

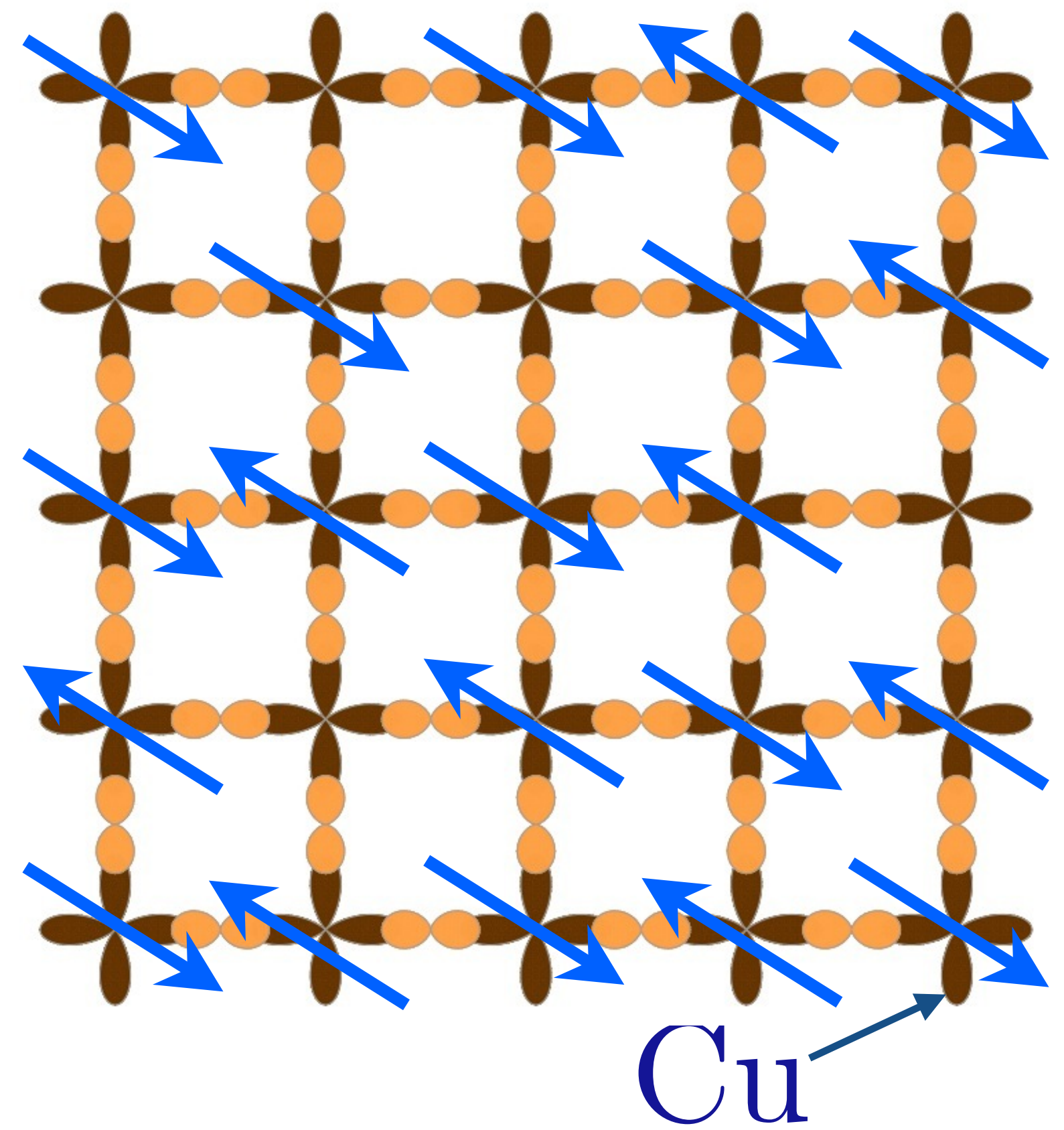
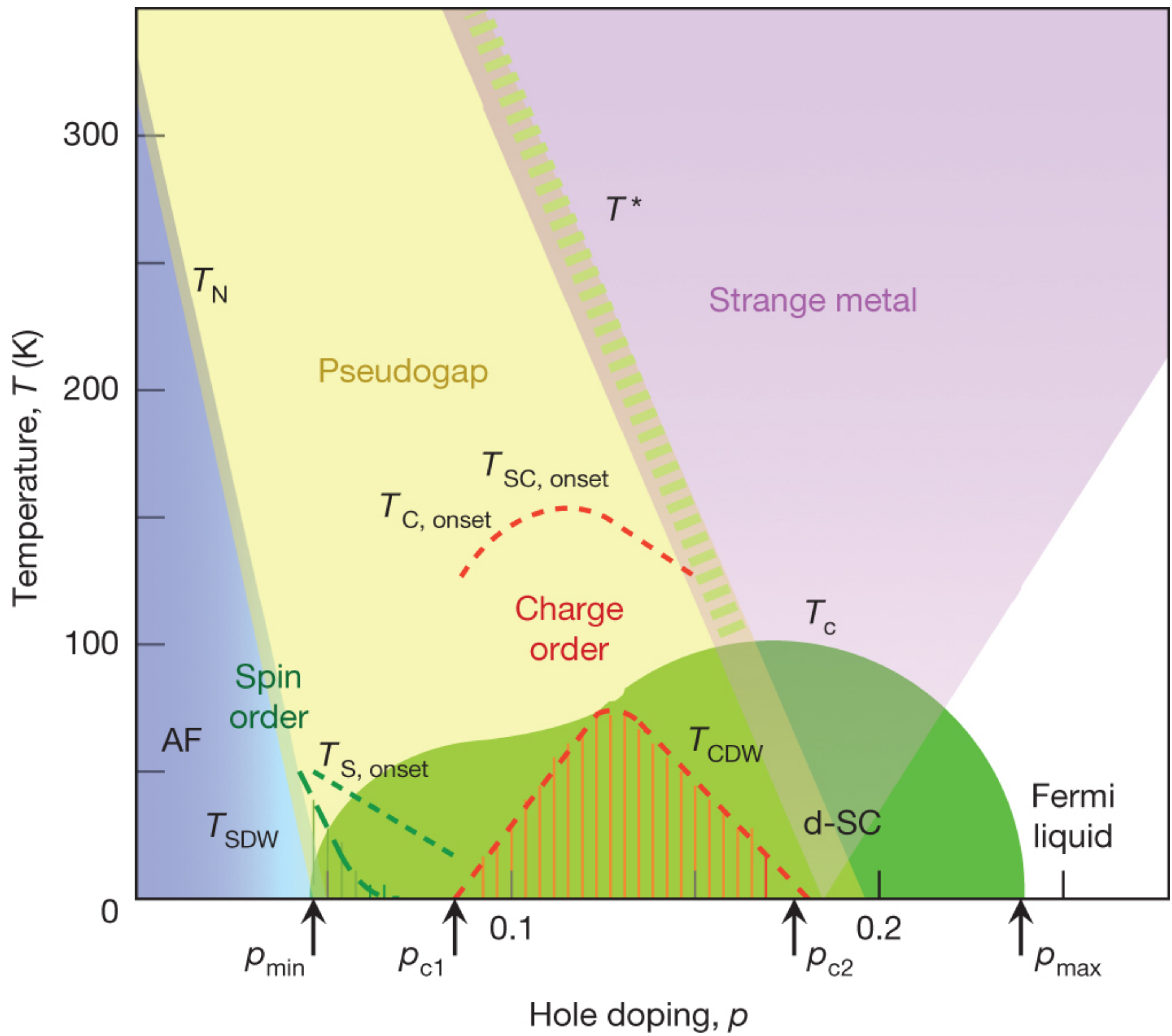
Fermiology of the pseudogap, and the cuprate phase diagram

CIFAR Quantum Materials Meeting
Whistler, British Columbia
May 6, 2026

Subir Sachdev



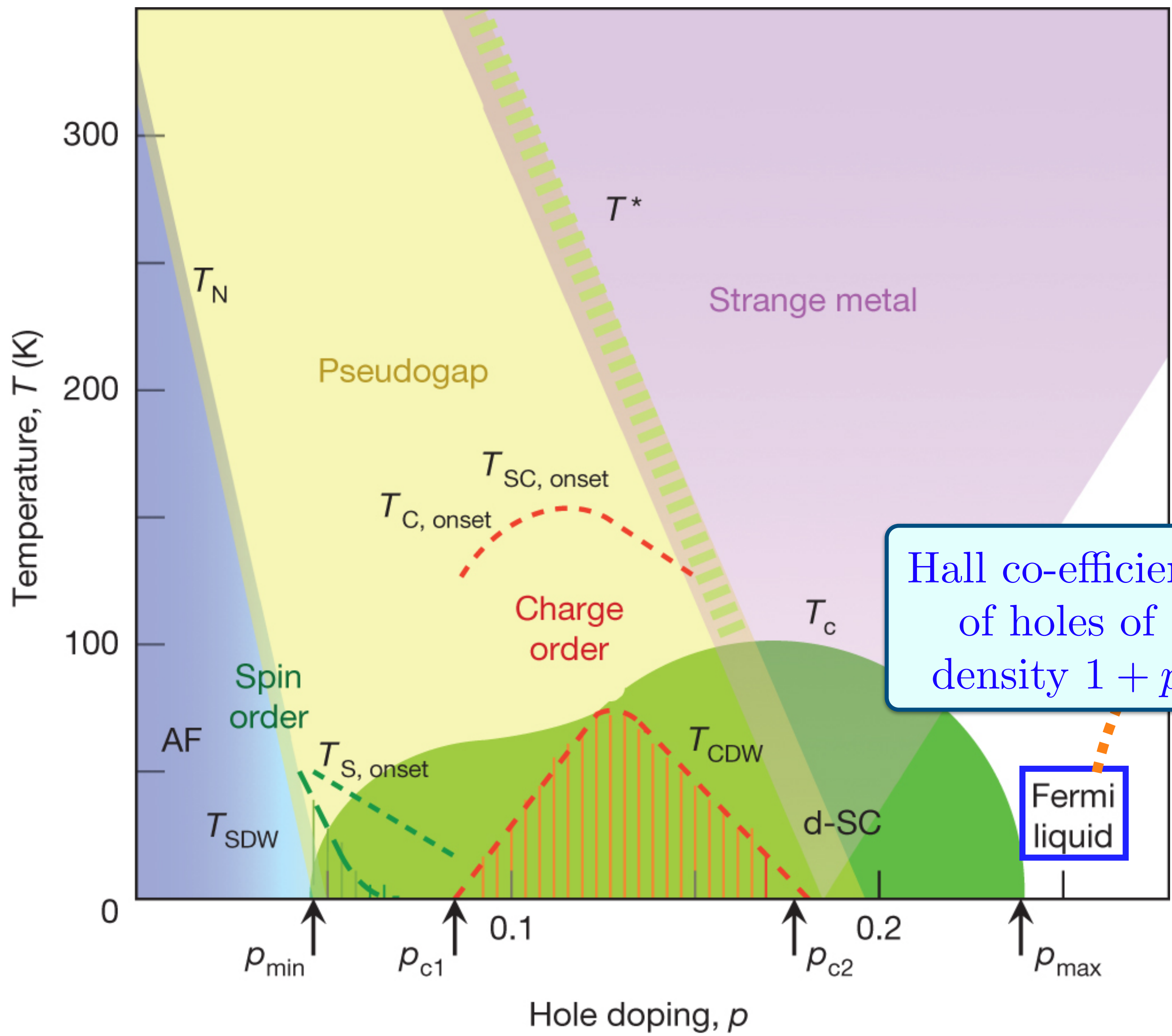
Old and new experiments



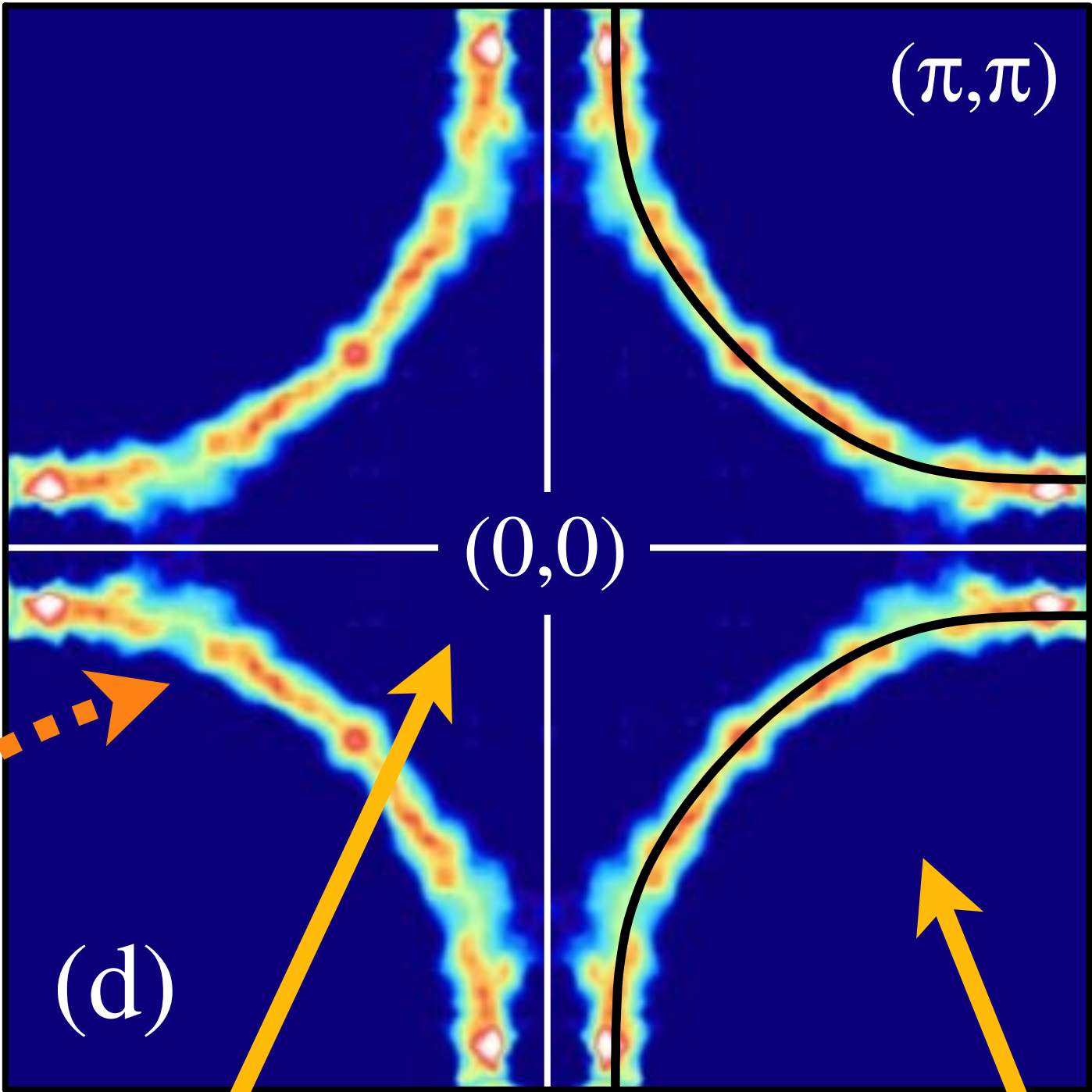
d-SC obtained upon doping AF with density p holes.
Hole density relative to the filled band $\rho = 1 + p$.
Electron density relative to the empty band $\rho_e = 1 - p$.

Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)

M. Pláté, J.D.F. Mottershead, I.S. Elfimov, D.C. Peets, Ruixing Liang, D.A. Bonn, W.N. Hardy, S. Chiuzaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, PRL **95**, 077001 (2005)



Hall co-efficient
of holes of
density $1 + p$

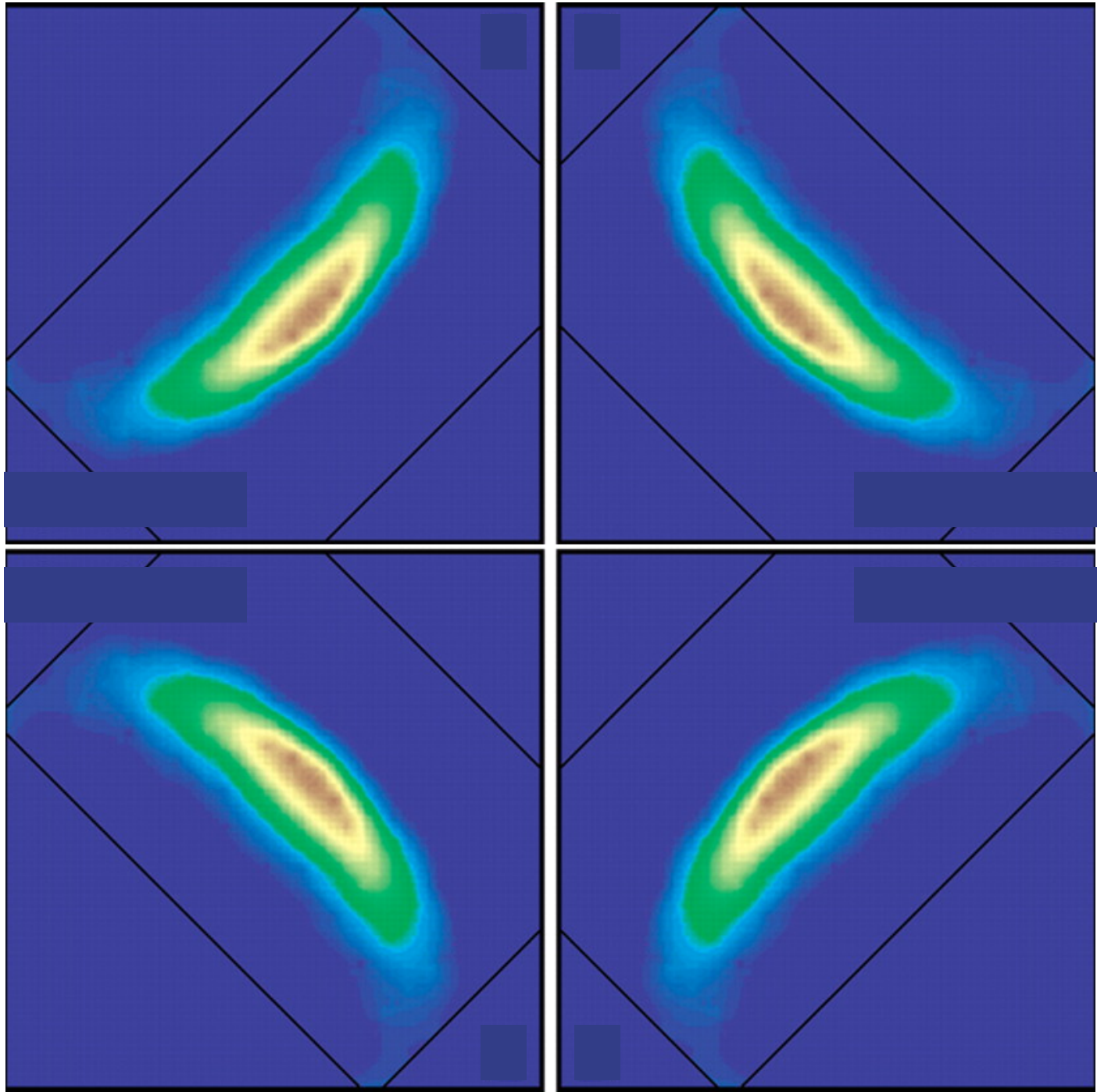
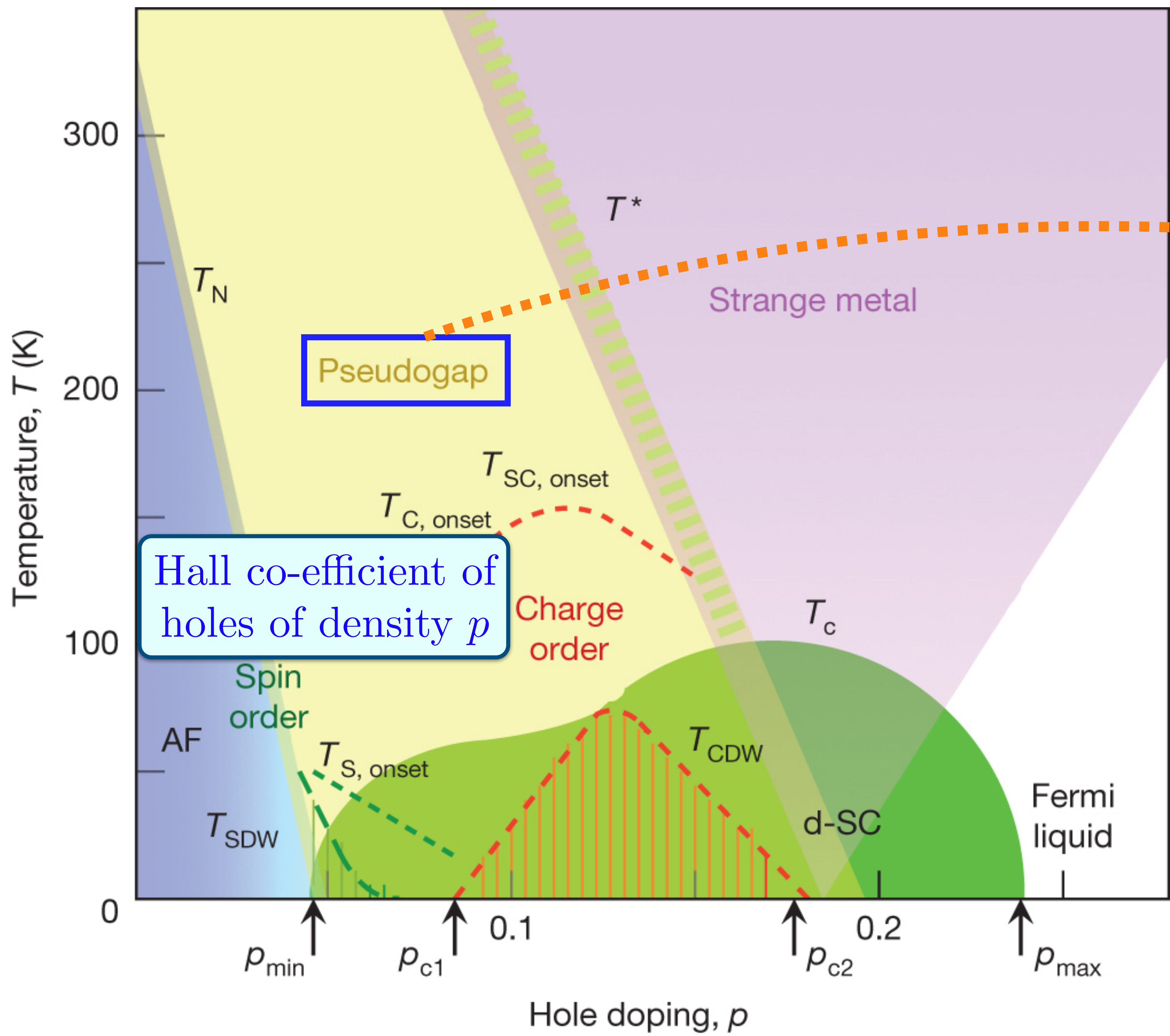


$1-p$ electrons

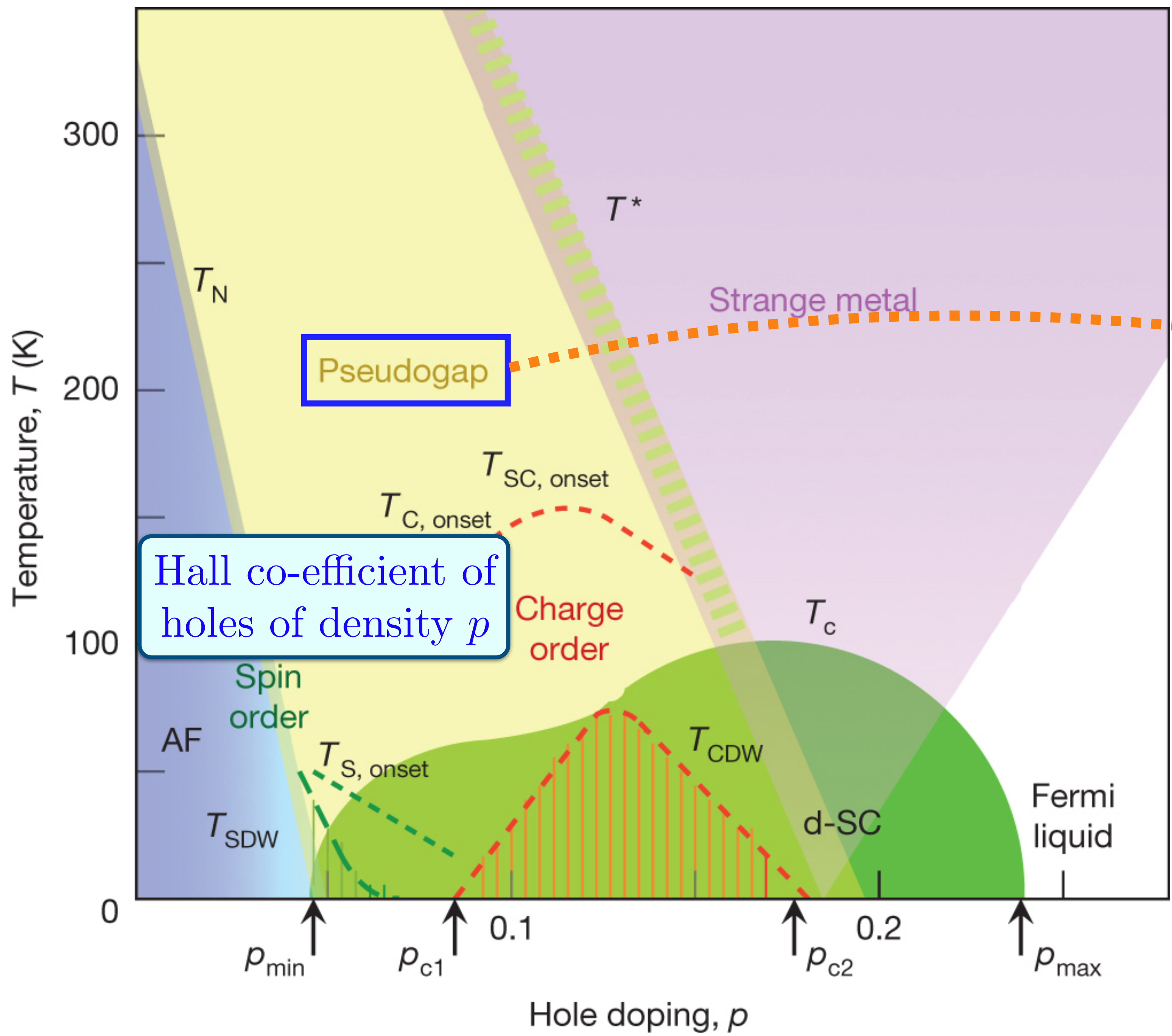
$1+p$ holes

Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)

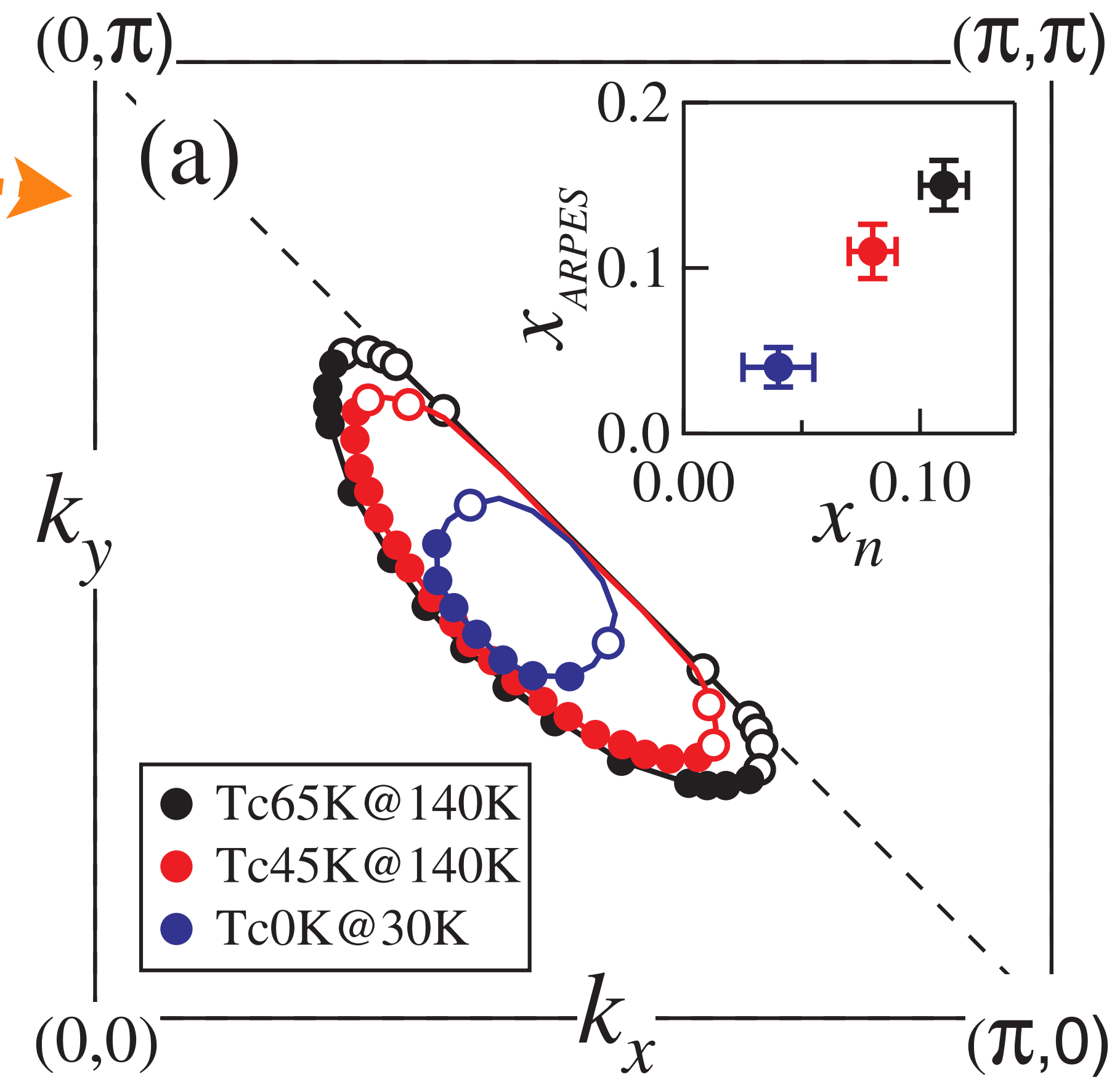
Kyle M. Shen, F. Ronning, D.H. Lu, F. Baumberger, N.J.C. Ingle, W.S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, *Science* **307**, 901 (2005)



‘Fermi arcs’ ?

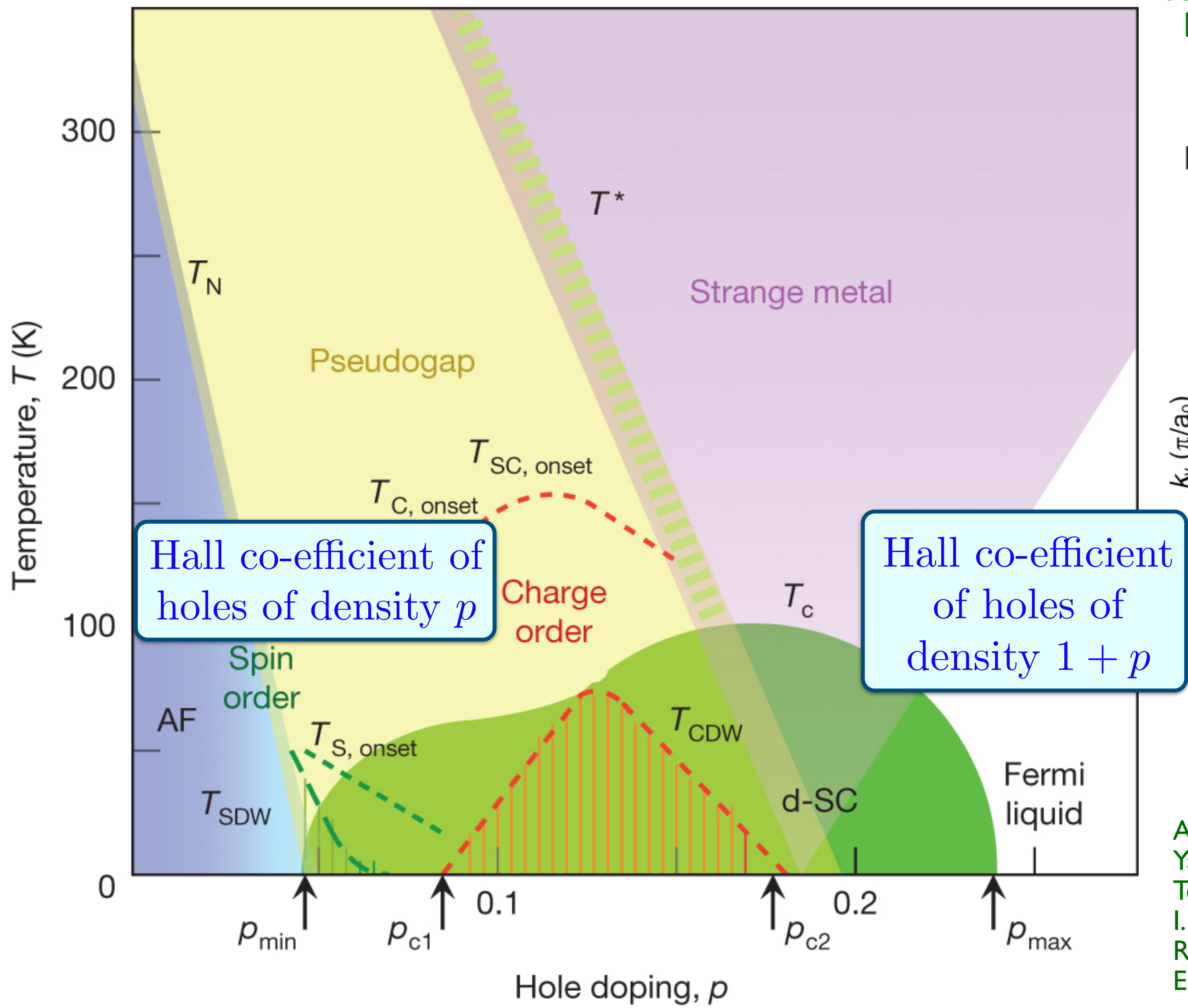


H.-B. Yang, J. D. Rameau, Z.-H. Pan, G. D. Gu, P. D. Johnson, H. Claus, D. G. Hinks, and T. E. Kidd, PRL **107**, 047003 (2011).

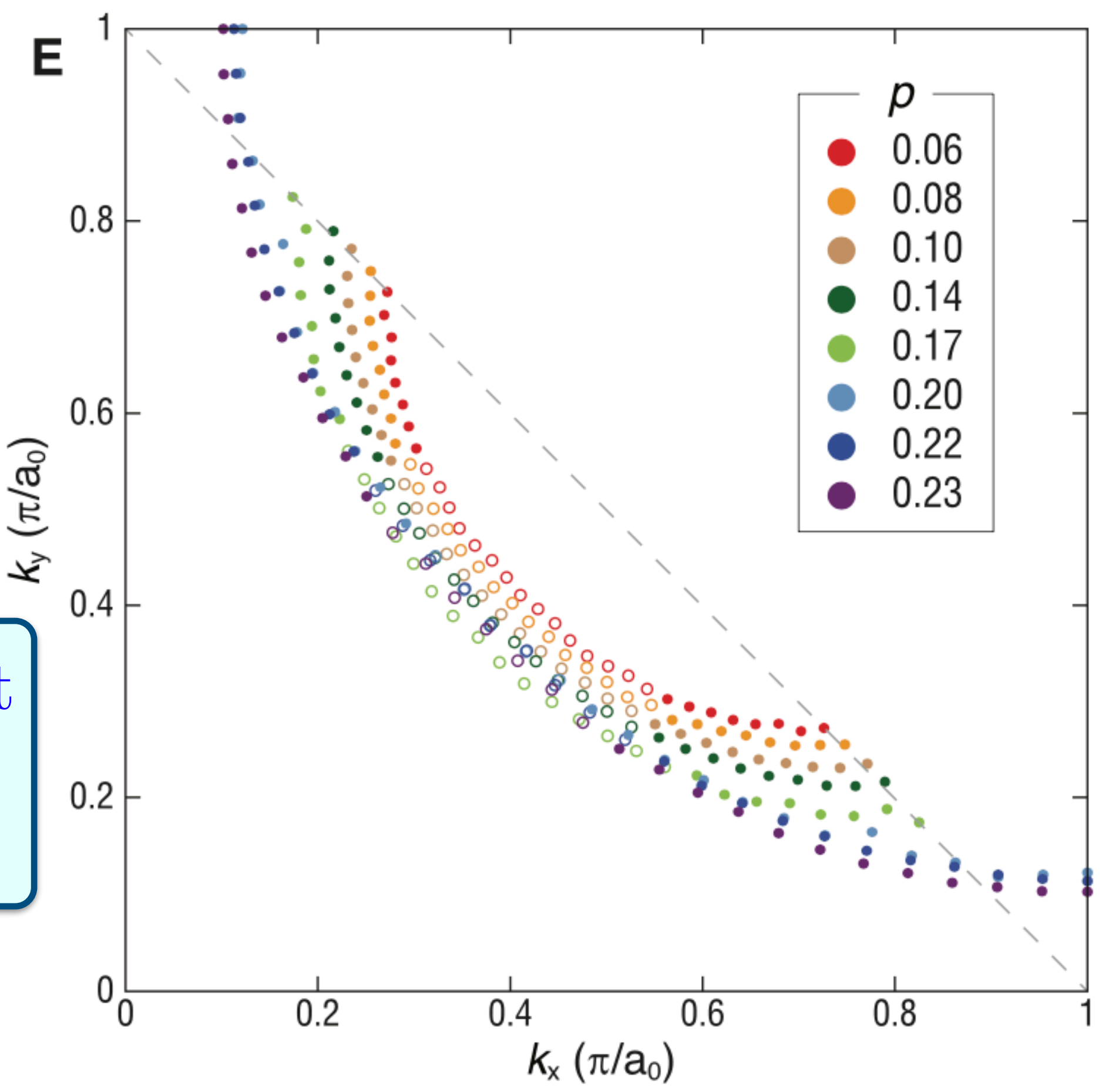


Or hole pockets ?

Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)



K. Fujita, Chung Koo Kim, Inhee Lee, Jinho Lee, M. H. Hamidian, I.A. Firmo, S. Mukhopadhyay, H. Eisaki, S. Uchida, M.J. Lawler, E. -A. Kim, J. C. Davis, *Science* **344**, 612 (2014)



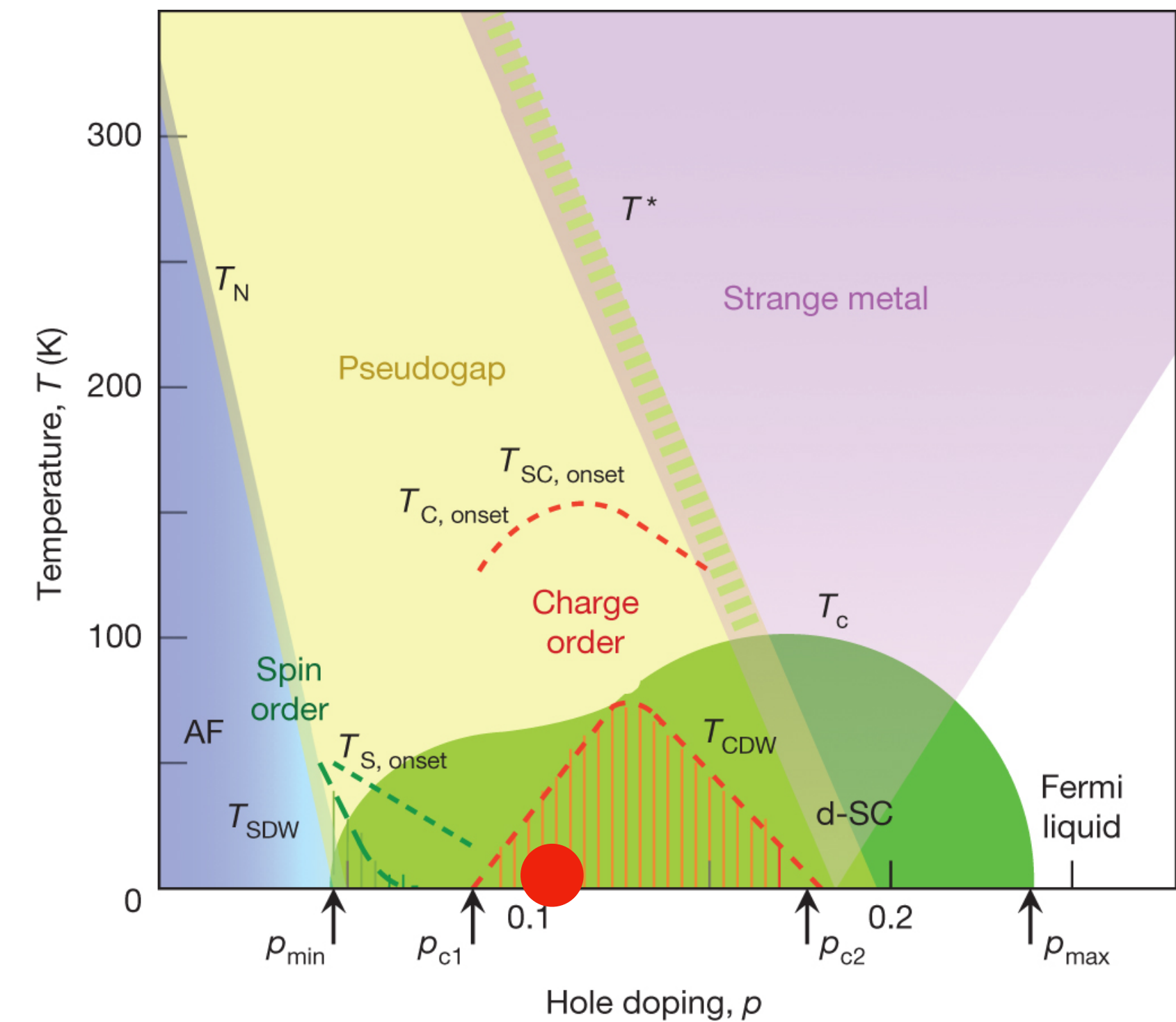
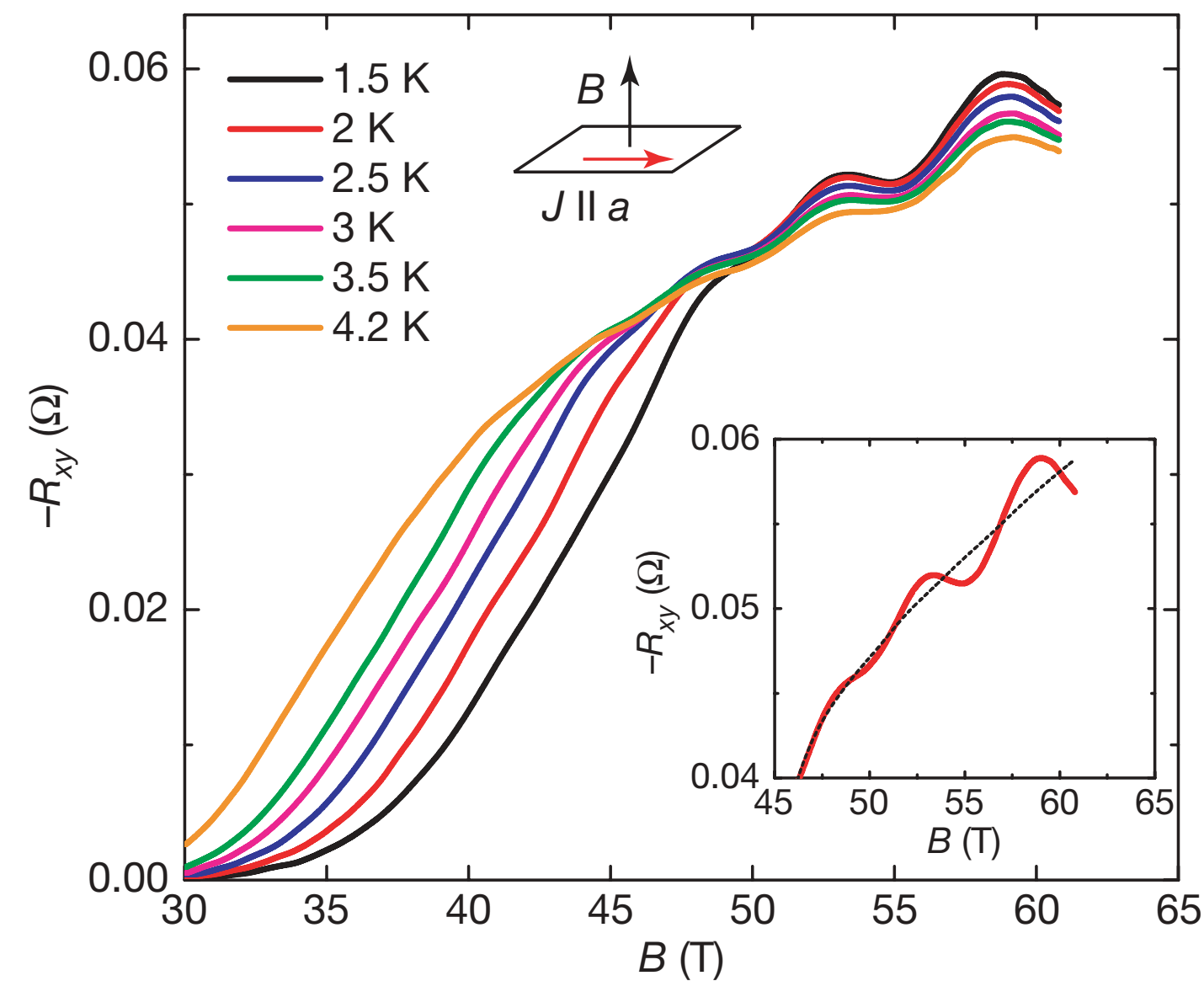
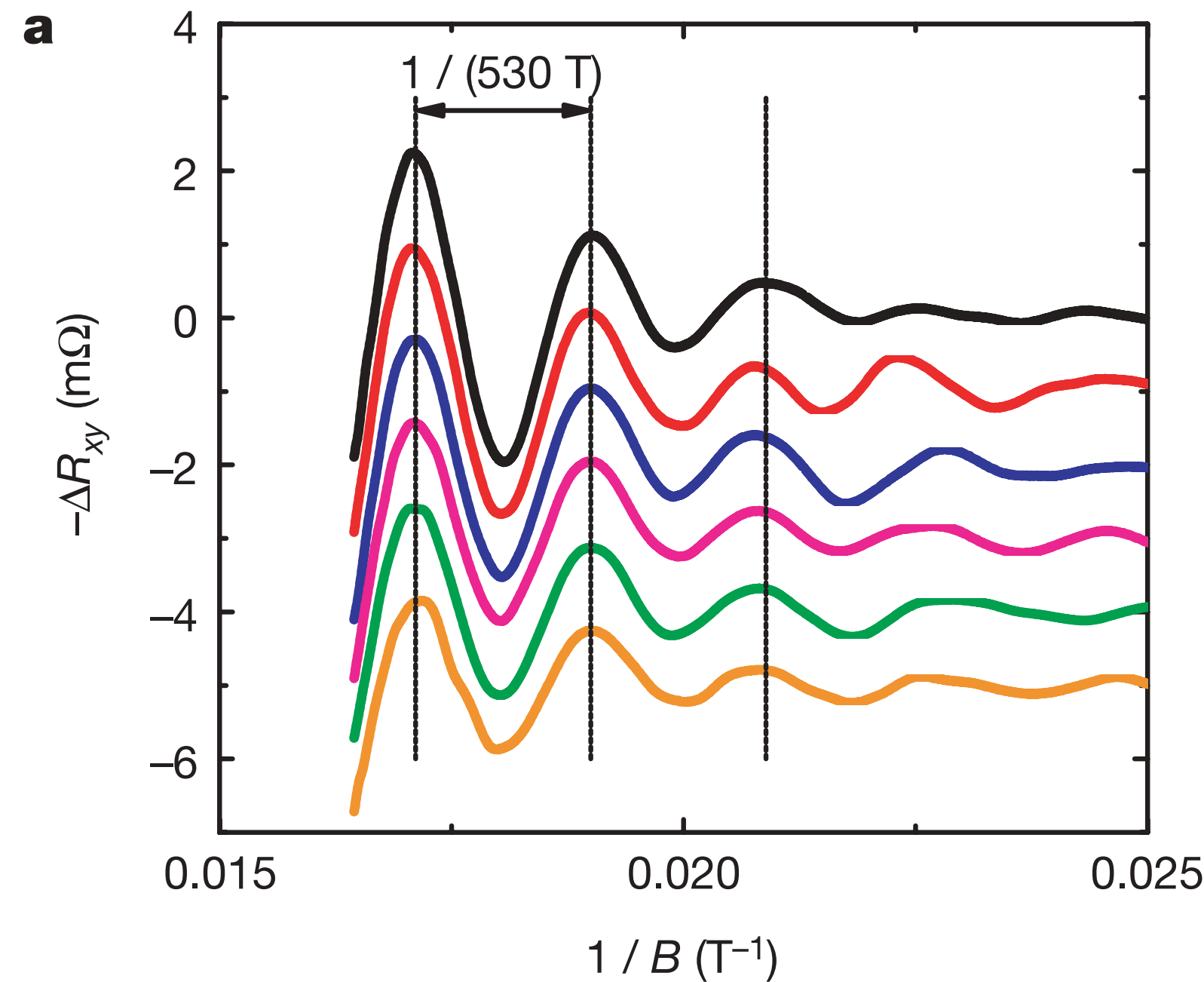
Also
Yang He, Yi Yin, M. Zech, Anjan Soumyanarayanan, M. M. Yee, Tess Williams, M. C. Boyer, Kamallesh Chatterjee, W. D. Wise, I. Zeljkovic, Takeshi Kondo, T. Takeuchi, H. Ikuta, Peter Mistark, Robert S. Markiewicz, Arun Bansil, Subir Sachdev, E.W. Hudson, Jennifer. E. Hoffman, *Science* **344**, 608 (2014)

Quantum oscillations and the Fermi surface in an underdoped high- T_c superconductor

Nicolas Doiron-Leyraud¹, Cyril Proust², David LeBoeuf¹, Julien Levallois², Jean-Baptiste Bonnemaïson¹, Ruixing Liang^{3,4}, D. A. Bonn^{3,4}, W. N. Hardy^{3,4} & Louis Taillefer^{1,4}

Nature 447 (2007) 565

YBCO, $p = 0.1$



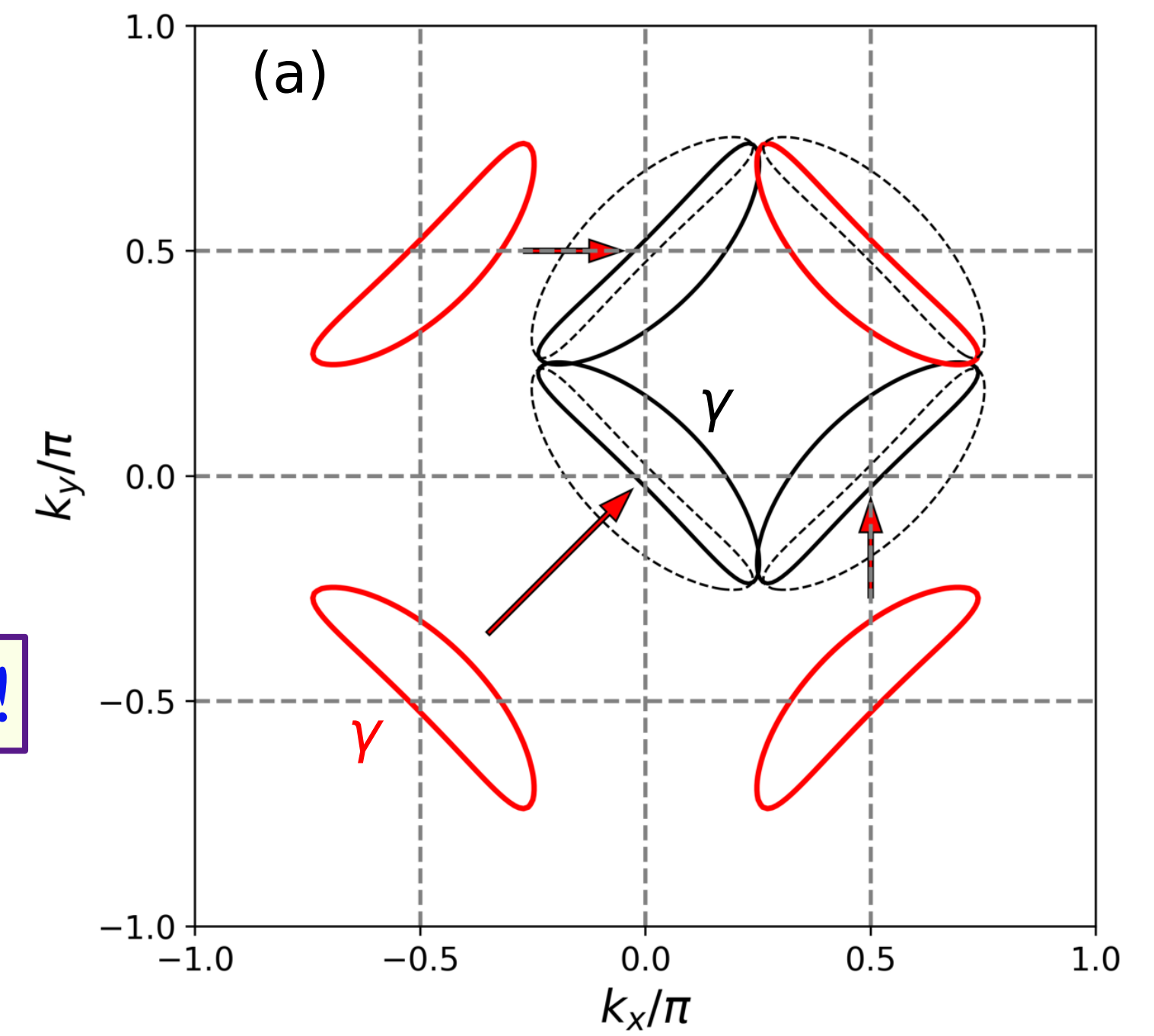
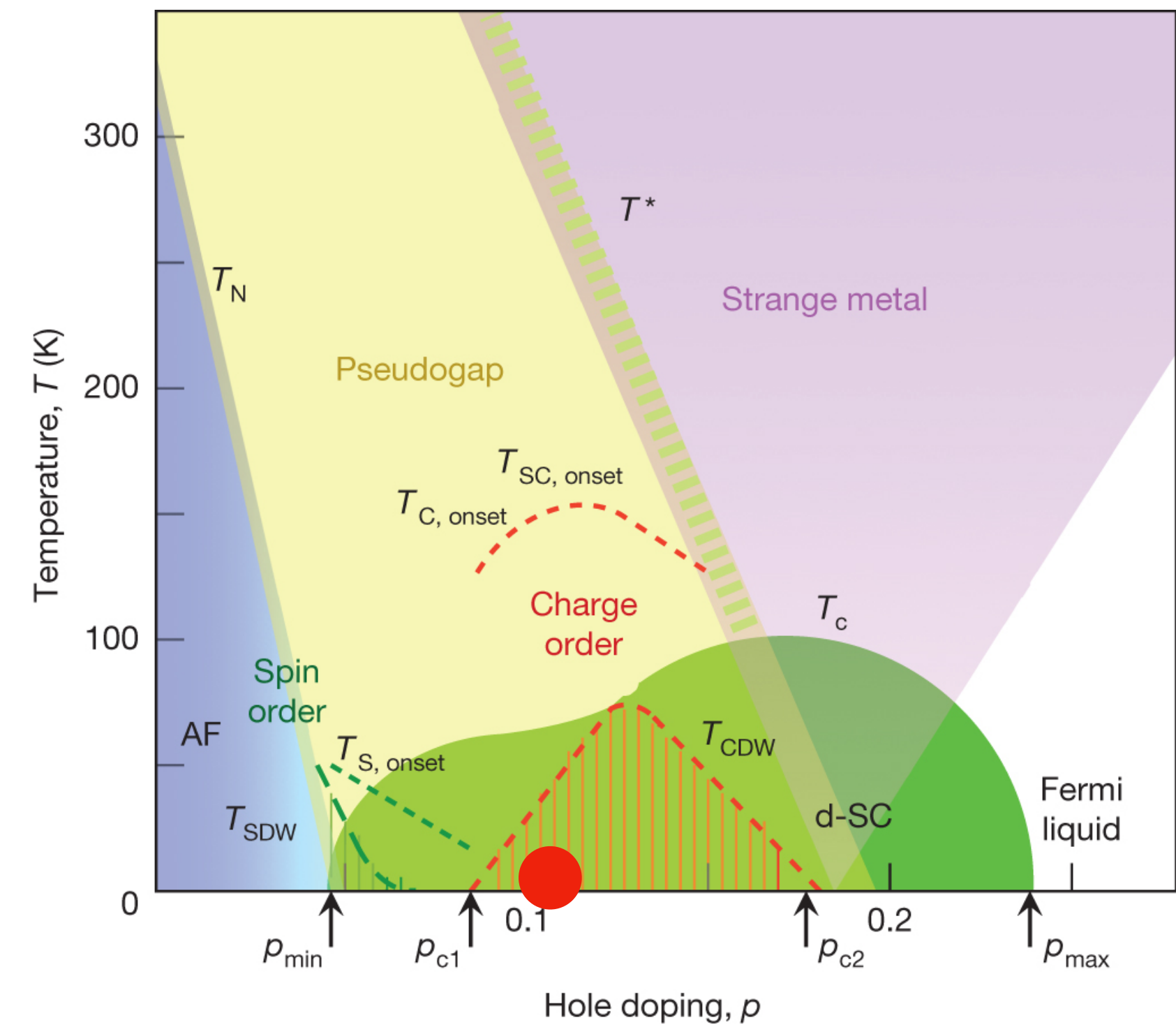
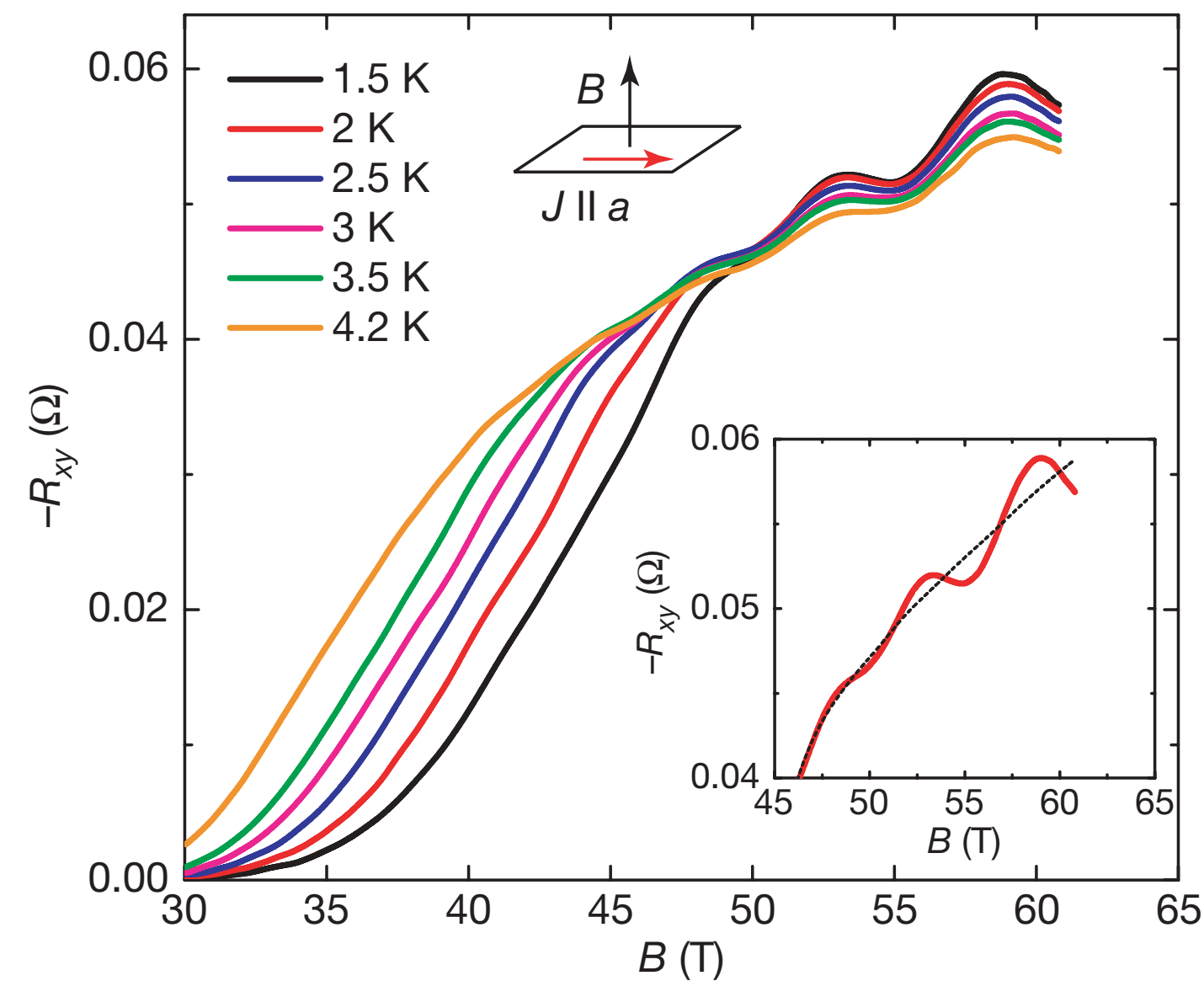
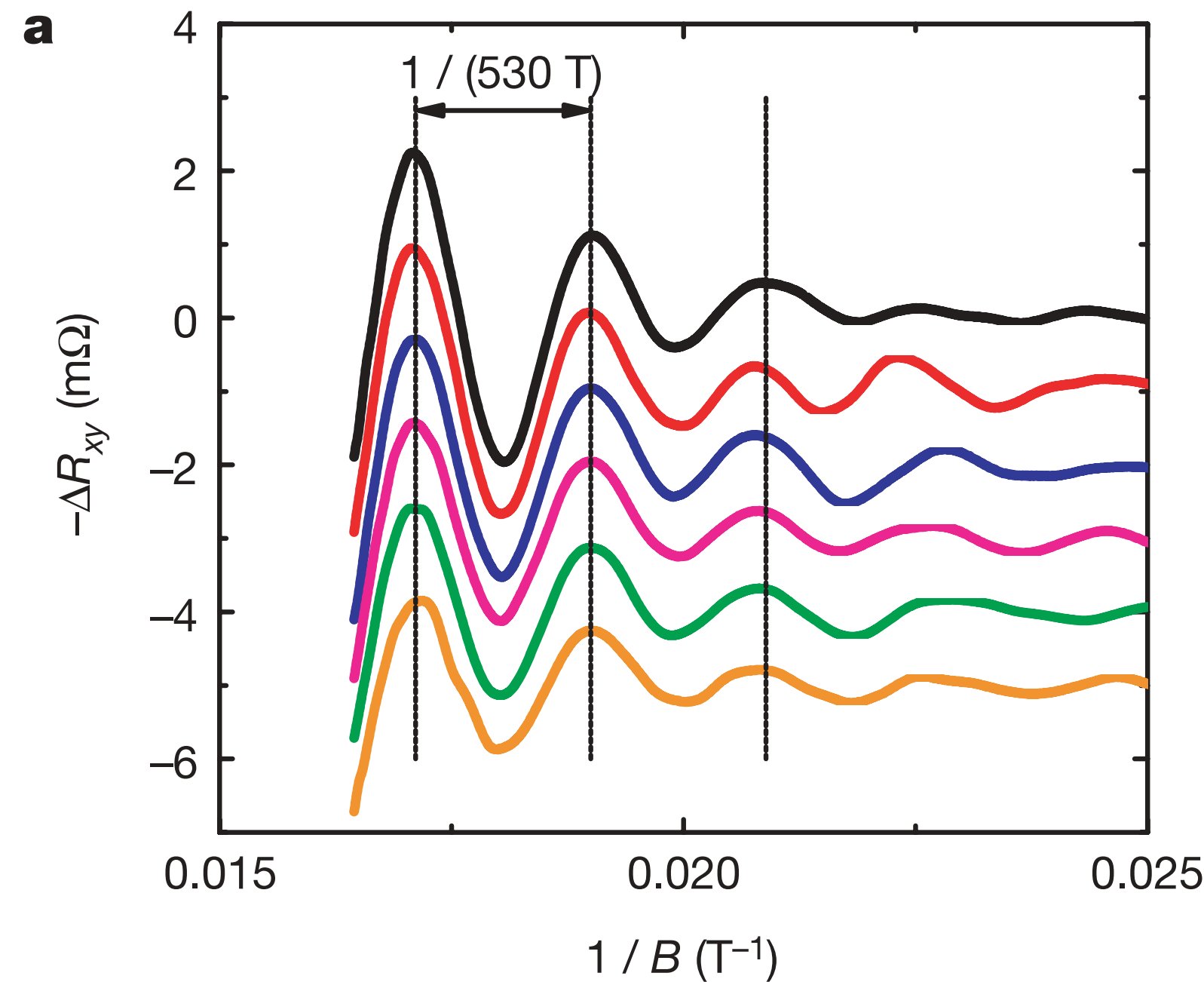
Surprise: small electron pockets!

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N. Harrison and S.E. Sebastian, PRL **106** (2011) 226402: Electron pockets produced by bi-directional CDW acting on 'Fermi arcs'.

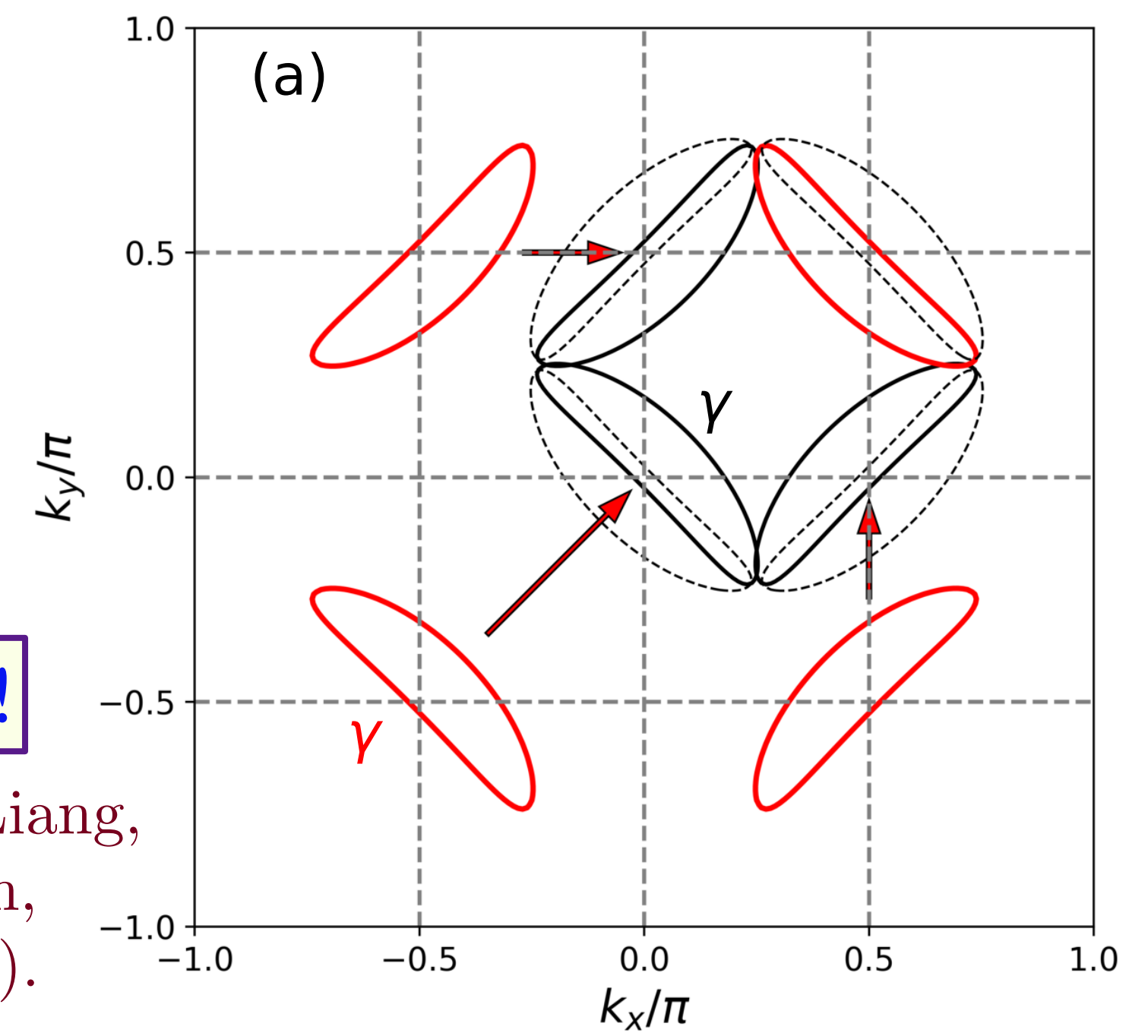
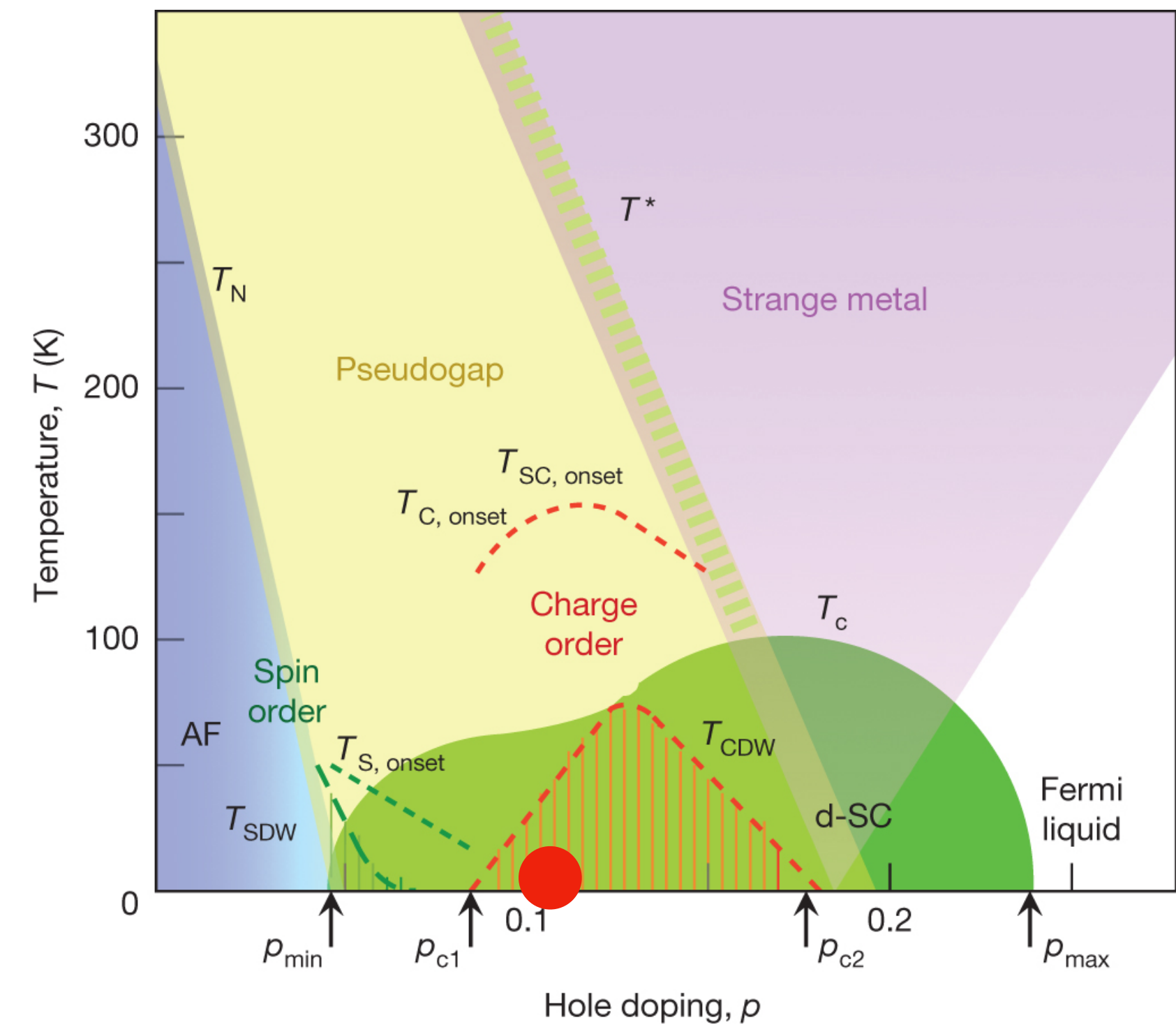
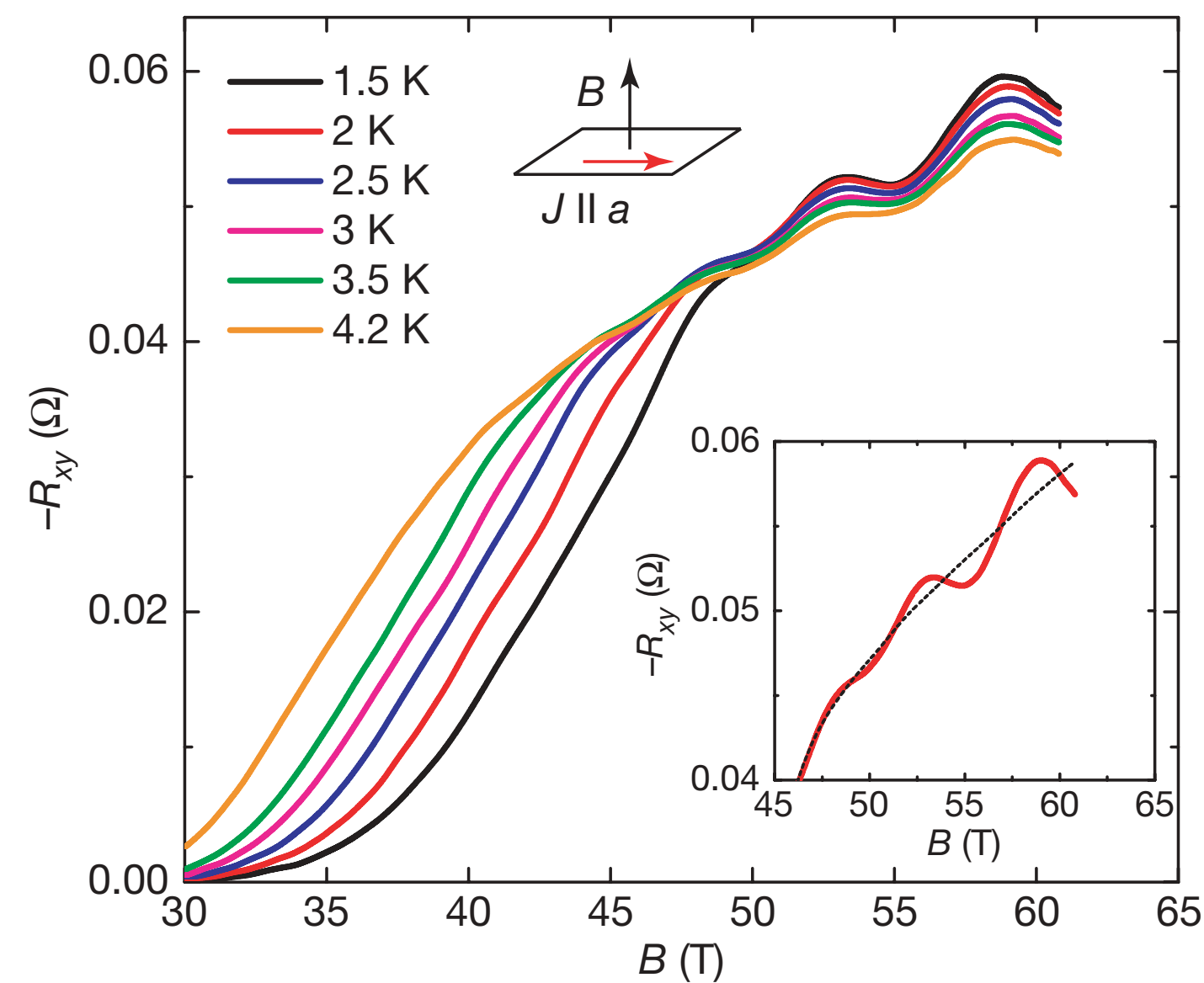
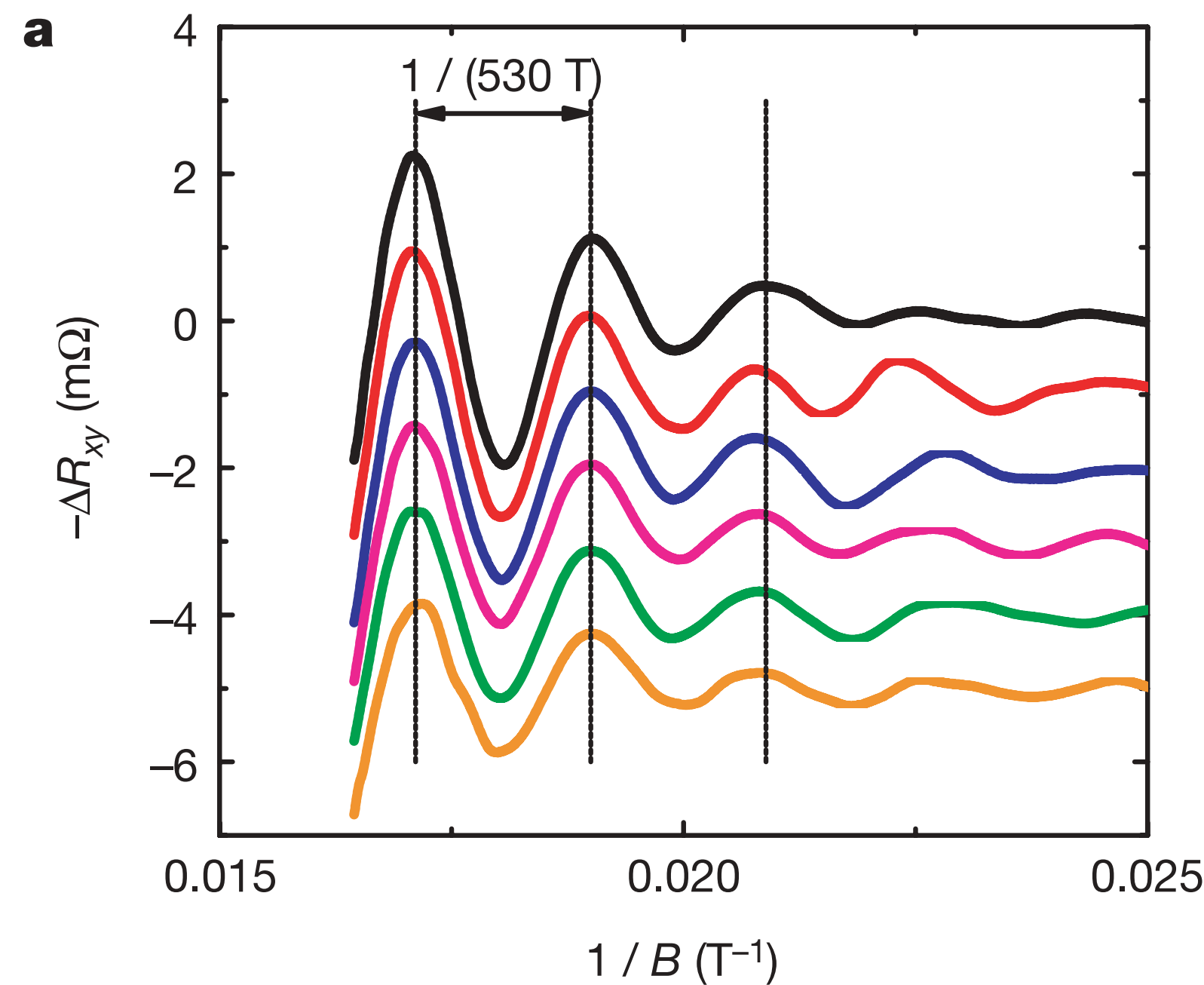
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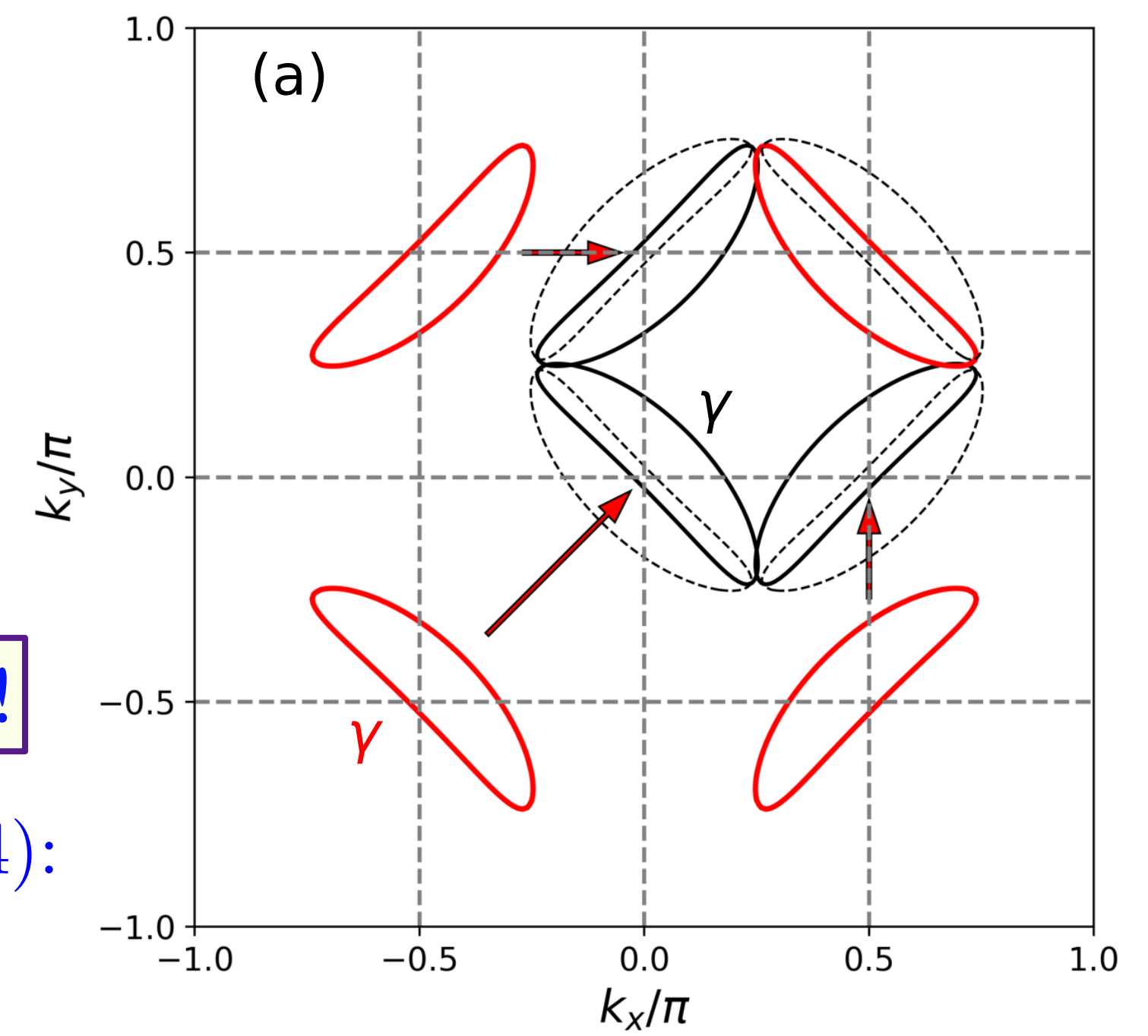
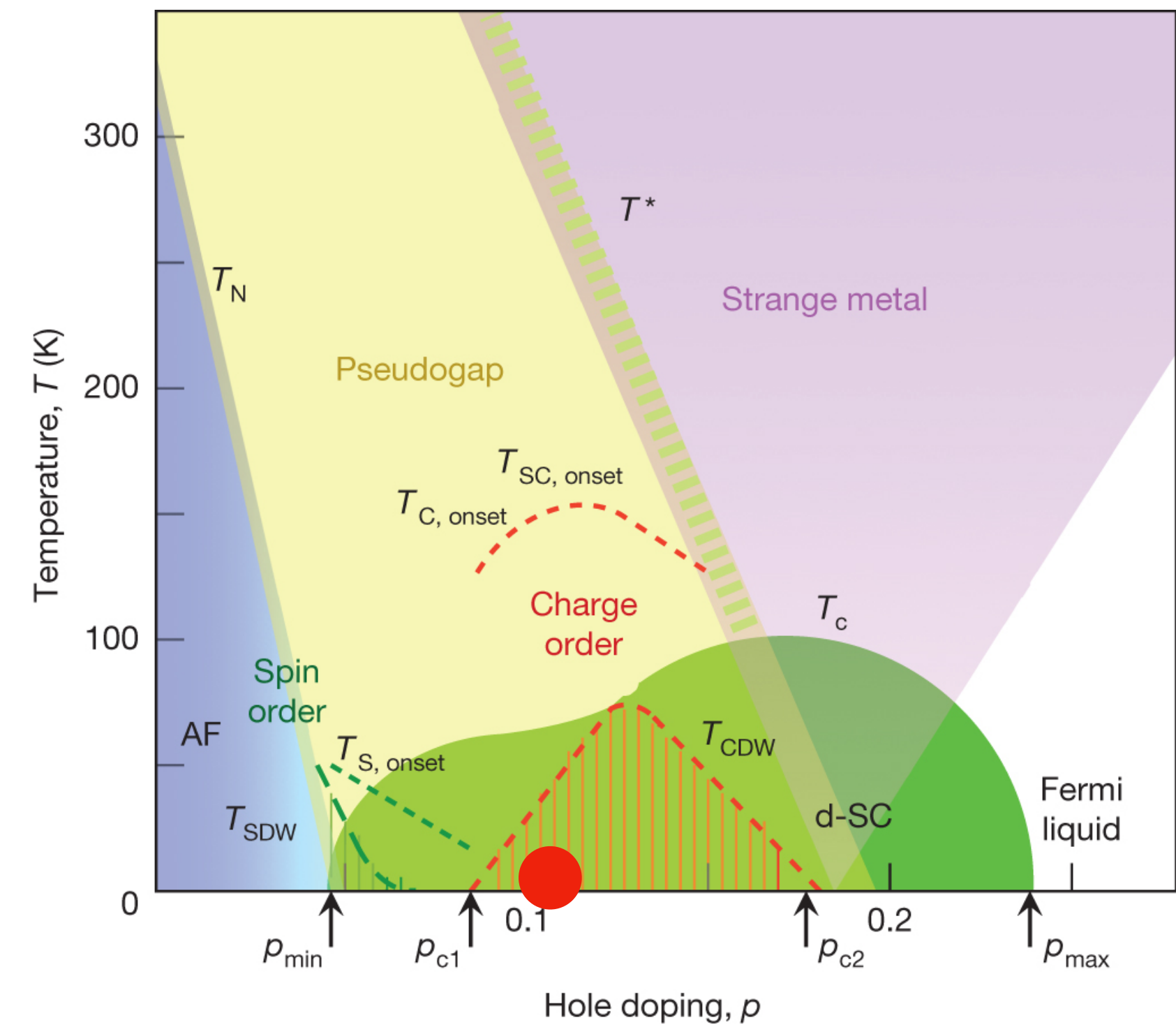
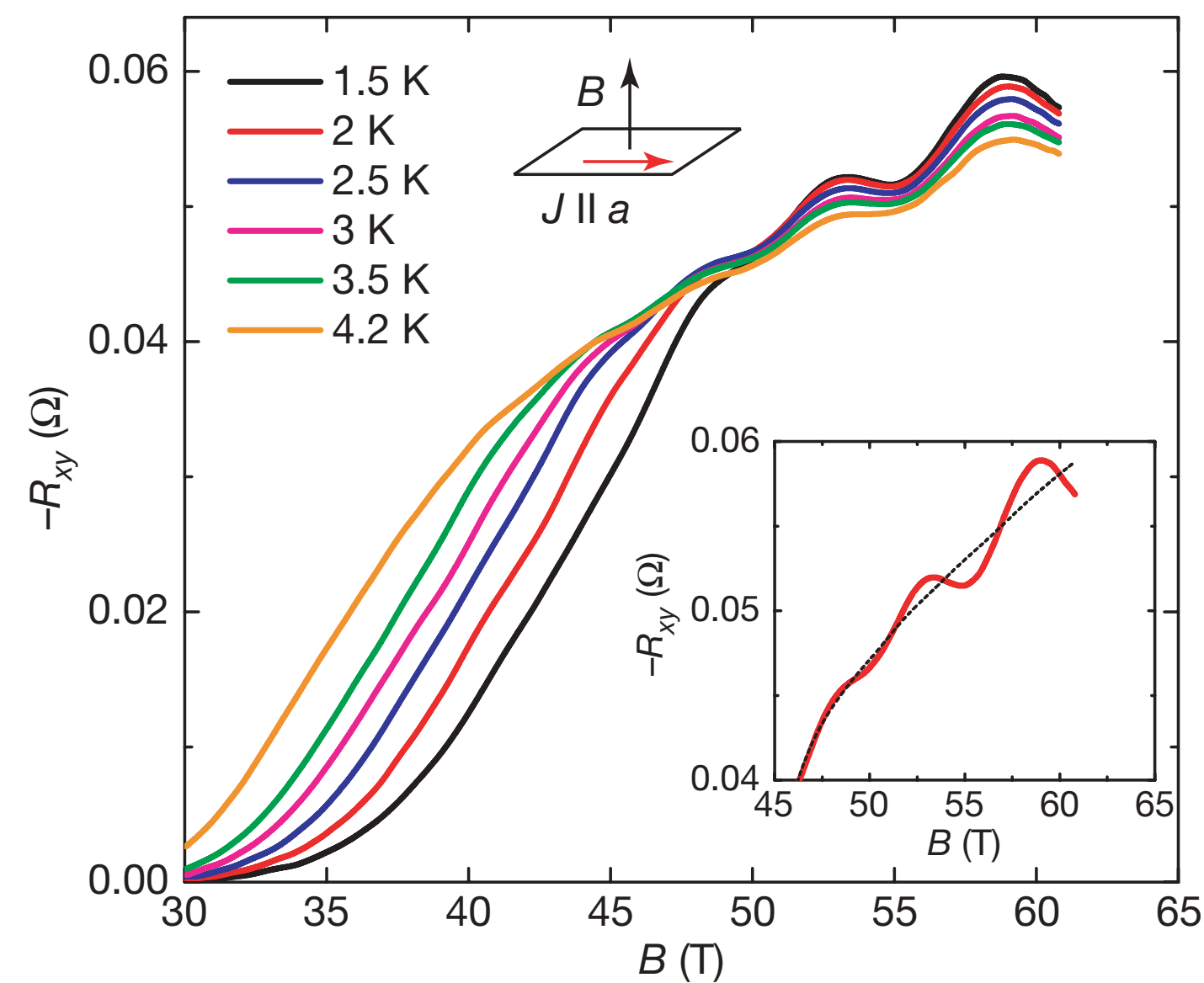
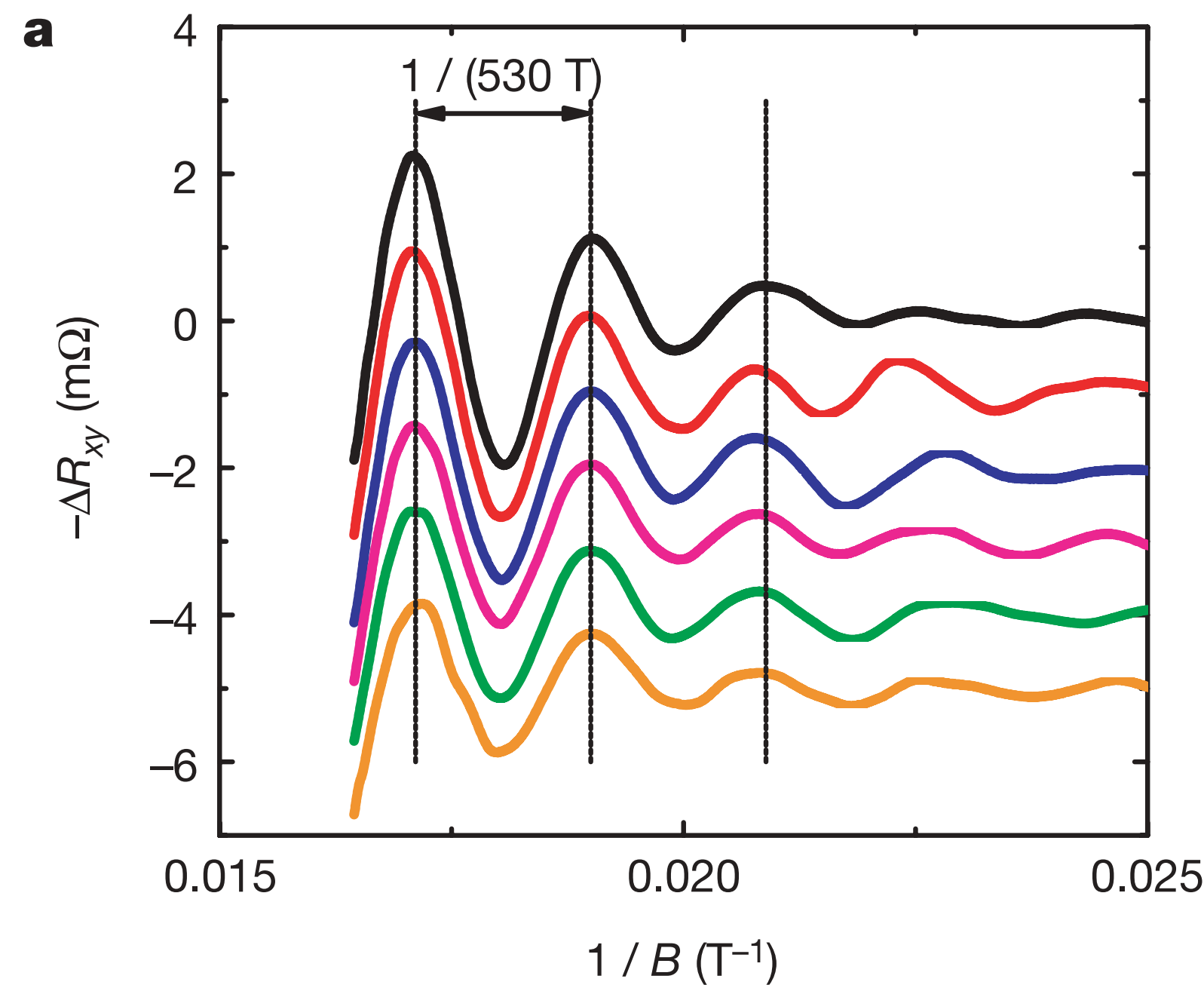
CDW observed: S. Gerber, H. Jang, H. Nojiri, S. Matsuzawa, H. Yasumura, D. A. Bonn, R. Liang, W. N. Hardy, Z. Islam, A. Mehta, S. Song, M. Sikorski, D. Stefanescu, Y. Feng, S. A. Kivelson, T. P. Devereaux, Z.-X. Shen, C.-C. Kao, W.-S. Lee, D. Zhu, J.-S. Lee, Science **350**, 949 (2015).

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Nicolas Doiron-Leyraud¹, Cyril Proust², David LeBoeuf¹, Julien Levallois², Jean-Baptiste Bonnemaïson¹, Ruixing Liang^{3,4}, D. A. Bonn^{3,4}, W. N. Hardy^{3,4} & Louis Taillefer^{1,4}

Nature **447** (2007) 565

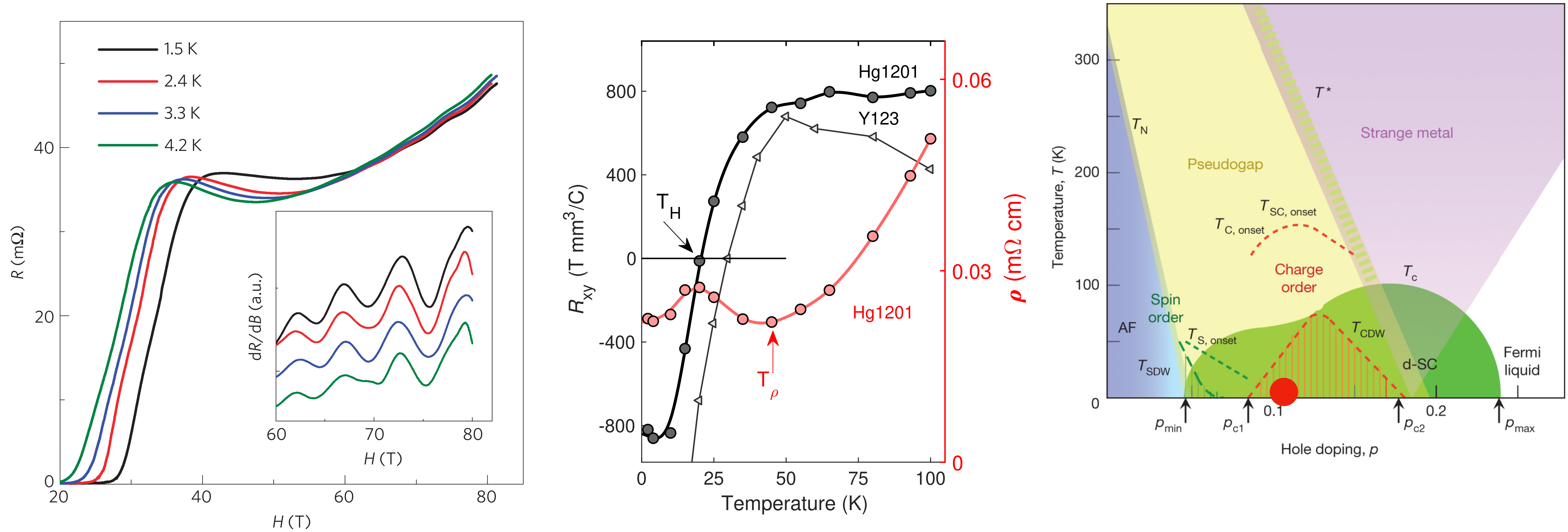
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N. Harrison and S.E. Sebastian, PRL **106** (2011) 226402: Electron pockets produced by bi-directional CDW acting on ‘Fermi arcs’.

Surprise: small electron pockets!

P. M. Bonetti, M. Christos and S. Sachdev (BCS), PNAS **121**, e2418633121 (2024): Removing back-sides of hole pockets requires fractionalized spinon excitations.



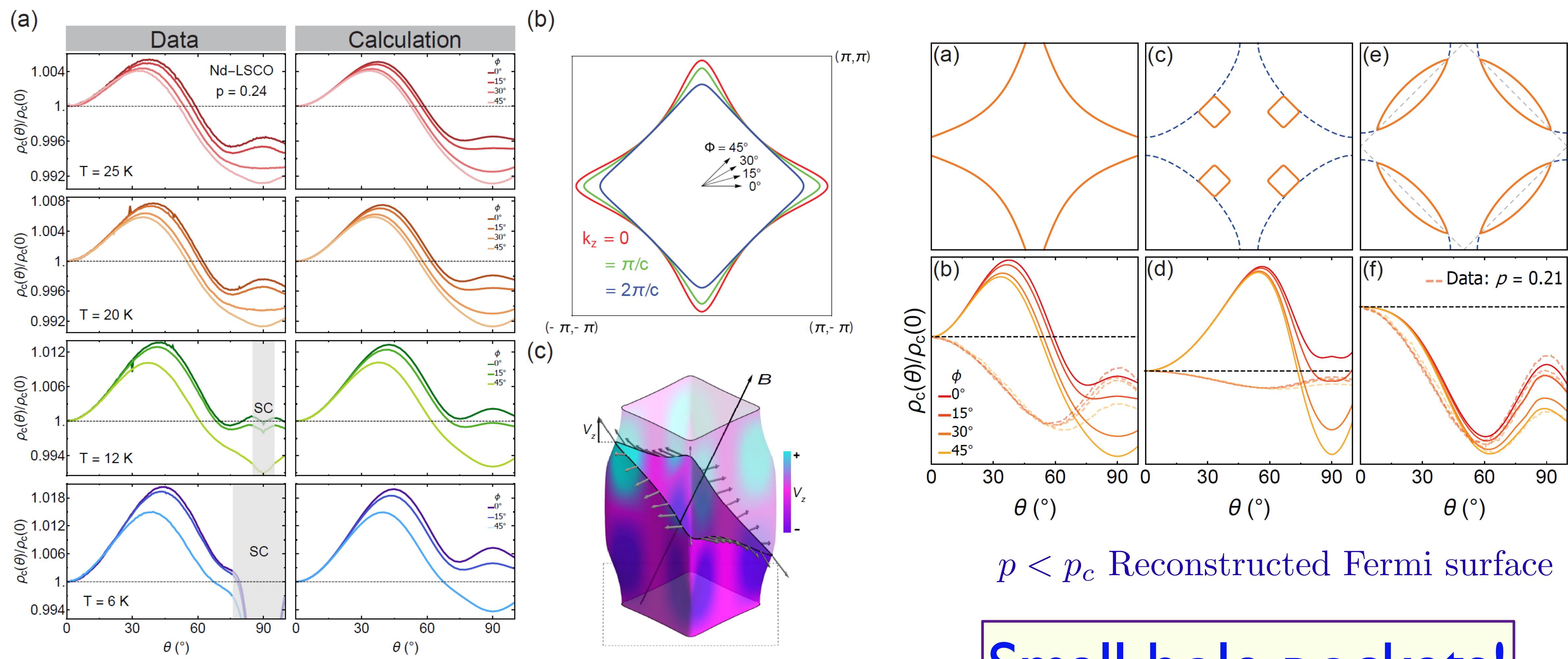
Electron pocket quantum oscillations also observed in Hg1201, along with CDW order, at low T .

N. Barisic, S. Badoux, M. K. Chan, C. Dorow, W. Tabis, B. Vignolle, Guichuan Yu, J. Beard, Xudong Zhao, C. Proust, M. Greven, *Nature Physics* **9**, 761 (2013).
W. Tabis, B. Yu, I. Bialo, M. Bluschke, T. Kolodziej, A. Kozlowski, E. Blackburn, K. Sen, E. M. Forgan, M. v. Zimmermann, Y. Tang, E. Weschke, B. Vignolle, M. Hepting, H. Gretarsson, R. Sutarto, F. He, M. Le Tacon, N. Barisic, G. Yu, and M. Greven, *PRB* **96**, 134510 (2017).
M. K. Chan, R. D. McDonald, B. J. Ramshaw, J. B. Betts, A. Shekhter, E. D. Bauer, N. Harrison, *PNAS* **117**, 9782 (2020).

Fermi surface transformation at the pseudogap critical point of a cuprate superconductor

Yawen Fang, Gaël Grissonnanche, Anaëlle Legros, Simon Verret, Francis Laliberté, Clément Collignon, Amirreza Ataei, Maxime Dion, Jianshi Zhou, David Graf, M. J. Lawler, Paul Goddard, Louis Taillefer, and B. J. Ramshaw, *Nature Physics* **18**, 558 (2022)

Angle-dependent magnetoresistance (ADMR) of $\text{La}_{1.6-x}\text{Nd}_{0.4}\text{Sr}_x\text{CuO}_4$



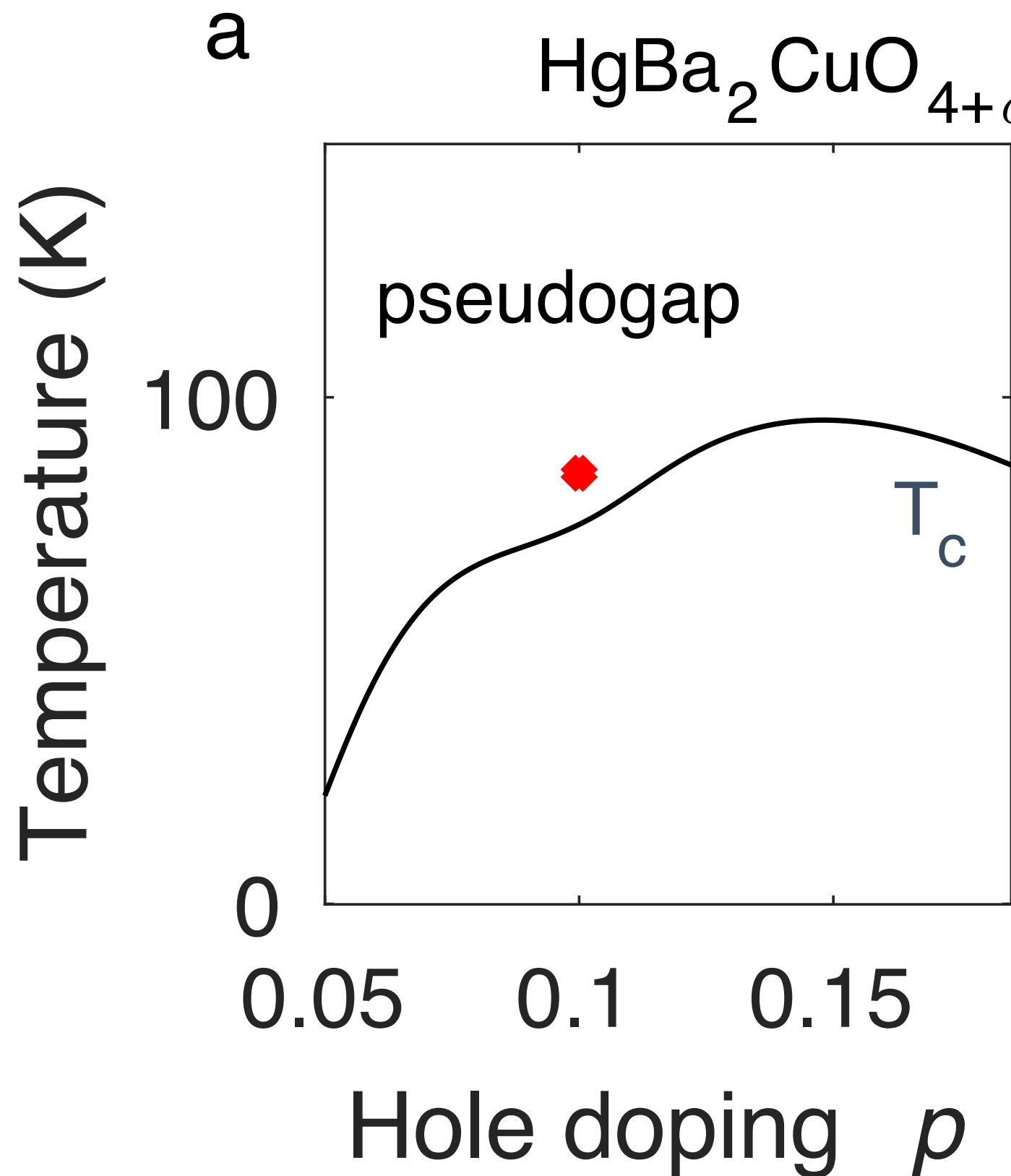
$p > p_c$ Large Fermi surface

$p < p_c$ Reconstructed Fermi surface

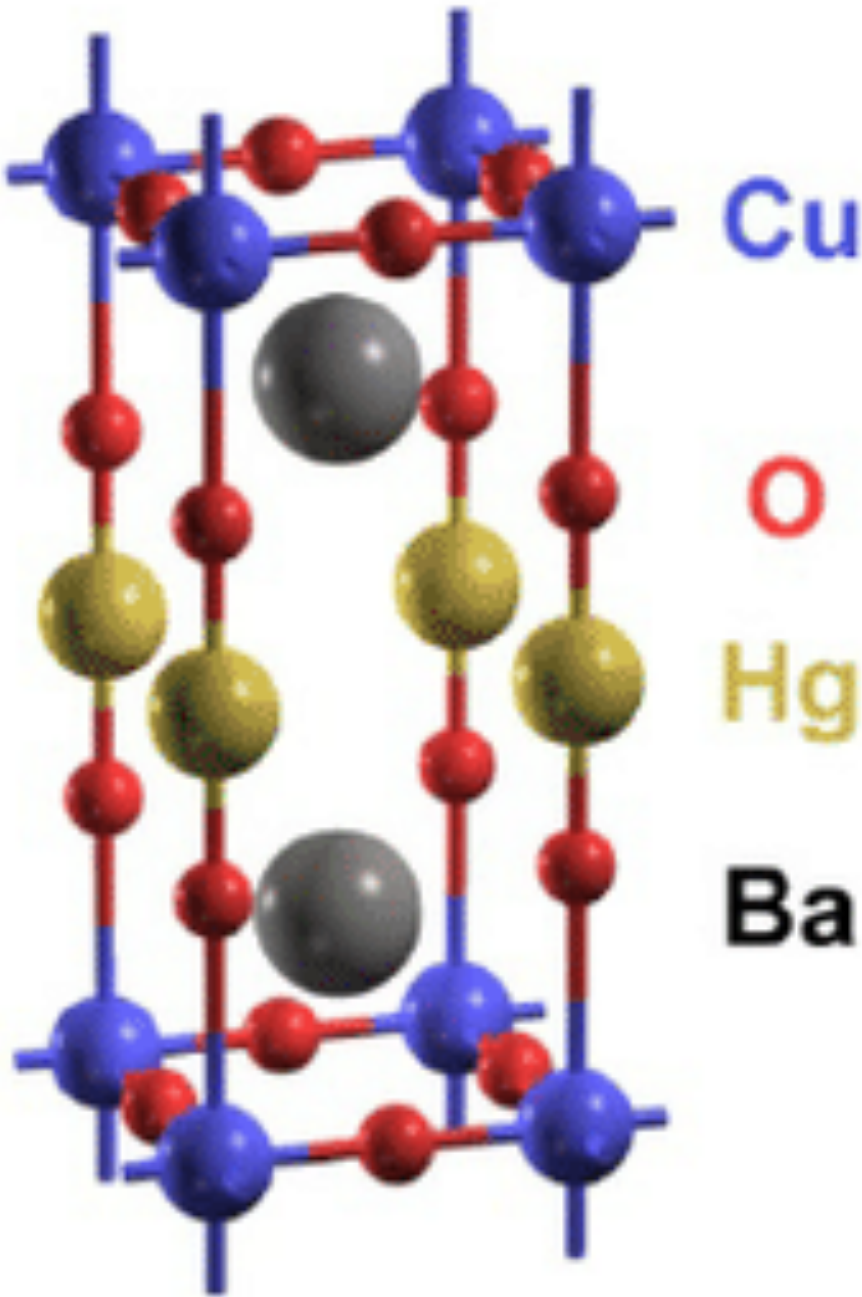
Small hole pockets!

Observation of the Yamaji effect in a cuprate superconductor

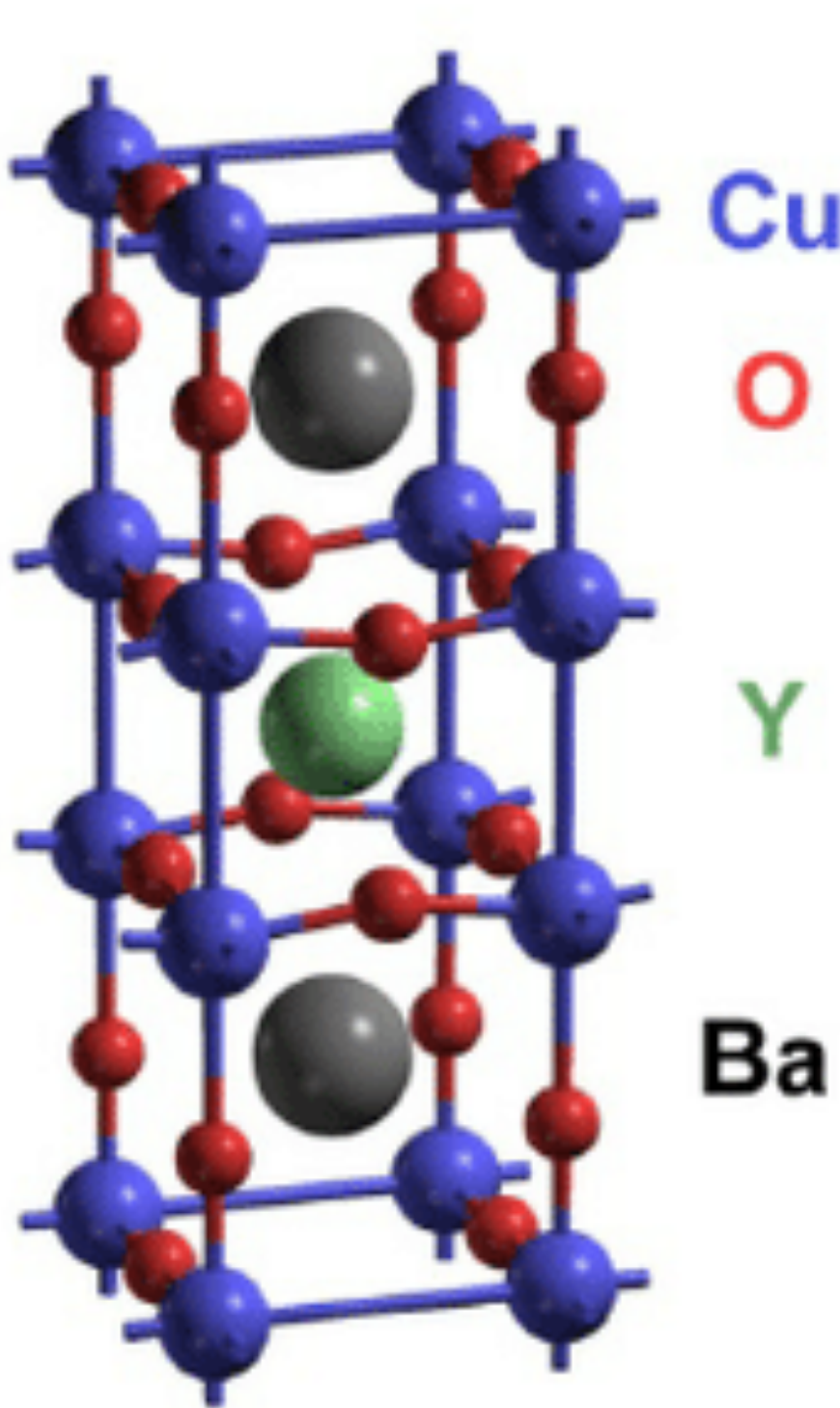
Mun K. Chan¹, Katherine A. Schreiber¹, Oscar E. Ayala-Valenzuela¹,
Eric D. Bauer², Arkady Shekhter¹ & Neil Harrison¹ Published online: 16 September 2025



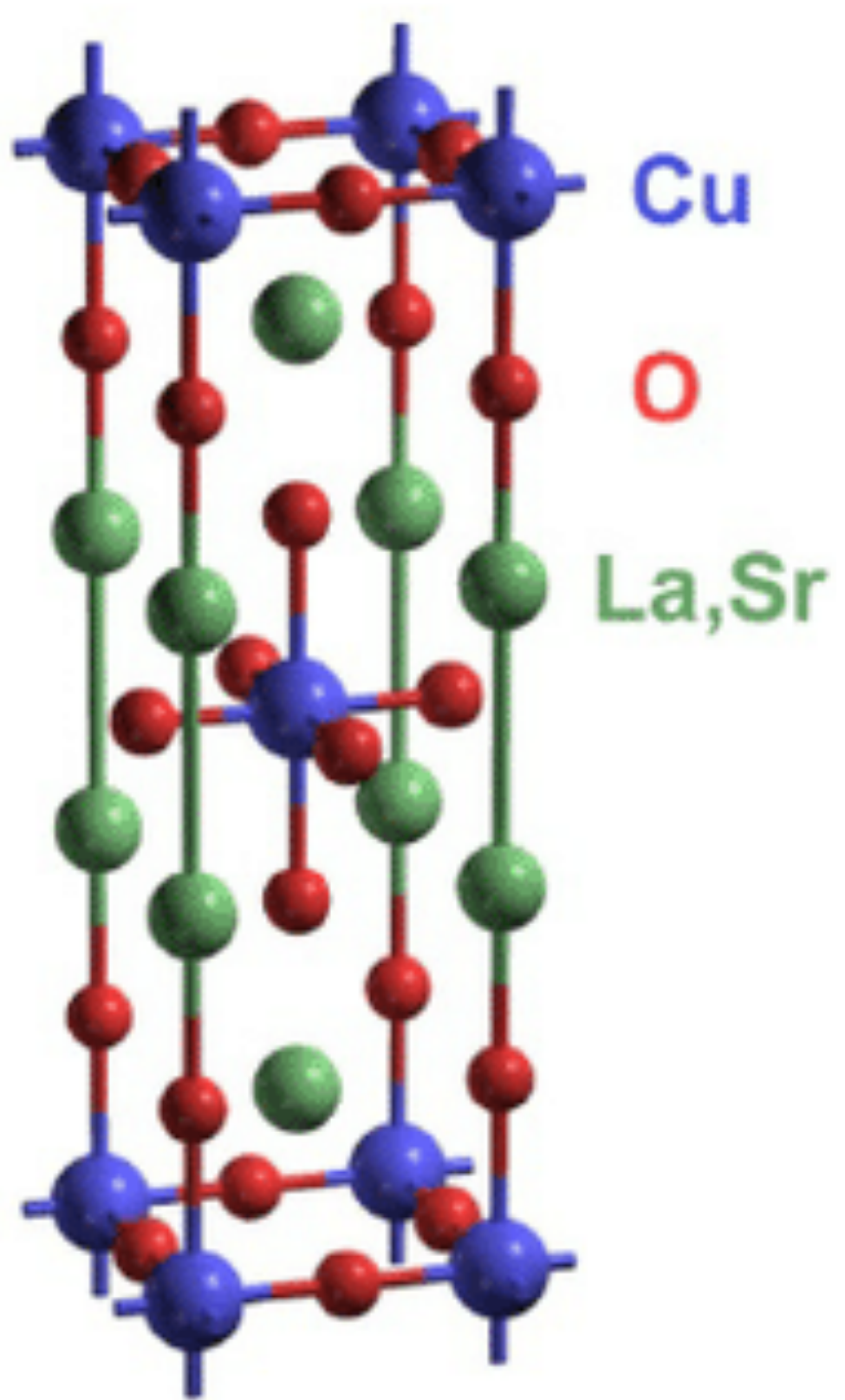
$\text{HgBa}_2\text{CuO}_{4+\delta}$
(Hg1201)

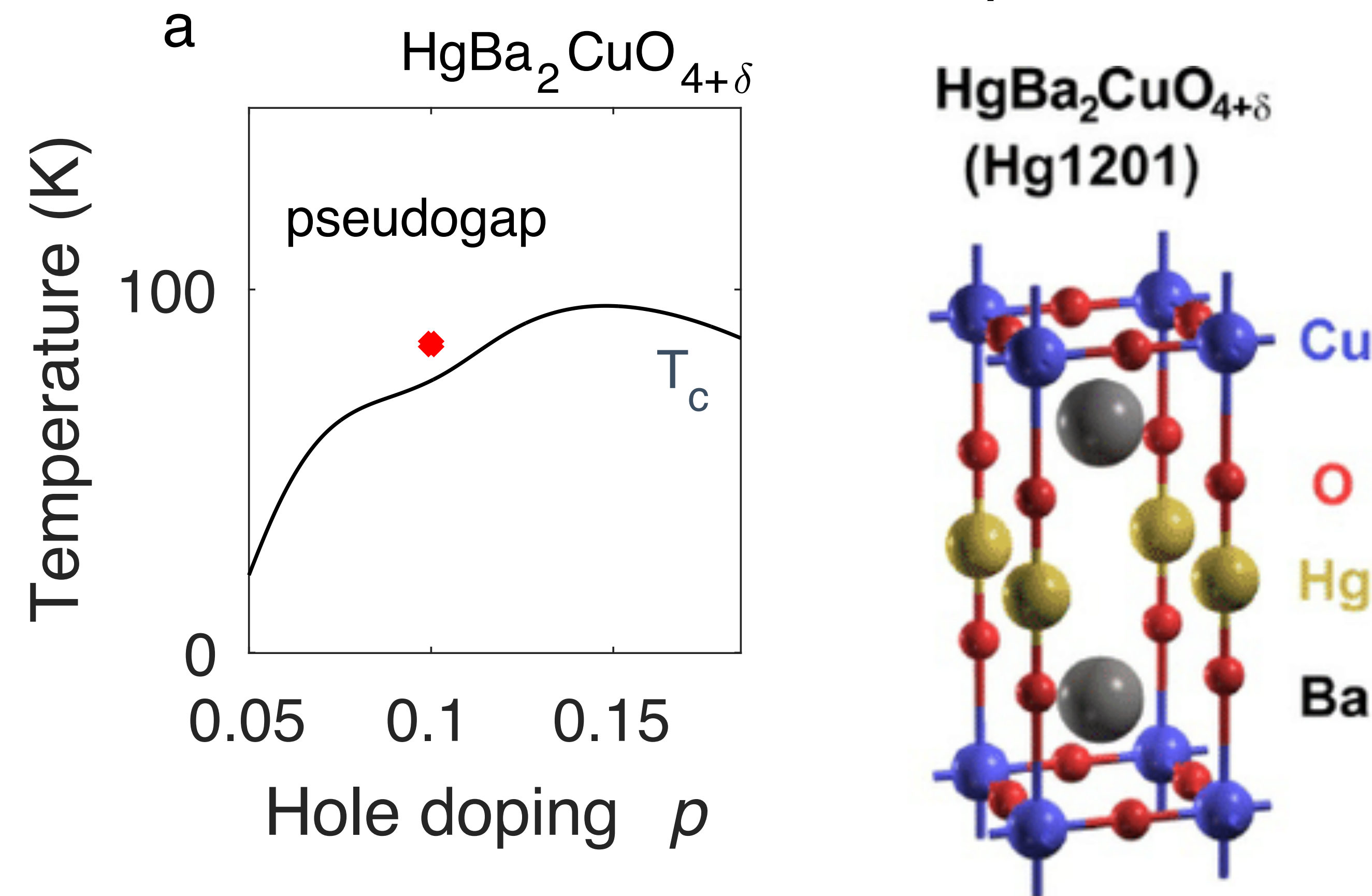


$\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$
(YBCO)



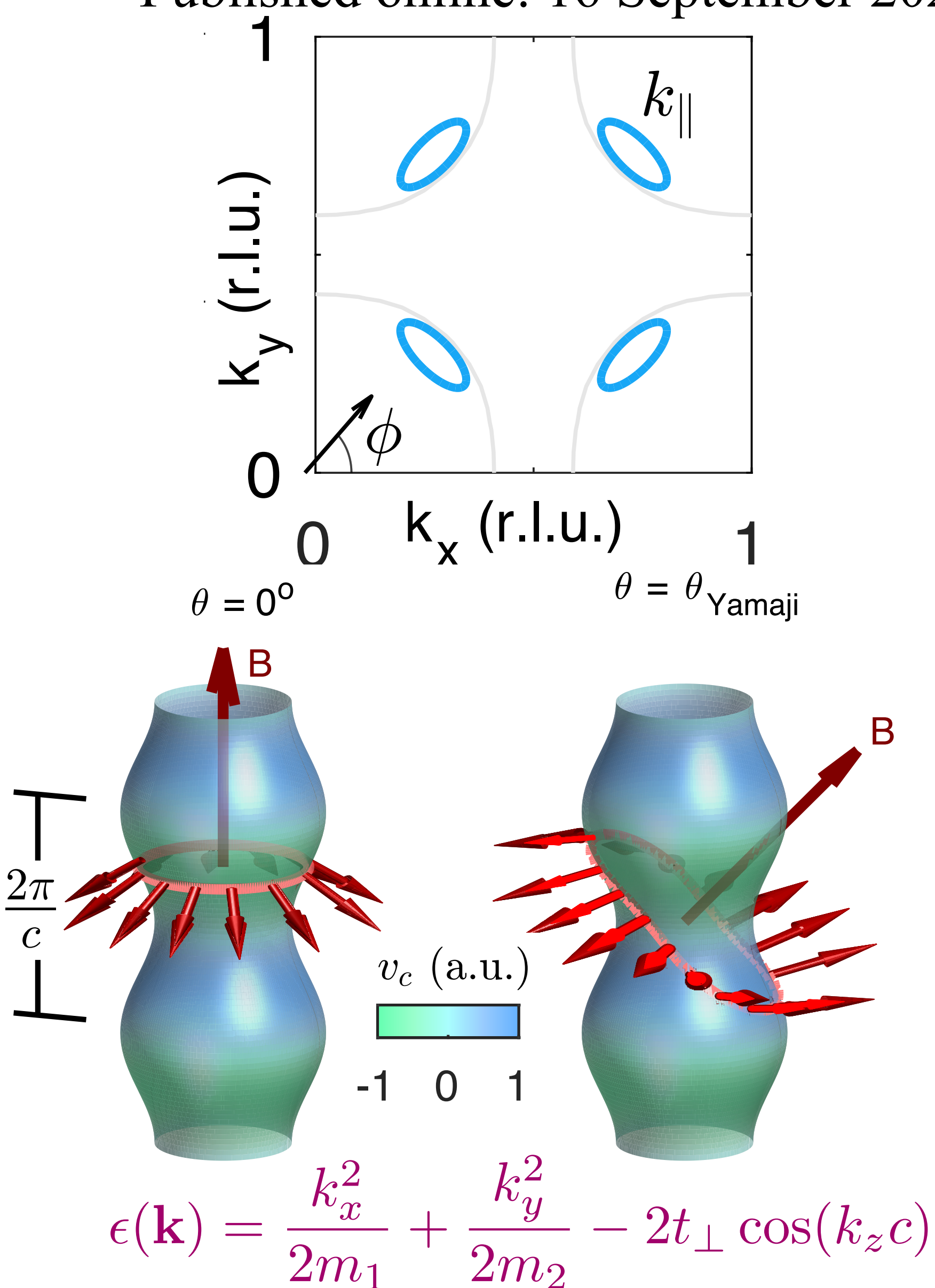
$\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$
(LSCO)





At the Yamaji angle, the orbits in the plane orthogonal to \mathbf{B} have an area which is independent of momentum in the c direction, to first order in the hopping along the c direction.

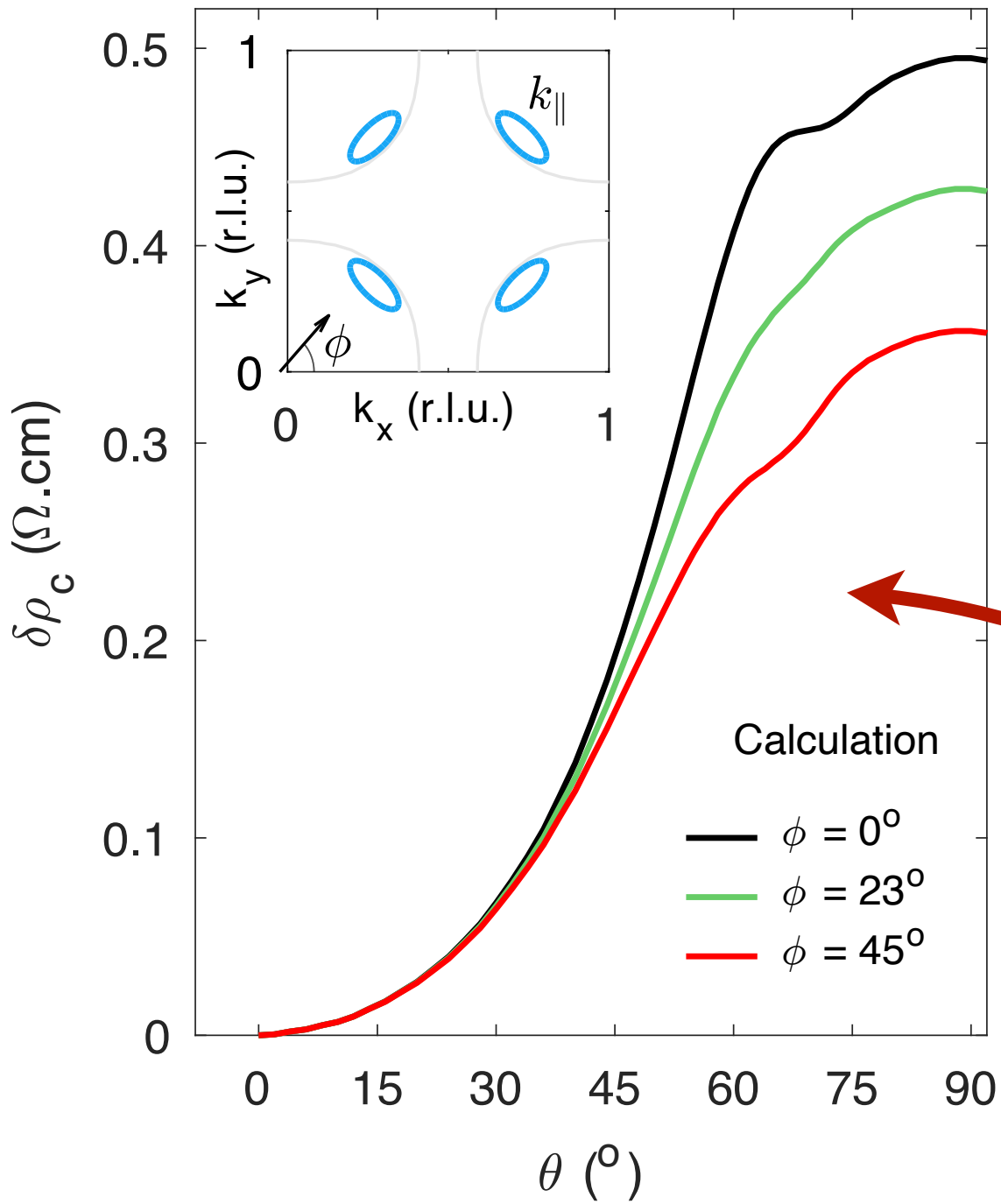
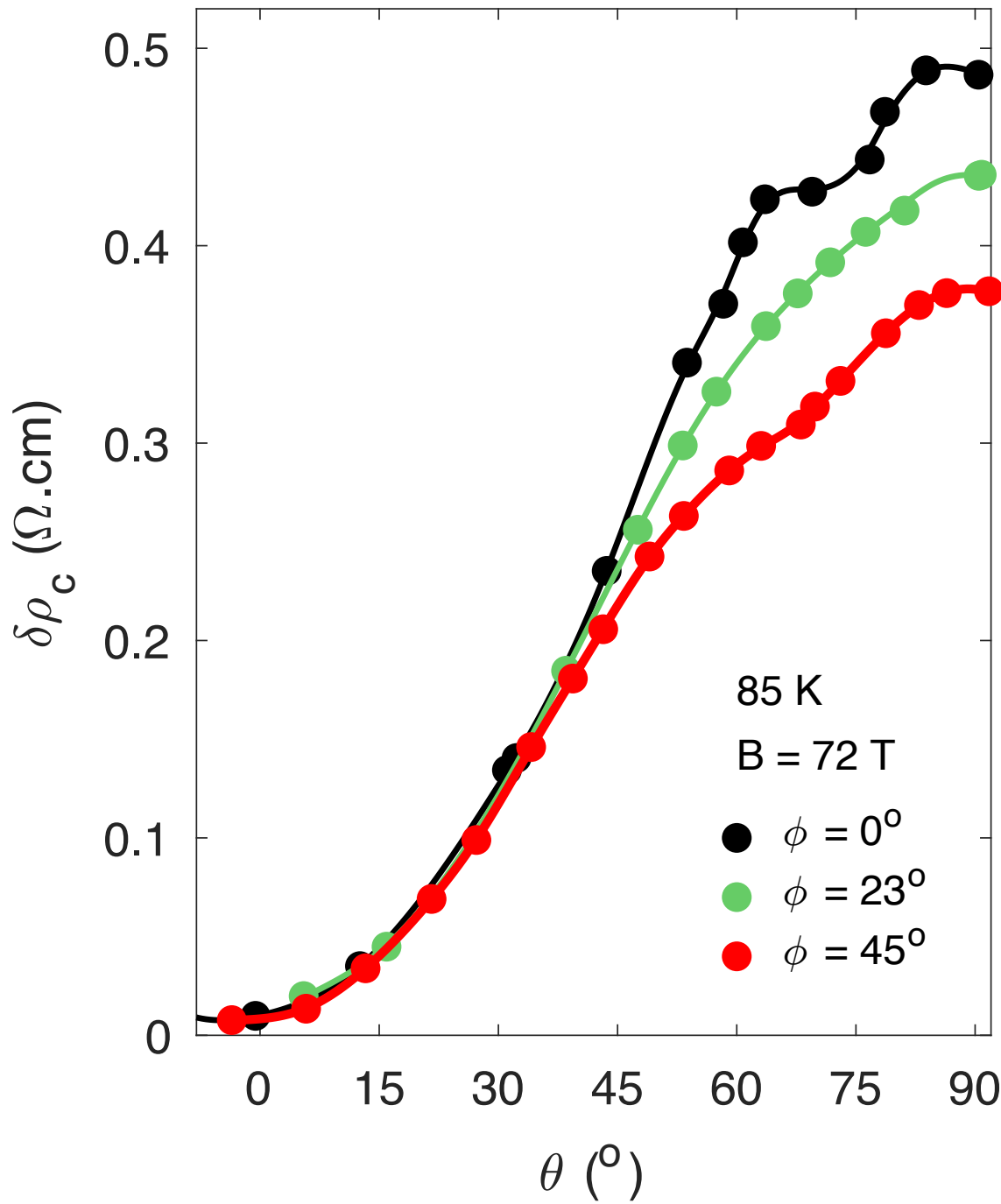
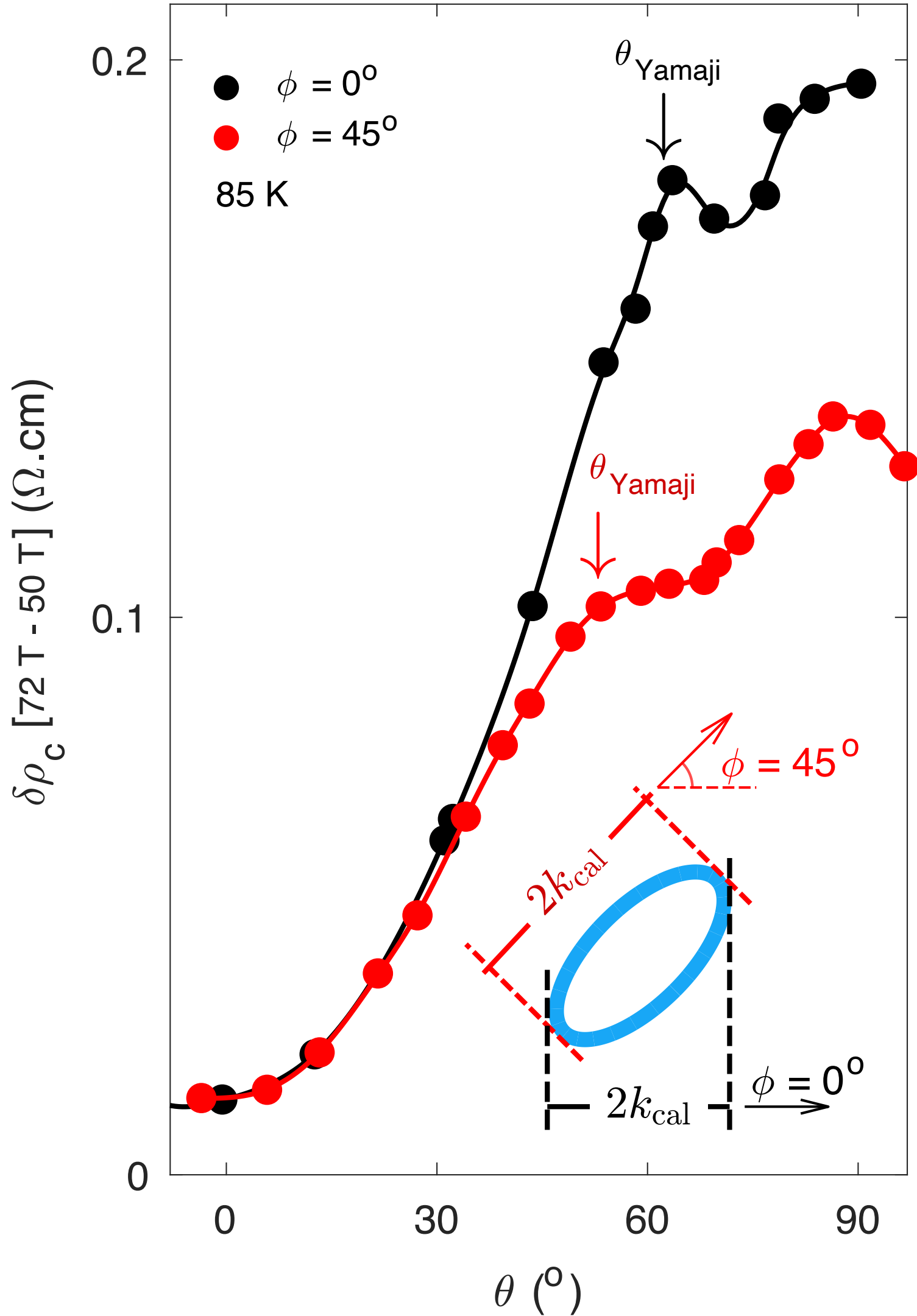
K.Yamaji JPSJ **58**, 1520 (1989)



Observation of the Yamaji effect in a cuprate superconductor

Mun K. Chan¹, Katherine A. Schreiber¹, Oscar E. Ayala-Valenzuela¹,
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Published online: 16 September 2025



Doping
 $p = 0.1$

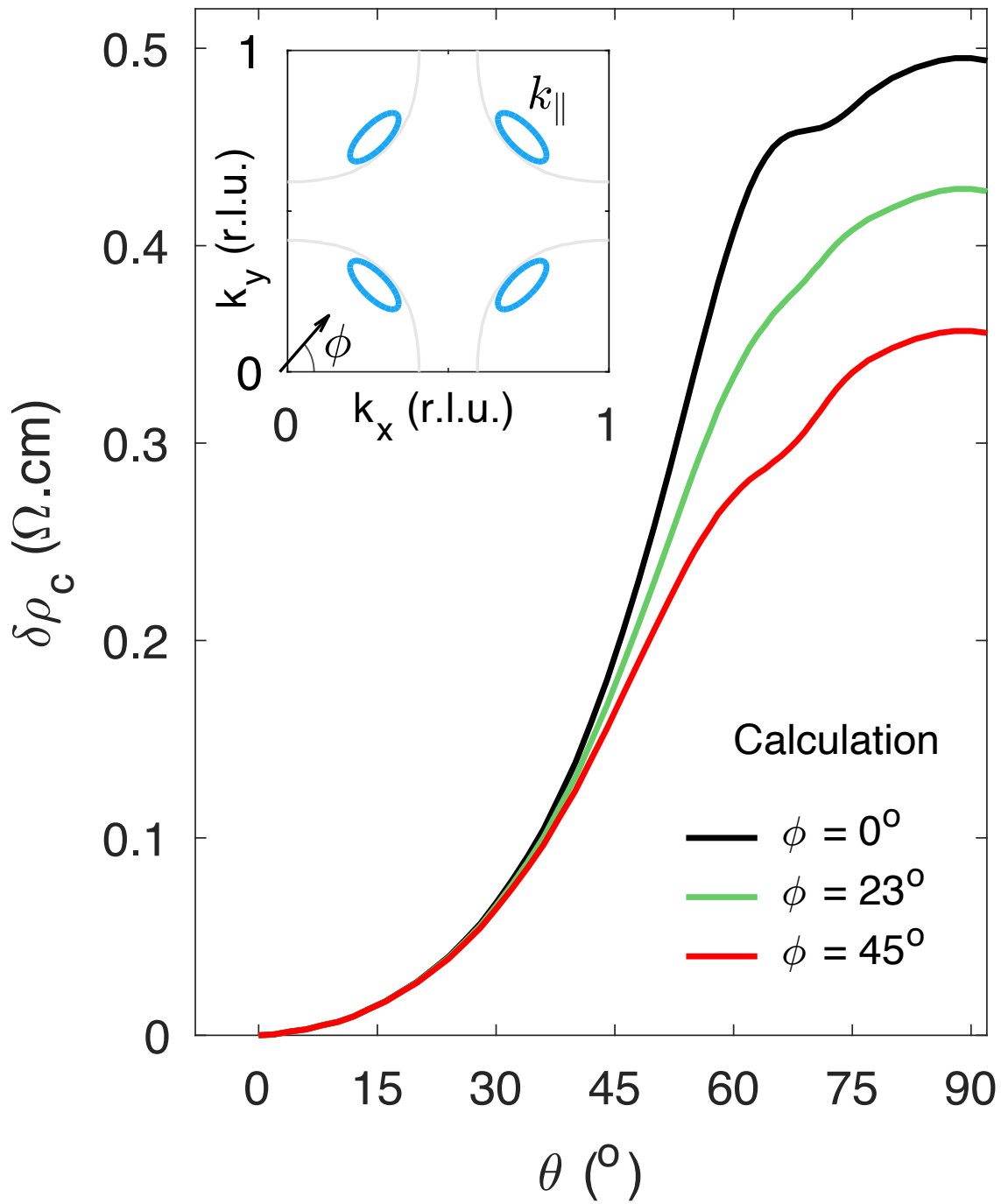
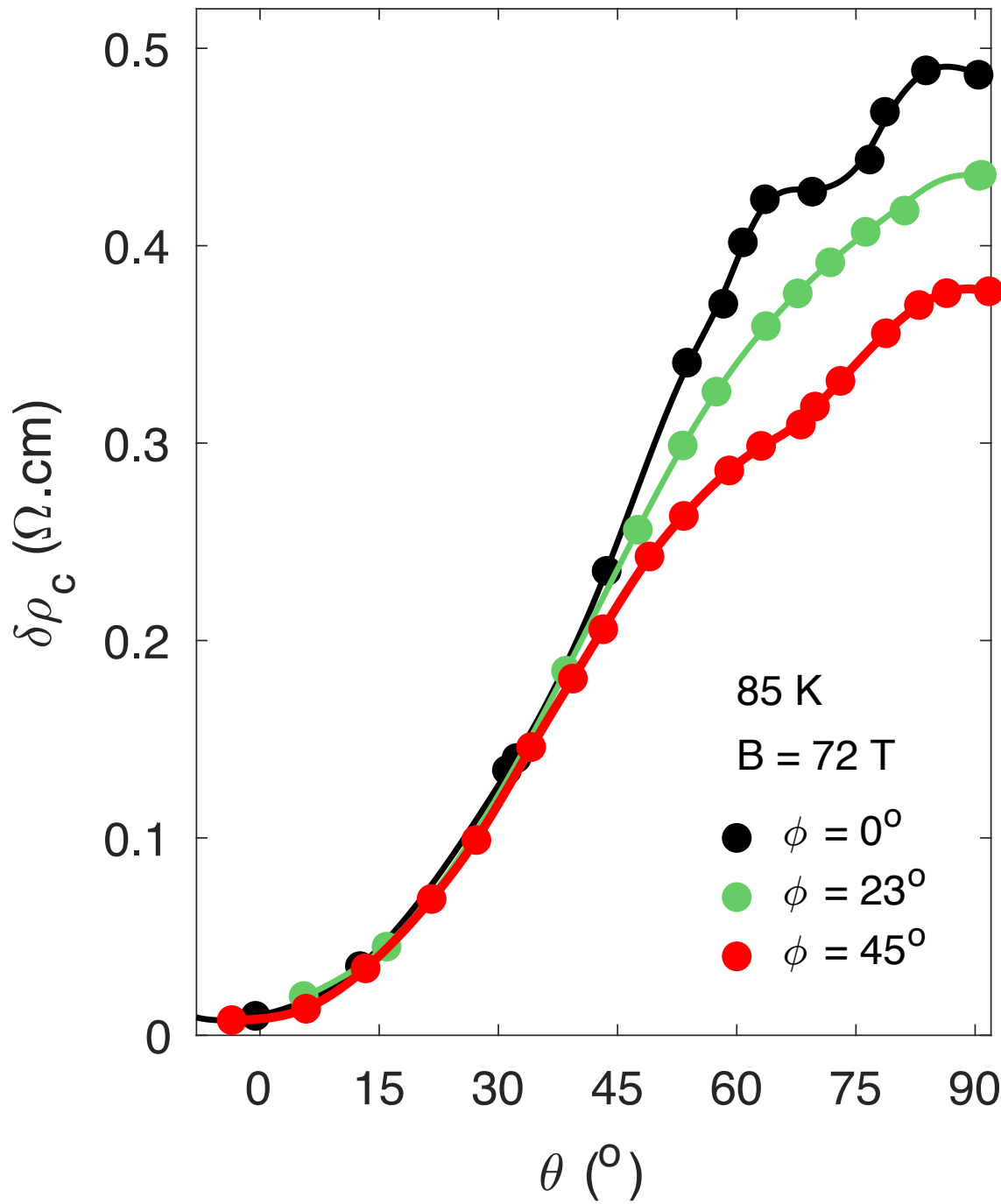
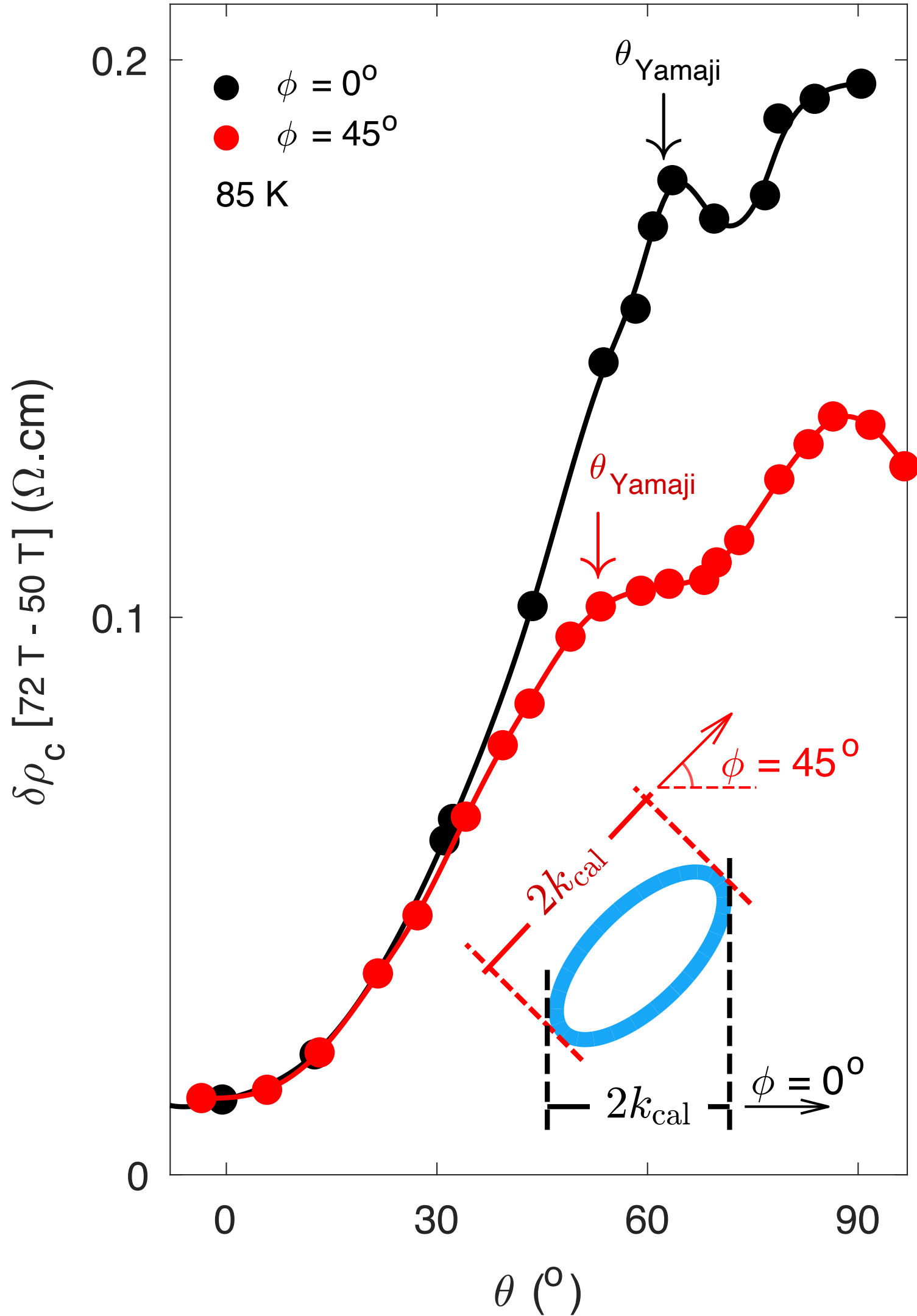
The observation of the Yamaji peak is evidence for small Fermi-surface pockets in the normal state of the pseudogap phase.

$$\frac{\partial f}{\partial t} + e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \mathbf{v} \left(-\frac{\partial f}{\partial \epsilon} \right) = -\frac{f - f_0}{\tau}$$
$$\mathbf{v} = \nabla_{\mathbf{k}} \epsilon(\mathbf{k}) ; f_0(\epsilon) = \frac{1}{e^{(\epsilon - \mu)/T} + 1}$$

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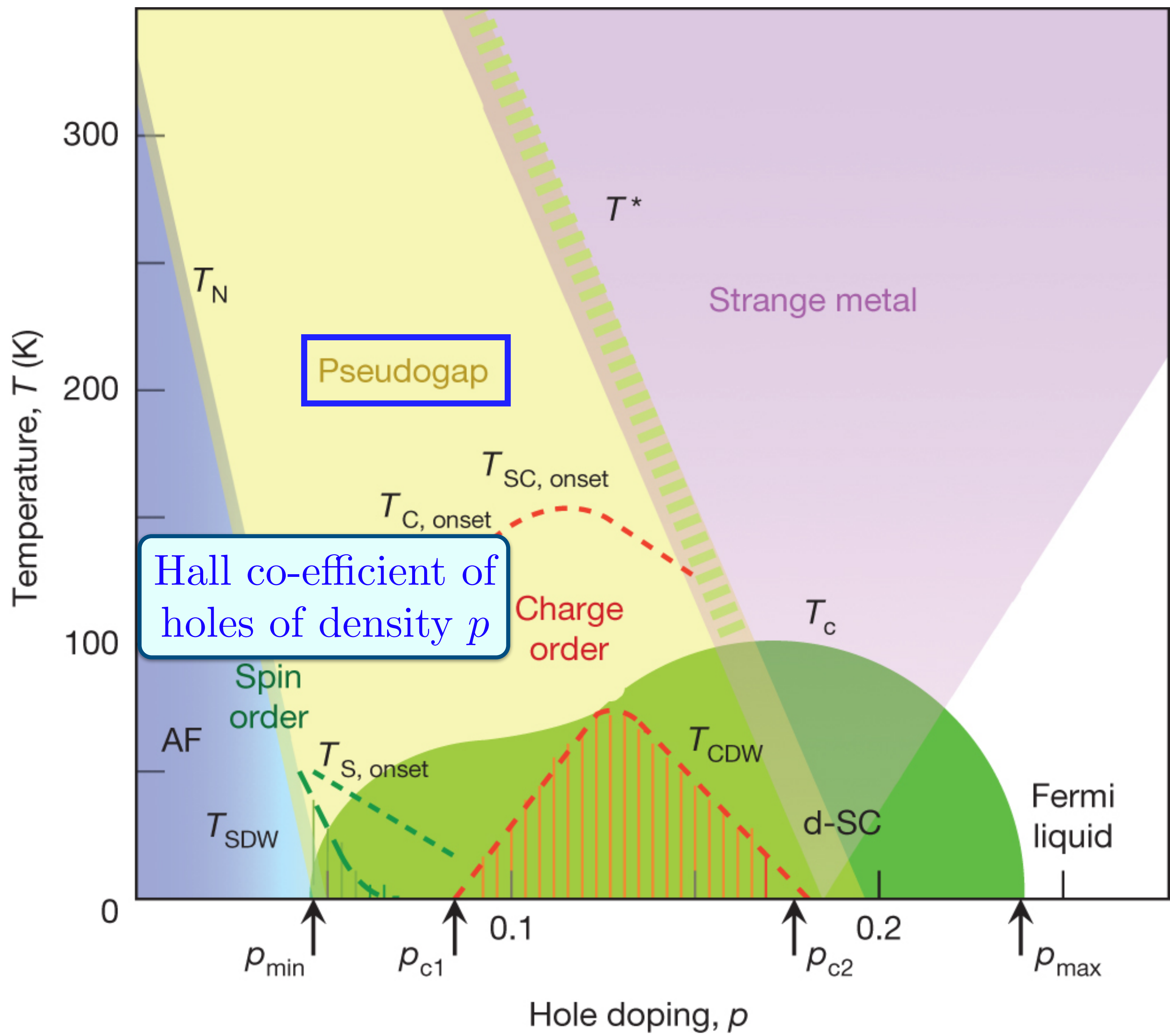


Doping
 $p = 0.1$

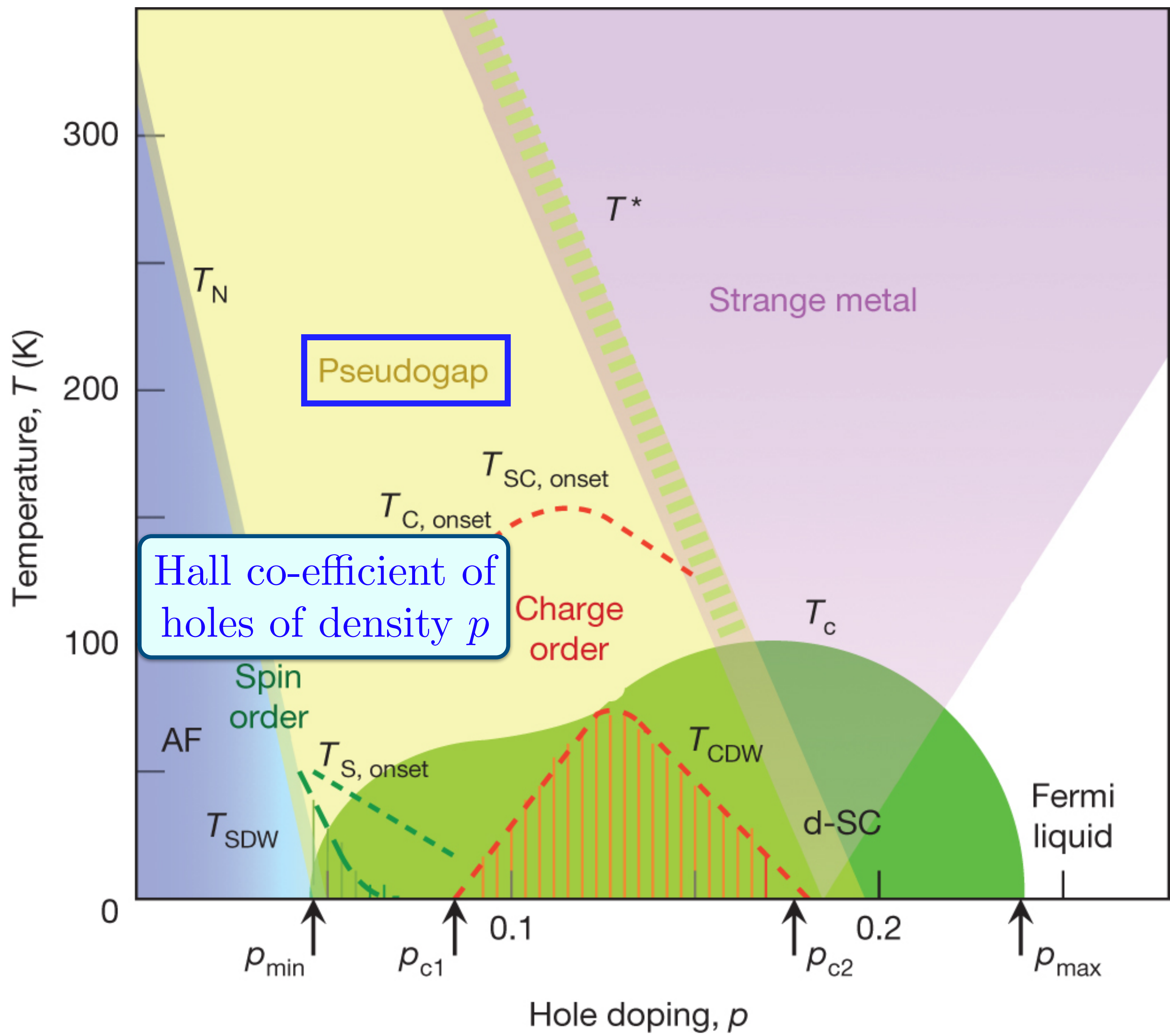
The observation of the Yamaji peak is evidence for small Fermi-surface pockets in the normal state of the pseudogap phase. The small size of the pockets, each estimated to occupy only 1.3% of the Brillouin zone area, is not expected given the absence of long-range broken translational symmetry.

Small hole pockets!

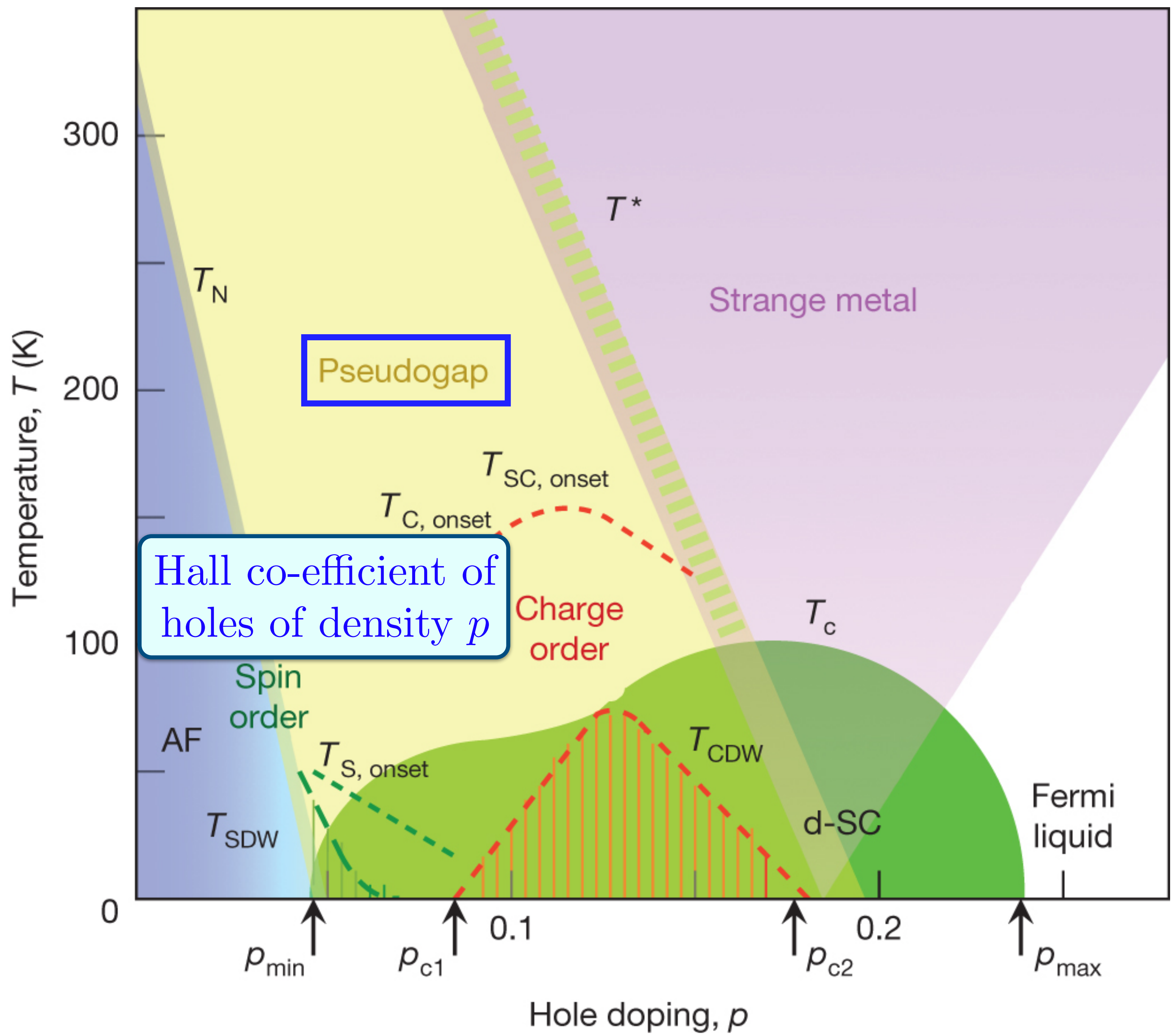
Fractionalized
Fermi liquids (FL^*)



Many theories with fluctuating and intertwined AFM, d-SC and charge orders.



I argue that a better starting point is a novel quantum ground state with no broken symmetry: the Fractionalized Fermi liquid (FL*)



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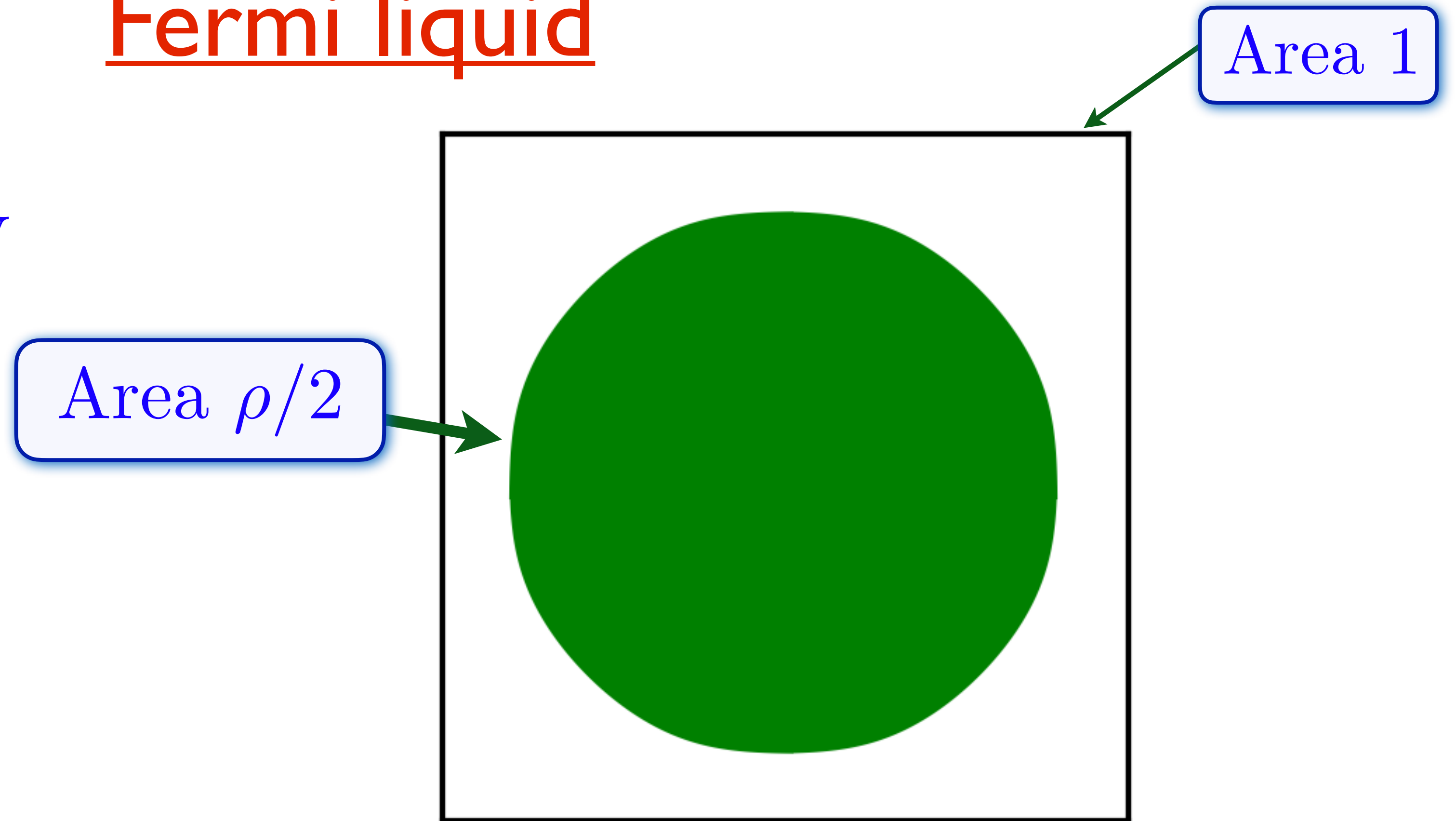
Fluctuations about this state are described by a SU(2) gauge theory which yields a fractionalized description of intertwined orders: the order parameters are gauge-invariant composites of a Higgs field B

Fermi liquid

Spin-1/2 holes of density

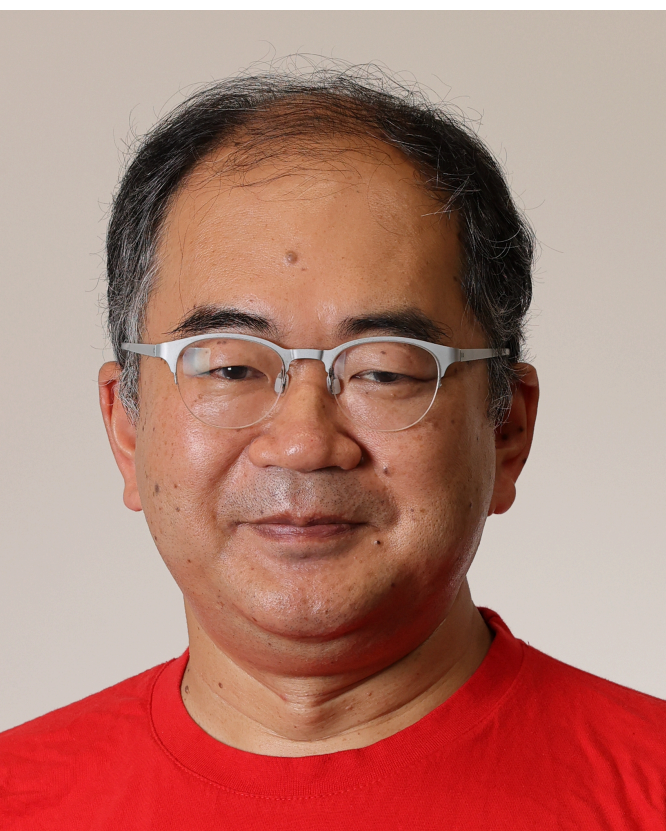
$$\rho = 1 + p$$

Positive Hall coefficient
of carrier density ρ



Luttinger, 1960: Area enclosed by the Fermi surface is the same as that for free fermions *with the same symmetry*.

Oshikawa, 2000: Area constrained by an anomaly-argument of global U(1) and translations



Fractionalized Fermi liquid (FL*)

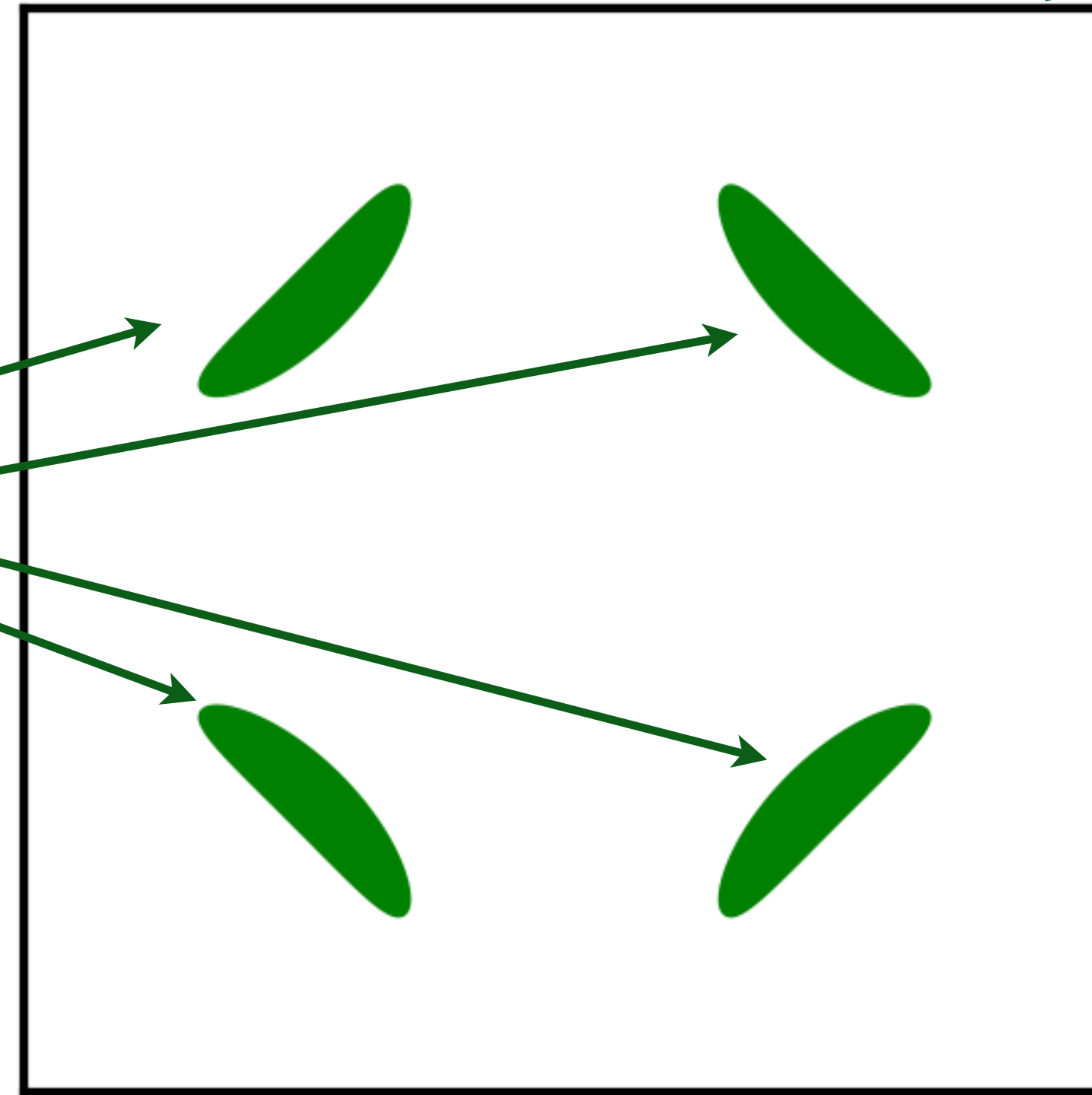
Area 1

Spin-1/2 holes of density

$$\rho = 1 + p$$

Positive Hall coefficient
of carrier density $\rho - 1$

Total area
 $(\rho - 1)/2$



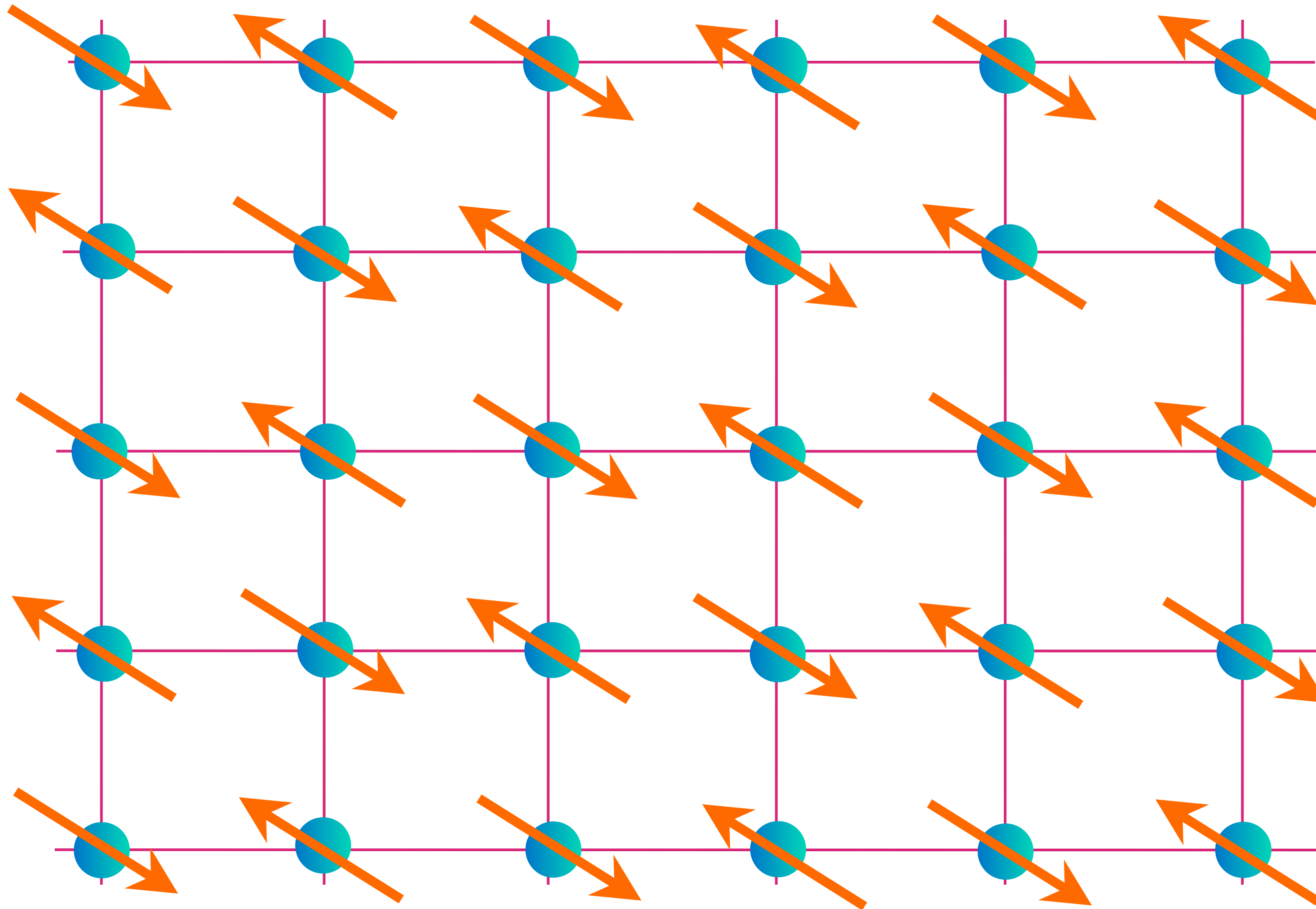
No
broken
symmetry.

Area per
pocket
 $= p/8$

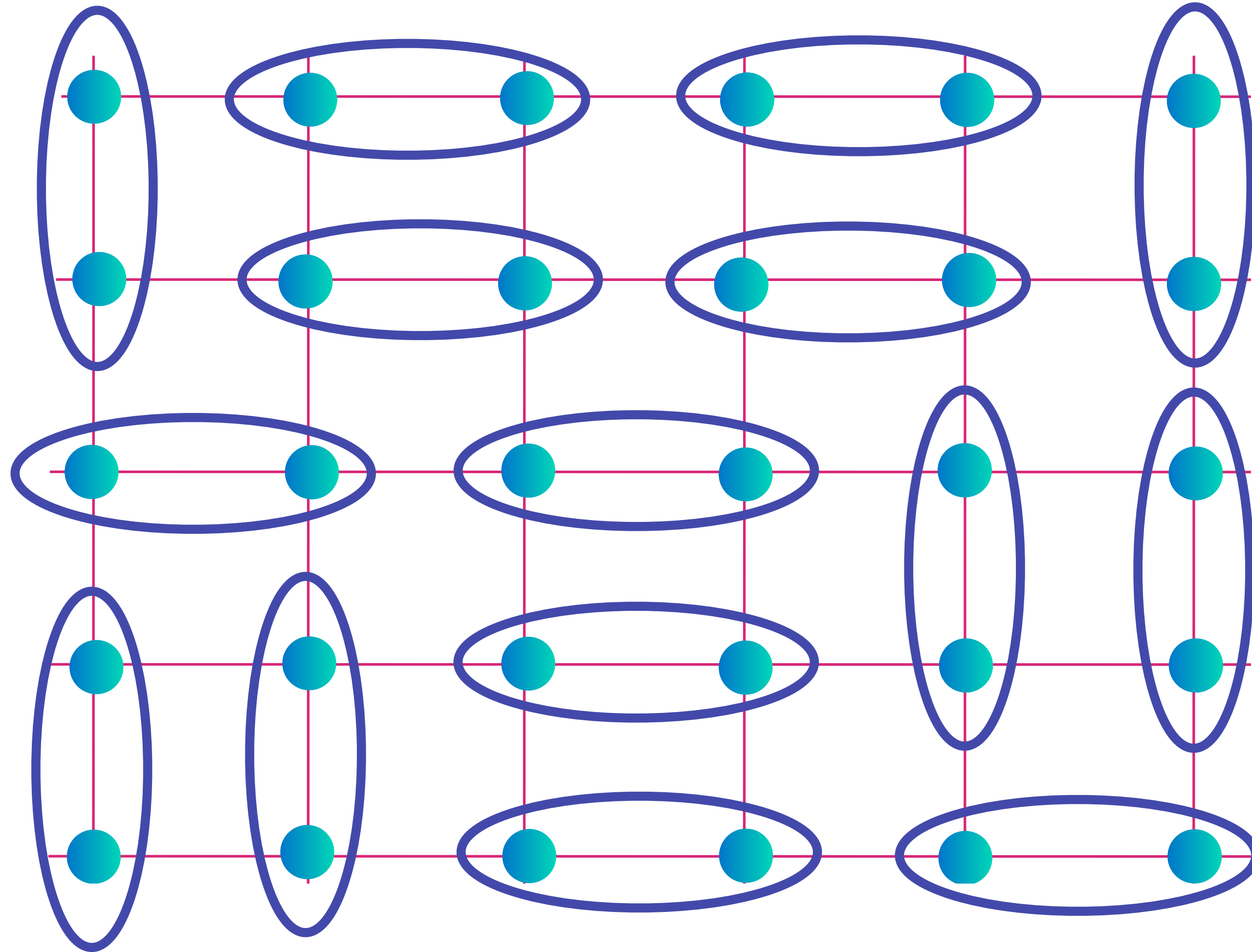
Oshikawa anomaly-argument is satisfied by
the sum of Fermi surface $(\rho - 1)$ and
quantized spin liquid (1) anomalies.



Antiferromagnet



Anderson's Resonating Valence Bond (1972, 1987)

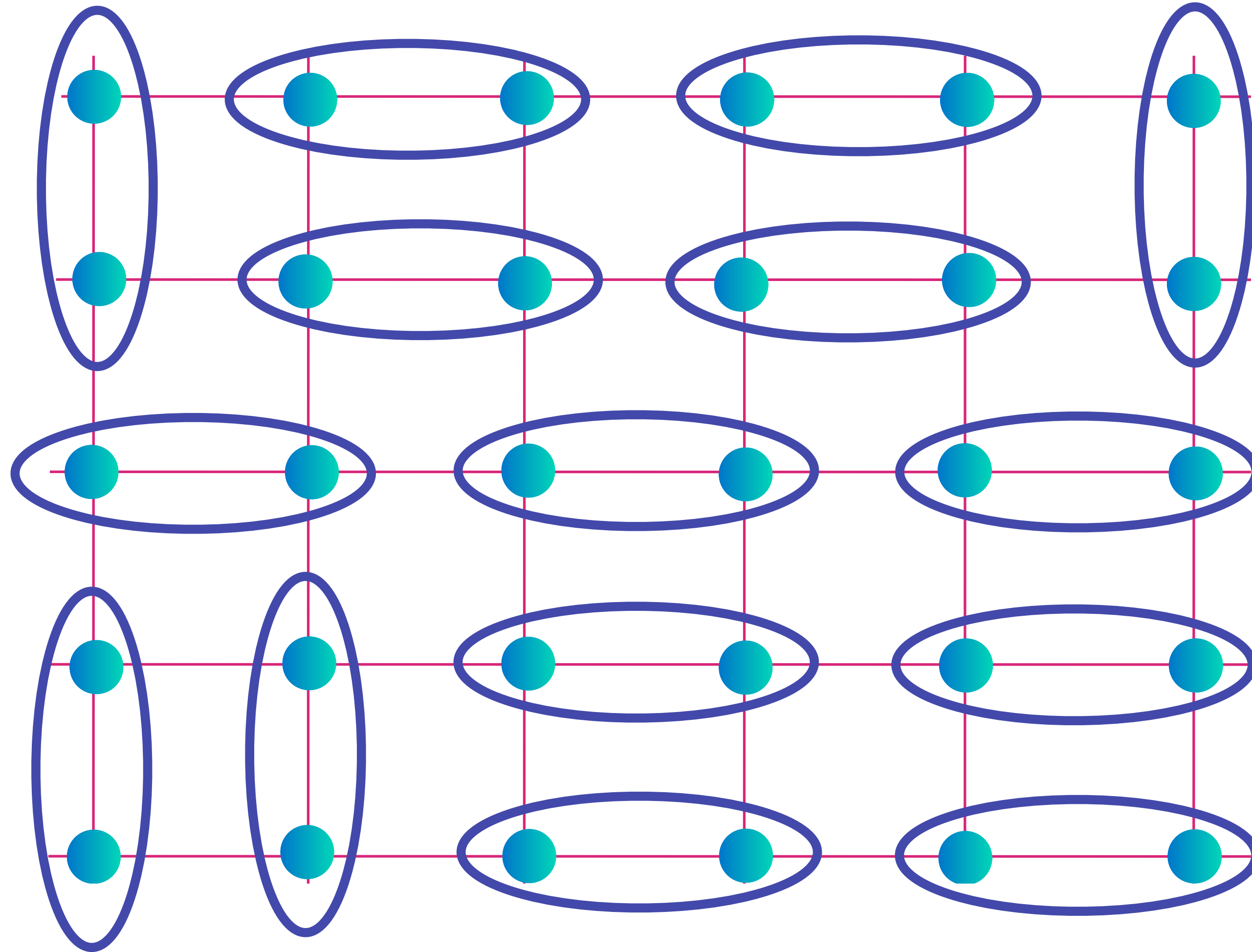


$$\text{blue oval with two dots} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

$$|G\rangle = \sum_{\mathcal{D}} c_{\mathcal{D}} |\mathcal{D}\rangle$$

$\mathcal{D} \rightarrow$ dimer covering
of lattice

Anderson's Resonating Valence Bond (1972, 1987)

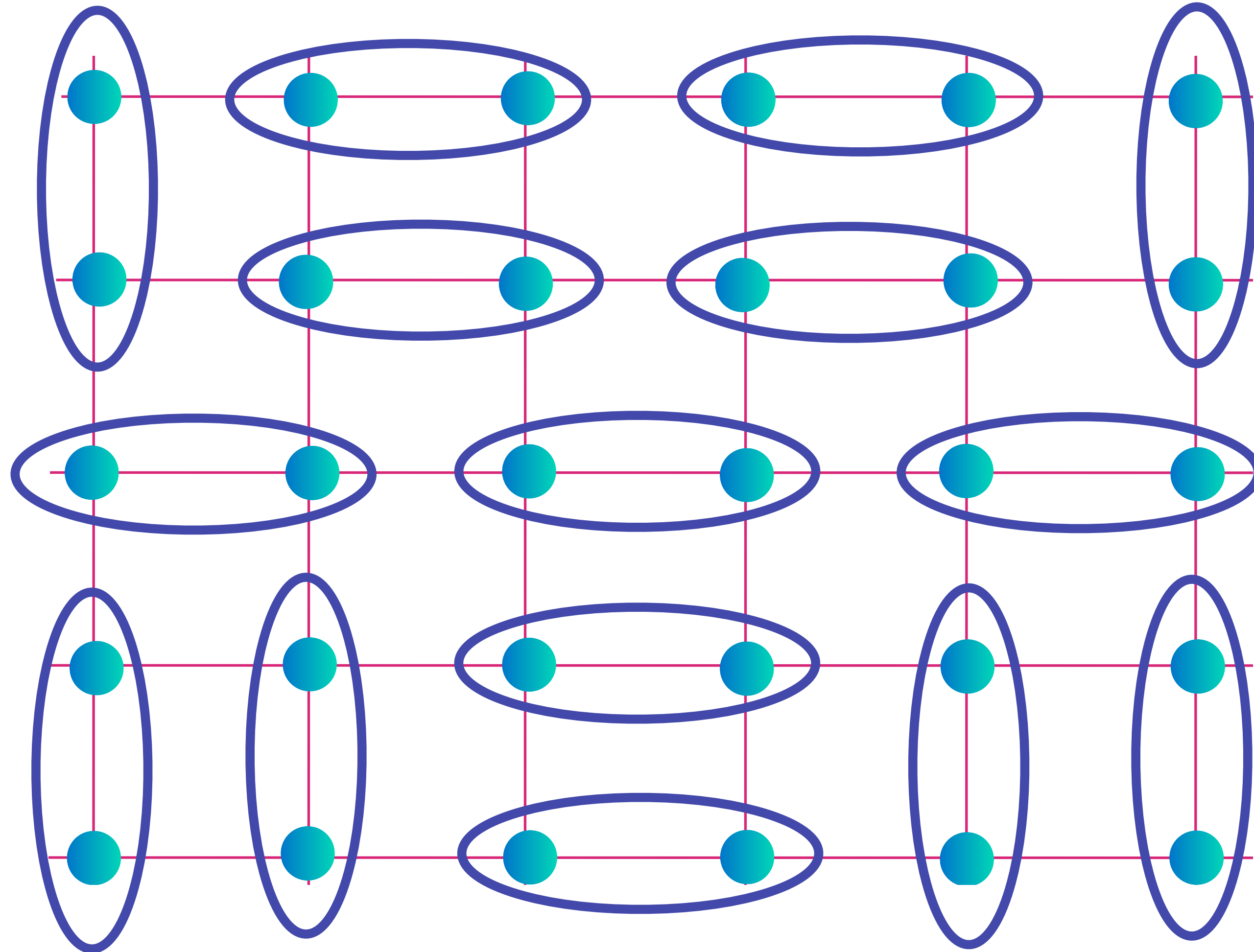


$$\text{oval} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

$$|G\rangle = \sum_{\mathcal{D}} c_{\mathcal{D}} |\mathcal{D}\rangle$$

$\mathcal{D} \rightarrow$ dimer covering
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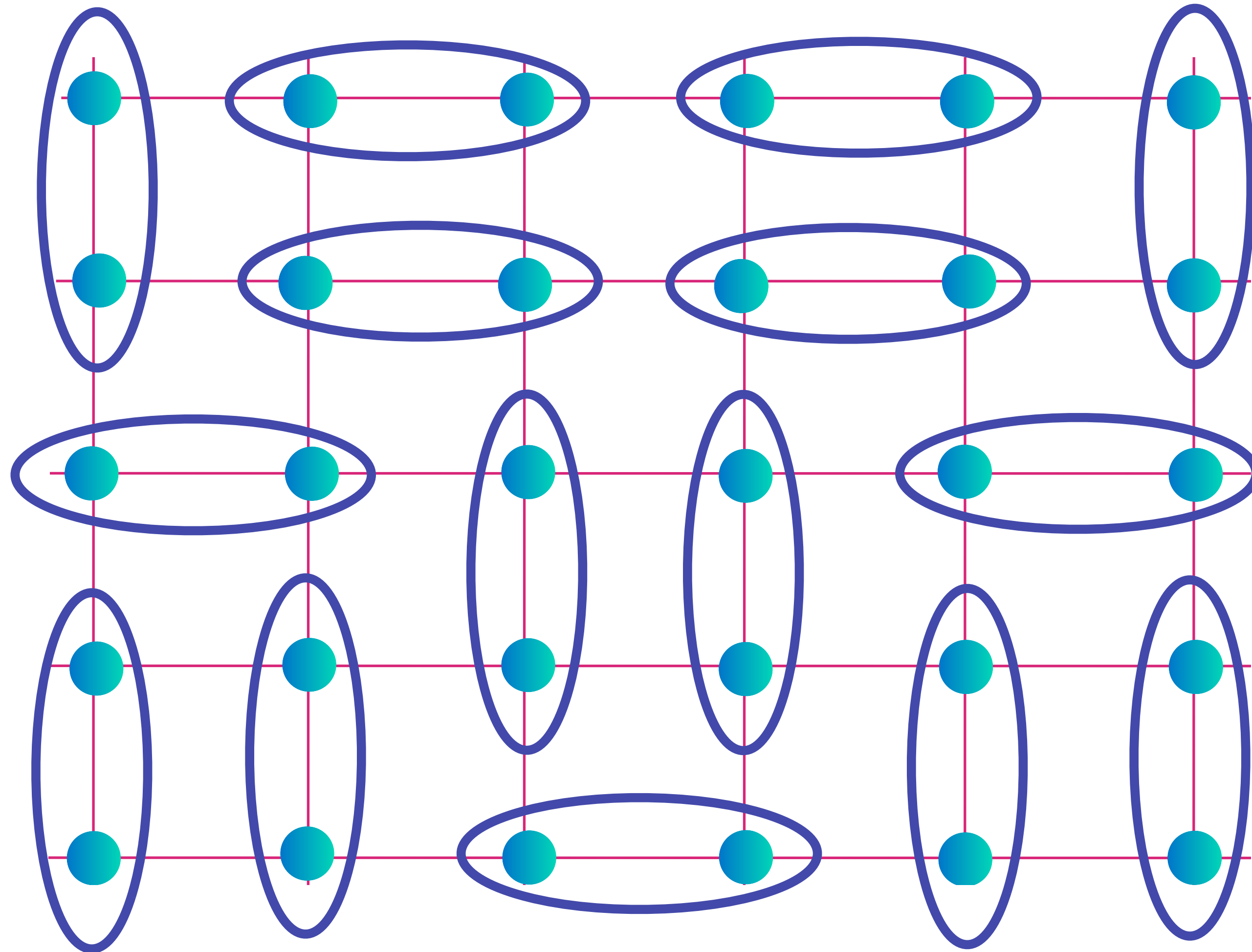


$$\text{dimer} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

$$|G\rangle = \sum_{\mathcal{D}} c_{\mathcal{D}} |\mathcal{D}\rangle$$

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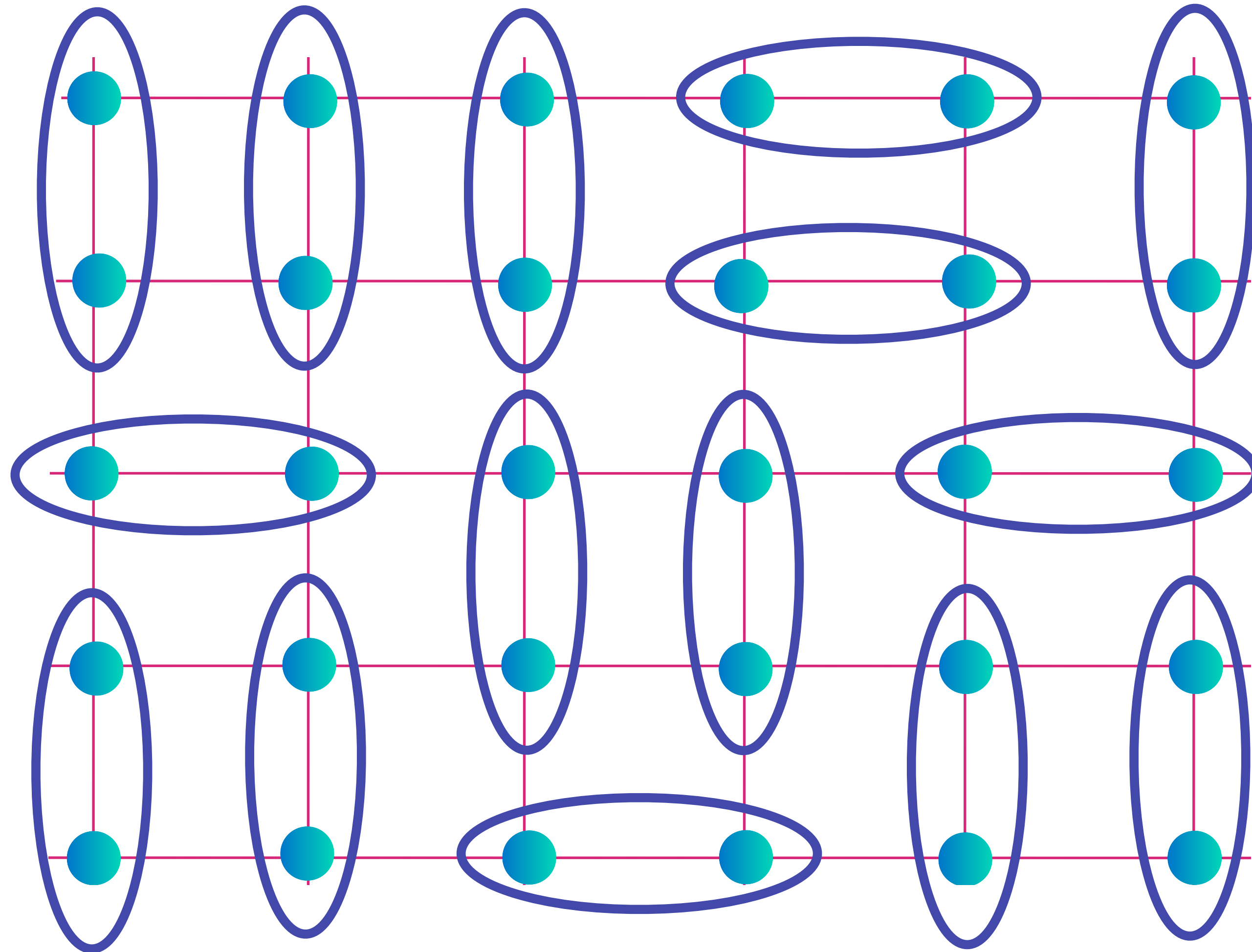


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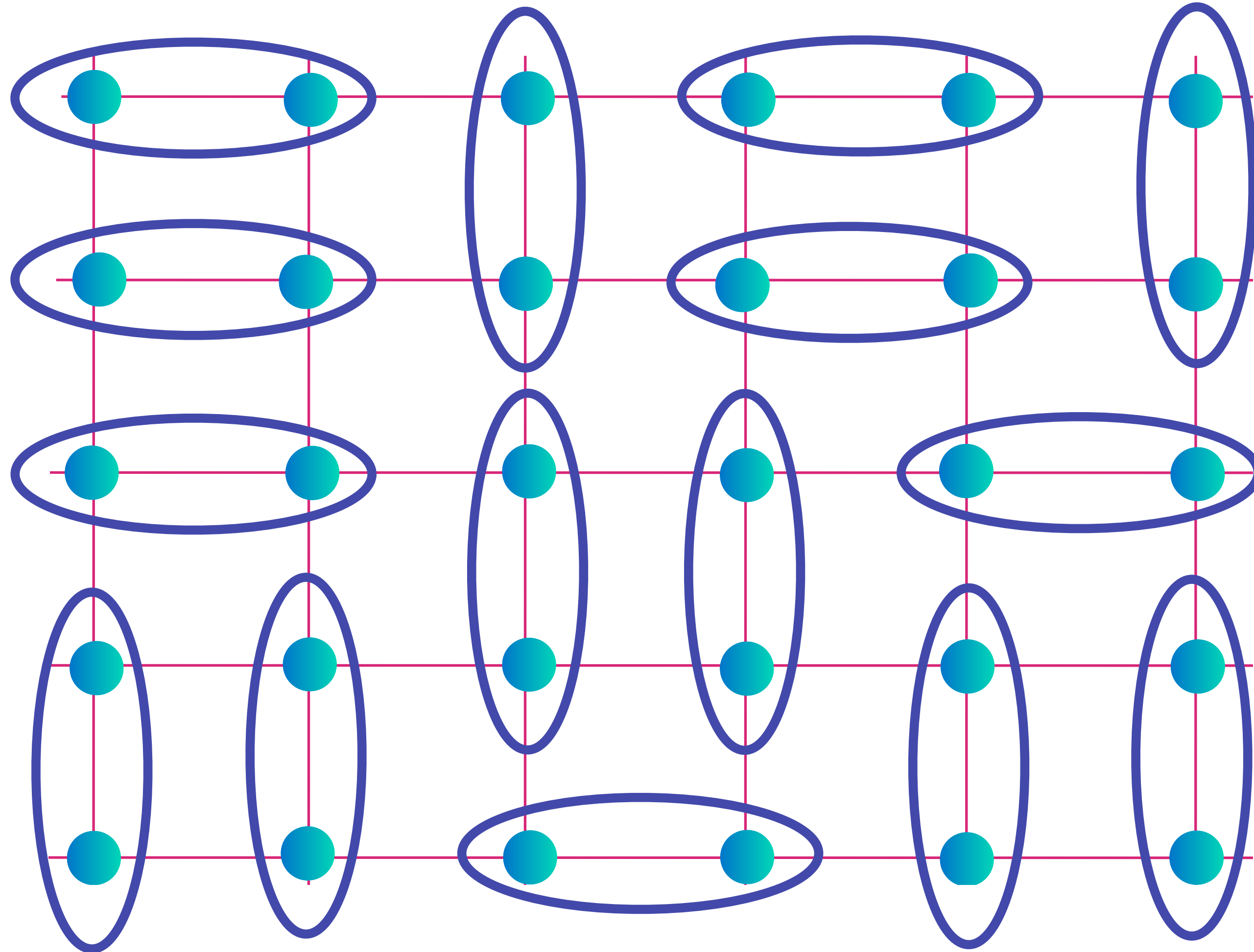


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$\mathcal{D} \rightarrow$ dimer covering
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Anderson's Resonating Valence Bond (1972, 1987)

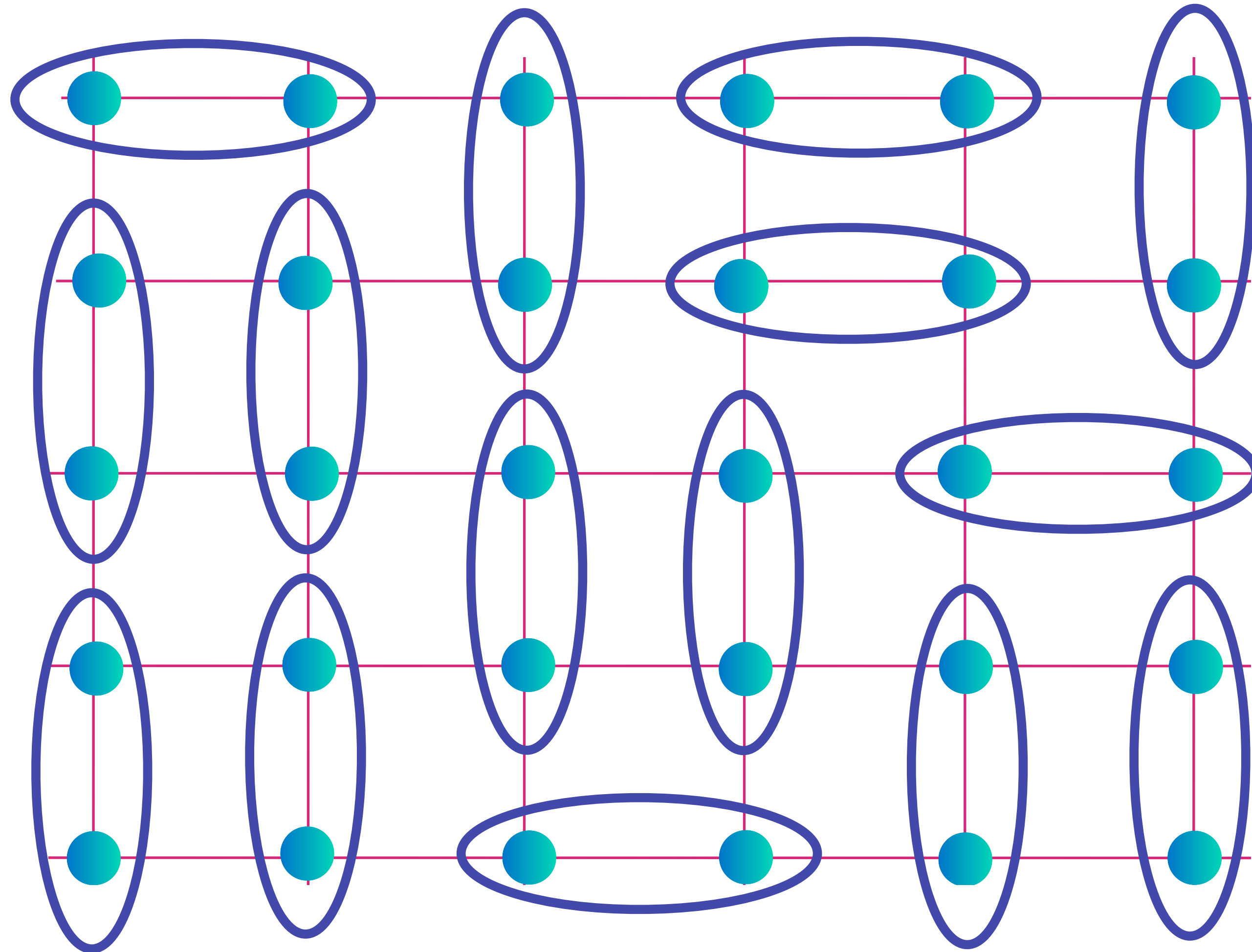


$$\text{oval} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

$$|G\rangle = \sum_{\mathcal{D}} c_{\mathcal{D}} |\mathcal{D}\rangle$$

$\mathcal{D} \rightarrow$ dimer covering
of lattice

Anderson's Resonating Valence Bond (1972, 1987)



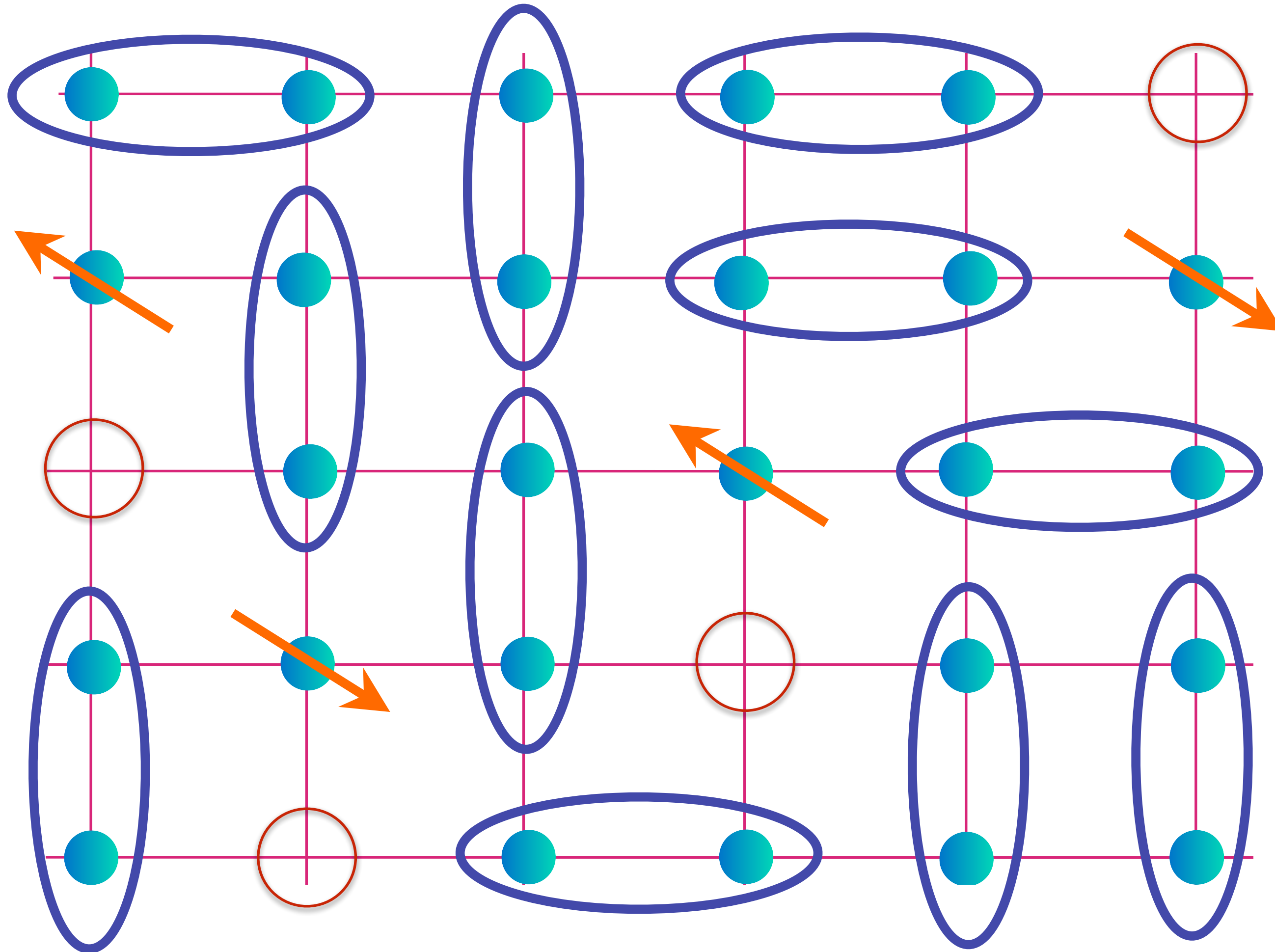
$$\text{oval} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

$$|G\rangle = \sum_{\mathcal{D}} c_{\mathcal{D}} |\mathcal{D}\rangle$$

$\mathcal{D} \rightarrow$ dimer covering
of lattice

To obtain a (super)conductor we have to
remove a density p of electrons

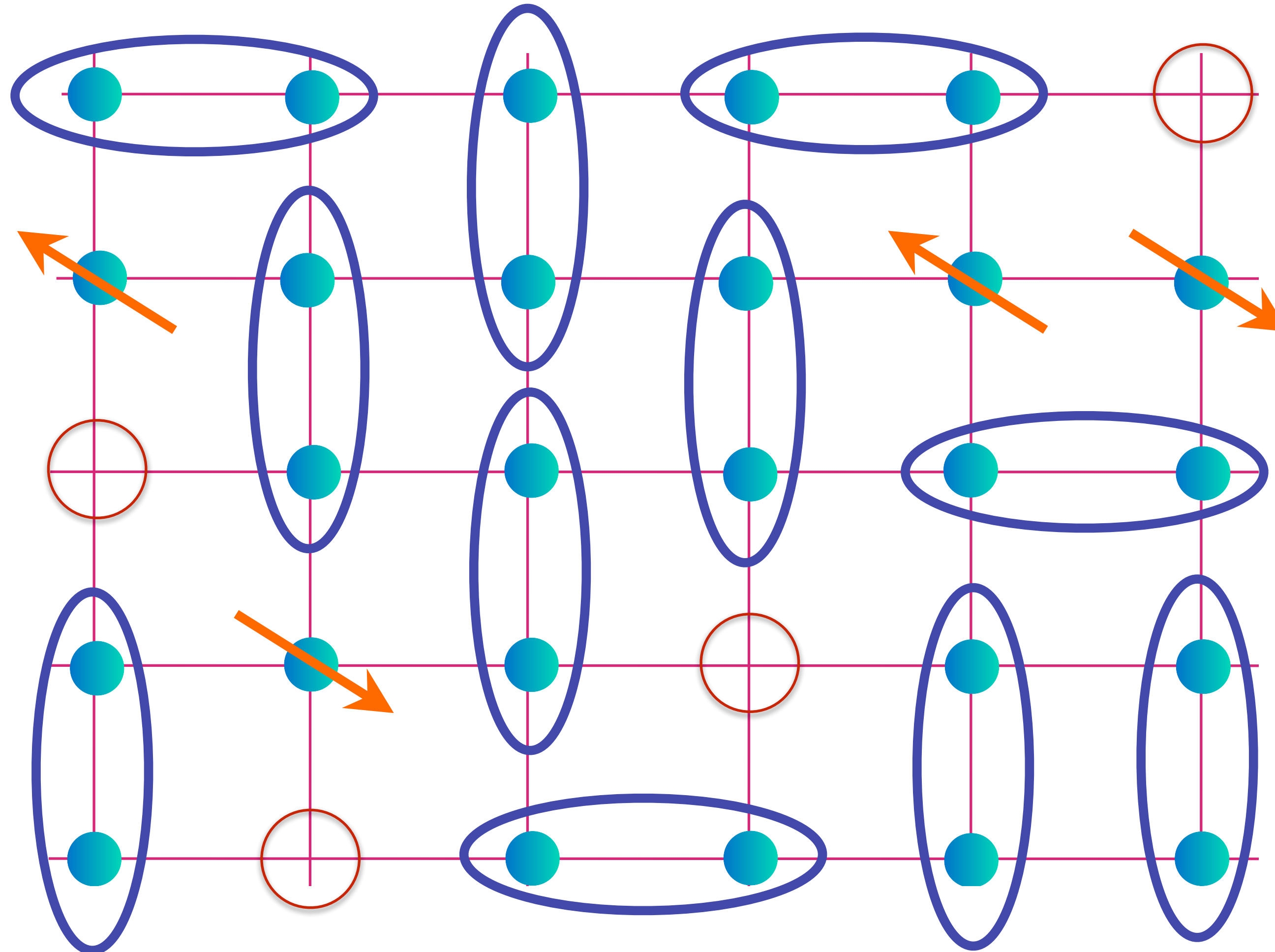
Energy cost to
create spinon $\sim J$



$$\text{[Teal dot in oval]} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

To obtain a (super)conductor we have to
remove a density p of electrons

Energy cost to
create spinon $\sim J$



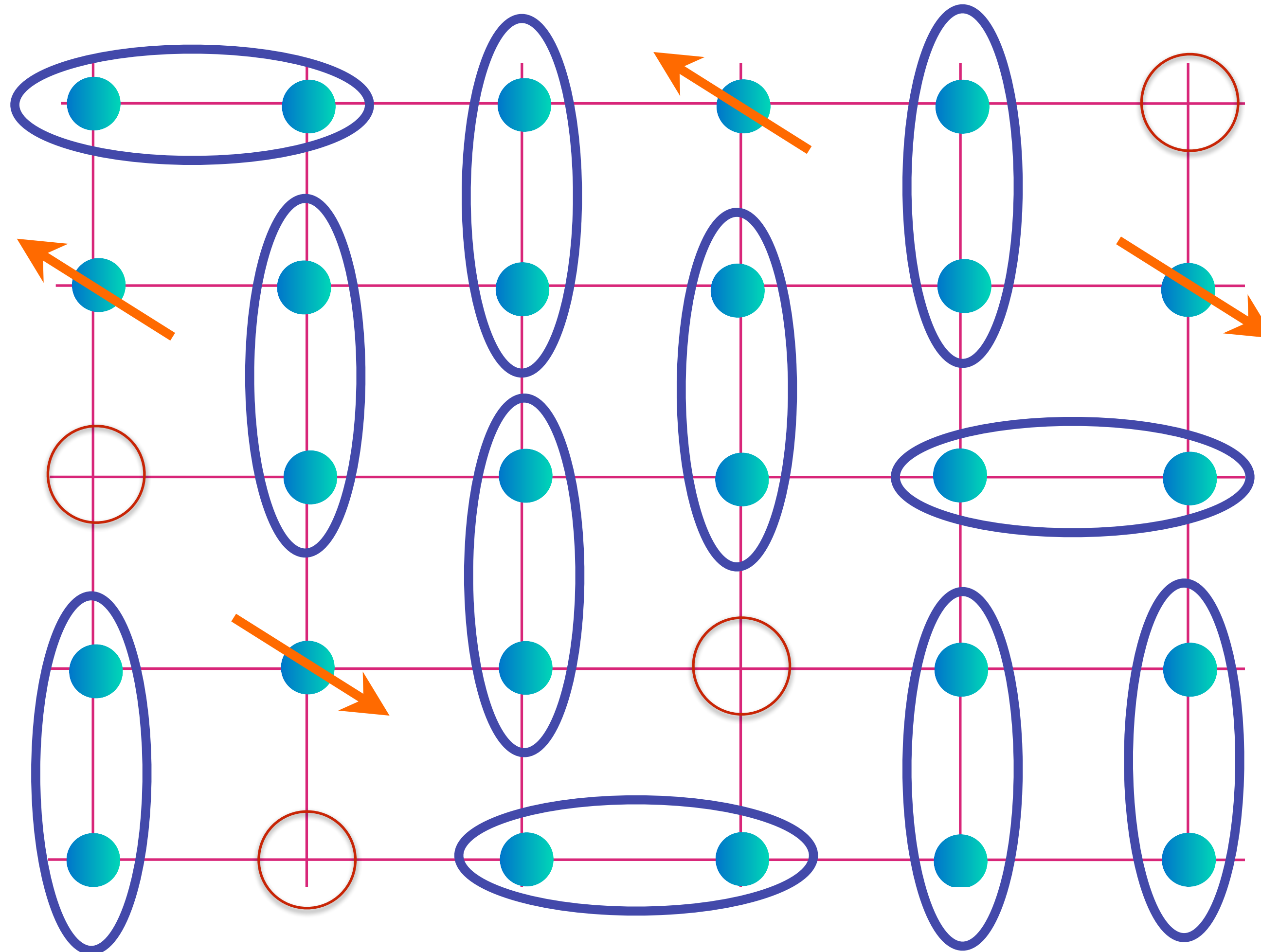
$$\text{blue oval with two dots} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

Holons
(charge e , spin 0)
and
spinons
(charge 0, spin $1/2$)
can move
independently

Holons cannot tunnel
between layers

To obtain a (super)conductor we have to
remove a density p of electrons

Energy cost to
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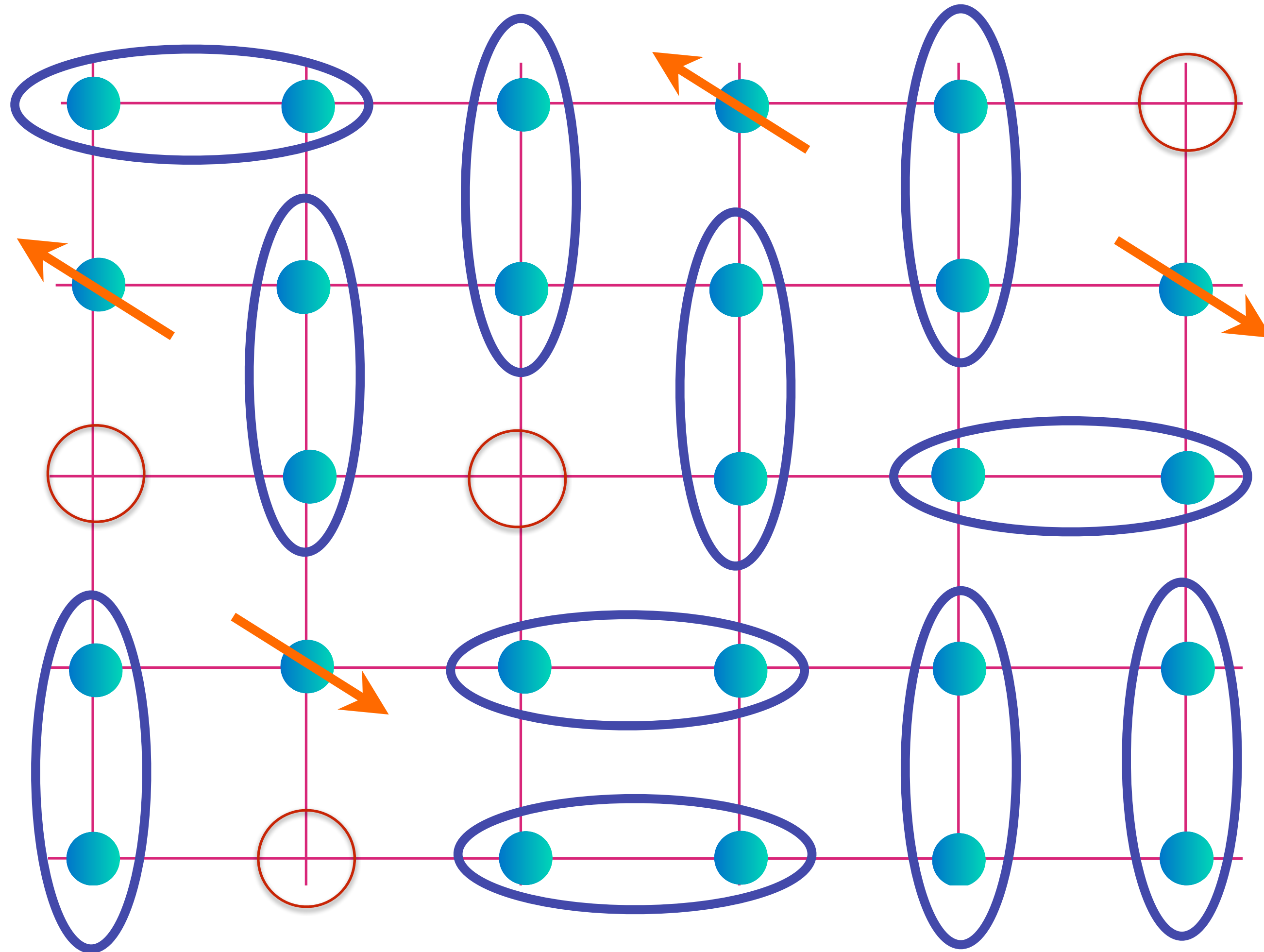
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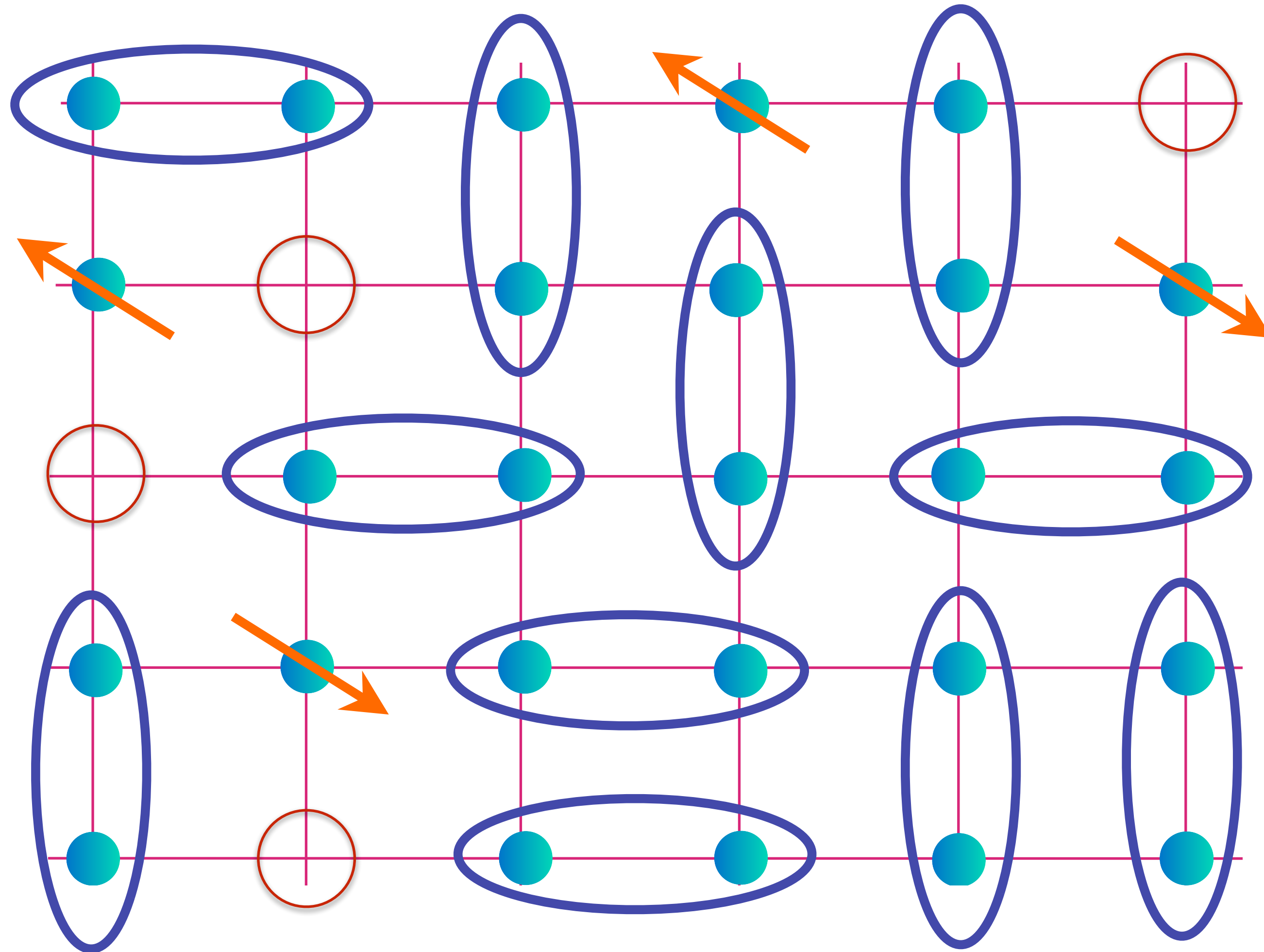
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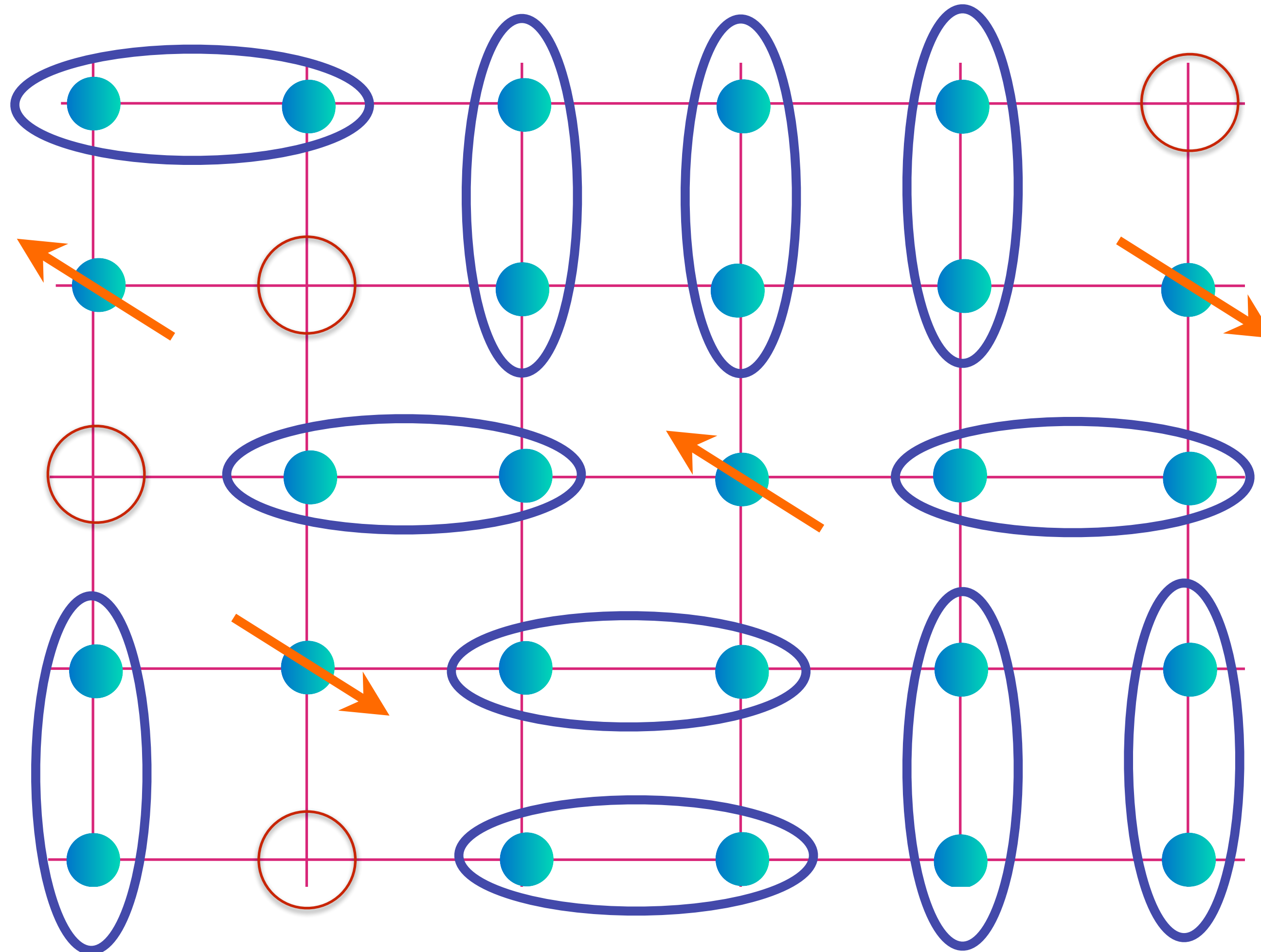
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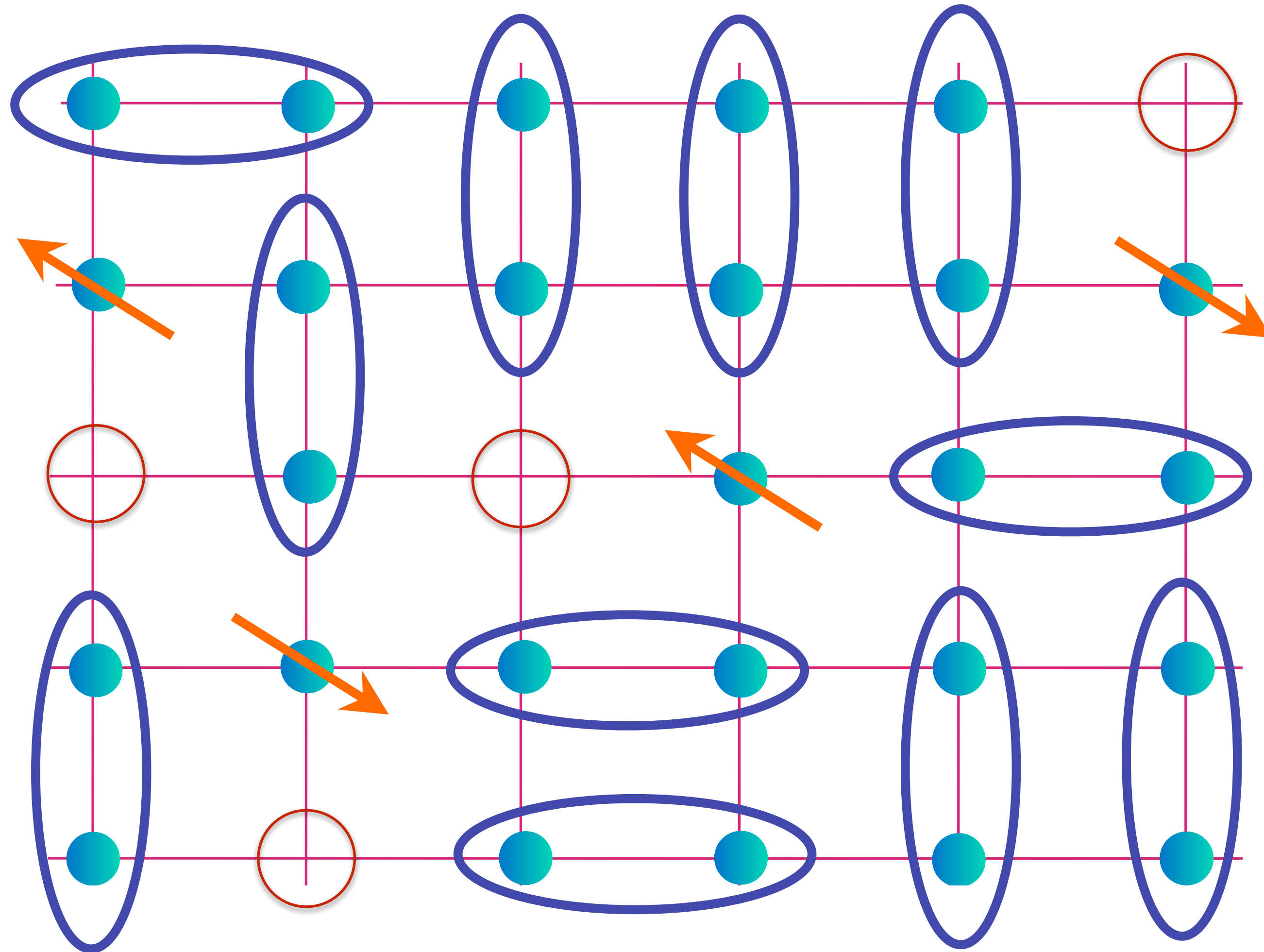
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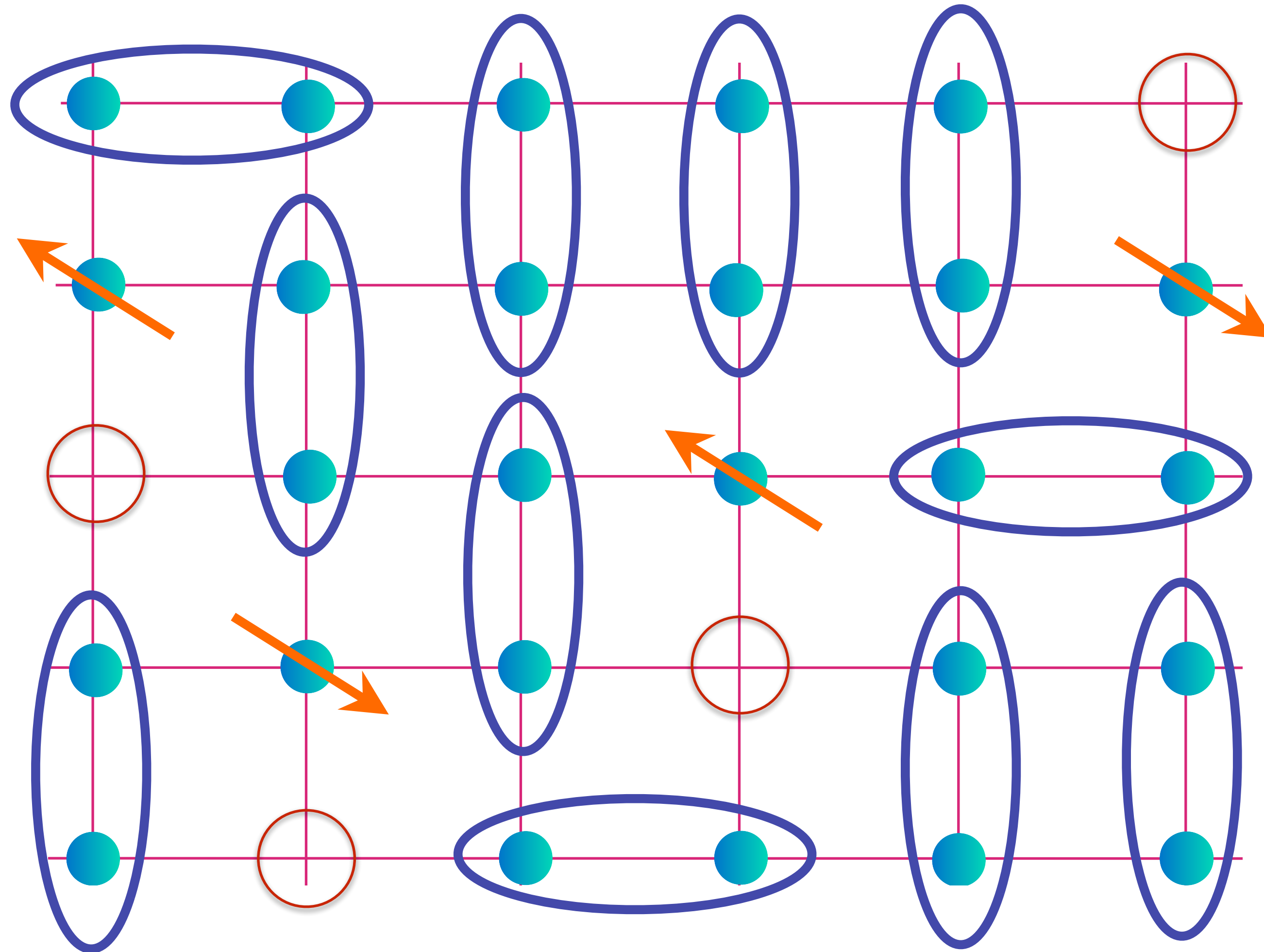
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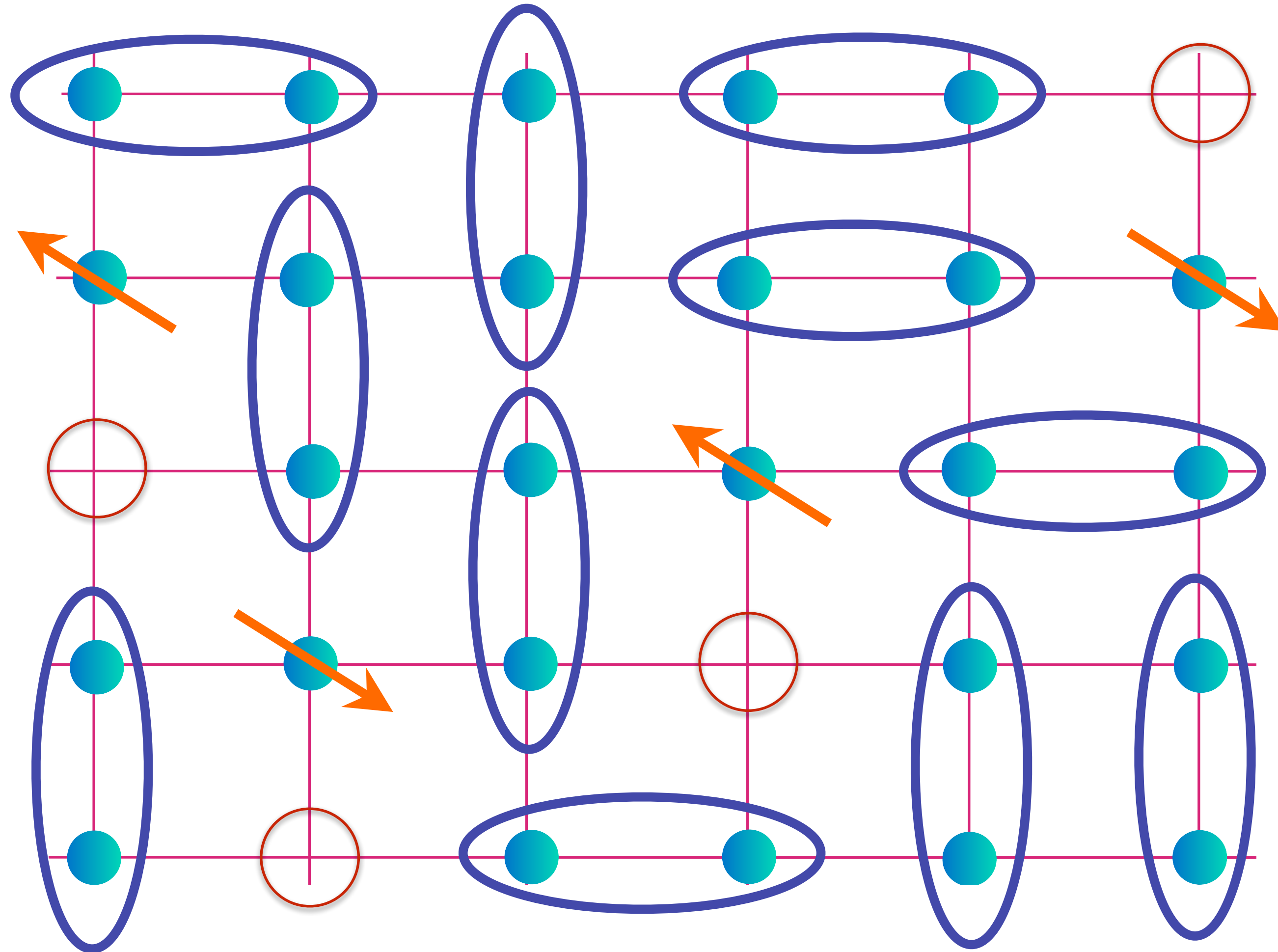


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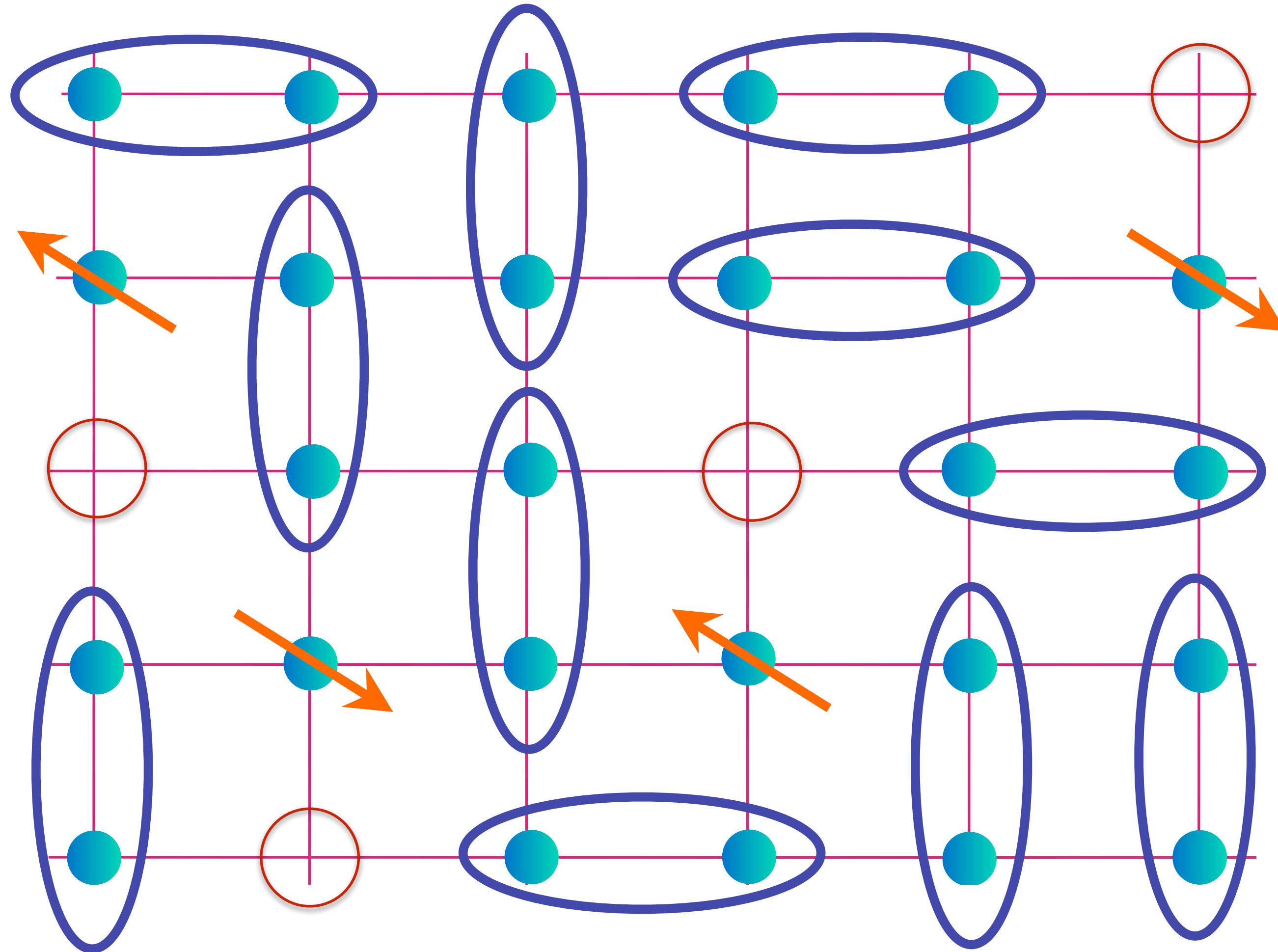
Energy cost to
create spinon $\sim J$

Energy gained by
bound state $\sim t$.

But the holons and
spinons can gain
energy by resonating
with each other

$$\text{blue oval with two cyan dots} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

To obtain a (super)conductor we have to
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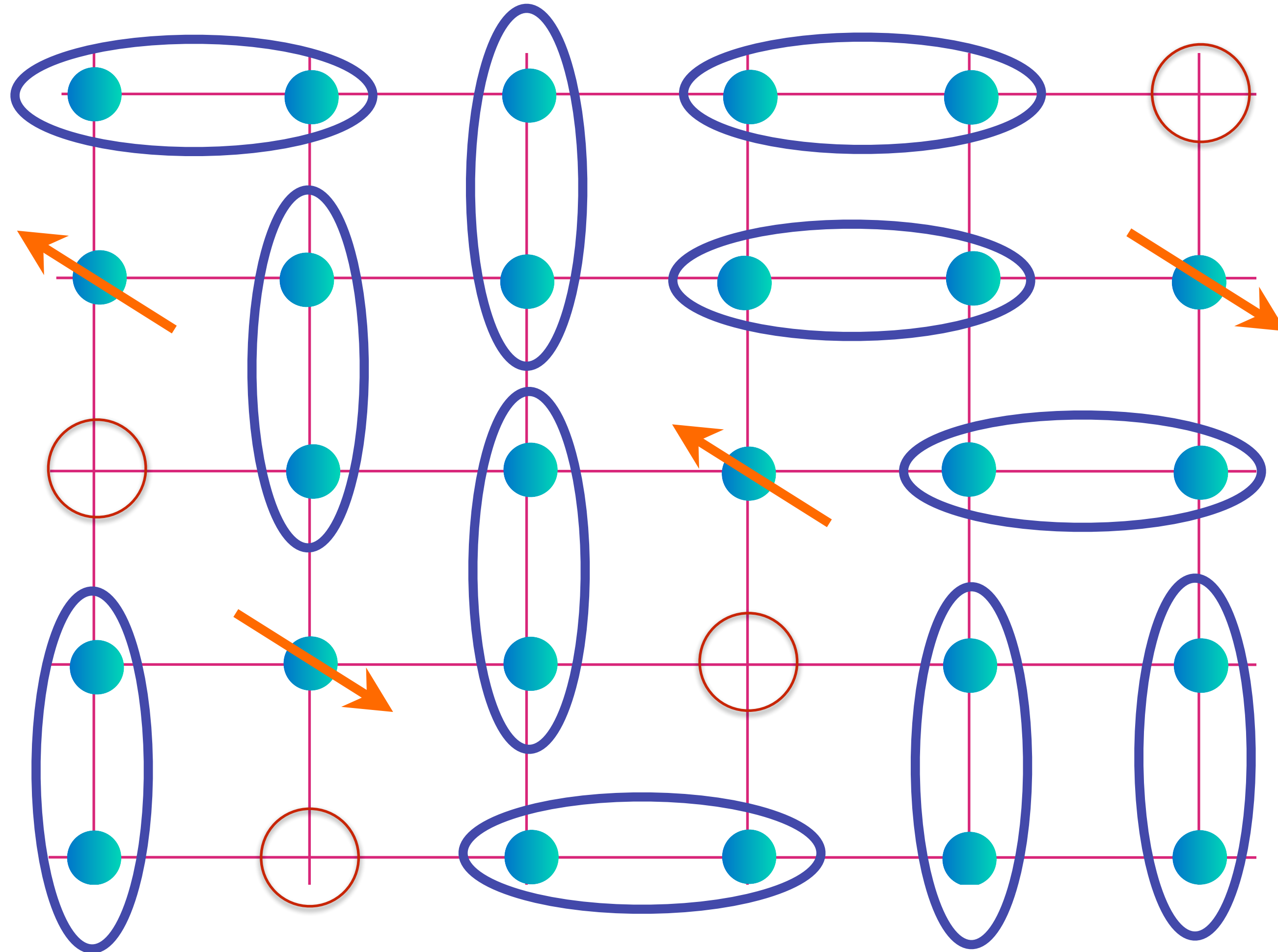
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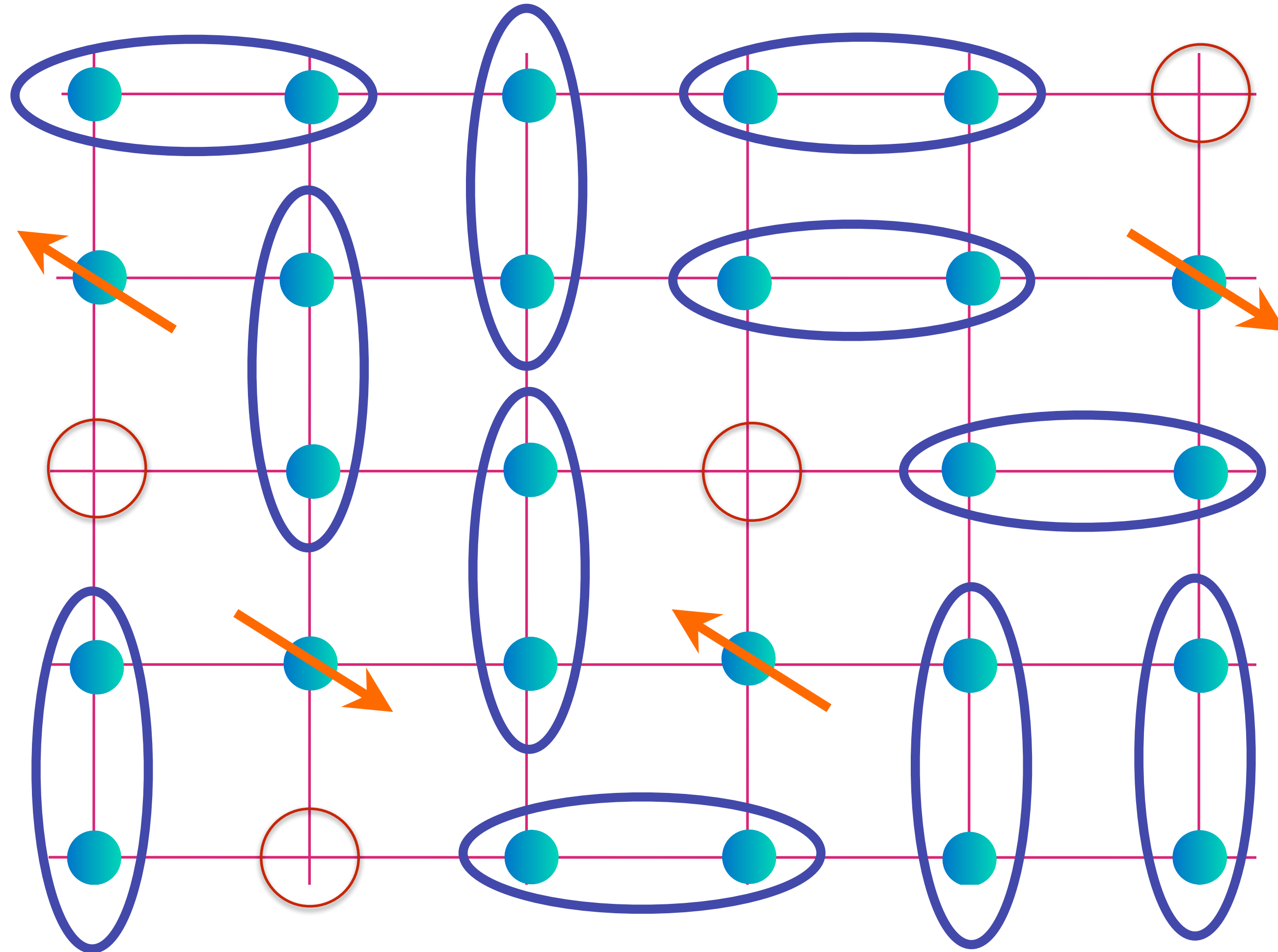
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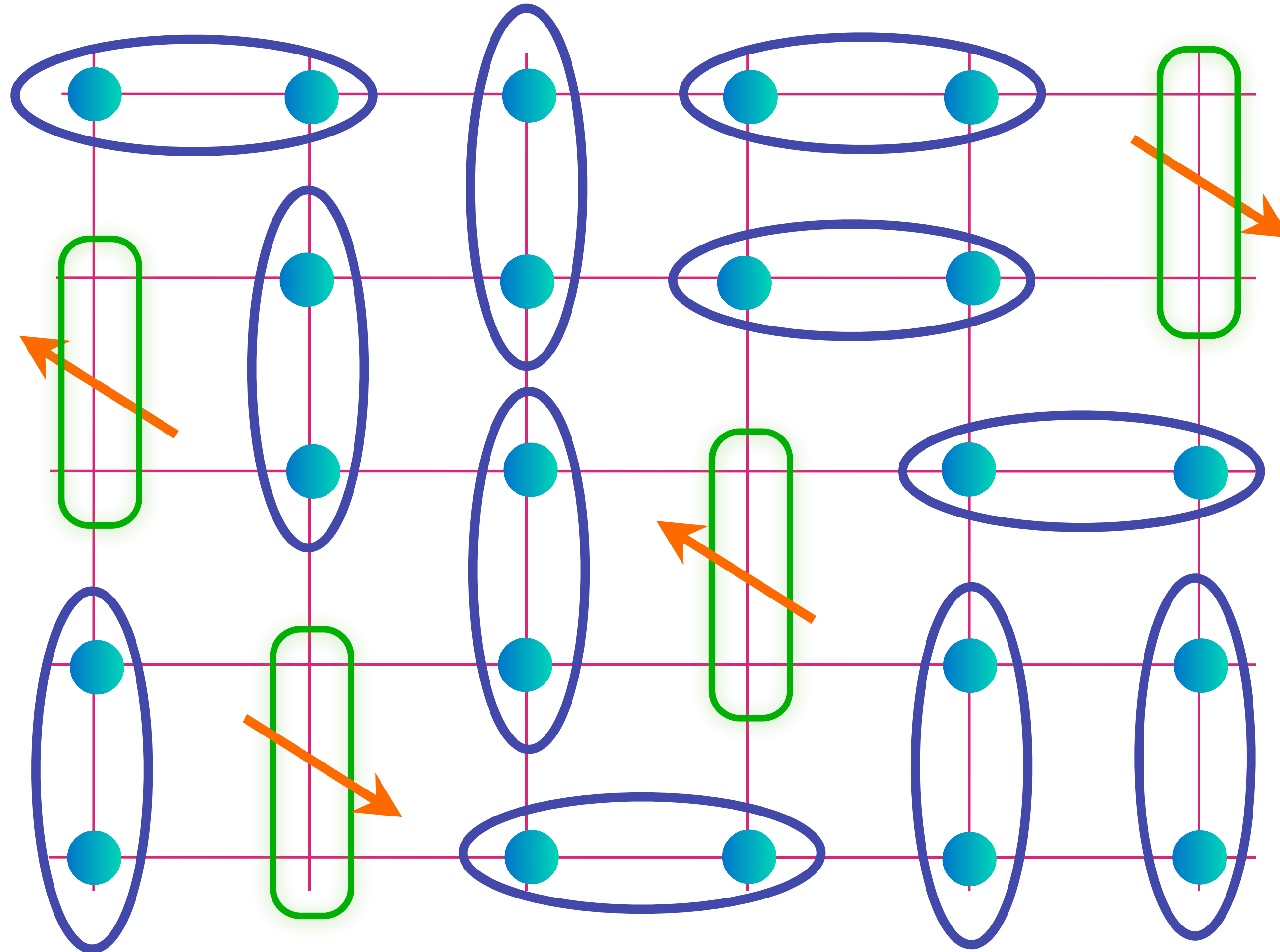
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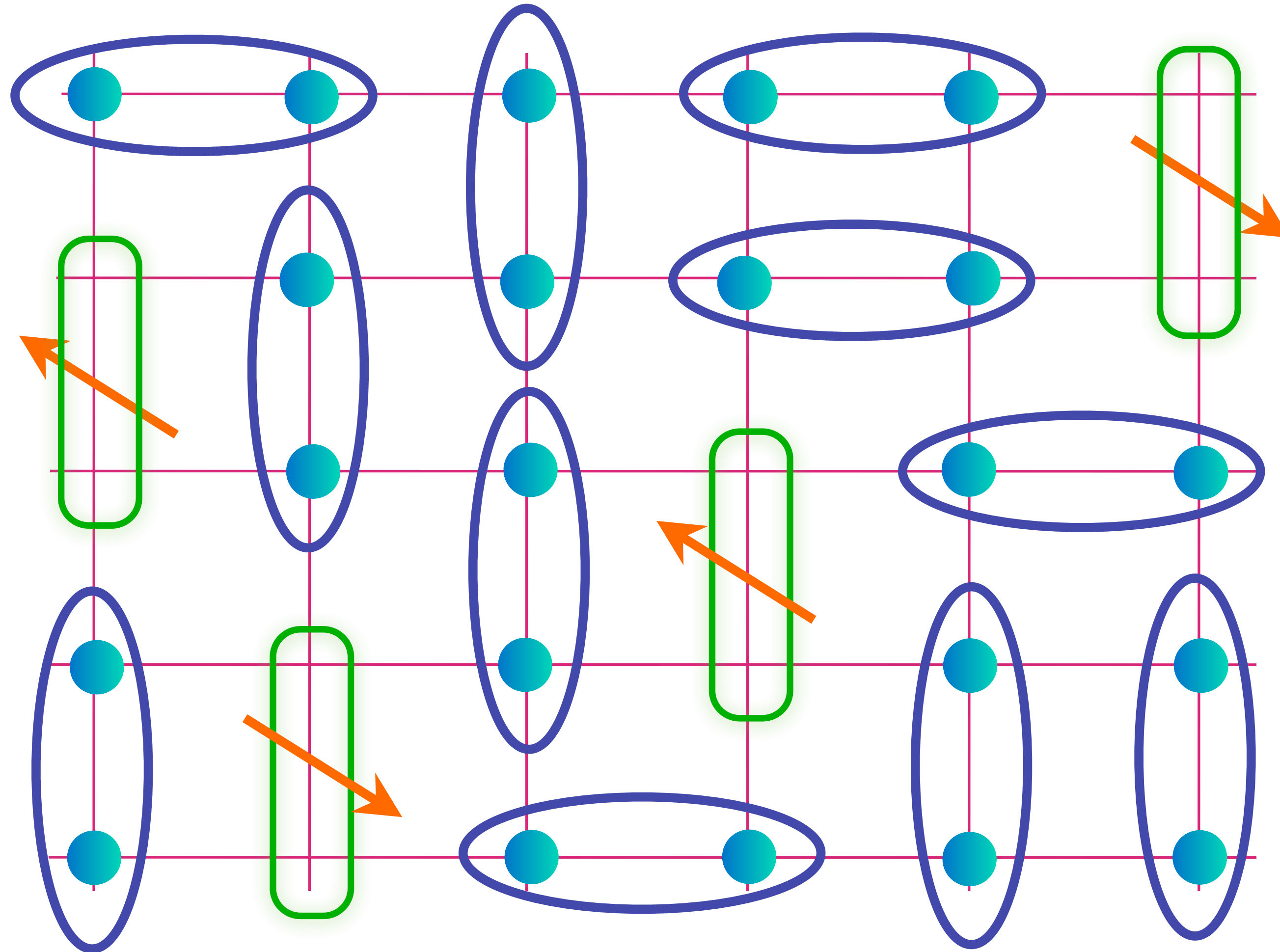
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Energy cost to
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Energy gained by
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FL*:

Fermi gas of
holon-spinon
bound states
(magnetic
polarons)

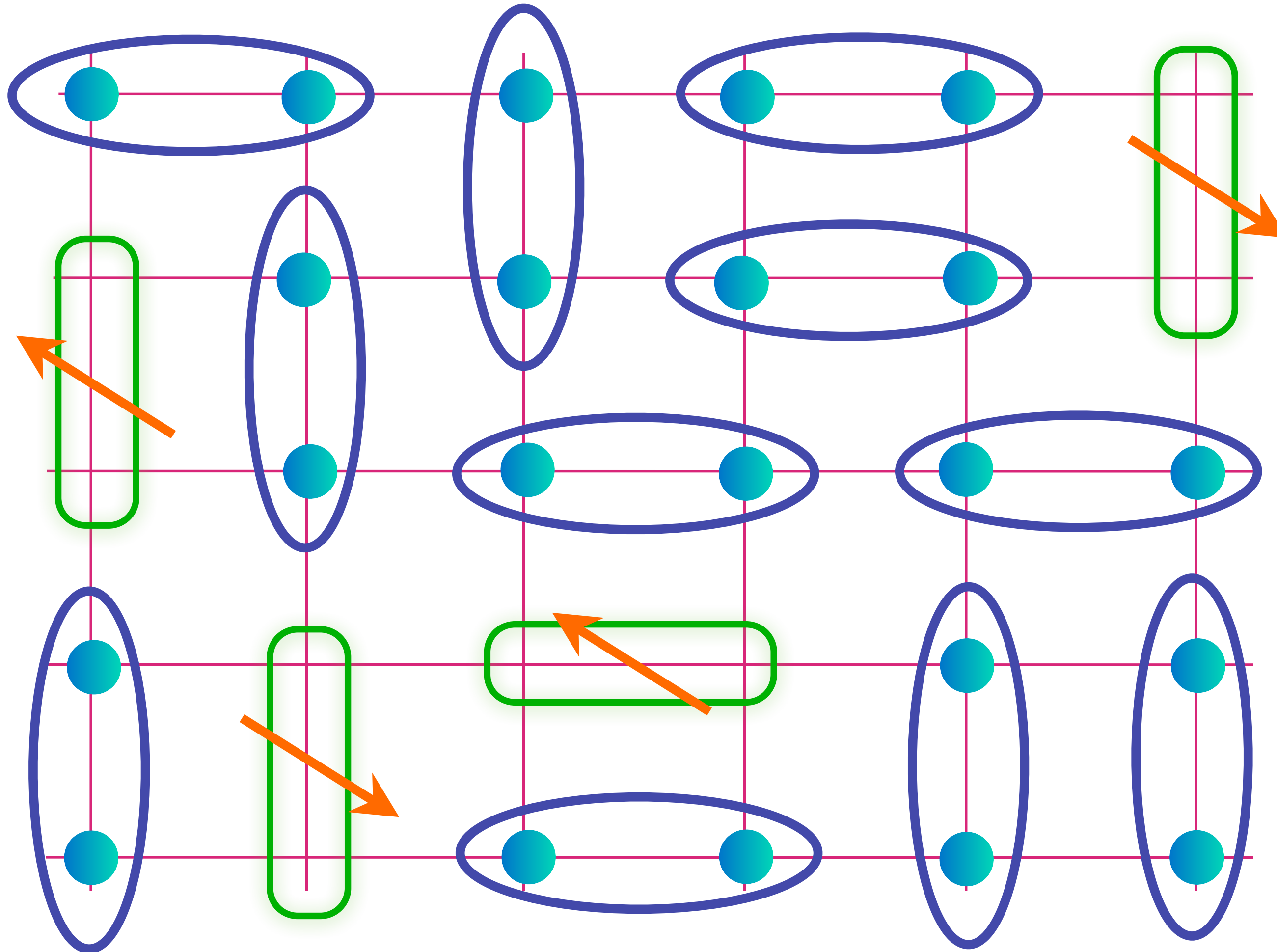
$$\text{blue ellipse with 2 dots} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

$$\text{green rectangle with arrow} = (|\uparrow\circ\rangle + |\circ\uparrow\rangle) / \sqrt{2}$$

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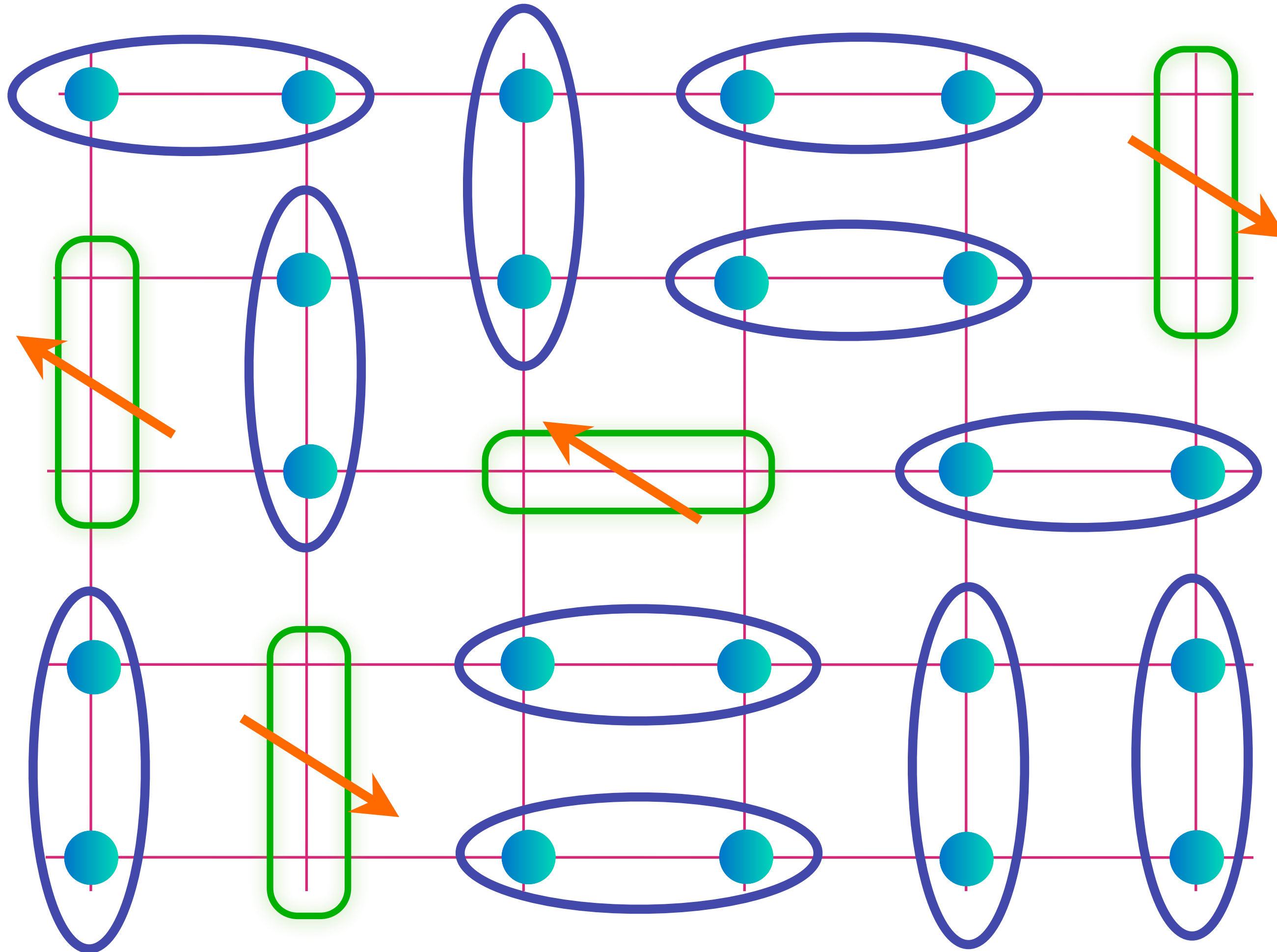
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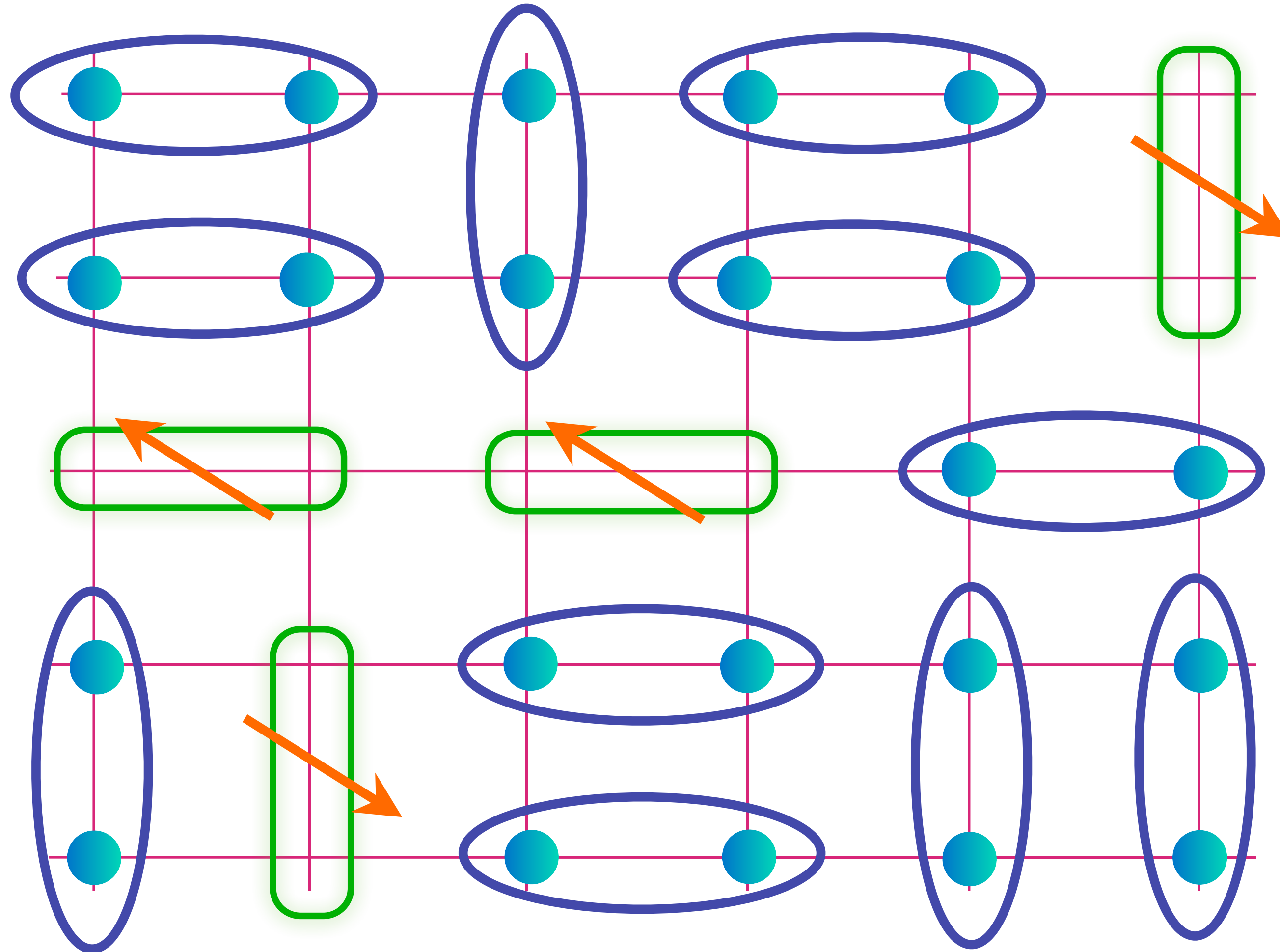
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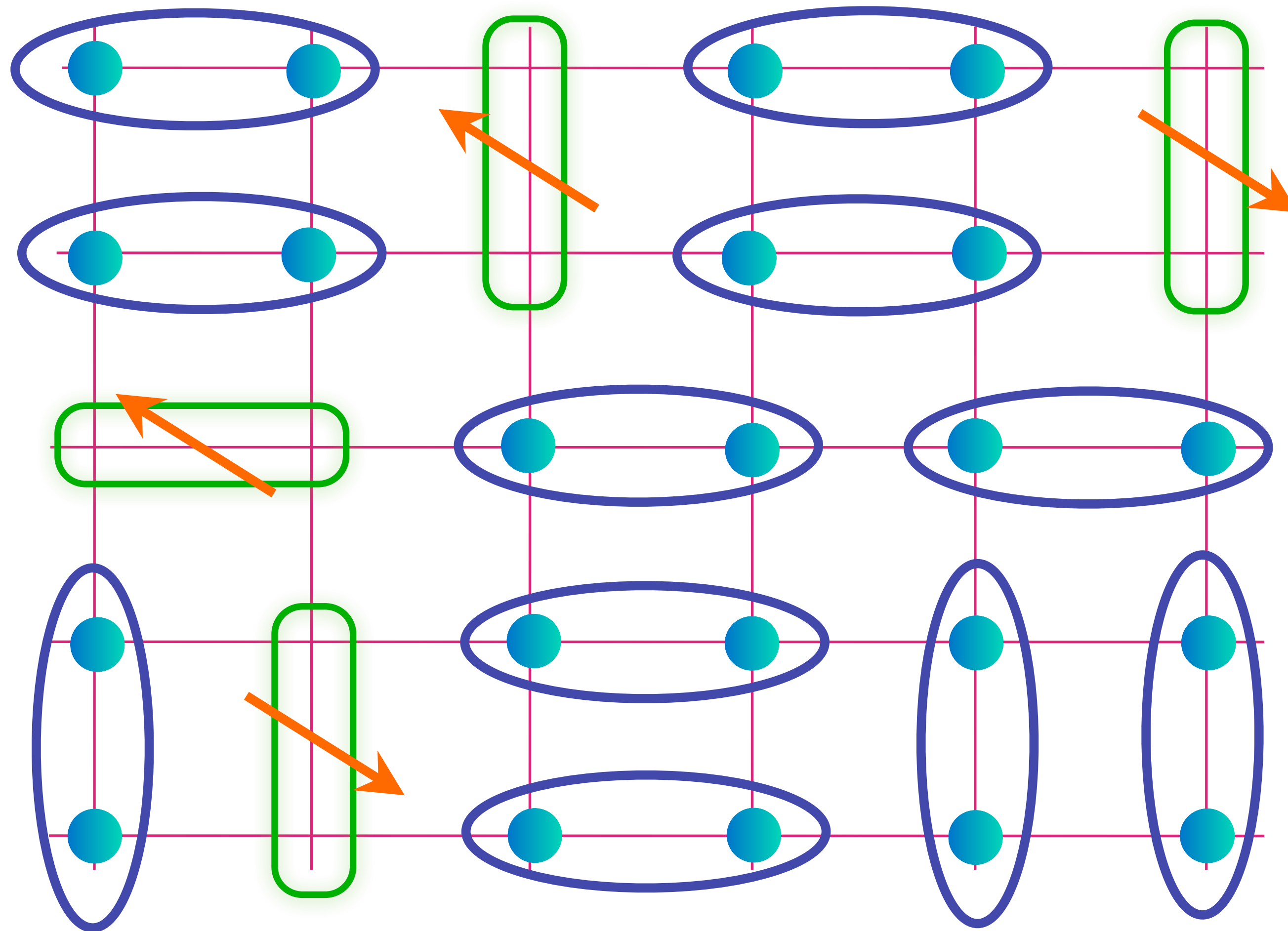
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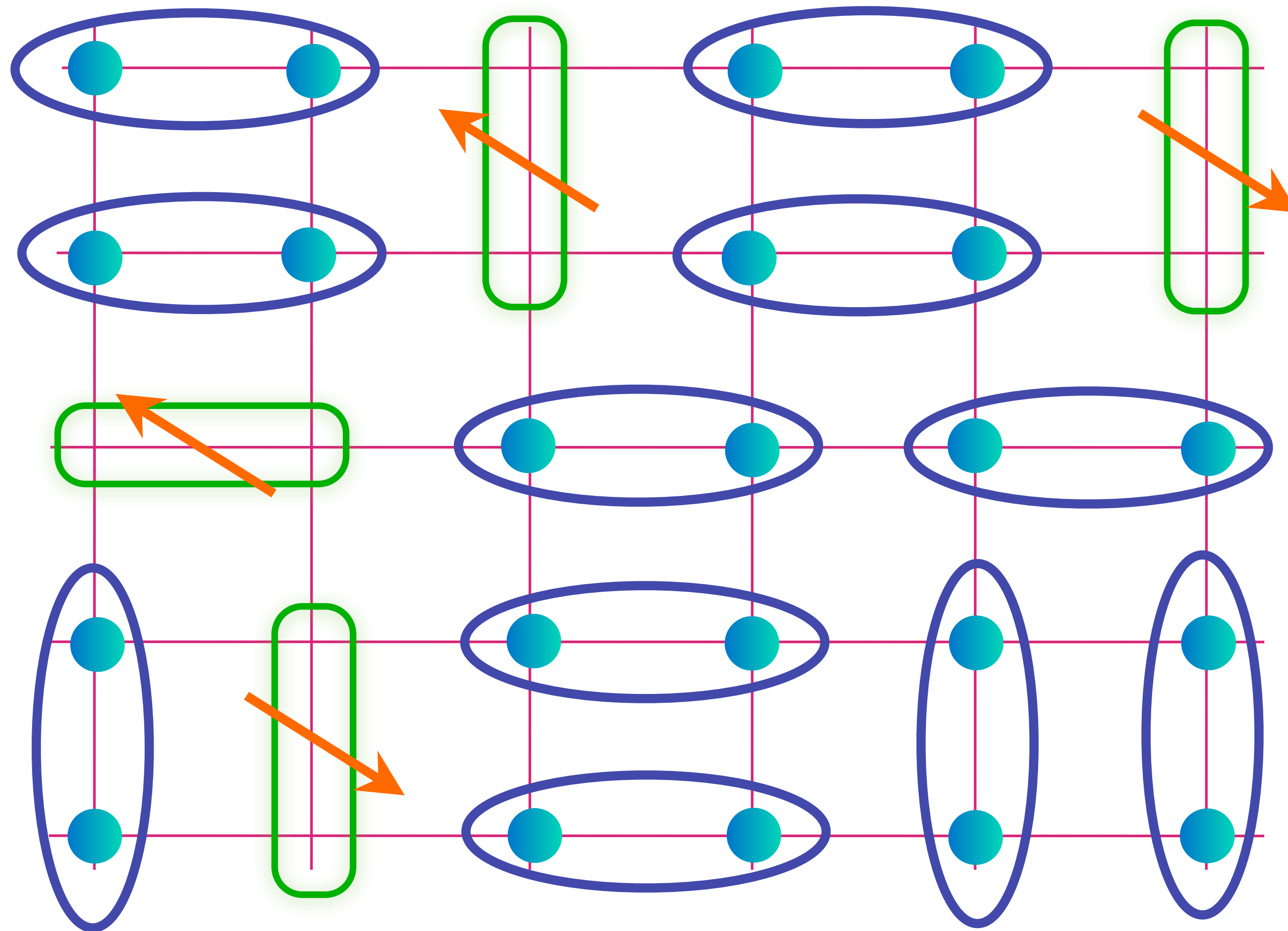
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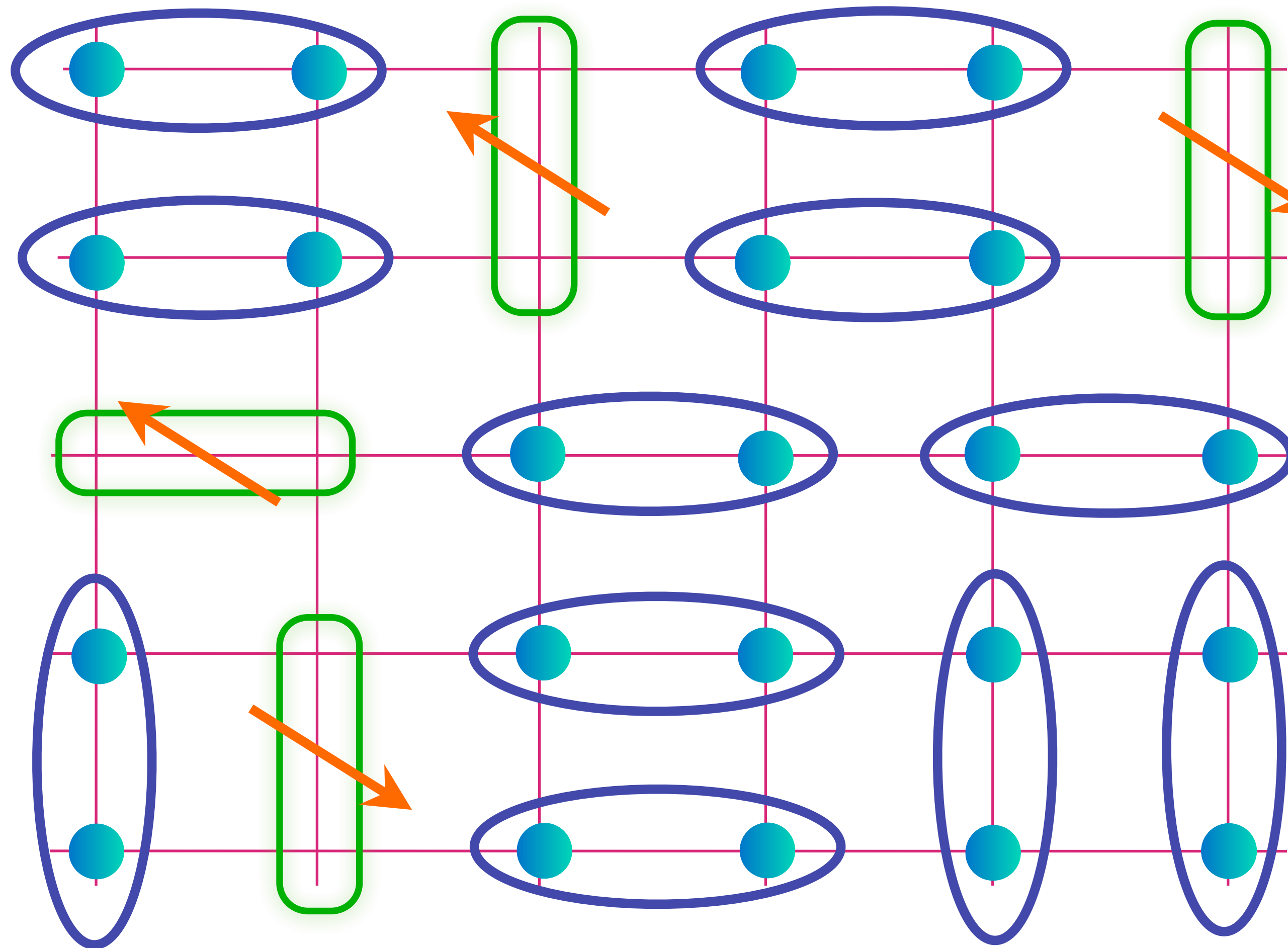


Fermi
surface?

$$\text{Blue oval with 2 dots} = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) / \sqrt{2}$$

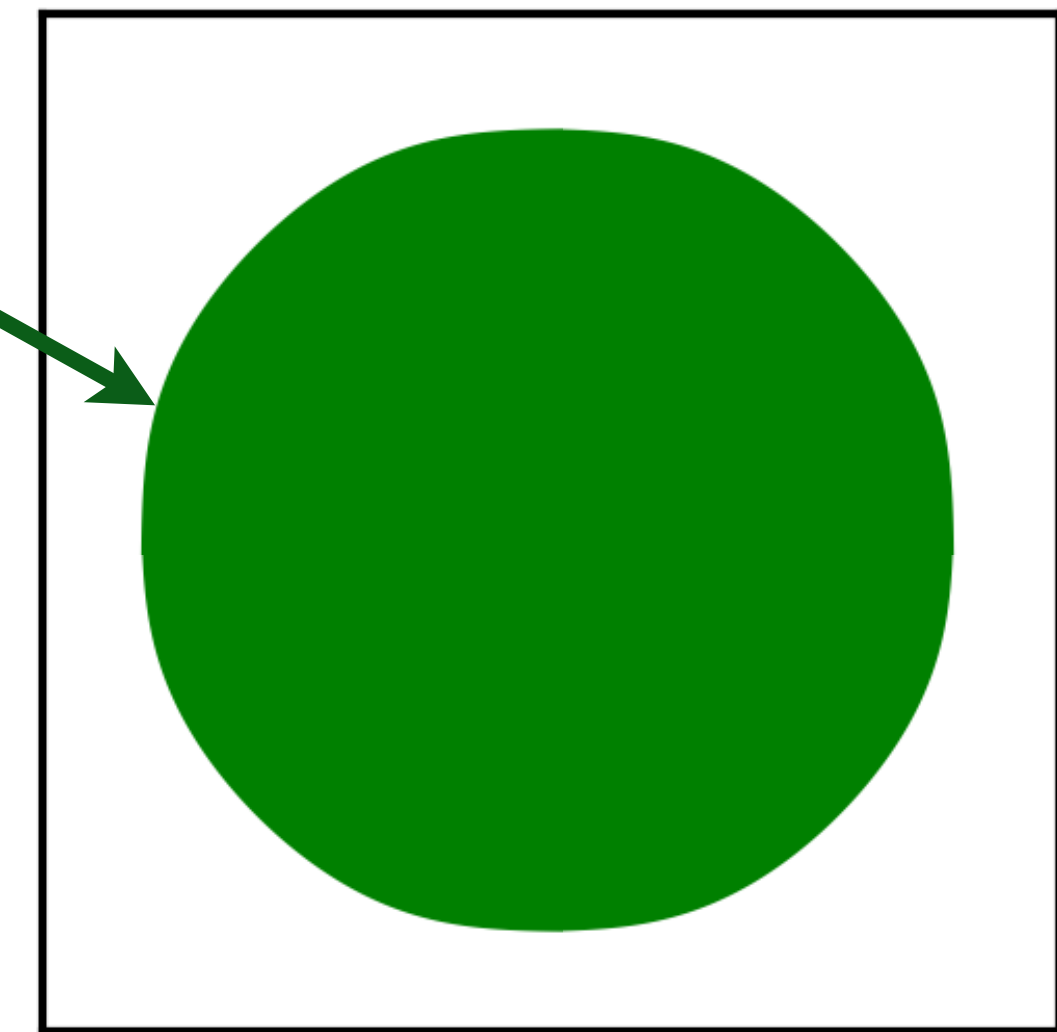
$$\text{Green rectangle with orange arrow} = (|\uparrow\circ\rangle + |\circ\uparrow\rangle) / \sqrt{2}$$

To obtain a (super)conductor we have to remove a density p of electrons



Luttinger
area
 $(1 + p)/2$

Count
all
electrons
 $= 1 - p$.
Holes
in a filled band $= 1 + p$.



FL

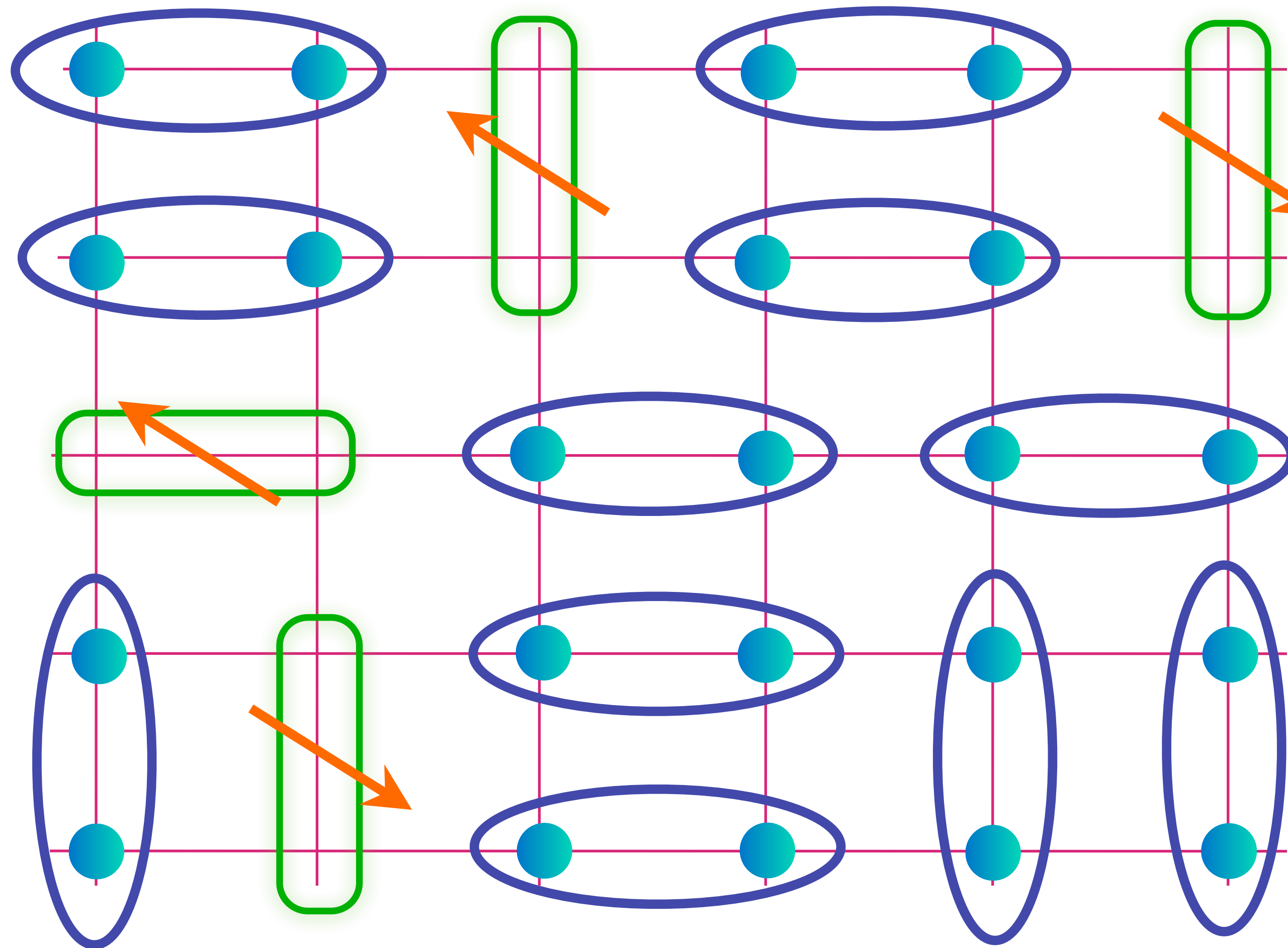
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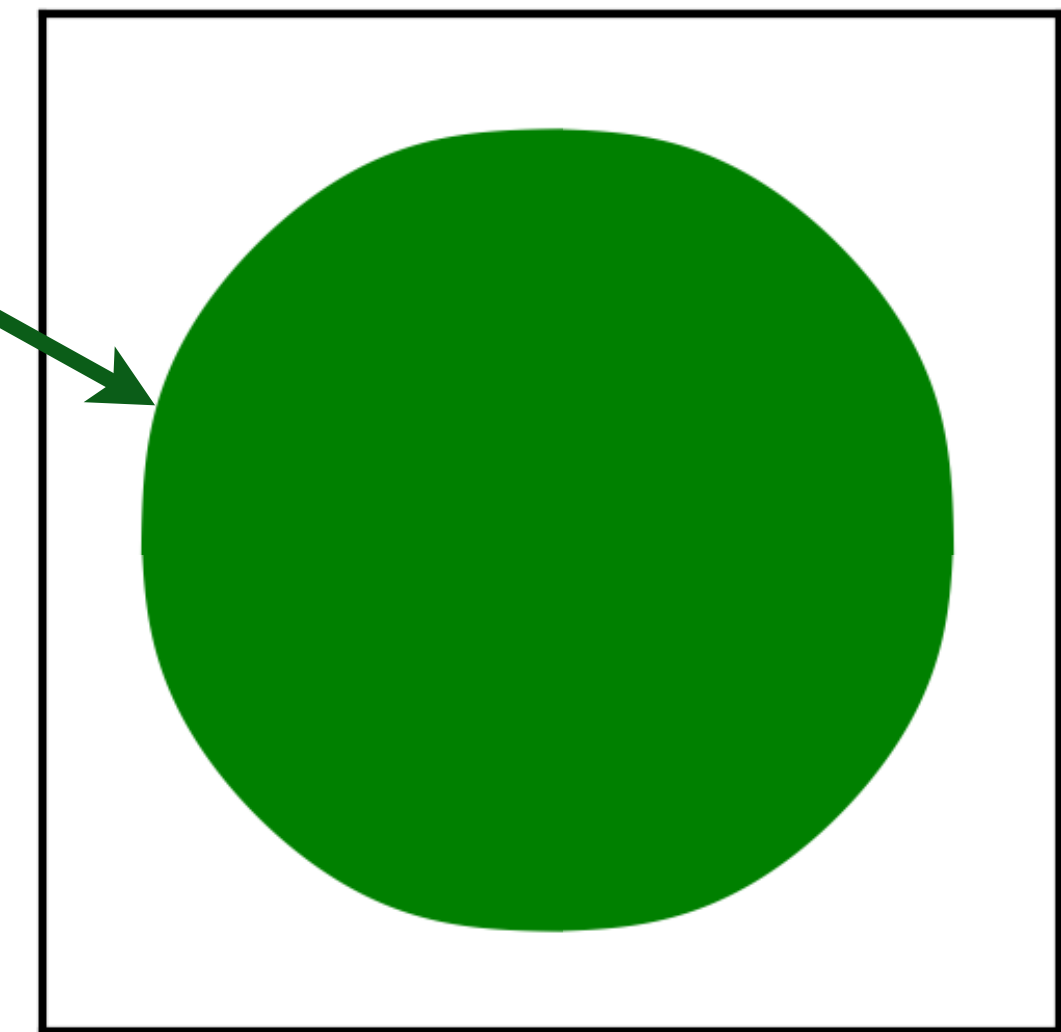
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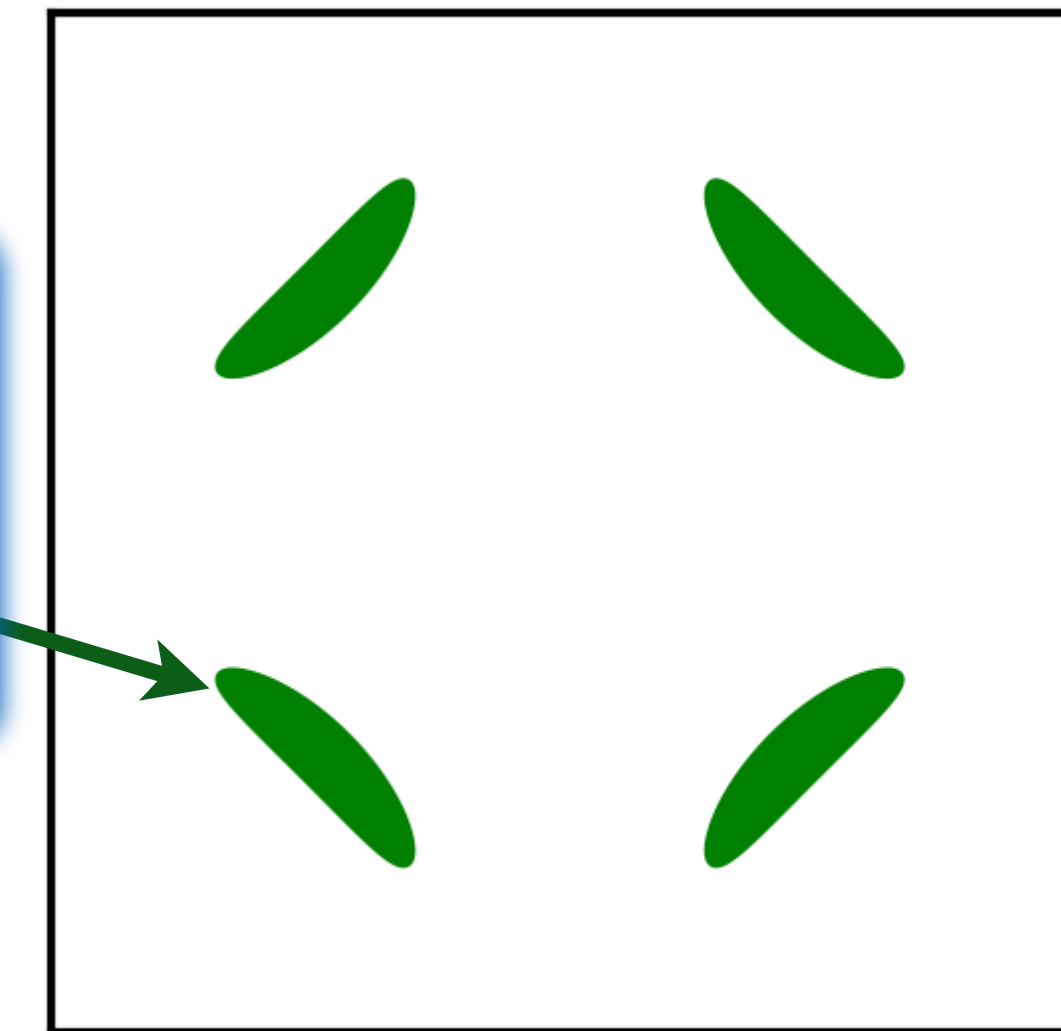
Luttinger
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FL

Non-
Luttinger
area $p/8$



FL*

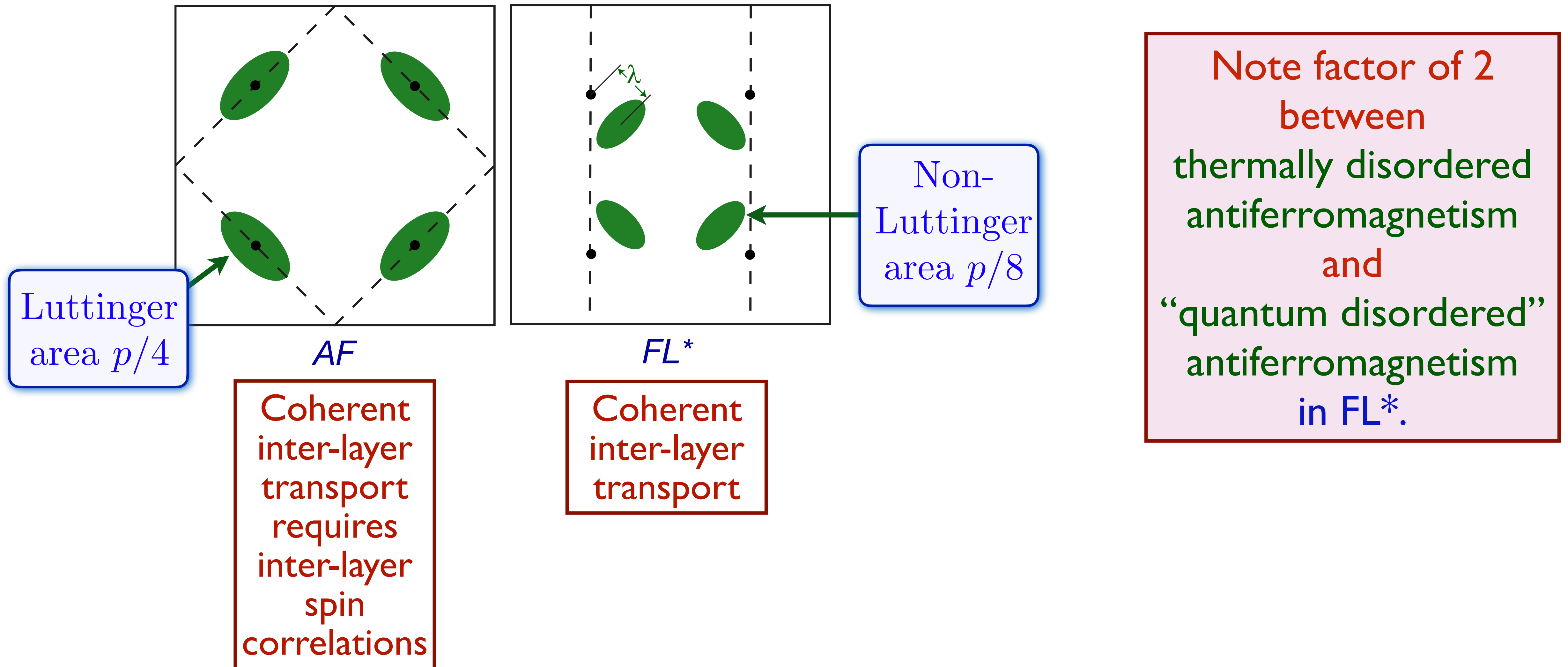
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$$\text{green rectangle with arrow} = (|\uparrow\circ\rangle + |\circ\uparrow\rangle) / \sqrt{2}$$

Count only green dimers

Hole dynamics in an antiferromagnet across a deconfined quantum critical point

Ribhu K. Kaul,¹ Alexei Kolezhuk,^{1,2} Michael Levin,¹ Subir Sachdev,¹ and T. Senthil^{3,4}



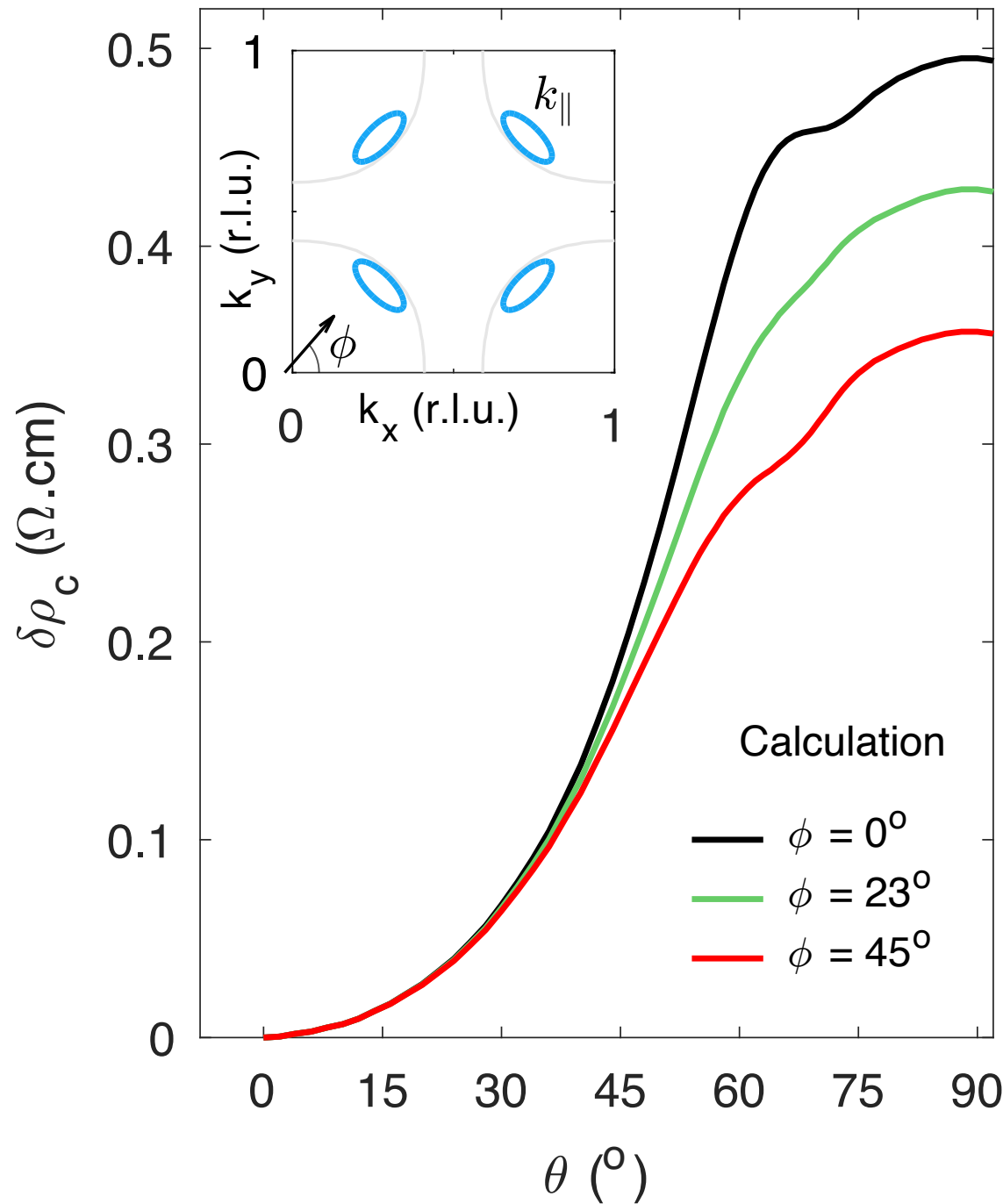
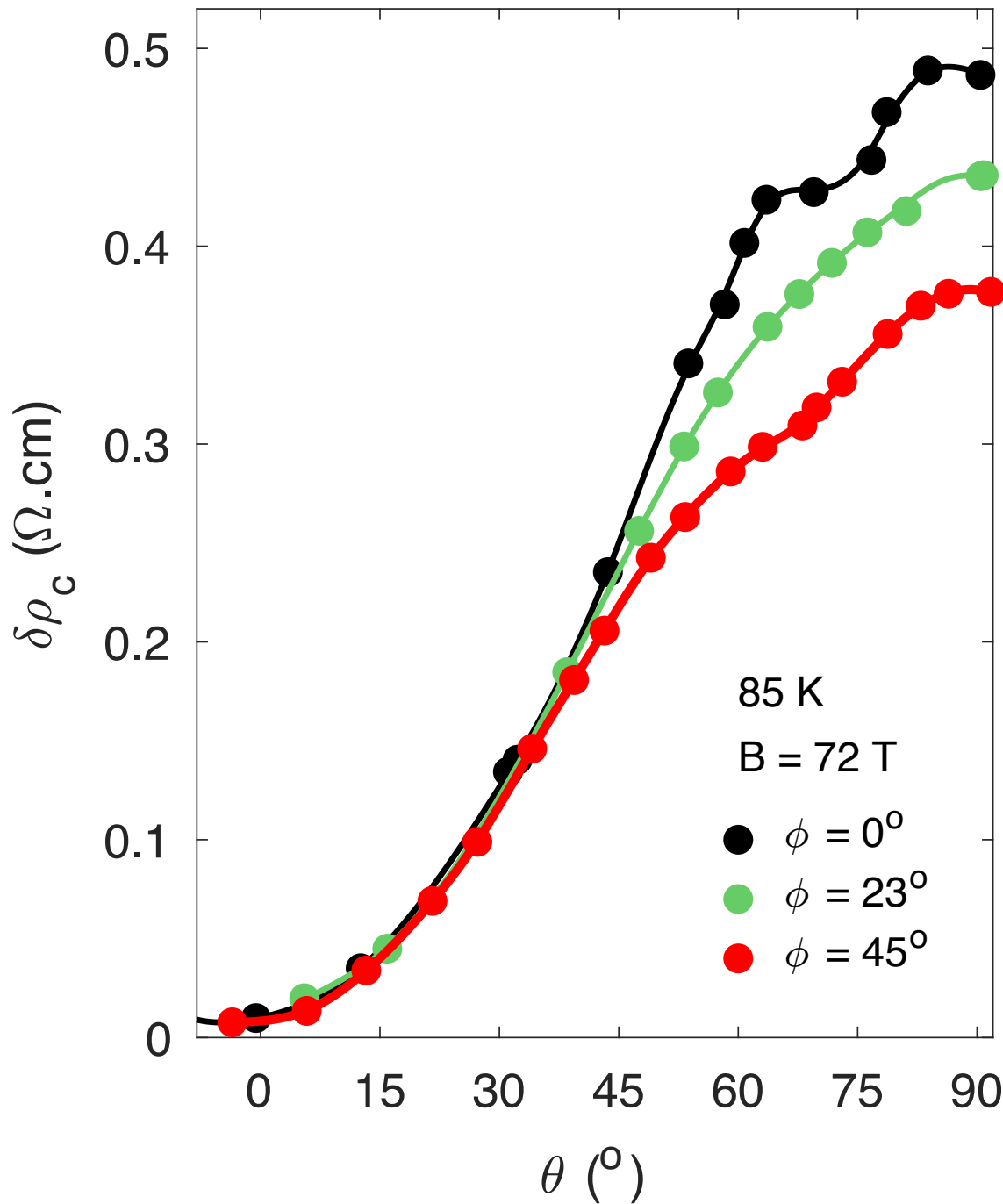
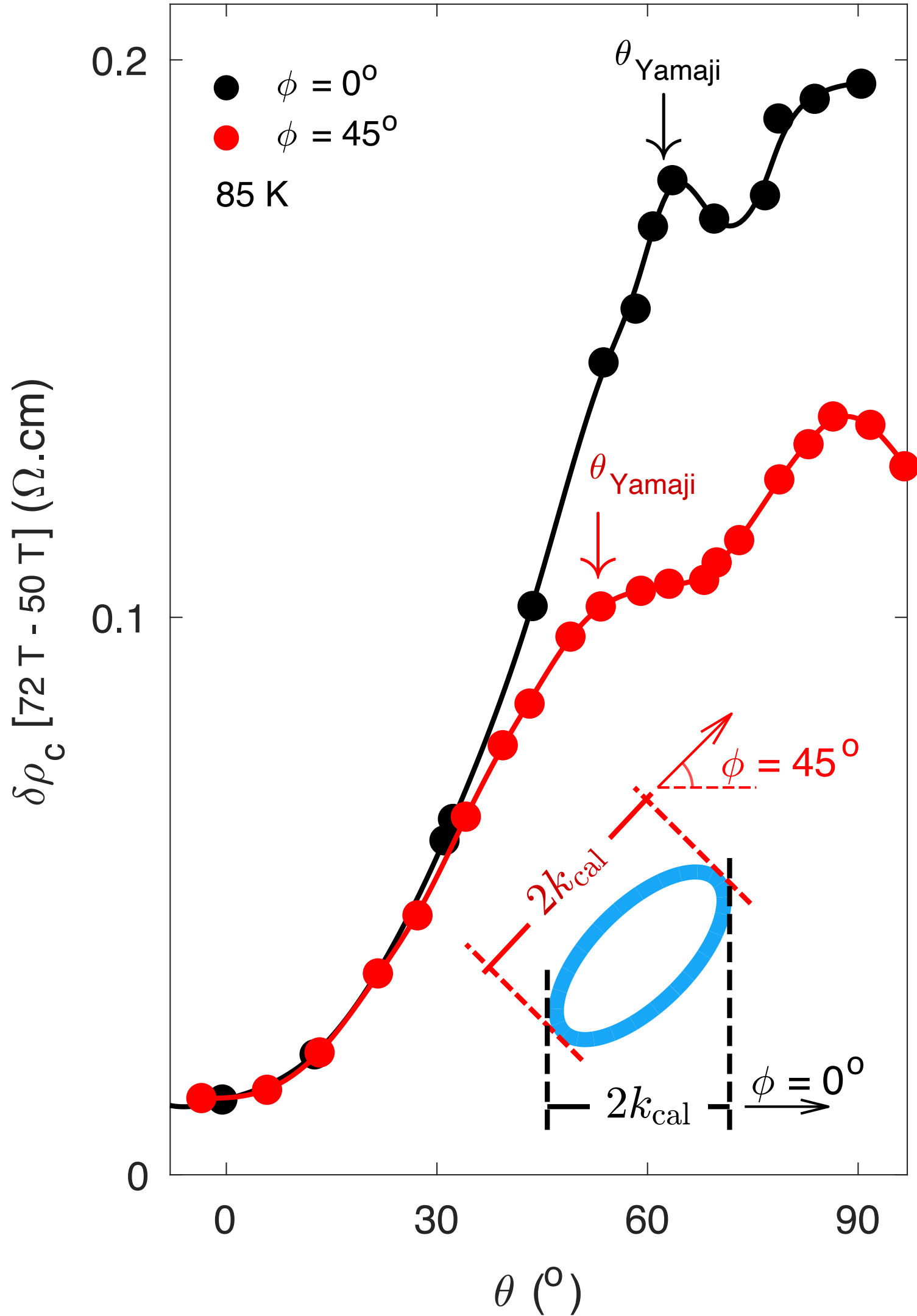
Observation of the Yamaji effect in a cuprate superconductor

nature physics

21, 1753 (2025)

Mun K. Chan¹, Katherine A. Schreiber¹, Oscar E. Ayala-Valenzuela¹,
Eric D. Bauer², Arkady Shekhter¹ & Neil Harrison¹

Published online: 16 September 2025



Doping
 $p = 0.1$

The observation of the Yamaji peak is evidence for small Fermi-surface pockets in the normal state of the pseudogap phase. The small size of the pockets, each estimated to occupy only 1.3% of the Brillouin zone area, is not expected given the absence of long-range broken translational symmetry.

Predicted FL* pocket fraction = $p/8 = 1.25\%$!

Fluctuating AF metal fraction = $p/4 = 2.5\%$.

($p/8$ also in Yang-Rice-Zhang ansatz, Peter Johnson photoemission, and Jenny Hoffman and Seamus Davis STMs; Stanescu-Kotliar)

Jing-Yu Zhao, S. Chatterjee, S. S., Ya-Hui Zhang, arXiv:2510.13943

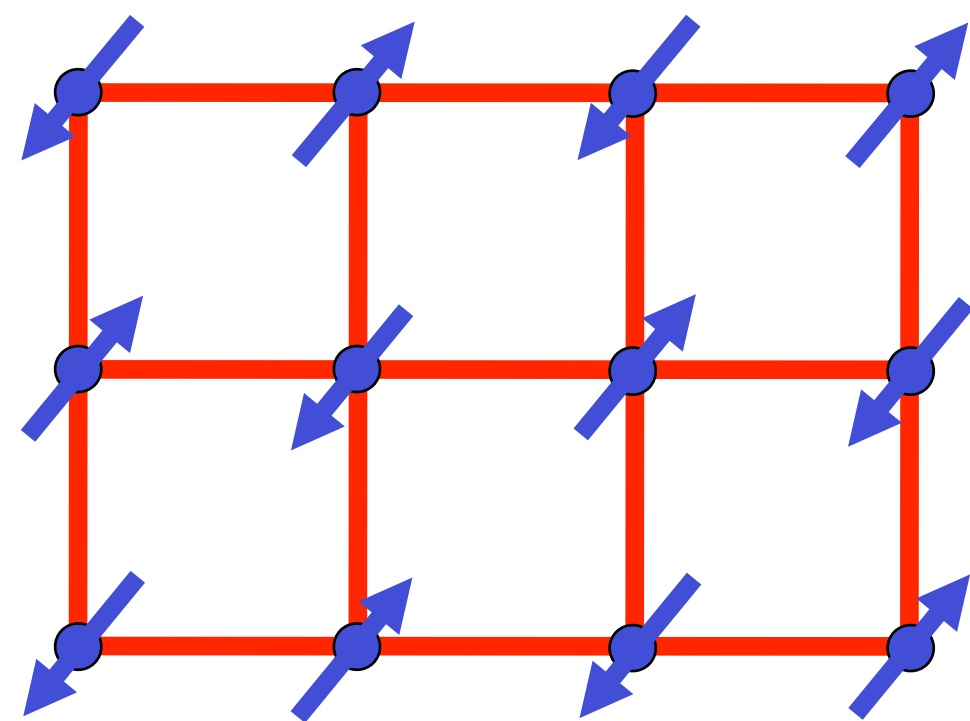
Critical quantum
spin liquid
on the
square lattice

$S=1/2$ square lattice

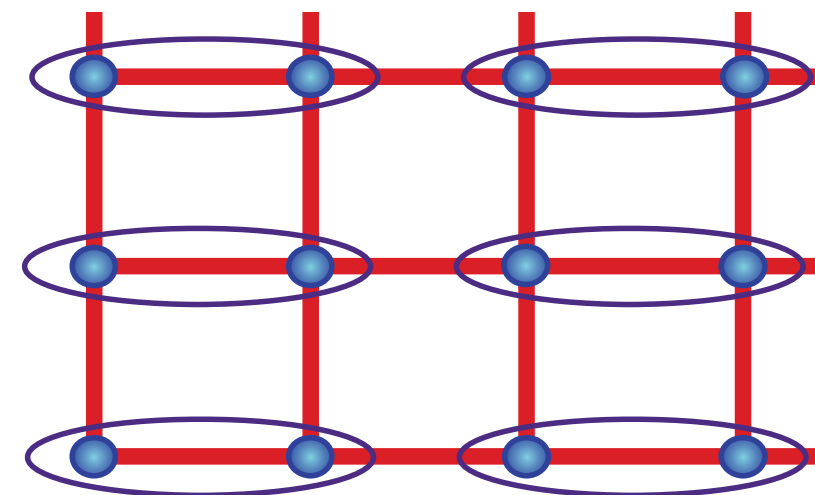
Represent spins in terms of
 $S = 1/2$ bosonic spinons $\mathbf{S} \sim b_{\alpha}^{\dagger} \boldsymbol{\sigma}_{\alpha\beta} b_{\beta}$

U(1) gauge symmetry: $b \rightarrow b e^{i\theta}$

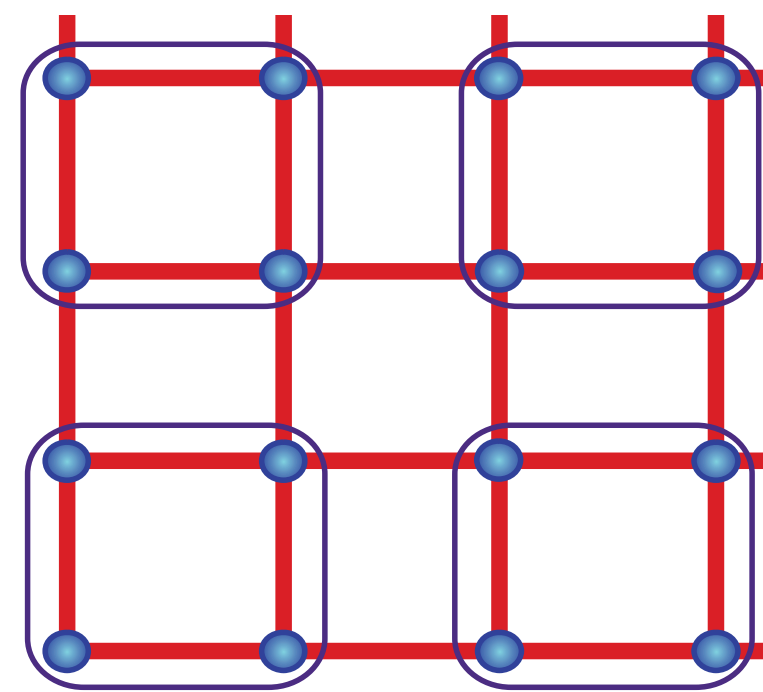
\mathbb{CP}^1 U(1) gauge theory.



$\langle b_{\alpha} \rangle \neq 0$:
Néel order



or



$\langle b_{\alpha} \rangle = 0$:
Valence bond solid (VBS)

J_2/J_1

N. Read and S. Sachdev, Phys. Rev. Lett. **62**, 1694 (1989)

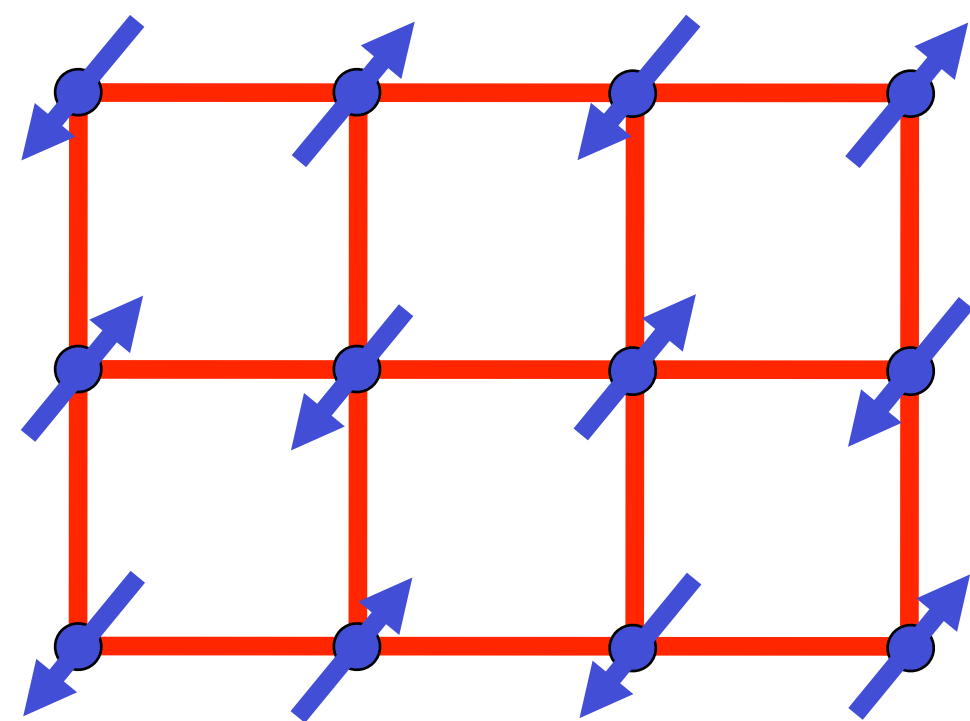
N. Read and S. Sachdev, Phys. Rev. B **42**, 4568 (1990)

$S=1/2$ square lattice

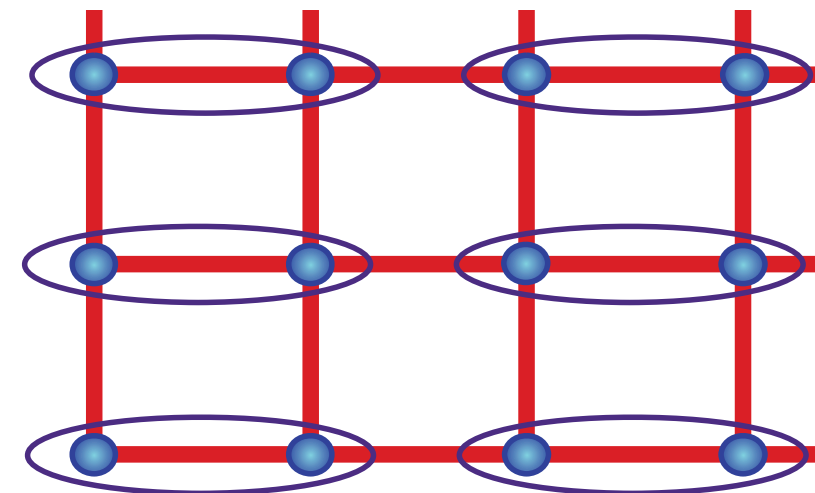
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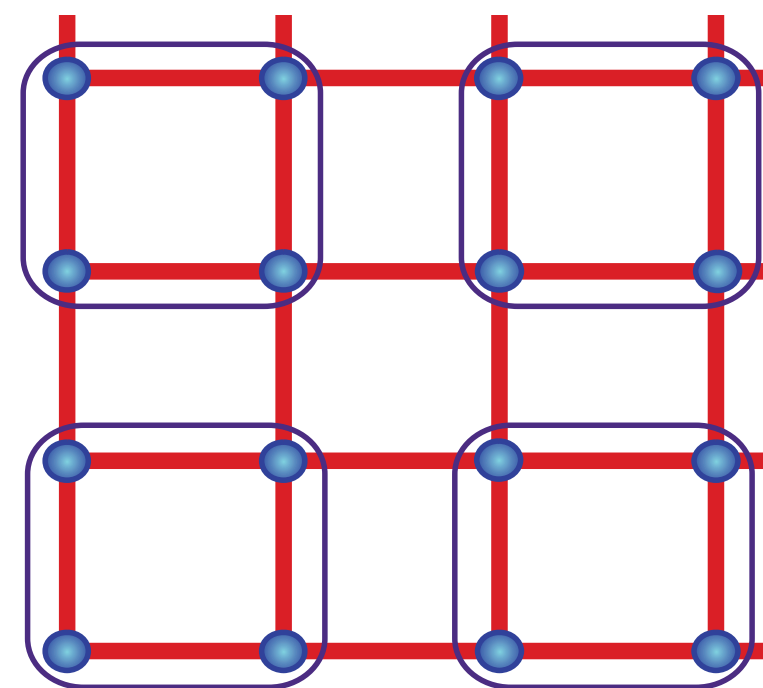
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Néel order



or



$\langle b_{\alpha} \rangle = 0$:
Valence bond solid (VBS)

J_2/J_1

Consistent with many
numerical studies

But no apparent
connection to d -SC?

Critical spin liquid
without quasiparticles?

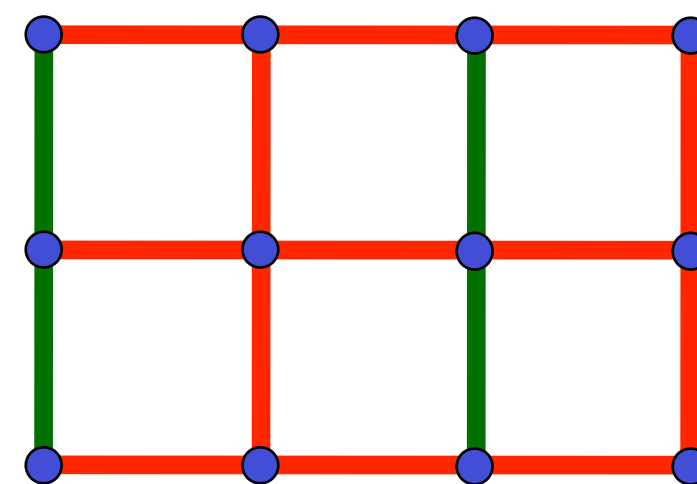
$S=1/2$ square lattice

Represent spins in terms of
 $S = 1/2$ fermionic spinons $\mathbf{S} \sim f_{\alpha}^{\dagger} \boldsymbol{\sigma}_{\alpha\beta} f_{\beta}$

I. Affleck and J.B. Marston, PRB **37**, 3774 (1988)



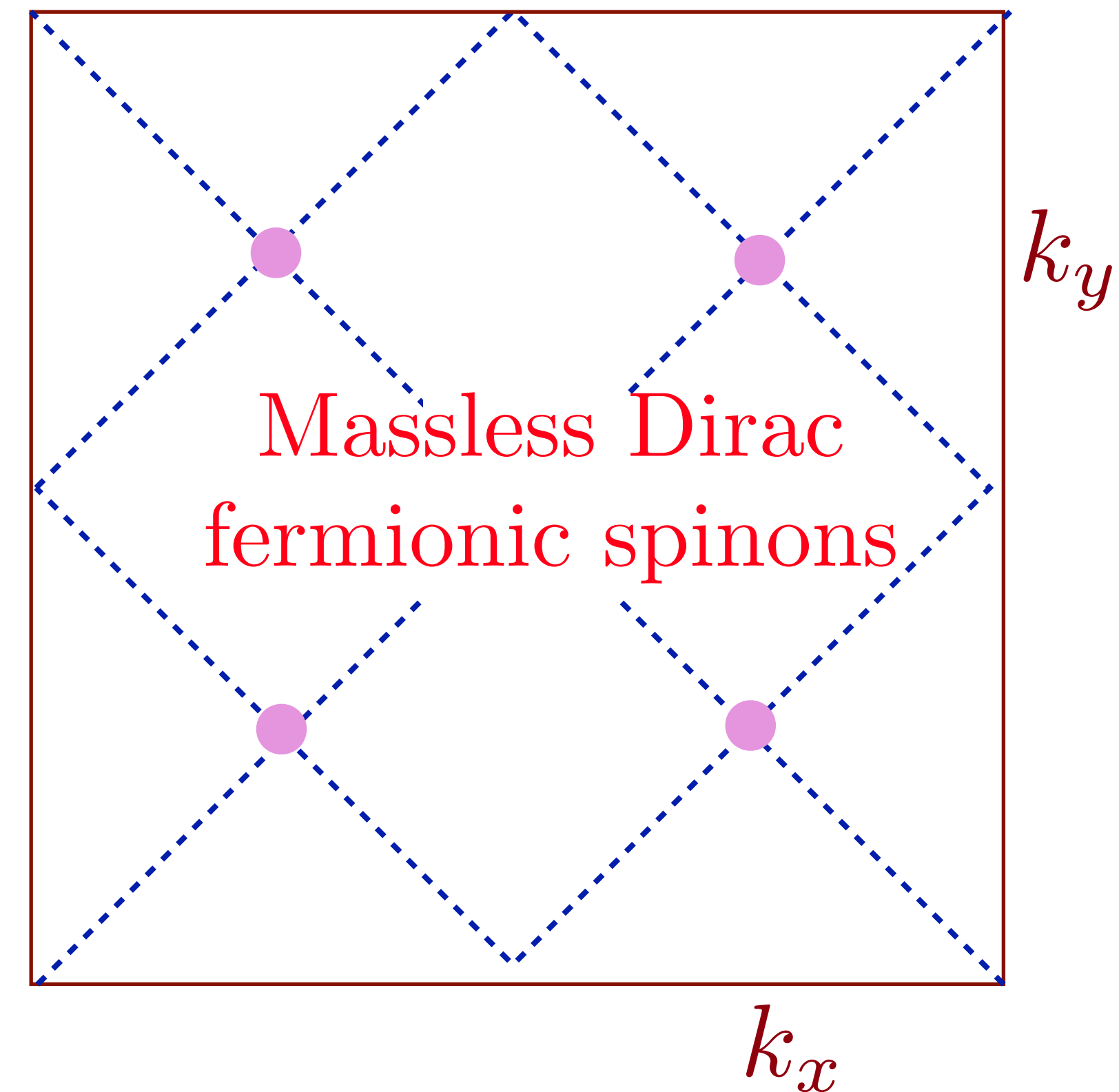
$$H_{\text{spin liquid}} = iJ \sum_{\langle ij \rangle} e_{ij} \left(\Psi_i^{\dagger} U_{ij} \Psi_j - \Psi_j^{\dagger} U_{ji} \Psi_i \right); \quad \Psi_i = \begin{pmatrix} f_{i\uparrow} \\ f_{i\downarrow}^{\dagger} \end{pmatrix}$$



$$e_{ij} = 1$$

$$e_{ij} = -1$$

$$\mathcal{L} = i\bar{\psi}\gamma_{\mu}D_{\mu}\psi.$$



$N_f = 2$ SU(2) QCD

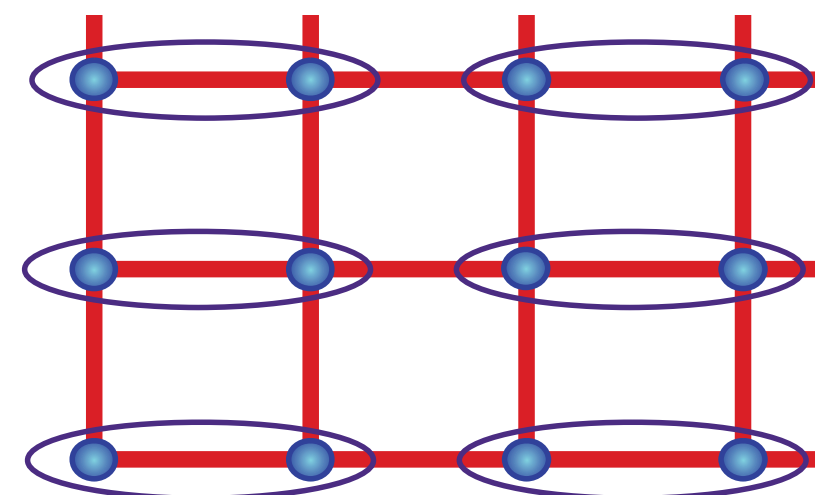
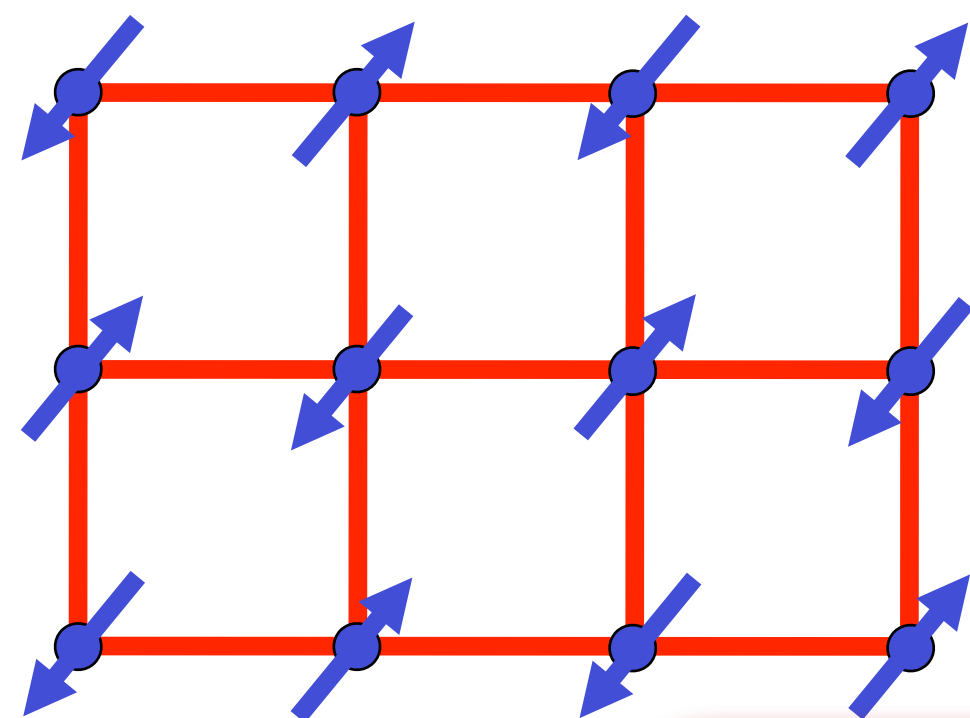
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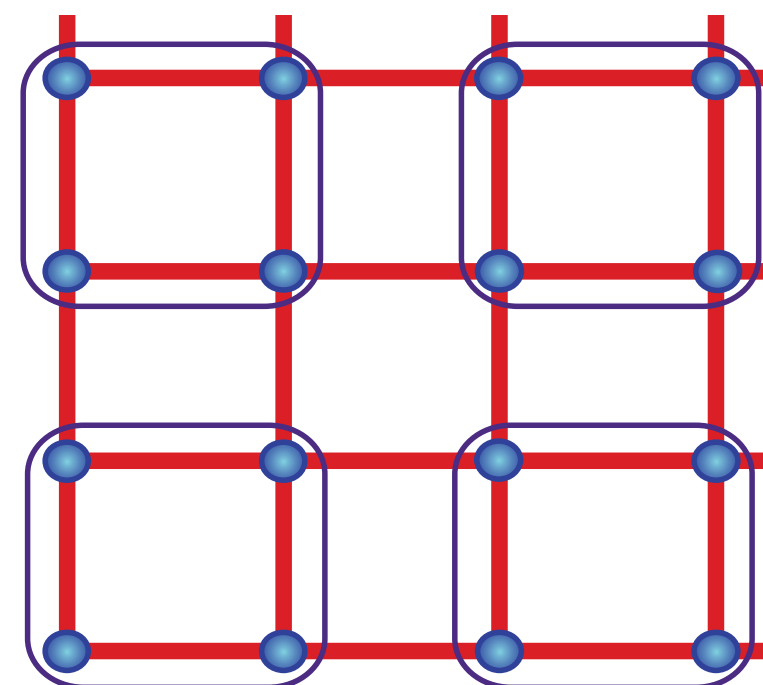
I. Affleck and J.B. Marston, PRB **37**, 3774 (1988)

Ying Ran, MIT Ph.D. thesis (2007)

C. Wang, A. Nahum, M. A. Metlitski, C. Xu,
T. Senthil, *Phys. Rev. X* **7**, 031051 (2017)



or

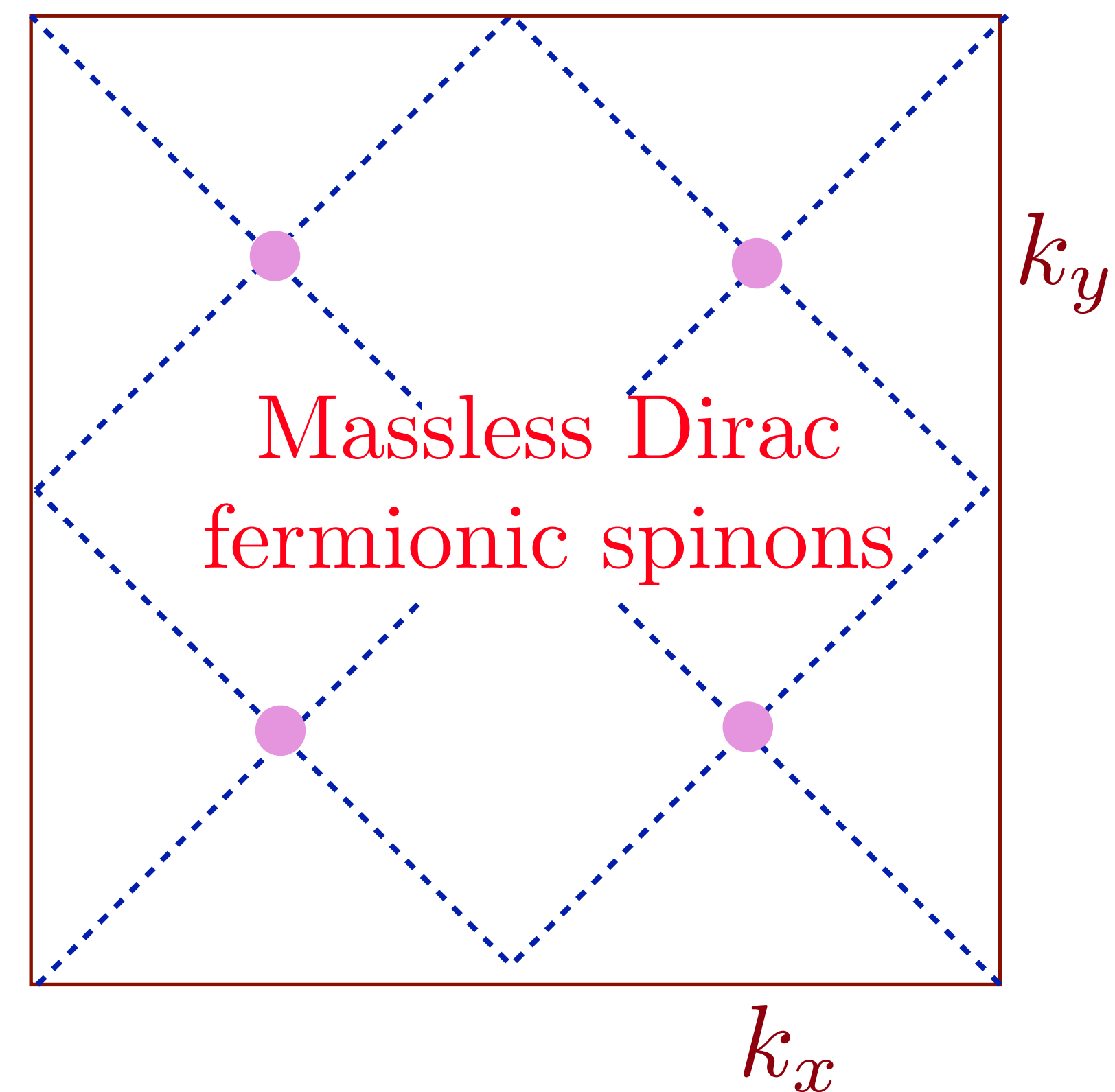


$$\mathcal{L} = i\bar{\psi}\gamma_\mu D_\mu\psi.$$

Néel order

Valence bond solid (VBS)

J_2/J_1



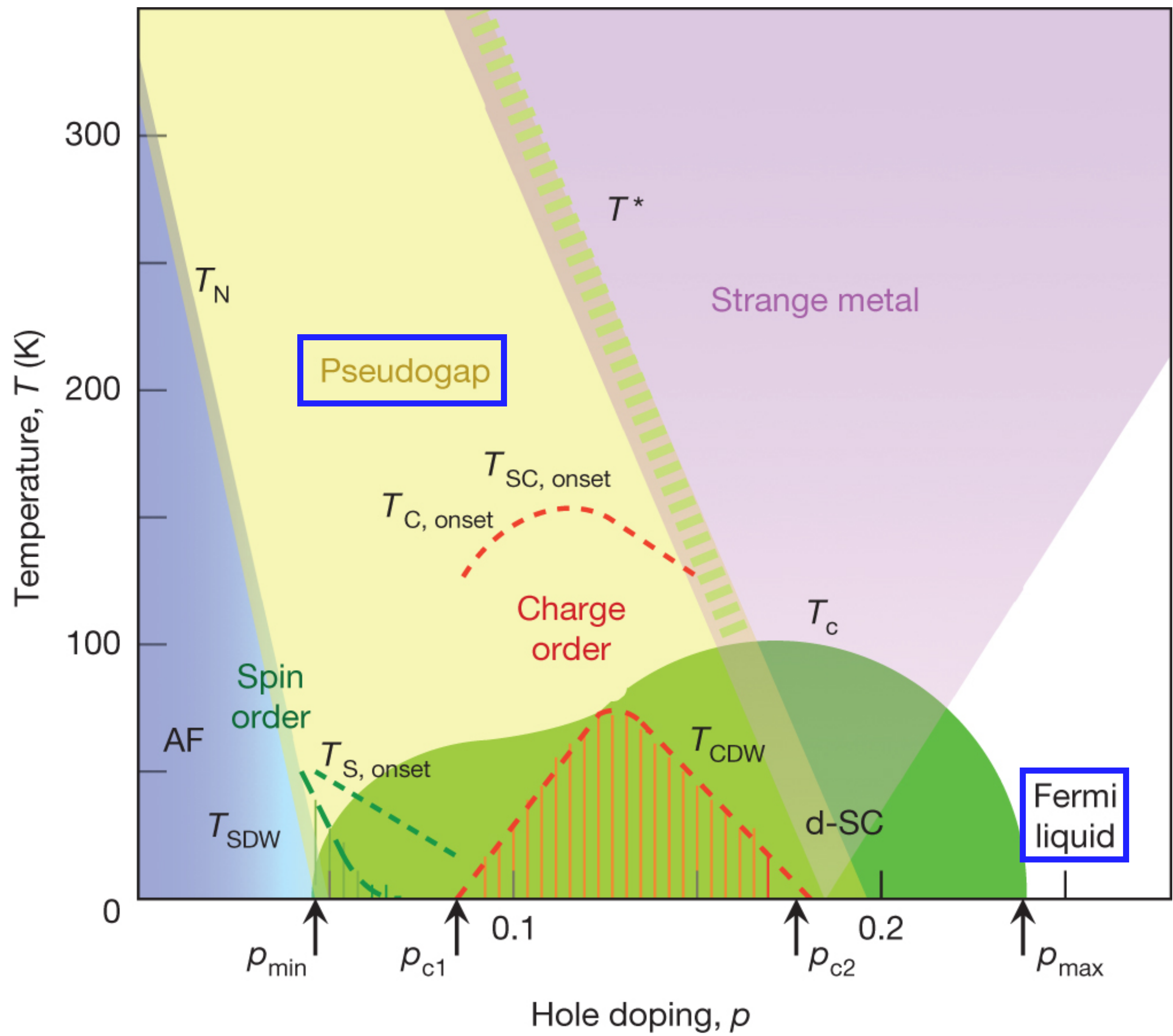
Massless Dirac
fermionic spinons

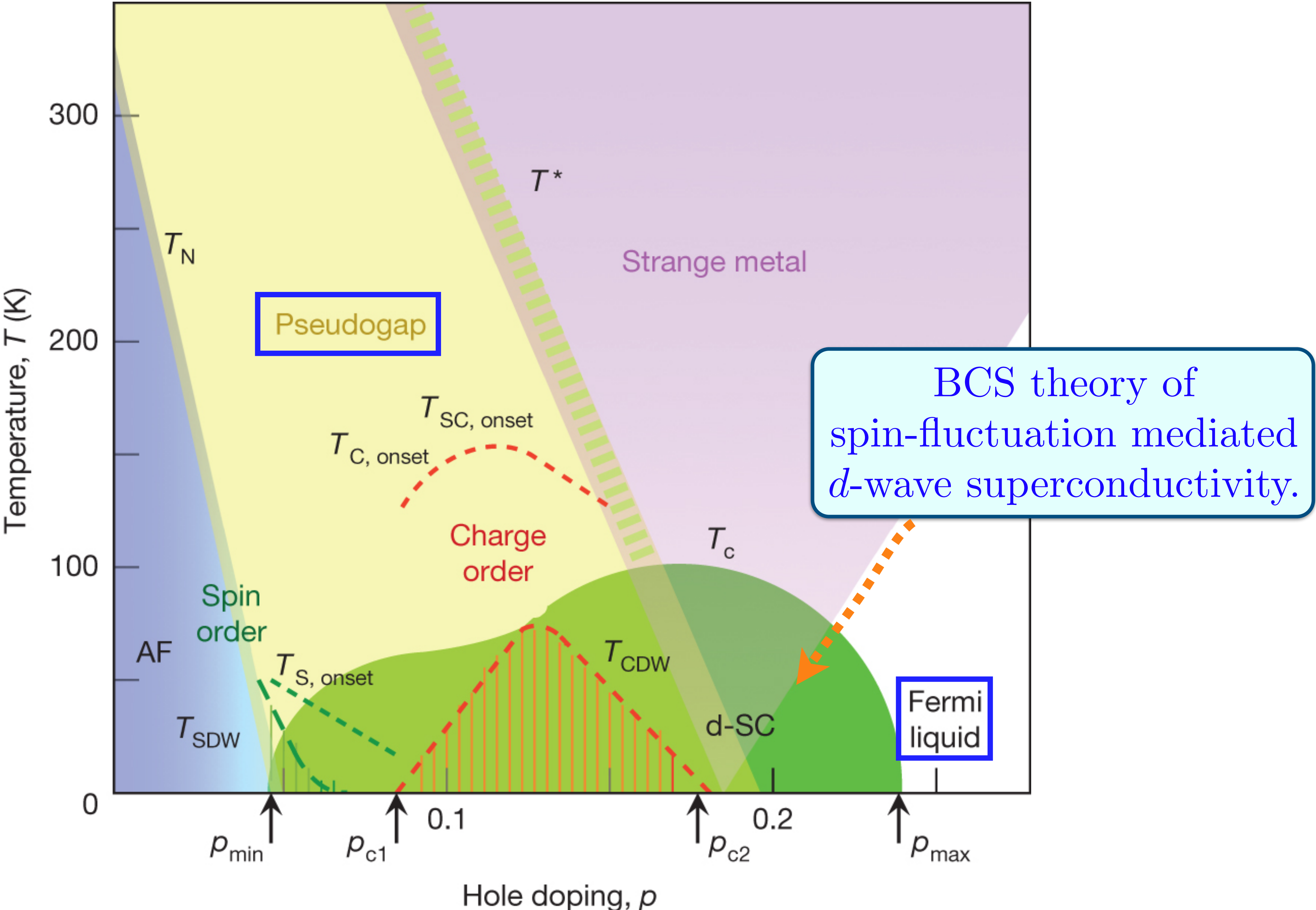
Critical spin liquid
without quasiparticles?

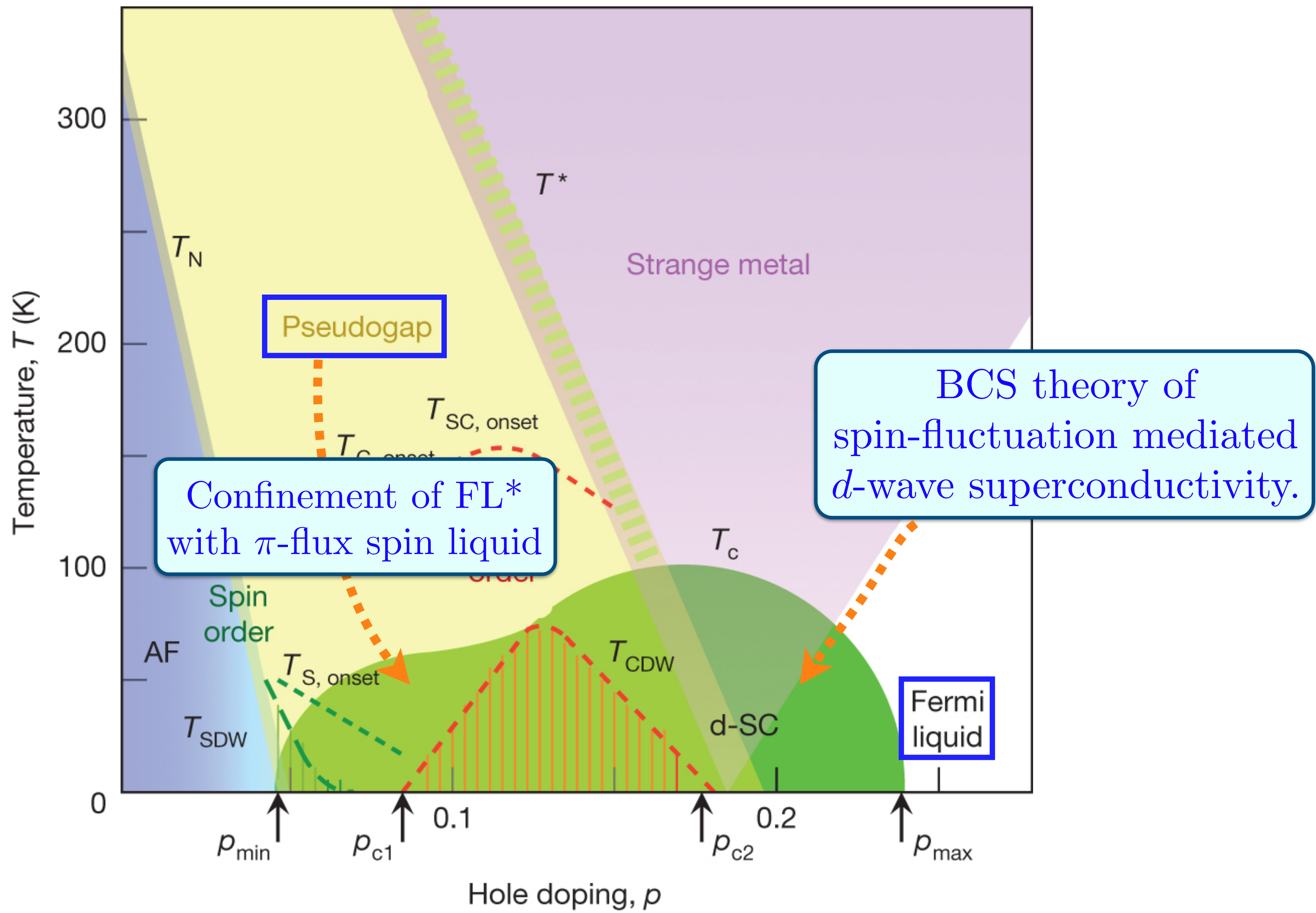
$N_f = 2$ SU(2) QCD

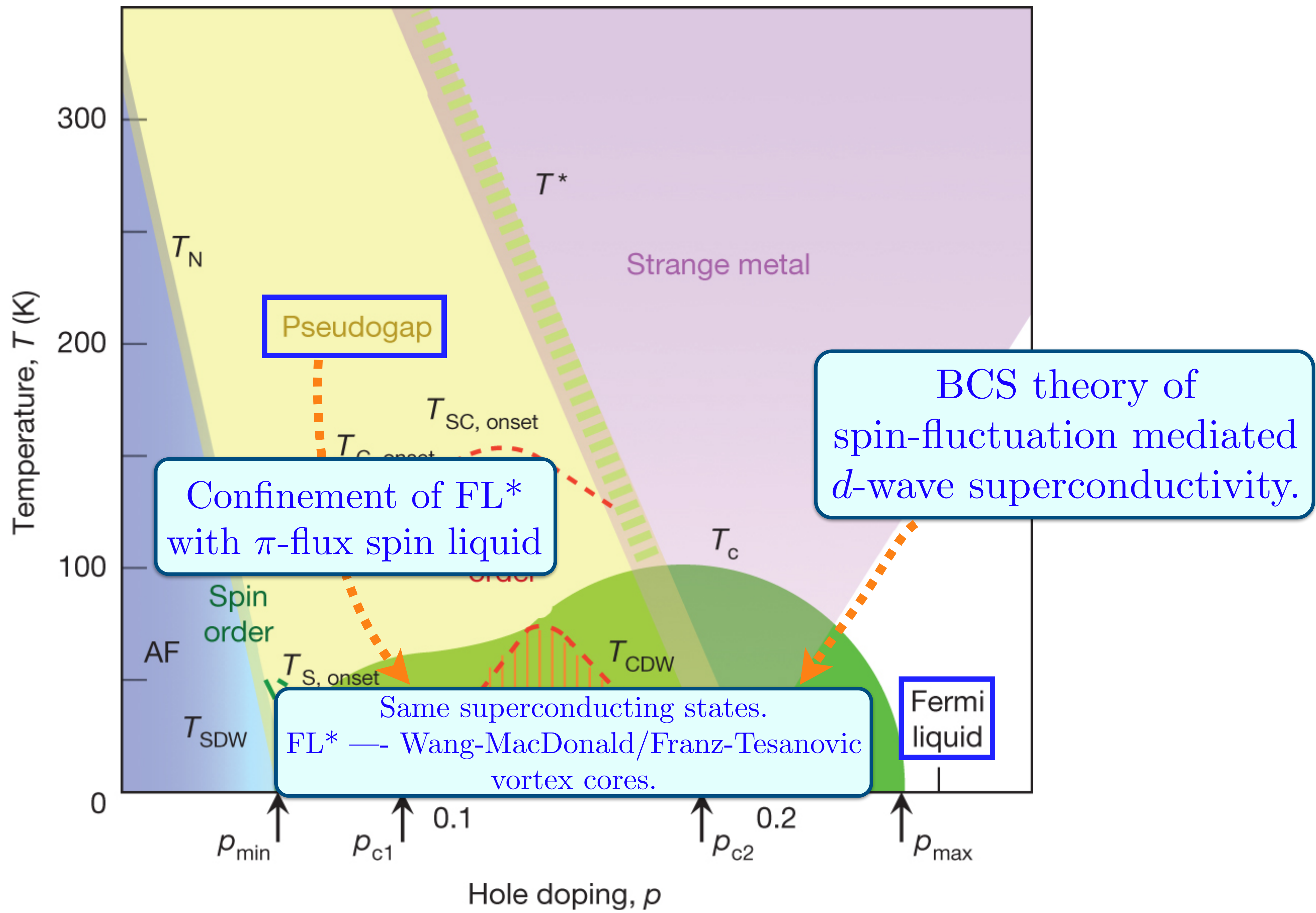
Dual to the \mathbb{CP}^1
theory of Read+SS!

Fractionalized Intertwined Orders









Adding charge fluctuations to the π -flux spin liquid

- Introduce a charge e , SU(2) fundamental (Higgs) boson B_i such that the composite of B_i and the spinons $f_{i\alpha}$ is an electron.
- The “Landau” theory of B_i has to be invariant under all symmetries, *upto a gauge transformation*.
- This is sufficient to determine the effective action, and the physical interpretation of *gauge-invariant* composites of B_i .

f_α and B both move in π -flux

Pairing: $\langle \varepsilon_{\alpha\beta} c_{i\alpha} c_{j\beta} \rangle \sim$

$$\Delta_{ij} = \Delta_{ji} = \varepsilon_{ab} B_{ai} e_{ij} U_{ij} B_{bj}$$

site charge density: $\langle c_{i\alpha}^\dagger c_{i\alpha} \rangle \sim \rho_i = B_i^\dagger B_i$

bond density: $\langle c_{i\alpha}^\dagger c_{j\alpha} + c_{j\alpha}^\dagger c_{i\alpha} \rangle$

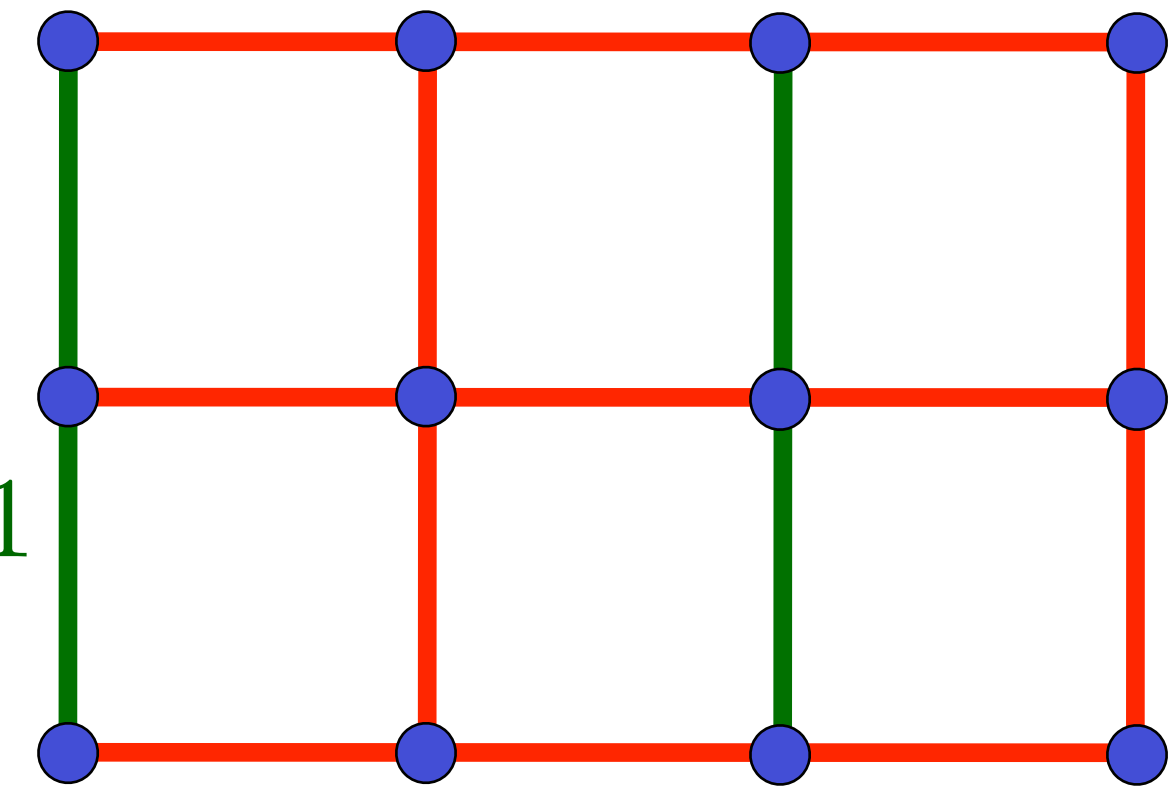
$$\sim Q_{ij} = Q_{ji} = \text{Im} \left(B_i^\dagger e_{ij} U_{ij} B_j \right)$$

bond current: $i \langle c_{i\alpha}^\dagger c_{j\alpha} - c_{j\alpha}^\dagger c_{i\alpha} \rangle$

$$\sim J_{ij} = -J_{ji} = \text{Re} \left(B_i^\dagger e_{ij} U_{ij} B_j \right)$$

$$e_{ij} = -1$$

$$e_{ij} = 1$$



Energy functional for B and U : $\mathcal{E}[B, U] = \mathcal{E}_2[B, U] + \mathcal{E}_4[B, U] + \mathcal{E}_{YM}[U]$

$$\mathcal{E}_2[B, U] = (r + 2\sqrt{2}w) \sum_i B_i^\dagger B_i + iw \sum_{\langle ij \rangle} e_{ij} \left(B_i^\dagger U_{ij} B_j - B_j^\dagger U_{ji} B_i \right)$$

$$\begin{aligned} \mathcal{E}_4[B, U] = & \frac{u}{2} \sum_i \rho_i^2 + V_1 \sum_i \rho_i (\rho_{i+\hat{x}} + \rho_{i+\hat{y}}) + g \sum_{\langle ij \rangle} |\Delta_{ij}|^2 + J_1 \sum_{\langle ij \rangle} Q_{ij}^2 + K_1 \sum_{\langle ij \rangle} J_{ij}^2 \\ & + V_{11} \sum_i \rho_i (\rho_{i+\hat{x}+\hat{y}} + \rho_{i+\hat{x}-\hat{y}}) + V_{22} \sum_i \rho_i (\rho_{i+2\hat{x}+2\hat{y}} + \rho_{i+2\hat{x}-2\hat{y}}) \end{aligned}$$

$$\mathcal{E}_{YM}[U] = \kappa \sum_{\square} \left[1 - \frac{1}{2} \text{ReTr} \prod_{ij \in \square} U_{ij} \right]$$

Adding charge fluctuations to the π -flux spin liquid

$$\langle B \rangle \neq 0$$

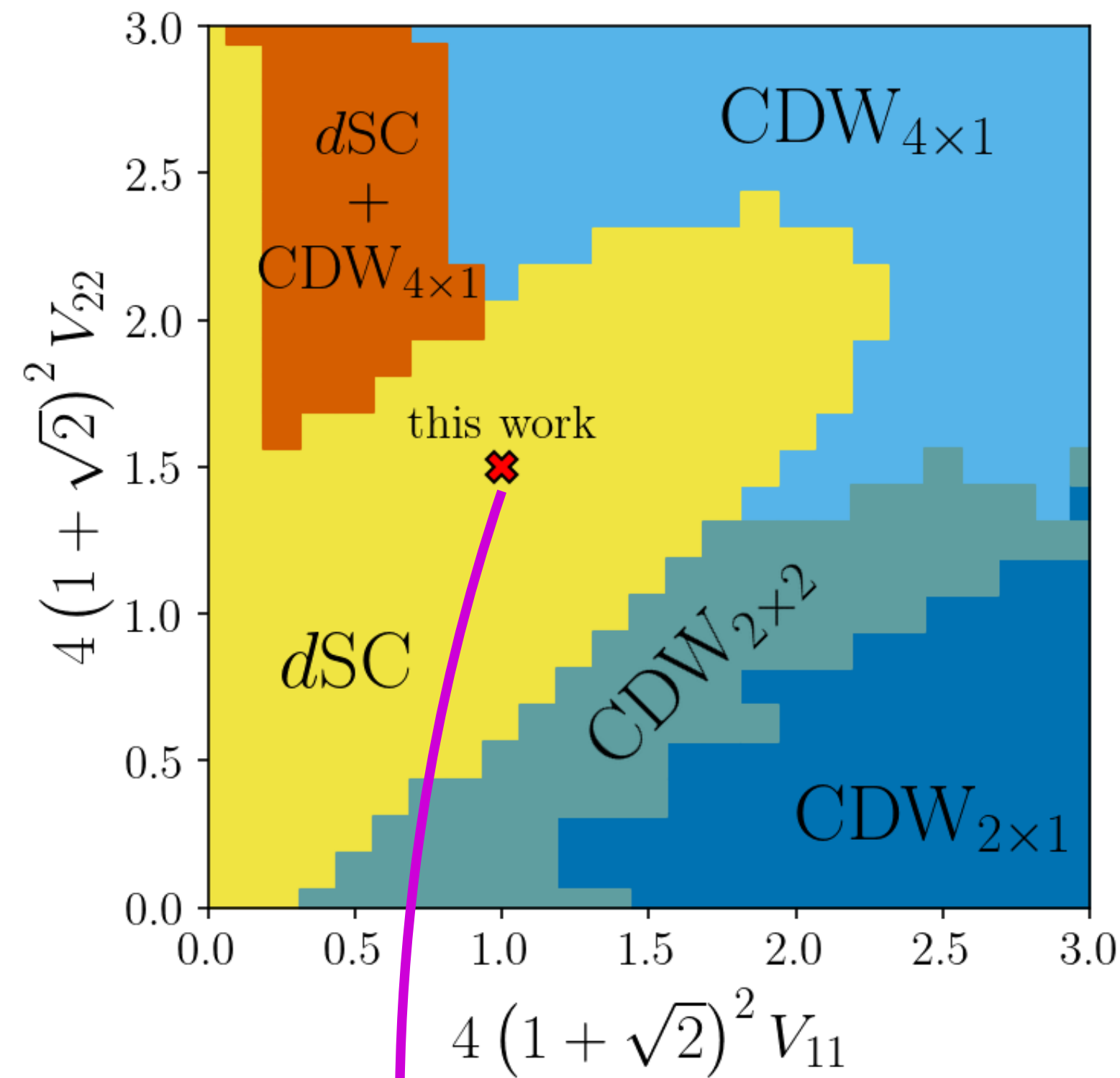
$$\langle B \rangle = 0$$

FL* state
with a critical
 π -flux spin liquid
of f_α spinons.

Adding charge fluctuations to the π -flux spin liquid

$$\langle B \rangle \neq 0$$

$$\langle B \rangle = 0$$



FL* state
with a critical
 π -flux spin liquid
of f_α spinons.

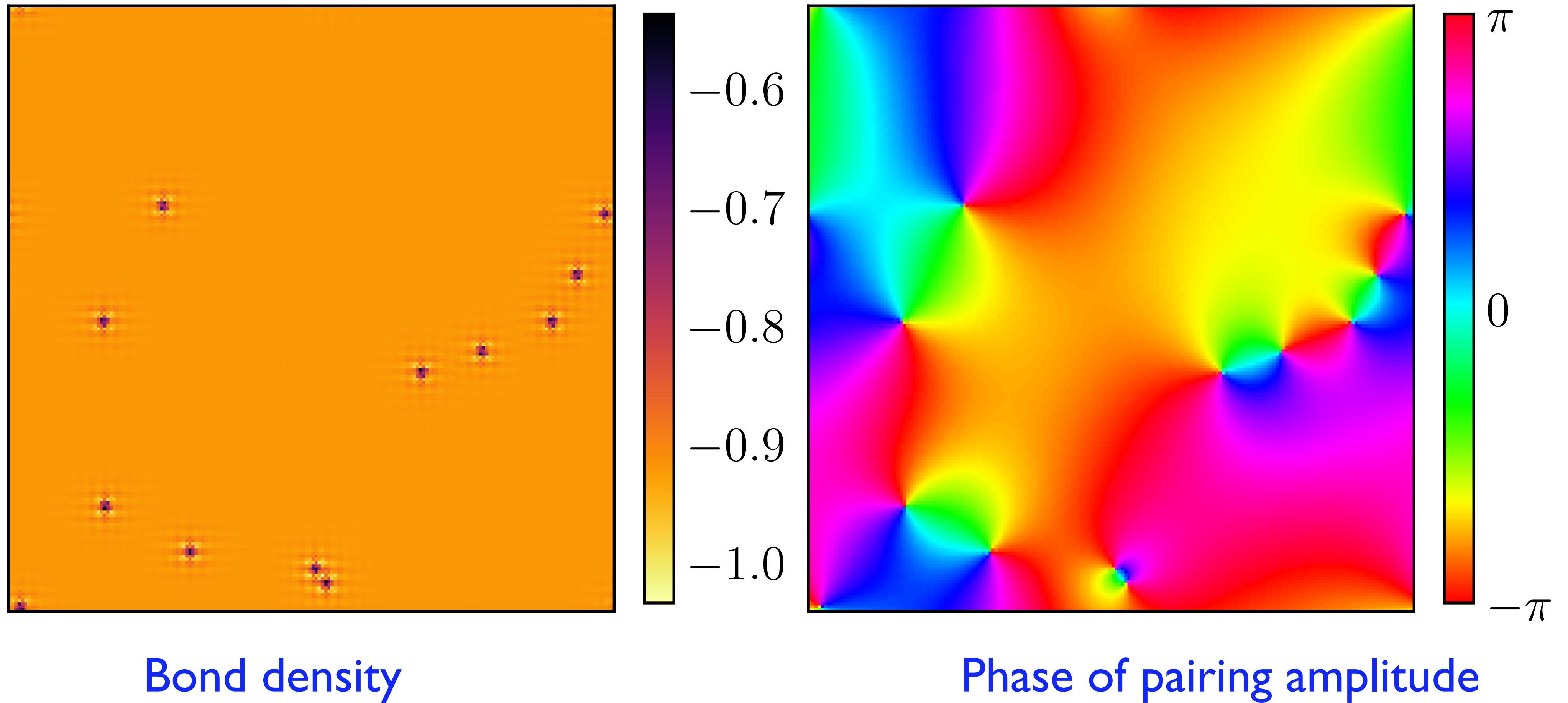
Parameters chosen so that the ground state is a d -wave superconductor (with 4 nodal quasiparticles) and the second best state is a period-4 stripe.

Monte Carlo at a temperature T

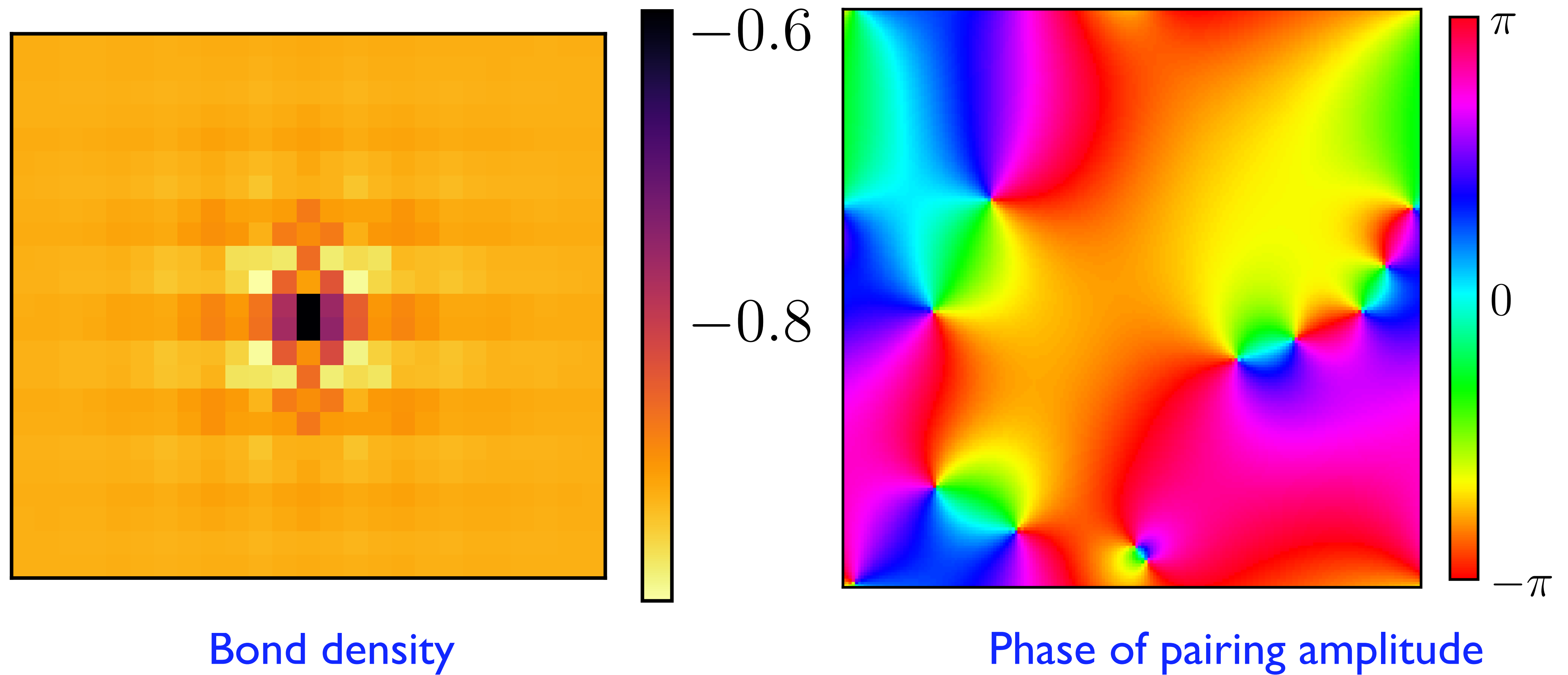
$$\mathcal{Z}_{2+0} = \int \prod_i \mathcal{D}B_i \int \prod_{\langle ij \rangle} \mathcal{D}U_{ij} \exp [-\mathcal{E}[B, U]/T]$$

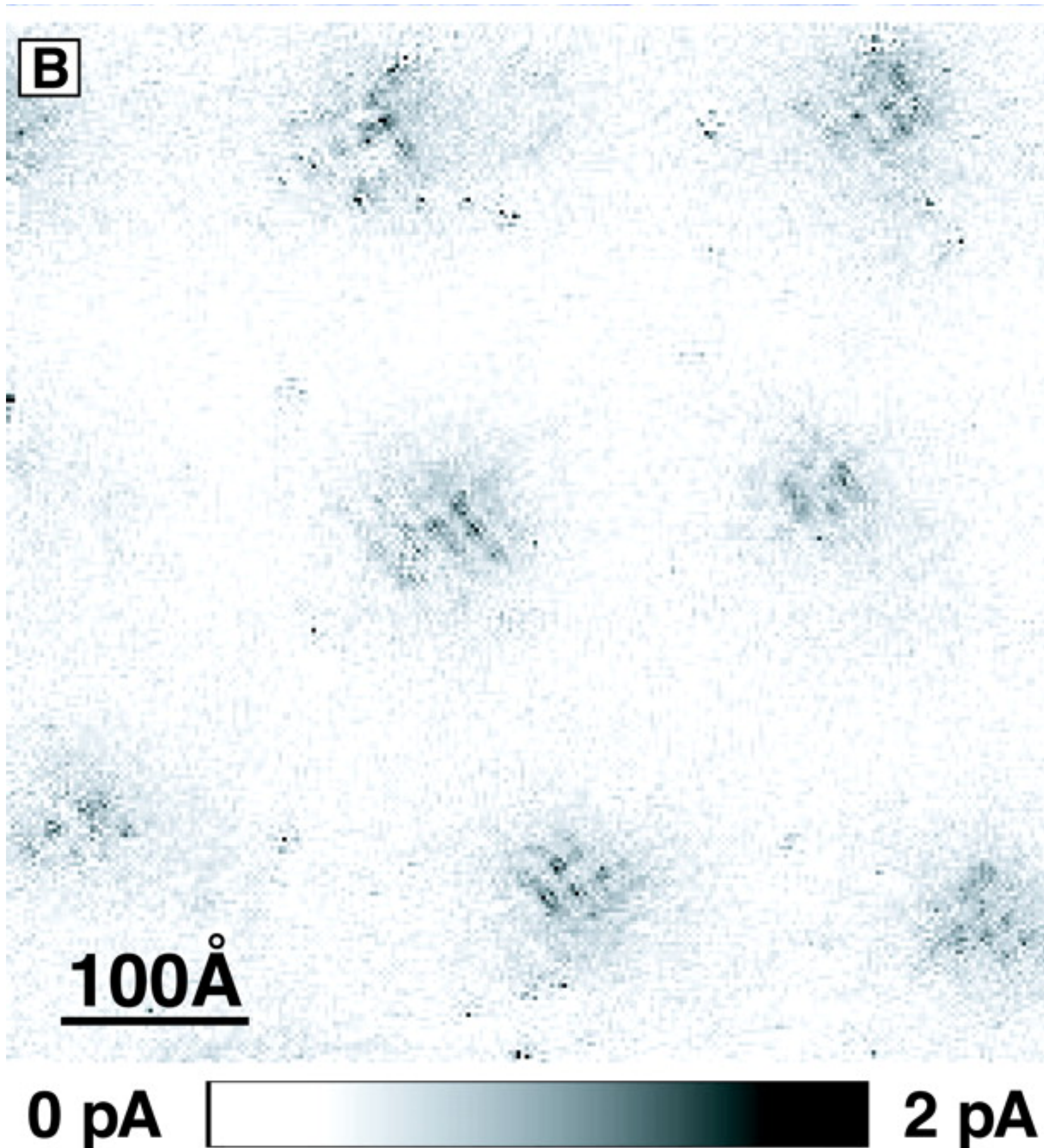
- Simulation of classical, thermal theory for bosons B, U defined by \mathcal{Z}_{2+0}

Monte Carlo at a temperature T



Monte Carlo at a temperature T





A Four Unit Cell Periodic Pattern of Quasi-Particle States Surrounding Vortex Cores in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

J. E. Hoffman, E. W. Hudson,
K. M. Lang, V. Madhavan,
H. Eisaki, S. Uchida, J.C. Davis
Science **295**, 466 (2002)

Theory of hole pockets

FL* in a single-band Hubbard model

- Fermionic spinons f moving in π -flux and an emergent SU(2) gauge field U .

Ya-Hui Zhang and S. Sachdev, *Phys. Rev. Res.* **2**, 023172 (2020)

M. Christos, Zhu-Xi Luo, L. Shackleton, Ya-Hui Zhang, M. S. Scheurer, and S. S., *PNAS* **120**, e2302701120 (2023)

FL* in a single-band Hubbard model

- Fermionic spinons f moving in π -flux and an emergent SU(2) gauge field U .
- Realize hole pockets by hybridizing electrons c , with a separate band of spinons f_1 forming a spinon Fermi surface. Hole density $1 + p + 1 = p(\text{mod } 2)$.

Ya-Hui Zhang and S. Sachdev, *Phys. Rev. Res.* **2**, 023172 (2020)

M. Christos, Zhu-Xi Luo, L. Shackleton, Ya-Hui Zhang, M. S. Scheurer, and S. S., *PNAS* **120**, e2302701120 (2023)

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FL* in a single-band Hubbard model

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- Symmetries yield a unique Yukawa coupling between Higgs boson B , and spinons f and f_1 .

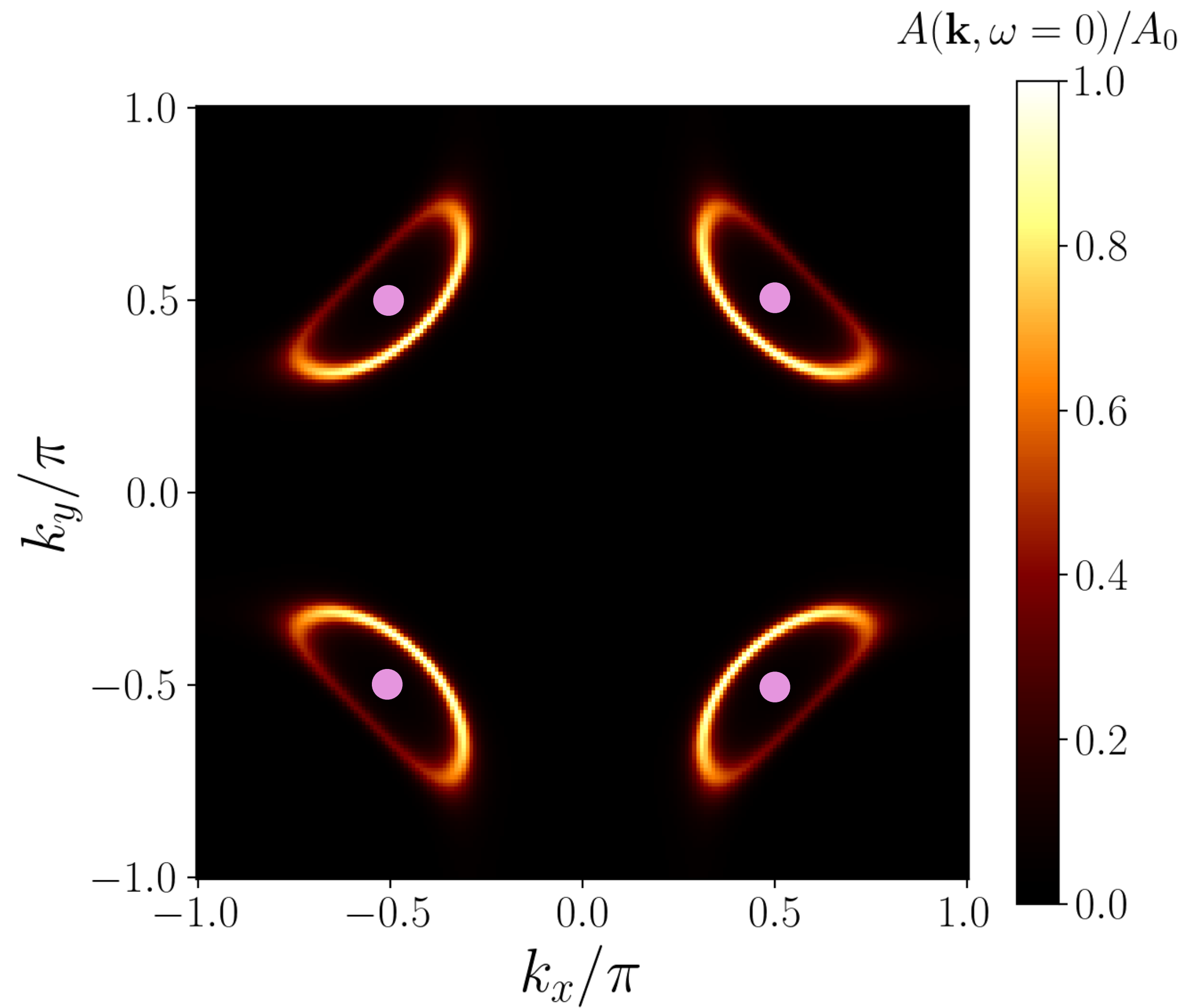
Ya-Hui Zhang and S. Sachdev, *Phys. Rev. Res.* **2**, 023172 (2020)

M. Christos, Zhu-Xi Luo, L. Shackleton, Ya-Hui Zhang, M. S. Scheurer, and S. S., PNAS **120**, e2302701120 (2023)

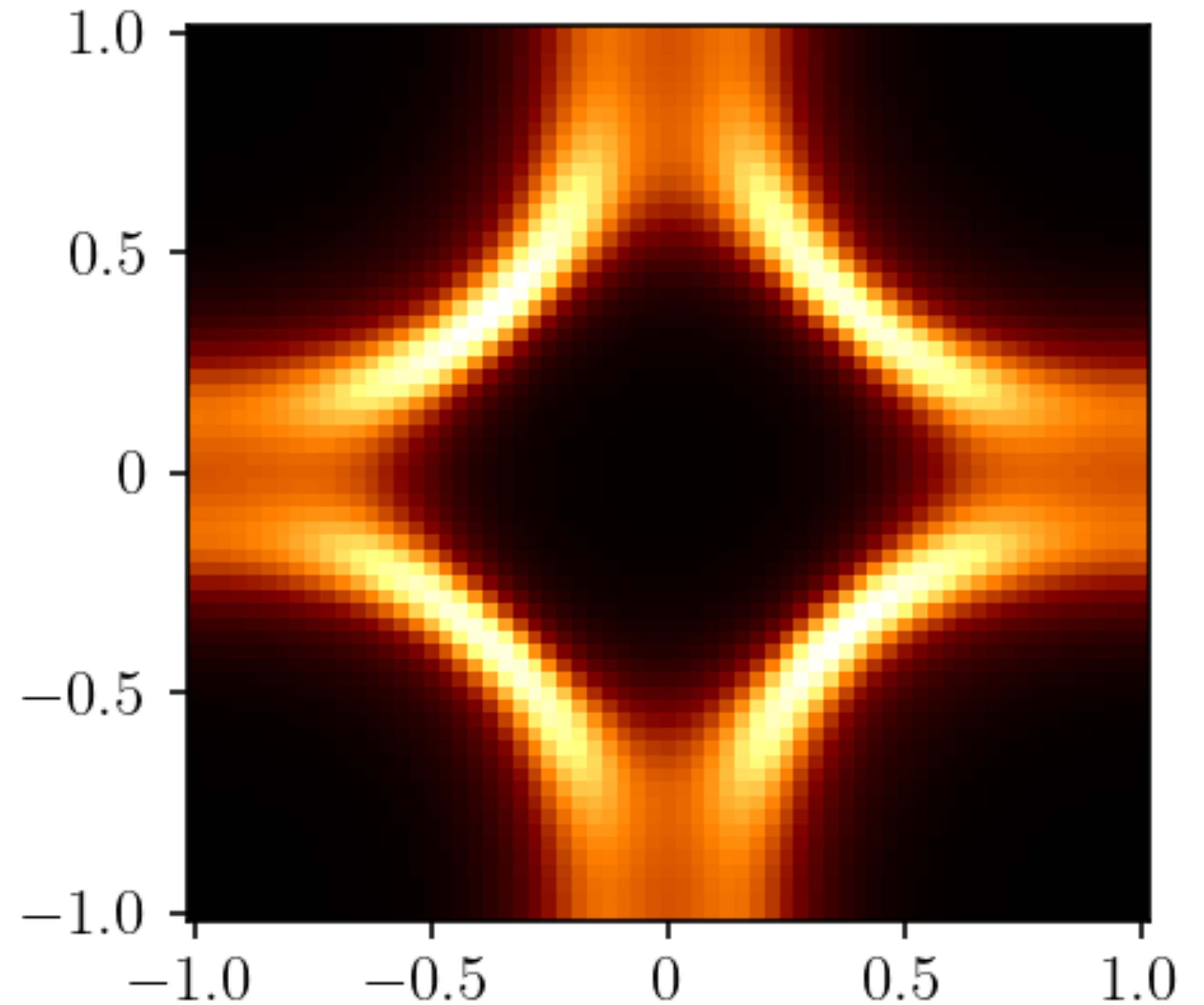
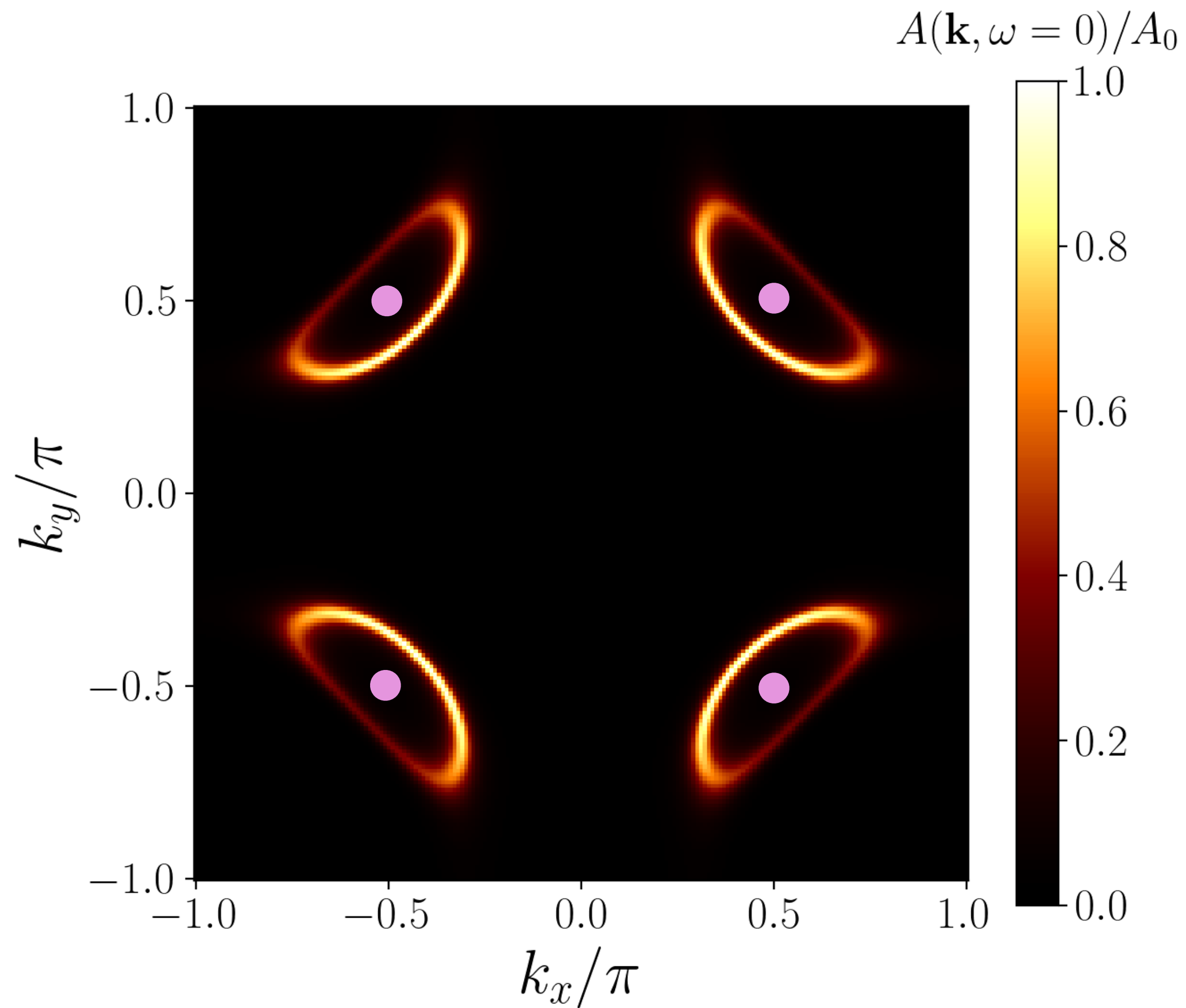
Monte Carlo at a temperature T

$$\mathcal{Z}_{2+0} = \int \prod_i \mathcal{D}B_i \int \prod_{\langle ij \rangle} \mathcal{D}U_{ij} \exp [-\mathcal{E}[B, U]/T]$$

- Simulation of classical, thermal theory for bosons B, U defined by \mathcal{Z}_{2+0}
- Diagonalize 3-layer fermion Hamiltonian for c, f_1, f for each snapshot of B, U , and average.

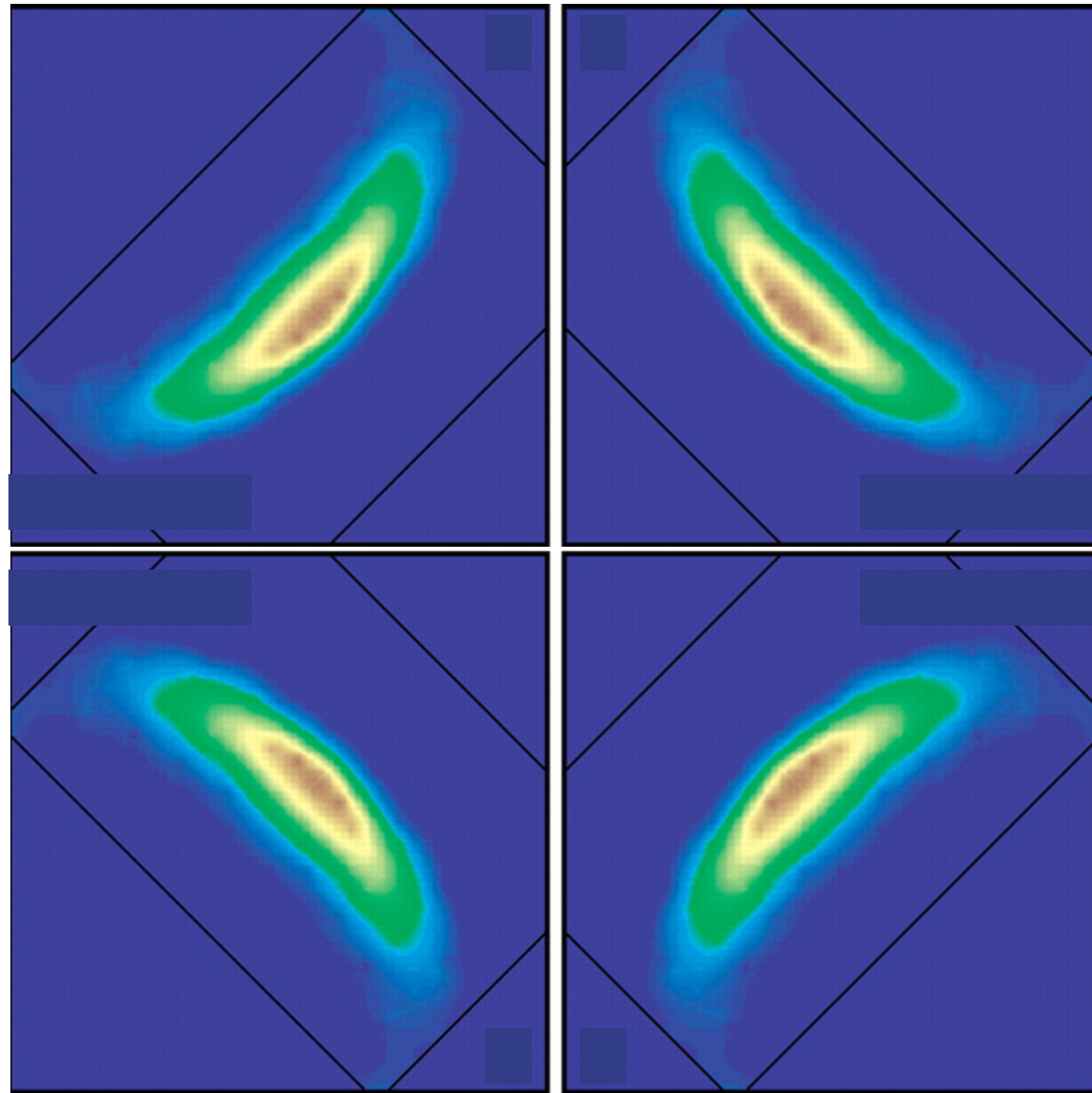


FL* fermionic spectrum with $B = 0$, $U = 1$
 4 holes pockets of size $p/8$;
 4 nodal spinons



FL* fermionic spectrum with $B = 0$, $U = 1$
 4 holes pockets of size $p/8$;
 4 nodal spinons

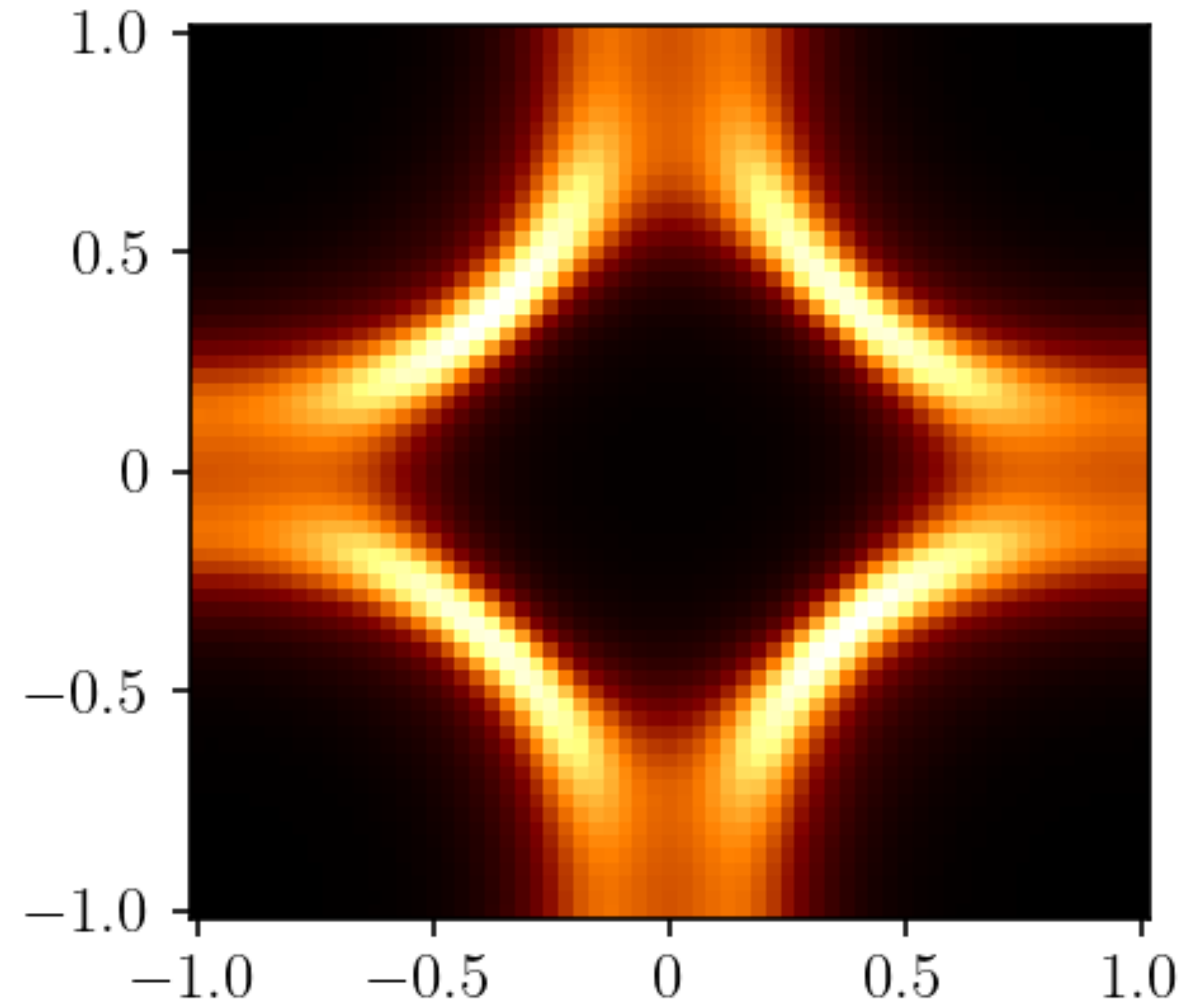
Monte Carlo at a
 temperature $T > T_{KT}$



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

Photoemission observations

H. Pandey, M. Christos, P. M. Bonetti, R. Shanker, S. Sharma, S.S., PNAS **123**, e2606117123 (2026).



Monte Carlo at a
temperature $T > T_{KT}$

Quantum oscillations at high fields, even when photoemission shows arcs.

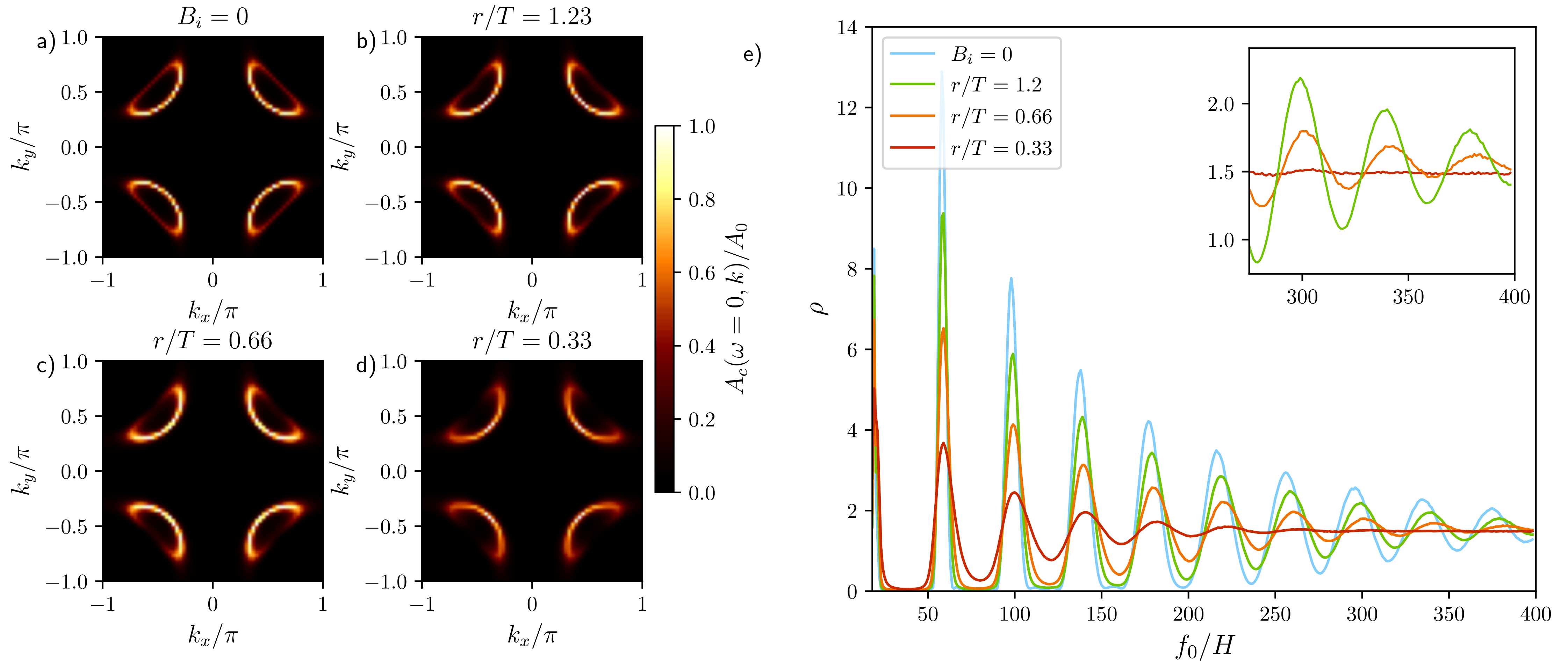
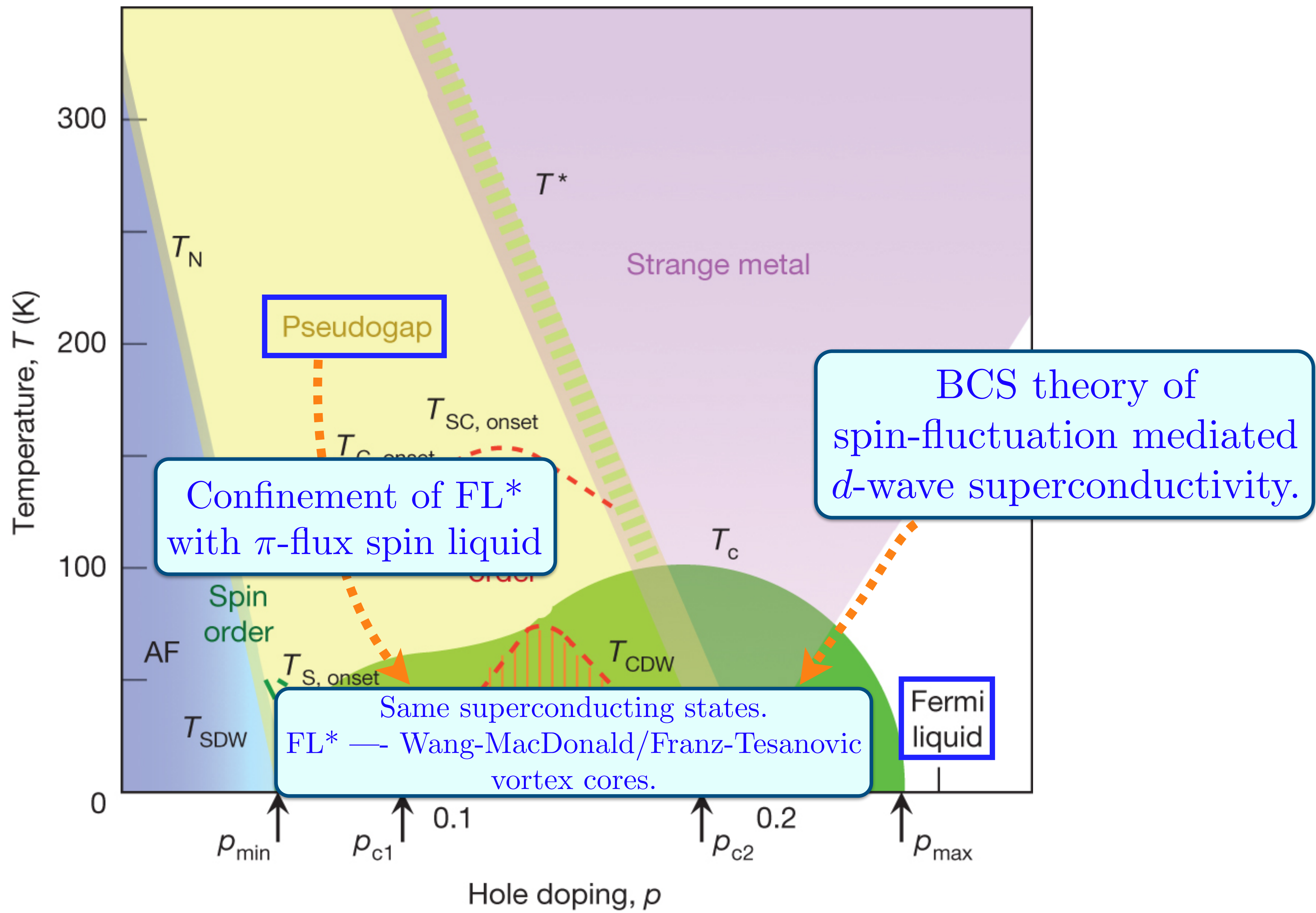


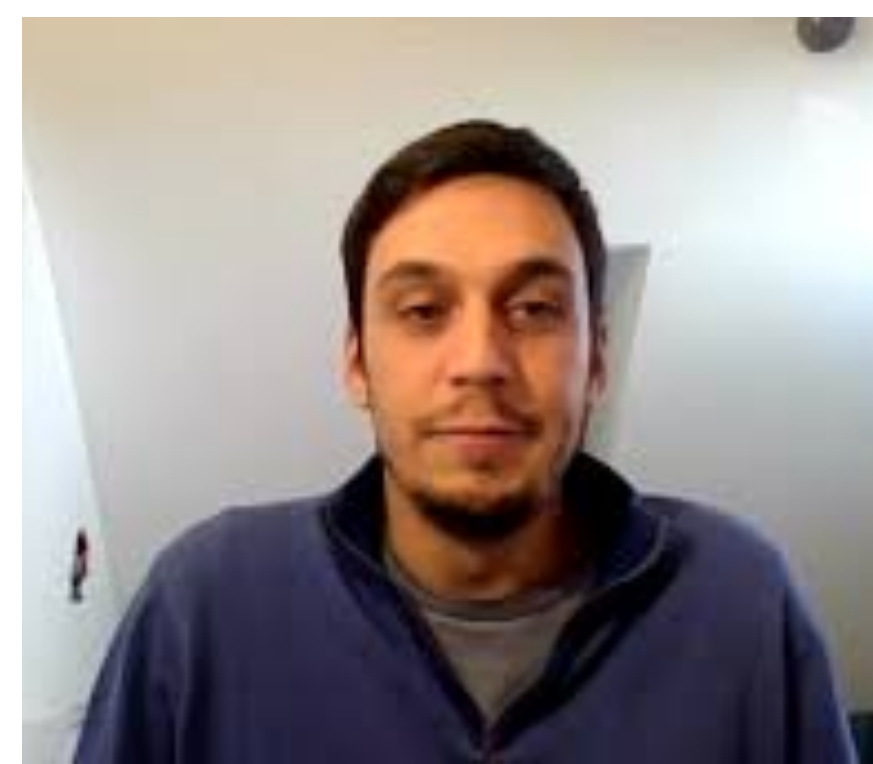
Fig. 9. (a) Zero frequency electronic spectral weight in the presence of gaussian distributed thermal fluctuations of B mediating a coupling to spinons. We use only the gaussian contributions to the quadratic free energy Eq. (2) about the saddle point $U_{ij} = 1$ with $w = 0.2/(2\sqrt{2})$ and averaged over 100 samples each with a broadening parameter $\eta = 0.01$. The spin liquid hopping is $J = 0.2/\sqrt{2}$. All other model parameters used are the same as Fig. 8. (b) The density of states ρ as a function of the inverse of the magnetic field $1/H$ for the parameter values of the plots in (a). The inset is an expanded view of the data at smaller values of H . The frequency $f_0 = h/(ea_0^2)$ corresponds to the area of the Brillouin zone; for the cuprates $f_0 \approx 28600$ T.





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- *Lectures on insulating and conducting quantum spin liquids*, S. Sachdev, arXiv:2512.23962
- *Fractionalized Fermi liquids and the cuprate phase diagram*, P. M. Bonetti, M. Christos, A. Nikolaenko, A.A. Patel, and S. Sachdev, Reports on Progress in Physics **89** 044501 (2026).
- *Thermal $SU(2)$ lattice gauge theory for intertwined orders and hole pockets in the cuprates*, H. Pandey, M. Christos, P. M. Bonetti, R. Shanker, S. Sharma, and S. Sachdev, PNAS **123**, e2606117123 (2026).