Quantum spin liquids and the phases of the cuprates

International Centre for Theoretical Physics, Trieste
May 29, 2023
Subir Sachdev

Maine Christos, Zhu-Xi Luo, Henry Shackleton, Ya-Hui Zhang, Mathias Scheurer, and S. S., PNAS **120**, e2302701120 (2023)
Alexander Nikolaenko, Jonas v. Milczewski, Darshan G. Joshi, and S.S., arXiv:2211.10452

Talk online: sachdev.physics.harvard.edu

PHYSICS
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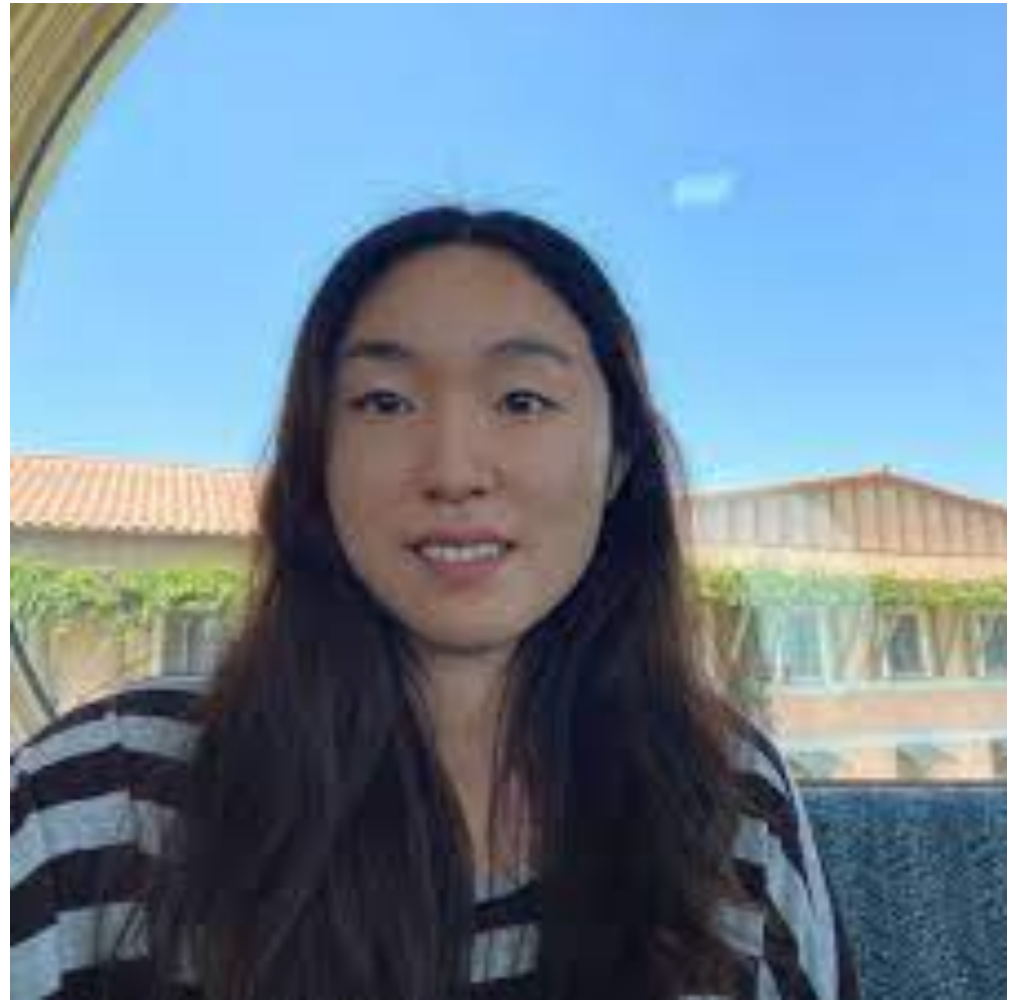
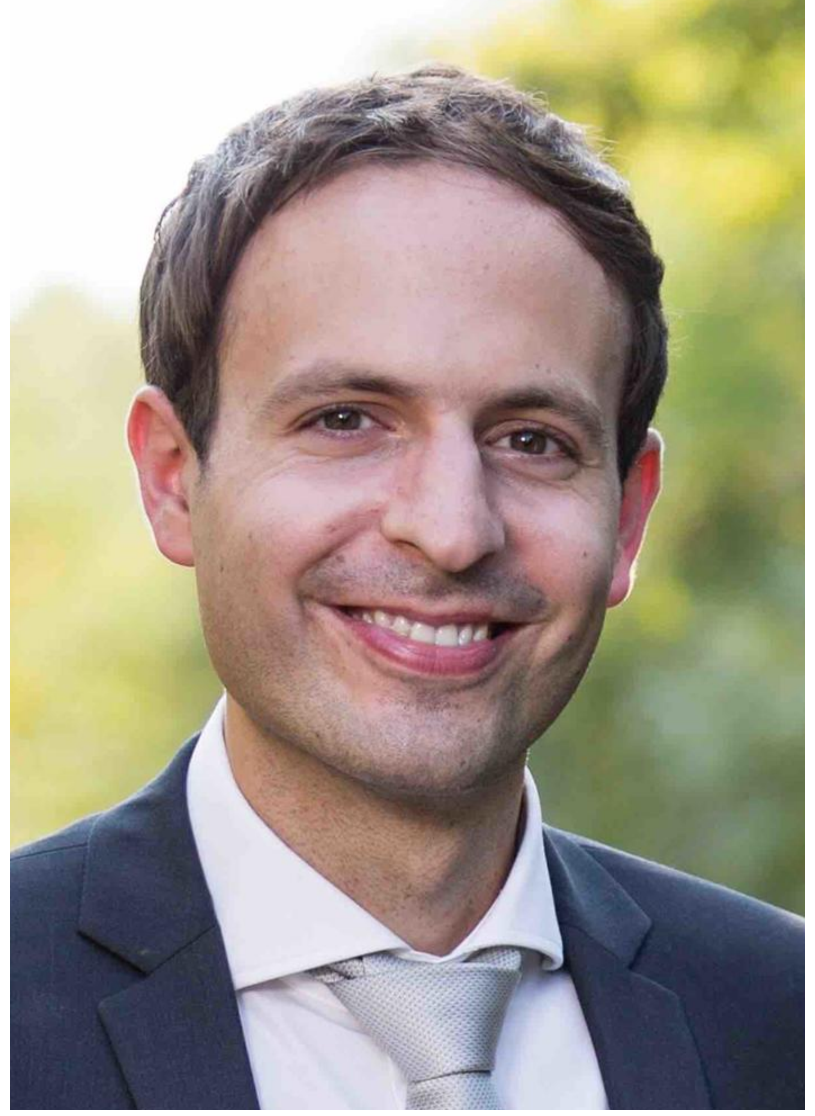
Maine Christos

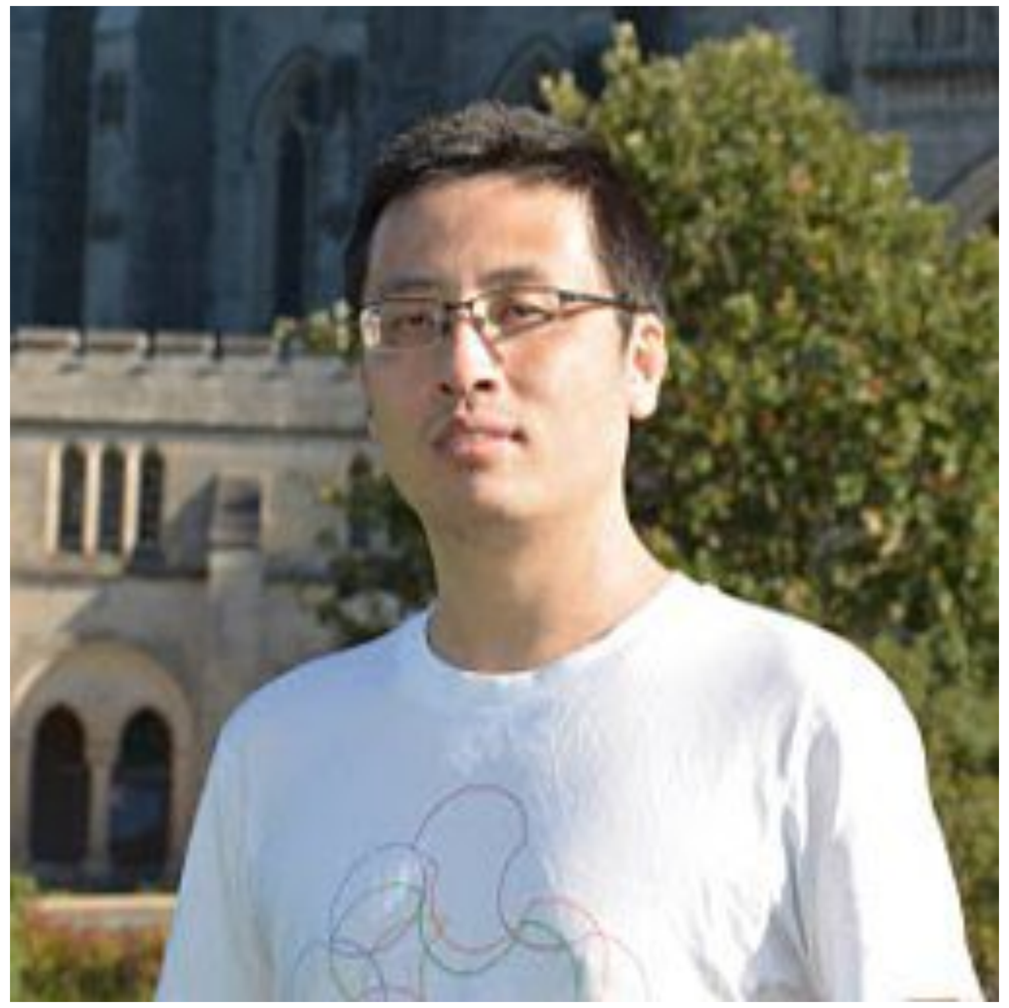


Zhu-Xi Luo
→GA Tech

Henry
Shackleton



Mathias Scheurer
Innsbruck→Stuttgart



Ya-Hui Zhang
Johns Hopkins

Alexander
Nikolaenko

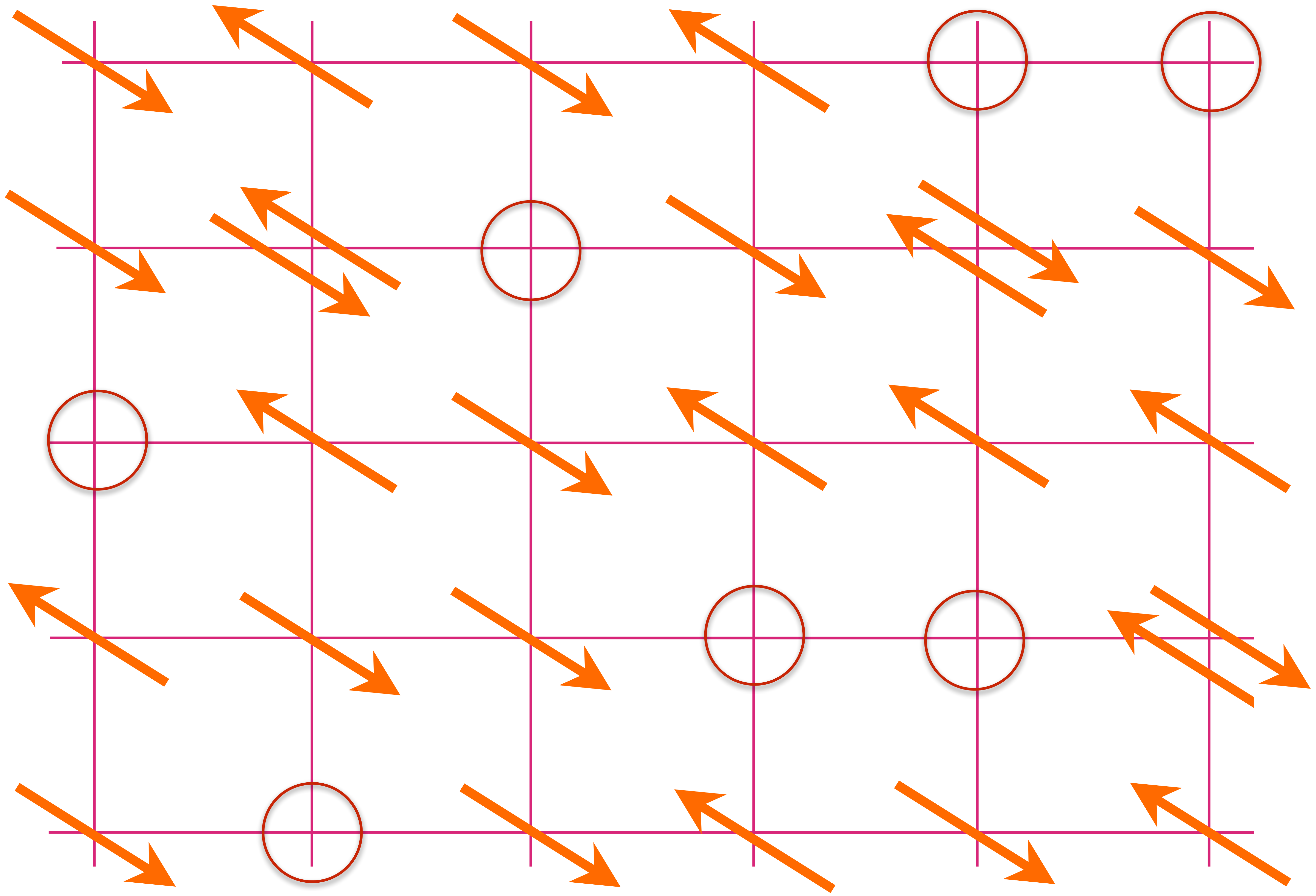
Darshan Joshi
TIFR Hyderabad

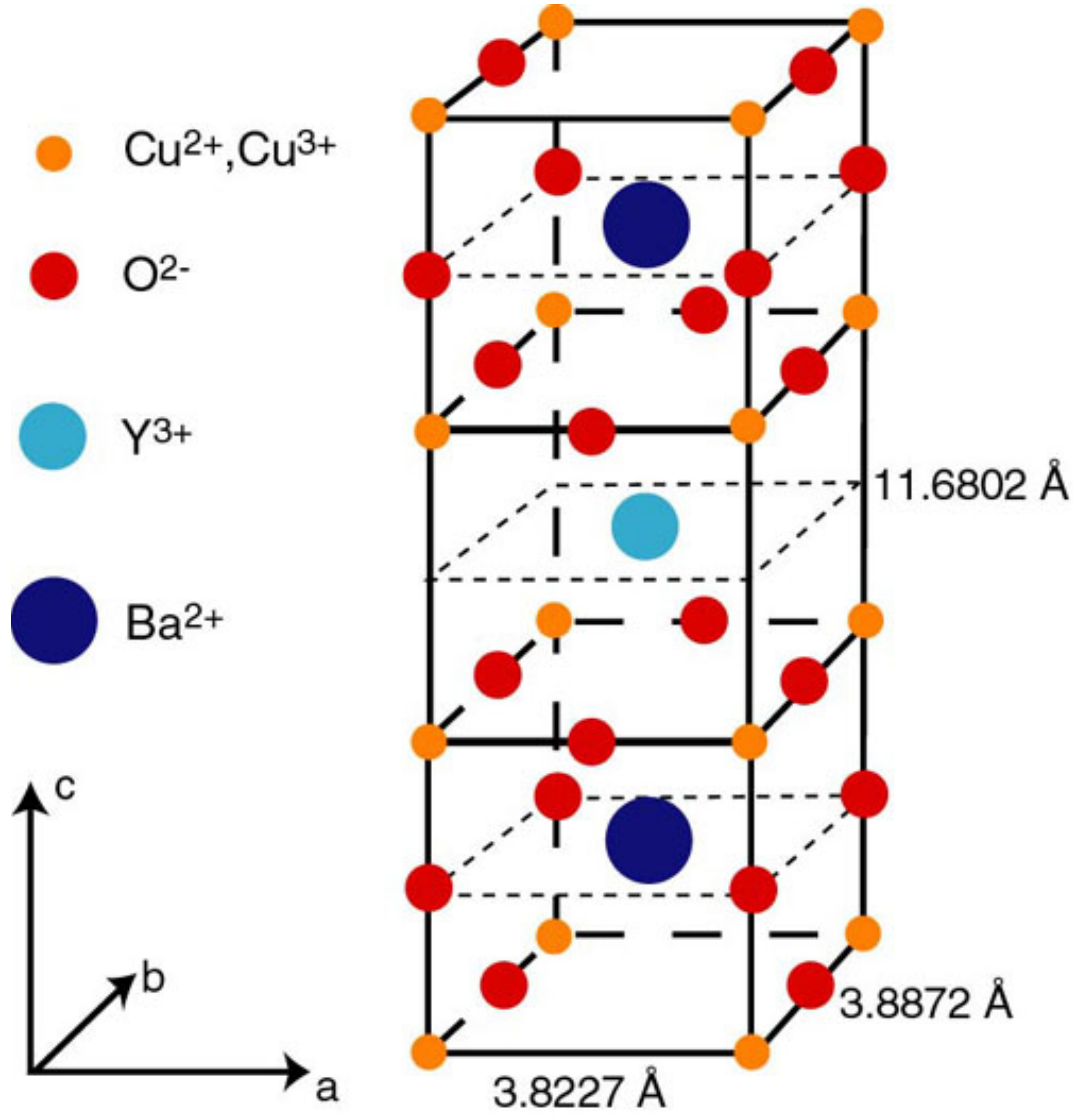
Jonas von Milczewski

1. Open questions on the cuprate phase diagram
2. Theory of the pseudogap metal
3. The π-flux spin liquid
4. Confinement transitions of the π-flux spin liquid
5. Recap

Square lattice Hubbard model with electron density $1 - p$.

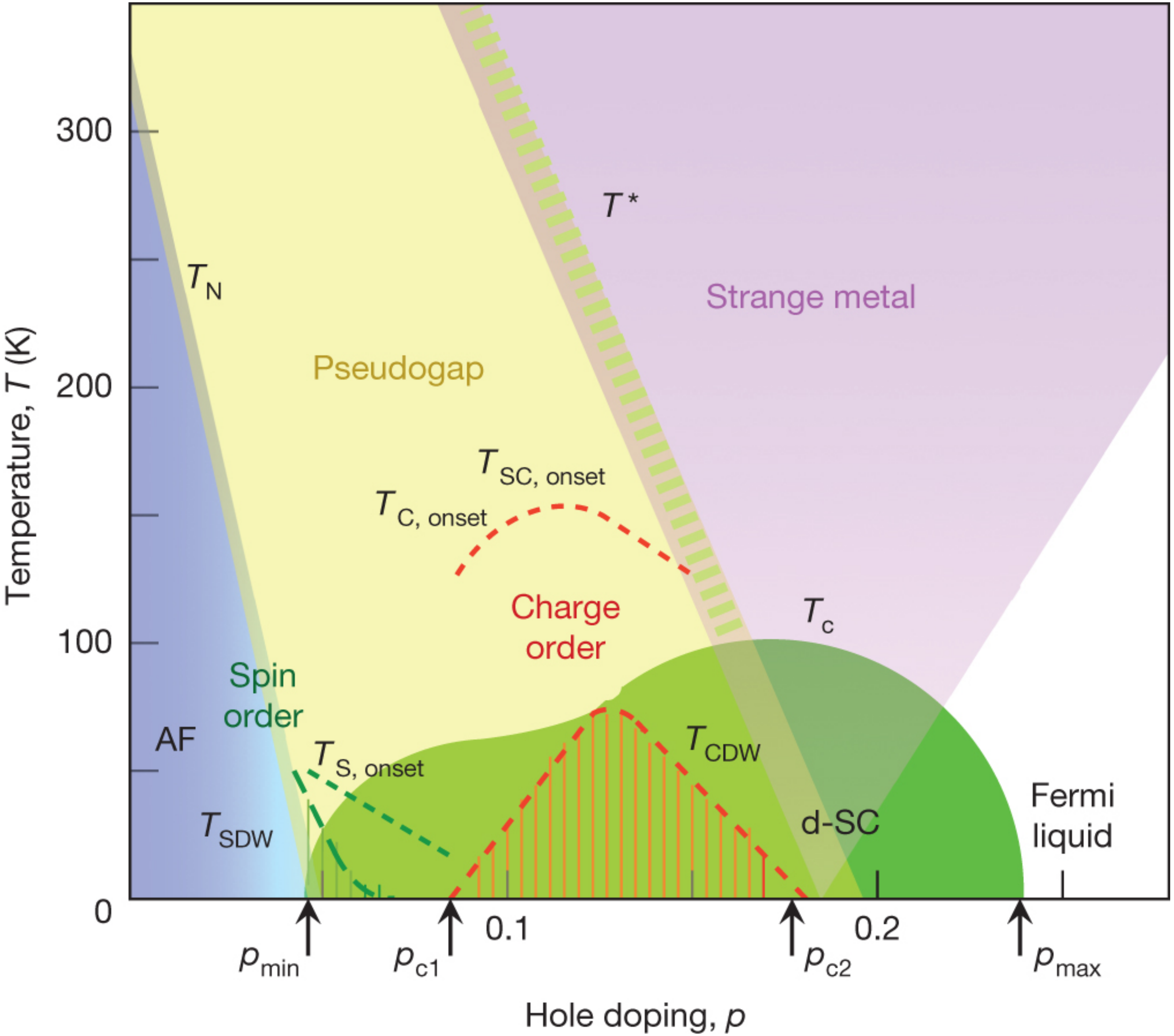
$$\mathcal{H}_{\text{Hubbard}} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^{\dagger}_{\mathbf{p}\alpha} c_{\mathbf{p}\alpha} + U \sum_{i} n_{i\uparrow} n_{i\downarrow} + \ldots$$

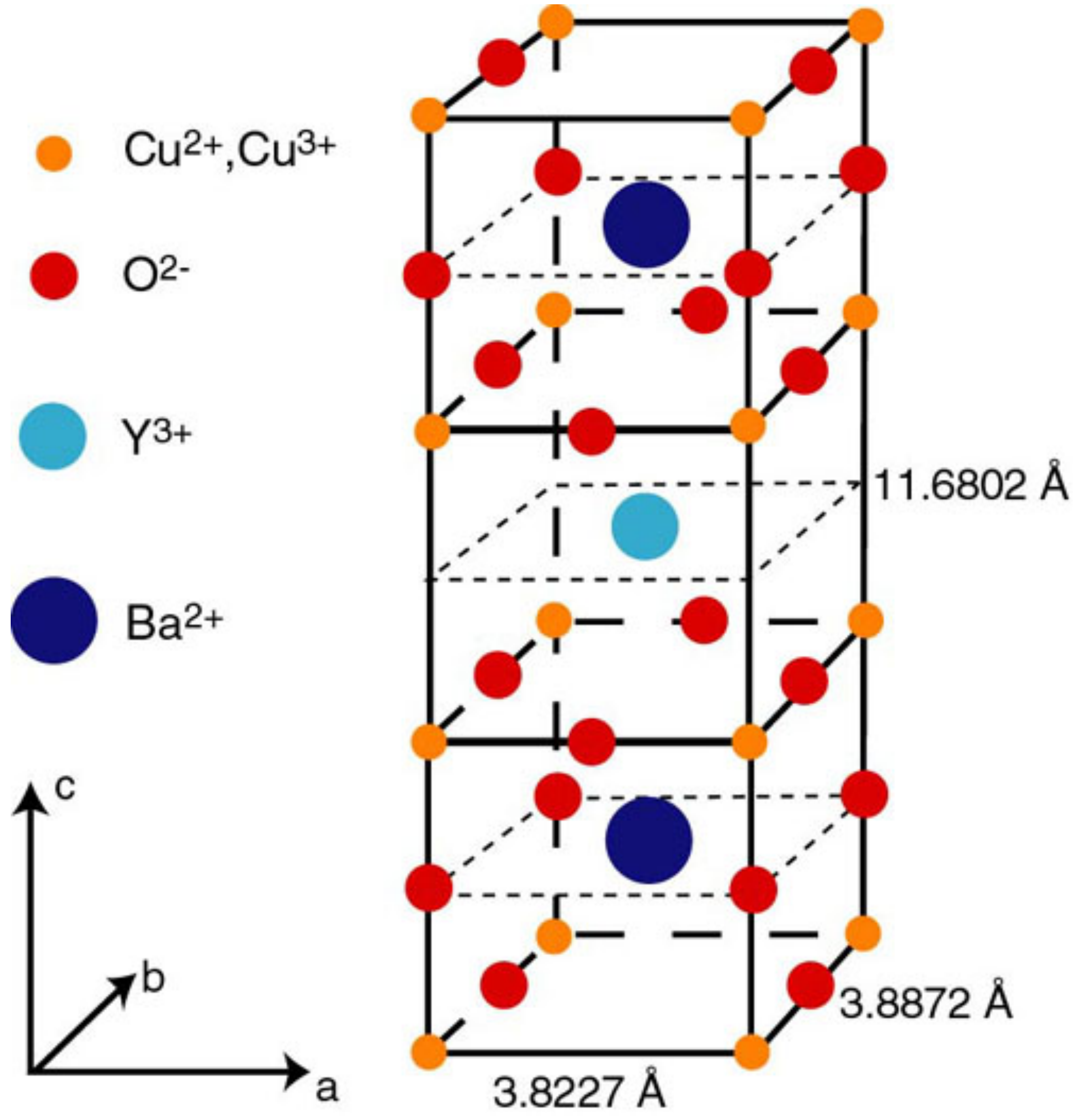




$YBa_2Cu_3O_{6+x}$

B Keimer *et al.* *Nature* **518**, 179-186 (2015)





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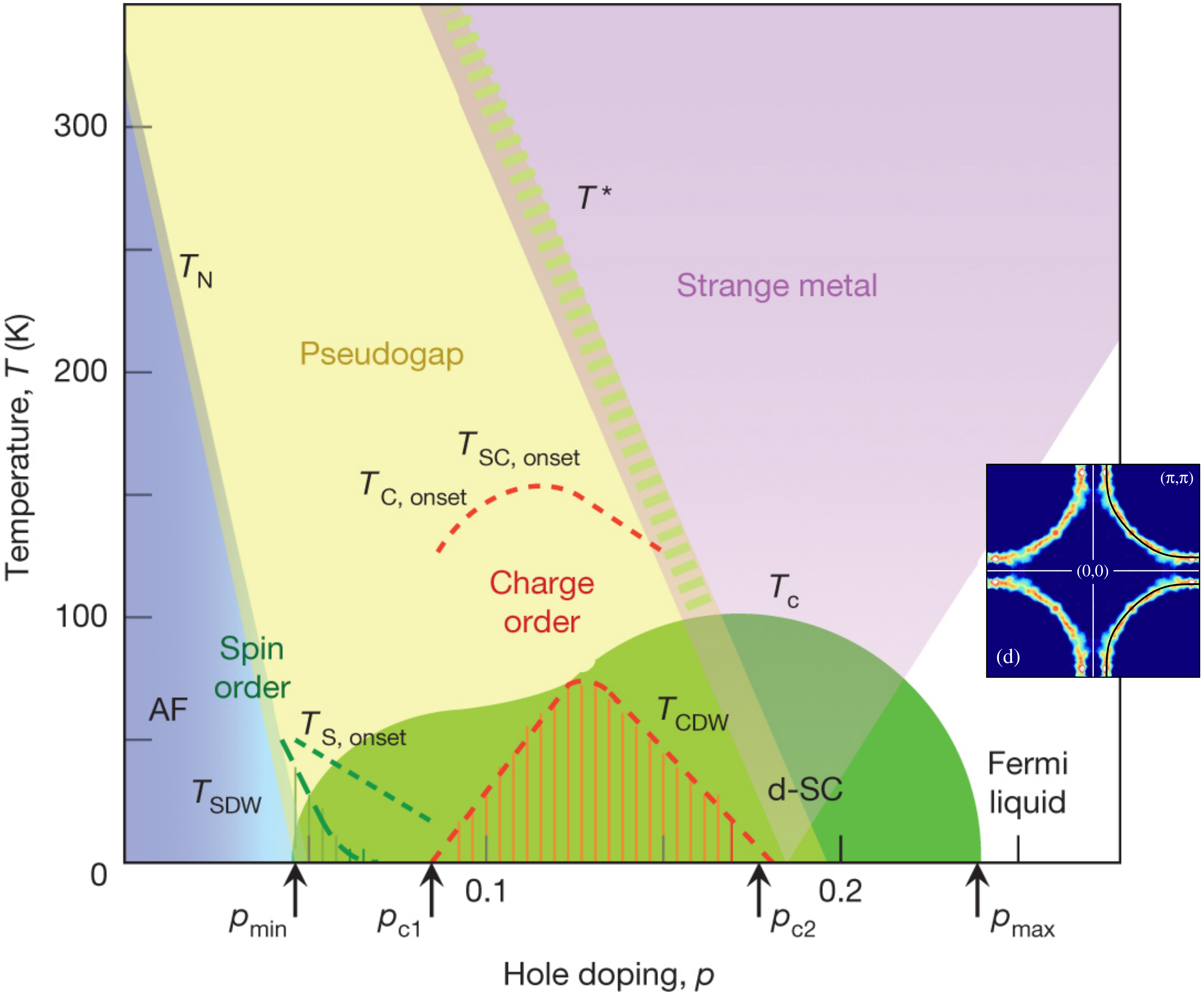

Fermi liquid
in the
overdoped metal

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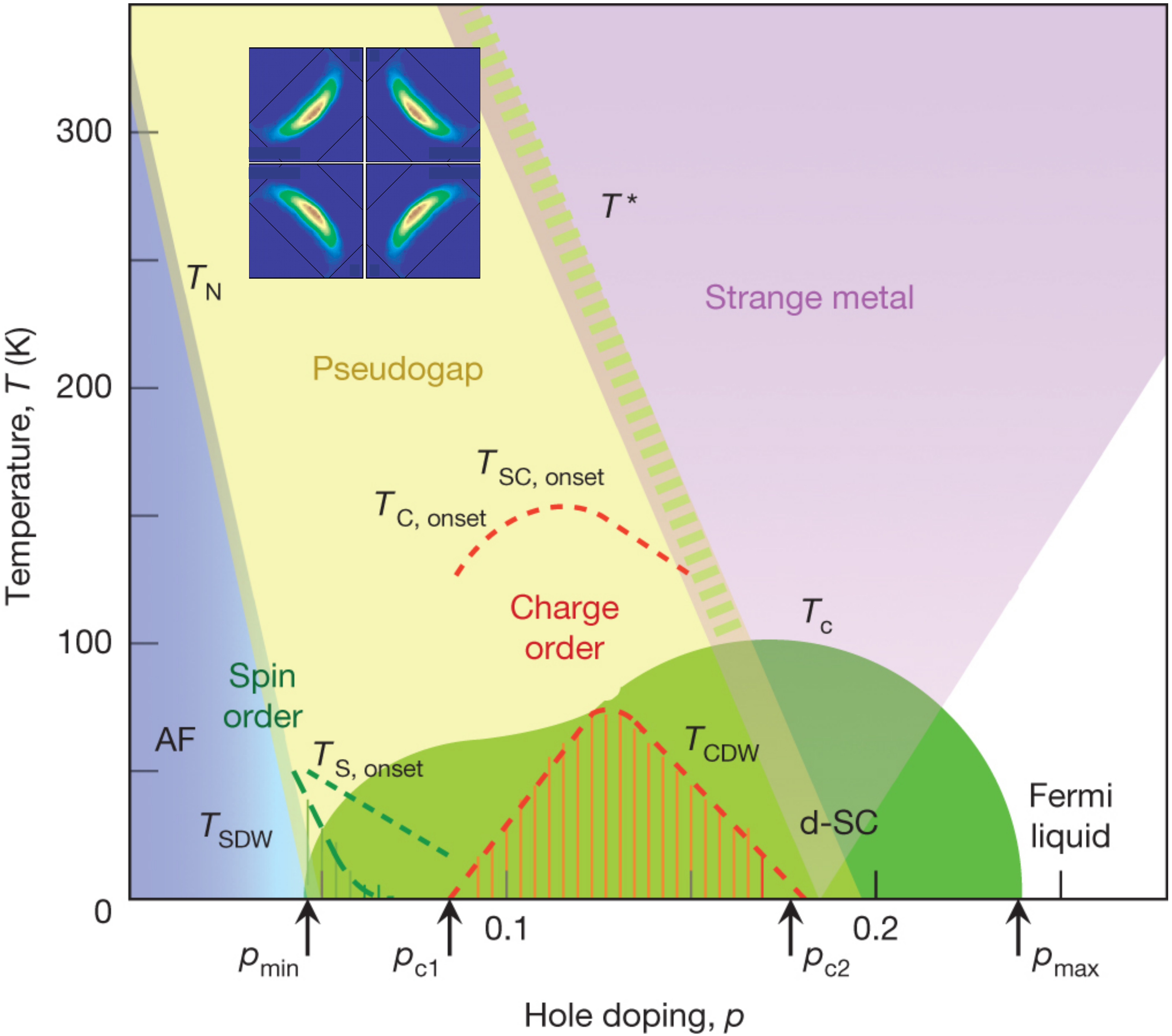
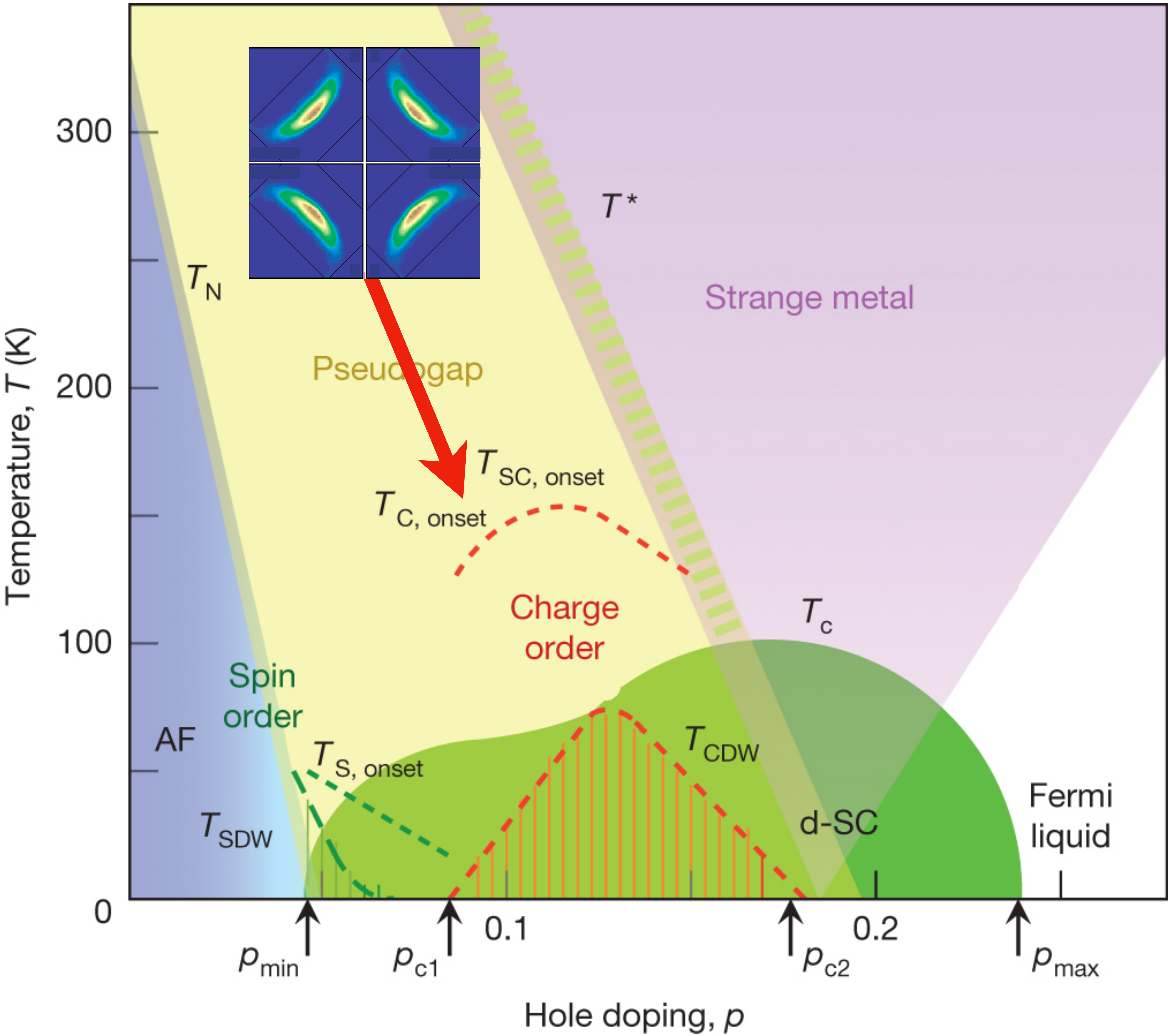


Theory for "pseudogap metal" with "Fermi arcs"?

B Keimer *et al.* *Nature* **518**, 179-186 (2015)



Needed: a theory for the onset of charge order and d-wave superconductivity from the pseudogap metal.

Why are T_c and $T_{\rm CDW}$ about the same?

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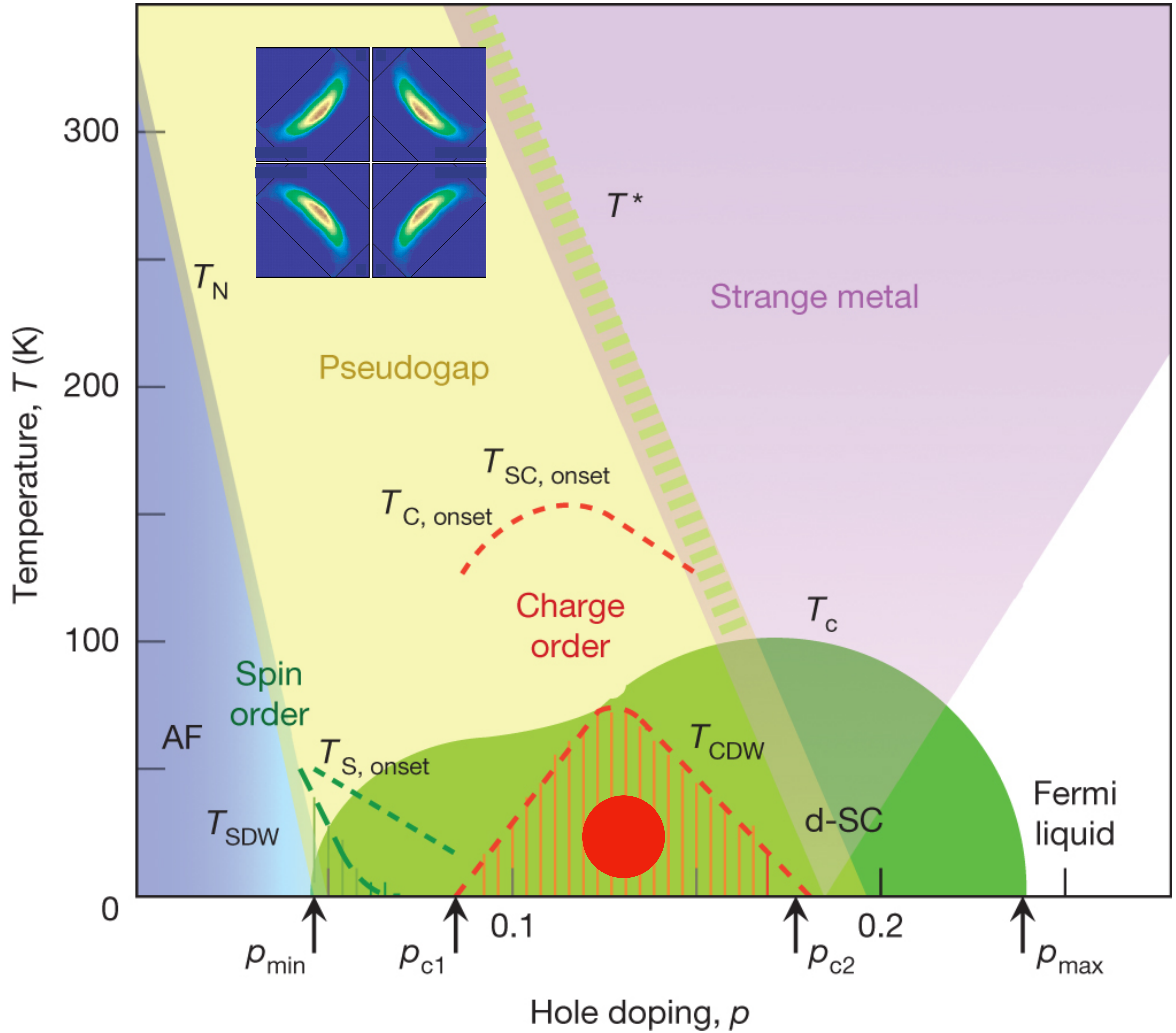

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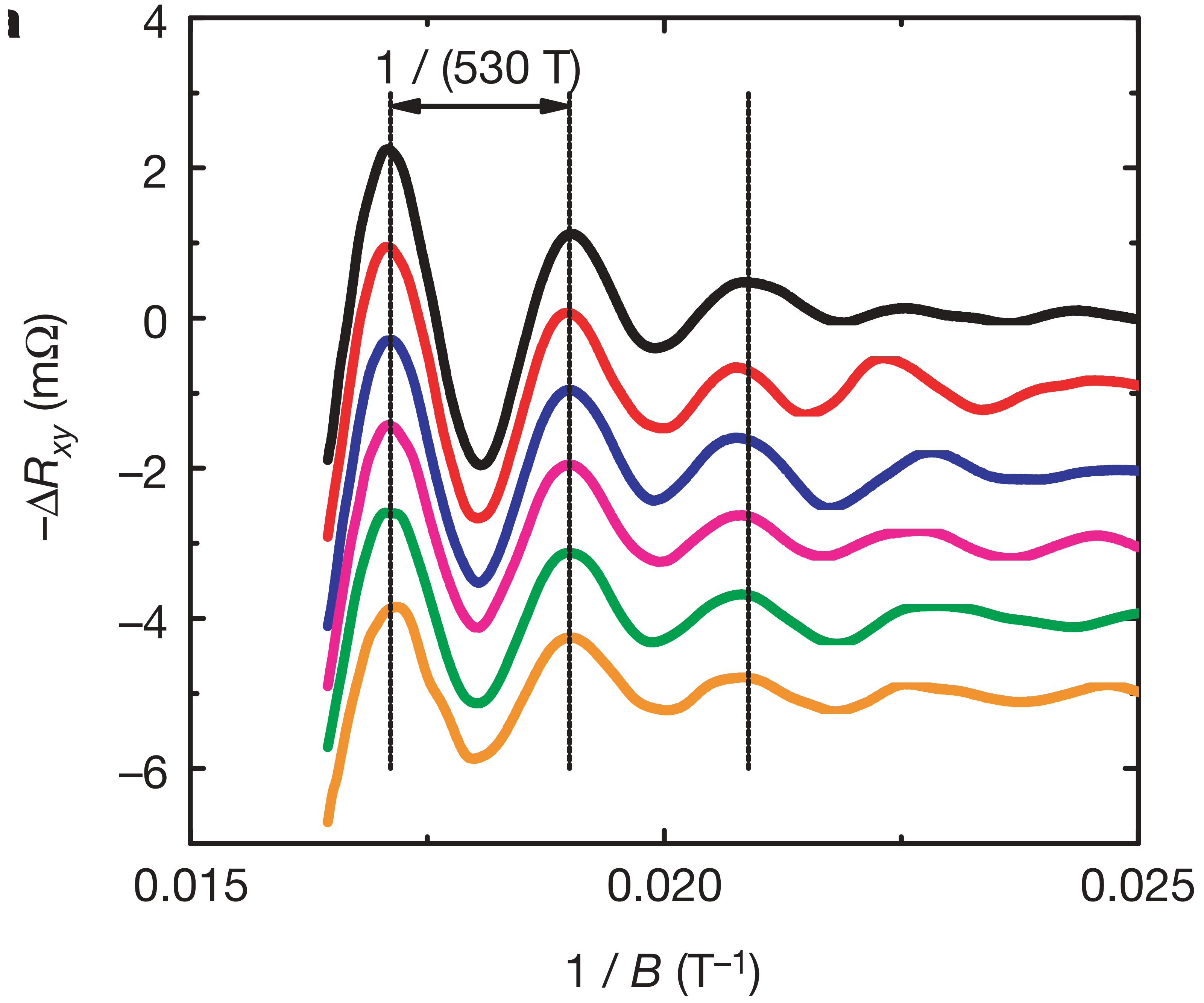

Quantum oscillations in the CDW phase at low T show only a single electron pocket of size p.

This cannot be obtained in the theory of CDWs in a Fermi liquid.

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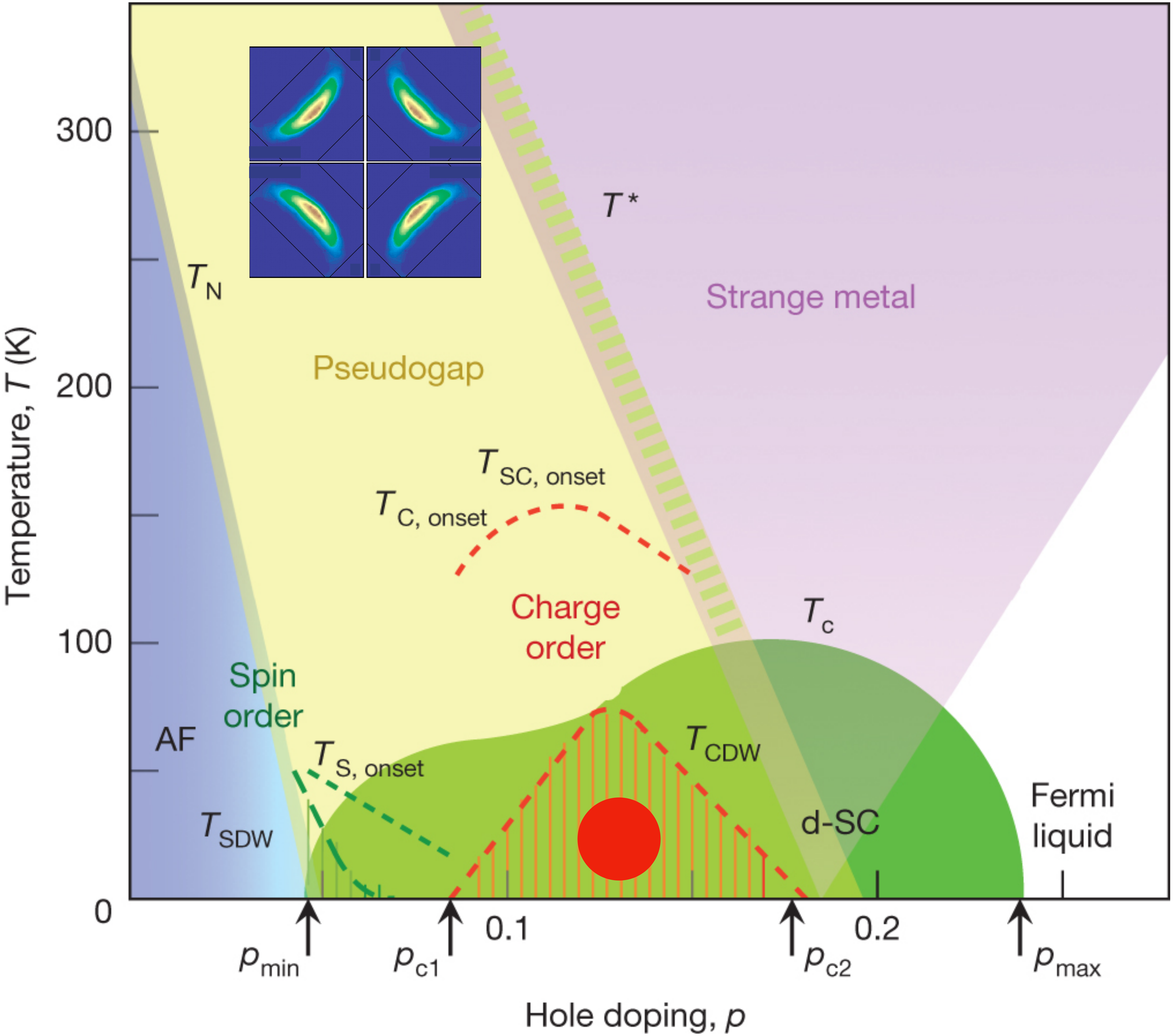
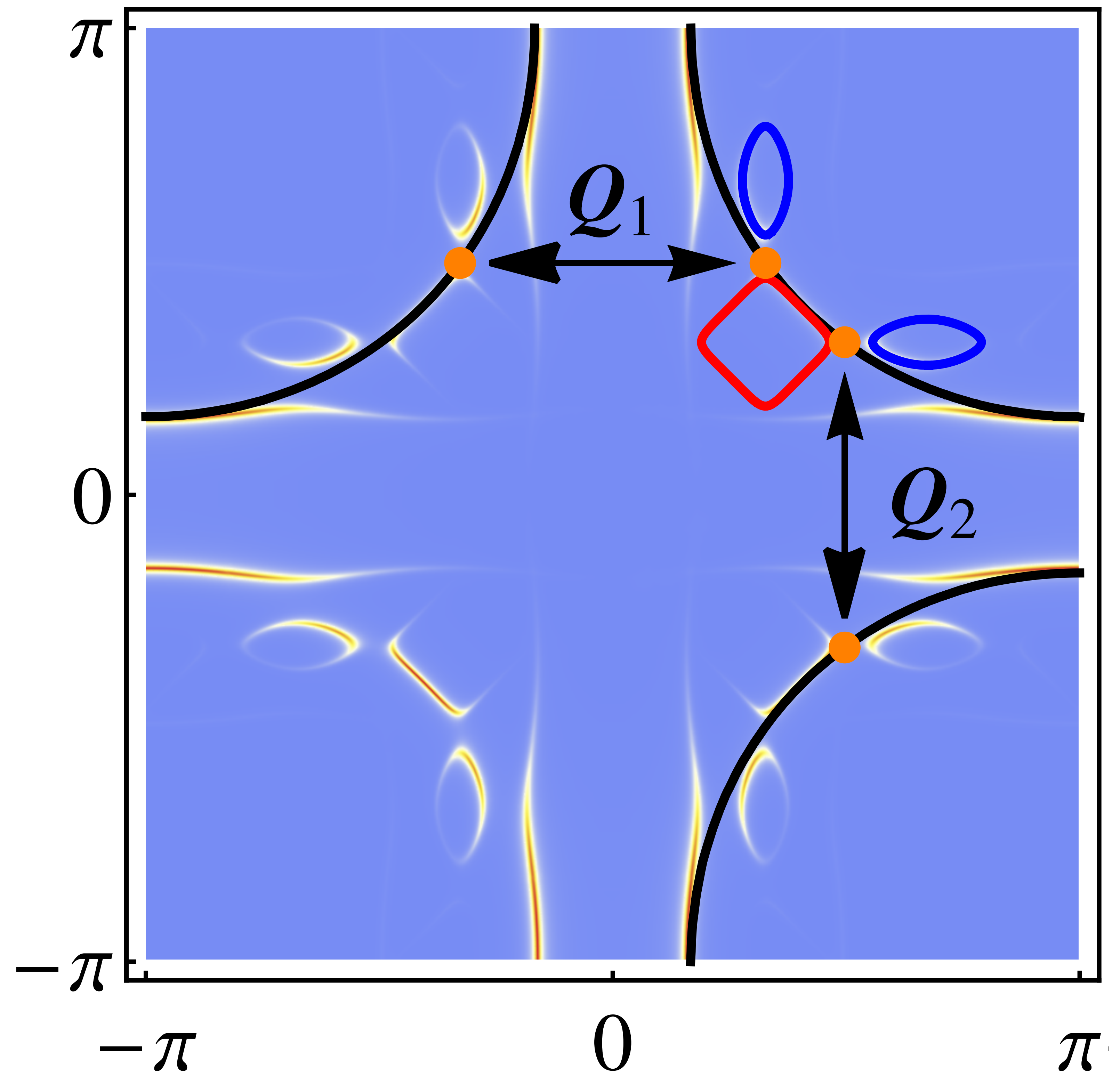


A. Allais, D. Chowdhury, and S.S., Nature Comm. **5**, 5771 (2014)

N. Harrison and S. E. Sebastian PRL **106**, 226402 (2011)



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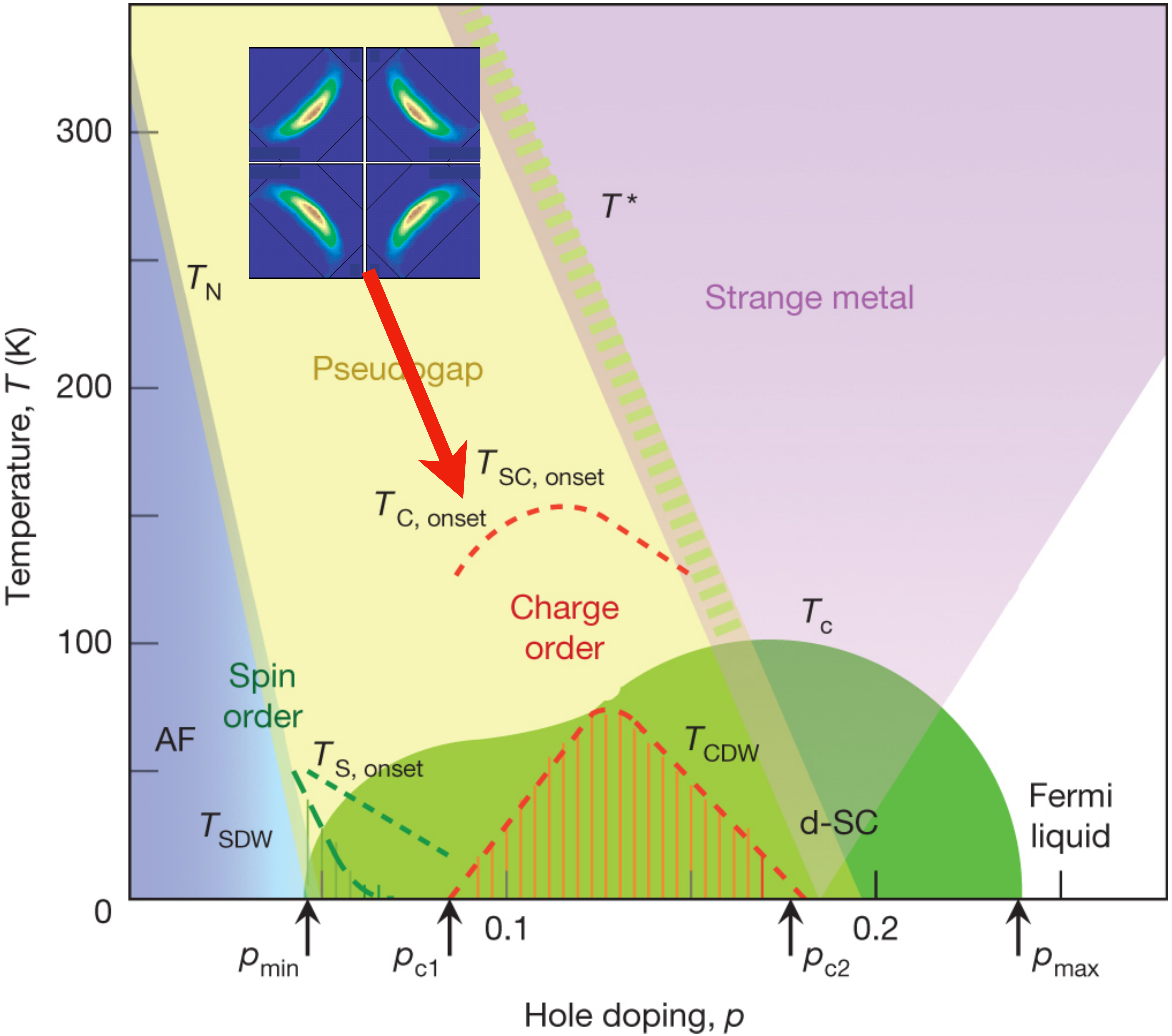

Theory for "pseudogap metal" with "Fermi arcs"?

Use the pseudogap metal in place of the Fermi liquid as the 'parent' to *conventional* *d*-wave superconductor, charge density wave, spin density wave, pair density wave ...

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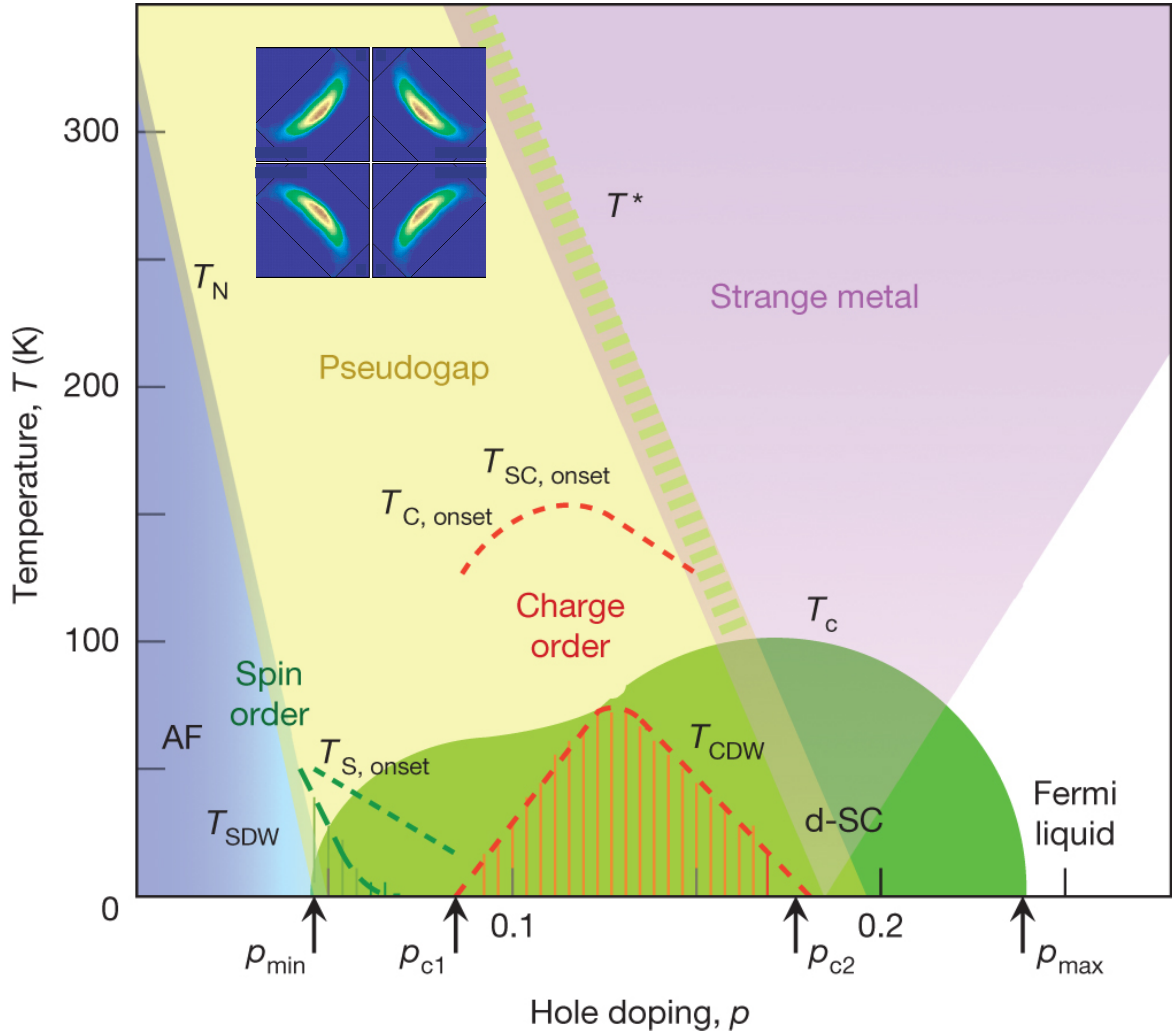

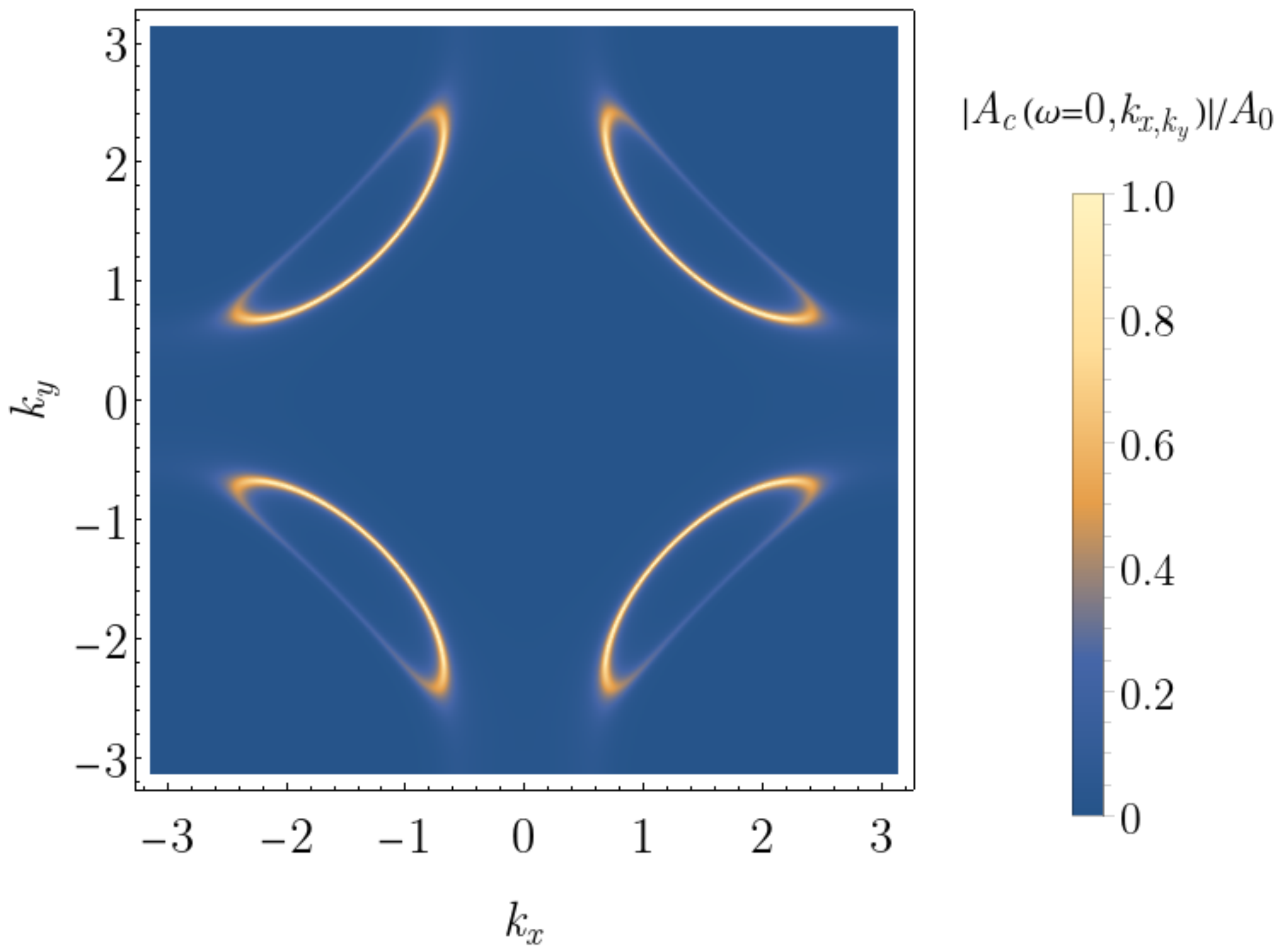

E. Mascot,
A. Nikolaenko,
M. Tikhanovskaya,
Ya-Hui Zhang,
D. K. Morr, and
S. S., PRB **105**,
075146 (2022)

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

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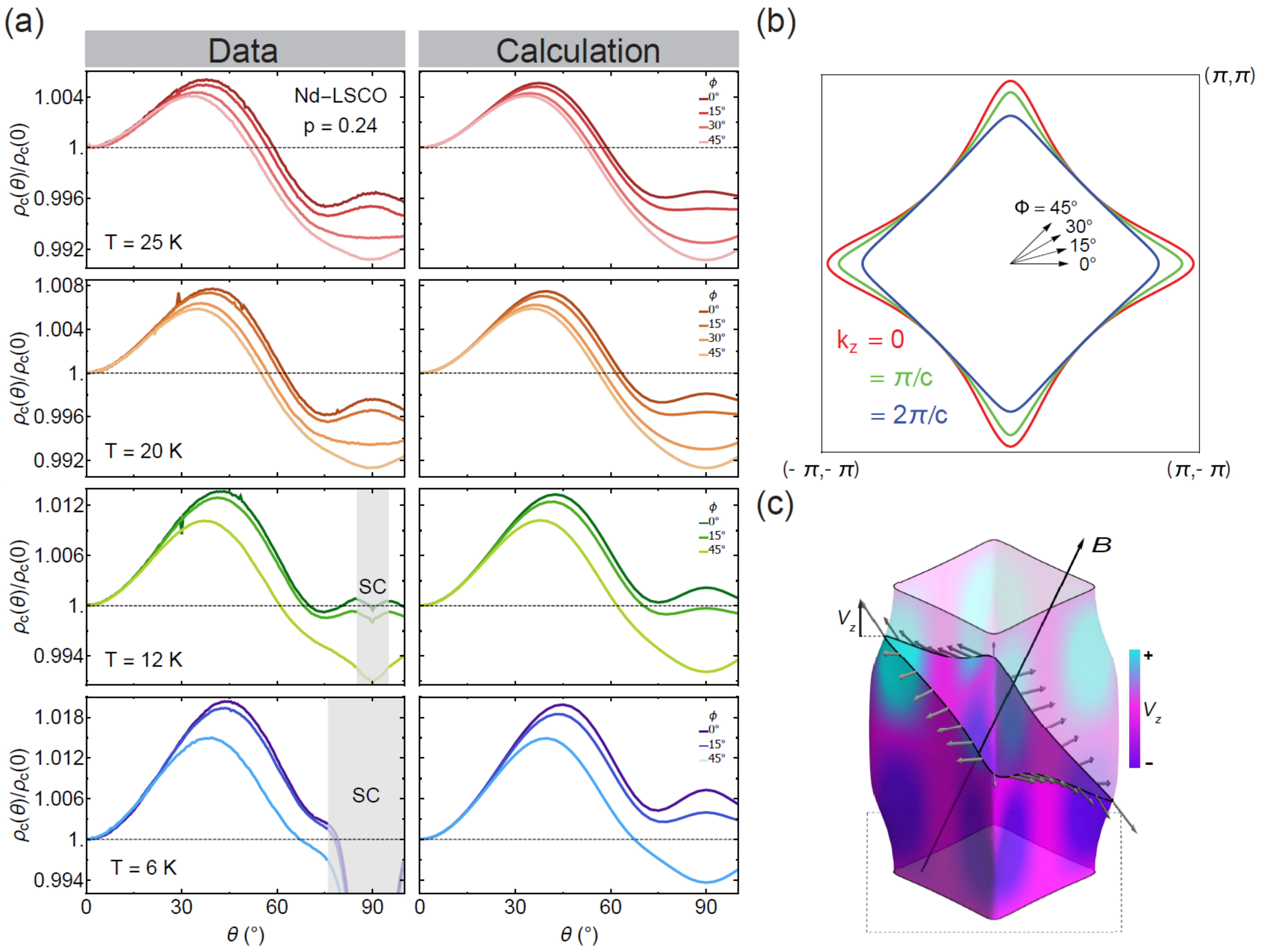
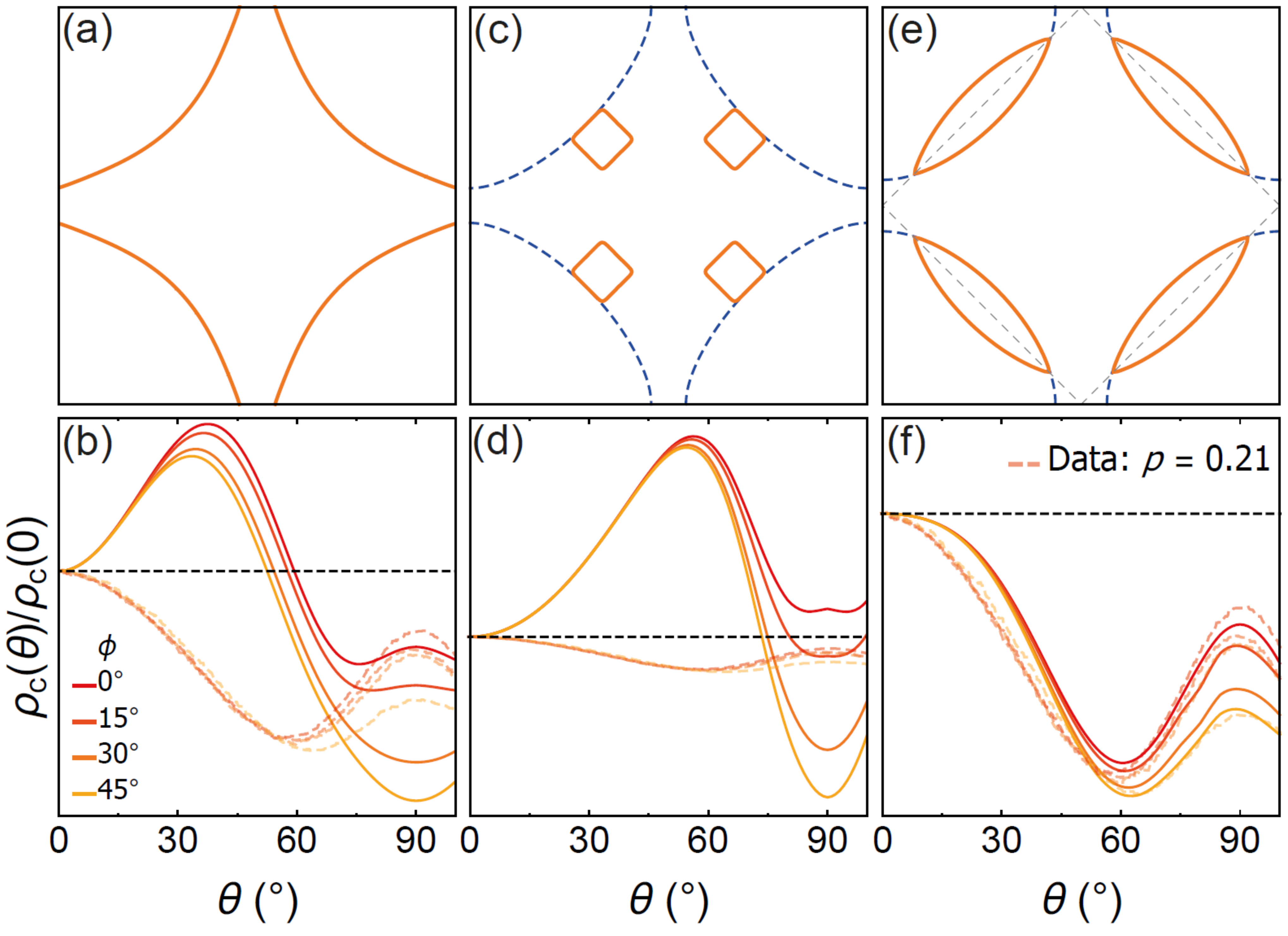
PRB **73**, 174501 (2006).
T. D. Stanescu and G. Kotliar,
PRB **74**, 125110 (2006).
C. Berthod, T. Giamarchi, S. Biermann, and A. Georges,
PRL **97**, 136401 (2006).
S. Sakai, Y. Motome, M. Imada,
PRL **102**, 056404 (2009).
J. Skolimowski and M. Fabrizio,
PRB **106**, 045109 (2022).

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

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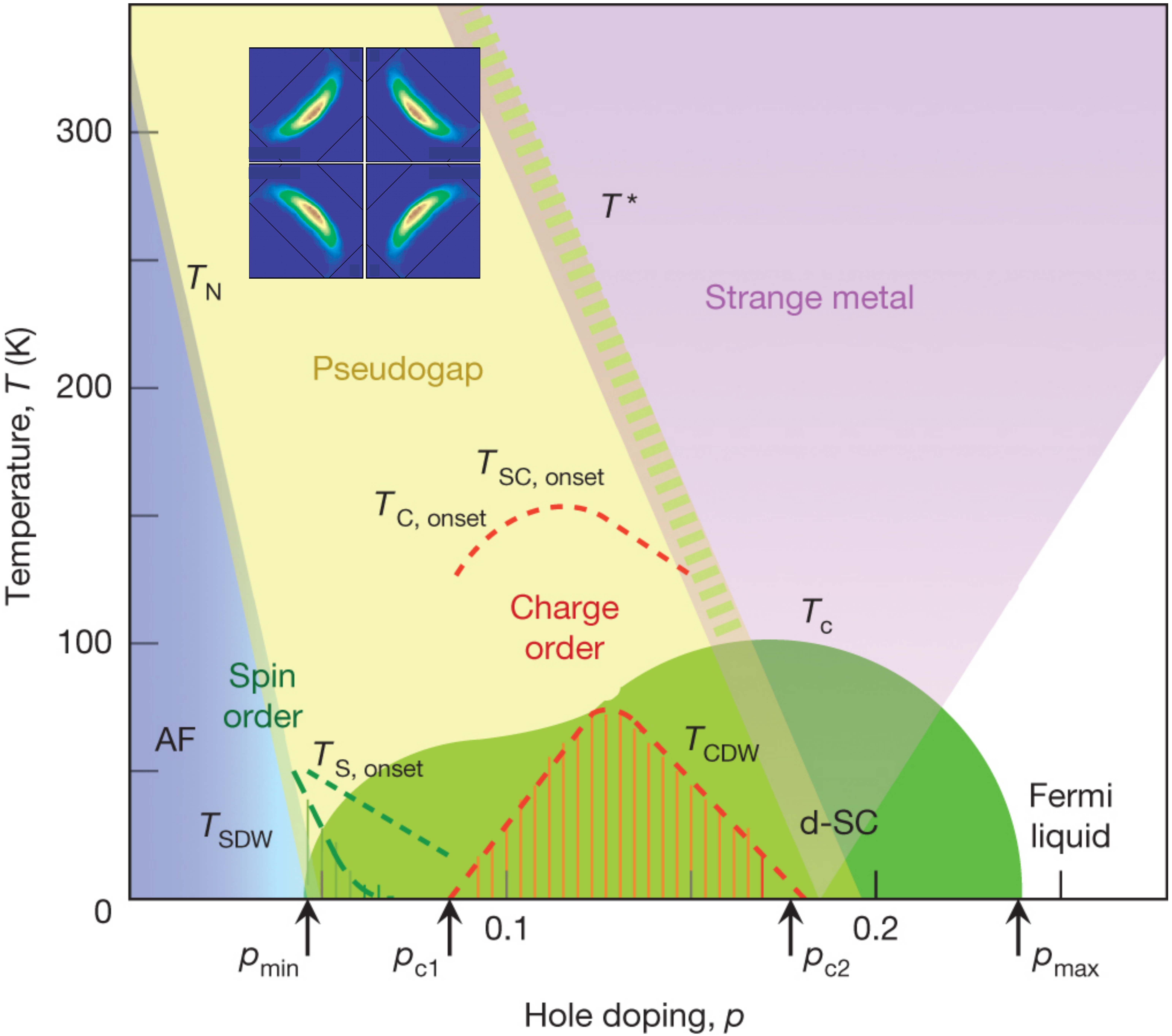

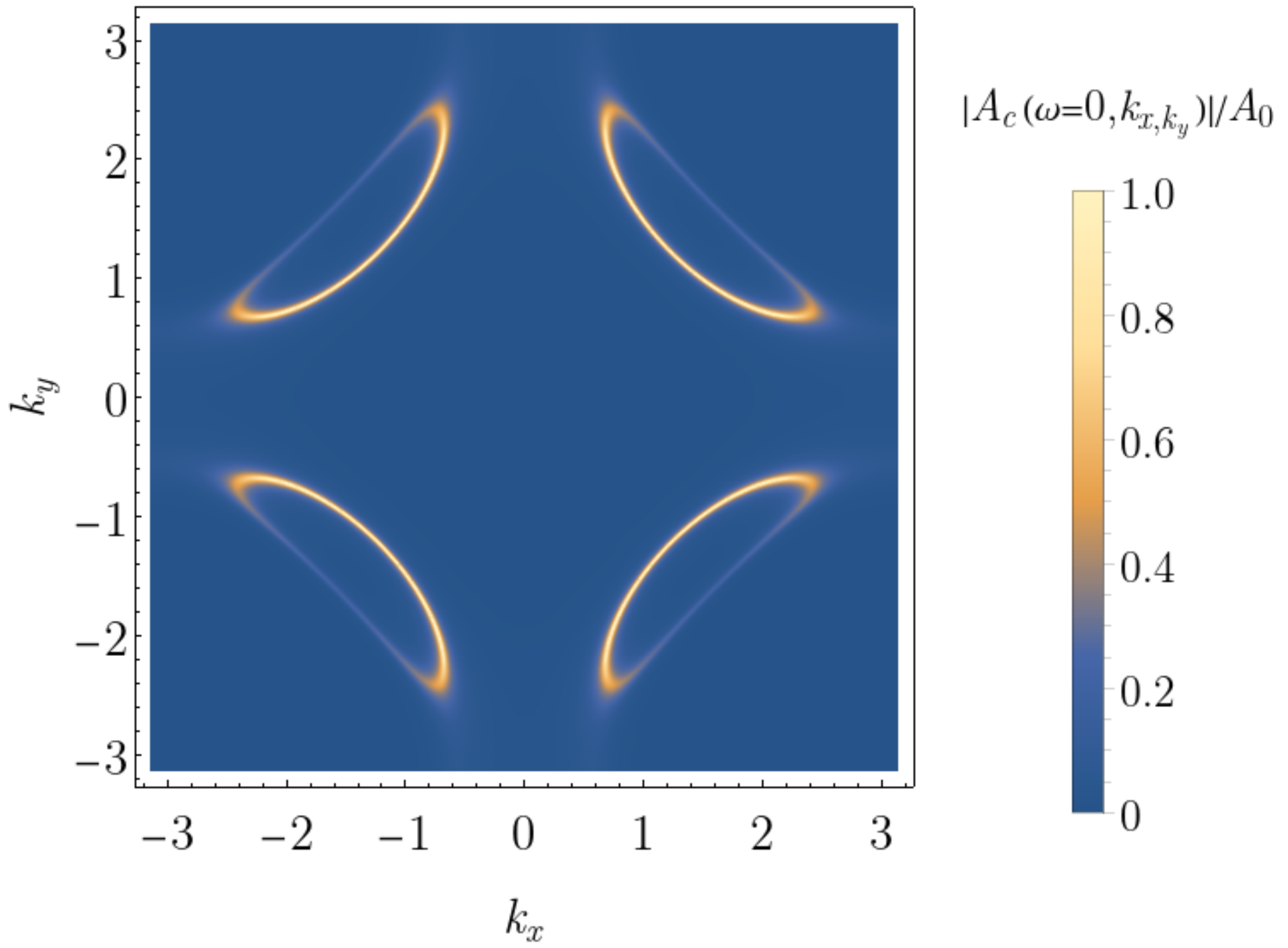

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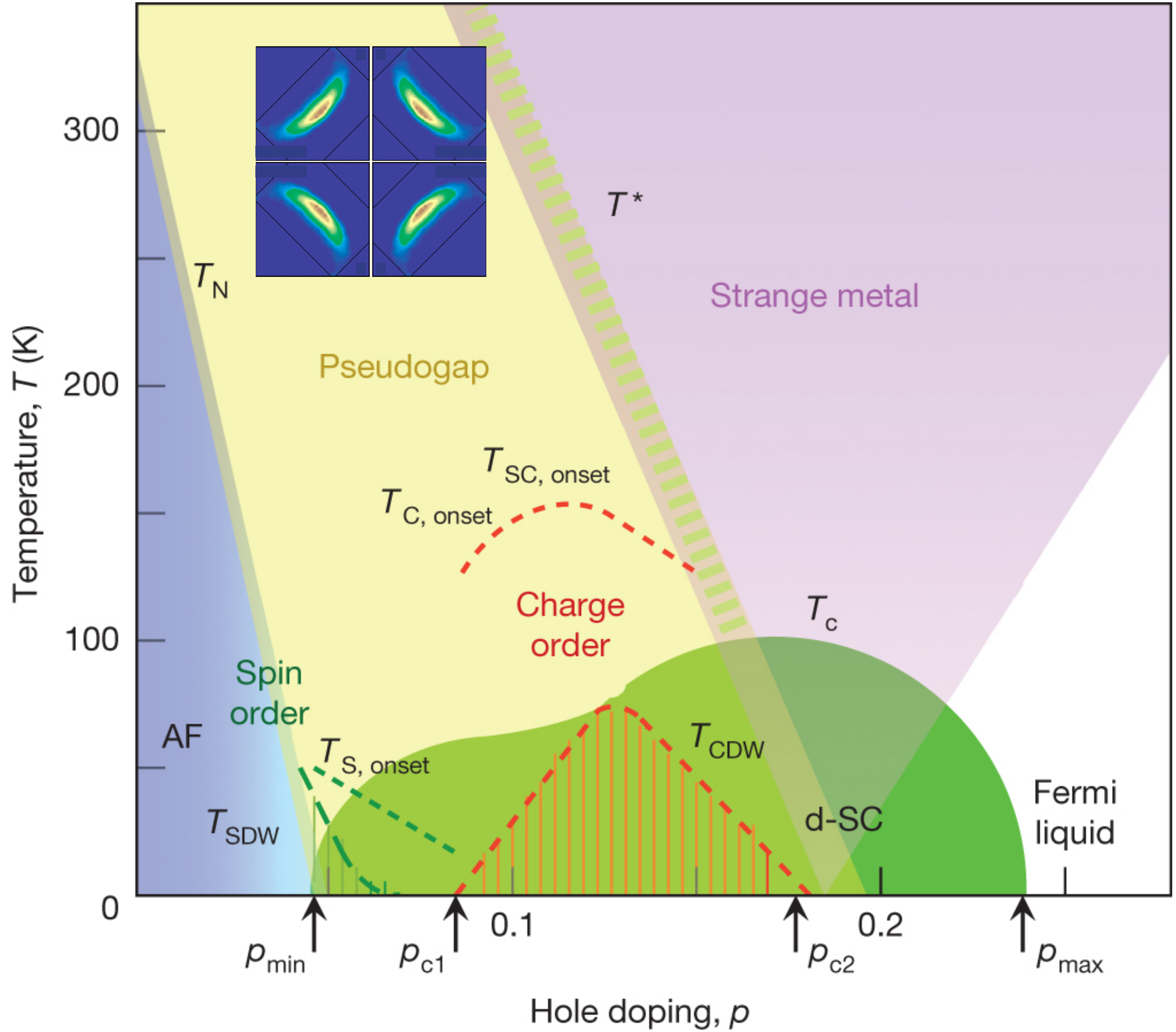

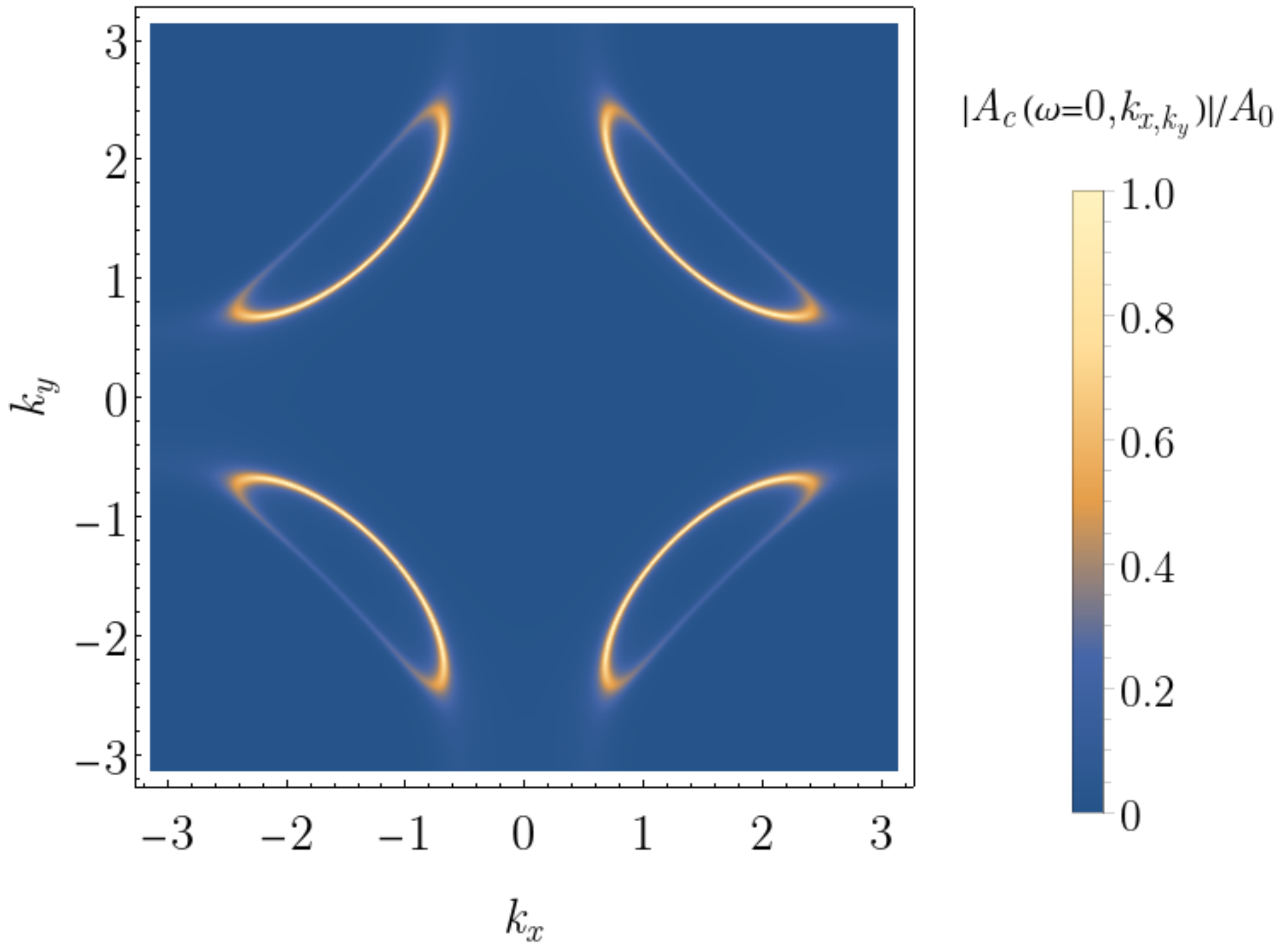

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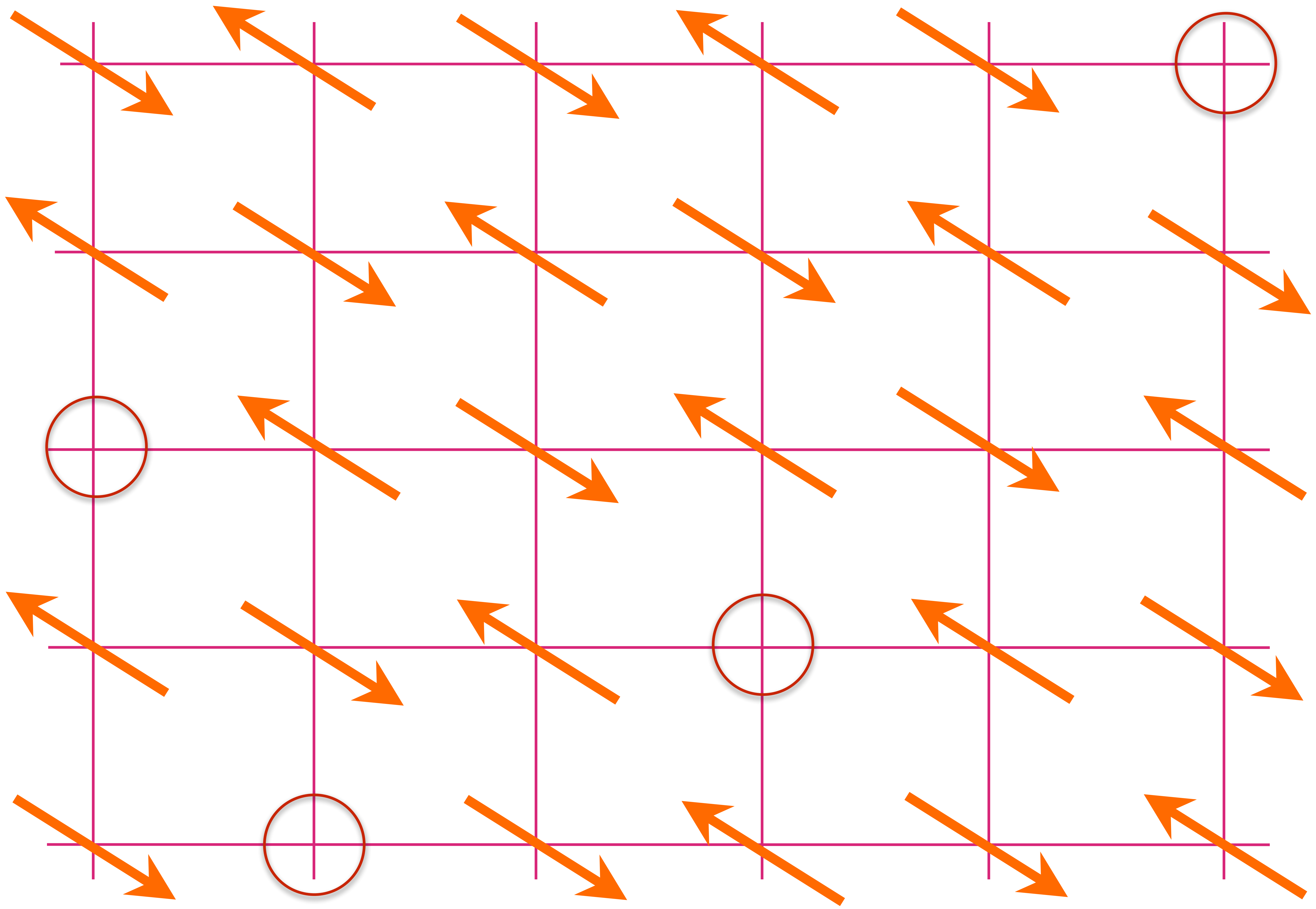
Hole pocket Fermi surfaces of size p with charge e, spin-1/2 quasiparticles
$+$
'spectator' square lattice spin liquid *at half-filling.*

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



Anti-ferromagnet with p holes per square

Holon metal

G. Baskaran, Z. Zou, P.W. Anderson, Solid State Comm. **63**, 973 (1987)
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, PRB **35**, 8865 (1987)
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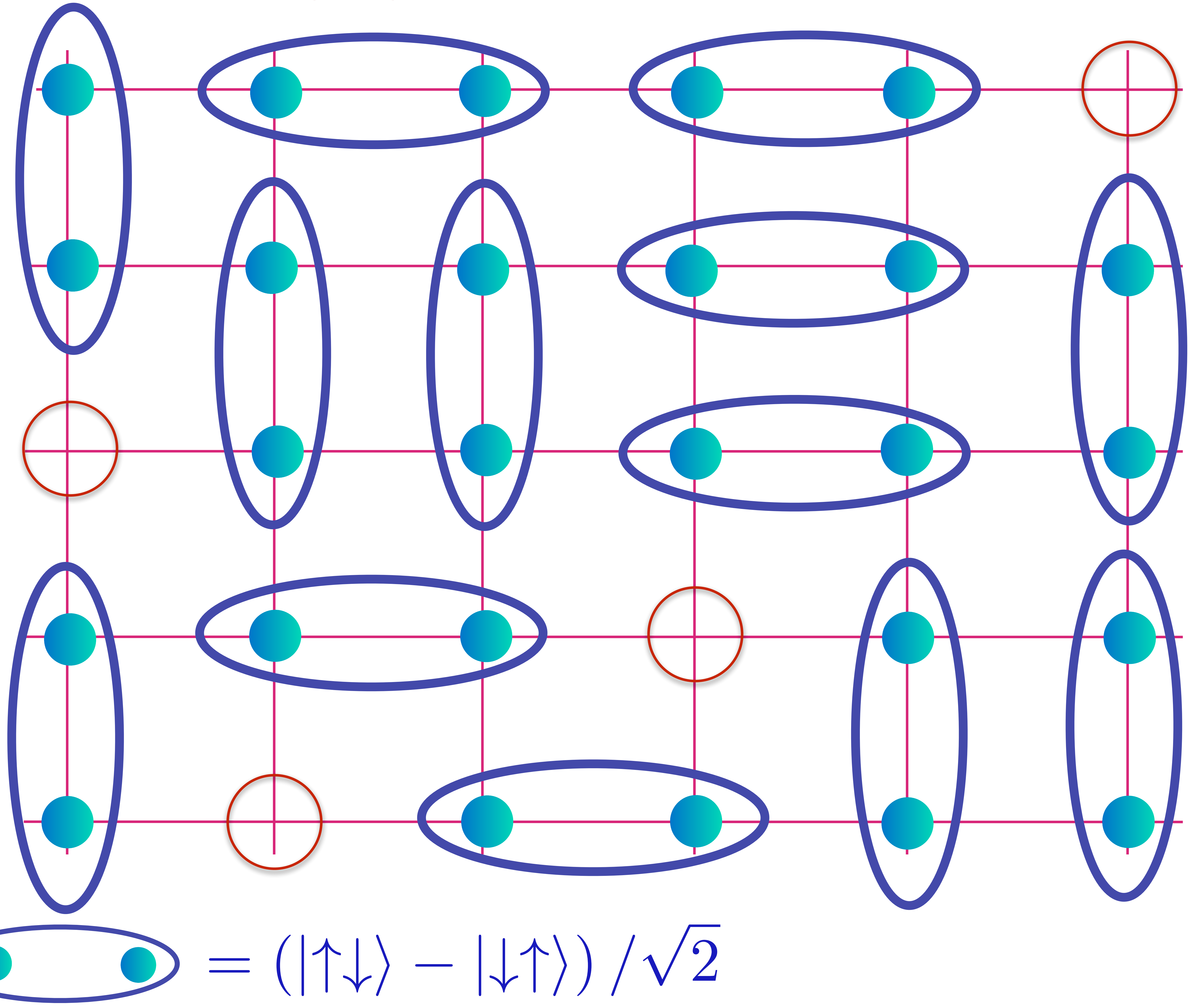

Spin liquid with density p of spinless, charge +e "holons".

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

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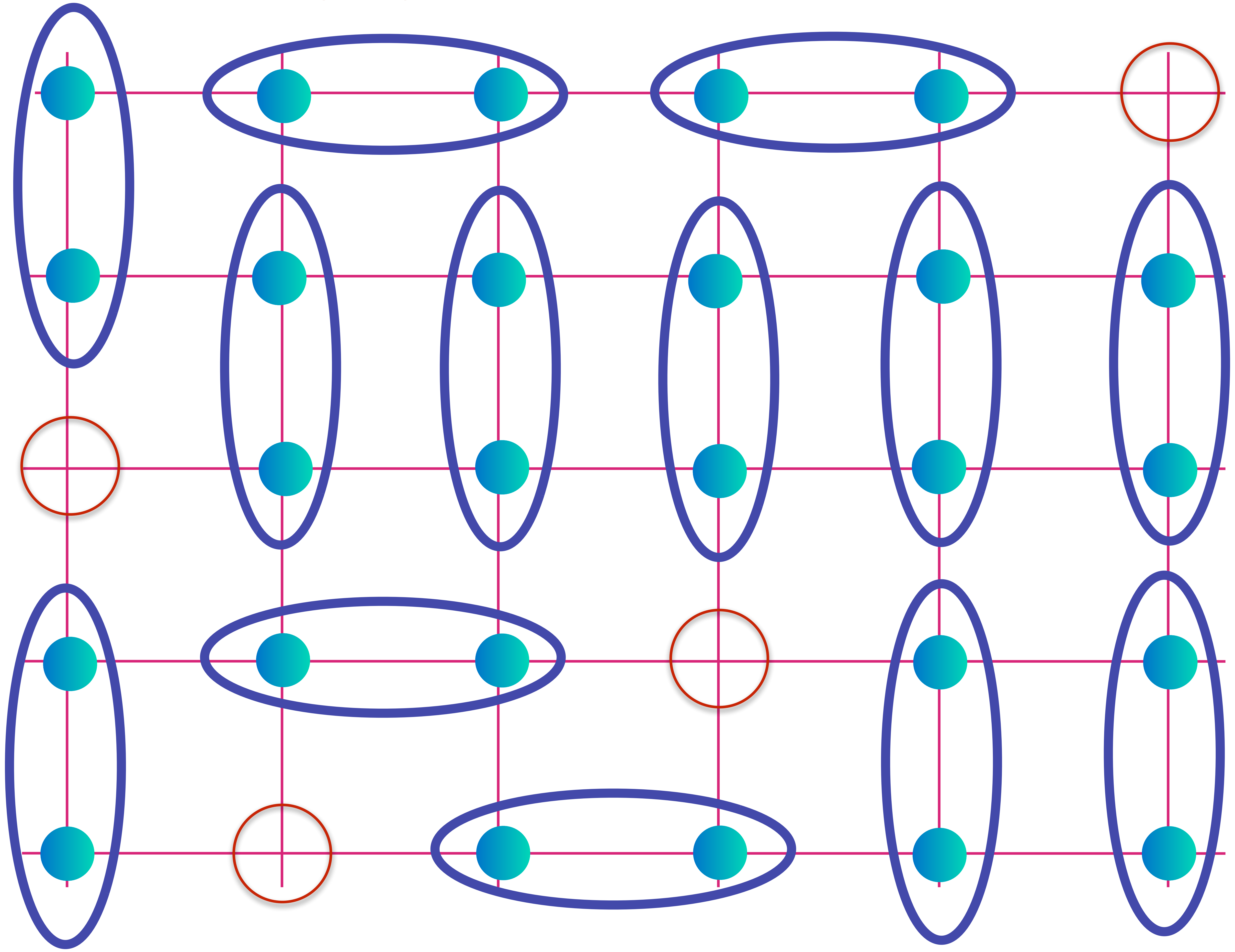

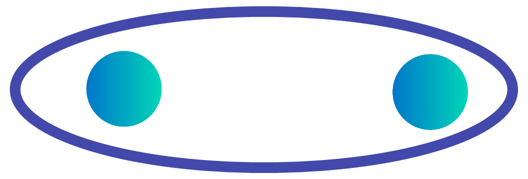

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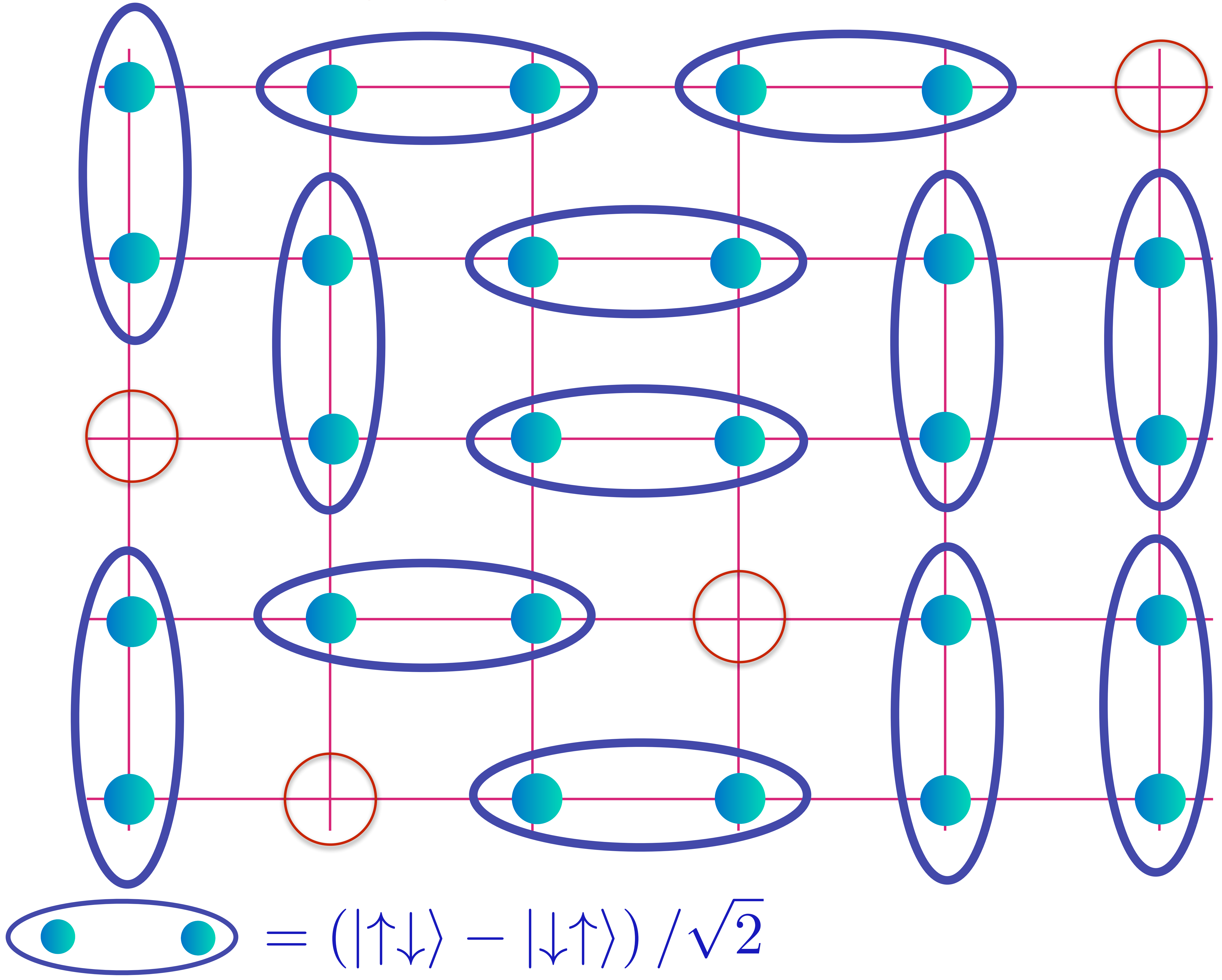

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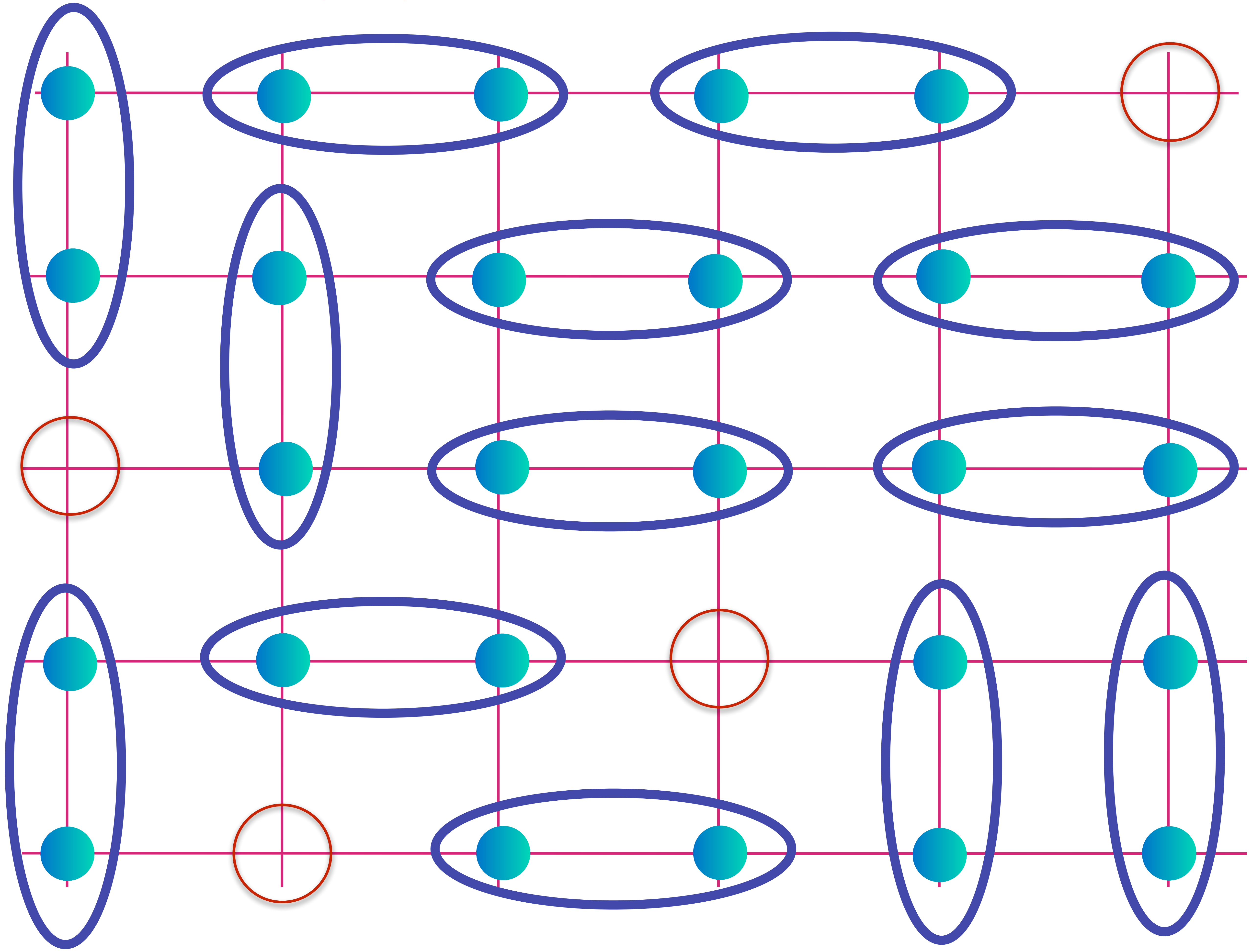

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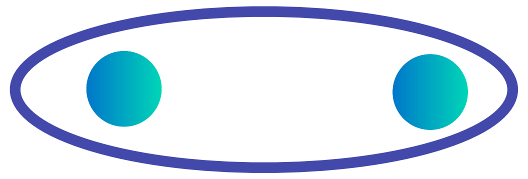 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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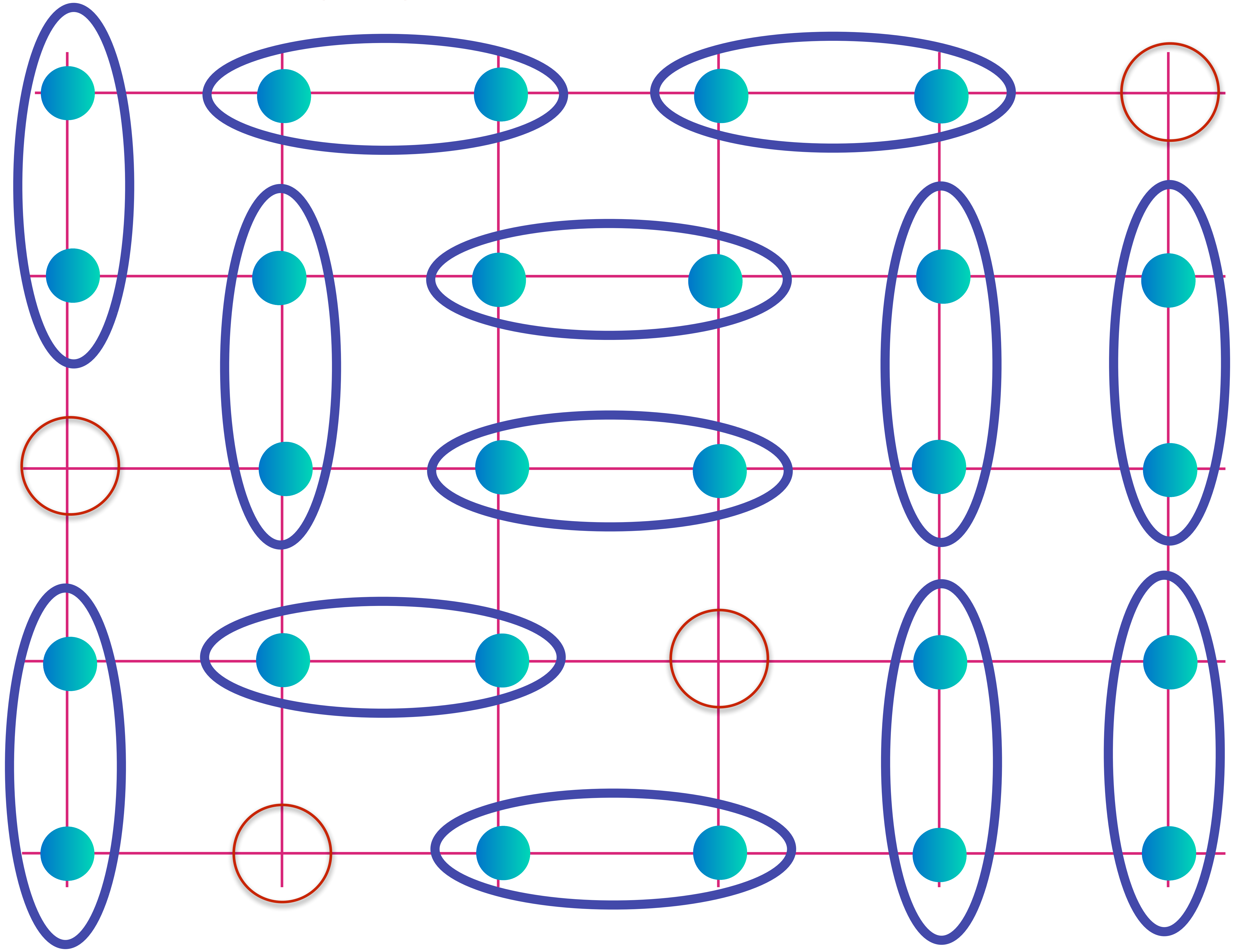

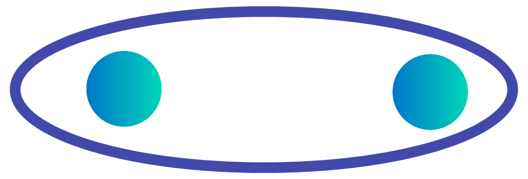 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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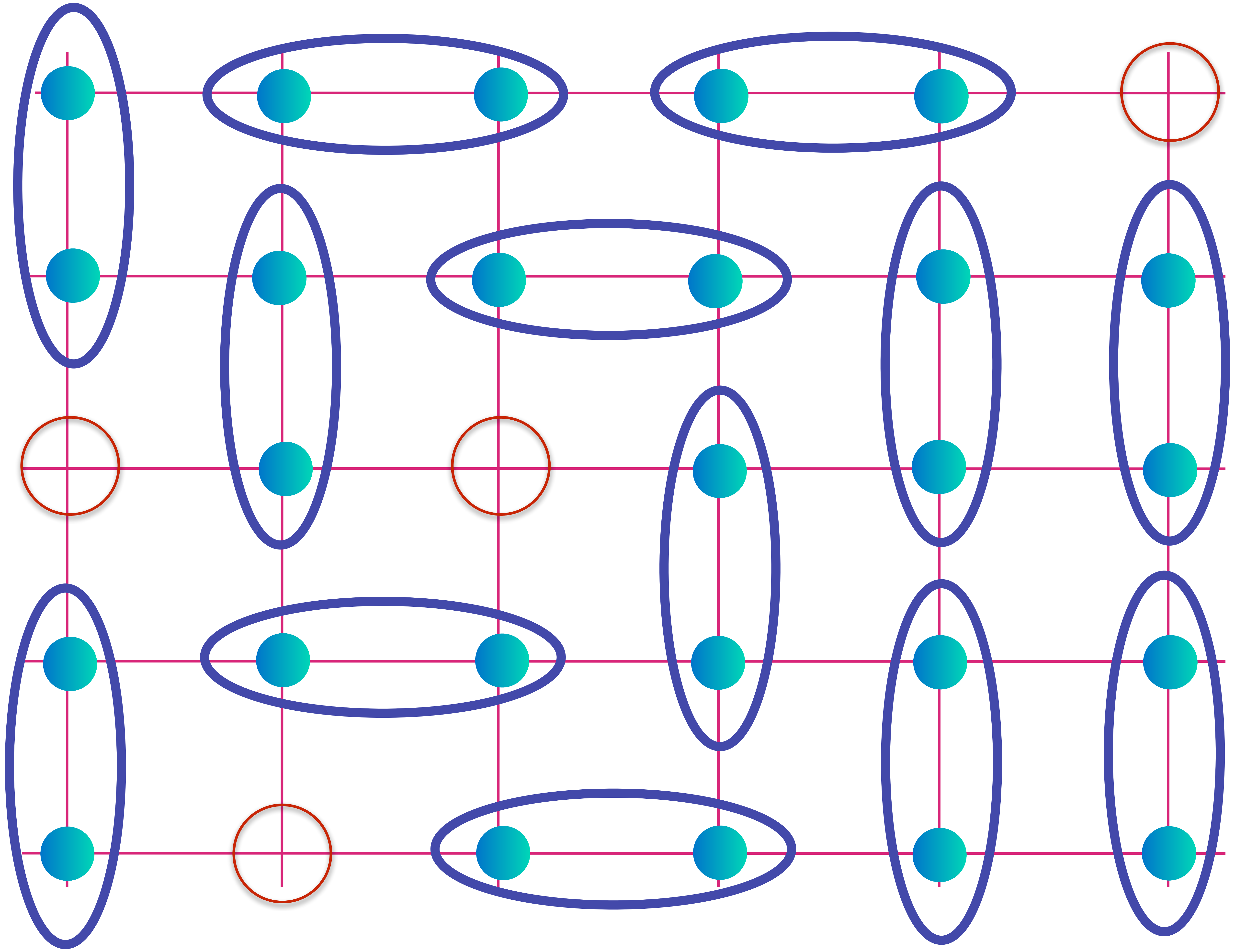

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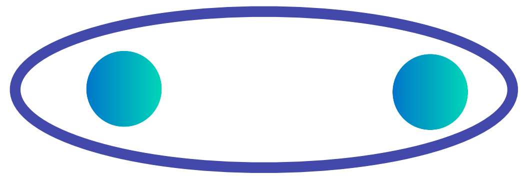 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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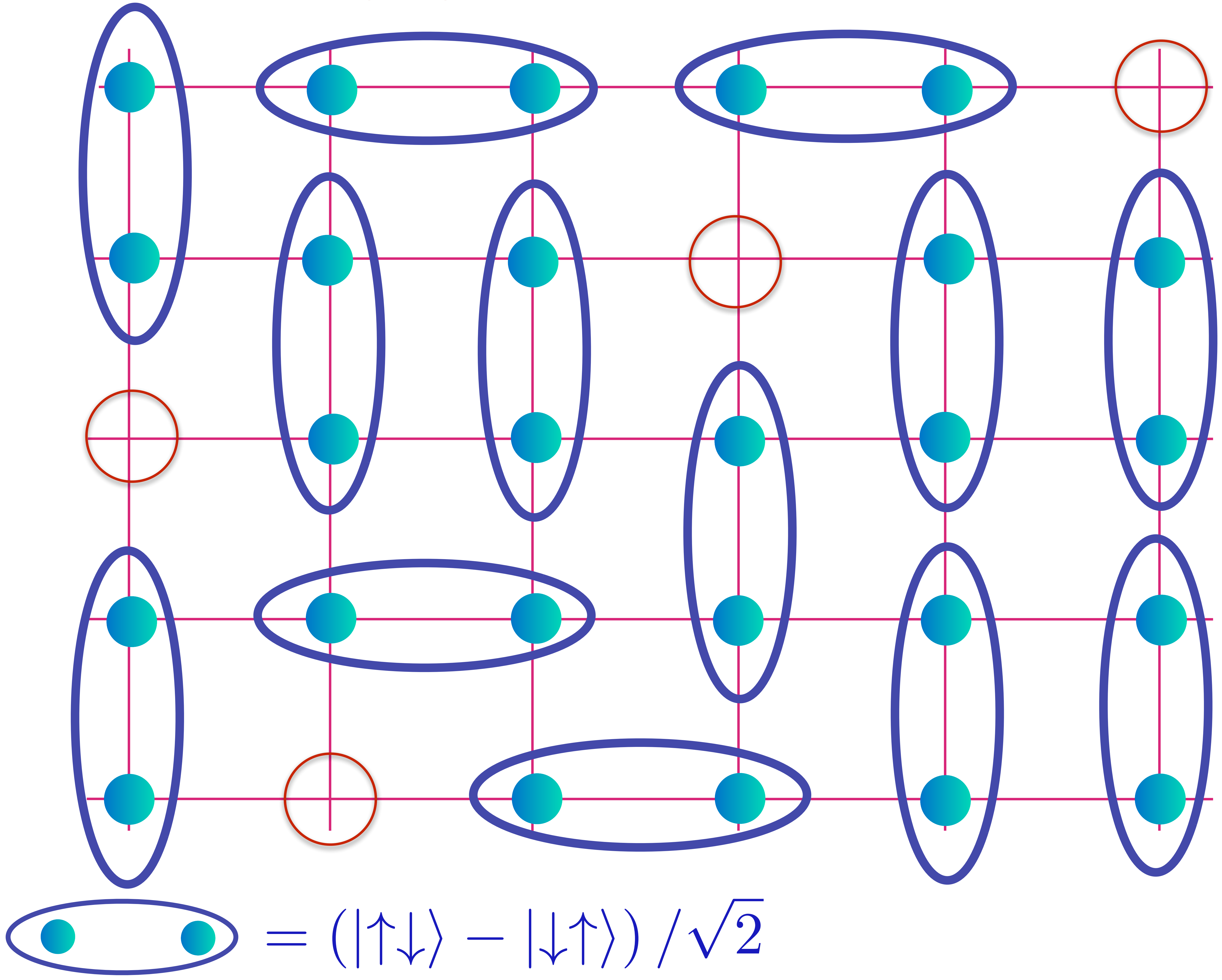

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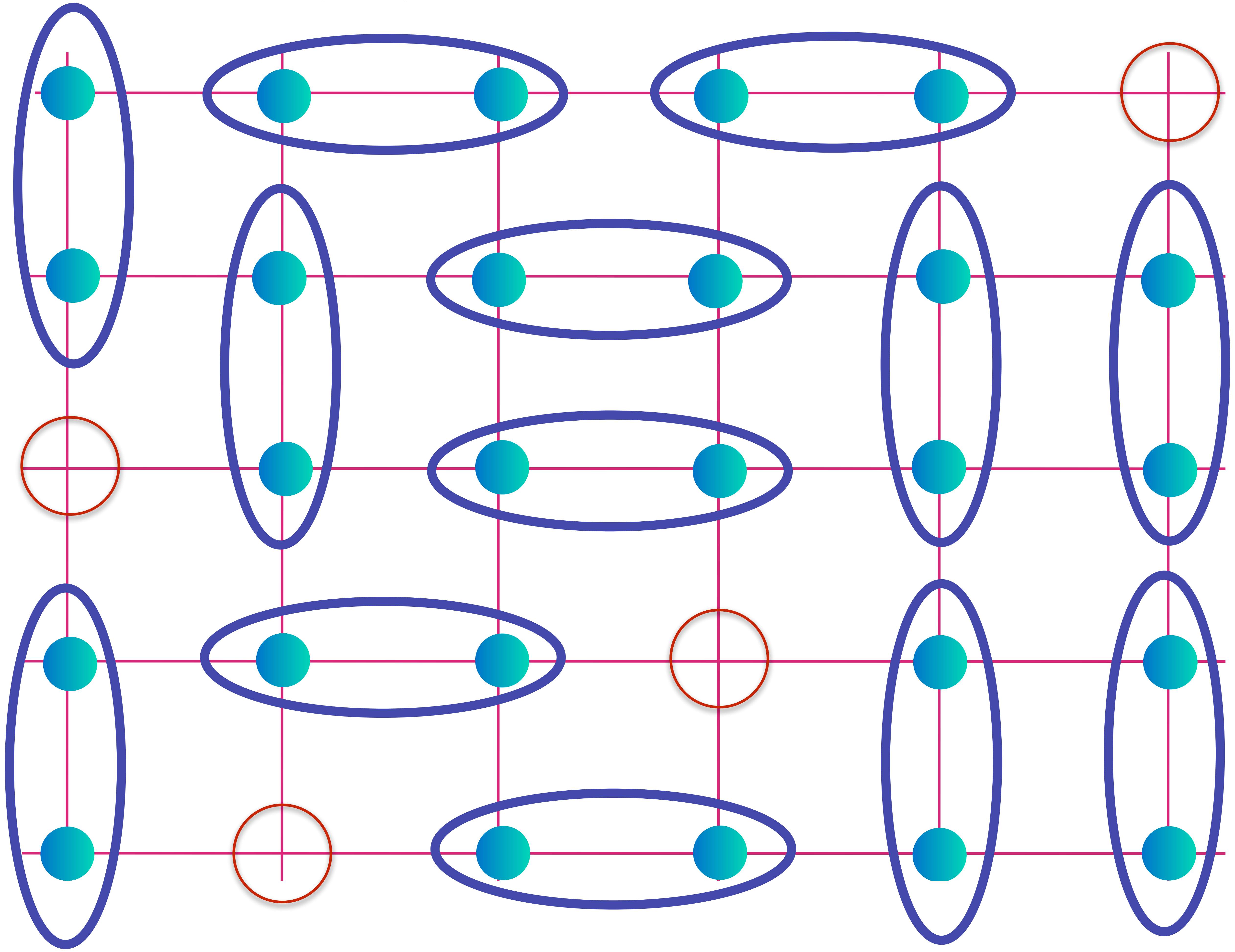

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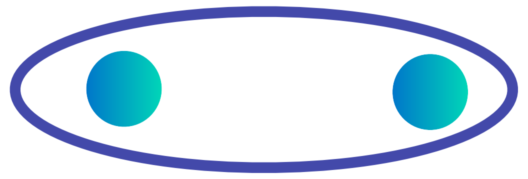

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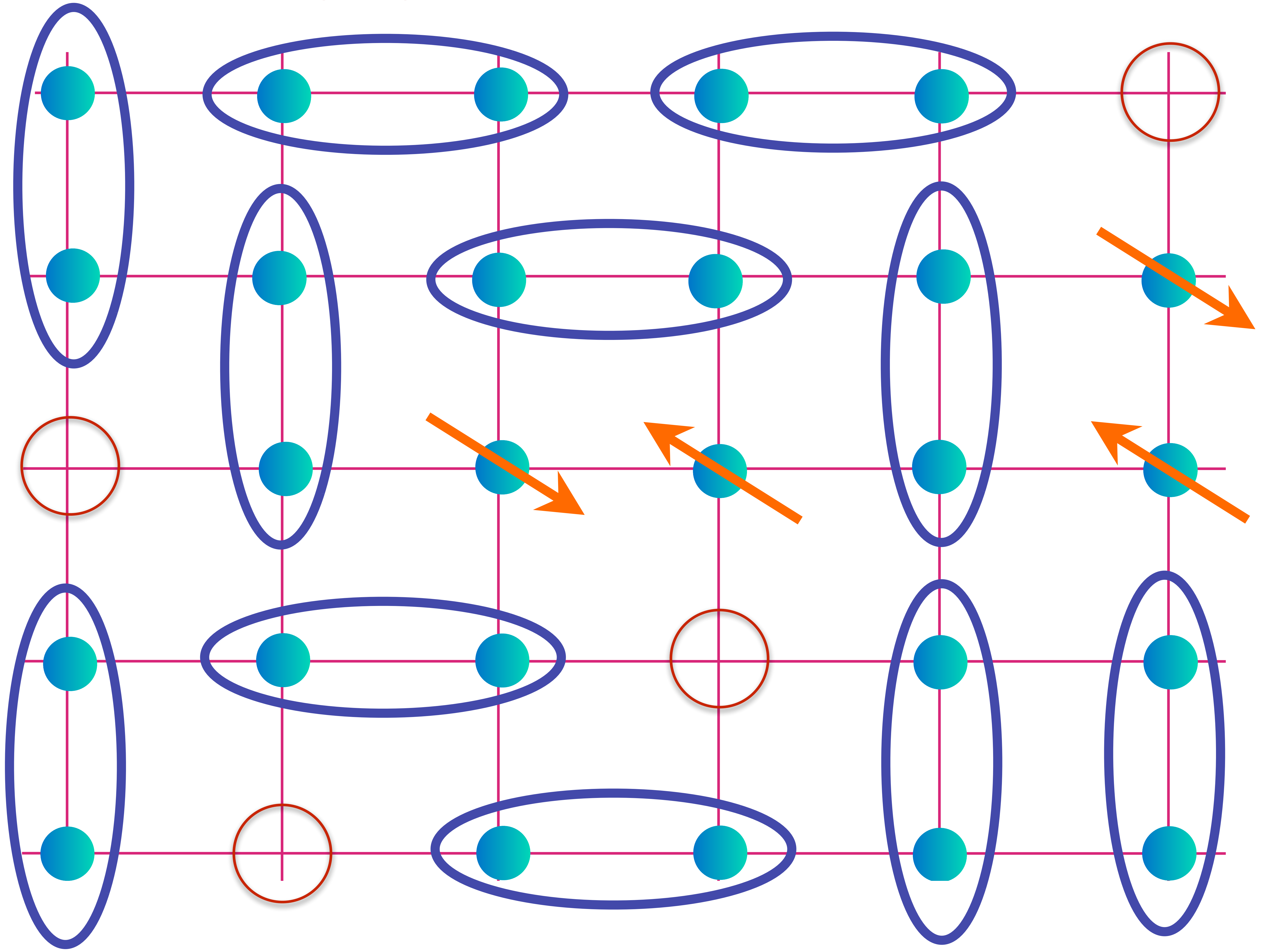

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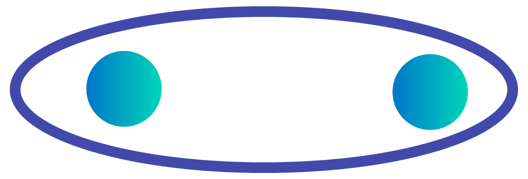

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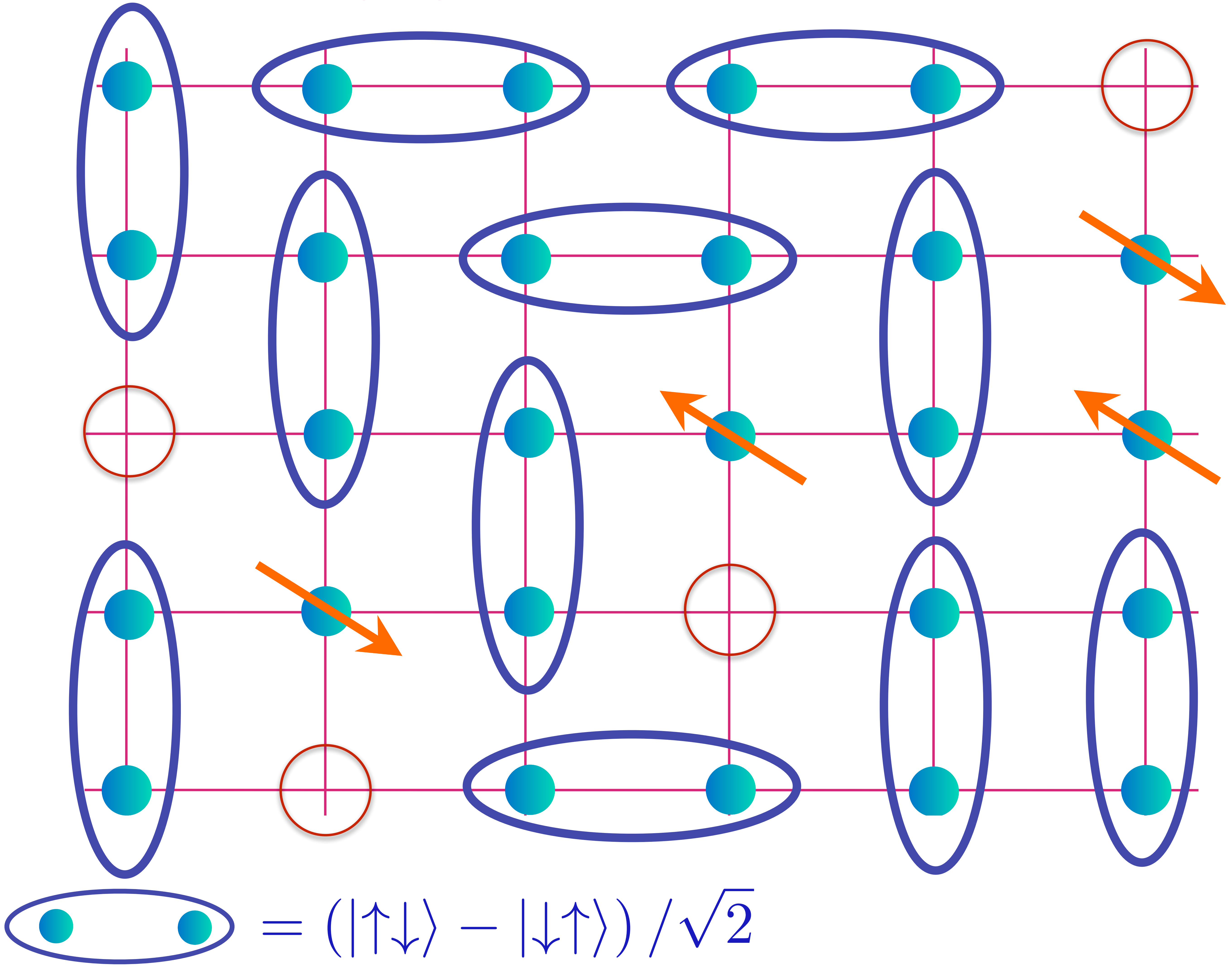

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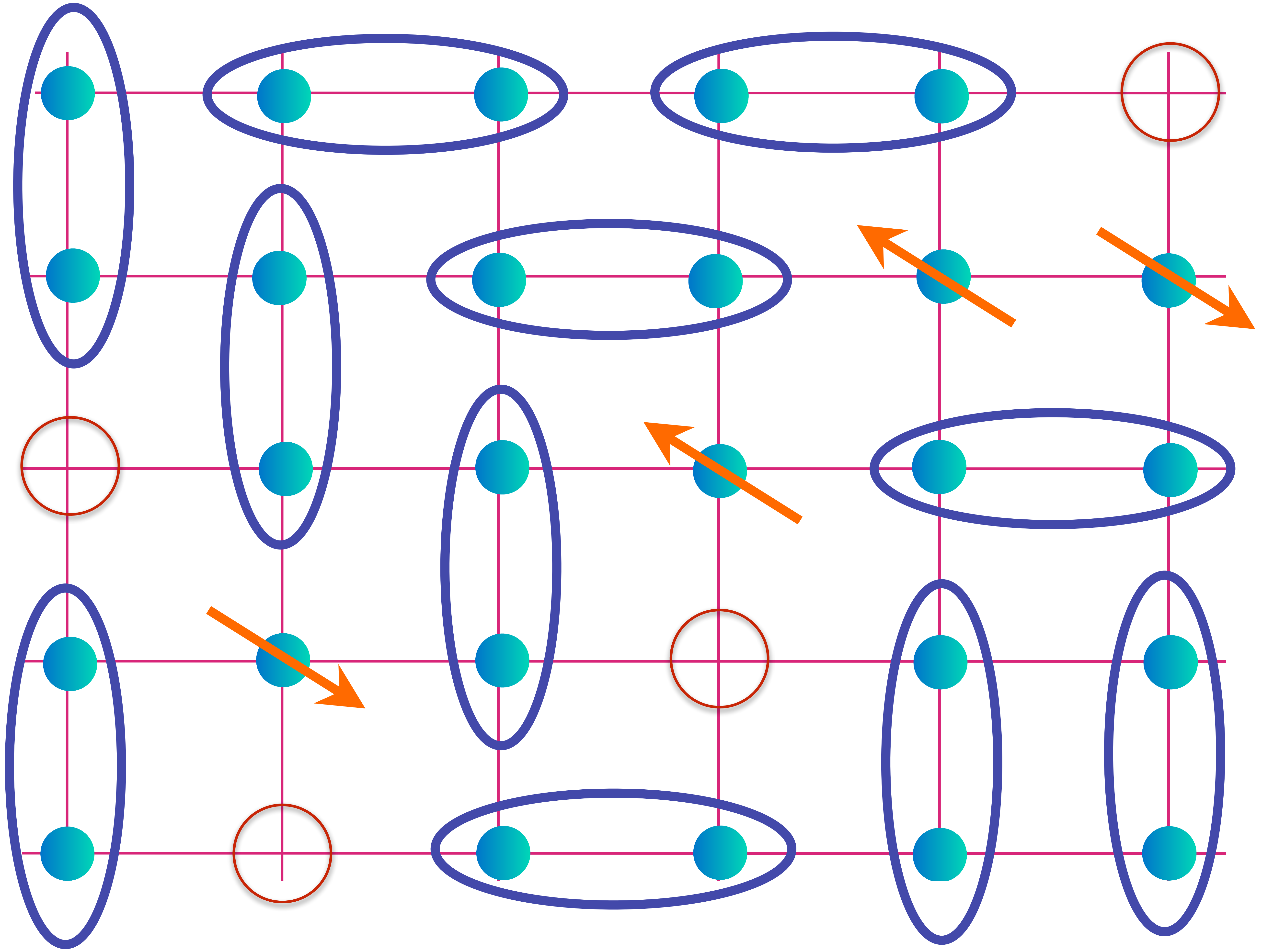

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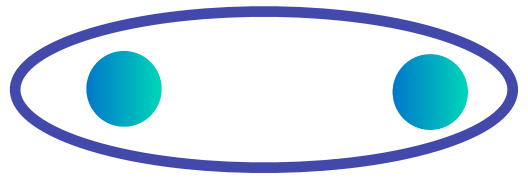 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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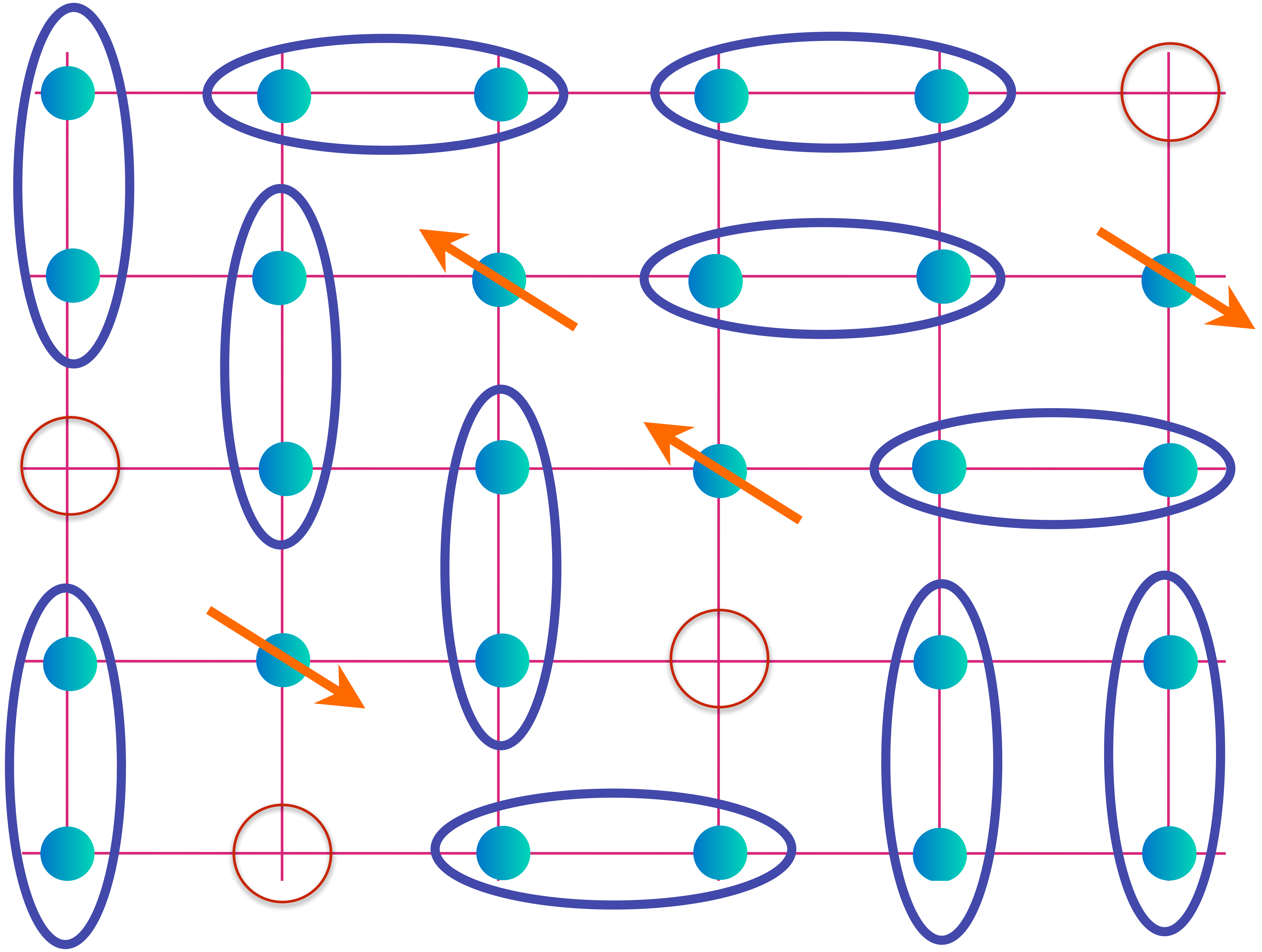

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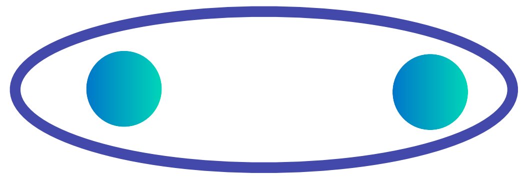

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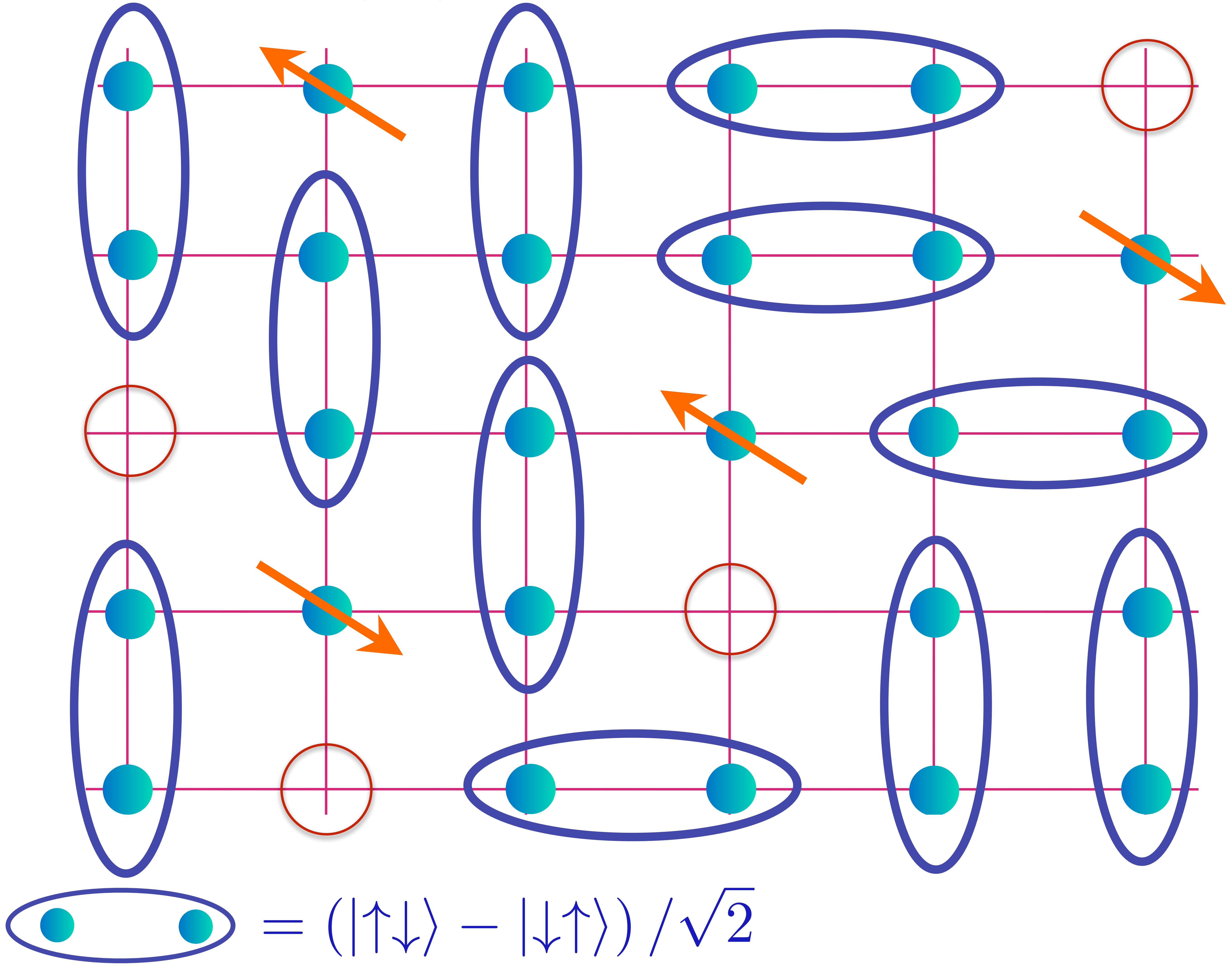
S.A. Kivelson, D.S. Rokhsar and J.P. Sethna, PRB **35**, 8865 (1987)
D. Rokhsar and S.A. Kivelson, PRL **61**, 2376 (1988)



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

Spin liquid with density p of spinless, charge +e "holons" and charge 0, spin-1/2 "spinons".

Holon metal

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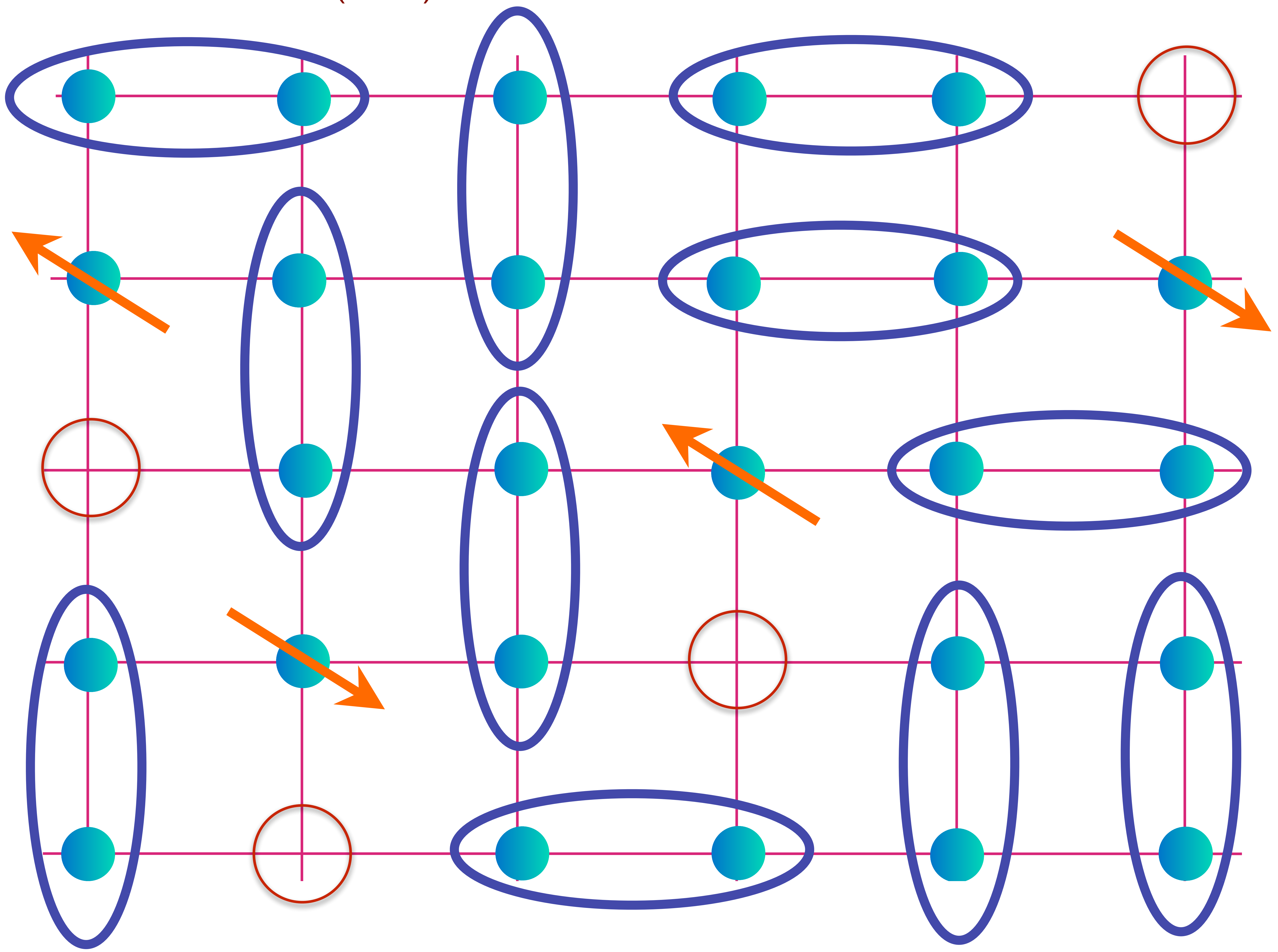

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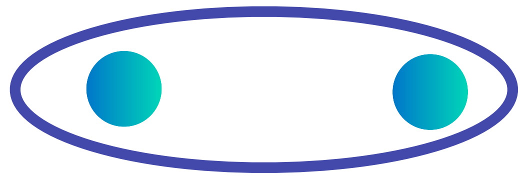 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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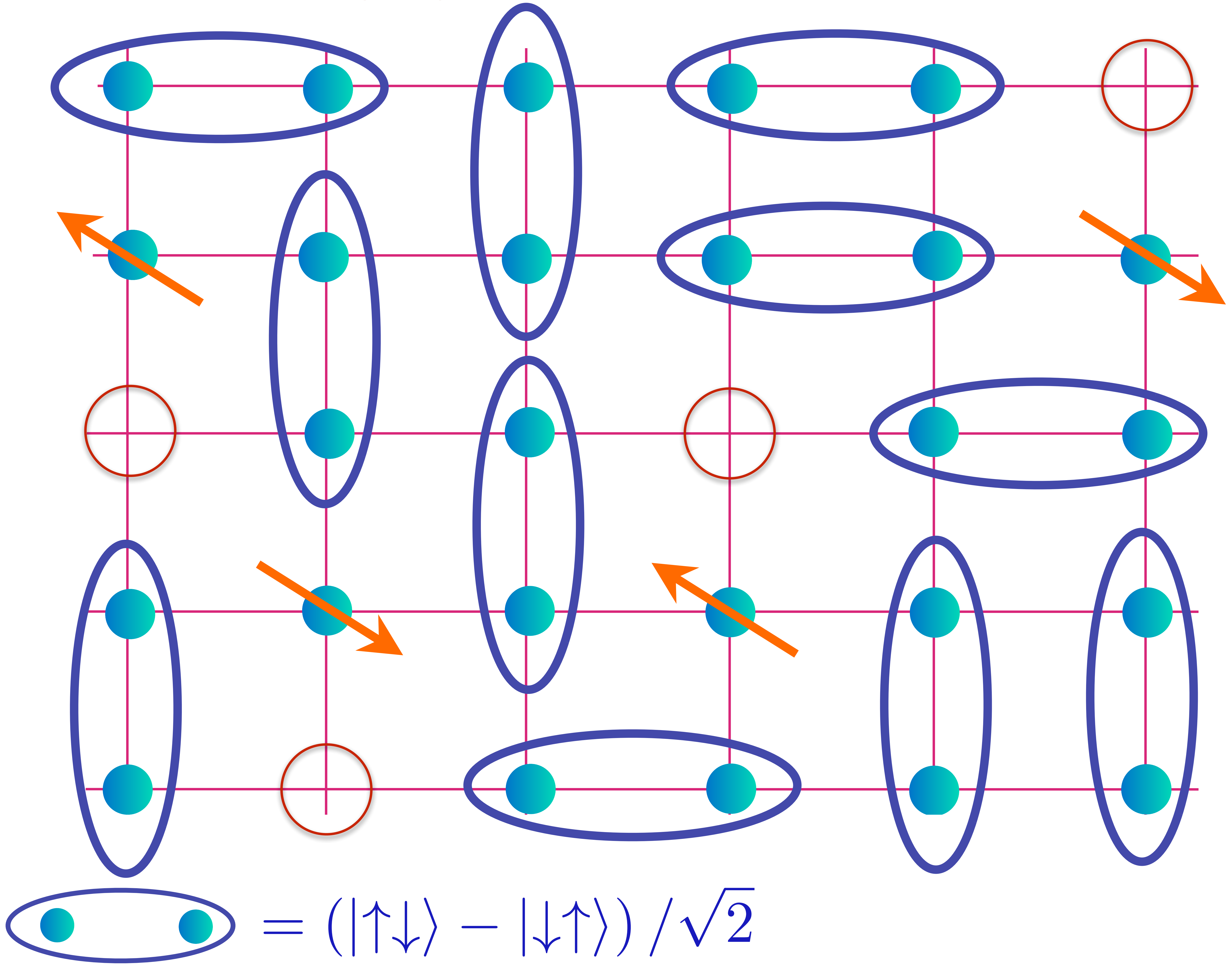

$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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Holon metal

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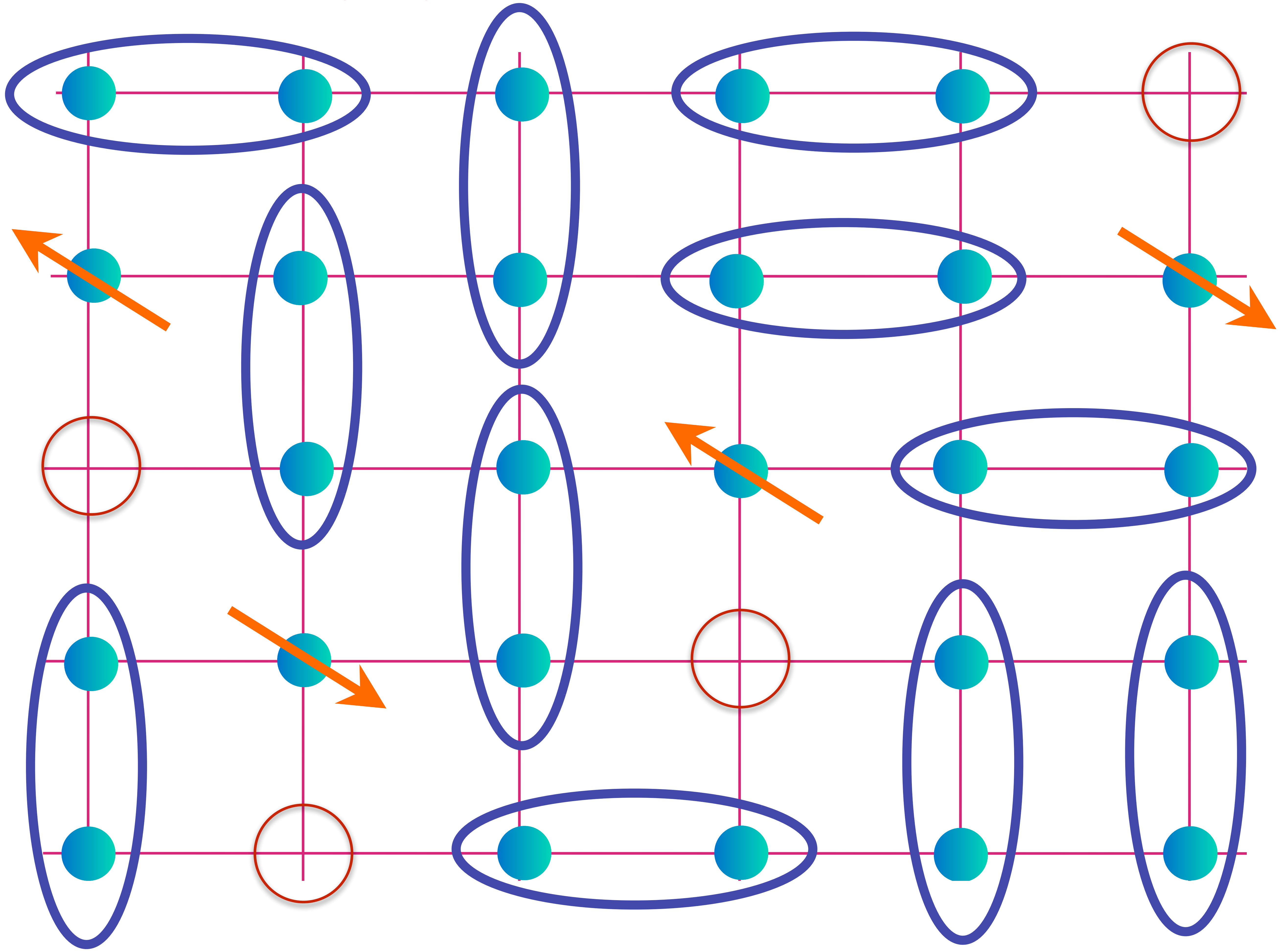
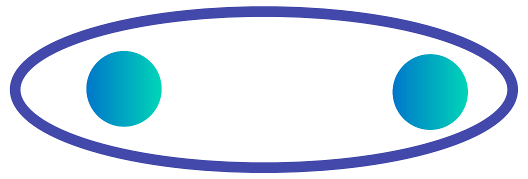


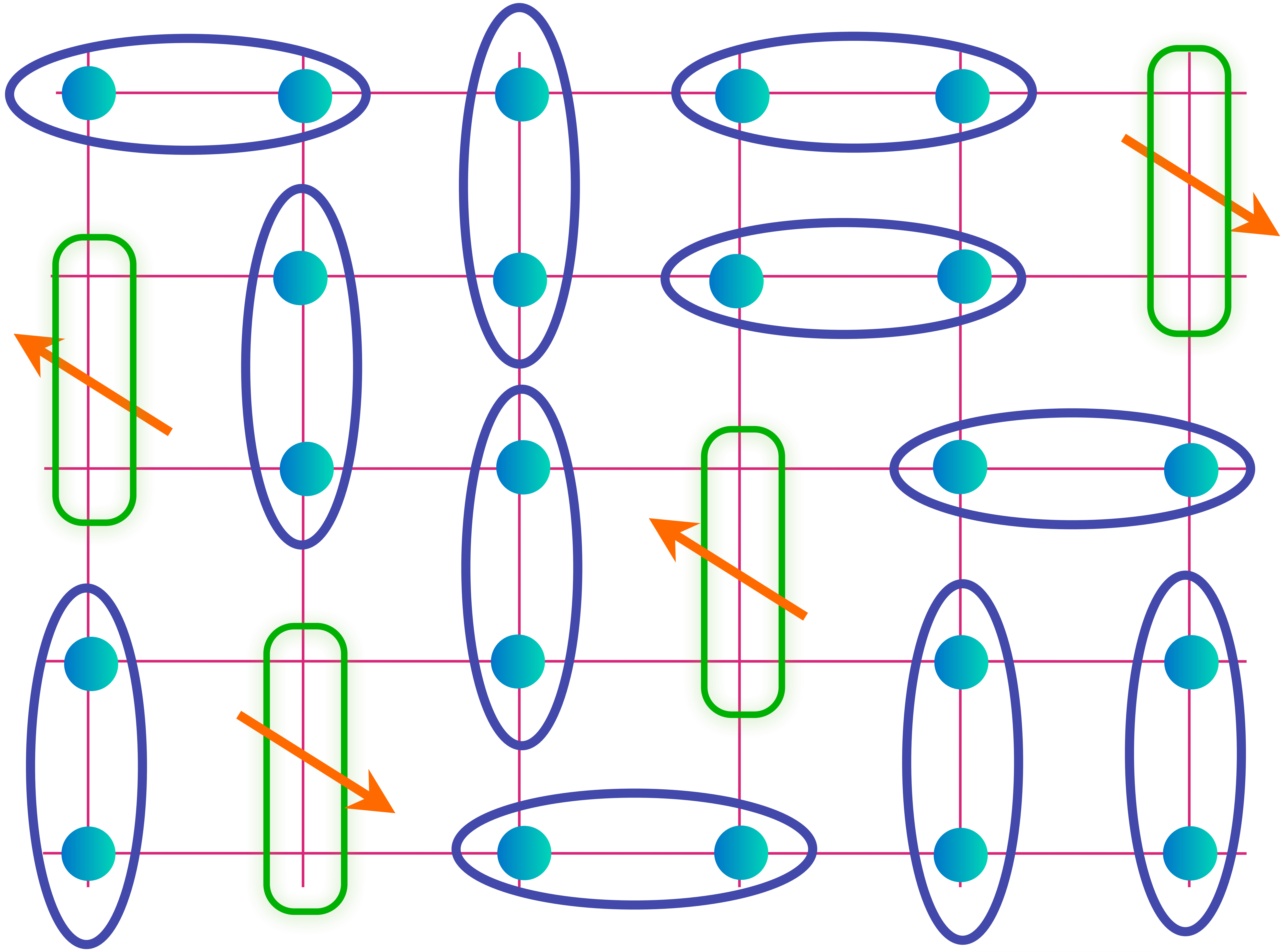
Spin liquid with density p of spinless, charge +e "holons" and charge 0, spin-1/2 "spinons".



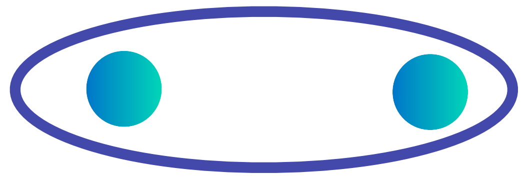
$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$$

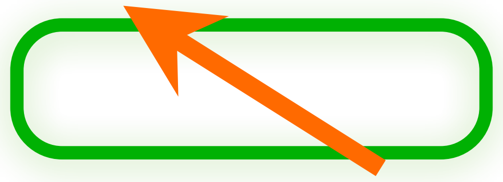
FL* in a ***one-band*** model

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



Each green "dimer" is a "bound state" of a vacancy and a free spin

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

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

E. G. Moon and S. Sachdev, PRB **83**, 224508 (2011); M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

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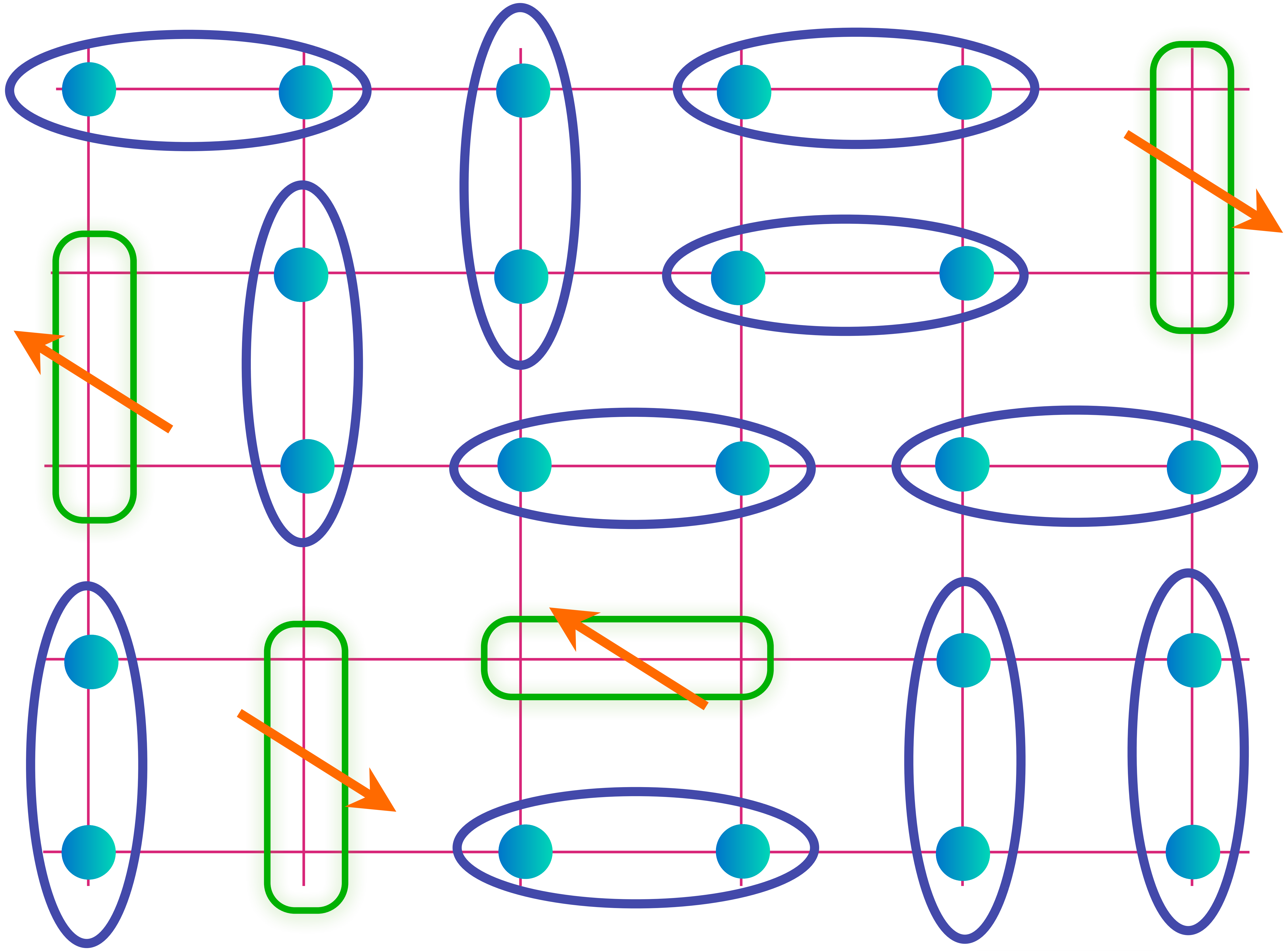
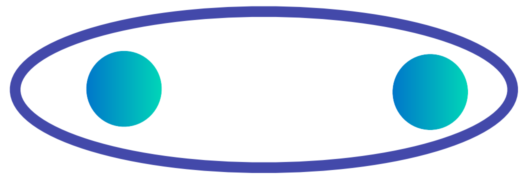
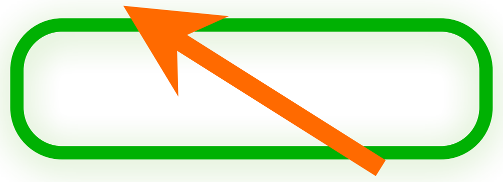


Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

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

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

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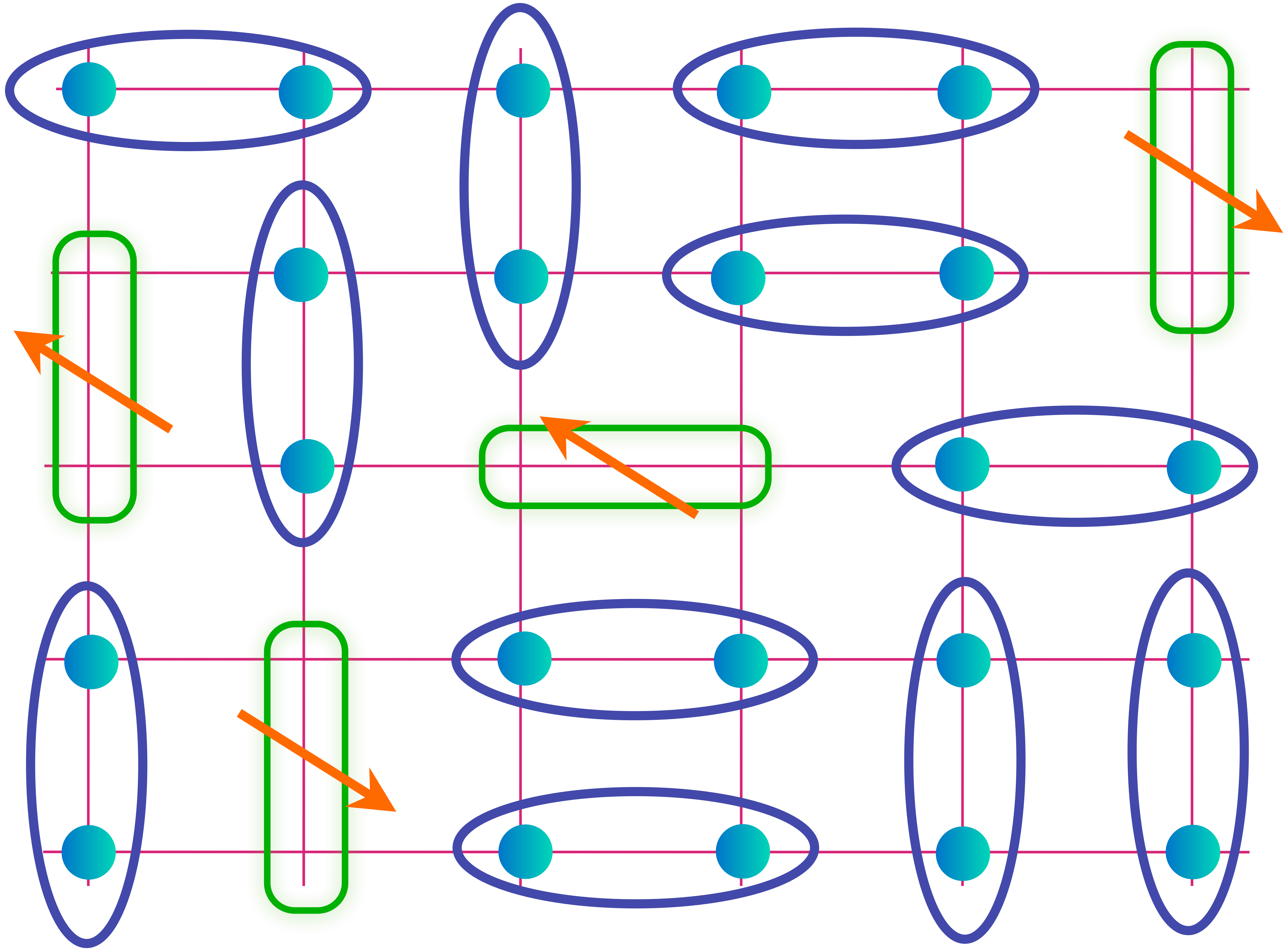
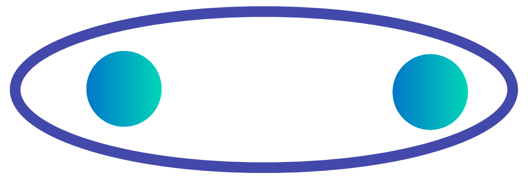
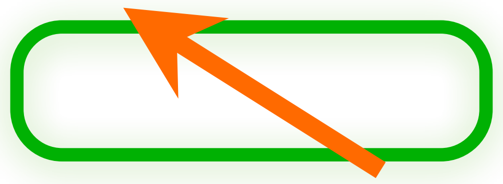


Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

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

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

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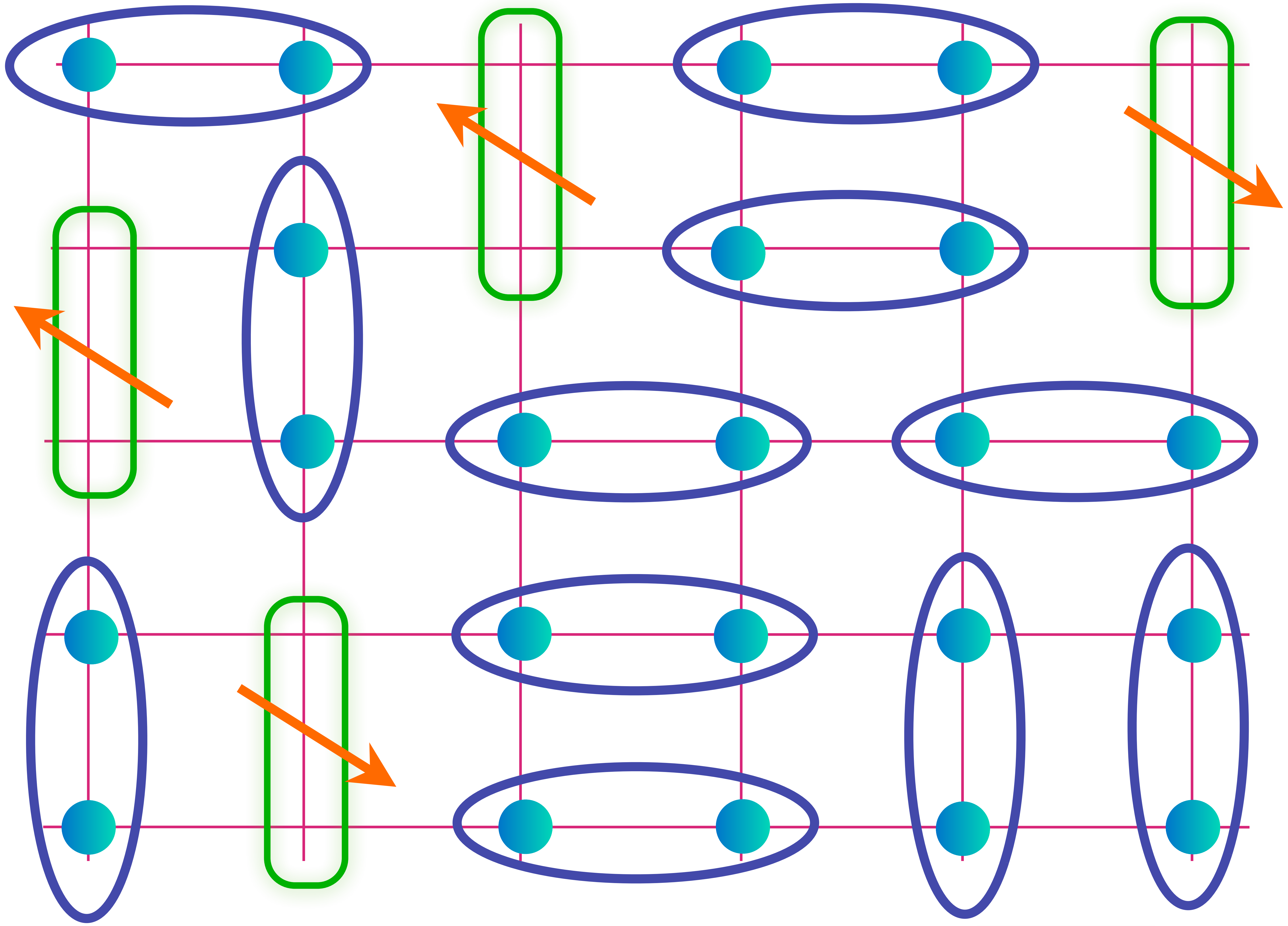
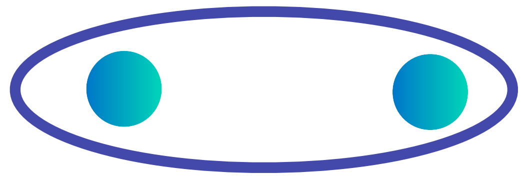
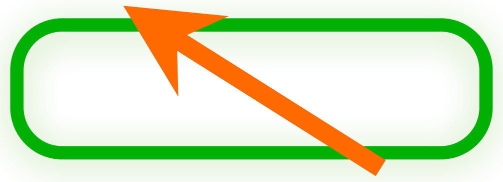


Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

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

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

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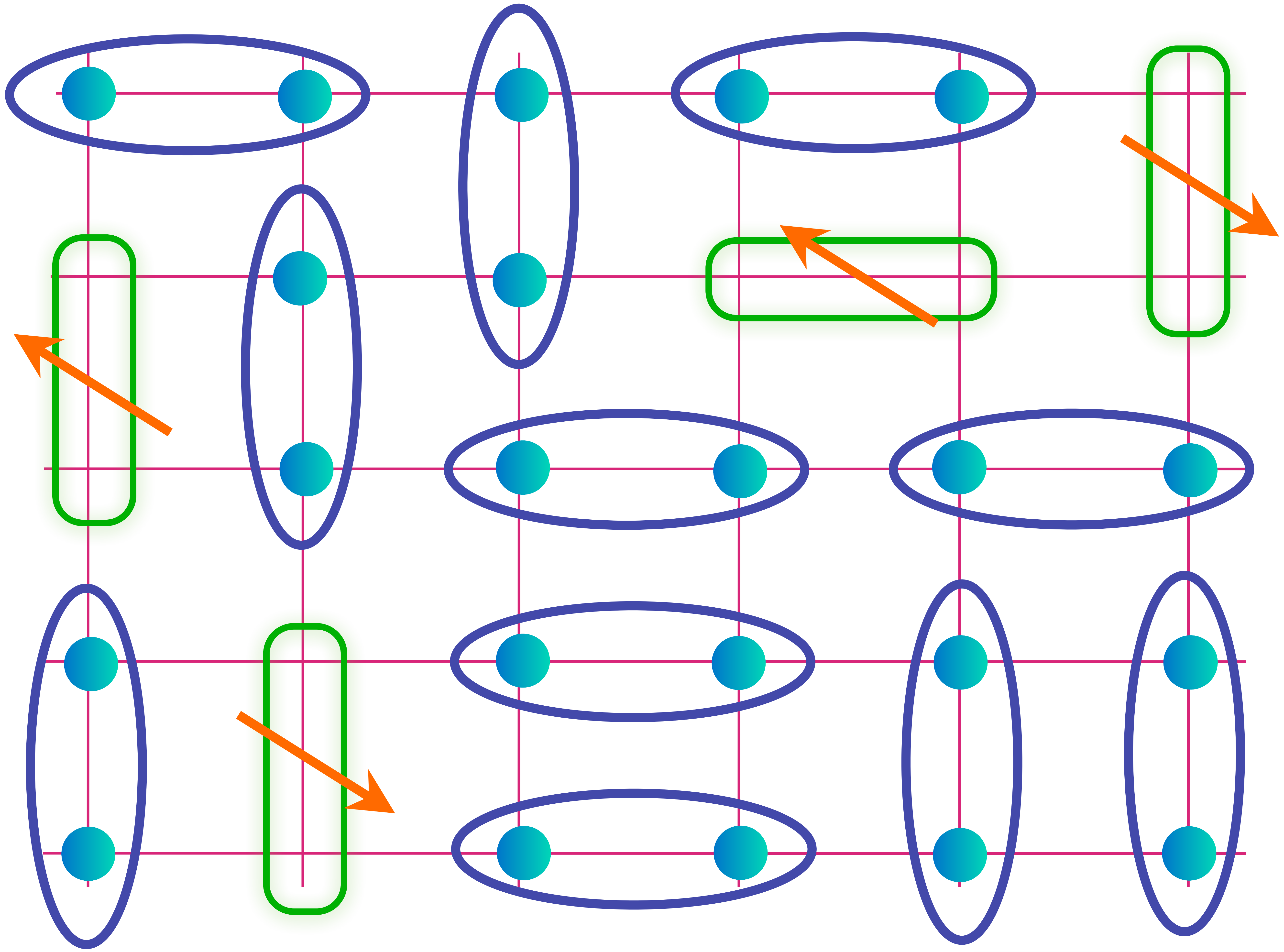

Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

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

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

E. G. Moon and S. Sachdev, PRB **83**, 224508 (2011); M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

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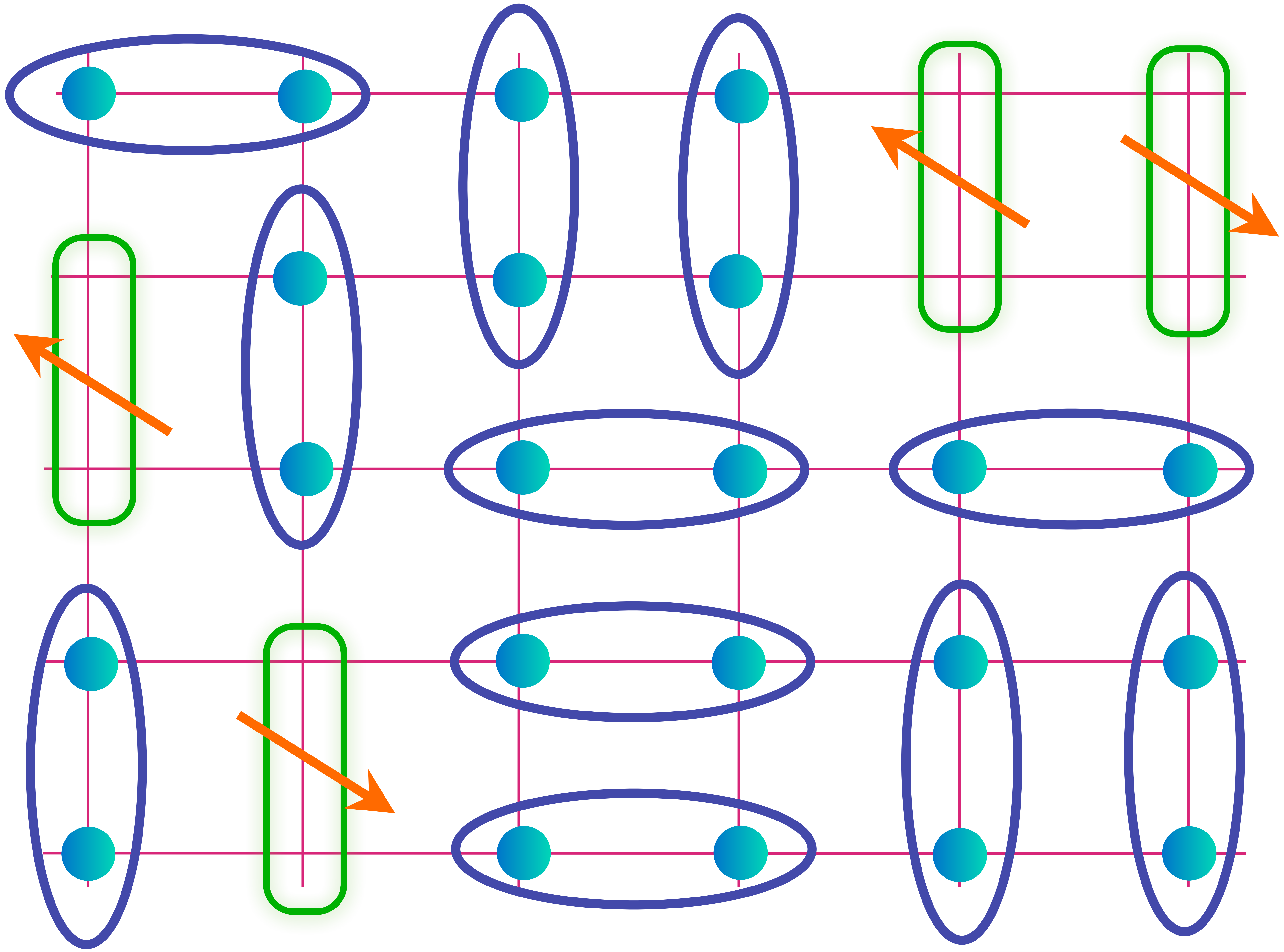
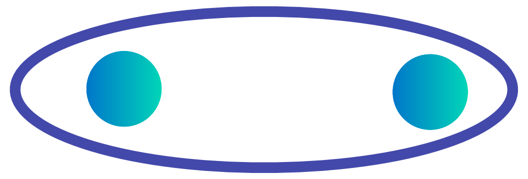
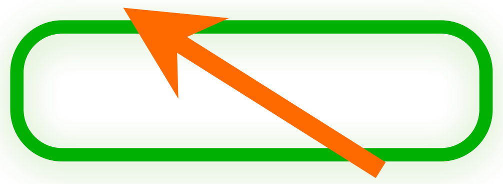


Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

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

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

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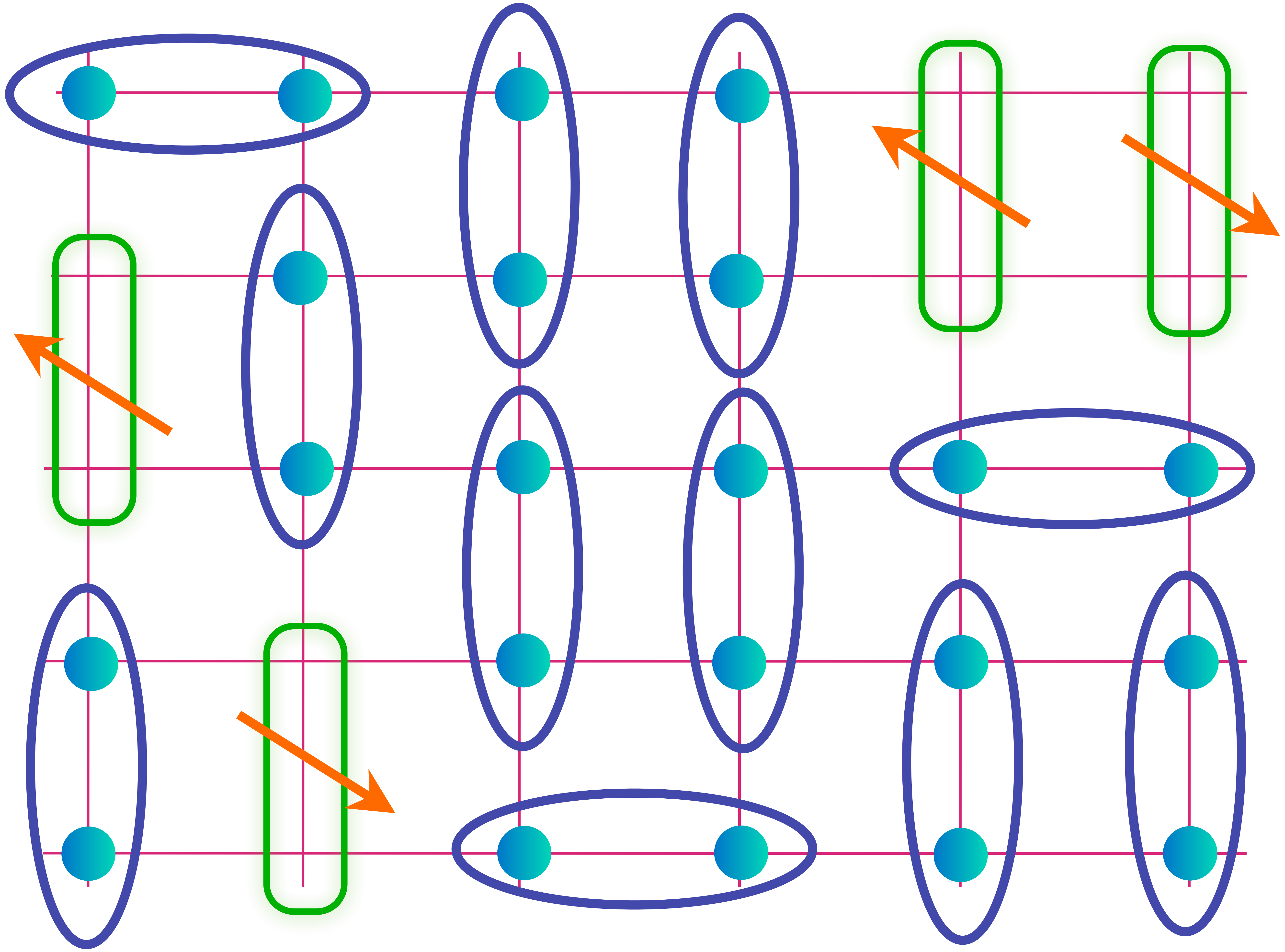

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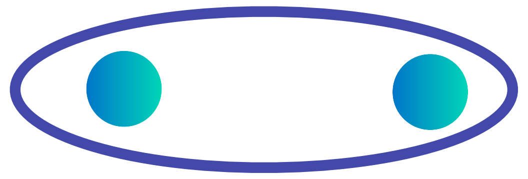
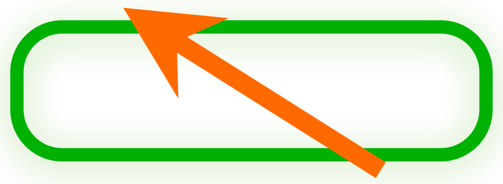
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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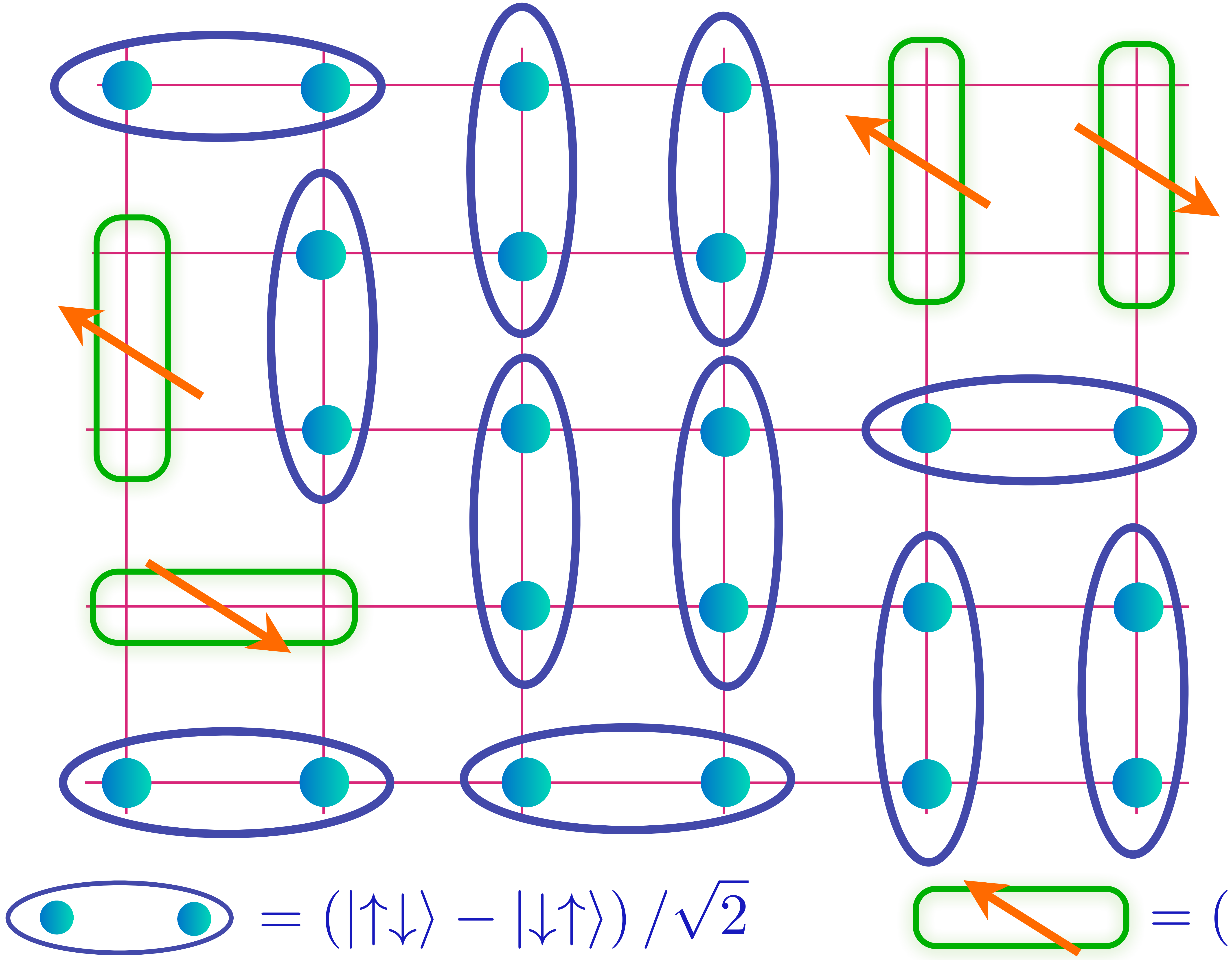
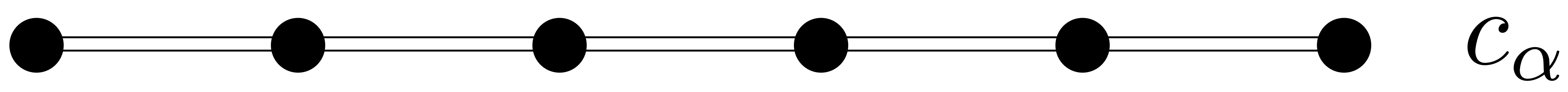


Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

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

E. G. Moon and S. Sachdev, PRB **83**, 224508 (2011); M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

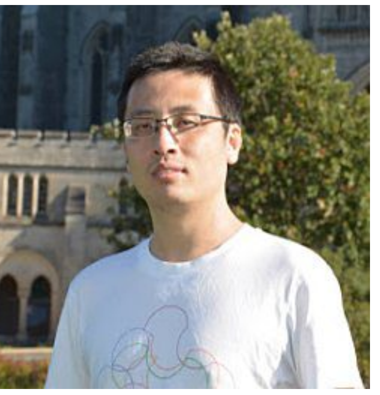
Ancilla theory of the Hubbard model



Hubbard model of hole density 1+p

Ancilla theory of the Hubbard model

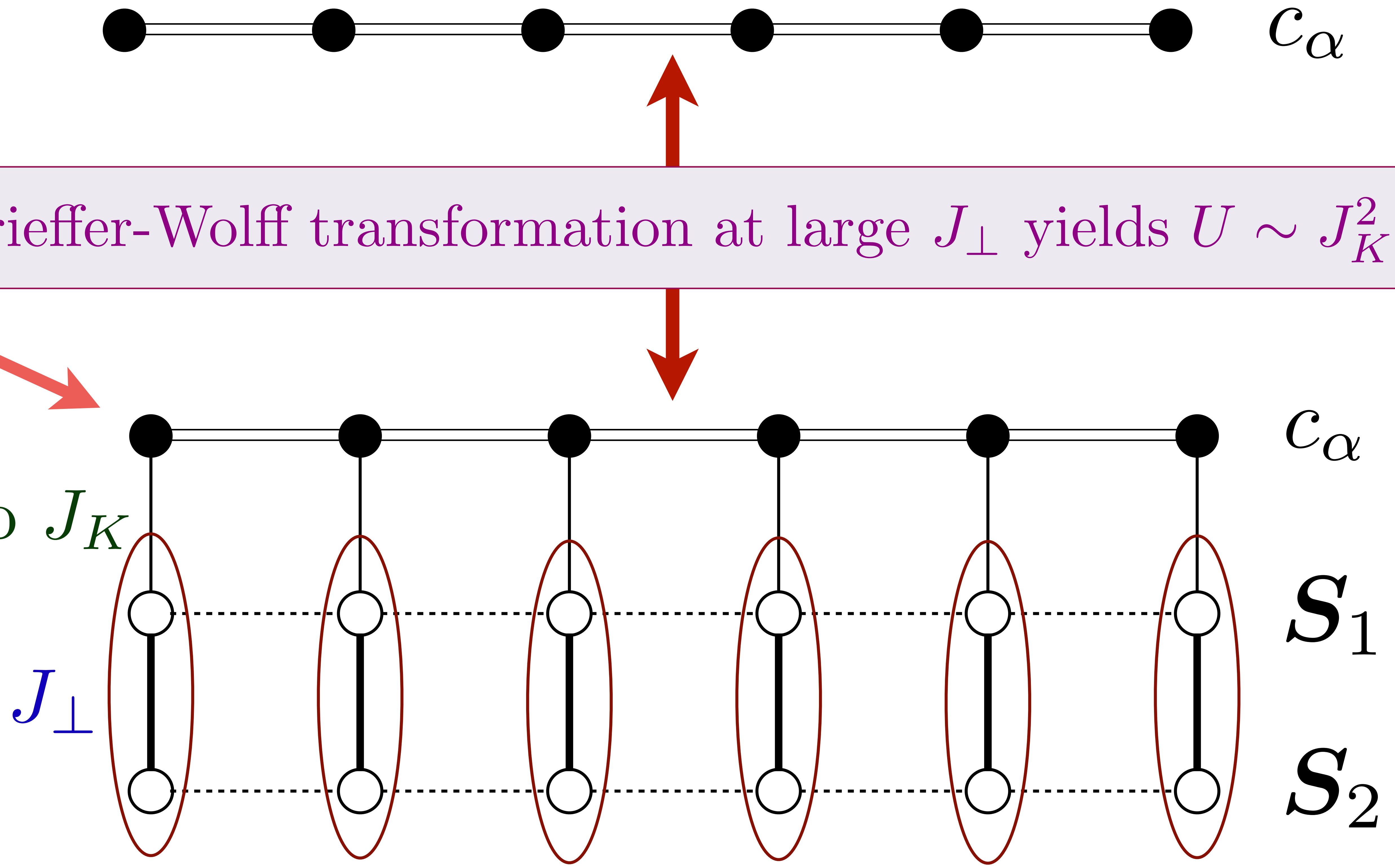
Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)



Ya-Hui Zhang

Free holes of density 1+p

Hubbard model of hole density 1+p



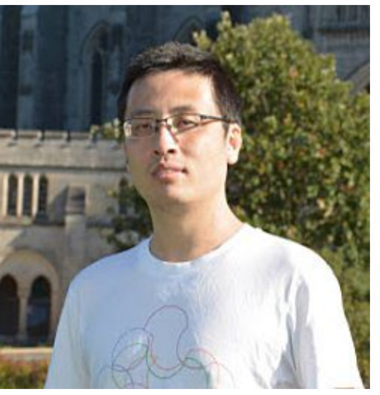
Antiferromagnetic Kondo J_K

Ancilla qubits

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

Ancilla theory of the Hubbard model

Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)



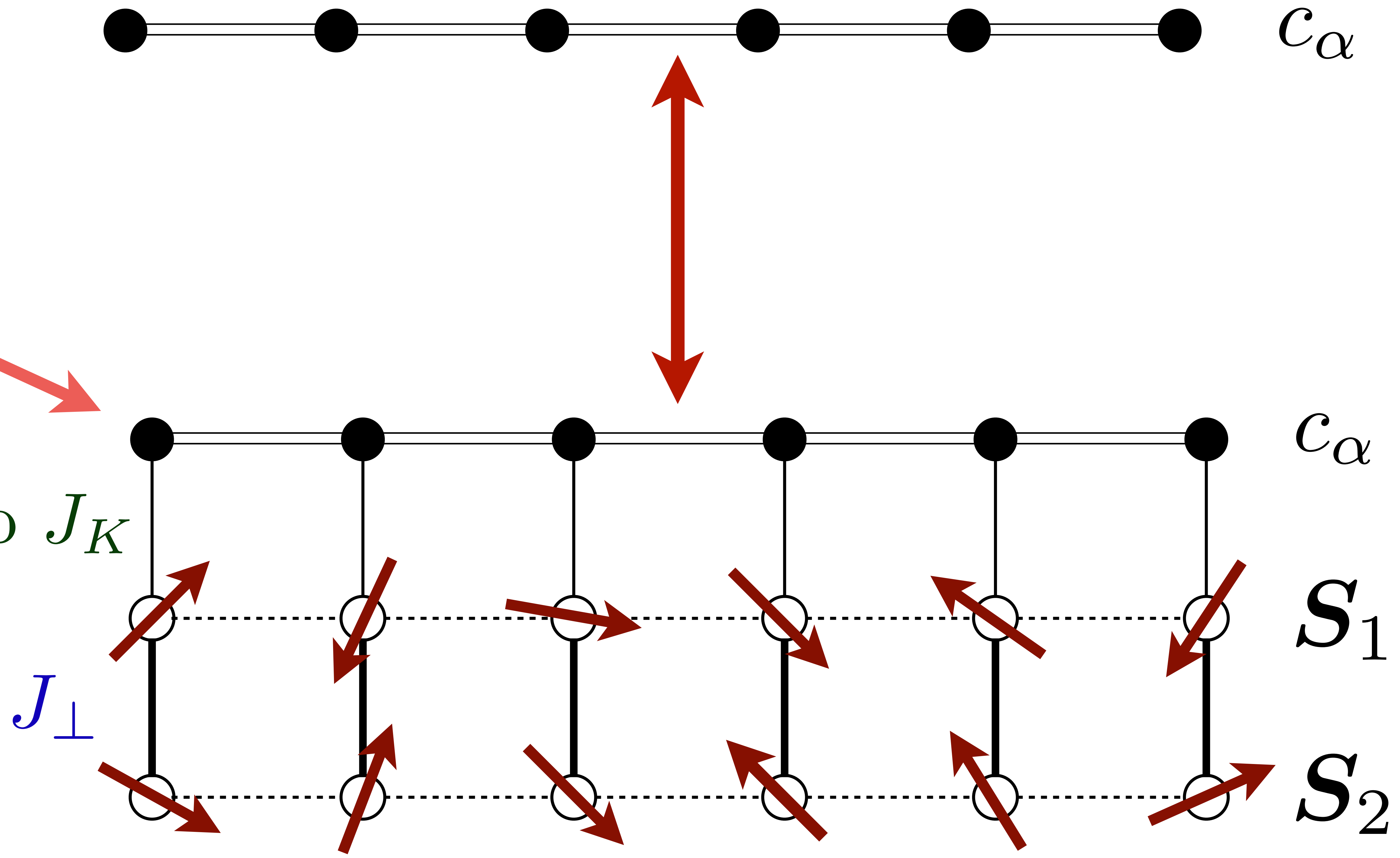
Ya-Hui Zhang

Free holes of density 1+p

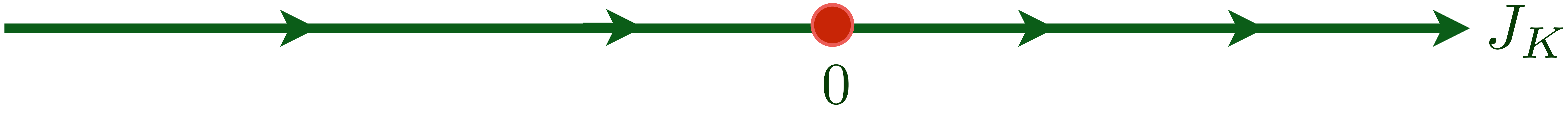
Hubbard model of hole density 1+p

Antiferromagnetic Kondo J_K

Ancilla qubits



Ferromagnetic Kondo $\widetilde{J}_K$



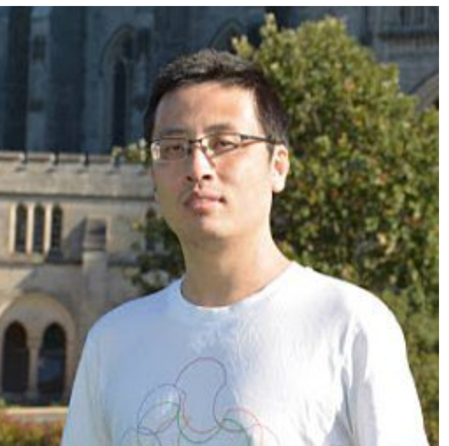
Kondo RG

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

Ancilla theory of the Hubbard model

Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)

Ya-Hui Zhang



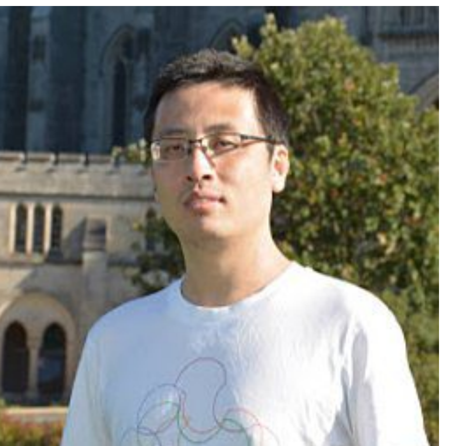
Ancilla theory of the Hubbard model

Ya-Hui Zhang and S. S., PRR **2**, 023172 (2020)

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

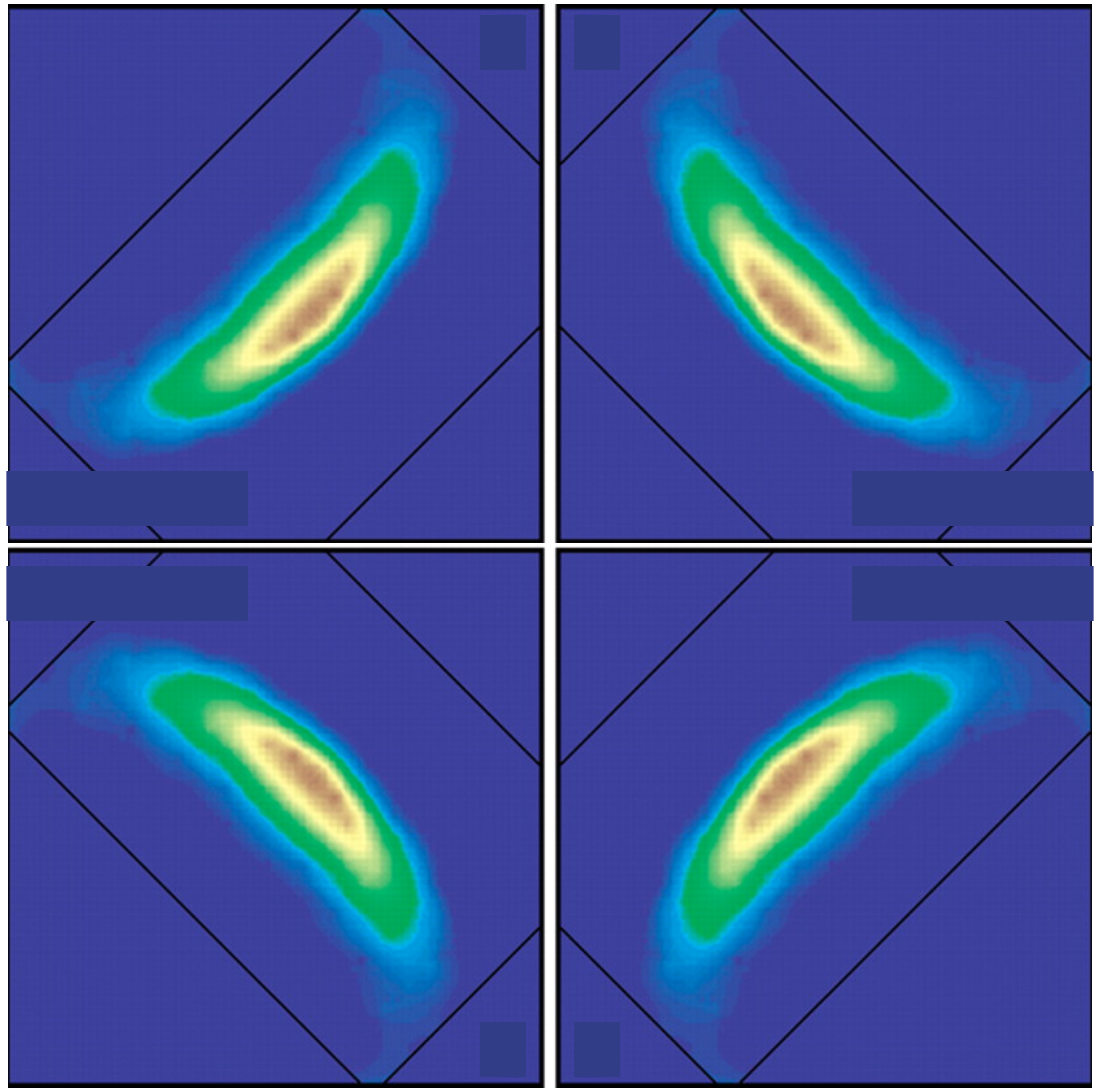
$\langle c_\alpha^\dagger f_{1\alpha} \rangle \neq 0$

Ya-Hui Zhang

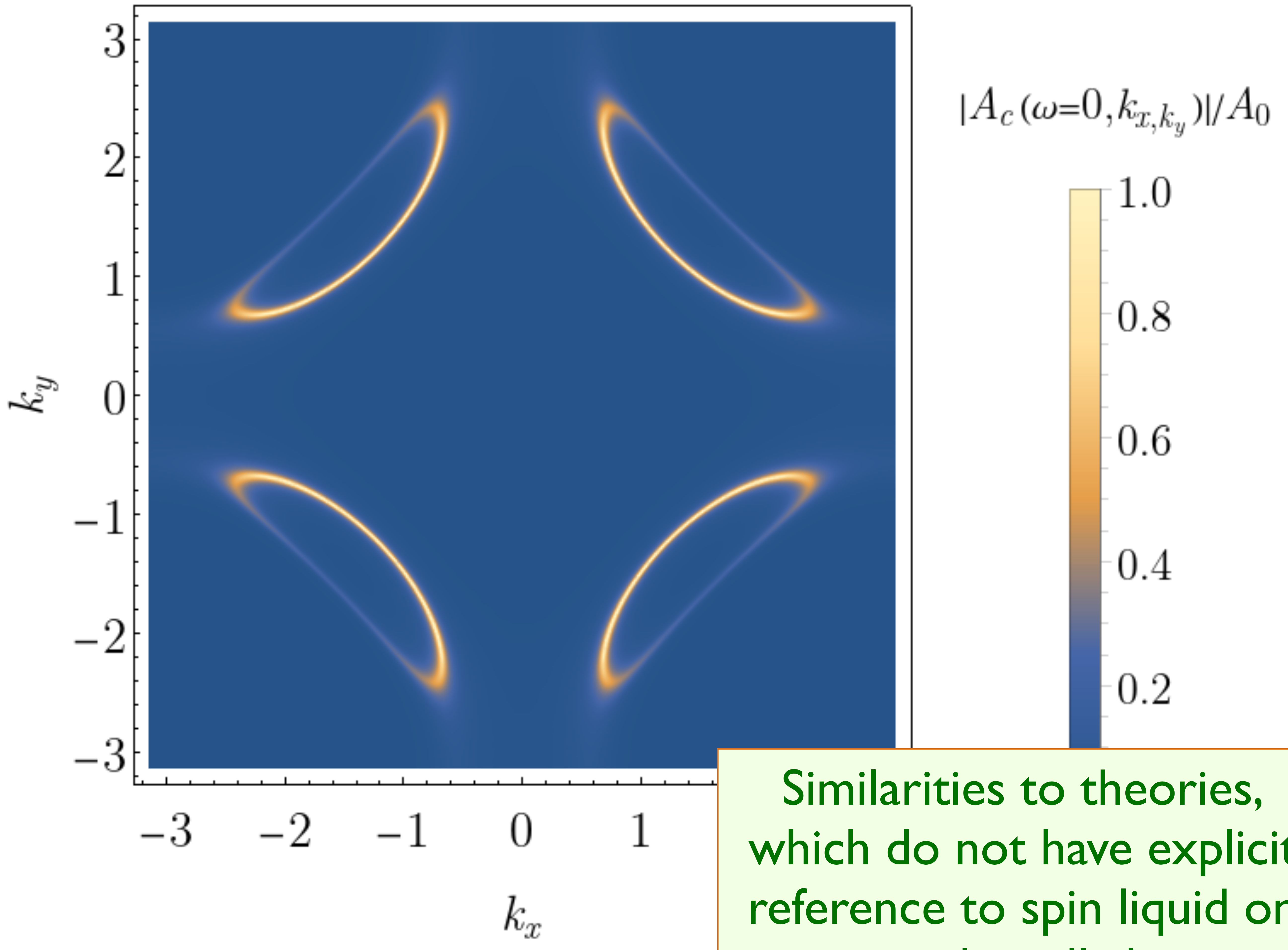


Photoemission at small p

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



$Ca_{2-x}Na_xCuO_2Cl_2$
at $x = 0.10$



"Fermi arcs"

Similarities to theories, which do not have explicit reference to spin liquid on second ancilla layer

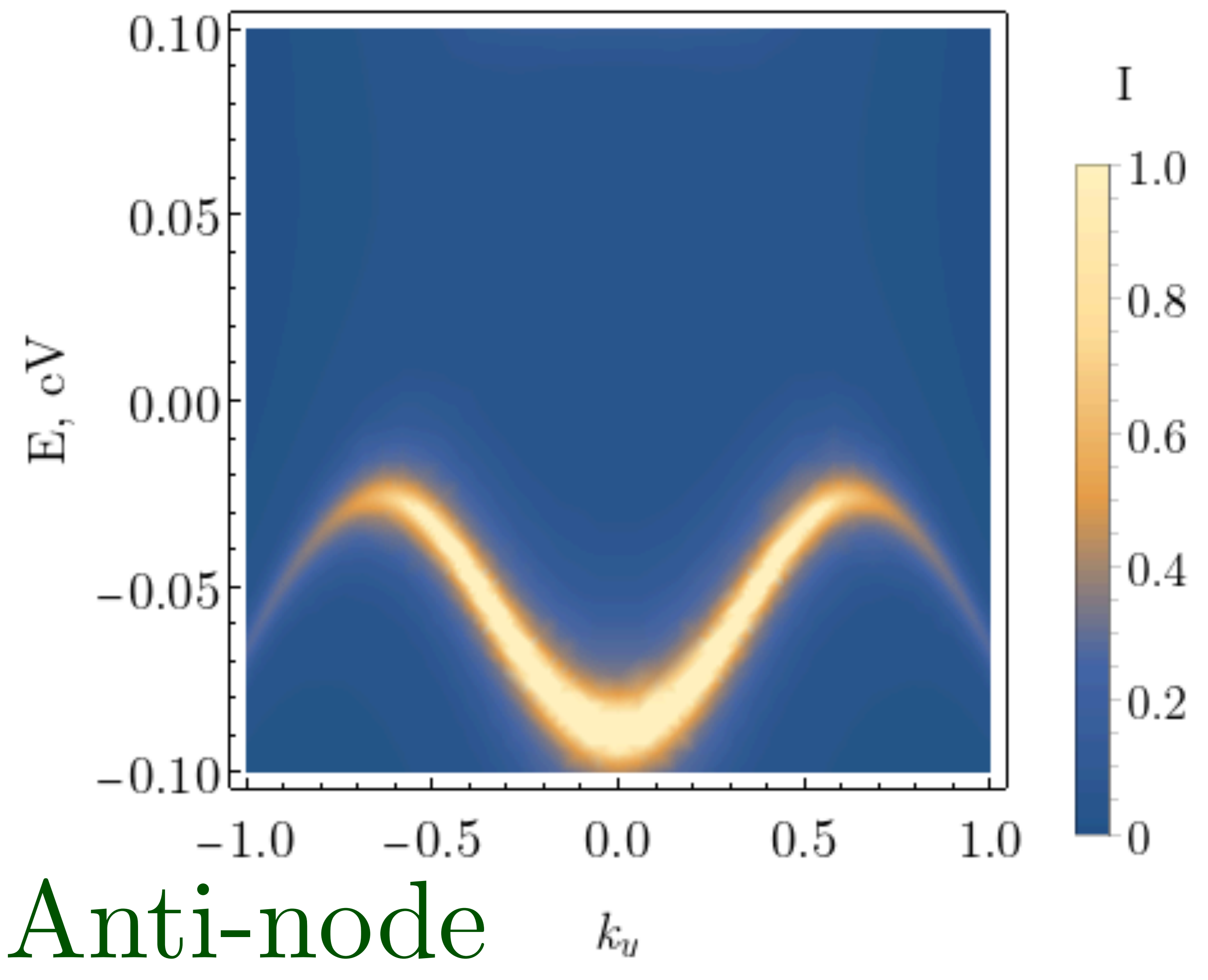
Kai-Yu Yang, T. M. Rice, Fu-Chun Zhang, PRB **73**, 174501 (2006)
S. Sakai, Y. Motome, M. Imada, PRL **102**, 056404 (2009)

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)

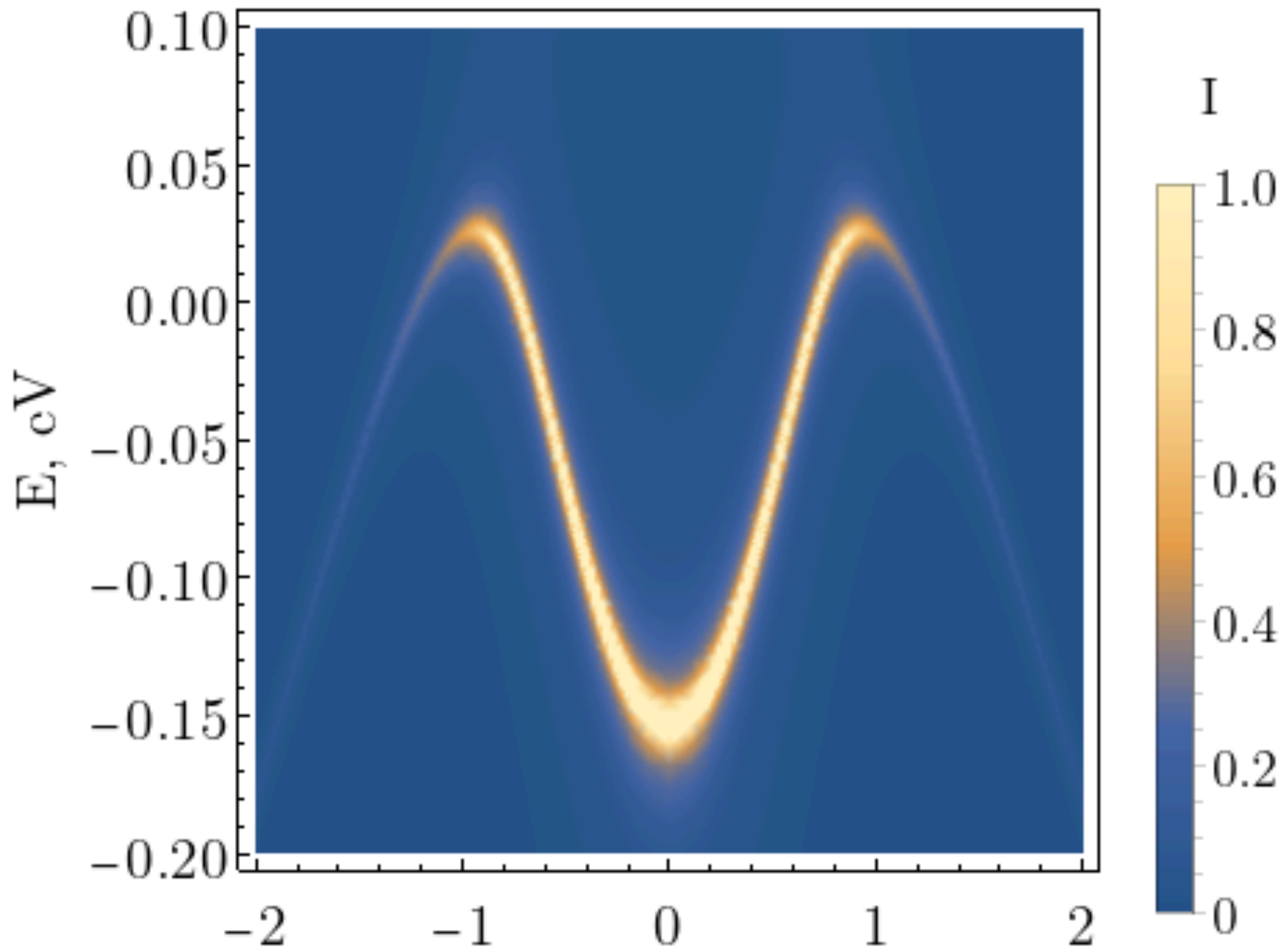
E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, and S. S., PRB **105**, 075146 (2022)

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

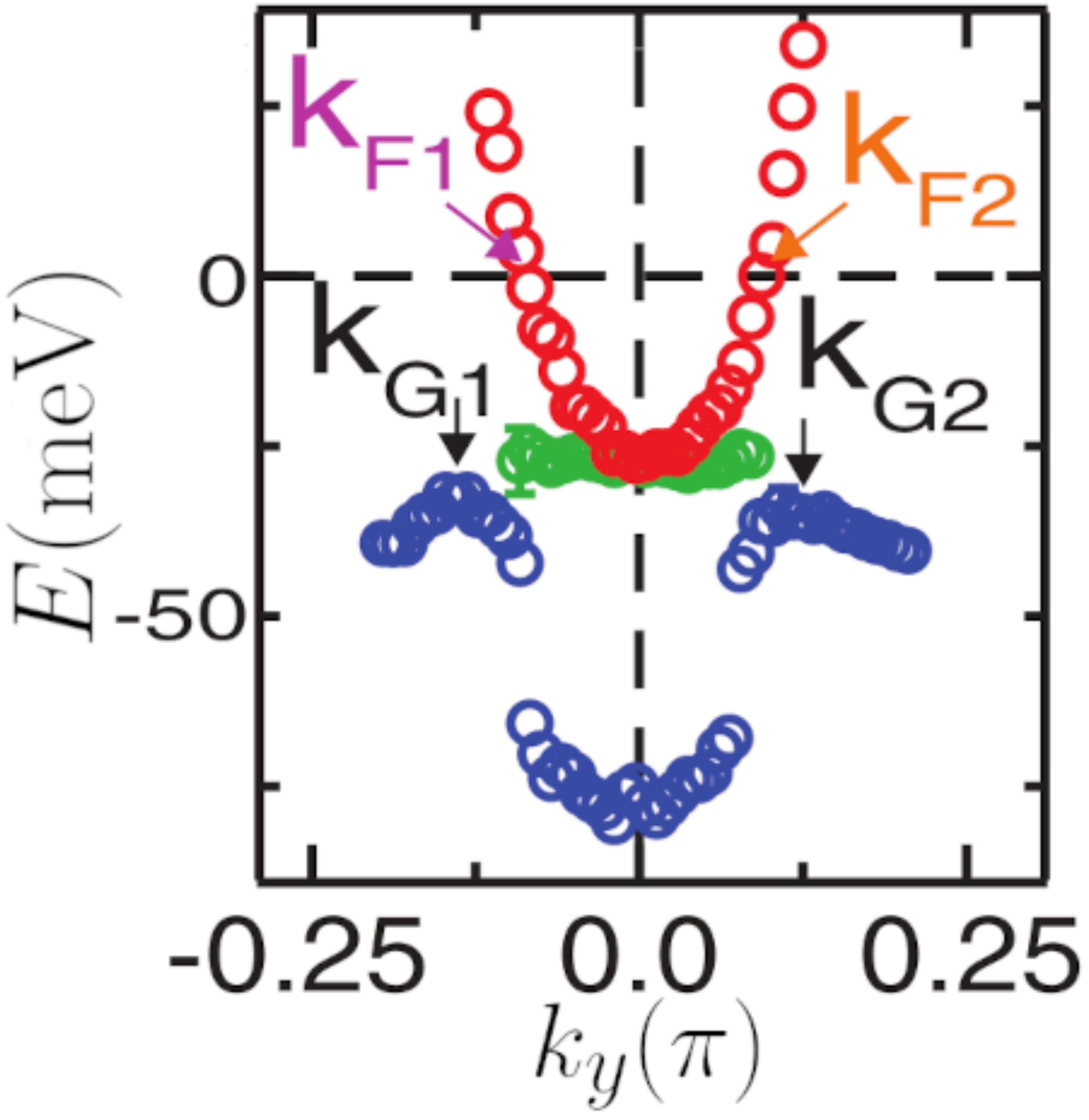
Second ancilla layer is needed to describe MDC and EDC

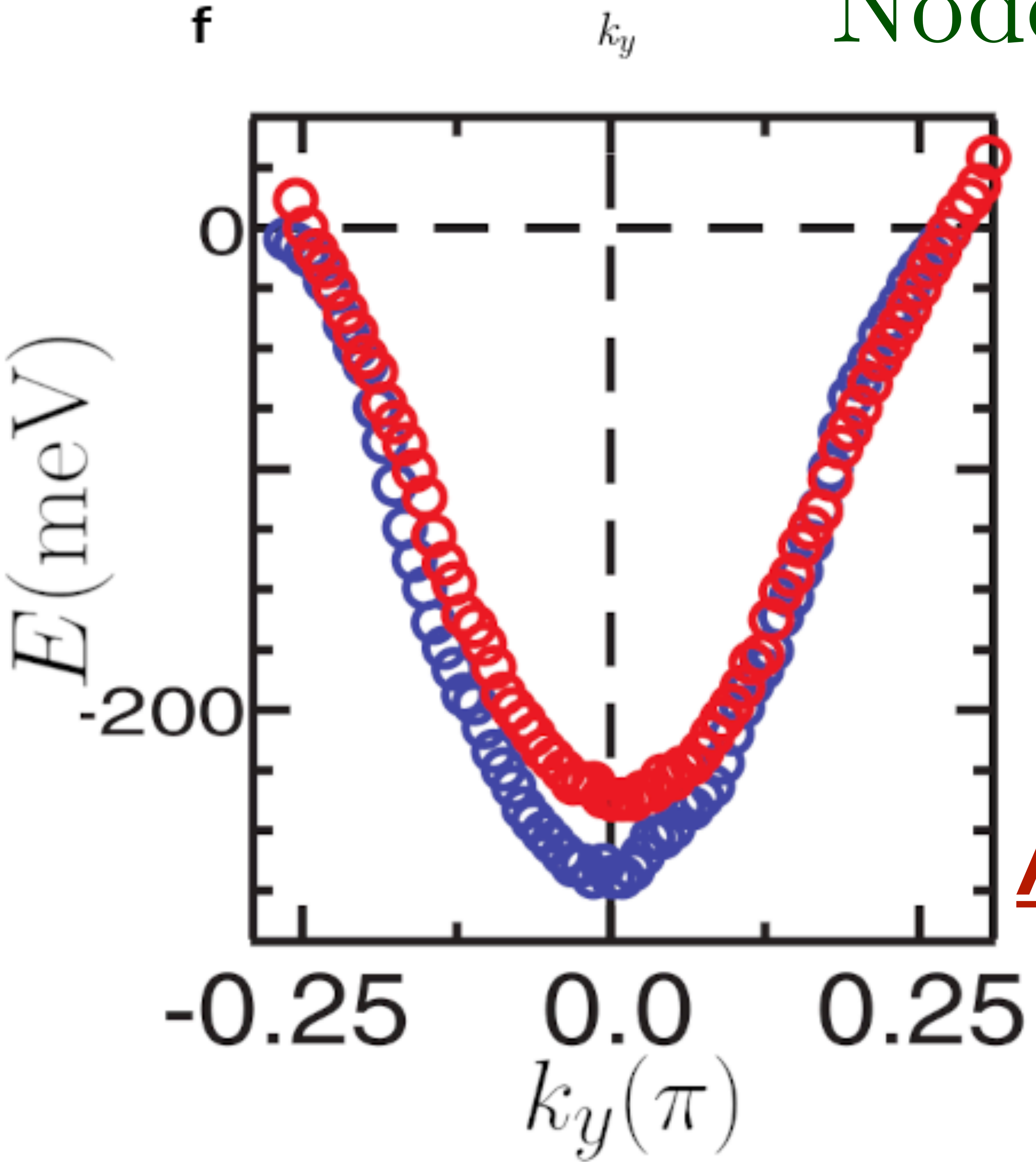


Anti-node



Node





R.-H. He, M. Hashimoto, H. Karapetyan, J. D. Koralek, J. P. Hinton, J. P. Testaud, V. Nathan, Y. Yoshida, H. Yao, K. Tanaka, W. Meevasana, R. G. Moore, D. H. Lu, S. K. Mo, M. Ishikado, H. Eisaki, Z. Hussain, T. P. Devereaux, S. A. Kivelson, J. Orenstein, A. Kapitulnik, and Z.-X. Shen, *Science* **331**, 1579 (2011)

ARPES on Bi2201

Similarities to theories, which do not have explicit reference to spin liquid on second ancilla layer

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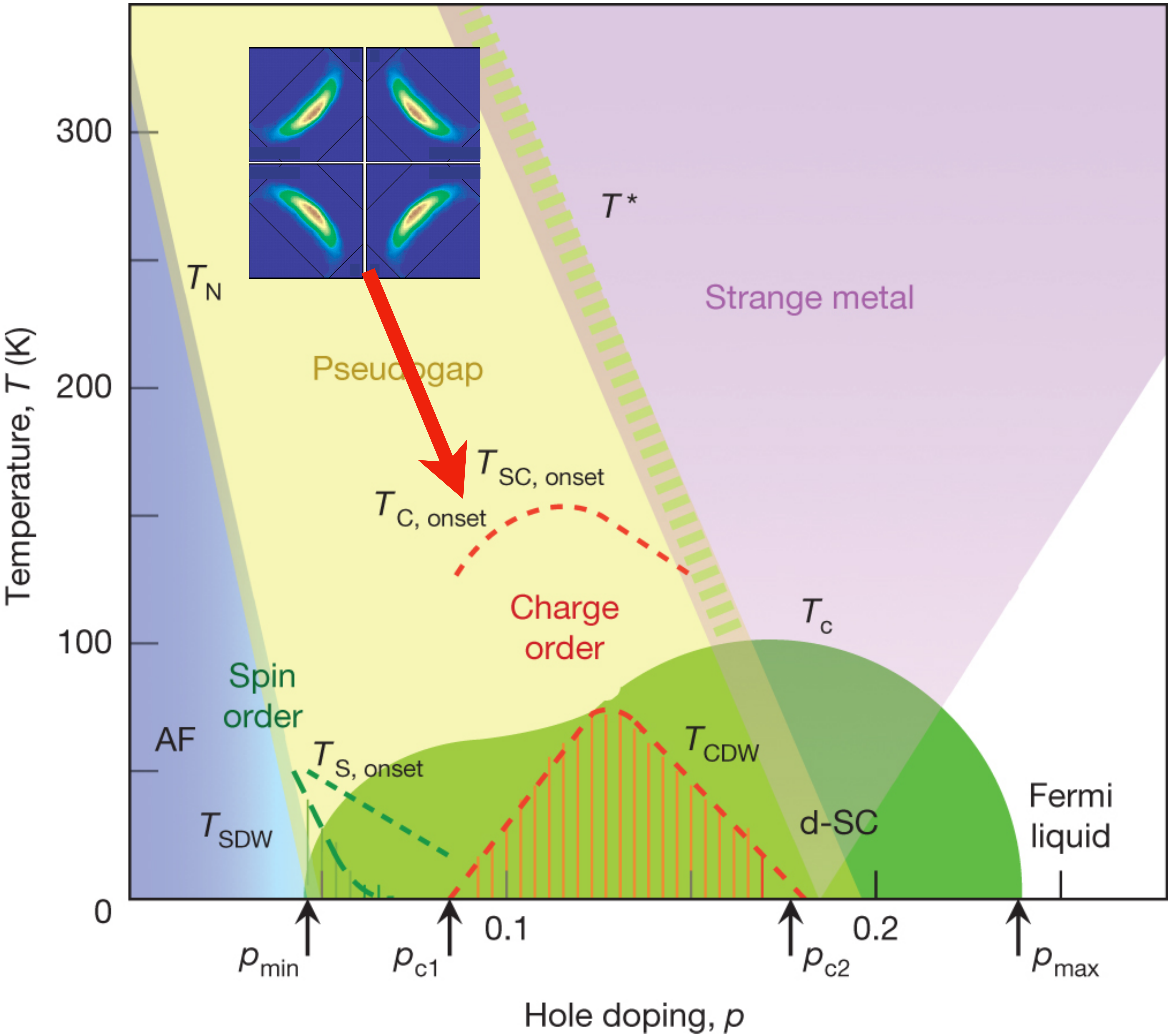
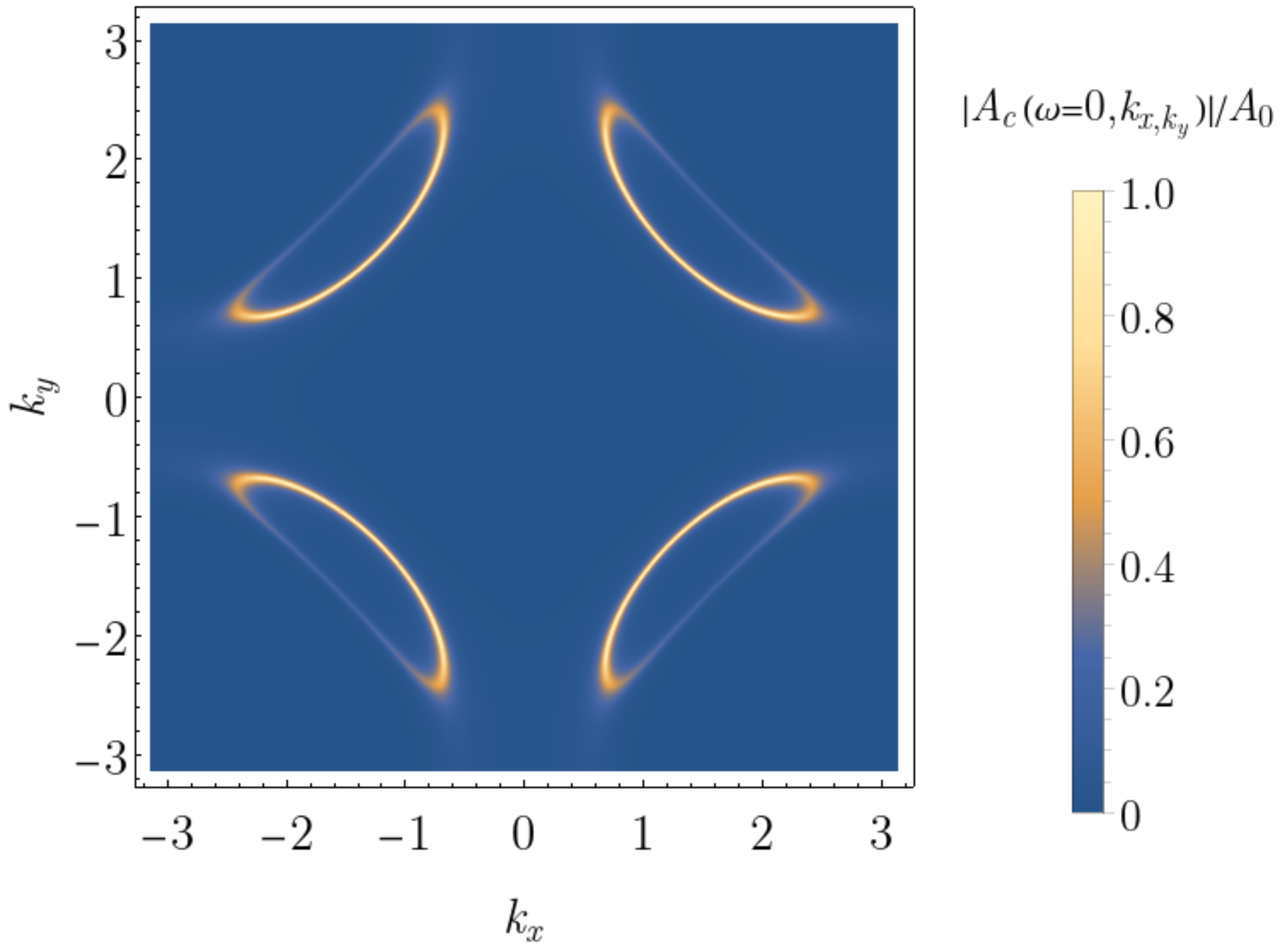
B Keimer *et al.* *Nature* **518**, 179-186 (2015)





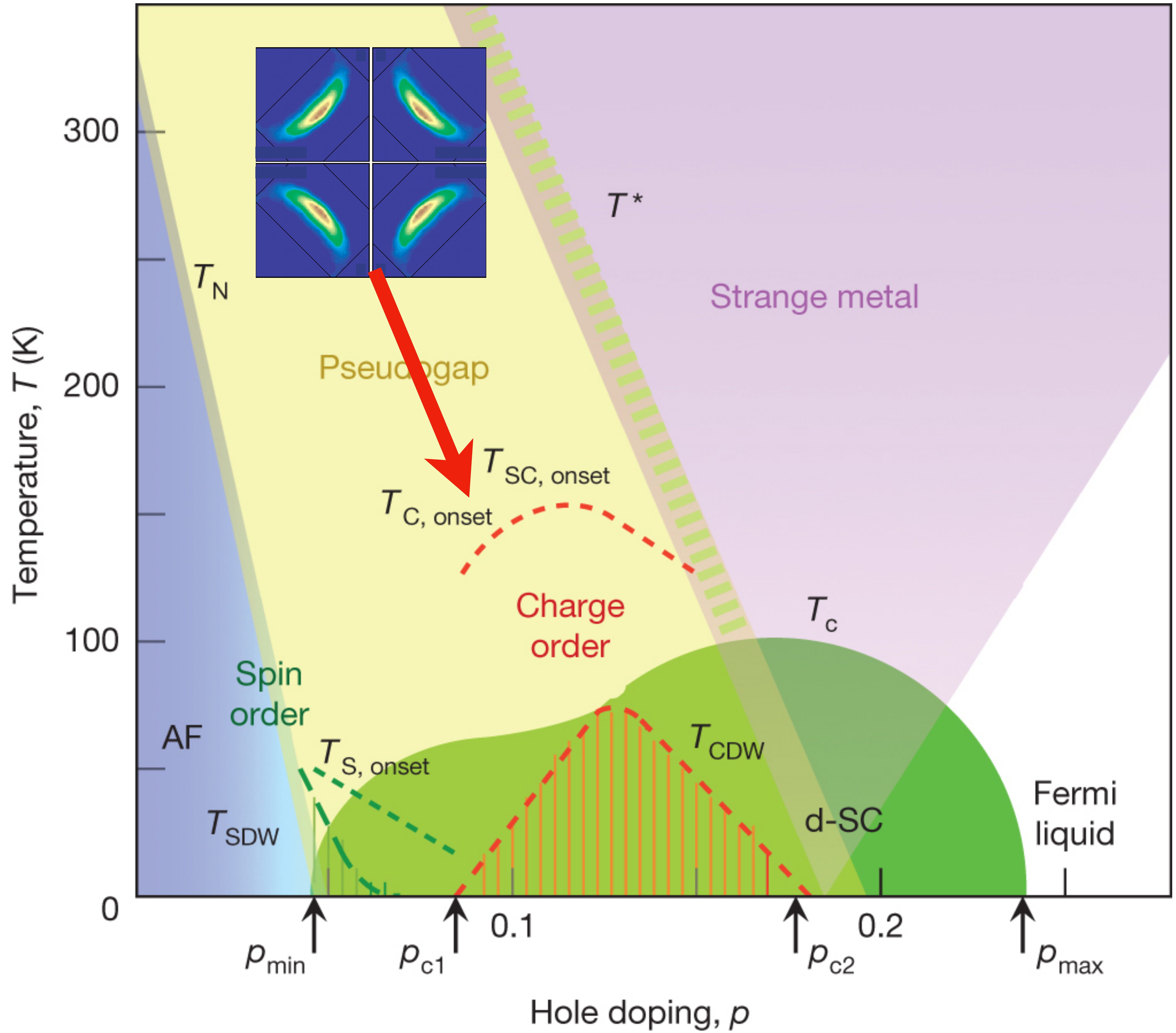
E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, and S. S., PRB **105**, 075146 (2022)

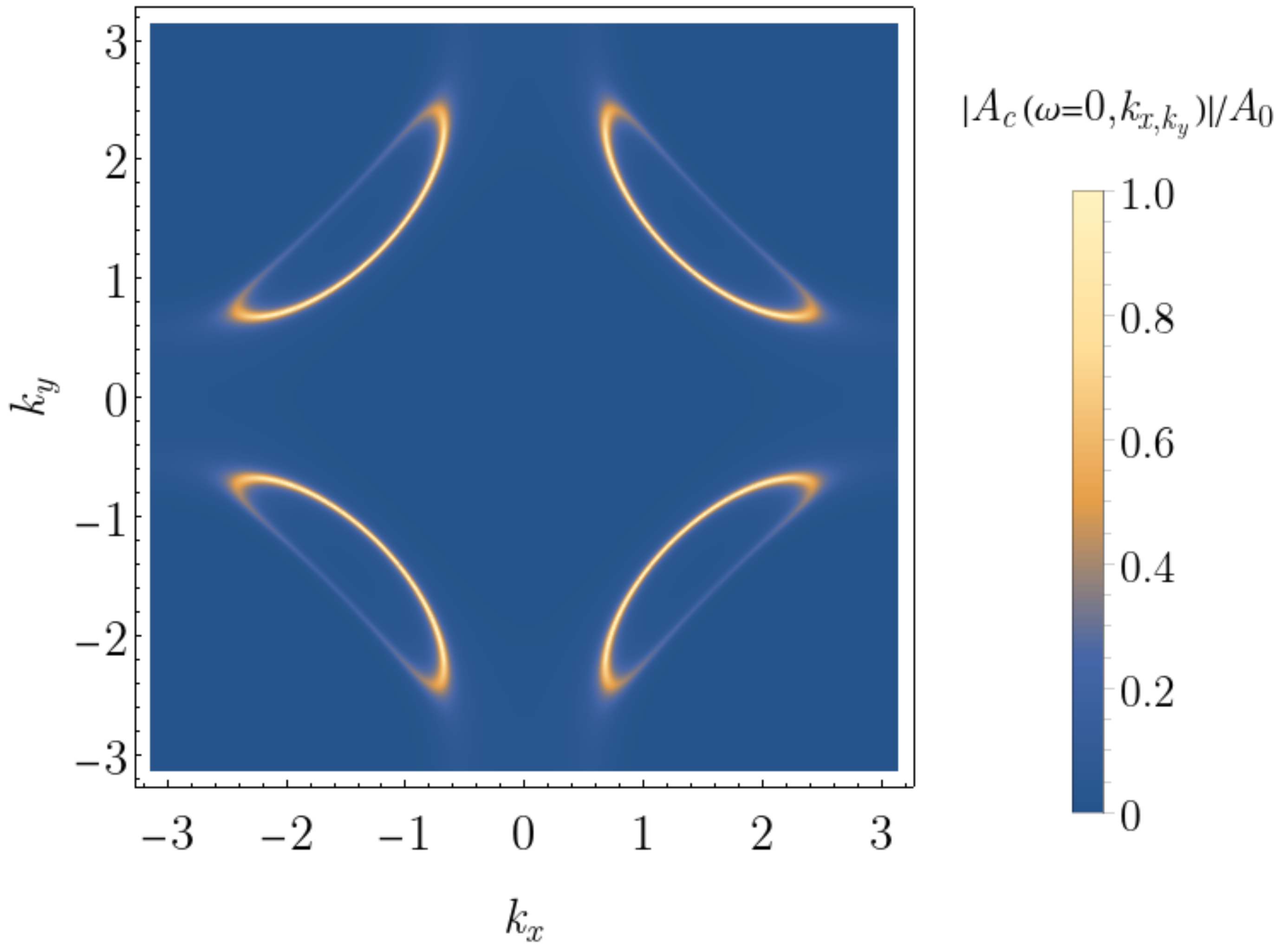
Hole pocket Fermi surfaces of size p with charge e, spin-1/2 quasiparticles

$+$

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

B Keimer *et al.* *Nature* **518**, 179-186 (2015)





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

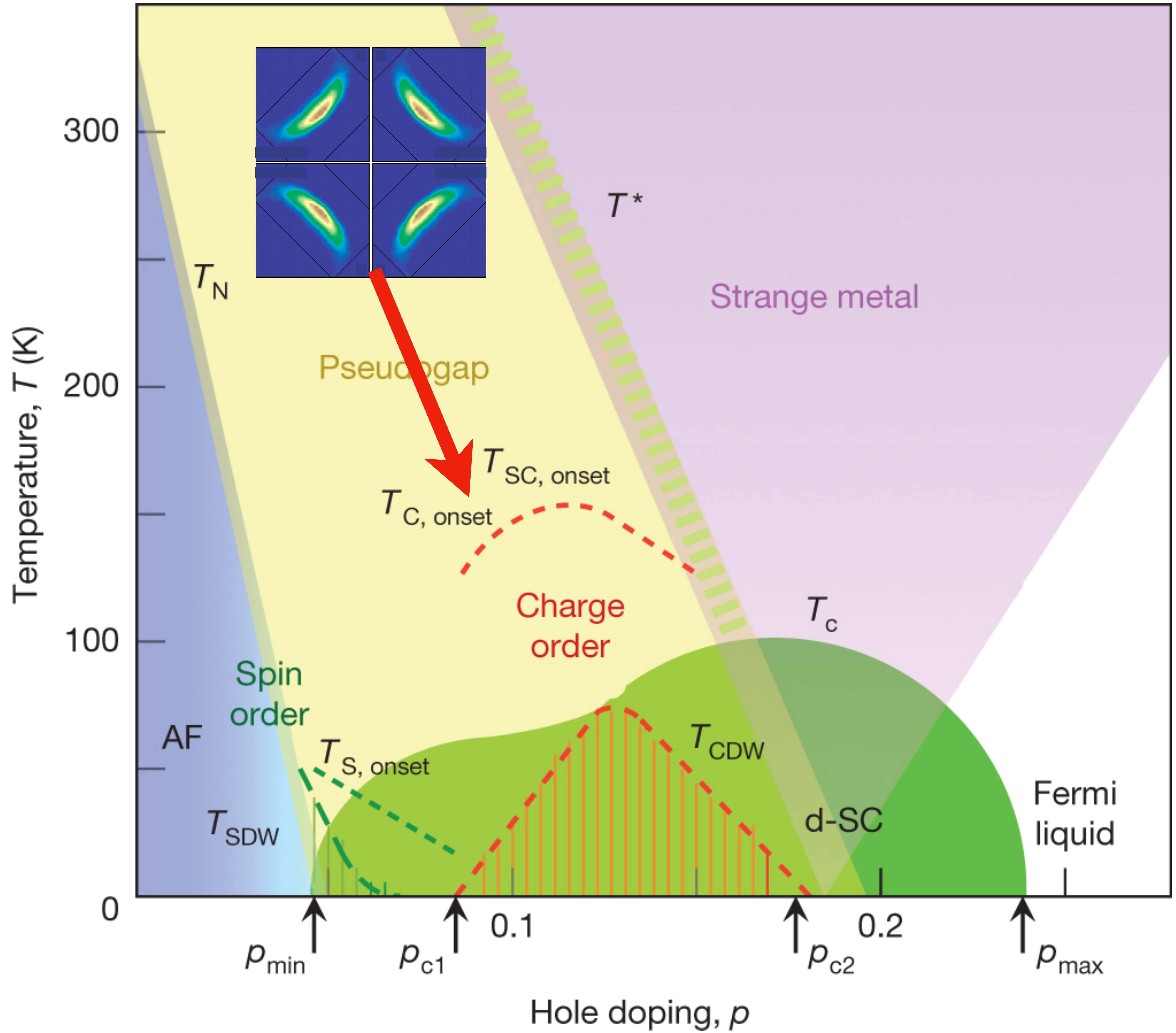
Hole pocket Fermi surfaces of size p with charge e, spin-1/2 quasiparticles

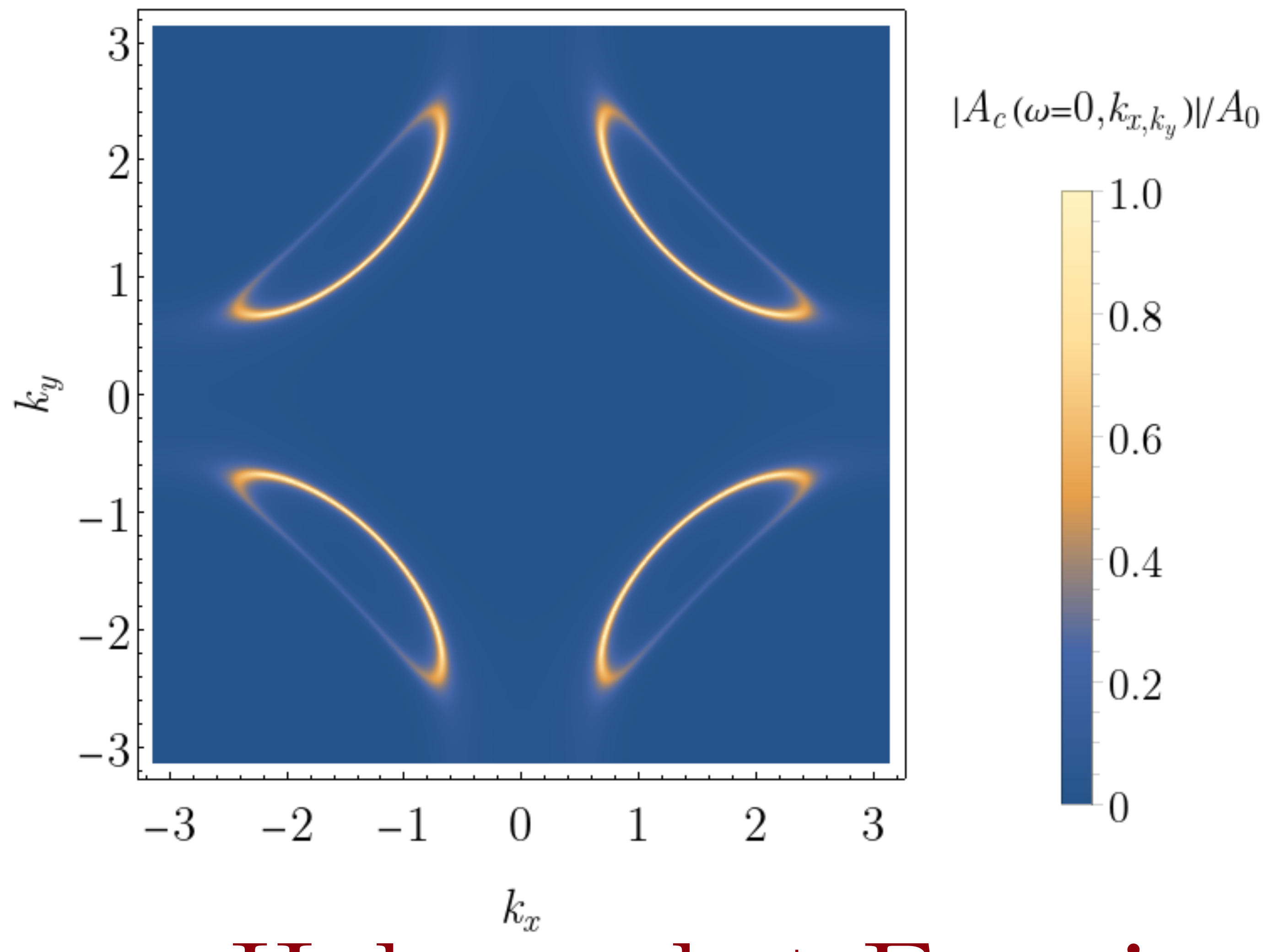
$+$

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

But which spin liquid?

B Keimer *et al.* *Nature* **518**, 179-186 (2015)





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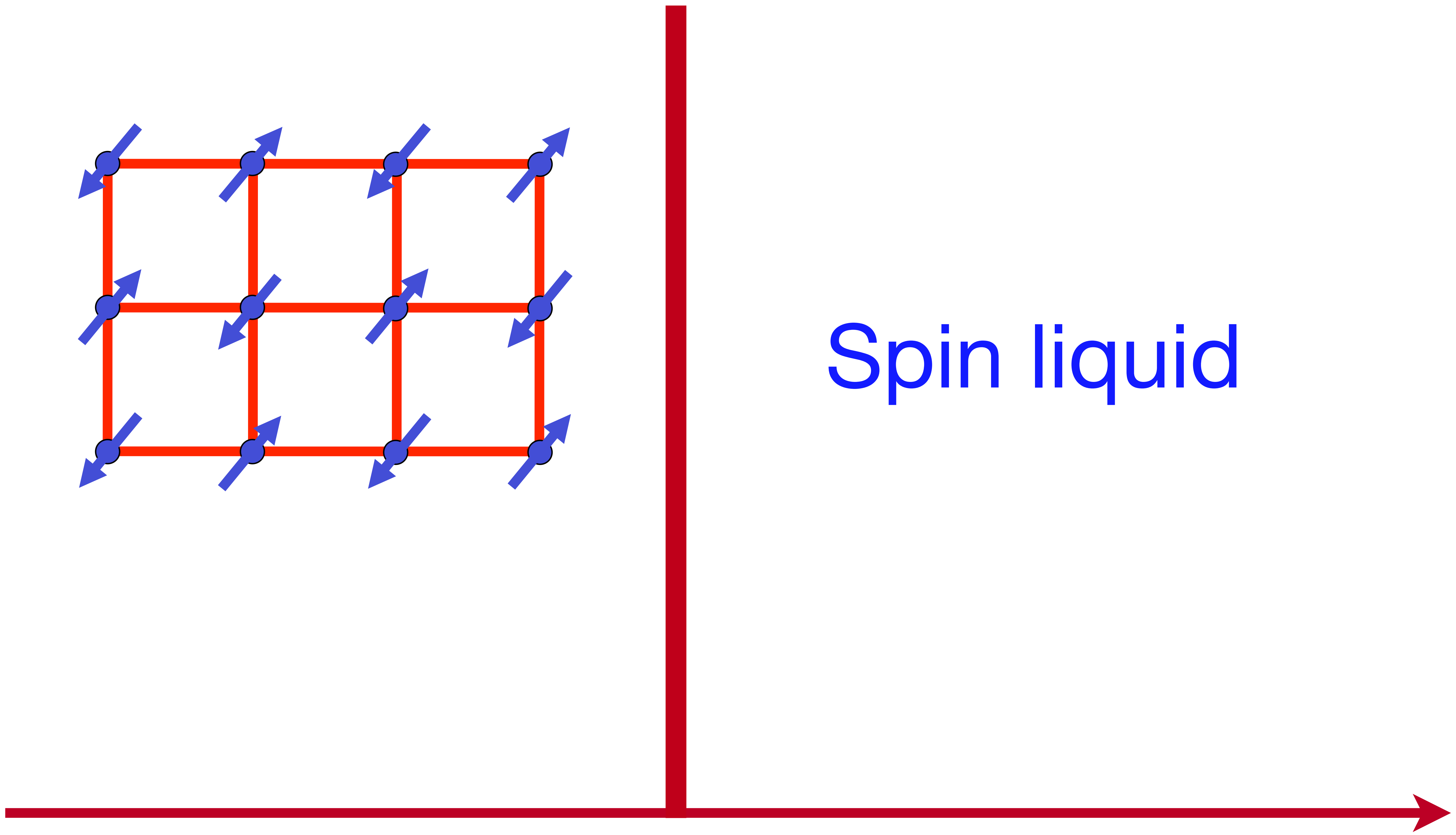
But which spin liquid?

A spin liquid which is ultimately IR-unstable to confinement

1. Open questions on the cuprate phase diagram
2. Theory of the pseudogap metal
3. The π-flux spin liquid
4. Confinement transitions of the π-flux spin liquid
5. Recap

Insulating S=1/2 antiferromagnet



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

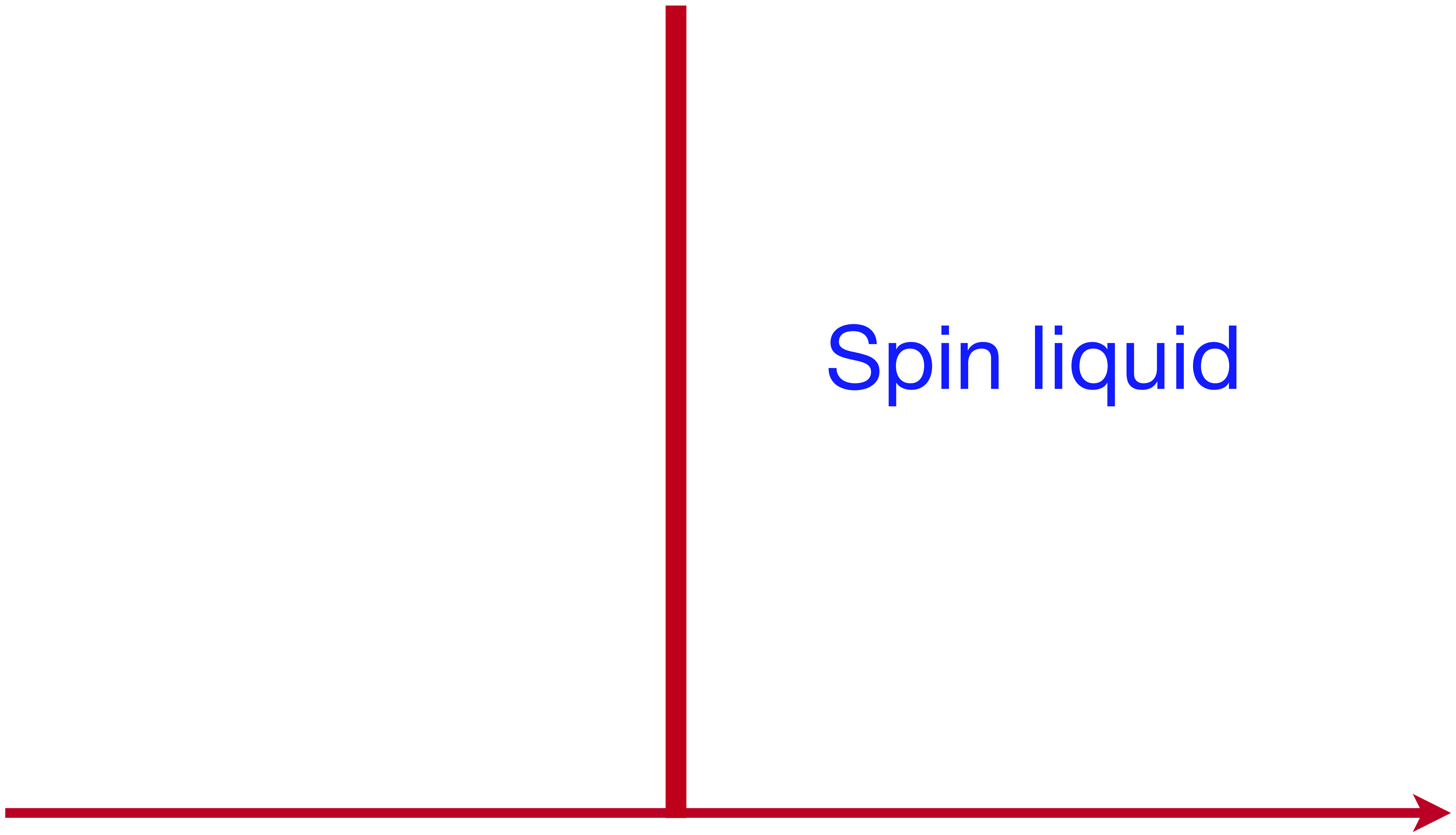
Schwinger bosons

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

Mean-field spin liquid
with gapped bosonic spinons.

D.P. Arovas and A. Auerbach, PRB **38**, 316 (1988)

Insulating S=1/2 antiferromagnet



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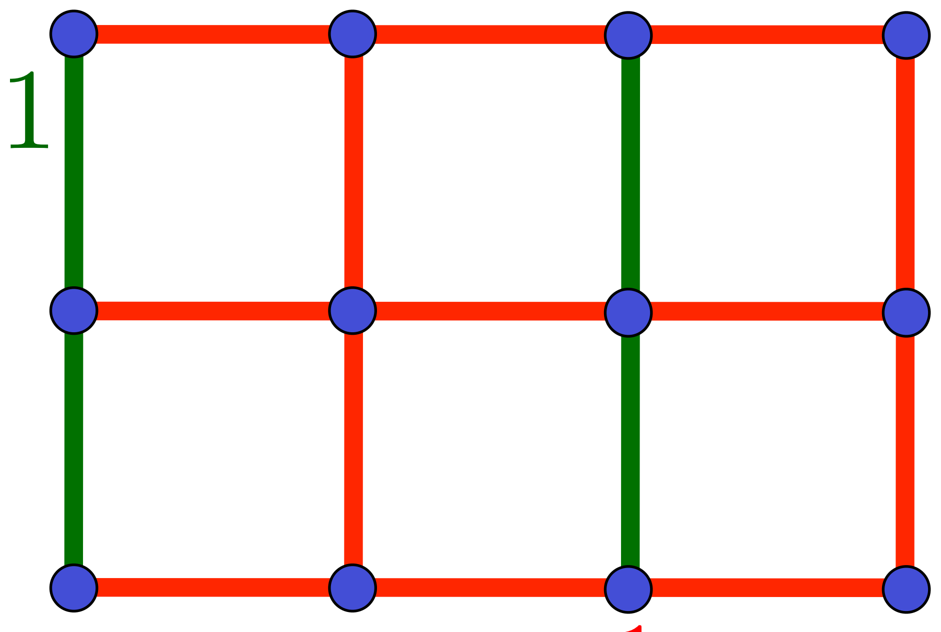
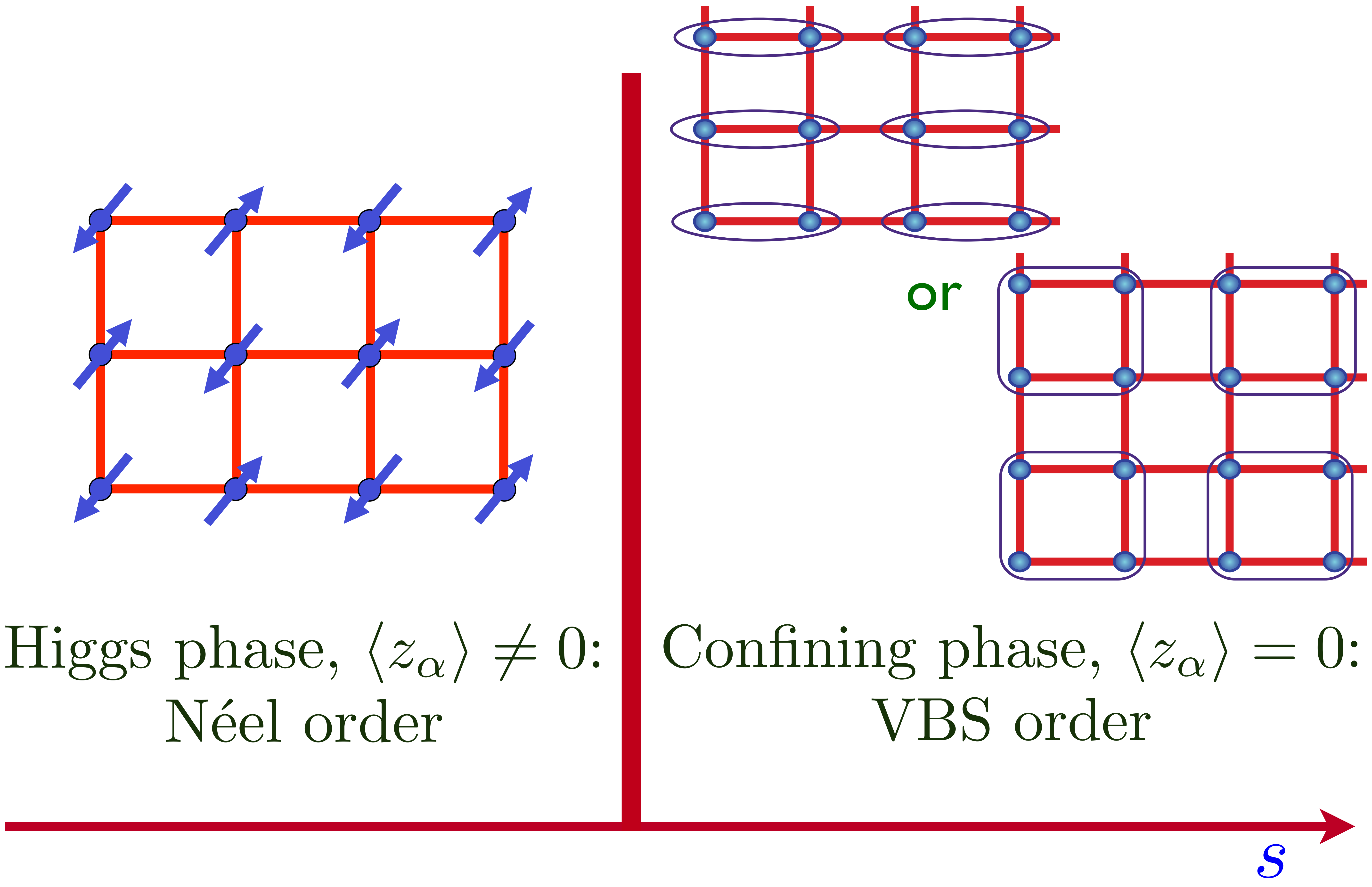
π-flux mean-field theory
with gapless spinons at 2 Dirac points.

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



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

Insulating S=1/2 antiferromagnet



Higgs phase, $\langle z_\alpha \rangle \neq 0$:
Néel order

Confining phase, $\langle z_\alpha \rangle = 0$:
VBS order

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

Schwinger bosons

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

Mean-field spin liquid
with gapped bosonic spinons.

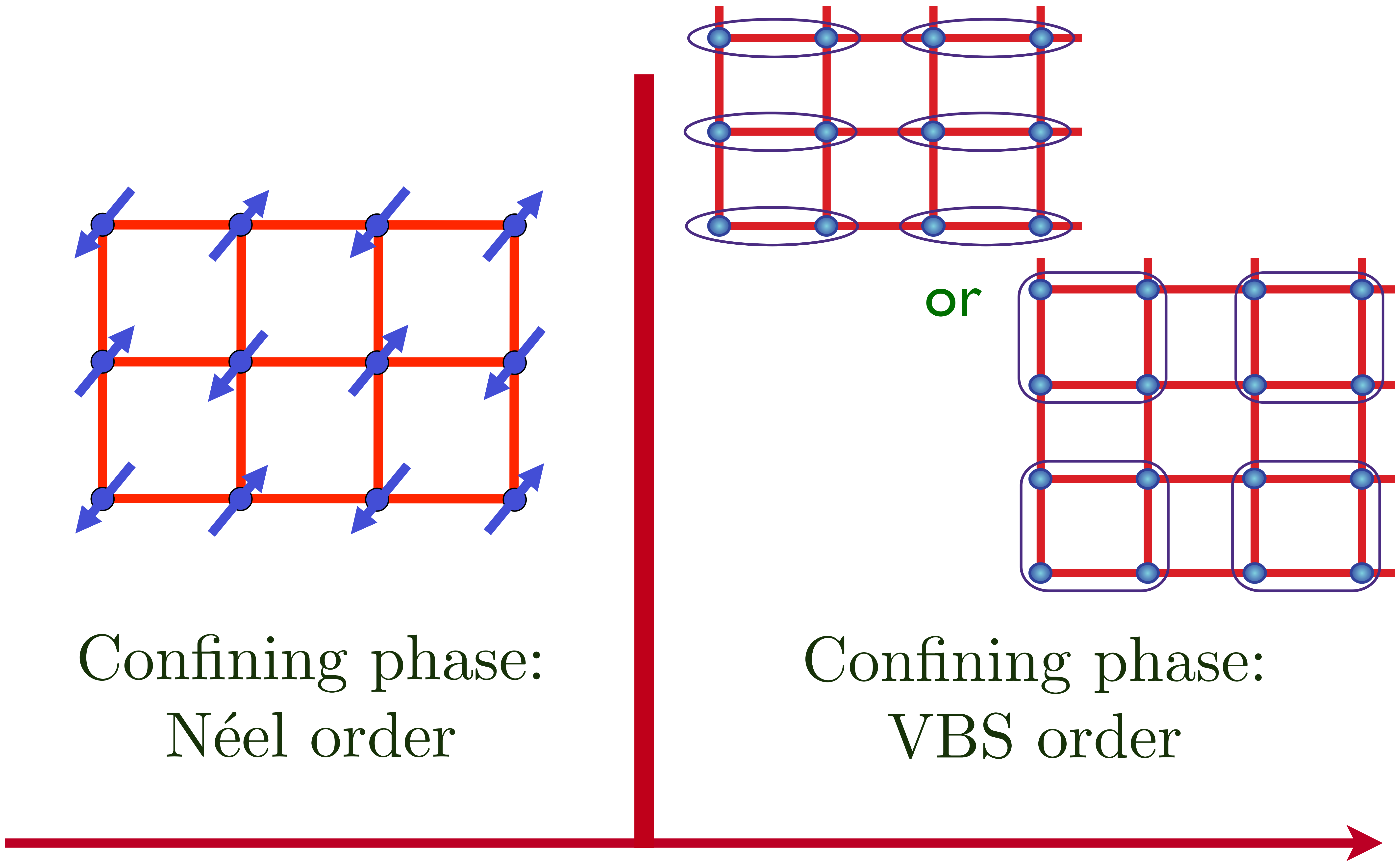
Low energy $\mathbb{CP}^1$ U(1) gauge theory

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

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

N. Read and S. S., PRL **62**, 1694 (1989)

Insulating S=1/2 antiferromagnet



$$\mathcal{L} = i\overline{\Psi}_s \gamma_\mu D_\mu \Psi_s + \ldots$$

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

Schwinger fermions

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

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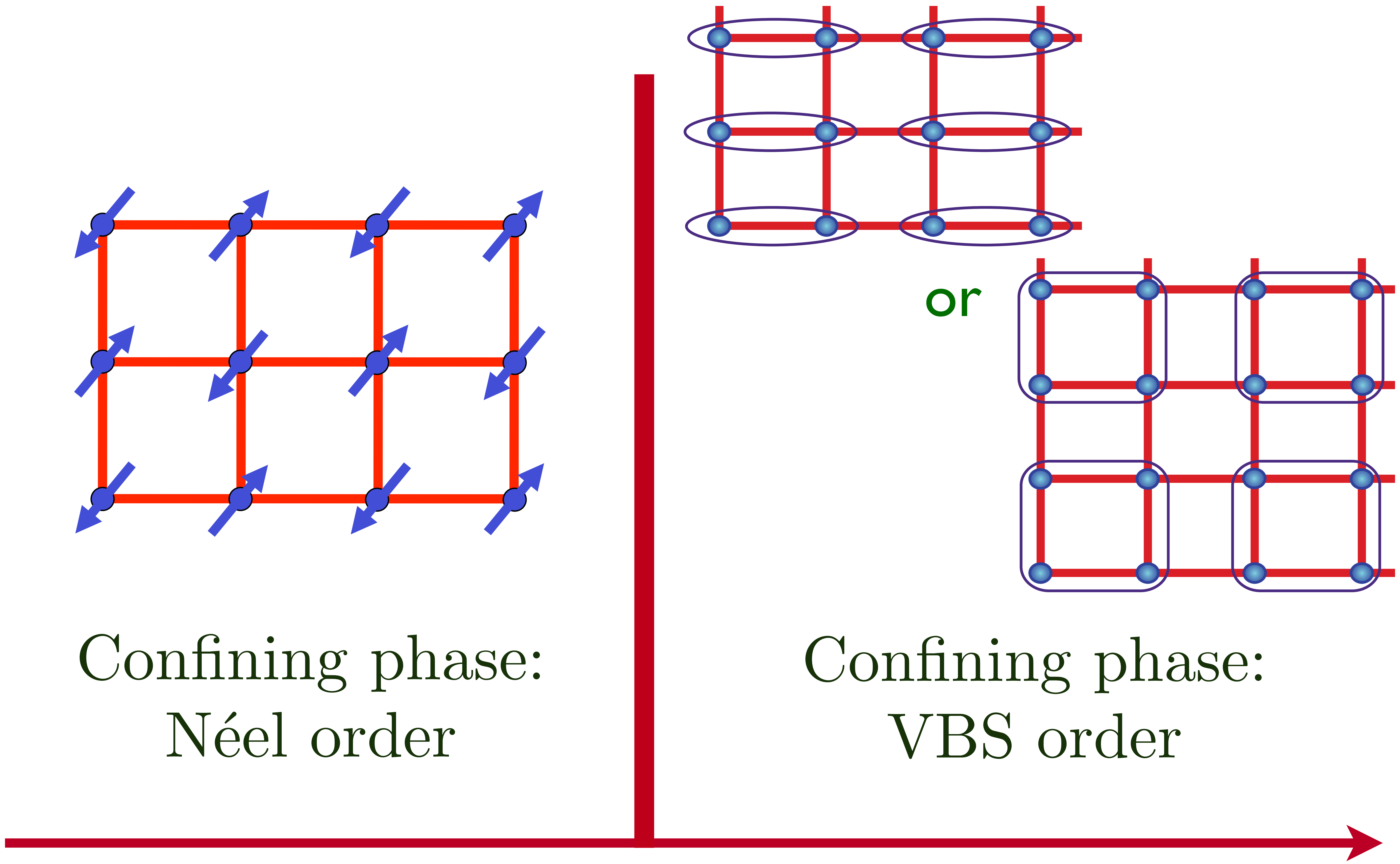
Low energy theory of $N_f = 2$
Dirac fermions Ψ_s coupled to
an emergent $\mathrm{SU}(2)_N$ gauge field.
Confining order parameters
are Néel and VBS states,
with a global $\mathrm{SO}(5)_f$ symmetry!

A. Tanaka and X. Hu, PRL **95**, 036402 (2005); T. Senthil and M.P.A. Fisher PRB **74**, 064405 (2006); Ying Ran and X.-G. Wen, cond-mat/0609620

Insulating S=1/2 antiferromagnet



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

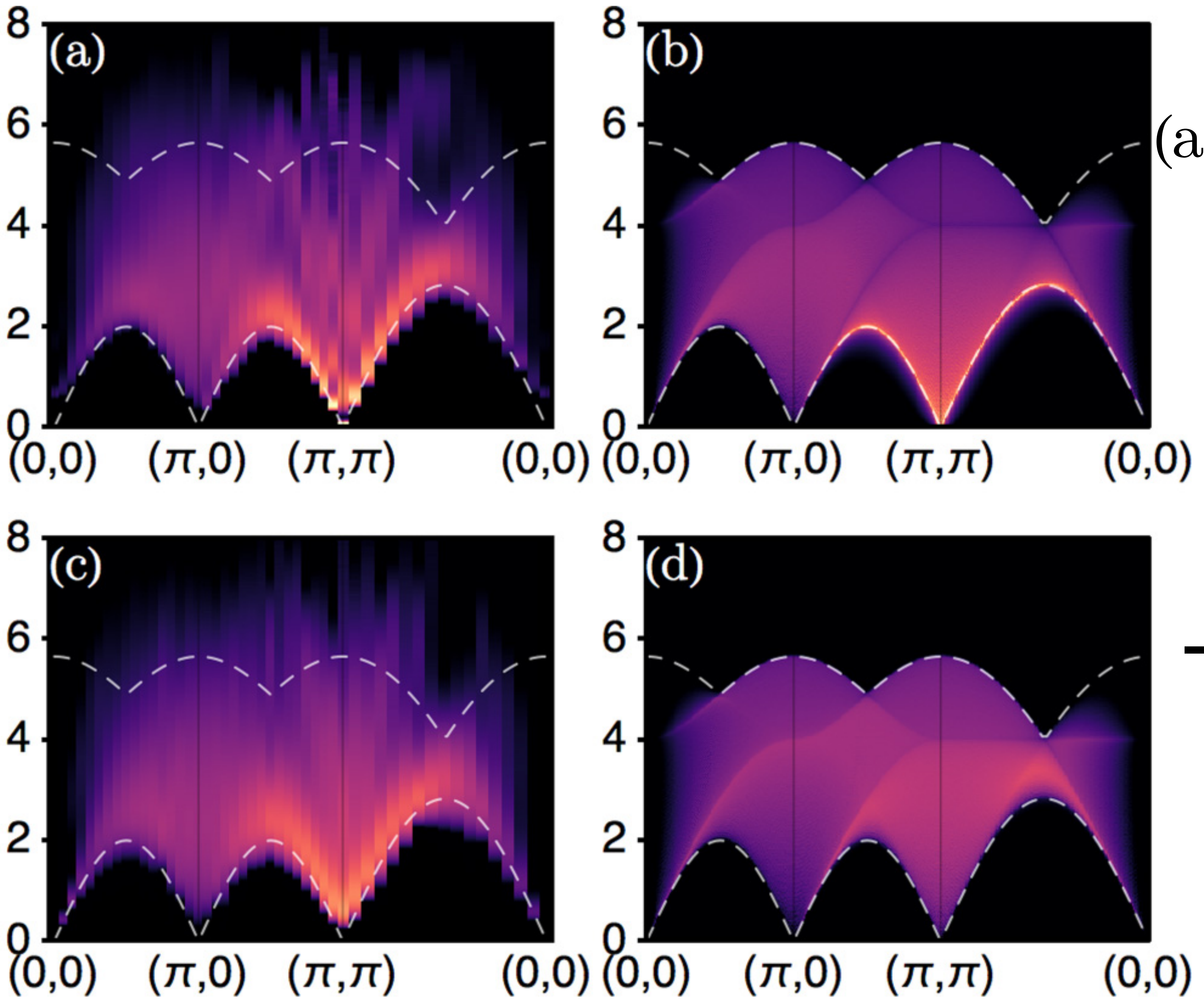
A. Tanaka and X. Hu, PRL **95**, 036402 (2005); T. Senthil and M.P.A. Fisher PRB **74**, 064405 (2006); Ying Ran and X.-G. Wen, cond-mat/0609620
C. Wang, A. Nahum, M. A. Metlitski, C. Xu, and T. Senthil, Physical Review X **7**, 031051 (2017)

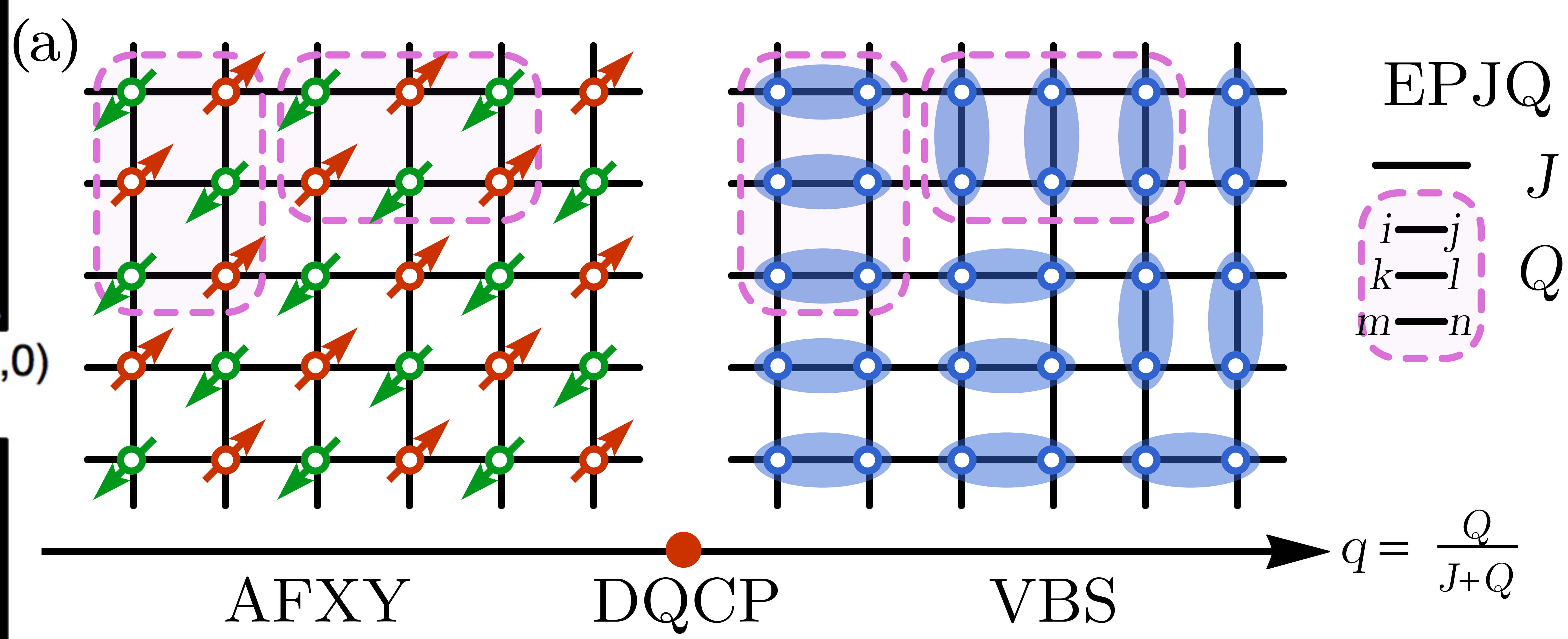
QMC

Free fermion spinons in π-flux

XX

ZZ



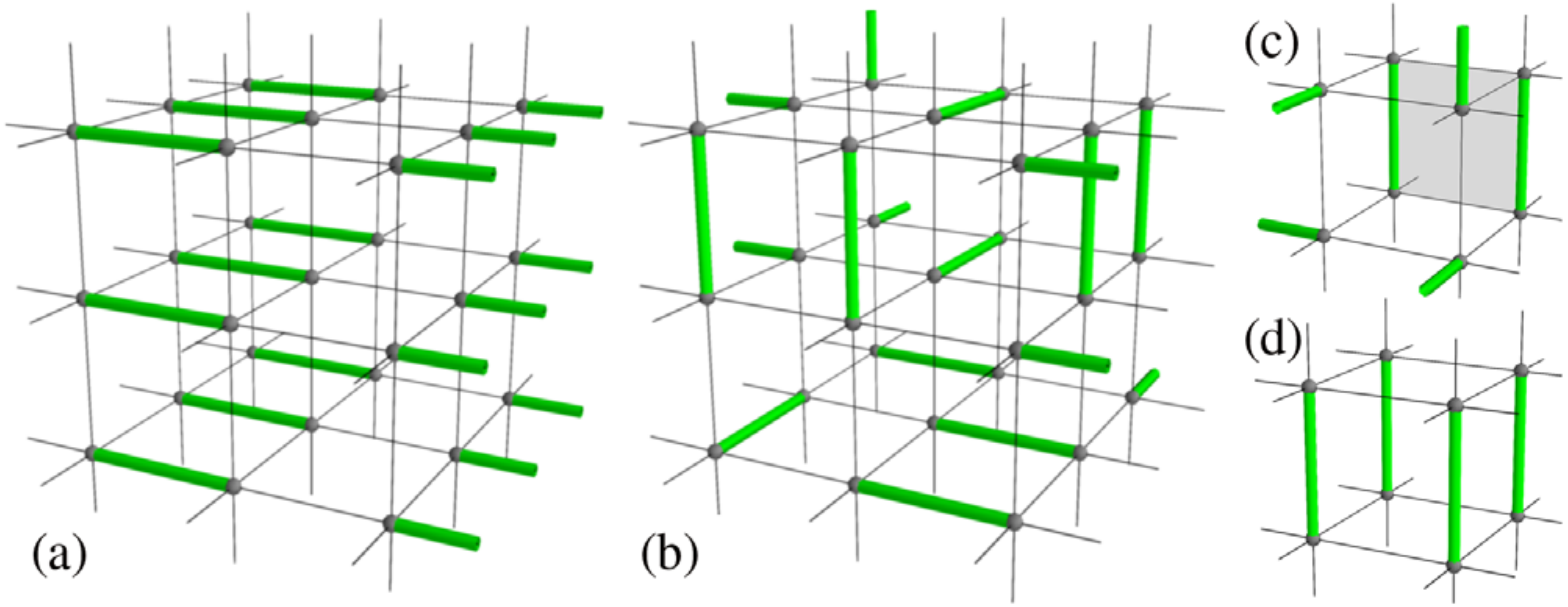


Nvsen Ma, Guang-Yu Sun, Yi-Zhuang You, Cenke Xu, Ashvin Vishwanath, Anders W. Sandvik, and Zi Yang Meng, PRB **98**, 174421 (2018)

Emergent SO(5) Symmetry at the Columnar Ordering Transition in the Classical Cubic Dimer Model

PRL **122**, 080601 (2019)

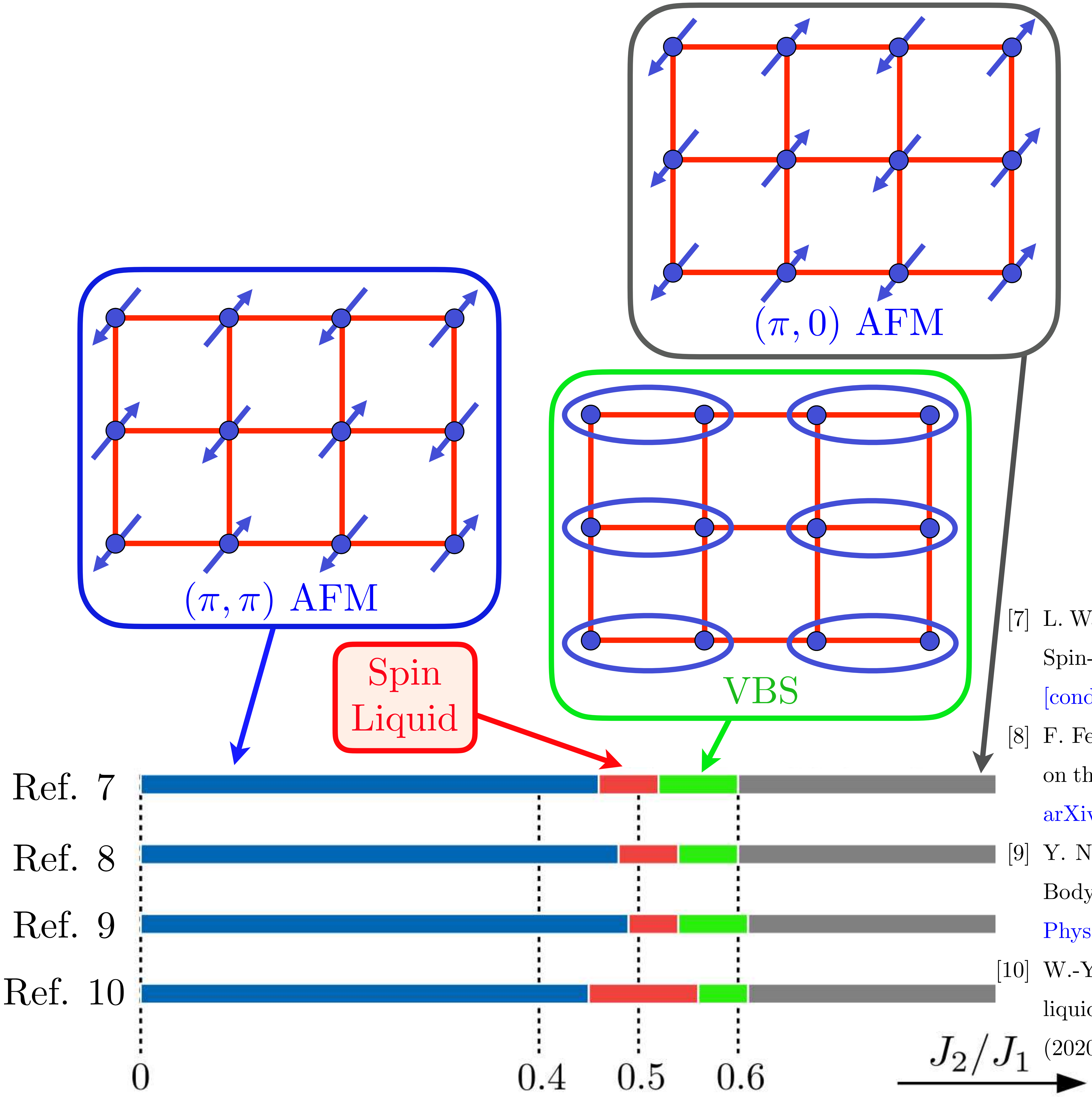
G. J. Sreejith,[1] Stephen Powell,[2] and Adam Nahum[3]

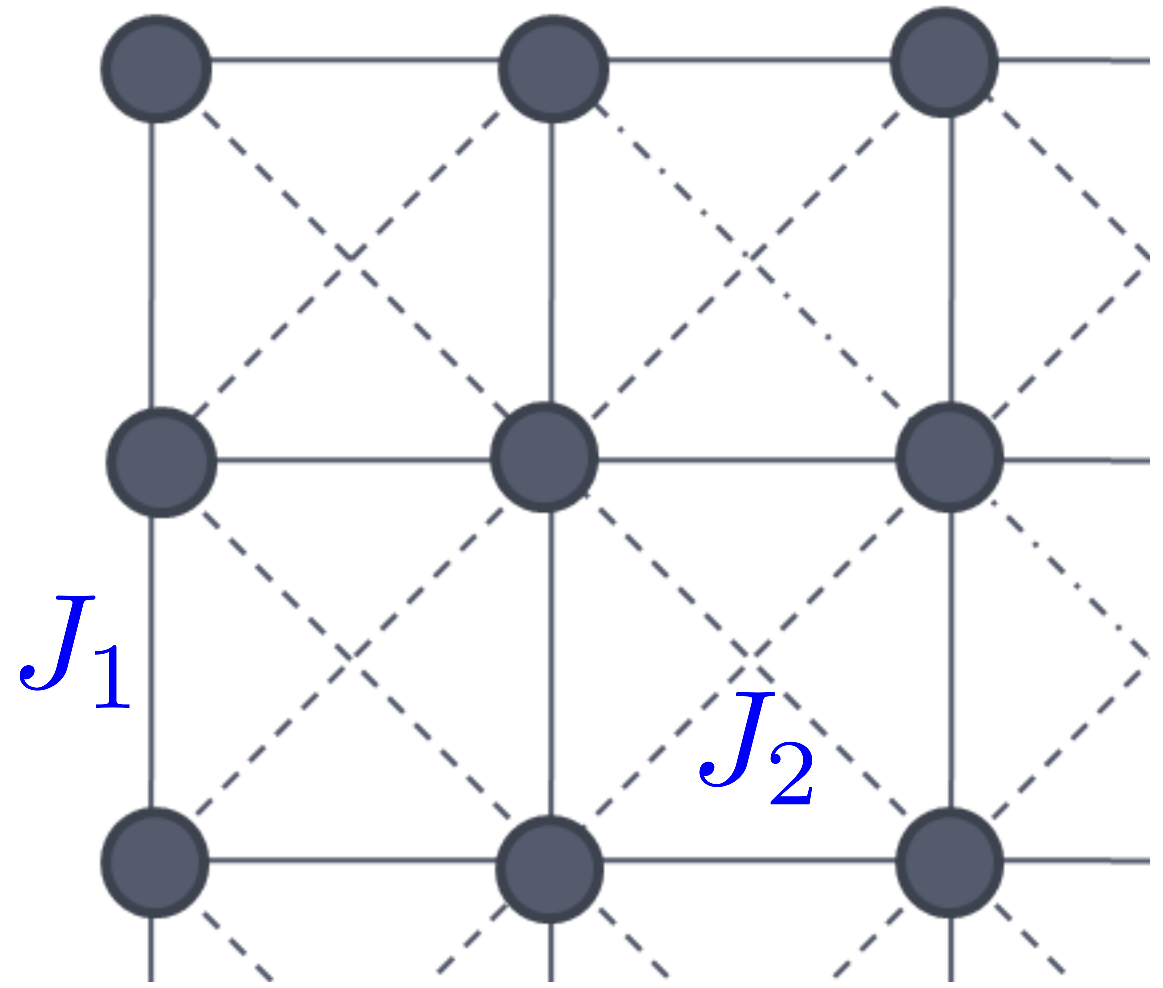


$$\mathcal{L} = \frac{\kappa}{2}|\vec{\nabla}\times\vec{A}|^2 + |(\vec{\nabla} - \mathrm{i}\vec{A})z|^2 + s|z|^2 + u(|z|^2)^2,$$

Using Monte Carlo simulations, we show that this transition has emergent SO(5) symmetry relating quantities characterizing the two phases. While the low-temperature phase has a conventional order parameter, the defining property of the Coulomb liquid on the high-temperature side is deconfinement of monomers, and so SO(5) relates fundamentally different types of objects. Studying linear system sizes up to L=96, we find that this symmetry applies with an excellent precision, consistently improving with system size over this range. It is remarkable that SO(5) emerges in a system as basic as the cubic dimer model, with only simple discrete degrees of freedom. Our results are important evidence for the generality of the SO(5) symmetry that has been proposed for the noncompact CP^1 field theory.

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





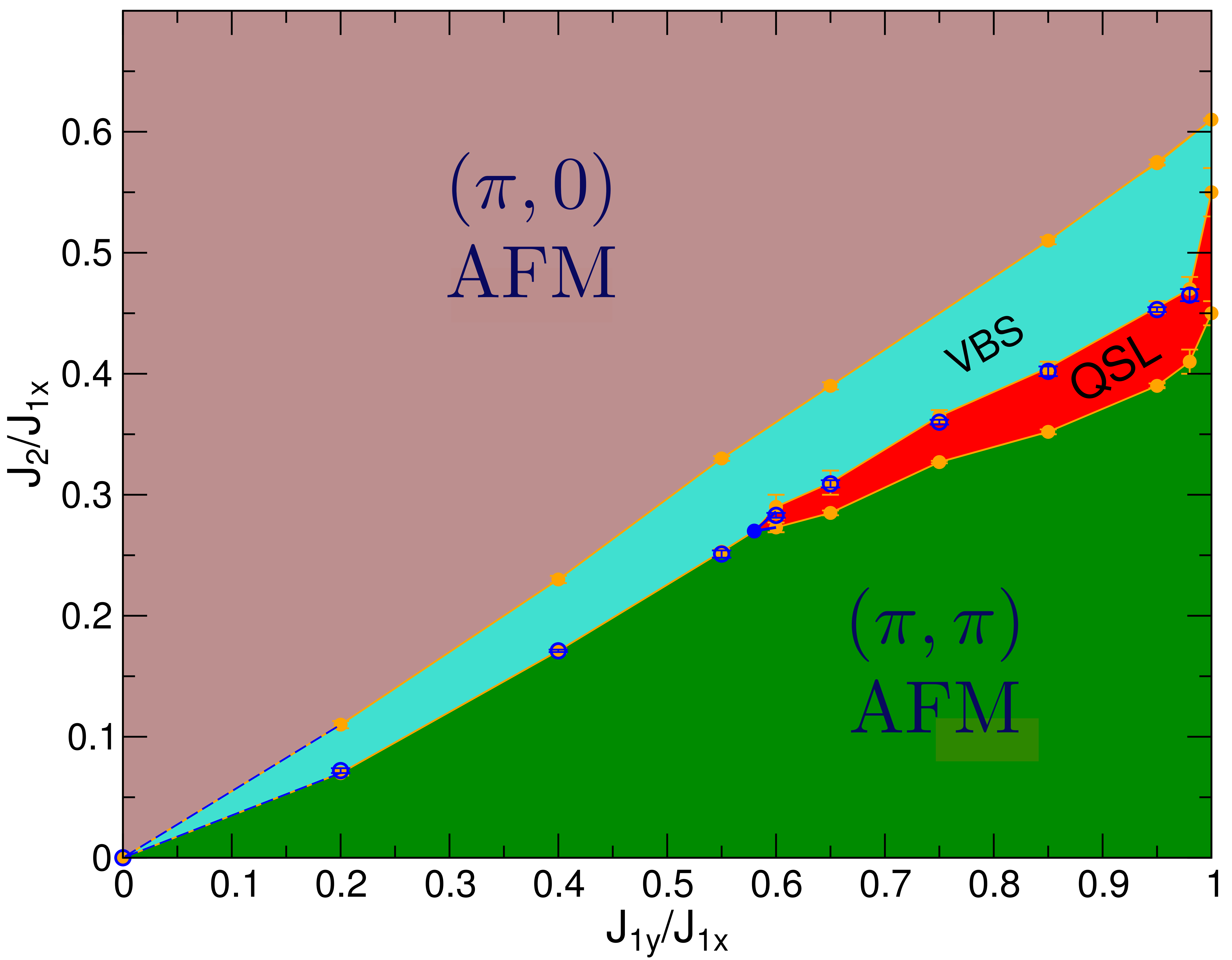
[7] L. Wang and A. W. Sandvik, "Critical Level Crossings and Gapless Spin Liquid in the Square-Lattice Spin-1 /2 J_1-J_2 Heisenberg Antiferromagnet," Phys. Rev. Lett. **121**, 107202 (2018), arXiv:1702.08197 [cond-mat.str-el].

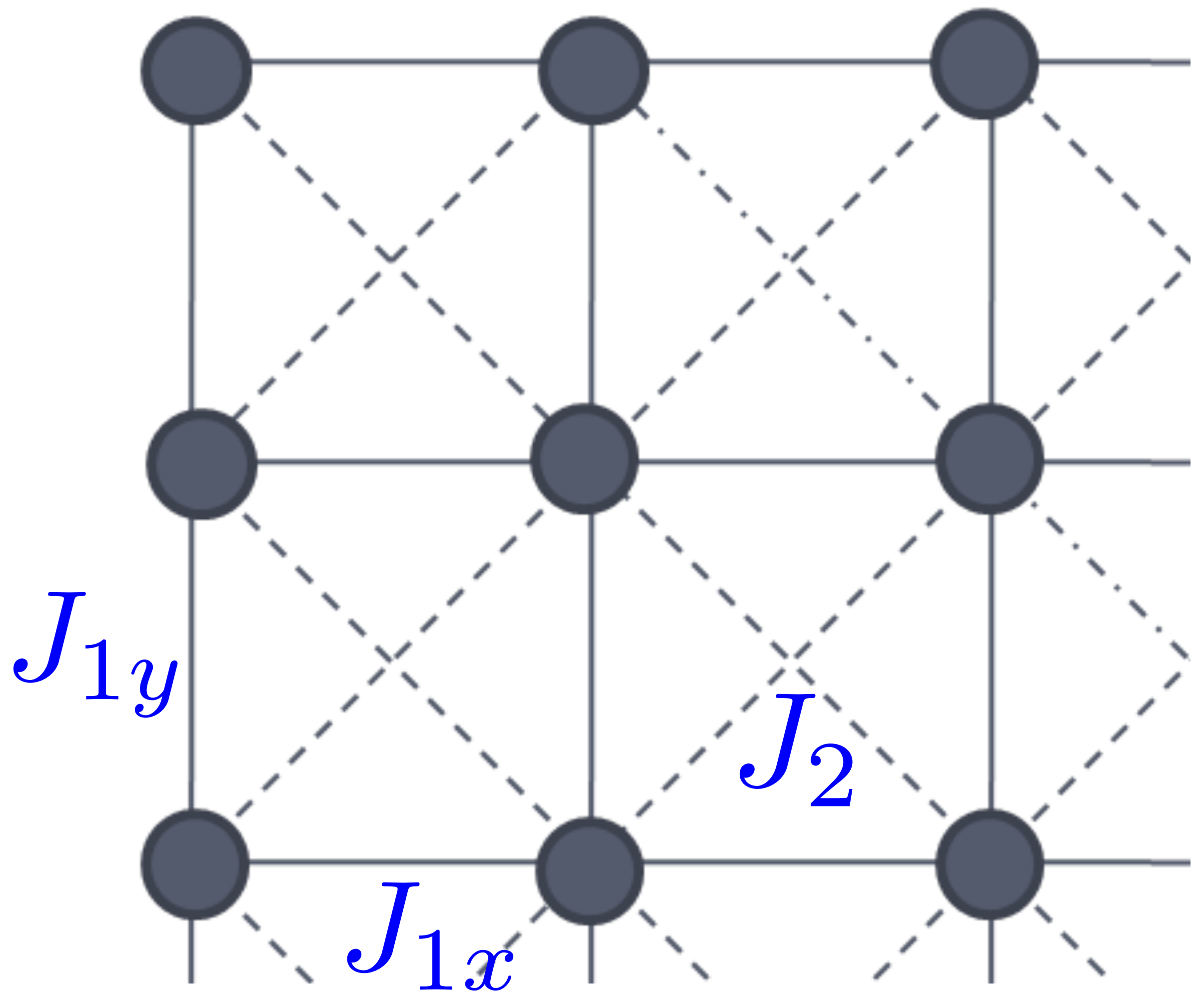
[8] F. Ferrari and F. Becca, "Gapless spin liquid and valence-bond solid in the J_1-J_2 Heisenberg model on the square lattice: Insights from singlet and triplet excitations," Phys. Rev. B **102**, 014417 (2020), arXiv:2005.12941 [cond-mat.str-el].

[9] Y. Nomura and M. Imada, "Dirac-Type Nodal Spin Liquid Revealed by Refined Quantum Many-Body Solver Using Neural-Network Wave Function, Correlation Ratio, and Level Spectroscopy," Phys. Rev. X **11**, 031034 (2021), arXiv:2005.14142 [cond-mat.str-el].

[10] W.-Y. Liu, S.-S. Gong, Y.-B. Li, D. Poilblanc, W.-Q. Chen, and Z.-C. Gu, "Gapless quantum spin liquid and global phase diagram of the spin-1/2 J_1-J_2 square antiferromagnetic Heisenberg model," (2020), arXiv:2009.01821 [cond-mat.str-el].

$$H = J_{1x} \sum_{\langle i,j \rangle_x} \mathbf{S_i} \cdot \mathbf{S_j} + J_{1y} \sum_{\langle i,j \rangle_y} \mathbf{S_i} \cdot \mathbf{S_j} + J_2 \sum_{\langle\langle i,j \rangle\rangle} \mathbf{S_i} \cdot \mathbf{S_j}.$$



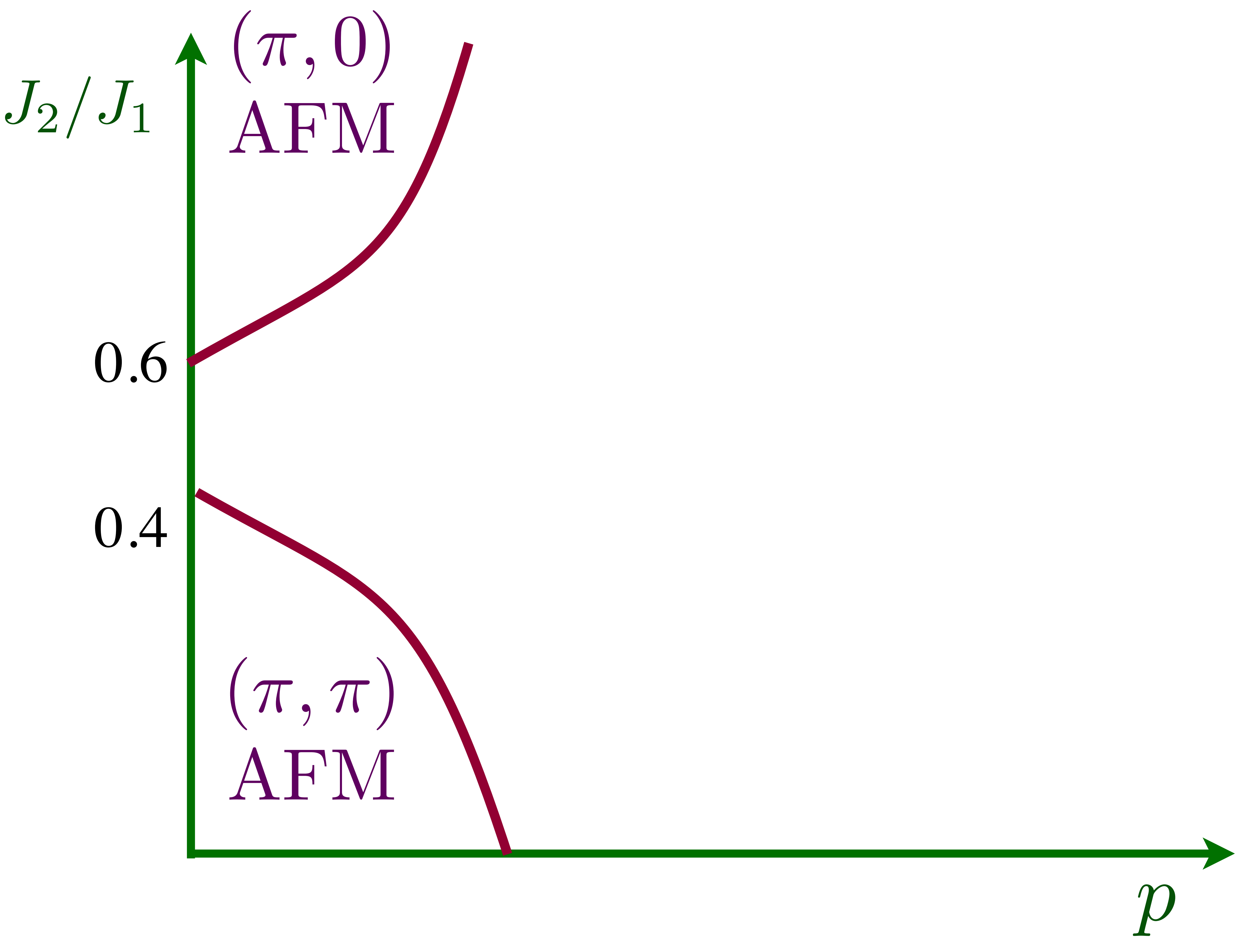


Wen-Yuan Liu,
Shou-Shu Gong,
Wei-Qiang Chen,
and Zheng-Cheng Gu,
arXiv:2212.00707

High Temperature Superconductivity in a Lightly Doped Quantum Spin Liquid

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

PHYSICAL REVIEW LETTERS **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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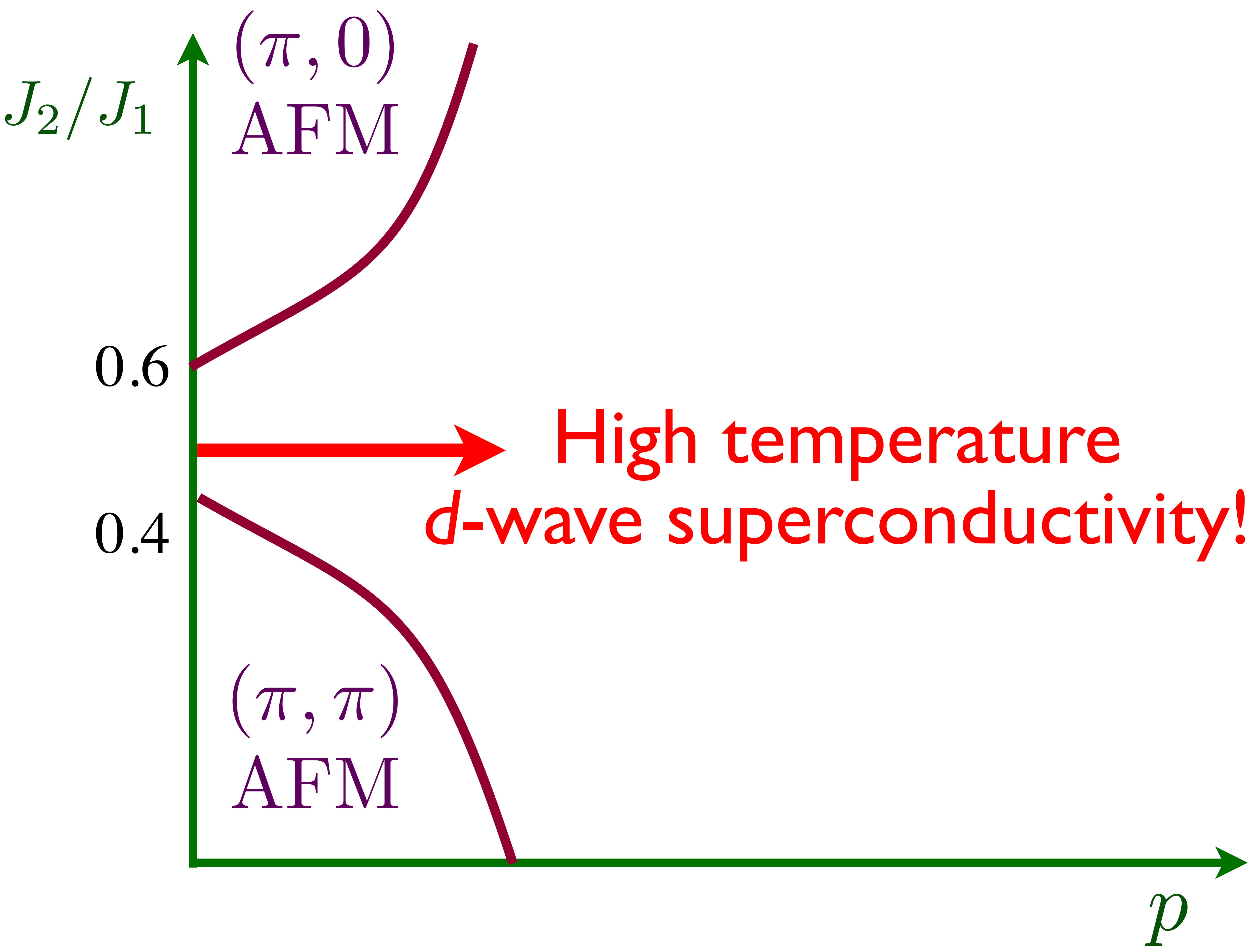

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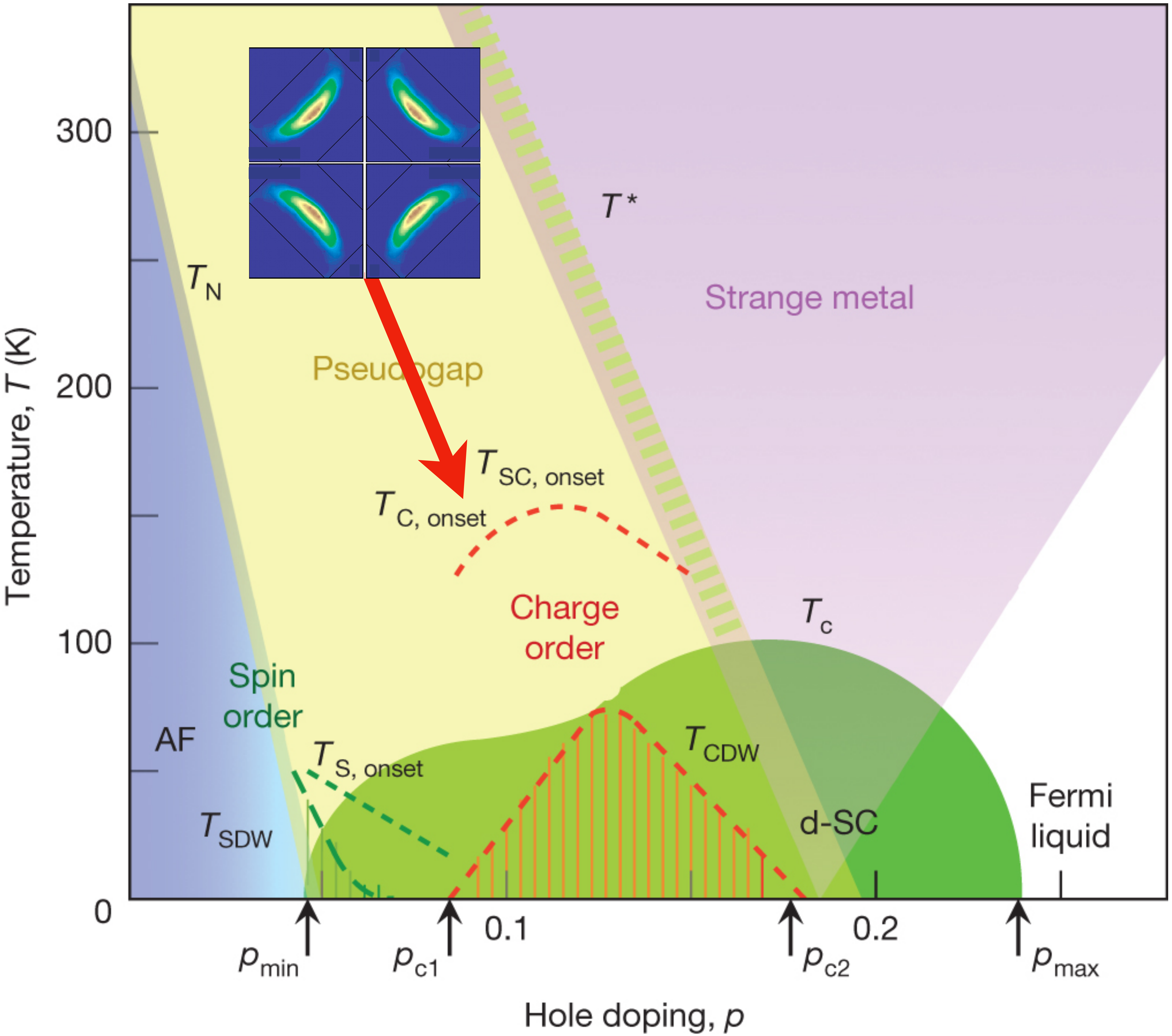
B Keimer *et al.* *Nature* **518**, 179-186 (2015)



A theory for the confinement of fractionalized excitations in the *π-flux spin liquid with fermionic spinons* dual to the *$\mathbb{CP}^1$ spin liquid with bosonic spinons* from electrically charged excitations.

Ancilla theory of the Hubbard model

Pseudogap metal: $\langle c_\alpha^\dagger f_{1\alpha} \rangle \neq 0$

f_α form π-flux spin liquid with $\mathrm{SU}(2)_N$ gauge field

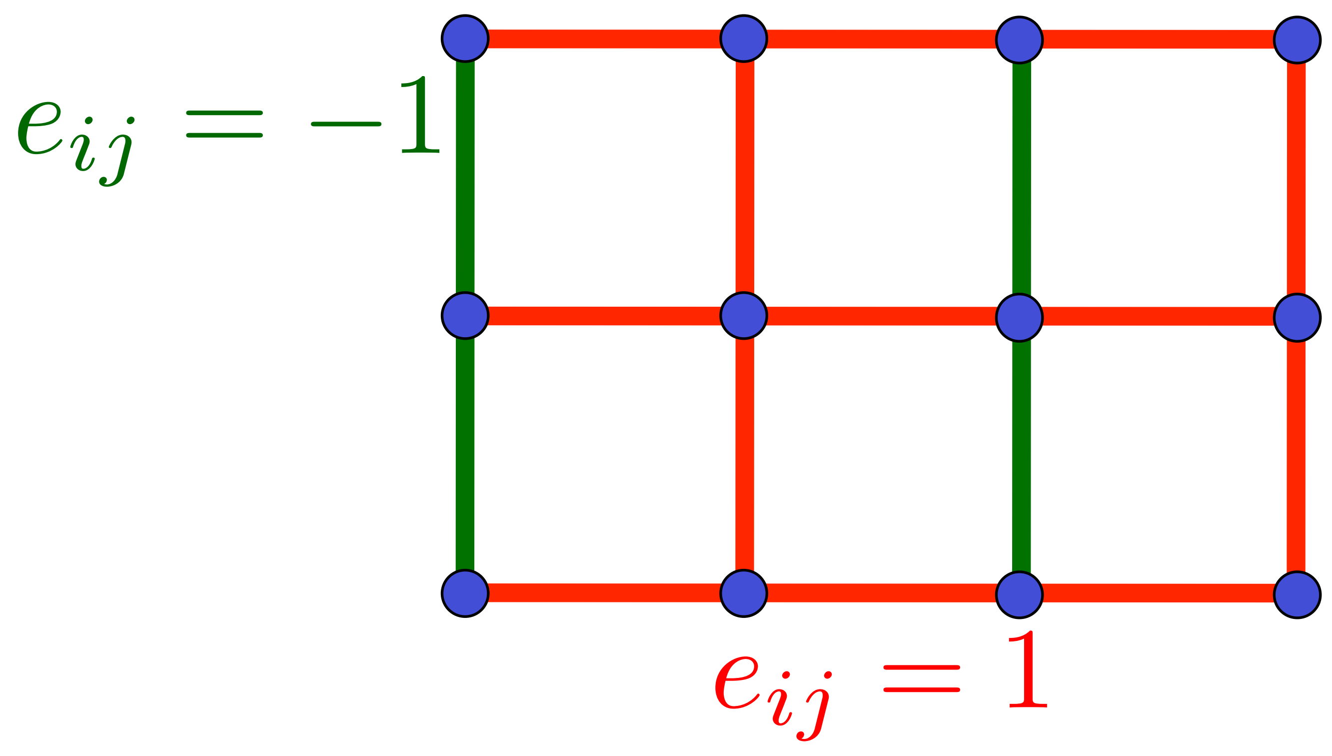
Charge e, $\mathrm{SU}(2)_N$ fundamental, Higgs boson $B \sim \begin{pmatrix} f_{1\alpha}^\dagger f_\alpha \\ \varepsilon_{\alpha\beta} f_{1\alpha}^\dagger f_\beta^\dagger \end{pmatrix}$

Boson with same quantum numbers in X.-G. Wen and P.A. Lee, PRL **76**, 503 (1996)

Confinement of SU(2)$_N$ gauge theory by charge fluctuations

- Begin with the π-flux spin liquid in the fermionic spinon description.

$$H_f = iJ \sum_{\langle ij \rangle} e_{ij} \left(f_{i\alpha}^\dagger f_{j\alpha} - f_{j\alpha}^\dagger f_{i\alpha} \right)$$



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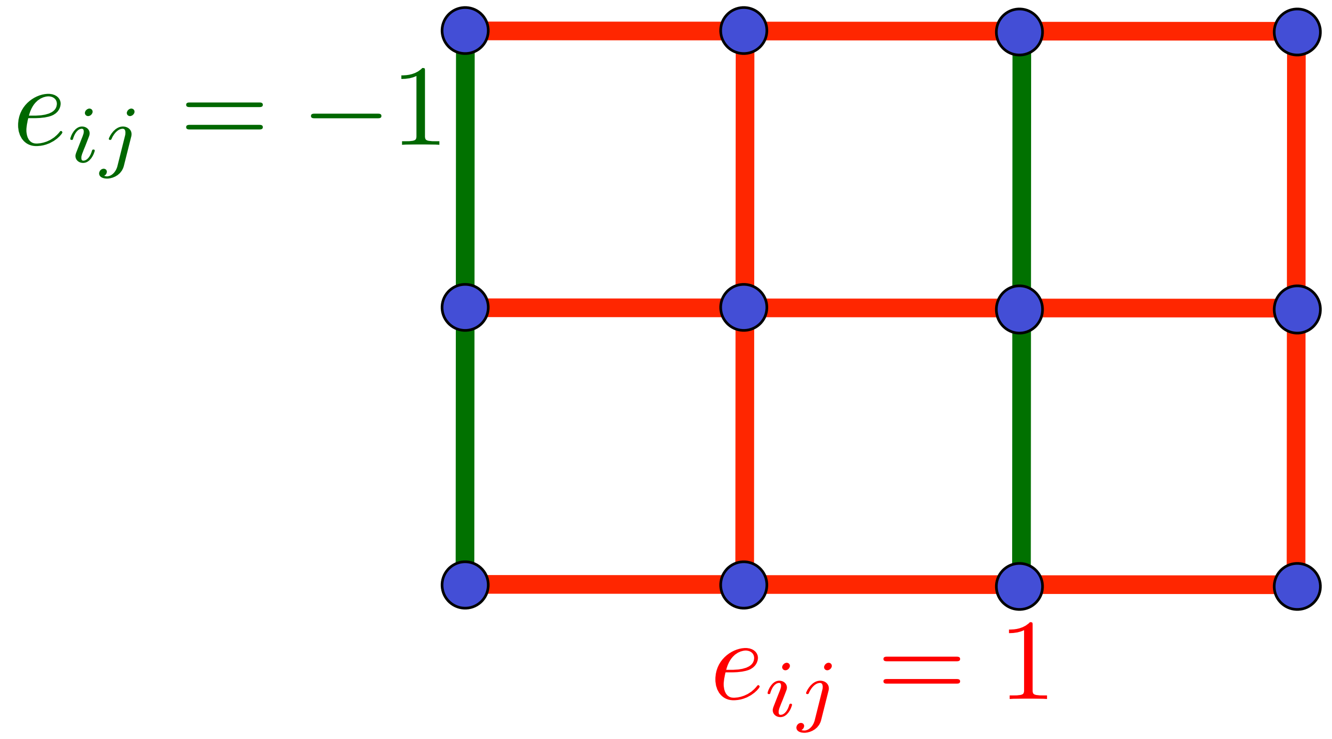
$$H_f = iJ \sum_{\langle ij \rangle} e_{ij} \left(f^\dagger_{i\alpha} f_{j\alpha} - f^\dagger_{j\alpha} f_{i\alpha} \right) = iJ \sum_{\langle ij \rangle} e_{ij} \left(\Psi^\dagger_i U_{ij} \Psi_j - \Psi^\dagger_j U_{ji} \Psi_i \right) ; \quad \Psi_i = \begin{pmatrix} f_{i\uparrow} \\ f^\dagger_{i\downarrow} \end{pmatrix}$$

H_f is invariant under SU(2) rotations in spin and SU(2)$_N$ rotations in Nambu space; U_{ij} is the SU(2)$_N$ gauge field.



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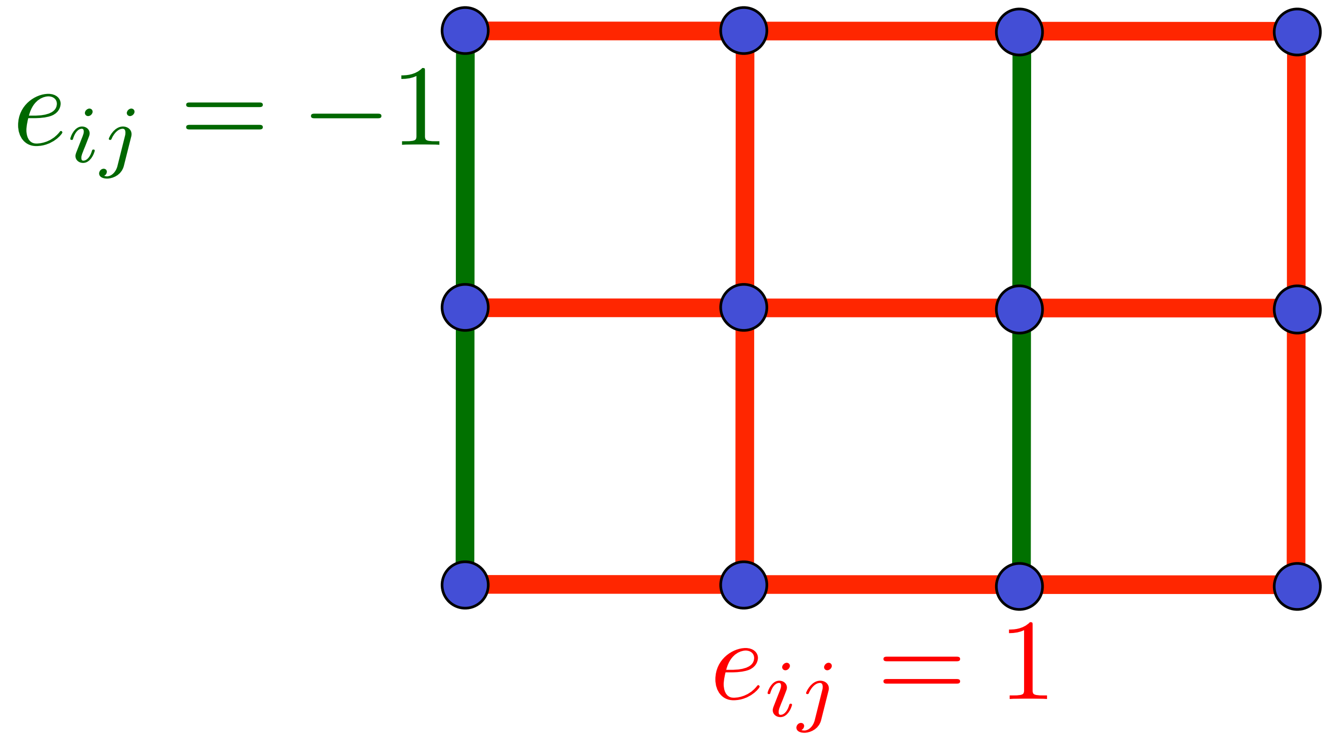


- The nearest-neighbor effective Hamiltonian for charge e, SU(2)$_N$ fundamental boson B_i is constrained by the fact that the composite of B_i and Ψ_i is an electron:

$$H_B = r \sum_i B_i^\dagger B_i + iw \sum_{\langle ij \rangle} e_{ij} \left(B_i^\dagger U_{ij} B_j - B_j^\dagger U_{ji} B_i \right) + \dots$$

Confinement of SU(2)$_N$ gauge theory by charge fluctuations

$$\mathcal{L}(B) = H_B + \frac{u}{2}\sum_{\boldsymbol{i}} \rho_{\boldsymbol{i}}^2 + V_1 \sum_{\boldsymbol{i}} \rho_{\boldsymbol{i}} \left(\rho_{\boldsymbol{i}+\hat{\boldsymbol{x}}} + \rho_{\boldsymbol{i}+\hat{\boldsymbol{y}}}\right) + g \sum_{\langle \boldsymbol{ij}\rangle} |\Delta_{\boldsymbol{ij}}|^2 + J_1 \sum_{\langle \boldsymbol{ij}\rangle} Q_{\boldsymbol{ij}}^2 + K_1 \sum_{\langle \boldsymbol{ij}\rangle} J_{\boldsymbol{ij}}^2 .$$

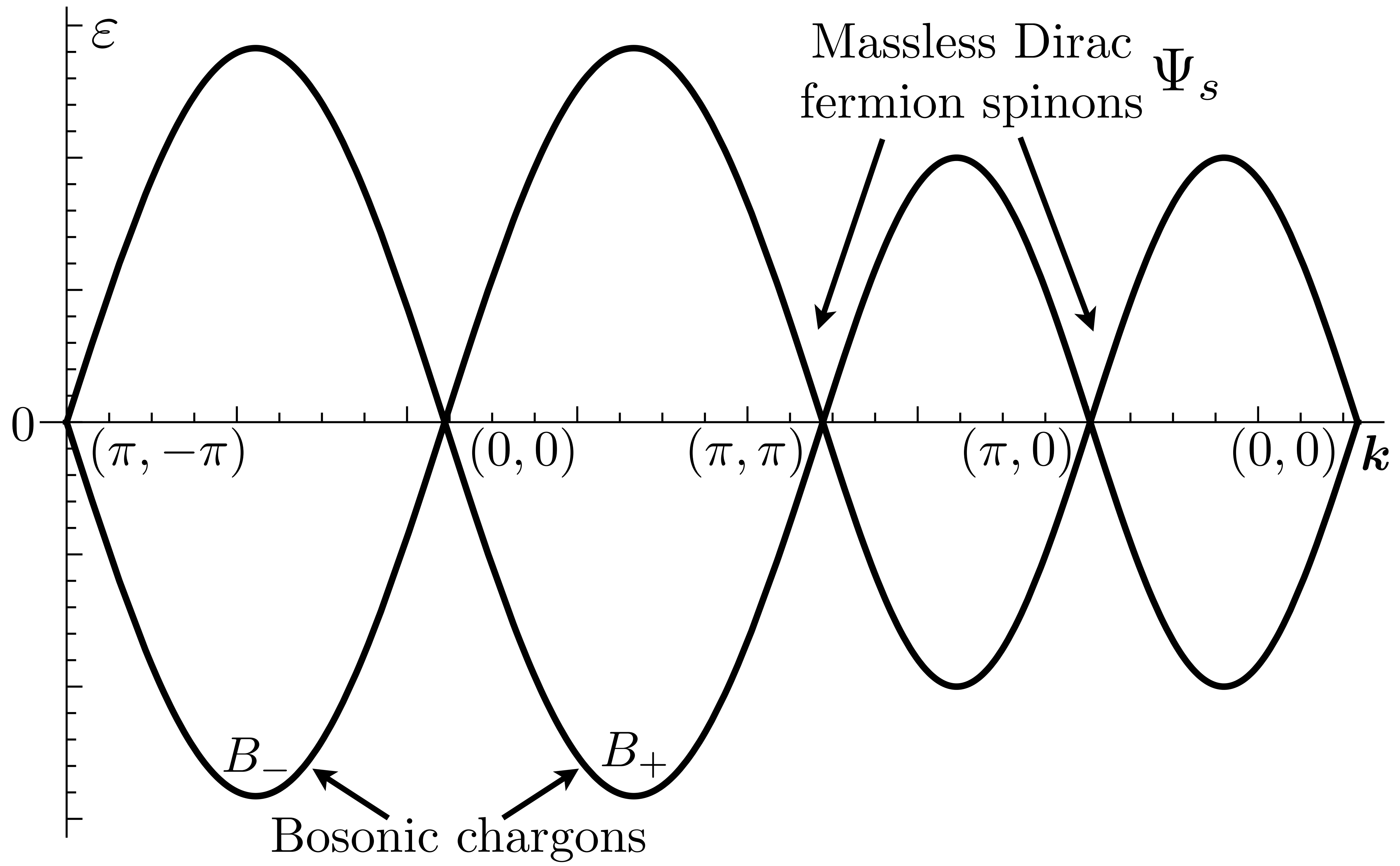
site charge density: $\left\langle c_{\boldsymbol{i}\alpha}^\dagger c_{\boldsymbol{i}\alpha} \right\rangle \sim \rho_{\boldsymbol{i}} = B_{\boldsymbol{i}}^\dagger B_{\boldsymbol{i}}$

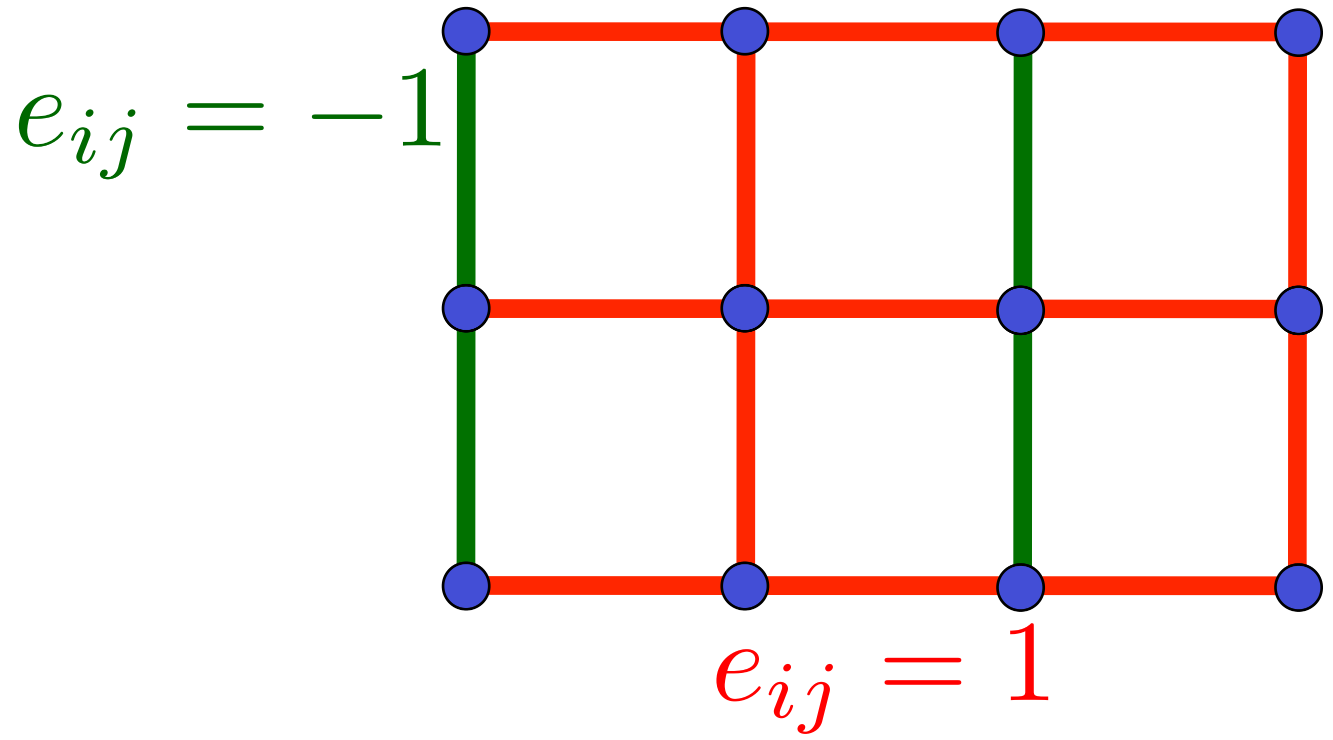
bond density: $\left\langle c_{\boldsymbol{i}\alpha}^\dagger c_{\boldsymbol{j}\alpha} + c_{\boldsymbol{j}\alpha}^\dagger c_{\boldsymbol{i}\alpha} \right\rangle \sim Q_{\boldsymbol{ij}} = Q_{\boldsymbol{ji}} = \mathrm{Im}\left(B_{\boldsymbol{i}}^\dagger e_{\boldsymbol{ij}} U_{\boldsymbol{ij}} B_{\boldsymbol{j}}\right)$

bond current: $i\left\langle c_{\boldsymbol{i}\alpha}^\dagger c_{\boldsymbol{j}\alpha} - c_{\boldsymbol{j}\alpha}^\dagger c_{\boldsymbol{i}\alpha} \right\rangle \sim J_{\boldsymbol{ij}} = -J_{\boldsymbol{ji}} = \mathrm{Re}\left(B_{\boldsymbol{i}}^\dagger e_{\boldsymbol{ij}} U_{\boldsymbol{ij}} B_{\boldsymbol{j}}\right)$

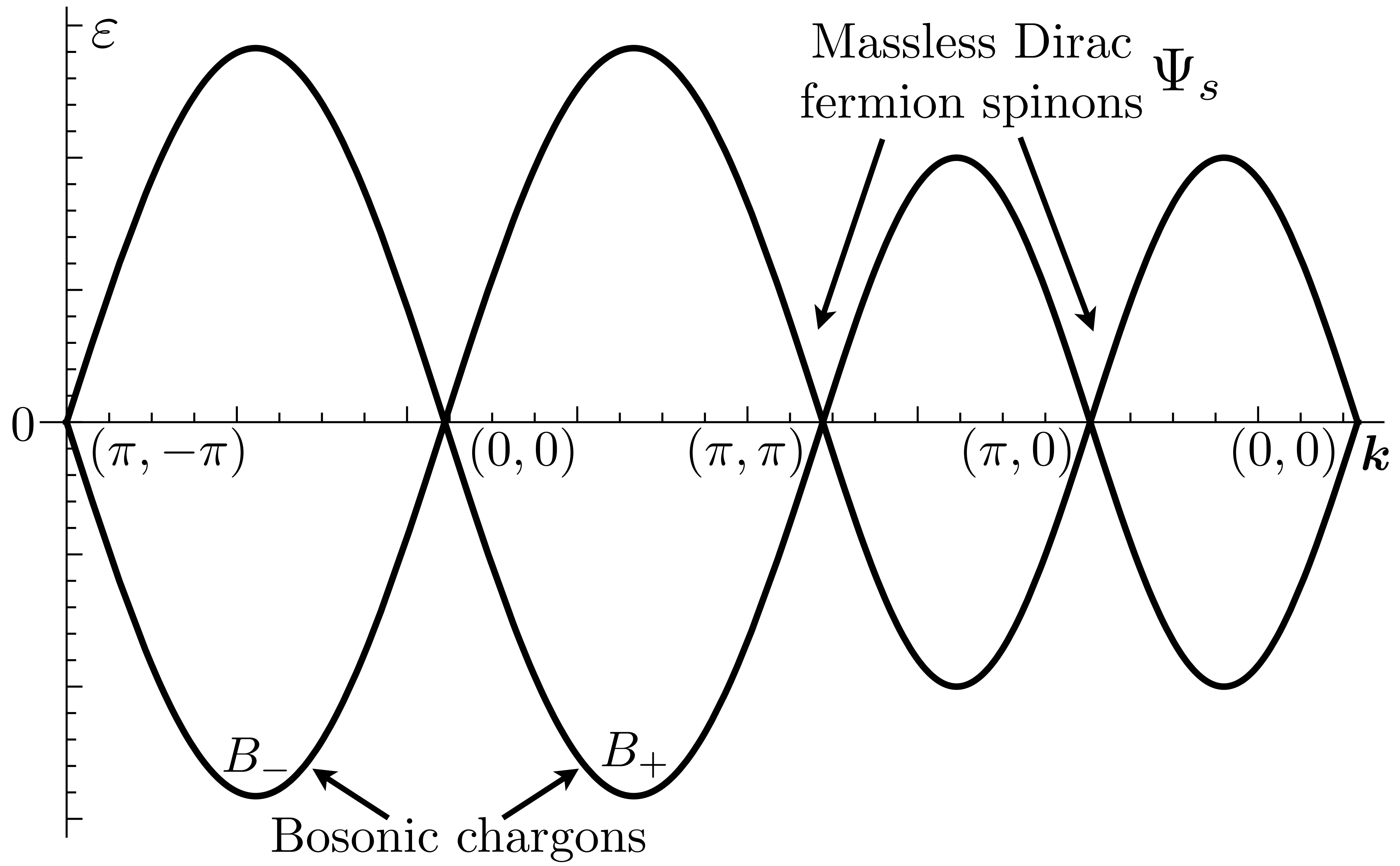
Pairing: $\langle \varepsilon_{\alpha\beta} c_{i\alpha} c_{j\beta} \rangle \sim \Delta_{\boldsymbol{ij}} = \Delta_{\boldsymbol{ji}} = \varepsilon_{ab} B_{a\boldsymbol{i}} e_{\boldsymbol{ij}} U_{\boldsymbol{ij}} B_{b\boldsymbol{j}}$.

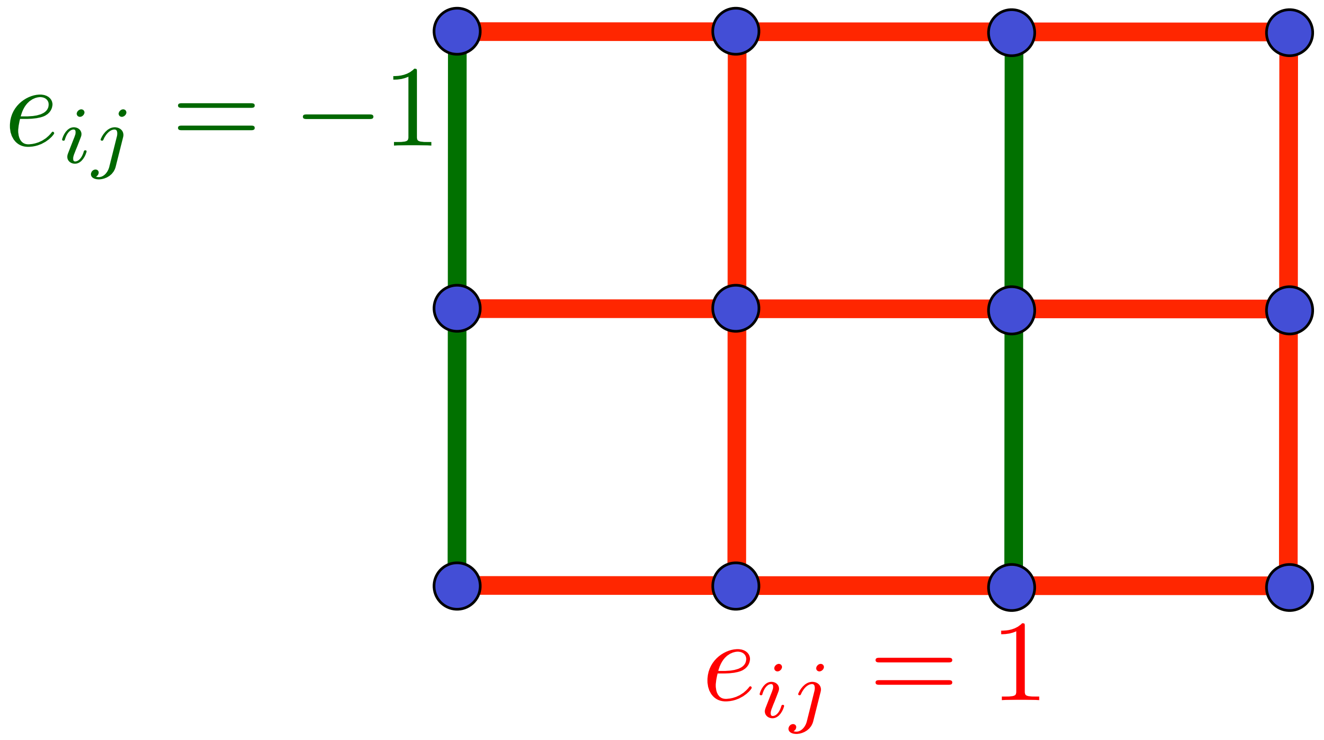
Confinement of SU(2)$_N$ gauge theory by charge fluctuations





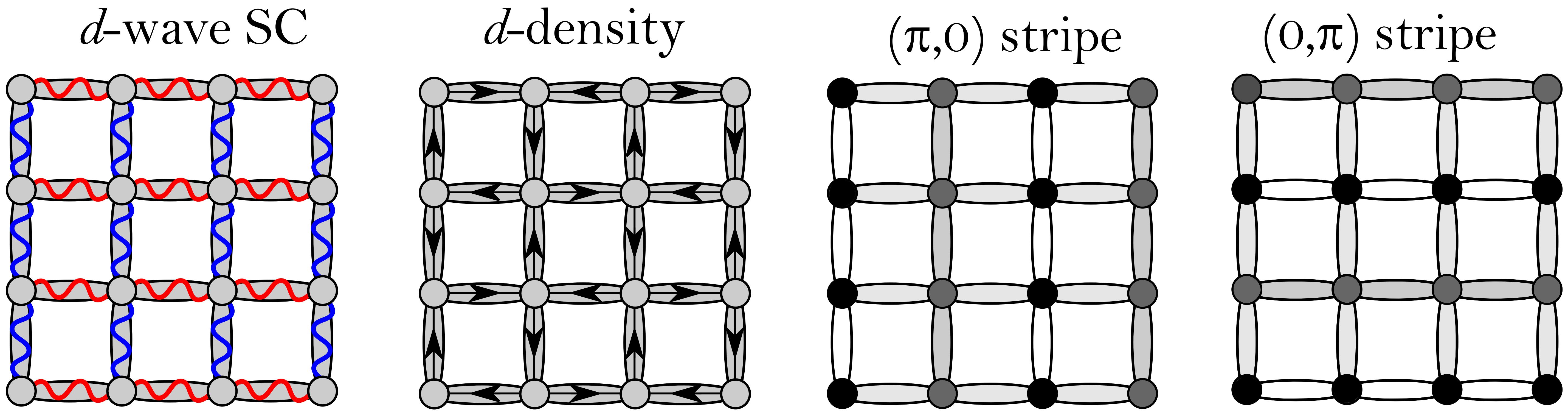
Confinement of SU(2)$_N$ gauge theory by charge fluctuations





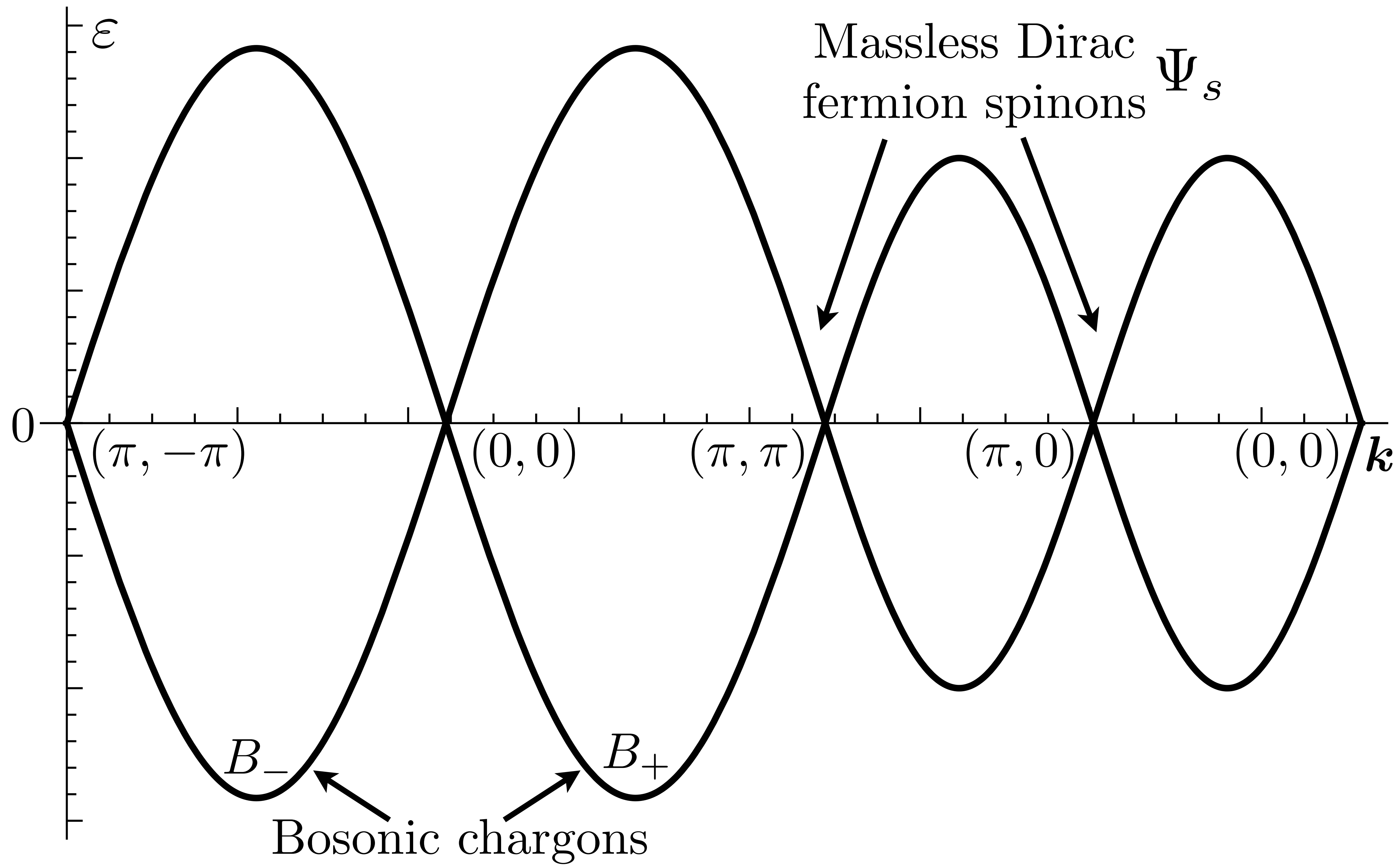
SU(2)$_N$ gauge-invariant and SU(2) spin invariant order parameters of Higgs phases:

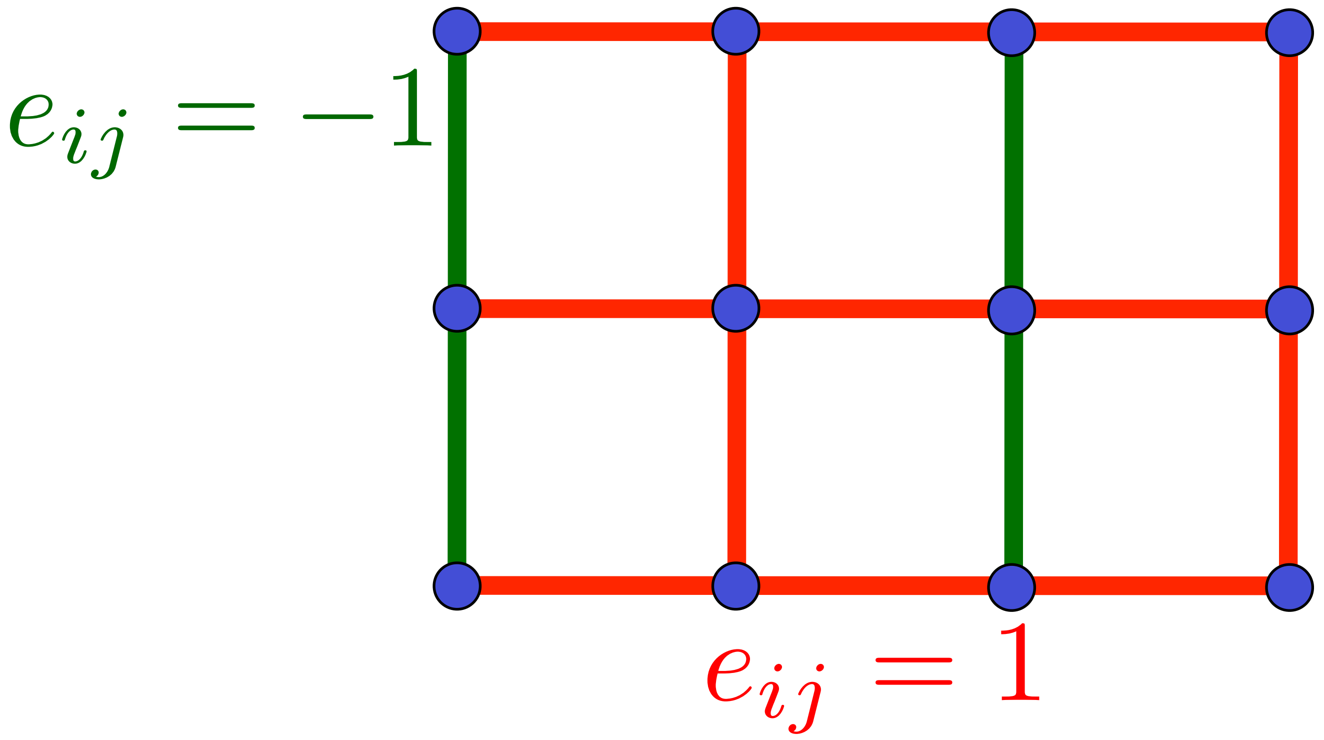
$$
\begin{aligned}
x\text{-CDW}: &\quad \rho_{(\pi,0)} = B^*_{a+}B_{a+} - B^*_{a-}B_{a-} \\
y\text{-CDW}: &\quad \rho_{(0,\pi)} = B^*_{a+}B_{a-} + B^*_{a-}B_{a+} \\
d\text{-density wave}: &\quad D = i\left(B^*_{a+}B_{a-} - B^*_{a-}B_{a+}\right) \\
d\text{-wave superconductor}: &\quad \Delta = \varepsilon_{ab}B_{a+}B_{b-}
\end{aligned}
$$



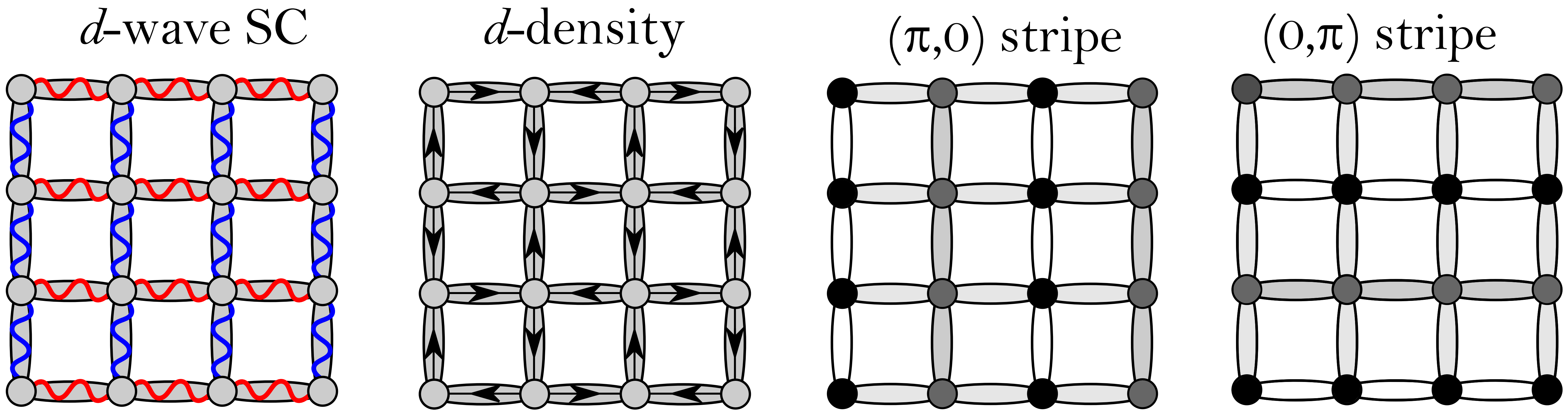
The $\mathcal{O}(B^2_{a\pm})$ terms in the energy have a SO(5)$_b$ rotation symmetry between these orders.

Confinement of SU(2)$_N$ gauge theory by charge fluctuations





The B_{av}
($a \to$ SU(2)$_N$ gauge, $v \to$ valley)
are the "square roots" of
conventional
d-wave superconductor,
charge density wave,
pair density wave
. . .



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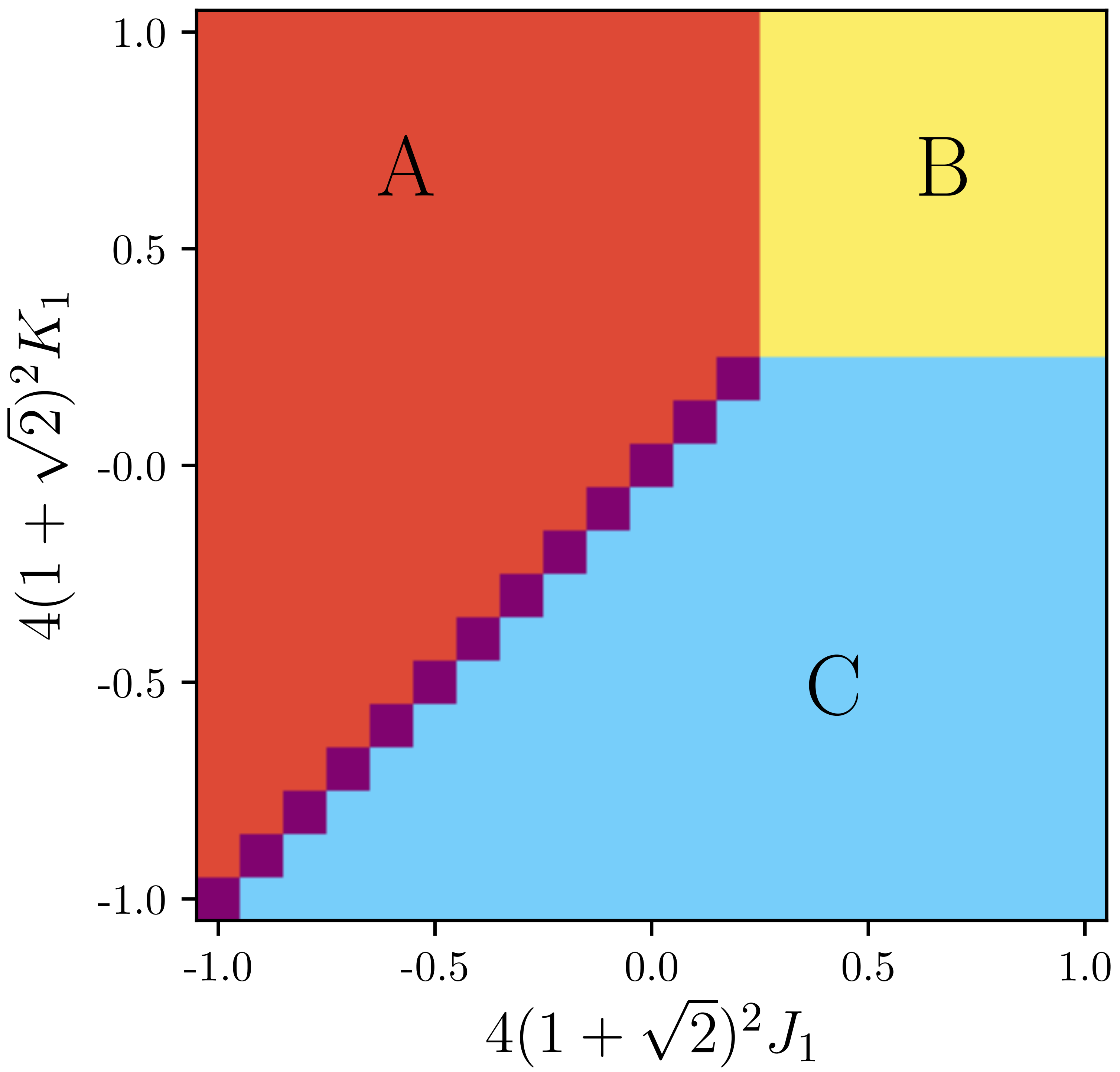
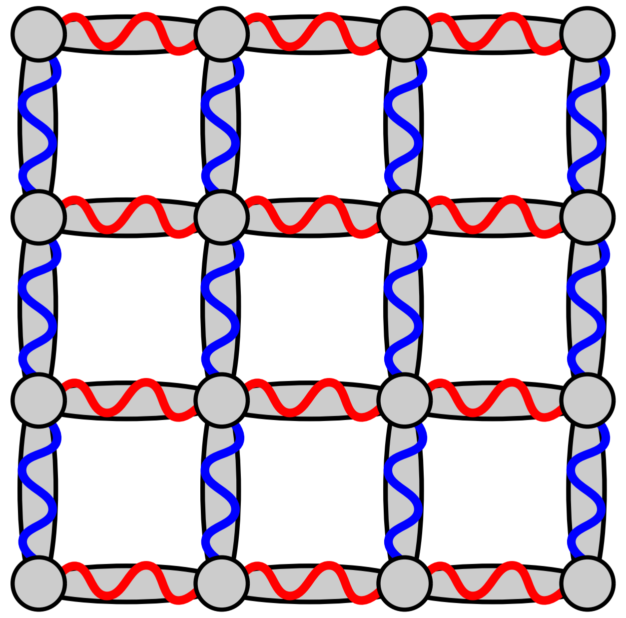
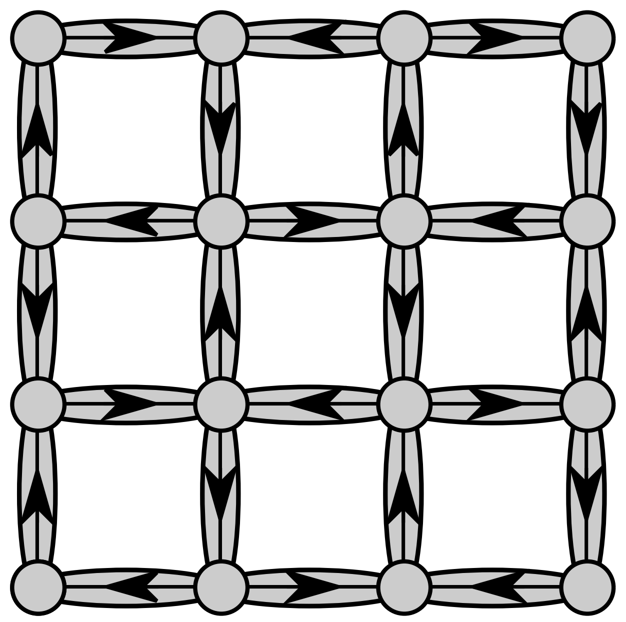


$$\langle B \rangle \neq 0$$

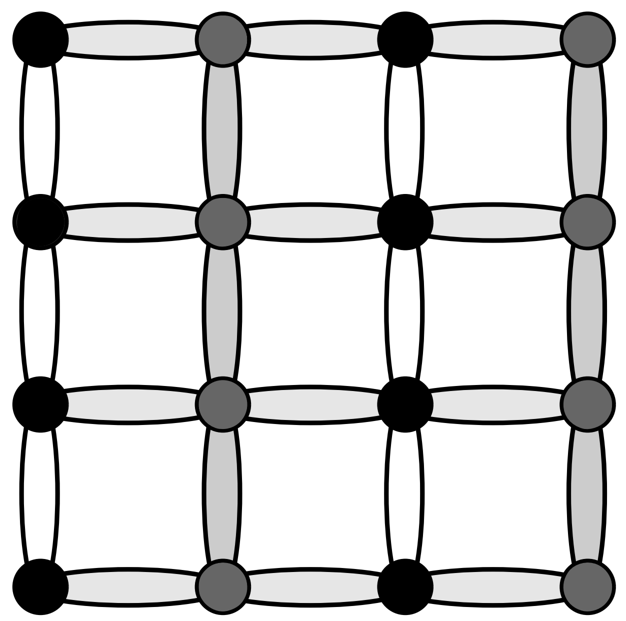
Phase B
d-wave SC



Phase C
d-density



Phase A
(π,0) stripe



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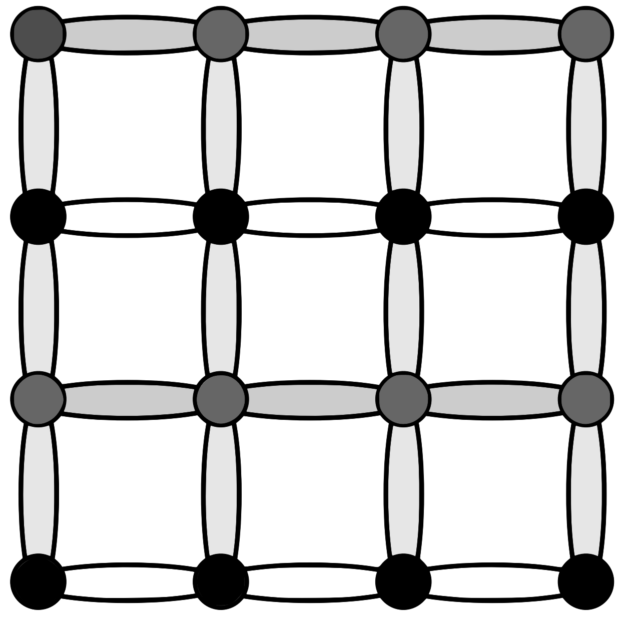

Global phase diagram of SU(2)$_N$ gauge theory

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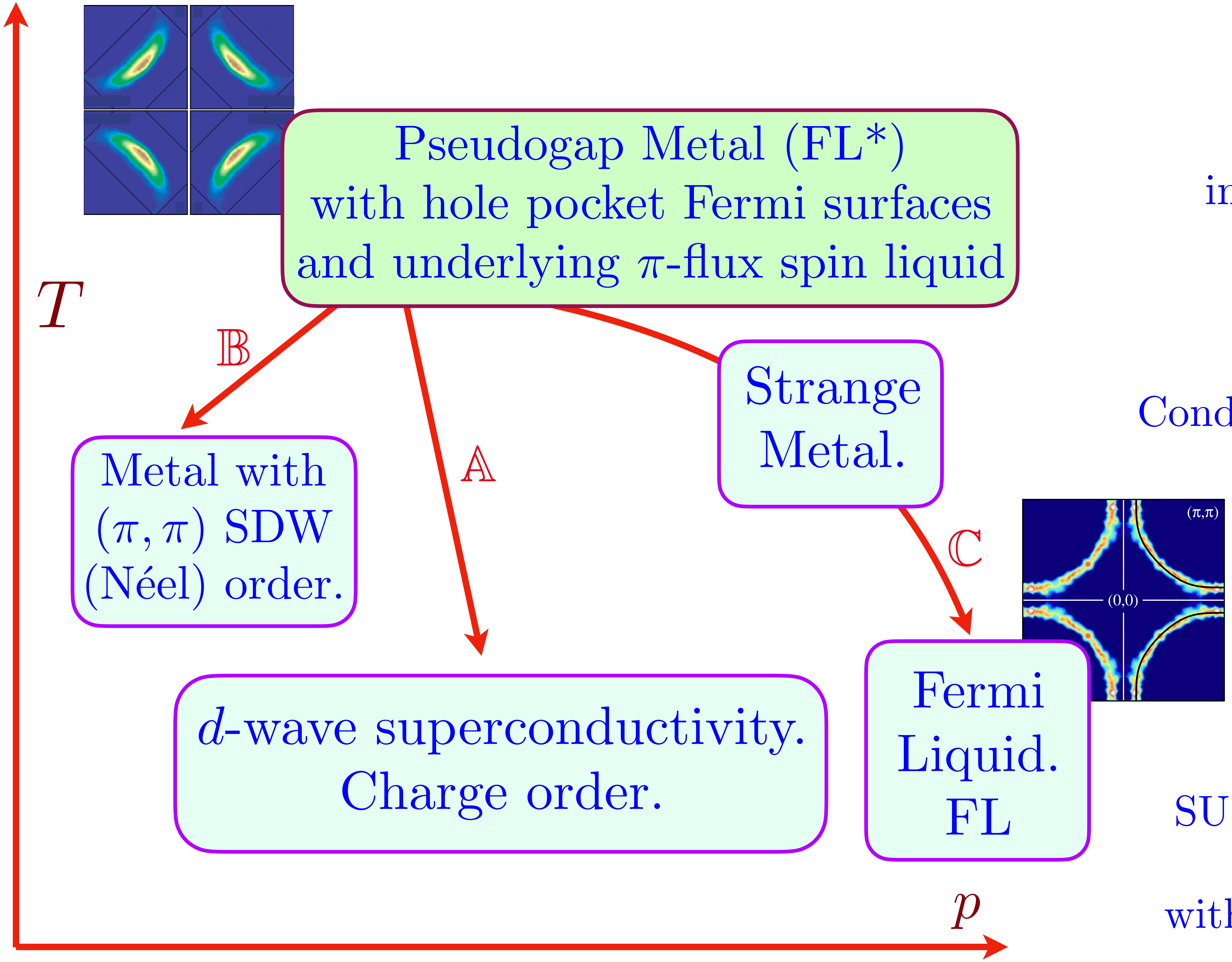

<u>Arrow $\mathbb{A}$</u>

Condensation of B
in SU(2)$_N$ gauge theory.

<u>Arrow $\mathbb{B}$</u>

Condensation of z_α in dual $\mathbb{CP}^1$
U(1) gauge theory.

<u>Arrow $\mathbb{C}$</u>

SU(2)$_s \times$U(1)$_a$ gauge theory
in ancilla model
with Higgs field $H_{\alpha a} \sim c_\alpha^\dagger f_{1a}$

Can the underlying spin liquid help understand experimental observations of spin dynamics ?

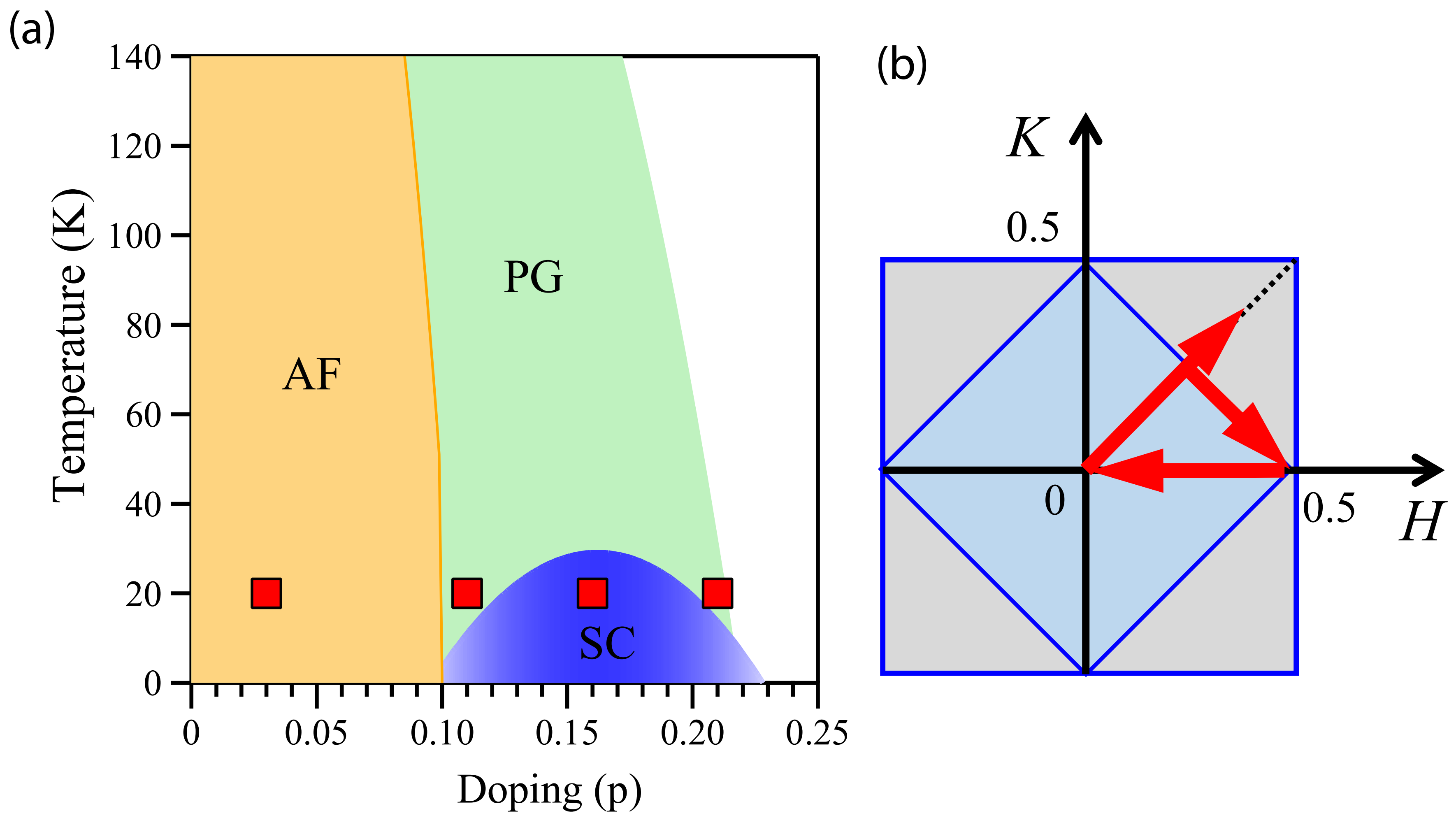

FIG. 1. (a) Schematic temperature-doping phase diagram of (Bi,Pb)$_2$(Sr,La)$_2$CuO$_{6+\delta}$. It shows the antiferromagnetic (AF), superconducting (SC), and the pseudogap (PG) regions. Here we study four doping levels as indicated by the solid red squares. (b) 2D reciprocal lattice for the pseudotetragonal structure and the first Brillouin zones (structural in light grey, magnetic in light blue). Coordinates H and K are in r.l.u.. The path followed for the measurements is indicated by the red arrows, starting at (0.25,0.25) and ending around (0.30,0.30) via (0.5,0) and (0,0).

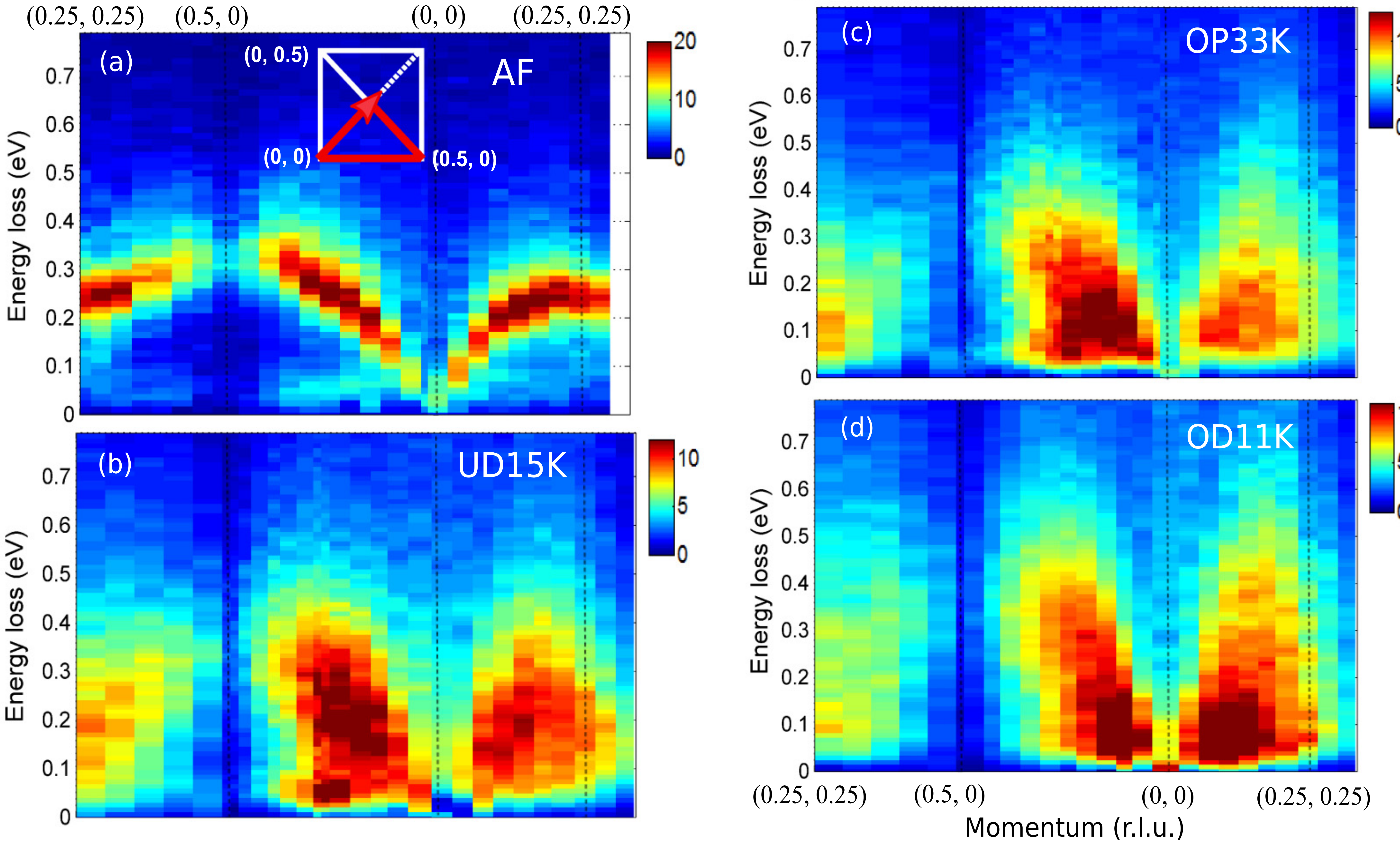

FIG. 2. Energy/momentum intensity maps of RIXS spectra for (a) AF ($p \simeq 0.03$), (b) UD15K ($p \simeq 0.11$), (c) OP33K ($p \simeq 0.16$), and (d) OD11K ($p \simeq 0.21$) along the high-symmetry momentum trajectory indicated in Fig. 1(b) and in the inset of (a). The intensity is in unit of photons/s/eV. Data were taken with π-polarized incident light at 20 K. Elastic peaks were subtracted for a better visualization of the low energy features.

Dispersion, damping, and intensity of spin excitations in the monolayer (Bi,Pb)$_2$(Sr,La)$_2$CuO$_{6+\delta}$ cuprate superconductor family, Y.Y. Peng *et al.*, PRB **98**, 144507 (2018)

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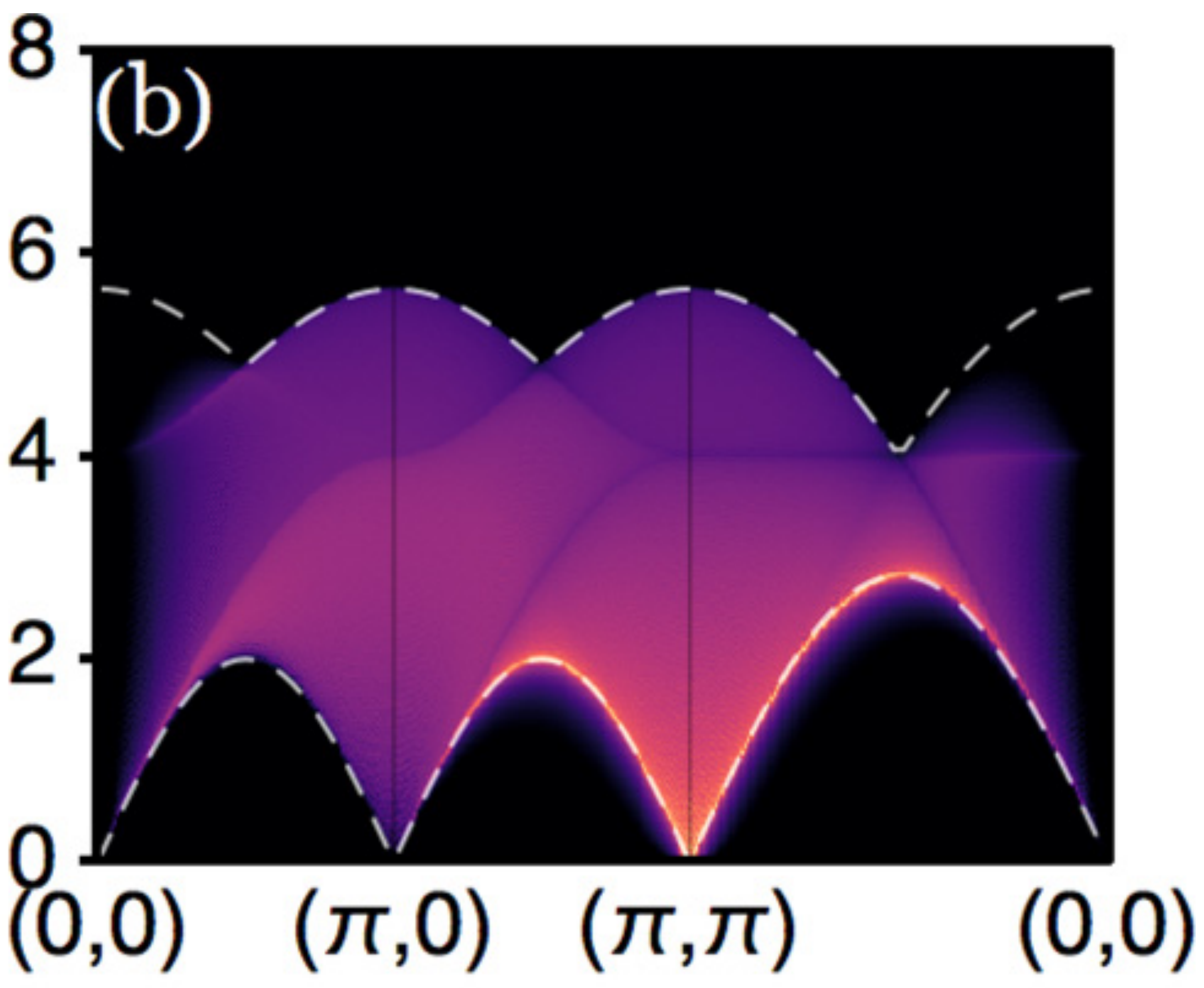
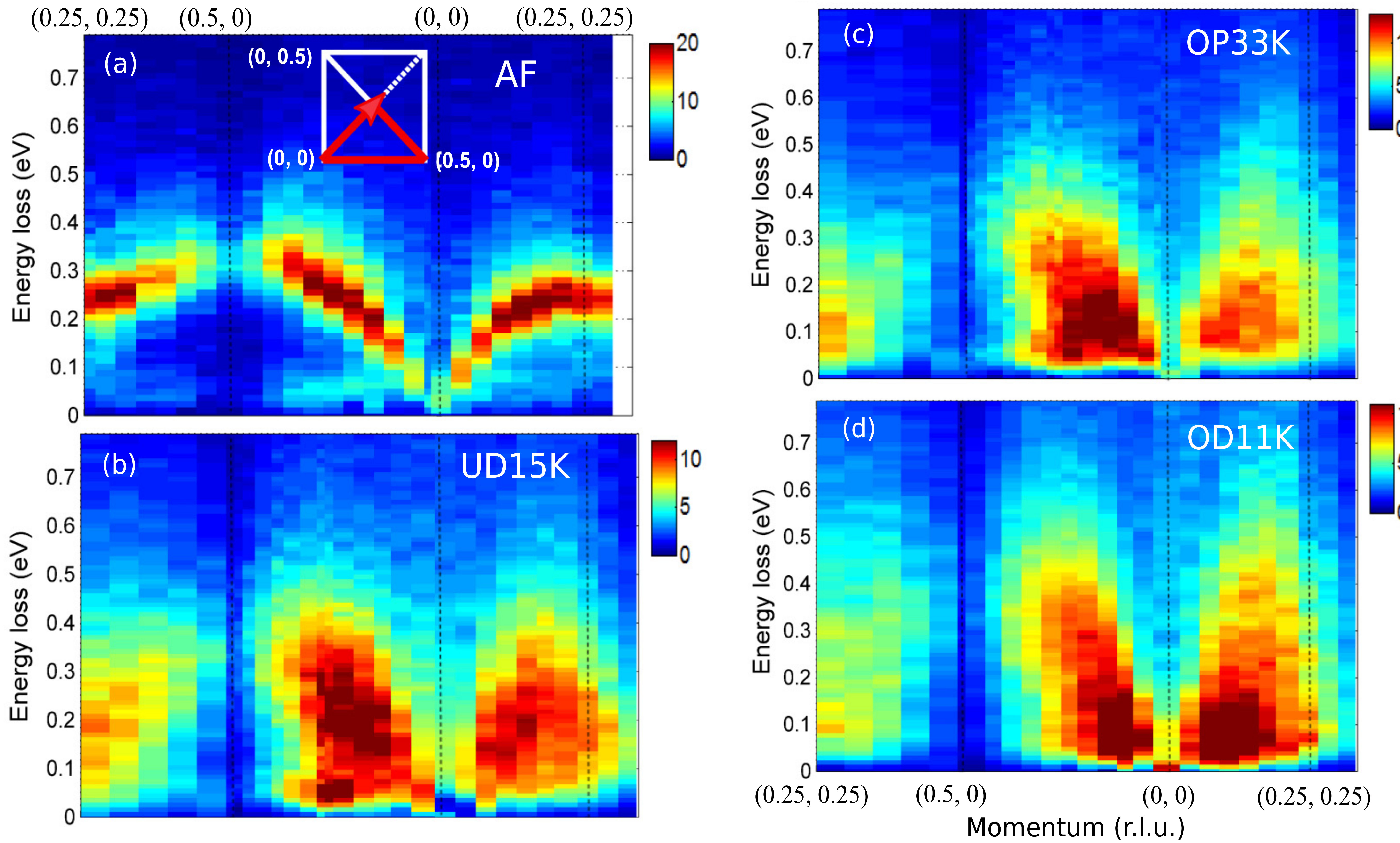


Free fermion spinons in π-flux



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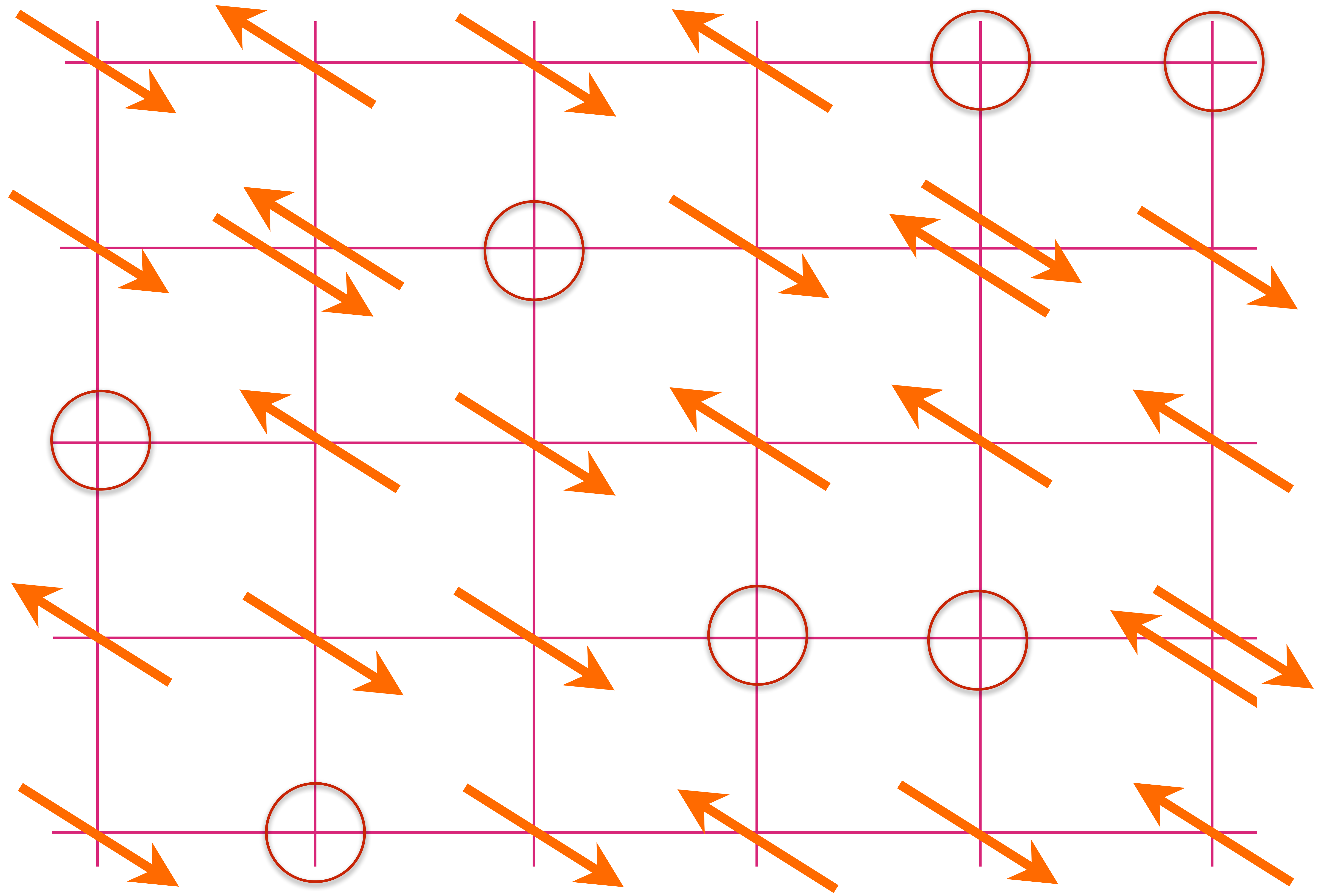
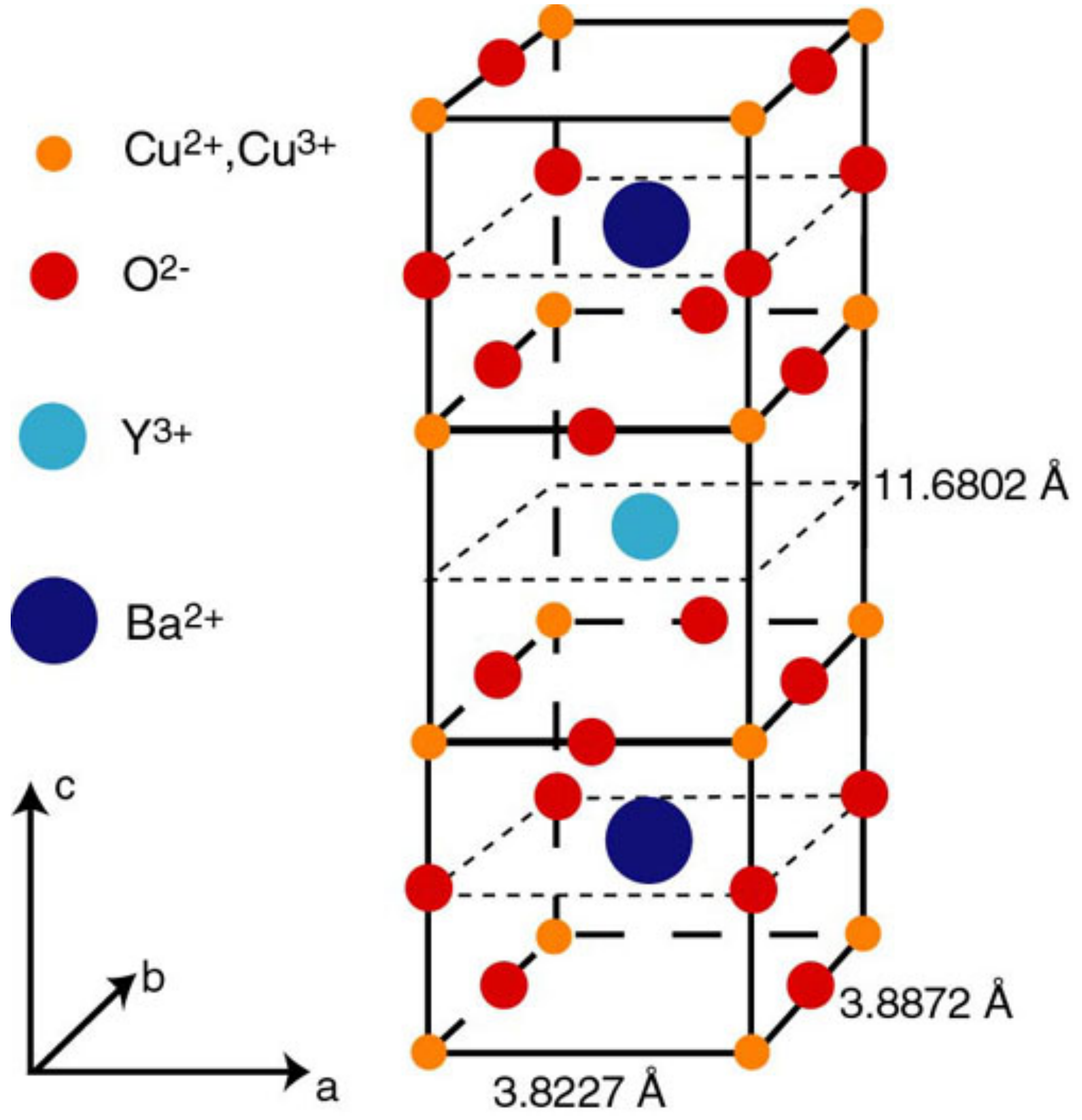
1. Open questions on the cuprate phase diagram
2. Theory of the pseudogap metal
3. The π-flux spin liquid
4. Confinement transitions of the π-flux spin liquid
5. Recap

Square lattice Hubbard model with electron density $1 - p$.

$$\mathcal{H}_{\text{Hubbard}} = \sum_{\mathbf{p}} \varepsilon_{\mathbf{p}} c^\dagger_{\mathbf{p}\alpha} c_{\mathbf{p}\alpha} + U \sum_i n_{i\uparrow} n_{i\downarrow} + \dots$$





$YBa_2Cu_3O_{6+x}$

Unified SU(2)xU(1) gauge theory of spinons, electrons and Higgs bosons:

uncanny similarities to the Salam-Weinberg-Glashow theory of weak interactions

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- The fermionic spinons transform as a fundamental of gauge SU(2), with a massless Dirac spectrum

$$H_f = iJ \sum_{\langle ij \rangle} e_{ij} \left(\Psi_i^\dagger U_{ij} \Psi_j - \Psi_j^\dagger U_{ji} \Psi_i \right) ,$$

where U_{ij} is the (lattice) SU(2) gauge field. The spinons are the analog of the neutrinos

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$$H_B = r \sum_i B_i^\dagger B_i + iw \sum_{\langle ij \rangle} e_{ij} \left(B_i^\dagger U_{ij} B_j - B_j^\dagger U_{ji} B_i \right) + \mathcal{O}(B_i^4)$$

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- The hole pockets in the nodal region of the Brillouin zone are described by electron $\bar{c}_{i\alpha}$ which have a Yukawa coupling to the spinons and the Higgs field $B_i = (B_{1i}, B_{2i})$:

$$H_Y = \sum_{ij} \bar{t}_{ij} \bar{c}_{i\alpha}^\dagger \bar{c}_{j\alpha} + i \sum_i \left(B_{1i} f_{i\alpha}^\dagger \bar{c}_{i\alpha} - B_{2i} \varepsilon_{\alpha\beta} f_{i\alpha} \bar{c}_{i\beta} \right) + \text{H.c.} \,.$$