Angular fluctuations of a multi-component order describe the pseudogap regime of the cuprate superconductors

CIFAR meeting
Vancouver, October 17, 2013

Subir Sachdev

PHYSICS
VE RI TAS
HARVARD

Talk online: sachdev.physics.harvard.edu

Lauren Hayward

Roger Melko

David Hawthorn

University of Waterloo

Jay Deep Sau

Erez Berg

Max Metlitski

Rolando La Placa

PHYSICS

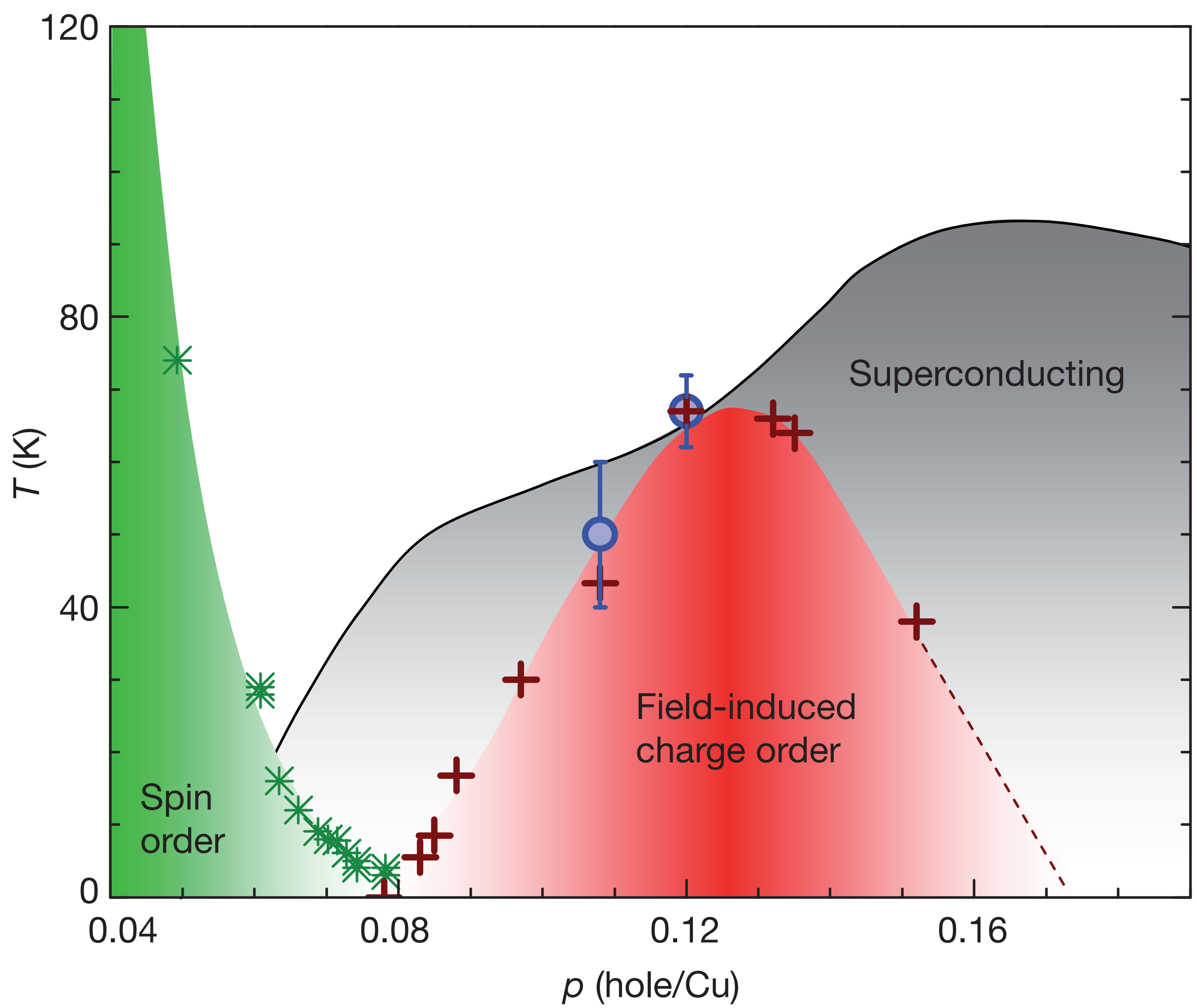
VE RI TAS

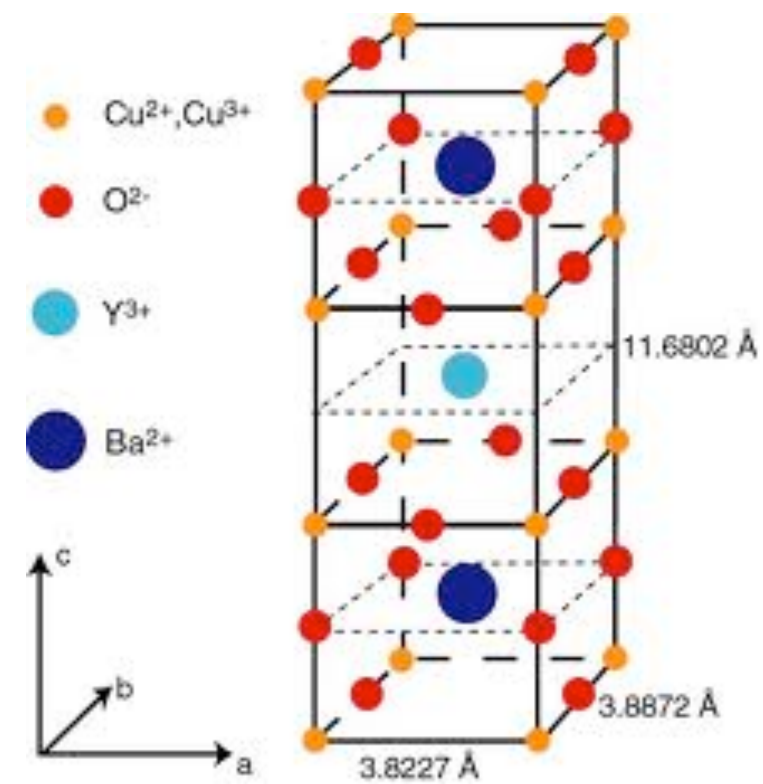
HARVARD

Magnetic-field-induced charge-stripe order in the high-temperature superconductor $YBa_2Cu_3O_y$

Tao Wu[1], Hadrien Mayaffre[1], Steffen Krämer[1], Mladen Horvatić[1], Claude Berthier[1], W. N. Hardy[2,3], Ruixing Liang[2,3], D. A. Bonn[2,3] & Marc-Henri Julien[1]

8 SEPTEMBER 2011 | VOL 477 | NATURE | 191



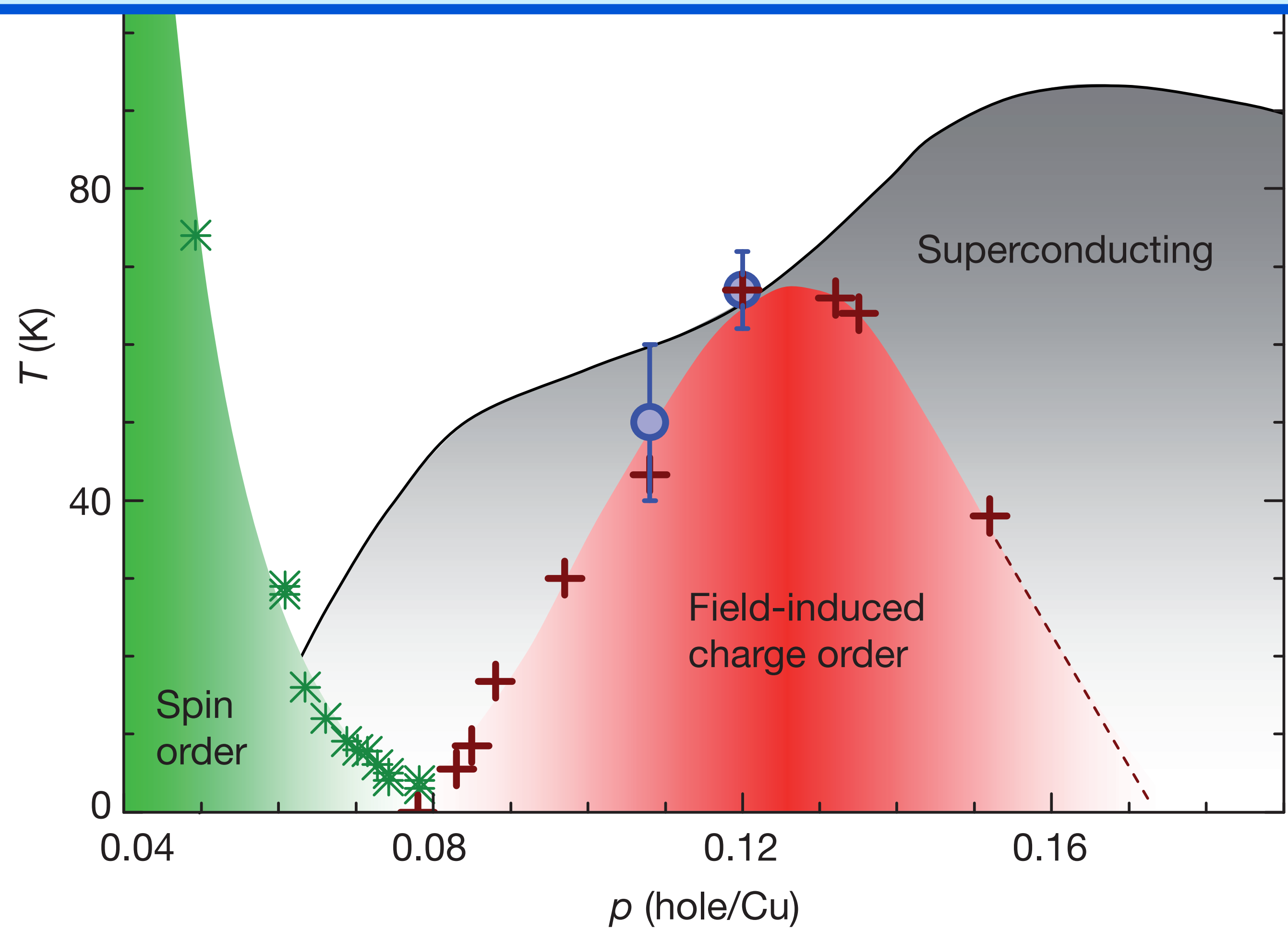


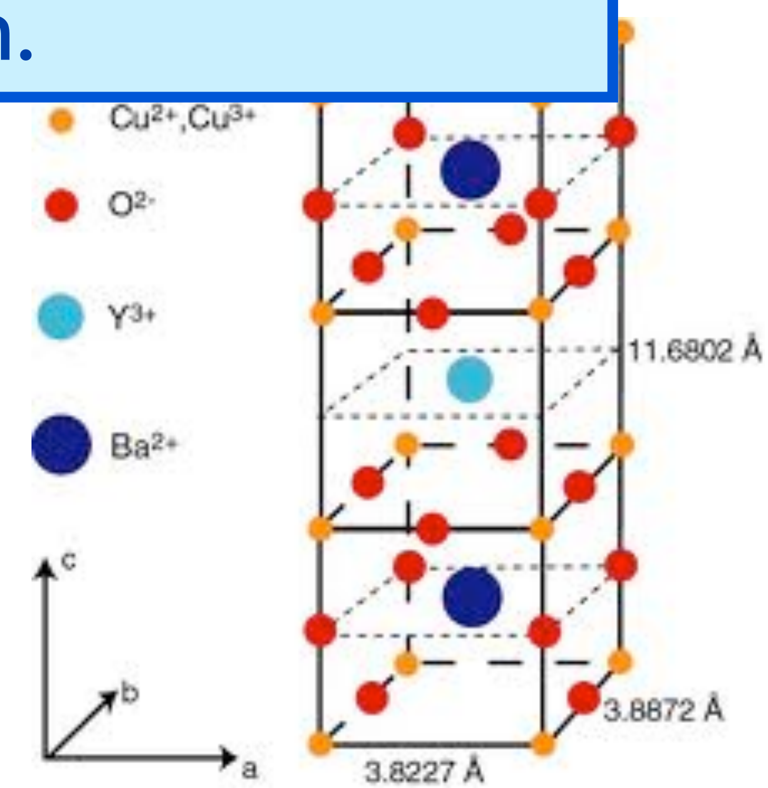
Magnetic-field-induced charge-stripe order in the high-temperature superconductor $YBa_2Cu_3O_y$

Tao Wu[1], Hadrien Mayaffre[1], Steffen Krämer[1], Mladen Horvatić[1], Claude Berthier[1], W. N. Hardy[2,3], Ruixing Liang[2,3], D. A. Bonn[2,3] & Marc-Henri Julien[1]

8 SEPTEMBER 2011 | VOL 477 | NATURE | 191

Clear separation of regions of spin and charge order is an important simplifying feature of YBCO. Focus on the region where only charge order is seen.





A.J. Achkar et al., to appear

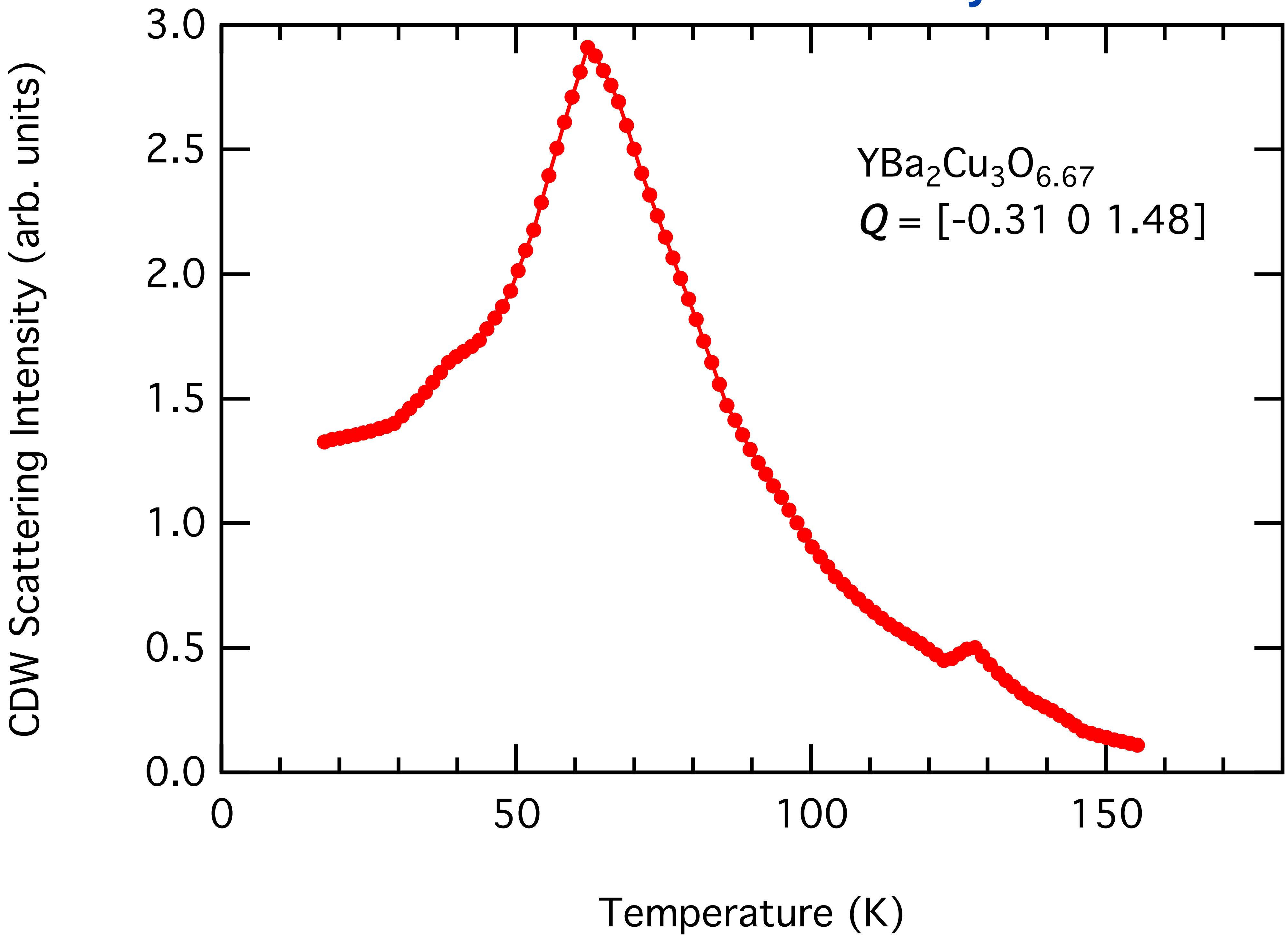


FIG. 1: The temperature dependence of the CDW scattering intensity at **Q** = [-0.31 0 1.48] in $YBa_2Cu_3O_{6.67}$ measured by resonant x-ray scattering in Ref. [4]. This sample has $T_c \approx 65.5$K.

PHYSICAL REVIEW B **69**, 144504 (2004)

Competing orders in thermally fluctuating superconductors in two dimensions

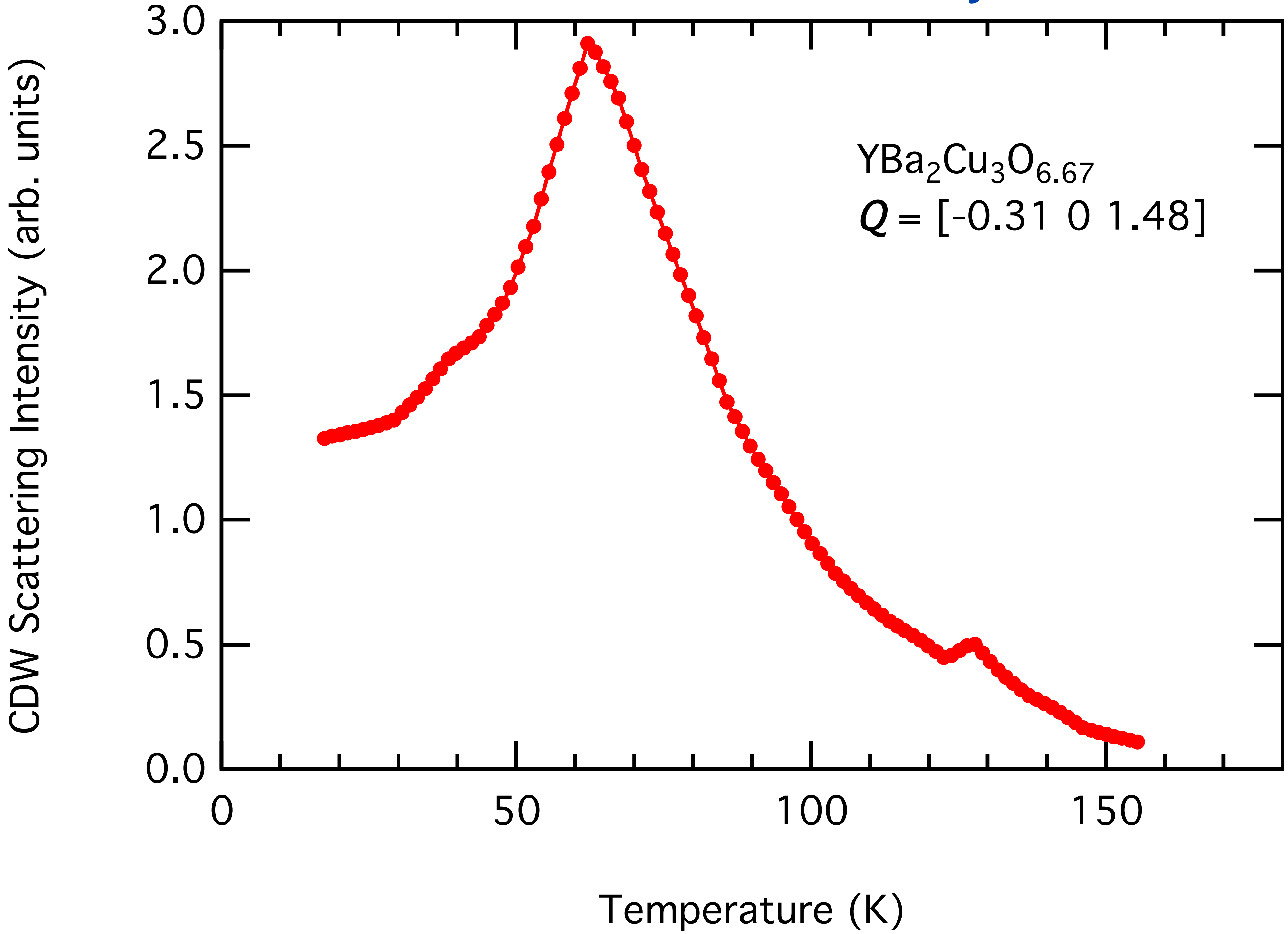
Subir Sachdev
Department of Physics, Yale University, P.O. Box 208120, New Haven, Connecticut 06520-8120, USA

Eugene Demler
Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

(Received 6 August 2003; revised manuscript received 24 November 2003; published 6 April 2004)

We extend recent low-temperature analyses of competing orders in the cuprate superconductors to the pseudogap regime where all orders are fluctuating. A universal continuum limit of a classical Ginzburg-Landau functional is used to characterize fluctuations of the superconducting order: this describes the crossover from Gaussian fluctuations at high temperatures to the vortex-binding physics near the onset of global phase coherence. These fluctuations induce affiliated corrections in the correlations of other orders, and in particular, in the different realizations of charge order. Implications for scanning tunneling spectroscopy and neutron-scattering experiments are noted: there may be a regime of temperatures near the onset of superconductivity where the charge order is enhanced with increasing temperatures.

A.J. Achkar et al., to appear



At high T, onset is unlike an arrested ordering transition, or precursor critical fluctuations.

At low T, "competing order" effect is remarkably large.

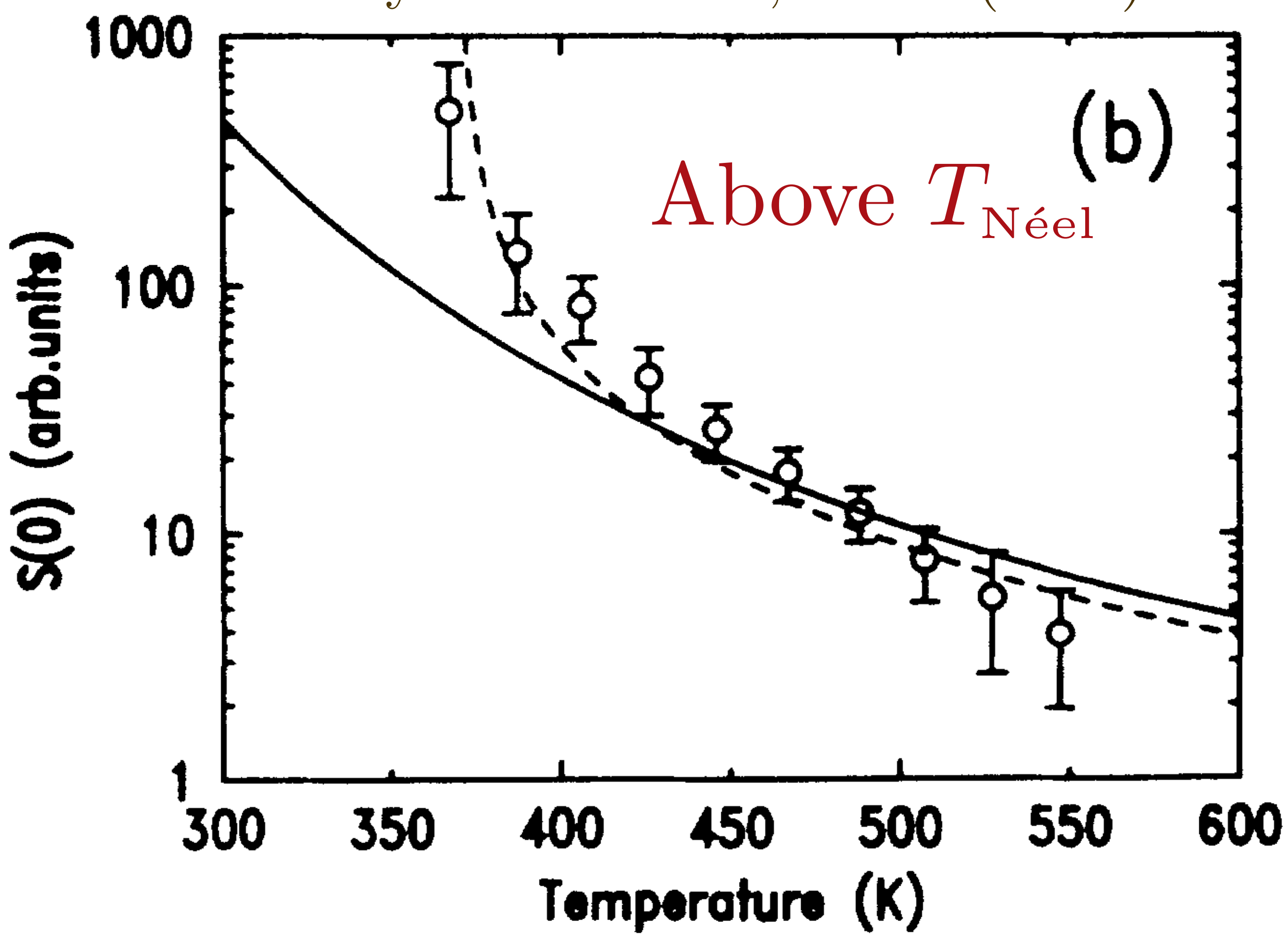
Key idea: analogy with the onset of antiferromagnetism in the *insulator* La_2CuO_4

Gradual onset of intensity over a wide range of T is a consequence of *angular thermal* fluctuations of an order parameter with 3 or more components in 2 spatial dimensions

Polyakov, 1975
Chakravarty, Halperin, Nelson 1989

$$T_{\text{Néel}} = 325\text{K}$$

B. Keimer *et al.*,
Phys. Rev. B **46**, 14034 (1992).



Multi-component order parameter

Superconducting order $\Psi(\mathbf{r})$:

$$\left\langle c_{i\alpha}^{\dagger} c_{j\beta}^{\dagger} \right\rangle = \varepsilon_{\alpha\beta} \left[\sum_{\mathbf{k}} \Delta_S(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] \Psi\left((\mathbf{r}_i + \mathbf{r}_j)/2 \right)$$

Charge/bond order $\Phi_{x,y}(\mathbf{r})$ at wavevectors $\mathbf{Q}_{x,y}$:

$$\left\langle c_{i\alpha}^{\dagger} c_{j\beta} \right\rangle = \delta_{\alpha\beta} \left[\sum_{\mathbf{k}} P_{\mathbf{Q}_x}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}_x\cdot(\mathbf{r}_i + \mathbf{r}_j)/2} \Phi_x\left((\mathbf{r}_i + \mathbf{r}_j)/2 \right)$$
$$+ \delta_{\alpha\beta} \left[\sum_{\mathbf{k}} P_{\mathbf{Q}_y}(\mathbf{k}) e^{i\mathbf{k}\cdot(\mathbf{r}_i - \mathbf{r}_j)} \right] e^{i\mathbf{Q}_y\cdot(\mathbf{r}_i + \mathbf{r}_j)/2} \Phi_y\left((\mathbf{r}_i + \mathbf{r}_j)/2 \right)$$

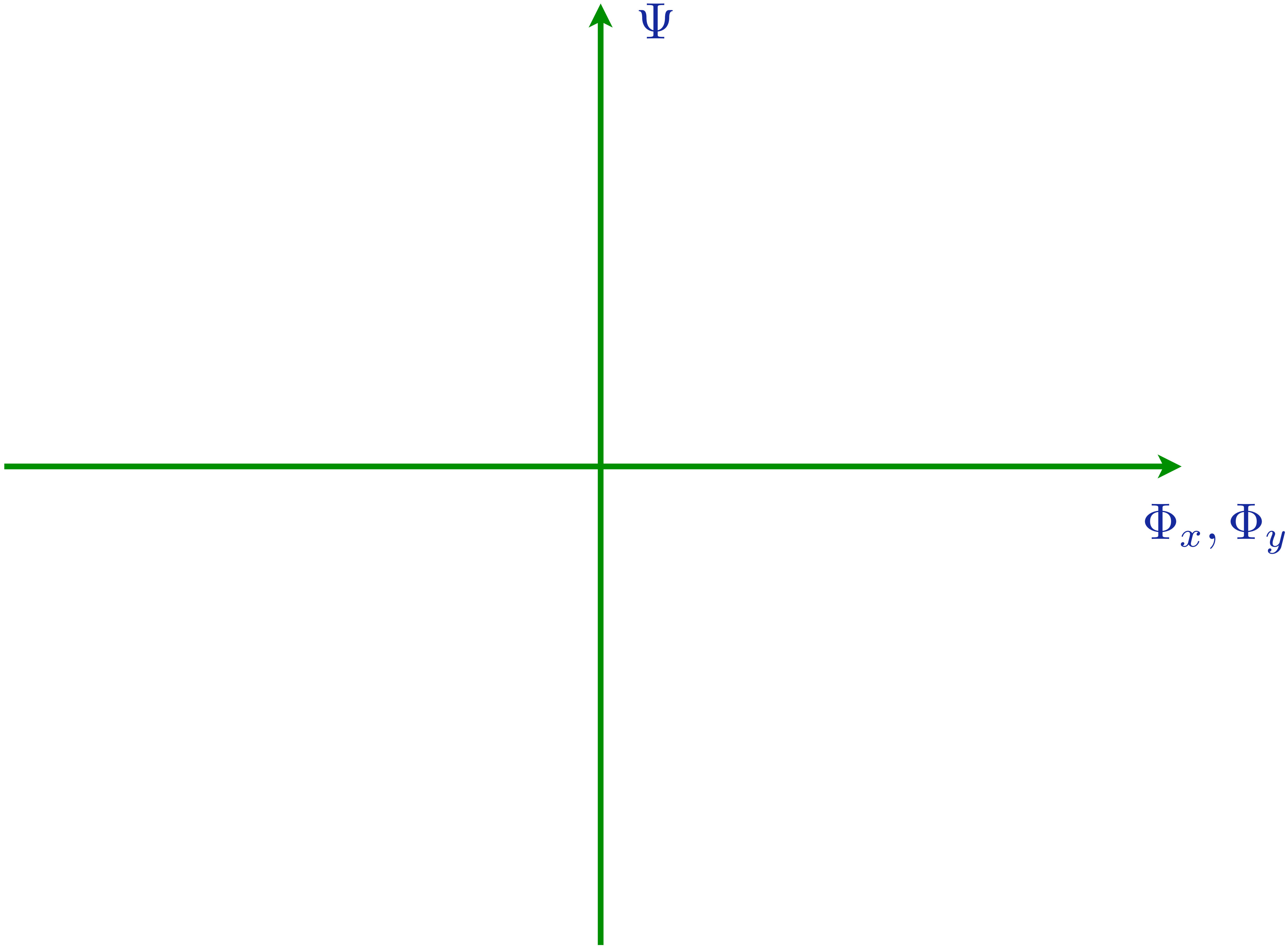
Multi-component order parameter

Symmetries:
Charge conservation (O(2)), x translations (O(2)), y translations (O(2)), $x \leftrightarrow y$ ($\mathbb{Z}_2$), inversion, time-reversal.
Landau-Ginzburg free energy:

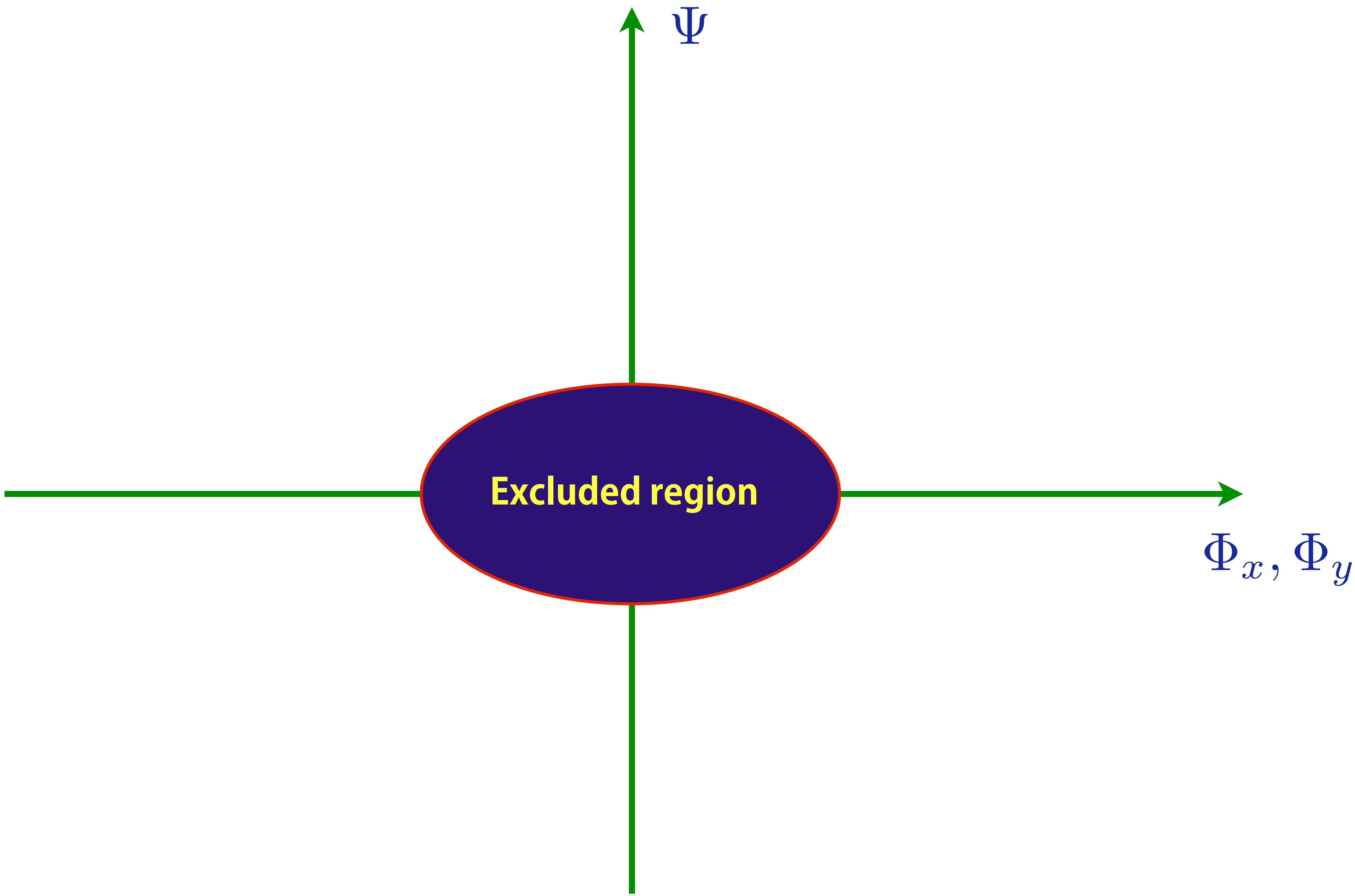
$$F = \int d^2 r \Big[|\nabla \Psi|^2 + s_1 |\Psi|^2 + u_1 |\Psi|^4$$
$$+|\nabla \Phi_x|^2 + |\nabla \Phi_y|^2 + s_2 \left(|\Phi_x|^2 + |\Phi_y|^2 \right)$$
$$+u_2 \left(|\Phi_x|^2 + |\Phi_y|^2 \right)^2 + w \left(|\Phi_x|^4 + |\Phi_y|^4 \right)$$
$$+v |\Psi|^2 \left(|\Phi_x|^2 + |\Phi_y|^2 \right) \Big]$$

Competing orders: Needed: a theory for large *v*

Multi-component order parameter



Multi-component order parameter

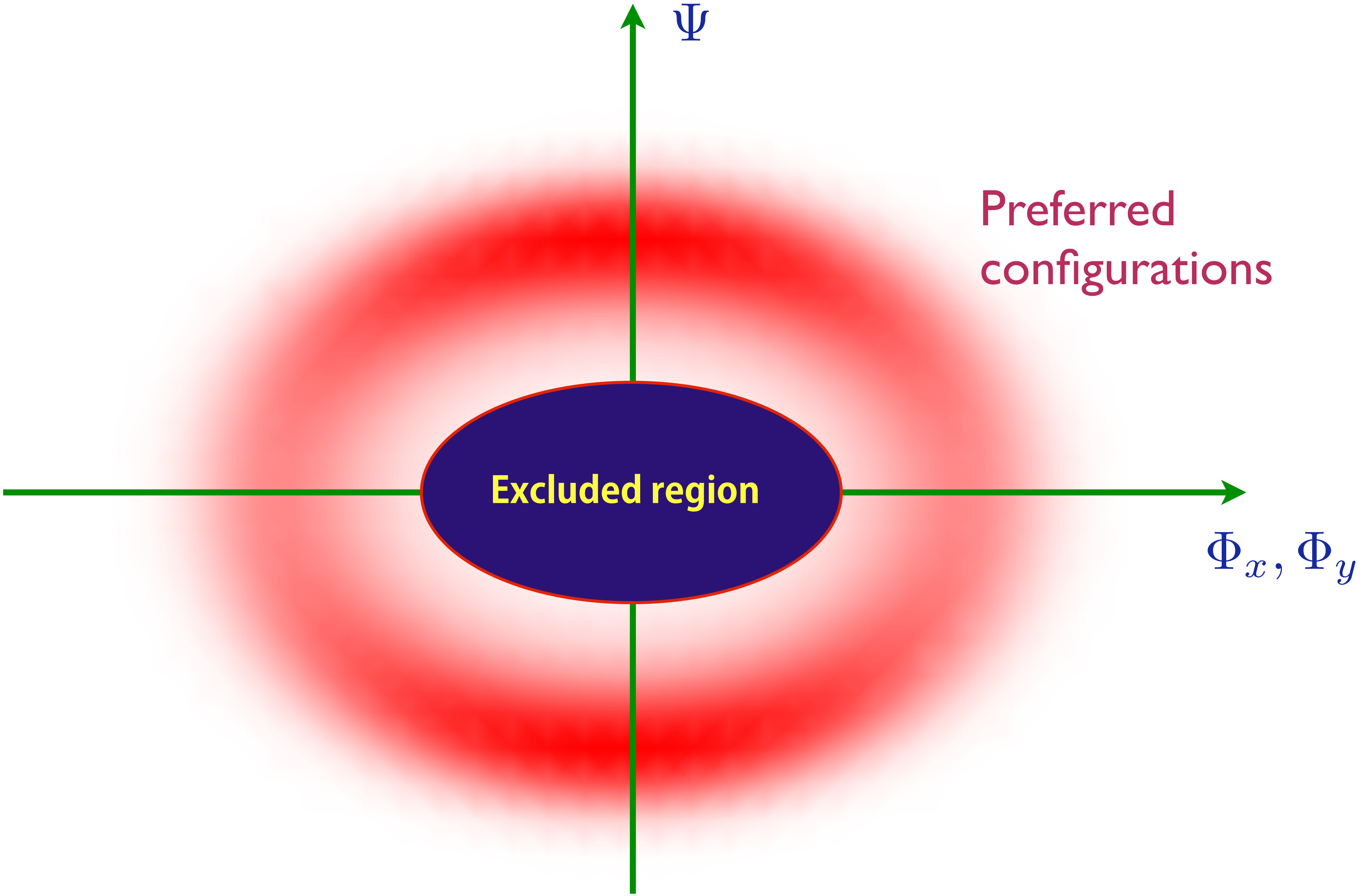


Support from theory of antiferromagnetic quantum criticality

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

K. B. Efetov, H. Meier, and C. Pepin, *Nature Physics* **9**, 442 (2013)

Multi-component order parameter

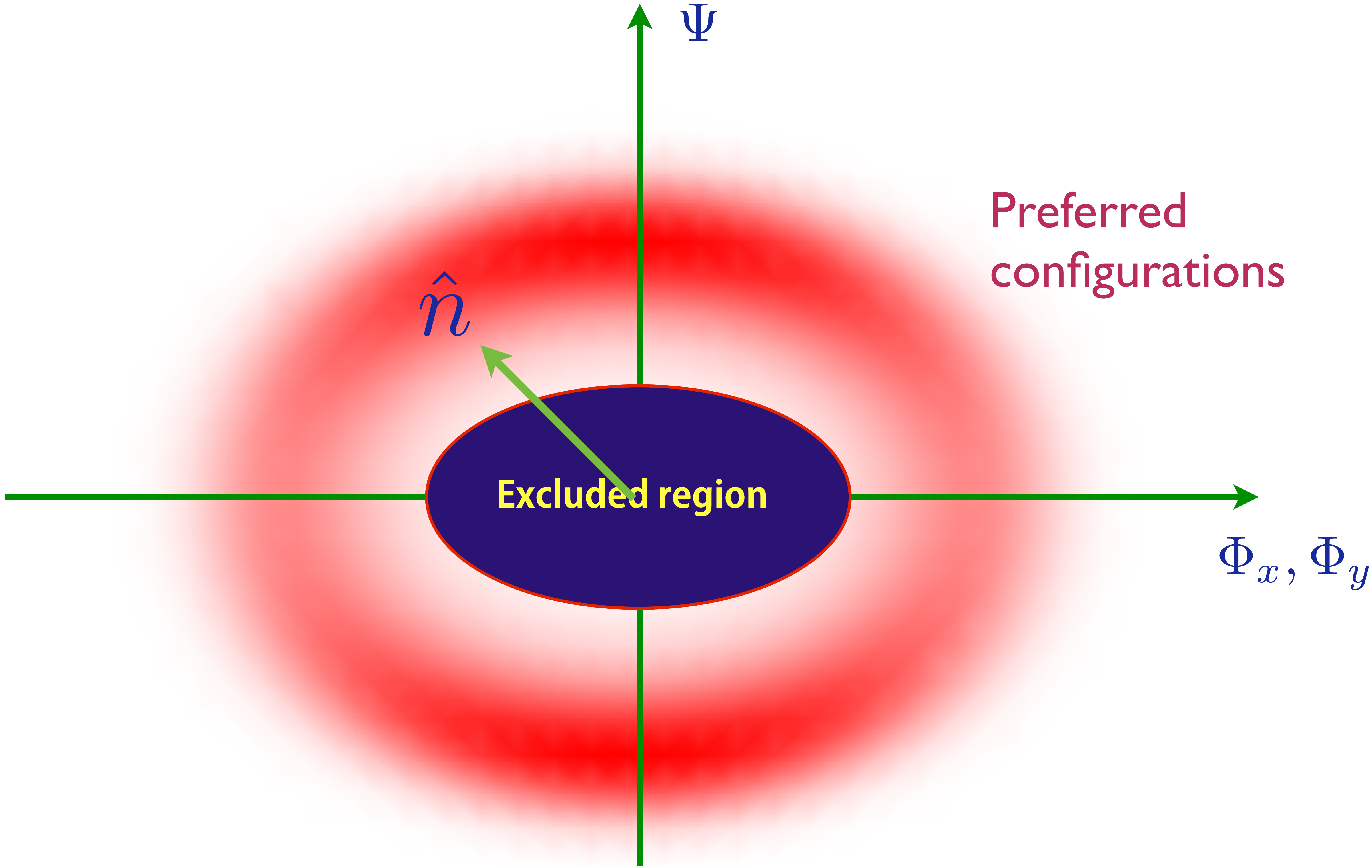


Support from theory of antiferromagnetic quantum criticality

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

K. B. Efetov, H. Meier, and C. Pepin, *Nature Physics* **9**, 442 (2013)

Multi-component order parameter



Label order parameter by a
6-component unit vector n_α with $\sum_\alpha n_\alpha^2 = 1$

O(6) non-linear sigma model

$$\mathcal{Z} = \int \mathcal{D}n_\alpha(\mathbf{r})\, \delta\left(\sum_{\alpha=1}^{6} n_\alpha^2(\mathbf{r}) - 1\right) \exp\Bigg(- \frac{\rho_s}{2T} \int d^2 r \Bigg[\sum_{\alpha=1}^{2} (\nabla n_\alpha)^2 + \lambda \sum_{\alpha=3}^{6} (\nabla n_\alpha)^2 + g \sum_{\alpha=3}^{6} n_\alpha^2 + w \left[\left(n_3^2 + n_4^2\right)^2 + \left(n_5^2 + n_6^2\right)^2 \right] \Bigg] \Bigg).$$

where $\Psi \propto n_1 + i n_2$, $\Phi_x \propto n_3 + i n_4$, $\Phi_y \propto n_5 + i n_6$.

Describes $O(6) \Rightarrow O(2)\times O(2)\times O(2)\times \mathbb{Z}_2$. The coupling g determines the anisotropy between superconductivity and charge order.

Solve by cluster Monte Carlo and $1/N$ expansion.

L. E. Hayward, D. G. Hawthorn, R. G. Melko, and S. Sachdev, arXiv:1309.6639

O(6) non-linear sigma model

$$\mathcal{Z} = \int \mathcal{D}n_\alpha(\mathbf{r})\, \delta\left(\sum_{\alpha=1}^{6} n_\alpha^2(\mathbf{r}) - 1\right) \exp\Bigg(- \frac{\rho_s}{2T} \int d^2 r \Bigg[\sum_{\alpha=1}^{2} (\nabla n_\alpha)^2 + \lambda \sum_{\alpha=3}^{6} (\nabla n_\alpha)^2 + g \sum_{\alpha=3}^{6} n_\alpha^2 + w \left[\left(n_3^2 + n_4^2\right)^2 + \left(n_5^2 + n_6^2\right)^2 \right] \Bigg] \Bigg).$$

where $\Psi \propto n_1 + i n_2$, $\Phi_x \propto n_3 + i n_4$, $\Phi_y \propto n_5 + i n_6$.

Describes $\mathrm{O}(6) \Rightarrow \mathrm{O}(2)\times\mathrm{O}(2)\times\mathrm{O}(2)\rtimes\mathbb{Z}_2$. The coupling g determines the anisotropy between superconductivity and charge order.

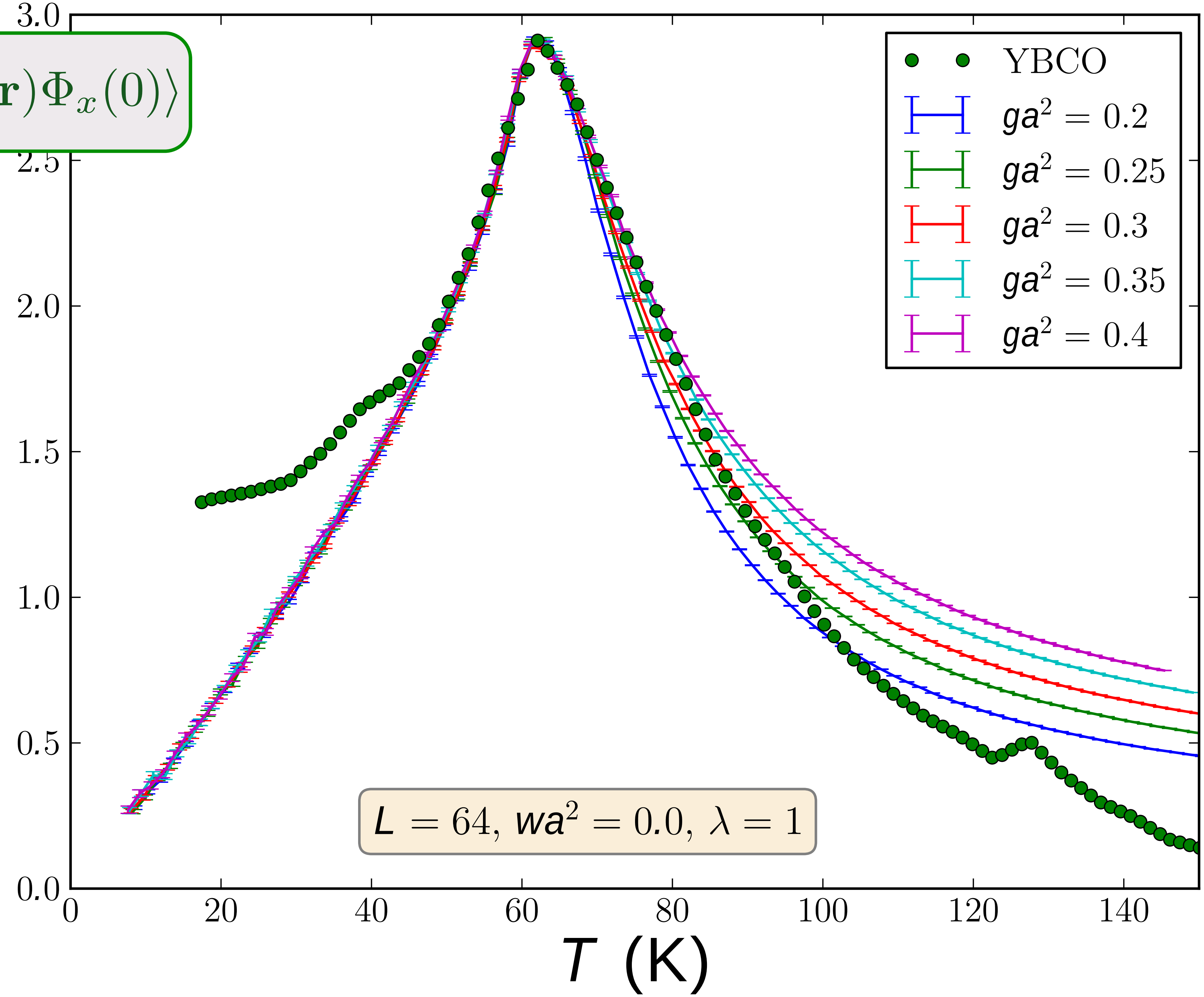
Solve by cluster Monte Carlo and $1/N$ expansion.

L. E. Hayward, D. G. Hawthorn, R. G. Melko, and S. Sachdev, arXiv:1309.6639

Comparison of Monte Carlo with experiments

$$S_{\Phi_x} = \int d^2 r \, \langle \Phi_x(\mathbf{r}) \Phi_x(0) \rangle$$

Charge order structure factor S_{Φ_x}



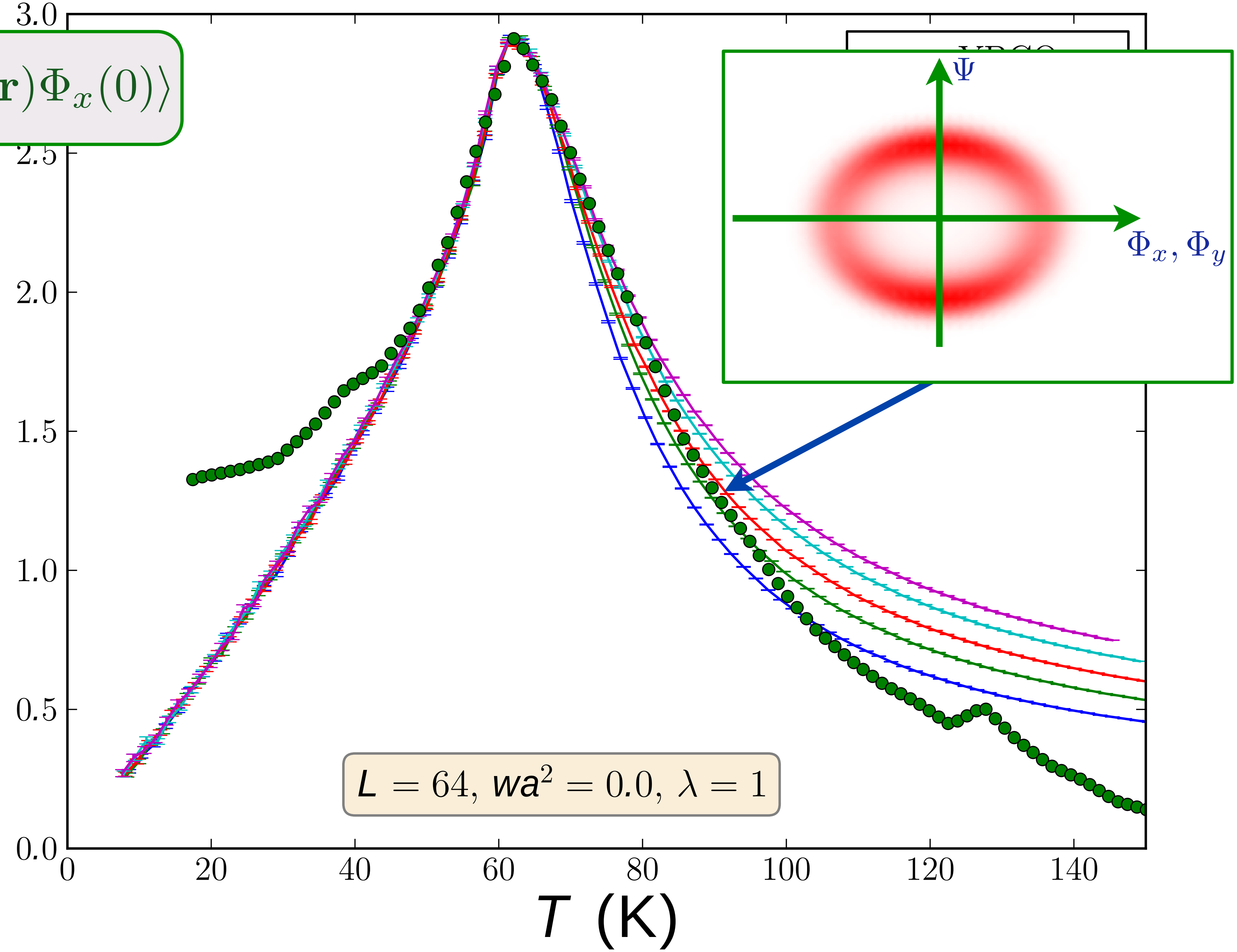
For $ga^2 = 0.30$ and $wa^2 = 0.0$ we have $\rho_s = 160$K.
The height was also rescaled to make the peak heights match.

L. E. Hayward, D. G. Hawthorn, R. G. Melko, and S. Sachdev, arXiv:1309.6639

Comparison of Monte Carlo with experiments

$$S_{\Phi_x} = \int d^2 r \, \langle \Phi_x(\mathbf{r}) \Phi_x(0) \rangle$$

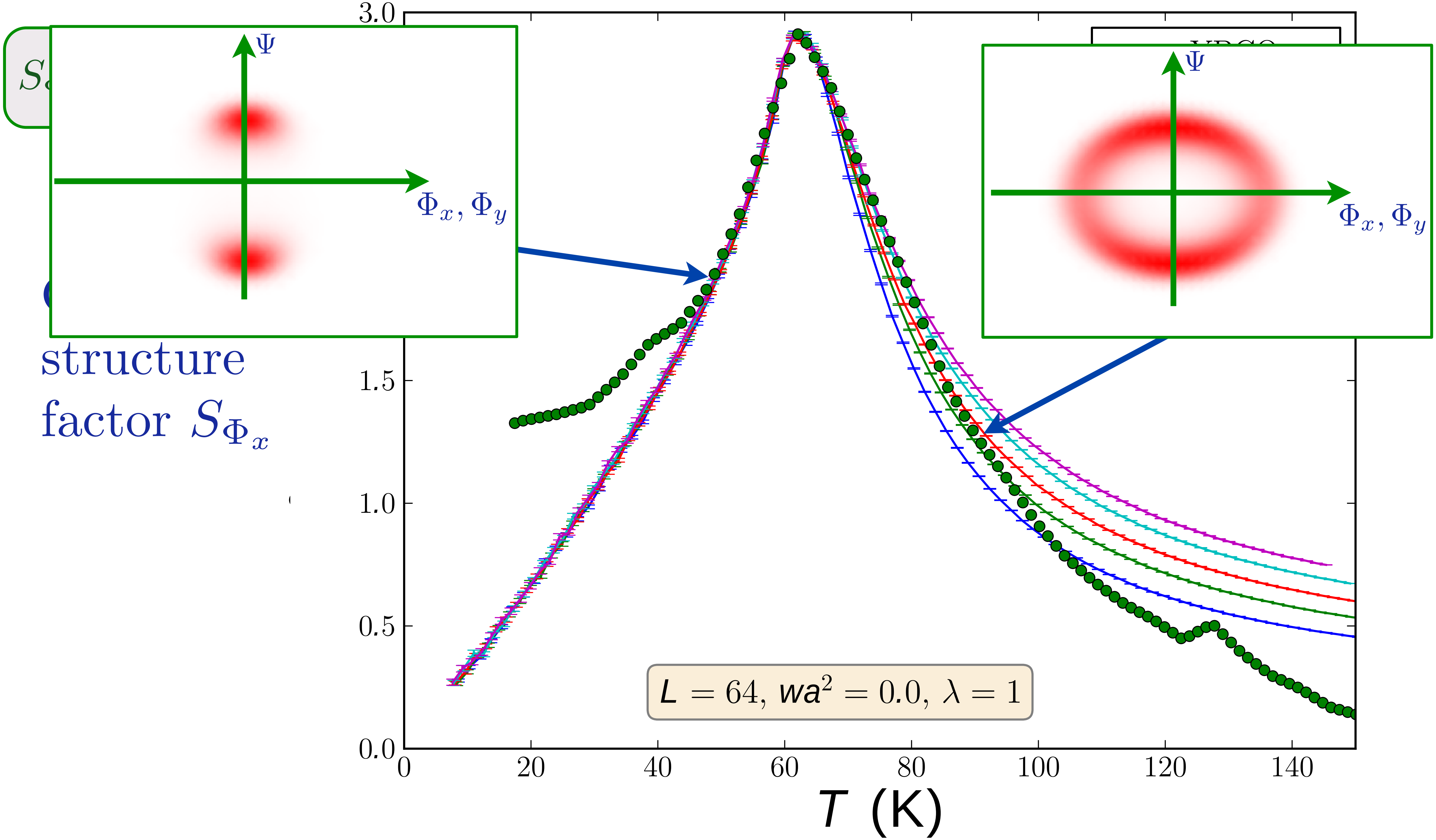
Charge order structure factor S_{Φ_x}



For $ga^2 = 0.30$ and $wa^2 = 0.0$ we have $\rho_s = 160$K.
The height was also rescaled to make the peak heights match.

L. E. Hayward, D. G. Hawthorn, R. G. Melko, and S. Sachdev, arXiv:1309.6639

Comparison of Monte Carlo with experiments



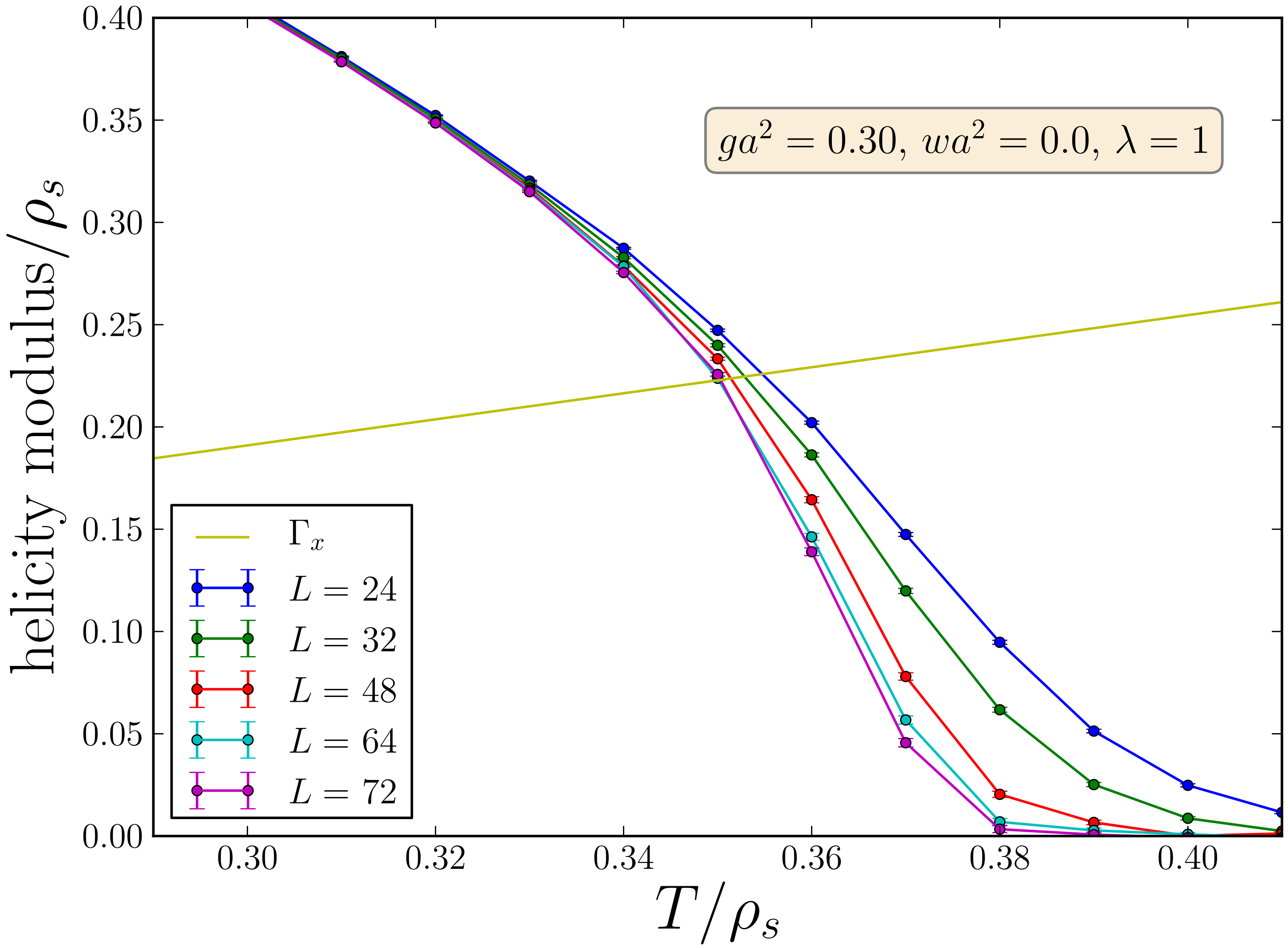
structure factor S_{Φ_x}

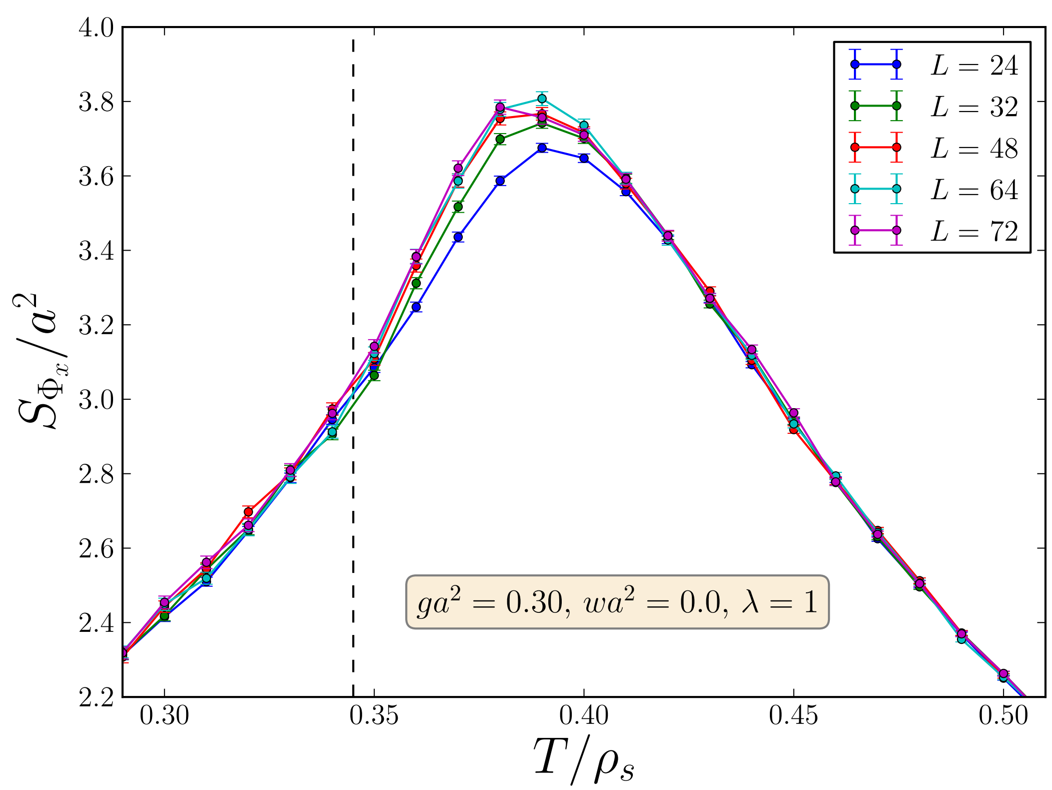
For $ga^2 = 0.30$ and $wa^2 = 0.0$ we have $\rho_s = 160\text{K}$.

The height was also rescaled to make the peak heights match.

L. E. Hayward, D. G. Hawthorn, R. G. Melko, and S. Sachdev, arXiv:1309.6639

Onset of superconductivity in Monte Carlo

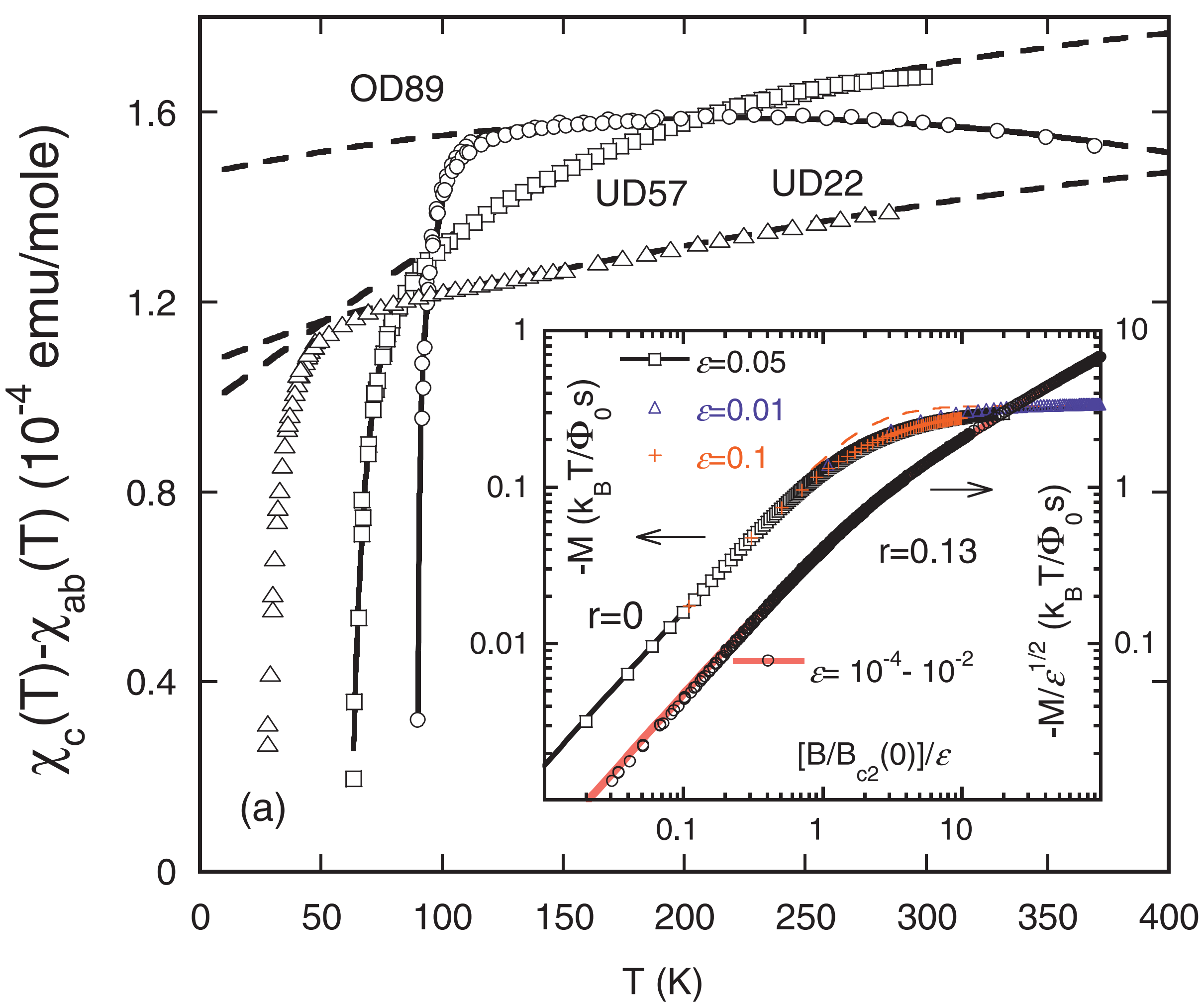




L. E. Hayward, D. G. Hawthorn,
R. G. Melko, and S. Sachdev, arXiv:1309.6639

Other experiments in the pseudogap

- The *same* set of parameters used to describe X-ray scattering, also predict the strength of superconducting fluctuations above T_c. Indeed $YBa_2Cu_3O_{6+x}$ shows significant fluctuation diamagnetism over the same range of temperatures. (S. Chatterjee et al, in progress).



PHYSICAL REVIEW B **88**, 060505(R) (2013)

I. Kokanović,[1,2,*] D. J. Hills,[1] M. L. Sutherland,[1] R. Liang,[3] and J. R. Cooper[1]

Diamagnetism of $YBa_2Cu_3O_{6+x}$ crystals above T_c: Evidence for Gaussian fluctuations

Pseudospin symmetry of the exchange interaction

$$H_{tJ} = -\sum_{i,j} t_{ij} c^\dagger_{i\alpha} c_{j\alpha} + \sum_{i<j} J_{ij}\, \vec{S}_i \cdot \vec{S}_j$$

with $\vec{S}_i = \frac{1}{2} c^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} c_{i\beta}$ is the antiferromagnetic exchange interaction. Introduce the Nambu spinor

$$D_{i\uparrow} = \begin{pmatrix} c_{i\uparrow} \\ c^\dagger_{i\downarrow} \end{pmatrix} \quad , \quad D_{i\downarrow} = \begin{pmatrix} c_{i\downarrow} \\ -c^\dagger_{i\uparrow} \end{pmatrix}$$

Then we can write

$$H_J = \frac{1}{8} \sum_{i<j} J_{ij} \left(D^\dagger_{i\alpha a} \vec{\sigma}_{\alpha\beta} D_{i\beta a} \right) \cdot \left(D^\dagger_{j\gamma b} \vec{\sigma}_{\gamma\delta} D_{j\delta b} \right)$$

where a, b are the Nambu indices. This form makes explicit the symmetry under *independent* SU(2) pseudospin transformations on each site

$$D_{i\alpha a} \to U_{i,ab} D_{i\alpha b}$$

This pseudospin (gauge) symmetry is important in classifying spin liquid ground states of H_J. It is fully broken by the electron hopping t_{ij} but does have remnant consequences in doped spin liquid states.

I. Affleck, Z. Zou, T. Hsu, and P. W. Anderson, Phys. Rev. B **38**, 745 (1988)
E. Dagotto, E. Fradkin, and A. Moreo, Phys. Rev. B **38**, 2926 (1988)
P. A. Lee, N. Nagaosa, and X.-G. Wen, Rev. Mod. Phys. **78**, 17 (2006)

Pseudospin symmetry of the exchange interaction

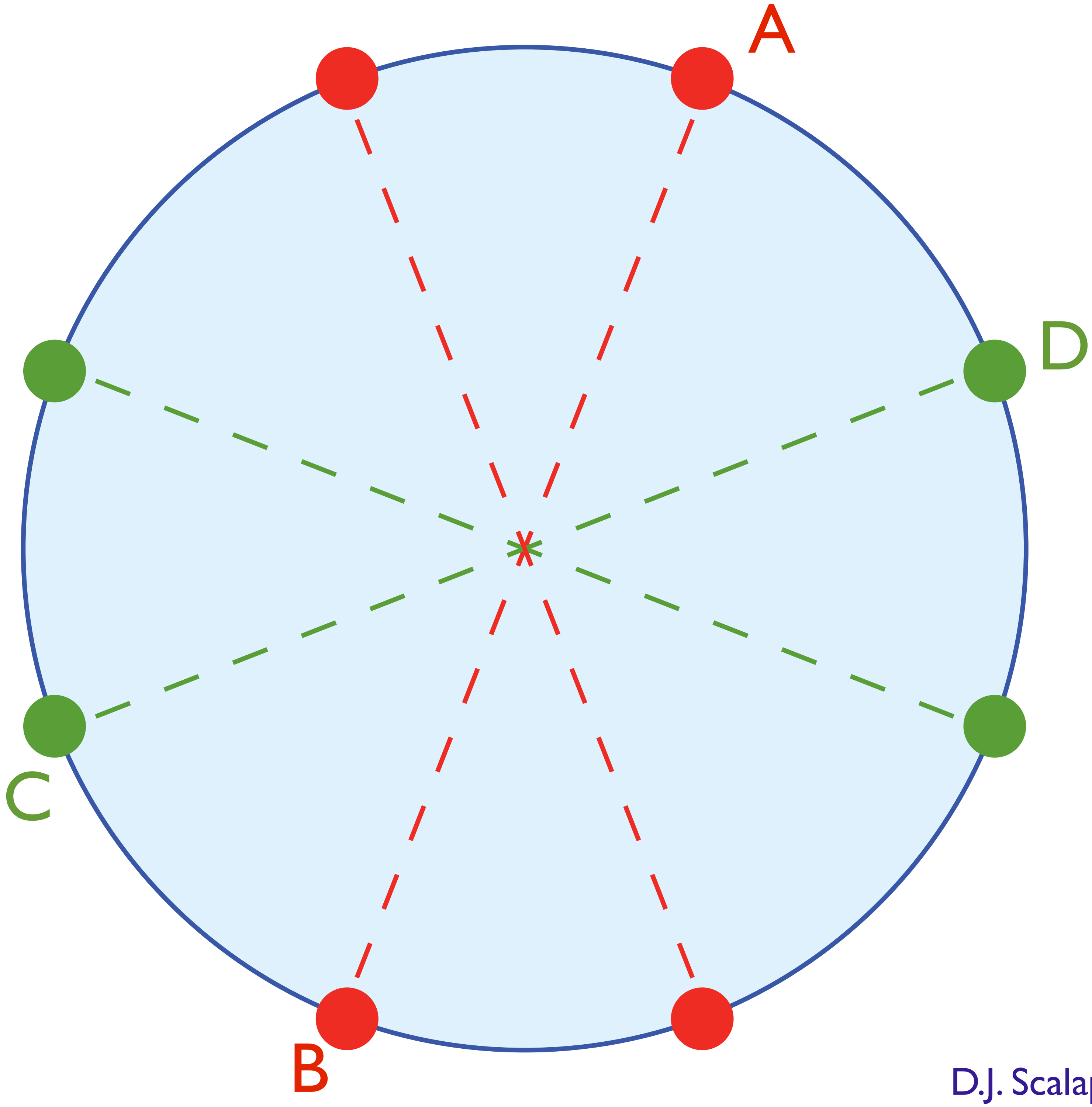
We will find important consequences of the pseudospin symmetry in ordinary metals with antiferromagnetic correlations.

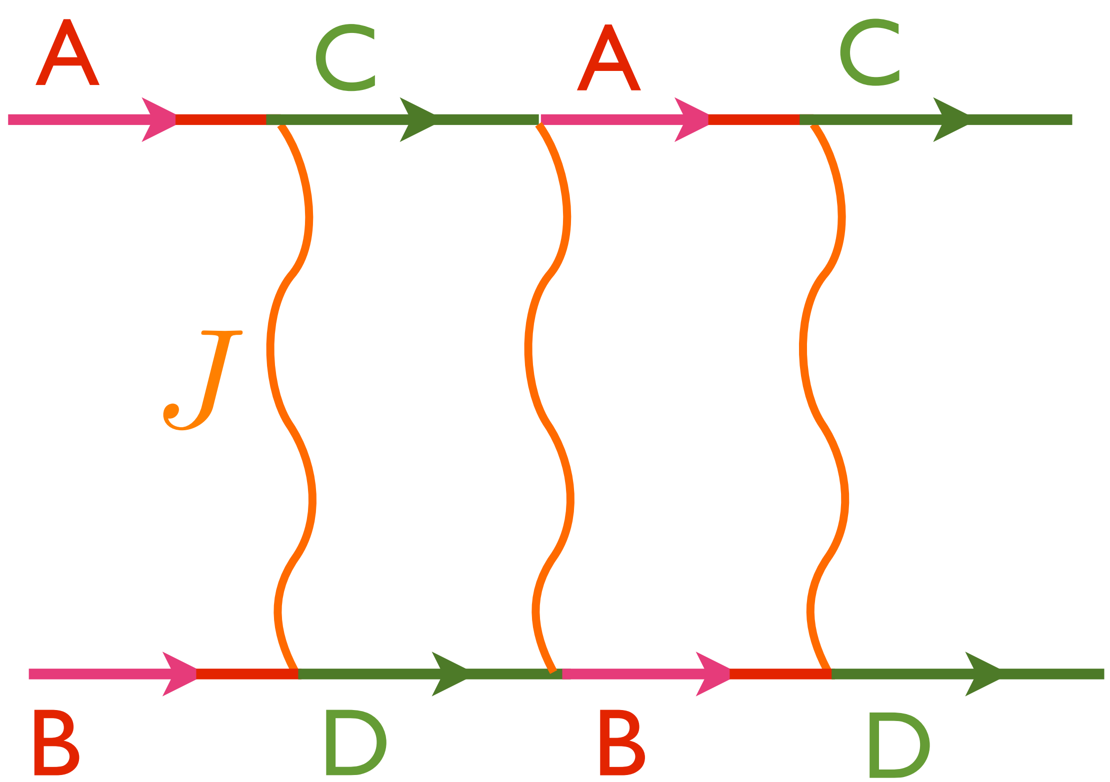
$$H_{tJ} = -\sum_{i,j} t_{ij} c_{i\alpha}^{\dagger} c_{j\alpha} + \sum_{i<j} J_{ij} \vec{S}_i \cdot \vec{S}_j$$

In Fourier space, the exchange interaction $J(\mathbf{q})$ is maximum near $\mathbf{q} = \mathbf{K} \equiv (\pi, \pi)$. So it is most effective near points on the Fermi surface which are separated by $\mathbf{K}$, the so-called "hot spots". Exchange interactions near the hot spots are expected to lead to d-wave superconductivity at low temperatures.

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

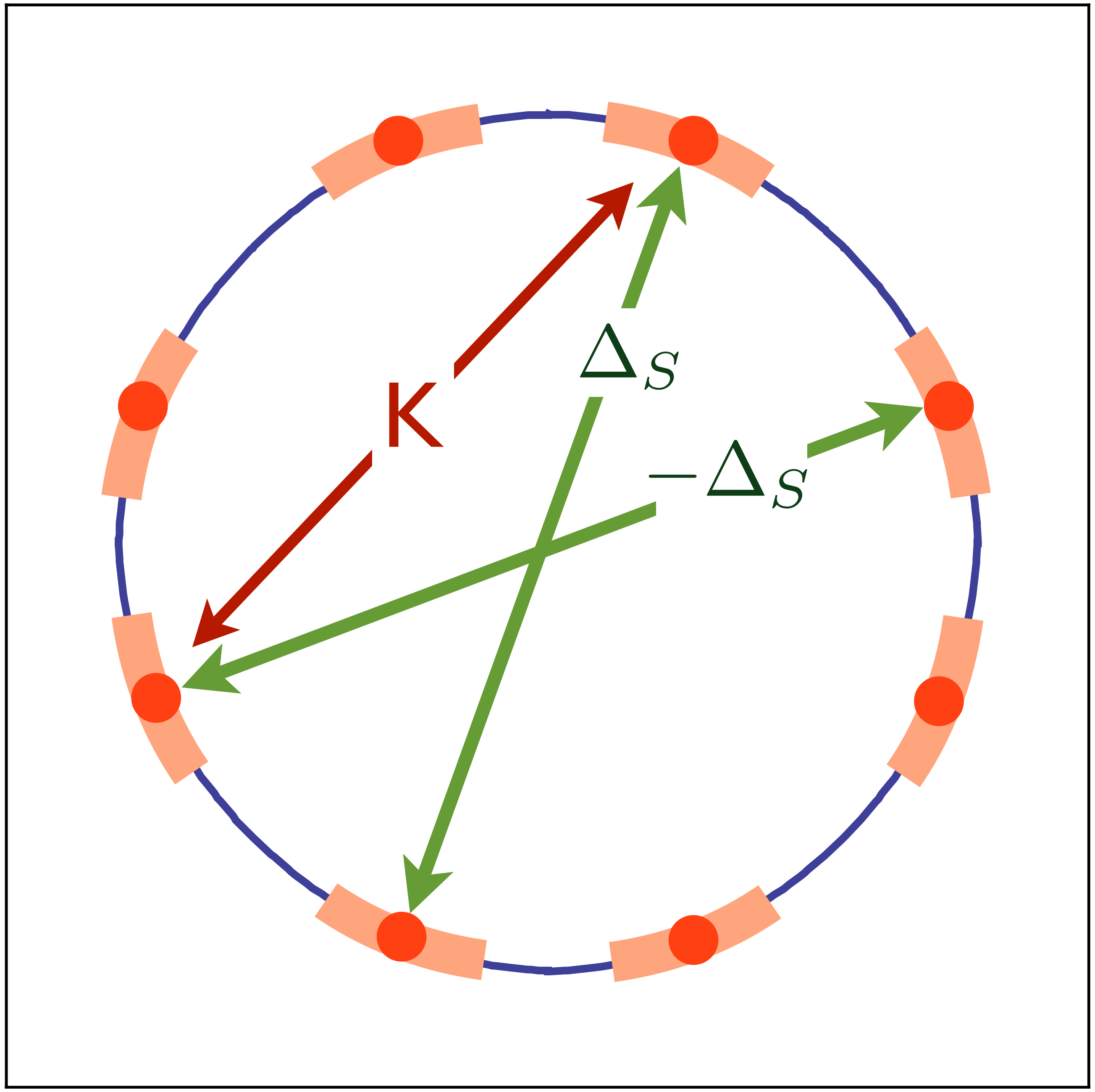
Pairing "glue" from antiferromagnetic fluctuations near "hot spots" on the Fermi surface



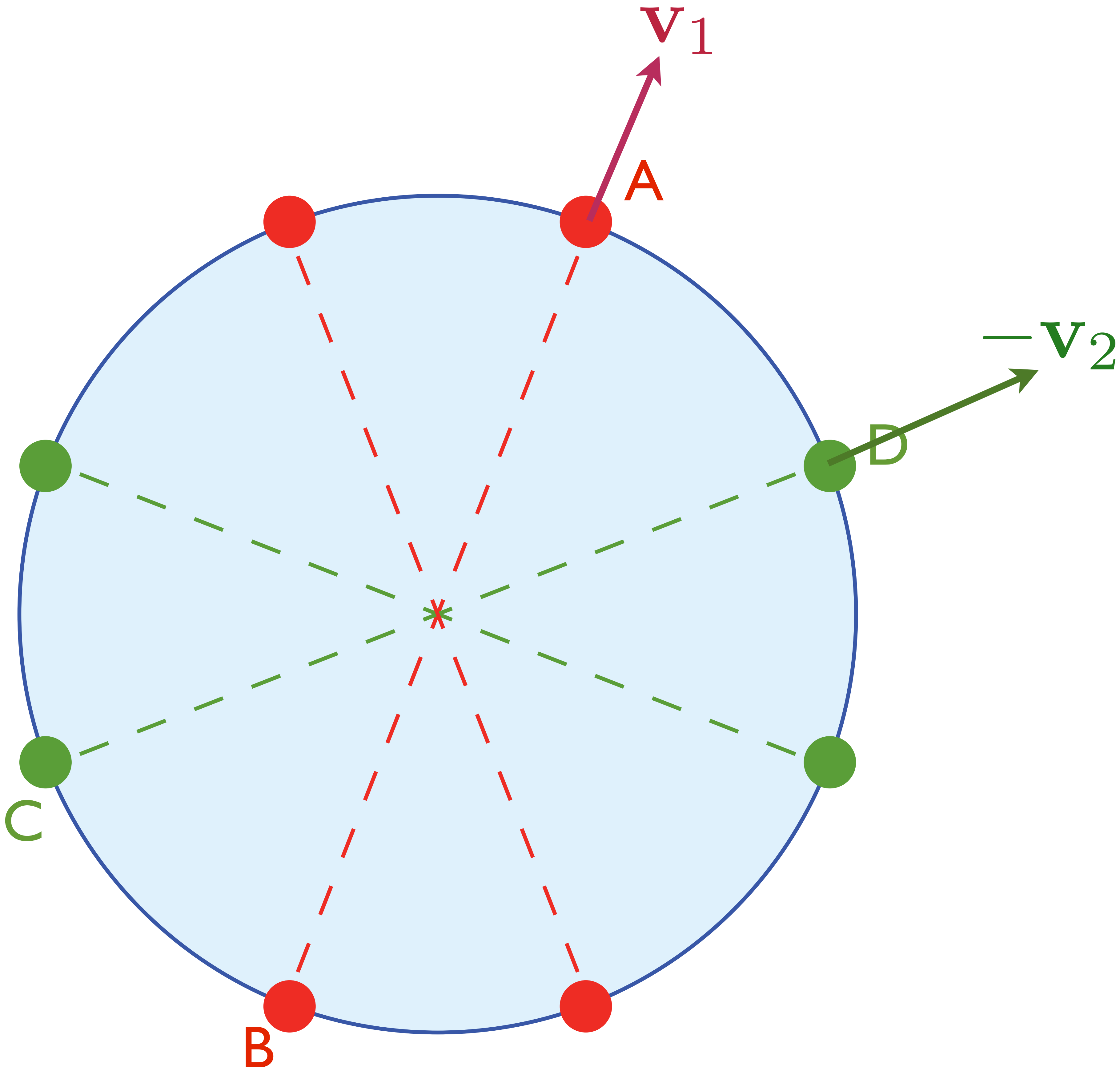


V. J. Emery, *J. Phys. (Paris) Colloq.* **44**, C3-977 (1983)
D.J. Scalapino, E. Loh, and J.E. Hirsch, *Phys. Rev. B* **34**, 8190 (1986)
K. Miyake, S. Schmitt-Rink, and C. M. Varma, *Phys. Rev. B* **34**, 6554 (1986)
S. Raghu, S.A. Kivelson, and D.J. Scalapino, *Phys. Rev. B* **81**, 224505 (2010)
E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012)

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



d-wave superconductor: particle-particle pairing at *and near* hot spots, with sign-changing pairing amplitude



$\mathbf{v}_1$
A
$-\mathbf{v}_2$
D
C
B

Hamiltonian at and *near* hot spots

$$H = \sum_{\mathbf{k}} \Bigg[\left[\mathbf{v}_1 \cdot \mathbf{k} \qquad\qquad \right] c_{A\alpha}^{\dagger}(\mathbf{k}) c_{A\alpha}(\mathbf{k})$$

$$+ \left[\mathbf{v}_2 \cdot \mathbf{k} \qquad\qquad \right] c_{C\alpha}^{\dagger}(\mathbf{k}) c_{C\alpha}(\mathbf{k})$$

$$+ \left[-\mathbf{v}_1 \cdot \mathbf{k} \qquad\qquad \right] c_{B\alpha}^{\dagger}(\mathbf{k}) c_{B\alpha}(\mathbf{k})$$

$$+ \left[-\mathbf{v}_2 \cdot \mathbf{k} \qquad\qquad \right] c_{D\alpha}^{\dagger}(\mathbf{k}) c_{D\alpha}(\mathbf{k})$$

$$+ \int d^2x \Bigg[-J \left(c_{A\alpha}^{\dagger} \vec{\sigma}_{\alpha\beta} c_{C\beta} + c_{C\alpha}^{\dagger} \vec{\sigma}_{\alpha\beta} c_{A\beta} \right)$$

$$\cdot \left(c_{B\gamma}^{\dagger} \vec{\sigma}_{\gamma\delta} c_{D\delta} + c_{D\gamma}^{\dagger} \vec{\sigma}_{\gamma\delta} c_{B\delta} \right)$$

$$\Bigg]$$

Hamiltonian at and *near* hot spots

$$H = \sum_{\mathbf{k}} \Big[[\mathbf{v}_1 \cdot \mathbf{k} \quad] c^\dagger_{A\alpha}(\mathbf{k}) c_{A\alpha}(\mathbf{k})$$

$$+ [\mathbf{v}_2 \cdot \mathbf{k} \quad] c^\dagger_{C\alpha}(\mathbf{k}) c_{C\alpha}(\mathbf{k})$$

$$+ [-\mathbf{v}_1 \cdot \mathbf{k} \quad] c^\dagger_{B\alpha}(\mathbf{k}) c_{B\alpha}(\mathbf{k})$$

$$+ [-\mathbf{v}_2 \cdot \mathbf{k} \quad] c^\dagger_{D\alpha}(\mathbf{k}) c_{D\alpha}(\mathbf{k})$$

$$+ \int d^2x \Big[-J \left(c^\dagger_{A\alpha} \vec{\sigma}_{\alpha\beta} c_{C\beta} + c^\dagger_{C\alpha} \vec{\sigma}_{\alpha\beta} c_{A\beta} \right)$$

$$\cdot \left(c^\dagger_{B\gamma} \vec{\sigma}_{\gamma\delta} c_{D\delta} + c^\dagger_{D\gamma} \vec{\sigma}_{\gamma\delta} c_{B\delta} \right)$$

$$\Big]$$

This Hamiltonian has an exact SU(2)xSU(2) pseudospin symmetry !

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

Hamiltonian at and *near* hot spots

$$H = \sum_{\mathbf{k}} \Big[\left[\mathbf{v}_1 \cdot \mathbf{k} + \alpha(\mathbf{v}_1 \times \mathbf{k})^2\right] c^\dagger_{A\alpha}(\mathbf{k}) c_{A\alpha}(\mathbf{k})$$

$$+ \left[\mathbf{v}_2 \cdot \mathbf{k} + \alpha(\mathbf{v}_2 \times \mathbf{k})^2\right] c^\dagger_{C\alpha}(\mathbf{k}) c_{C\alpha}(\mathbf{k})$$

$$+ \left[-\mathbf{v}_1 \cdot \mathbf{k} + \alpha(\mathbf{v}_1 \times \mathbf{k})^2\right] c^\dagger_{B\alpha}(\mathbf{k}) c_{B\alpha}(\mathbf{k})$$

$$+ \left[-\mathbf{v}_2 \cdot \mathbf{k} + \alpha(\mathbf{v}_2 \times \mathbf{k})^2\right] c^\dagger_{D\alpha}(\mathbf{k}) c_{D\alpha}(\mathbf{k})$$

Fermi surface curvature; breaks pseudospin symmetry

$$+ \int d^2x \Big[-J \left(c^\dagger_{A\alpha} \vec{\sigma}_{\alpha\beta} c_{C\beta} + c^\dagger_{C\alpha} \vec{\sigma}_{\alpha\beta} c_{A\beta} \right)$$

$$\cdot \left(c^\dagger_{B\gamma} \vec{\sigma}_{\gamma\delta} c_{D\delta} + c^\dagger_{D\gamma} \vec{\sigma}_{\gamma\delta} c_{B\delta} \right)$$

Coulomb repulsion; breaks pseudospin symmetry

$$-V \left(c^\dagger_{A\alpha} c_{C\alpha} + c^\dagger_{C\alpha} c_{A\alpha} \right) \left(c^\dagger_{B\beta} c_{D\beta} + c^\dagger_{D\beta} c_{B\beta} \right) \Big]$$

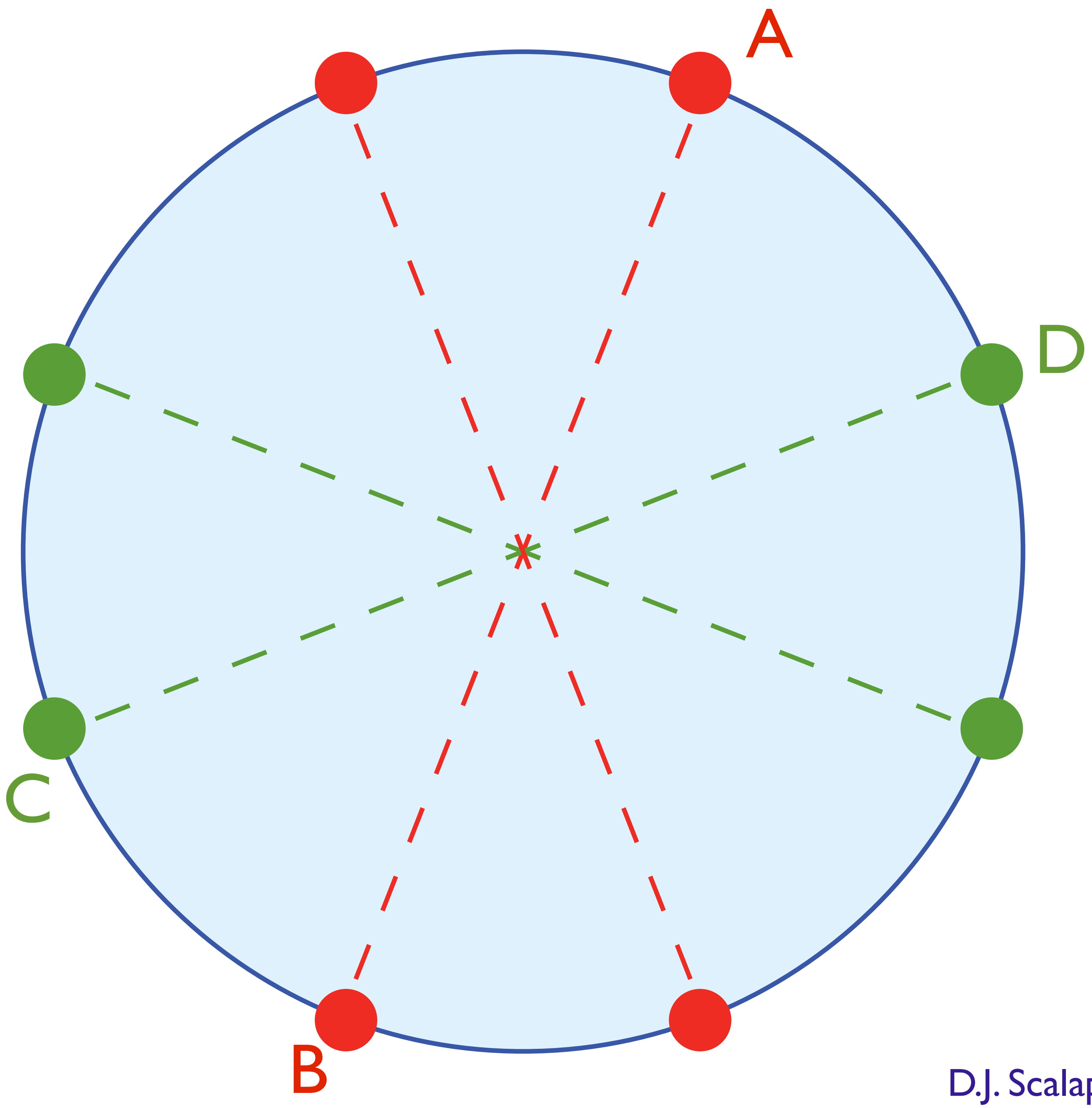
Perform standard Hartree-Fock-BCS factorizations into

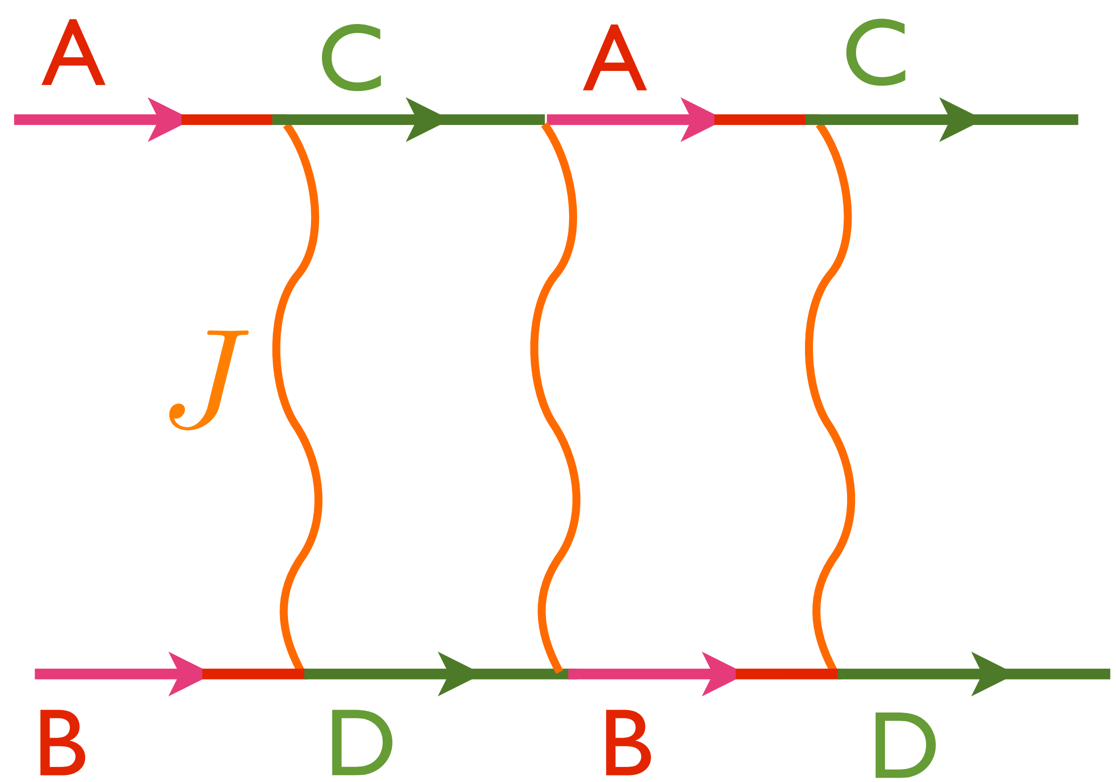
$$\Delta_S = \langle \varepsilon_{\alpha\beta} \Psi_{A\alpha} \Psi_{B\beta} \rangle = -\langle \varepsilon_{\alpha\beta} \Psi_{C\alpha} \Psi_{D\beta} \rangle$$

$$P_{\mathbf{Q}} = \left\langle \Psi^\dagger_{A\alpha} \Psi_{B\alpha} \right\rangle = -\left\langle \Psi^\dagger_{C\alpha} \Psi_{D\alpha} \right\rangle$$

With pseudospin symmetry, energy depends only on $|\Delta_S|^2 + |P_{\mathbf{Q}}|^2$.

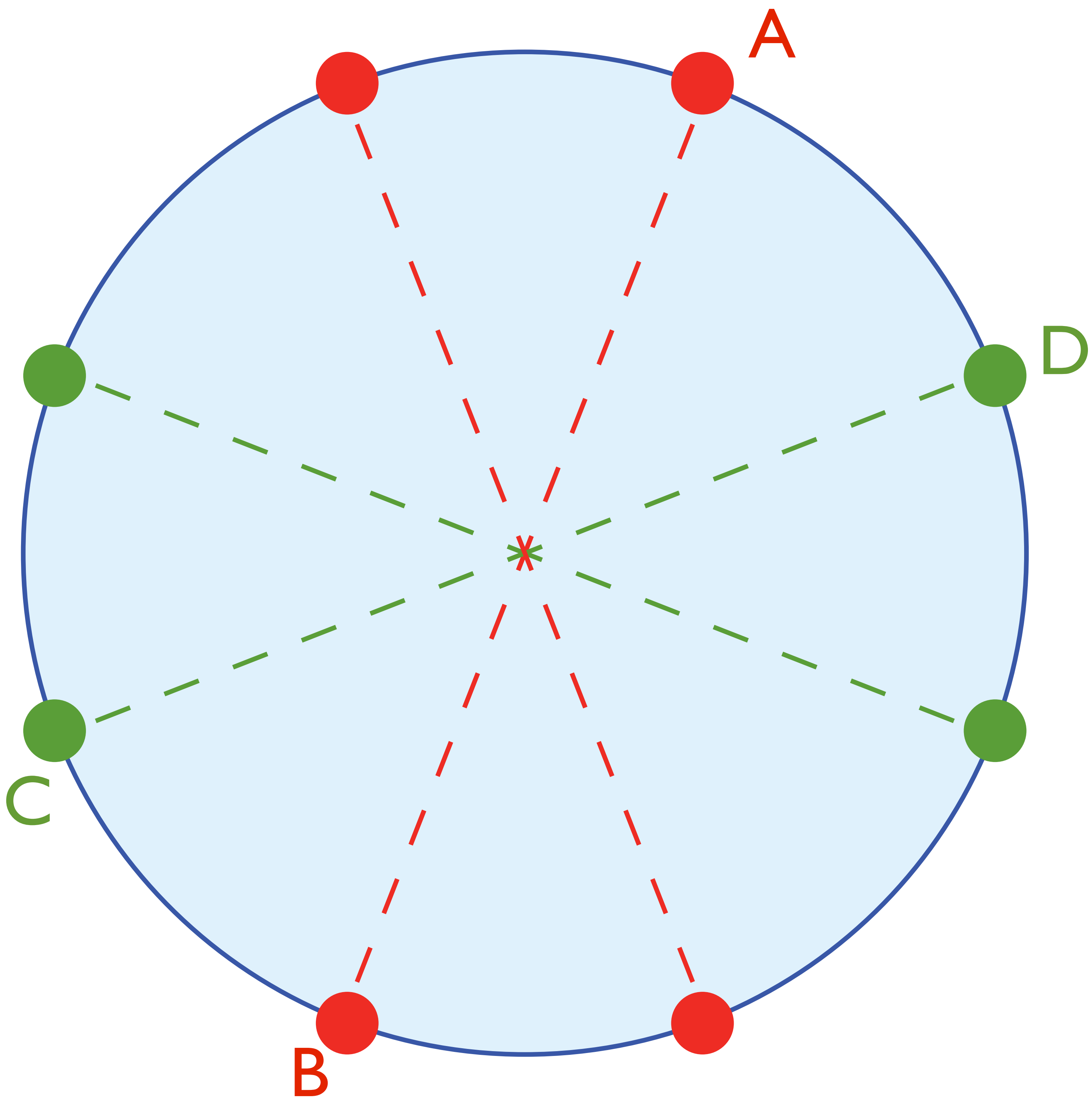
Pairing "glue" from antiferromagnetic fluctuations

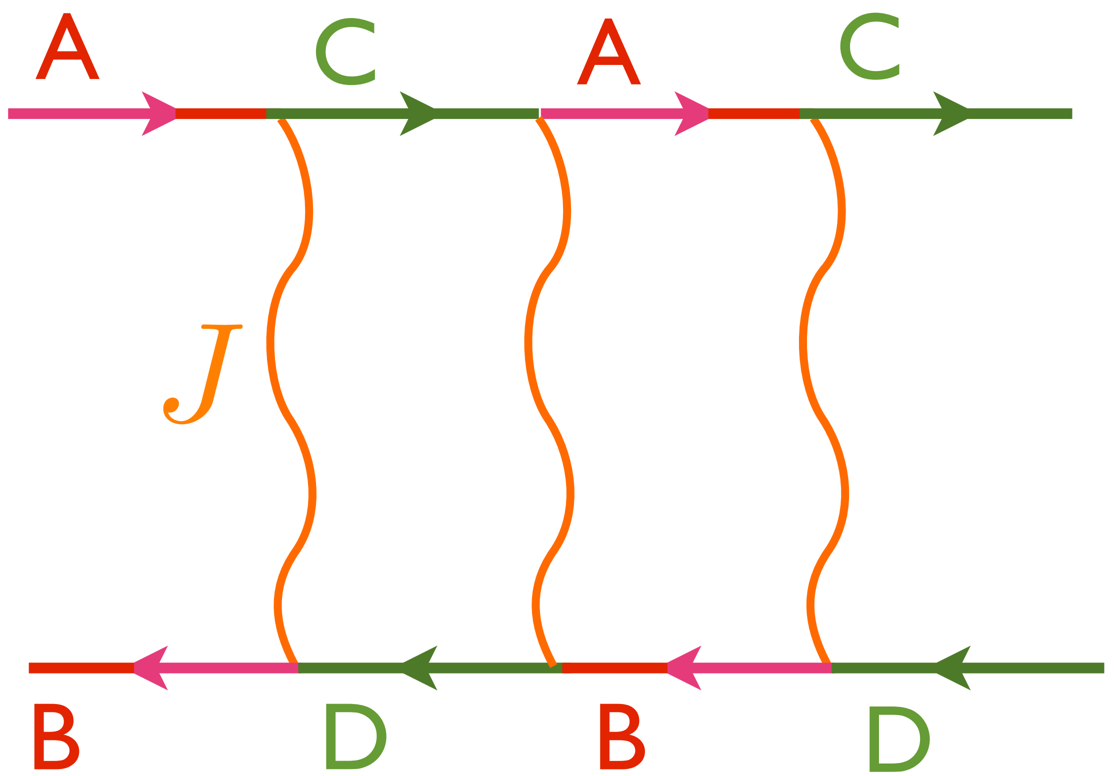




V. J. Emery, *J. Phys. (Paris) Colloq.* **44**, C3-977 (1983)
D.J. Scalapino, E. Loh, and J.E. Hirsch, *Phys. Rev. B* **34**, 8190 (1986)
K. Miyake, S. Schmitt-Rink, and C. M. Varma, *Phys. Rev. B* **34**, 6554 (1986)
S. Raghu, S.A. Kivelson, and D.J. Scalapino, *Phys. Rev. B* **81**, 224505 (2010)
E. Berg, M. Metlitski, and S. Sachdev, *Science* **338**, 1606 (2012)

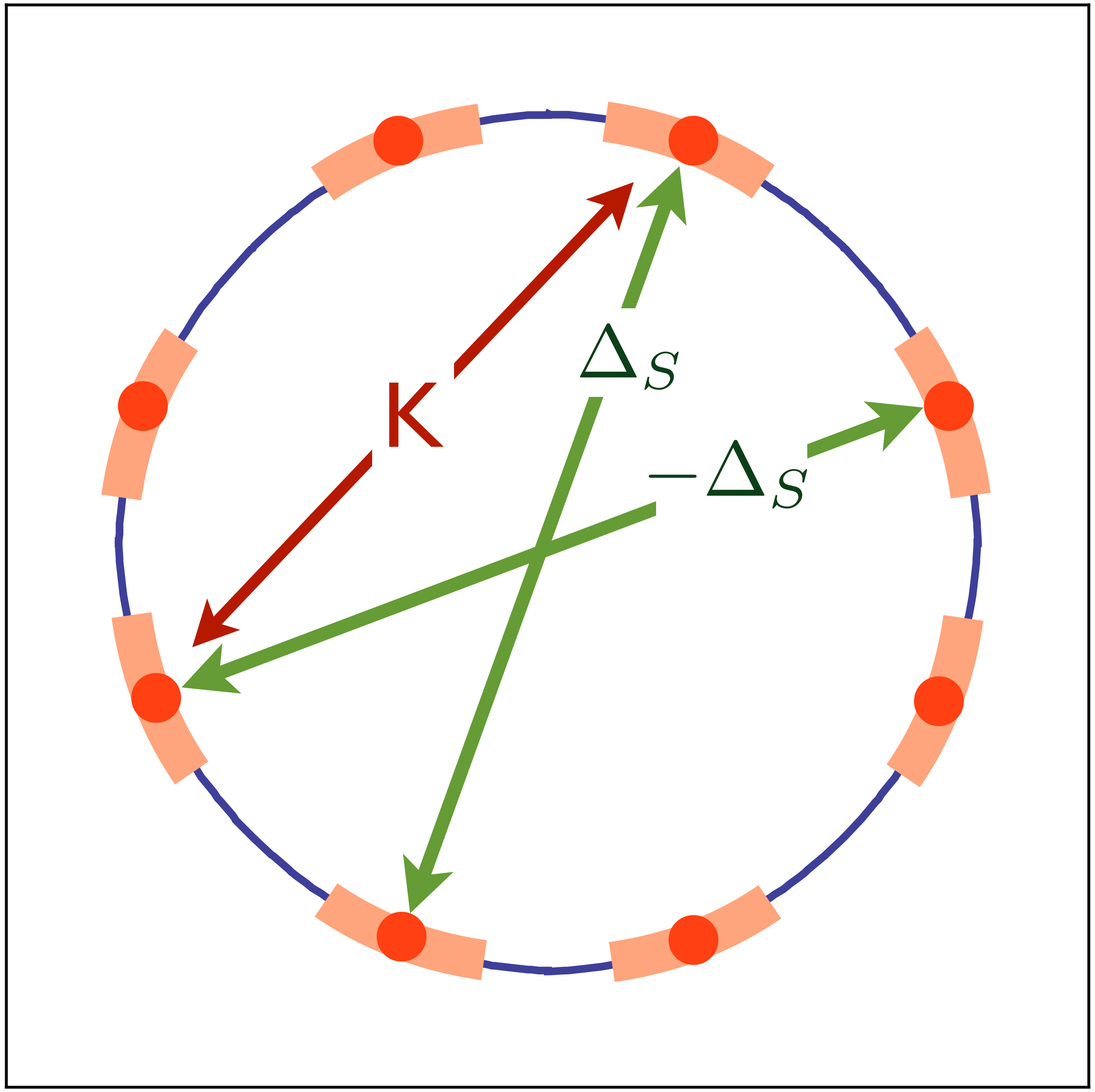
Same "glue" leads to particle-hole pairing !





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

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

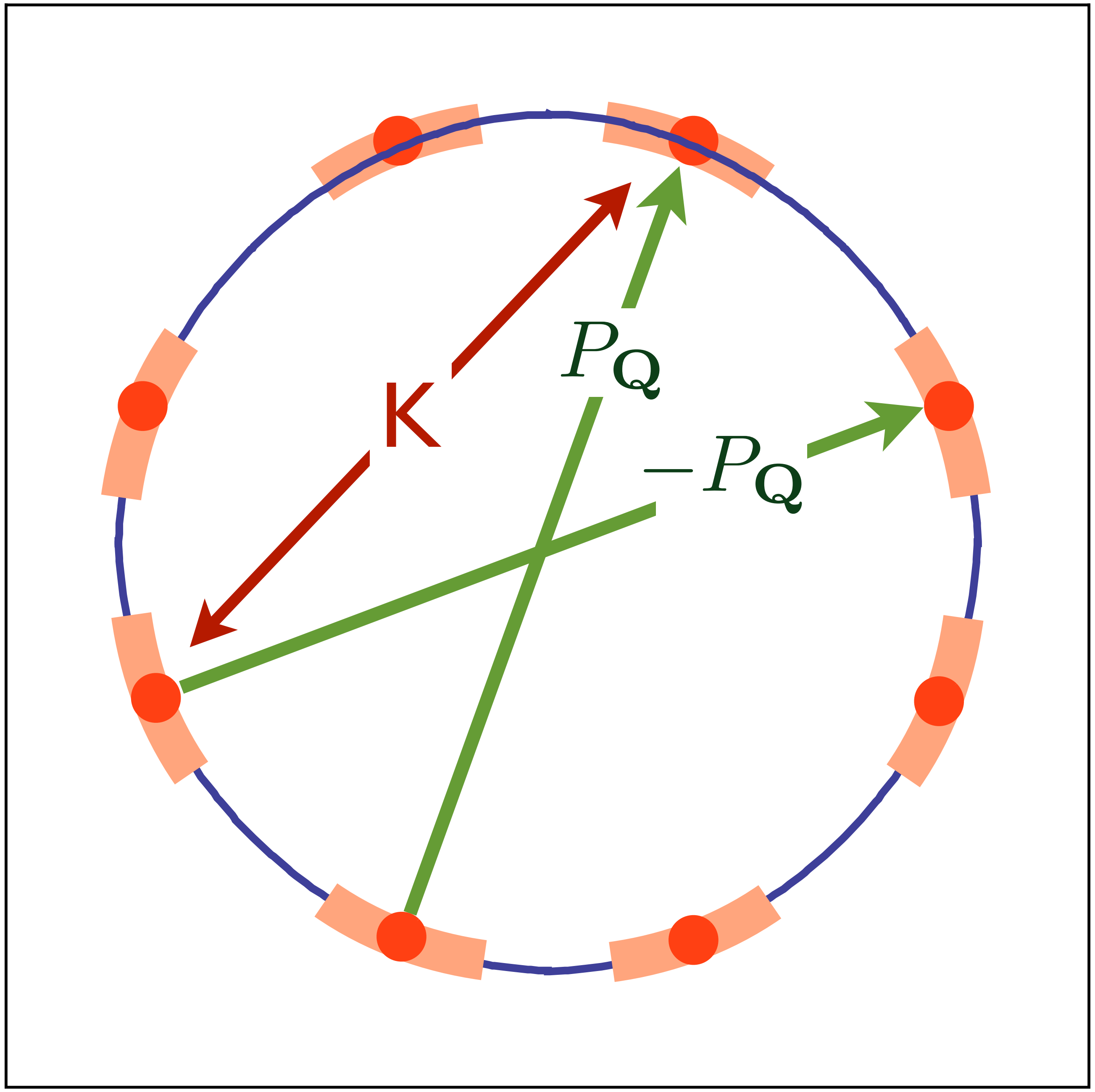


d-wave superconductor: particle-particle pairing
at *and near* hot spots, with
sign-changing pairing amplitude

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

After pseudospin rotation on *half* the hot-spots

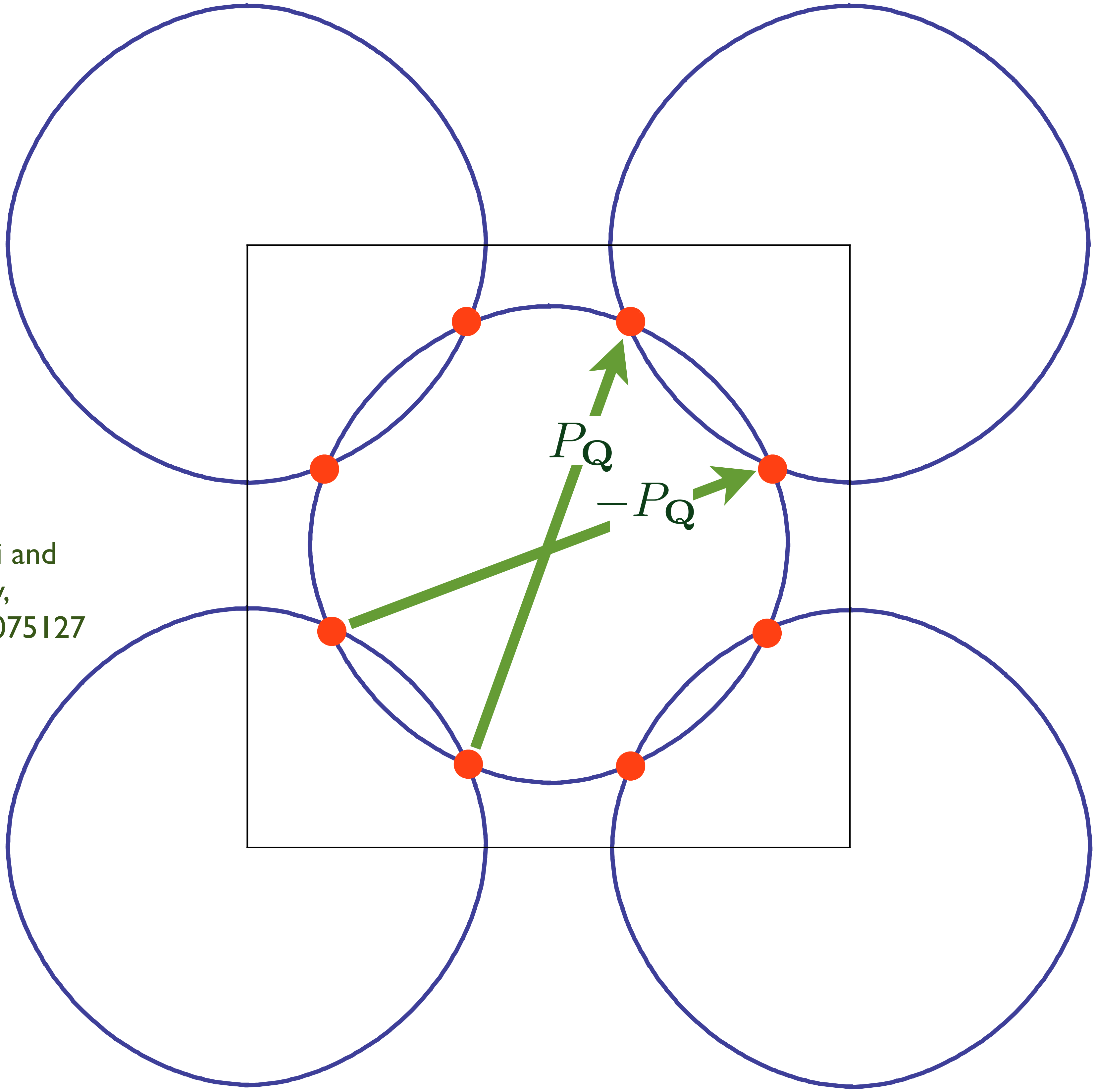
M.A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)



$\mathbf{Q}$ is '$2k_F$' wavevector

Incommensurate d-wave bond order: particle-hole pairing at *and near* hot spots, with sign-changing pairing amplitude

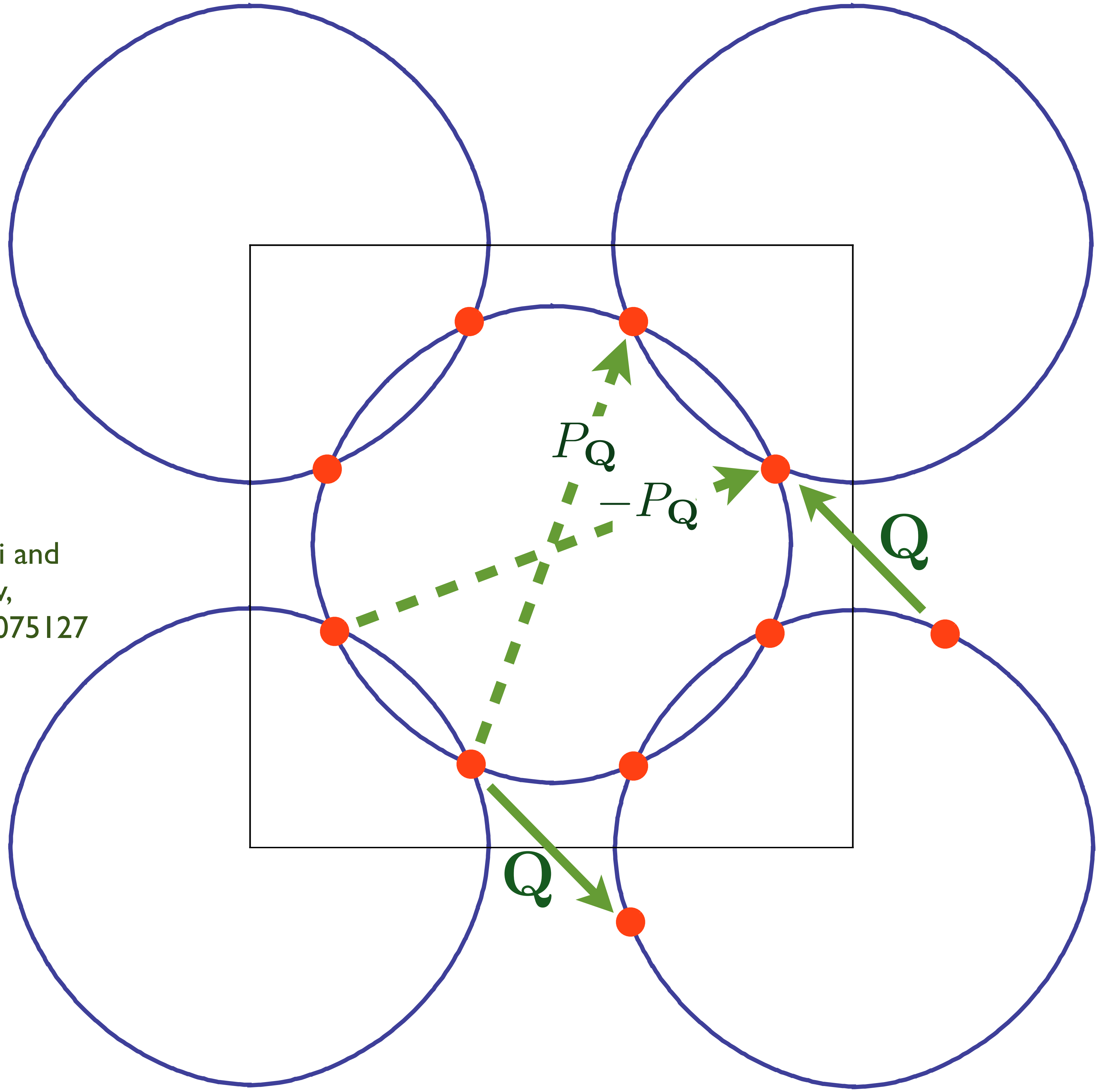
Incommensurate *d*-wave bond order



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

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

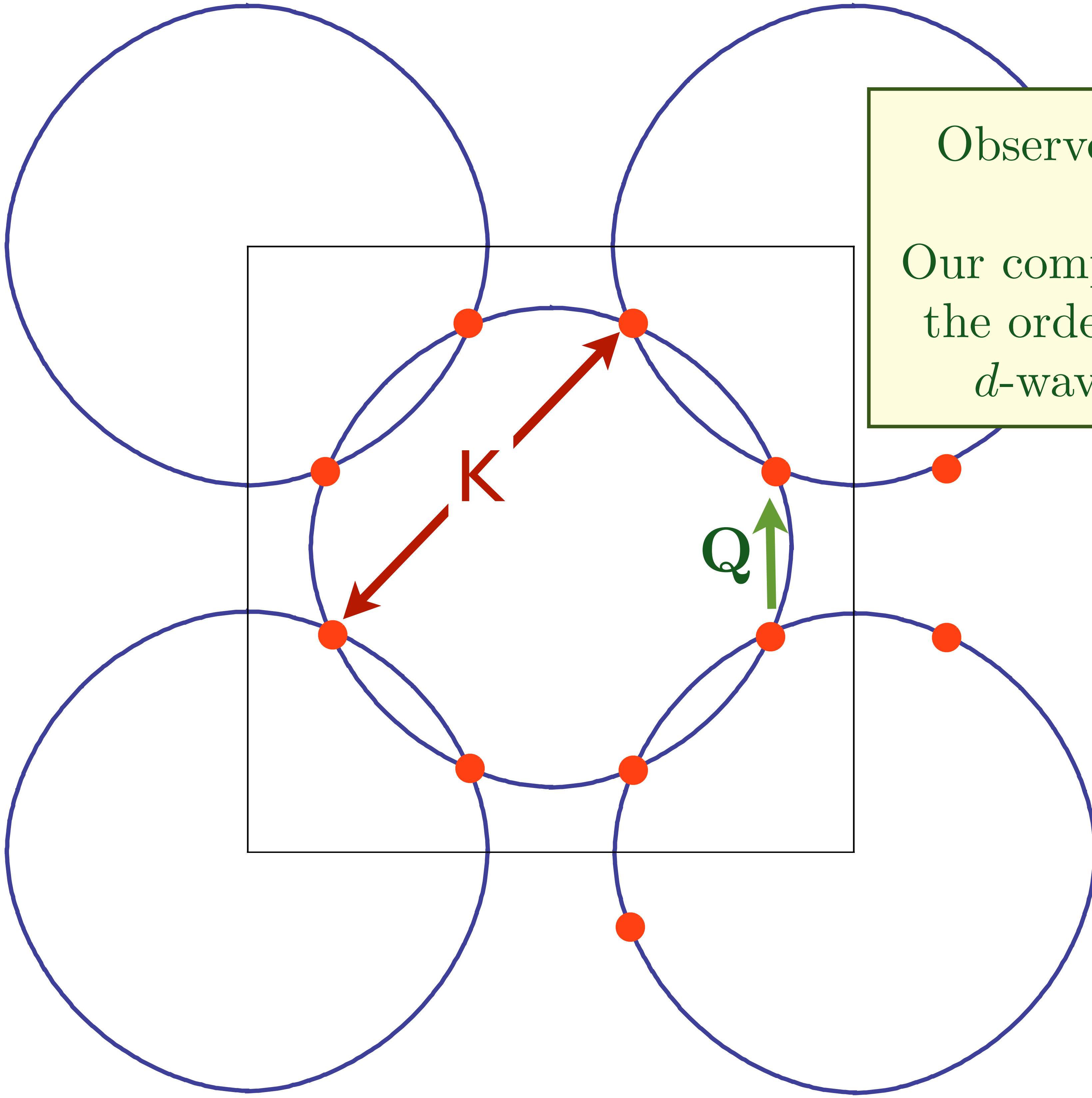
Incommensurate *d*-wave bond order



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

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

Incommensurate *d*-wave bond order

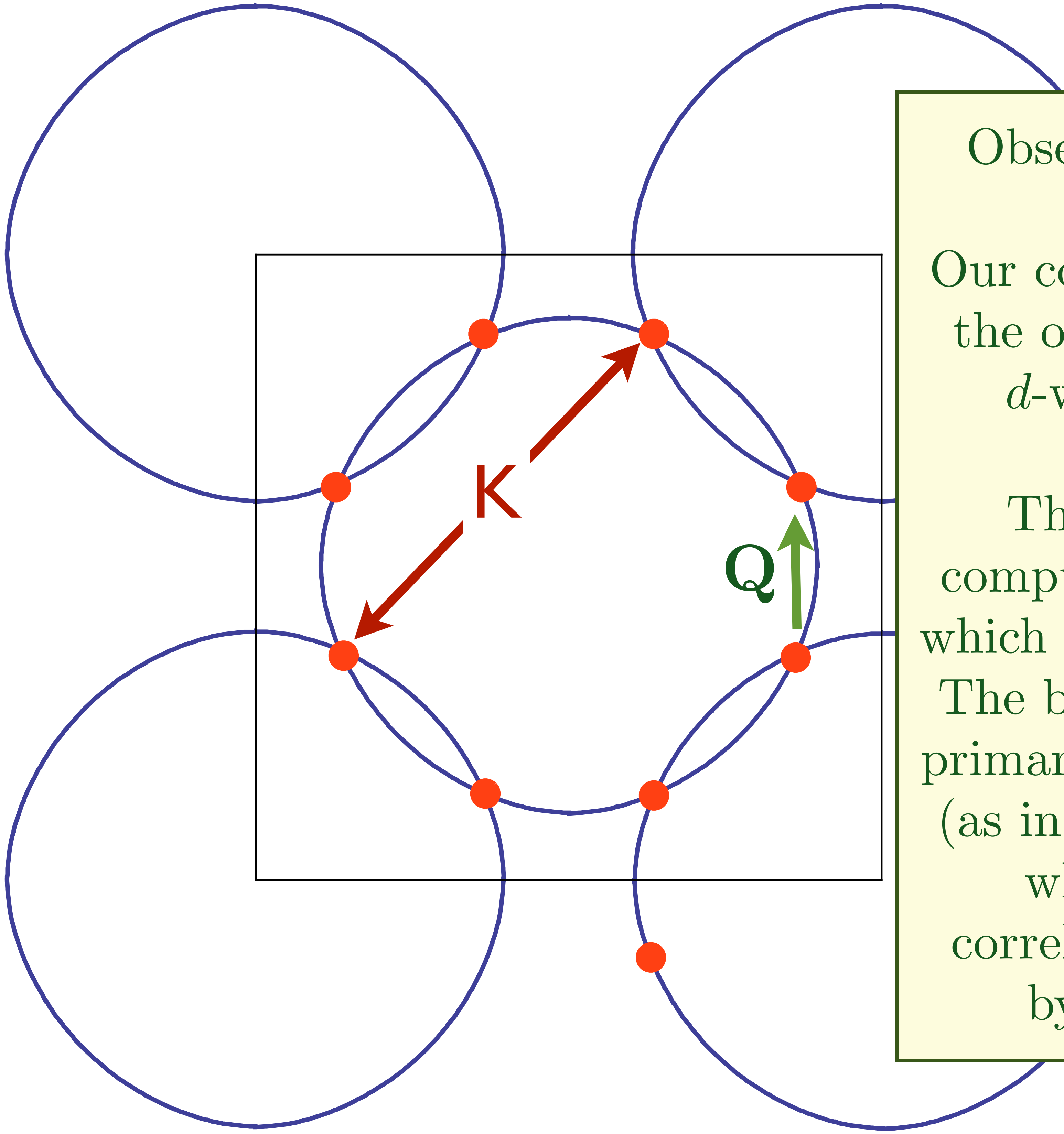


Observed low T ordering.

Our computations show that the order is predominantly d-wave also at this $\mathbf{Q}$.

S. Sachdev and R. La Placa, Physical Review Letters **111**, 027202 (2013)
M. Vojta and S. Sachdev, Physical Review Letters **83**, 3916 (1999)
M. Vojta and O. Rosch, Physical Review B 77, 094504 (2008)

Incommensurate *d*-wave bond order



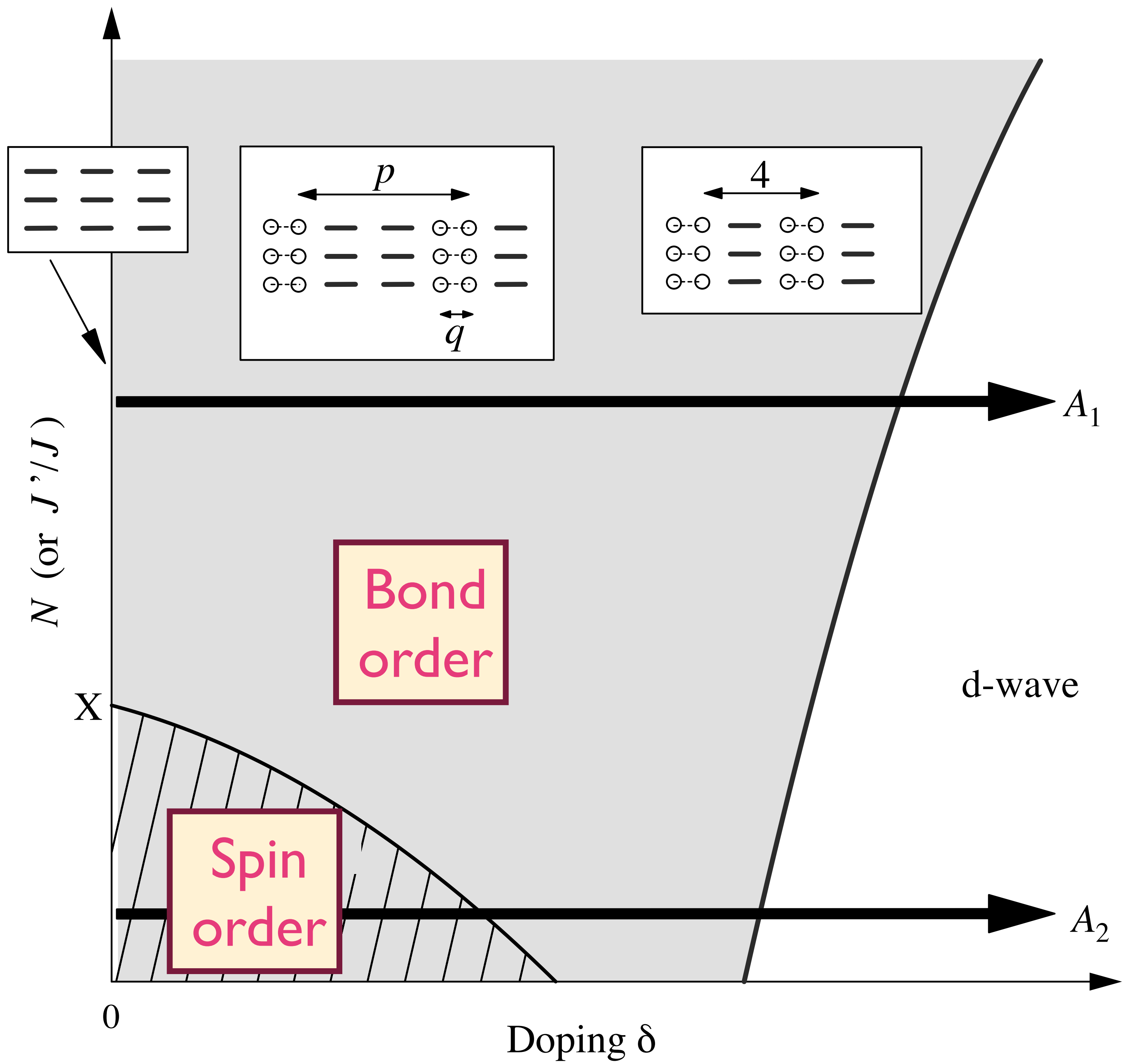
Observed low T ordering.

Our computations show that the order is predominantly d-wave also at this $\mathbf{Q}$.

This $\mathbf{Q}$ is preferred in computations of bond order which include large on-site U. The bond-ordering is driven primarily by spin correlations (as in a valence bond solid), while charge density correlations are suppressed by factors of $\sim t/U$.

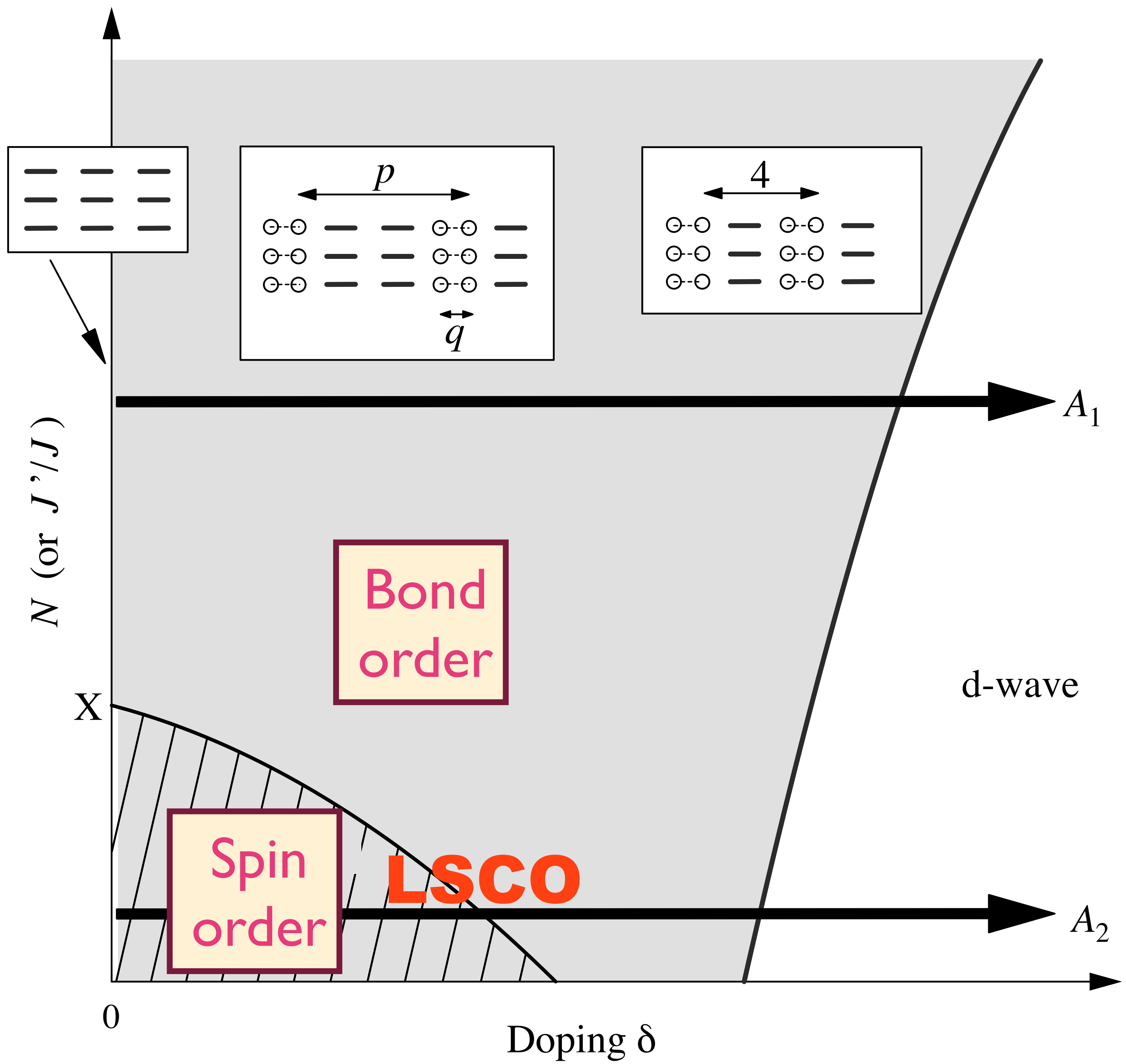
S. Sachdev and R. La Placa, Physical Review Letters **111**, 027202 (2013)
M. Vojta and S. Sachdev, Physical Review Letters **83**, 3916 (1999)
M. Vojta and O. Rosch, Physical Review B 77, 094504 (2008)

Phase diagram of doped antiferromagnets



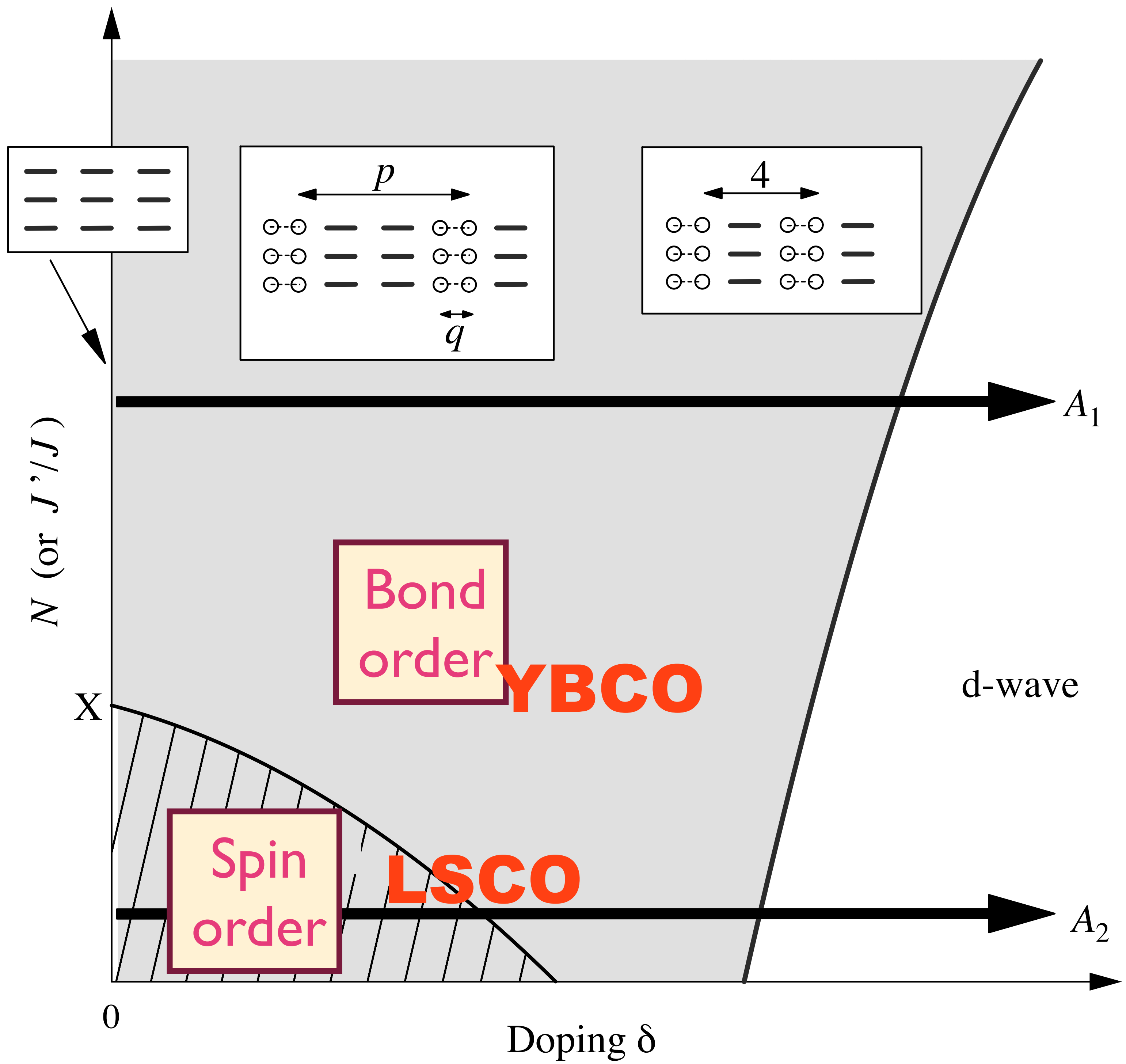
S. Sachdev and R. La Placa, Physical Review Letters **111**, 027202 (2013)
M. Vojta and S. Sachdev, Physical Review Letters **83**, 3916 (1999)
M. Vojta and O. Rosch, Physical Review B 77, 094504 (2008)
S. Sachdev and N. Read, Int. J. Mod. Phys. B **5**, 219 (1991)

Phase diagram of doped antiferromagnets



S. Sachdev and R. La Placa, Physical Review Letters **111**, 027202 (2013)
M. Vojta and S. Sachdev, Physical Review Letters **83**, 3916 (1999)
M. Vojta and O. Rosch, Physical Review B 77, 094504 (2008)
S. Sachdev and N. Read, Int. J. Mod. Phys. B **5**, 219 (1991)

Phase diagram of doped antiferromagnets



S. Sachdev and R. La Placa, Physical Review Letters **111**, 027202 (2013)
M. Vojta and S. Sachdev, Physical Review Letters **83**, 3916 (1999)
M. Vojta and O. Rosch, Physical Review B 77, 094504 (2008)
S. Sachdev and N. Read, Int. J. Mod. Phys. B **5**, 219 (1991)

- There is an approximate pseudospin symmetry in metals with antiferromagnetic spin correlations.

- There is an approximate pseudospin symmetry in metals with antiferromagnetic spin correlations.

- The pseudospin partner of *d*-wave superconductivity is an incommensurate *d*-wave bond order

- There is an approximate pseudospin symmetry in metals with antiferromagnetic spin correlations.

- The pseudospin partner of *d*-wave superconductivity is an incommensurate *d*-wave bond order

- These orders form a pseudospin doublet, whose fluctuations lead to the "pseudogap" phase, described by the angular fluctuations of an order parameter with 6 real components.