

# d-form factor density waves and transport near the nematic quantum critical point

Gordon Research Conference  
Mt. Holyoke College  
June 26, 2014  
Subir Sachdev

Talk online: [sachdev.physics.harvard.edu](http://sachdev.physics.harvard.edu)



# Outline

## 1. STM observation of $d$ -form factor density wave

*Close connection to pseudogap of cuprates;*

*Relationship to nematicity*

## 2. Transport near the Ising-nematic quantum critical point

*Domination of “drag” effects, and*

*random “field” perturbations*

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*Close connection to pseudogap of cuprates;*

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## 2. Transport near the Ising-nematic quantum critical point

*Domination of “drag” effects, and*

*random “field” perturbations*

**Direct phase-sensitive visualization of the  
*d*-form factor density wave in underdoped cuprates  
arXiv:1404.0362, PNAS to appear.**



J. C. Seamus Davis  
Cornell



Kazuhiro Fujita  
Cornell/ BNL



Mohammad Hamidian  
Cornell / BNL



Stephen Edkins  
St Andrews/Cornell



Yuhki Kohsaka  
RIKEN - Tokyo



Michael Lawler  
Cornell / Binghamton



Eun-Ah Kim  
Cornell

# Theorists at Harvard



Max Metlitski



Rolando  
La Placa



Andrea Allais



Johannes  
Bauer

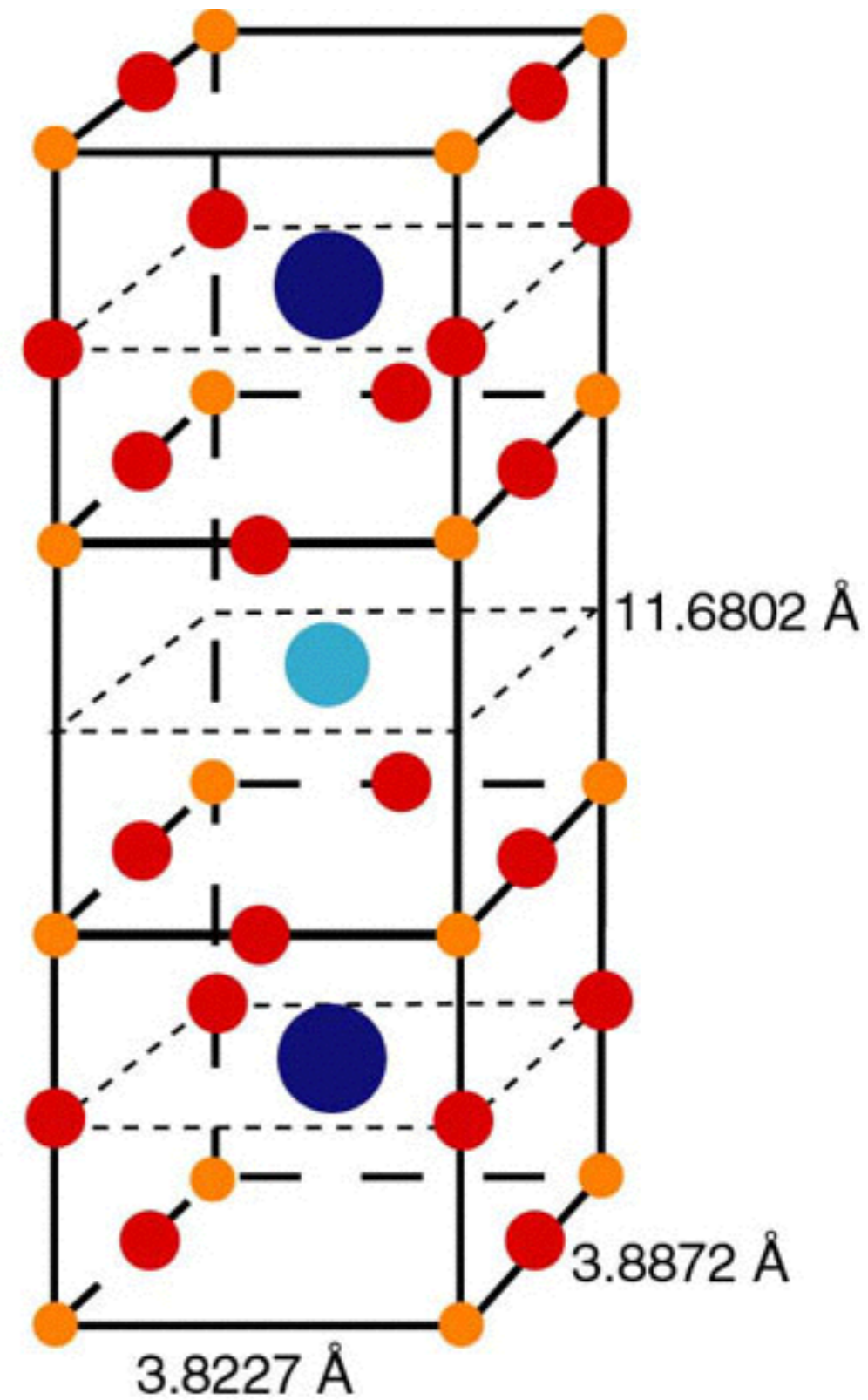
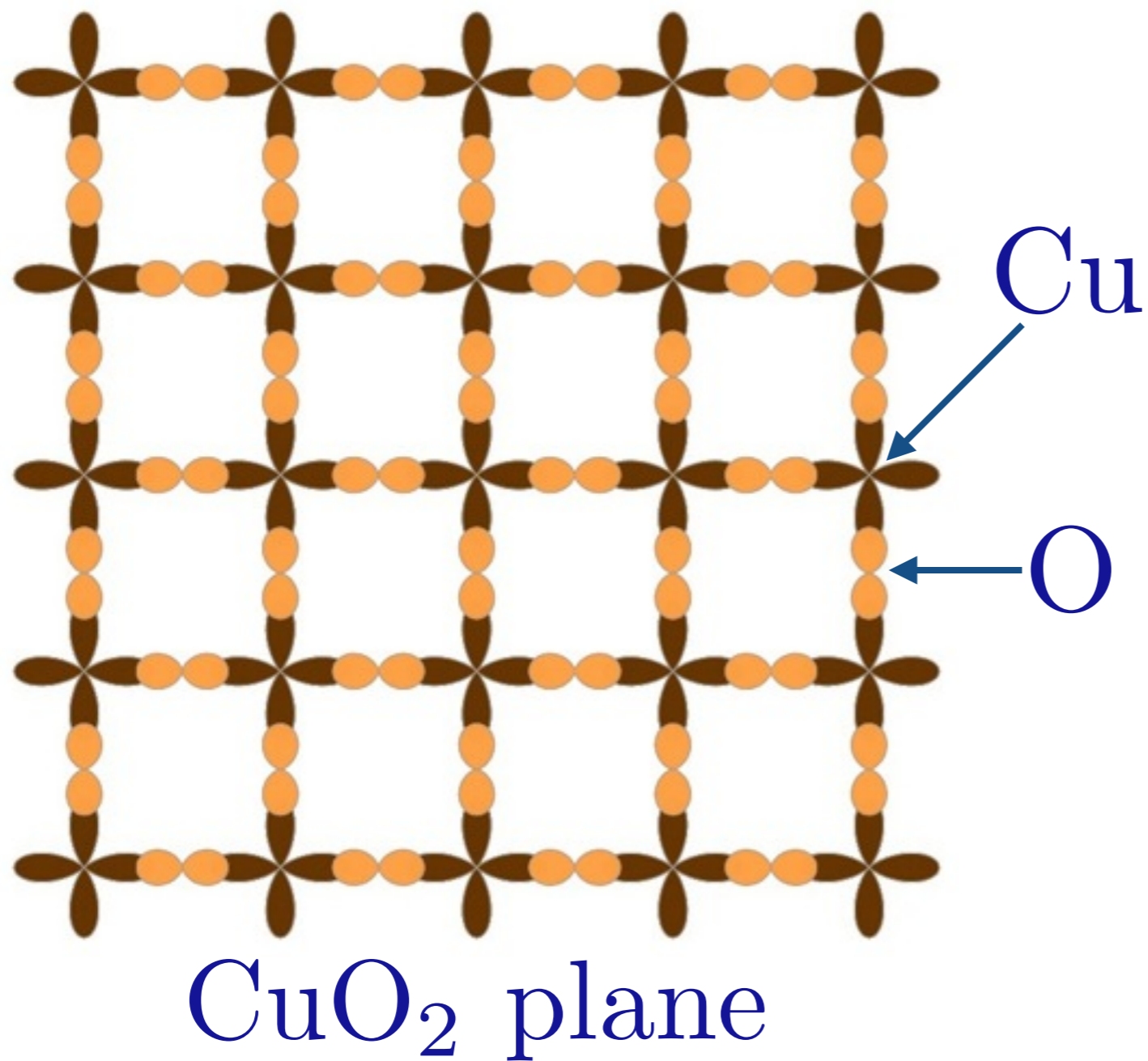


Debanjan  
Chowdhury



Jay Deep  
Sau

# High temperature superconductors

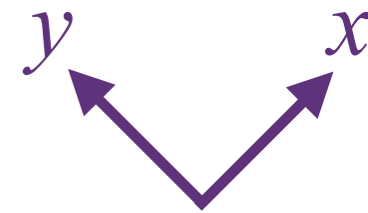
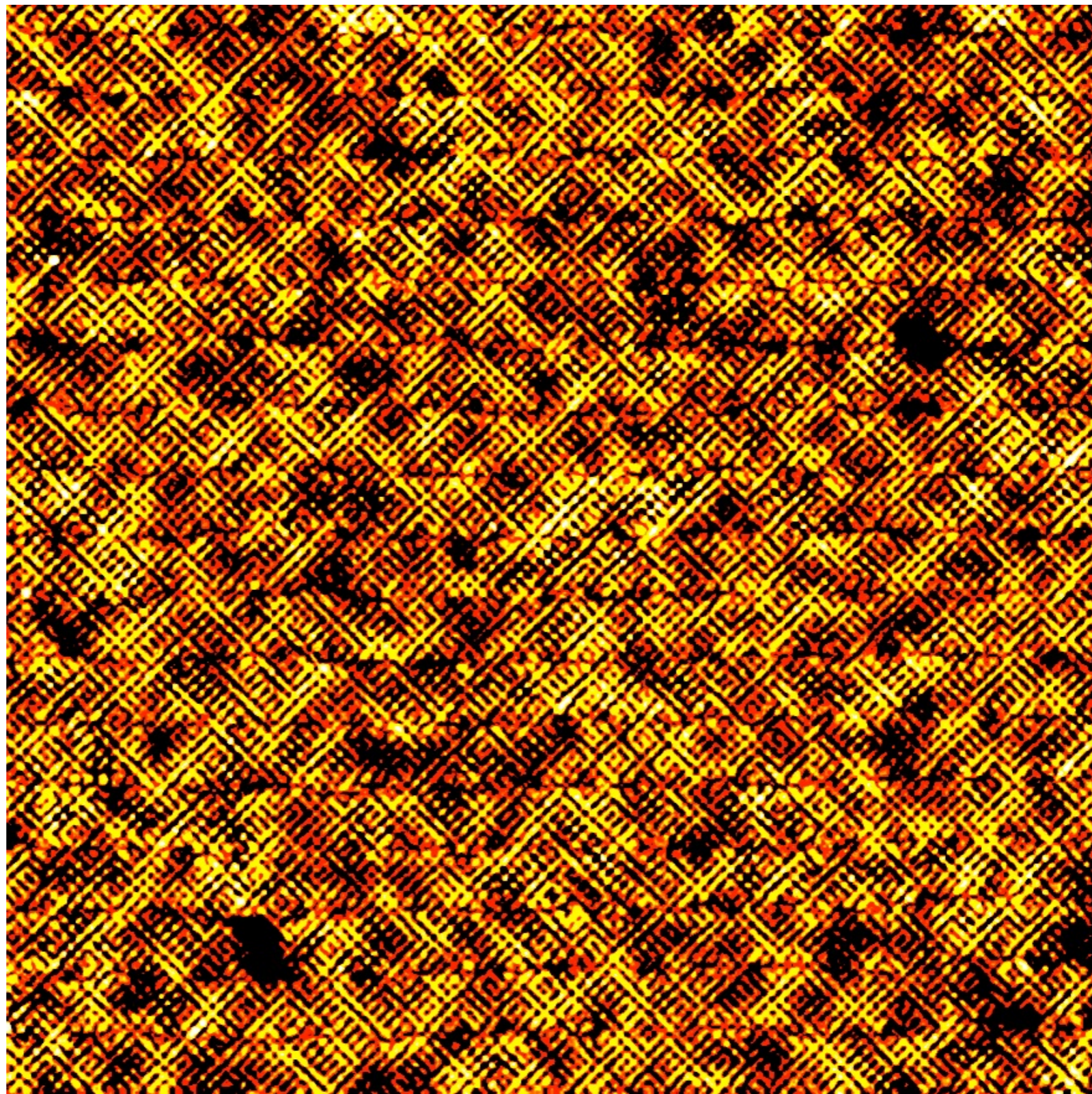


See also

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

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

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*Nature Phys.* **4**, 696  
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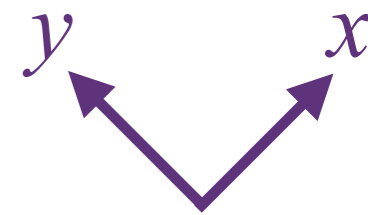
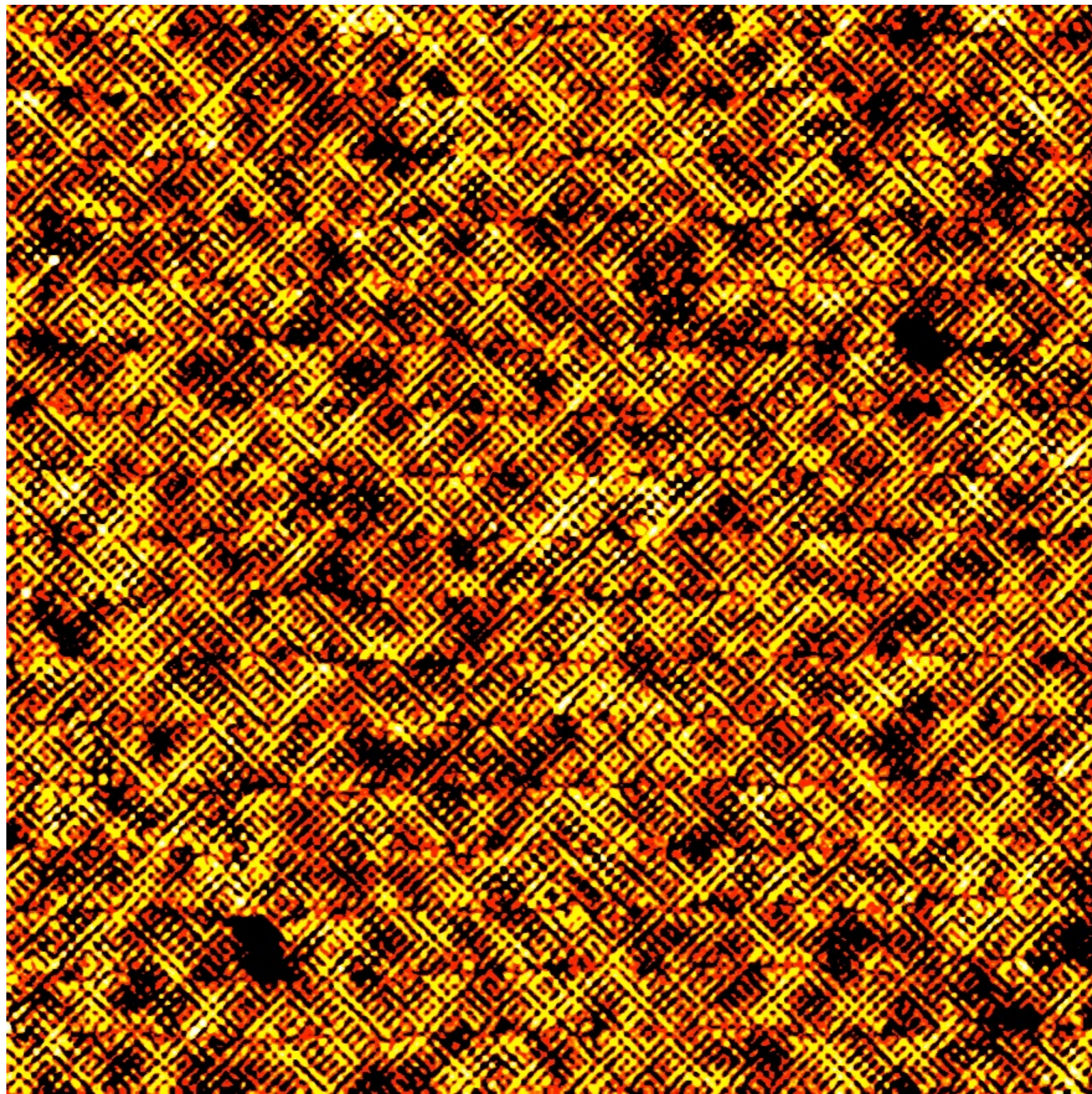
“R-map” of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007). **Davis group has sub-angstrom resolution capabilities, with lattice drift corrections, which make sublattice phase-resolved STM possible.**

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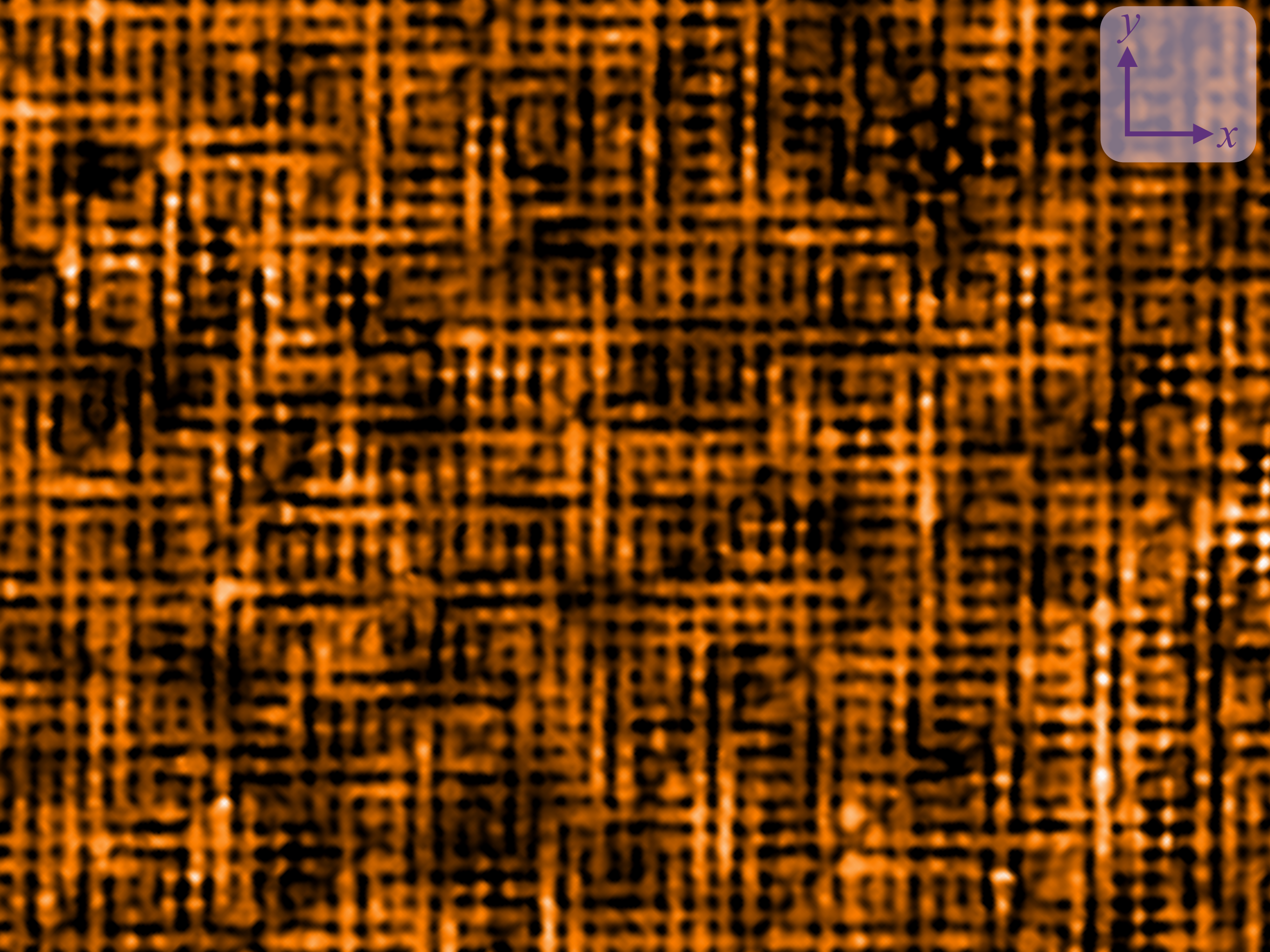
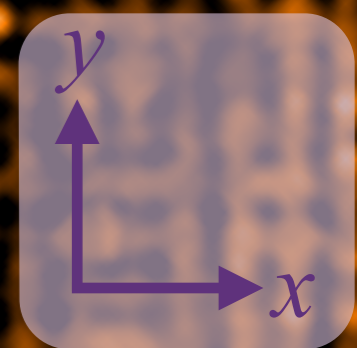
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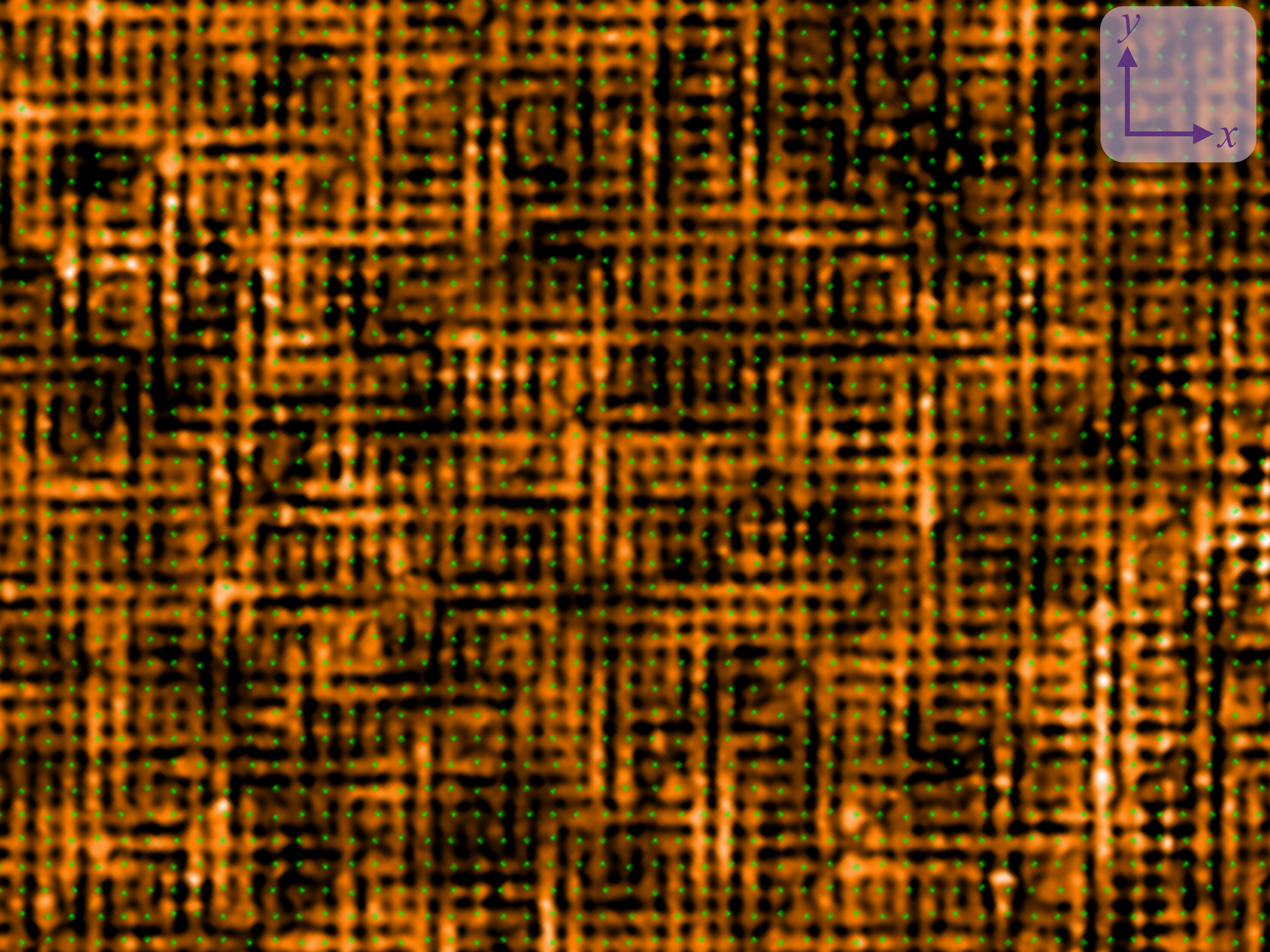
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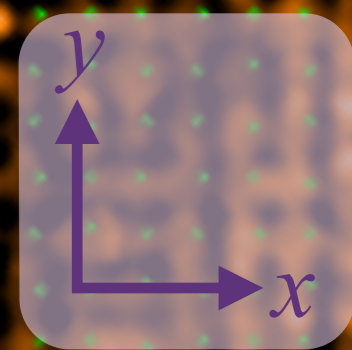


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A density wave with  
wavelength  $\approx 4$  lattice sites ?



# Charge density wave (CDW) order

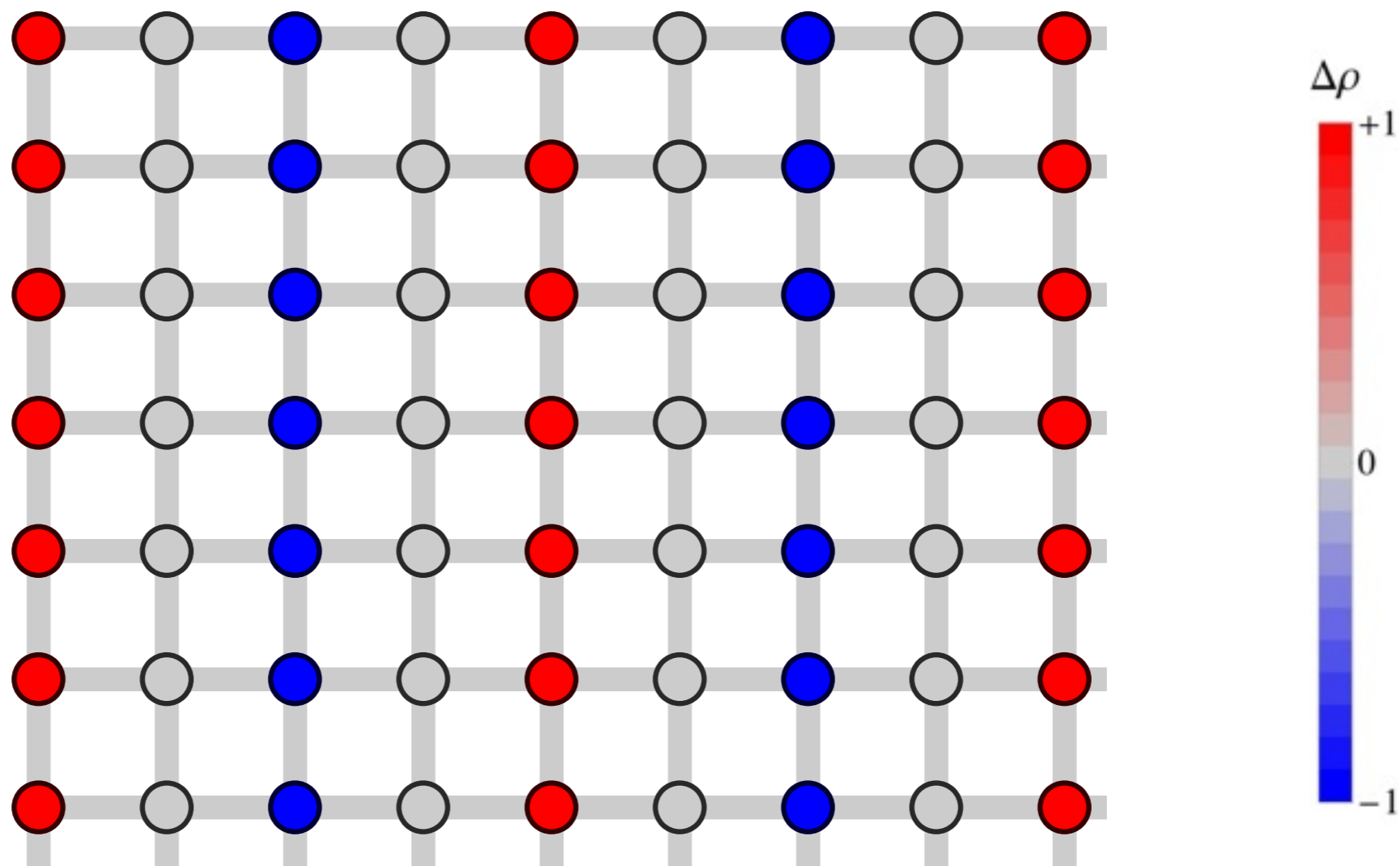
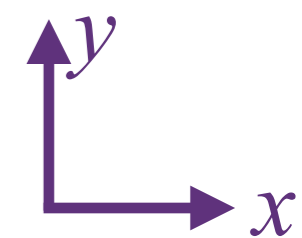
$$\langle c_{\alpha}^{\dagger}(\mathbf{r})c_{\alpha}(\mathbf{r}) \rangle = \Psi_{CDW}(\mathbf{r}) e^{i\mathbf{Q}\cdot\mathbf{r}} + \text{c.c.}$$

# CDW order.

Plot of  $P_{ii} = \langle c_{i\alpha}^\dagger c_{i\alpha} \rangle$  with

$$P_{ii} = e^{i\mathbf{Q}\cdot\mathbf{r}_i} + \text{c.c.}$$

with  $\mathbf{Q} = 2\pi(1/4, 0)$

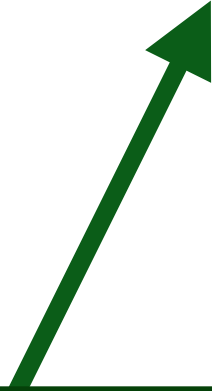


**Unconventional density wave (DW) :**  
**Bose condensation of particle-hole pairs**

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

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

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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)

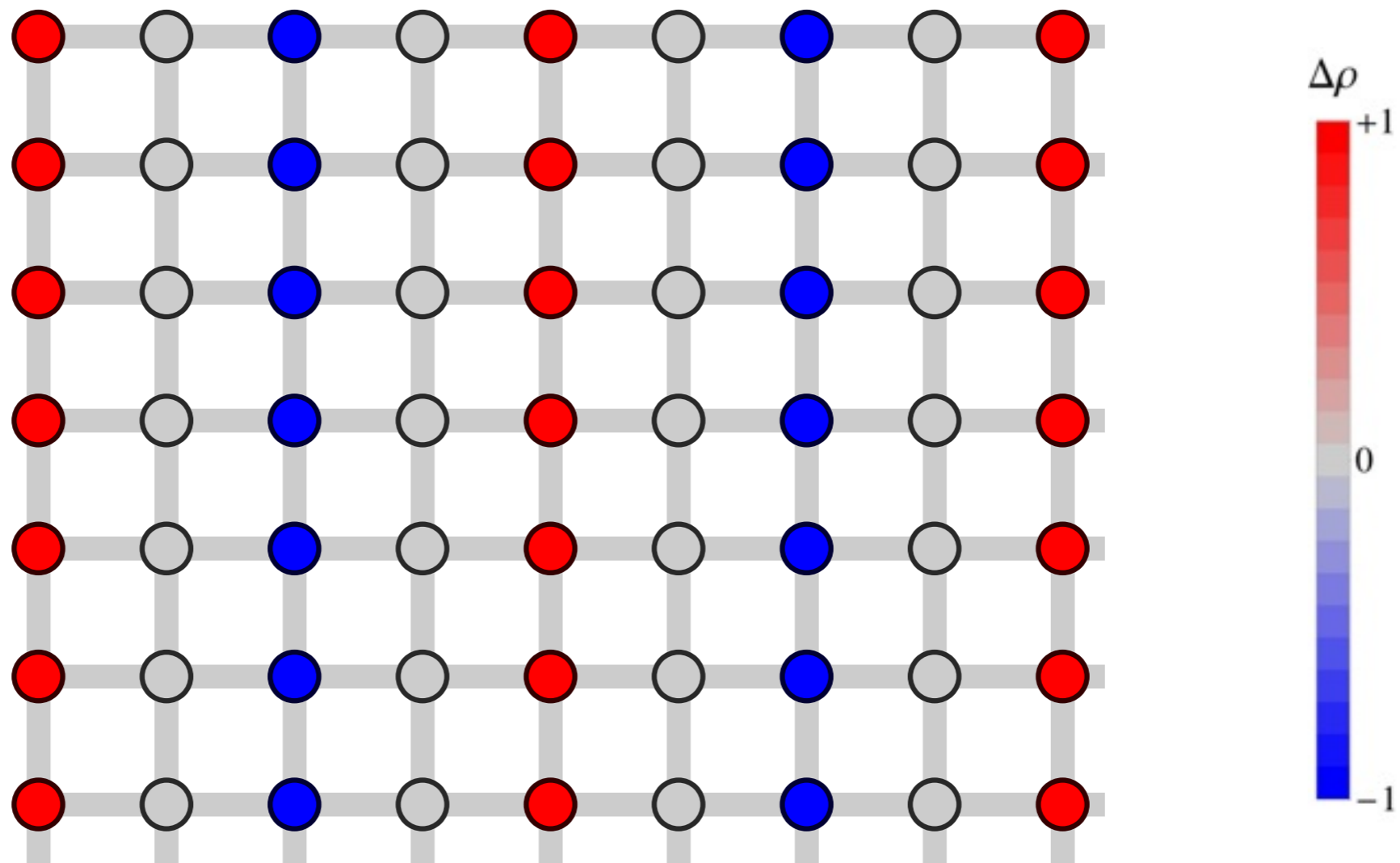
$$\mathcal{P}(\mathbf{k}) = \mathcal{P}_s + \mathcal{P}_{s'}(\cos k_x + \cos k_y) + \mathcal{P}_d(\cos k_x - \cos k_y)$$

# 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.

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

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

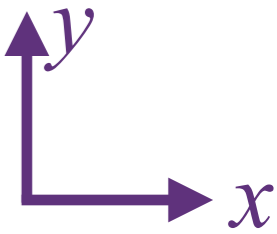
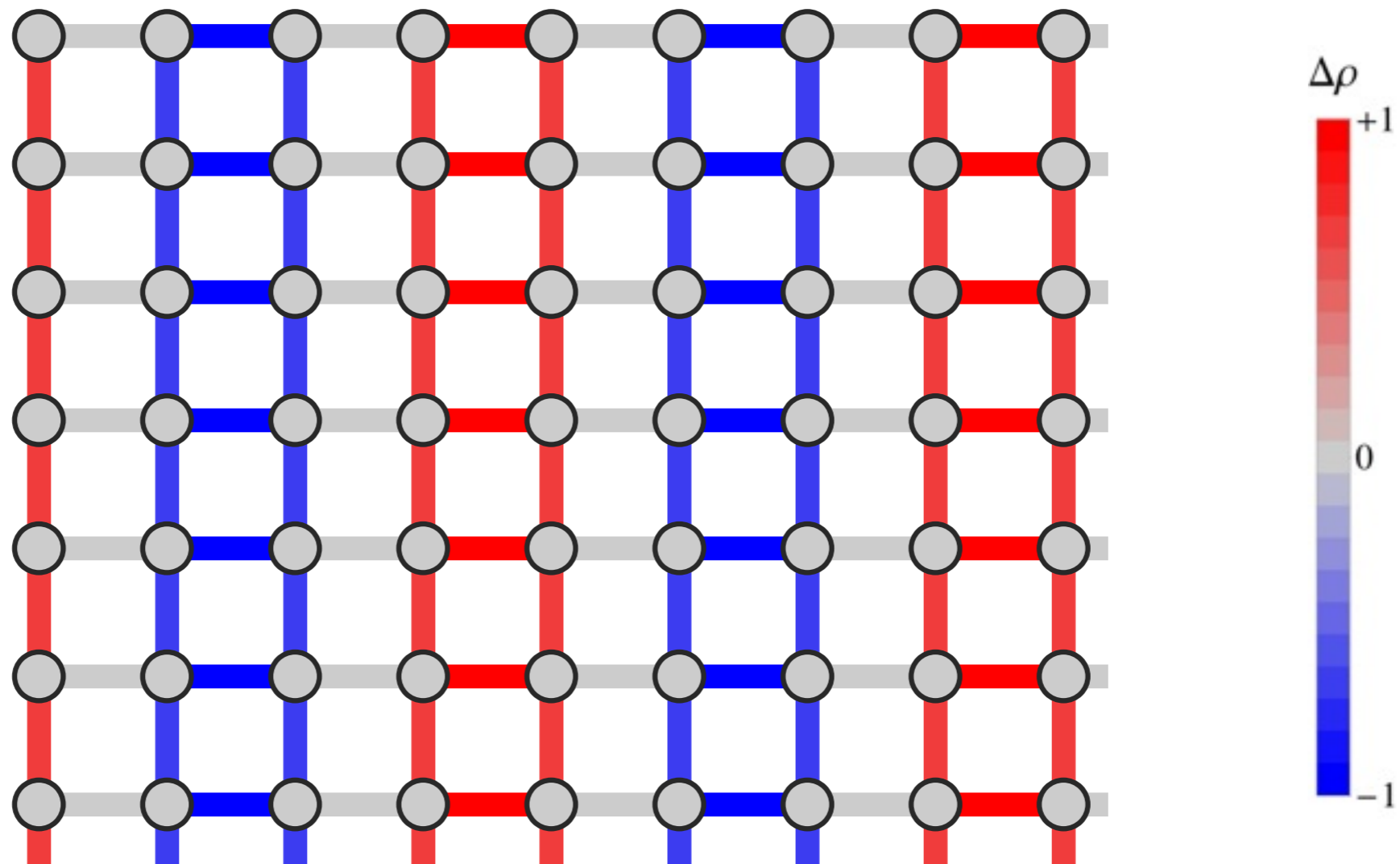


# Unconventional DW order: $s'$ -form factor

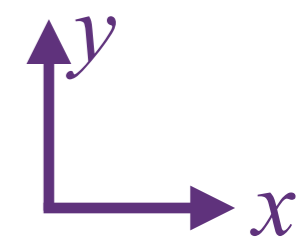
Plot of  $P_{ij} = \langle c_{i\alpha}^\dagger c_{j\alpha} \rangle$  for  $i = j$ , and  $i, j$  nearest neighbors.

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

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



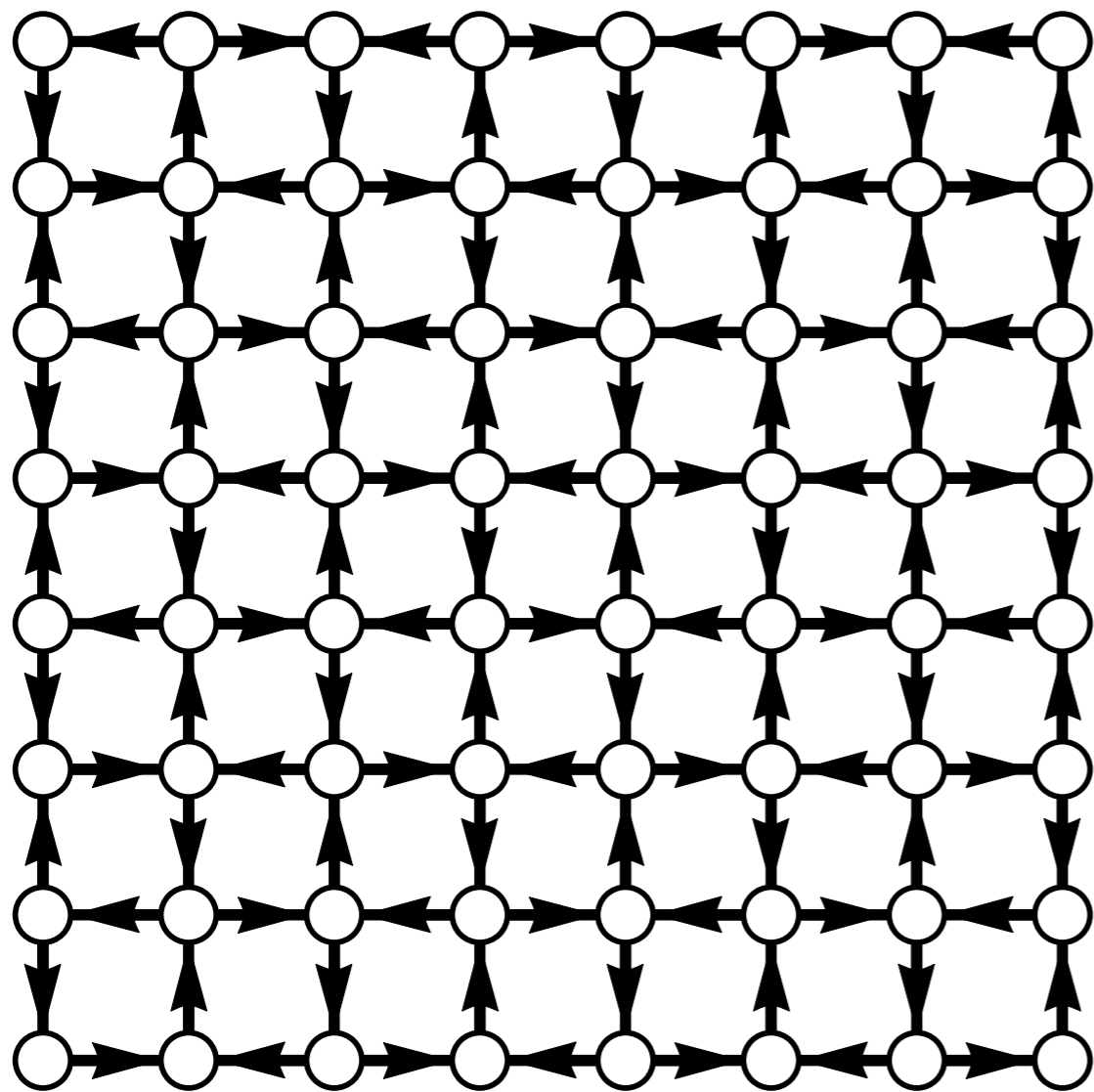
# Current order: $p$ -form factor



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.)

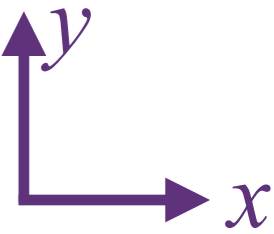
S. Chakravarty, R. B. Laughlin, D. K. Morr, and C. Nayak, Phys. Rev. B **63**, 094503 (2001).

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

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

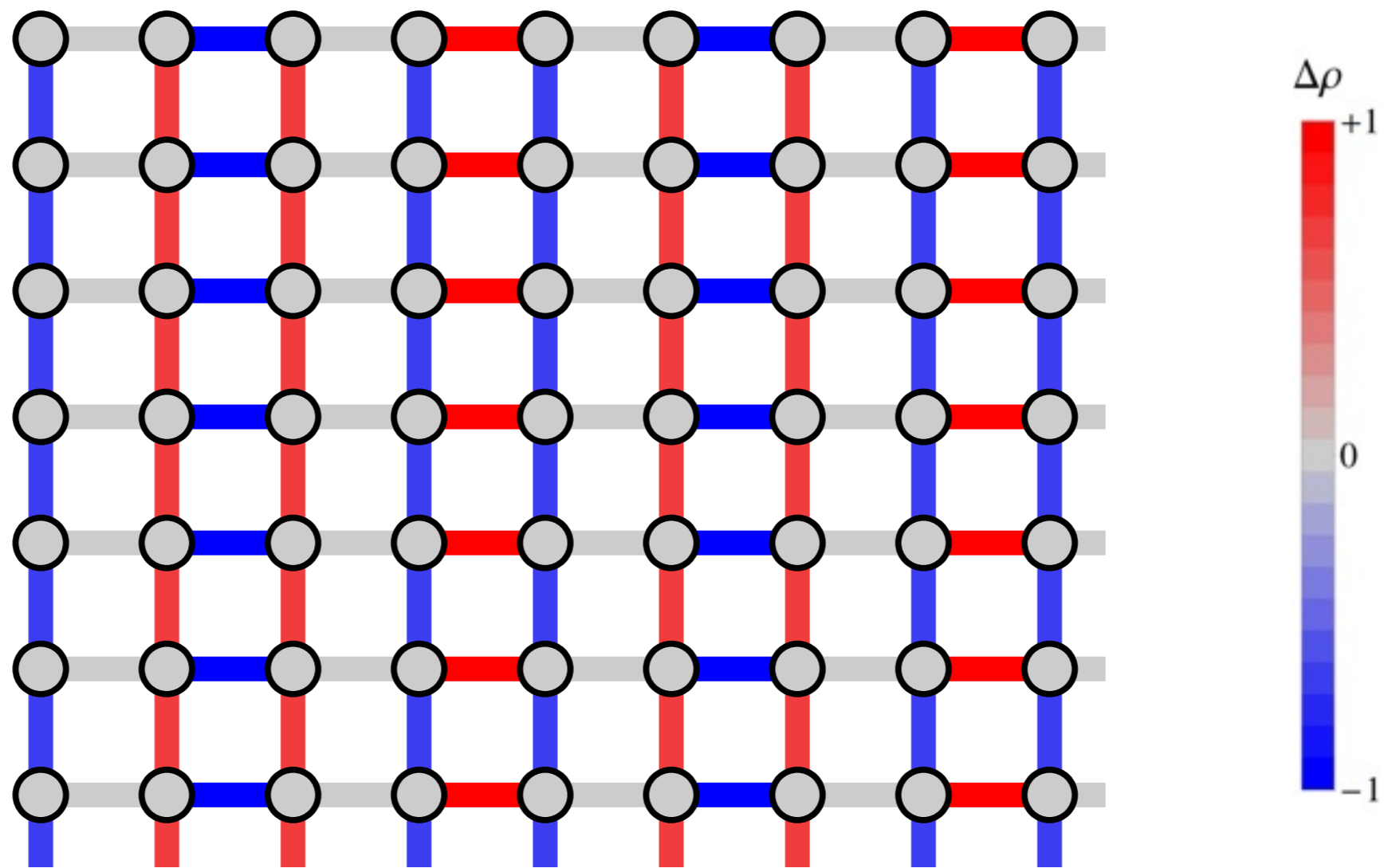
# Unconventional DW order: $d$ -form factor

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



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

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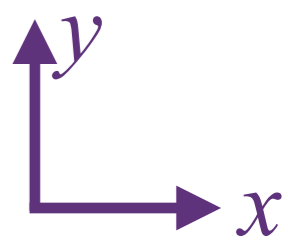
This specific  $d$ -form factor density wave order (with  $\mathbf{Q}$  along the axes) was first predicted in S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).

# Unconventional DW order: $d$ -form factor

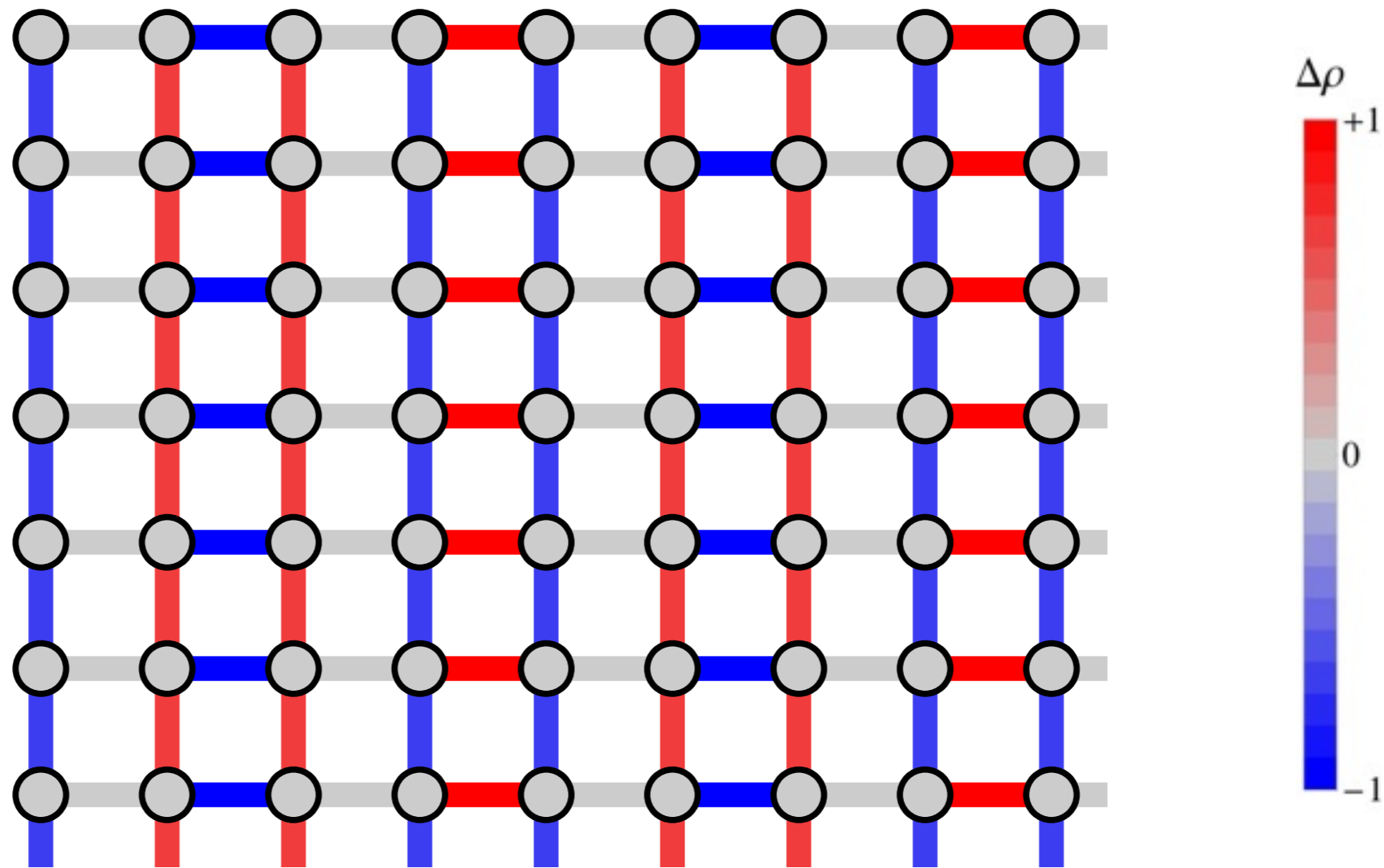
Plot of  $P_{ij} = \langle c_{i\alpha}^\dagger c_{j\alpha} \rangle$  for  $i = j$ , and  $i, j$  nearest neighbors.

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

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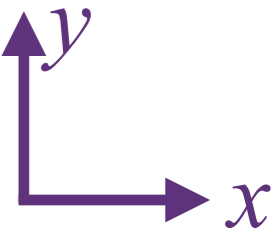
Density wave on horizontal bonds has a phase-shift of  $\pi$  relative to the wave on vertical bonds



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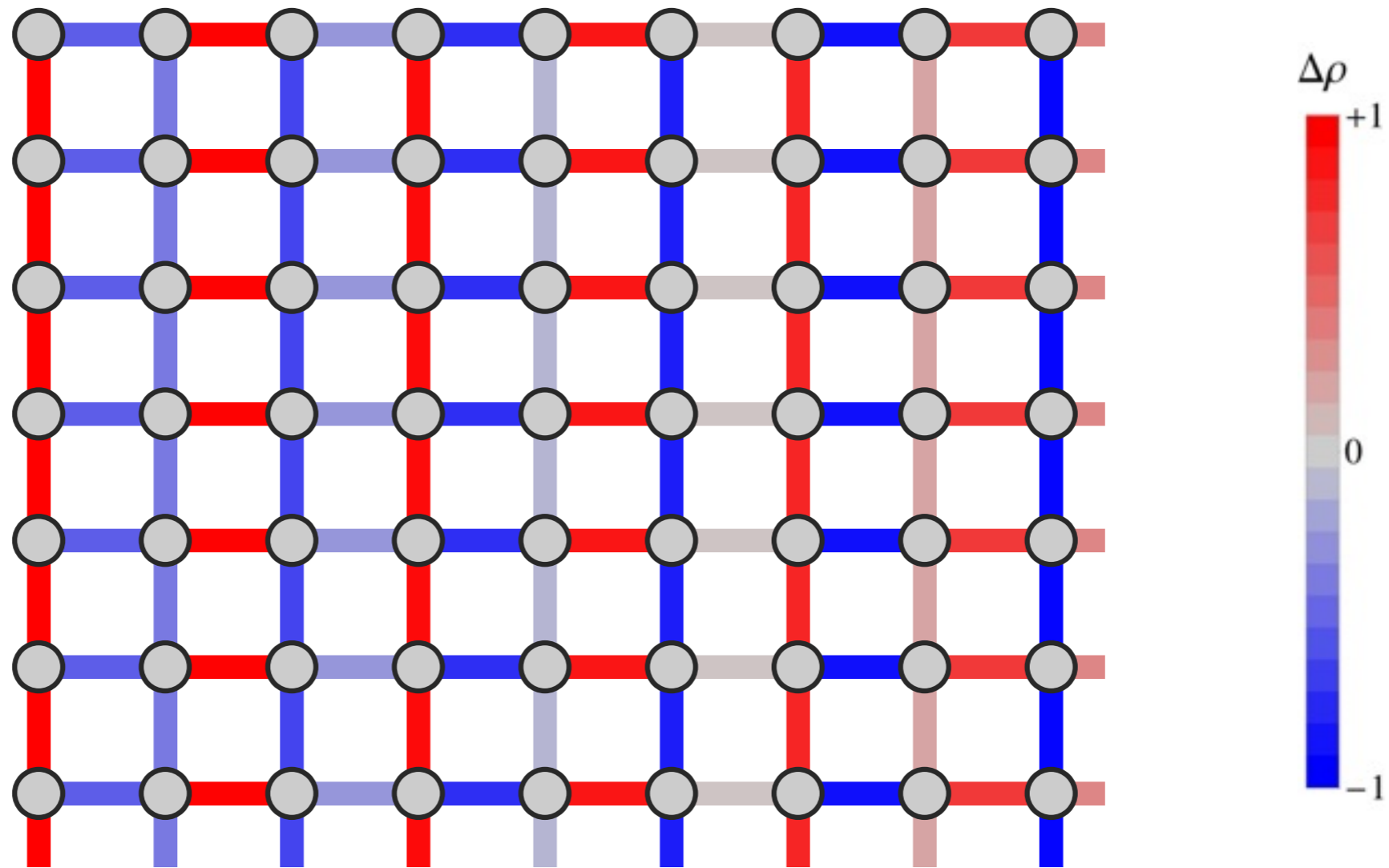
Plot of  $P_{ij} = \langle c_{i\alpha}^\dagger c_{j\alpha} \rangle$  for  $i = j$ , and  $i, j$  nearest neighbors.



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

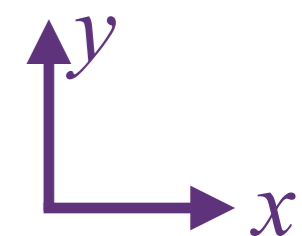
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} [\cos(k_x) - \cos(k_y)] \quad \text{and} \quad \mathbf{Q} = 2\pi(0.317, 0)$$

Density wave on horizontal bonds has a phase-shift of  $\pi$  relative to the wave on vertical bonds



This specific  $d$ -form factor density wave order (with  $\mathbf{Q}$  along the axes) was first predicted in S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).

# Unconventional DW order: $(d + s)$ -form factor

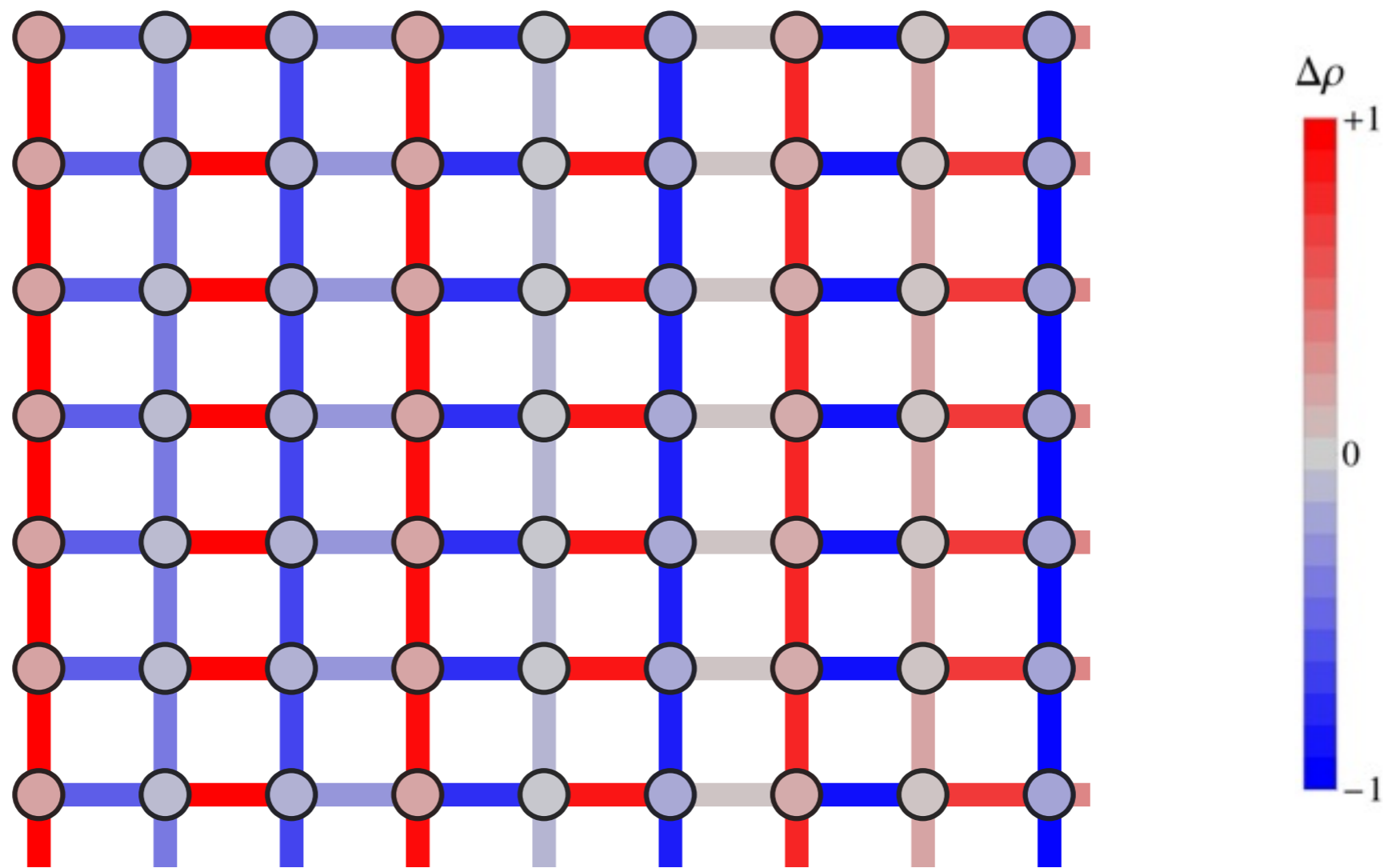


Plot of  $P_{ij} = \langle c_{i\alpha}^\dagger c_{j\alpha} \rangle$  for  $i = j$ , and  $i, j$  nearest neighbors.

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

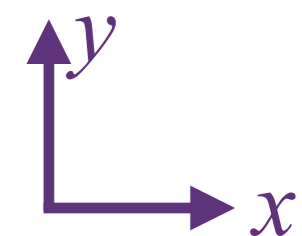
$$\mathcal{P}(\mathbf{k}) = e^{i\phi} [0.2 + \cos(k_x) - \cos(k_y)] \quad \text{and} \quad \mathbf{Q} = 2\pi(0.317, 0)$$

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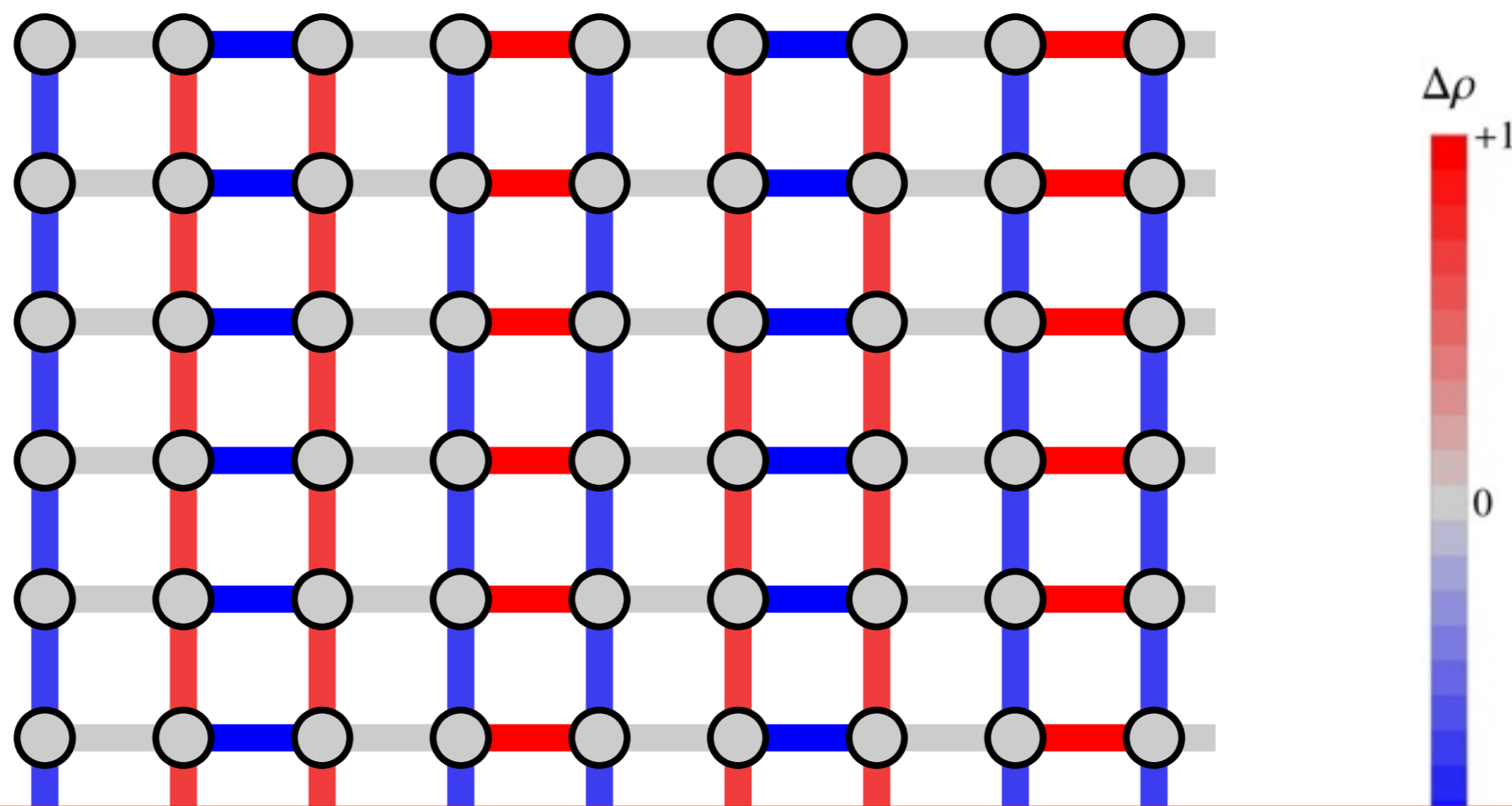
# Unconventional DW order: $d$ -form factor



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

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



A DW with  $d$ -form factor predominant is nearly degenerate with  $d$ -wave SC near the quantum-critical point for antiferromagnetism in a metal.

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

See also Y. Wang and A. V. Chubukov, arXiv:1401.0712;

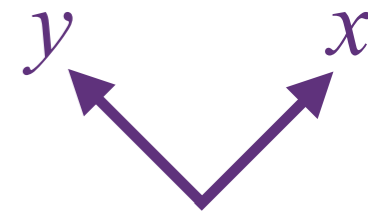
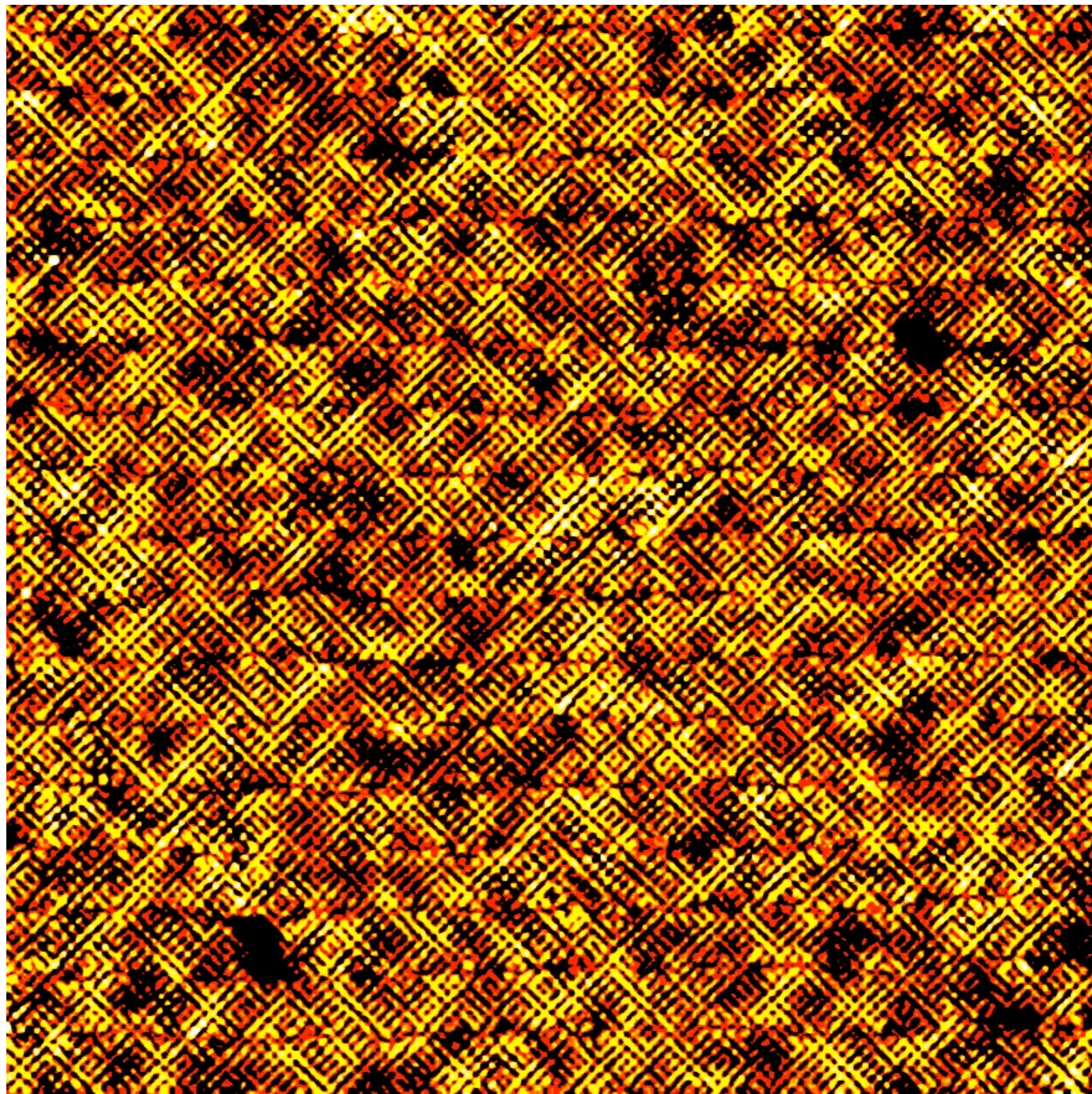
W. A. Atkinson, A. P. Kampf, and S. Bulut, arXiv:1404.1335 (3-band model).

See also

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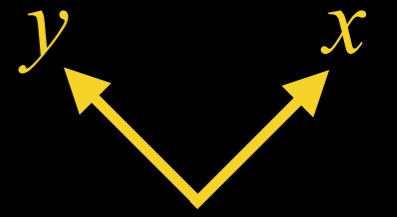
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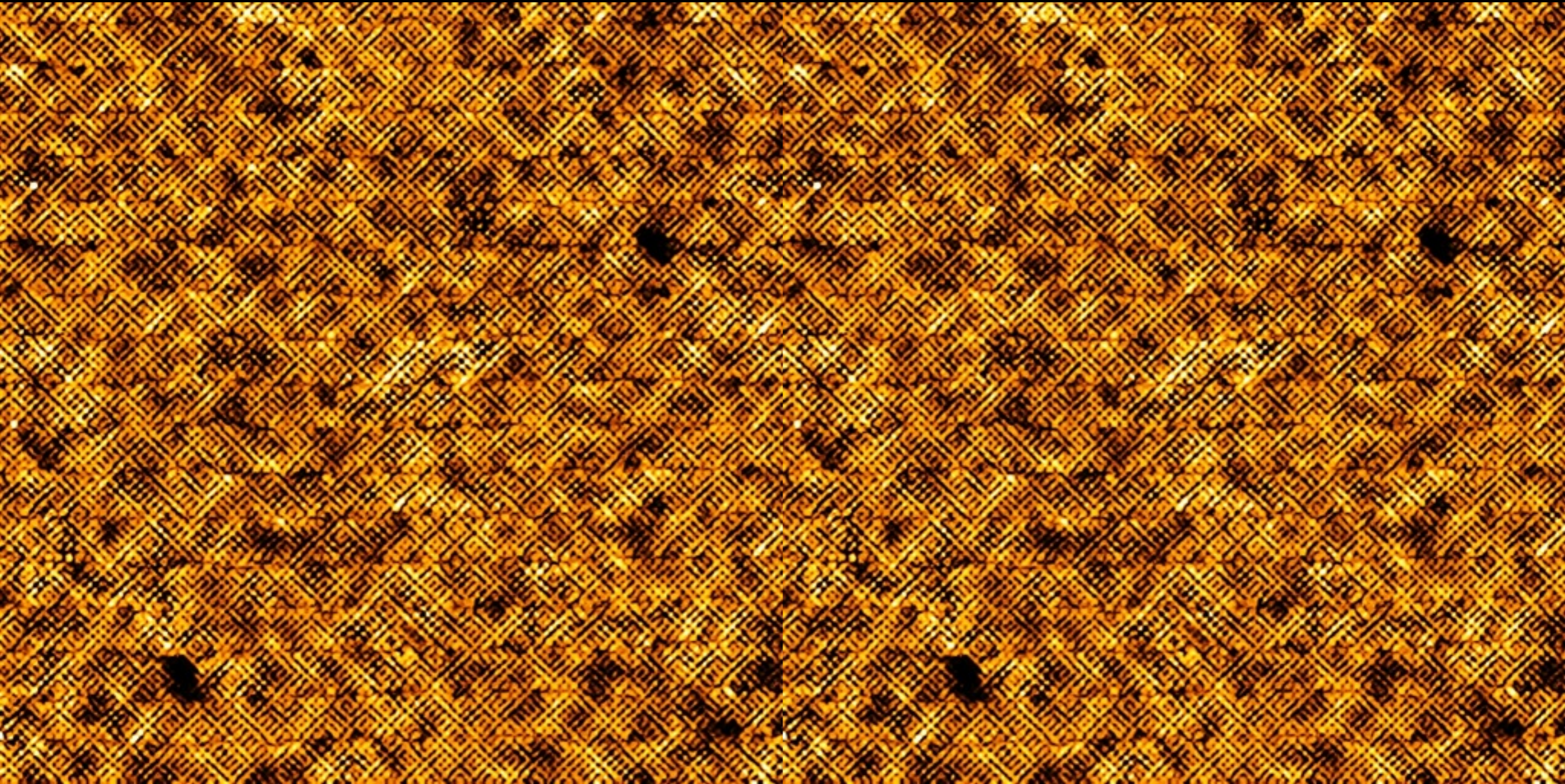
UD45K  
BSCCO

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



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

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



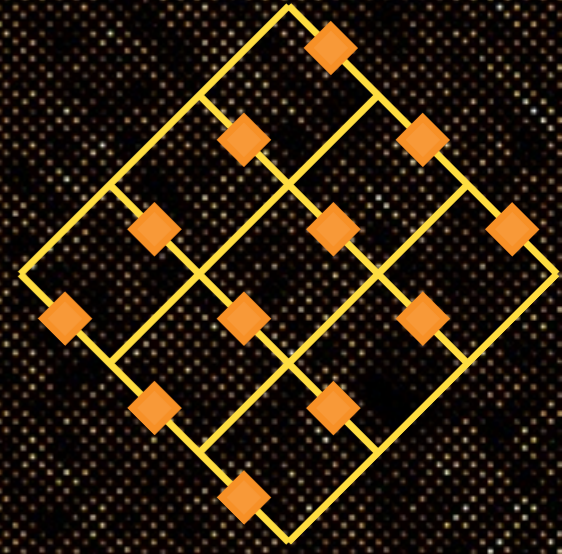
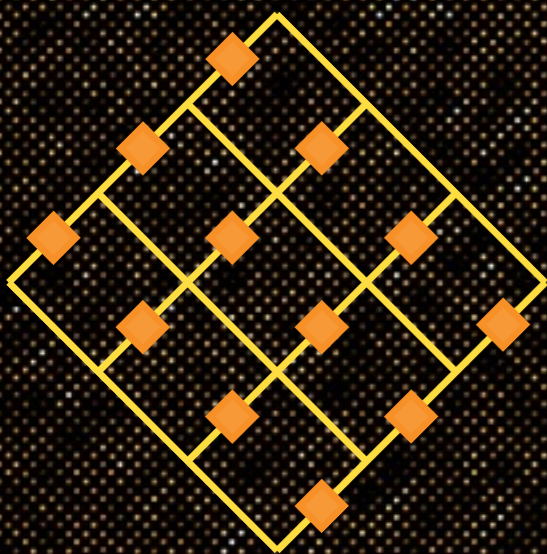
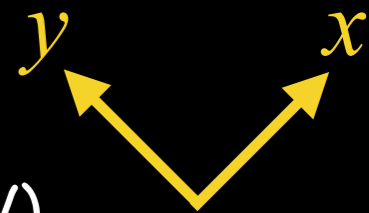
Note that these are identical images.

UD45K

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

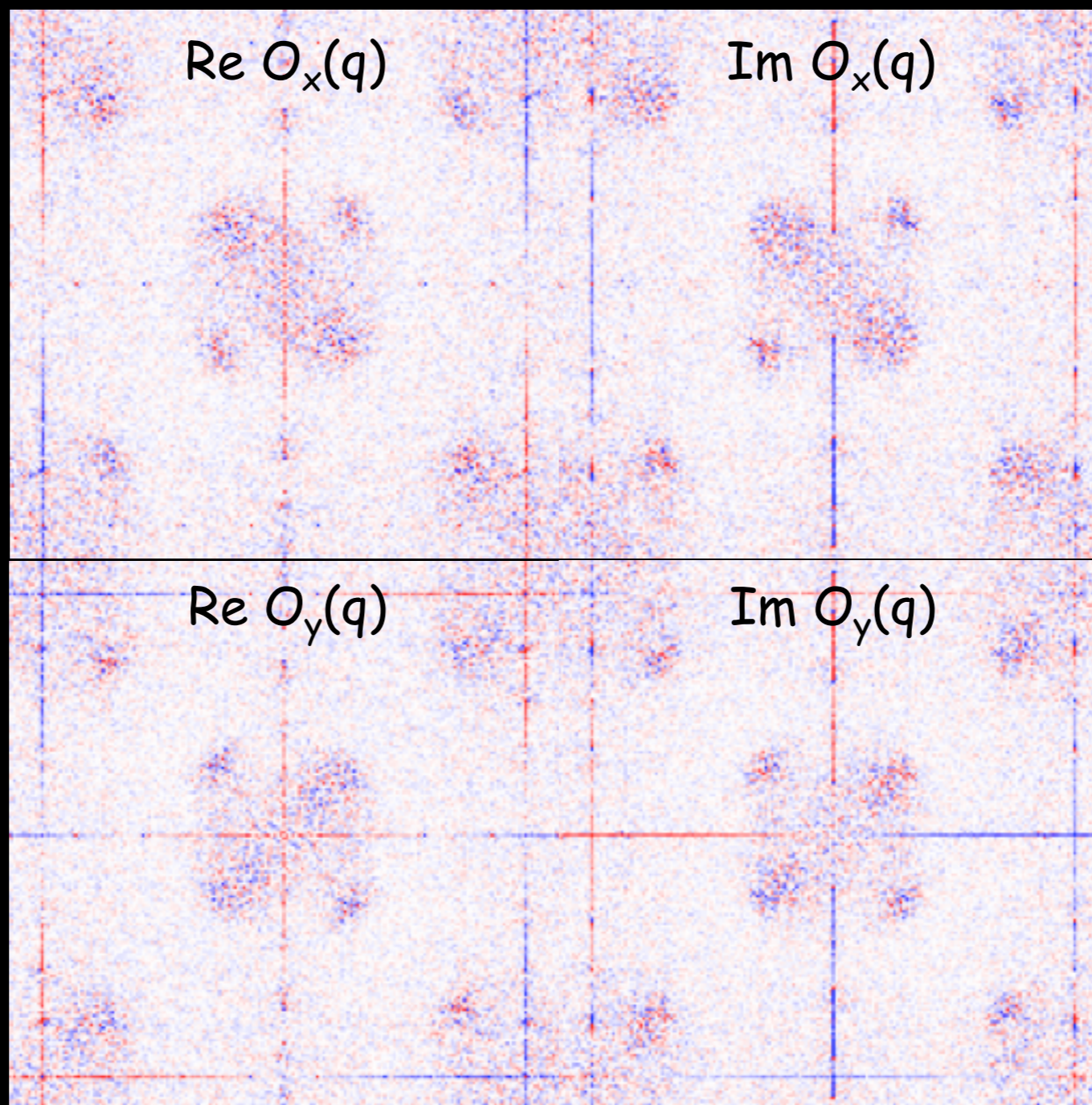
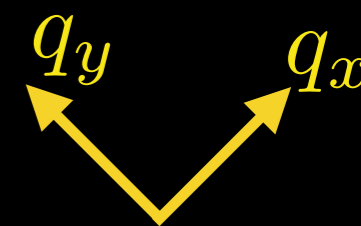
$R(r=O_x, 150\text{mV})$

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

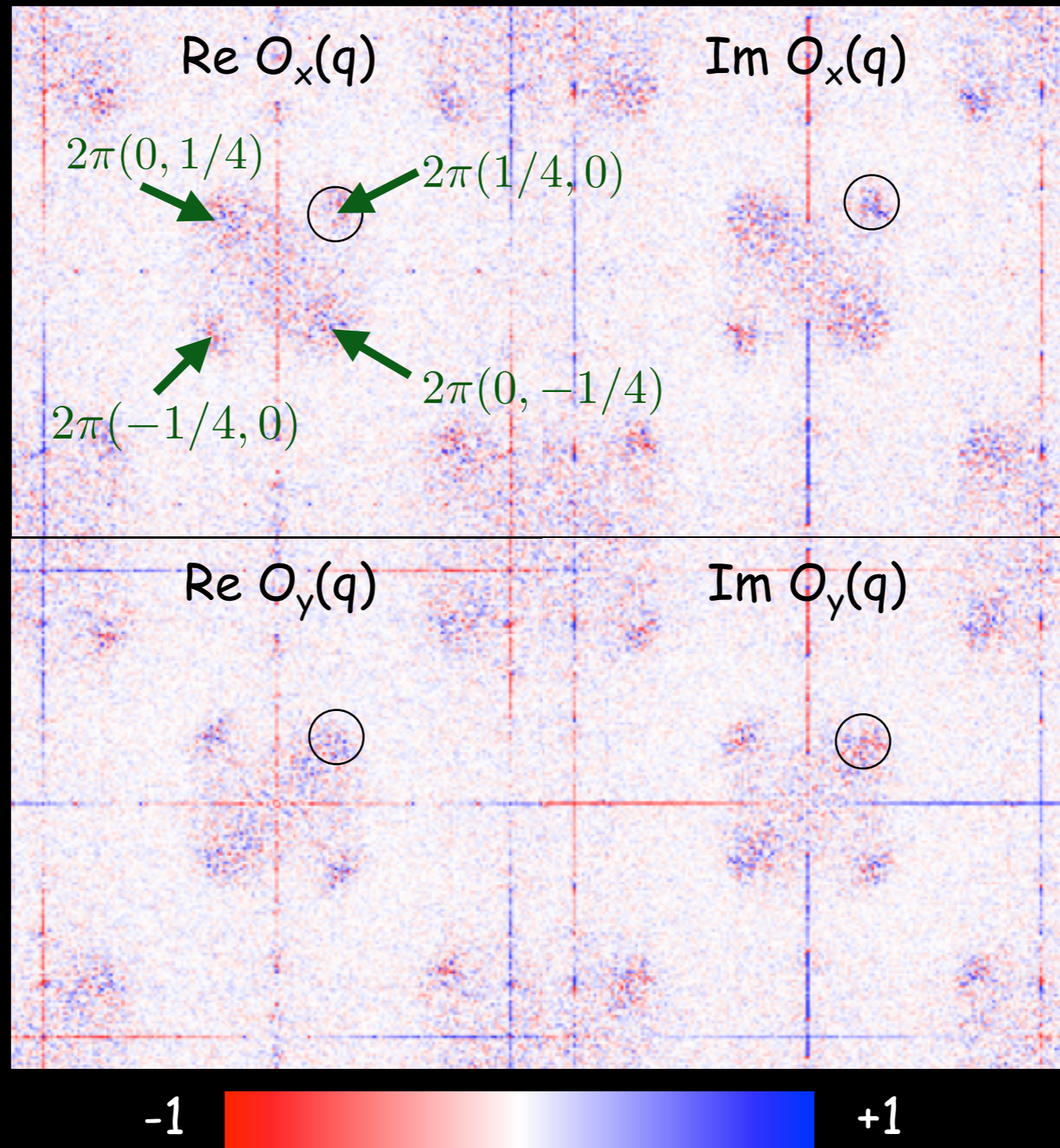
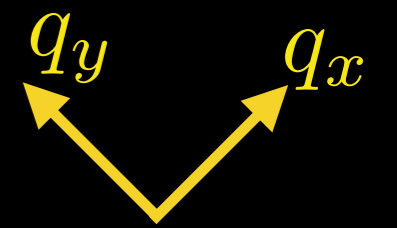


UD45K

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

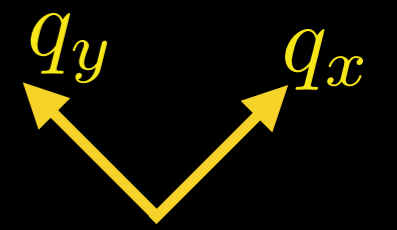


## Broad (0,Q) and (Q,0) DW Features

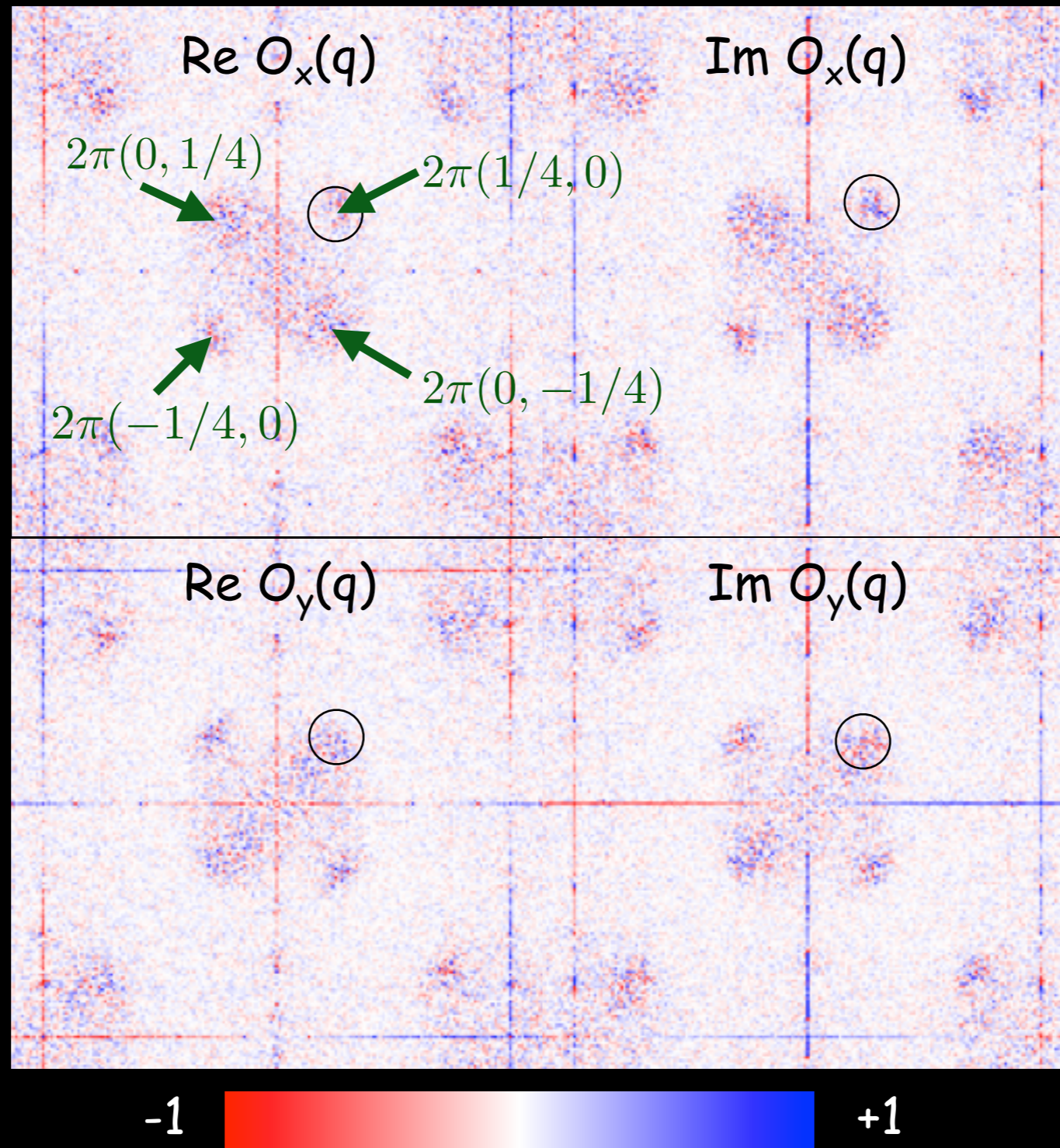


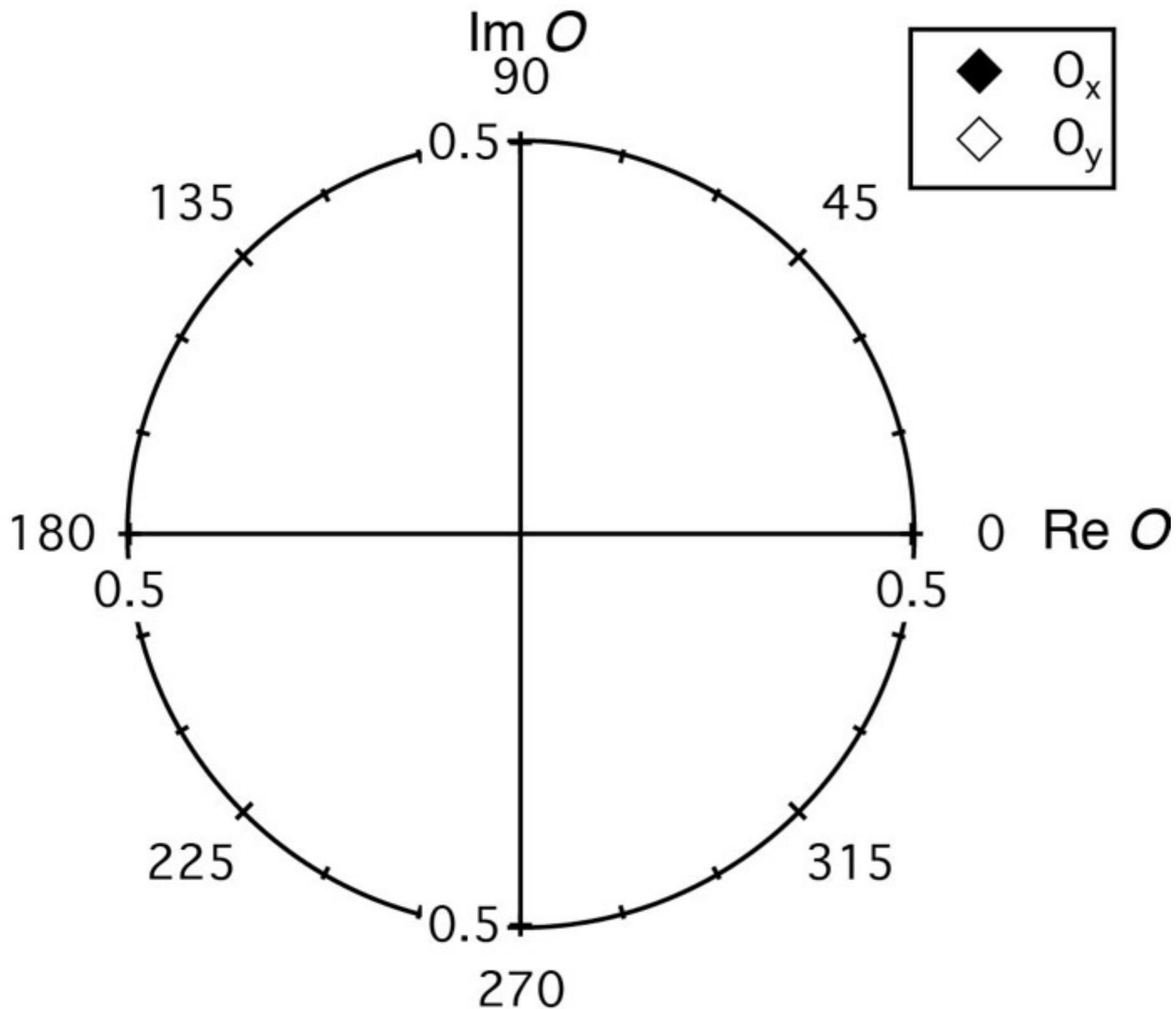
UD45K

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

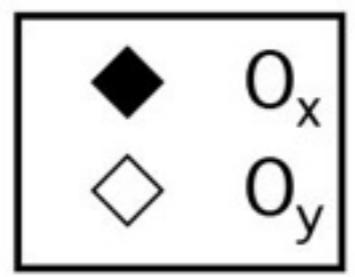
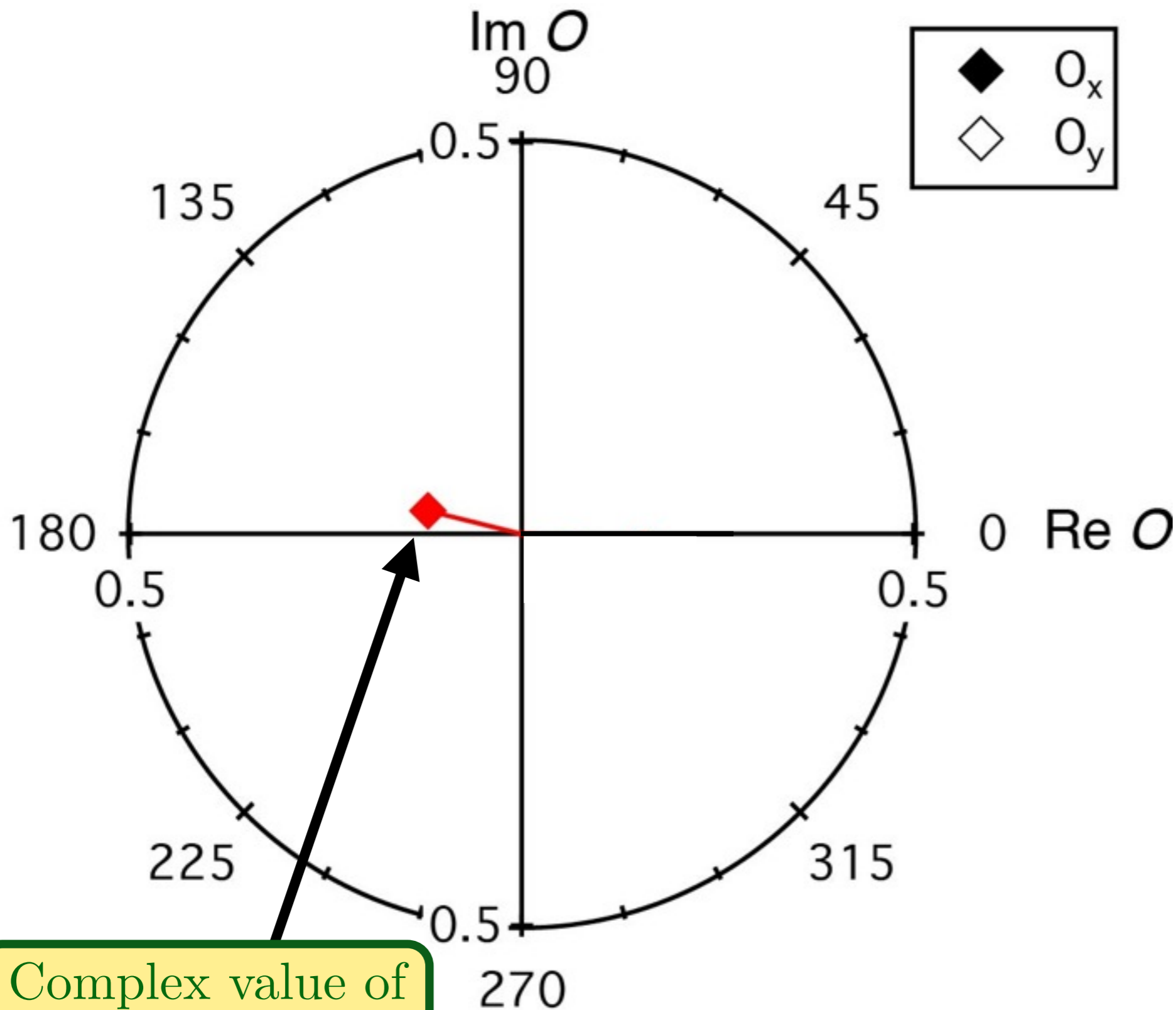


For each pixel in the circles, we obtain 2 complex numbers,  $O_x(q)$  and  $O_y(q)$ .



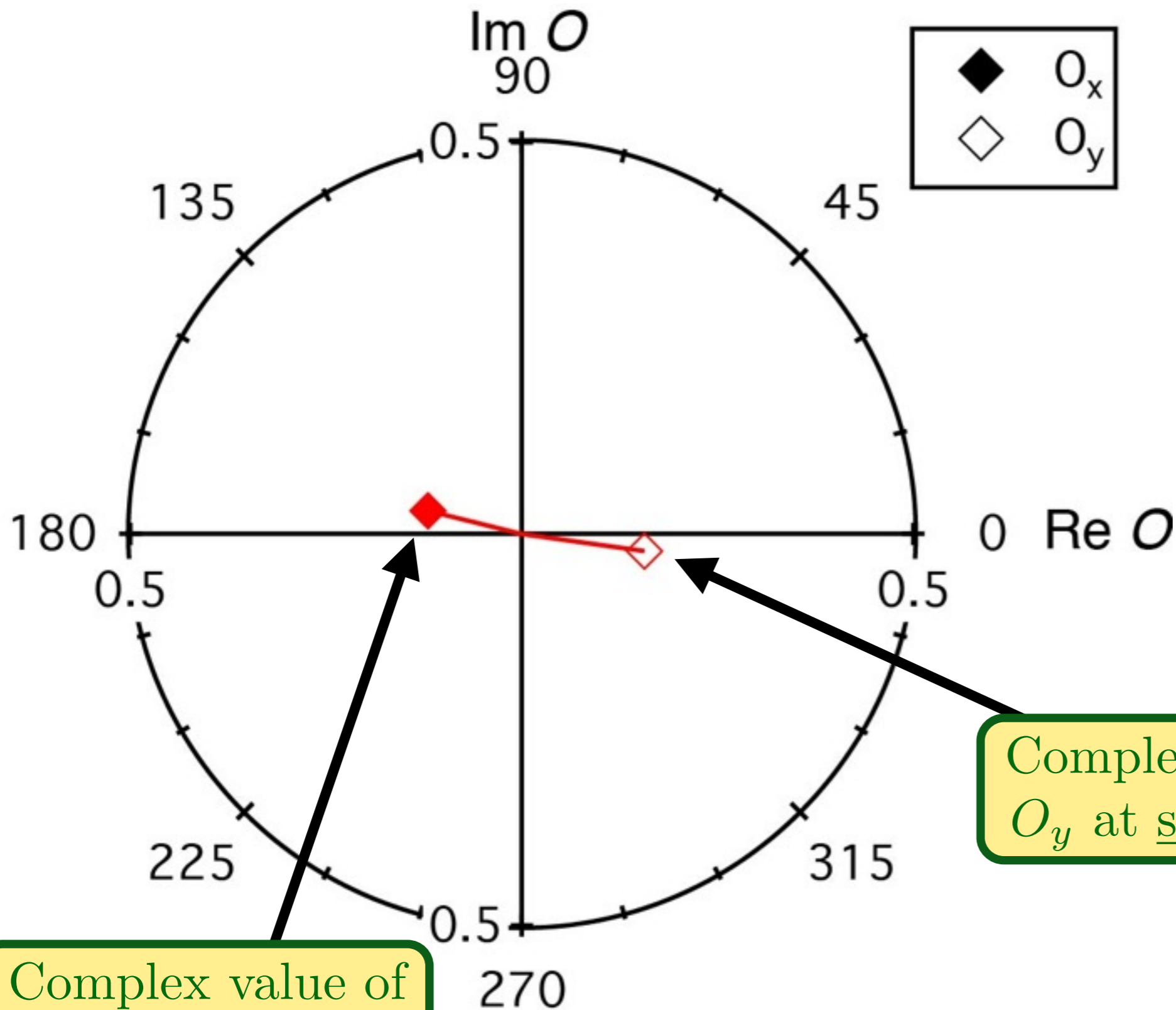


**Phase-sensitive measurement of the  $d$ -form factor of density wave order**



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

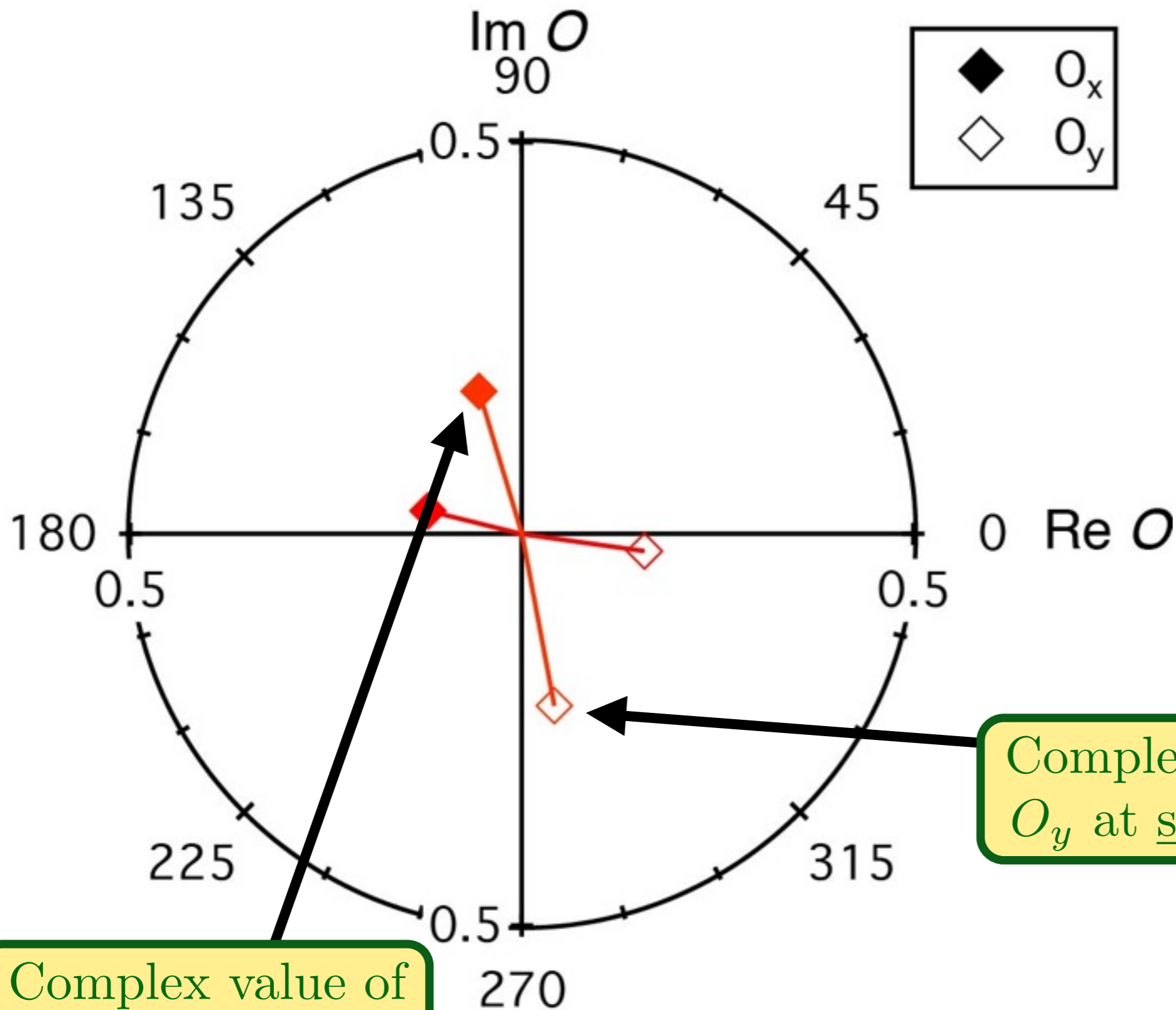
**Complex value of  $O_x$  at a pixel**



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

Complex value of  $O_x$  at a pixel

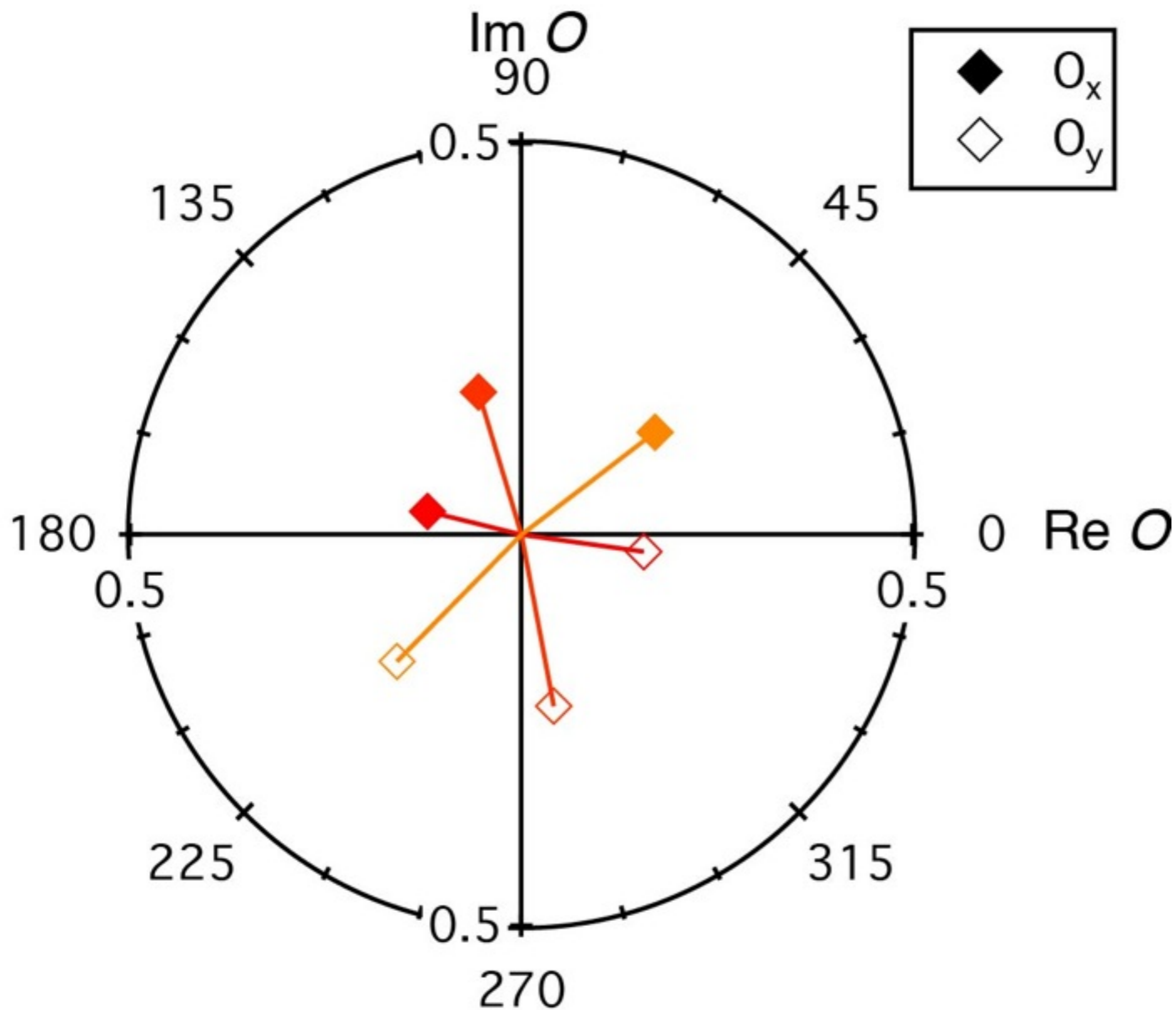
Complex value of  $O_y$  at same pixel



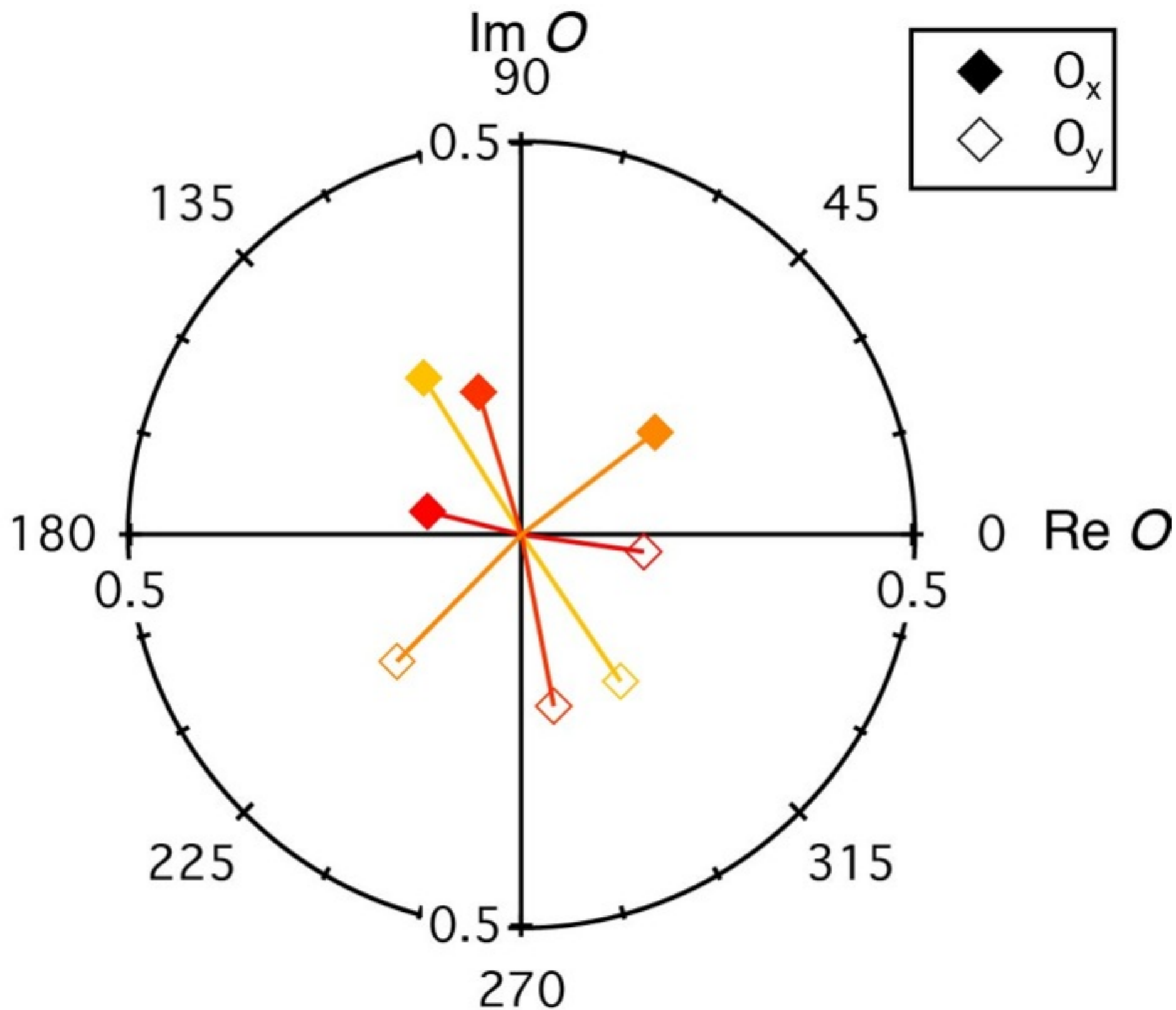
**Phase-sensitive measurement of the  $d$ -form factor of density wave order**

Complex value of  $O_x$  at a pixel

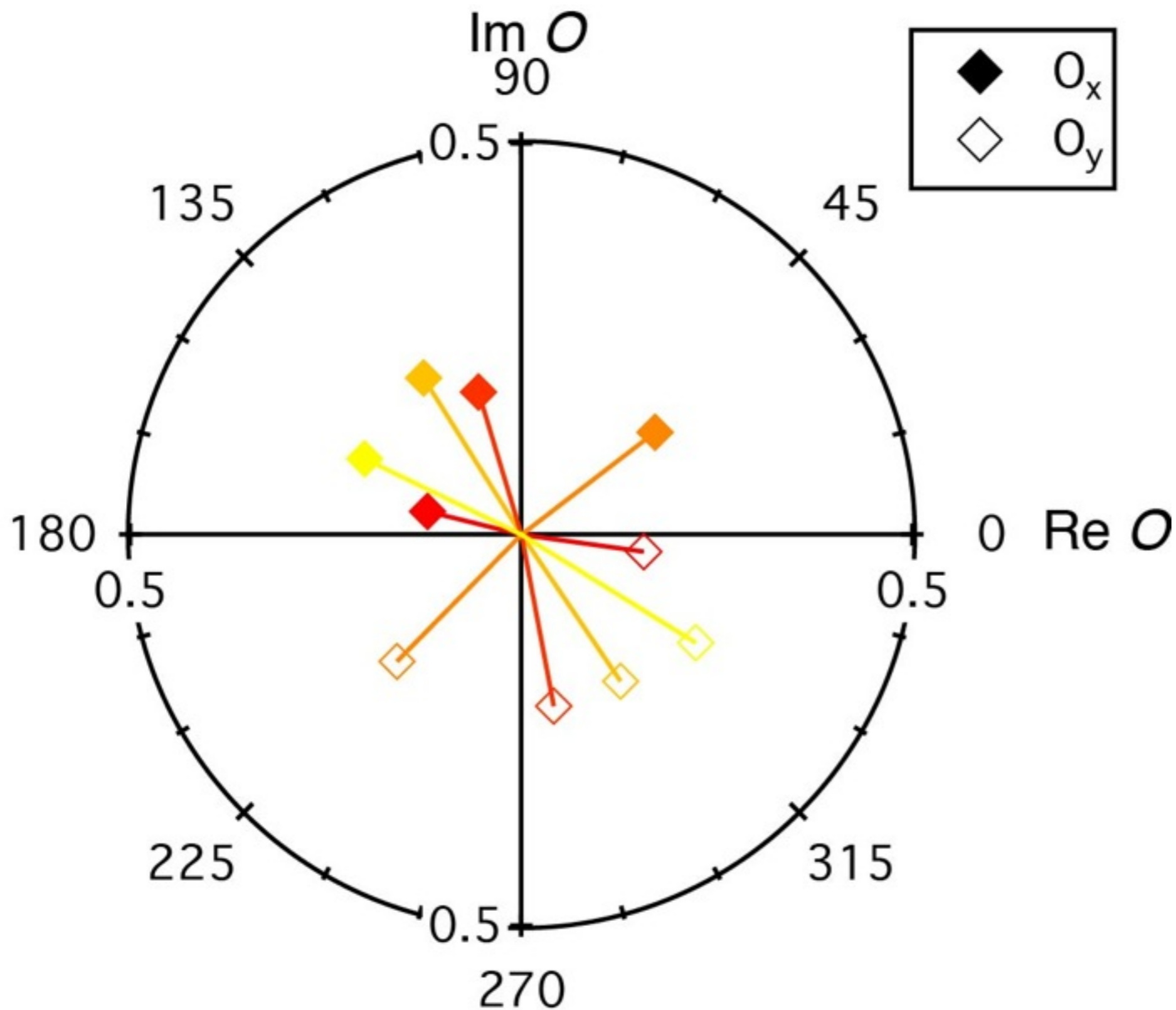
Complex value of  $O_y$  at same pixel



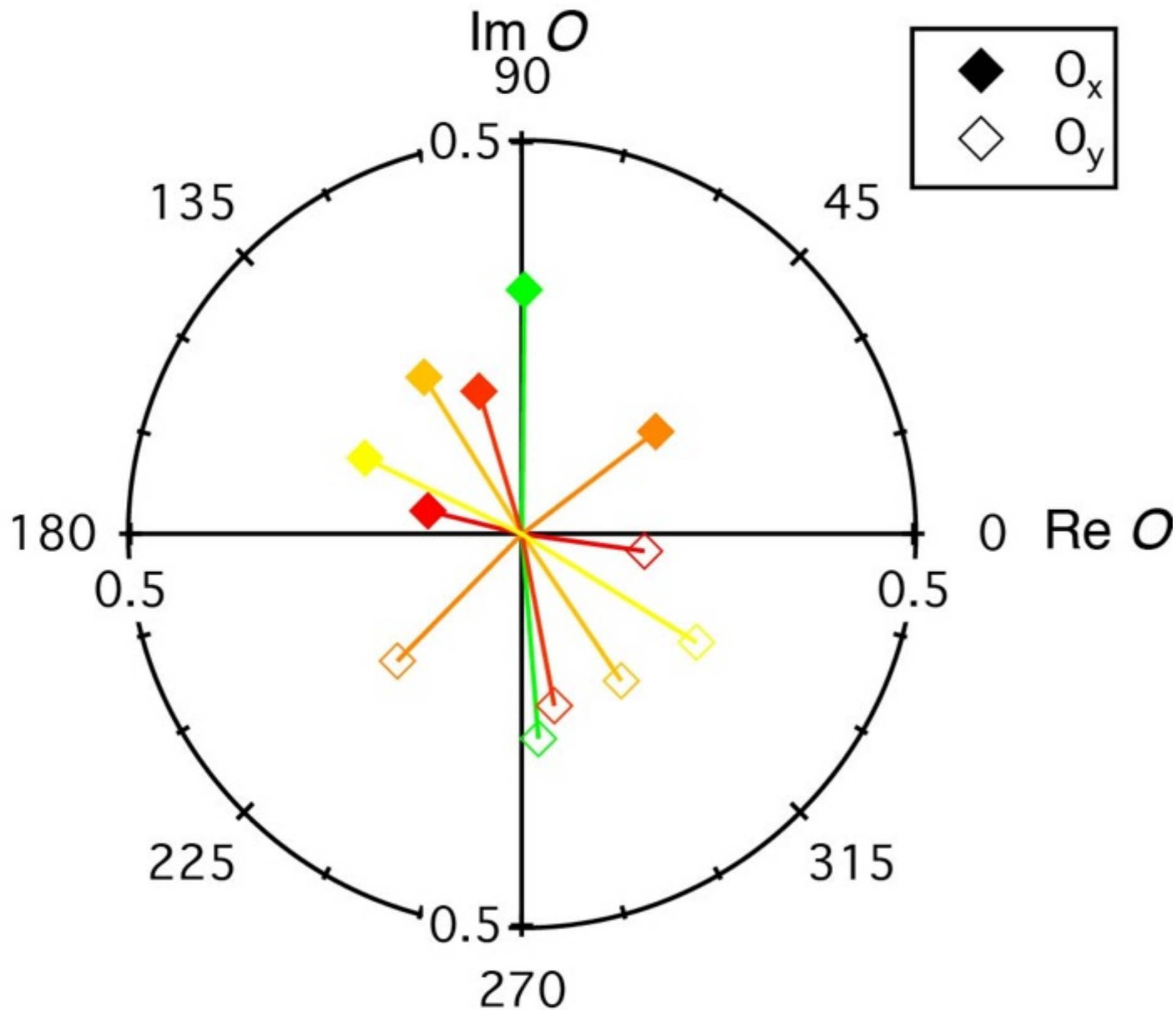
**Phase-sensitive measurement of the  $d$ -form factor of density wave order**



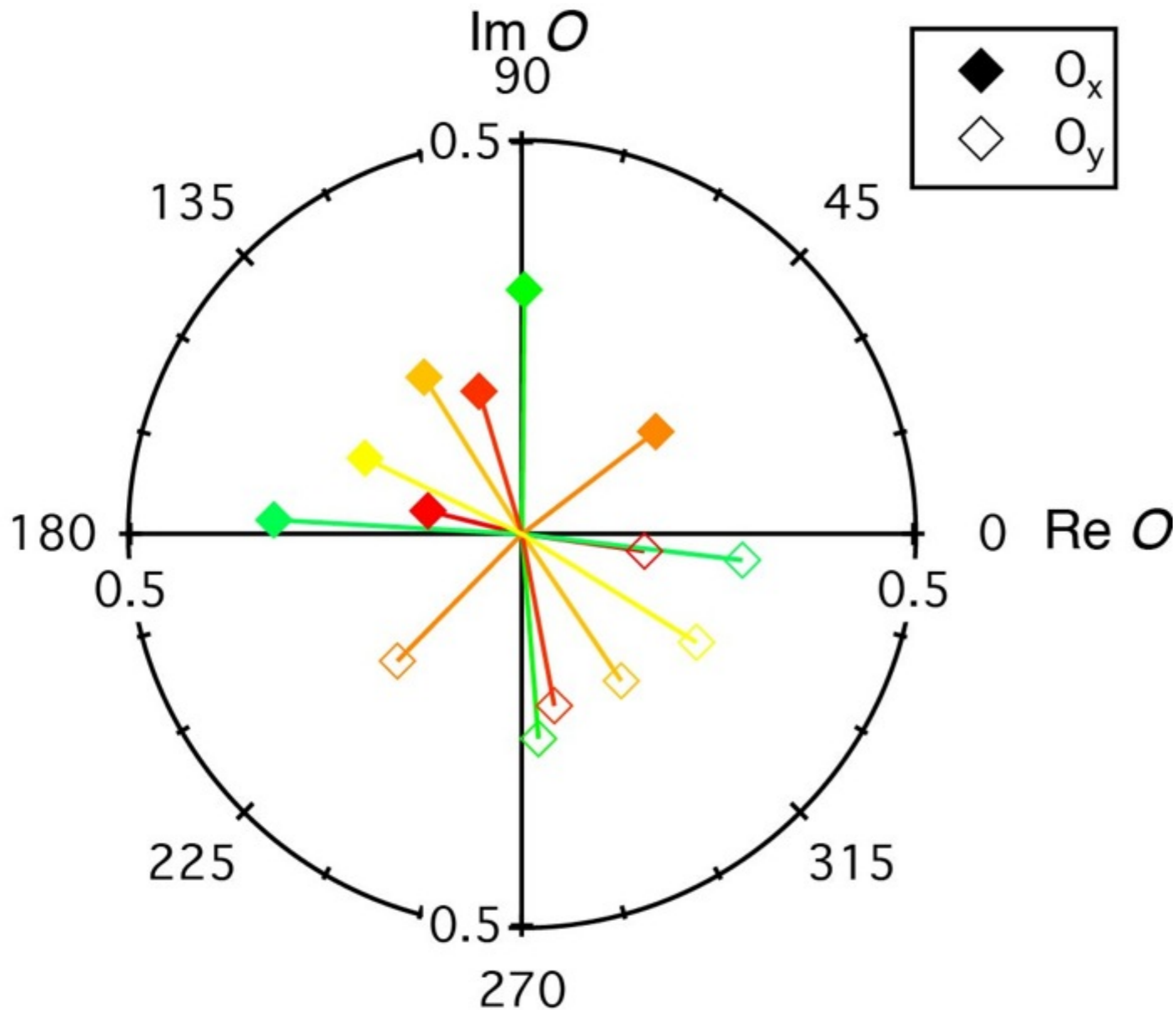
**Phase-sensitive measurement of the  $d$ -form factor of density wave order**



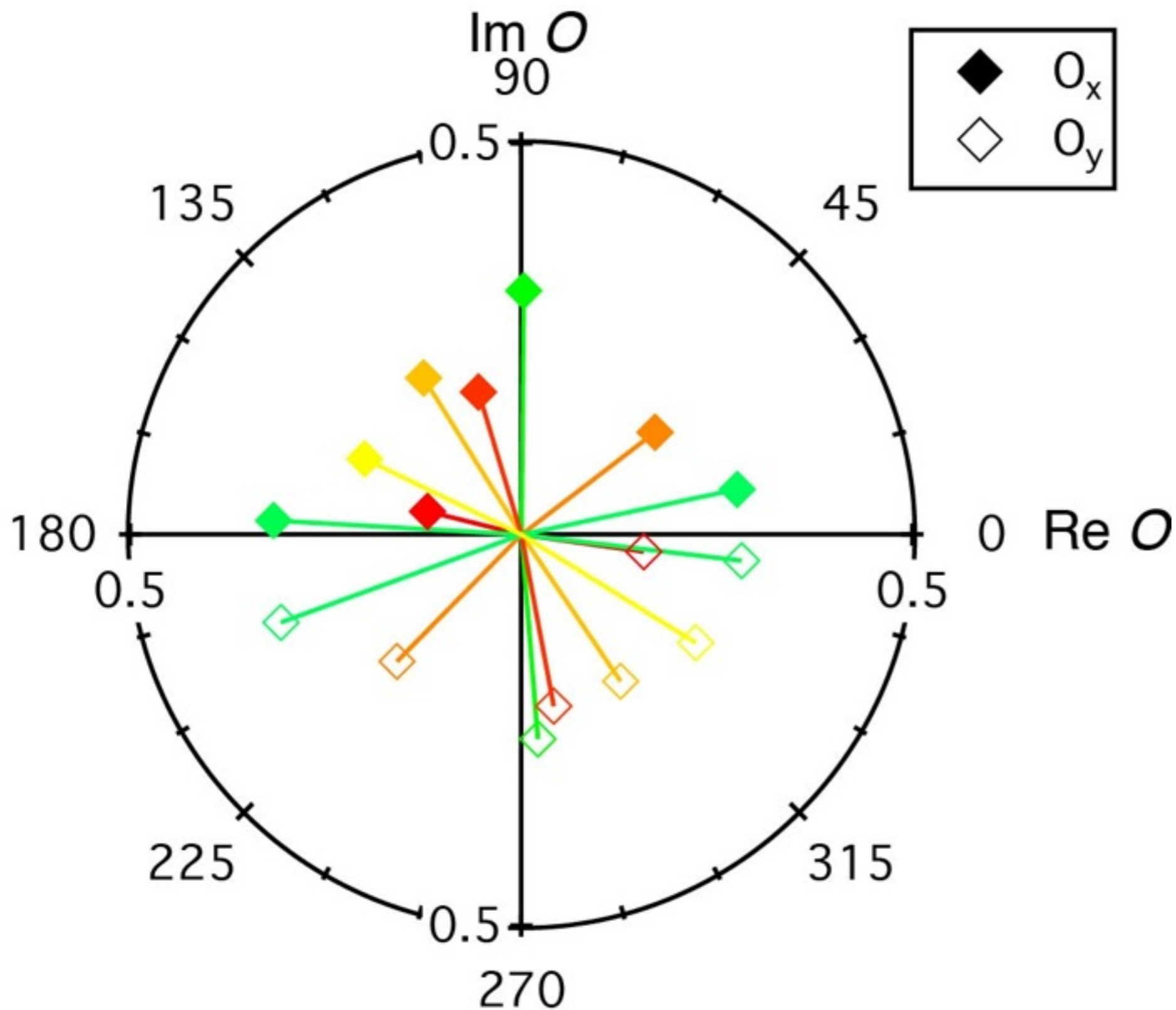
**Phase-sensitive  
measurement of  
the  $d$ -form factor  
of density wave  
order**



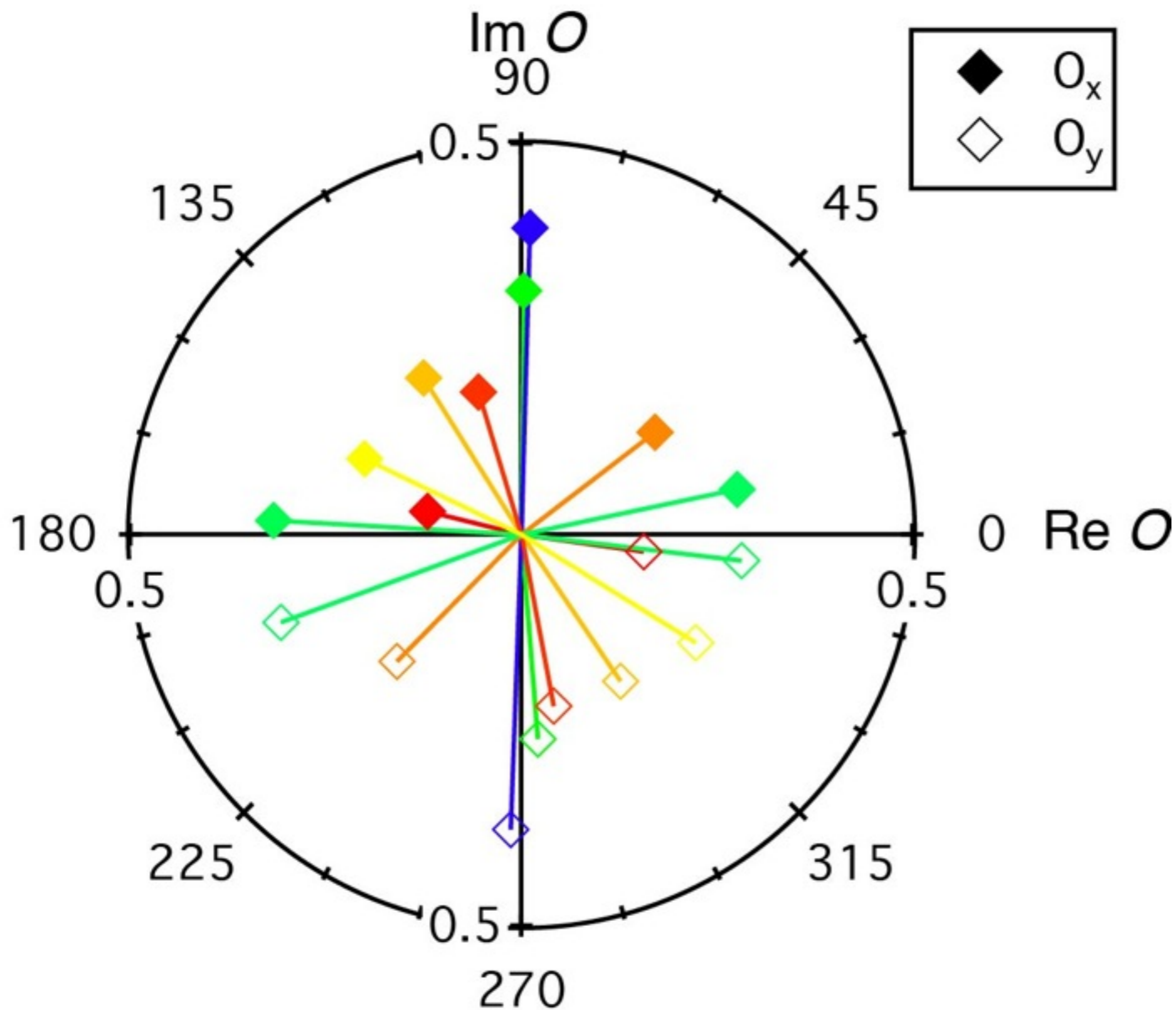
**Phase-sensitive measurement of the *d*-form factor of density wave order**



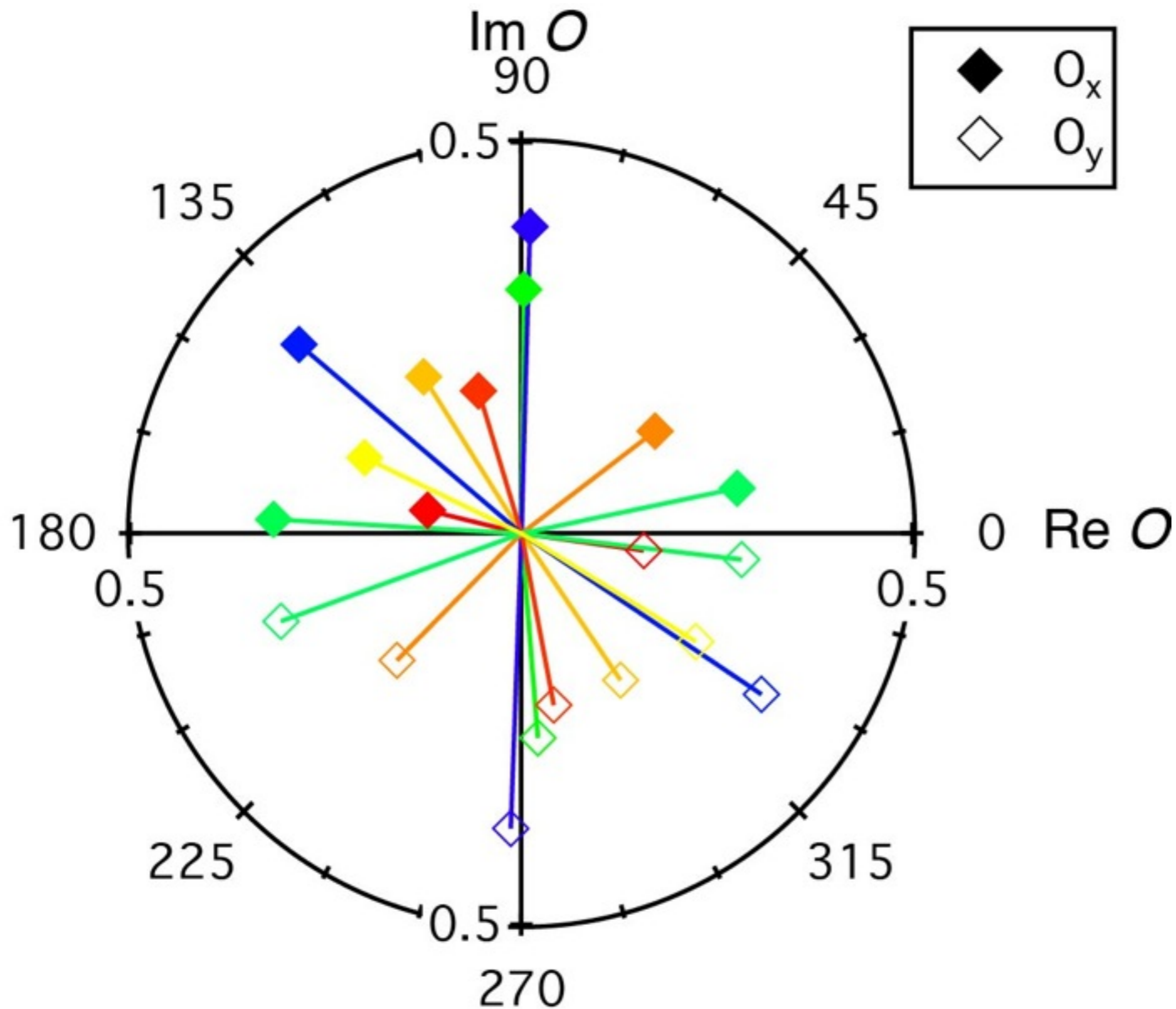
**Phase-sensitive measurement of the *d*-form factor of density wave order**



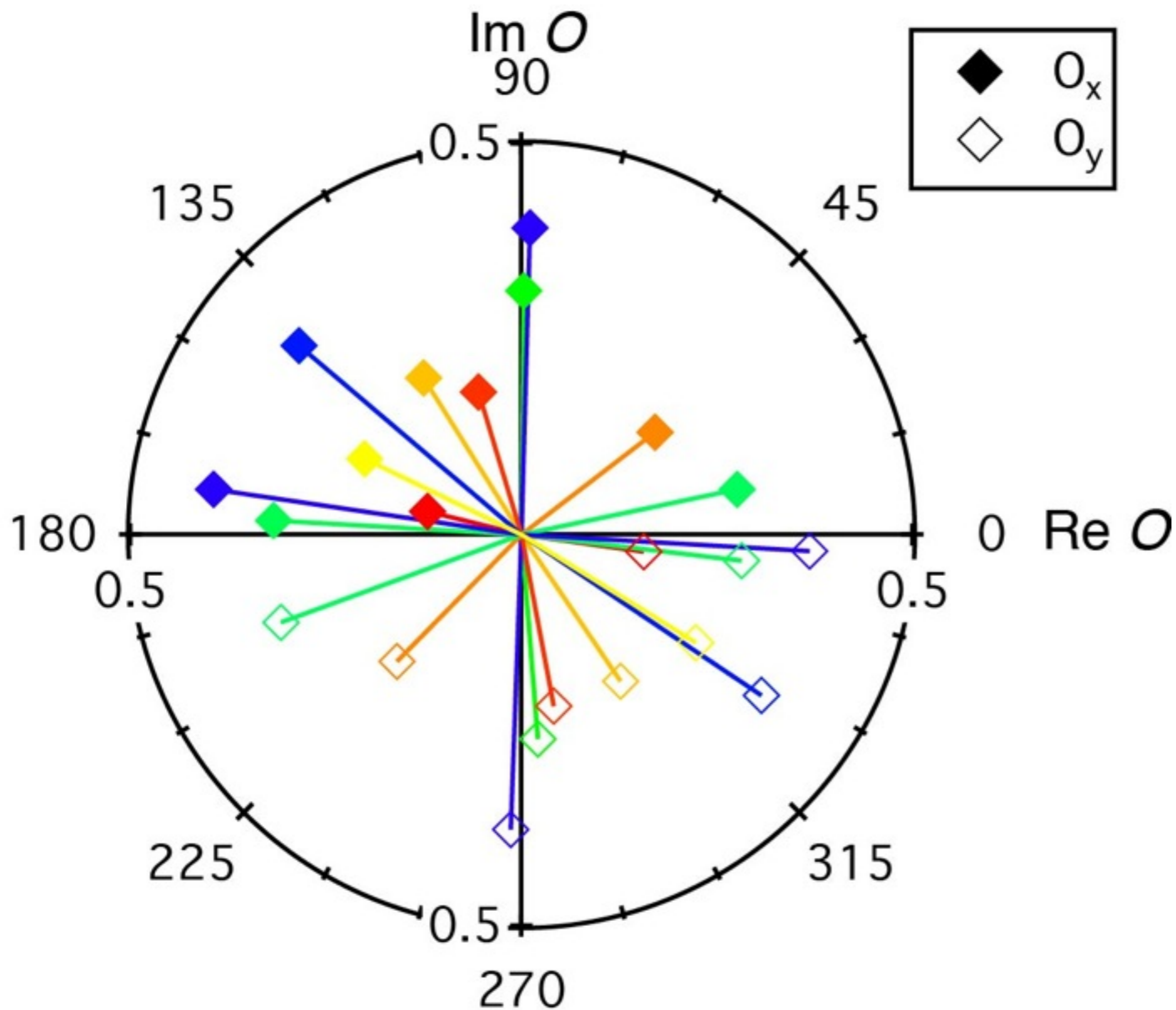
**Phase-sensitive measurement of the  $d$ -form factor of density wave order**



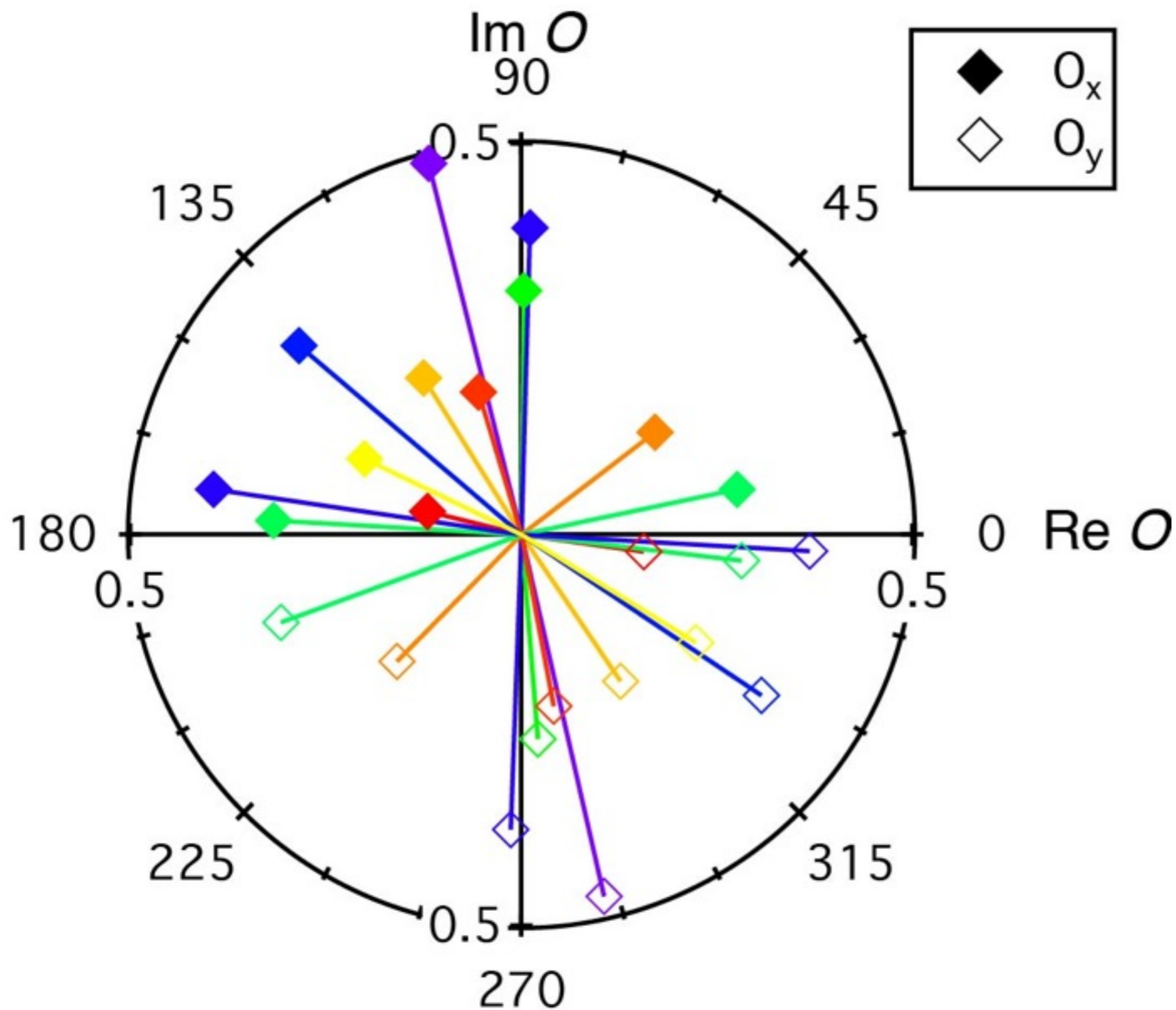
**Phase-sensitive measurement of the  $d$ -form factor of density wave order**



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

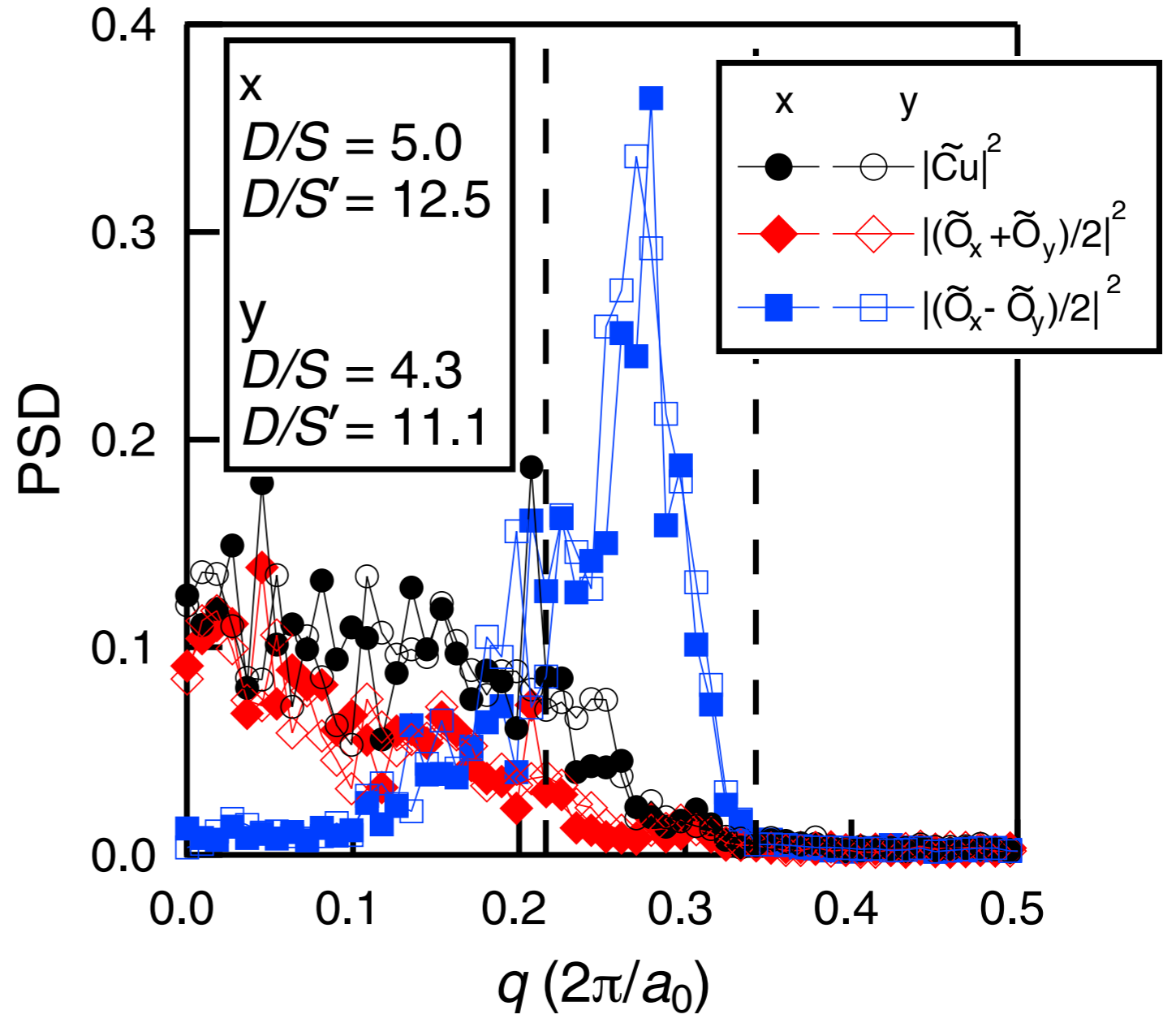
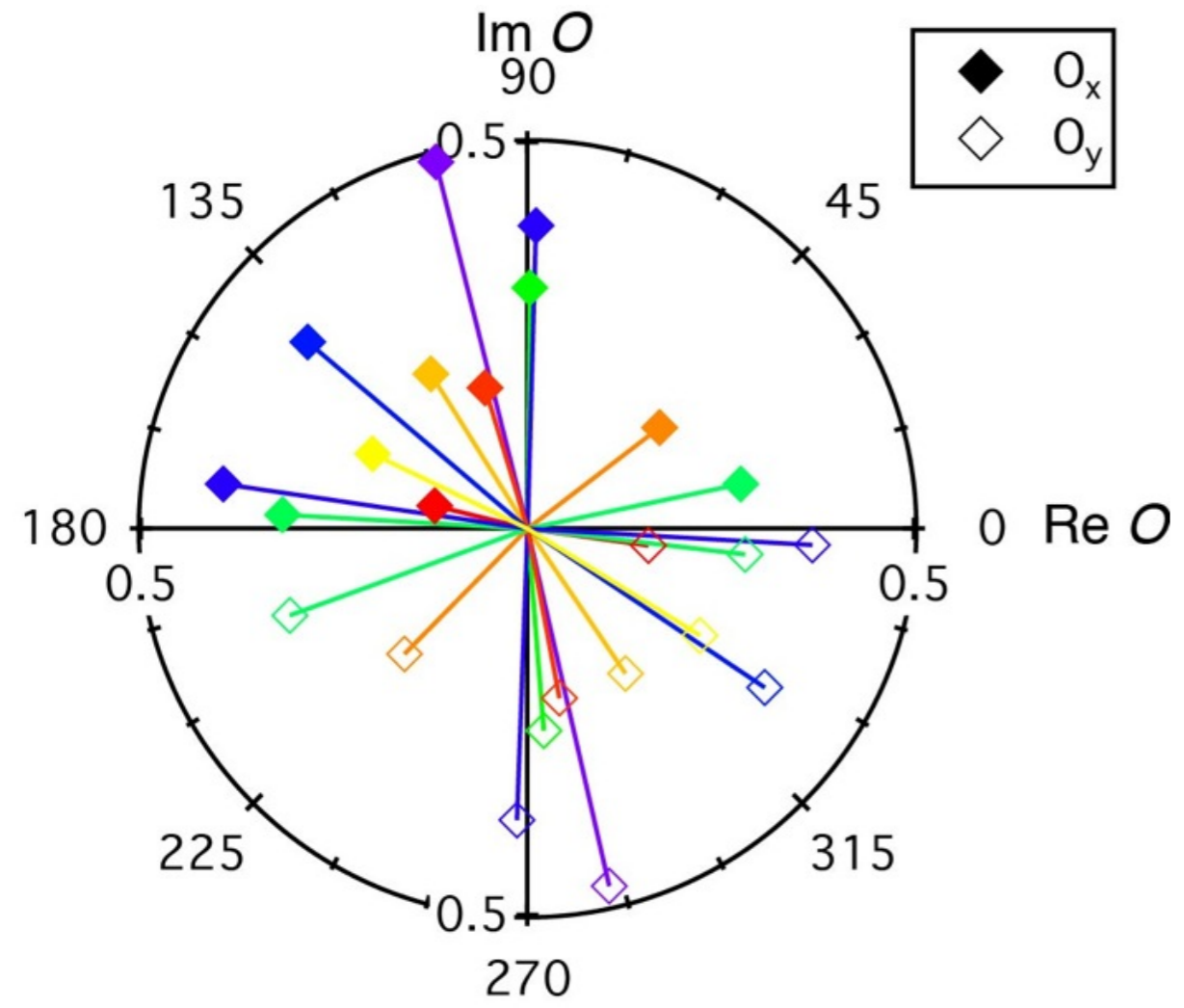


**Phase-sensitive  
measurement of  
the  $d$ -form factor  
of density wave  
order**



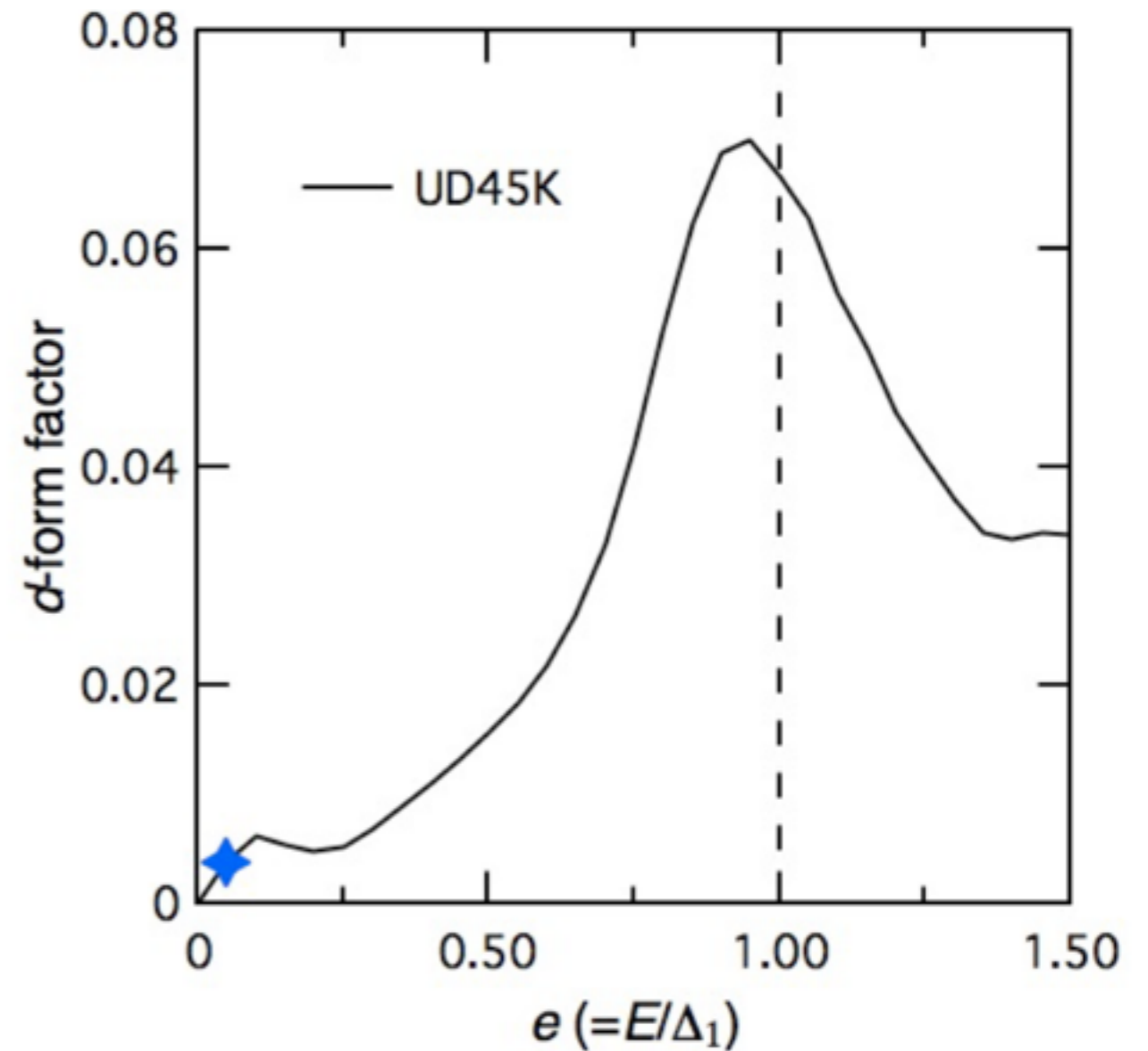
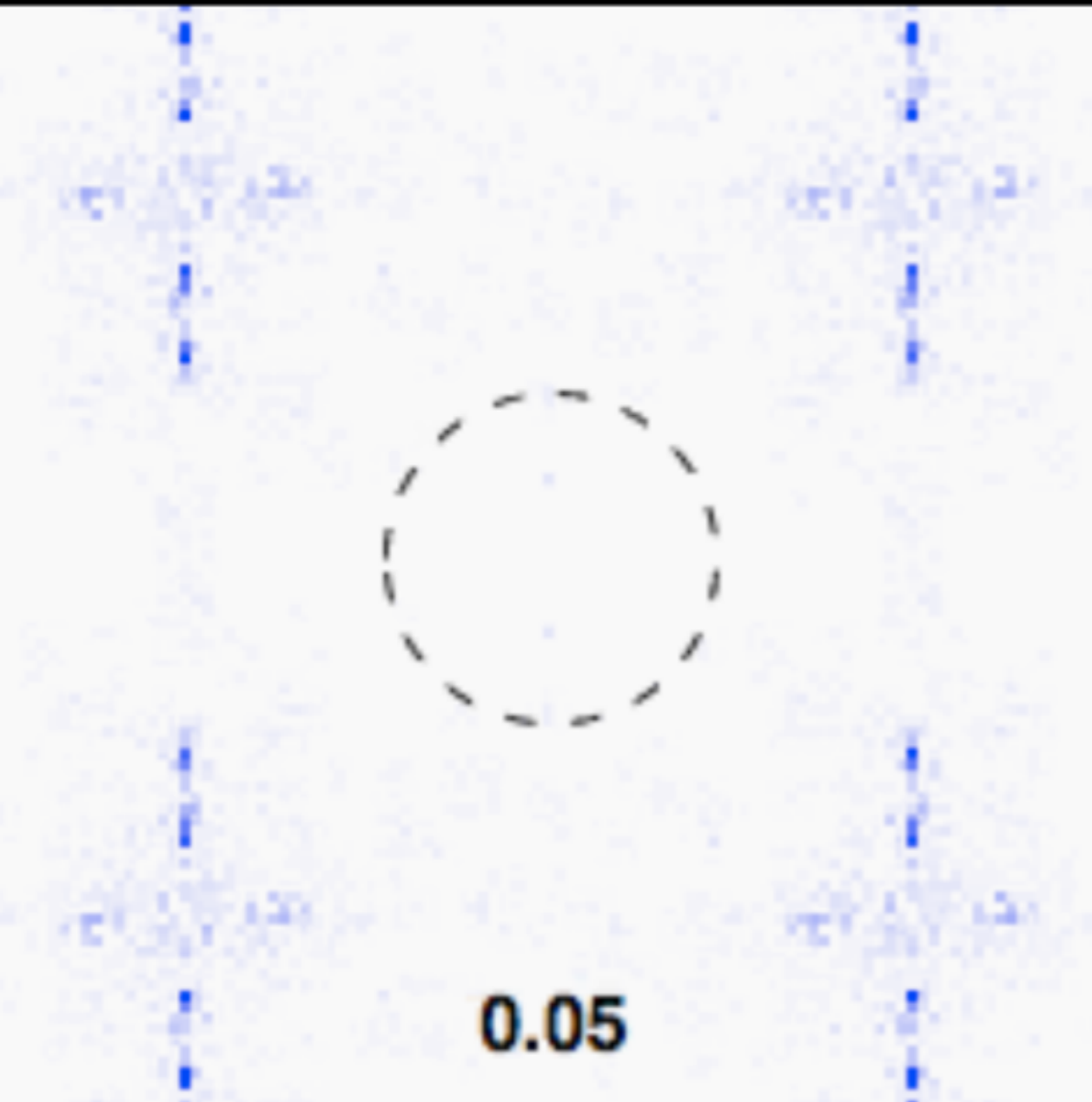
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**Phase-sensitive measurement of the  $d$ -form factor of density wave order**



K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS to appear, arXiv:1404.0362

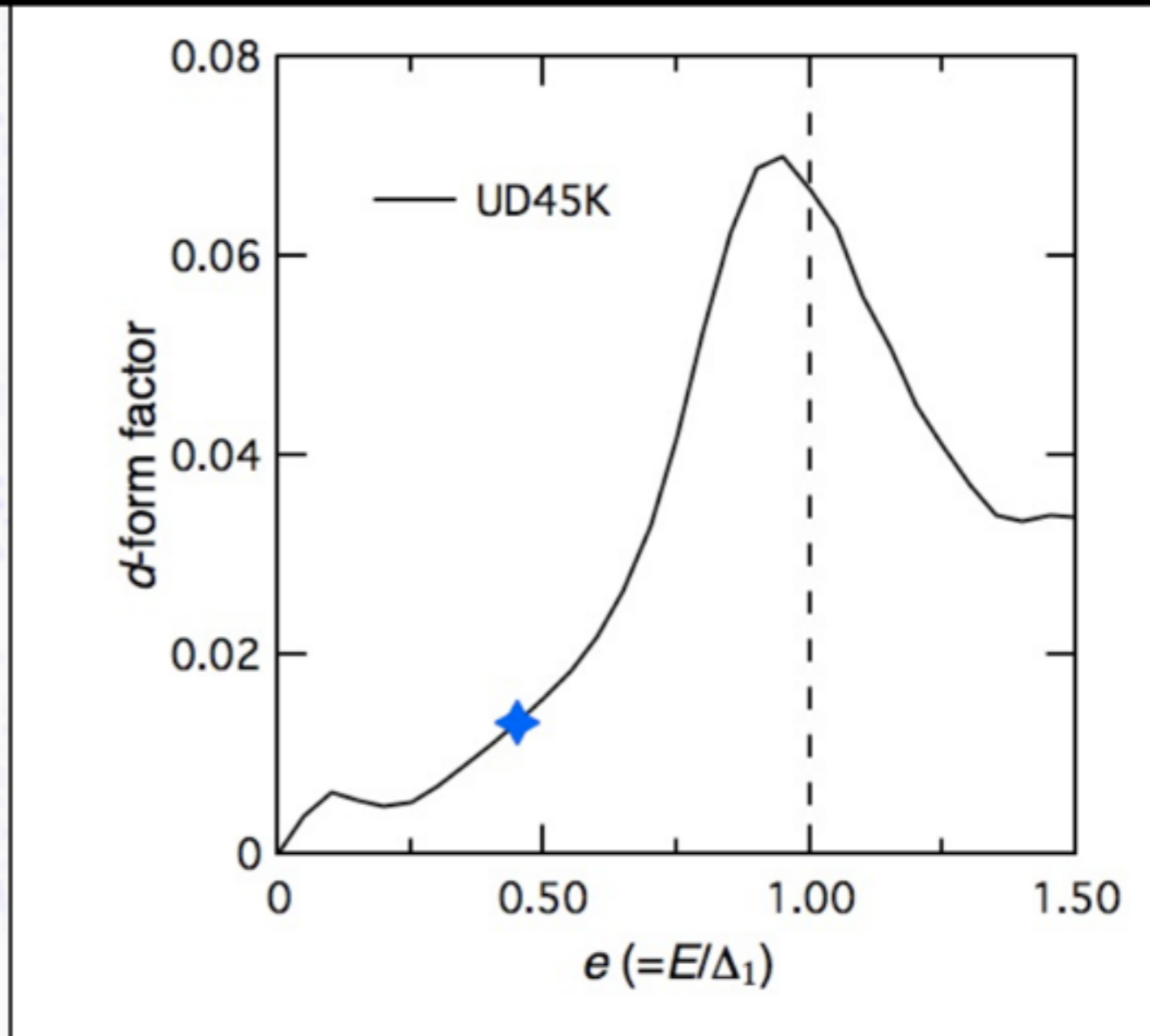
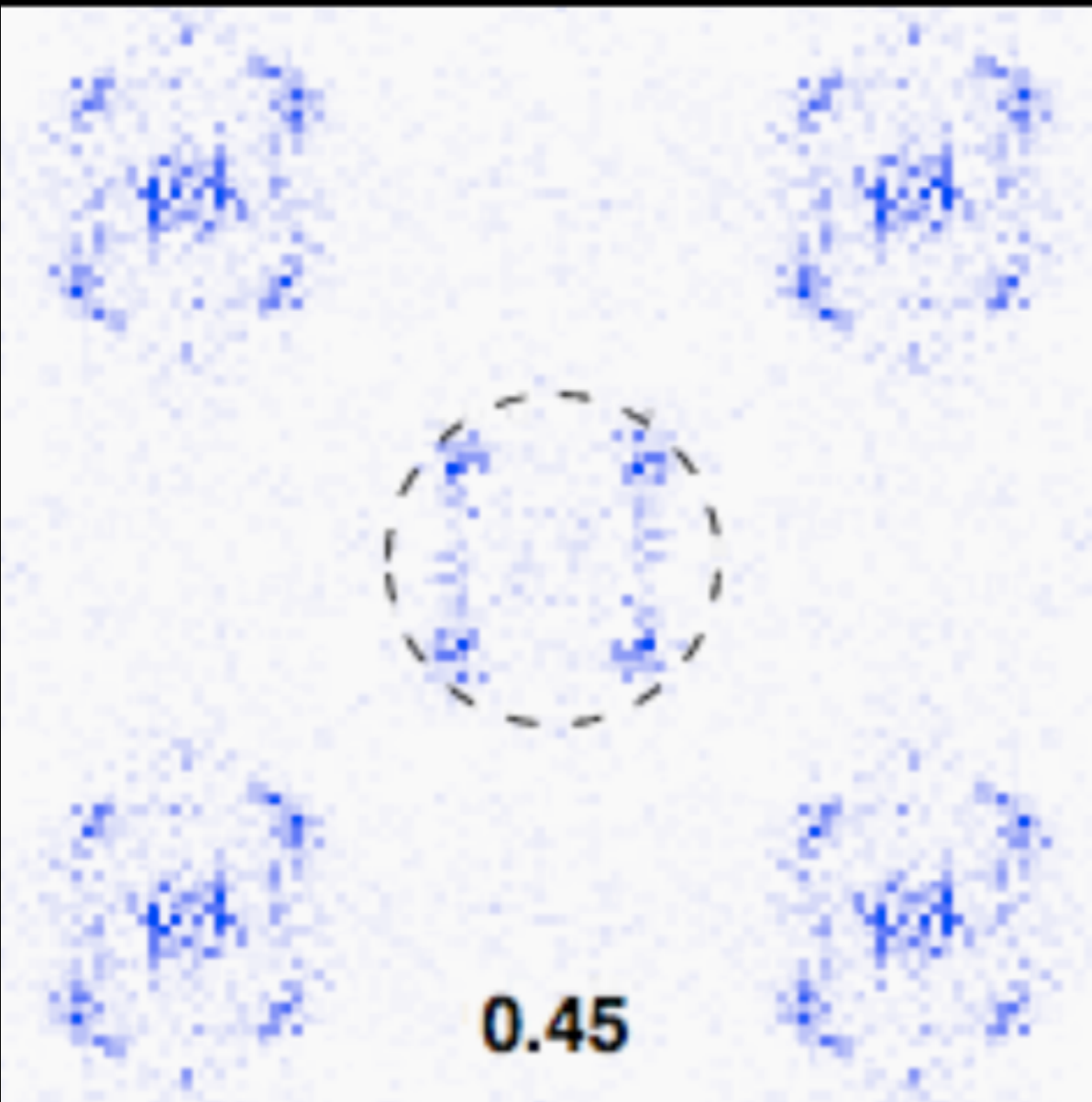
# *d*-form Factor Predominant at Pseudogap Energy



$$|(O_x(q,e) - O_y(q,e))/2|^2$$

Spectral weight  
inside the broken circle

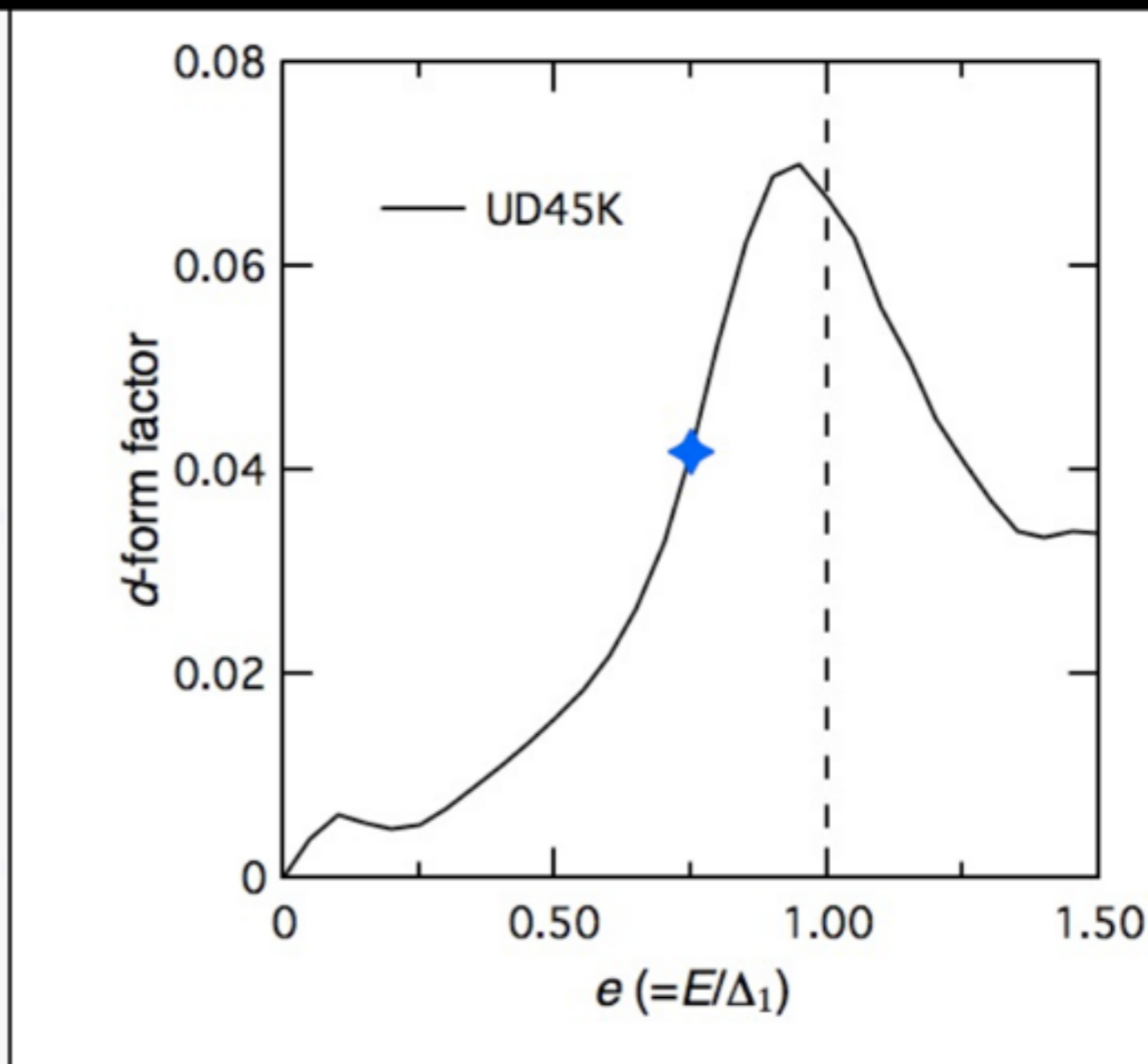
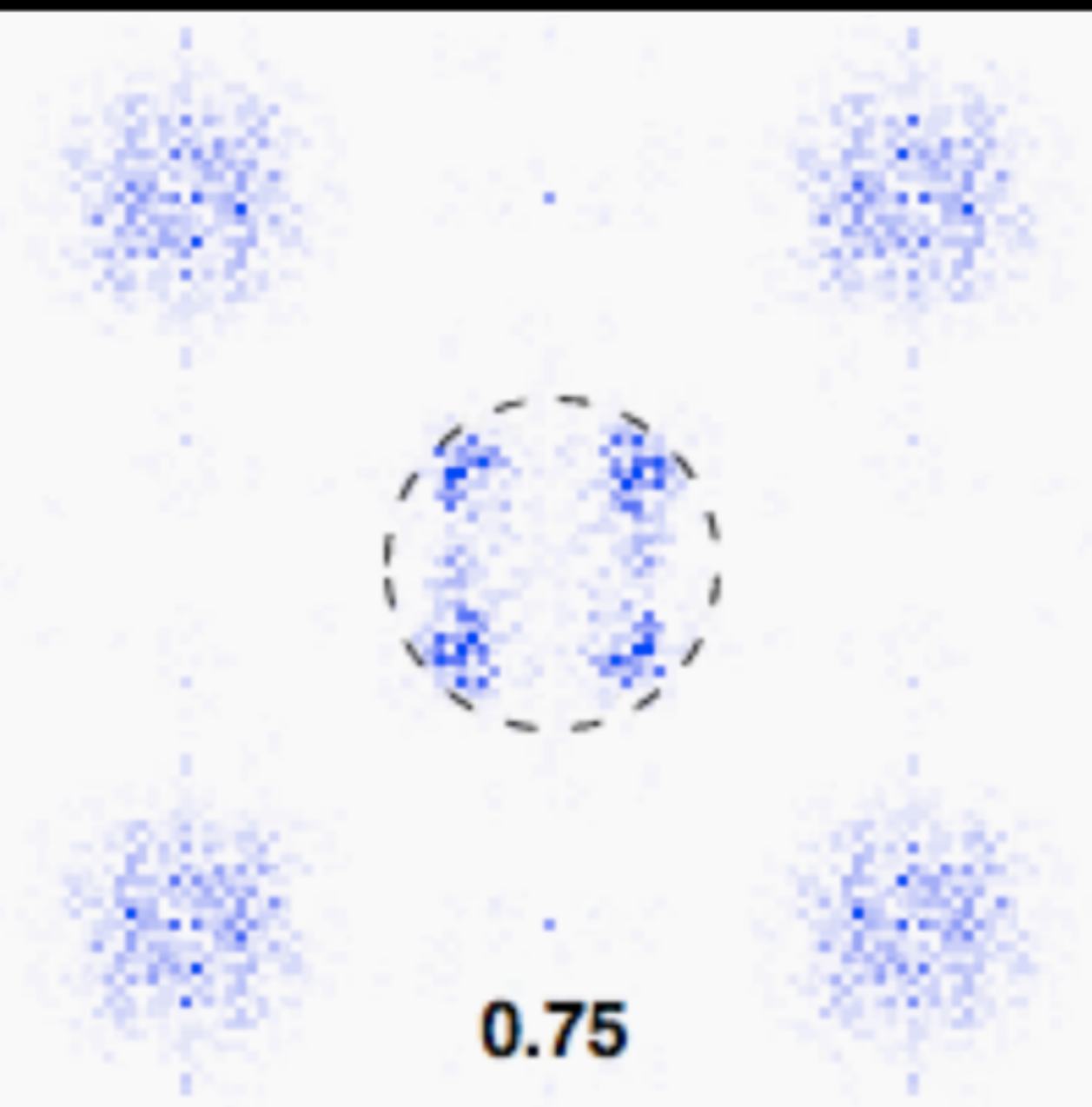
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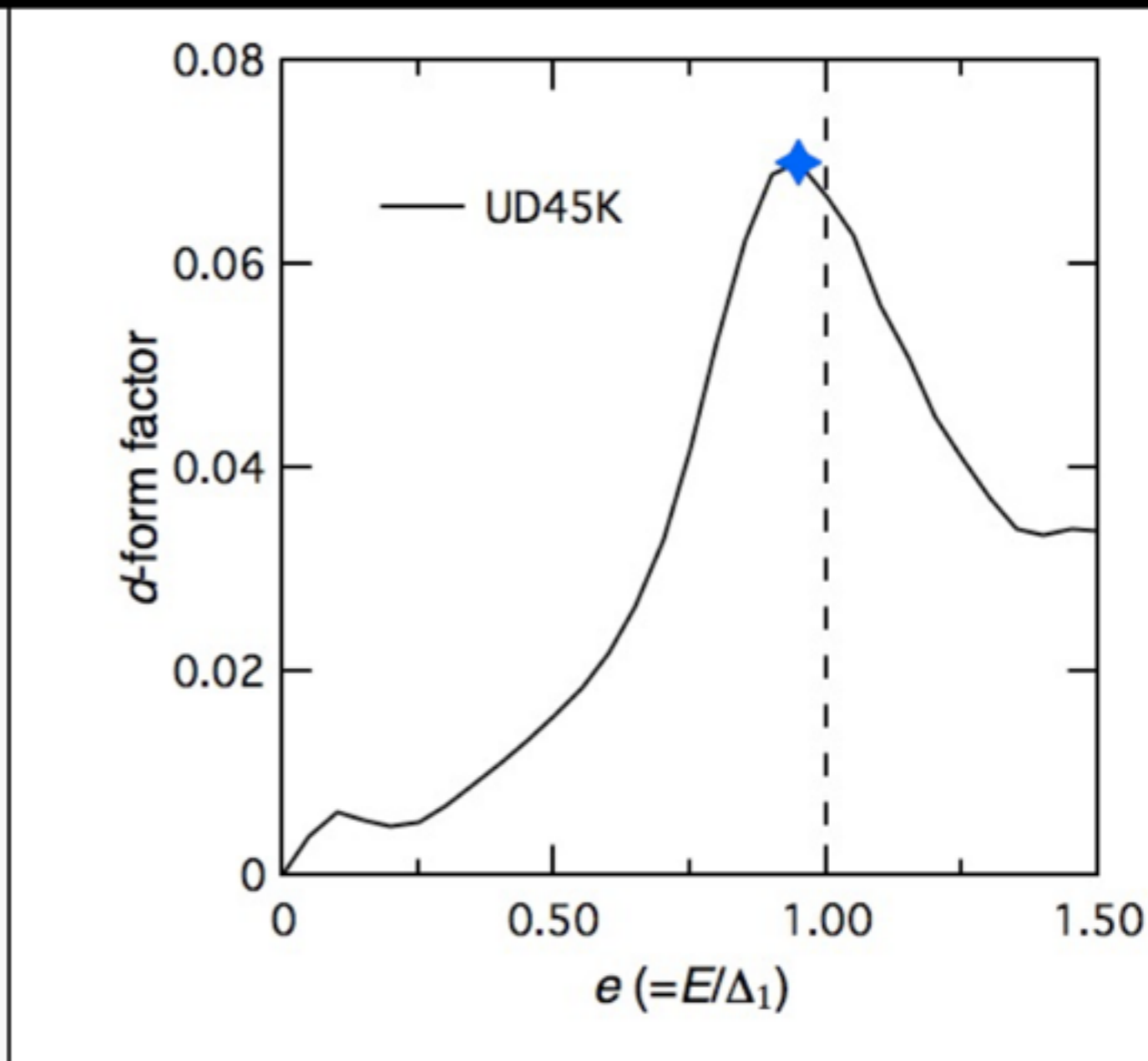
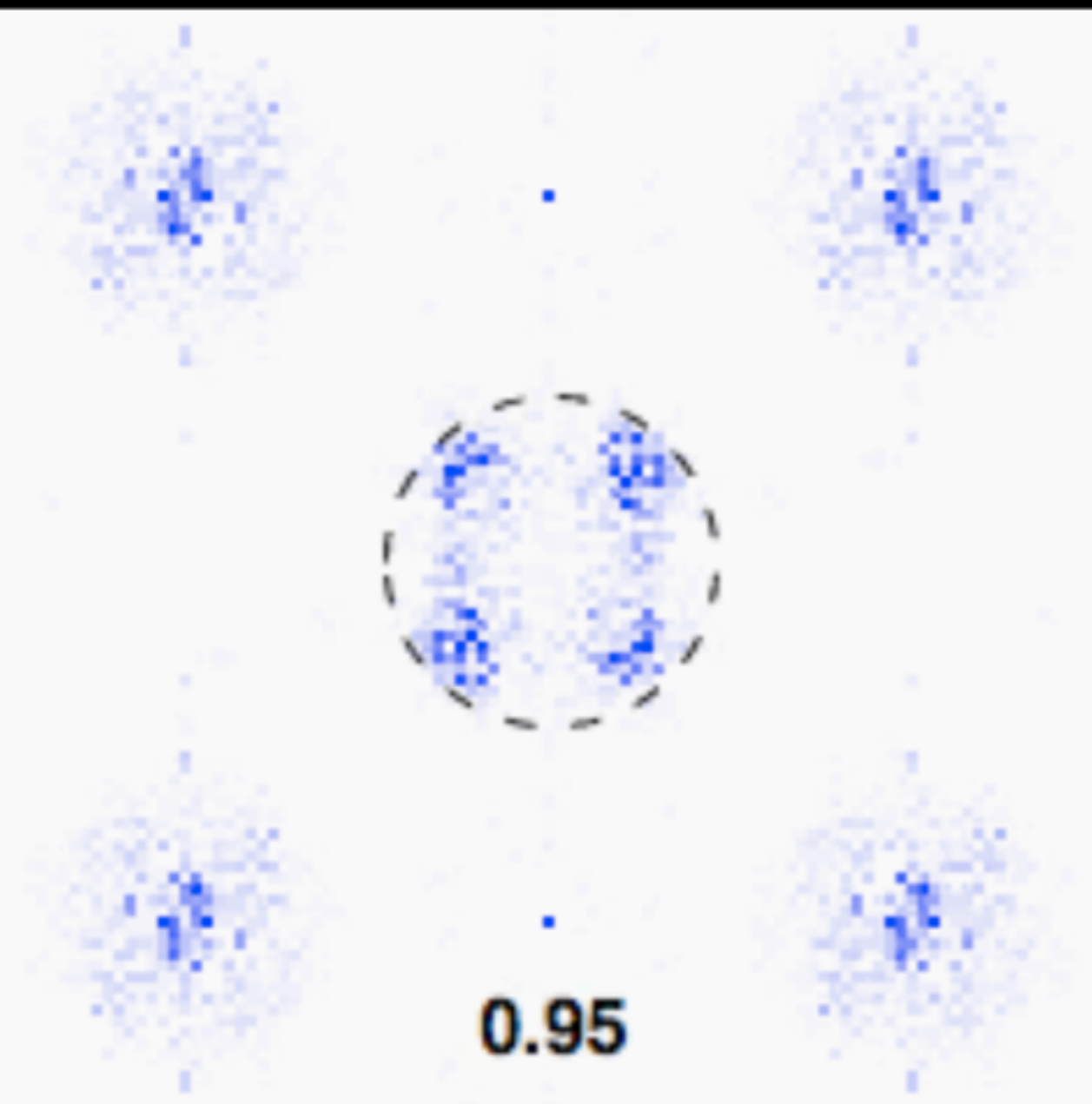
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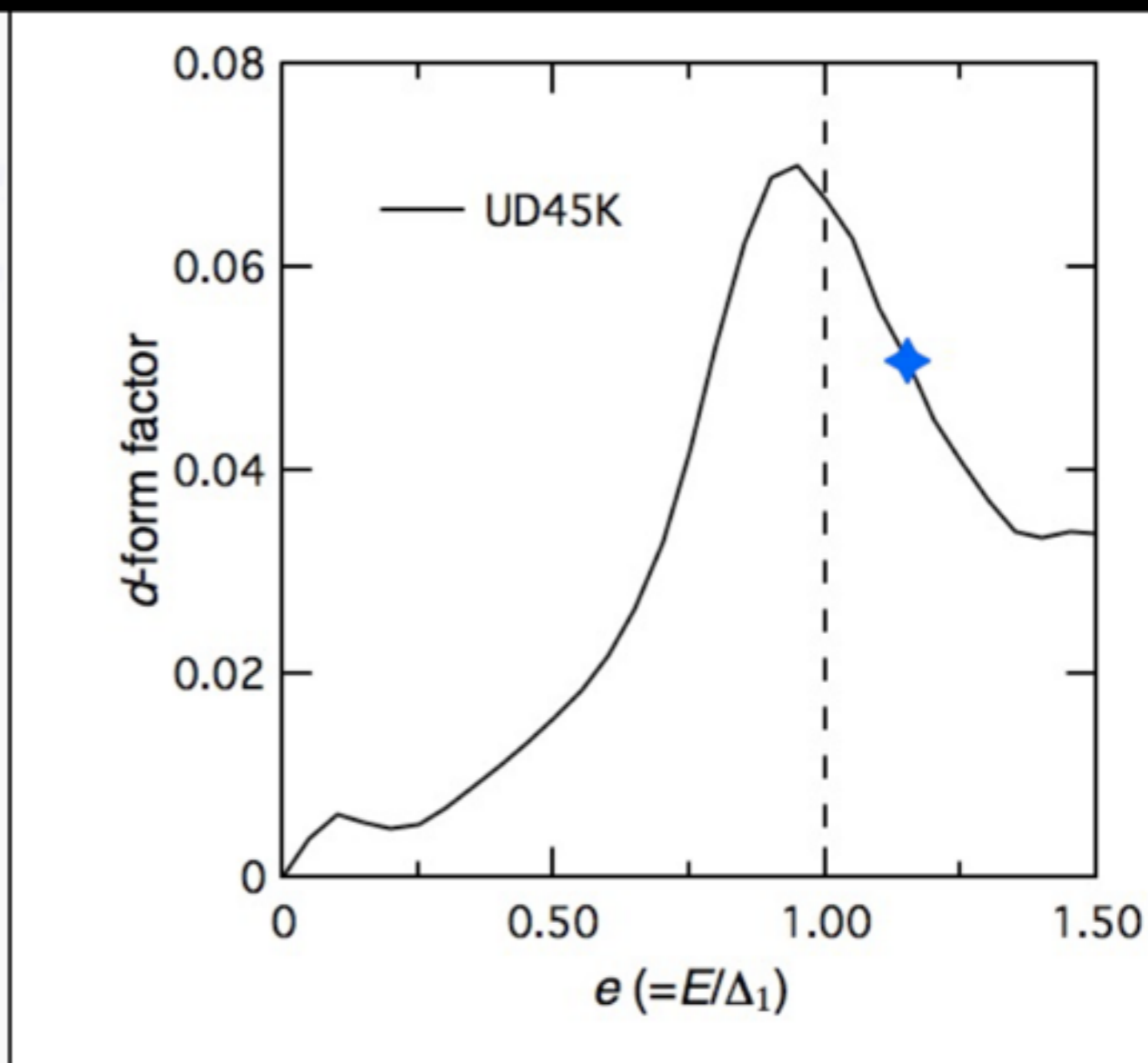
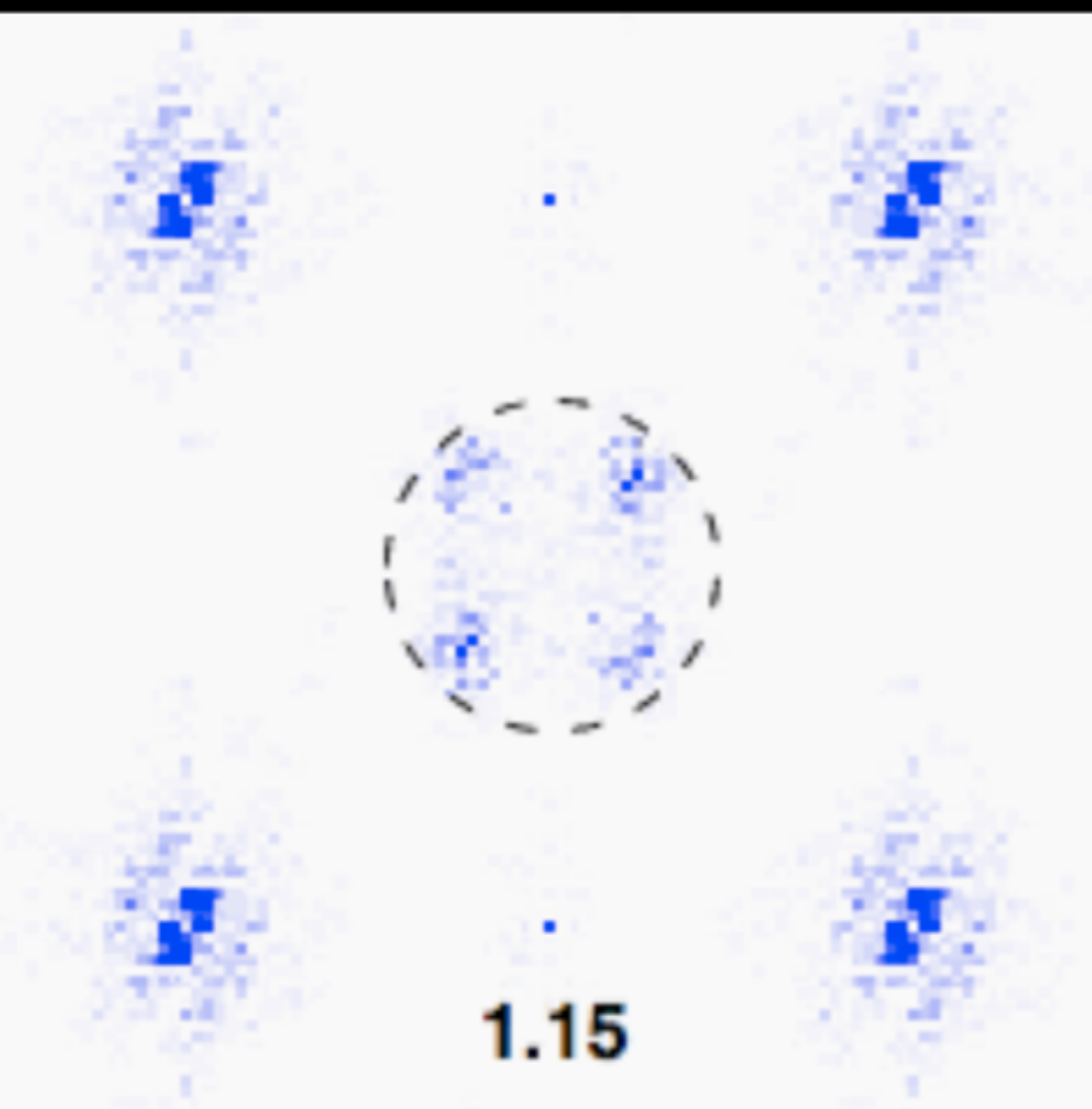
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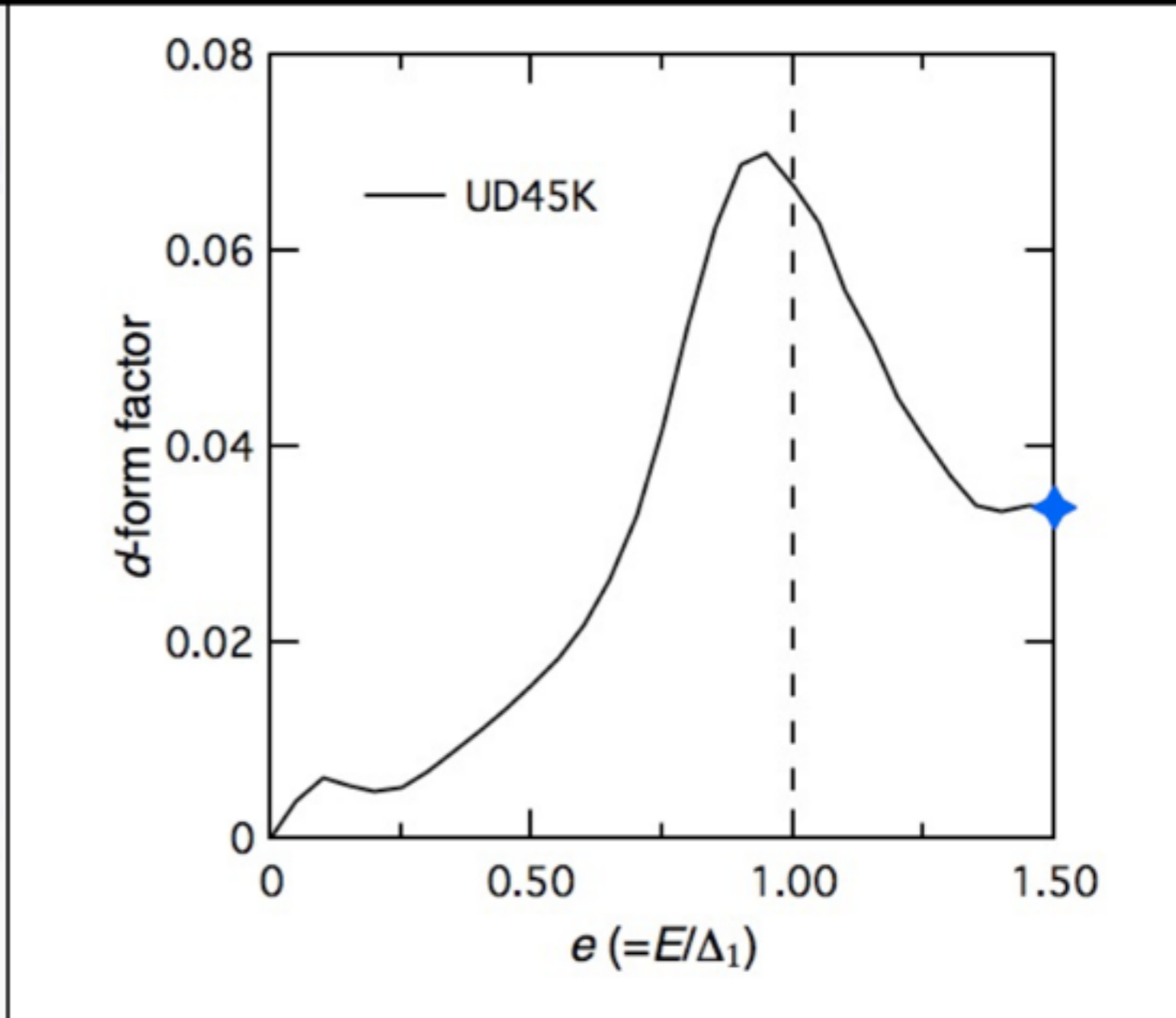
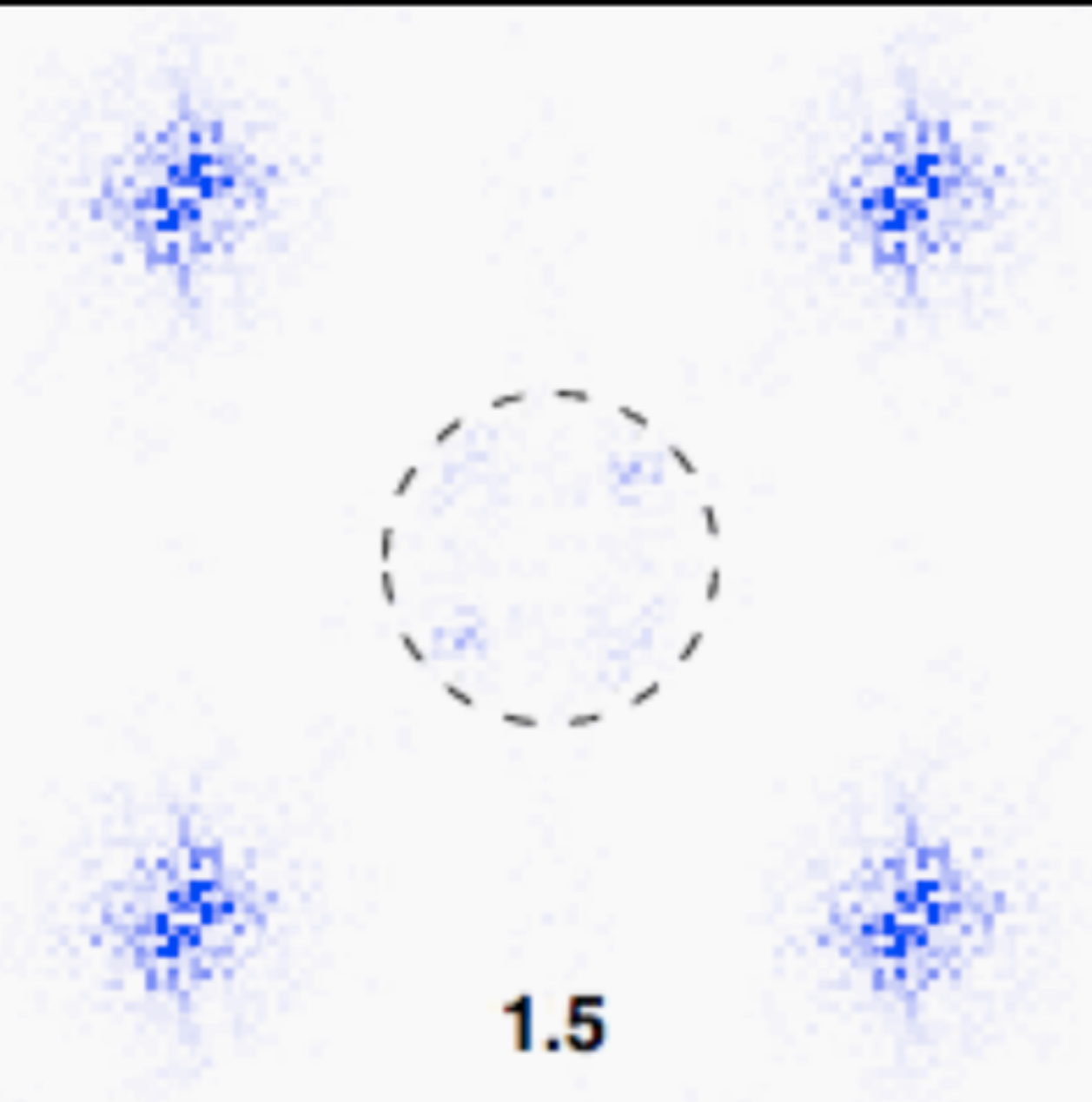
# *d*-form Factor Predominant at Pseudogap Energy



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Spectral weight  
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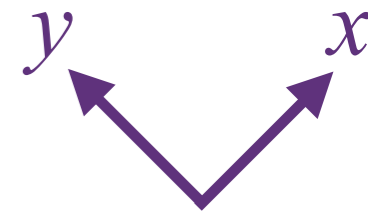
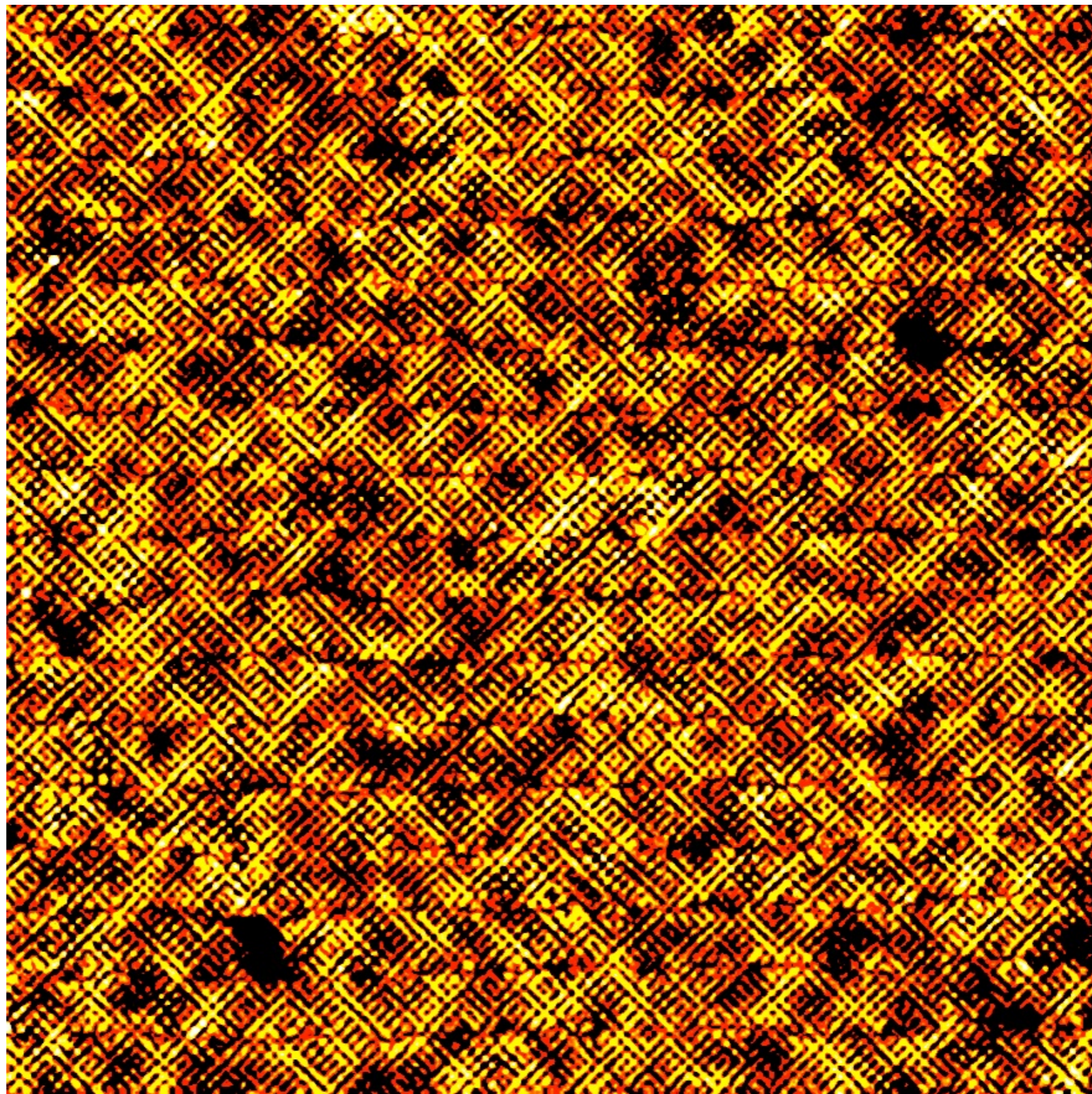
Spectral weight  
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See also

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).



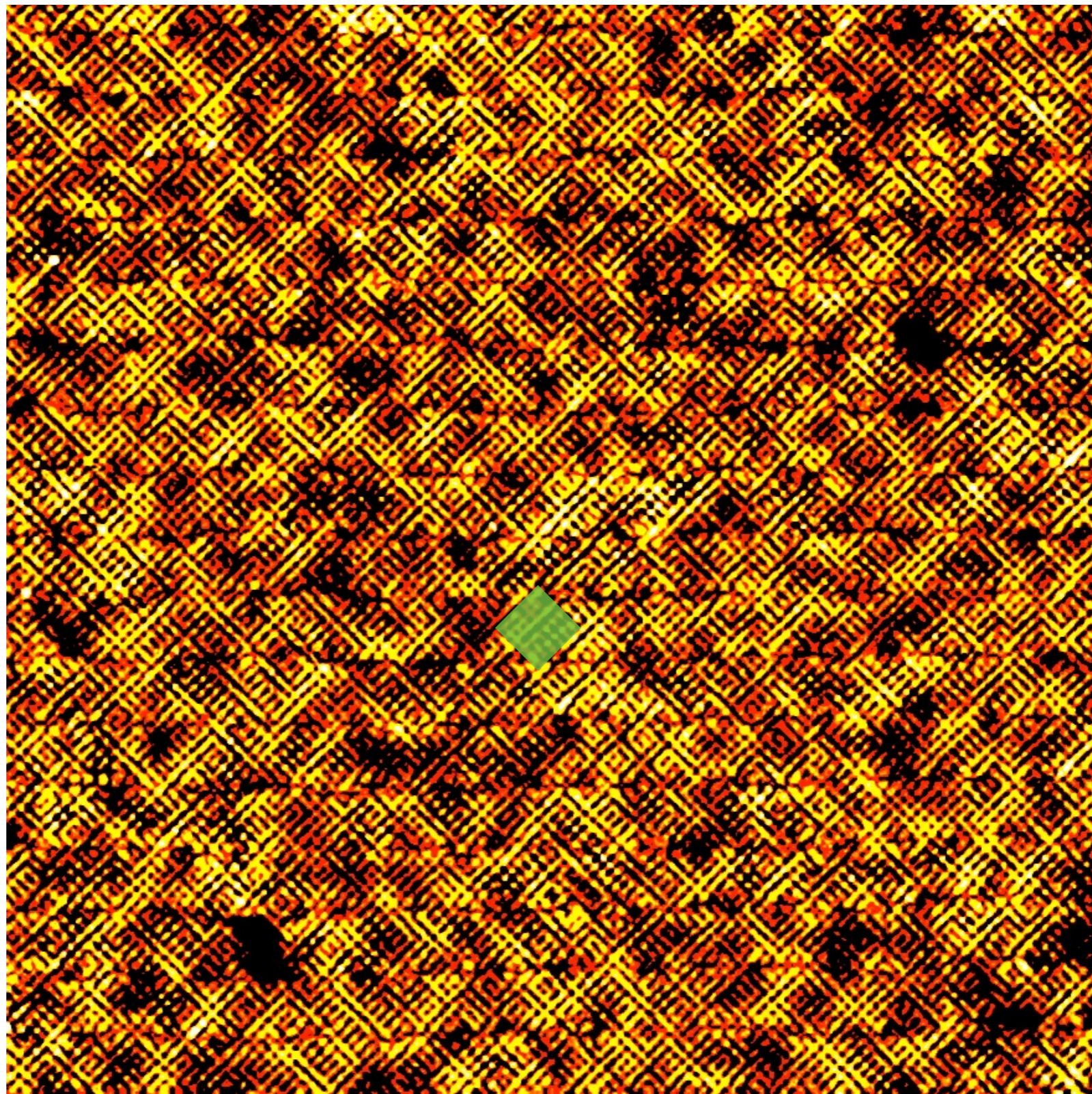
“R-map” of BSCCO in zero magnetic field, similar to those published in Y. Kohsaka, C. Taylor, K. Fujita, A. Schmidt, C. Lupien, T. Hanaguri, M. Azuma, M. Takano, H. Eisaki, H. Takagi, S. Uchida, and J. C. Davis, *Science* **315**, 1380 (2007). **Davis group has sub-angstrom resolution capabilities, with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

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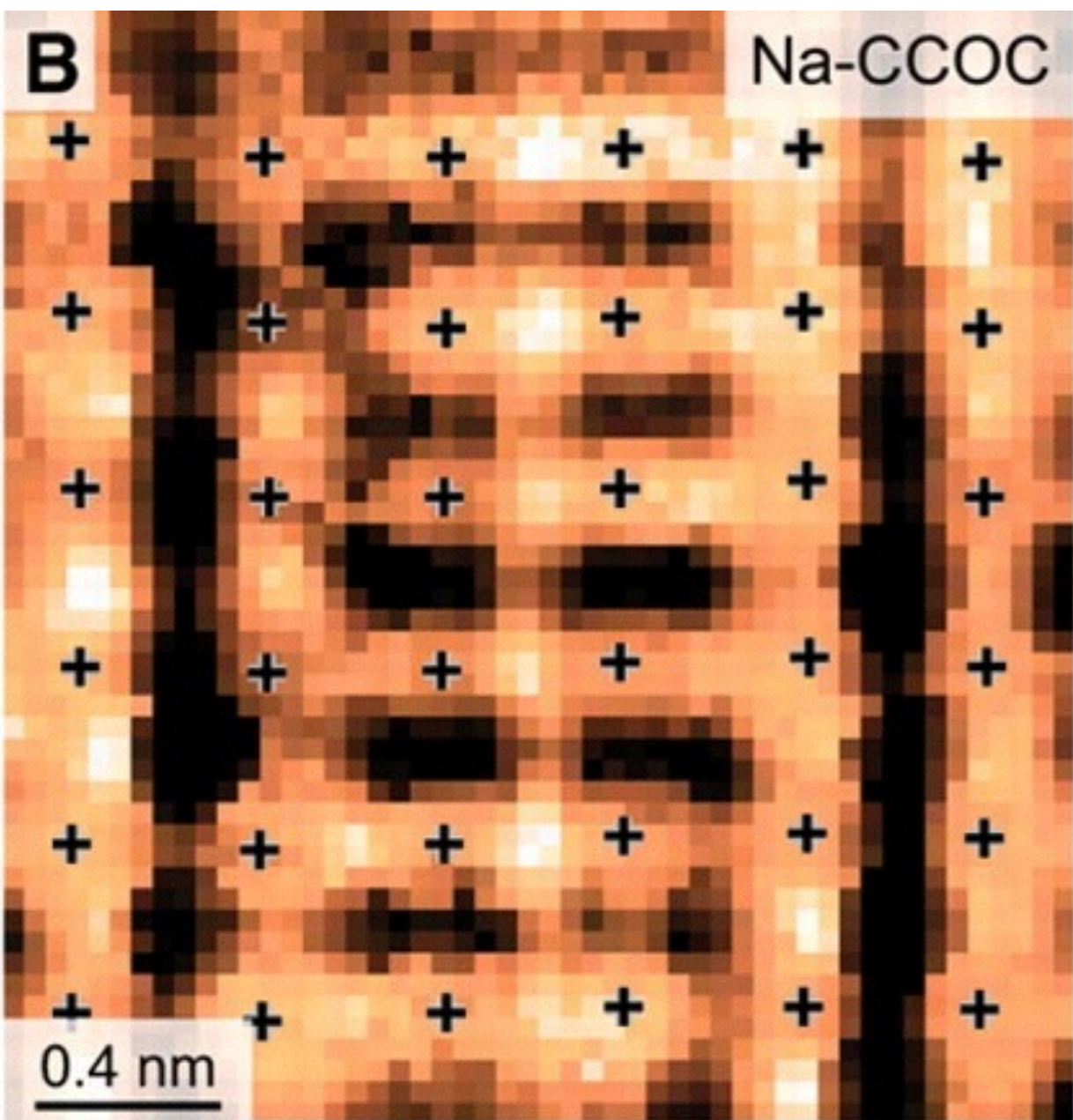
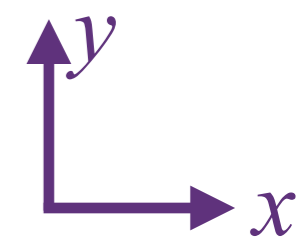
C. Howald, H. Eisaki,  
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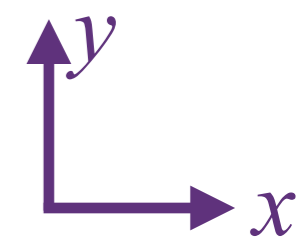
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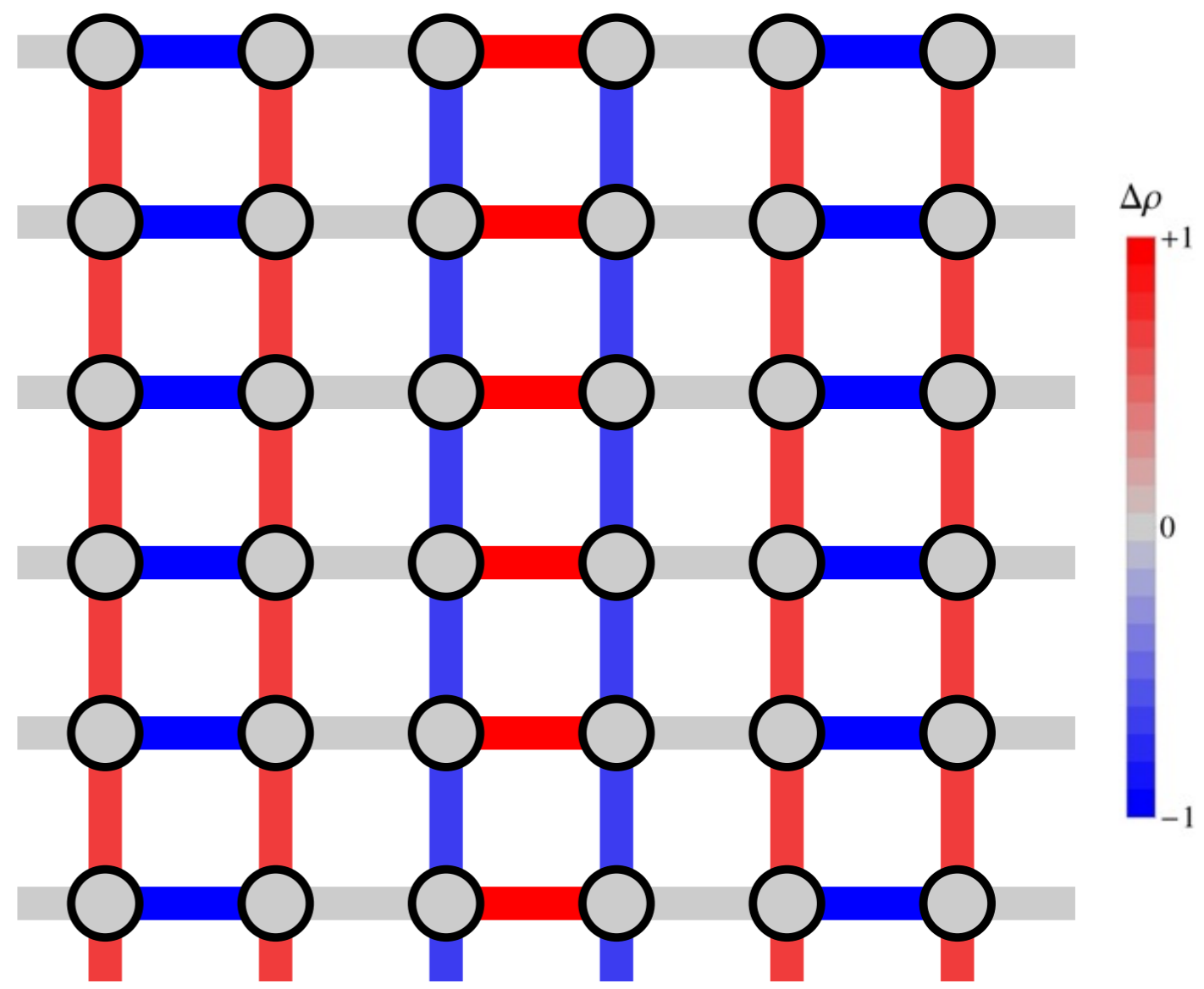
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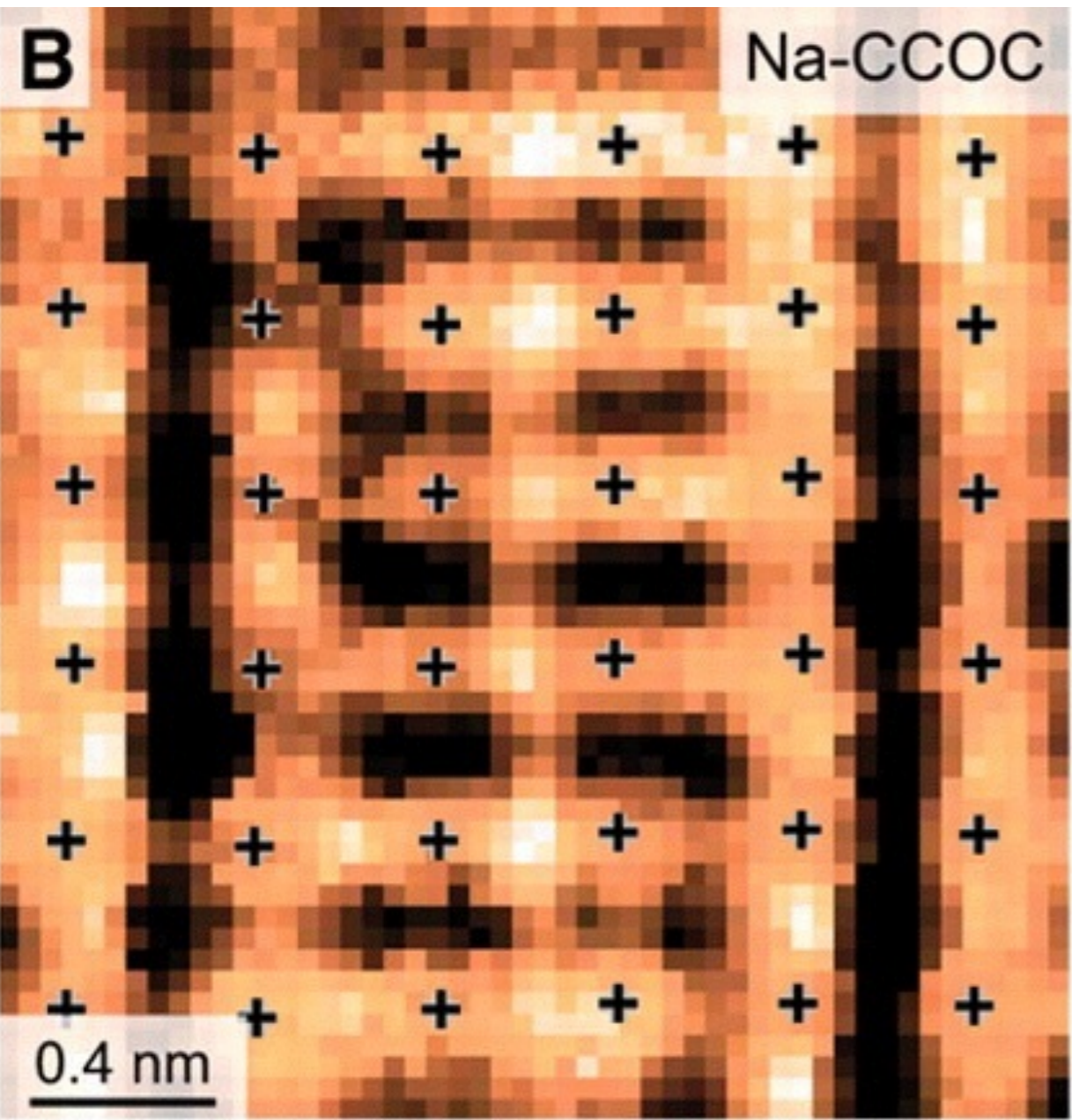
Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)



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

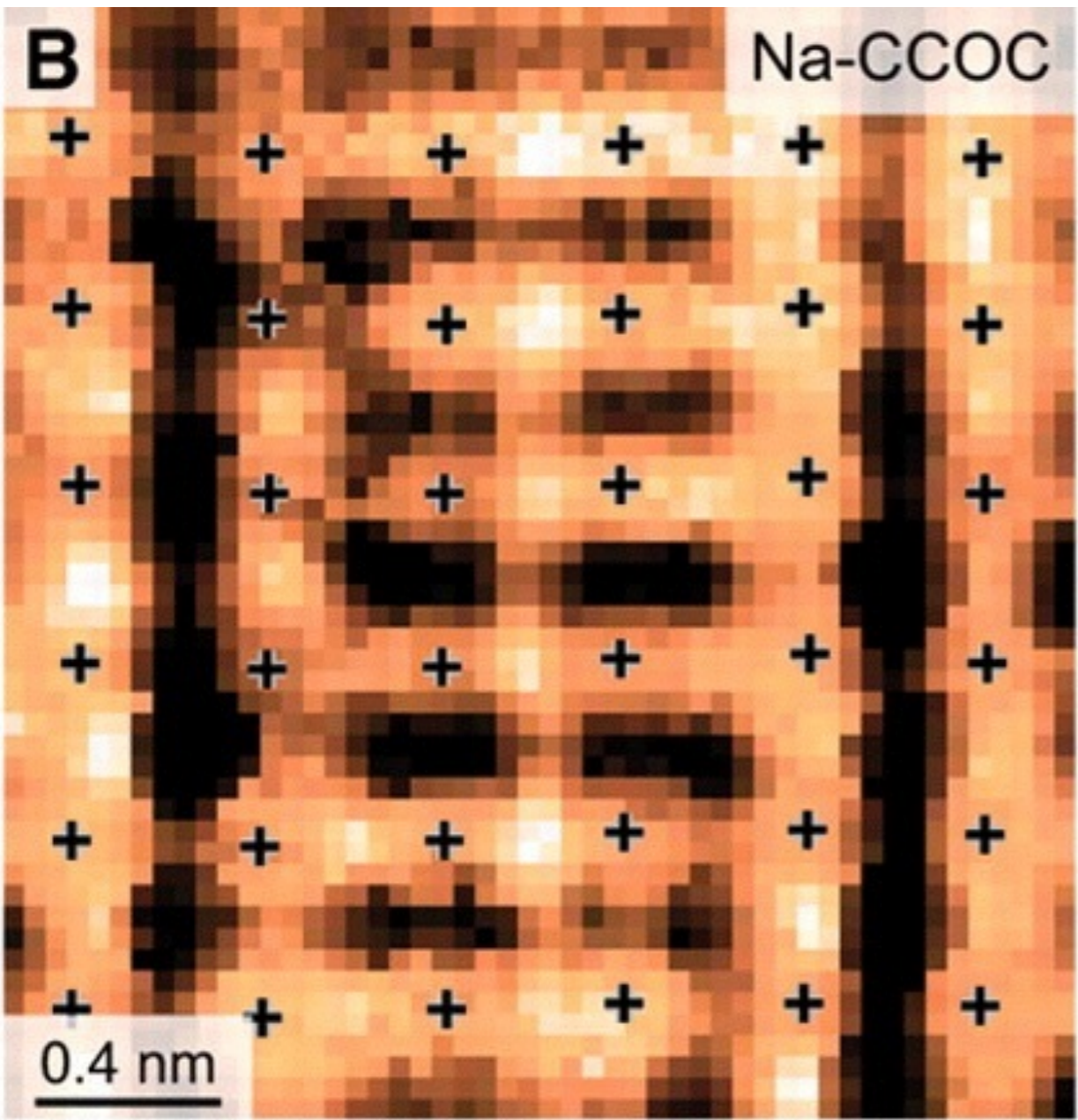
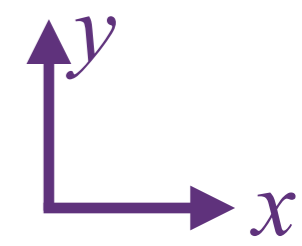


*d*-form factor density wave order

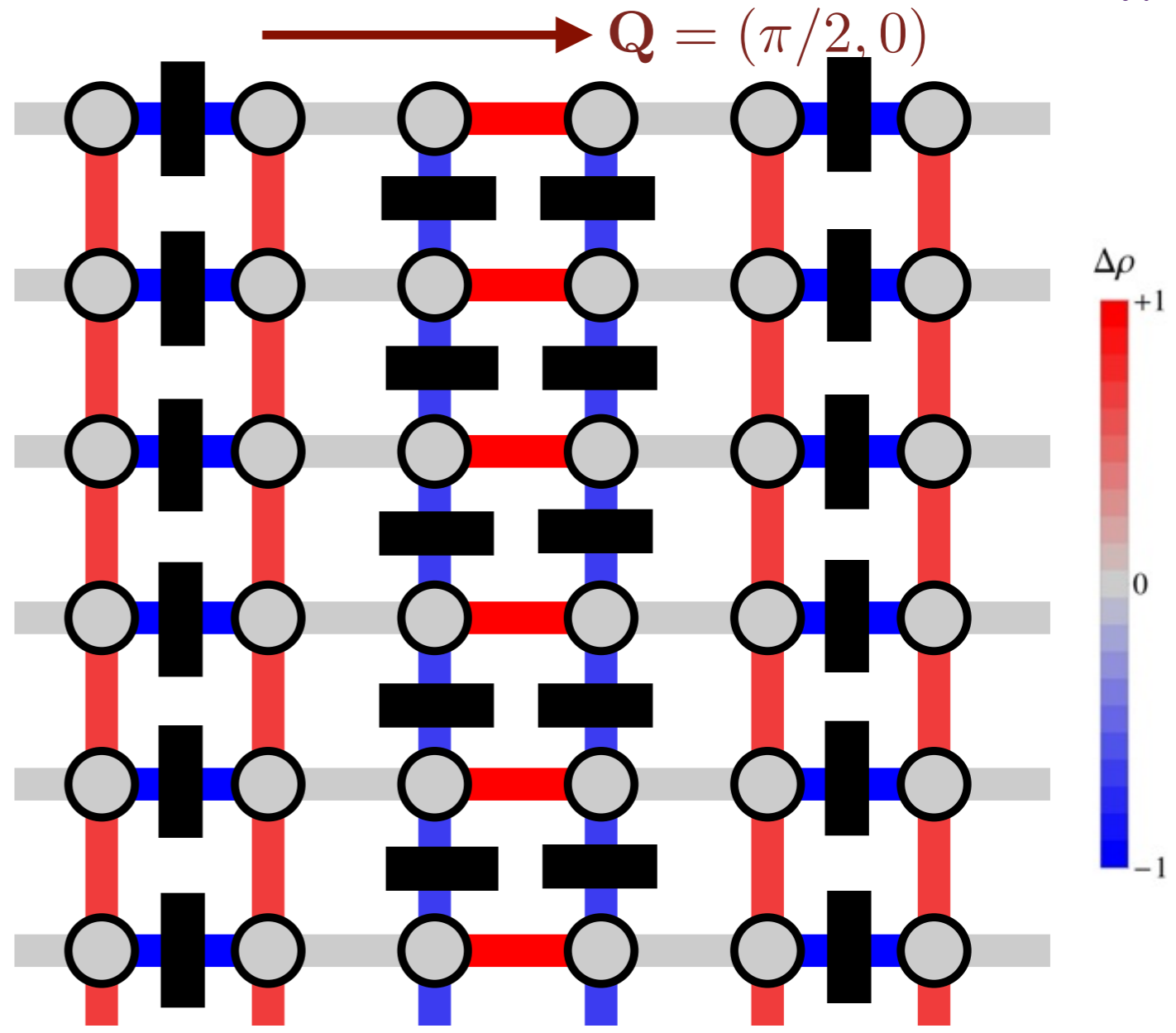


Y. Kohsaka *et al.*, SCIENCE **315**, 1380 (2007)

This specific *d*-form factor density wave order (with  $\mathbf{Q}$  along the axes) was first predicted in S. Sachdev and R. LaPlaca, Phys. Rev. Lett. **111**, 027202 (2013).

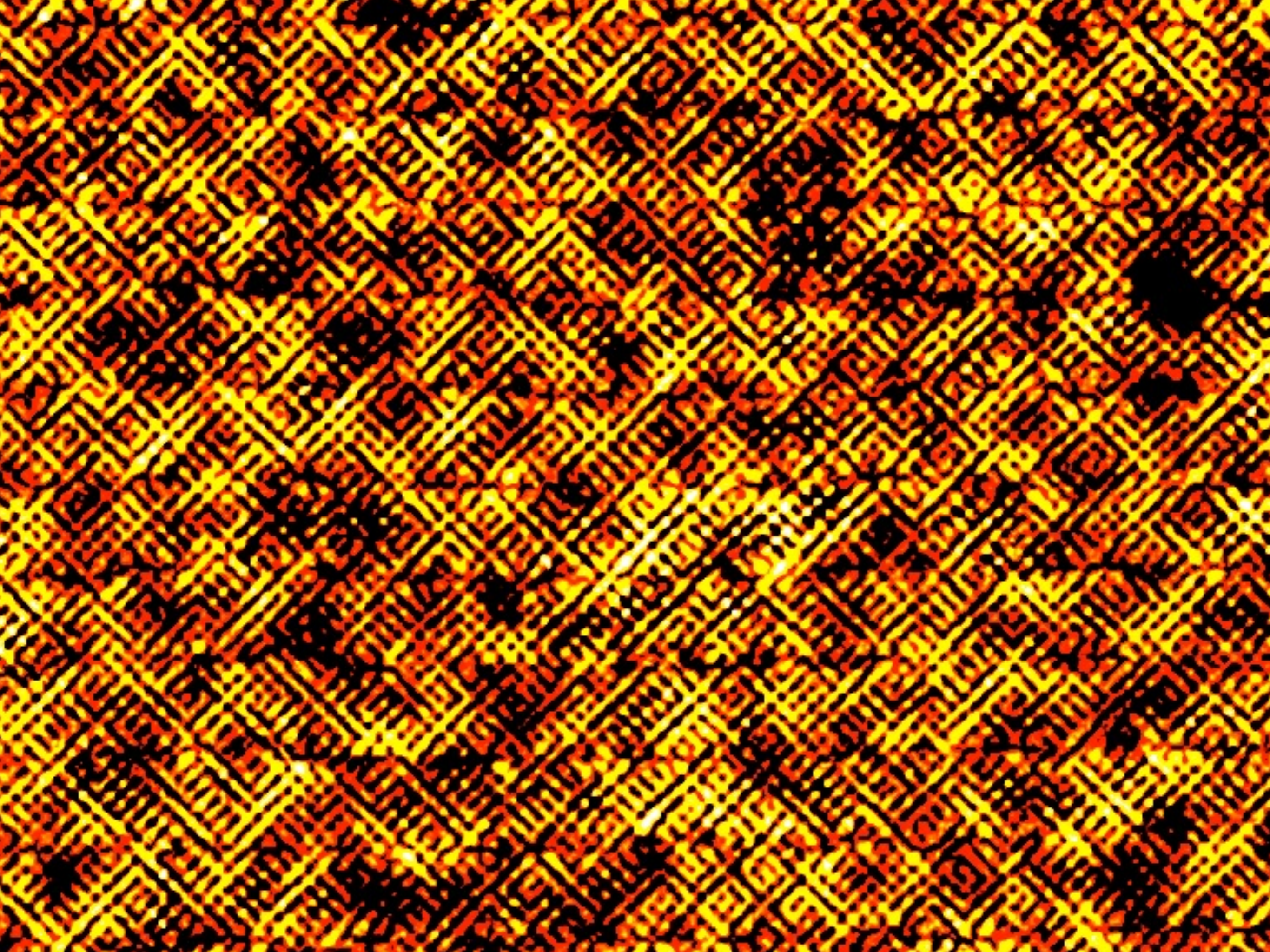


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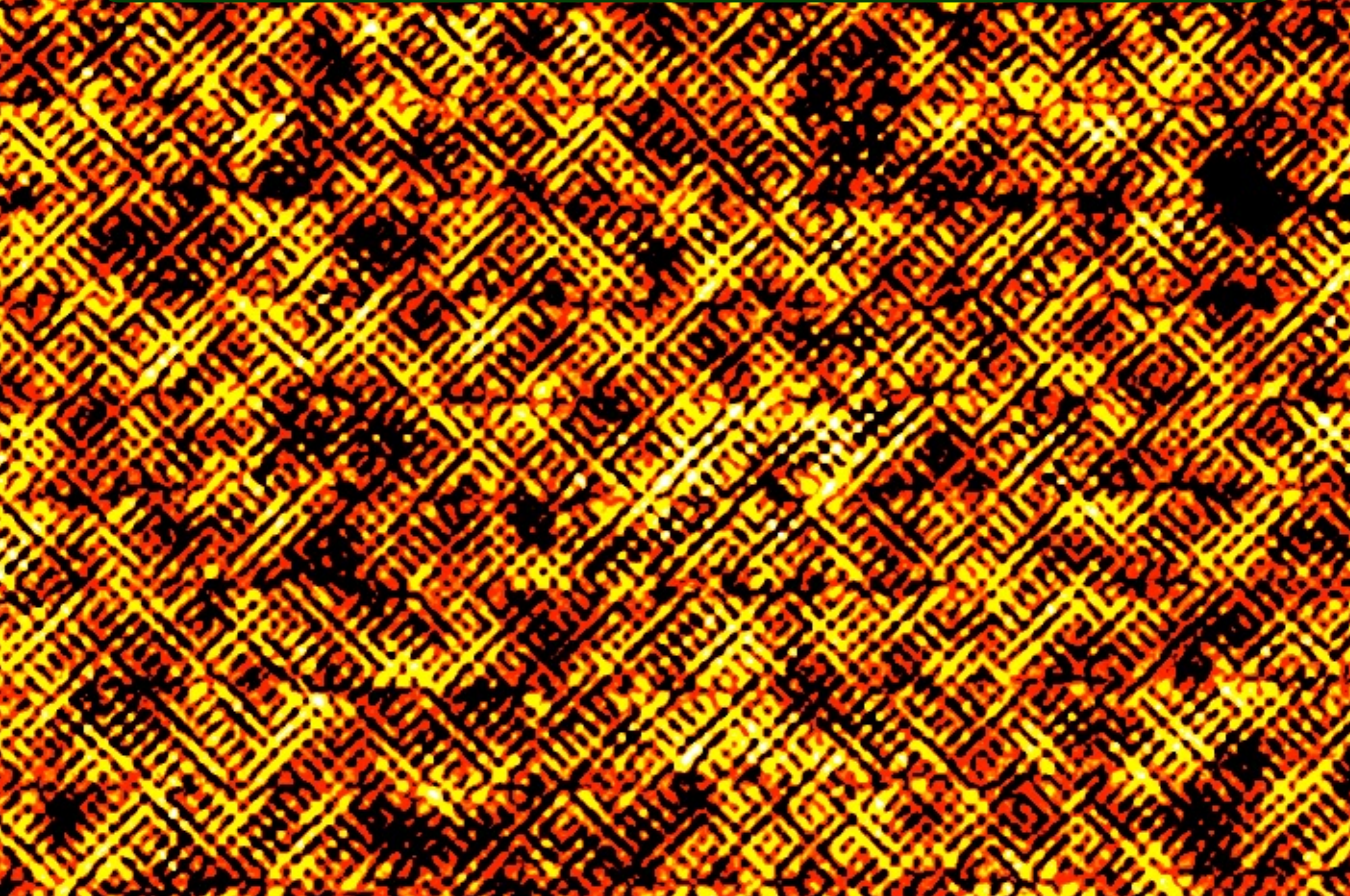


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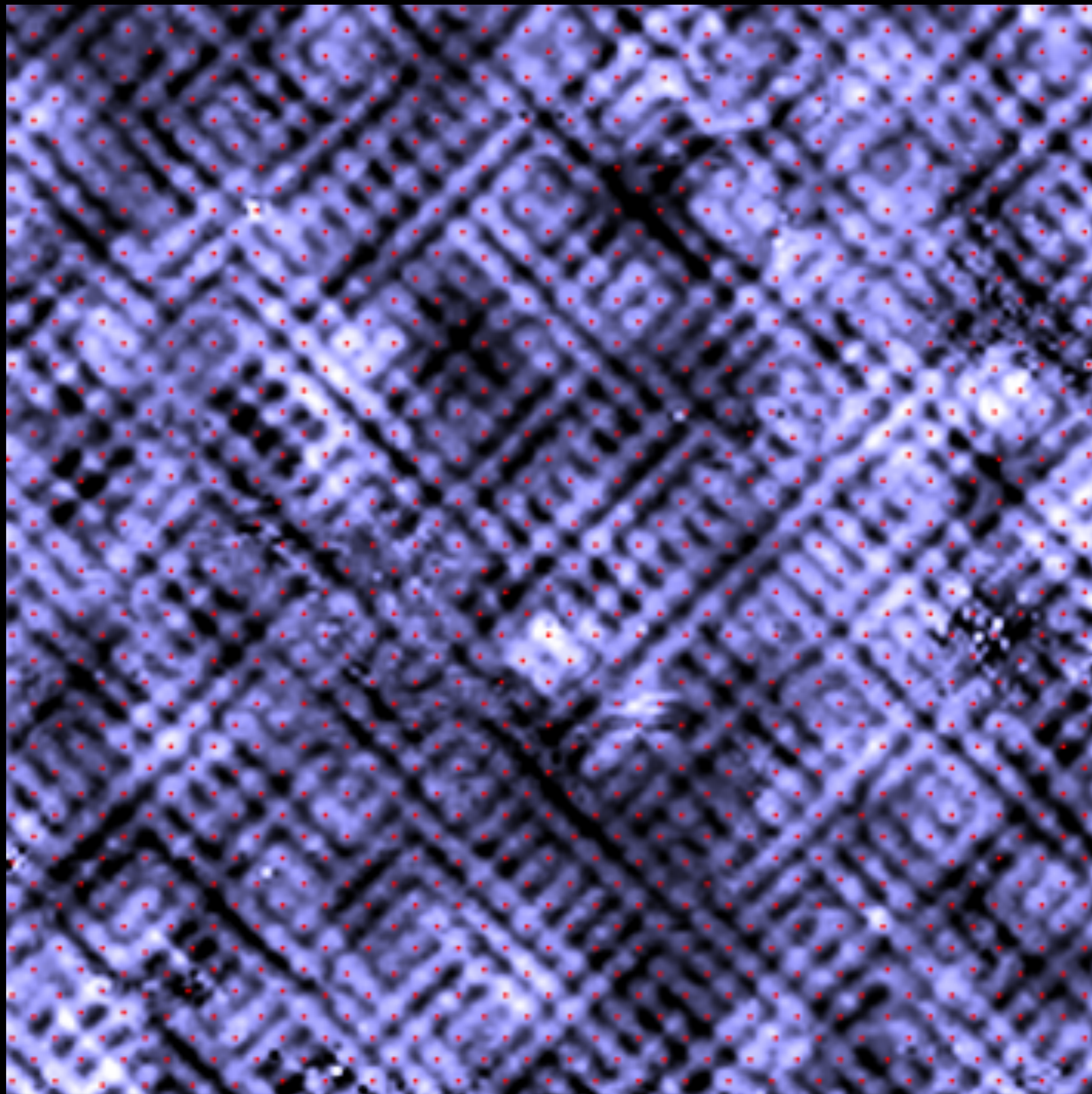
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$d$  form-factor density wave has unidirectional domains

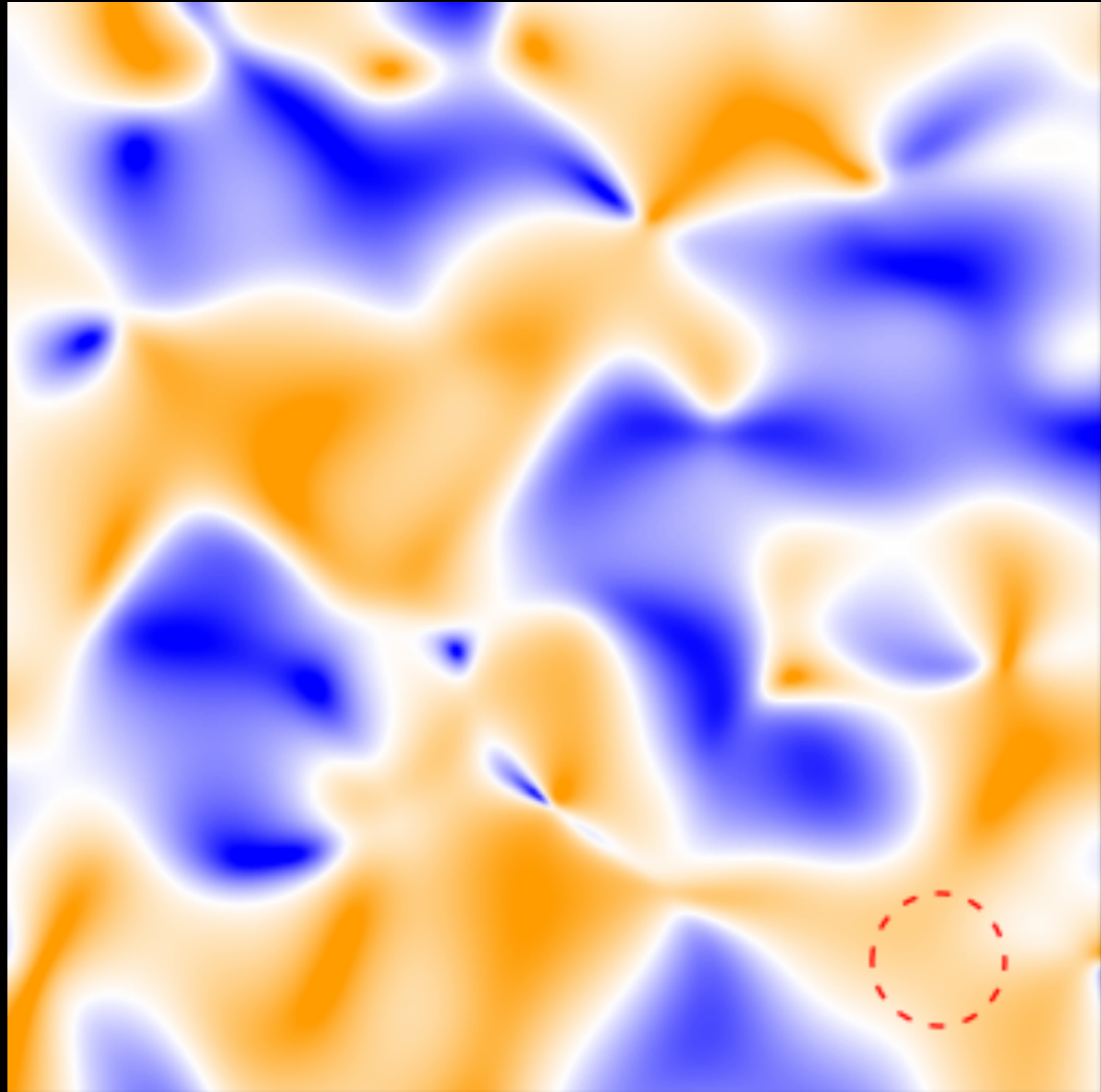


# dFF-DW Unidirectional Domains



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

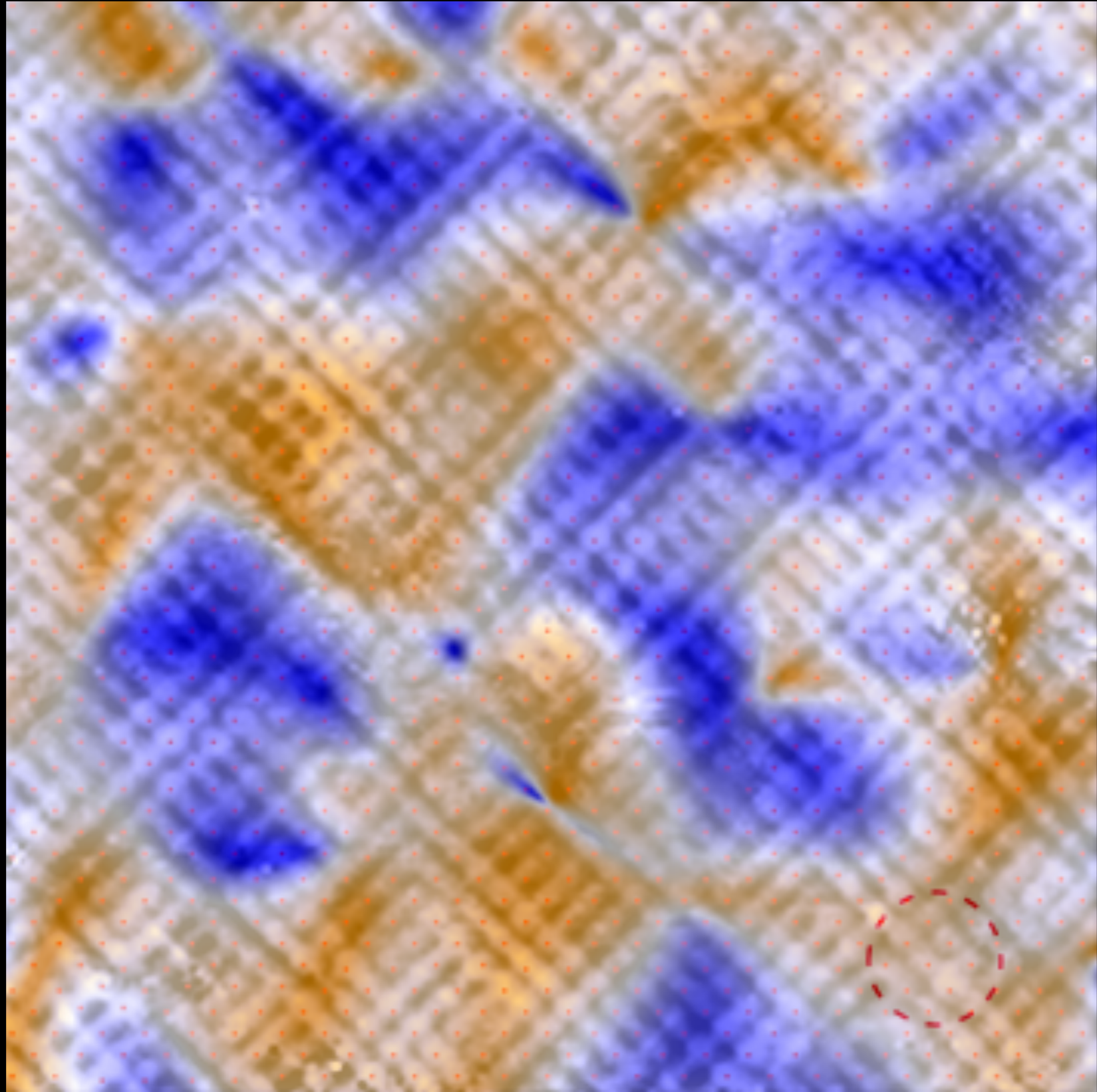
# dFF-DW Unidirectional Domains



$$\frac{(|O_y(r,q=Q_x)| - |O_x(r,q=Q_y)|)}{(|O_y(r,q=Q_x)| + |O_x(r,q=Q_y)|)}$$

Primary DW direction Orange :  $// (1,0)$ , Blue :  $// (0,1)$

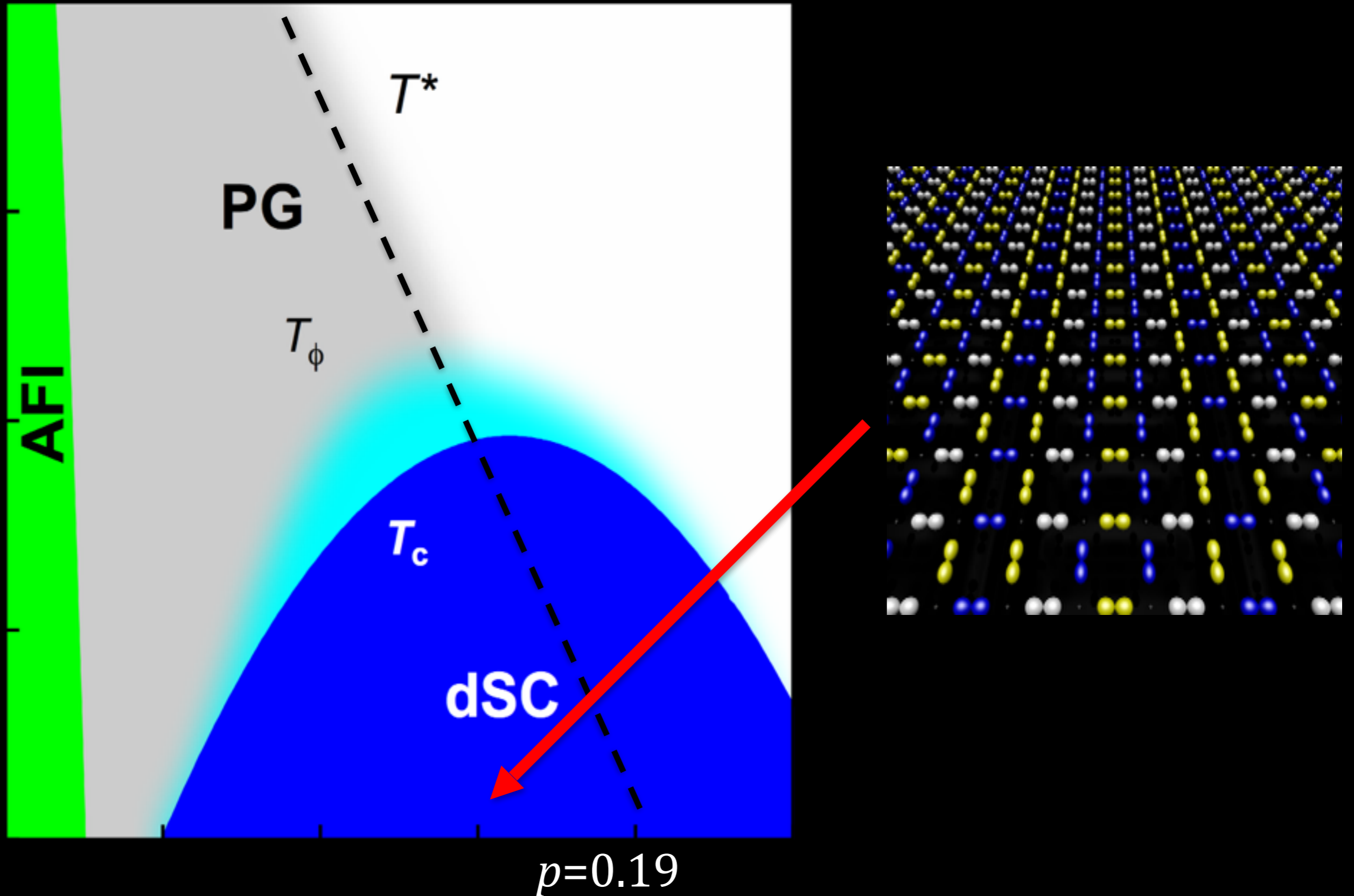
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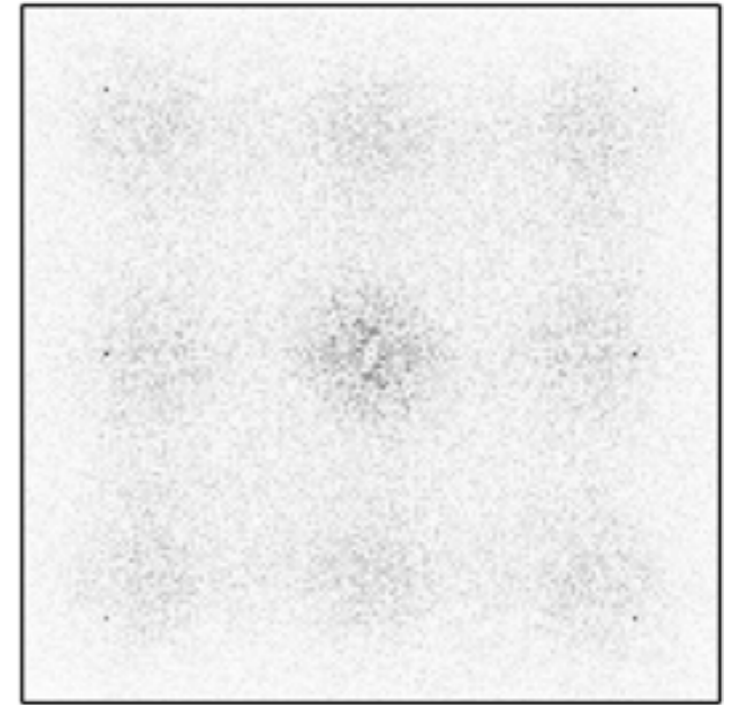
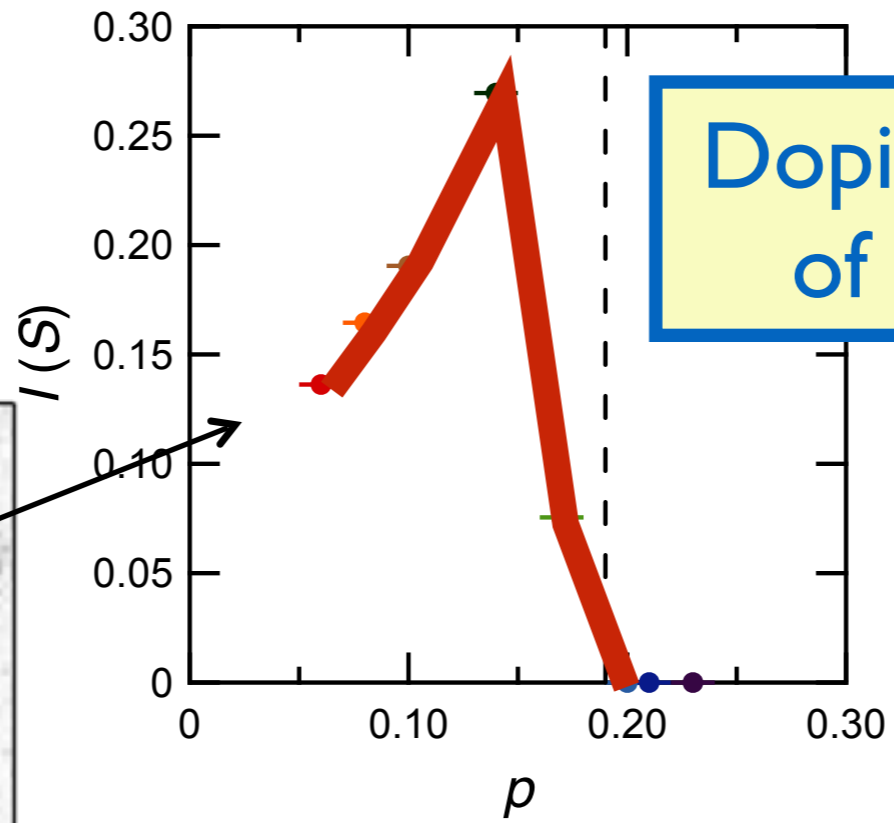
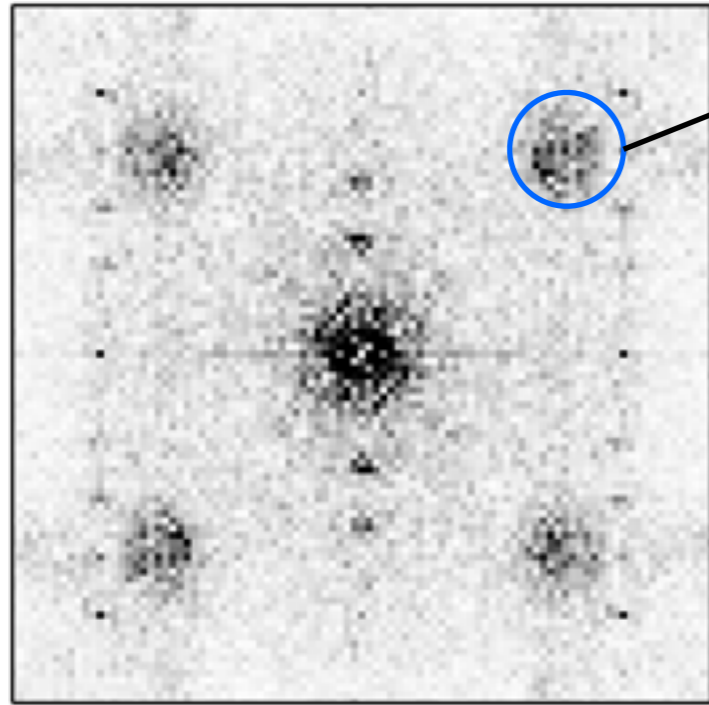


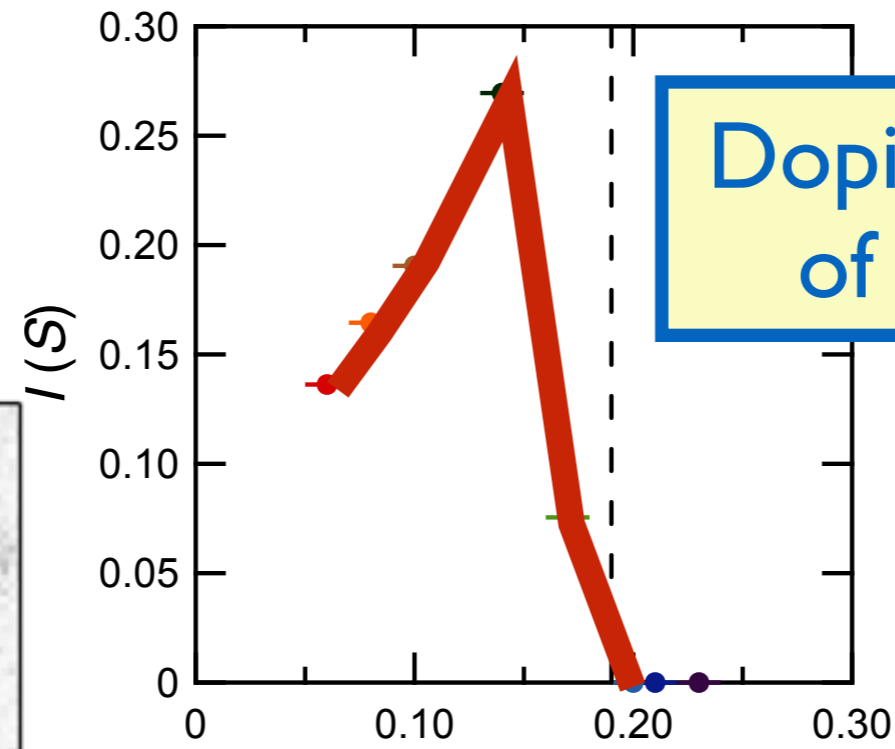
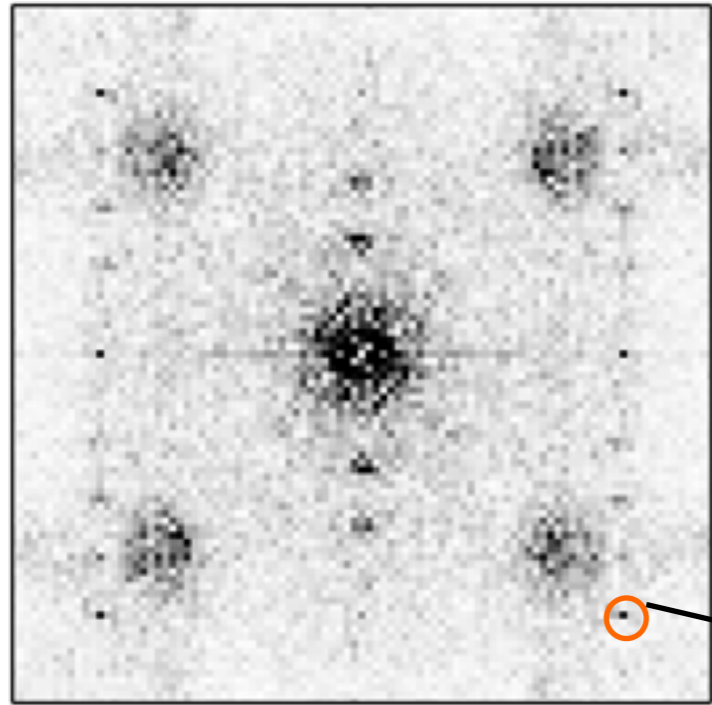
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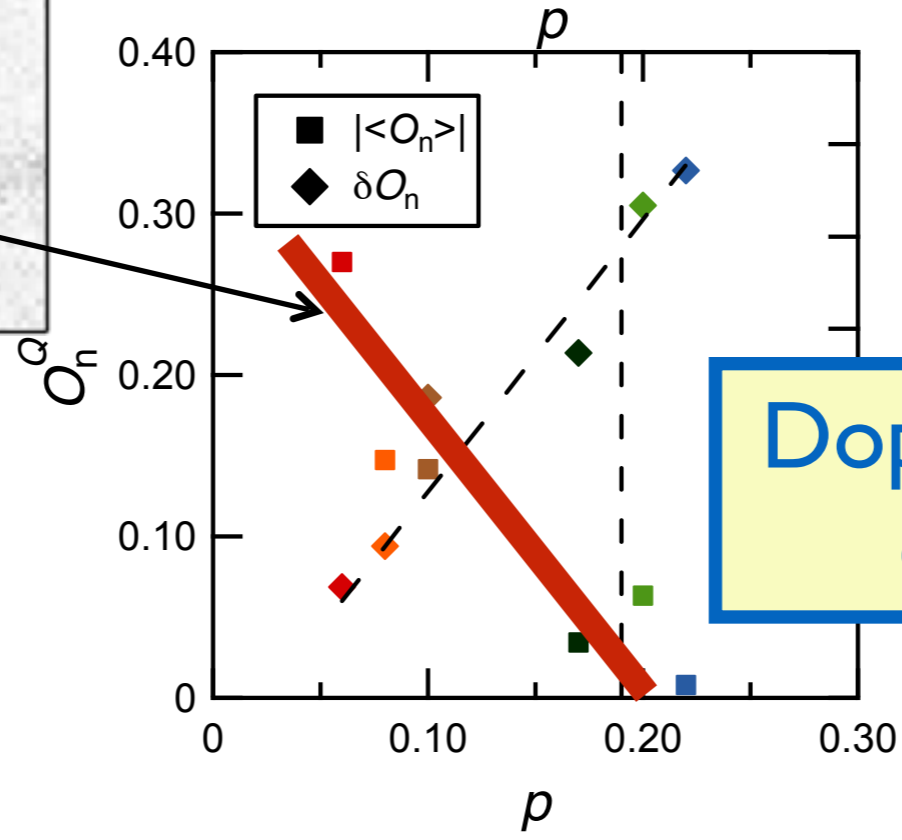
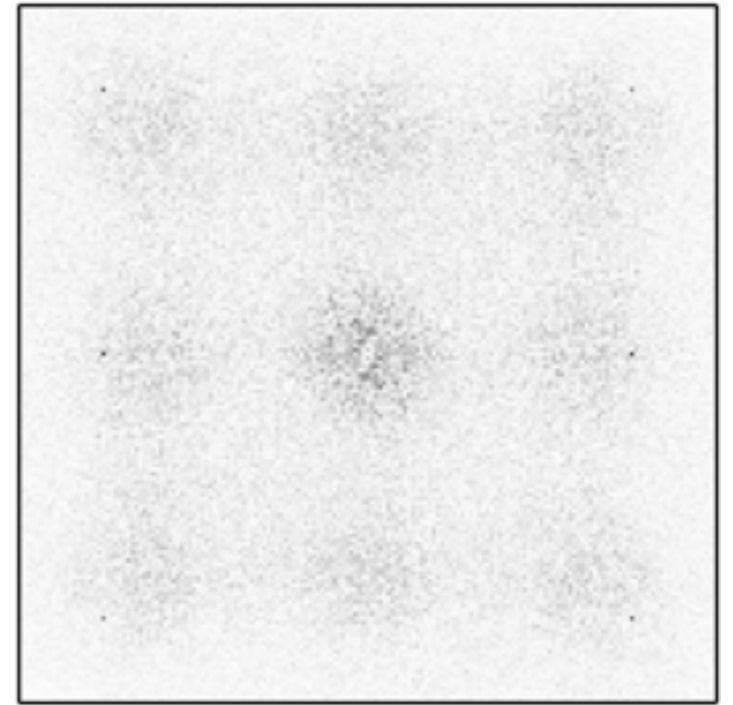
# Phase-resolved Visualization of $d$ -form factor DW in Cuprates



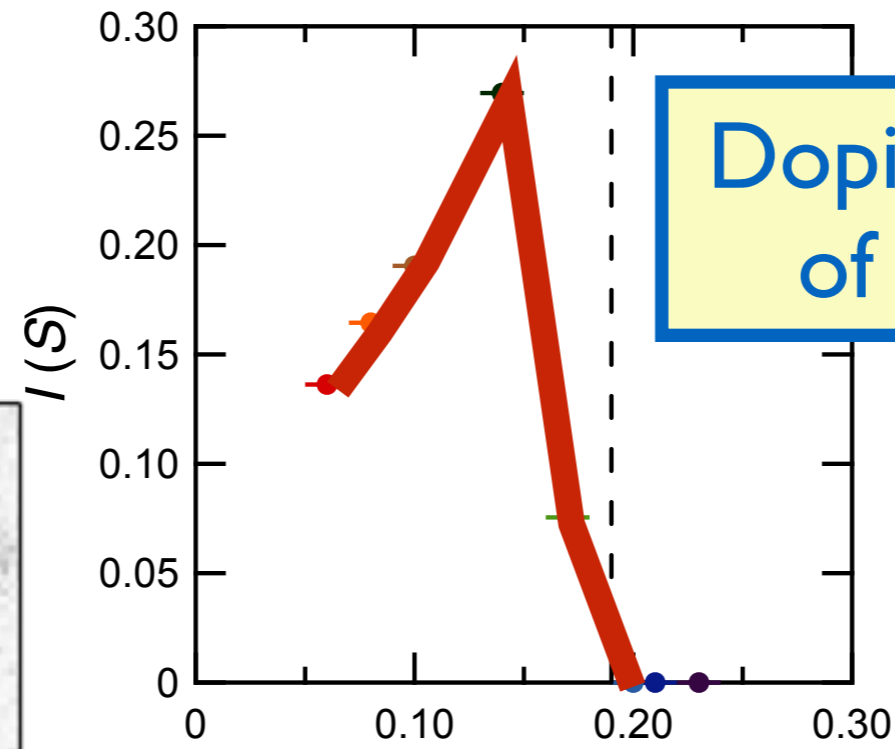
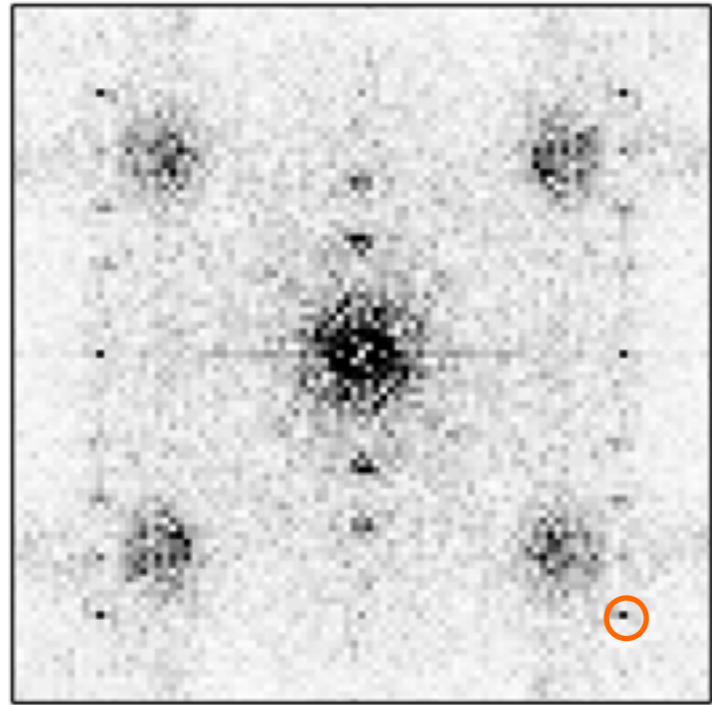




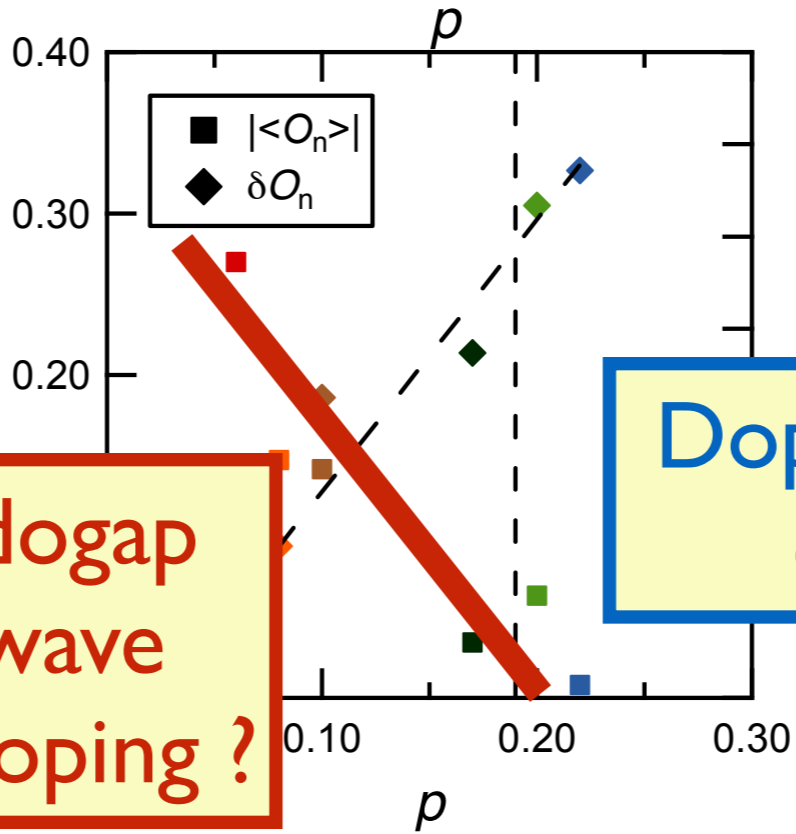
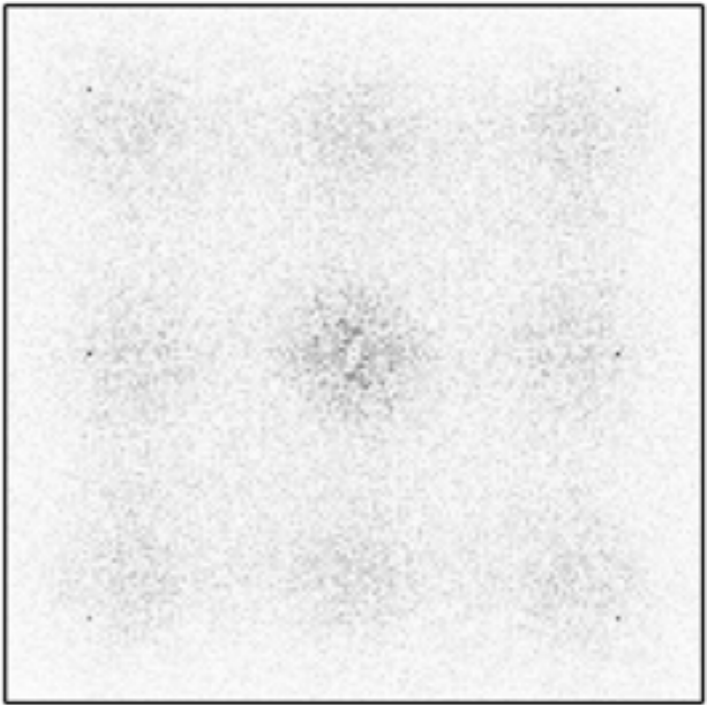
Doping dependence of density wave



Doping dependence of nematicity



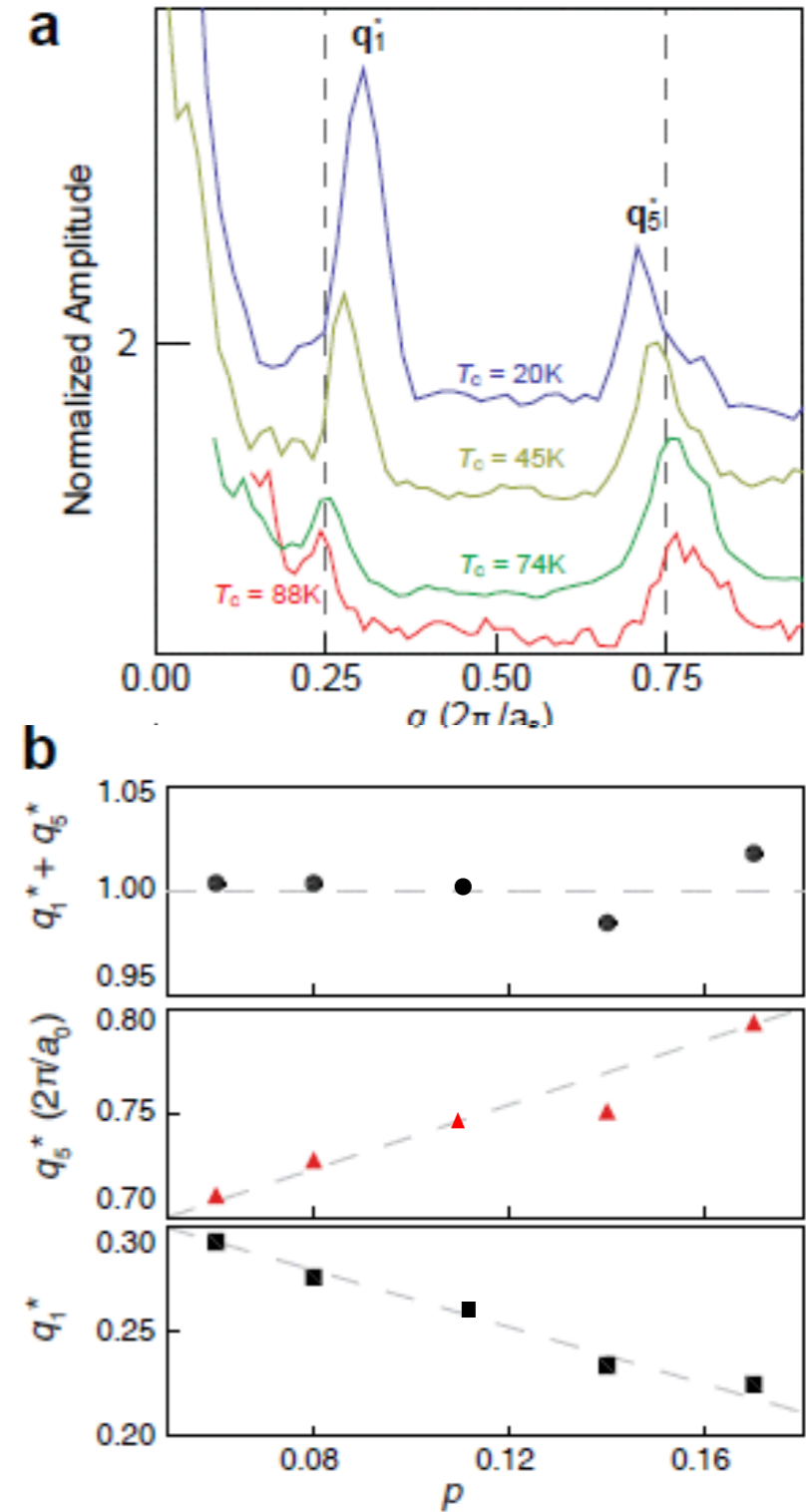
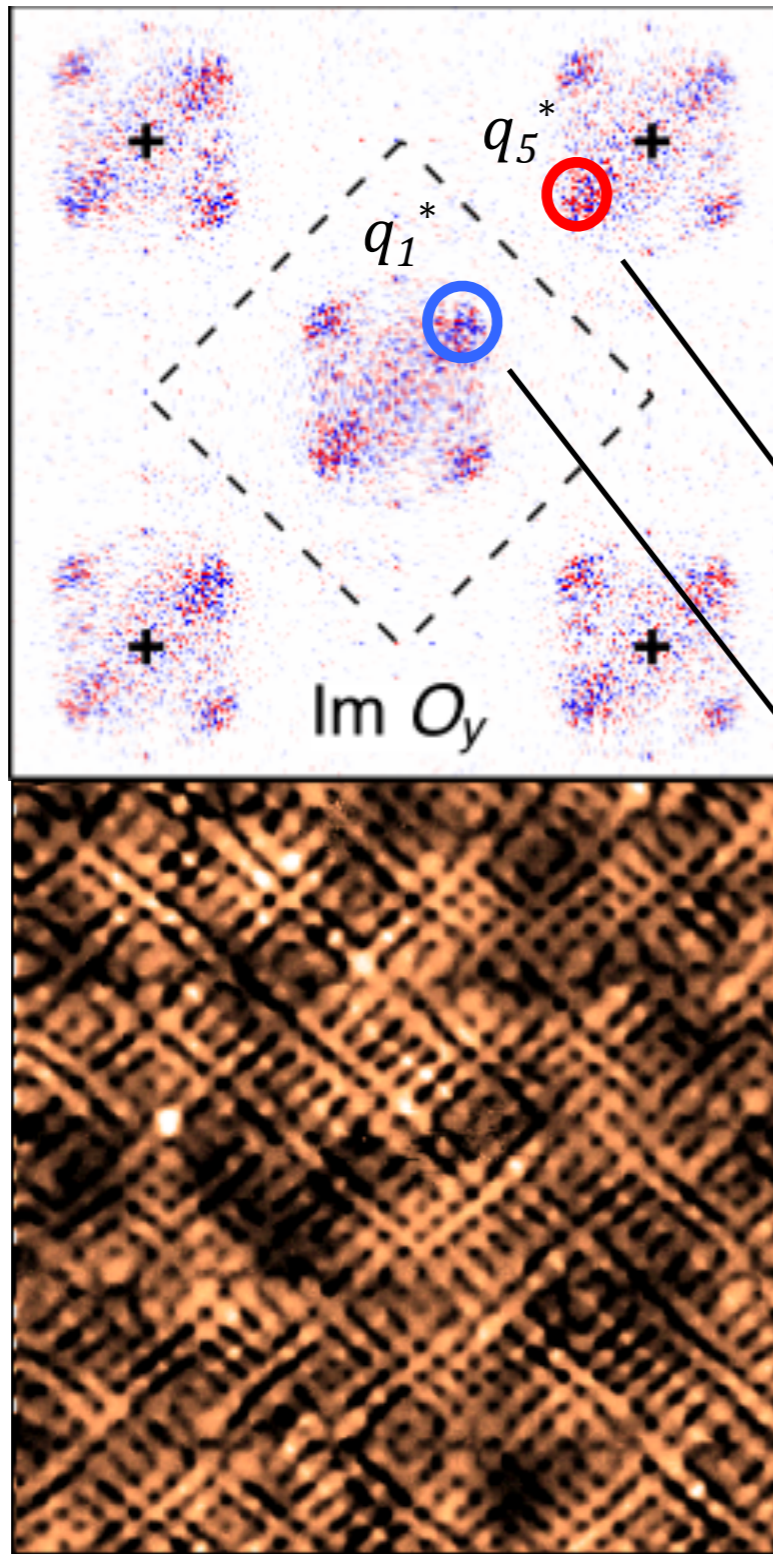
Doping dependence of density wave



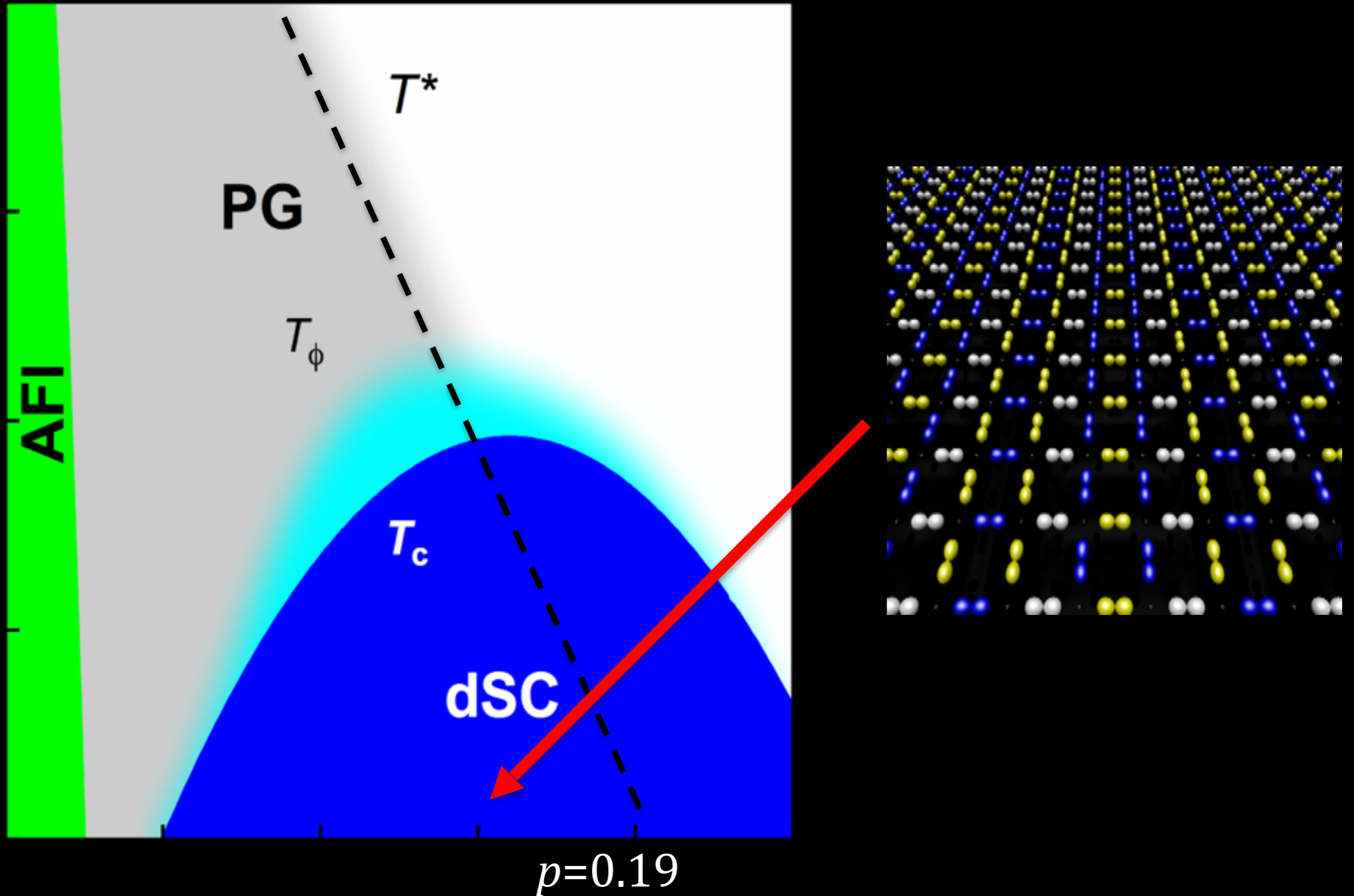
Doping dependence of nematicity

Nematicity and pseudogap tied to spin density wave fluctuations at lower doping ?

# Doping Dependence of DW Wavevector



# Phase-resolved Visualization of $d$ -form factor DW in Cuprates



# Outline

## 1. STM observation of $d$ -form factor density wave

*Close connection to pseudogap of cuprates;*

*Relationship to nematicity*

## 2. Transport near the Ising-nematic quantum critical point

*Domination of “drag” effects, and*

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## 1. STM observation of $d$ -form factor density wave

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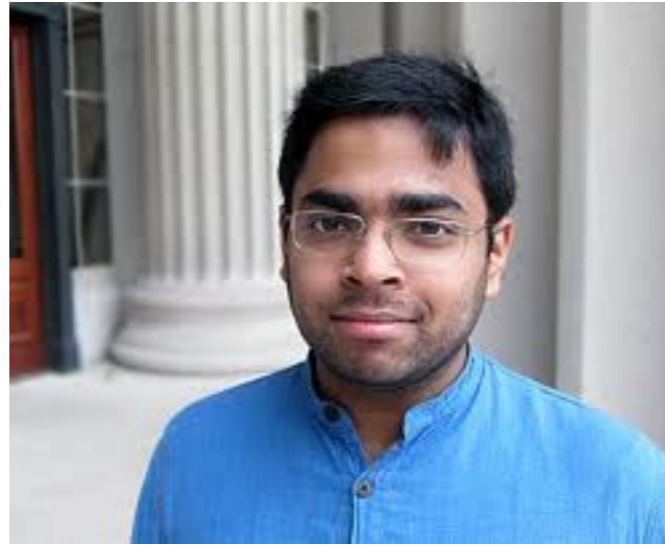
## 2. Transport near the Ising-nematic quantum critical point

*Domination of “drag” effects, and*

*random “field” perturbations*



Sean Hartnoll  
Stanford



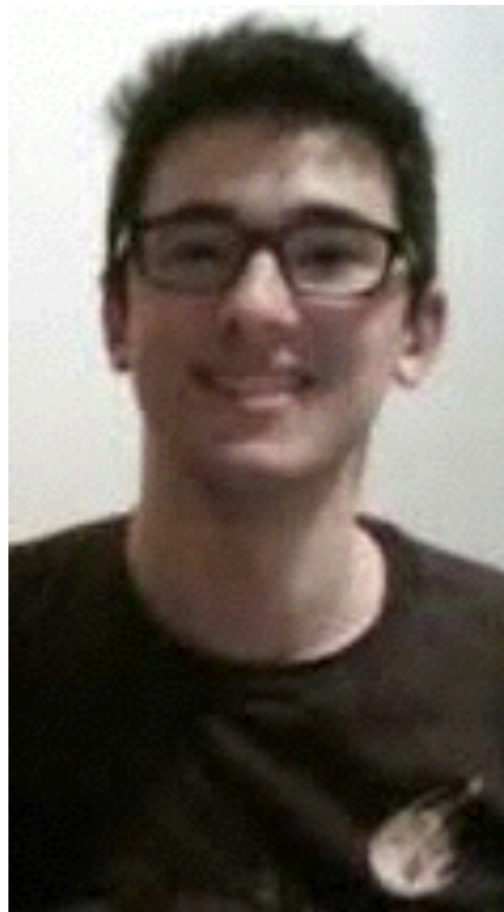
Raghu Mahajan  
Stanford



Matthias Punk  
Innsbruck

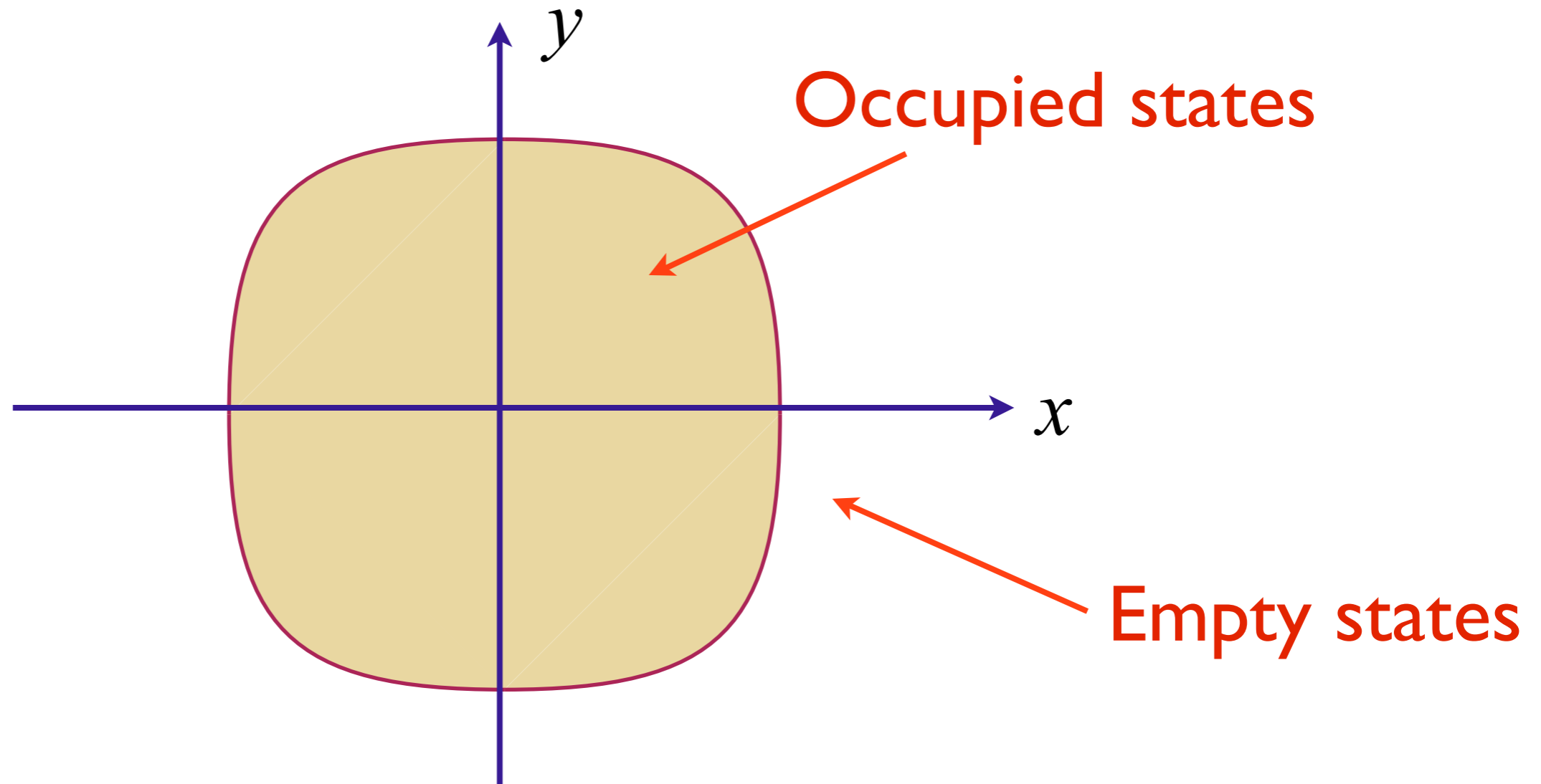


Koenraad Schalm  
Leiden



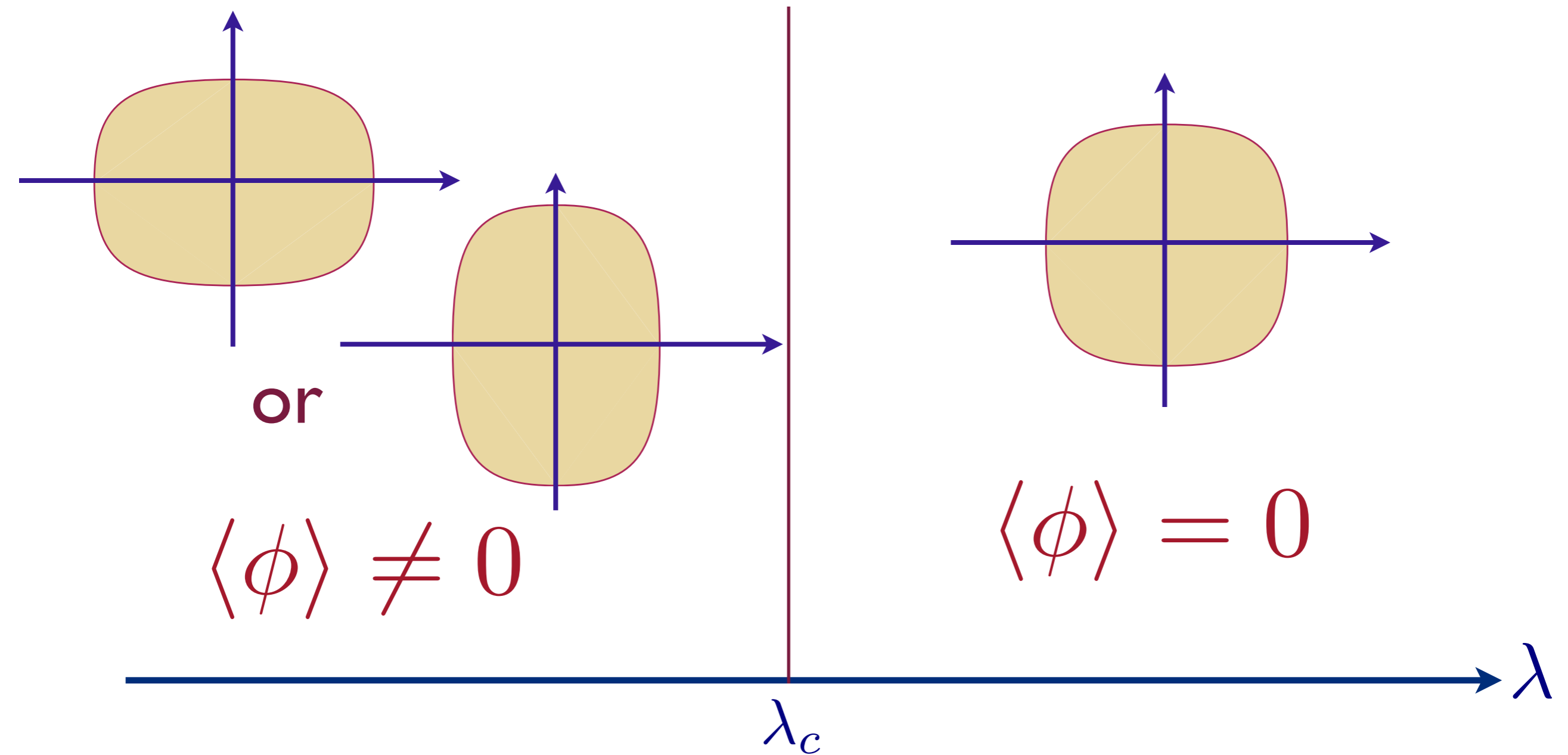
Andrew Lucas  
Harvard

# Quantum criticality of Ising-nematic ordering in a metal



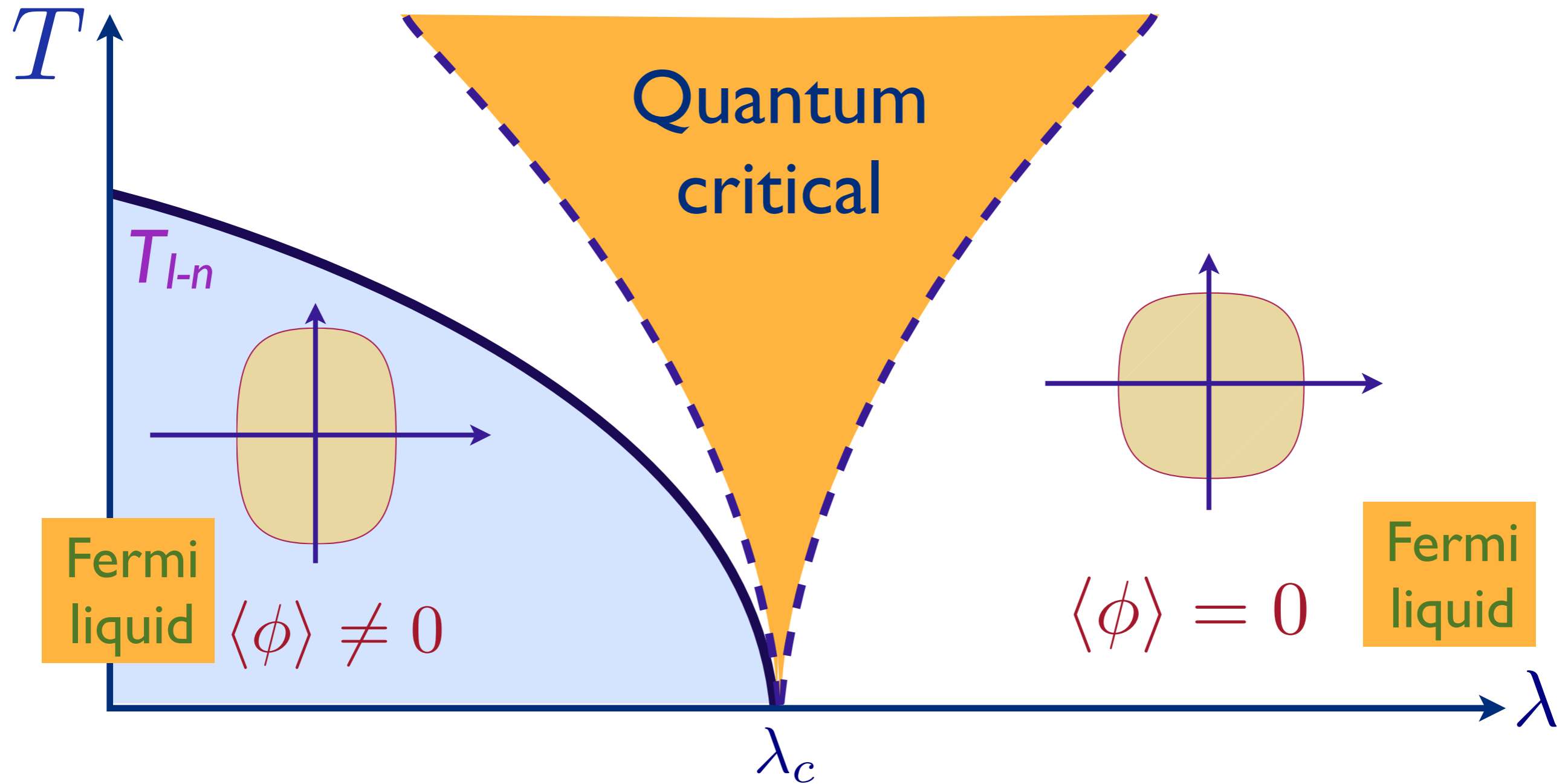
A metal with a Fermi surface  
with full square lattice symmetry

# Quantum criticality of Ising-nematic ordering in a metal



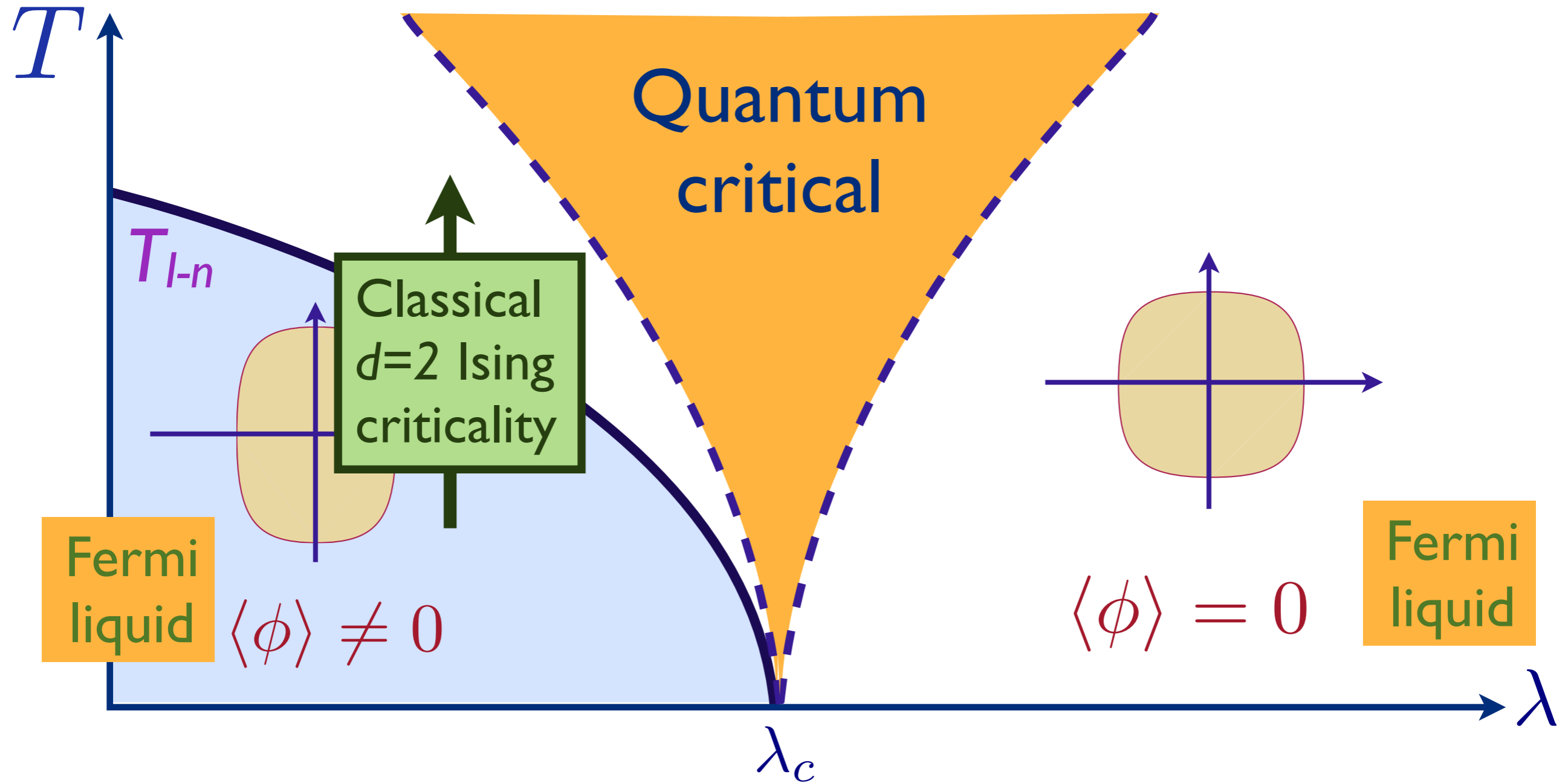
Pomeranchuk instability as a function of coupling  $\lambda$

# Quantum criticality of Ising-nematic ordering in a metal



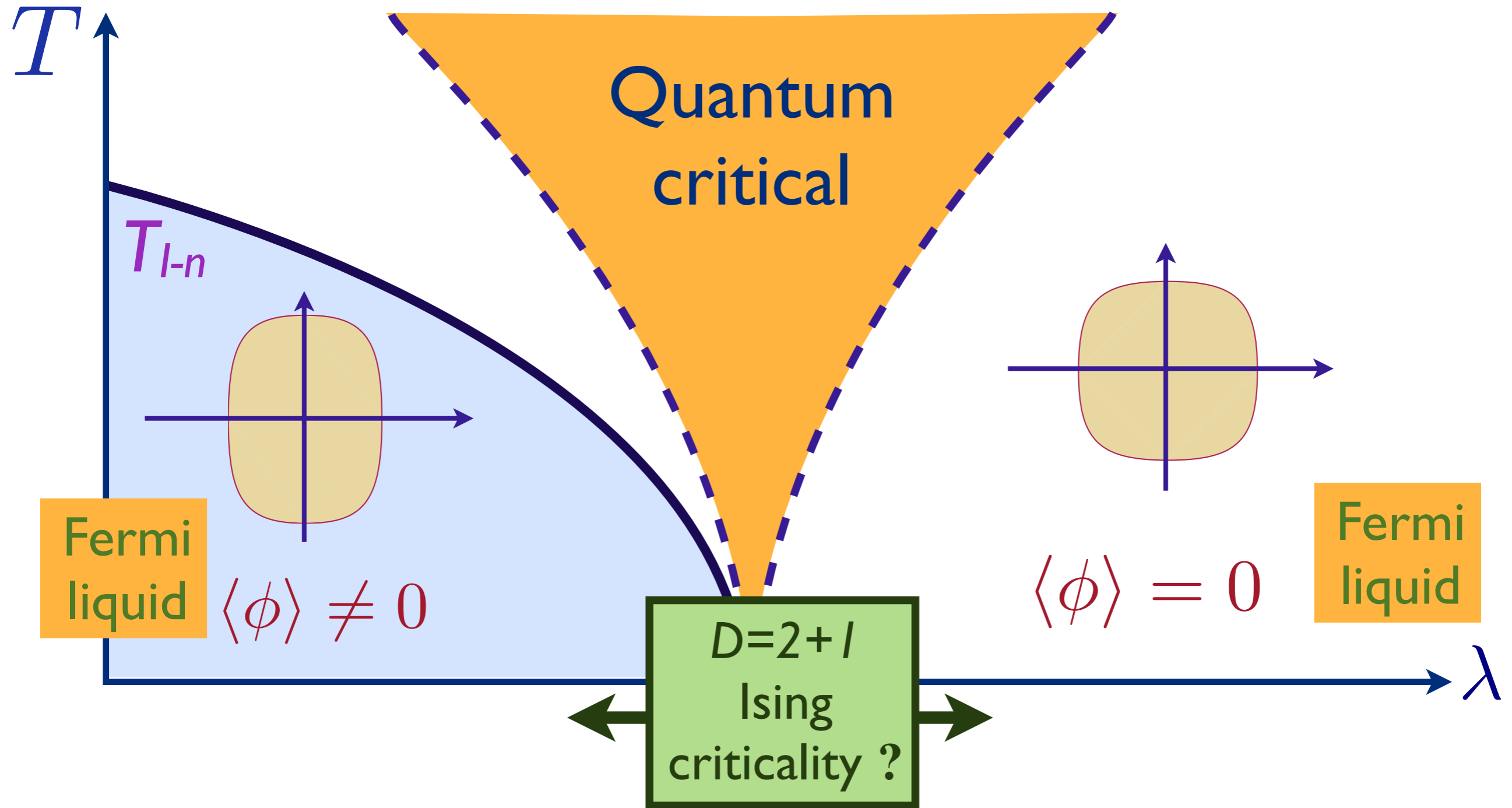
Phase diagram as a function of  $T$  and  $\lambda$

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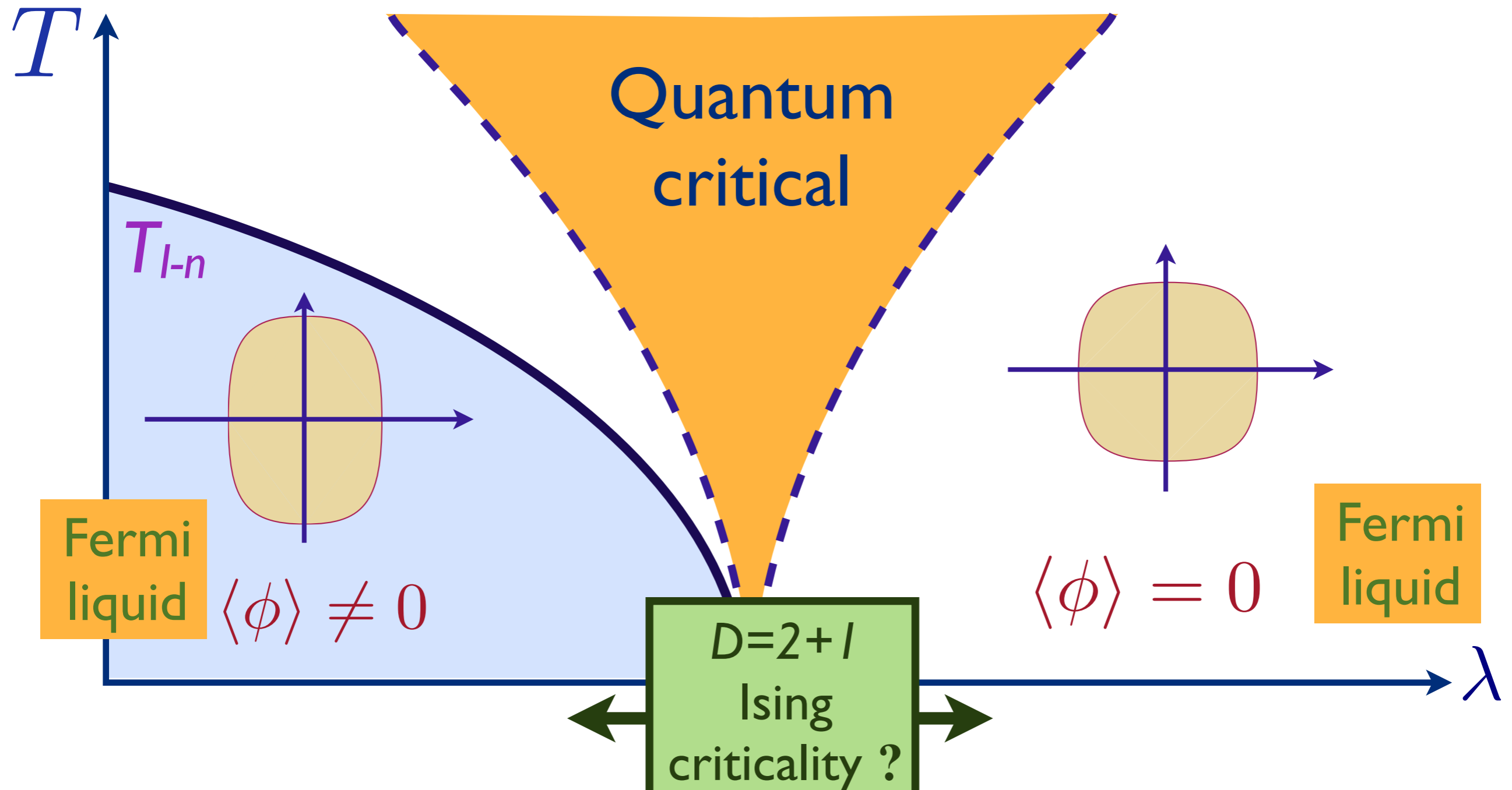
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Phase diagram as a function of  $T$  and  $\lambda$

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Only at higher energies; at the lowest energy bosonic  $\phi$  fluctuations are strongly coupled to fermionic excitations near Fermi surface.

Phase diagram as a function of  $T$  and  $\lambda$

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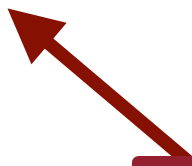
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Field theory of  
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Electrons with a  
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“Yukawa”  
coupling  
between bosons  
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- Identify charge carriers: electrons near the Fermi surface. Compute the scattering rate of these charged excitations off the bosonic  $\phi$  fluctuations.

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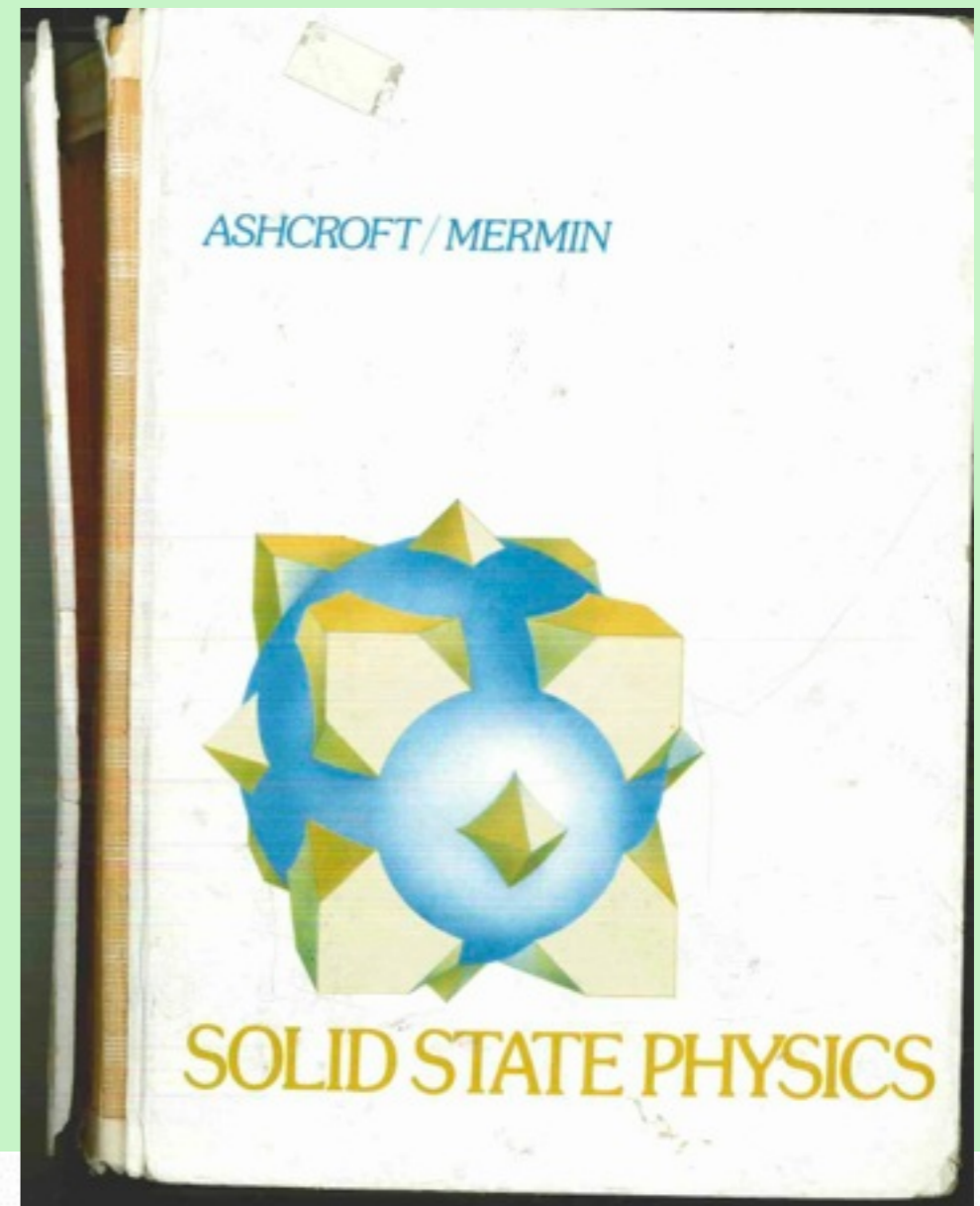
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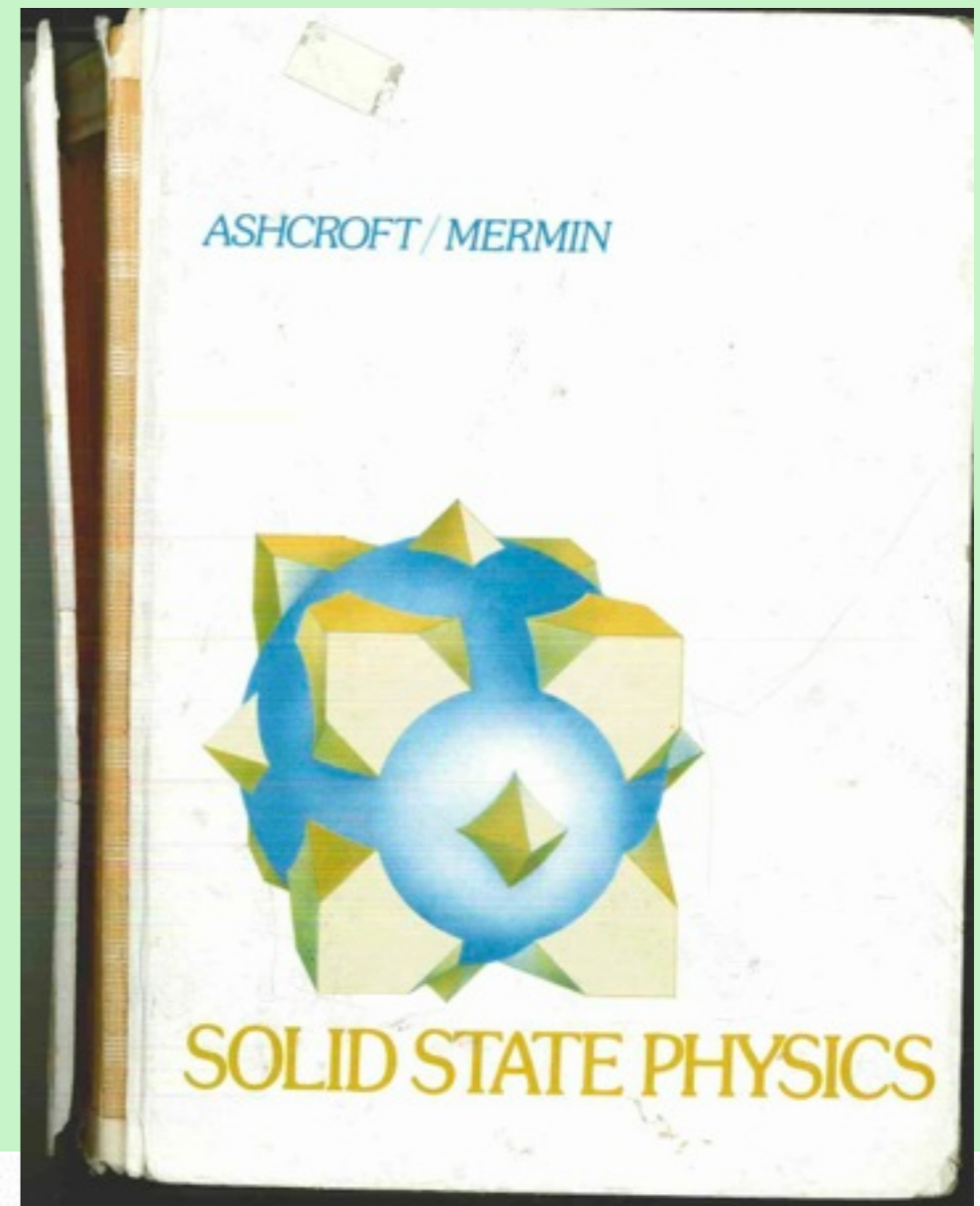
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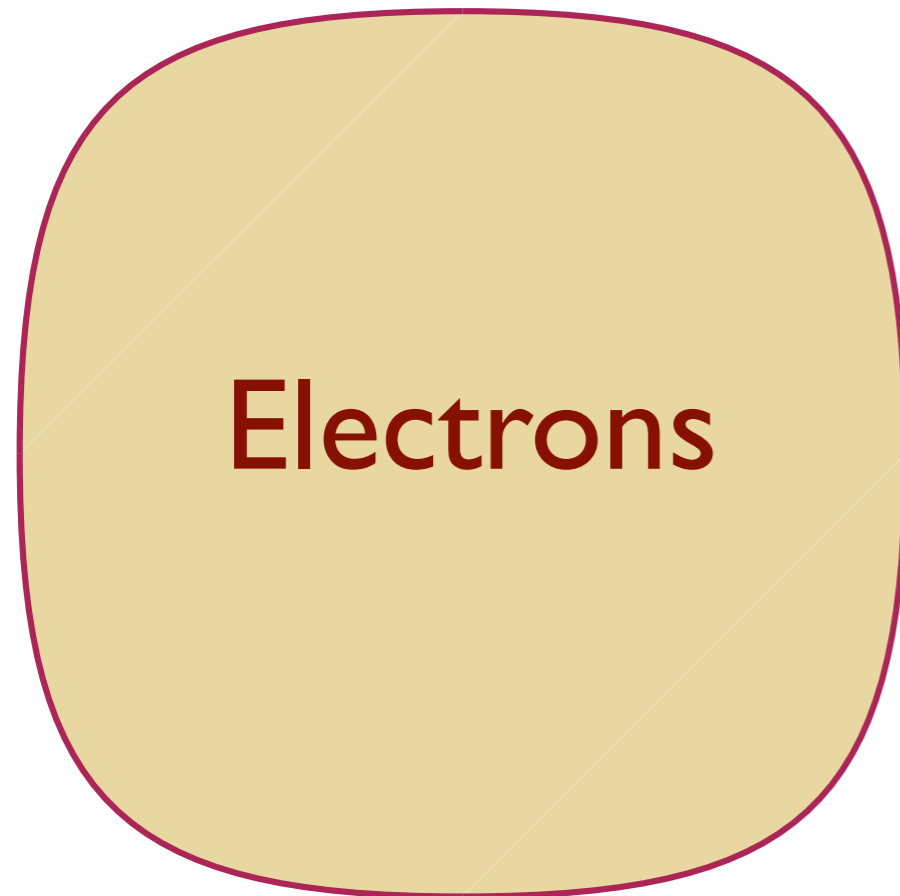
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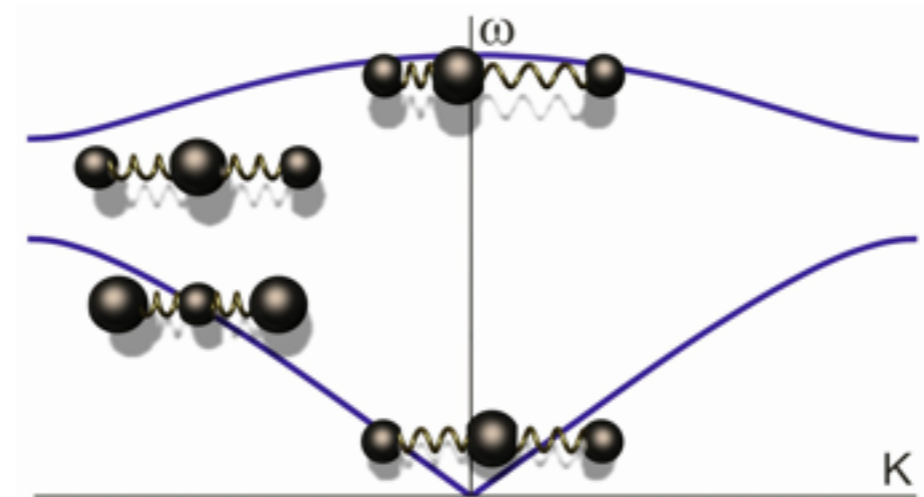
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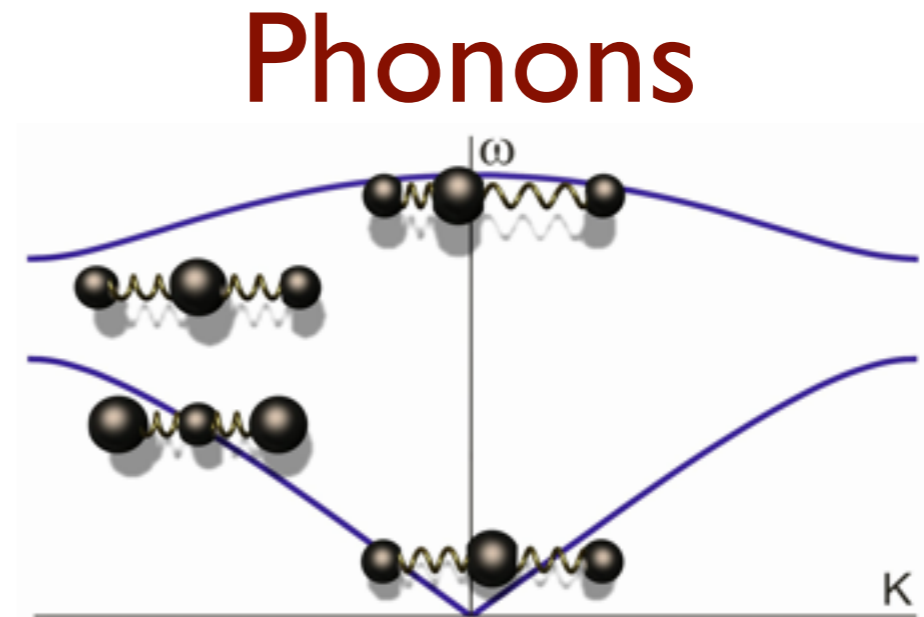
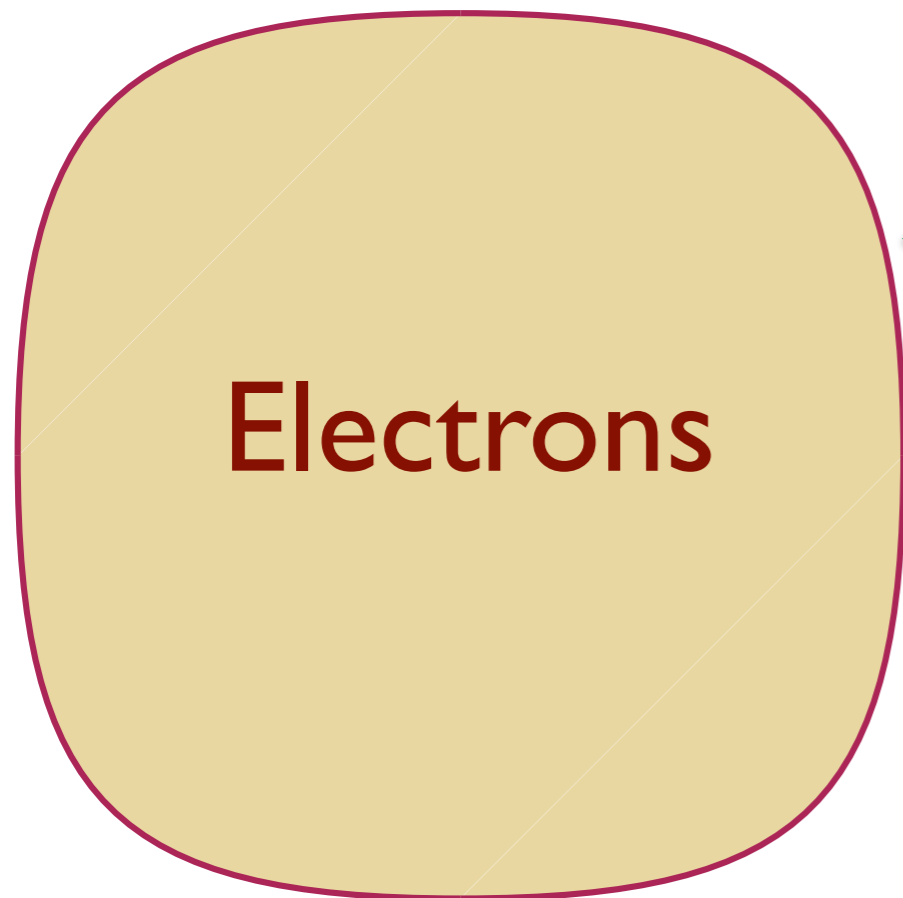
# Rates of Momentum Flow



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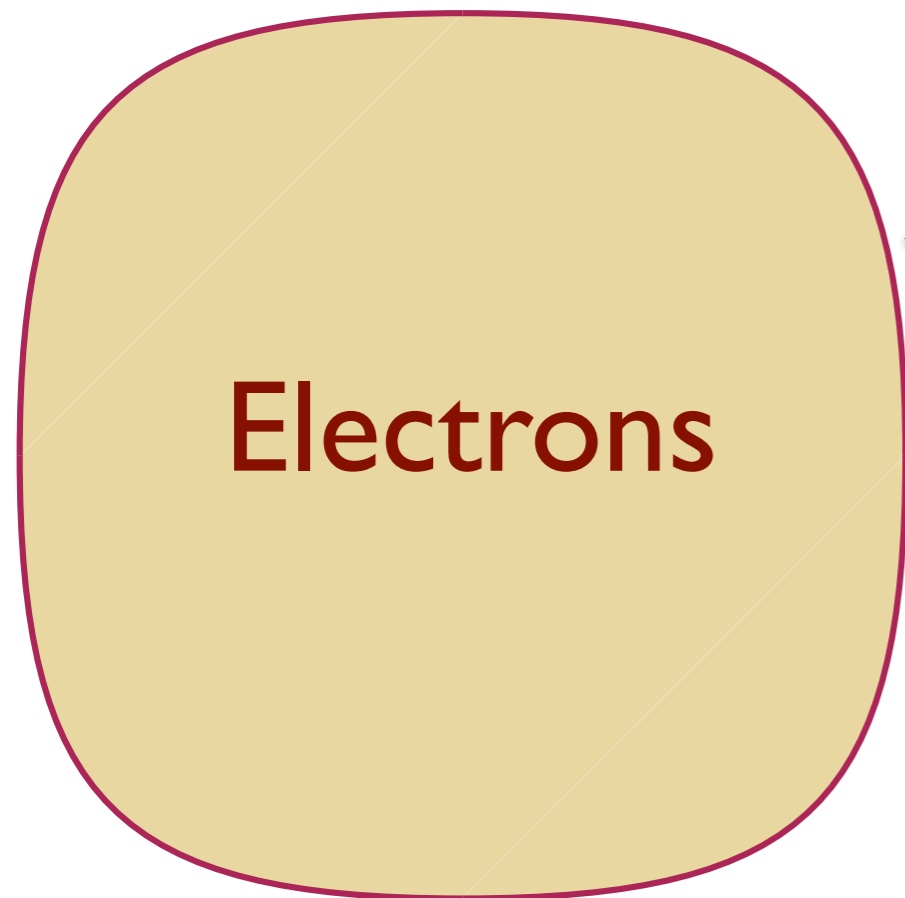


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Defects

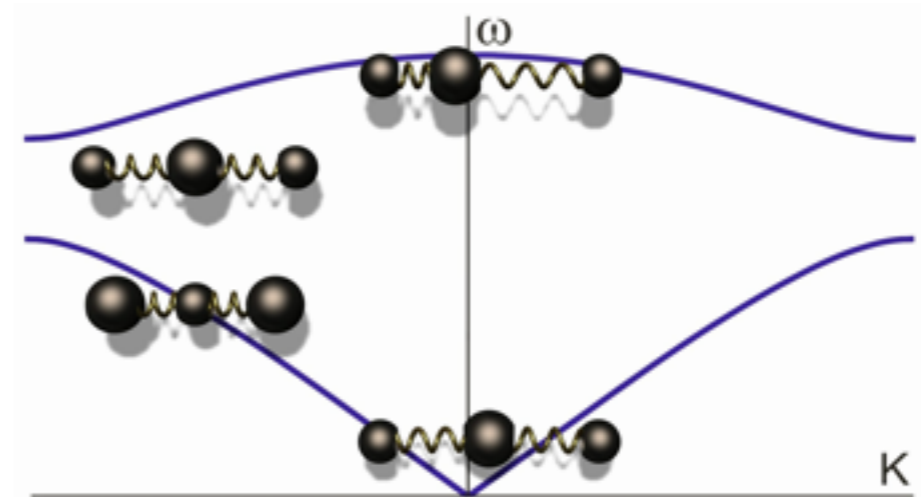
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**SLOW**

Process  
controlling  
resistivity

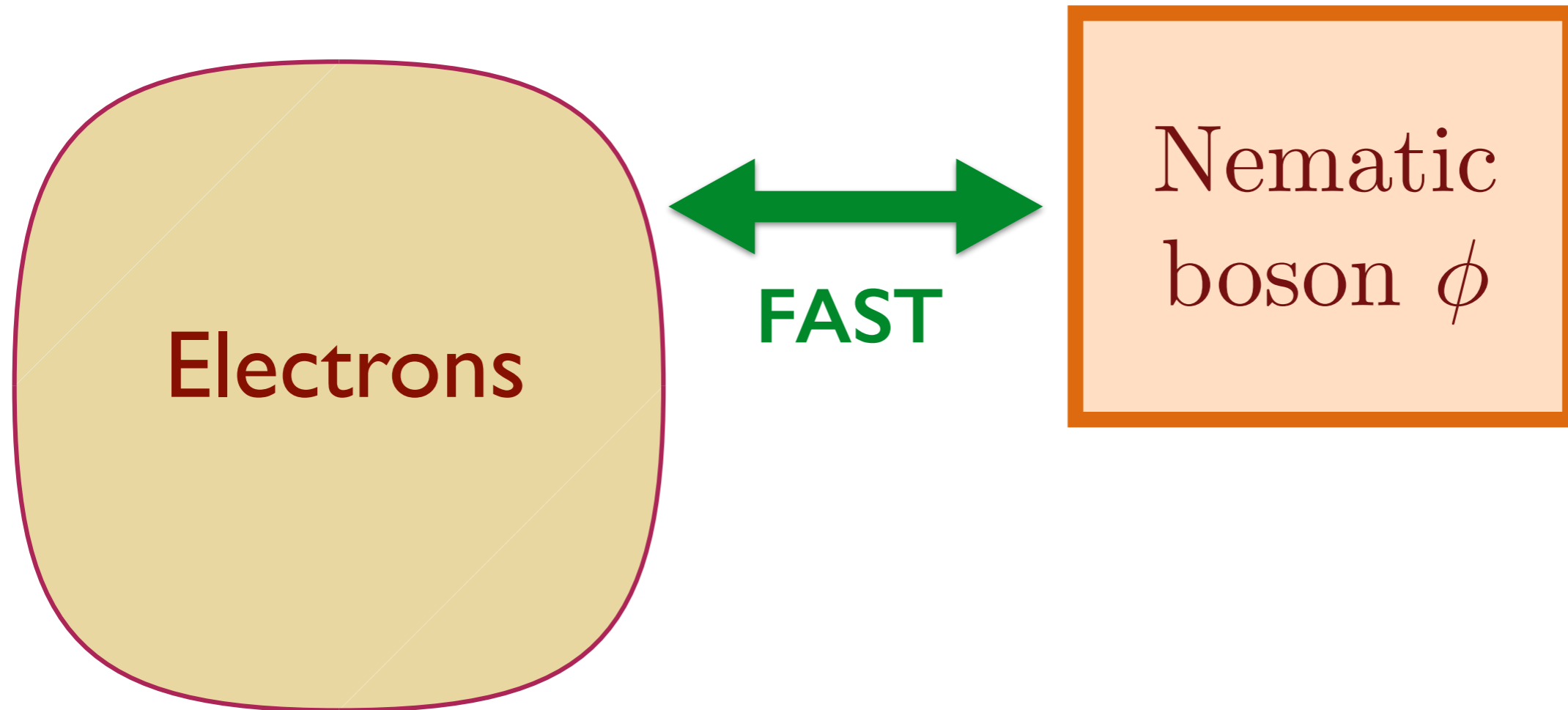
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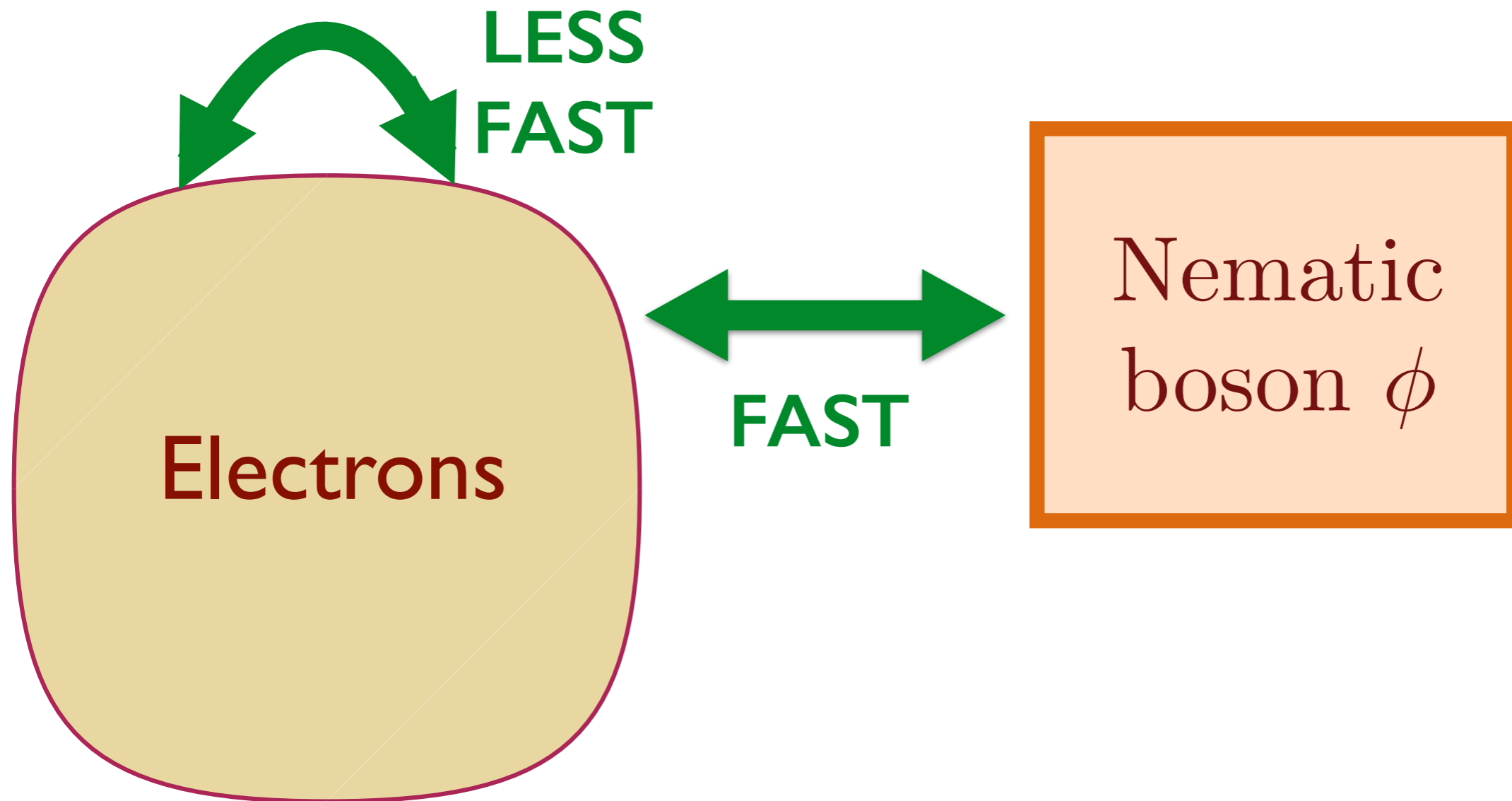
**FAST**

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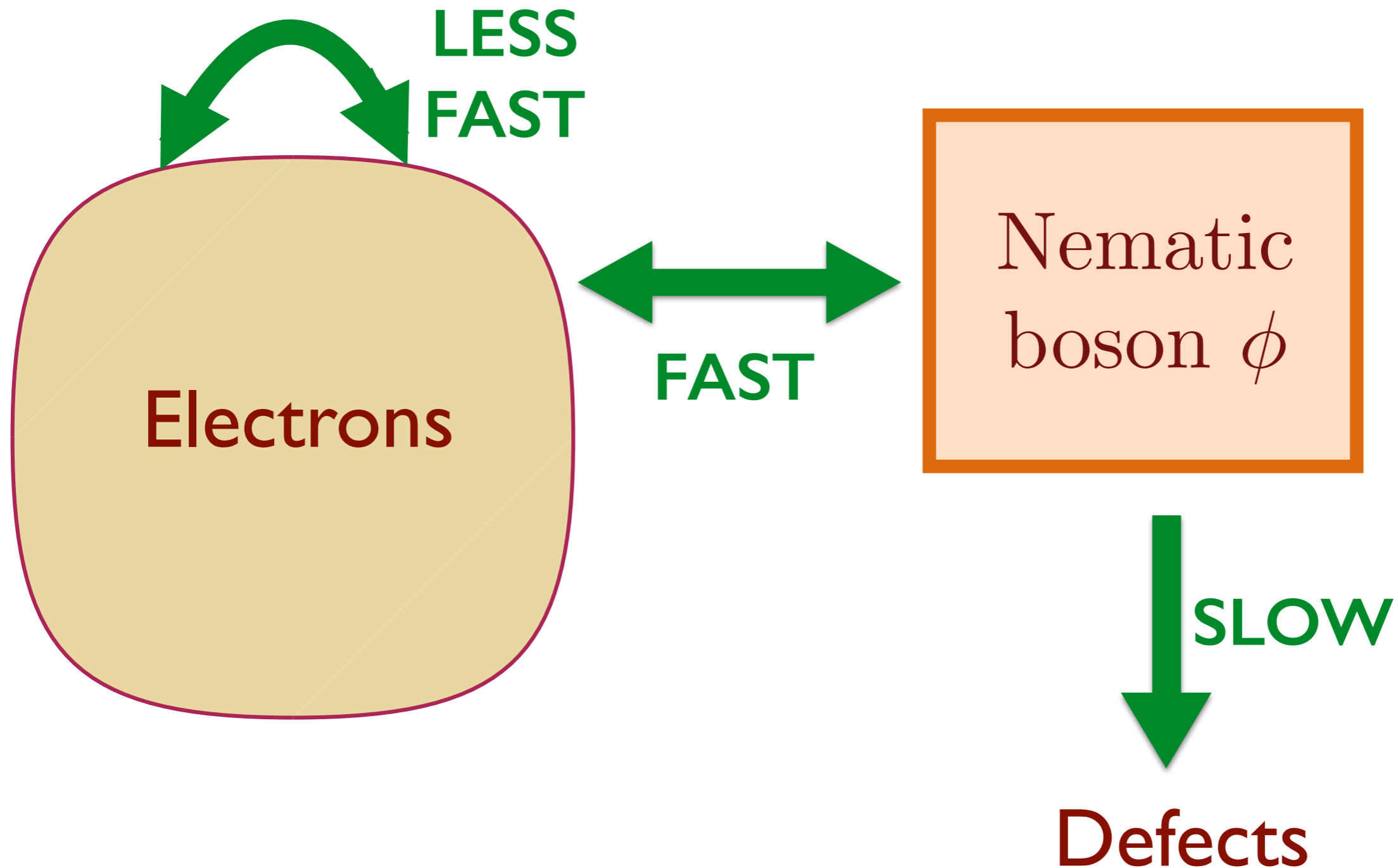
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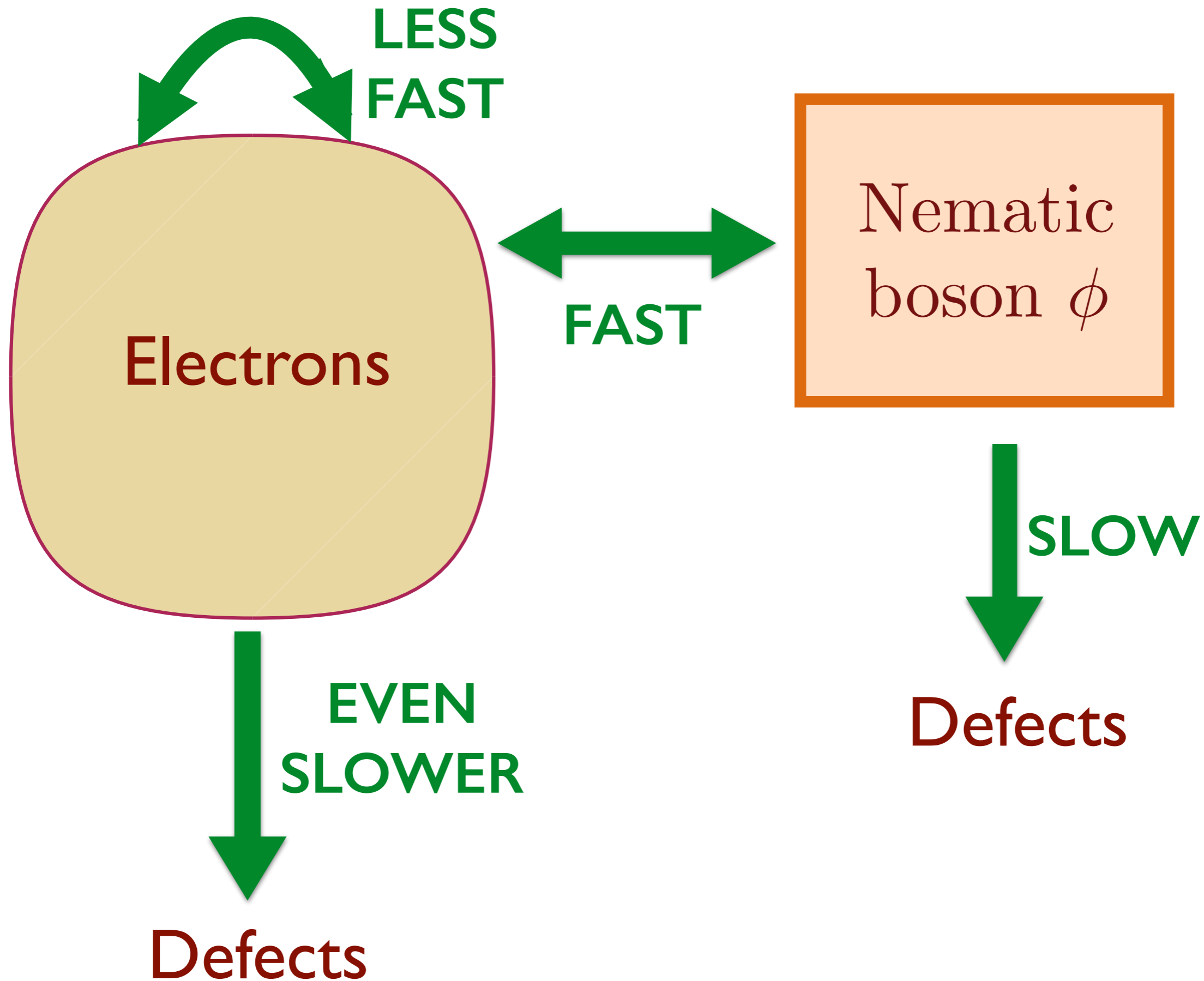
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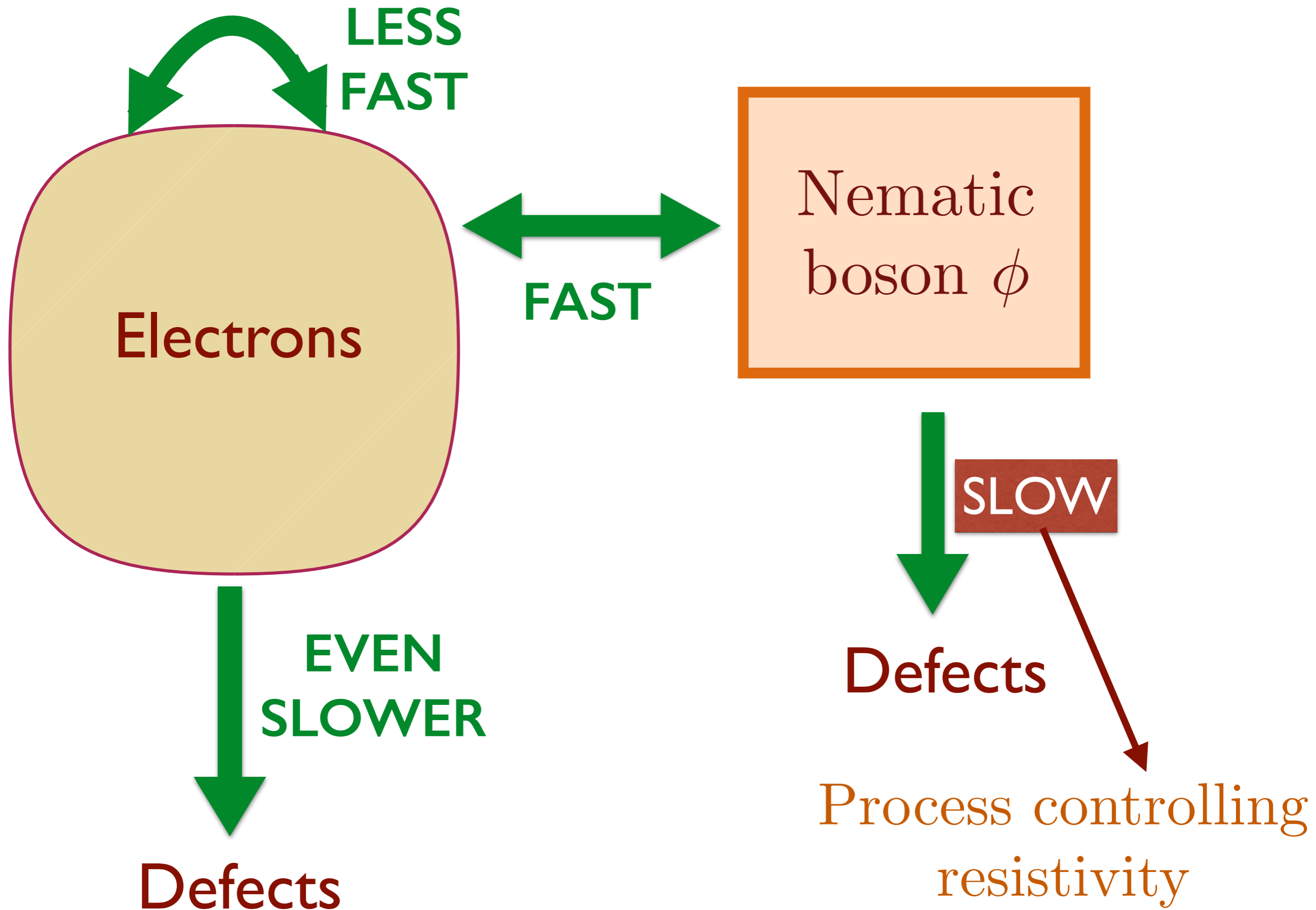
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$$\mathcal{S}_{\phi c} = -g \int d^2r d\tau \sum_{\alpha=1}^{N_f} \phi \left[ c_\alpha^\dagger \{ (\partial_x^2 - \partial_y^2 + \dots) c_\alpha \} \right. \\ \left. + \{ (\partial_x^2 - \partial_y^2 + \dots) c_\alpha^\dagger \} c_\alpha \right]$$

This continuum theory has strong electron- $\phi$  scattering, and no quasi-particle excitations. But it has a conserved momentum  $\mathbf{P}$ , and  $\chi_{\mathbf{J}, \mathbf{P}} \neq 0$  (“phonon drag”), and so the resistivity  $\rho(T) = 0$ .

# Quantum criticality of Ising-nematic ordering in a metal

## Transport without quasiparticles:

- Focus on the interplay between  $J_\mu$  and  $T_{\mu\nu}$  !



The most-probable state with a non-zero current  $\mathbf{J}$  has a non-zero momentum  $\mathbf{P}$  (and vice versa).

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The resistivity of this 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

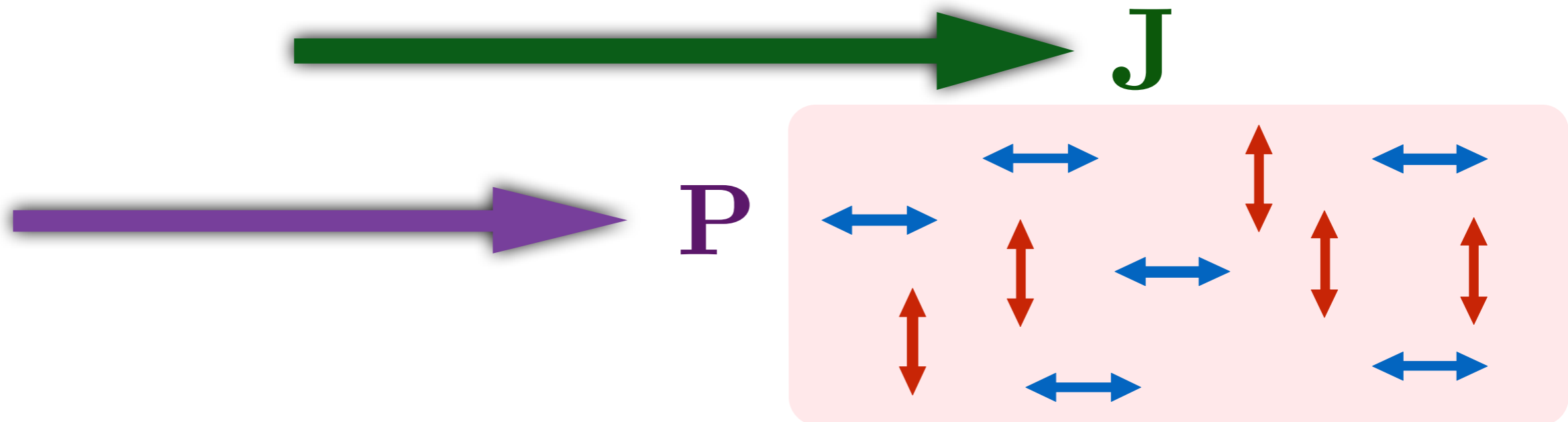
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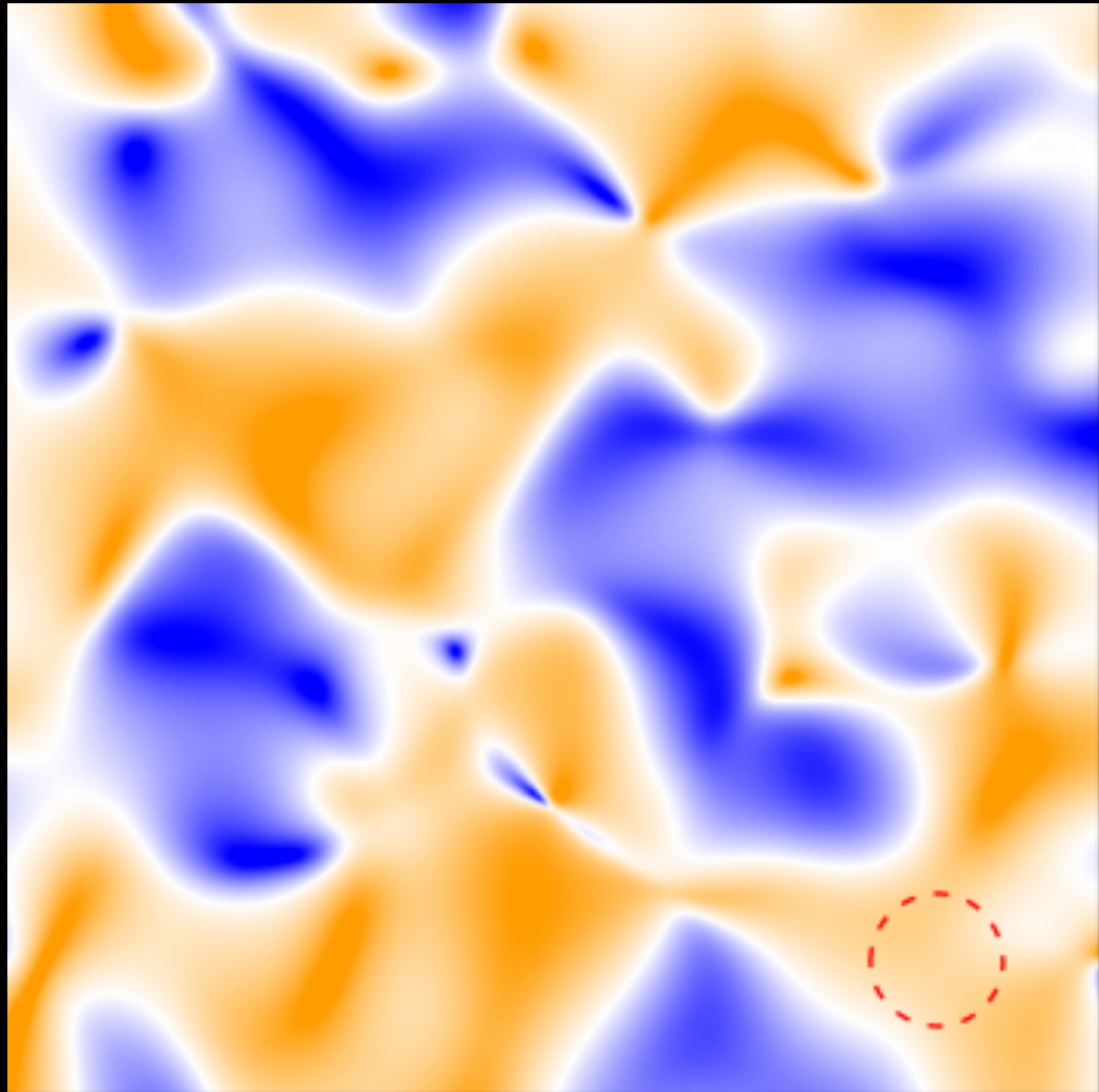
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The dominant momentum loss occurs via the scattering of the neutral bosonic  $\phi$  excitations off random fields.

This is good news for the AdS/CMT approaches, which do not capture the Fermi surface of most of the charged carriers.

# dFF-DW Unidirectional Domains



$$\frac{(|O_y(r,q=Q_x)| - |O_x(r,q=Q_y)|)}{(|O_y(r,q=Q_x)| + |O_x(r,q=Q_y)|)}$$

Primary DW direction Orange : // (1,0), Blue : // (0,1)

# Resistivity of strange metal

In the presence of weak disorder of quenched Gaussian random fields

$$\mathcal{S}_{\text{dis}} = \int d^2r d\tau [V(\mathbf{r}) c^\dagger c + h(\mathbf{r}) \phi] ,$$

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we use the memory-function approach to obtain the *resistivity* for current along angle  $\vartheta$

$$\rho(T) = \frac{1}{\chi_{\mathbf{J},\mathbf{P}}^2} \lim_{\omega \rightarrow 0} \int \frac{d^2k}{(2\pi)^2} k^2 \cos^2(\theta_{\mathbf{k}} - \vartheta) \left( V_0^2 \frac{\text{Im} \Pi_{c^\dagger c}^R(\omega, \mathbf{k})}{\omega} + h_0^2 \frac{\text{Im} D_\phi^R(\omega, \mathbf{k})}{\omega} \right) .$$

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Fermi surface term: Obtain  $T$ -dependent corrections to residual resistivity similar to earlier work

G. Zala, B. N. Narozhny, and I. L. Aleiner, Phys. Rev. B **64**, 214204 (2001)

I. Paul, C. Pépin, B. N. Narozhny, and D. L. Maslov, Phys. Rev. Lett. **95**, 017206 (2005).

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Bosonic term: Dominant contribution:

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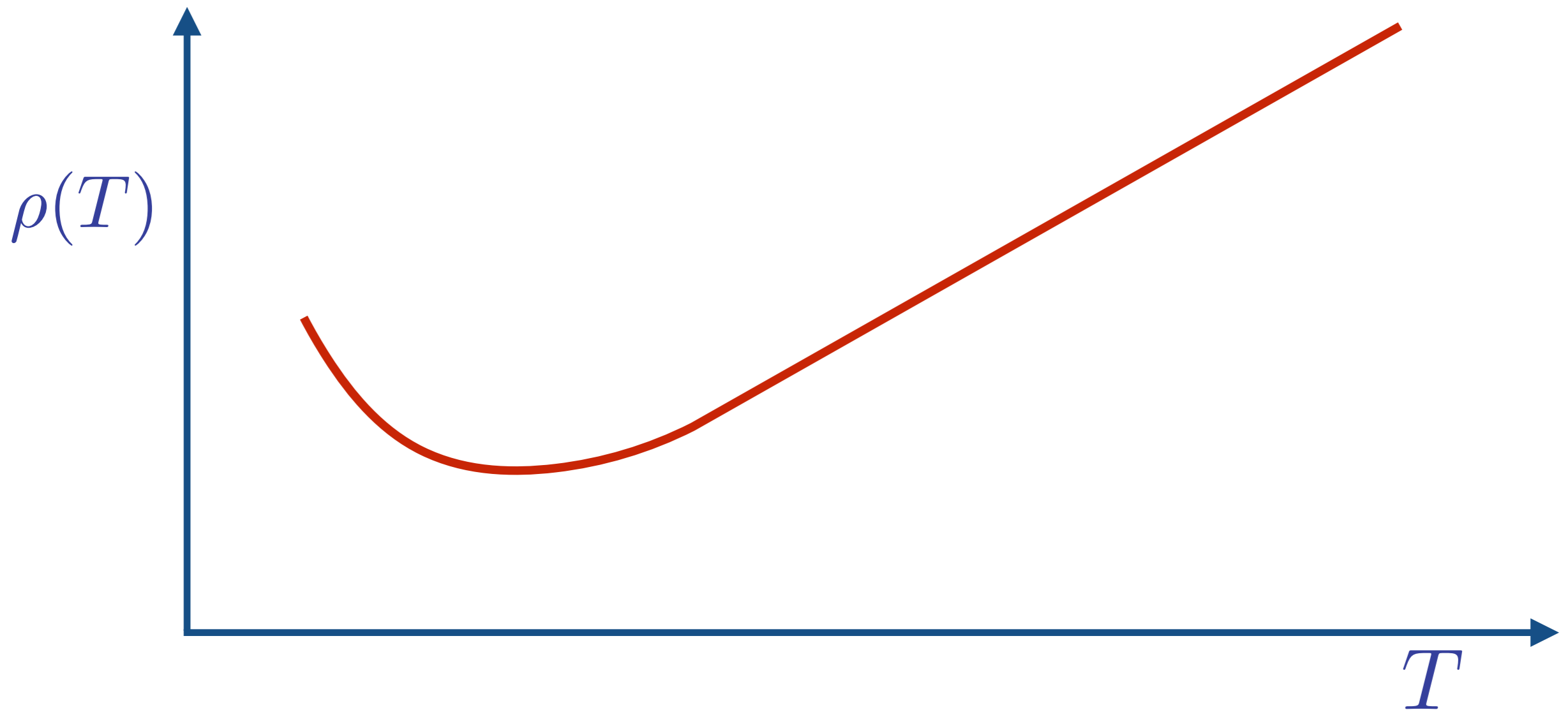
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## Transport without quasiparticles:

Resistivity from random-field disorder



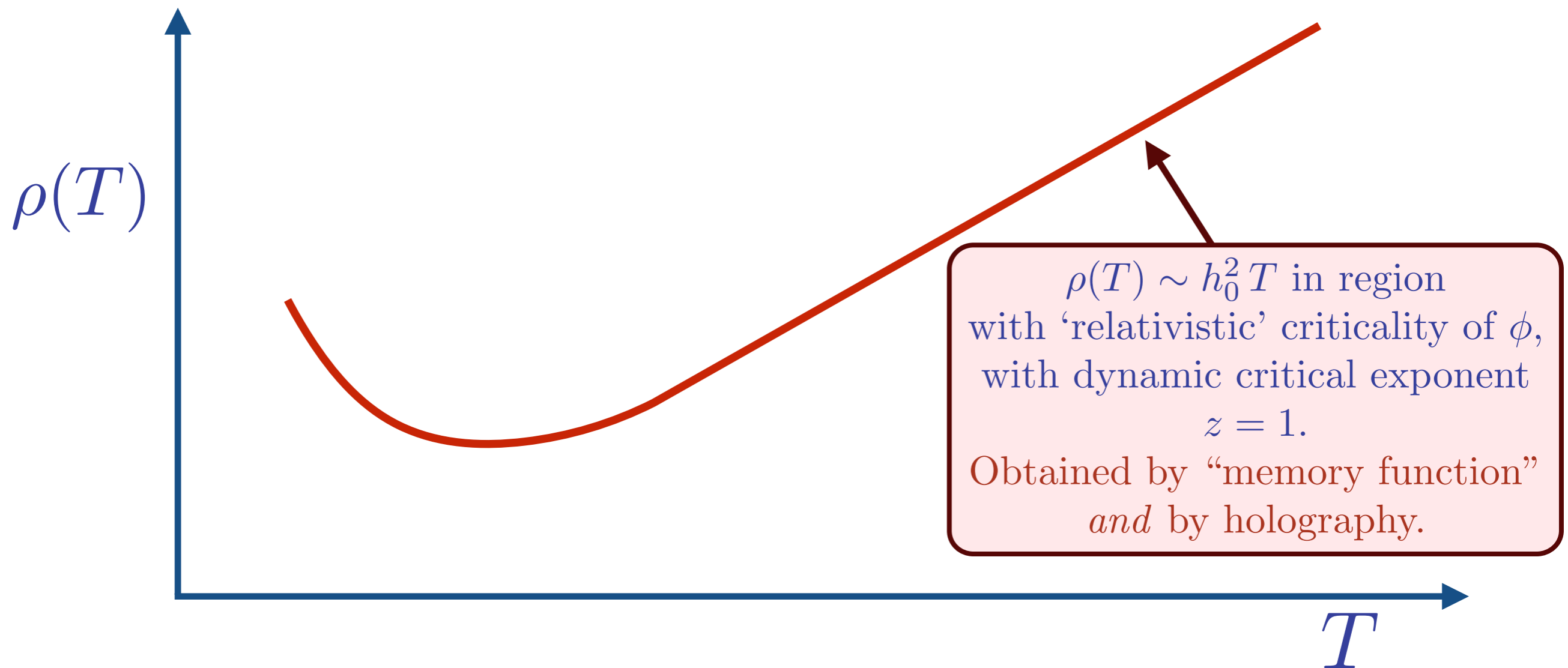
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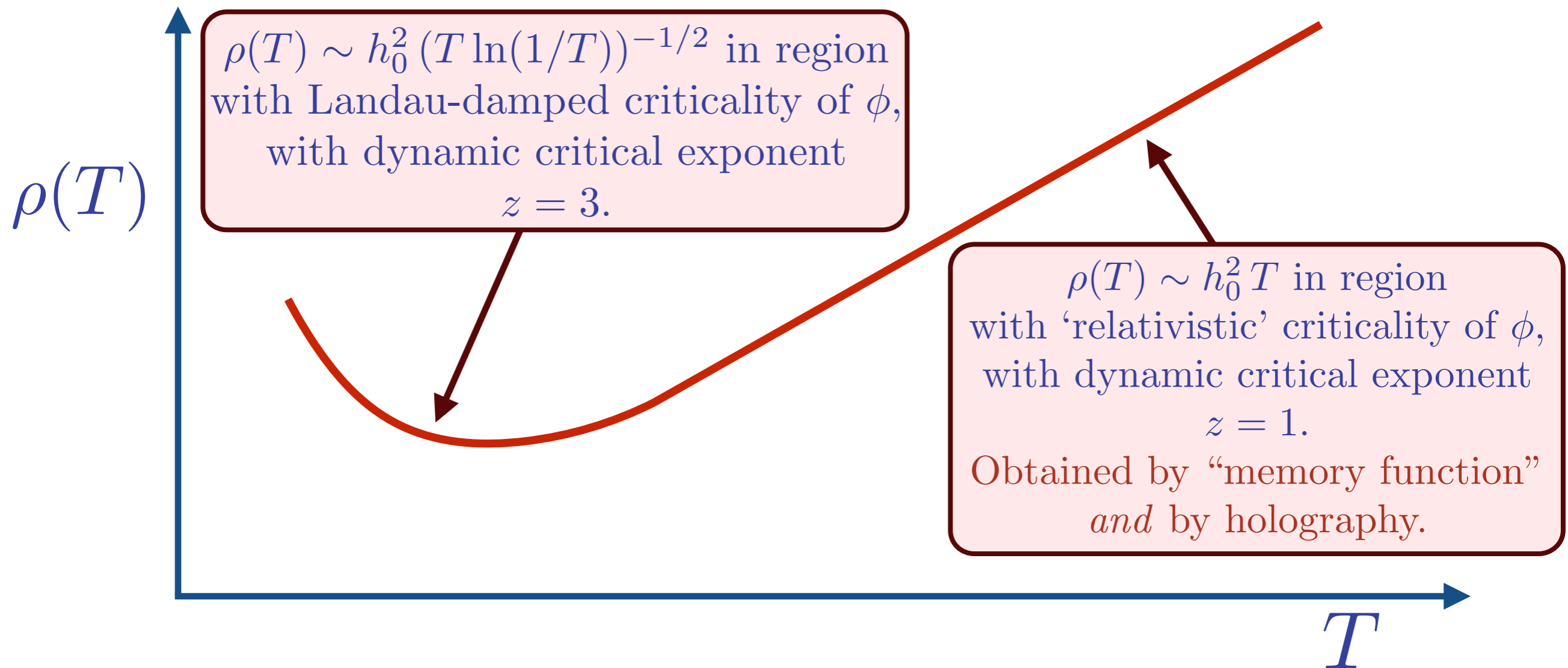
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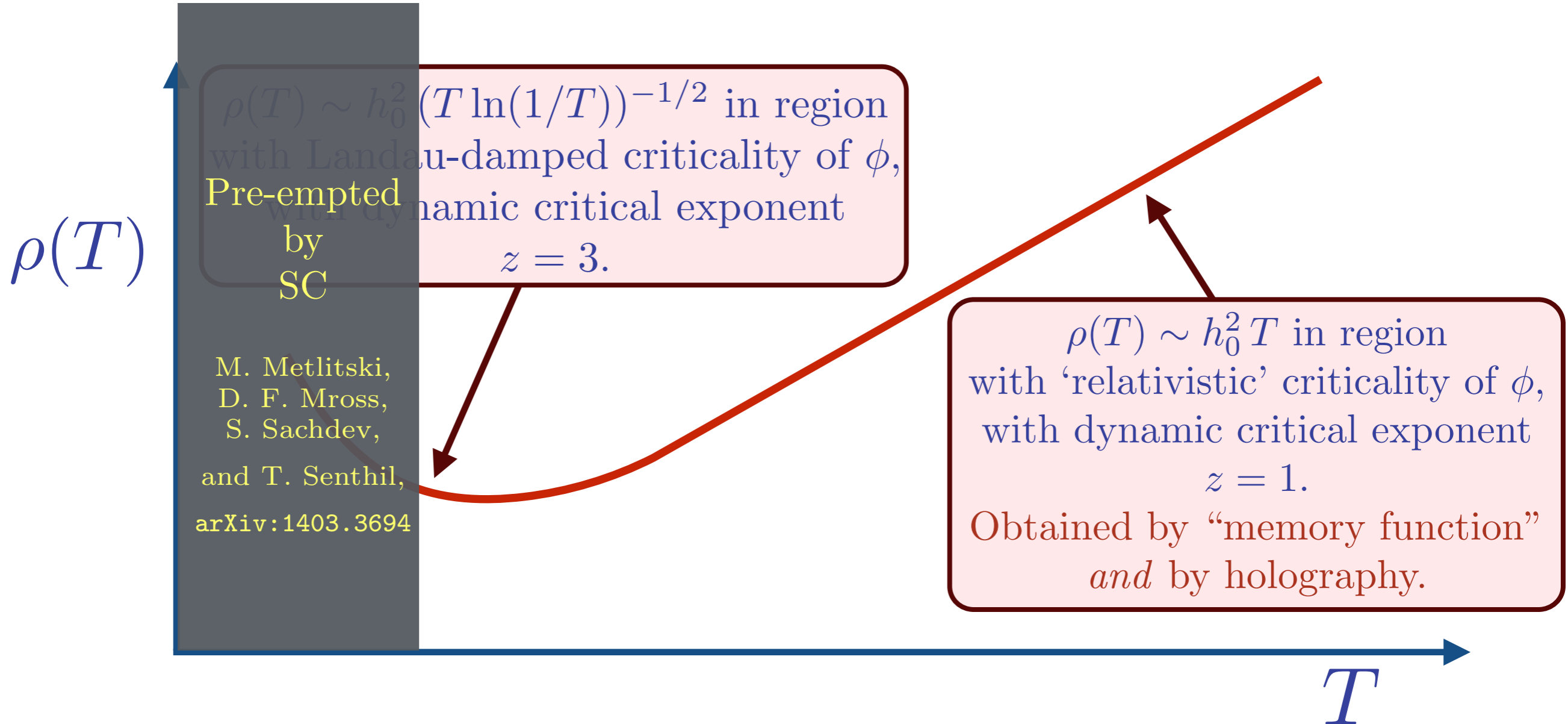
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# Conclusions

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