Quantum spin liquids and the cuprate high temperature superconductors

Jawaharlal Nehru Centre for Advanced Scientific Research
Bengaluru
December 27, 2023
Subir Sachdev

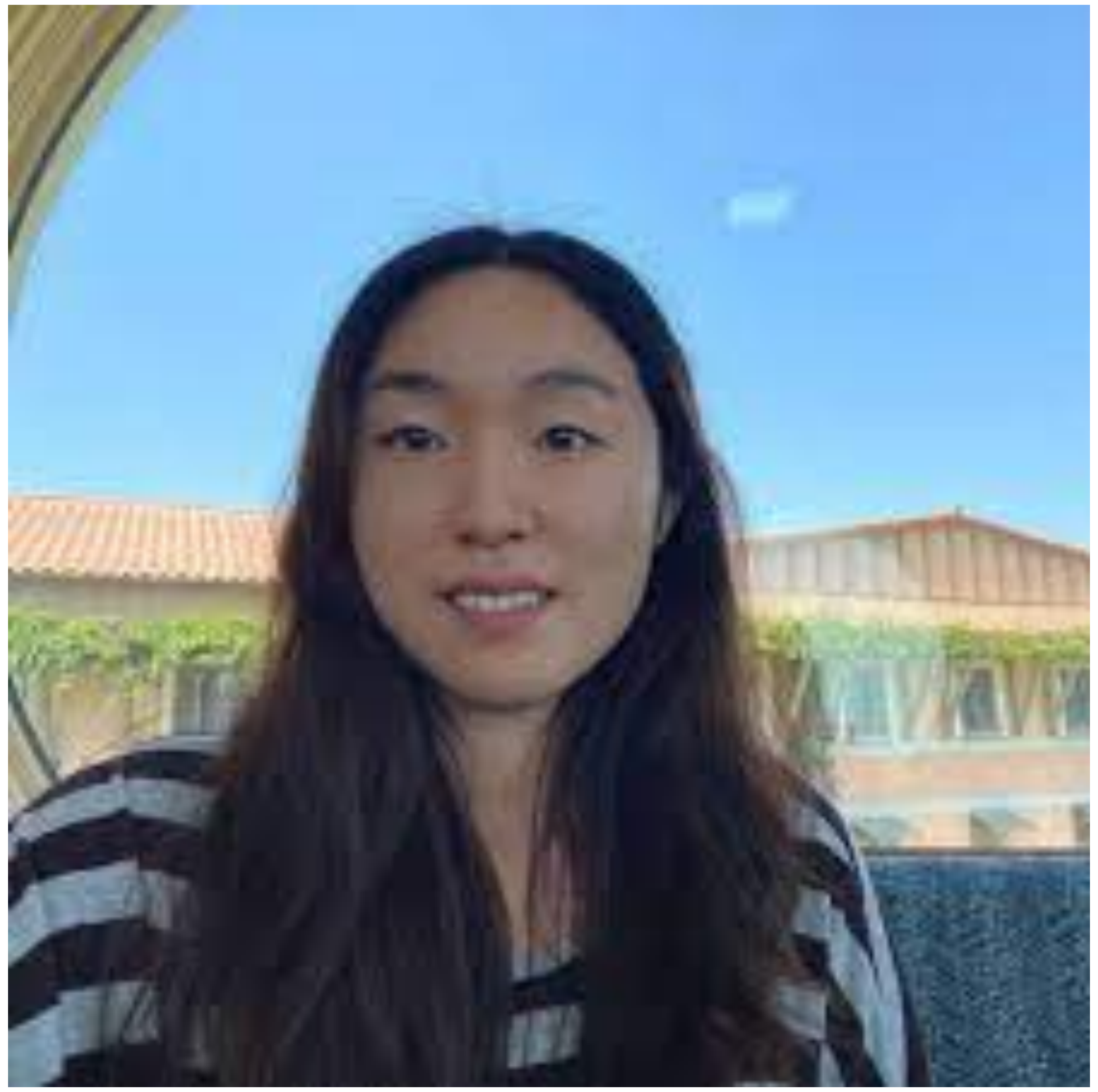
Maine Christos, Zhu-Xi Luo, Henry Shackleton, Ya-Hui Zhang, Mathias Scheurer, and S. Sachdev, *Proc. Nat. Acad. Sci.* **120**, e2302701120 (2023)

Alexander Nikolaenko, Jonas v. Milczewski, Darshan G. Joshi, and S.Sachdev, *Phys. Rev. B* **108**, 045123 (2023)

Maine Christos and S.Sachdev, arXiv:2308.03835

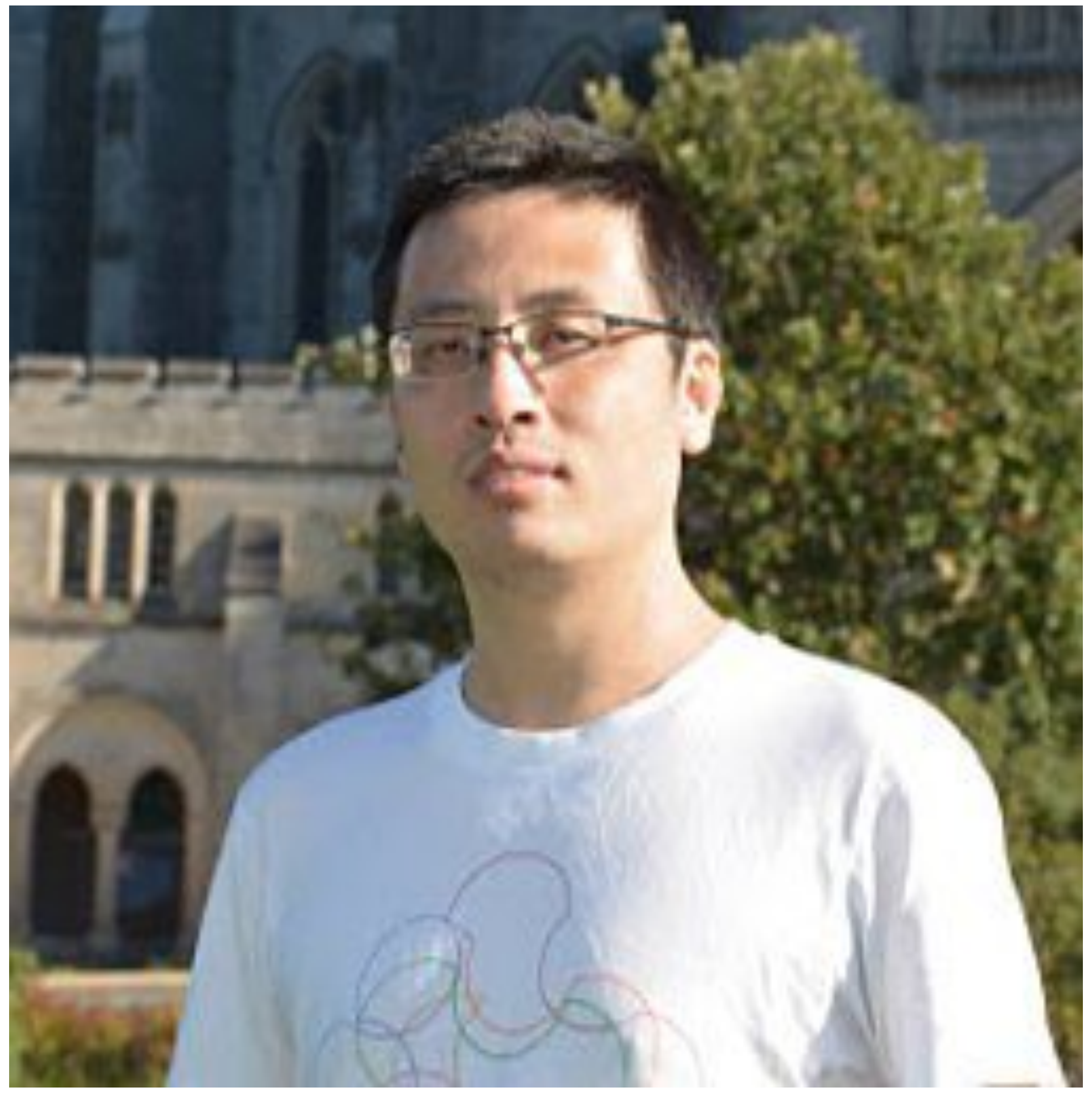
PHYSICS
HARVARD

Maine Christos



Zhu-Xi Luo

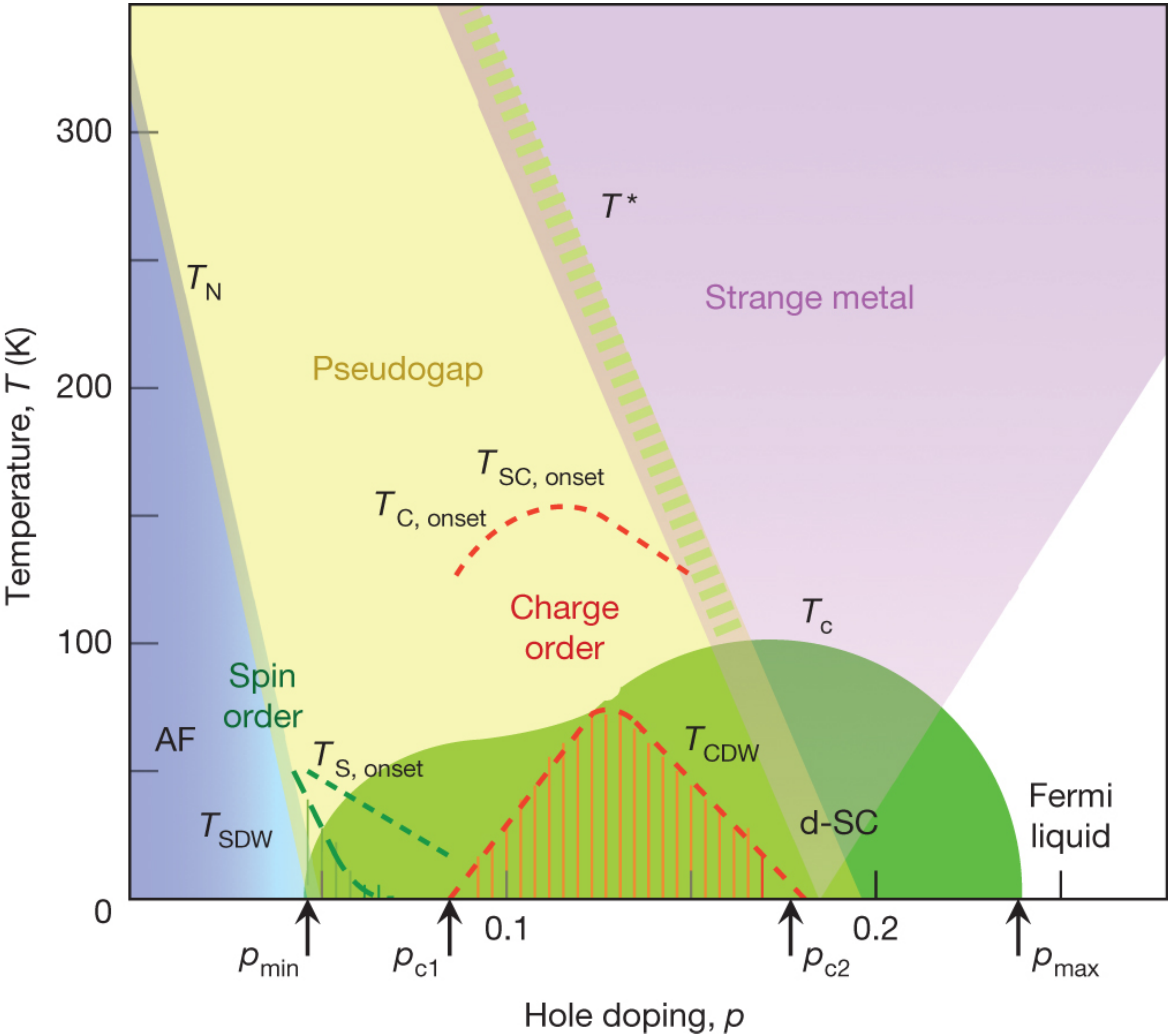
Mathias Scheurer

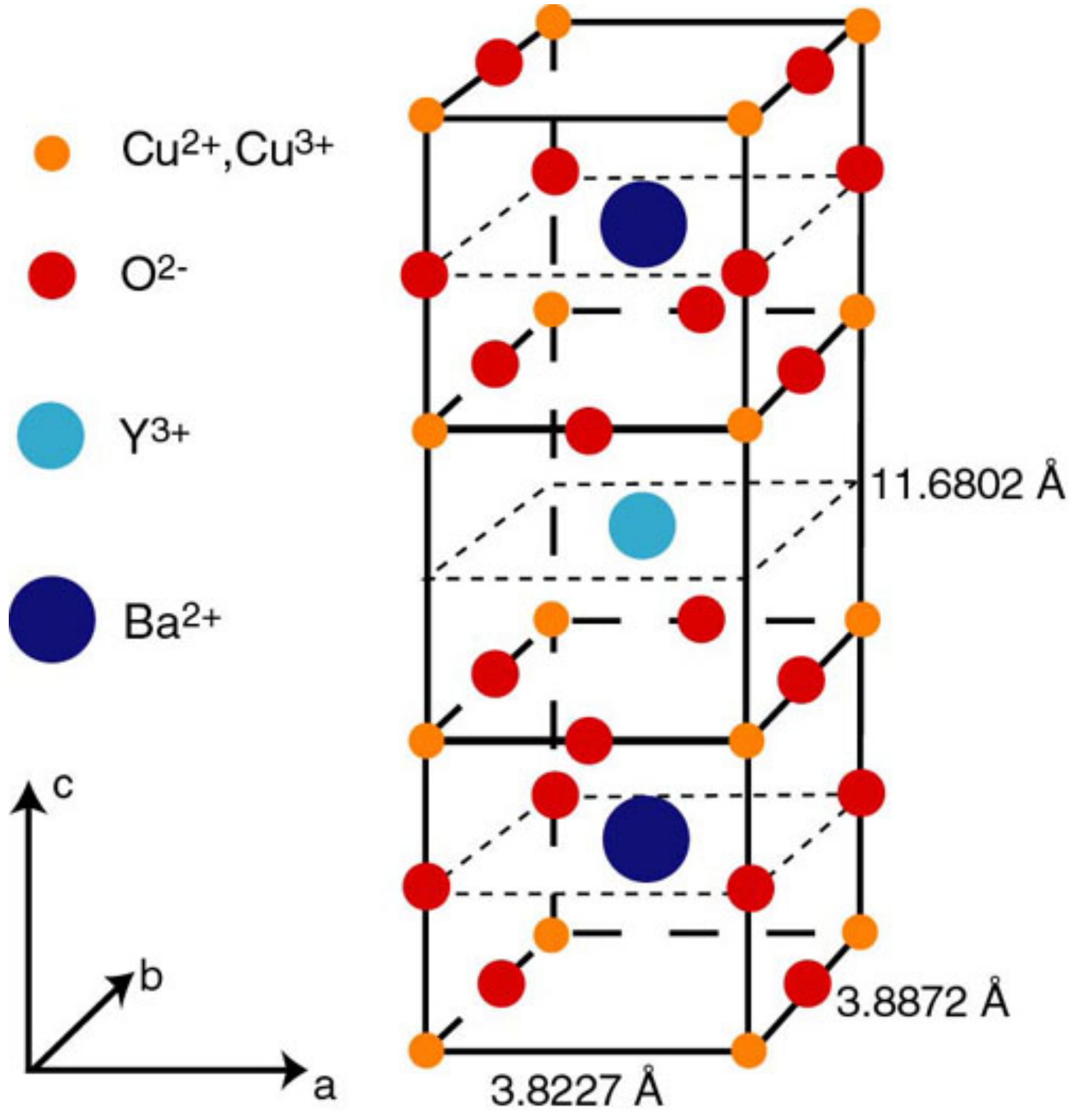


Ya-Hui Zhang

Henry Shackleton

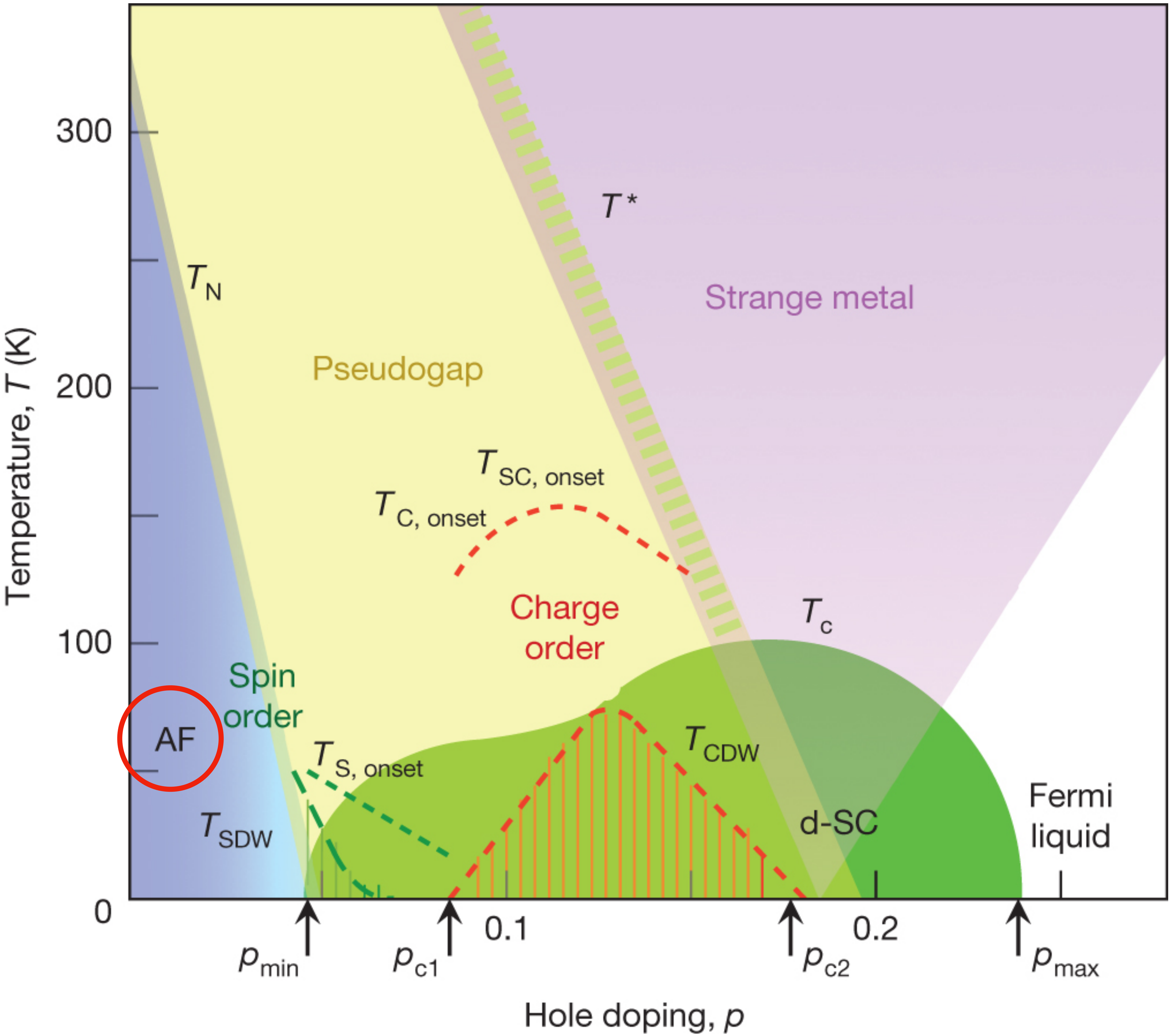
Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)

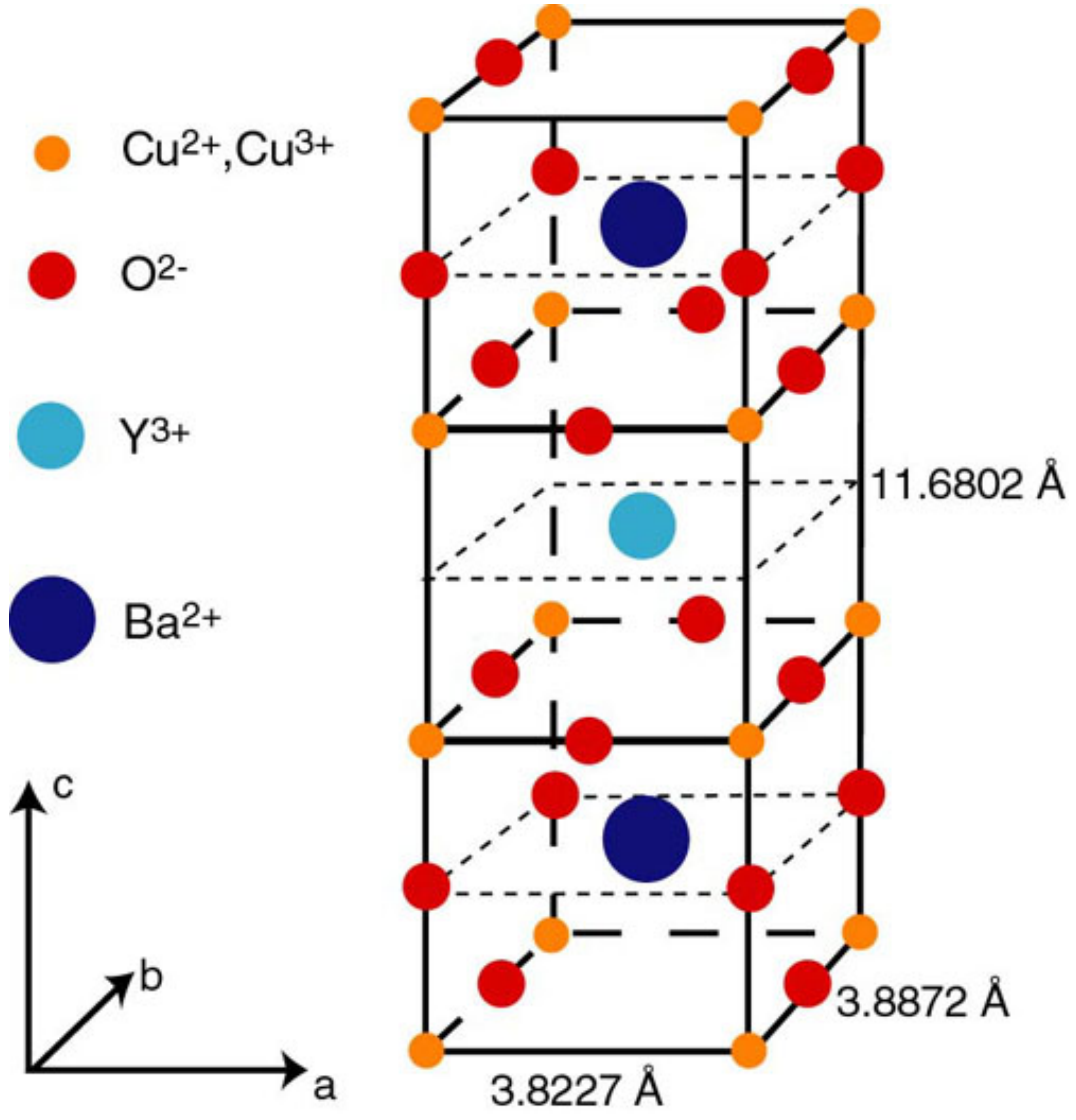




$YBa_2Cu_3O_{6+x}$

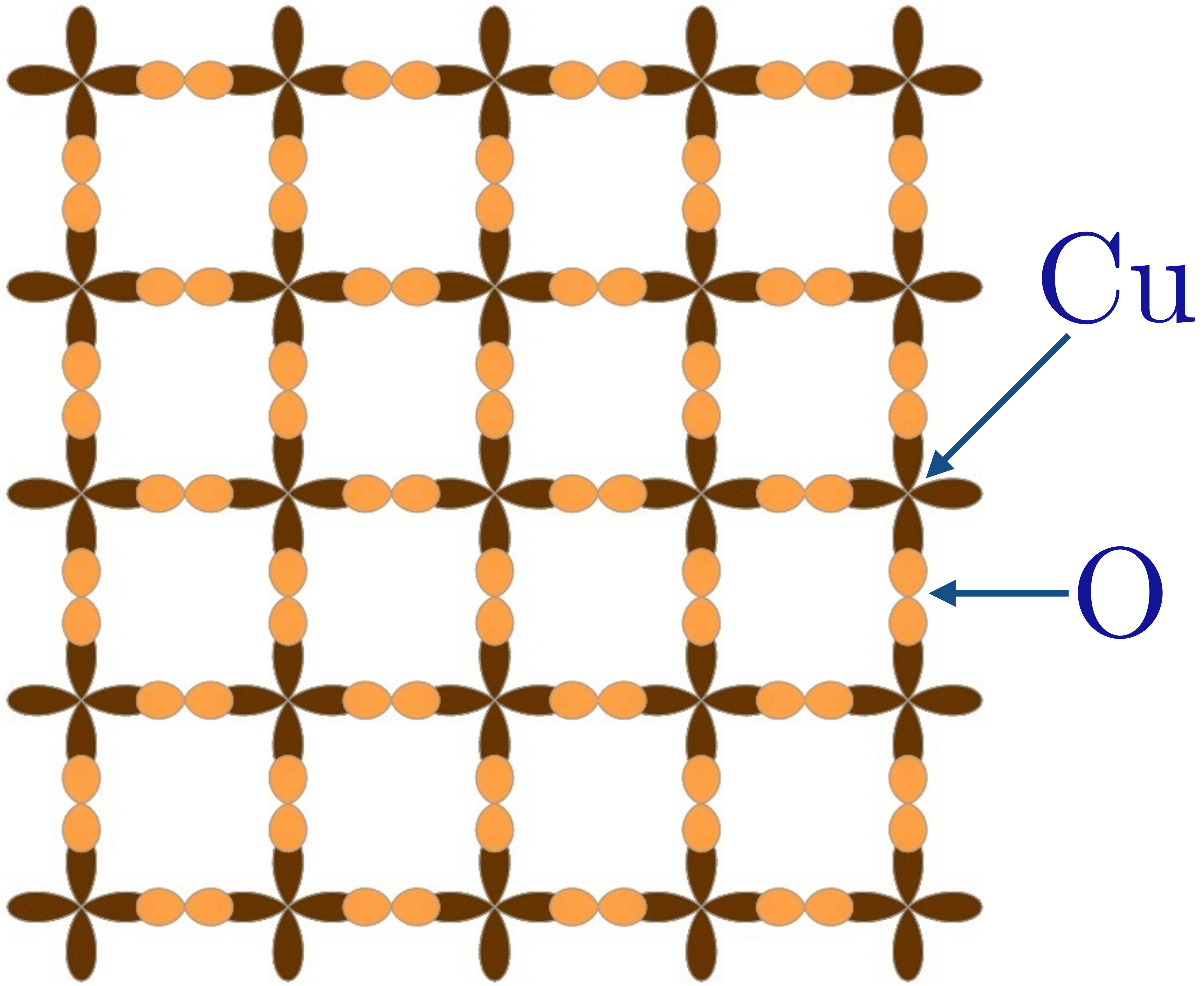
Keimer, Kivelson, Norman, Uchida, and Zaanen, *Nature* **518**, 179 (2015)



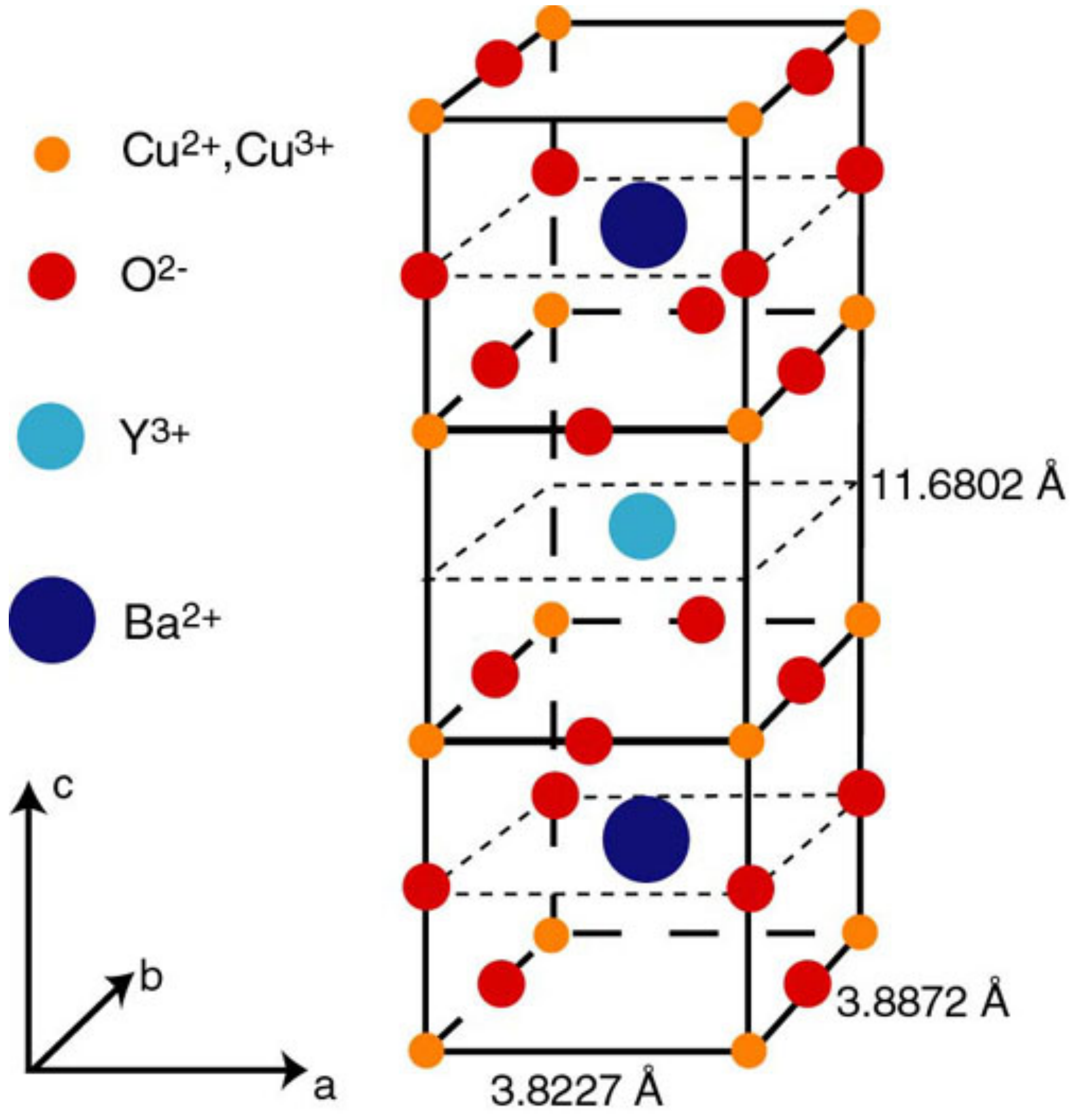


$YBa_2Cu_3O_{6+x}$

$$\mathcal{H}_H = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^{\dagger}_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow}$$



CuO_2 plane



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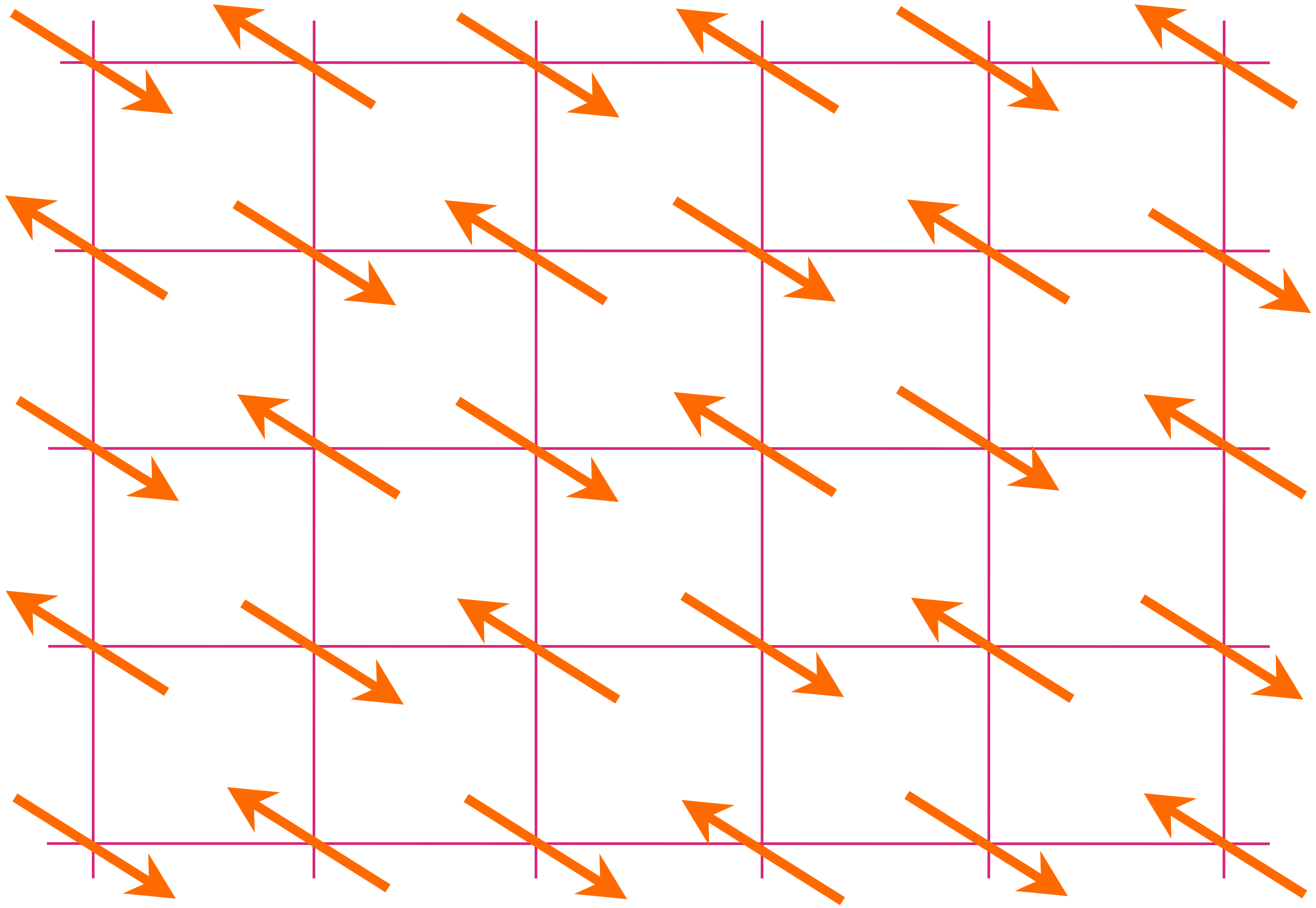
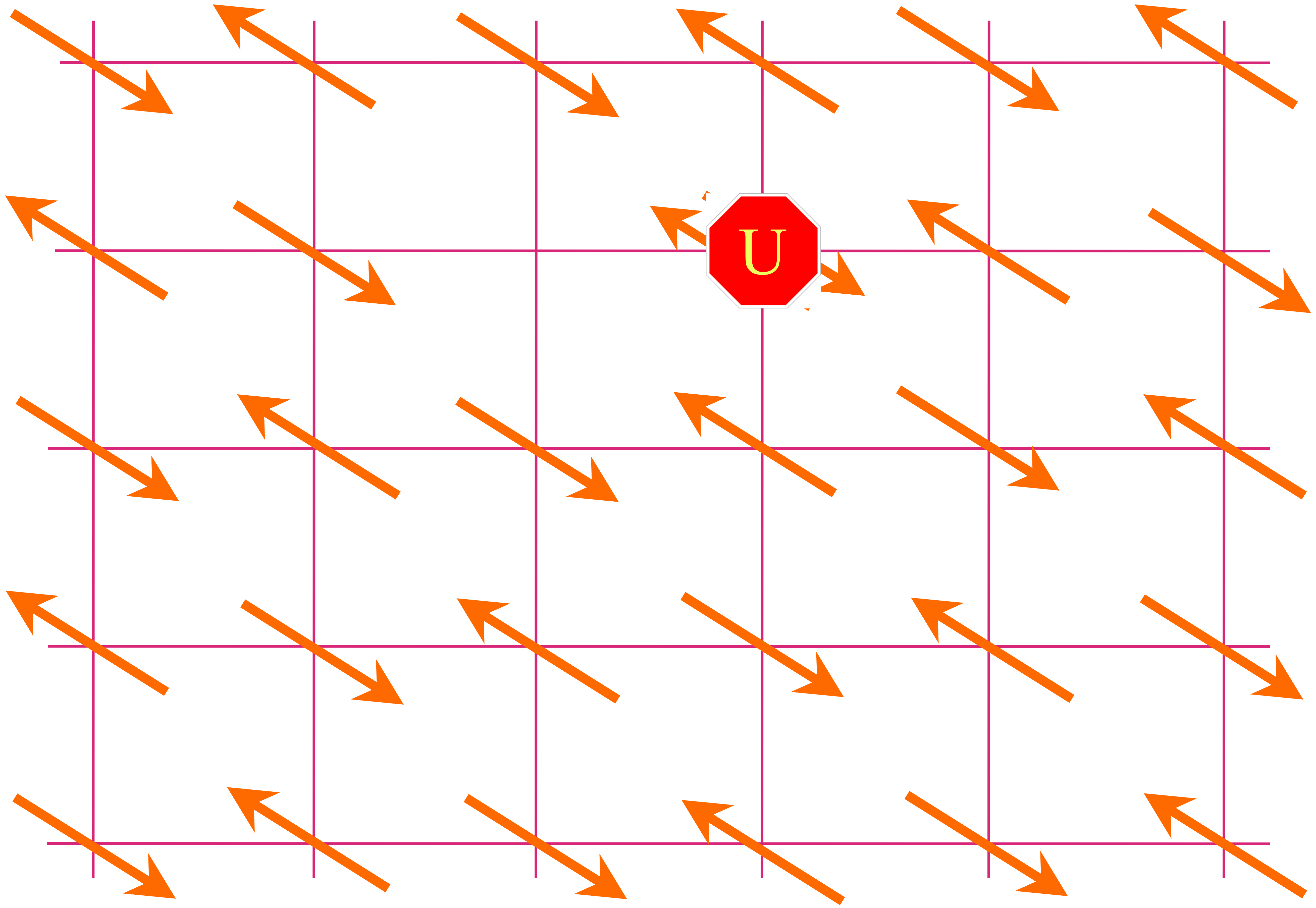


Insulating antiferromagnet

$$\mathcal{H}_H = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^\dagger_{\mathbf{p}\sigma} c_{\mathbf{p}\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow}$$



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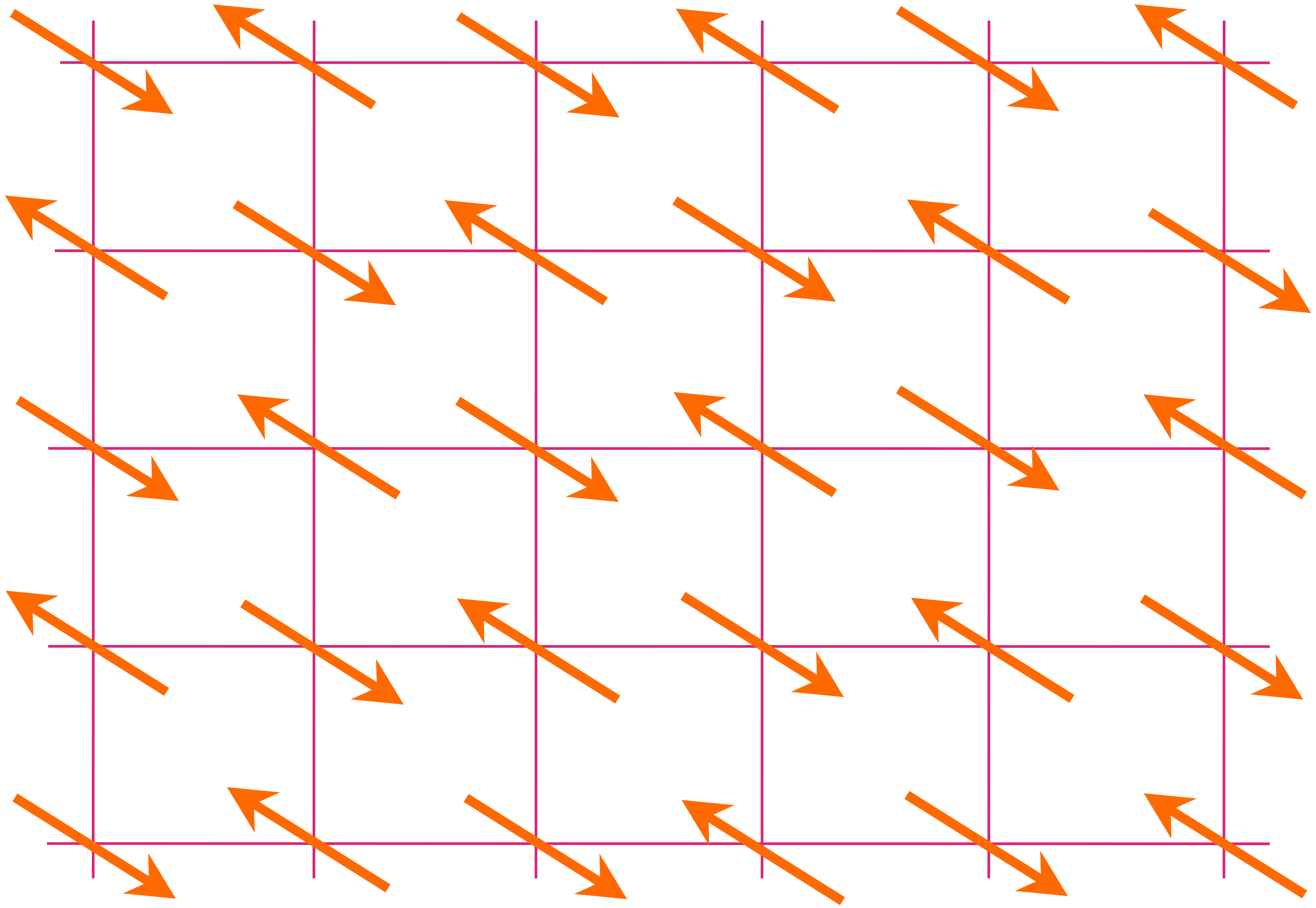

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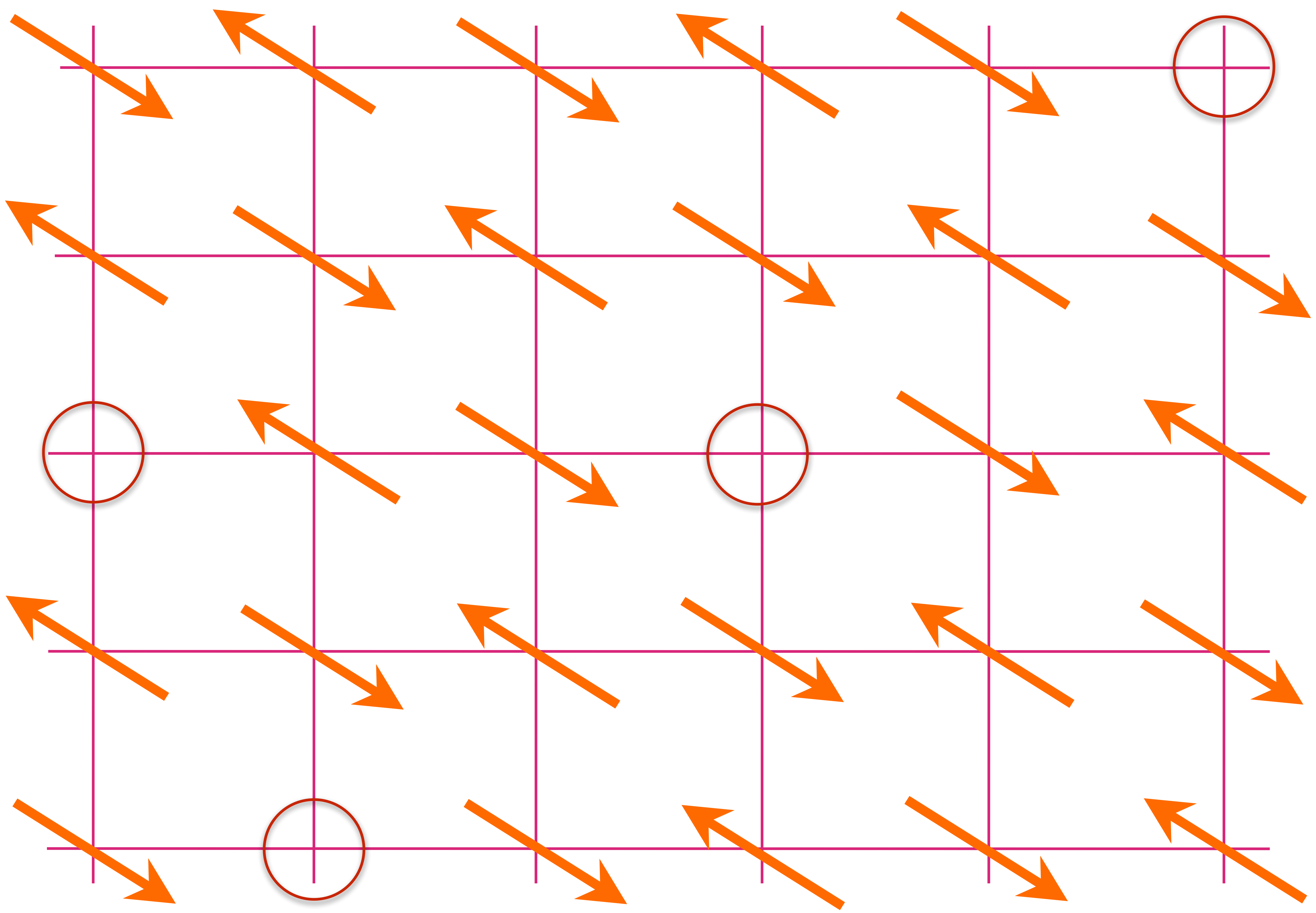

Antiferromagnet doped with hole density p

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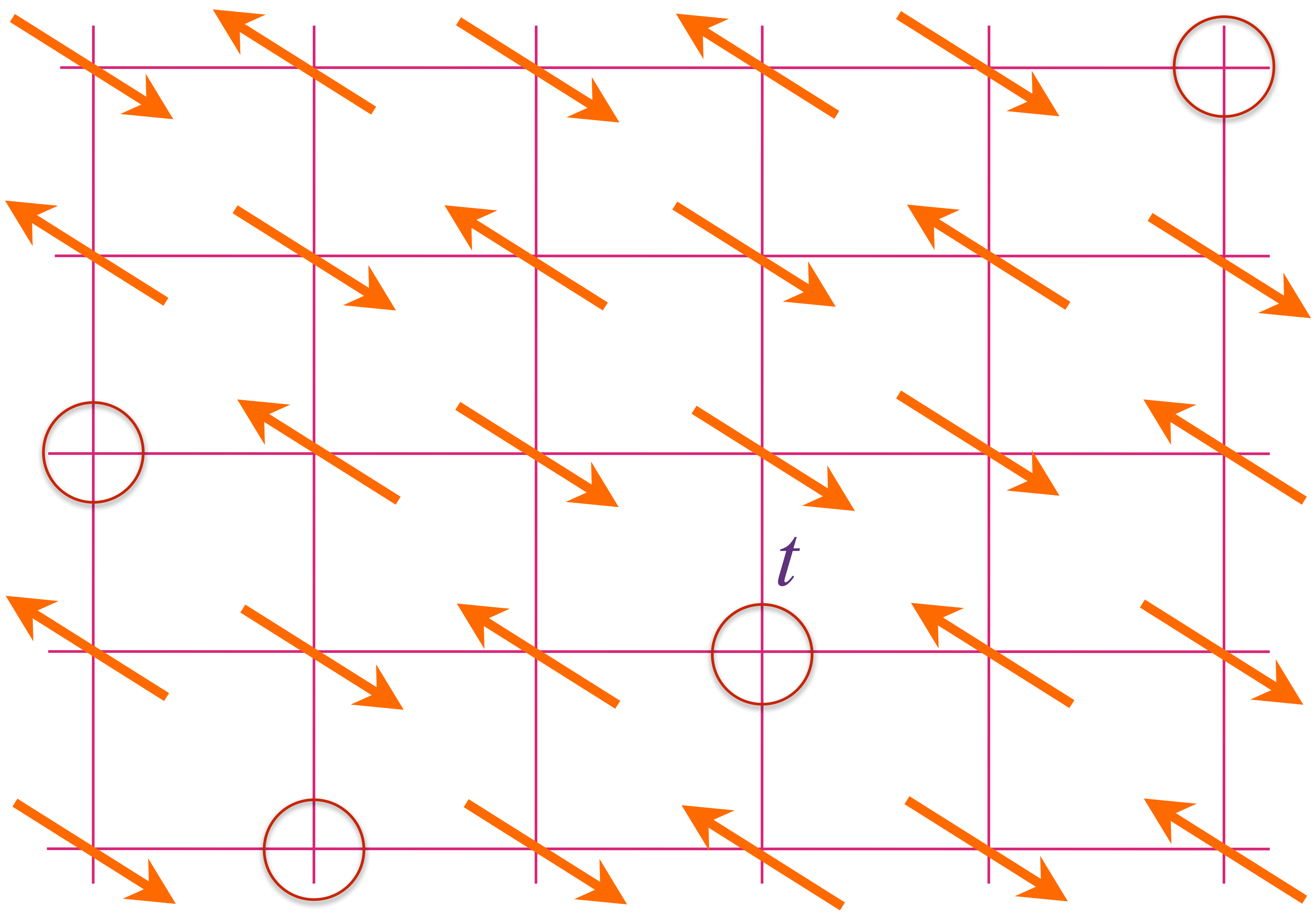

Antiferromagnet doped with hole density p

p mobile holes in a background of fluctuating spins

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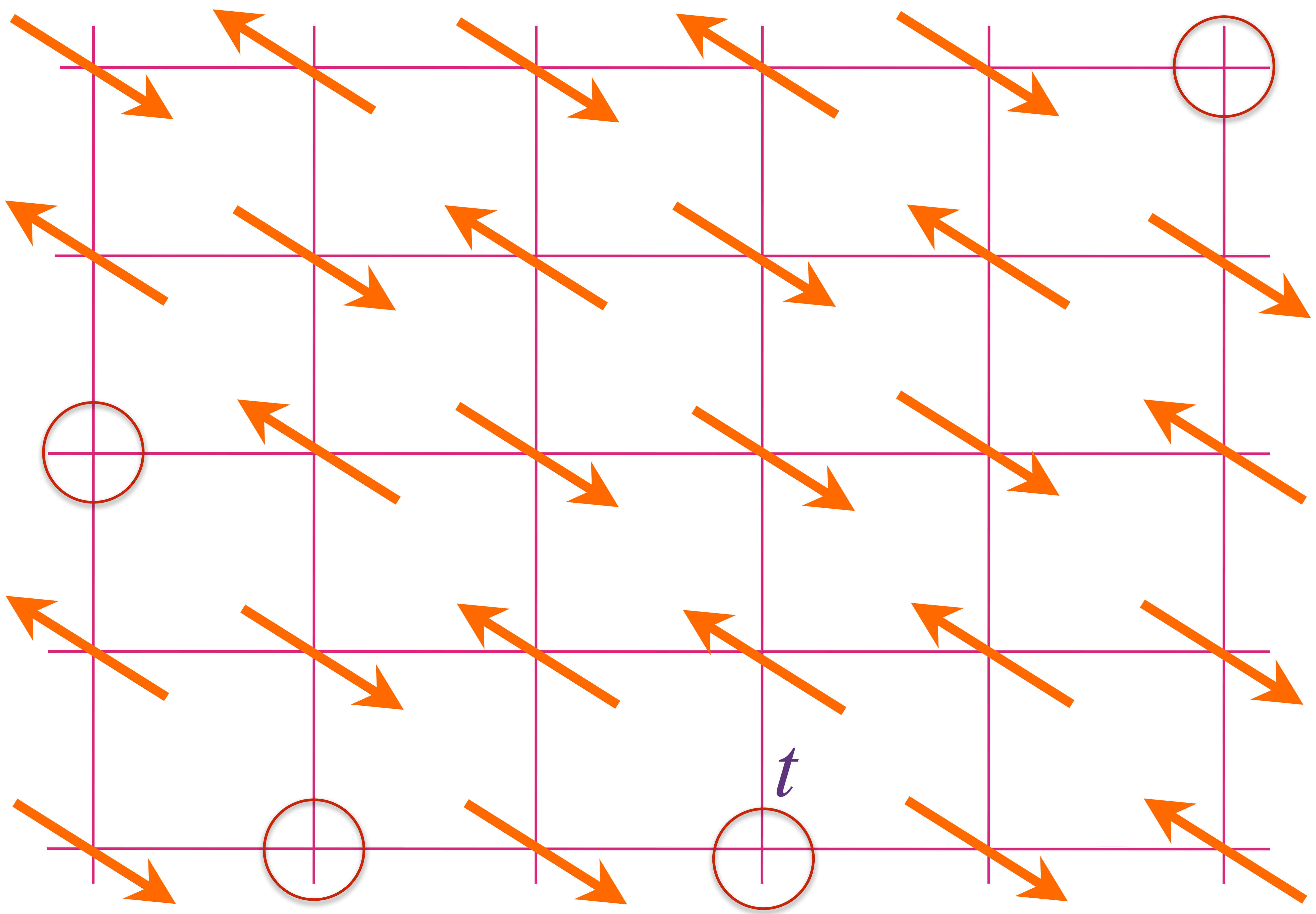

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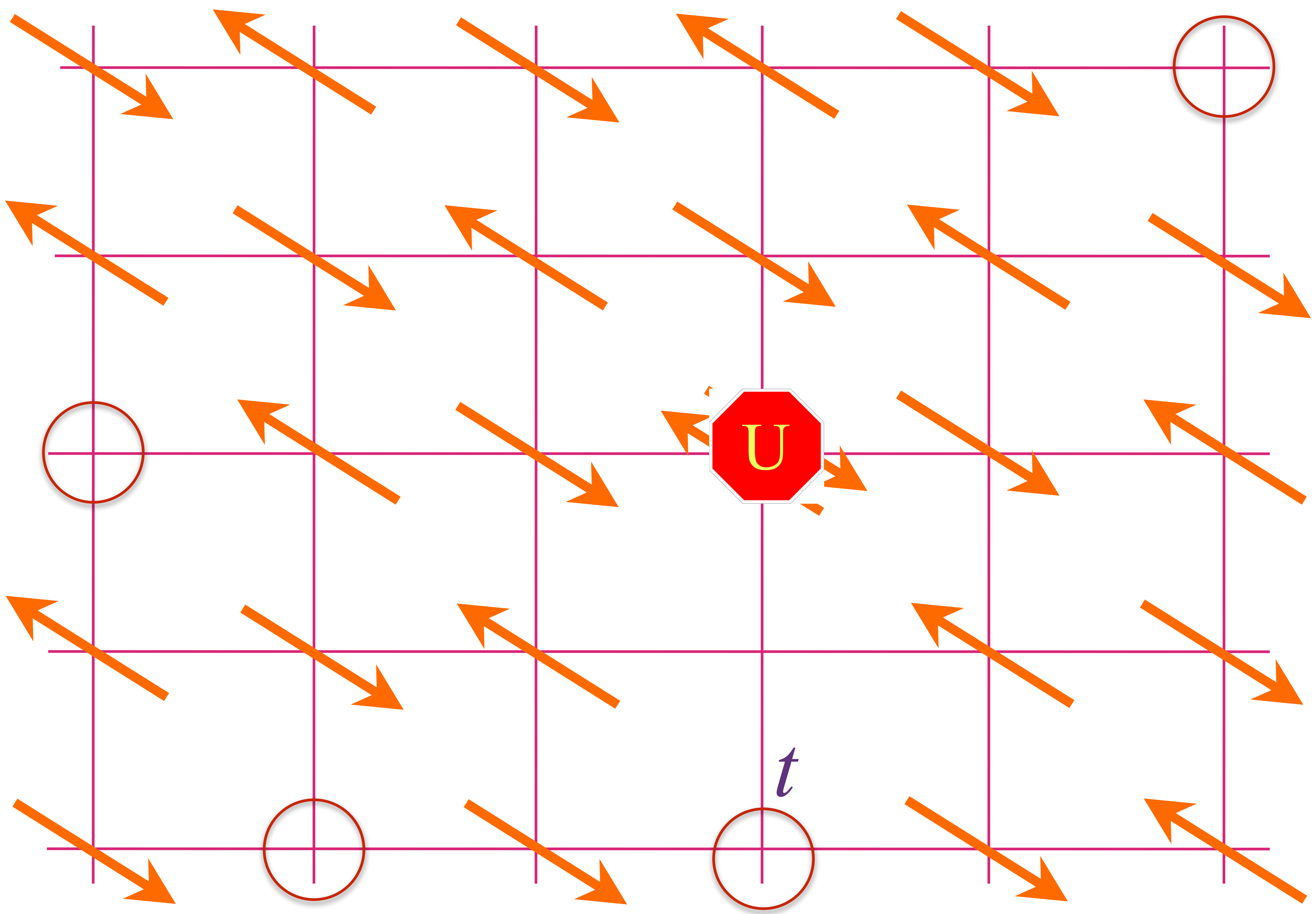

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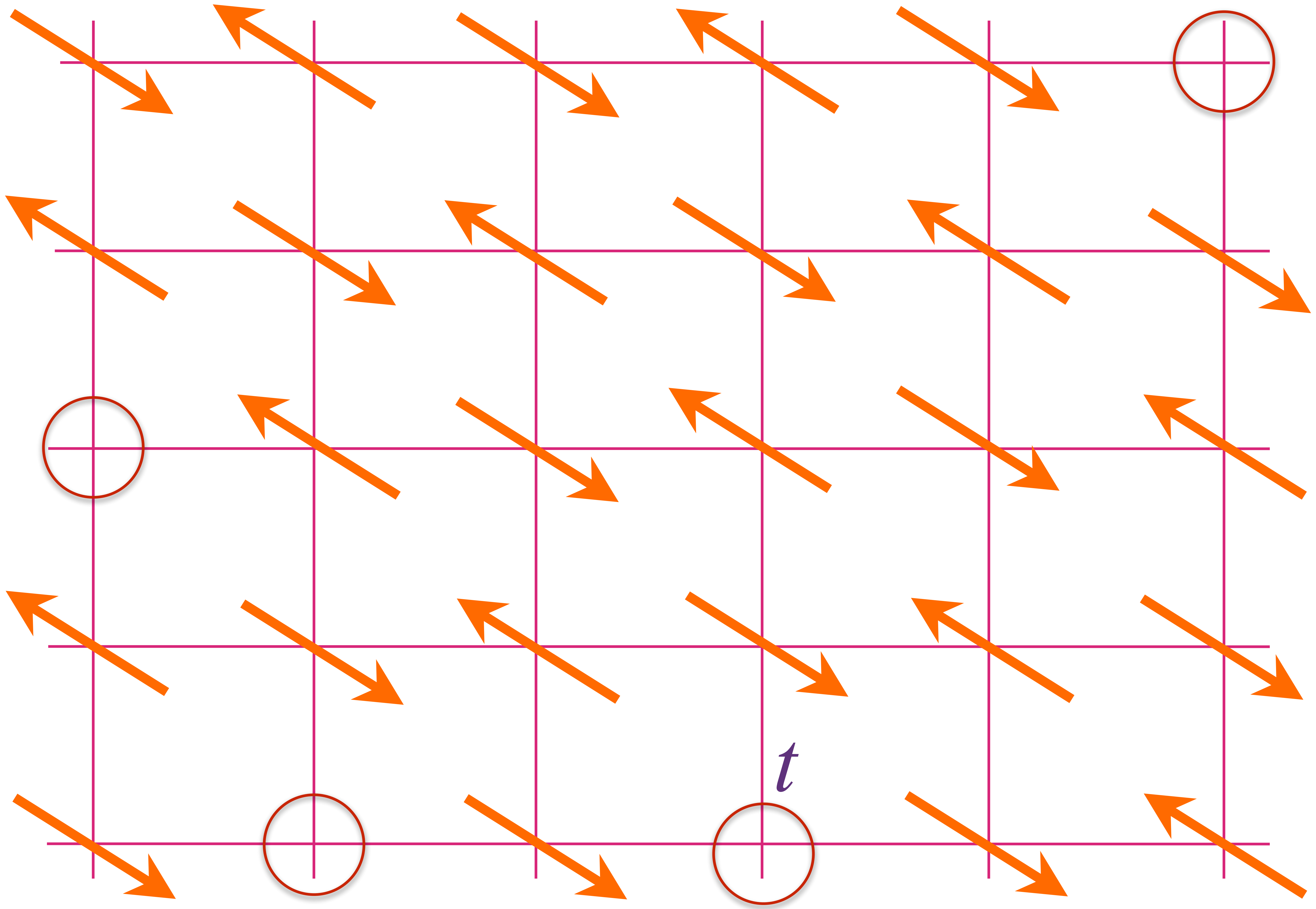

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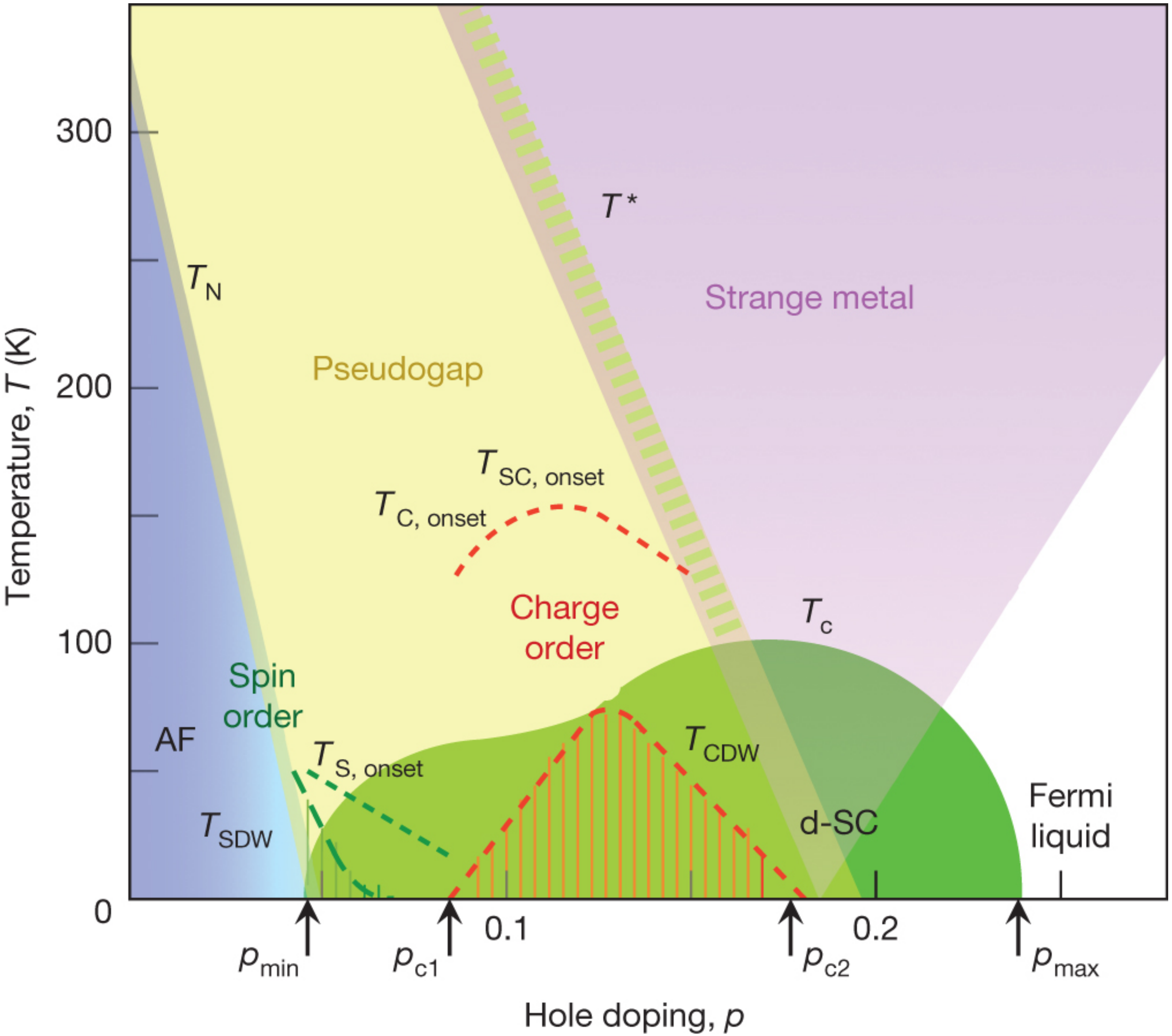

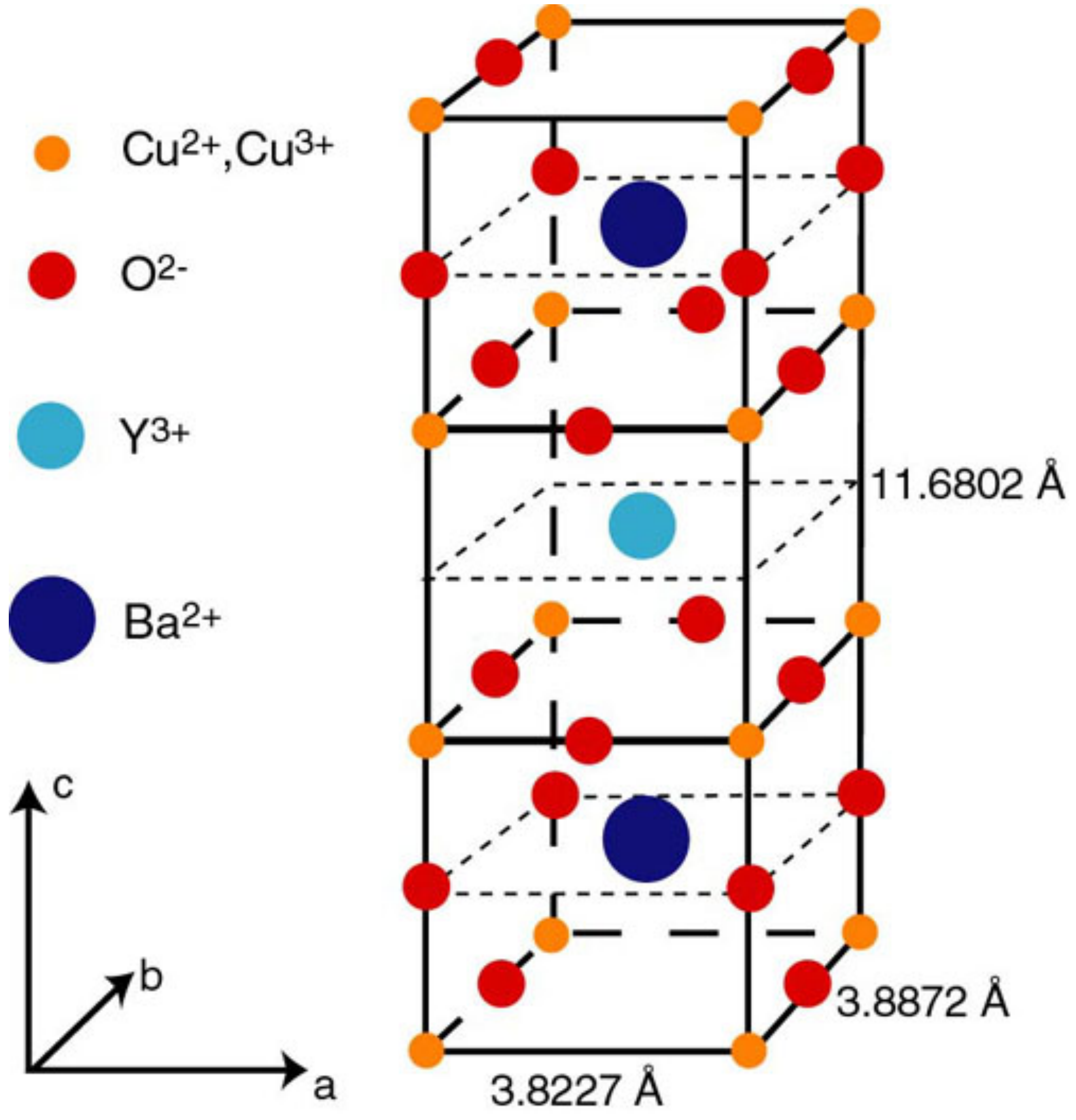

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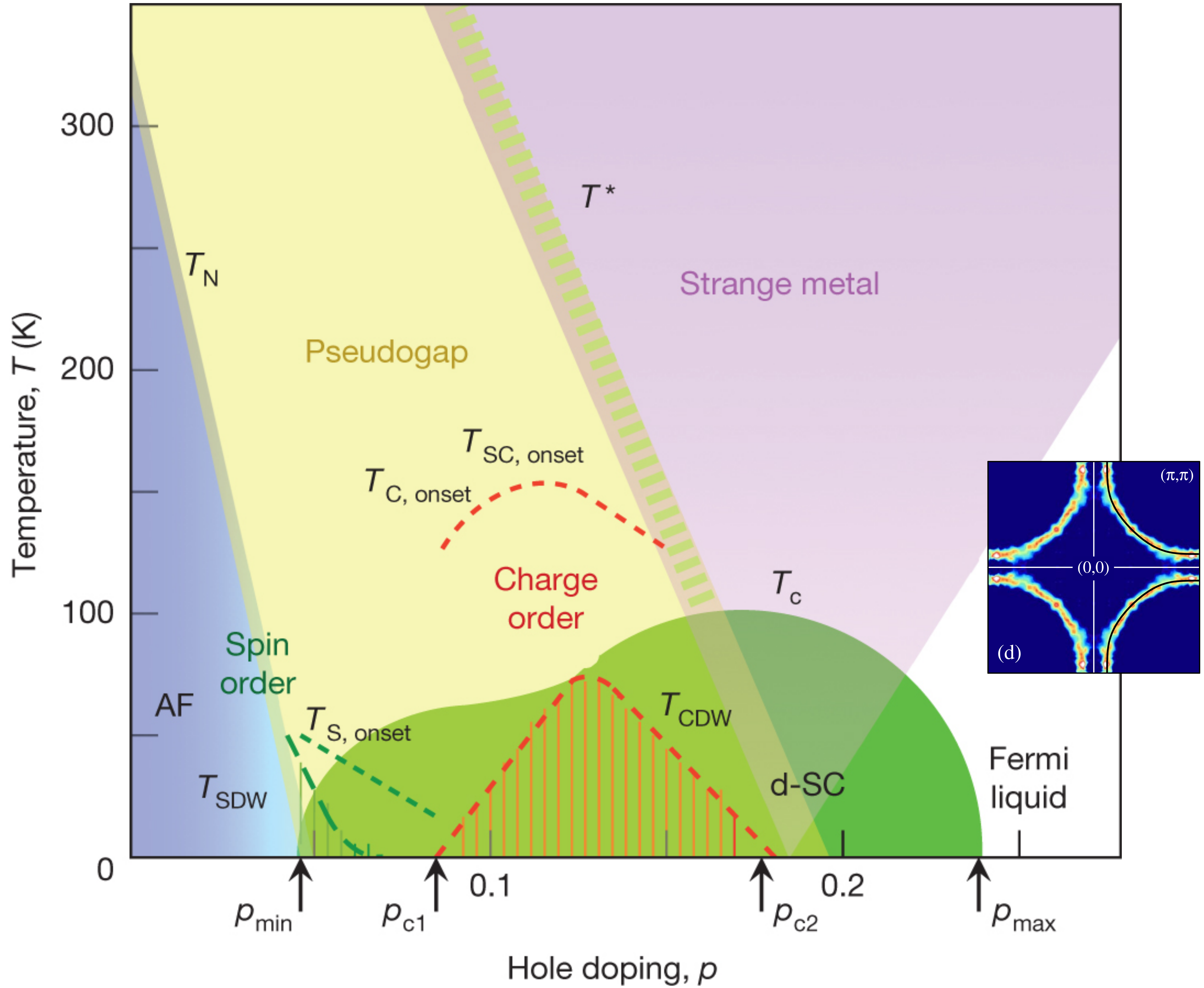
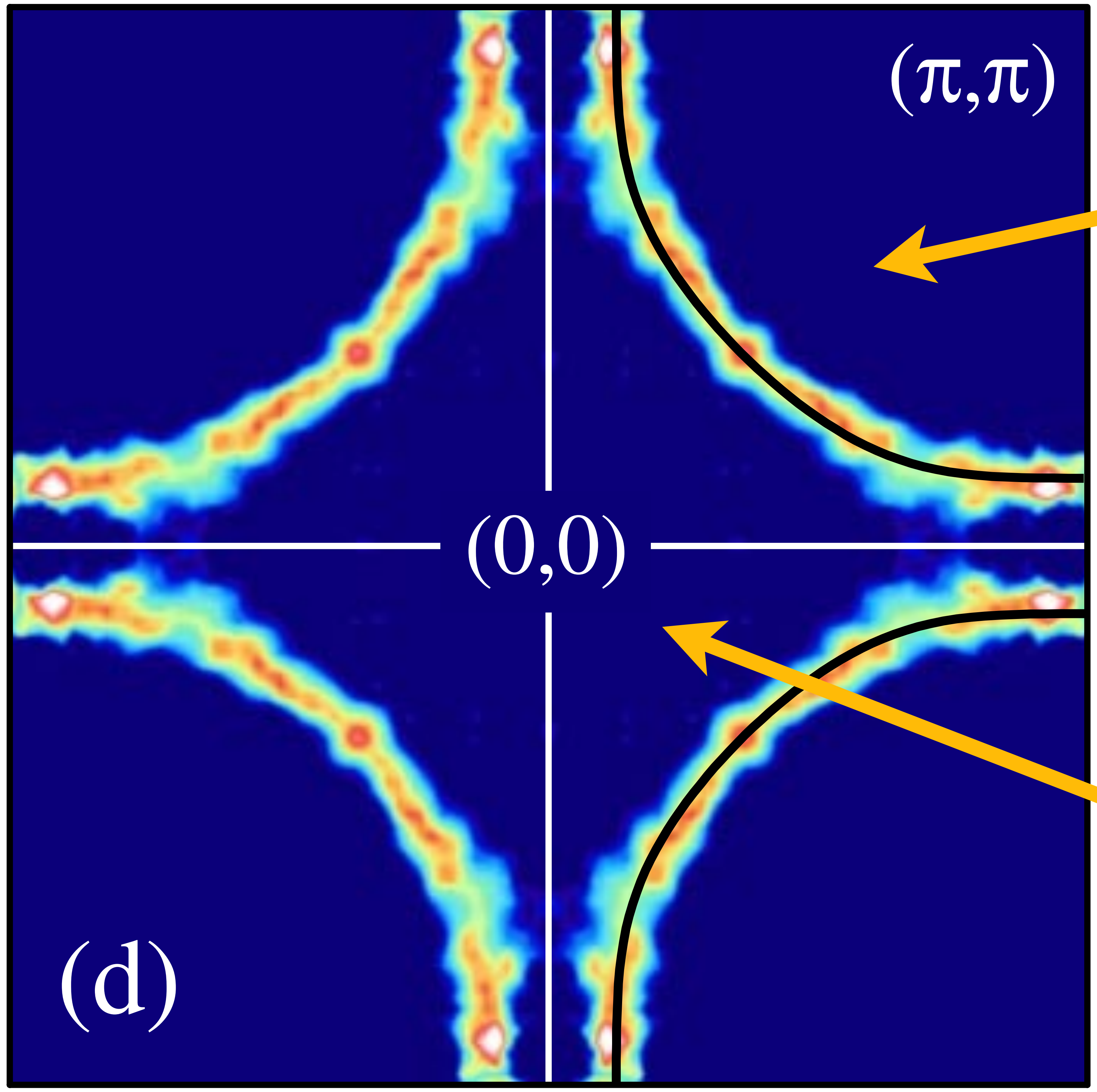


Fermi liquid in the overdoped metal

Photoemission at large p



$1+p$ holes

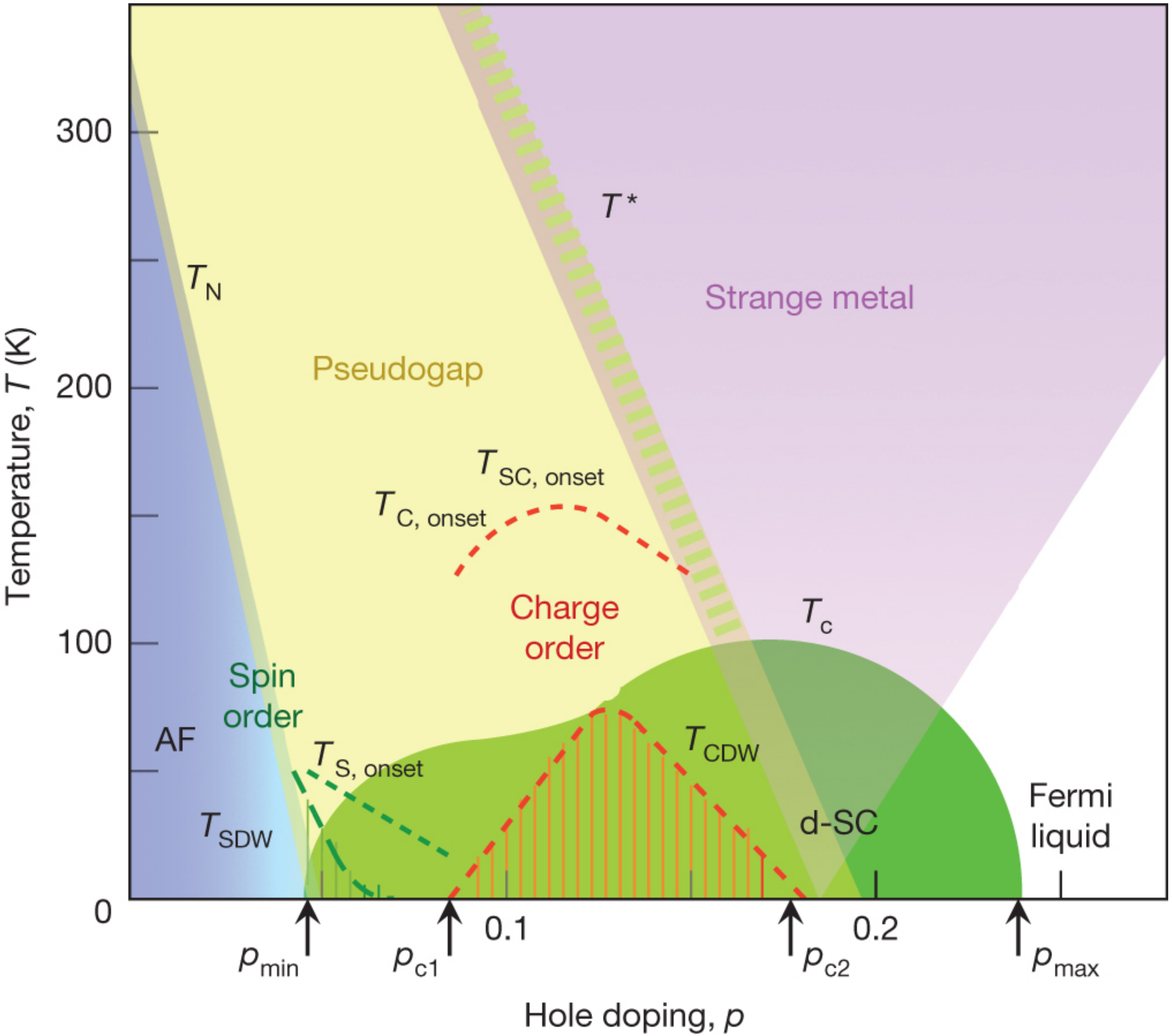
1-p electrons

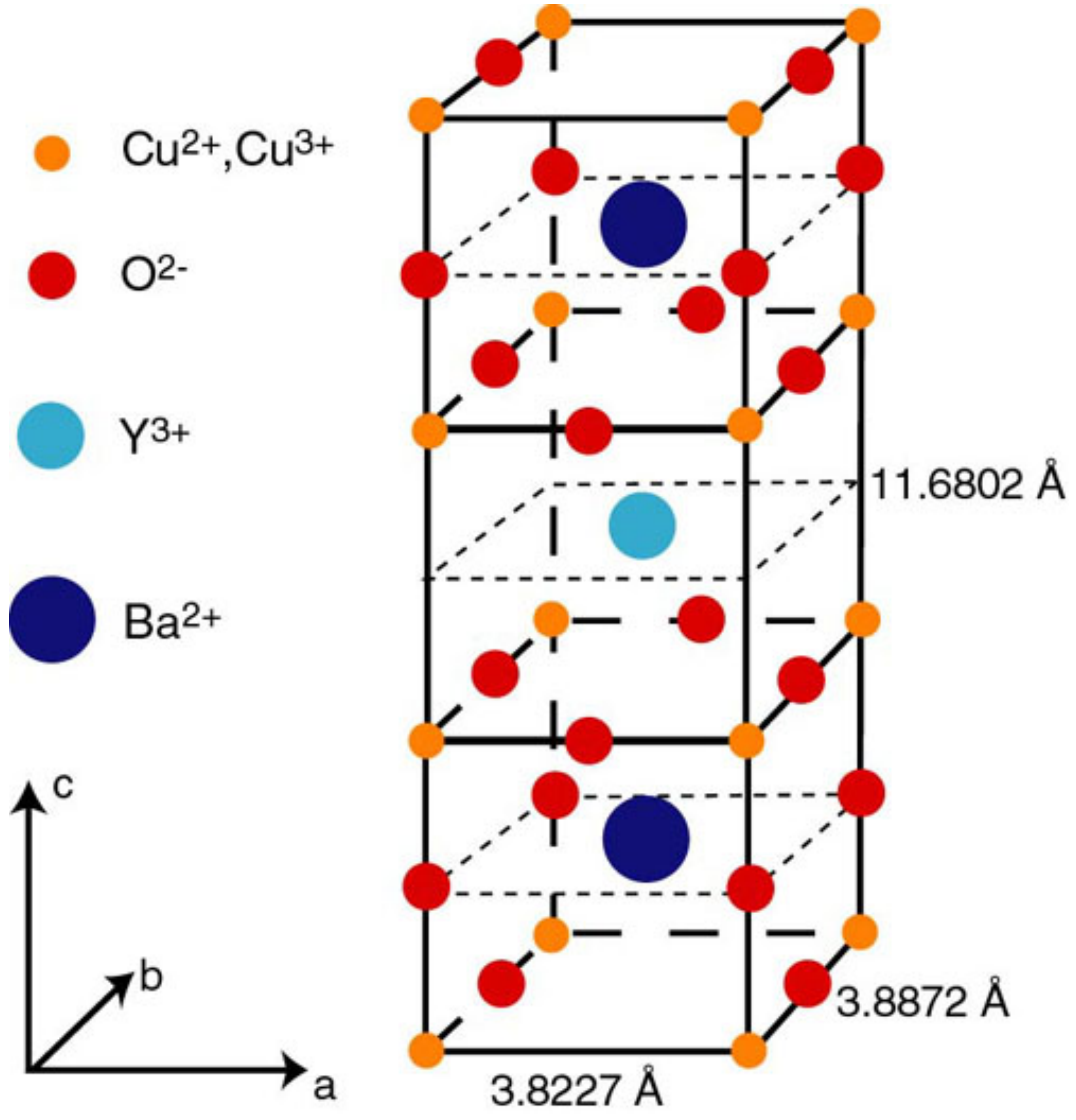
Overdoped $Tl_2Ba_2CuO_{6+\delta}$
$T_c = 30K$

$1+p$ mobile holes in a filled band of 2 electrons per site

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

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





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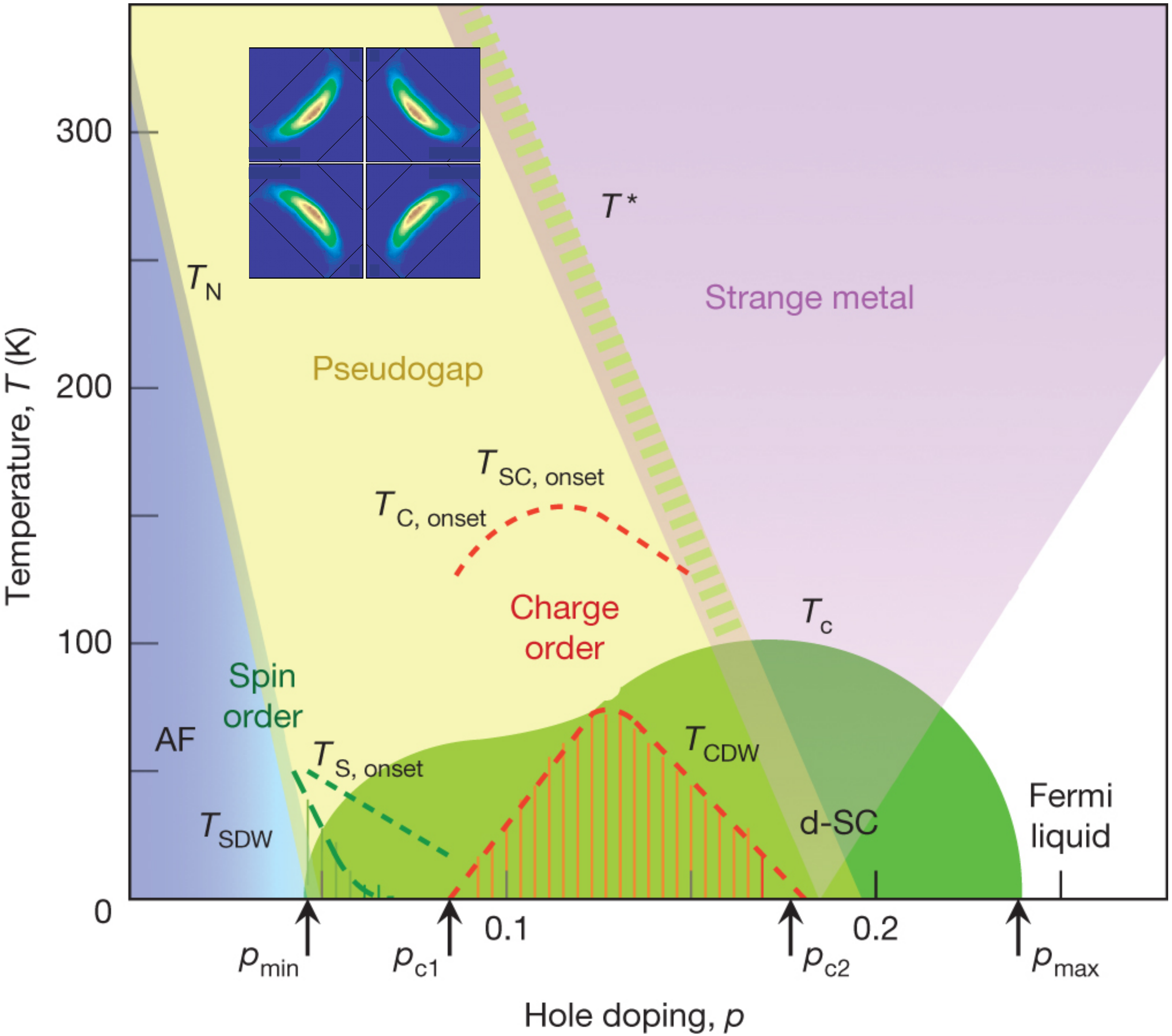
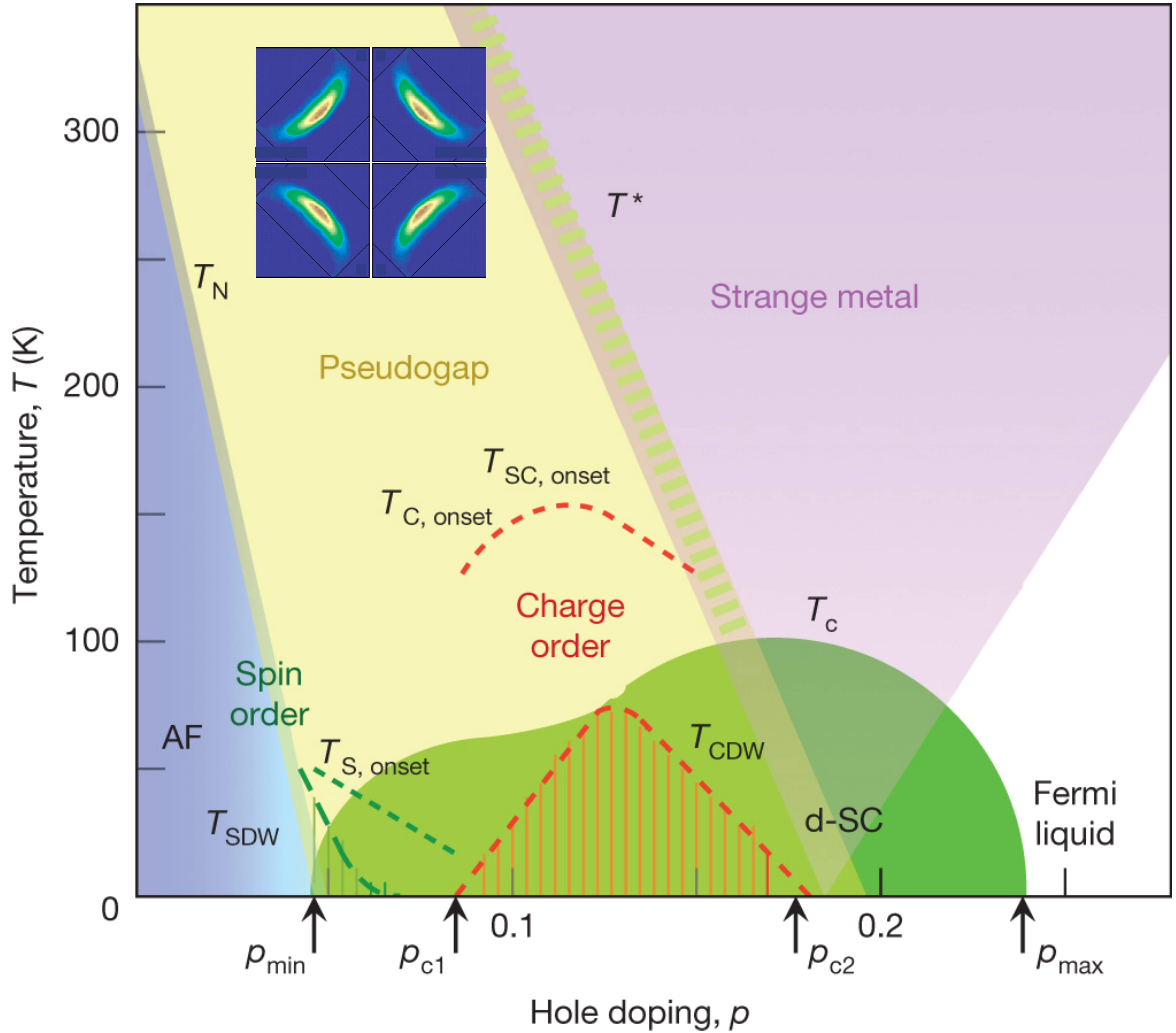
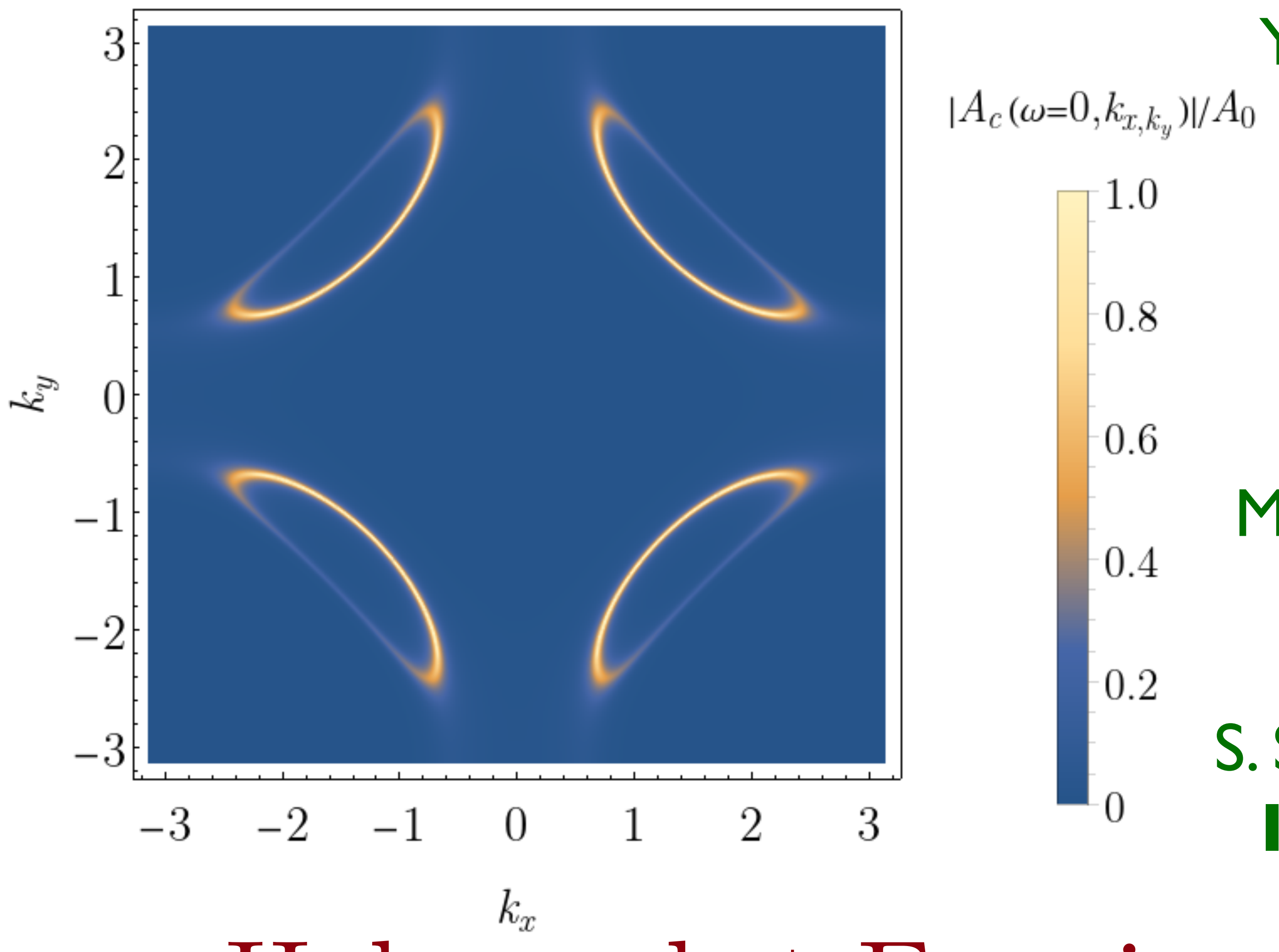


Pseudogap metal with "Fermi arcs"

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





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

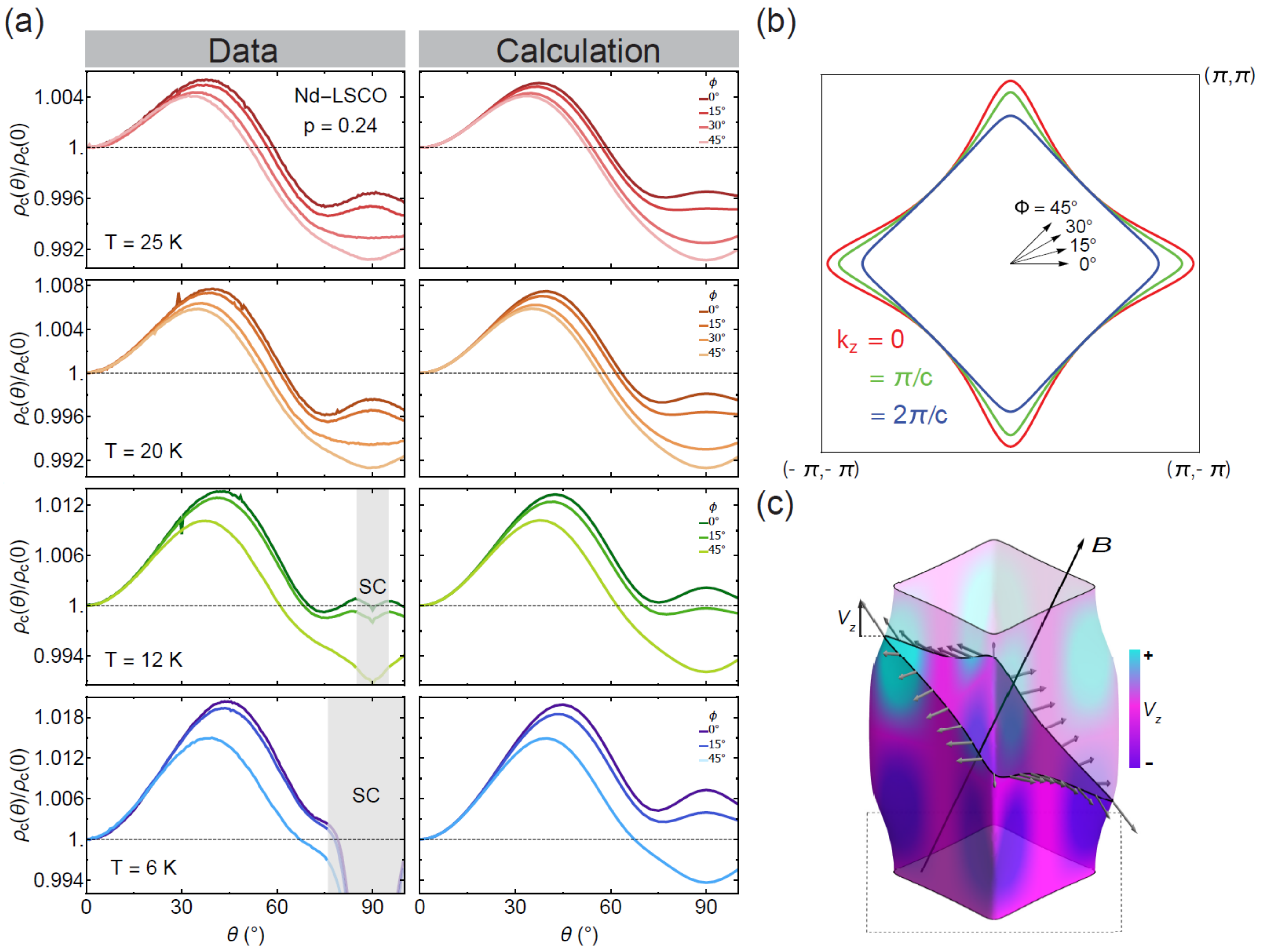
E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, and S. Sachdev, *Phys. Rev. B* **105**, 075146 (2022)

Hole pocket Fermi surfaces of size p with charge e, spin-1/2 quasiparticles

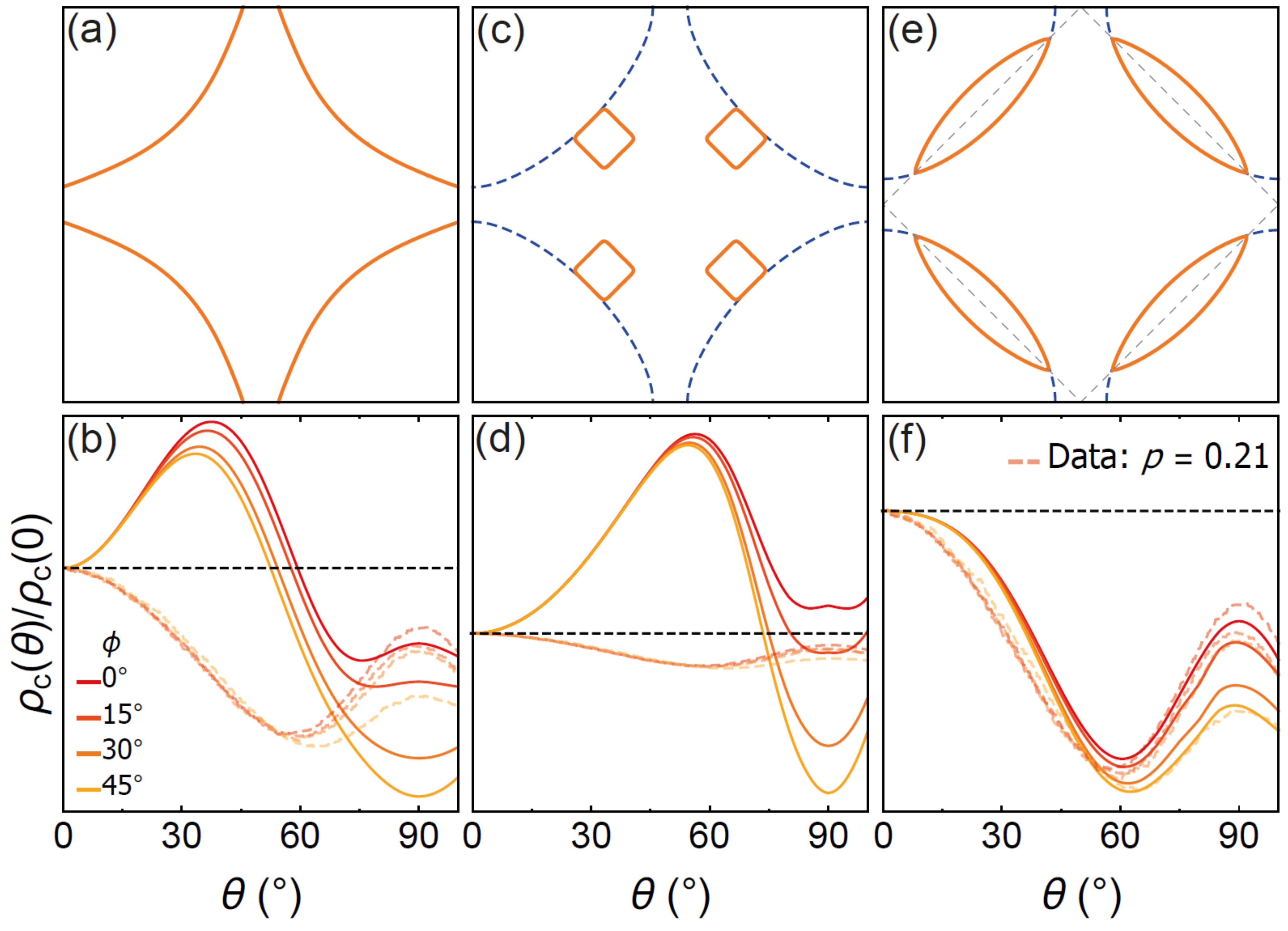
Kai-Yu Yang, T. M. Rice, Fu-Chun Zhang, *Phys. Rev. B* **73**, 174501 (2006).
T. D. Stanescu and G. Kotliar, *Phys. Rev. B* **74**, 125110 (2006).
C. Berthod, T. Giamarchi, S. Biermann, and A. Georges, *Phys. Rev. Lett.* **97**, 136401 (2006).
S. Sakai, Y. Motome, M. Imada, *Phys. Rev. Lett.* **102**, 056404 (2009).
J. Skolimowski and M. Fabrizio, *Phys. Rev. B* **106**, 045109 (2022).
N. Wagner….A. Georges, G. Sangiovanni, arXiv:2301.05588
Jinchao Zhao, Gabriele La Nave, Philip Phillips, arXiv:2304.04787.

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)

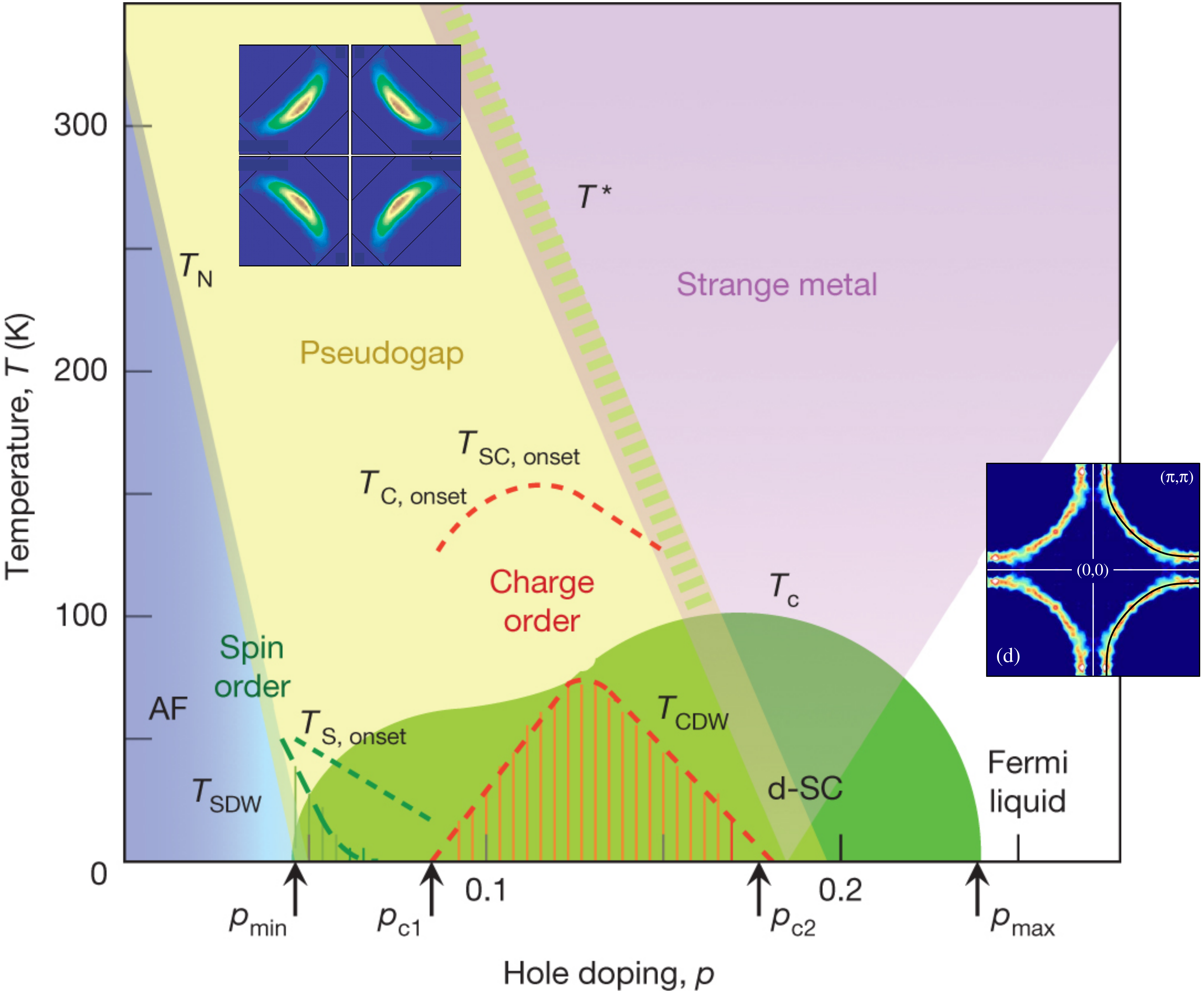


$p > p_c$ Large Fermi surface



$p < p_c$ Reconstructed Fermi surface

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



Build a theory for the phase diagram from a theory of the pseudogap metal as a 'metastable' $T = 0$ quantum phase.

Lowest T phases obtained from pseudogap metal should connect smoothly to conventionally order phases obtained from the Fermi liquid.

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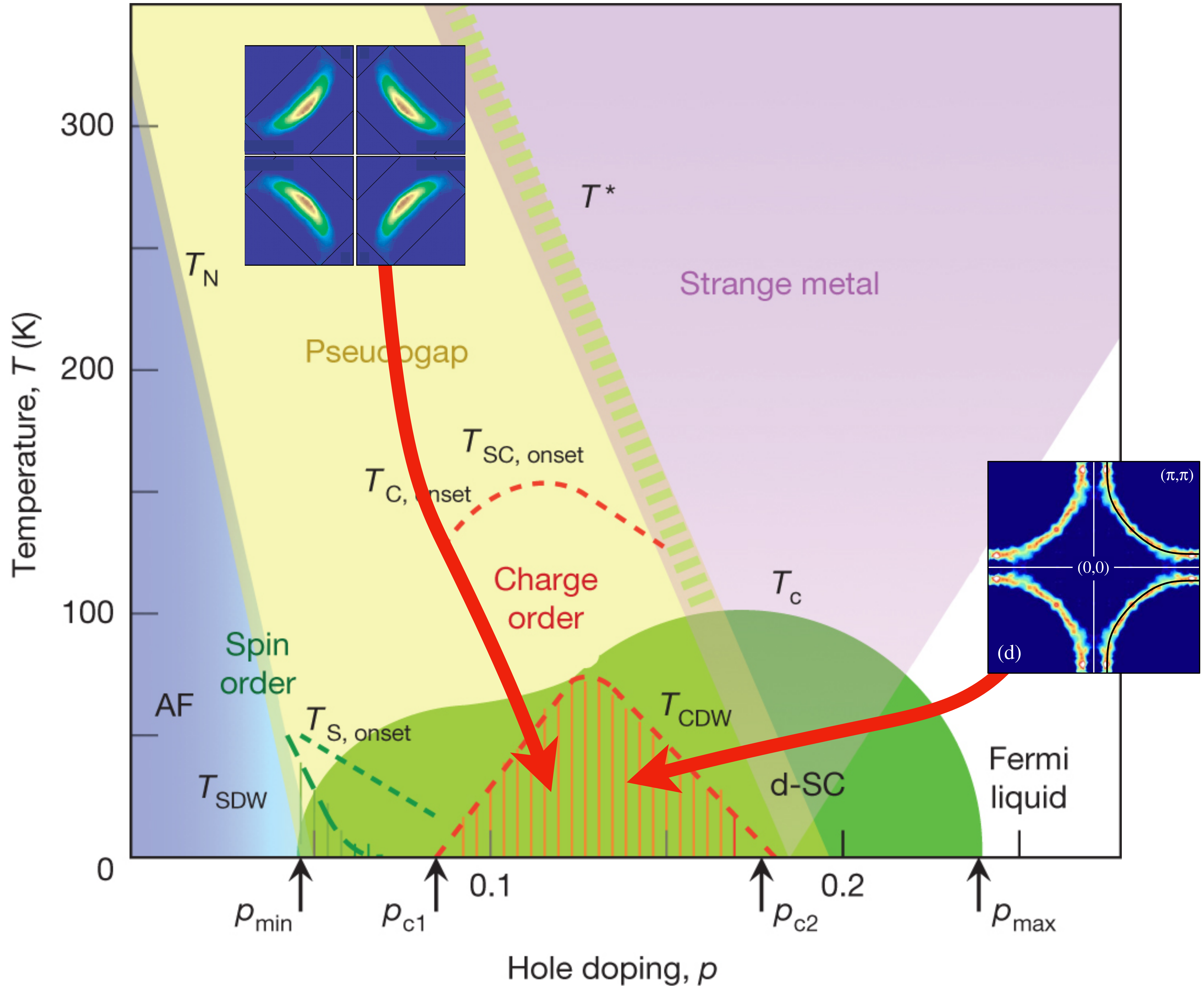

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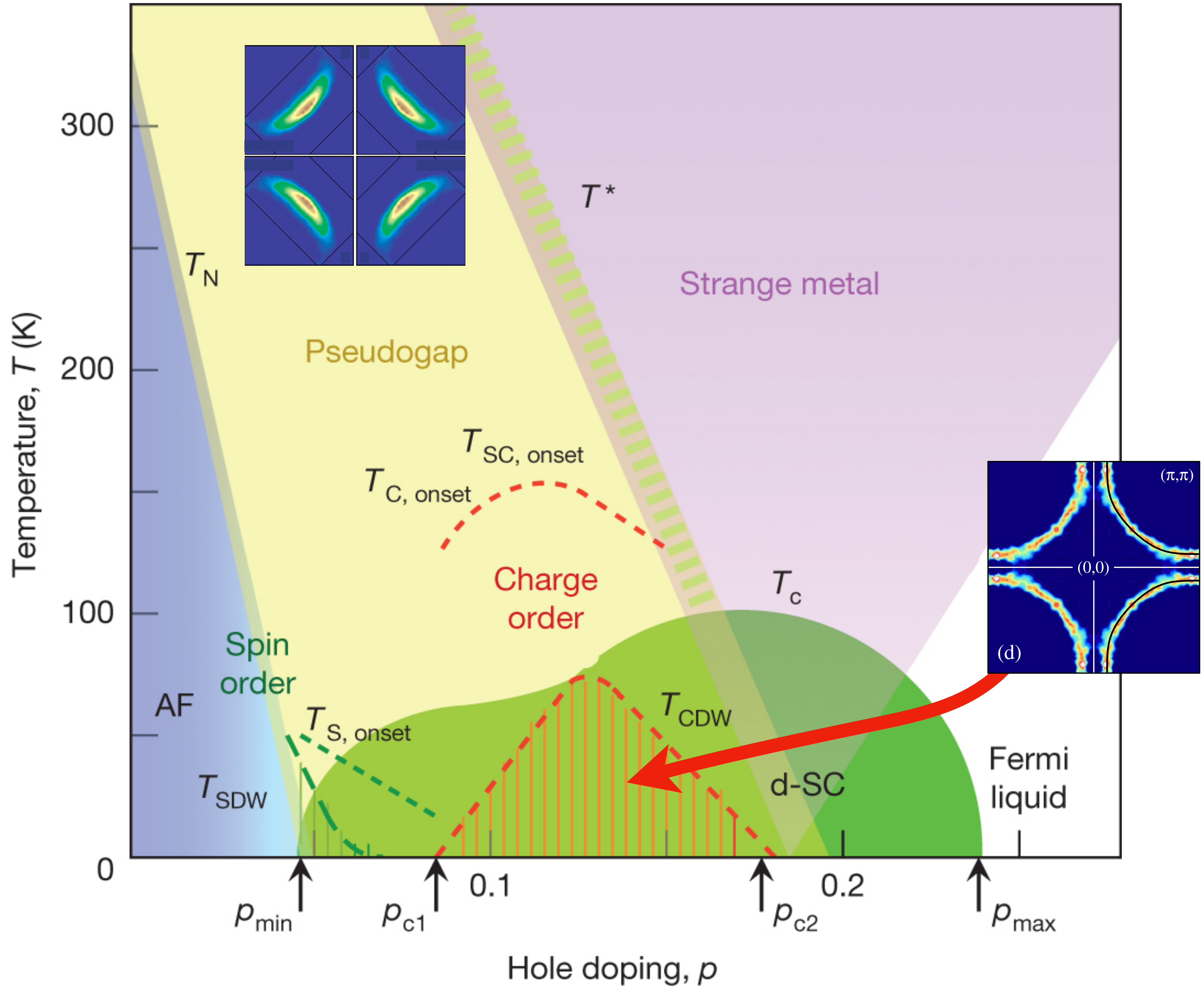

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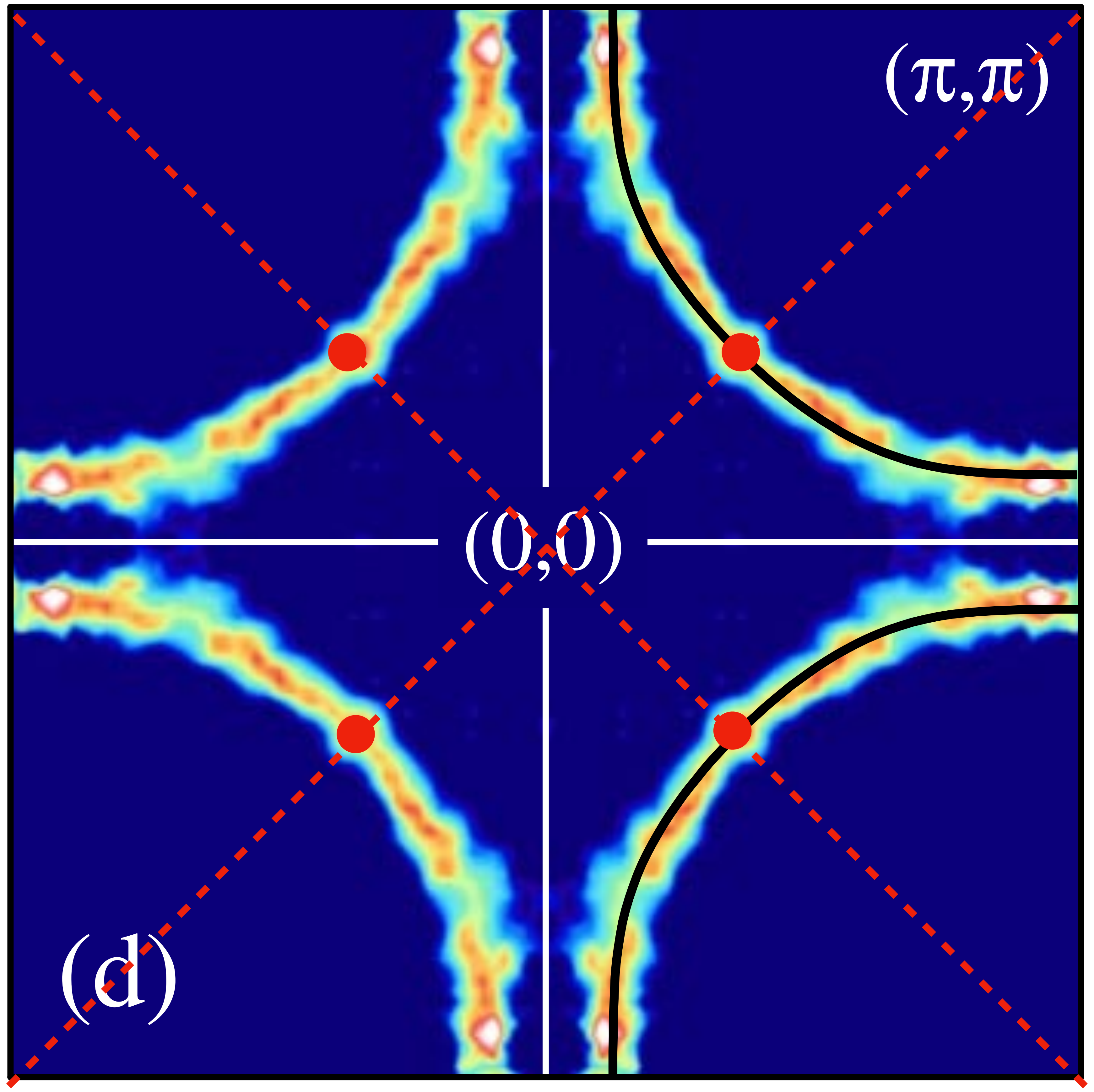


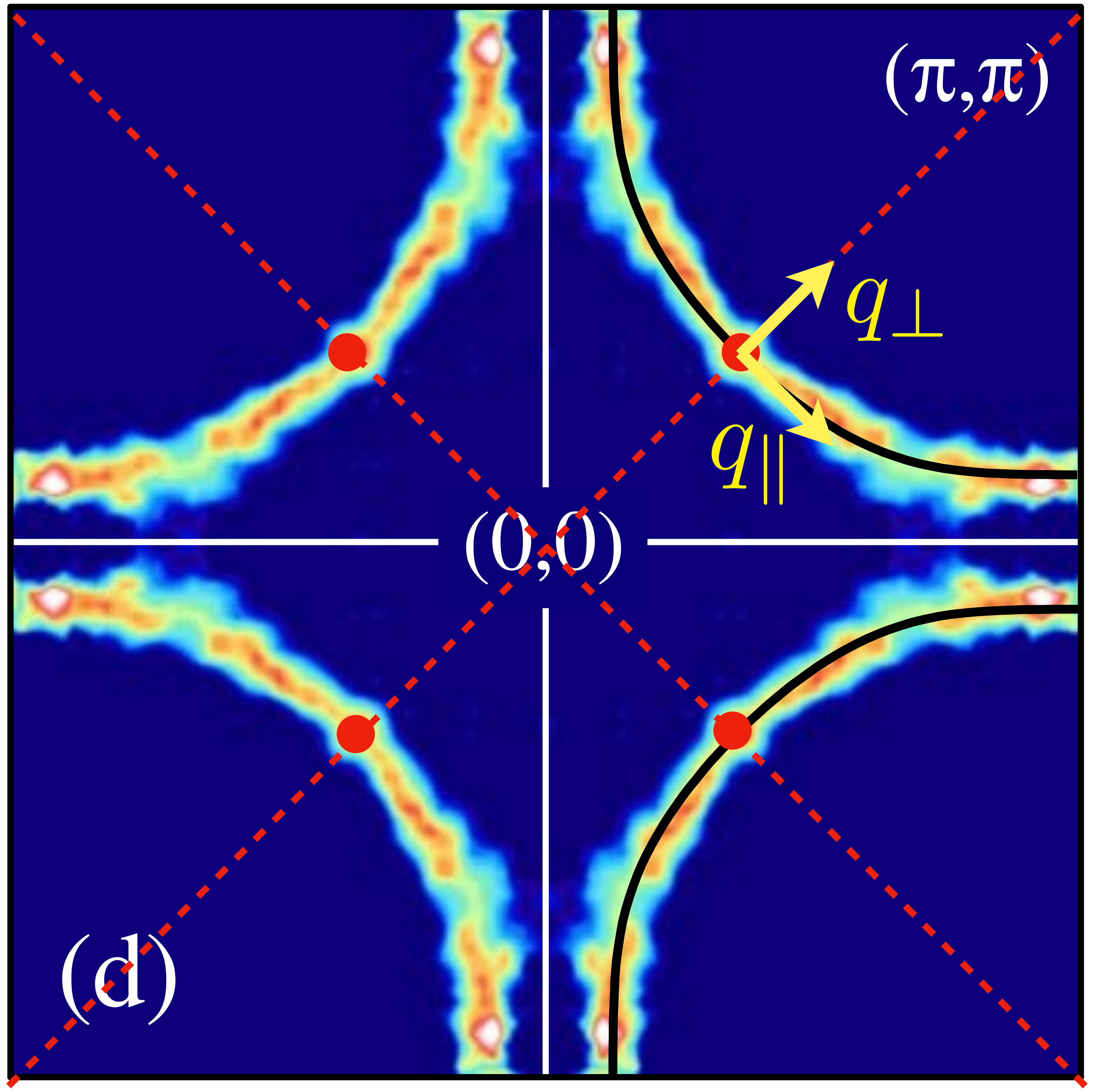
BCS/Bogoliubov quasiparticles in a d-wave superconductor

$$E_{\boldsymbol{k}} = \left(\varepsilon_{\boldsymbol{k}}^2 + \Delta_{\boldsymbol{k}}^2\right)^{1/2}$$
$$\Delta_{\boldsymbol{k}} = \Delta_0 \left(\cos k_x - \cos k_y\right)$$

4 nodal points where

$$E_{\boldsymbol{k}_0+\boldsymbol{q}} = \left(v_F^2 q_\perp^2 + v_\Delta^2 q_\parallel^2\right)^{1/2}$$

with $v_F \gg v_\Delta$.



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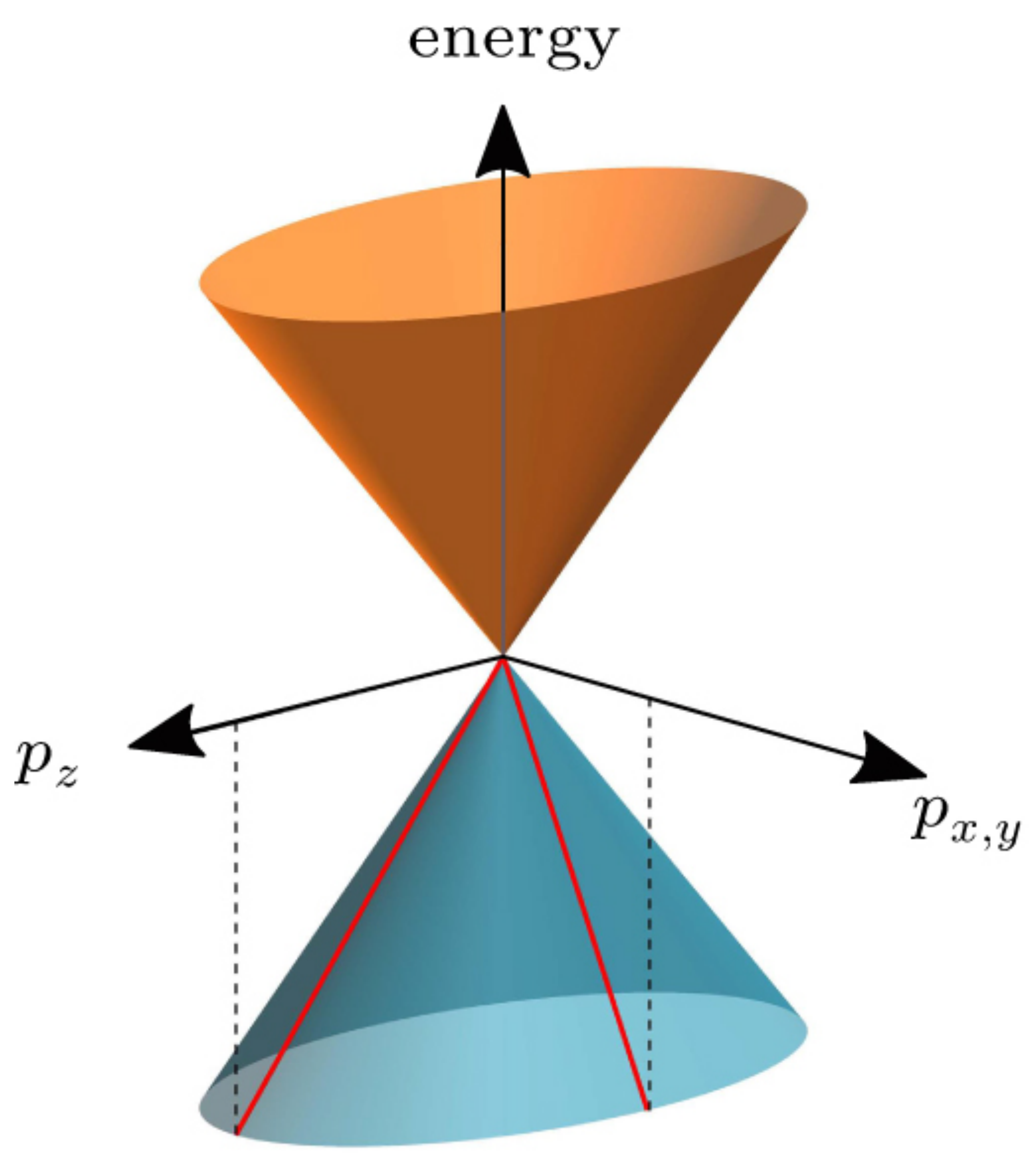

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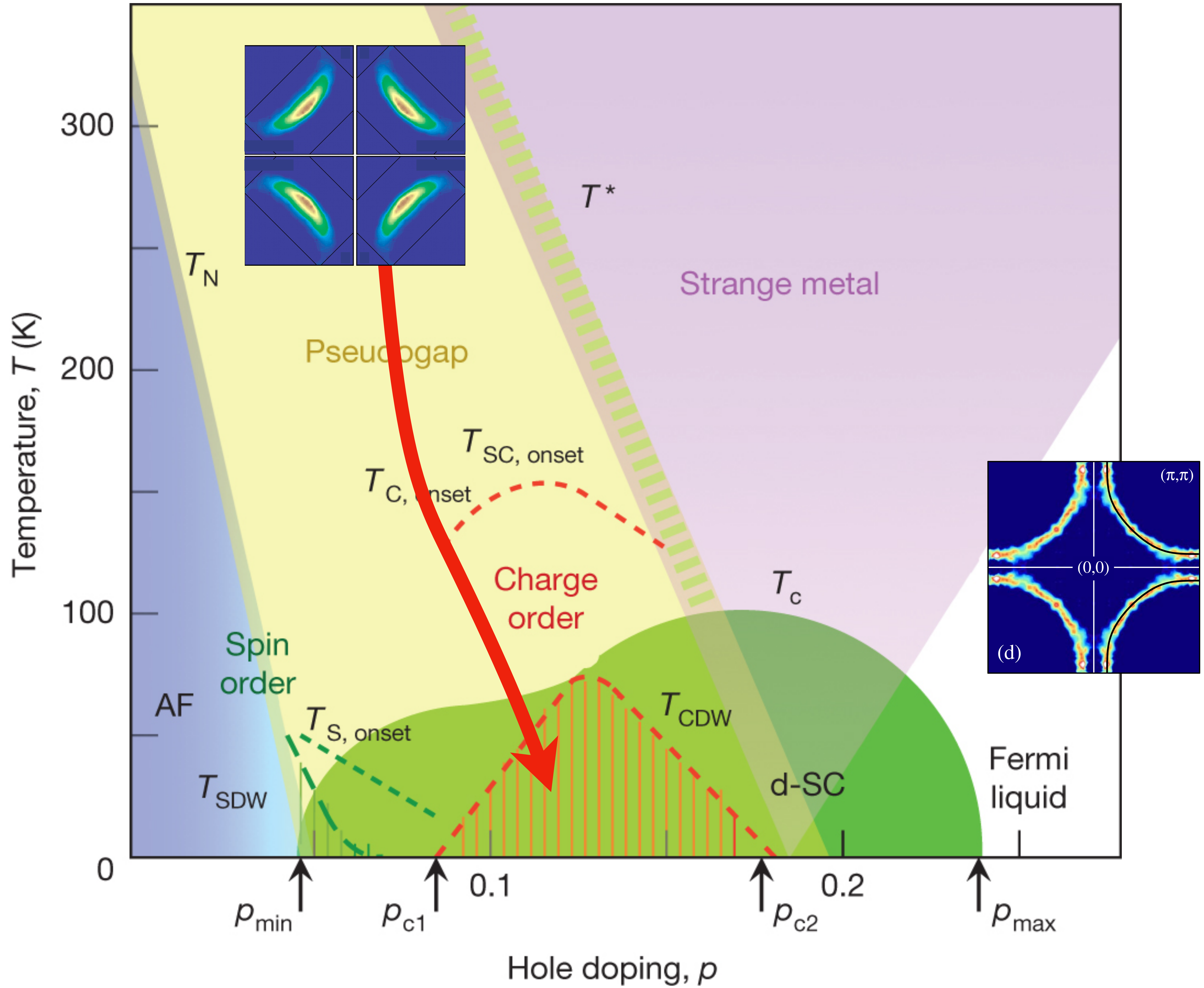

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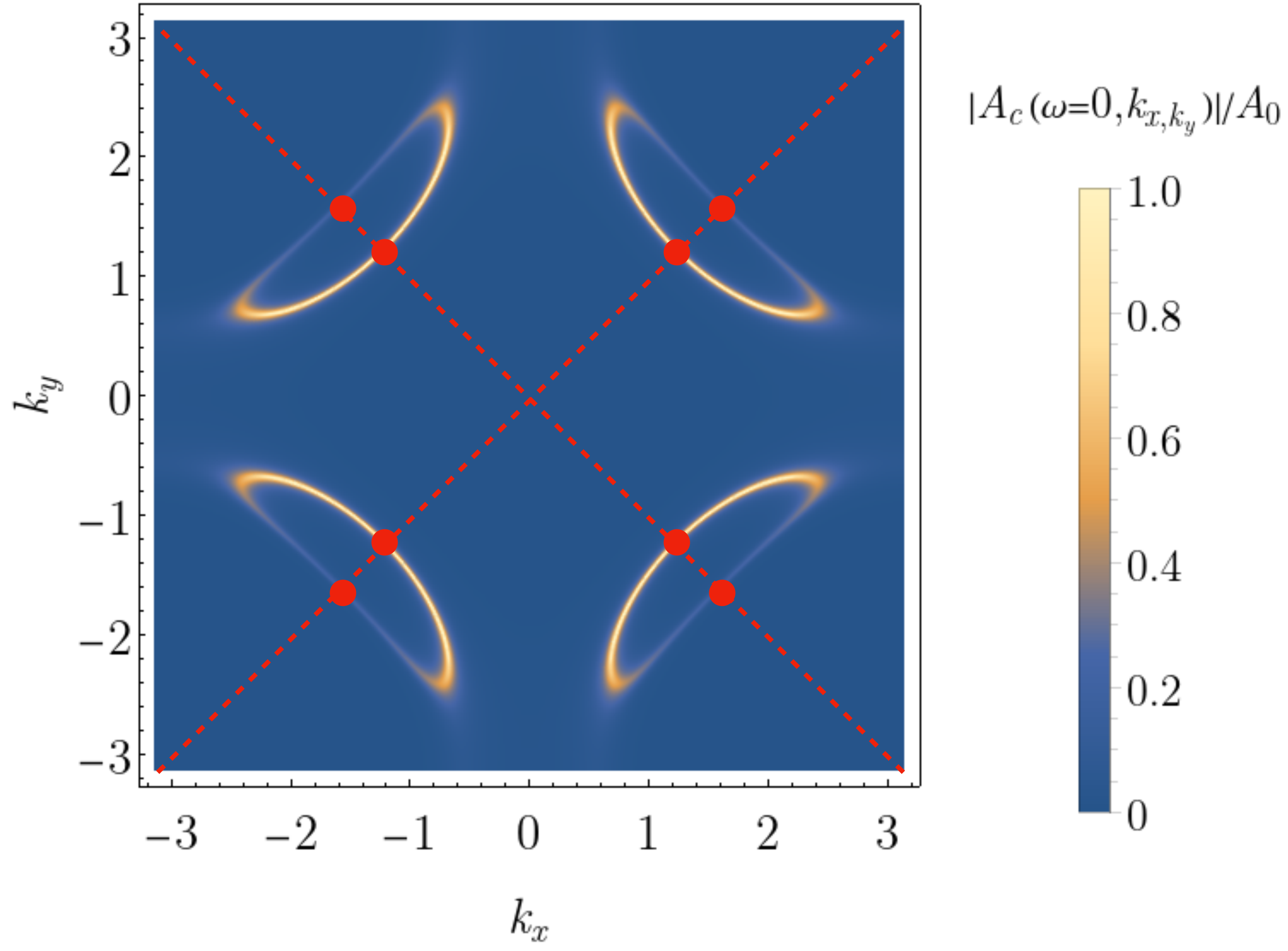

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Adding d-wave pairing
to the hole pockets
leads to 8 nodal points???

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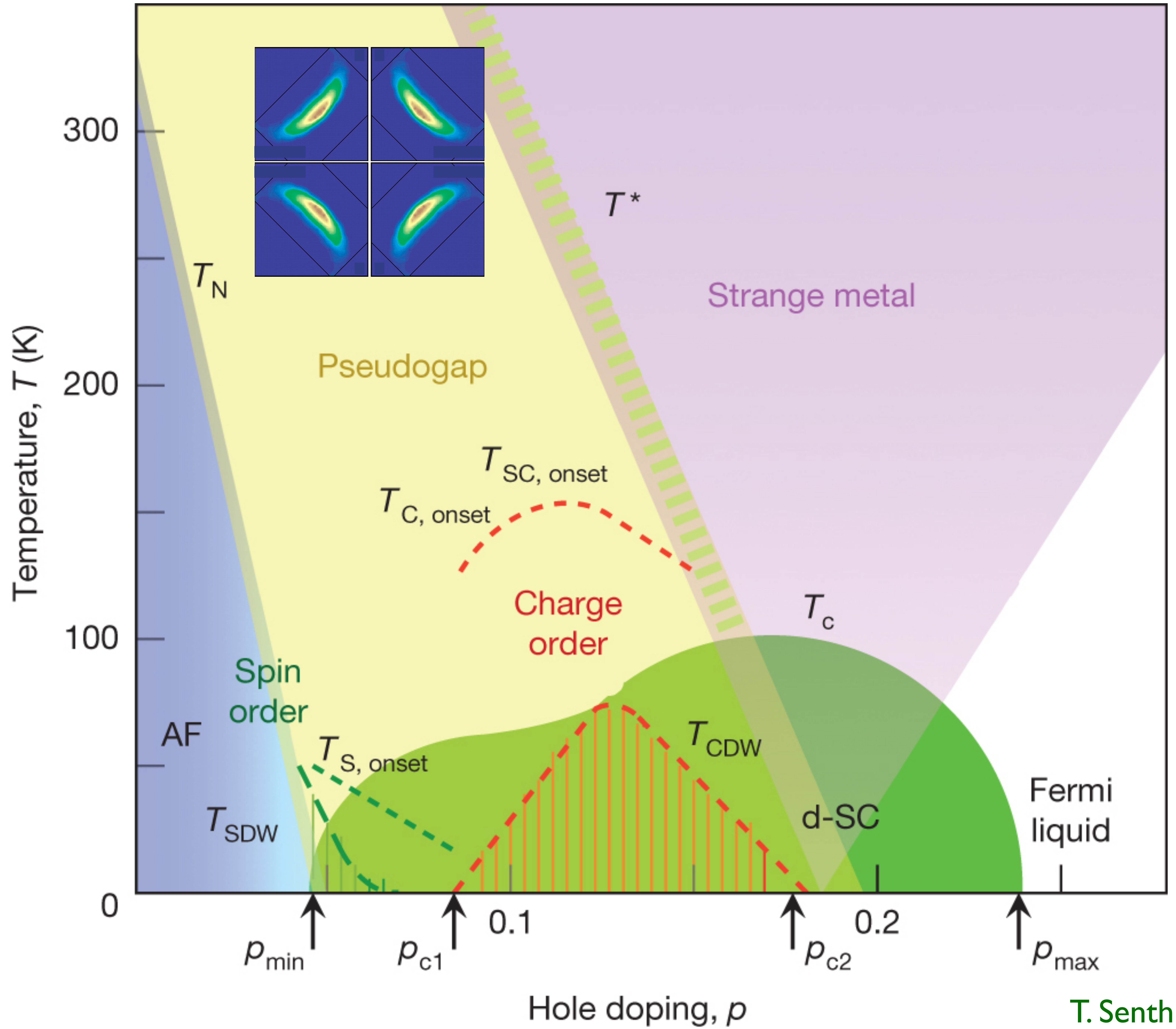

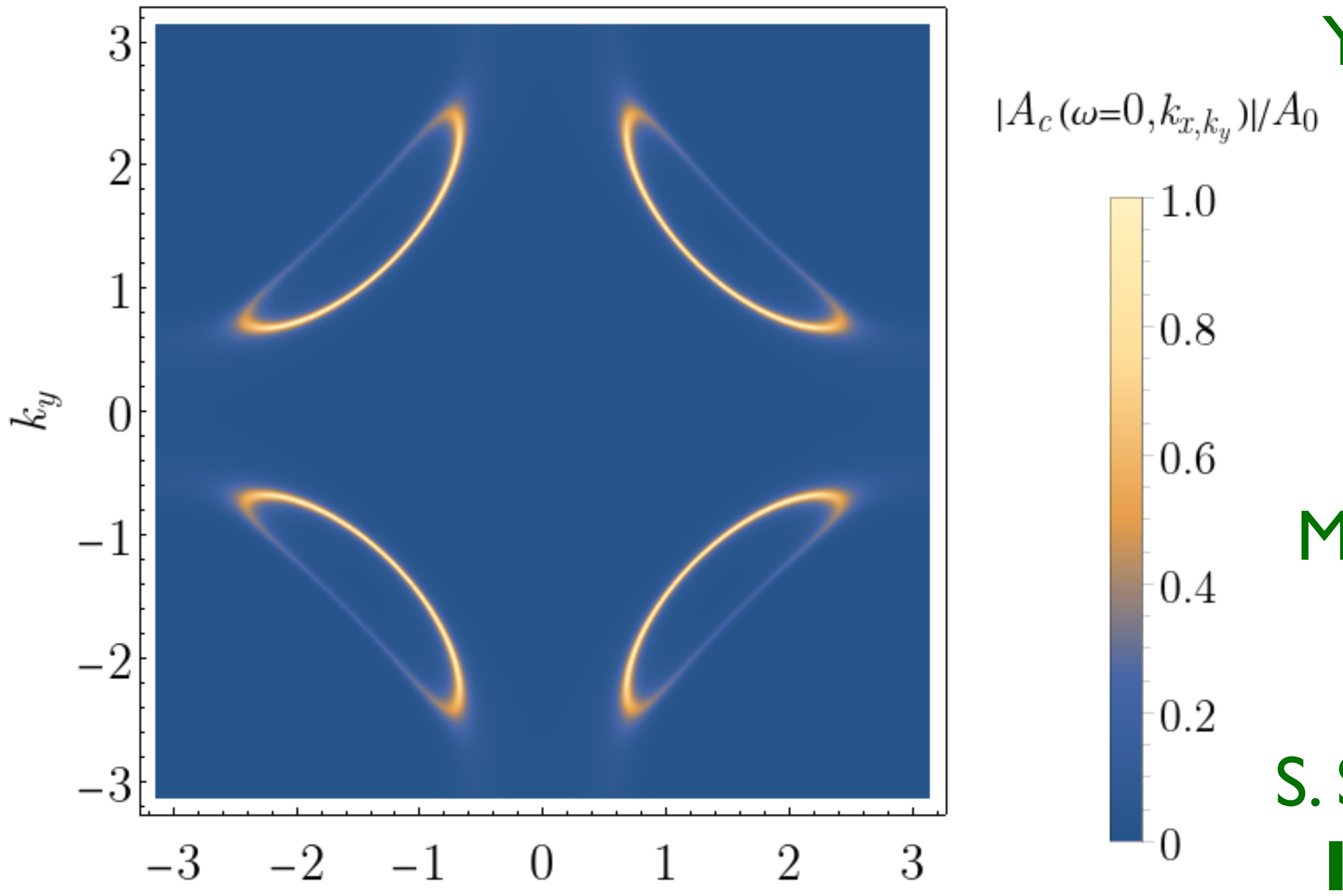

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Hole pocket Fermi surfaces of size p with charge e, spin-1/2 quasiparticles
+
'spectator' square lattice spin liquid *at half-filling*.

FL*: Spin liquid is *required* because the Fermi surface does not enclose the Luttinger volume $(1+p)$.

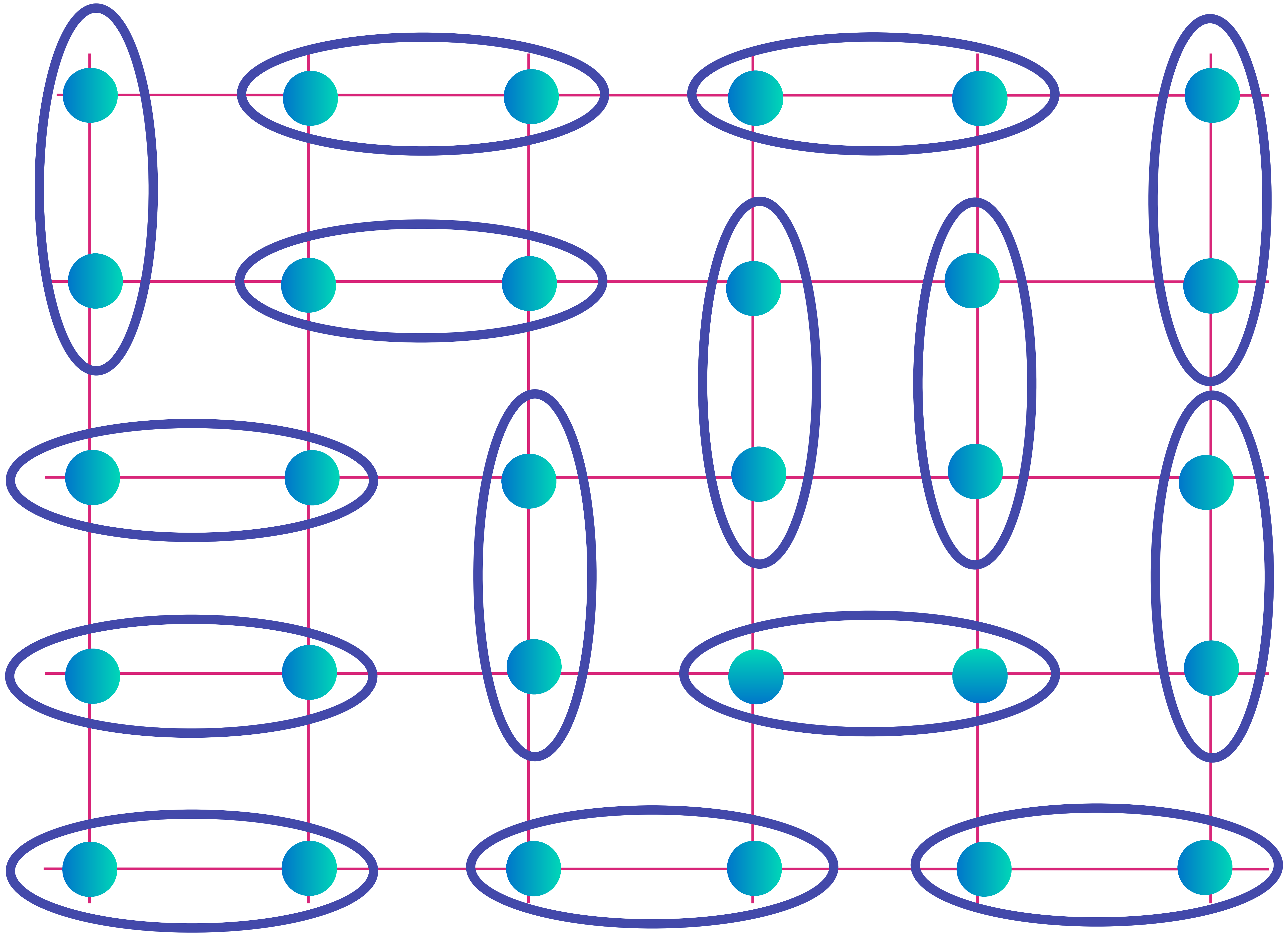
T. Senthil, M. Vojta, and S. Sachdev , *Phys. Rev. B* **69**, 035111 (2004)

From FL*
to
a cuprate phase diagram

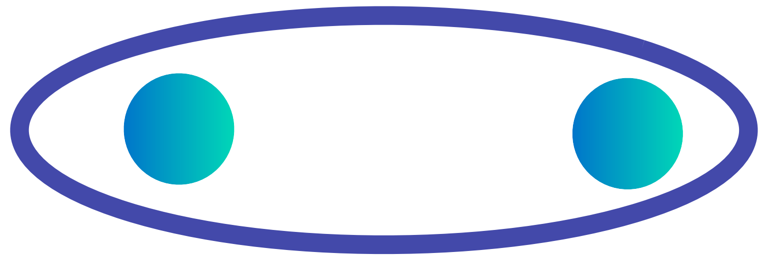
The dance of electrons on Cu atoms in YBCO

P.W. Anderson (1973)

Spin liquid



Electrons form entangled pairs, and the pairs entangle across the entire sample

 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

G. Baskaran, Z. Zou, P.W. Anderson, *Solid State Comm.* **63**, 973 (1987)
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D. Rokhsar and S.A. Kivelson, *Phys. Rev. Lett.* **61**, 2376 (1988)
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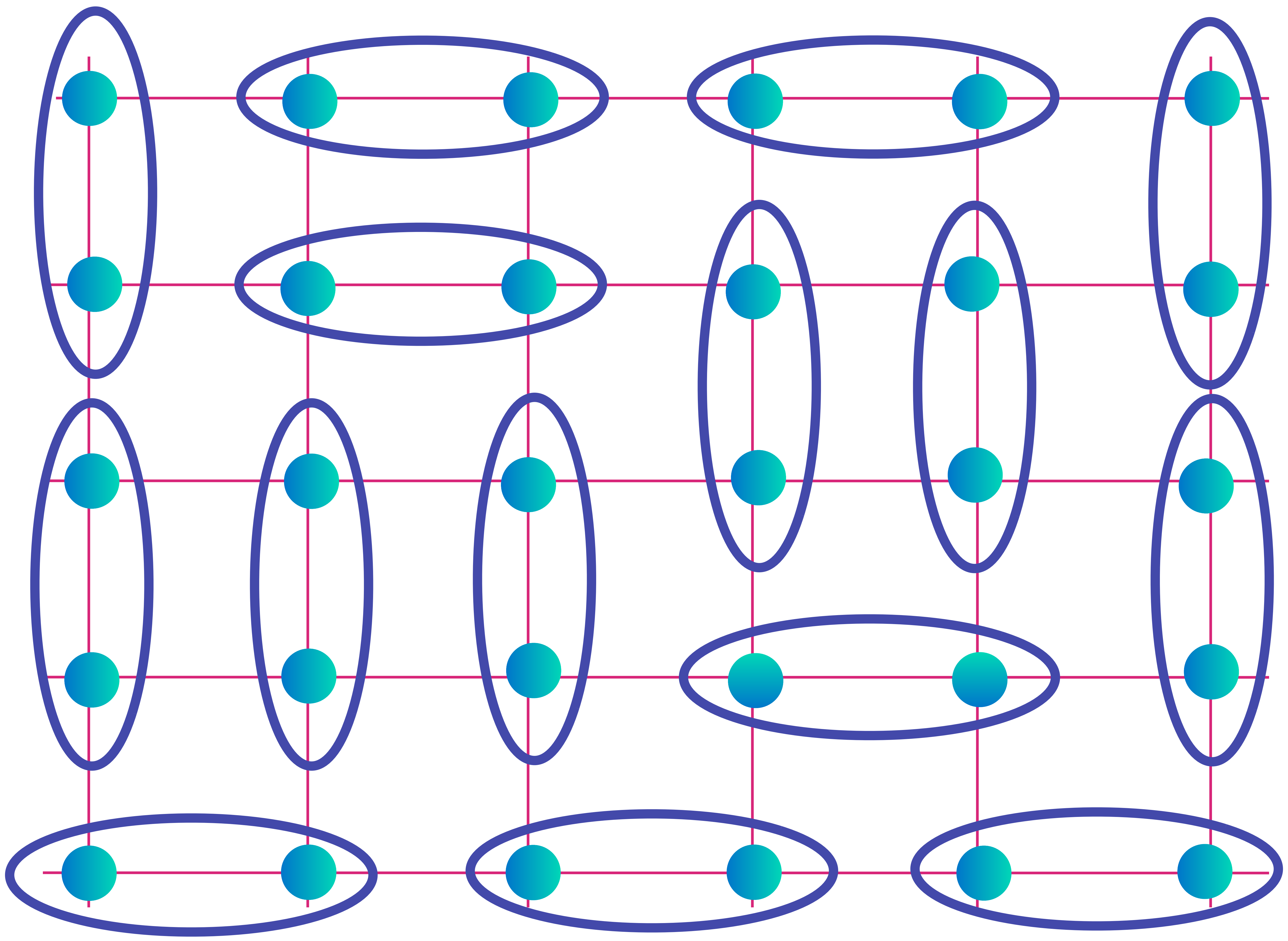

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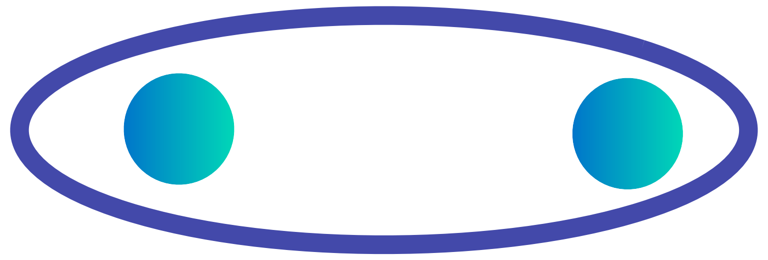 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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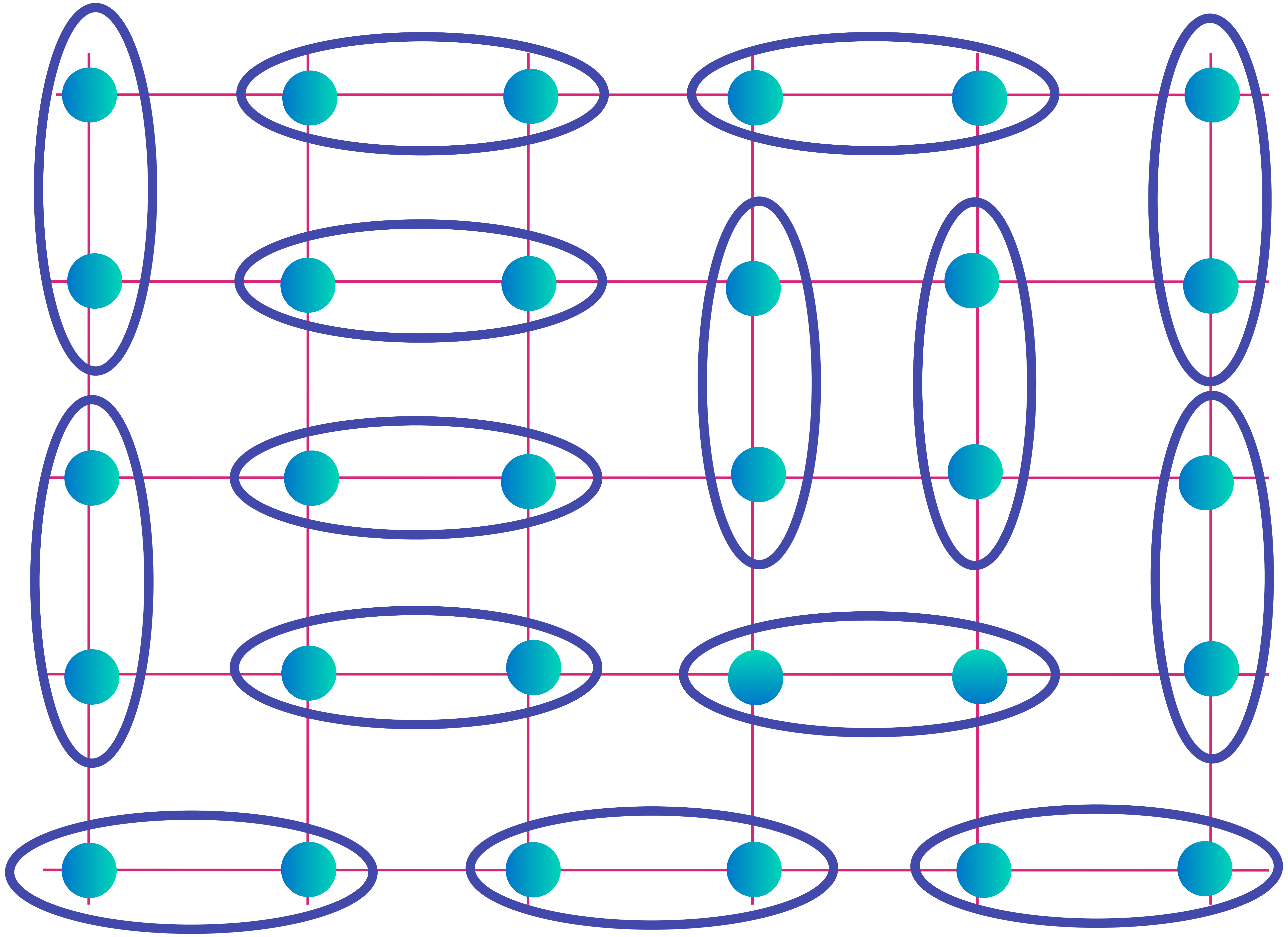

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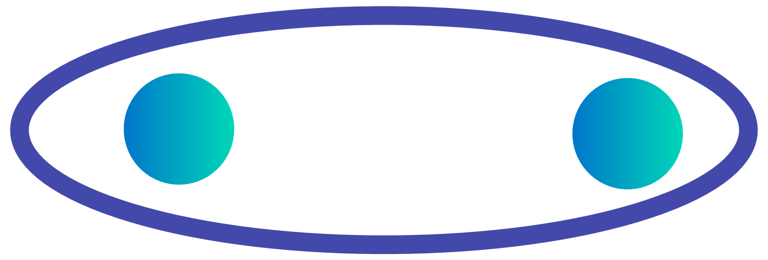

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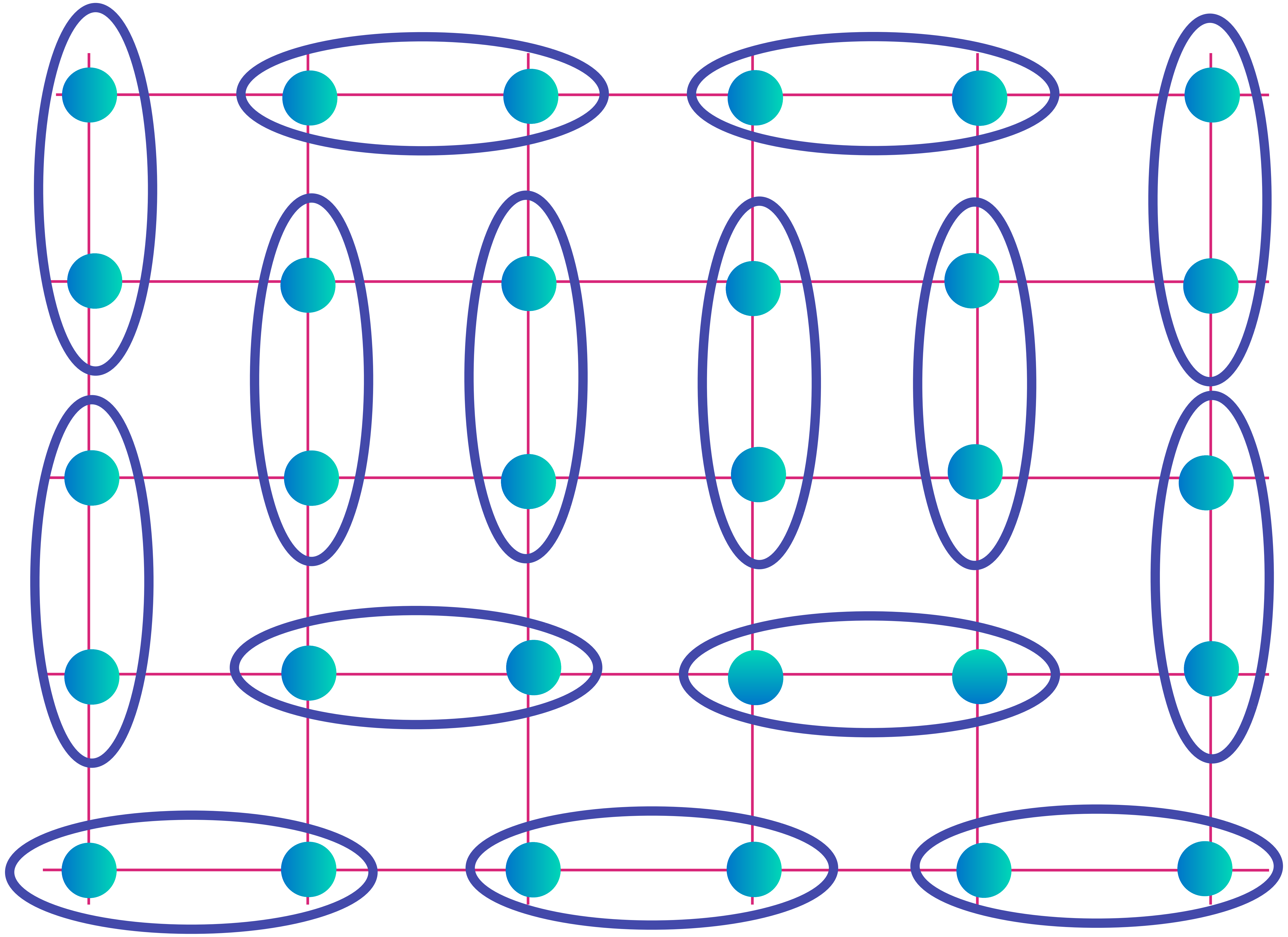

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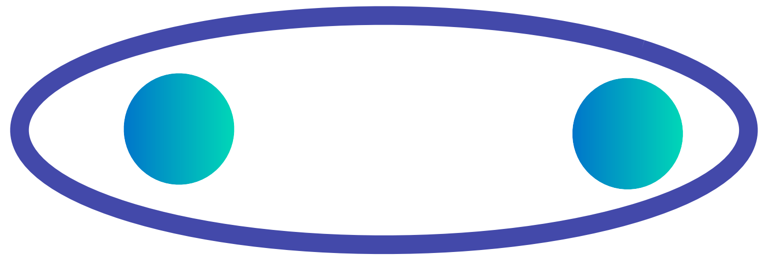 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, *Phys. Rev. B* **35**, 8865 (1987)
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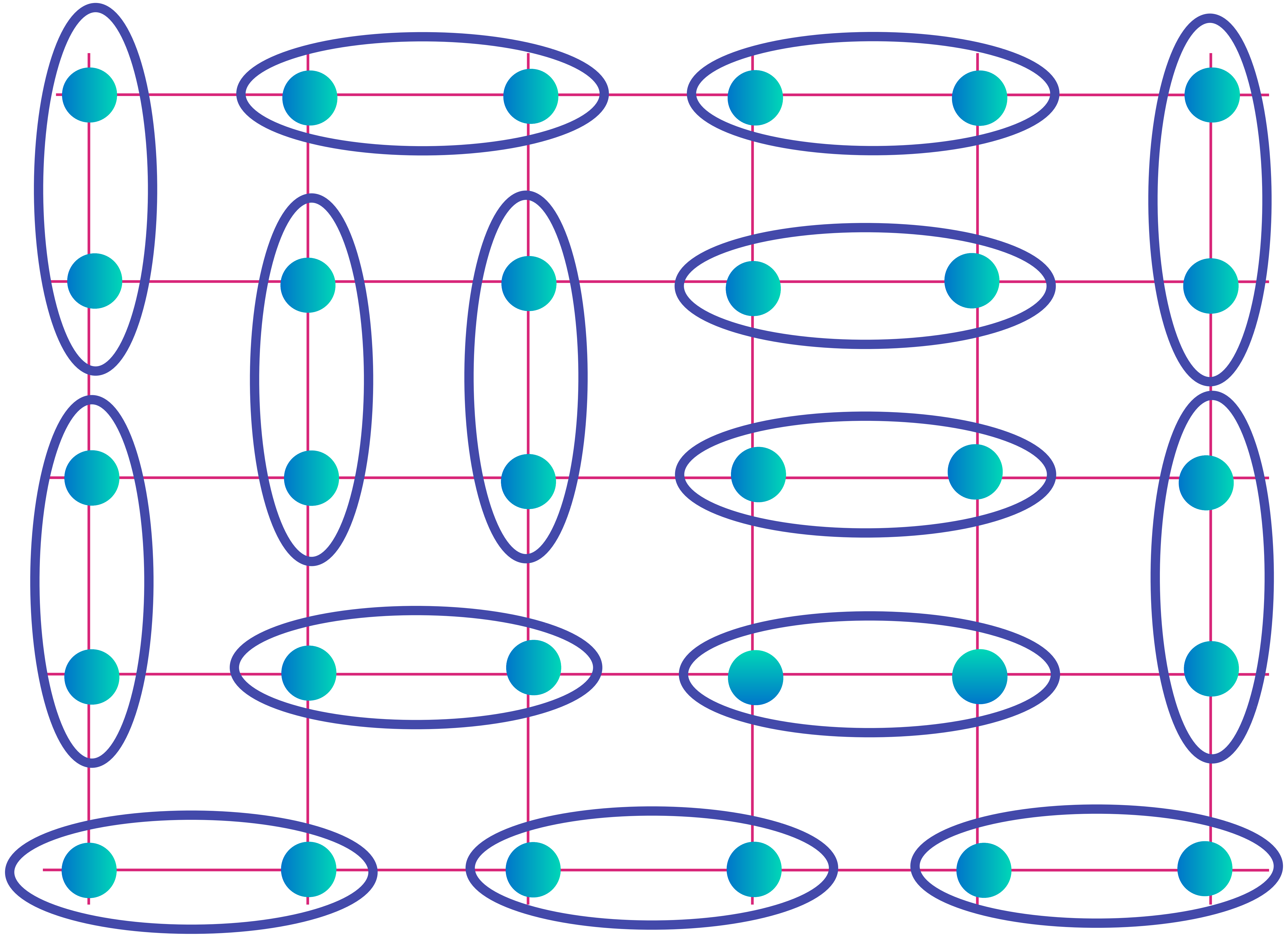
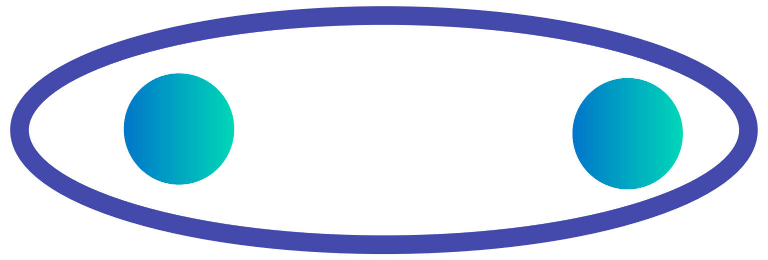
The dance of electrons on Cu atoms in YBCO

P.W. Anderson (1973)

Spin liquid



Electrons form entangled pairs, and the pairs entangle across the entire sample

 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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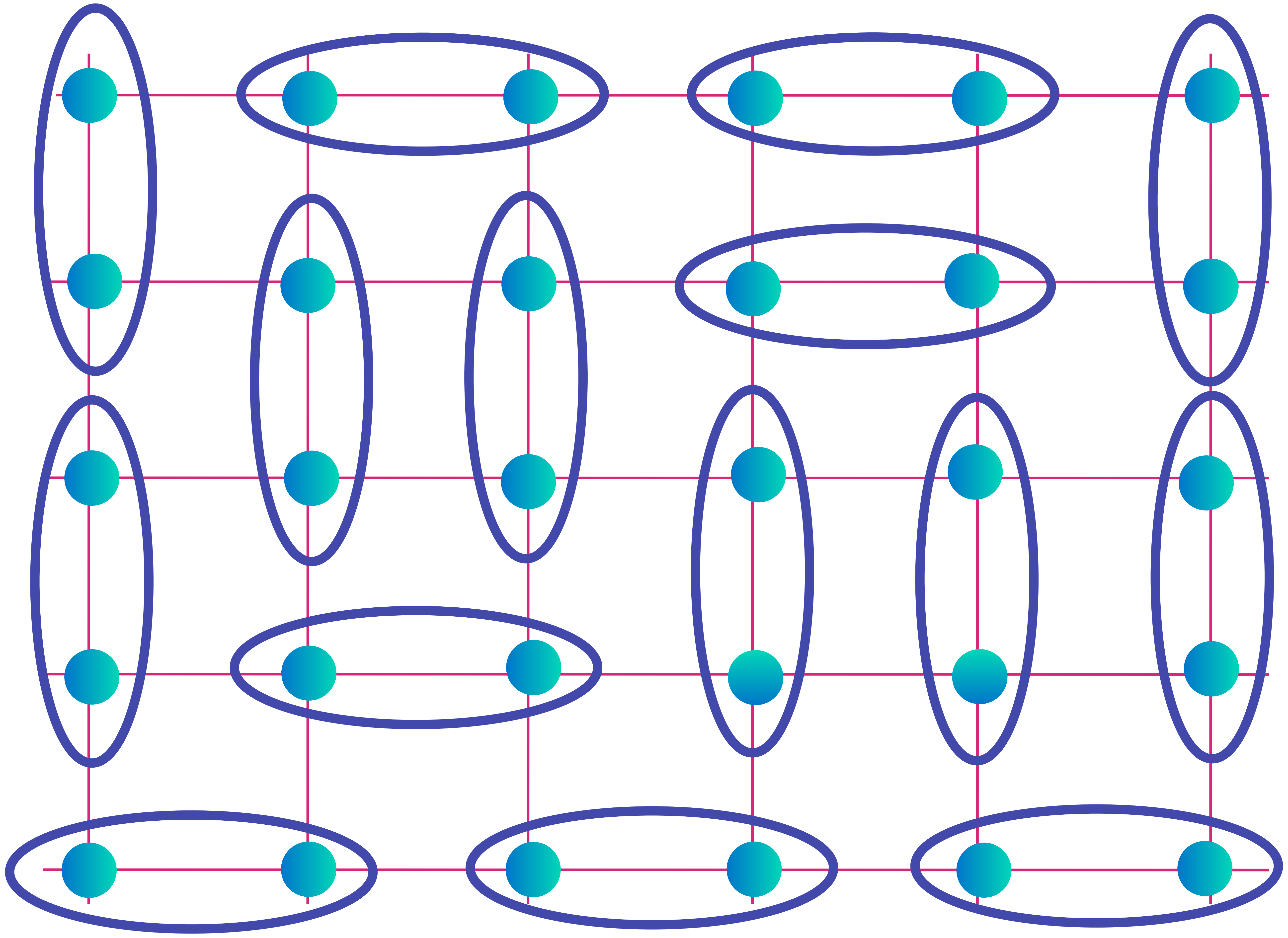

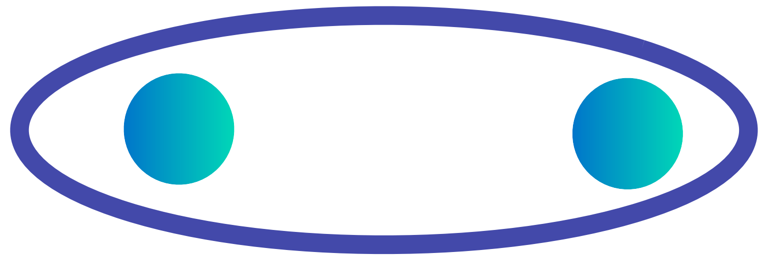 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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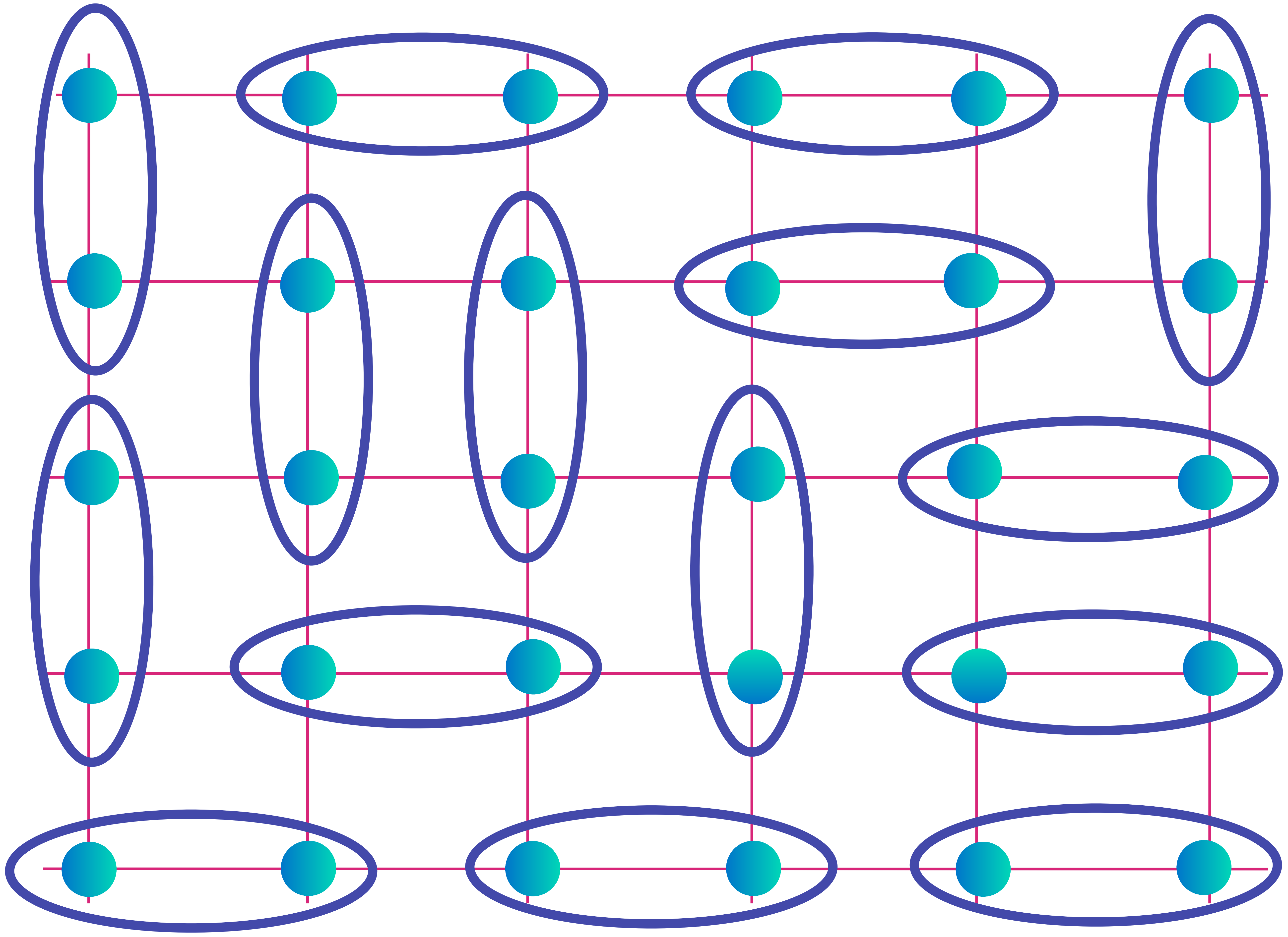

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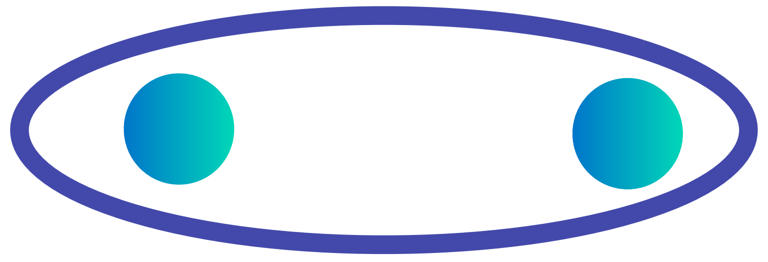

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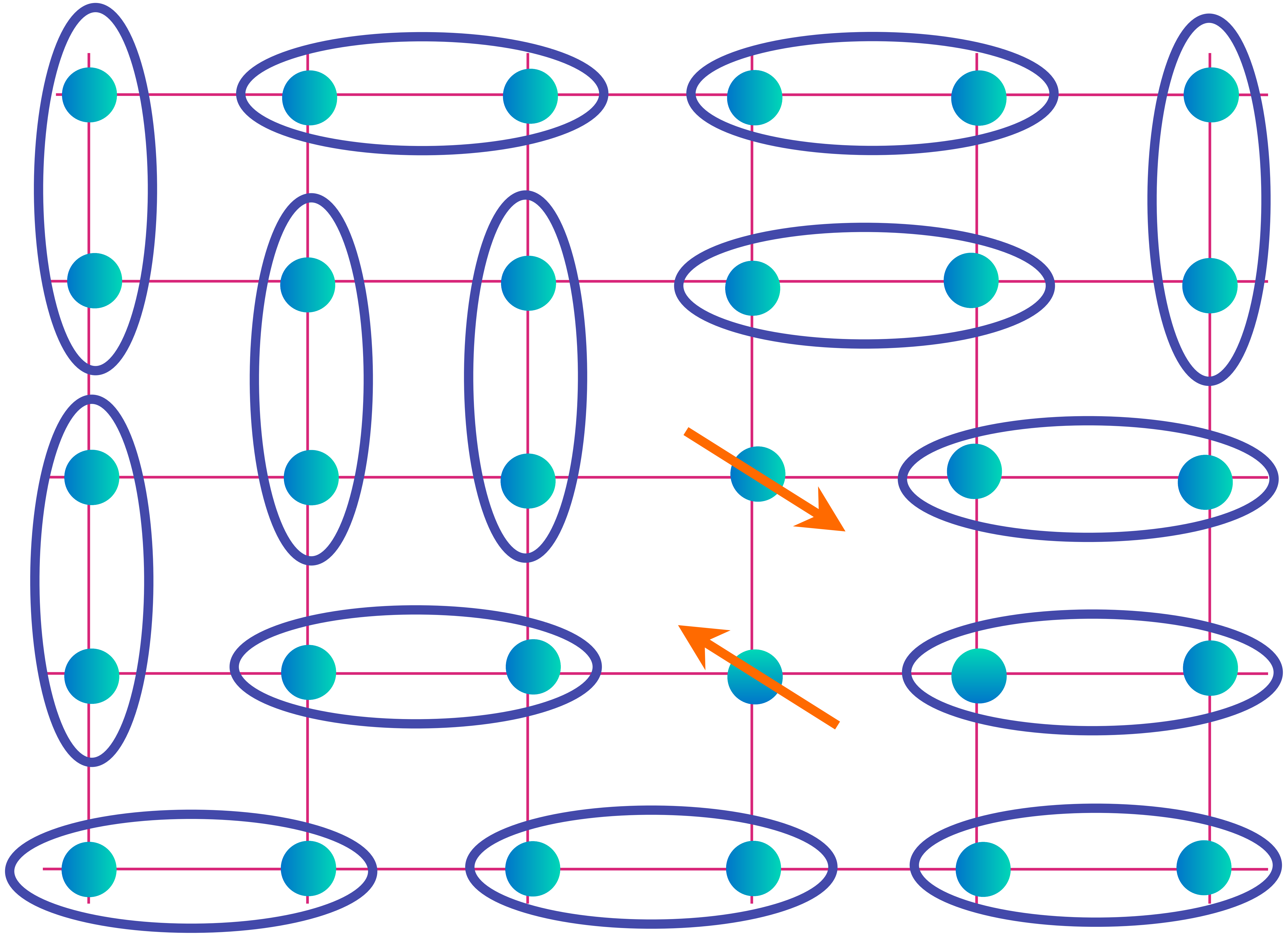

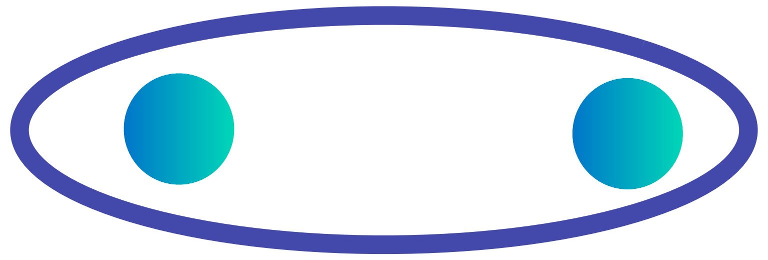

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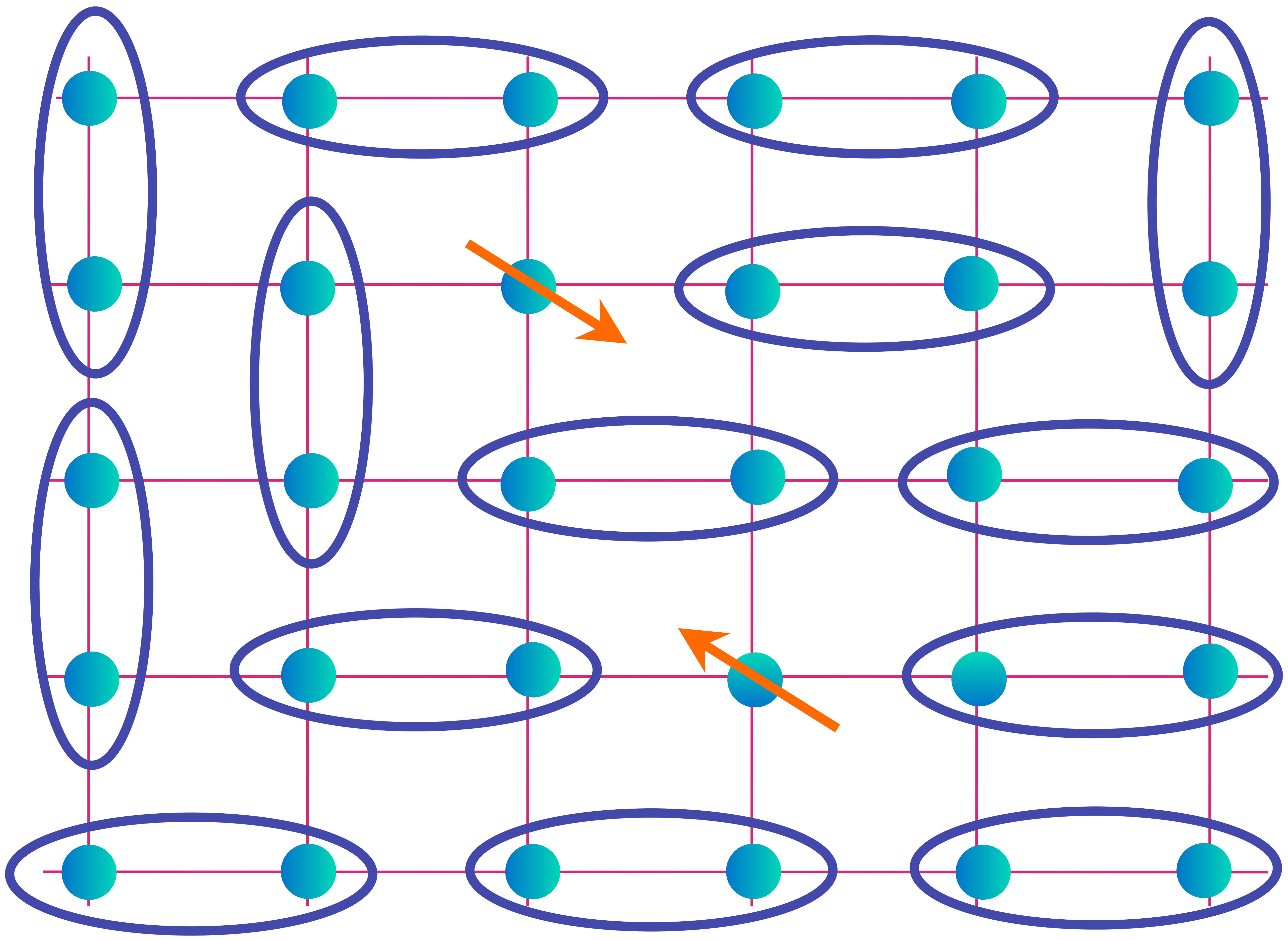

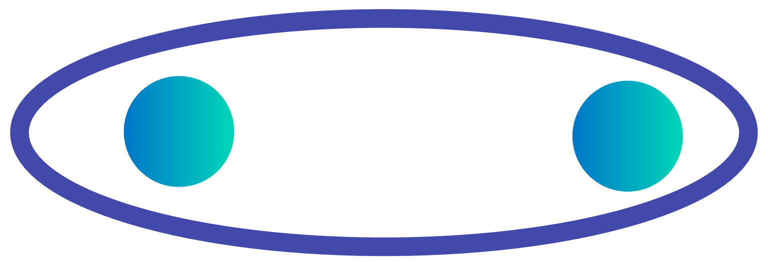

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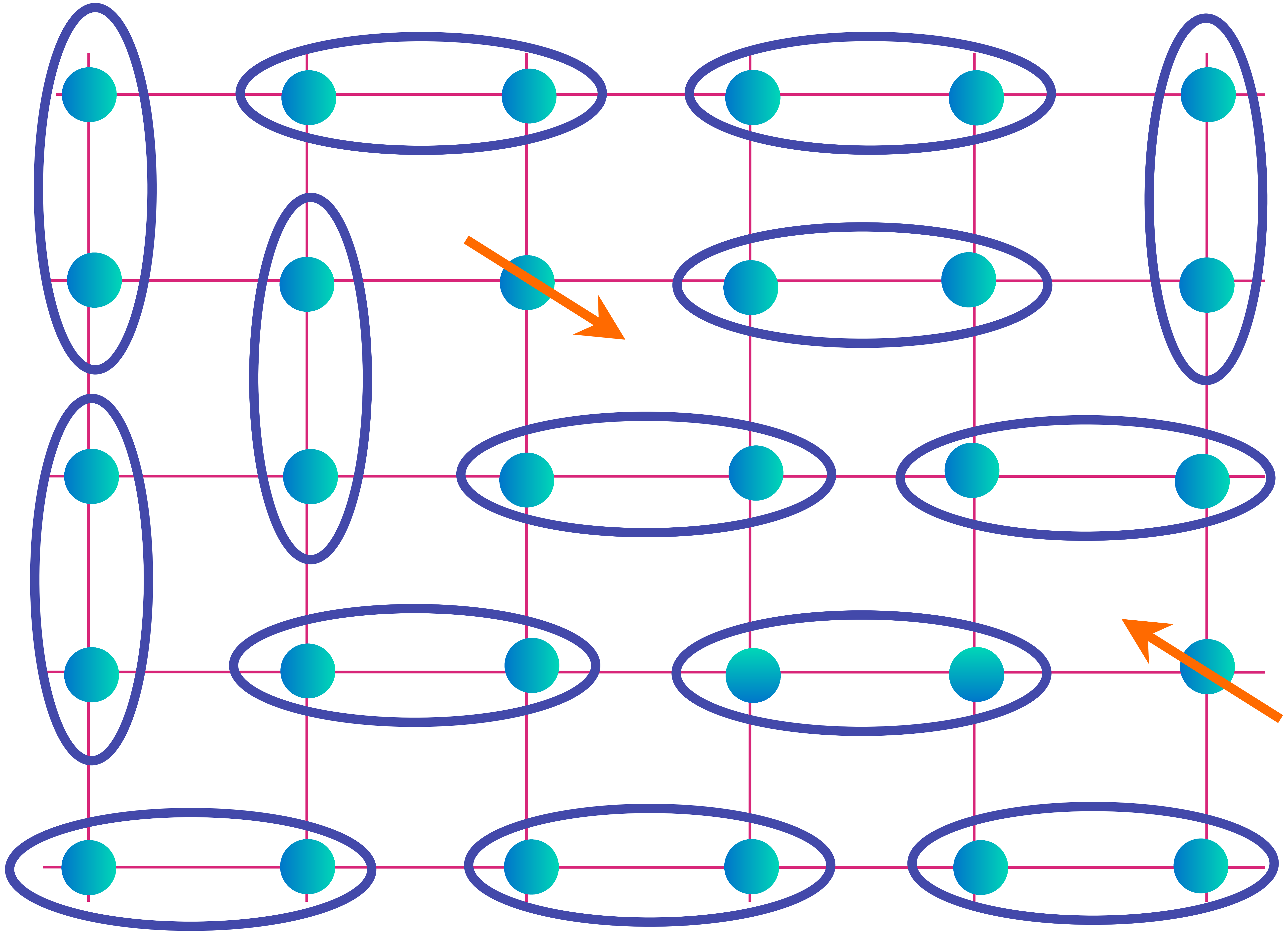

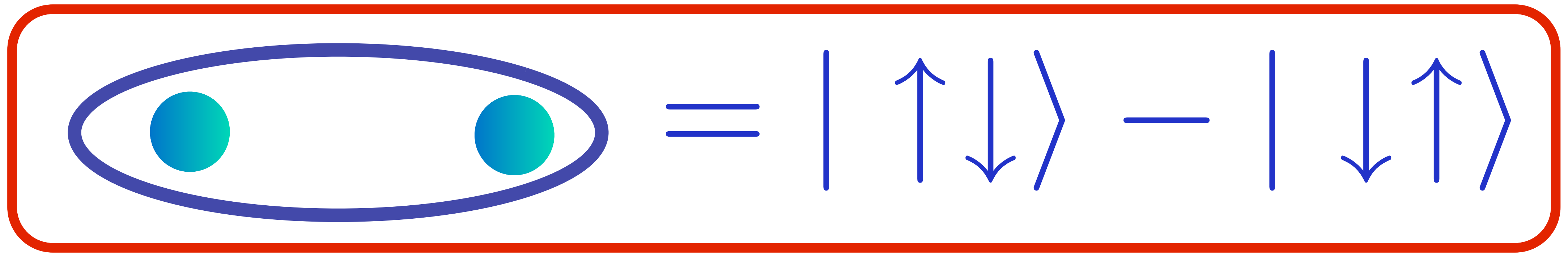

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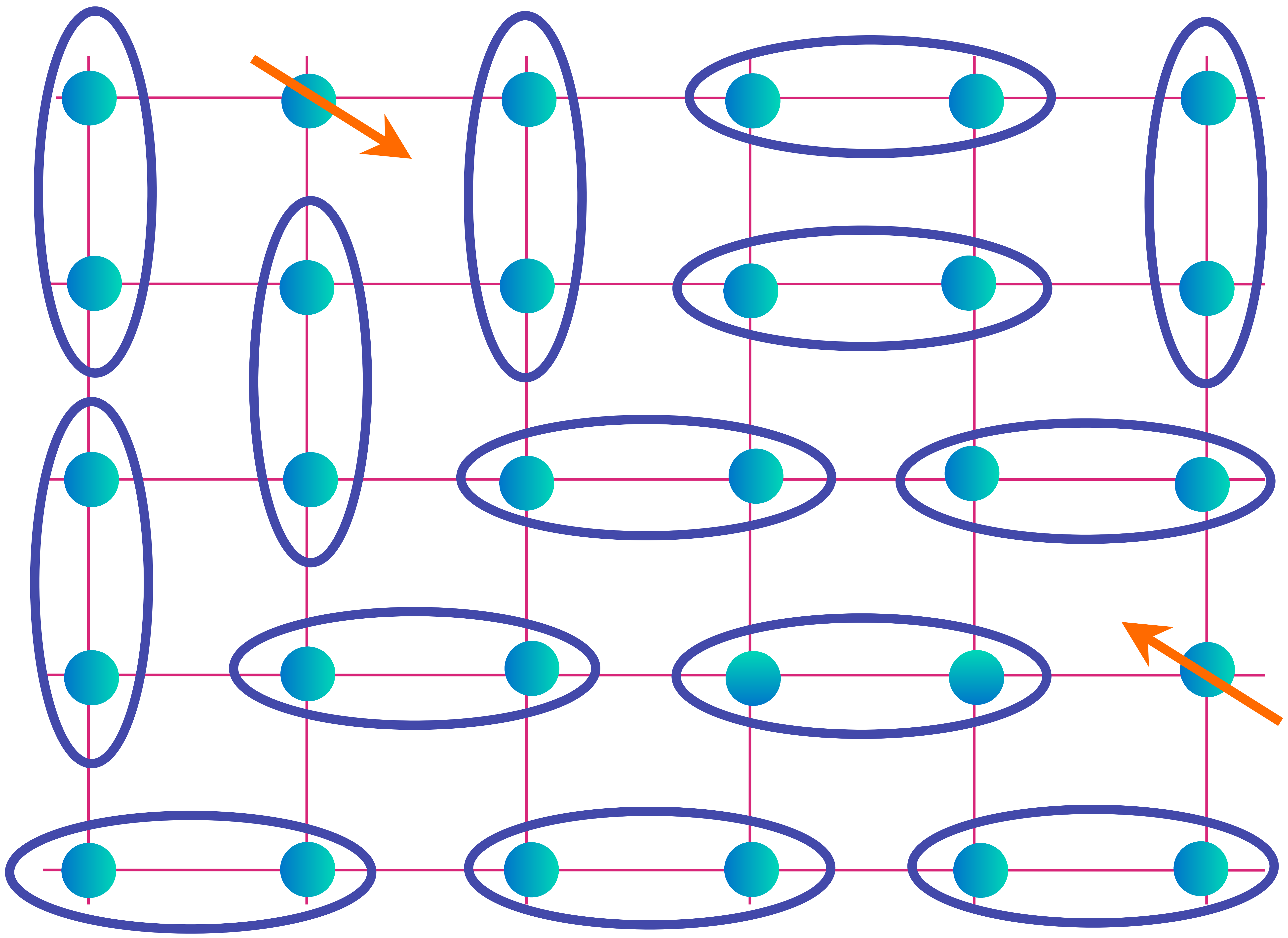

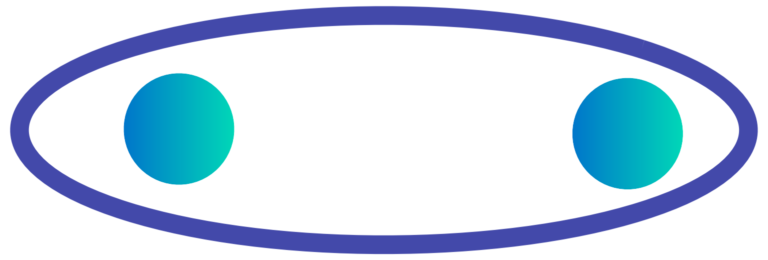

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Holons

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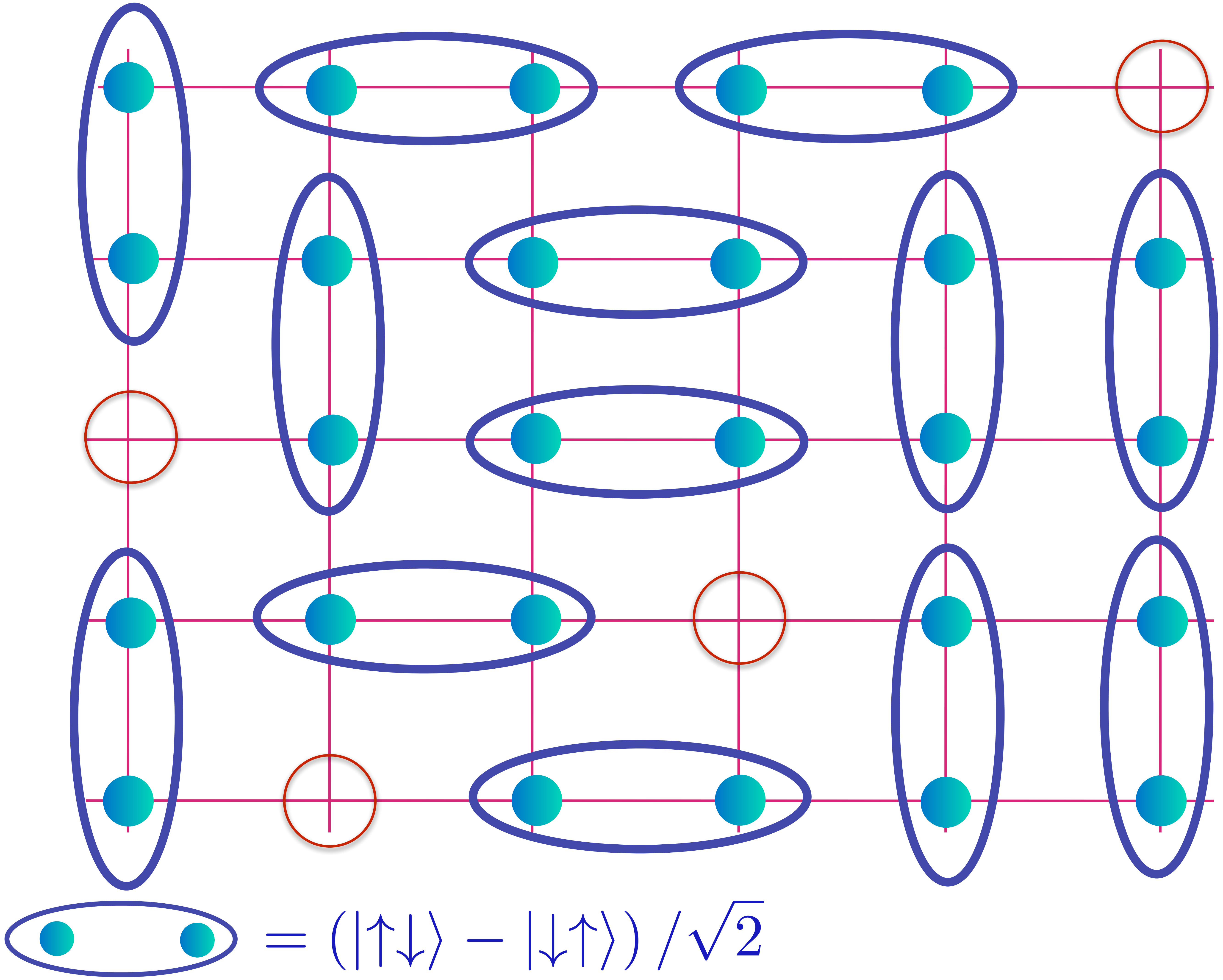

$$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$$

Spin liquid

Fractionalized holon excitations with spin S=0 and charge +e.

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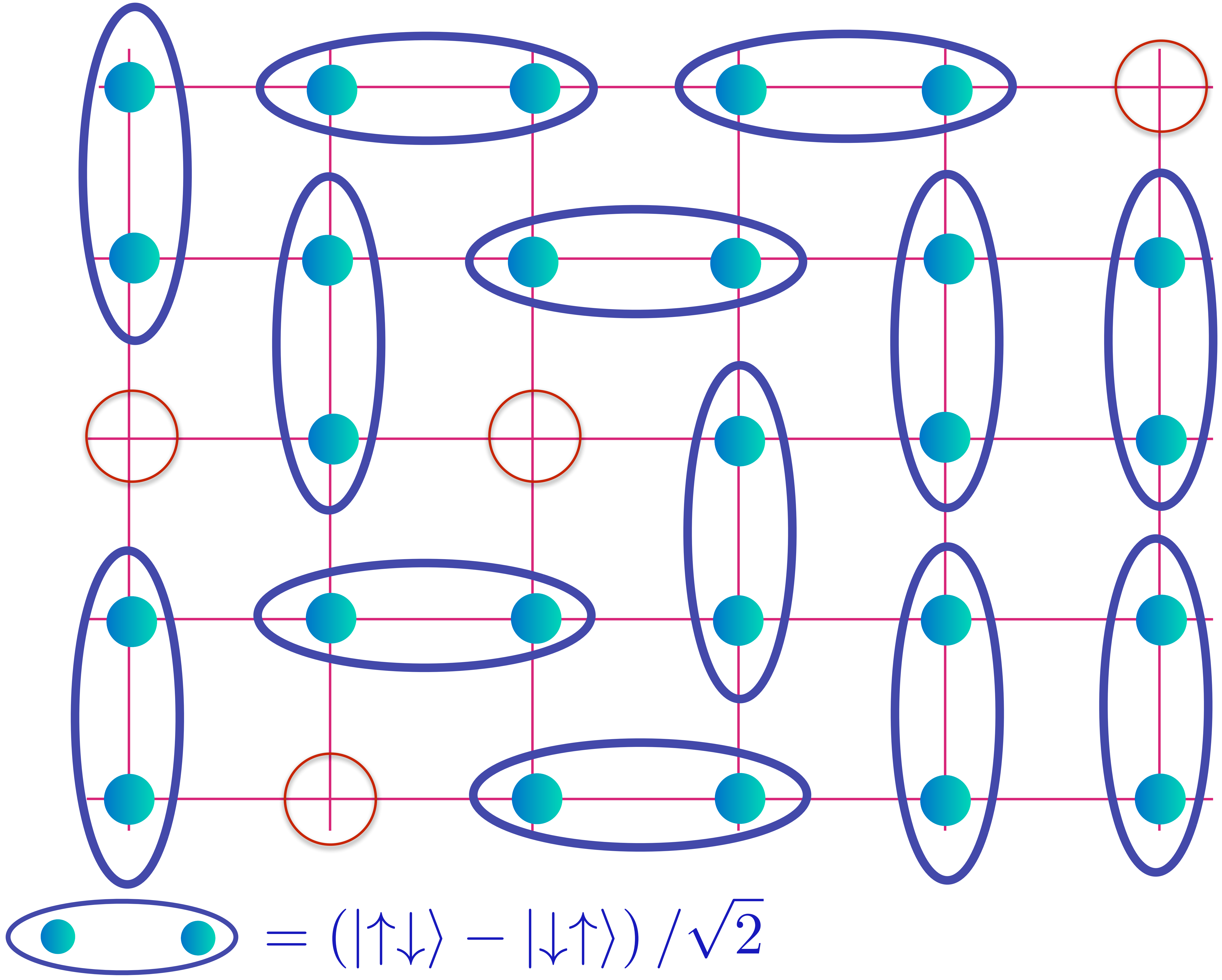

$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

Spin liquid

Fractionalized holon excitations with spin S=0 and charge +e.

Holon metal

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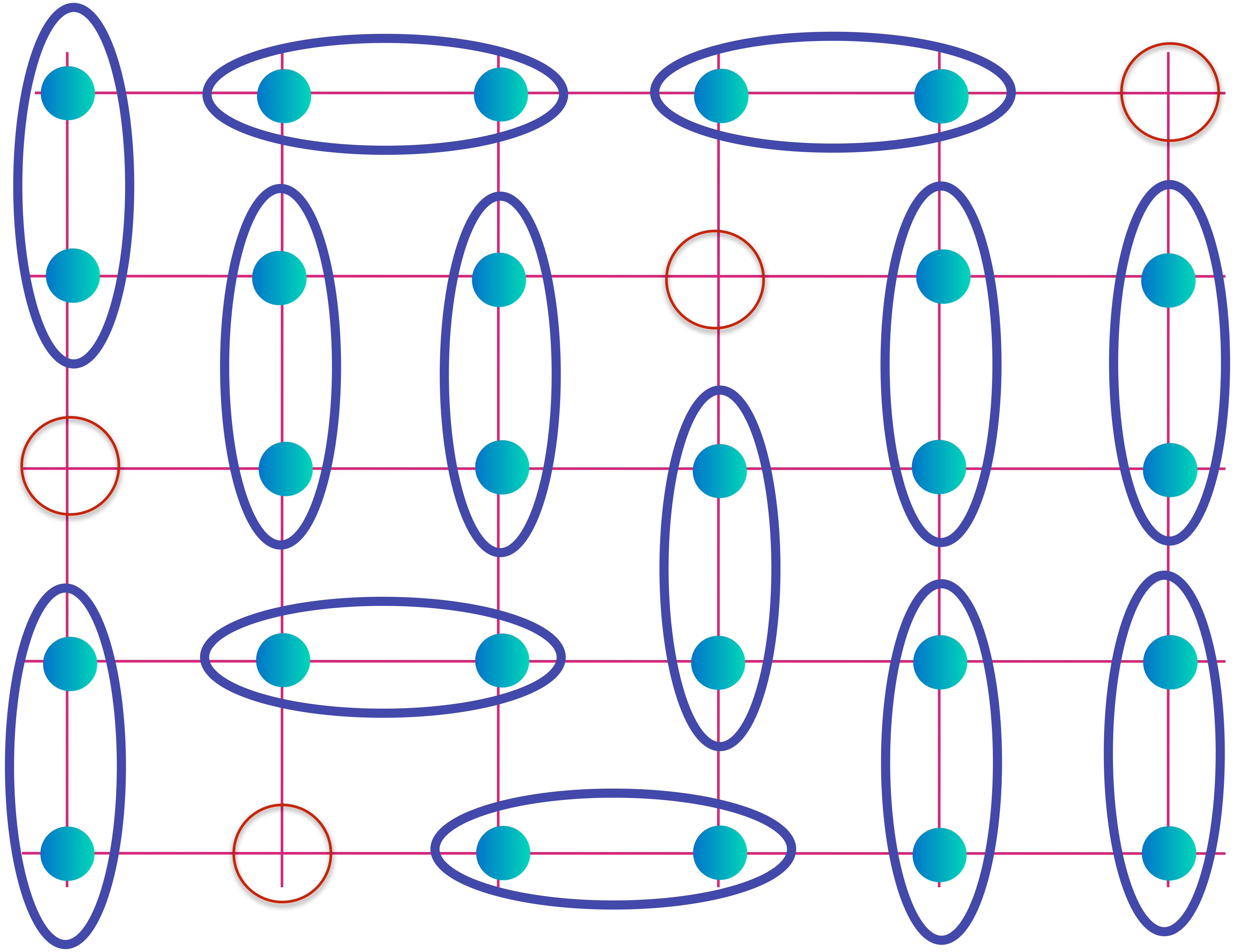
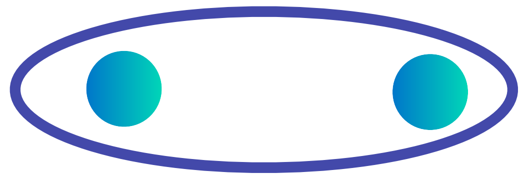


If each holon is
a fermion,
we obtain
a Fermi surface
of holons
of size p

 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

S. S., M.A. Metlitski, Y. Qi, and C. Xu, PRB **80**, 155129 (2009)
M. S. Scheurer, S. Chatterjee, Wei Wu, M. Ferrero, A. Georges, and S. S., PNAS **115**, E3665 (2018)
Pietro M. Bonetti and Walter Metzner, PRB **106**, 205152 (2022)

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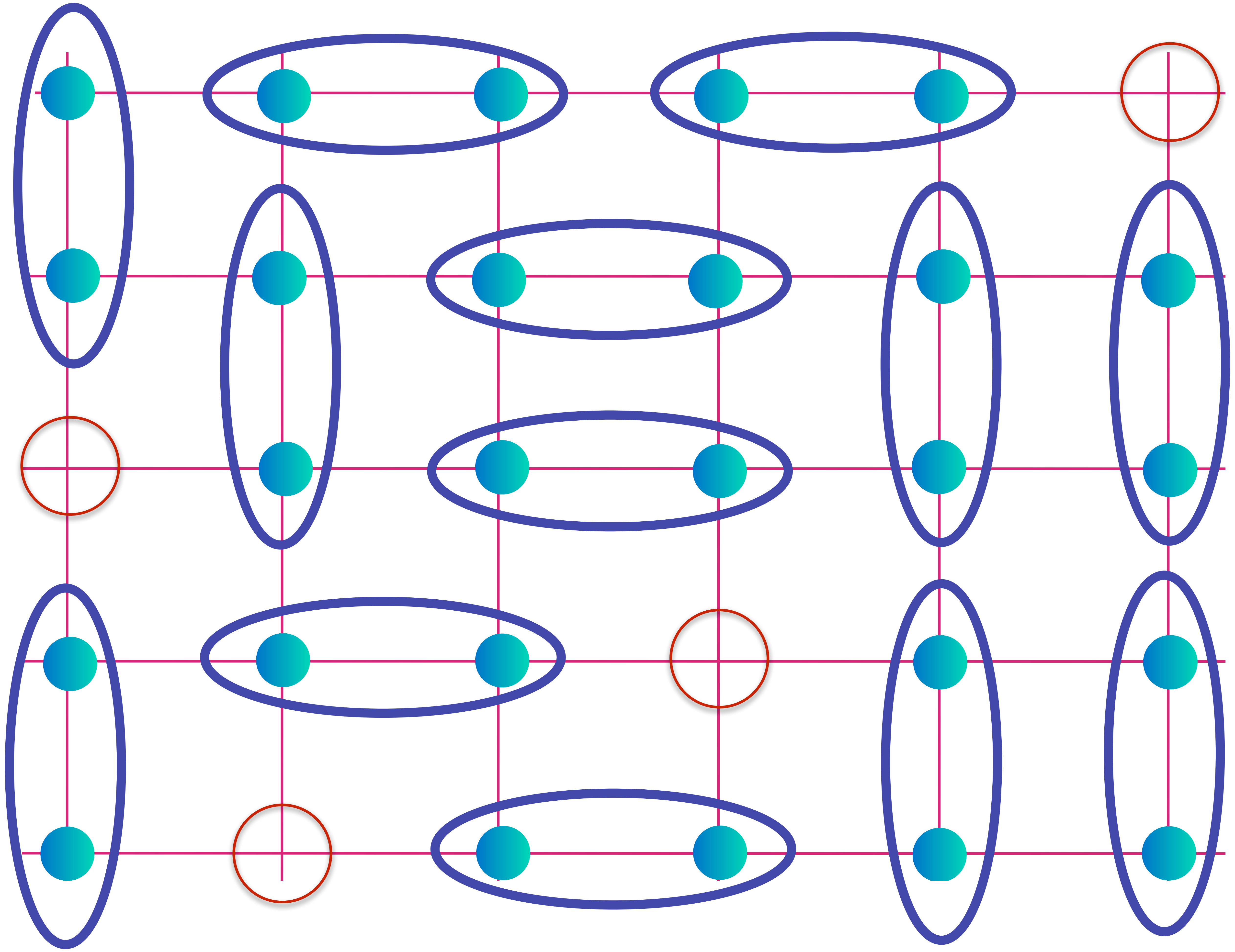

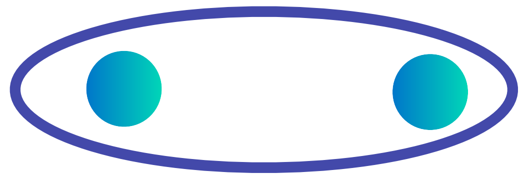
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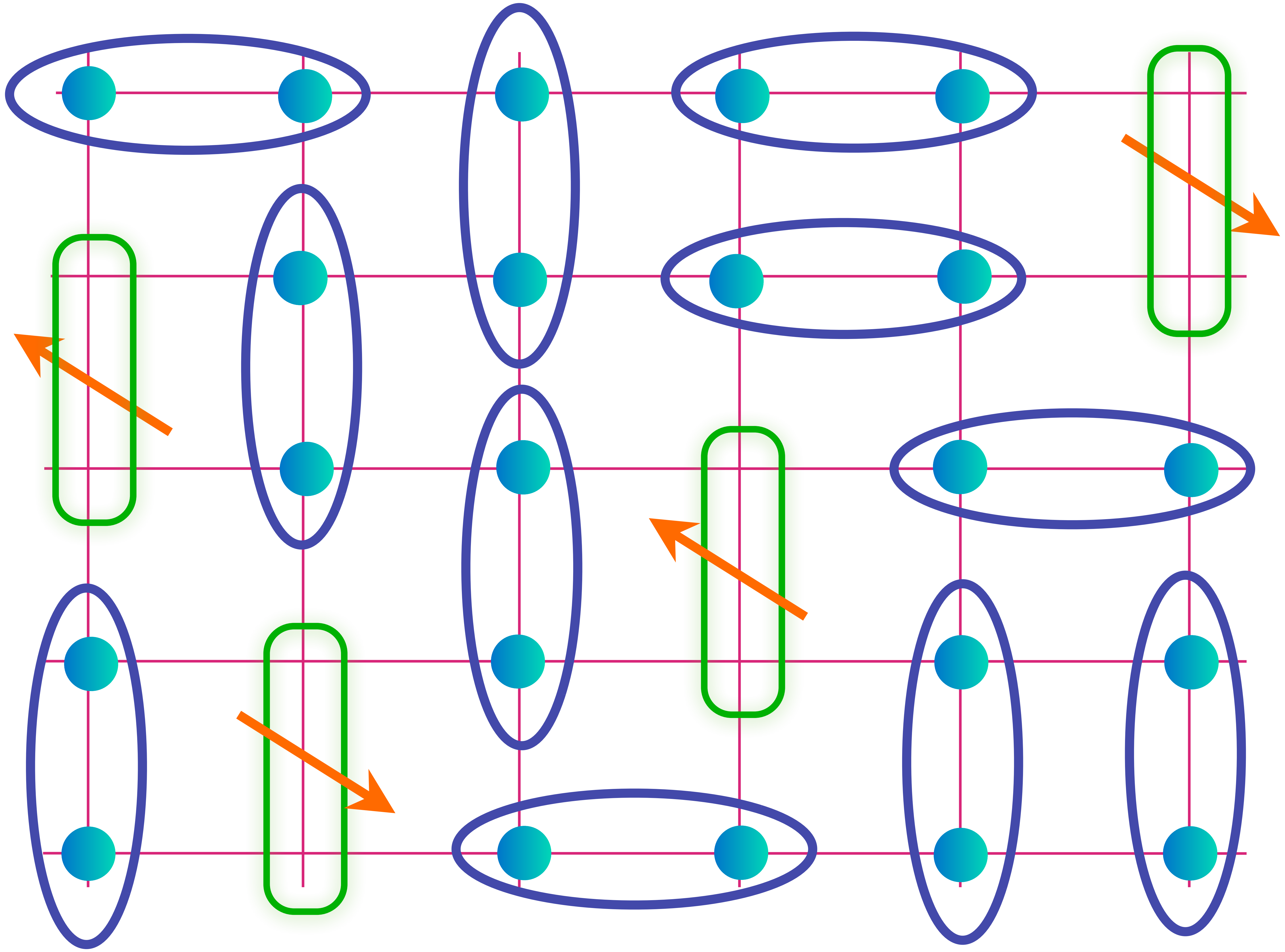
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, *Phys. Rev. B* **75**, 235122 (2007)



Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

Spinon-holon bound state

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

$$= (|\uparrow\circ\rangle + |\circ\uparrow\rangle)/\sqrt{2}$$

E. G. Moon and S. Sachdev, *Phys. Rev. B* **83**, 224508 (2011); M. Punk, A. Allais, and S. Sachdev, *Proc. Nat. Acad. Sci.* **112**, 9552 (2015)

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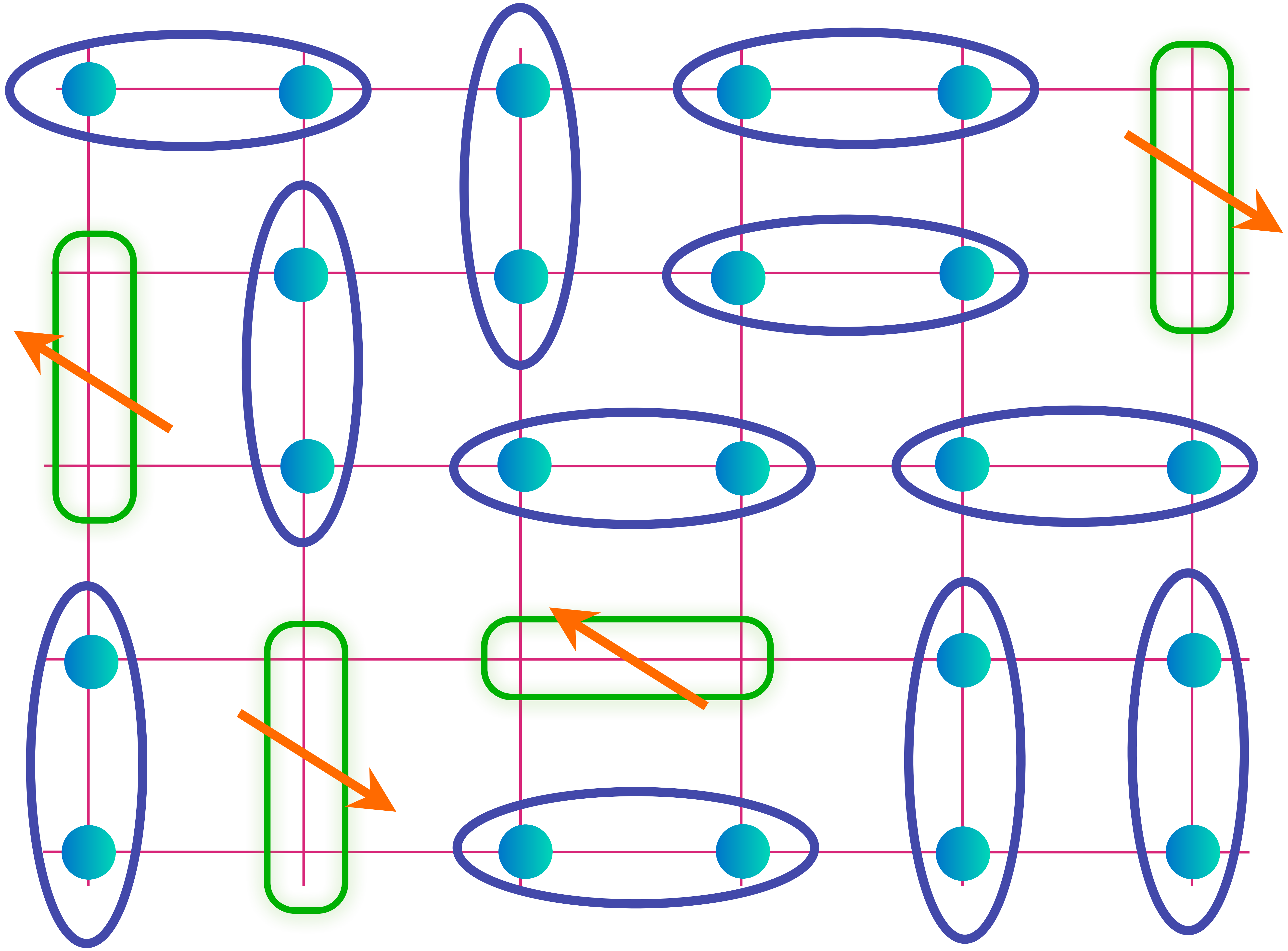

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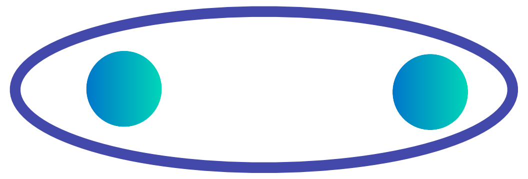
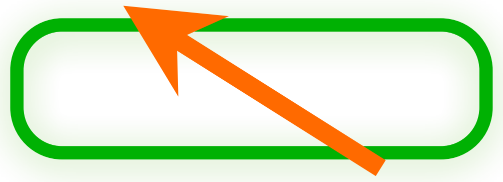
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

 $= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle\right)/\sqrt{2}$

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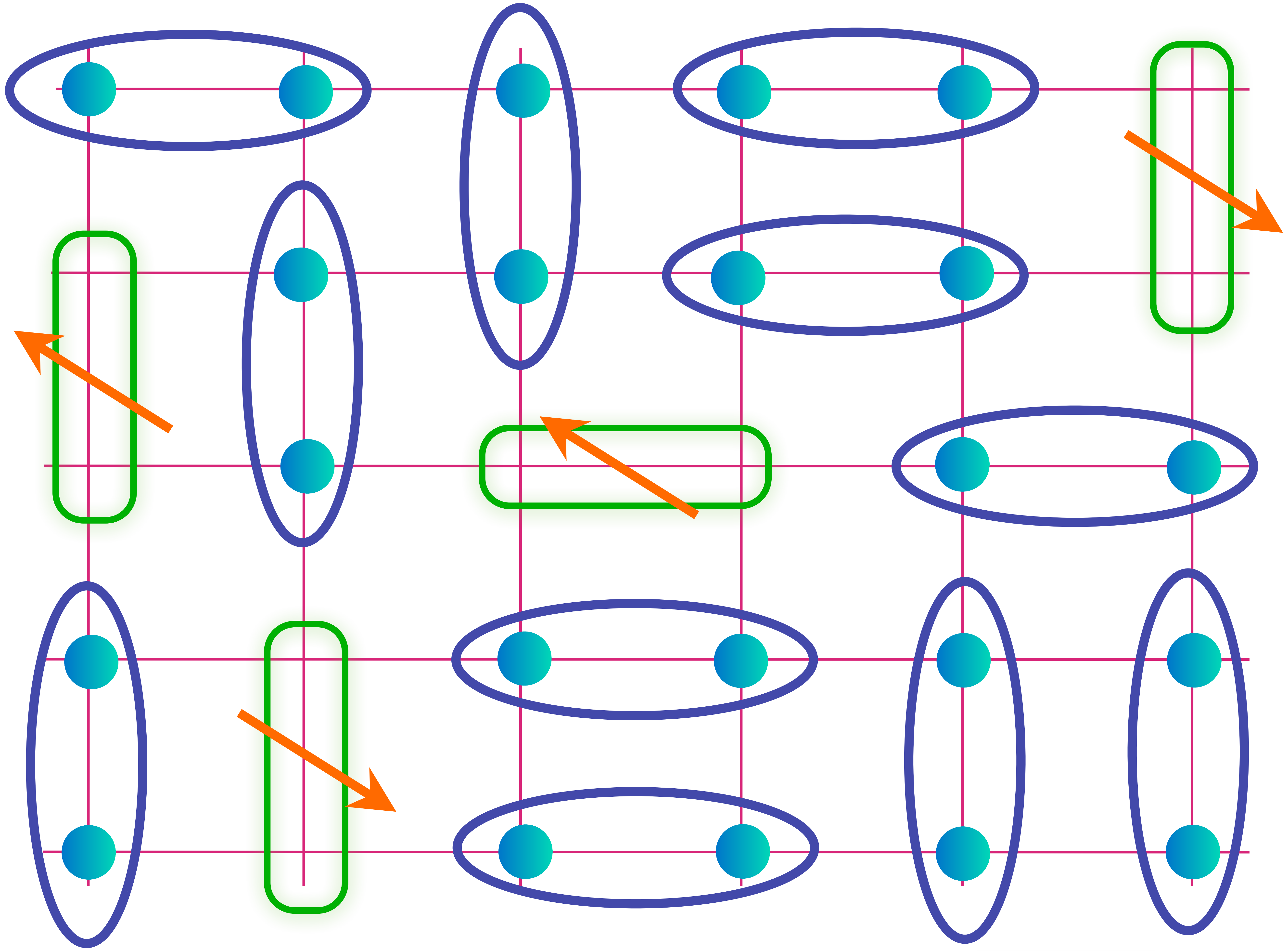

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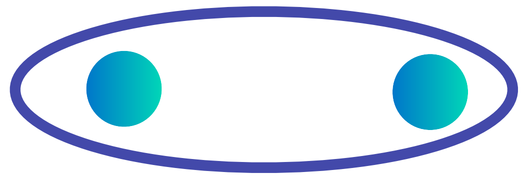
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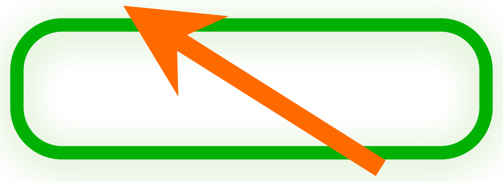
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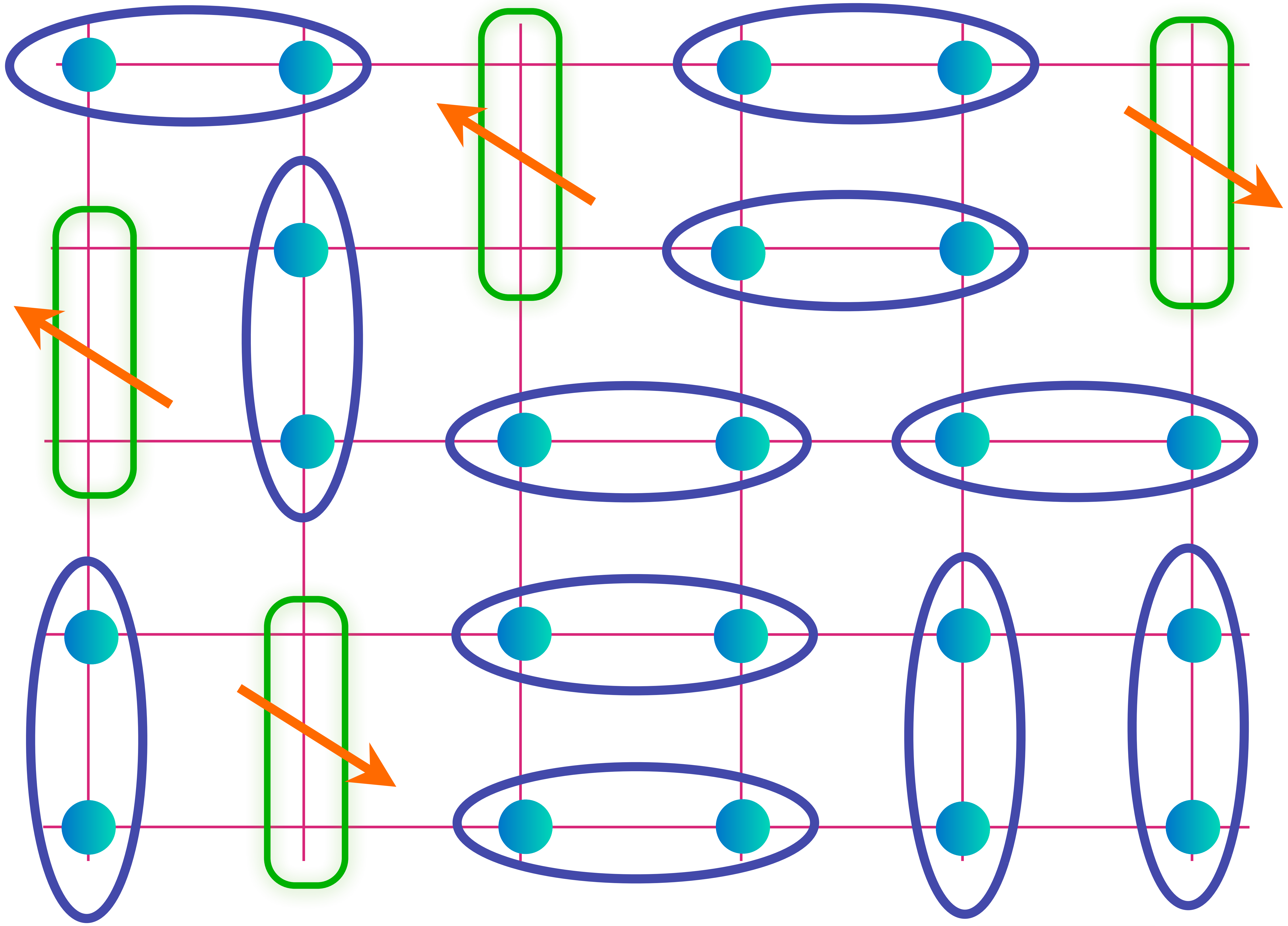

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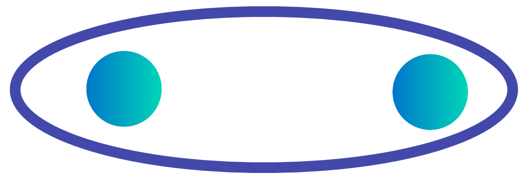
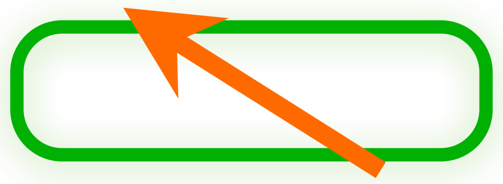
 $= \left(|{\uparrow\downarrow}\rangle - |{\downarrow\uparrow}\rangle \right) / \sqrt{2}$

 $= \left(|{\uparrow \circ}\rangle + |{\circ \uparrow}\rangle \right) / \sqrt{2}$

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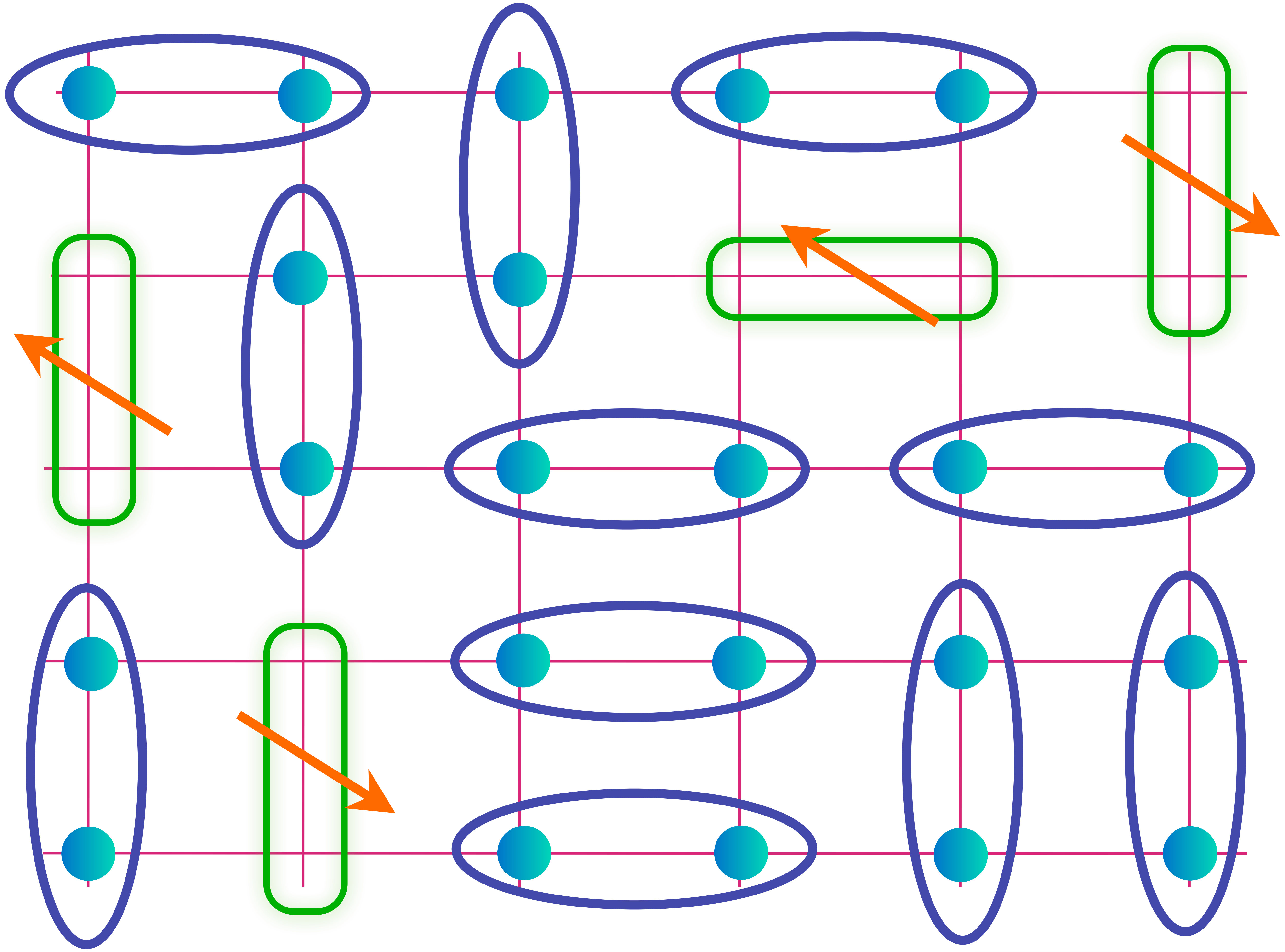

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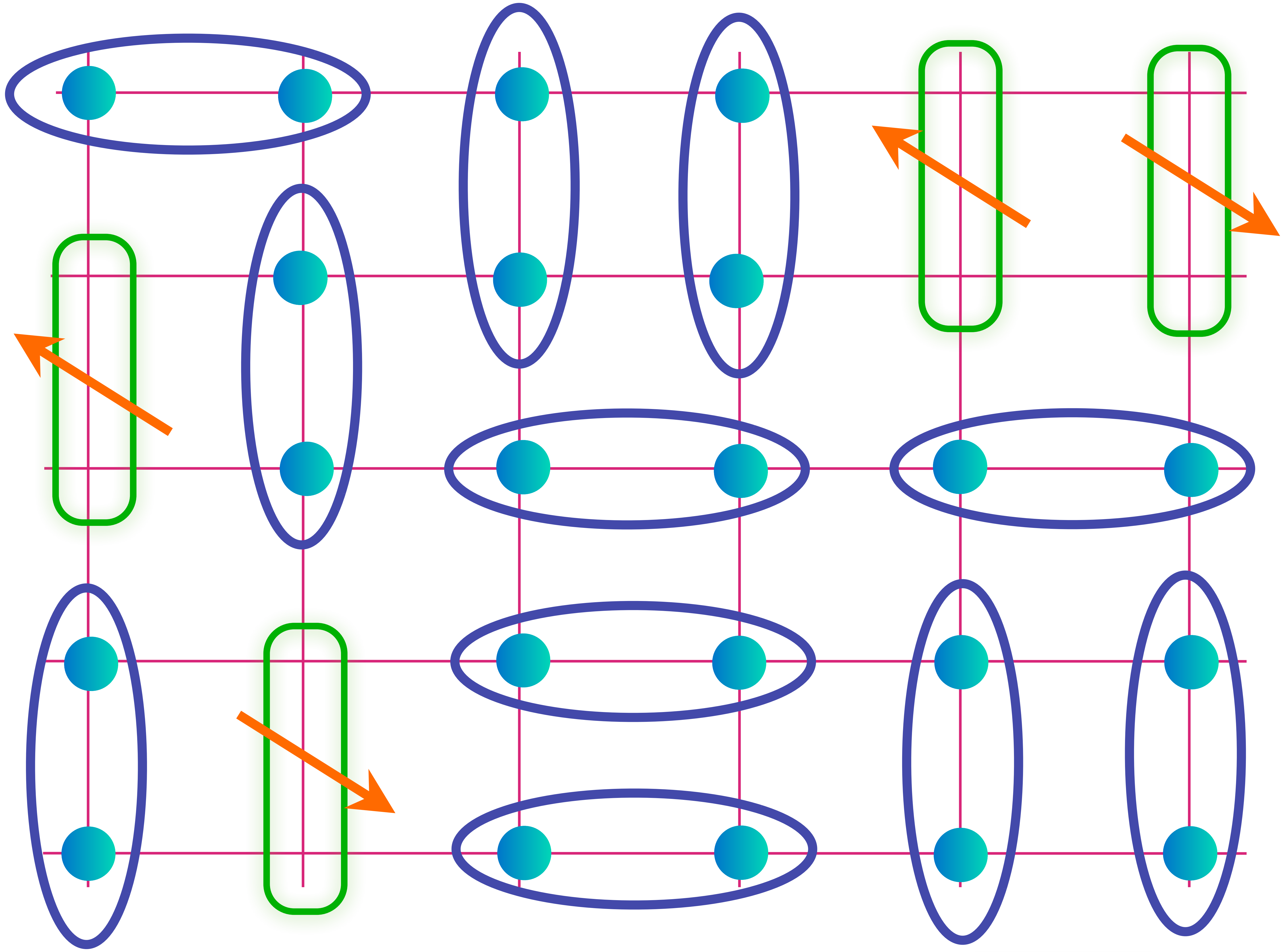

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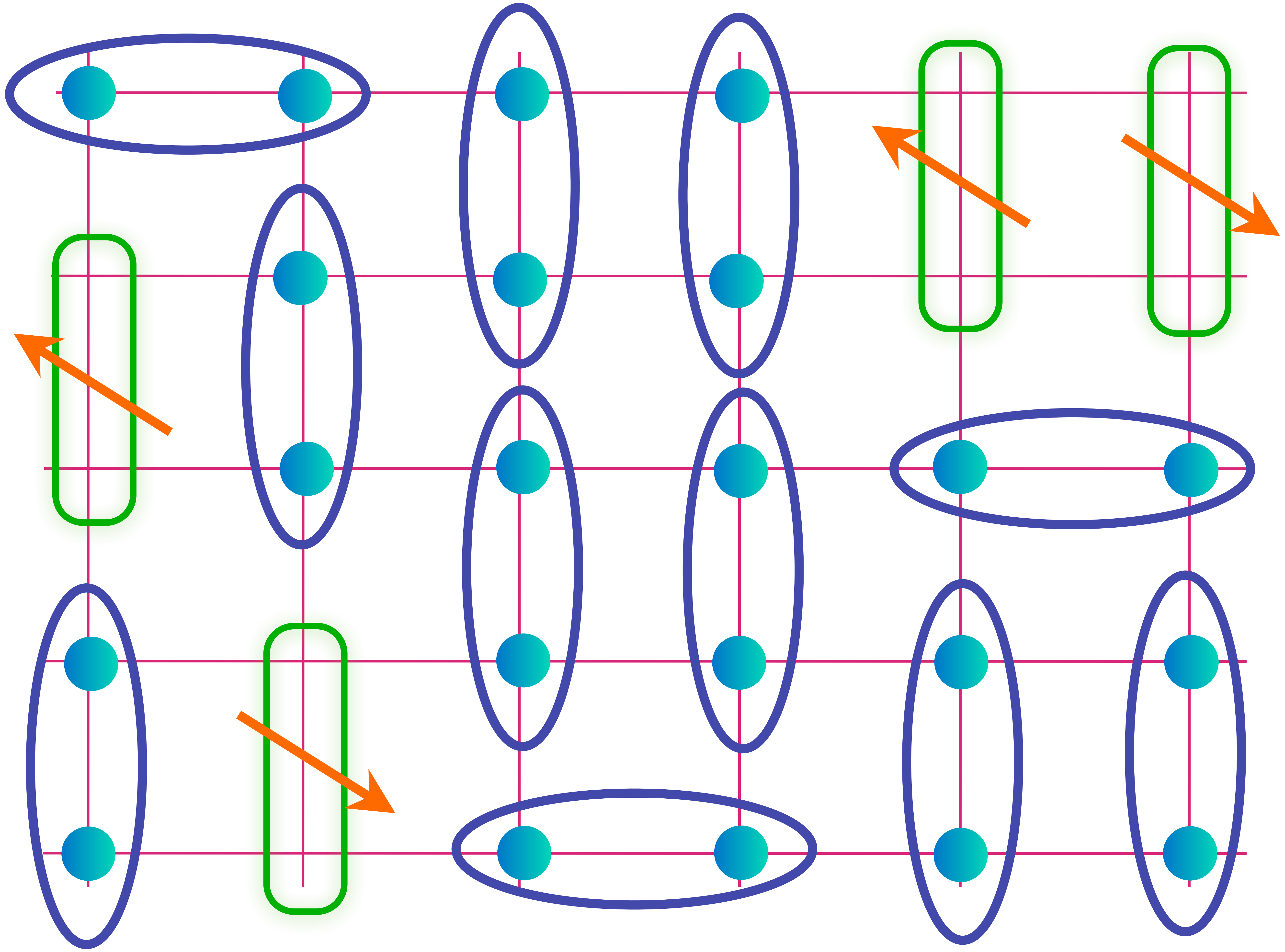

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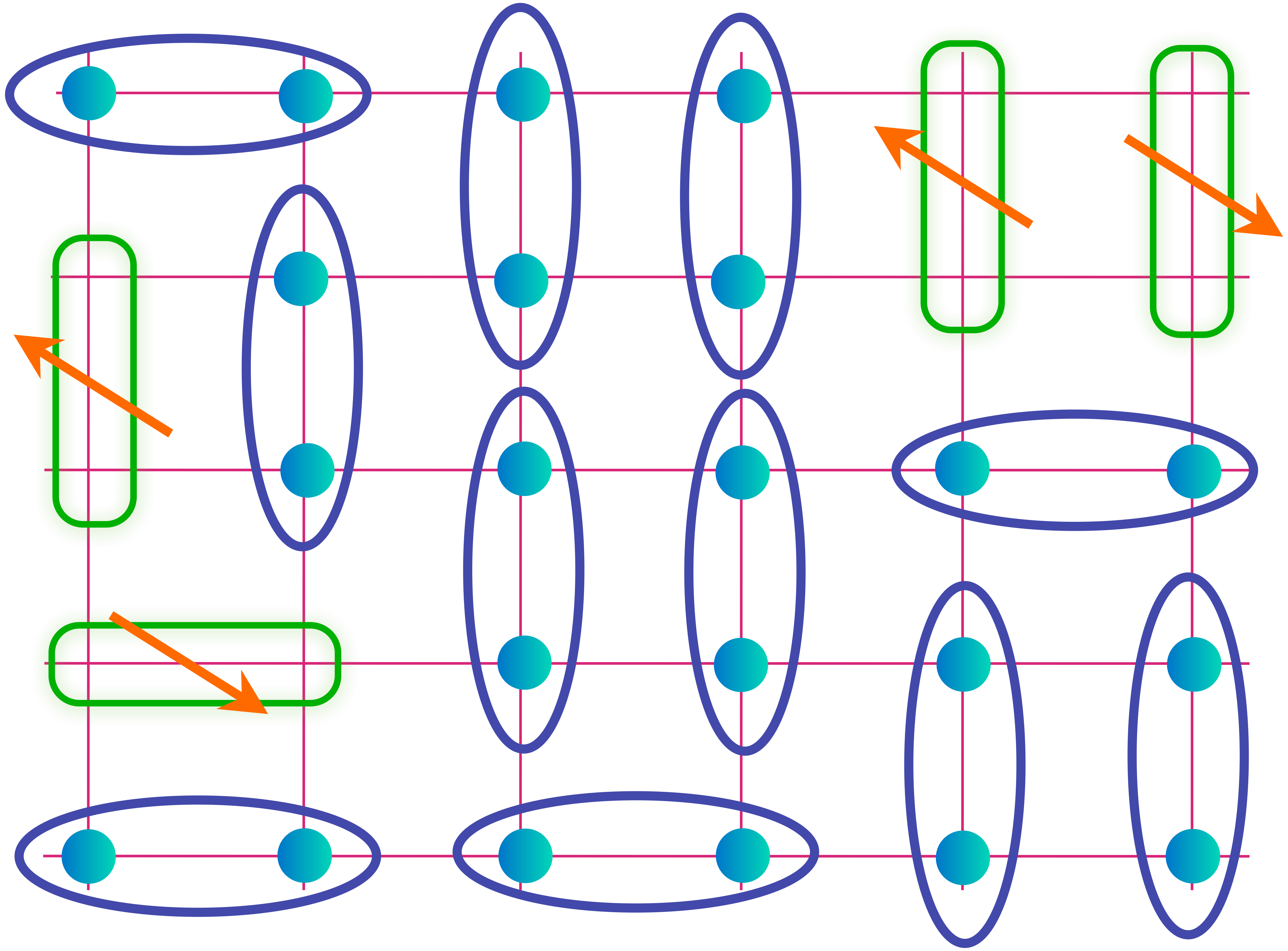

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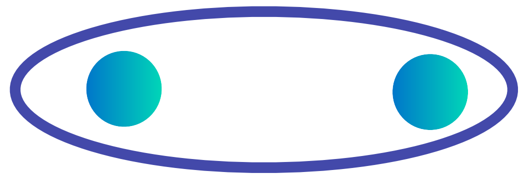
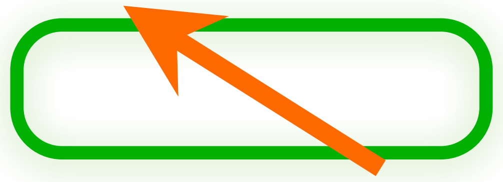
 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

 $= (|\uparrow \circ\rangle + |\circ \uparrow\rangle)/\sqrt{2}$

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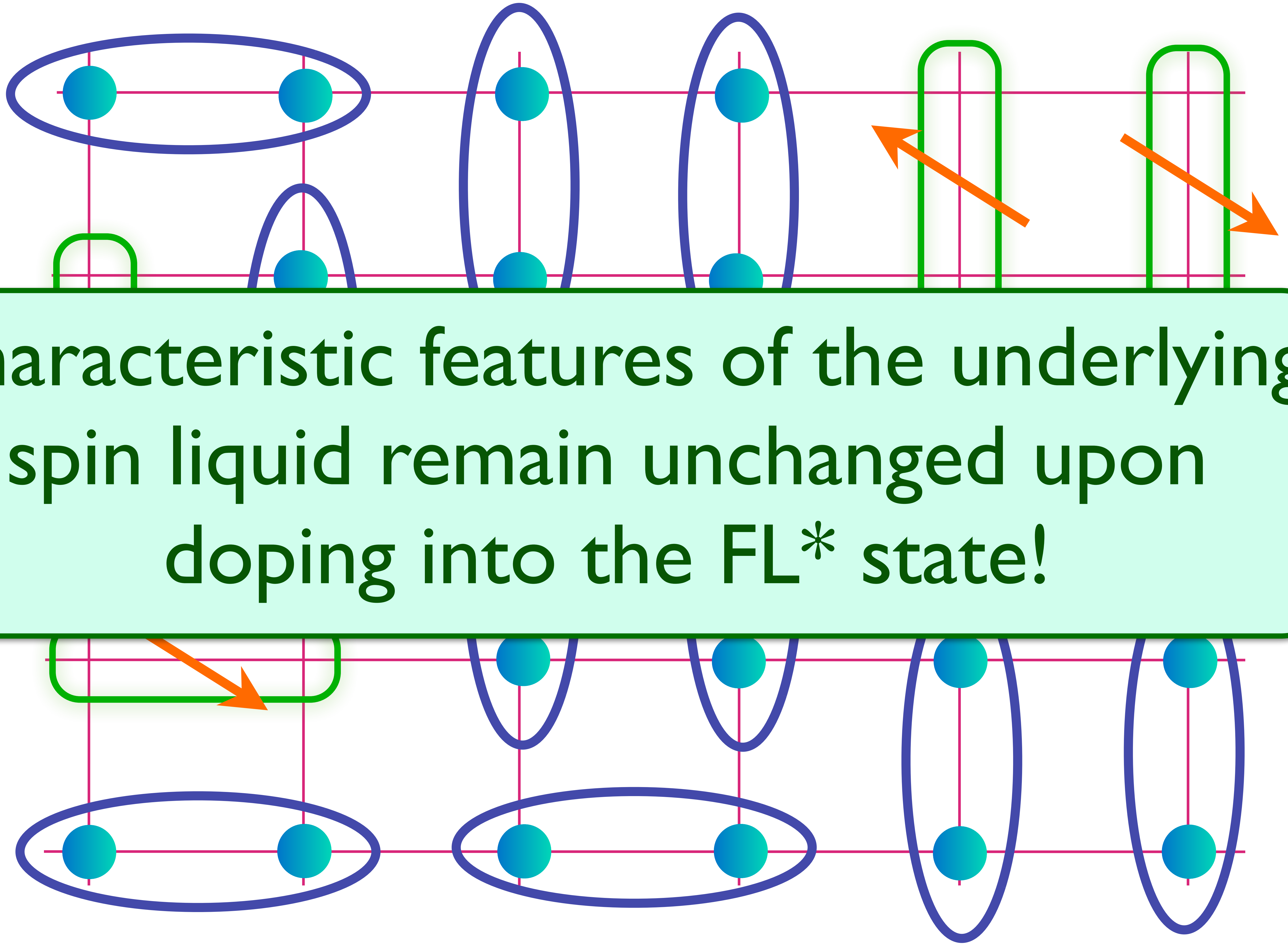
FL* in a ***one-band*** model

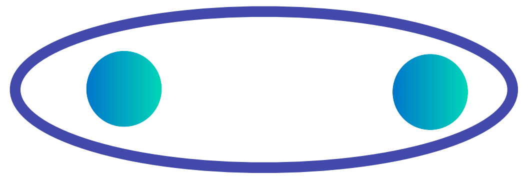
S. Sachdev *Phys. Rev. B* **49**, 6770 (1994); X.-G. Wen and P.A. Lee *Phys. Rev. Lett.* **76**, 503 (1996)
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, *Phys. Rev. B* **75**, 235122 (2007)

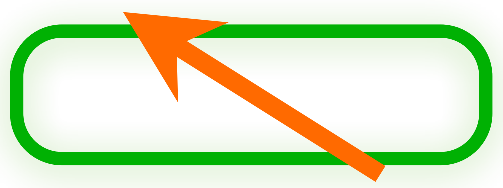


Characteristic features of the underlying spin liquid remain unchanged upon doping into the FL* state!

Metal with electron-like quasiparticles on a Fermi surface of size *p*, and emergent gauge fields

Spinon-holon bound state

 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

 $= \left(|\uparrow\circ\rangle + |\circ\uparrow\rangle\right)/\sqrt{2}$

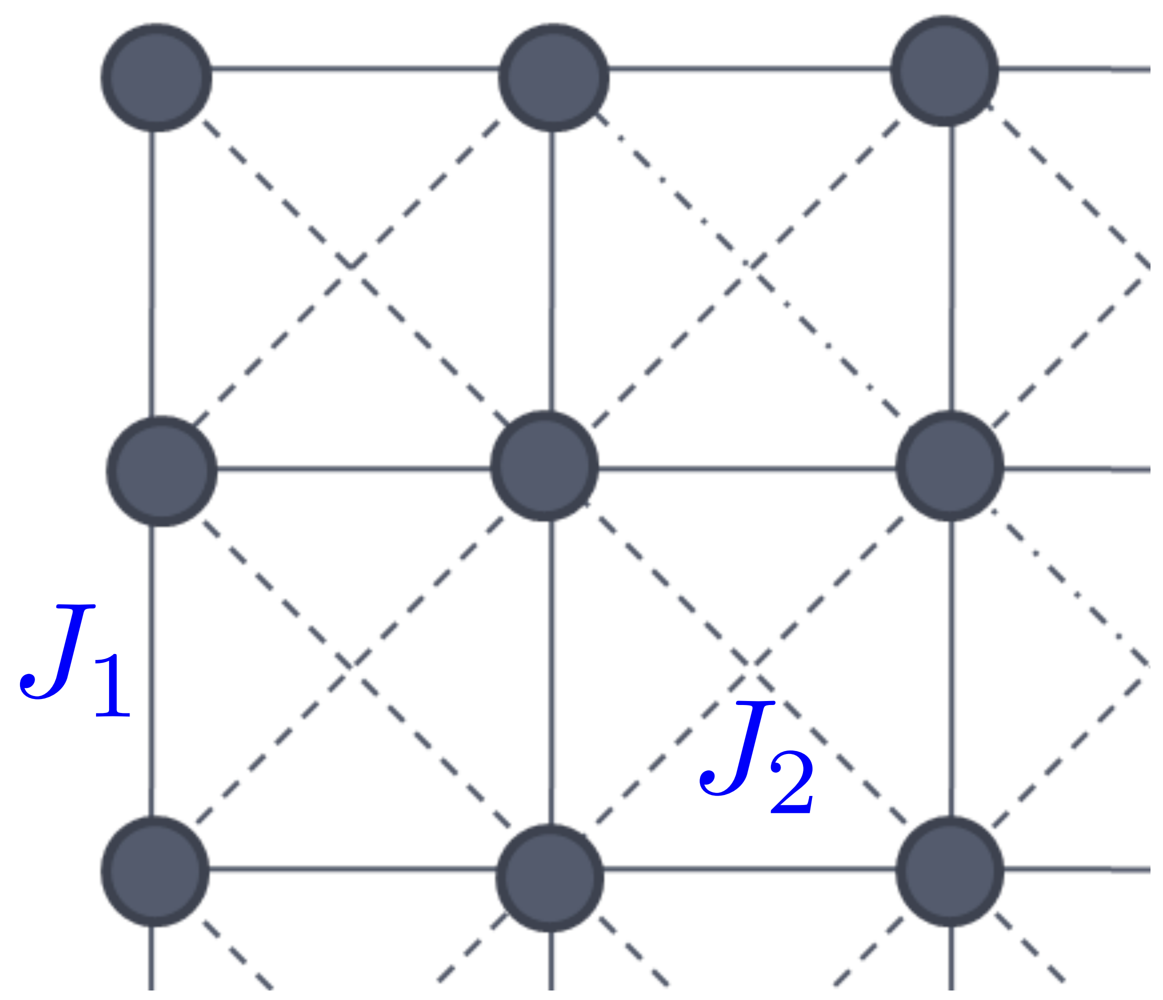
E. G. Moon and S. Sachdev, *Phys. Rev. B* **83**, 224508 (2011); M. Punk, A. Allais, and S. Sachdev, *Proc. Nat. Acad. Sci.* **112**, 9552 (2015)

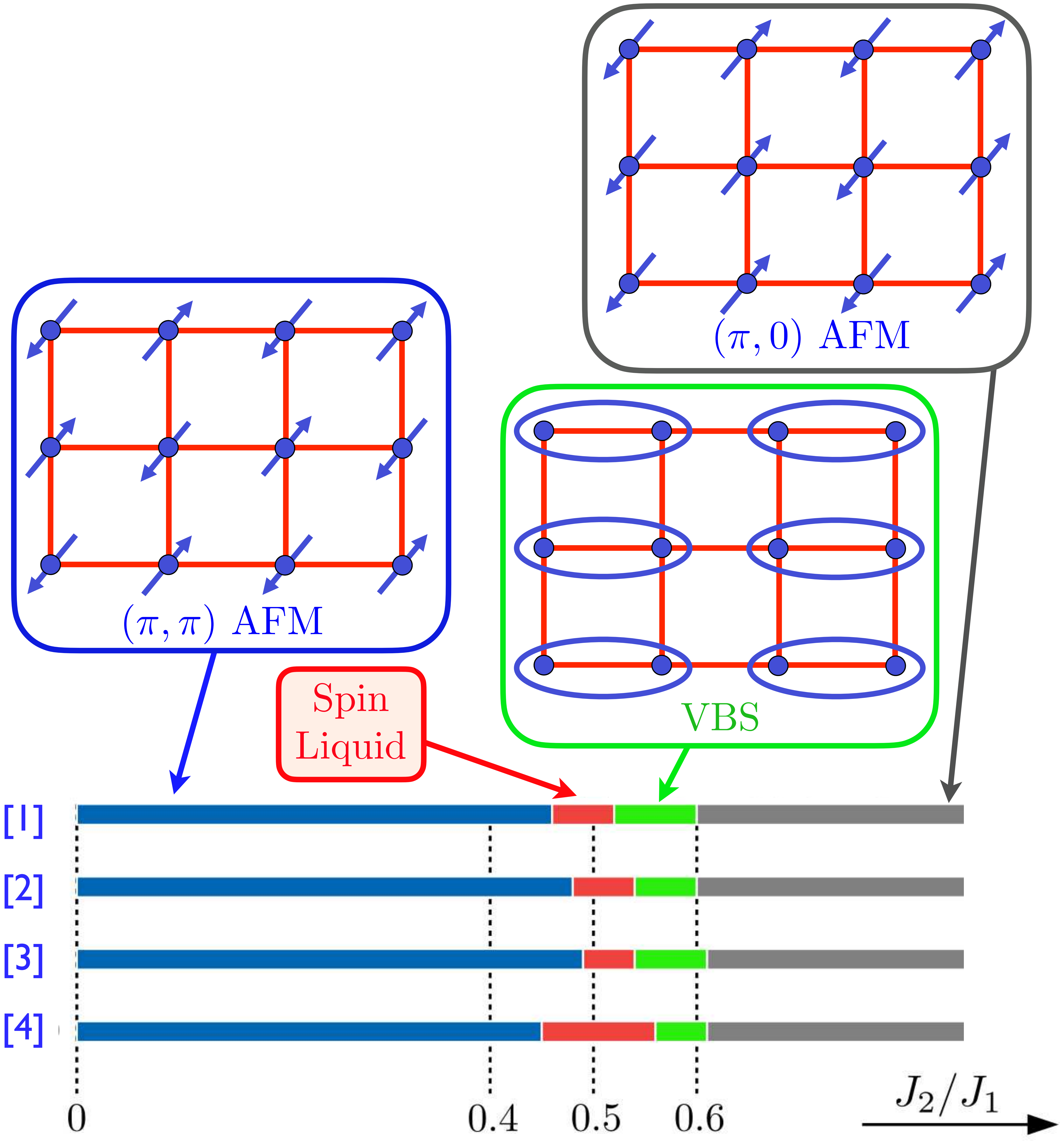
Which spin liquid describes the cuprates ?

Which spin liquid describes the cuprates ?

The CP^1/π-flux spin liquid

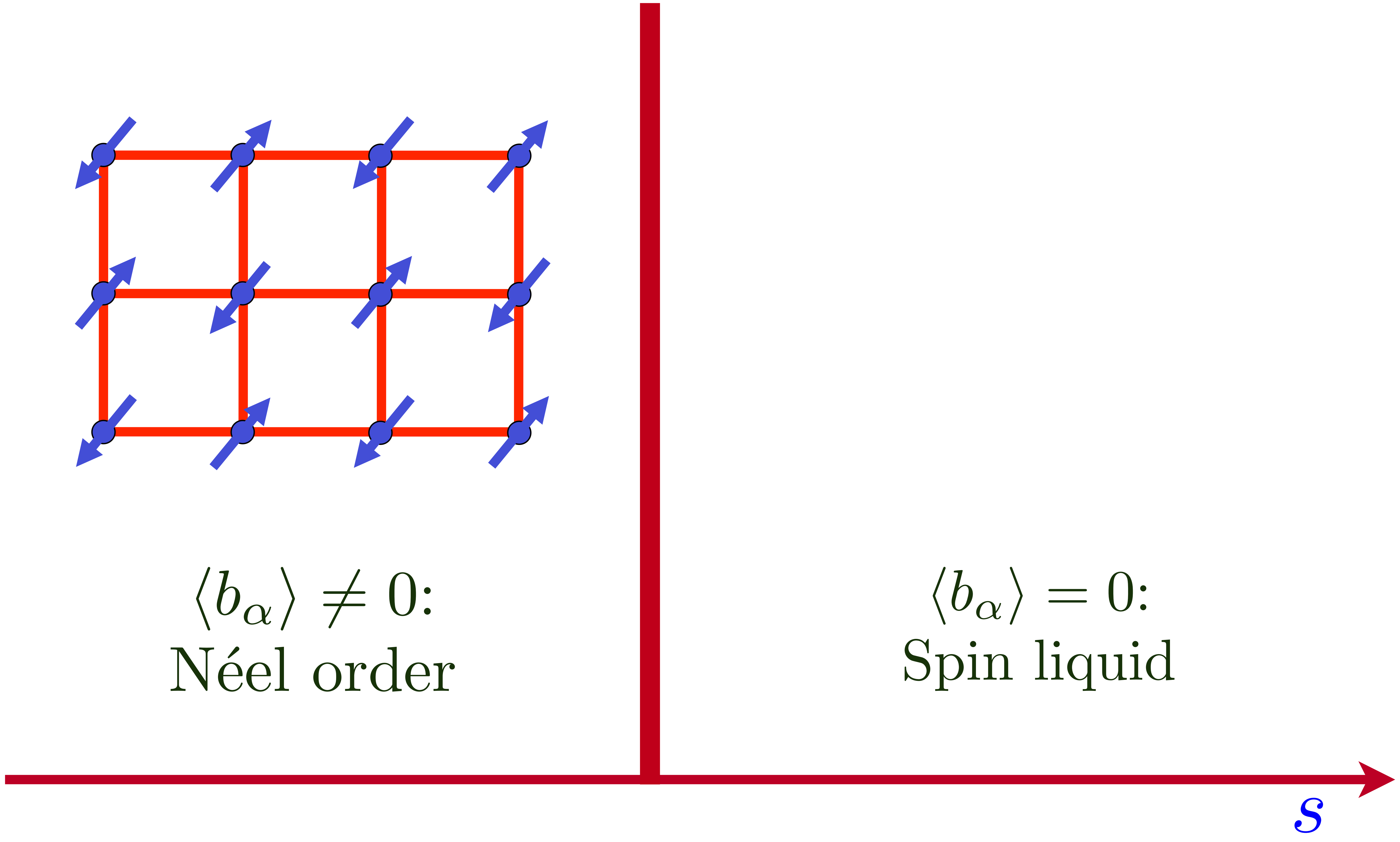
$$H = J_1 \sum_{\langle i,j\rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + J_2 \sum_{\langle\langle i,j\rangle\rangle} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$





1. L. Wang and A. W. Sandvik, *Phys. Rev. Lett.* **121**, 107202 (2018)
2. F. Ferrari and F. Becca, *Phys. Rev. B* **102**, 014417 (2020)
3. Y. Nomura and M. Imada, *Phys. Rev. X* **11**, 031034 (2021)
4. W.-Y. Liu, S.-S. Gong, Y.-B. Li, D. Poilblanc, W.-Q. Chen, and Z.-C. Gu, *Science Bulletin* **67,** 1034 (2022)

Insulating S=1/2 antiferromagnet



$$H = \sum_{i<j} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

Schwinger bosons

$$\boldsymbol{S}_i = \frac{1}{2} b_{i\alpha}^\dagger \boldsymbol{\sigma}_{\alpha\beta} b_{i\beta} \, , \quad \sum_{\alpha=\uparrow,\downarrow} b_{i\alpha}^\dagger b_{i\alpha} = 1$$

Mean-field spin liquid
with gapped bosonic spinons.

D.P. Arovas and A. Auerbach, *Phys. Rev. B* **38**, 316 (1988)

Insulating S=1/2 antiferromagnet

$$H = \sum_{i<j} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

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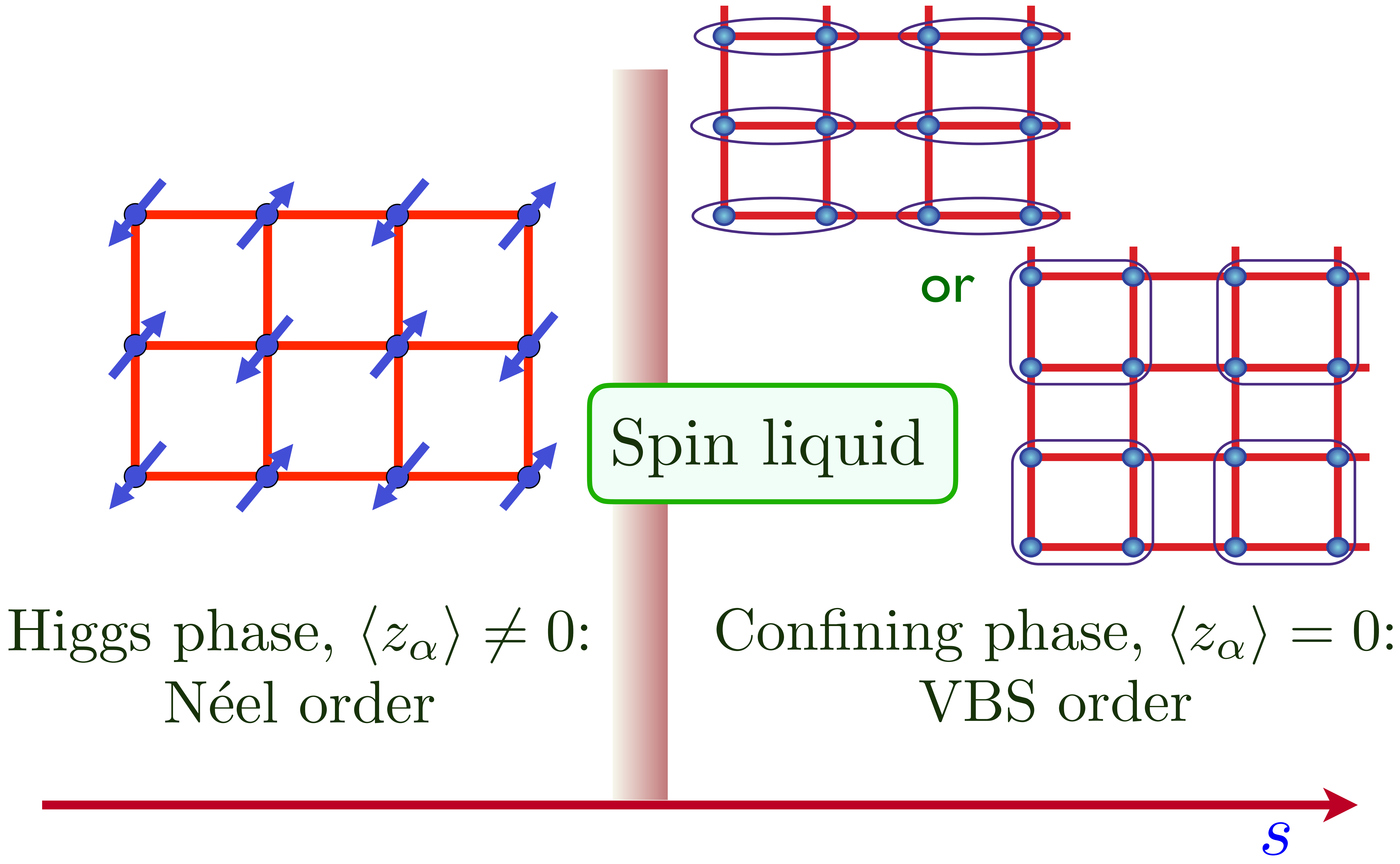
Mean-field spin liquid
with gapped bosonic spinons.

Low energy $\mathbb{CP}^1$ U(1) gauge theory

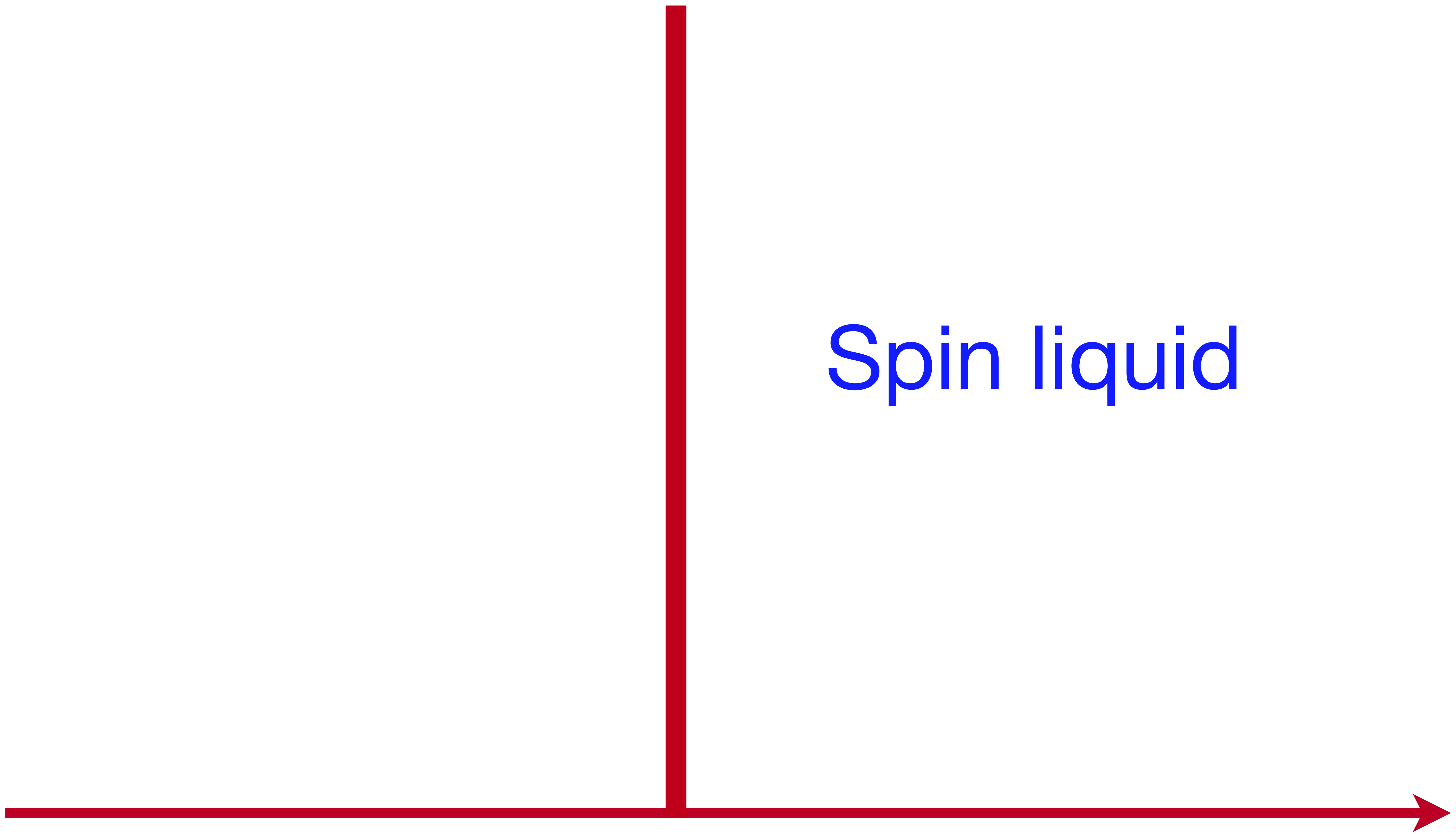
$$z_\alpha \sim b_{A\alpha} + \varepsilon_{\alpha\beta} b_{B\beta}$$



$$\mathcal{L} = |(\partial_\mu - i a_\mu) z_\alpha|^2 + s|z_\alpha|^2 + u|z_\alpha|^4 + \mathcal{L}_{\text{monopole}}$$

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

Insulating S=1/2 antiferromagnet



$$H = \sum_{i<j} J_{ij} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

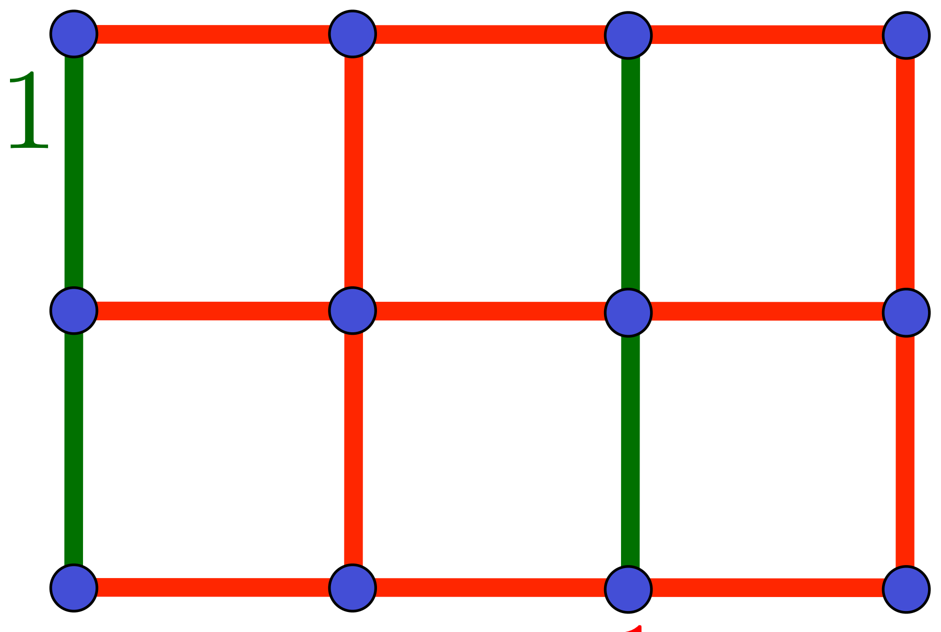
Schwinger fermions

$$\boldsymbol{S}_i = \frac{1}{2} f_{i\alpha}^\dagger \boldsymbol{\sigma}_{\alpha\beta} f_{i\beta} \, , \quad \sum_{\alpha=\uparrow,\downarrow} f_{i\alpha}^\dagger f_{i\alpha} = 1$$

π-flux mean-field theory
with gapless spinons at 2 Dirac points.

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

$e_{ij} = -1$



$e_{ij} = 1$

$$H_f = iJ \sum_{\langle ij \rangle} e_{ij} \left(f_{i\alpha}^\dagger f_{j\alpha} - f_{j\alpha}^\dagger f_{i\alpha} \right) \quad , \quad \varepsilon_{\mathbf{k}} = 2J\sqrt{\sin^2(k_x) + \sin^2(k_y)}$$

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

S=1/2
square
lattice anti-
ferromagnet

SU(2) gauge theory of $N_f = 2$ fundamental, massless, Dirac fermions.

Obtained from a saddle-point of fermionic spinons moving in π-flux.

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

SO(5) non-linear σ-model of Néel/VBS orders with $k = 1$ WZW term

A. Tanaka and X. Hu, *Phys. Rev. Lett.* **95**, 036402 (2005); T. Senthil and M.P.A. Fisher *Phys. Rev. B* **74**, 064405 (2006); Ying Ran and X.-G. Wen, cond-mat/0609620; C. Wang, A. Nahum, M. A. Metlitski, C. Xu, and T. Senthil, *Phys. Rev. X* **7**, 031051 (2017)

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

S=1/2 square lattice anti-ferromagnet

SU(2) gauge theory of $N_f = 2$ fundamental, massless, Dirac fermions.

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SO(5) non-linear σ-model of Néel/VBS orders with $k = 1$ WZW term

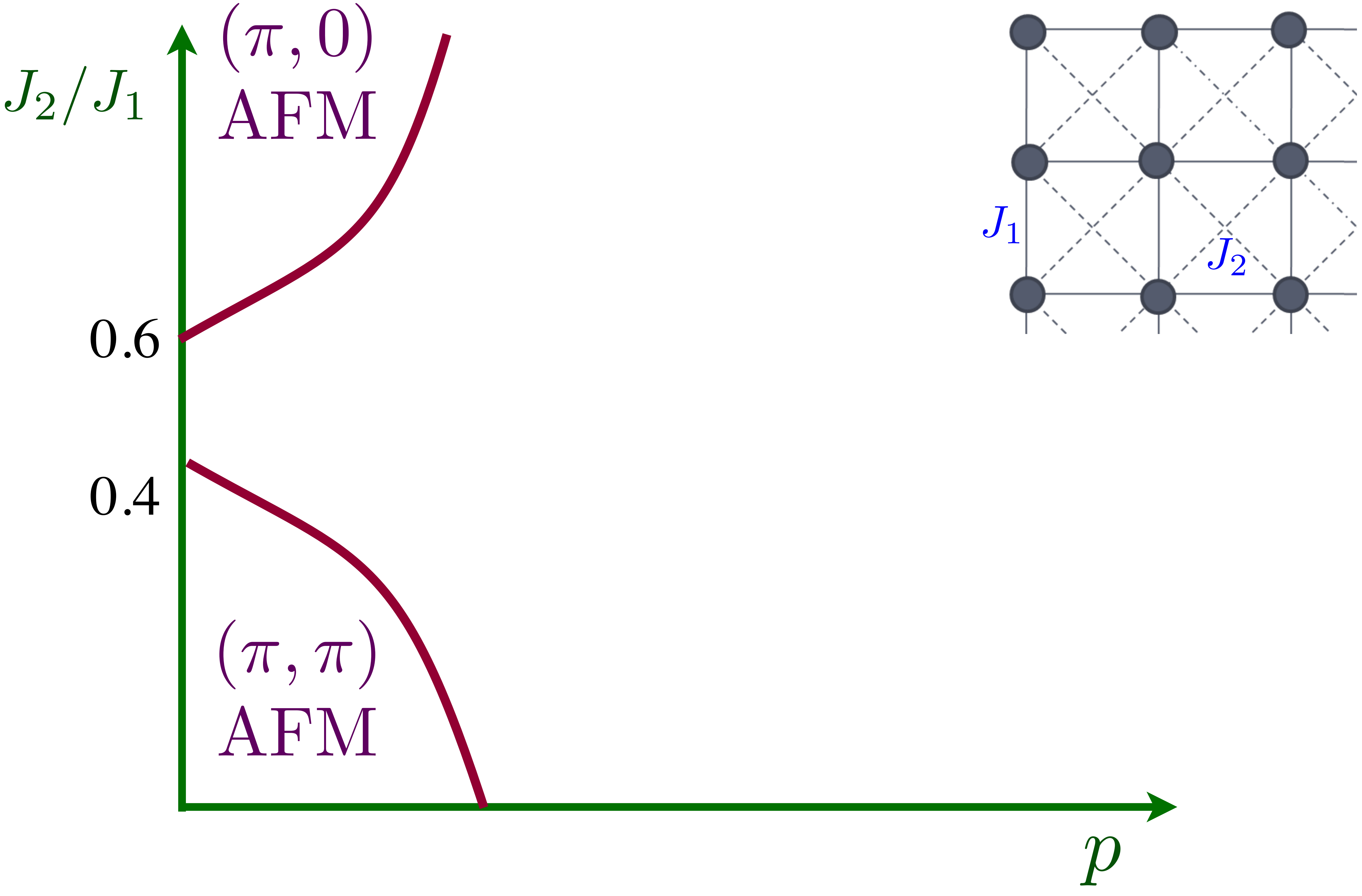
Many numerical works show that deconfined critical theory applies over a substantial length scale, but ultimately confines at the longest distances.

Anders W. Sandvik *Phys. Rev. Lett.* **98**, 227202 (2007)
Adam Nahum, P. Serna, J. T. Chalker, M. Ortuño, and A. M. Somoza, *Phys. Rev. Lett.* **115**, 267203 (2015)
Z. Zhou, L. Hu, W. Zhu, and Yin-Chen He, arXiv:2306.16435

High Temperature Superconductivity in a Lightly Doped Quantum Spin Liquid

Hong-Chen Jiang[1,*] and Steven A. Kivelson[2]

Phys. Rev. Lett. **127**, 097002 (2021)



Superconducting valence bond fluid in lightly doped 8-leg *t*-*J* cylinders
Hong-Chen Jiang, Steven A. Kivelson, and Dung-Hai Lee, arXiv:2302.11633

Upon increasing the cylinder width from 4 to 8, we observed a significant strengthening of the quasi-long-range superconducting correlations, and a dramatic suppression of any "competing" charge-density-wave order. Extrapolating from the observed behavior of the width 8 cylinders, we speculate that the system has a nodeless d-wave superconducting ground-state in the 2D limit.

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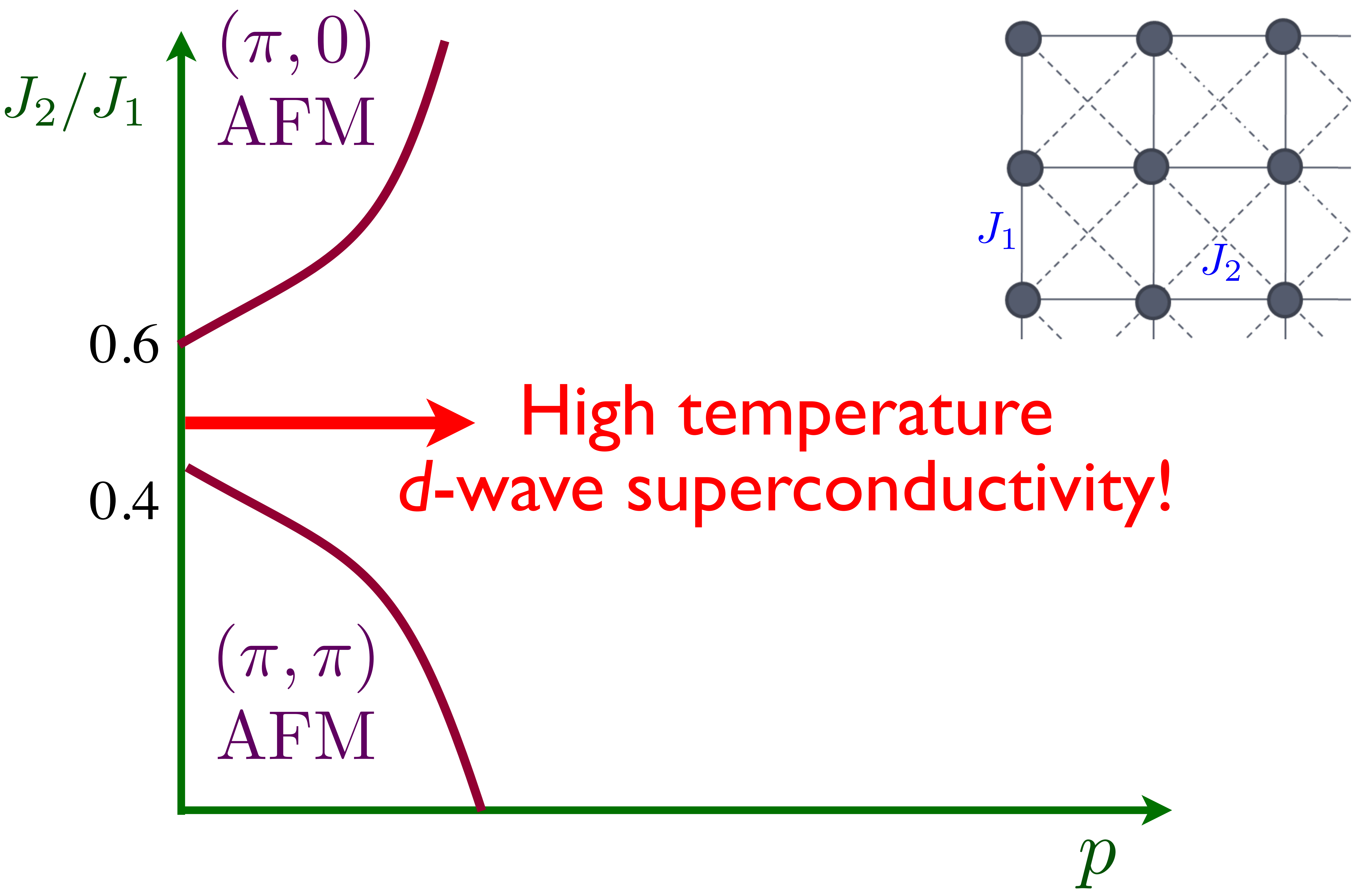
Phys. Rev. Lett. **127**, 097002 (2021)



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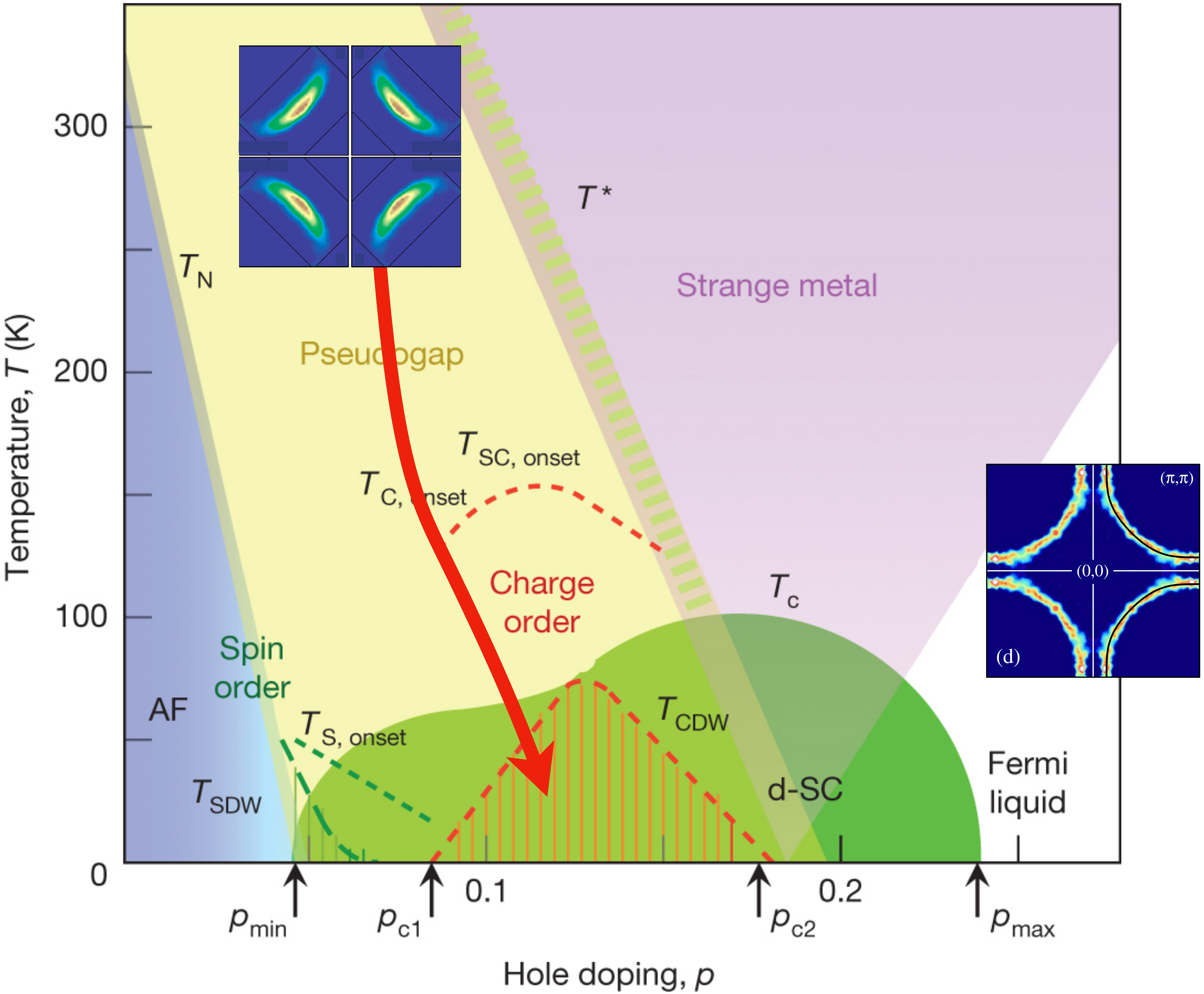
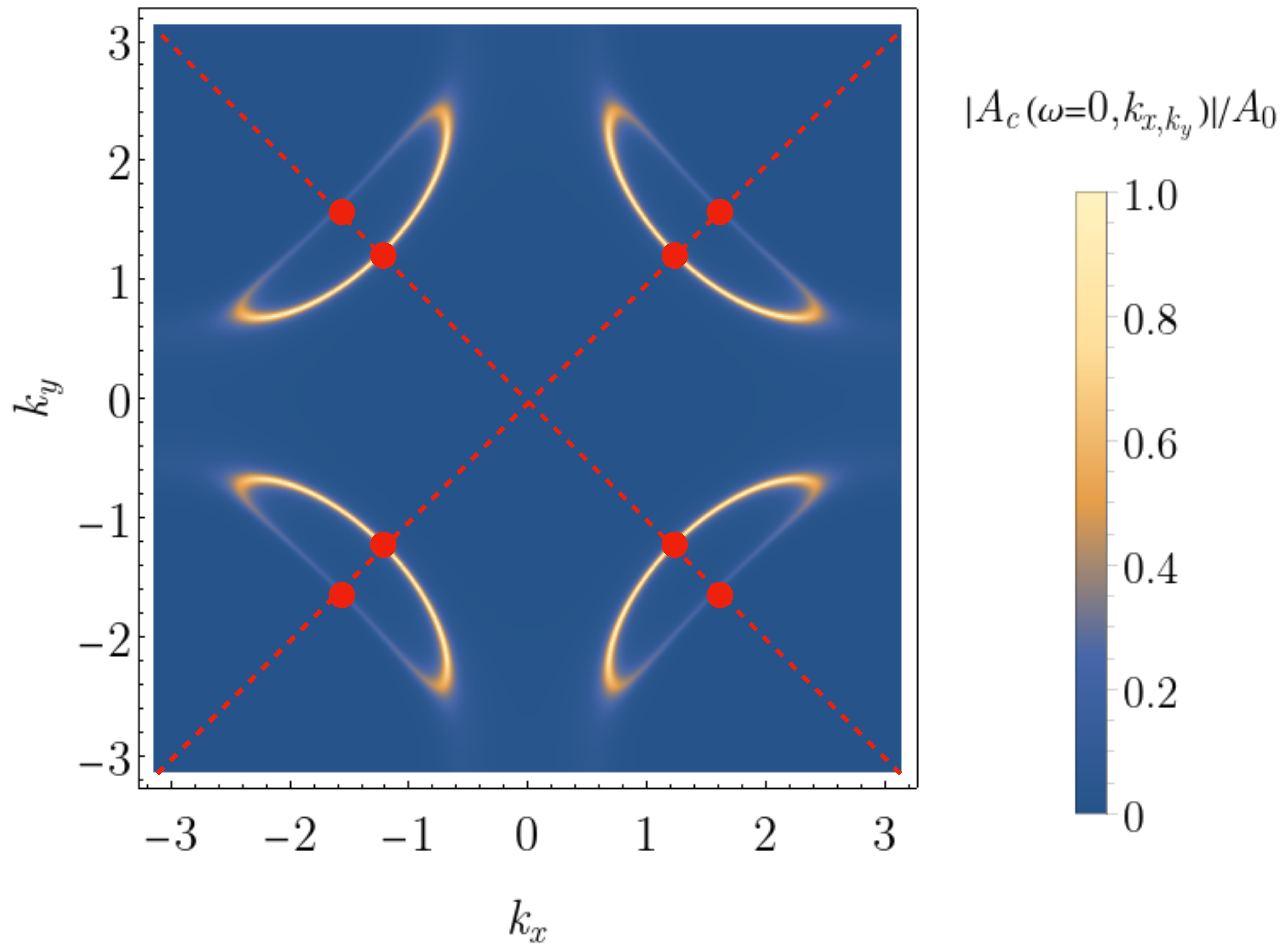
From FL* to d-wave superconductivity

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



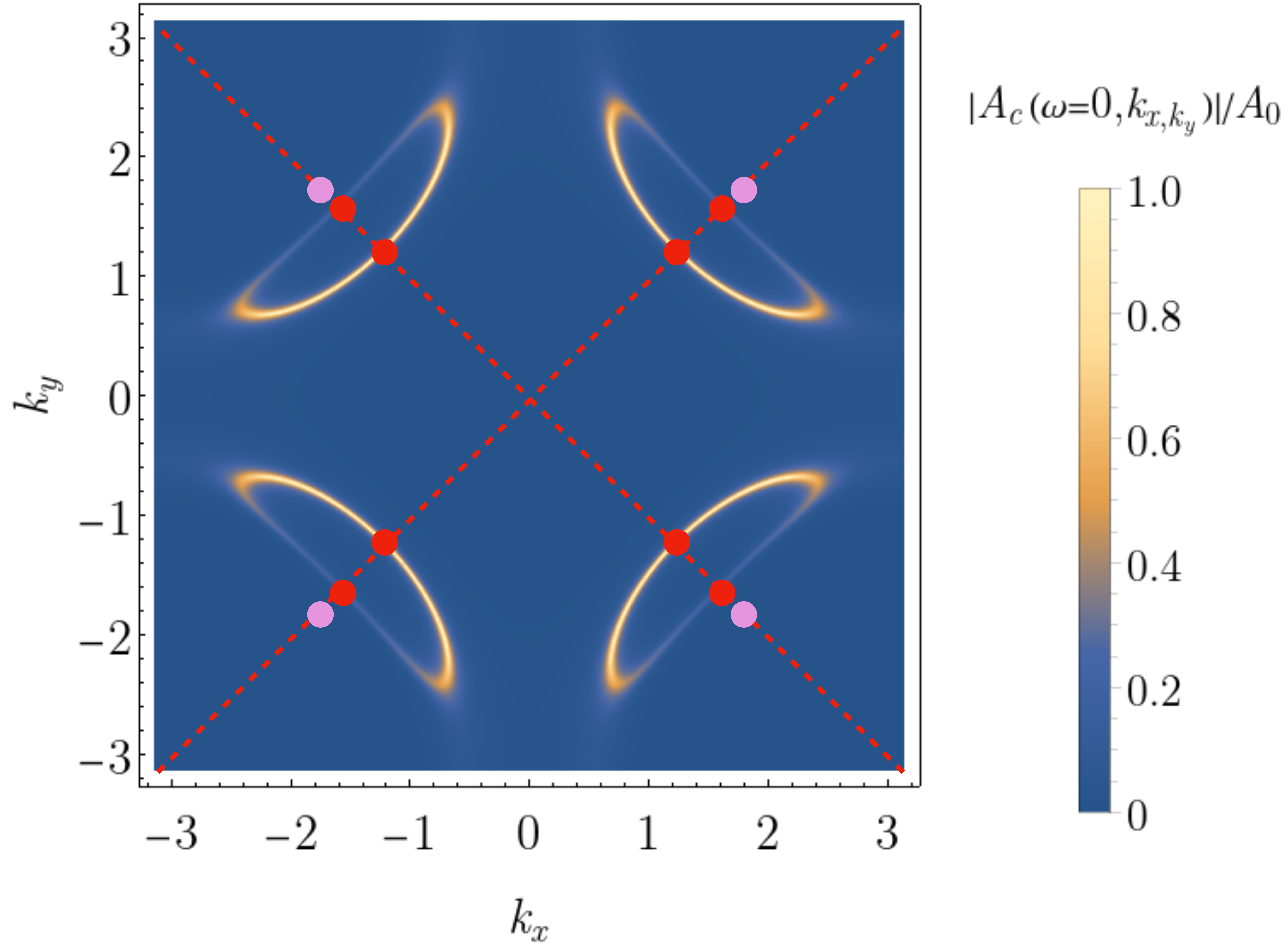
Build a theory for the phase diagram from a theory of the pseudogap metal as a 'metastable' $T = 0$ quantum phase.

Lowest T phases obtained from pseudogap metal should connect smoothly to conventionally order phases obtained from the Fermi liquid.



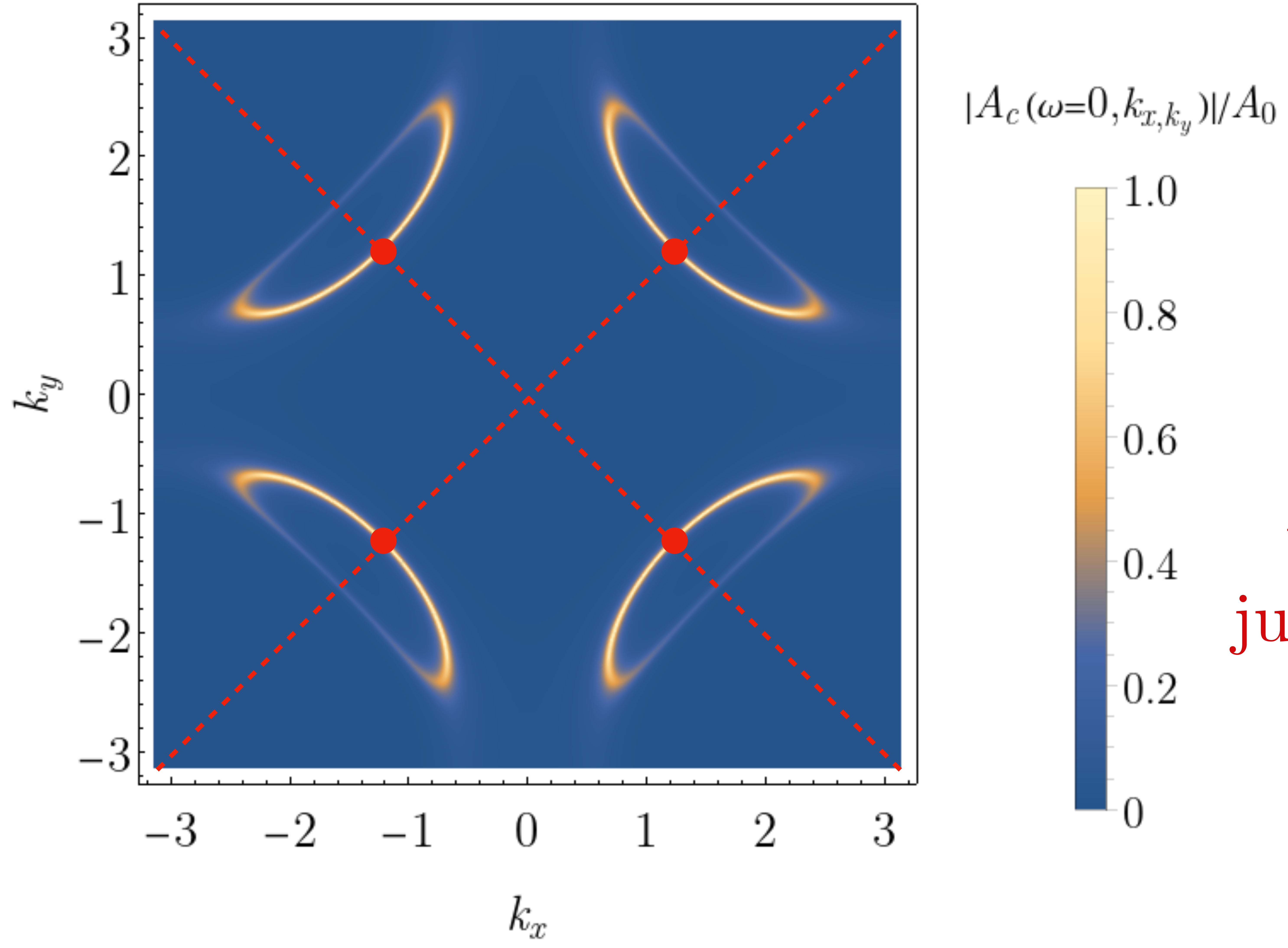
$$E_{\boldsymbol{k}} = \left(\varepsilon_{\boldsymbol{k}}^2 + \Delta_{\boldsymbol{k}}^2\right)^{1/2}$$
$$\Delta_{\boldsymbol{k}} = \Delta_0 \left(\cos k_x - \cos k_y\right)$$

Adding d-wave pairing
to the hole pockets
leads to 8 nodal points???



8 nodal points from the Fermi pockets
and
4 nodal points from the π-flux spin liquid

Shubhayu Chatterjee and S. Sachdev, PRB **94**, 205117 (2016)
Maine Christos and S.Sachdev, arXiv:2308.03835

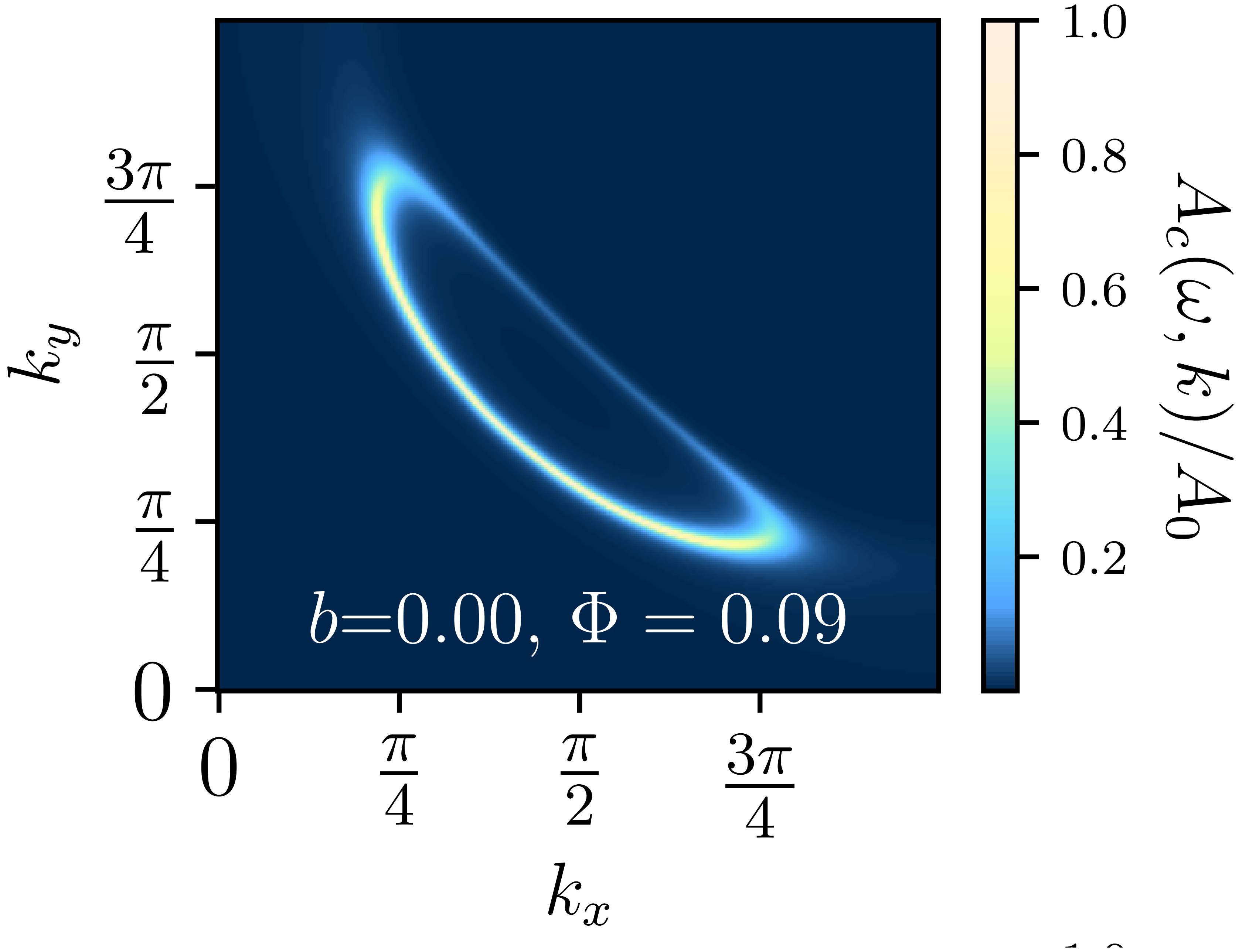


8 nodal points annihilate each other, leaving 4 nodal points with anisotropic velocities, just as in a BCS d-wave state.

Shubhayu Chatterjee and S. Sachdev, PRB **94**, 205117 (2016)

Maine Christos and S.Sachdev, arXiv:2308.03835

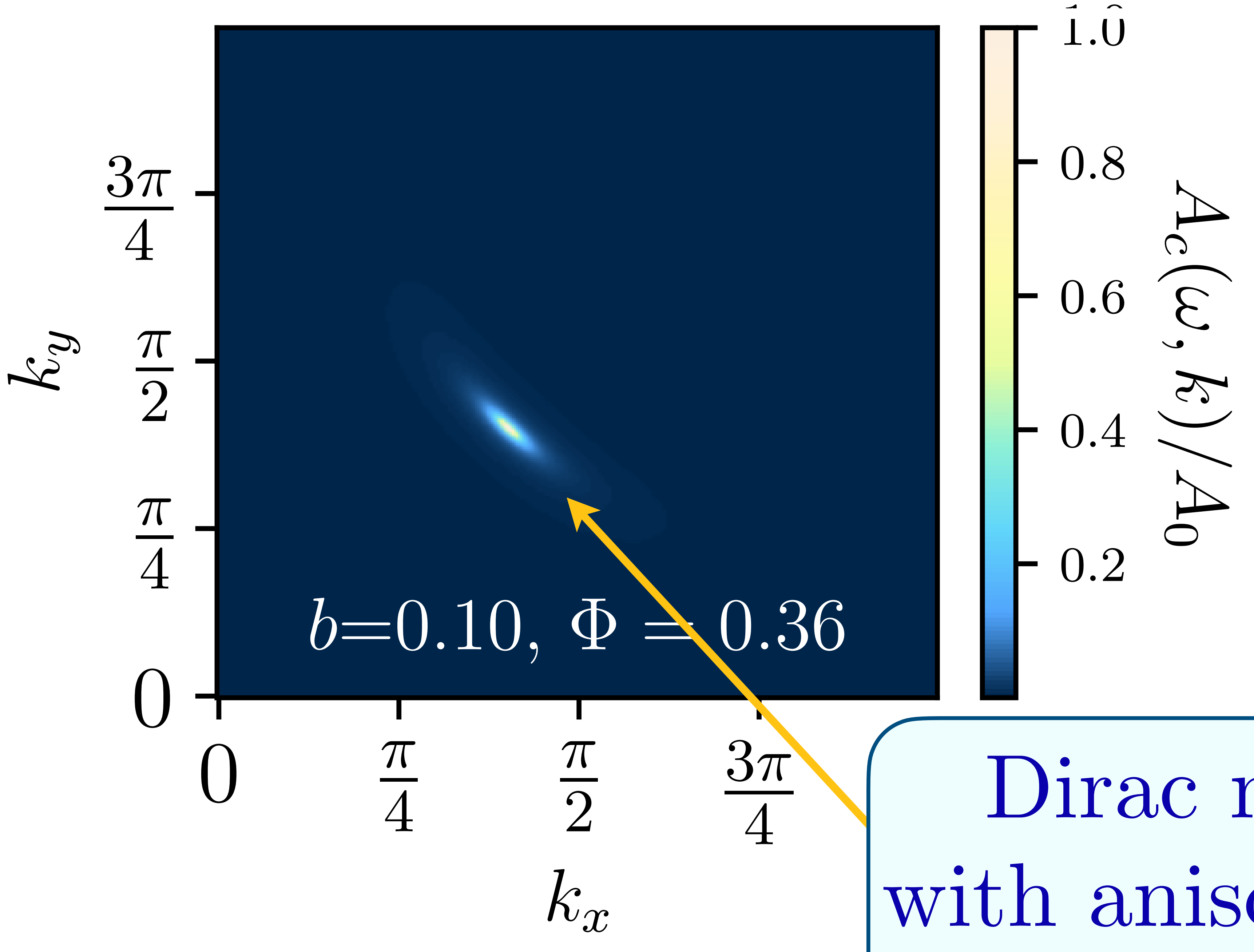
Electron spectral density in hole-doped cuprates



FL*

d-wave superconductor obtained by condensing charge-e, SU(2) fundamental boson.

Spinons of the π-flux state annihilate the extra nodes in the d-wave superconductor.

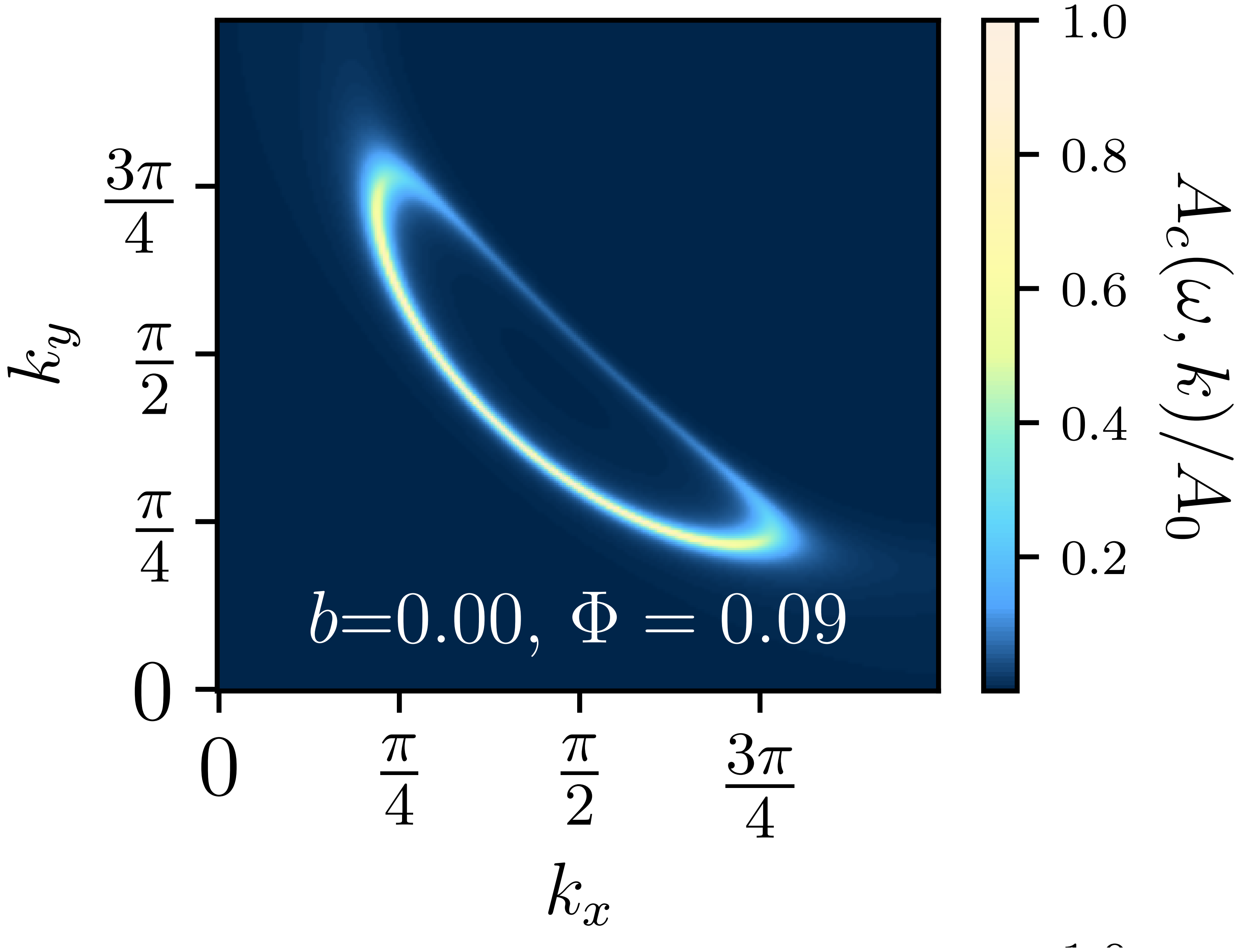


dSC

Dirac node with anisotropic velocities

Maine Christos and S.Sachdev, arXiv:2308.03835

Electron spectral density in hole-doped cuprates



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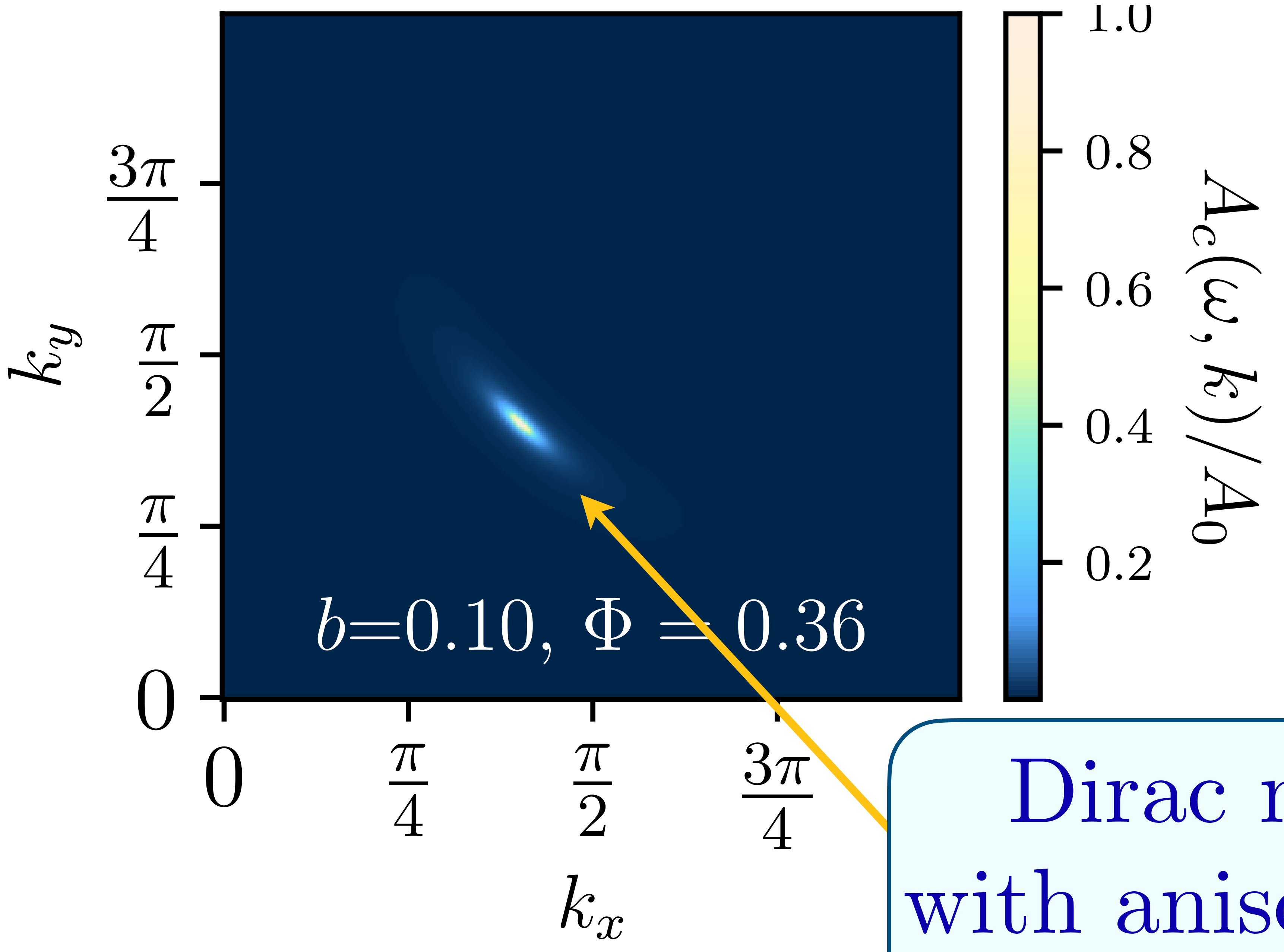

dSC

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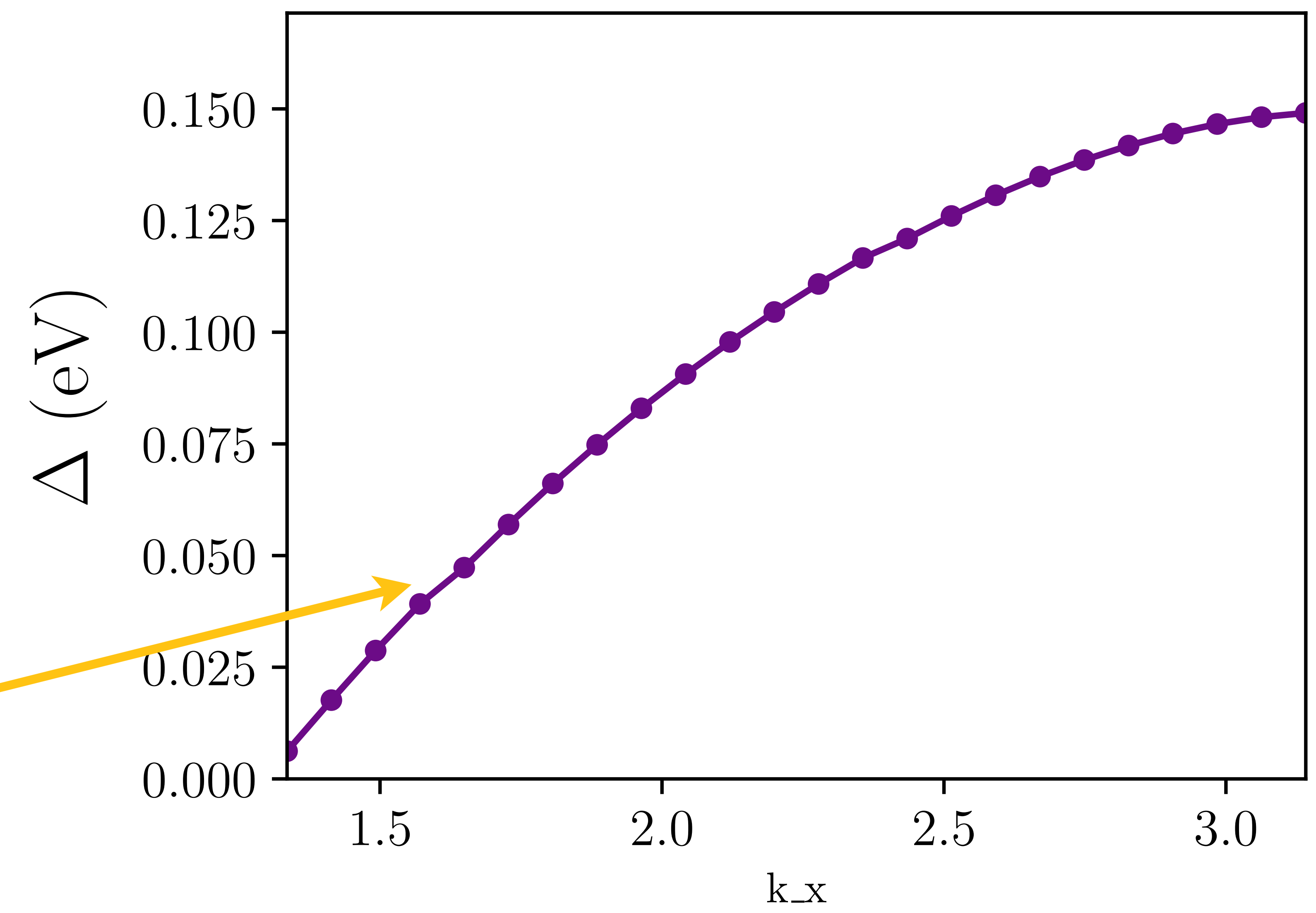
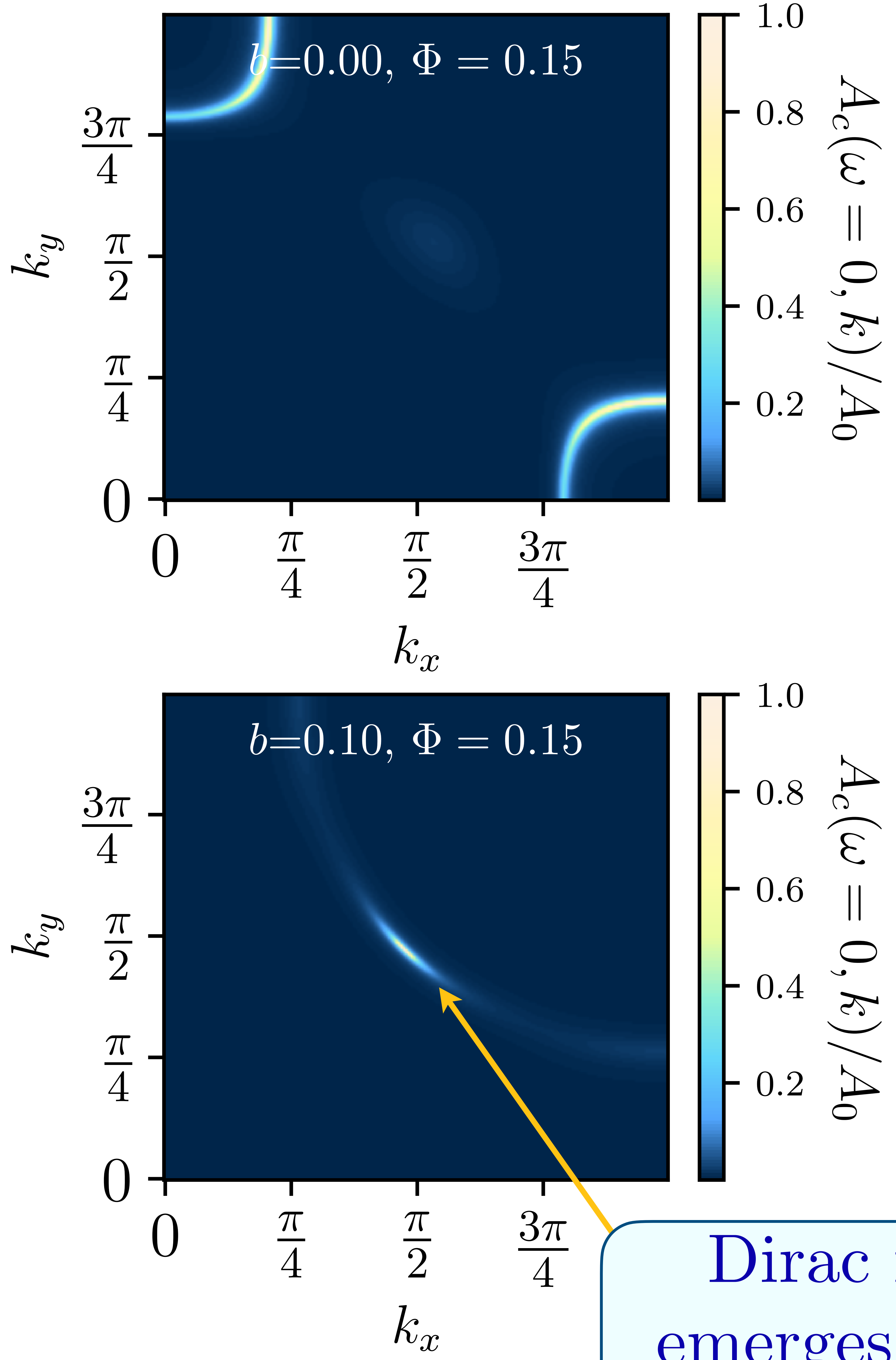


Maine Christos and S.Sachdev, arXiv:2308.03835

Electron spectral density in electron-doped cuprates



FL*

d-wave superconductor obtained by condensing charge-e, SU(2) fundamental boson.

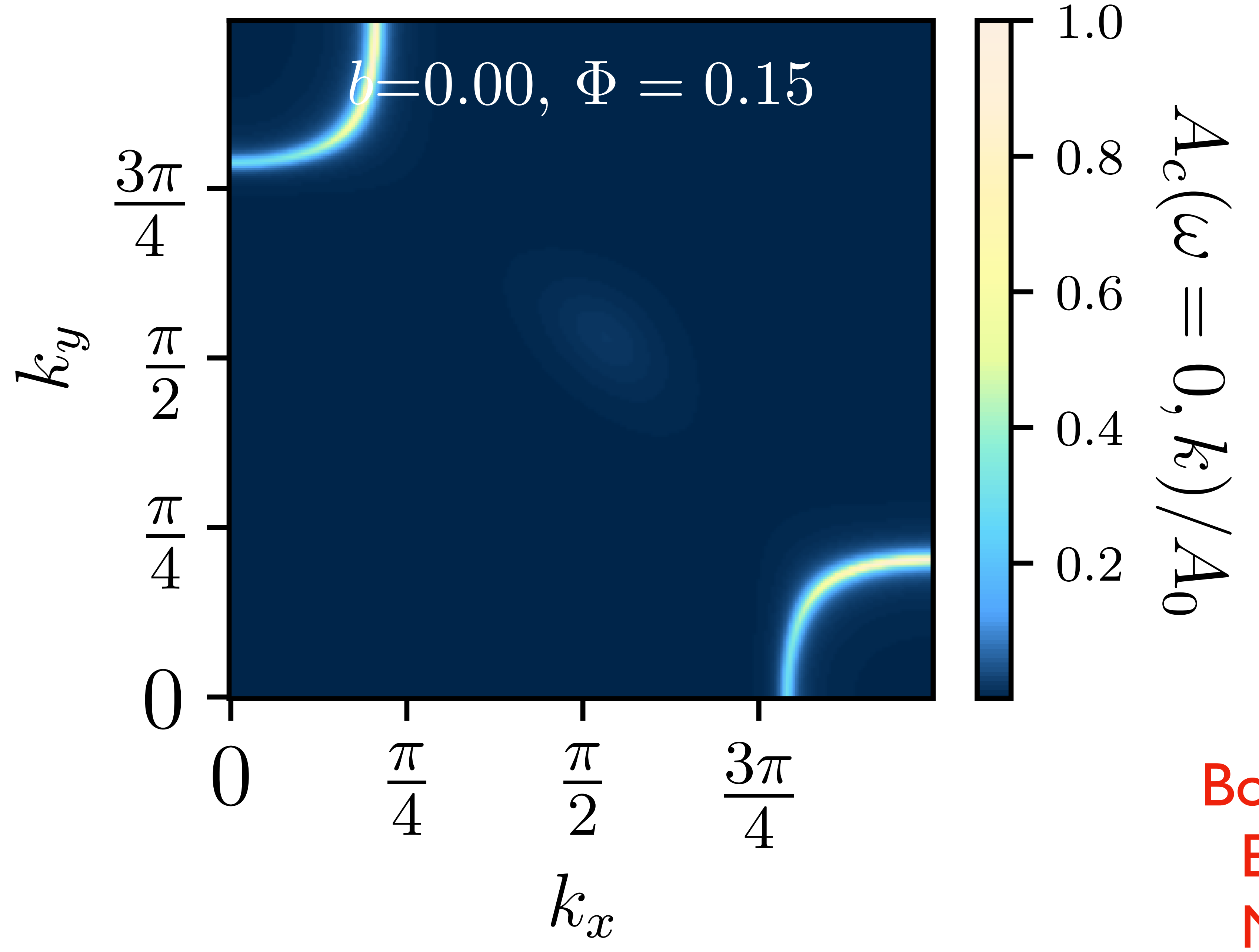
dSC

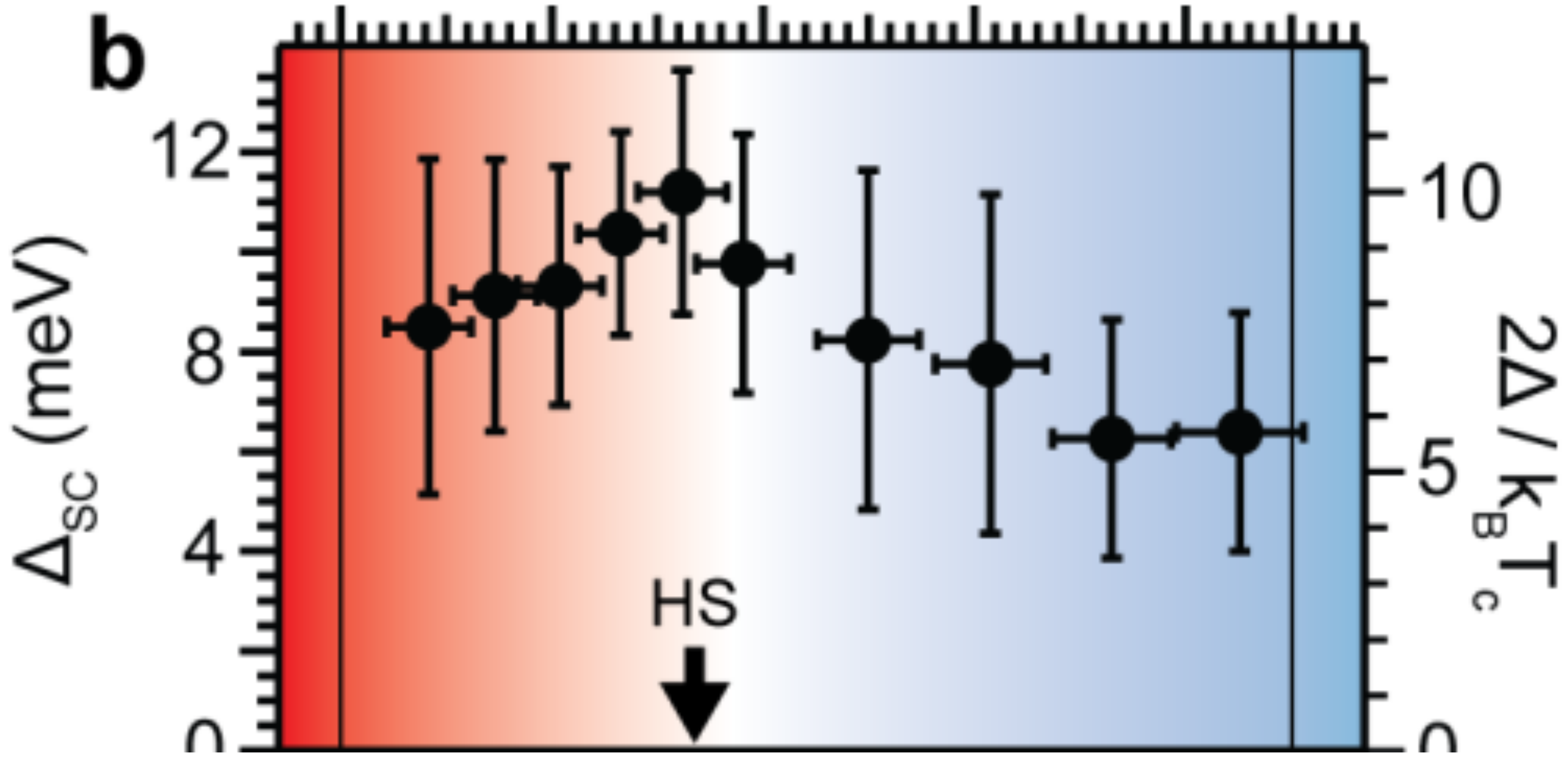
Nodes of the *d*-wave superconductor are remnants of the spinons of the π-flux state.

Dirac node emerges inside normal state gap

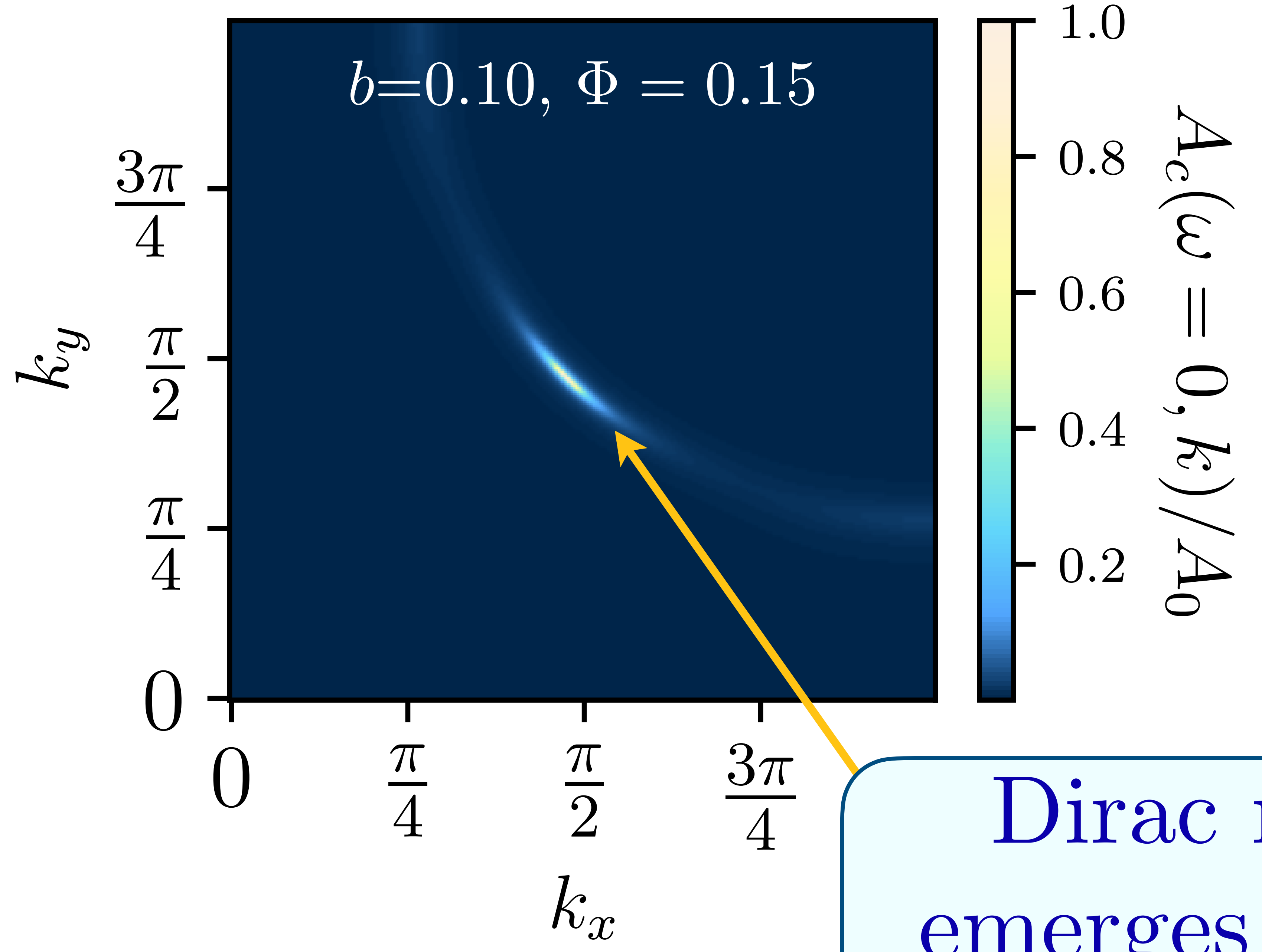
Maine Christos and S.Sachdev, arXiv:2308.03835

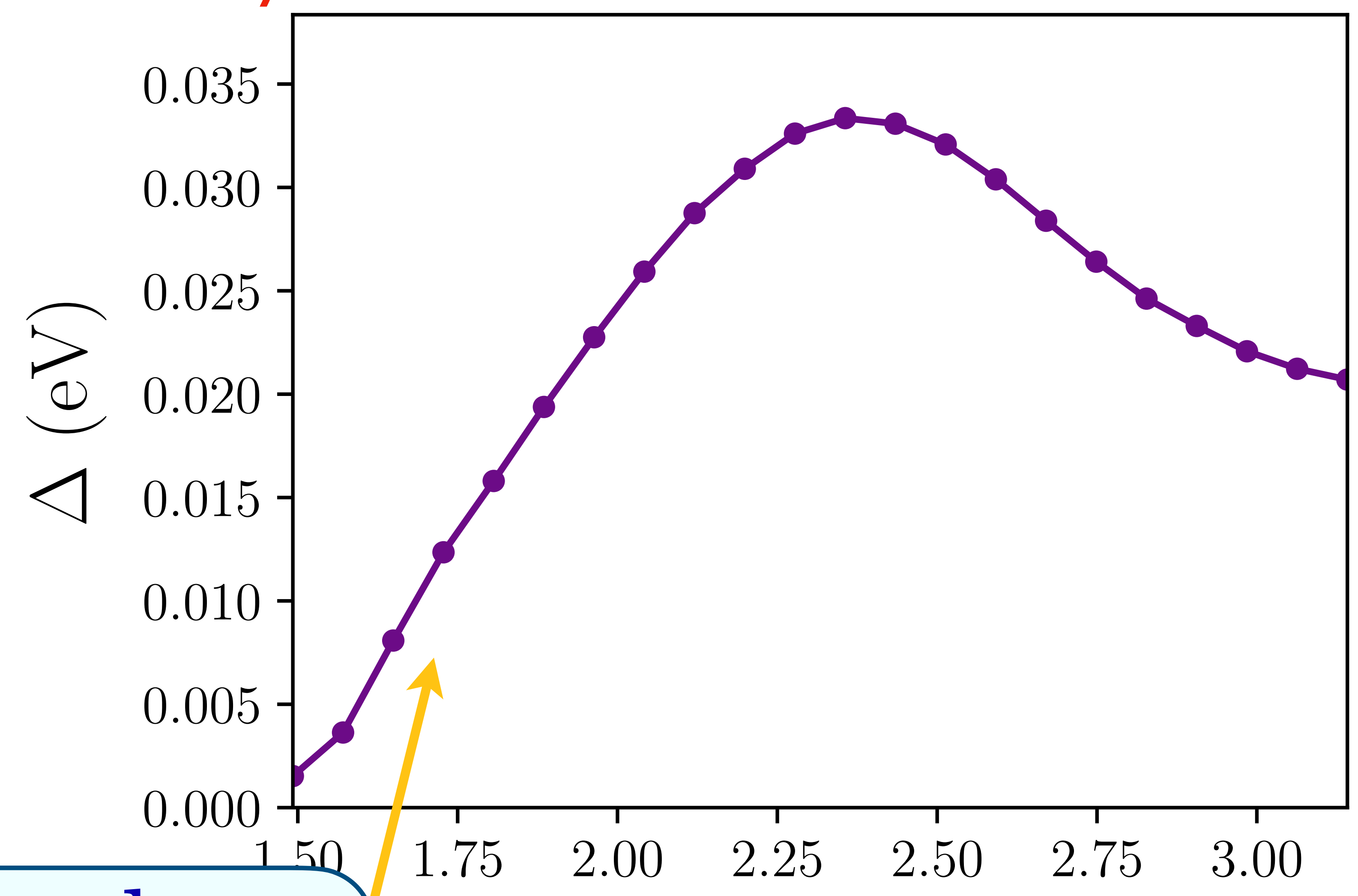
Electron spectral density in electron-doped cuprates





Bogoliubov Quasiparticle on the Gossamer Fermi Surface in Electron-Doped Cuprates, Ke-Jun Xu……Z.-X. Shen, arXiv:2308.05313; Nature Physics

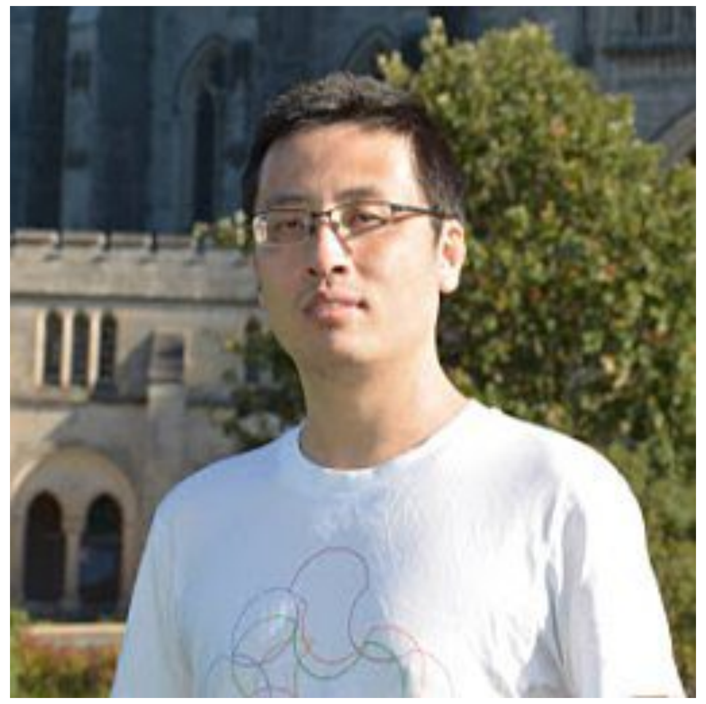




Maine Christos and S.Sachdev, arXiv:2308.03835

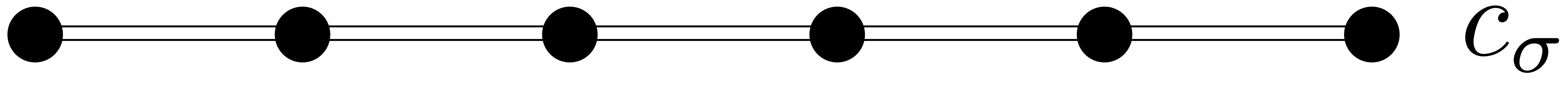
Dirac node emerges inside normal state gap

Ancilla theory of FL* in a single-band model



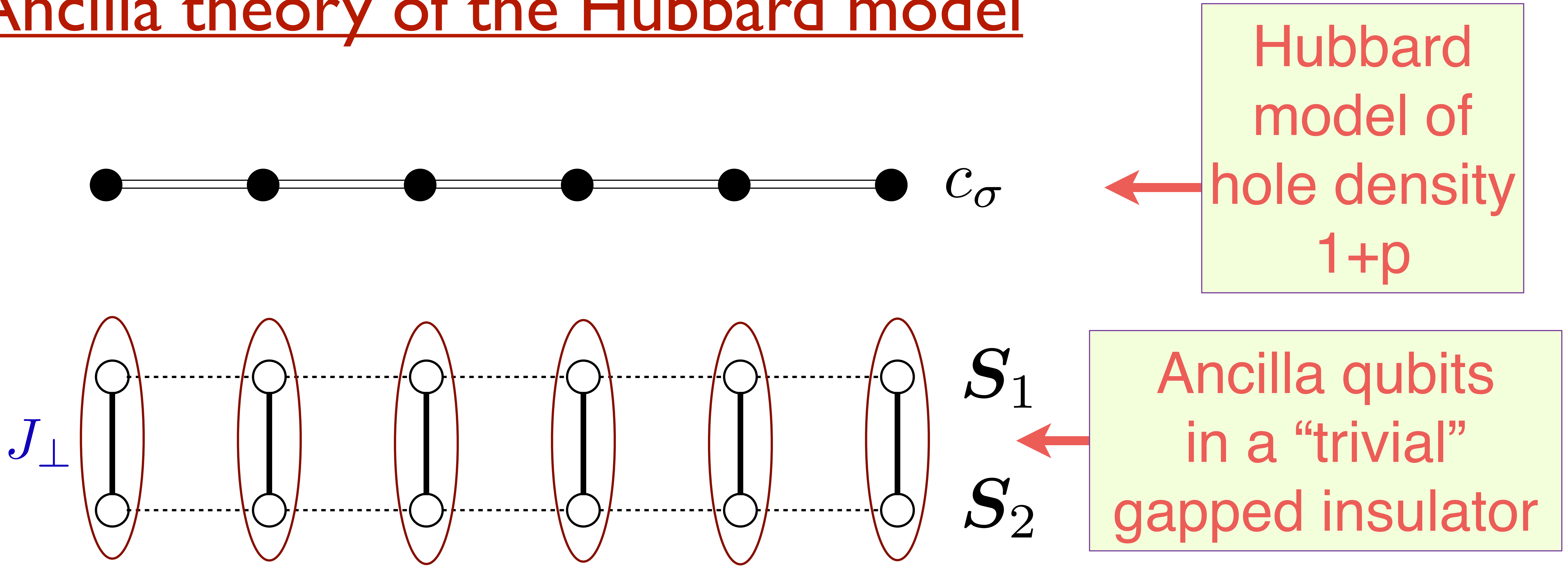
Ya-Hui Zhang

Ancilla theory of the Hubbard model



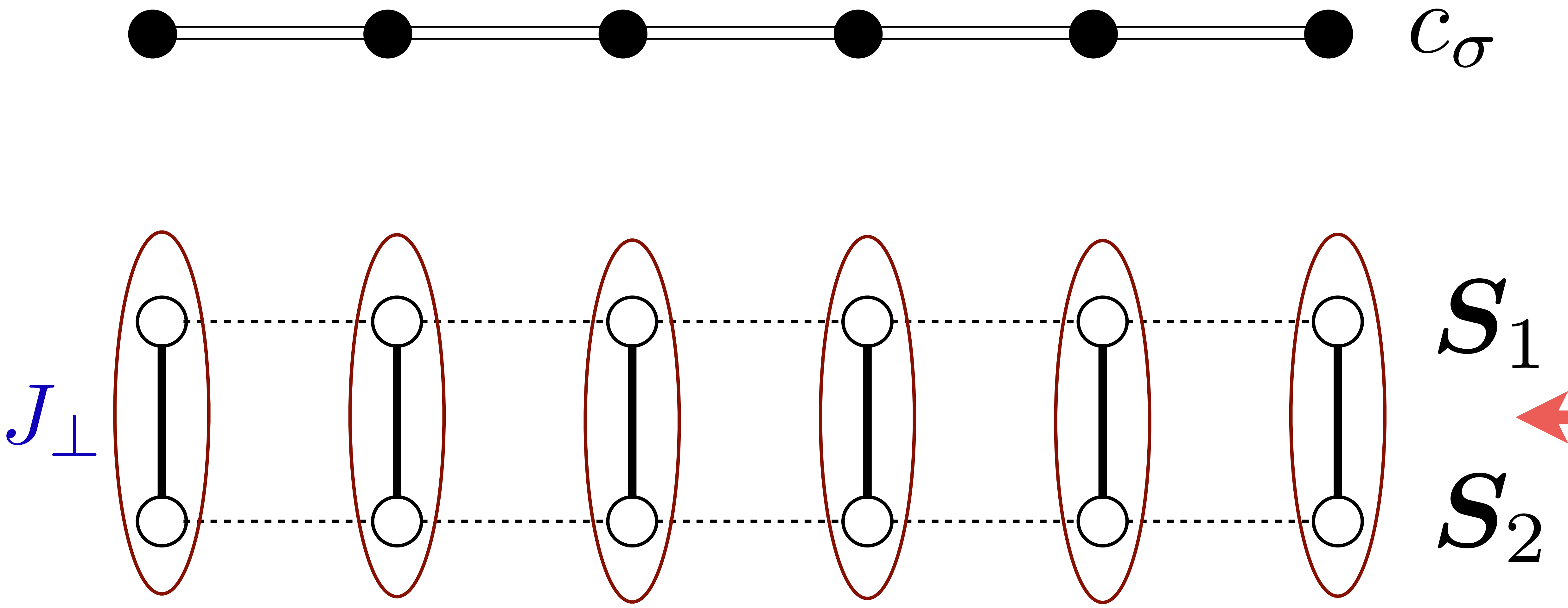
Hubbard model of hole density 1+p

Ancilla theory of the Hubbard model



$$\mathcal{H}_{\rm Hubbard} + \mathcal{H}_{\rm trivial\ \ insulator}$$

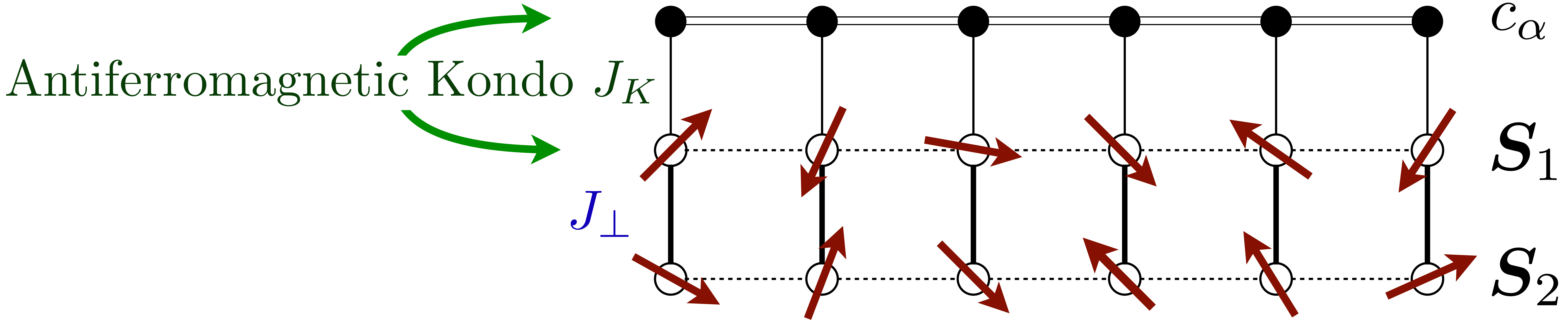
Ancilla theory of the Hubbard model



Hubbard model of hole density 1+p

Ancilla qubits in a “trivial” gapped insulator

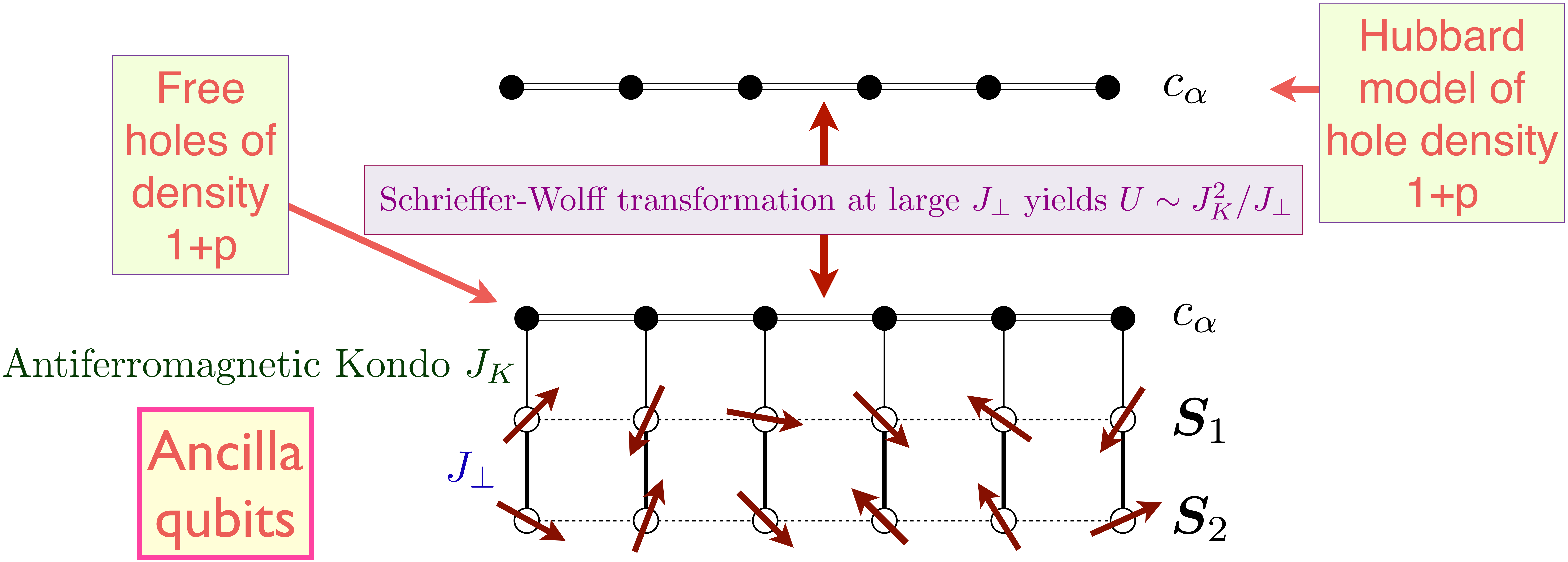
$$U\left(\mathcal{H}_{\rm Hubbard} + \mathcal{H}_{\rm trivial\ \ insulator}\right) U^{-1} = \mathcal{H}_{\rm ancilla}$$



Free holes of density 1+p

Ancilla theory of the Hubbard model

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

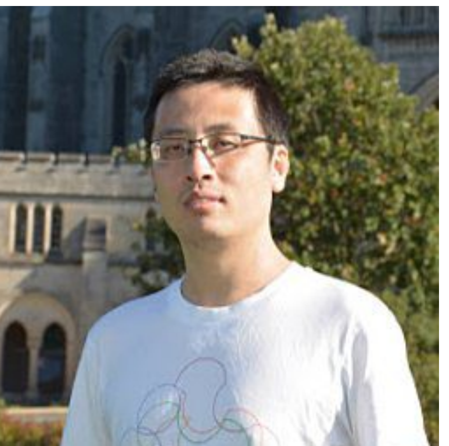


$$\mathcal{H}_{\rm ancilla} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c_{\mathbf{p}\alpha}^\dagger c_{\mathbf{p}\alpha} + J_K \sum_i c_{i\alpha}^\dagger \frac{\boldsymbol{\sigma}_{\alpha\alpha'}}{2} c_{i\alpha'} \cdot \boldsymbol{S}_{1i} + J_\perp \sum_i \boldsymbol{S}_{1i} \cdot \boldsymbol{S}_{2i}$$

Ancilla theory of the Hubbard model

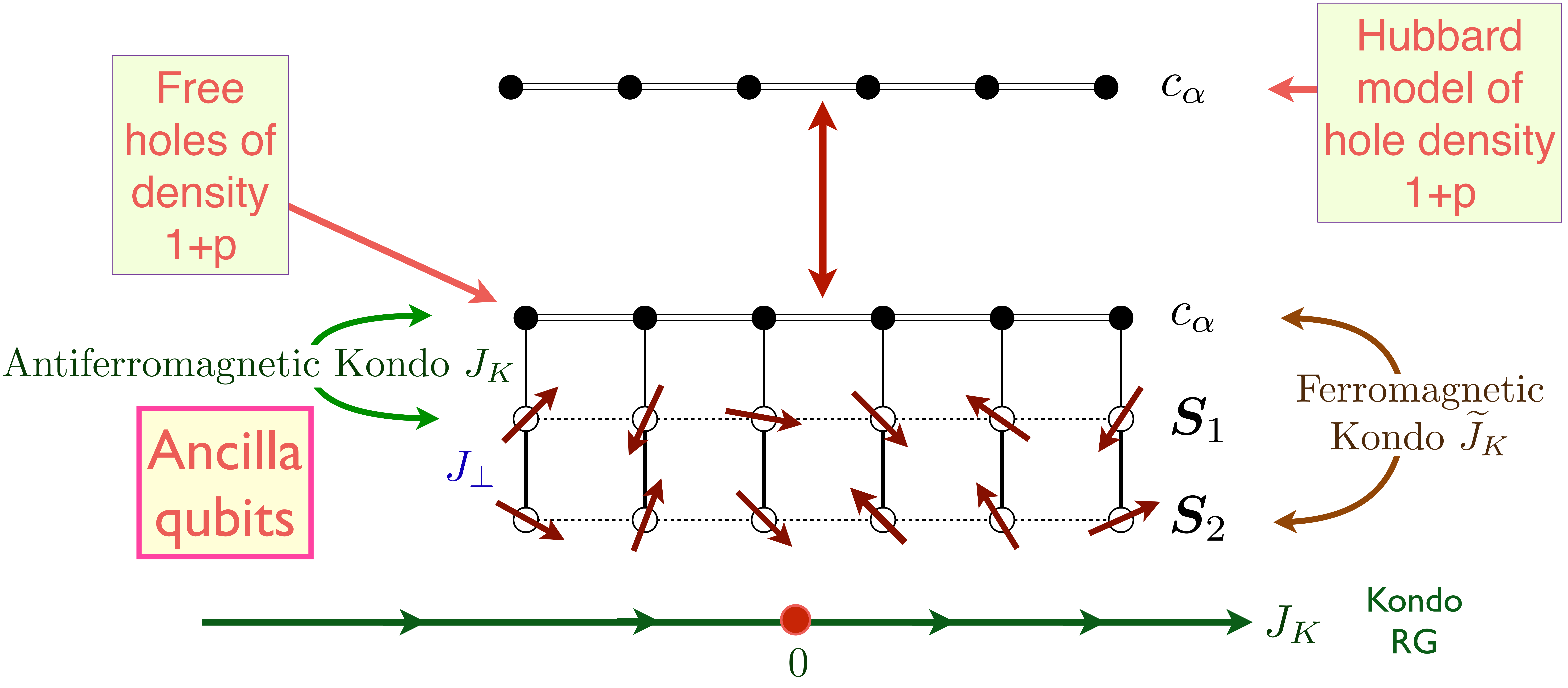
Ya-Hui Zhang and S. Sachdev, *Phys. Rev. Res.* **2**, 023172 (2020)

Ya-Hui Zhang



Ancilla theory of the Hubbard model

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



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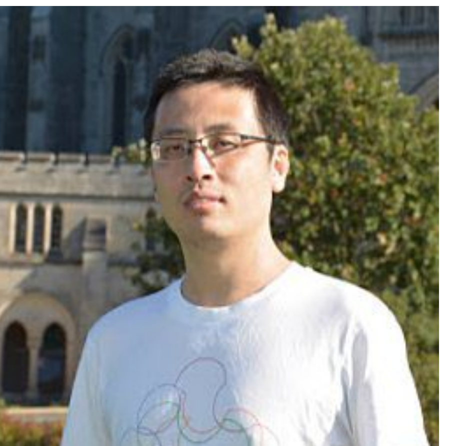
Ancilla theory of the Hubbard model

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

Ya-Hui Zhang

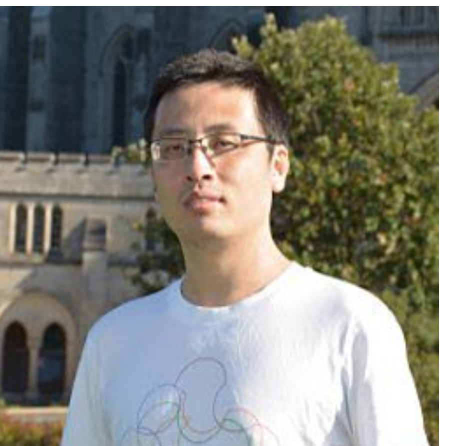


Ancilla theory of the Hubbard model

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

Pseudogap metal =
Kondo Lattice Heavy
Fermi Liquid
$\oplus$
Spin Liquid

Ya-Hui
Zhang



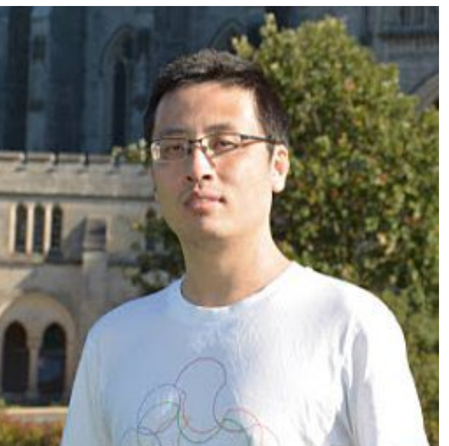
Ancilla theory of the Hubbard model

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

Pseudogap metal = Kondo Lattice Heavy Fermi Liquid $\oplus$ Spin Liquid

$|\text{FL}*\rangle = [\text{Projection onto rung singlets of } \boldsymbol{S}_1, \boldsymbol{S}_2]$
$\bowtie |\text{Slater determinant of } (c, f_1)\rangle$
$\otimes |\text{Spin liquid of } \boldsymbol{S}_2\rangle$

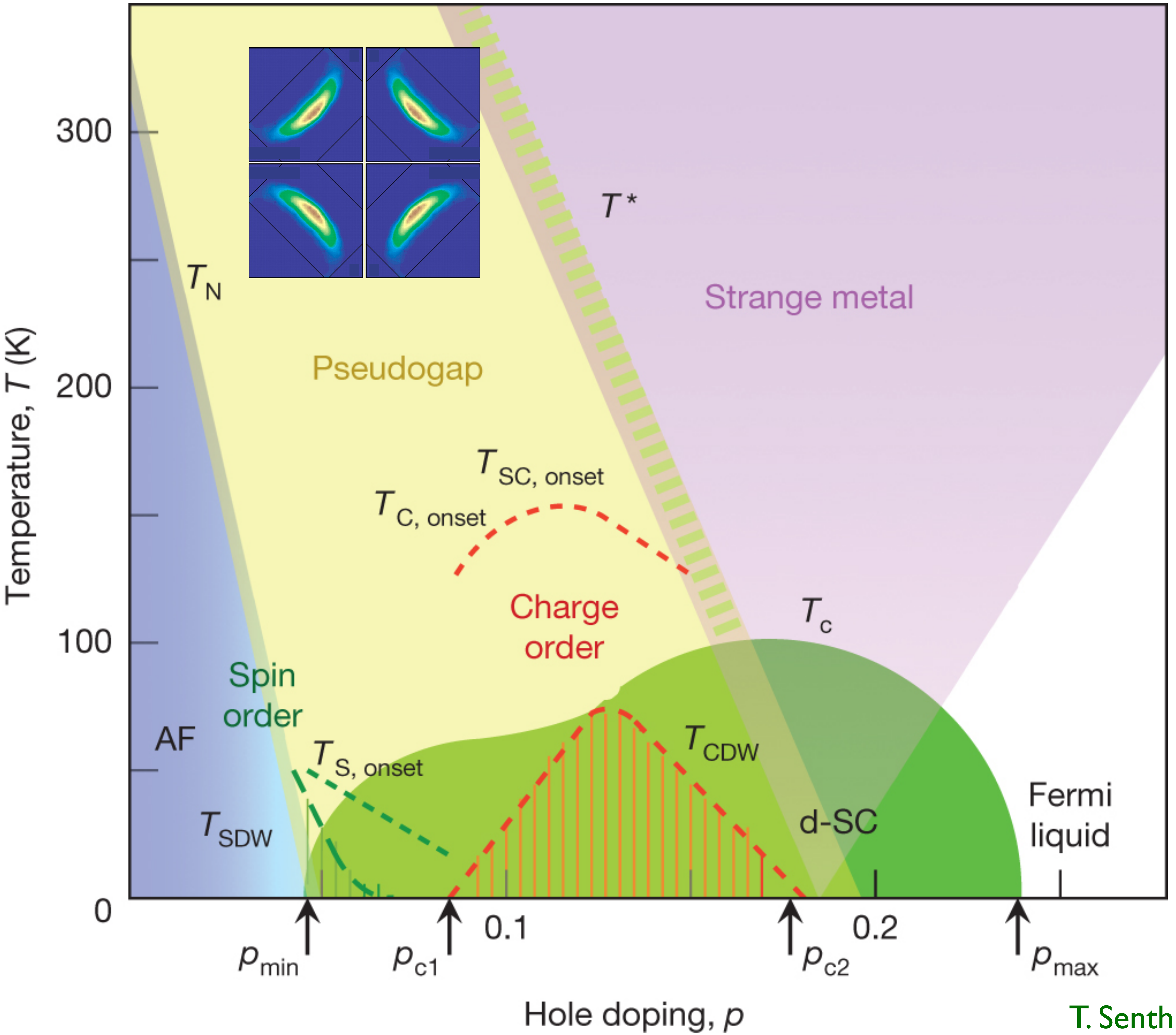
Ya-Hui Zhang

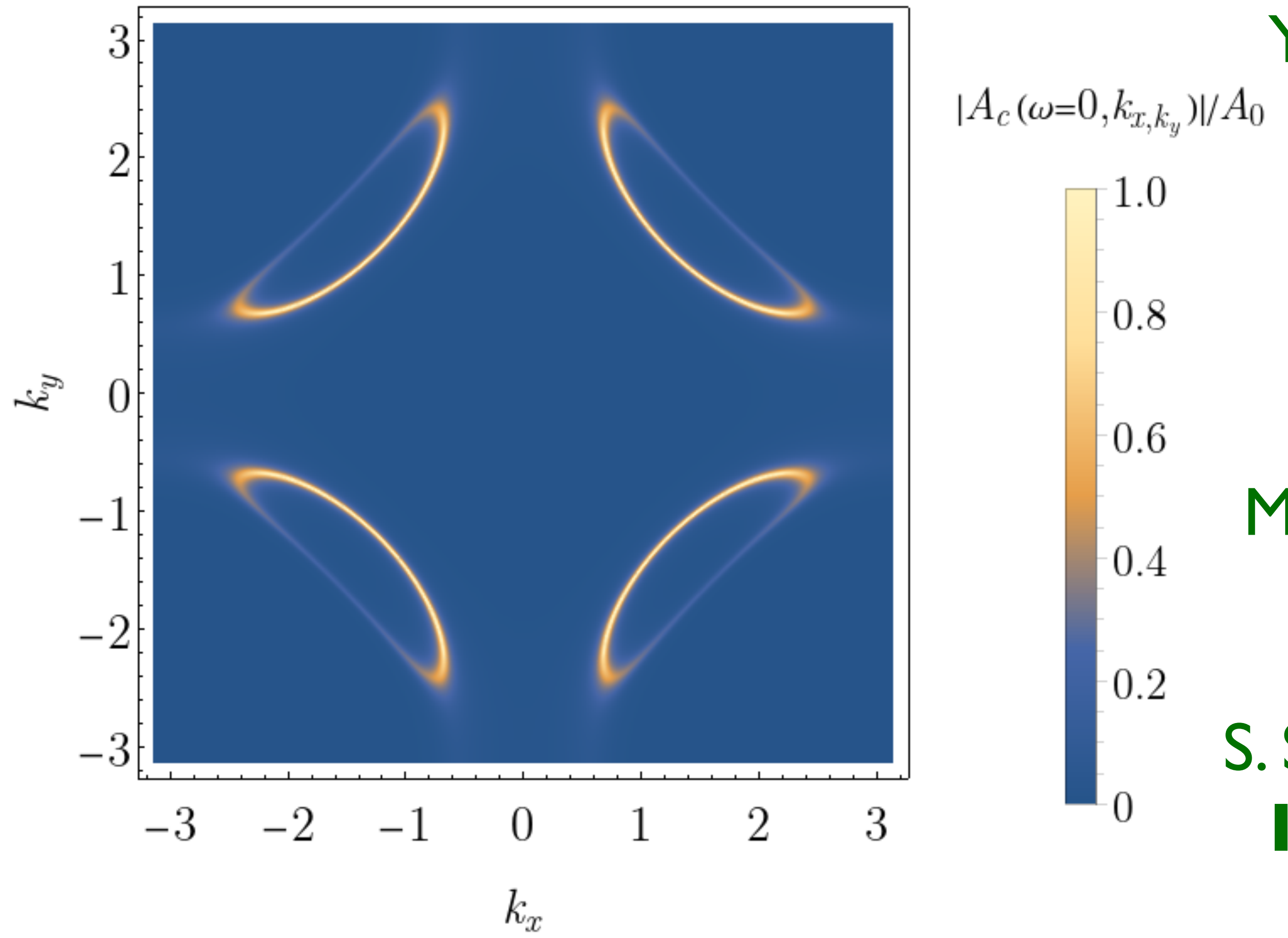


Replacement for “vanilla” Gutzwiller-projected Fermi liquid in the underdoped regime

Connections to experiments

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





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

E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, and S. Sachdev, *Phys. Rev. B* **105**, 075146 (2022)

Hole pocket Fermi surfaces of size p with charge e, spin-$1/2$ quasiparticles

$+$

'spectator' square lattice spin liquid *at half-filling.*

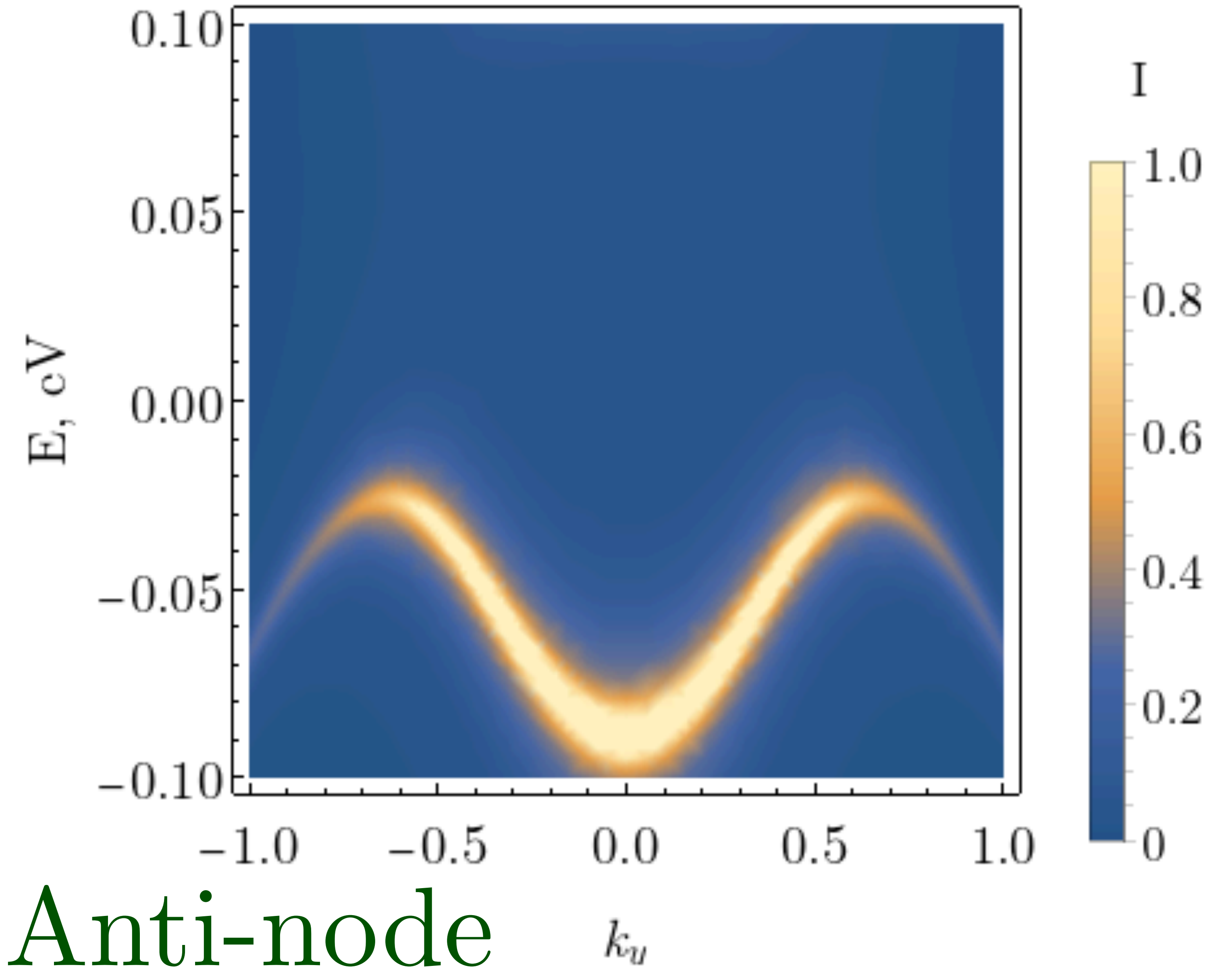
FL*: Spin liquid is *required* because the Fermi surface does not enclose the Luttinger volume $(1+p)$.

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

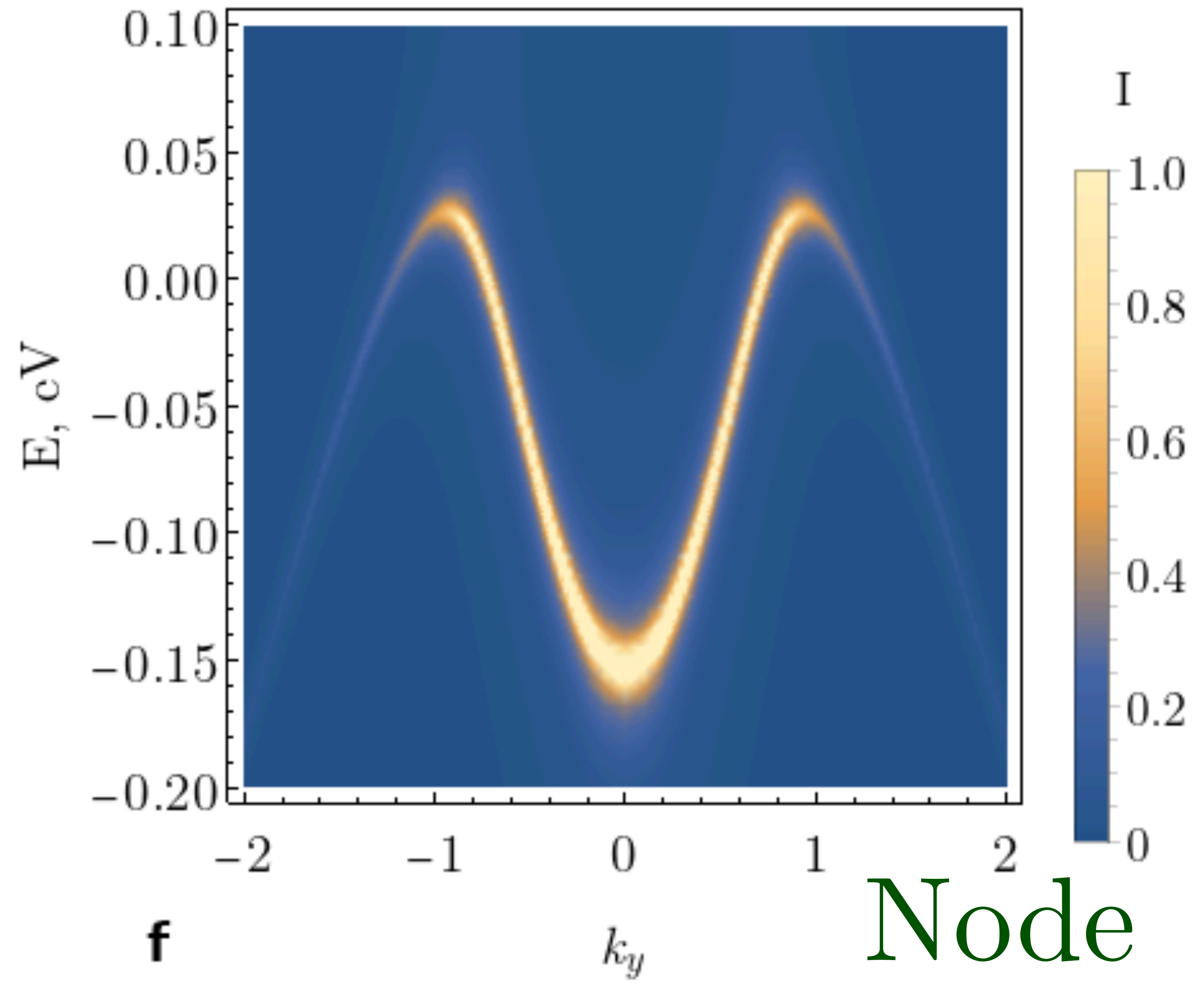
Mascot, Nikolaenko, Tikhanovskaya, Zhang, Morr, and Sachdev, *Phys. Rev. B* **105**, 075146 (2022)

FL* in a *one-band* model

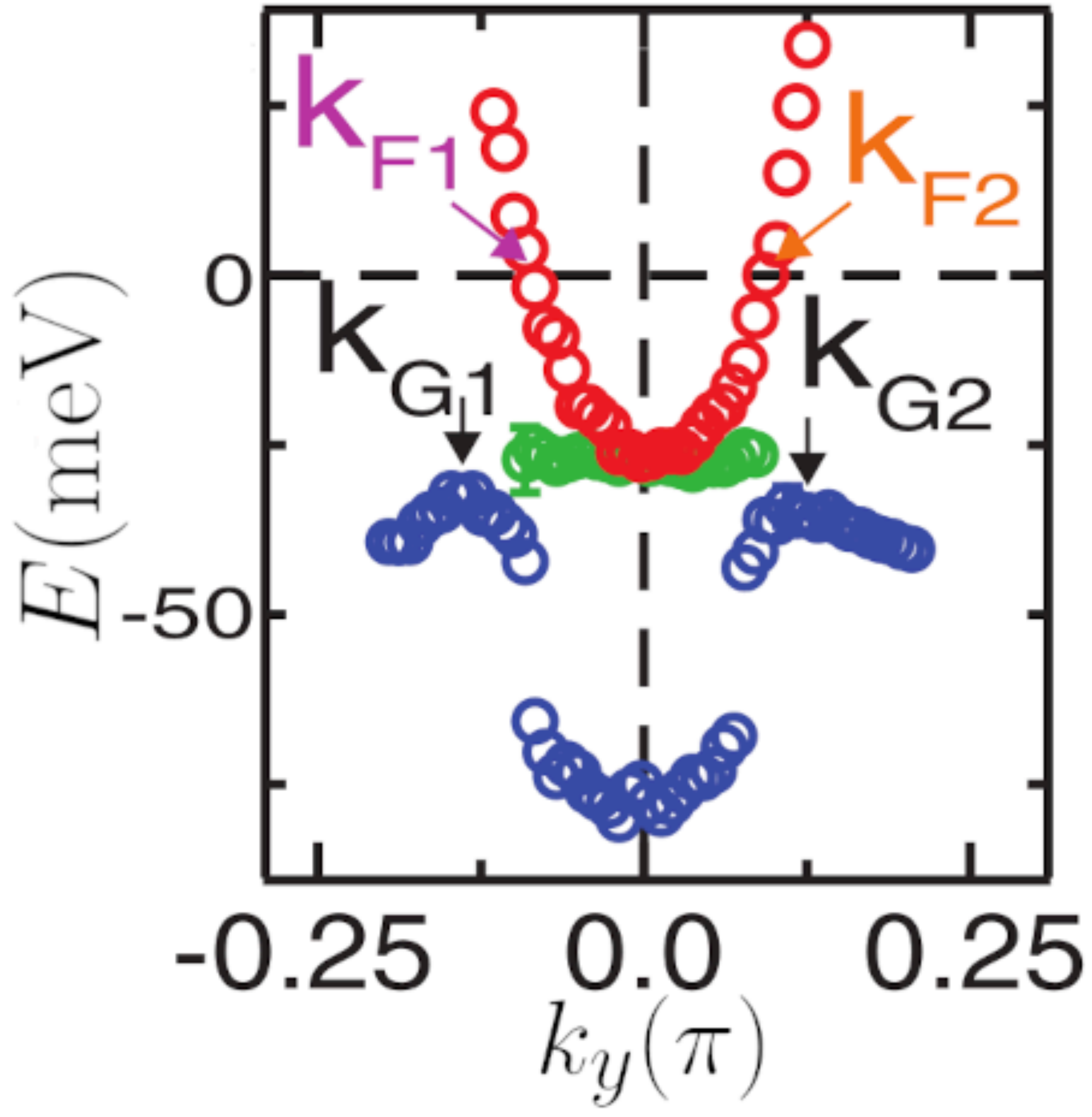
Broadening by second ancilla layer is needed to describe MDC and EDC

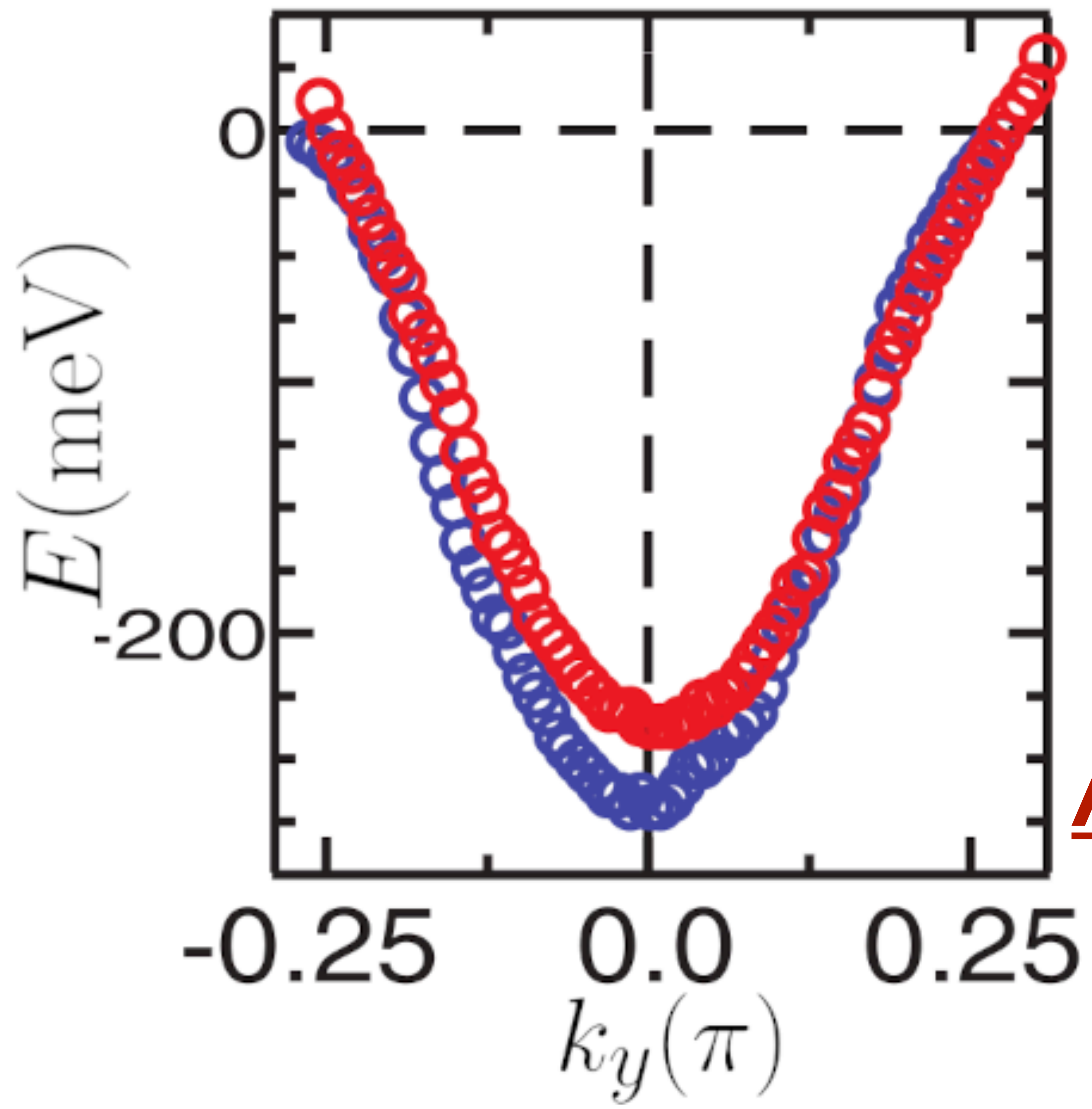


Anti-node



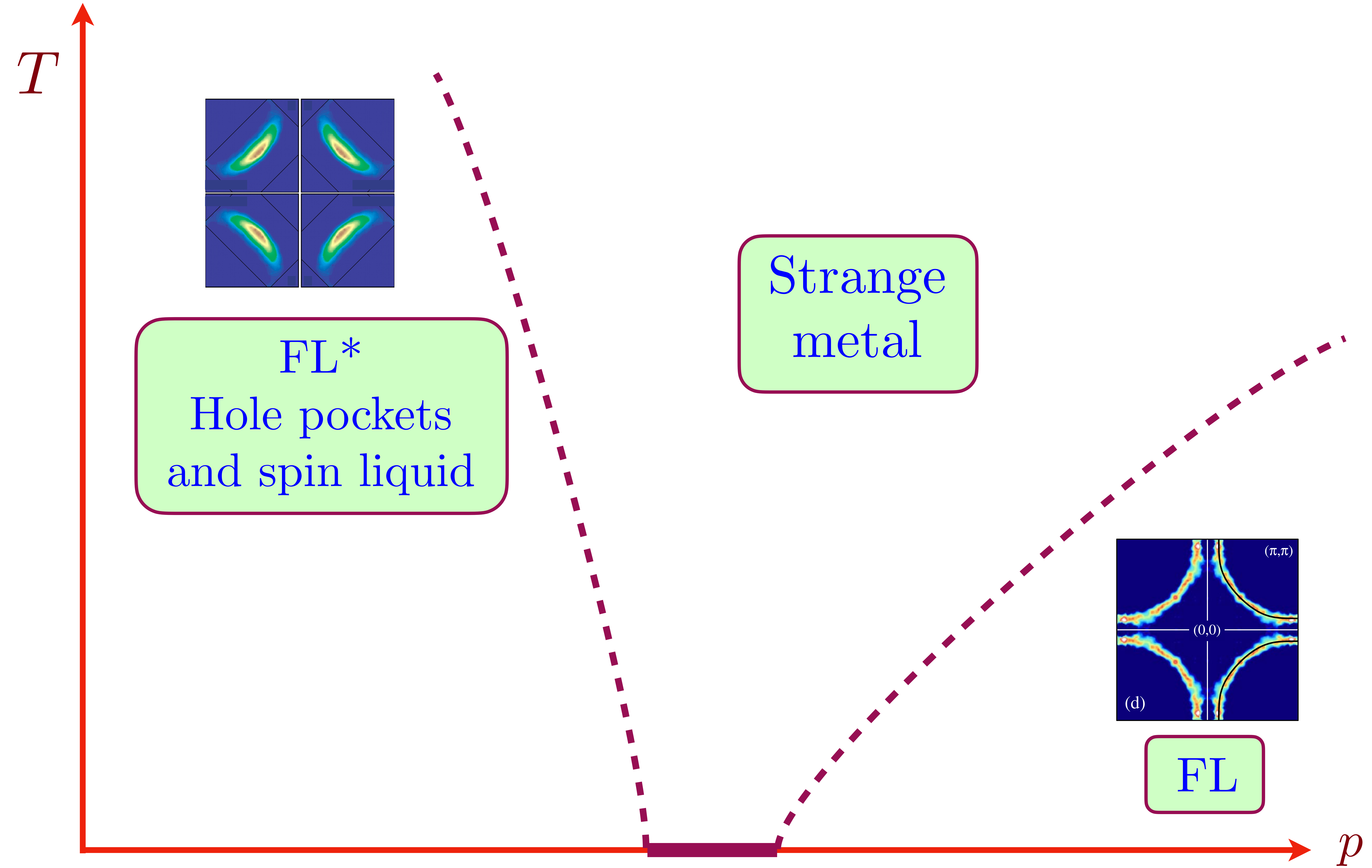
Node



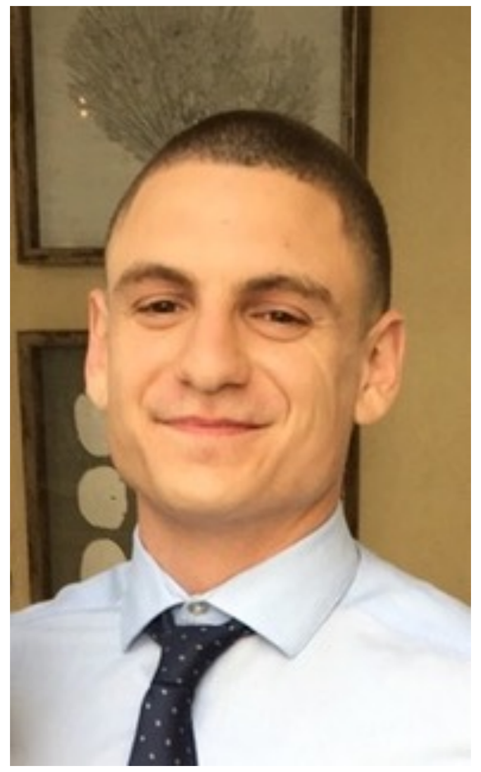


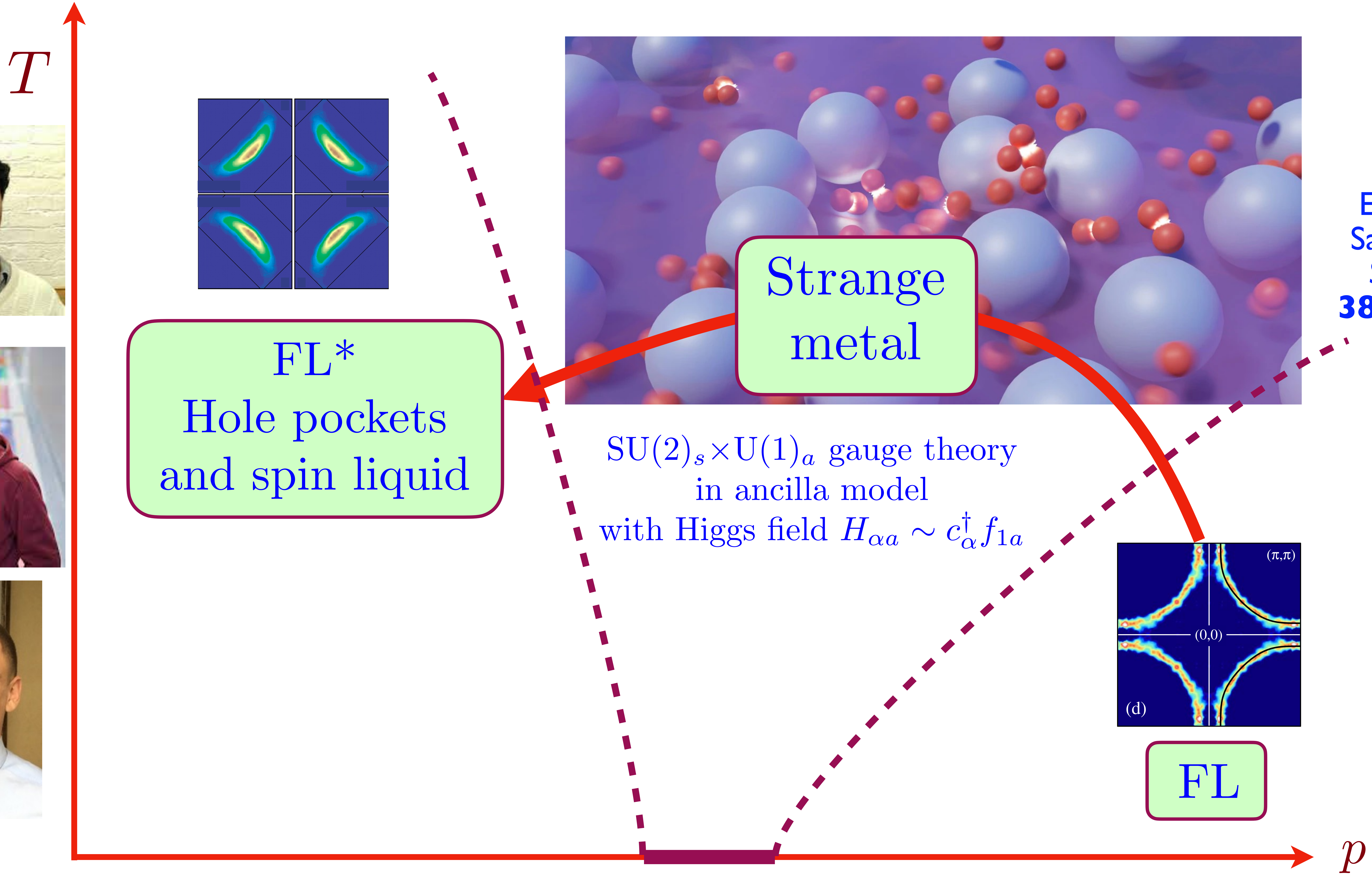
He, Hashimoto, Karapetyan, Koralek, Hinton, Testaud, Nathan, Yoshida, Yao, Tanaka, Meevasana, Moore, Lu, Mo, Ishikado, Eisaki, Hussain, Devereaux, Kivelson, Orenstein, Kapitulnik, and Shen, *Science* **331**, 1579 (2011)

ARPES on Bi2201

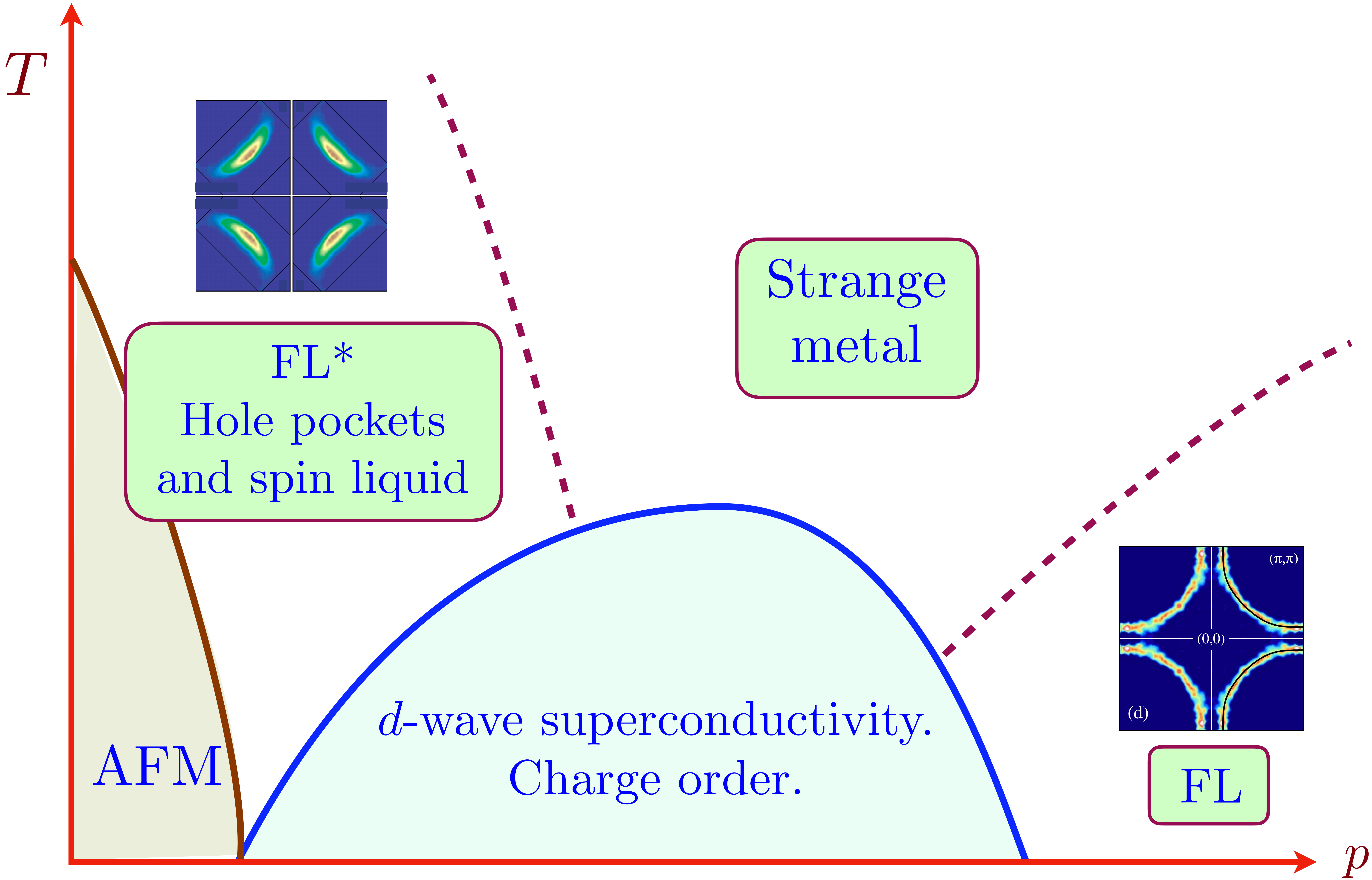


T
FL*
Hole pockets
and spin liquid
Strange
metal
(π,π)
(0,0)
(d)
FL
p

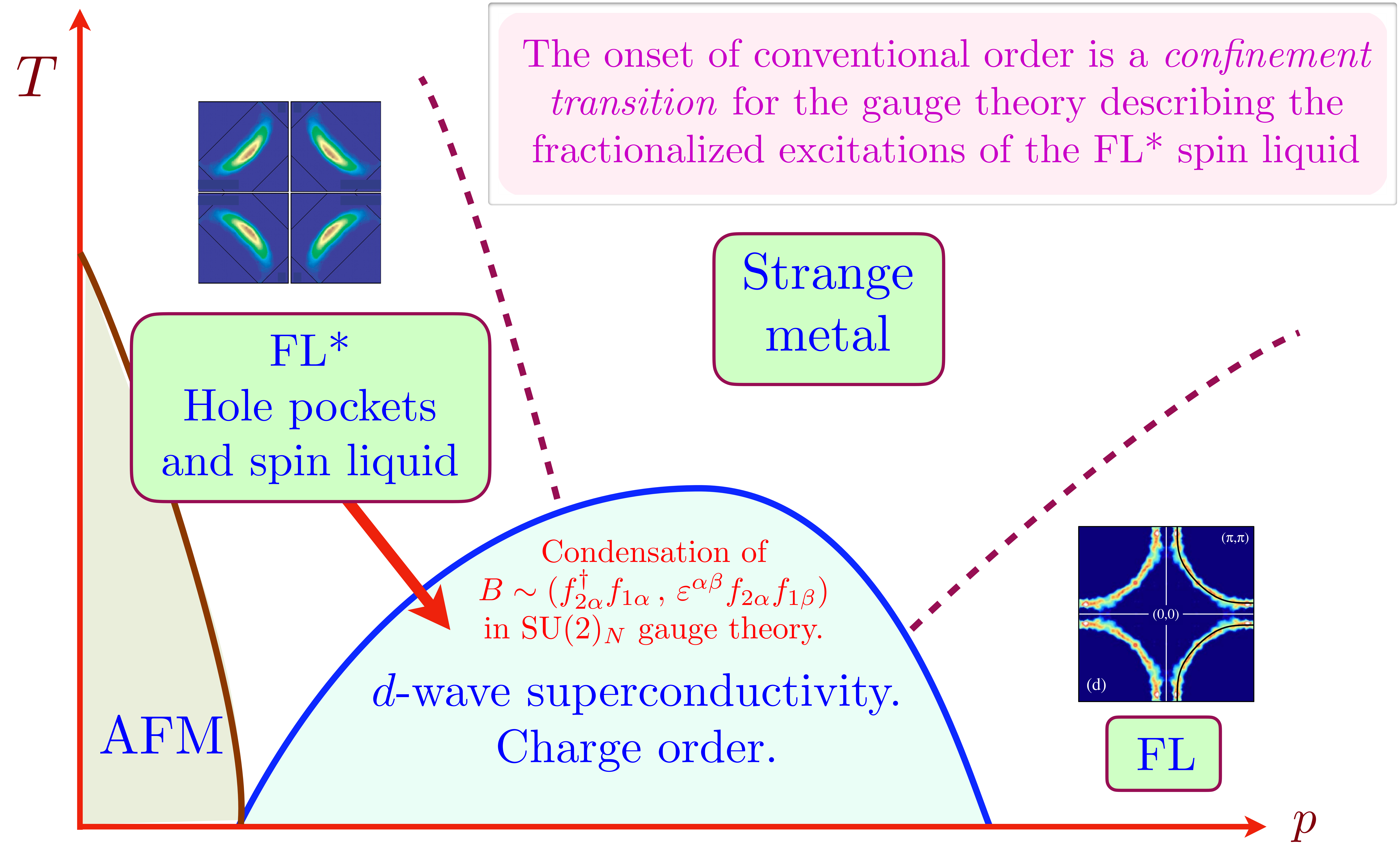




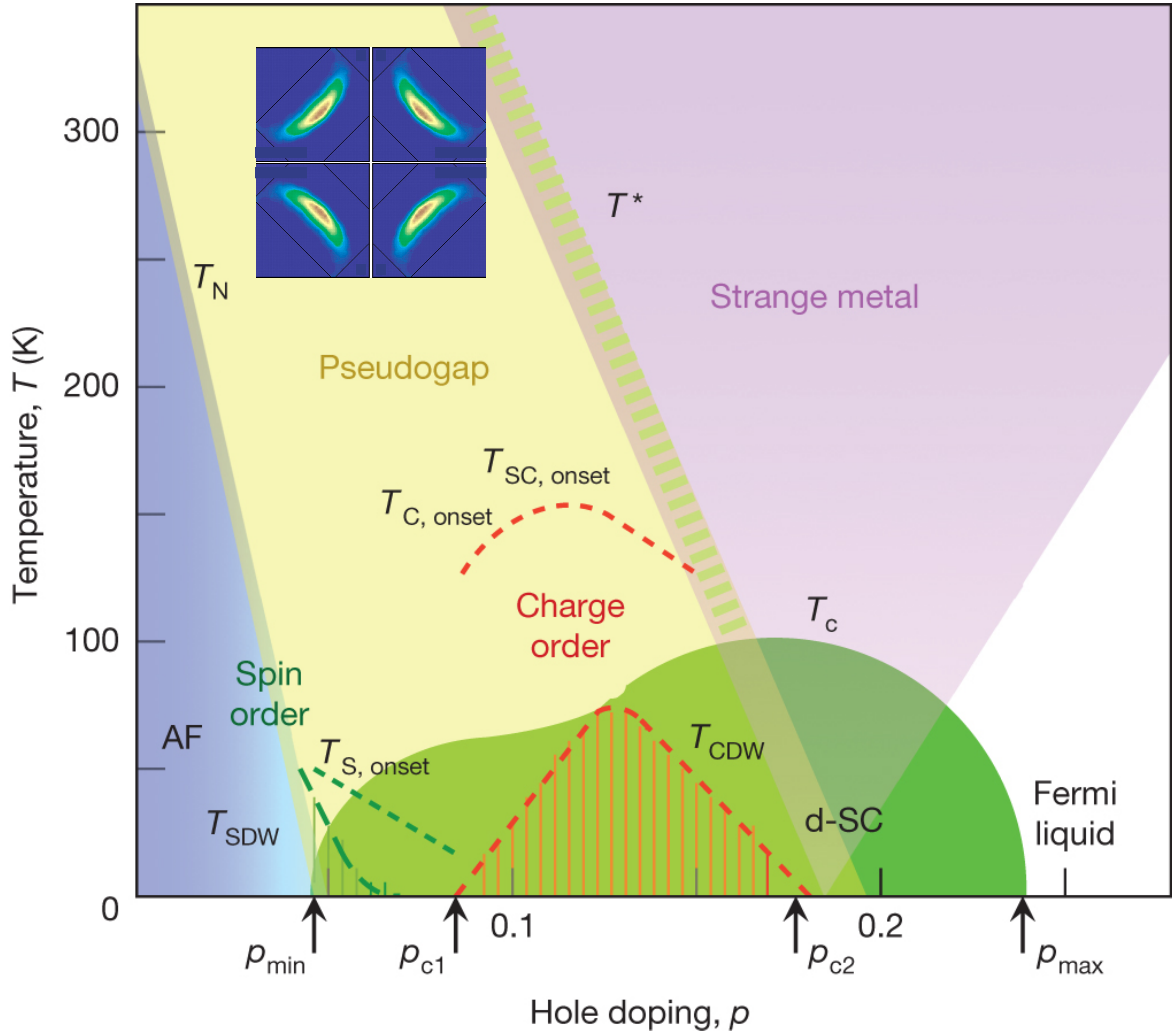
Patel, Haoyu Guo, Esterlis, Sachdev, *Science* **381**, 790 (2023)



T
FL*
Hole pockets
and spin liquid
Strange
metal
AFM
d-wave superconductivity.
Charge order.
(π,π)
(0,0)
(d)
FL
p


The onset of conventional order is a *confinement transition* for the gauge theory describing the fractionalized excitations of the FL* spin liquid
T
FL*
Hole pockets
and spin liquid
Strange
metal
Condensation of
$B \sim (f_{2\alpha}^\dagger f_{1\alpha}\,,\, \varepsilon^{\alpha\beta} f_{2\alpha} f_{1\beta})$
in $SU(2)_N$ gauge theory.
d-wave superconductivity.
Charge order.
AFM
(π,π)
(0,0)
(d)
FL
p

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



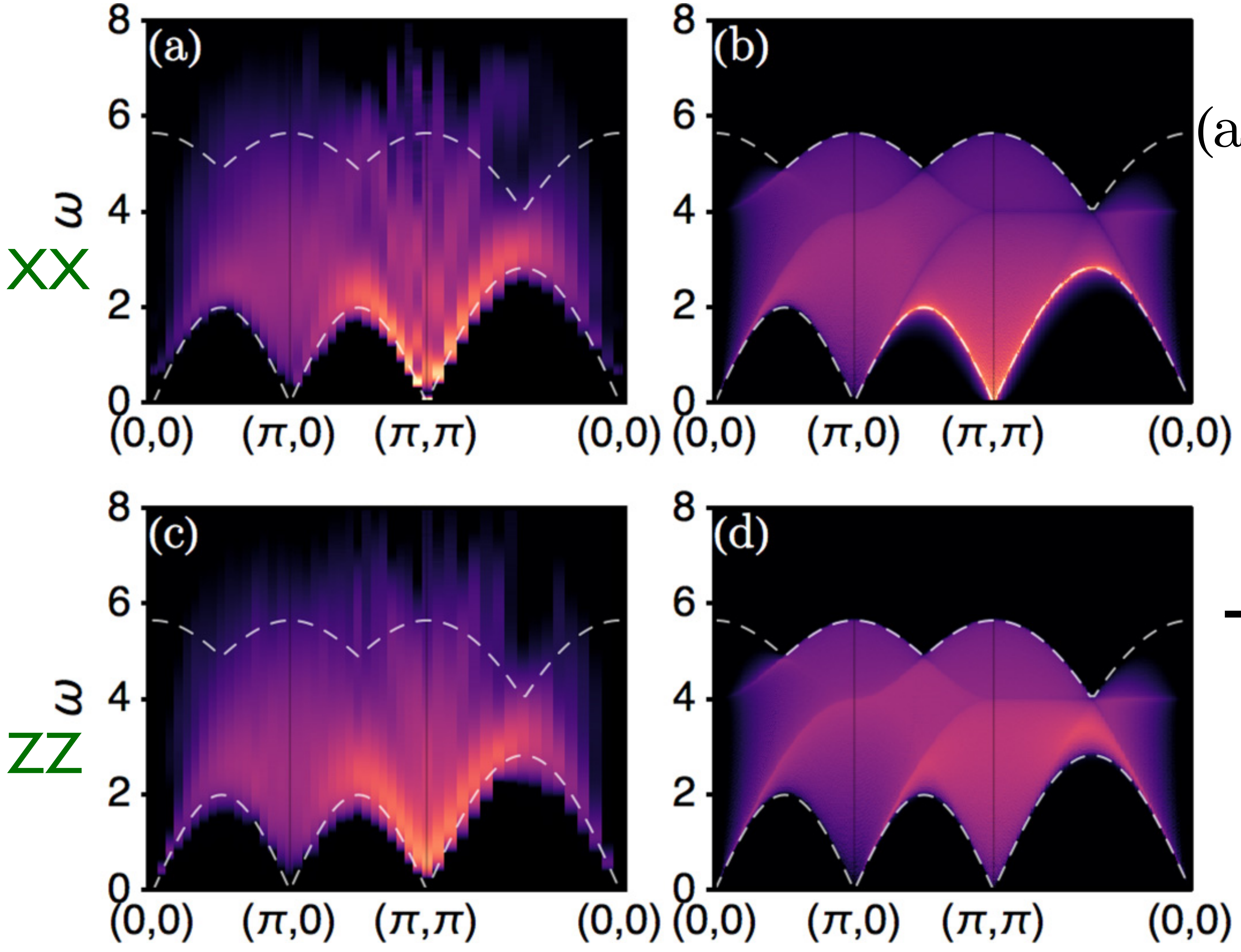
Emergent symmetry of the charge-e, SU(2) fundamental boson effective theory of the π-flux state provides a rationale for the near equality of the onset temperatures of d-wave superconductivity and charge order.

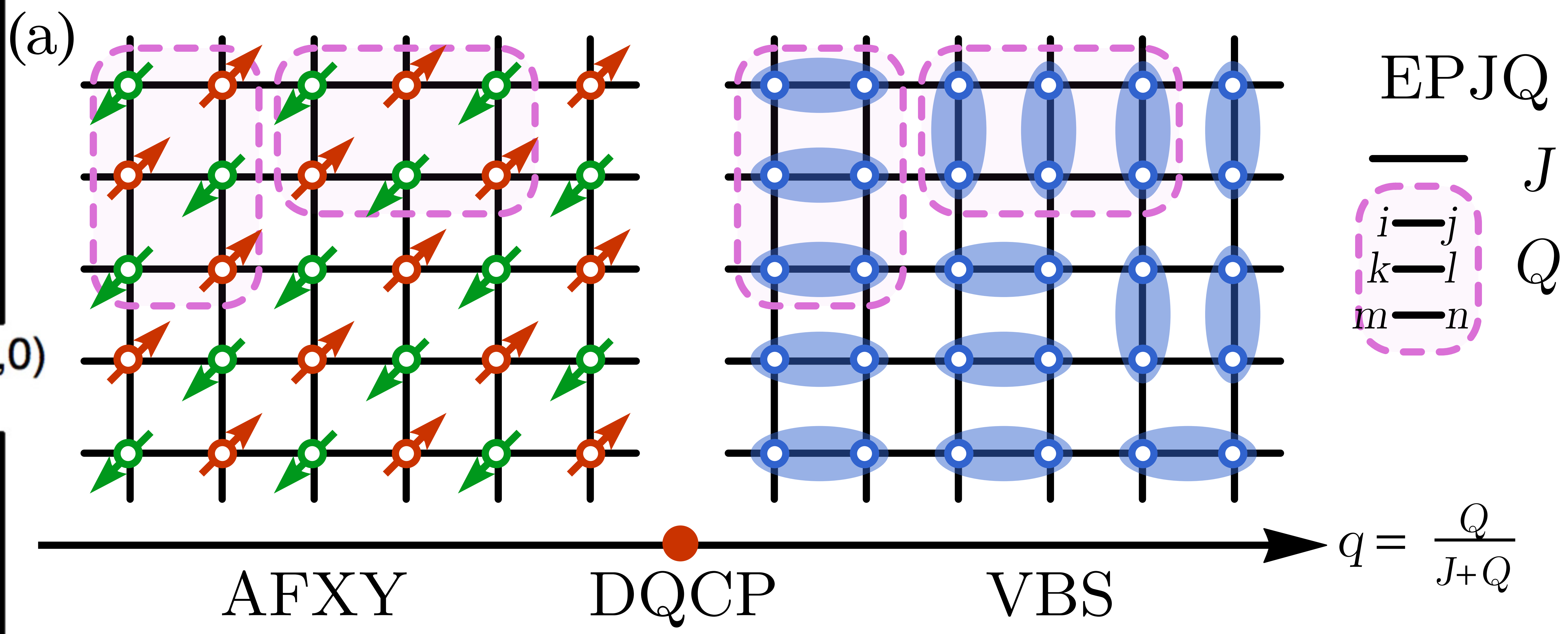
The onset of conventional order is a *confinement transition* for the gauge theory describing the fractionalized excitations of the FL* spin liquid
T
FL*
Hole pockets
and spin liquid
Strange
metal
Condensation
of z_α
in dual
$\mathbb{CP}^1$ theory.
(π,π)
(0,0)
(d)
AFM
d-wave superconductivity.
Charge order.
FL
p

Observable by neutron scattering in pseudogap ?

QMC

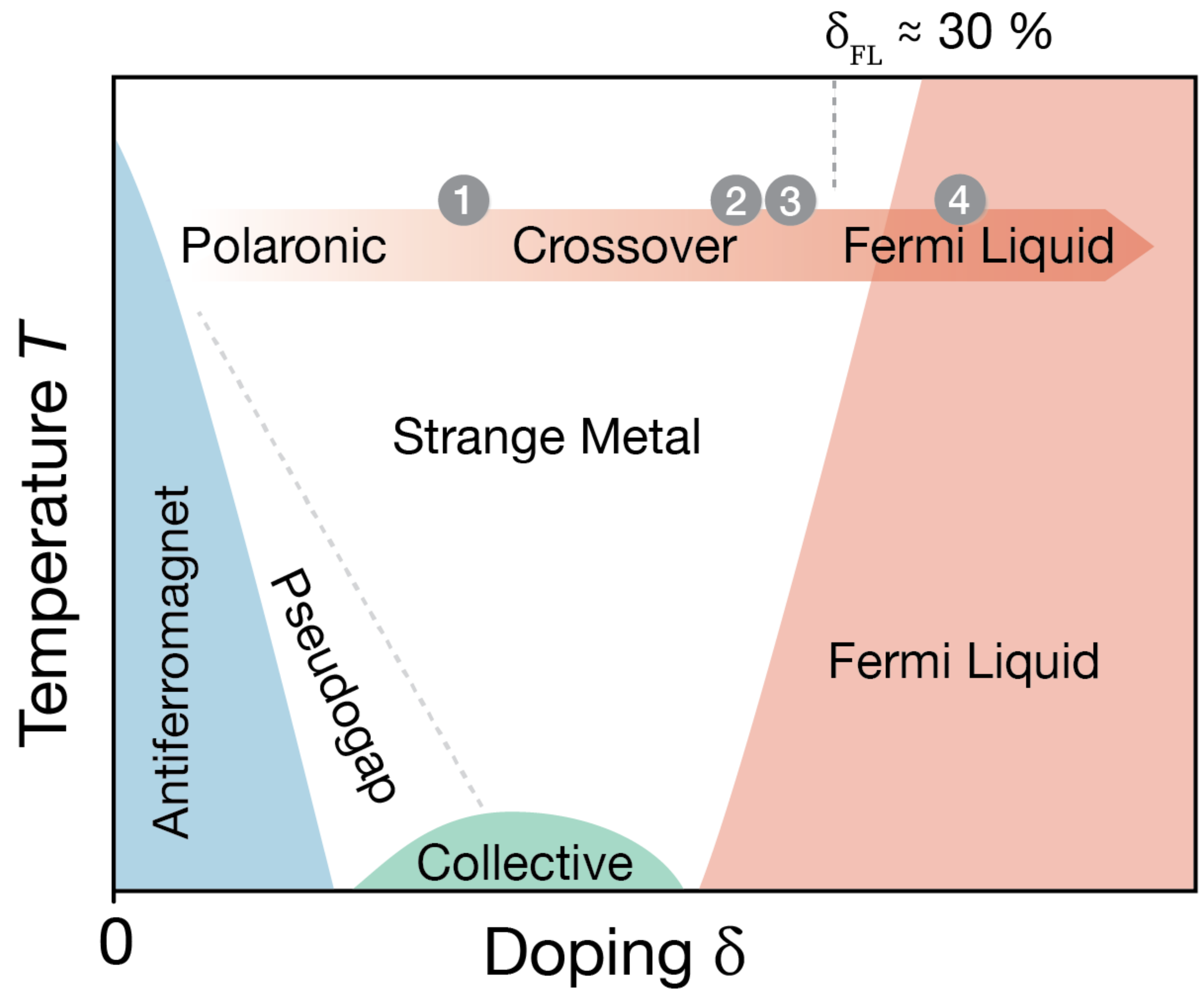
Free fermion
spinons in π-flux





Nvsen Ma, Guang-Yu Sun, Yi-Zhuang You, Cenke Xu, Ashvin Vishwanath, Anders W. Sandvik, and Zi Yang Meng,
Phys. Rev. B **98**, 174421 (2018)

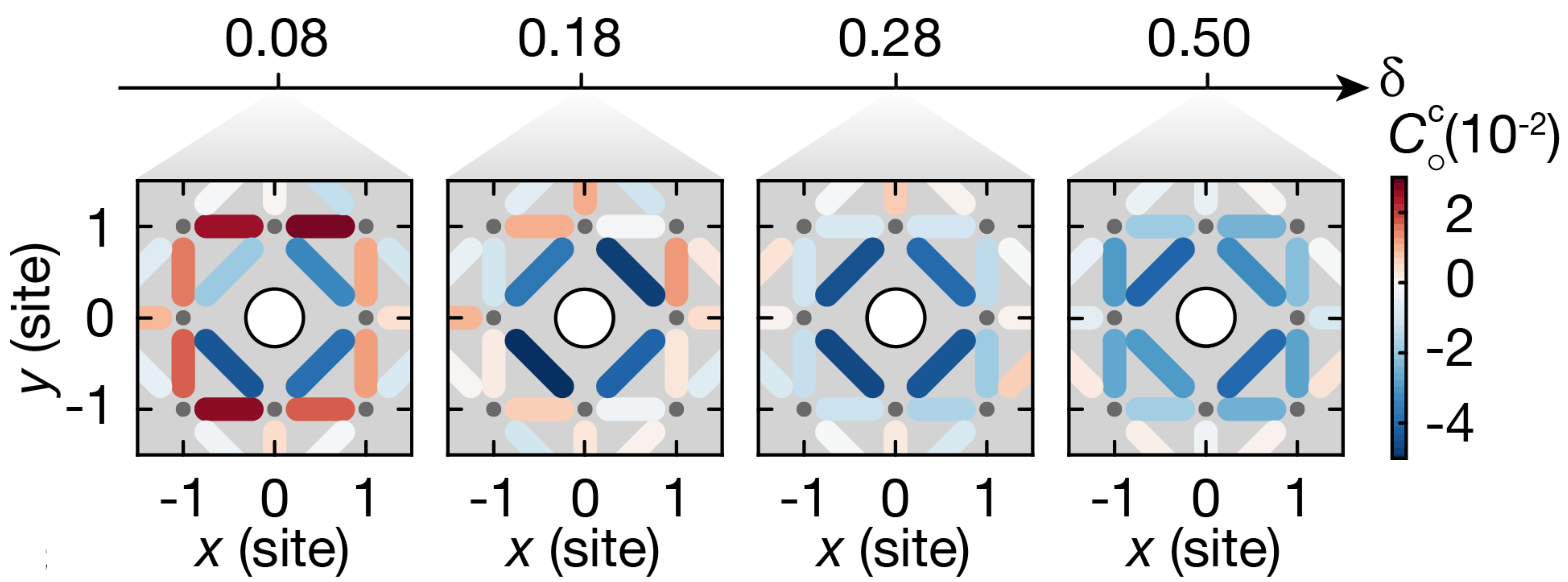
Ultracold fermionic atoms in optical lattices



Microscopic evolution of doped Mott insulators from polaronic metal to Fermi liquid

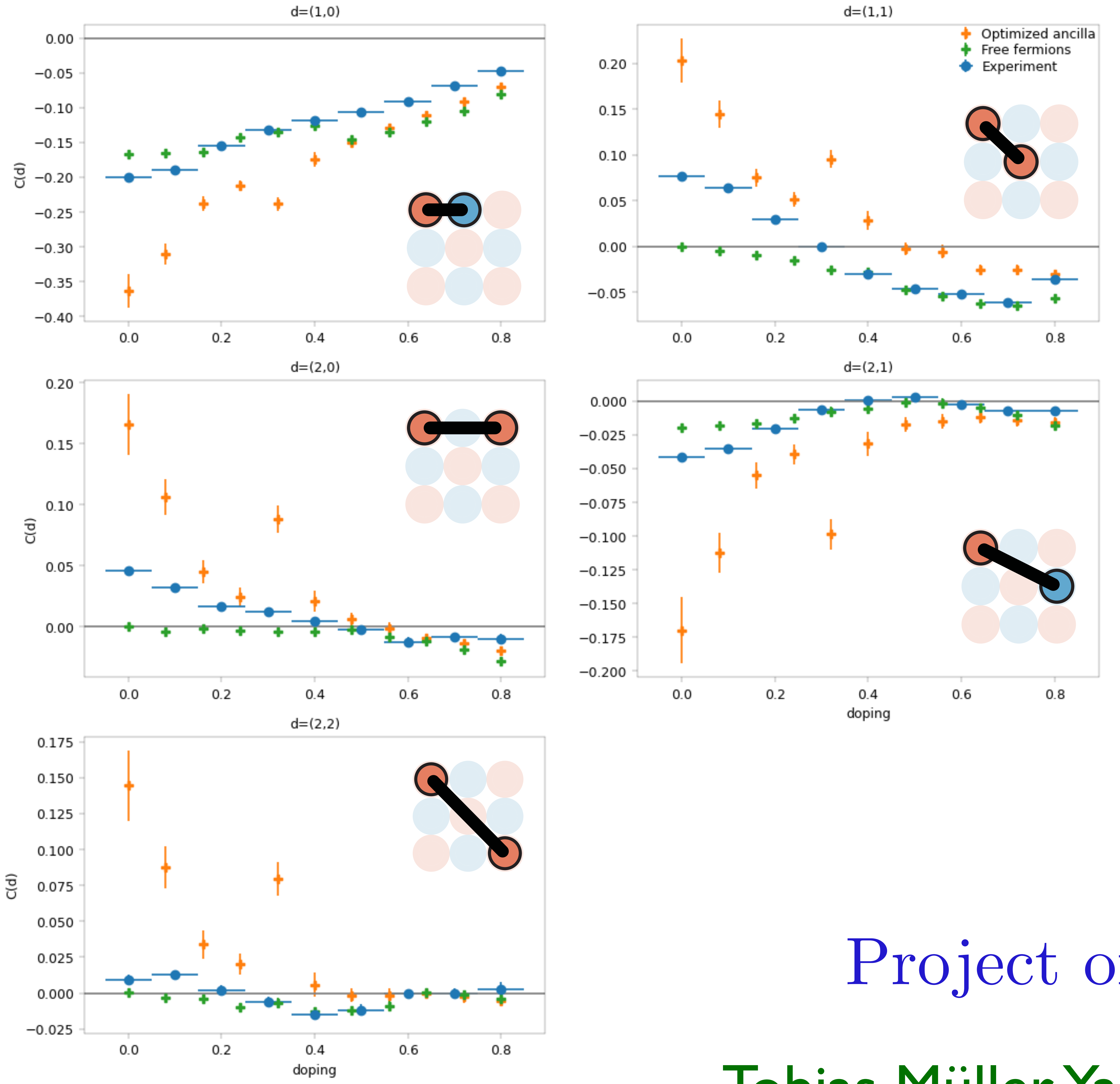
Joannis Koepsell, Dominik Bourgund, Pimonpan Sompet, Sarah Hirthe, Annabelle Bohrdt, Yao Wang, Fabian Grusdt, Eugene Demler, Guillaume Salomon, Christian Gross, Immanuel Bloch

Science **374** (2021) 82

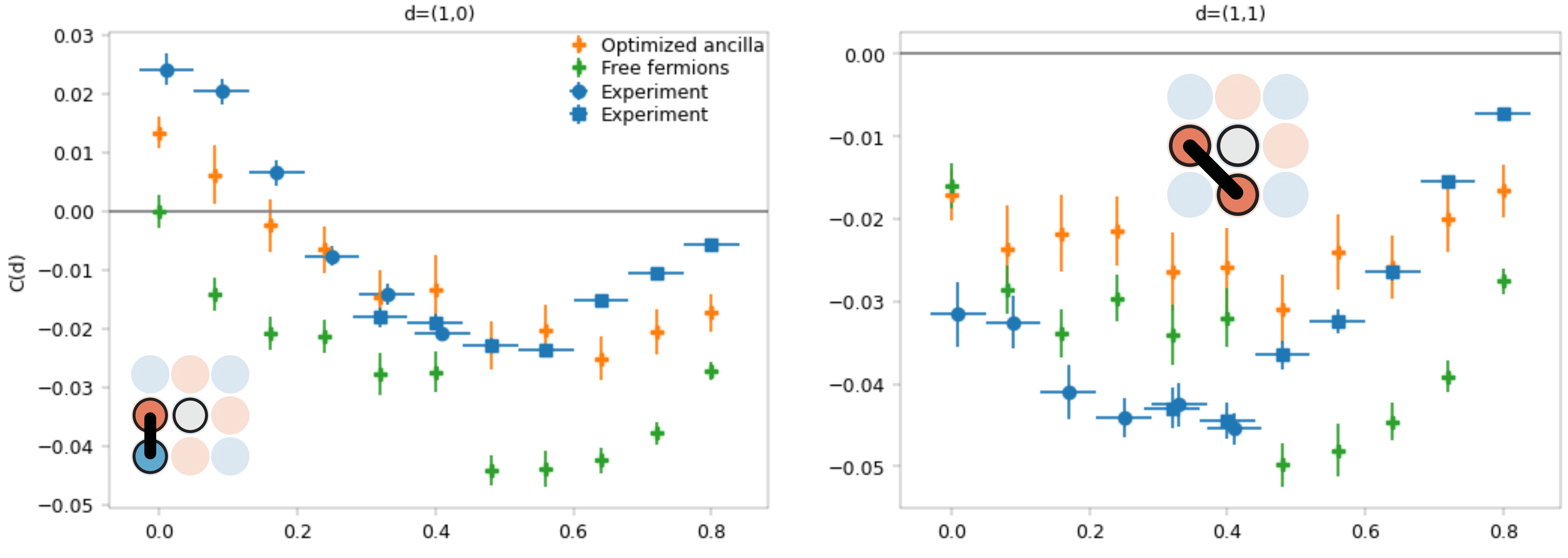


Results for Connected Correlators: Comparison with experiment

Bare Spin-Spin Correlators



Hole-induced Spin-Spin Correlators



Preliminary data

*Test different spin-liquid ansätze for second ancilla layer

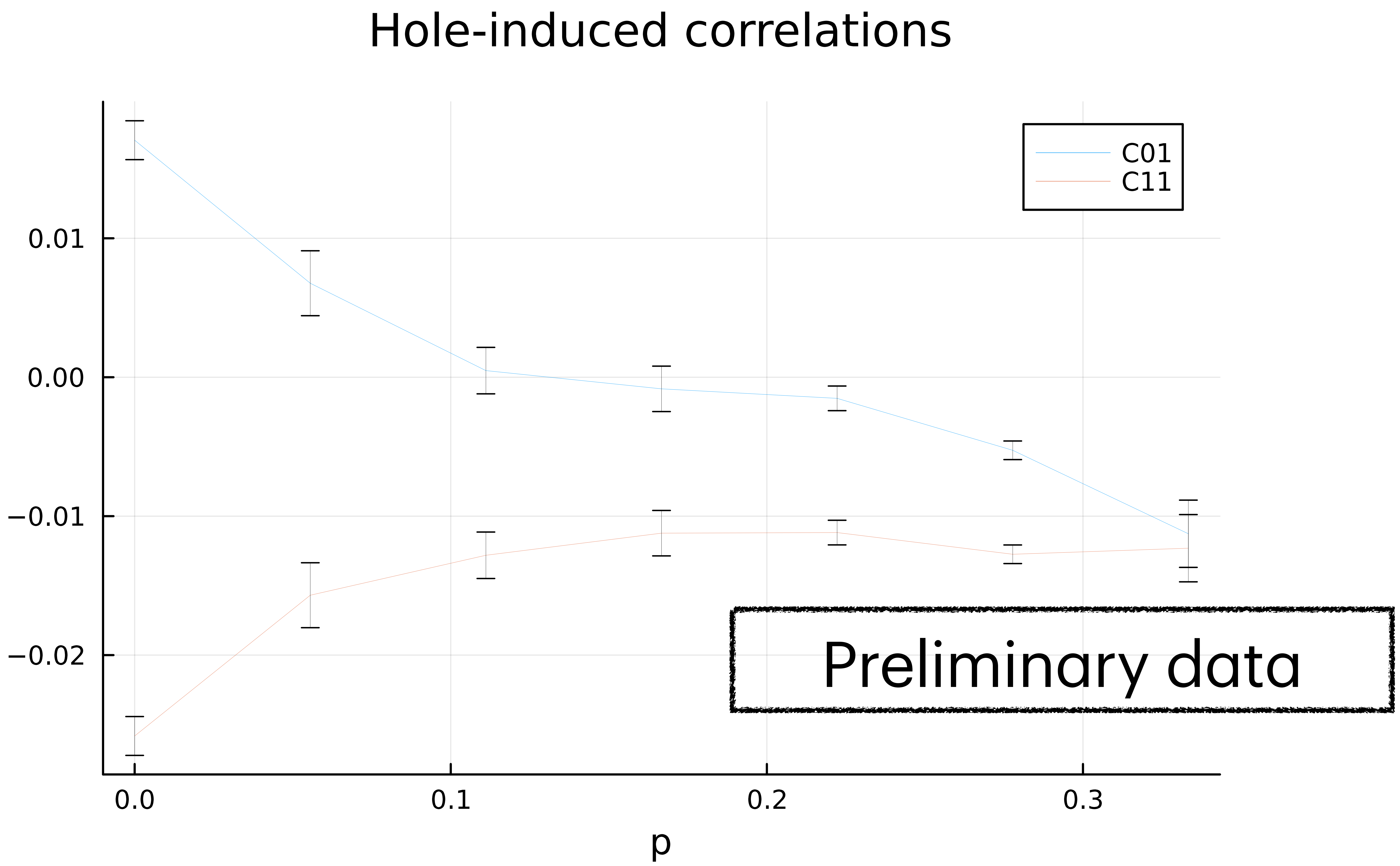
*Improve sampling of wave-functions

*Better statistics to obtain more reliable error-bars

Project only to $S_{1z} + S_{2z} = 0$

Tobias Müller, Yasir Iqbal, Ronny Thomale to appear

Ancilla theory of the Hubbard model



Project to $\boldsymbol{S}_1 + \boldsymbol{S}_2 = 0$

H. Shackleton, S.S., Shiwei Zhang, to appear

Summary

Ancilla theory of pseudogap metal with hole pockets and underlying π-flux spin liquid yields:

- Theory for Fermi arcs in hole-doped pseudogap metal.
- ADMR in pseudogap.
- Anti-nodal and nodal electronic dispersion.
- d-wave superconductor with 4 nodal points in both electron- and hole-doped cuprates.
- Near-equality of dSC and charge order onset temperatures
- Multipoint correlators measured by cold atom experiments
- Theory for strange metal in the crossover from FL* to FL