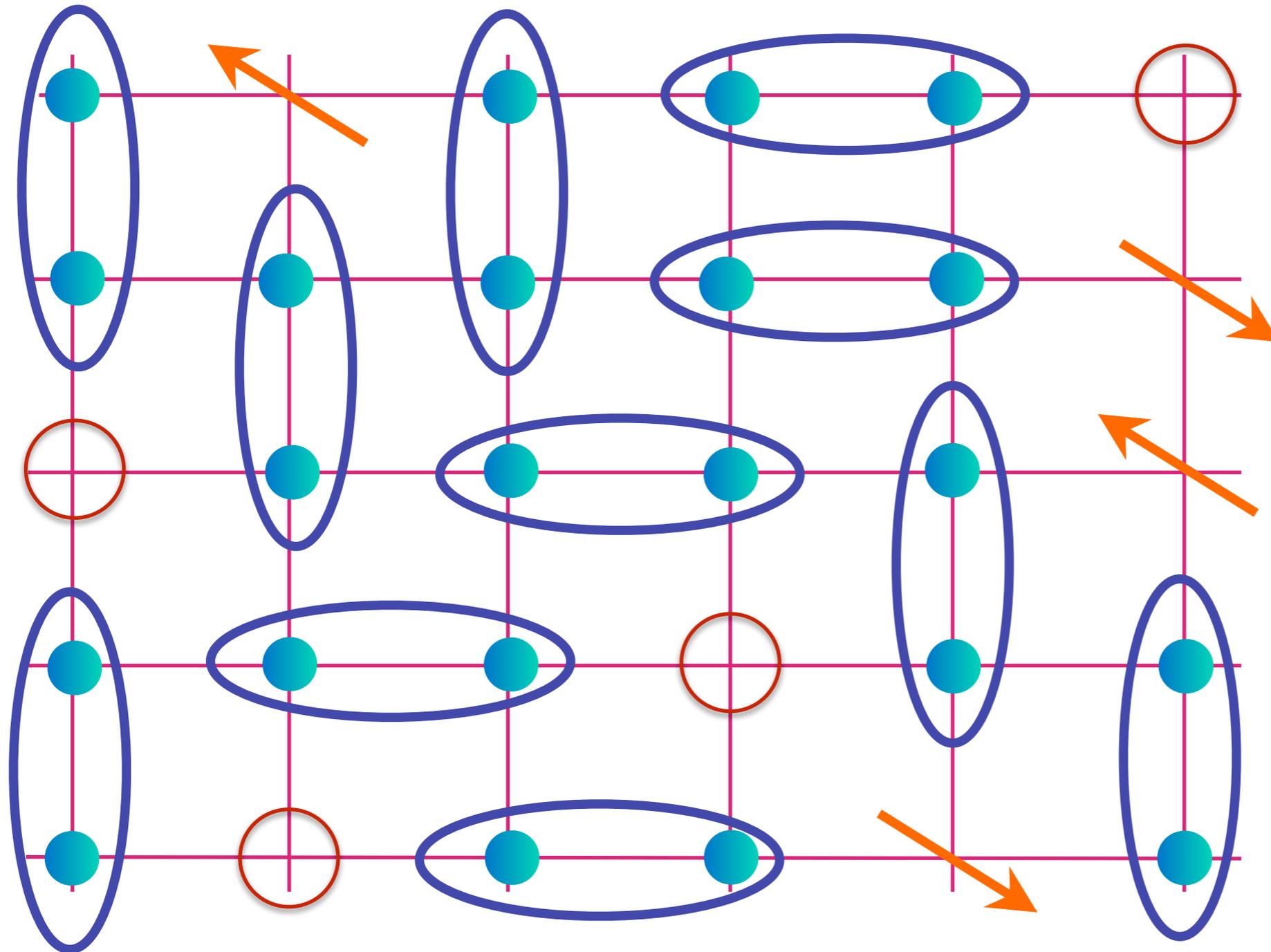
Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)



Spin
liquid

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

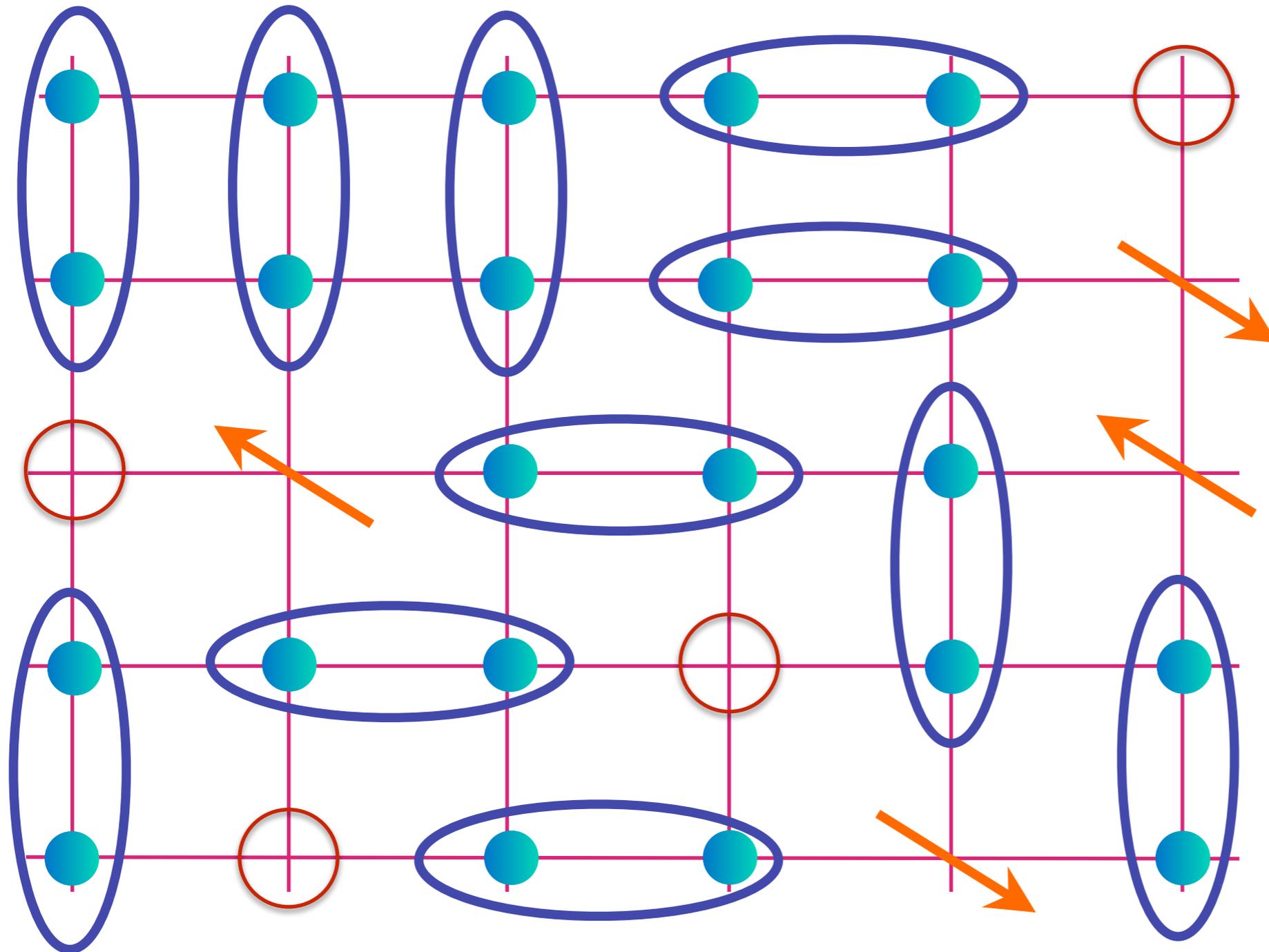
Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)



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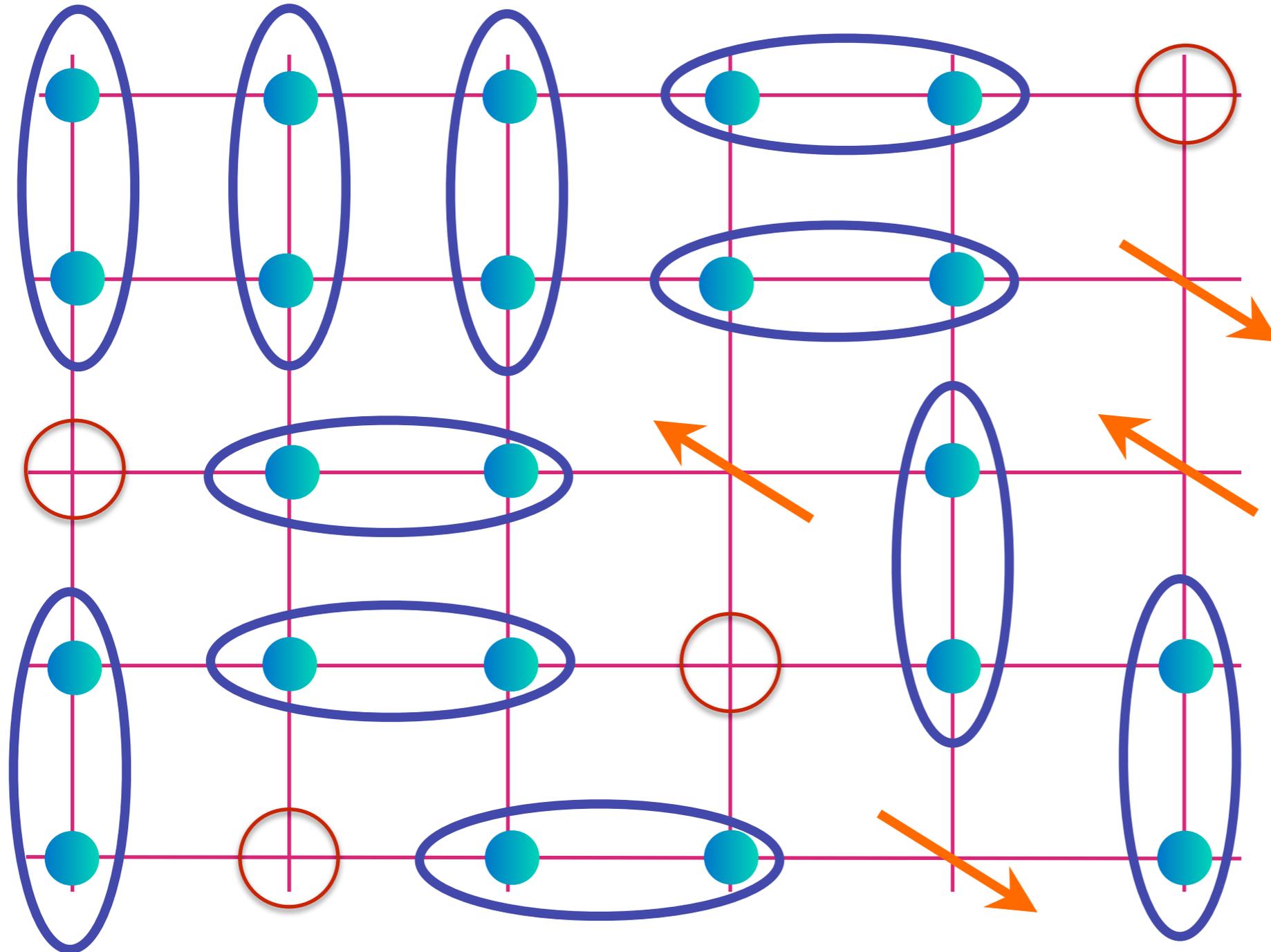
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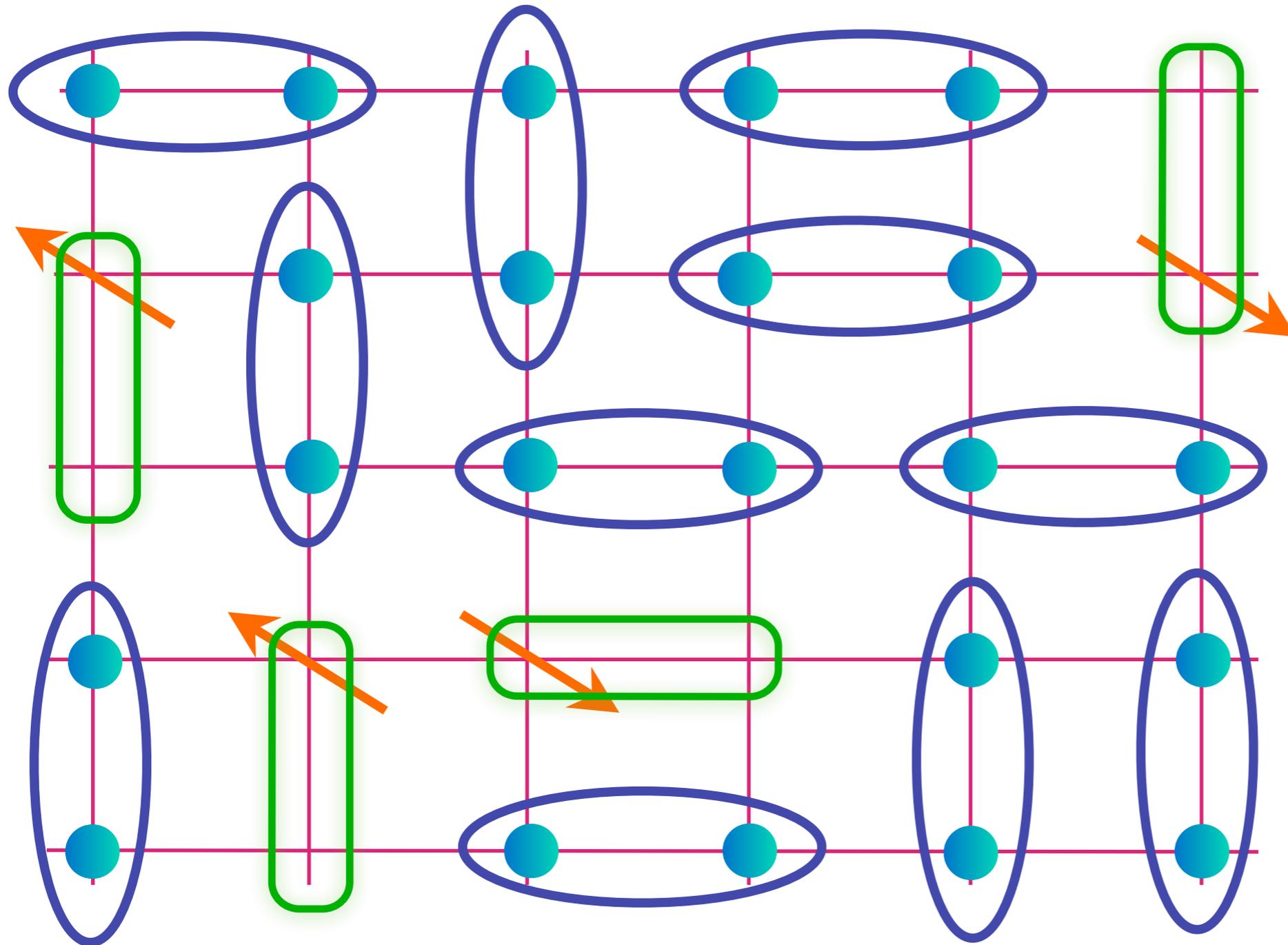
Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)



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

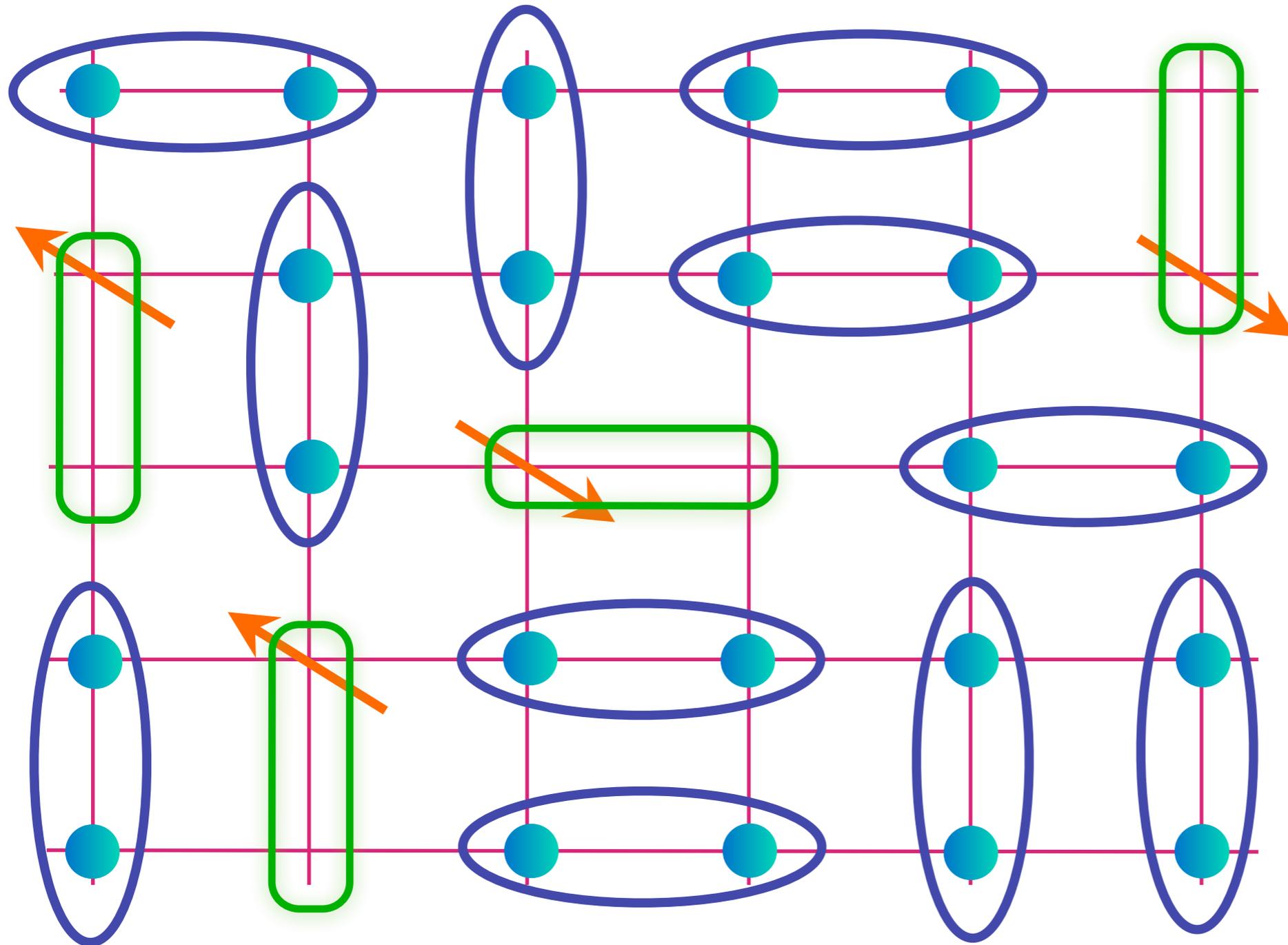


FL* !

Spin
singlets
and
charge $+e$
 $S=1/2$
neutral
holes

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

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

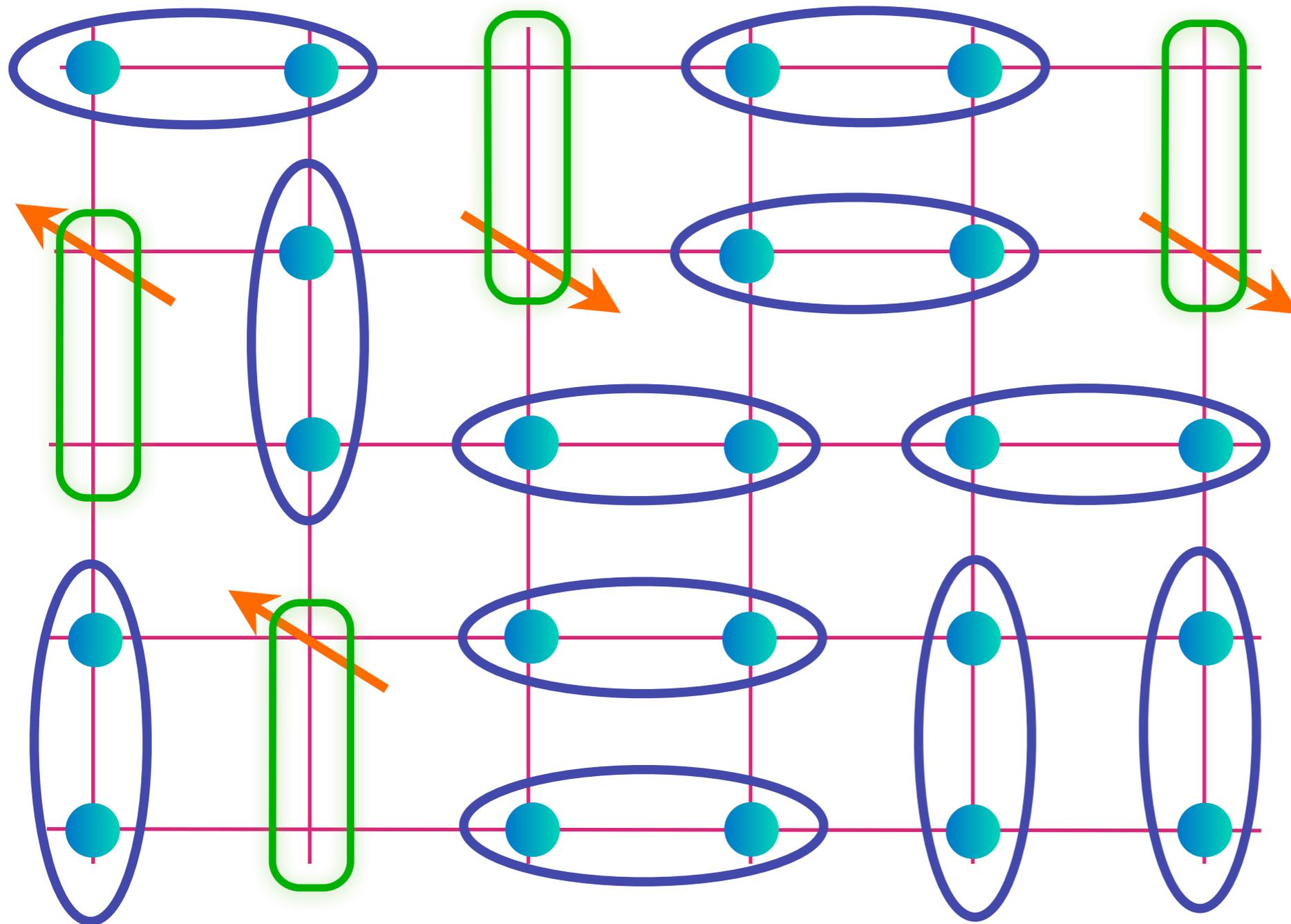


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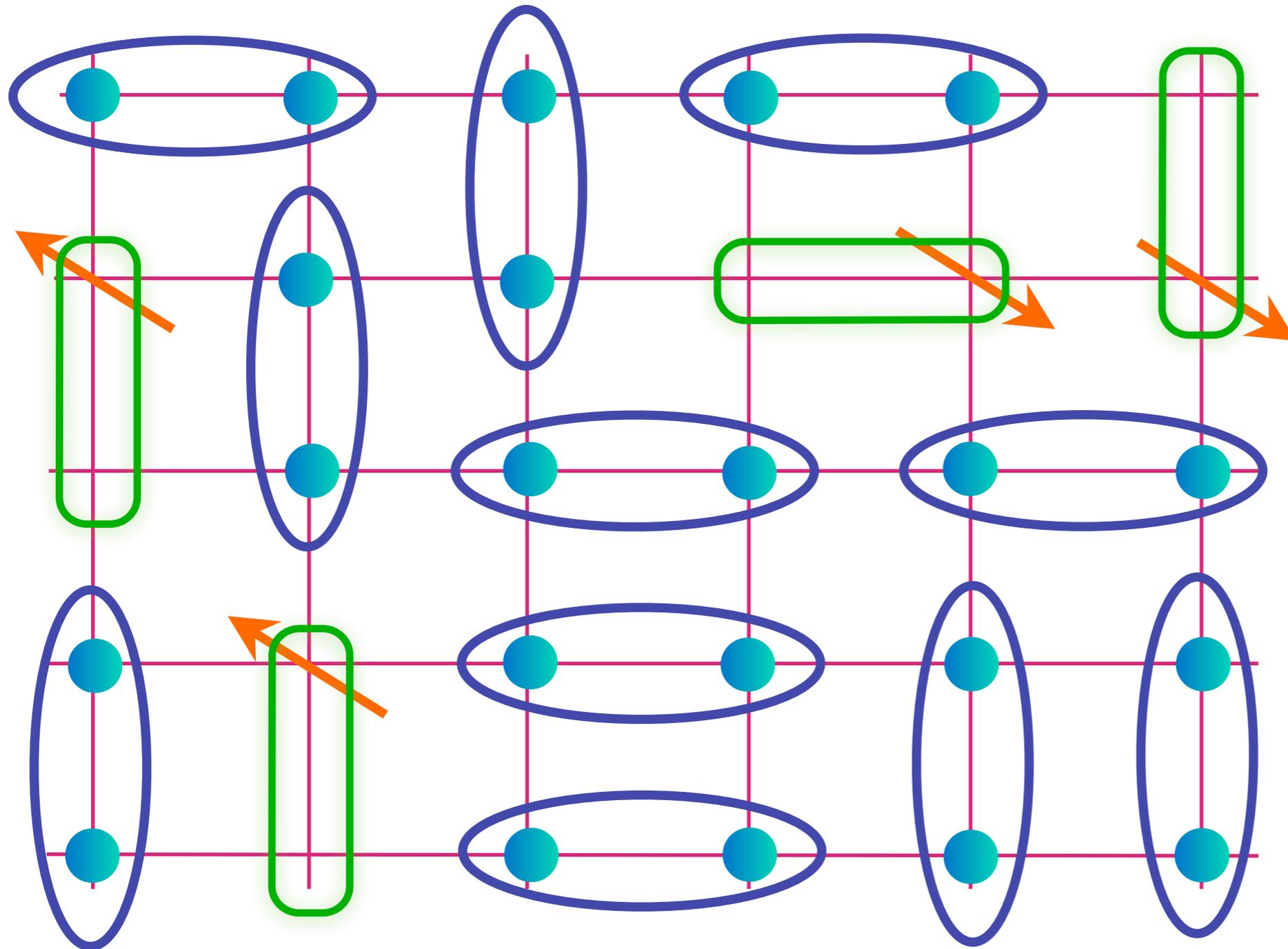


FL* !

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

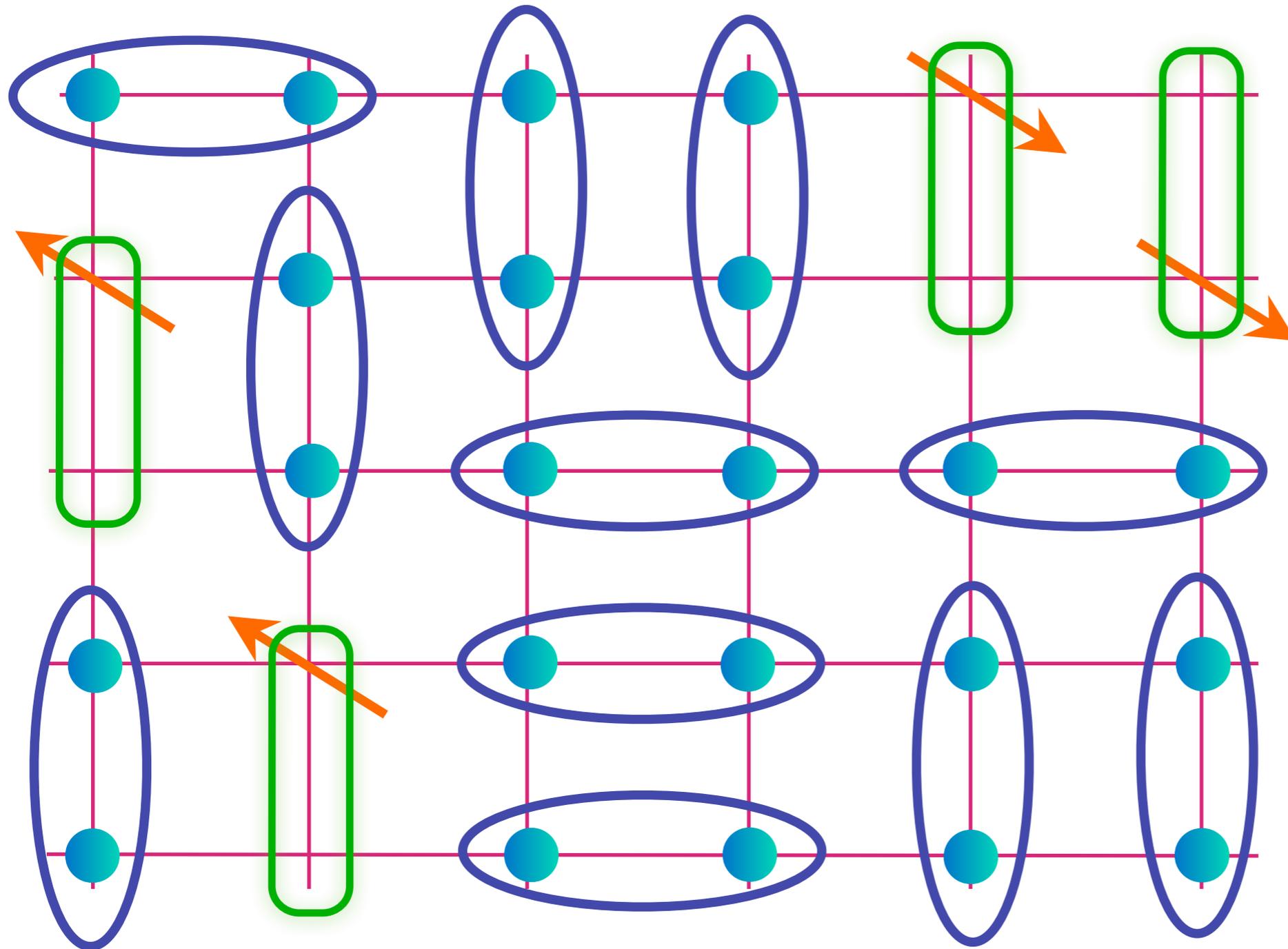


FL* !

Spin
singlets
and
charge $+e$
 $S=1/2$
neutral
holes

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

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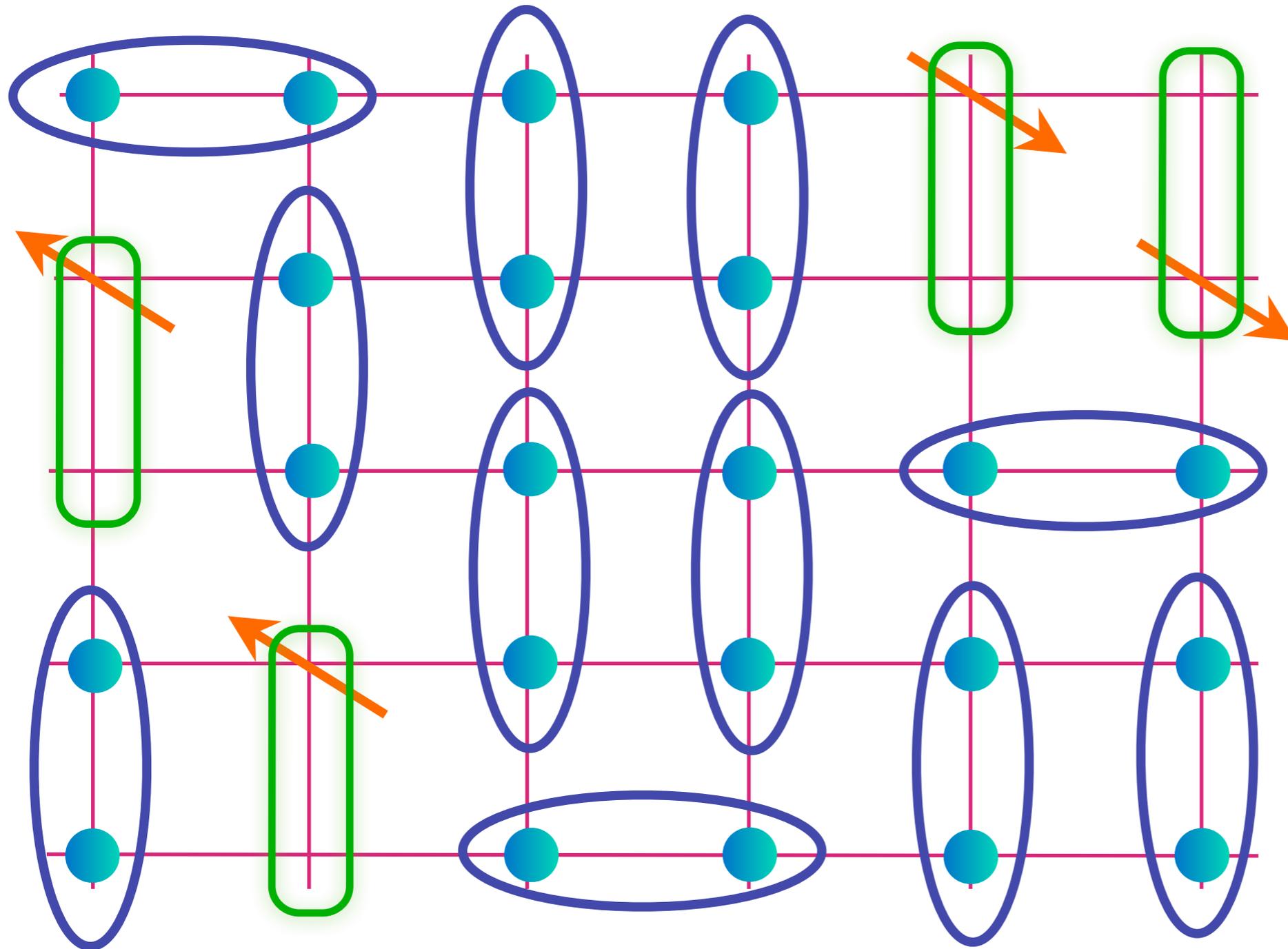


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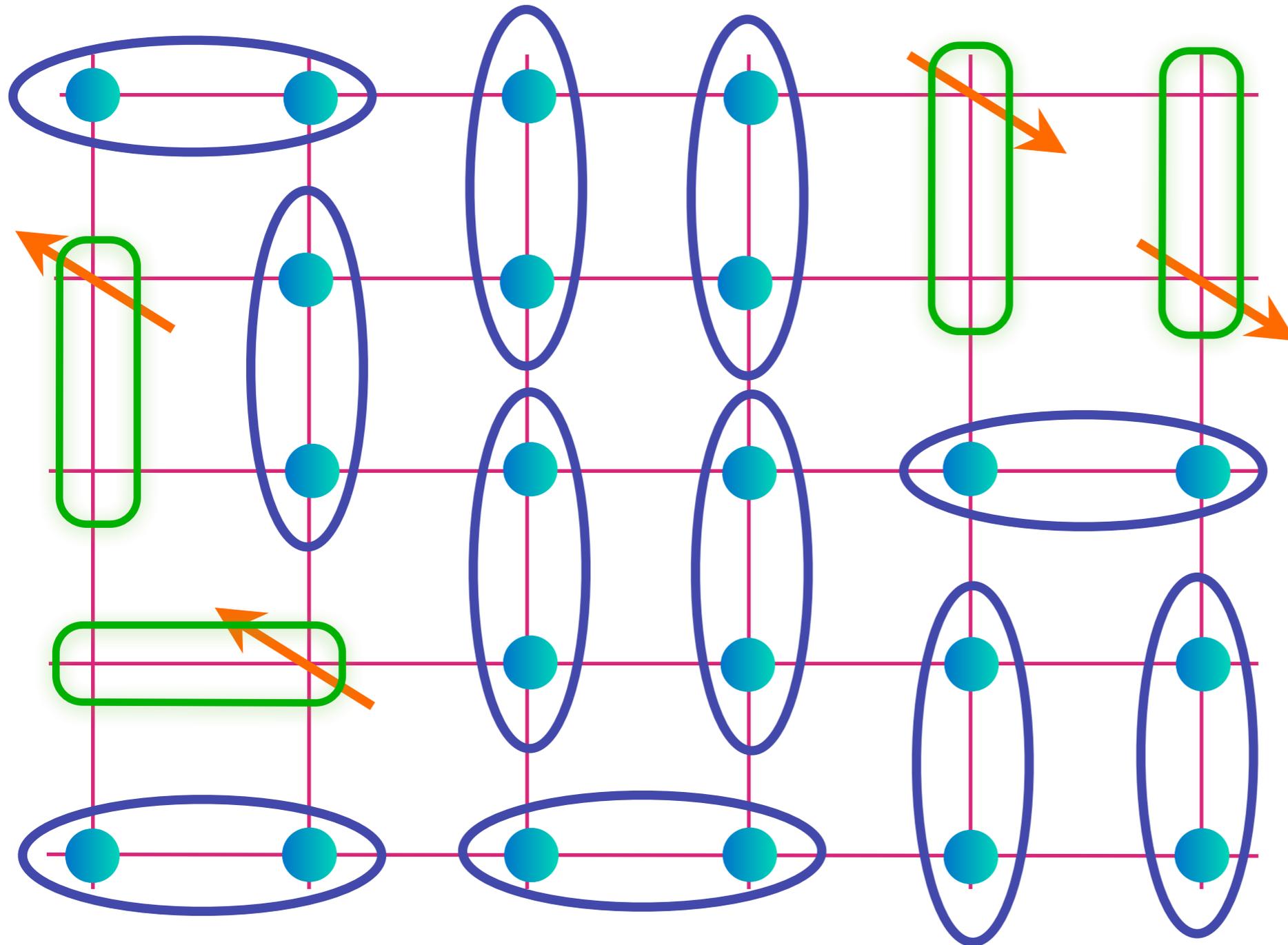


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Theory of the Pseudogap: Fractionalized Fermi liquid (FL*)



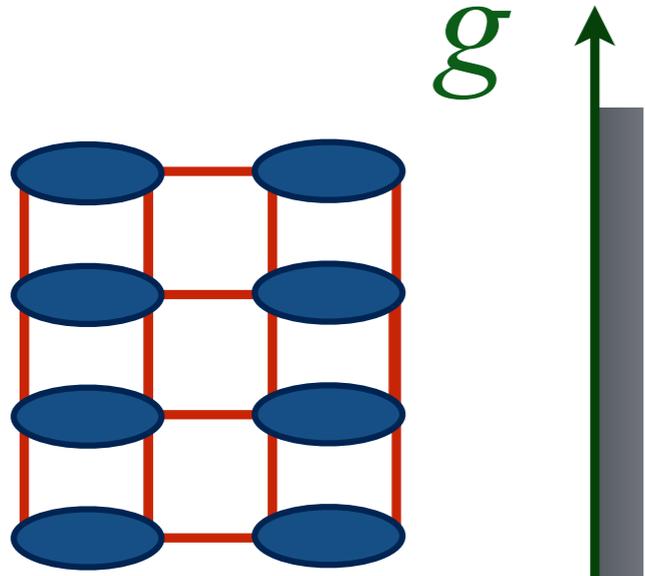
FL* !

Spin
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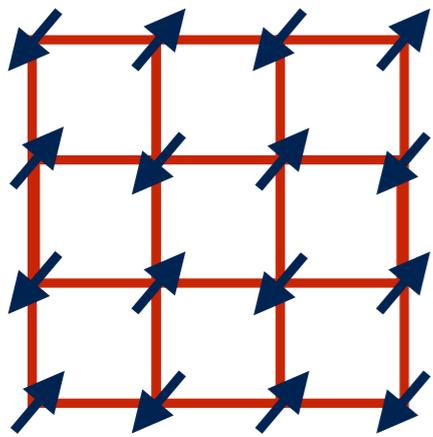
Characteristics of FL* phase

- Fermi surface volume does not count all electrons.
- Such a phase *must* have low energy collective gauge excitations (“topological” order).
- These low energy gauge excitations are needed to account for the deficit in the Fermi surface volume, in M. Oshikawa’s proof of the Luttinger theorem.



$U(1)$ SL \rightarrow VBS
+ confinement

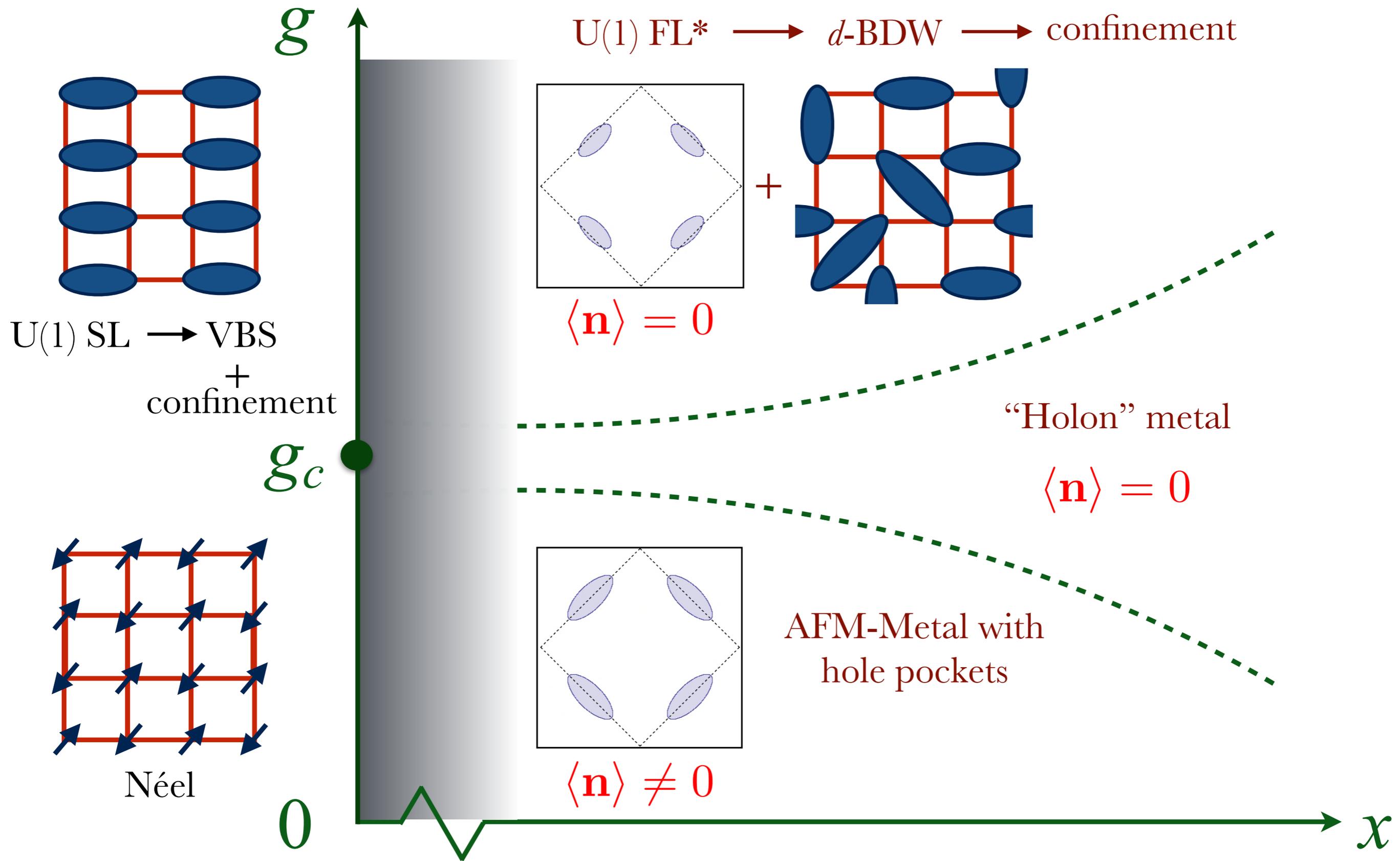
g_c



Néel

0

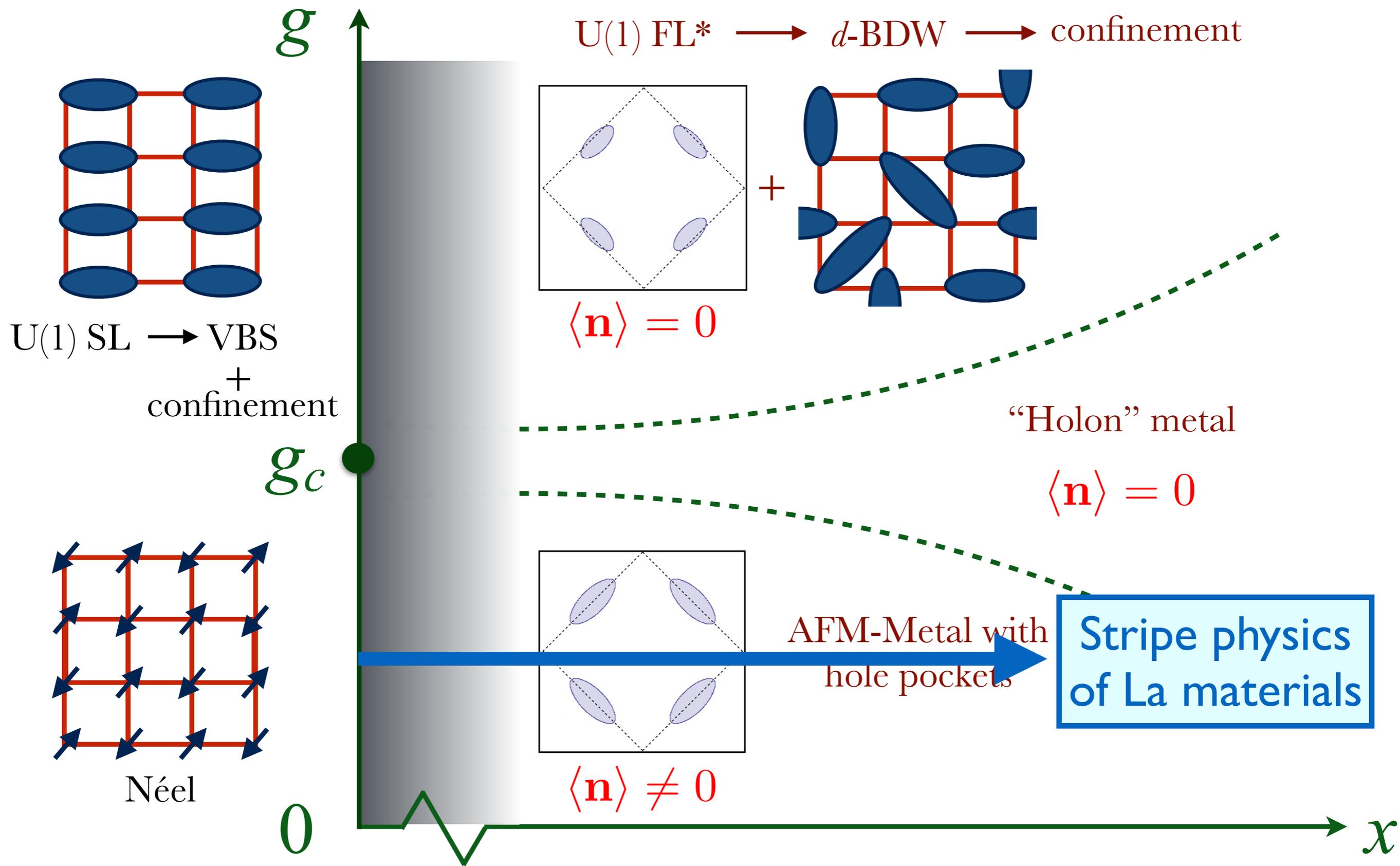




R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, Phys. Rev. B **75**, 235122 (2007)

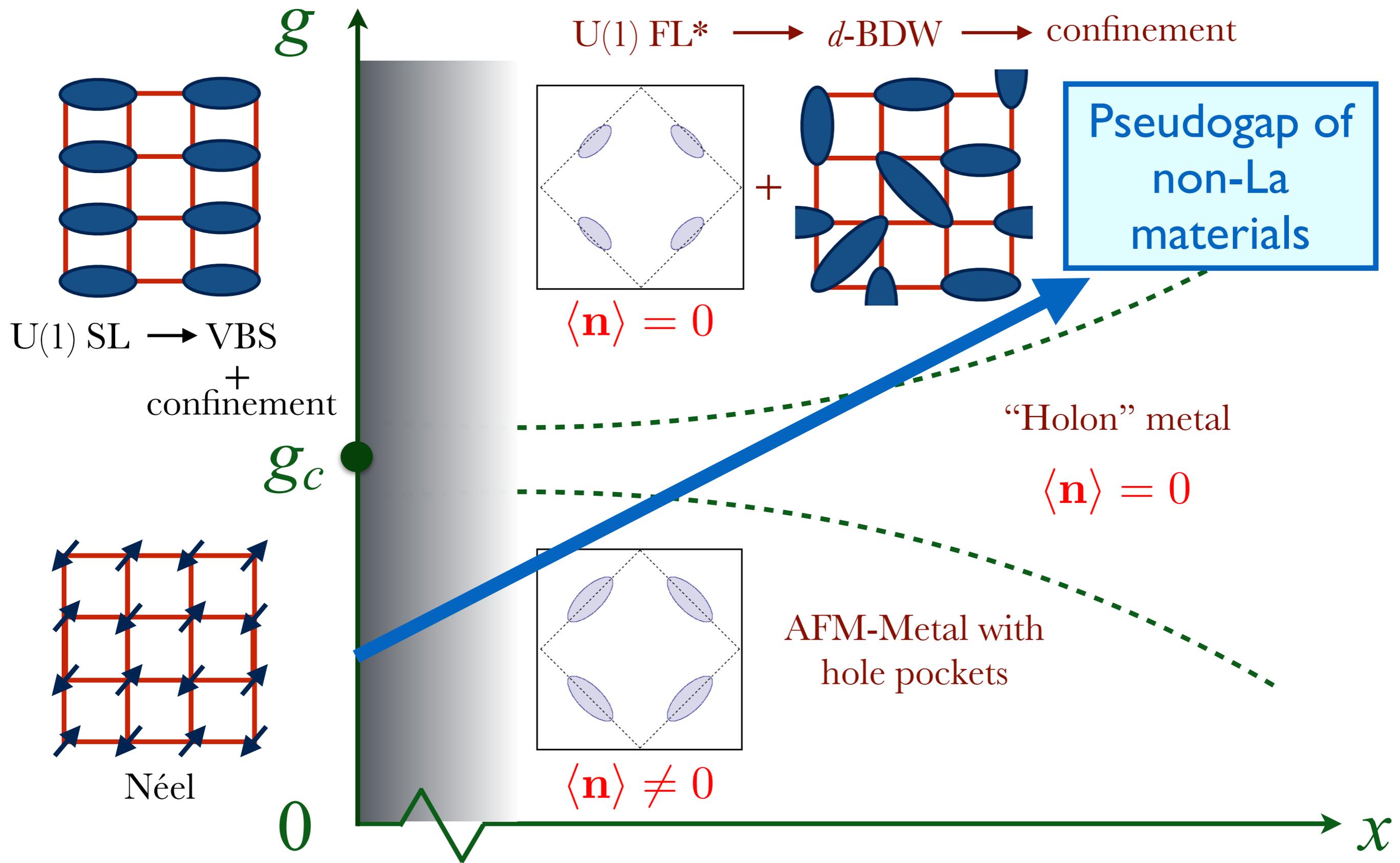
Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)

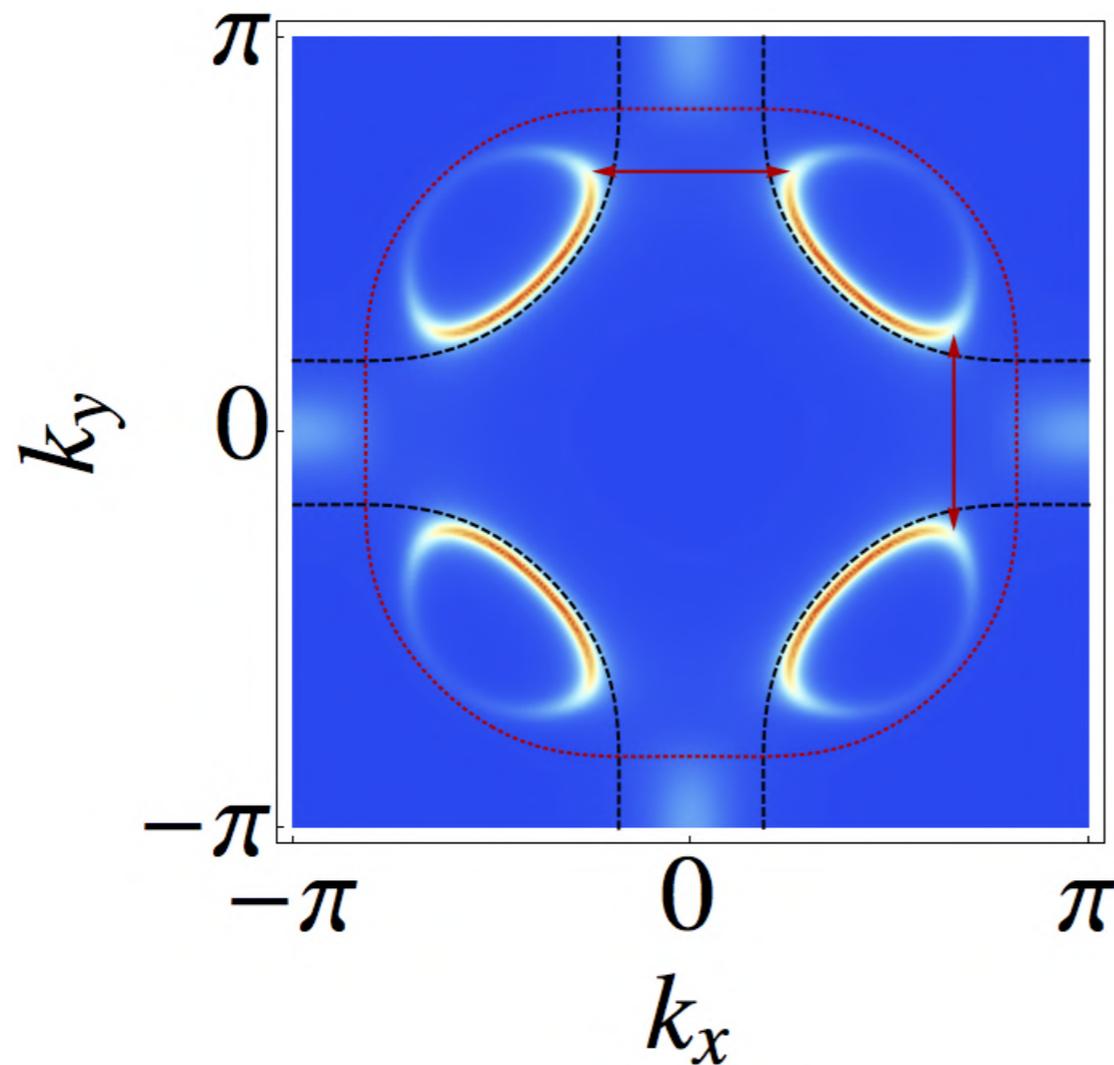
D. Chowdhury and S. Sachdev, arXiv:1409.5430



D. Chowdhury and S. Sachdev, arXiv:1409.5430

A. Thomson and S. Sachdev, arXiv:1410.3483

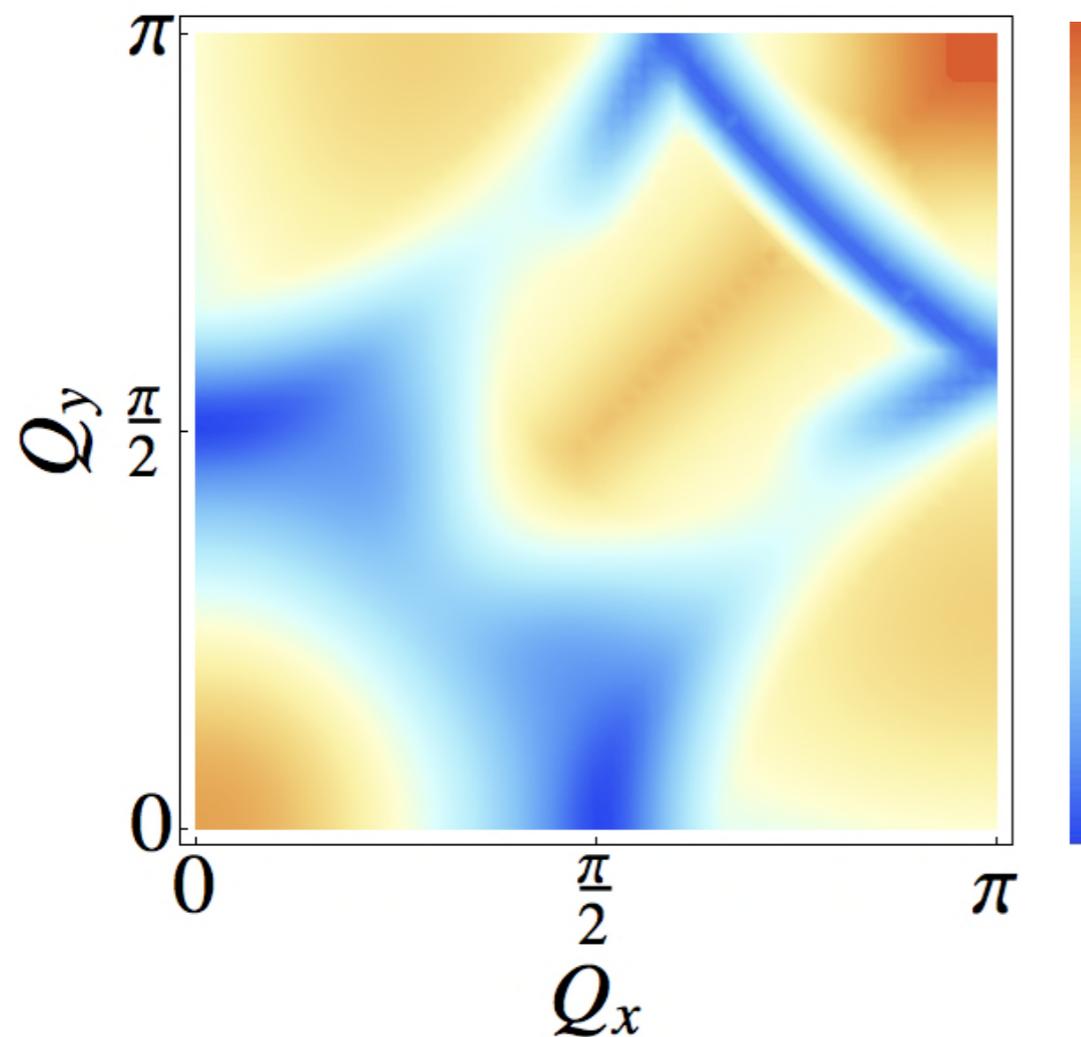




Electron spectral
function of FL*

The pseudogap is described by the U(1)-FL*: a state with hole pockets on a background of a spin-liquid described by a U(1) gauge theory. Its dominant density wave instability is a predominantly d -form factor density wave with a wavevector \mathbf{Q} along the $(1, 0)$ and $(0, 1)$ square lattice directions, in agreement with observations on the non-La-based cuprates.

- Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
M. Punk and S. Sachdev, Phys. Rev. B **85**, 195123 (2012)
D. Chowdhury and S. Sachdev, arXiv:1409.5430



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

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Conclusions

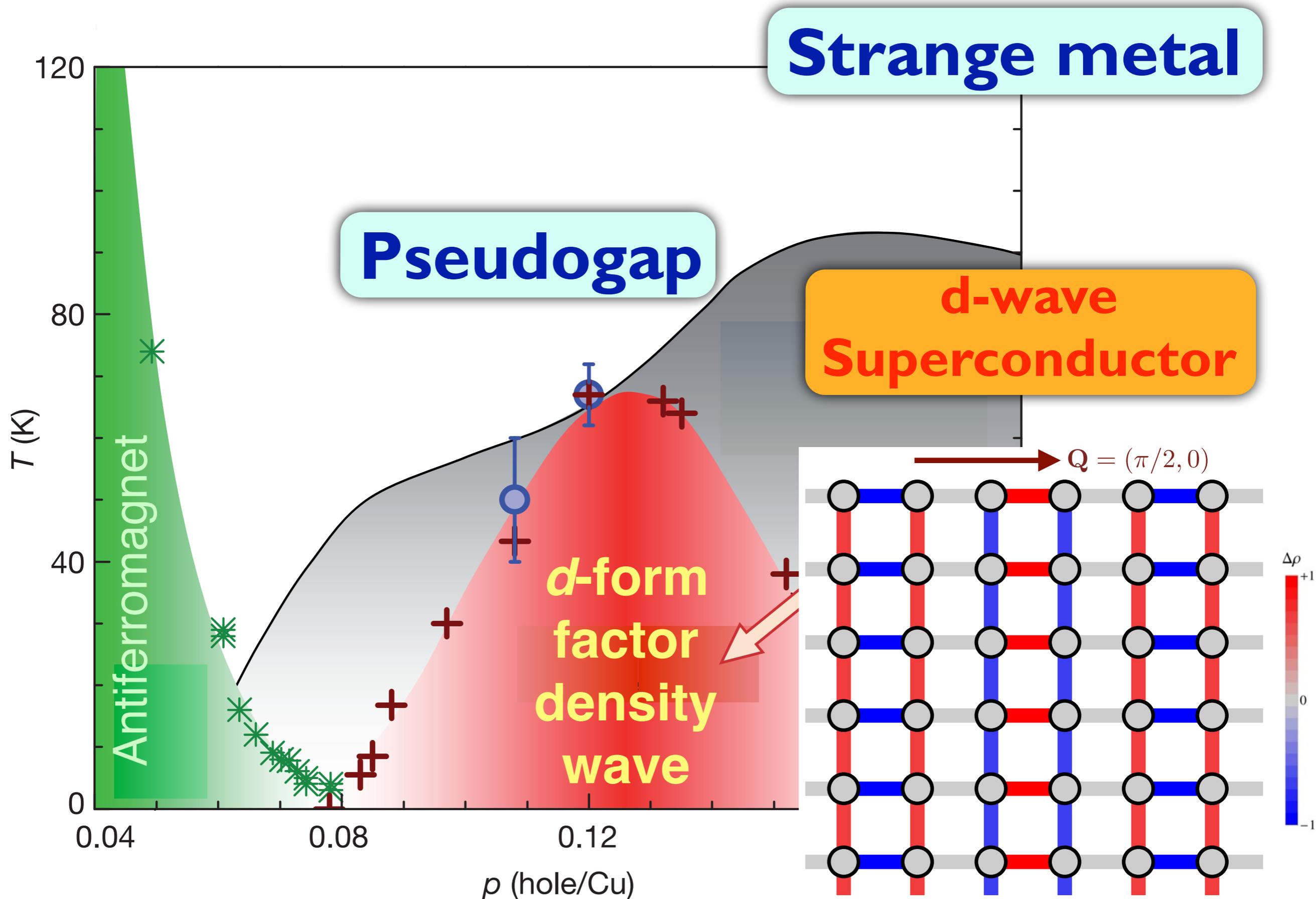
1. d -form factor density wave order observed in the non-La hole-doped cuprate superconductors.

Conclusions

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Conclusions

1. d -form factor density wave order observed in the non-La hole-doped cuprate superconductors.
2. The “stripe” model corresponds to a s' -form factor, and this describes the La-based, lower T_c , hole-doped cuprate superconductors.
3. The d -form factor is an unexpected window into the electronic structure of the pseudogap, with evidence for a fractionalized Fermi liquid (FL*) model.



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)