Stripes, d-wave superconductivity, and quantum spin liquids

Stripes, Planckian Dissipation and Quantum Supremacy

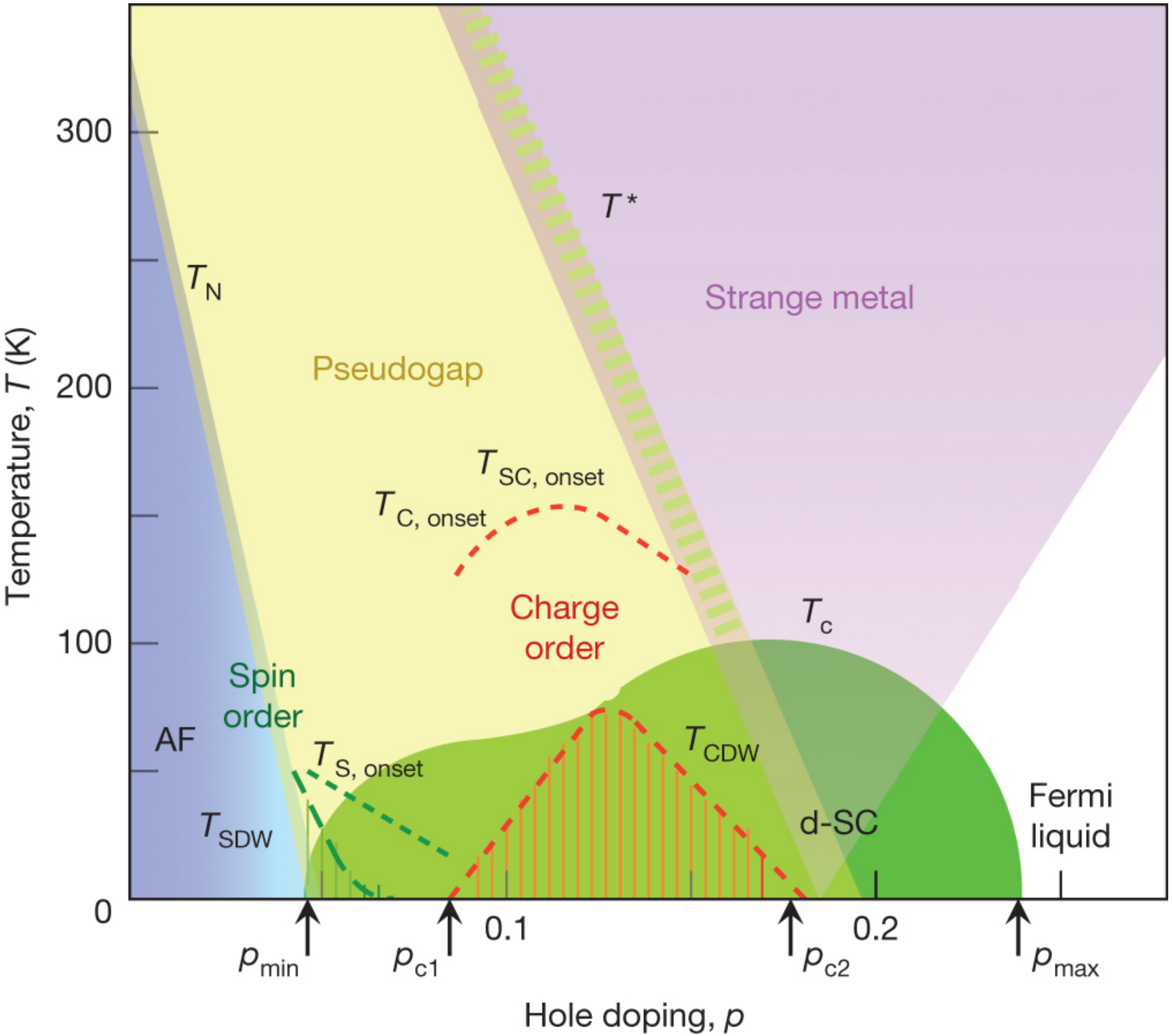
Zaanen Fest

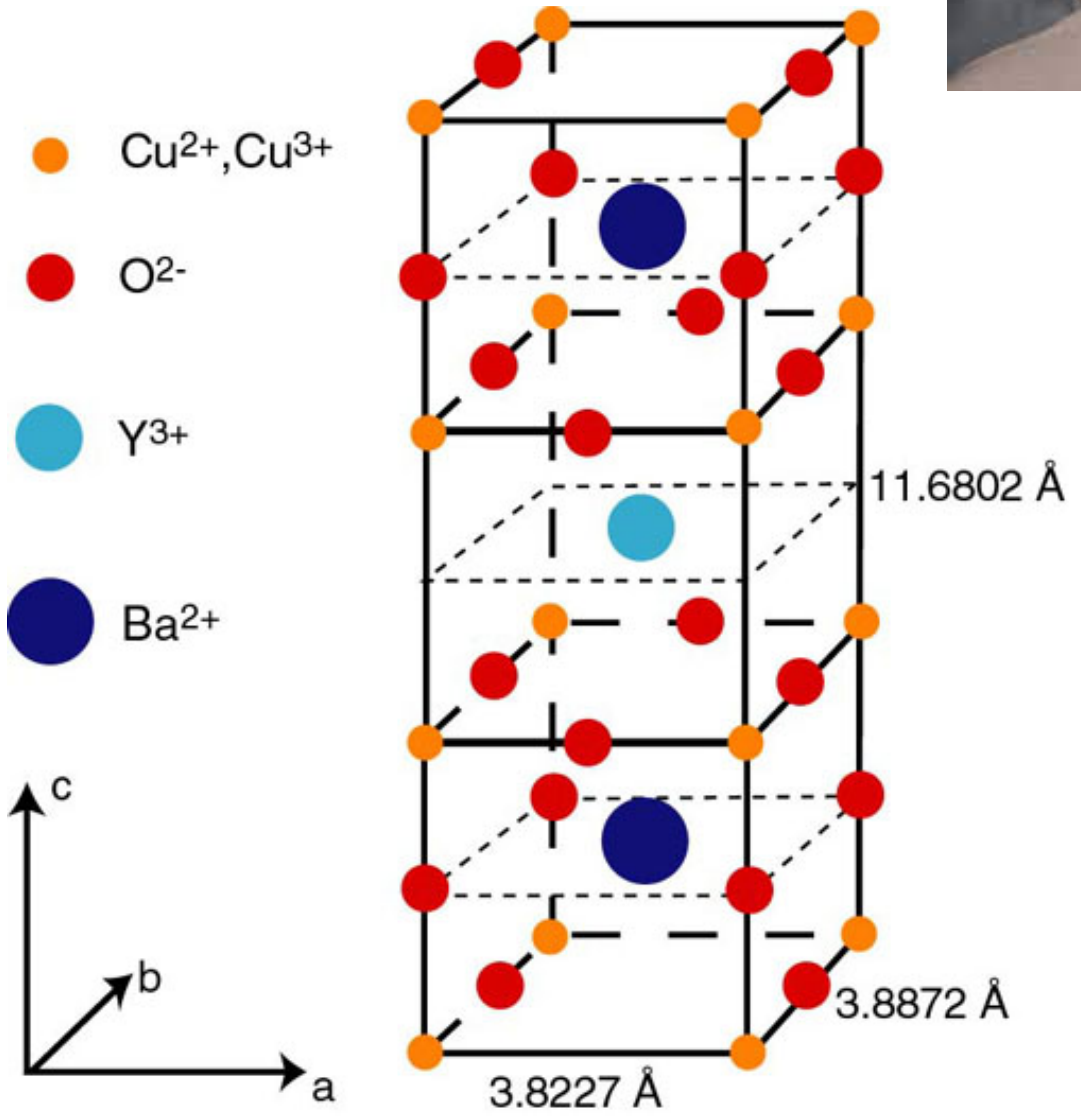
Leiden University
July 17, 2023
Subir Sachdev

Talk online: sachdev.physics.harvard.edu

PHYSICS
HARVARD

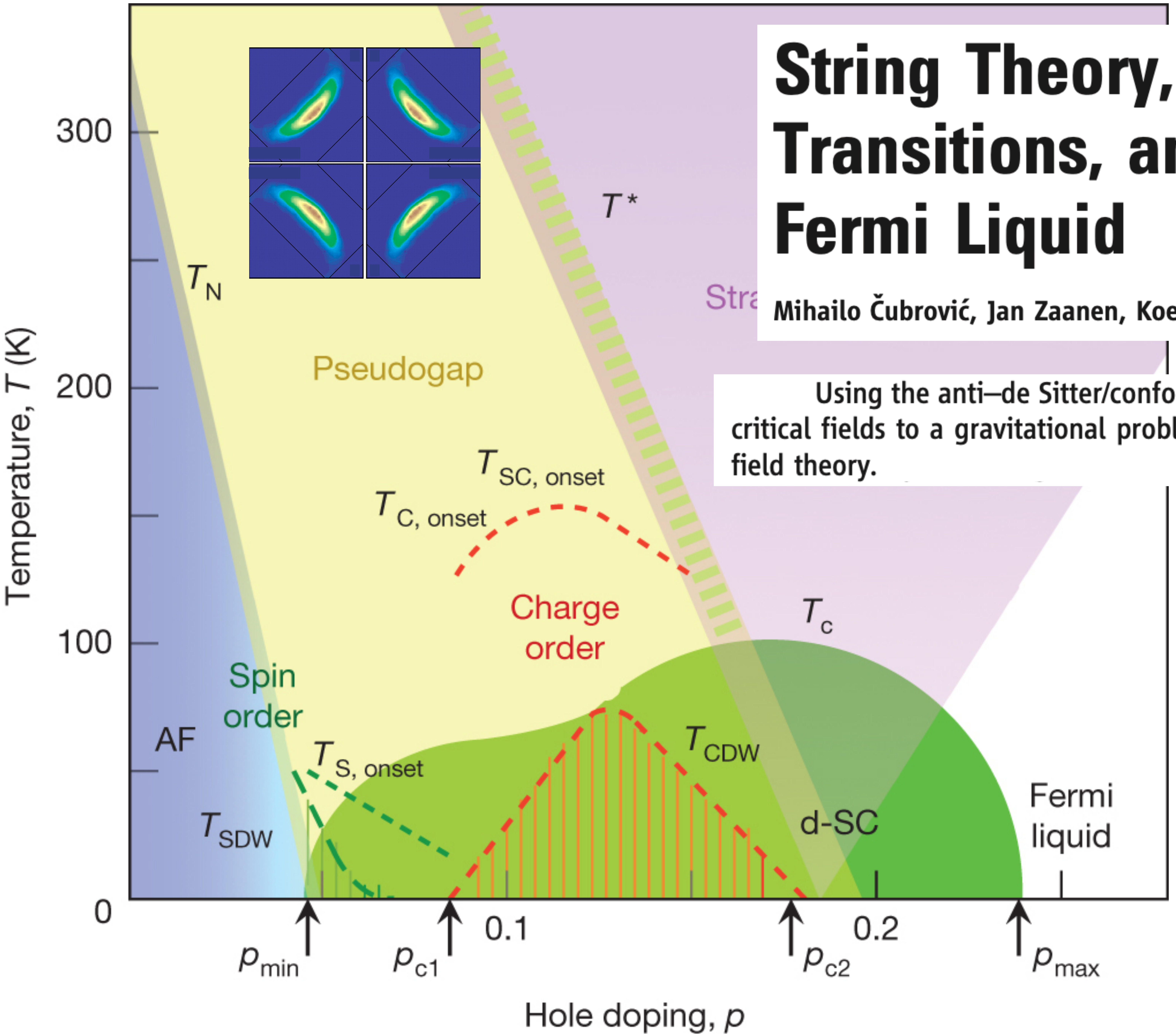
B Keimer, S.A. Kivelson, M.R. Norman, S. Uchida, **J. Zaanen**, *Nature* **518**, 179 (2015)





$YBa_2Cu_3O_{6+x}$

B Keimer, S.A. Kivelson, M.R. Norman, S. Uchida, **J. Zaanen**, *Nature* **518**, 179 (2015)



String Theory, Quantum Phase Transitions, and the Emergent Fermi Liquid

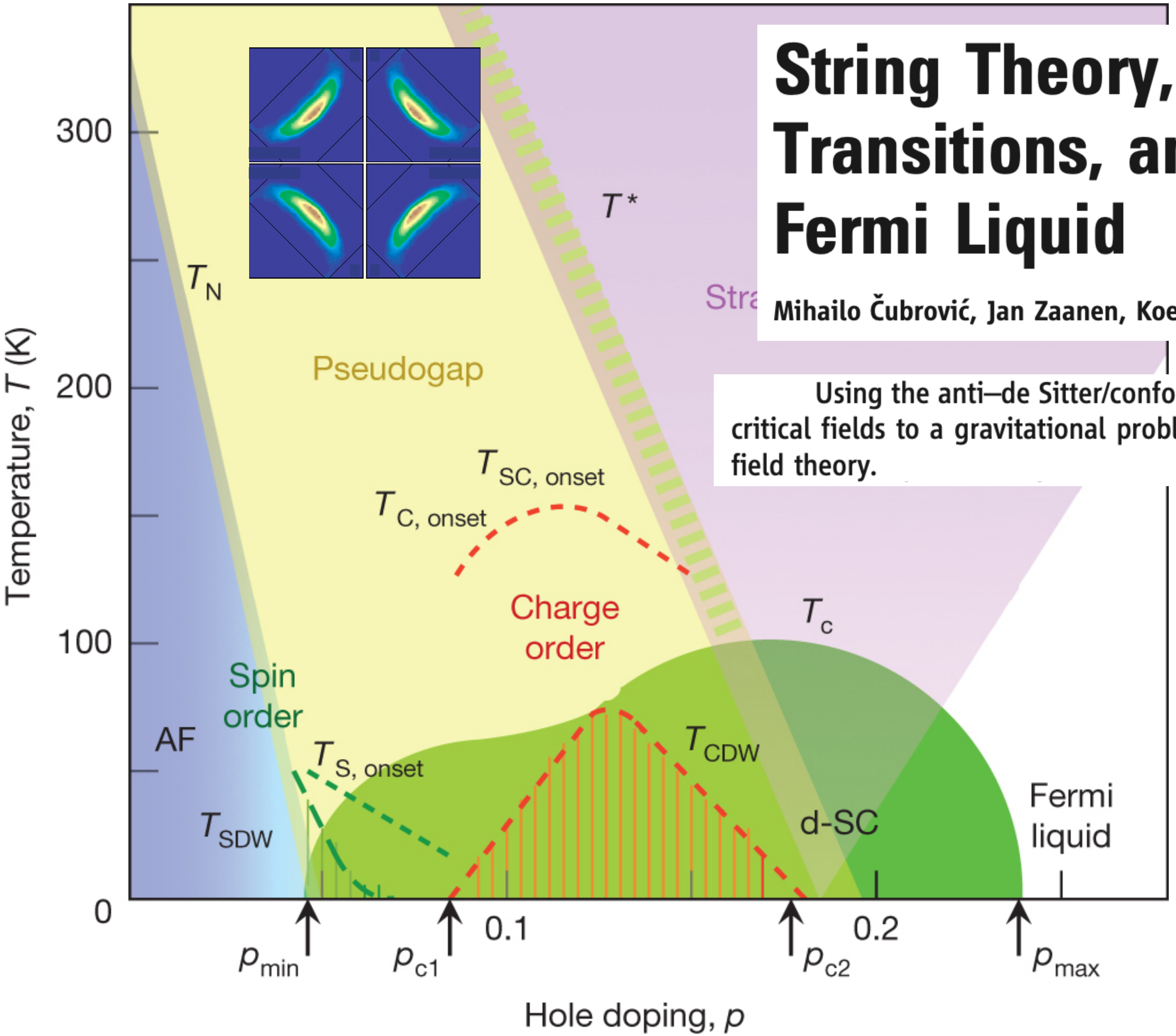
SCIENCE VOL 325 24 JULY 2009 **439**

Mihailo Čubrović, Jan Zaanen, Koenraad Schalm*

Using the anti–de Sitter/conformal field theory correspondence to relate fermionic quantum critical fields to a gravitational problem, we computed the spectral functions of fermions in the field theory.

"Probe" fermions form "small" Fermi surfaces in the presence of AdS_2 geometry describing a background "spin liquid".

B Keimer, S.A. Kivelson, M.R. Norman, S. Uchida, **J. Zaanen**, *Nature* **518**, 179 (2015)



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SS (2010): The AdS_2 spin liquid is described by the SY(K) model

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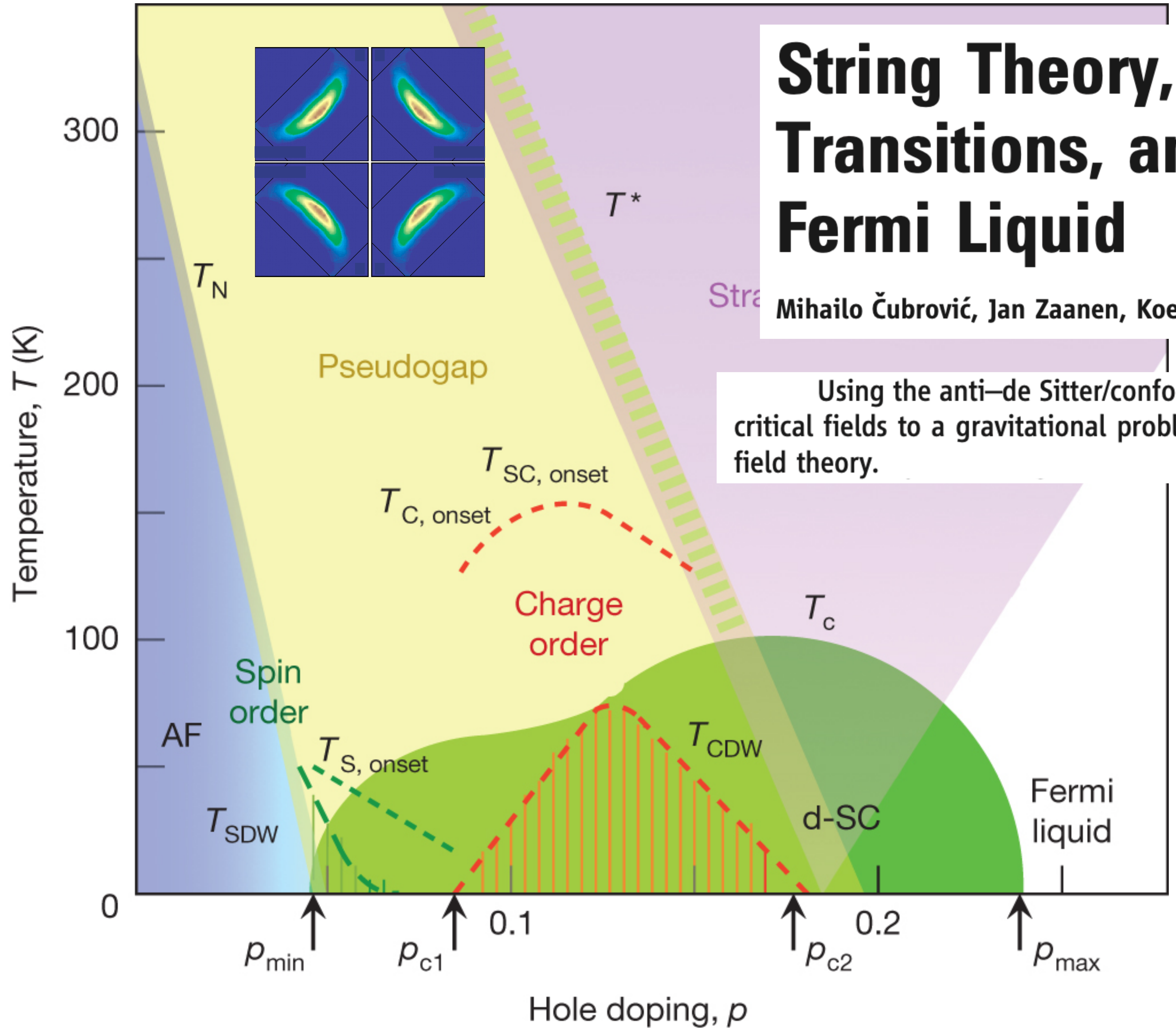

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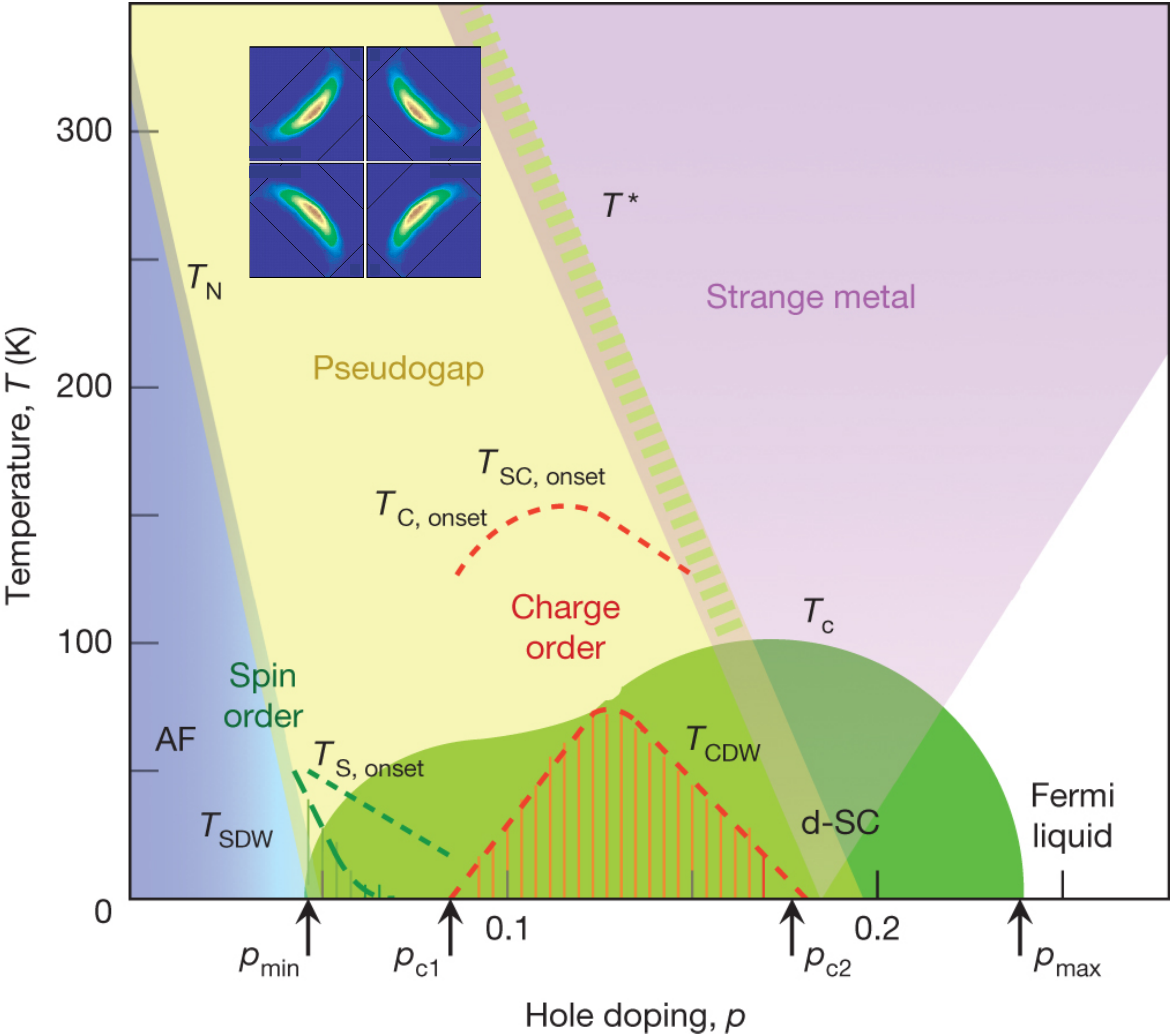
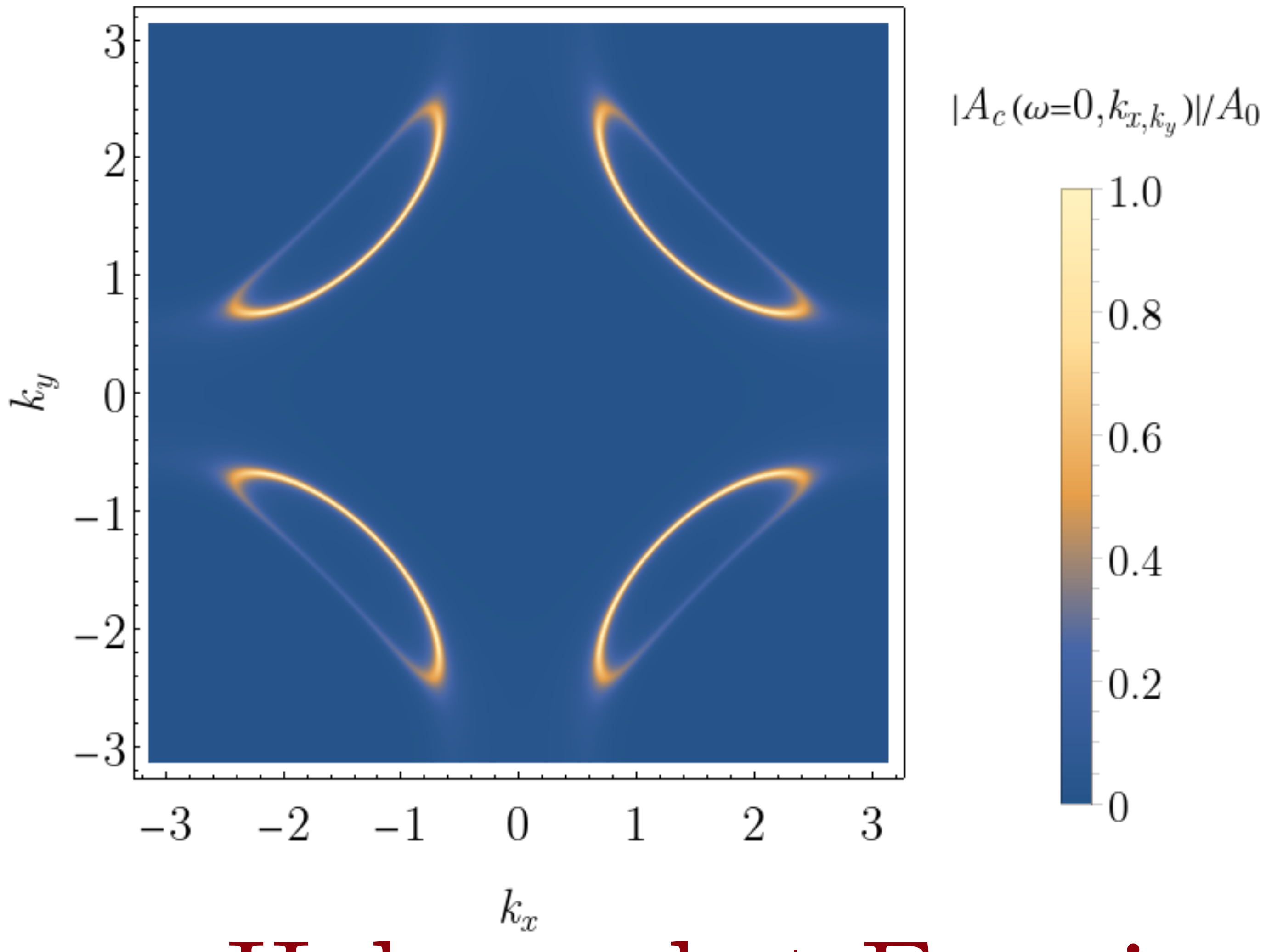
This has transformed quantum gravity studies of black holes, and has led to a (partial) resolution of Hawking's information paradox.

B Keimer, S.A. Kivelson, M.R. Norman, S. Uchida, **J. Zaanen**, *Nature* **518**, 179 (2015)



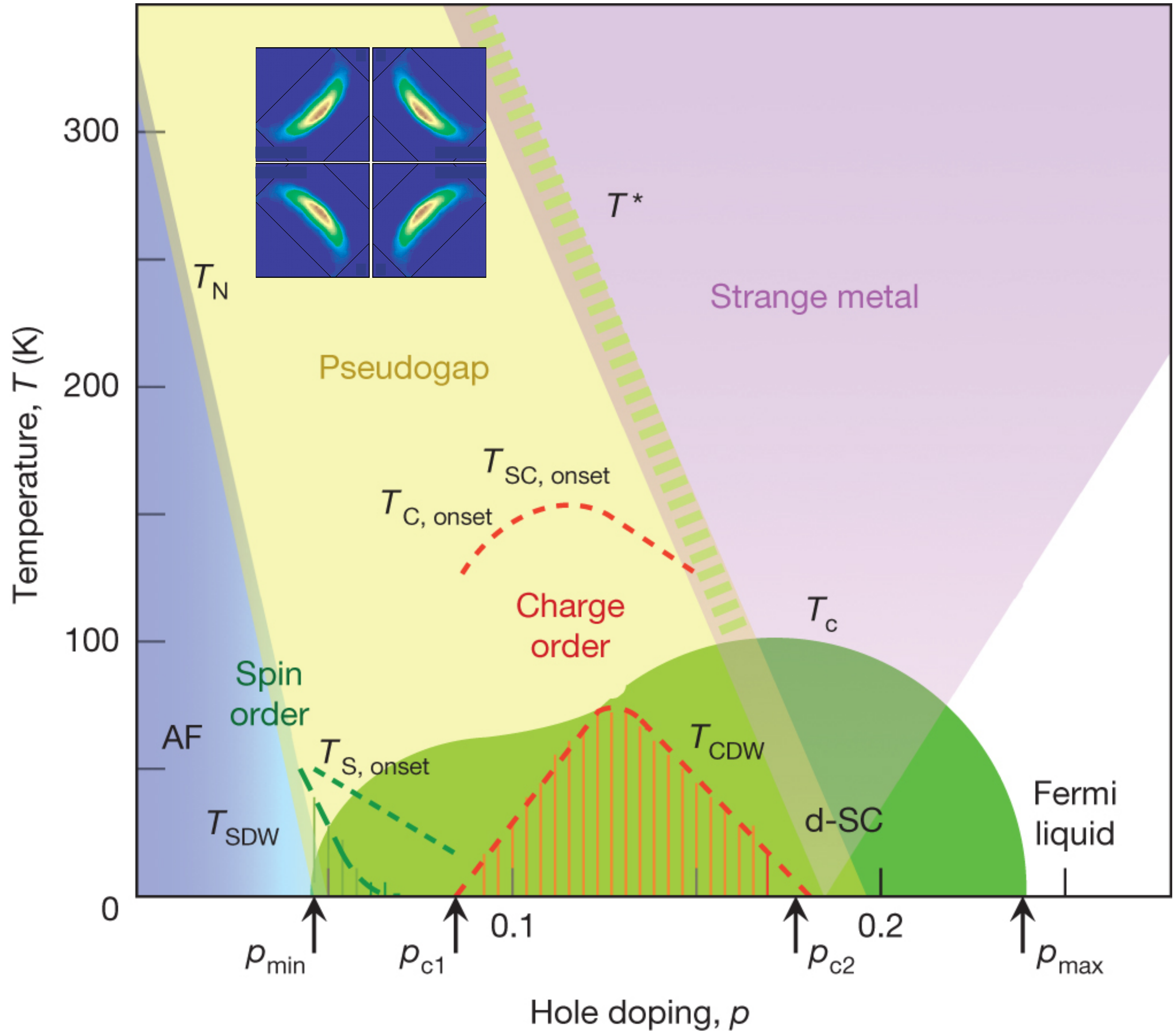


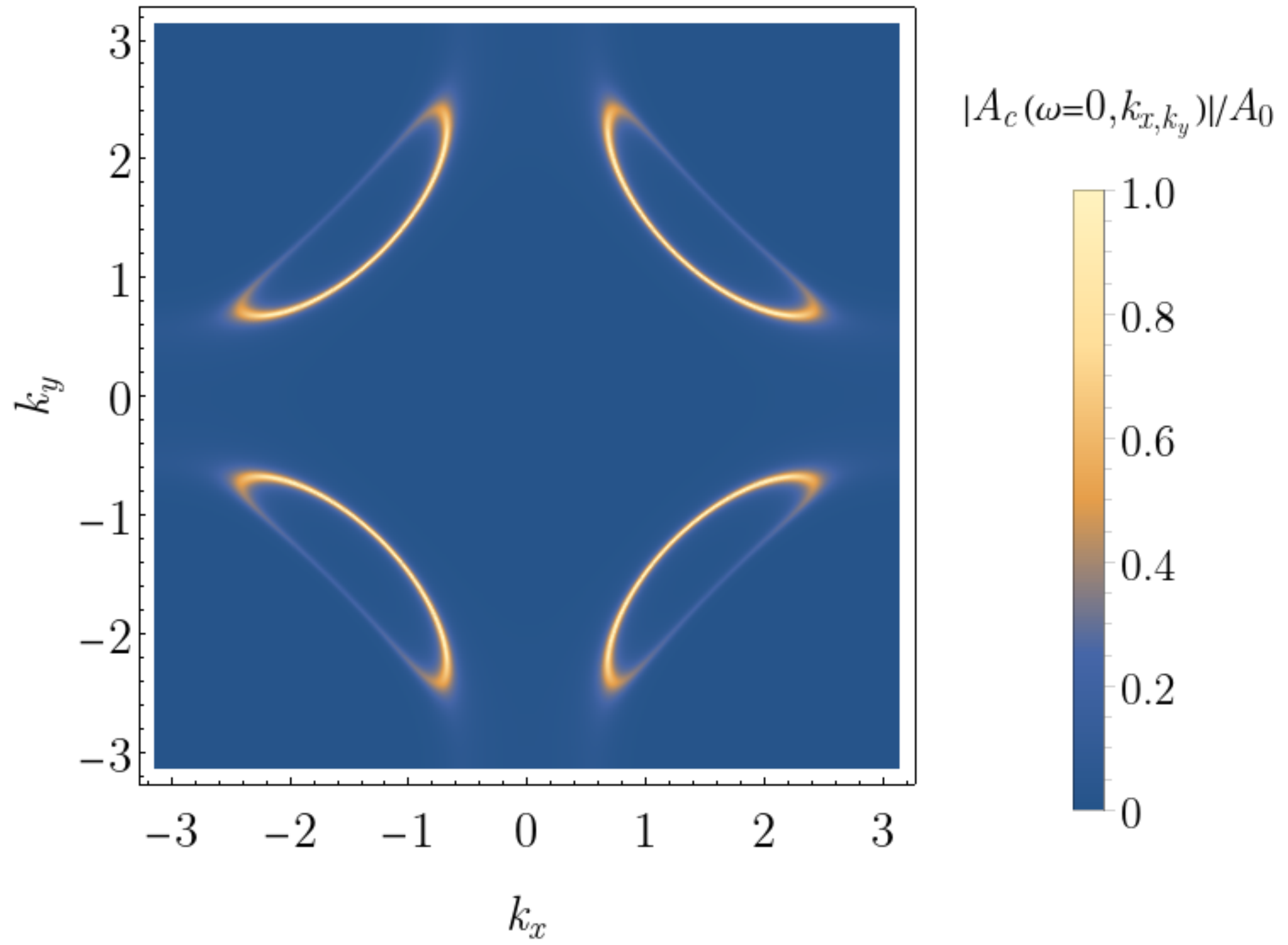
E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, and S. S., PRB **105**, 075146 (2022)

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

Kai-Yu Yang, T. M. Rice, Fu-Chun Zhang, 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).
Jinchao Zhao, Gabriele La Nave, Philip Phillips, arXiv:2304.04787.

B Keimer, S.A. Kivelson, M.R. Norman, S. Uchida, **J. Zaanen**, *Nature* **518**, 179 (2015)





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

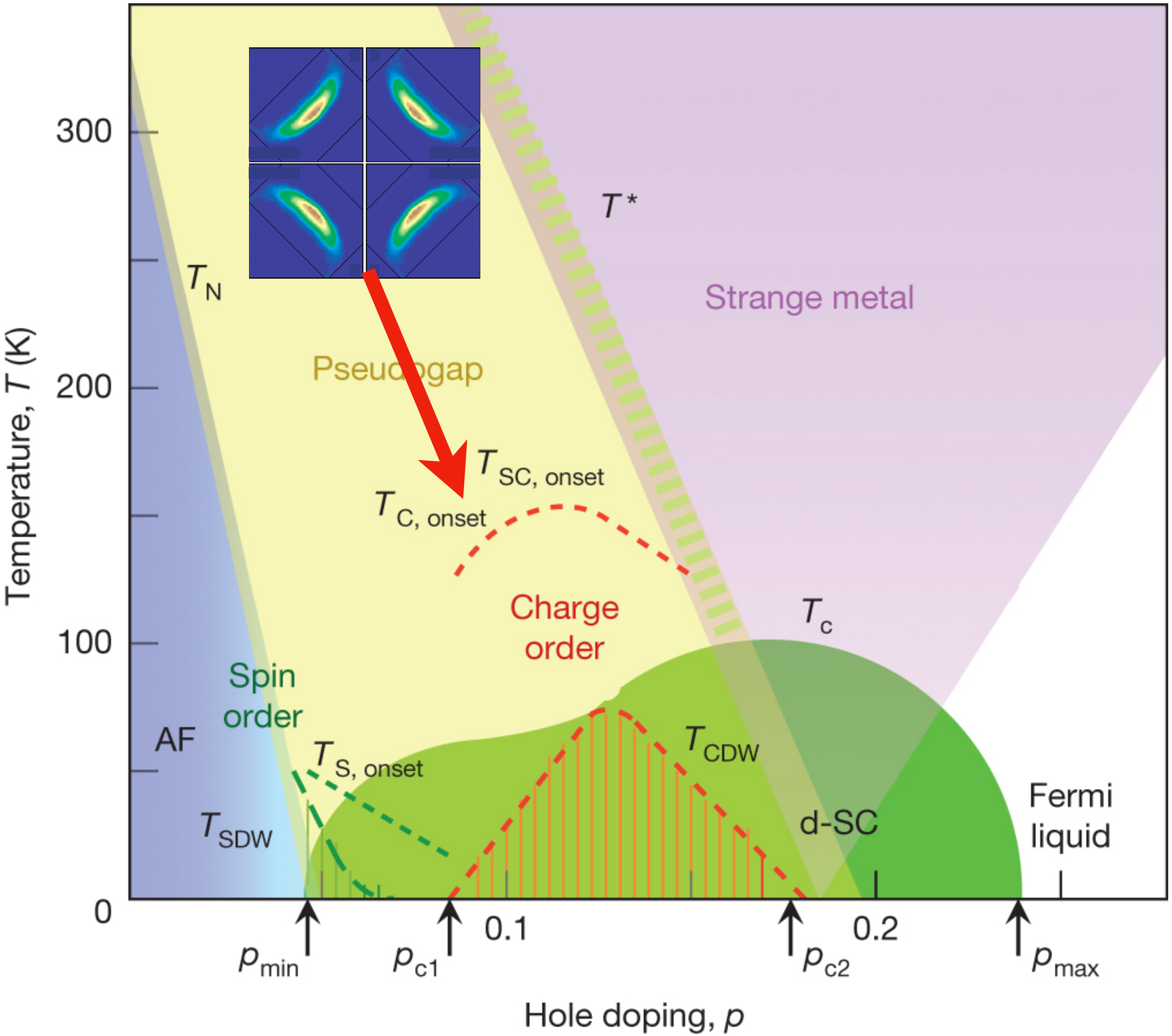
$+$

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

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

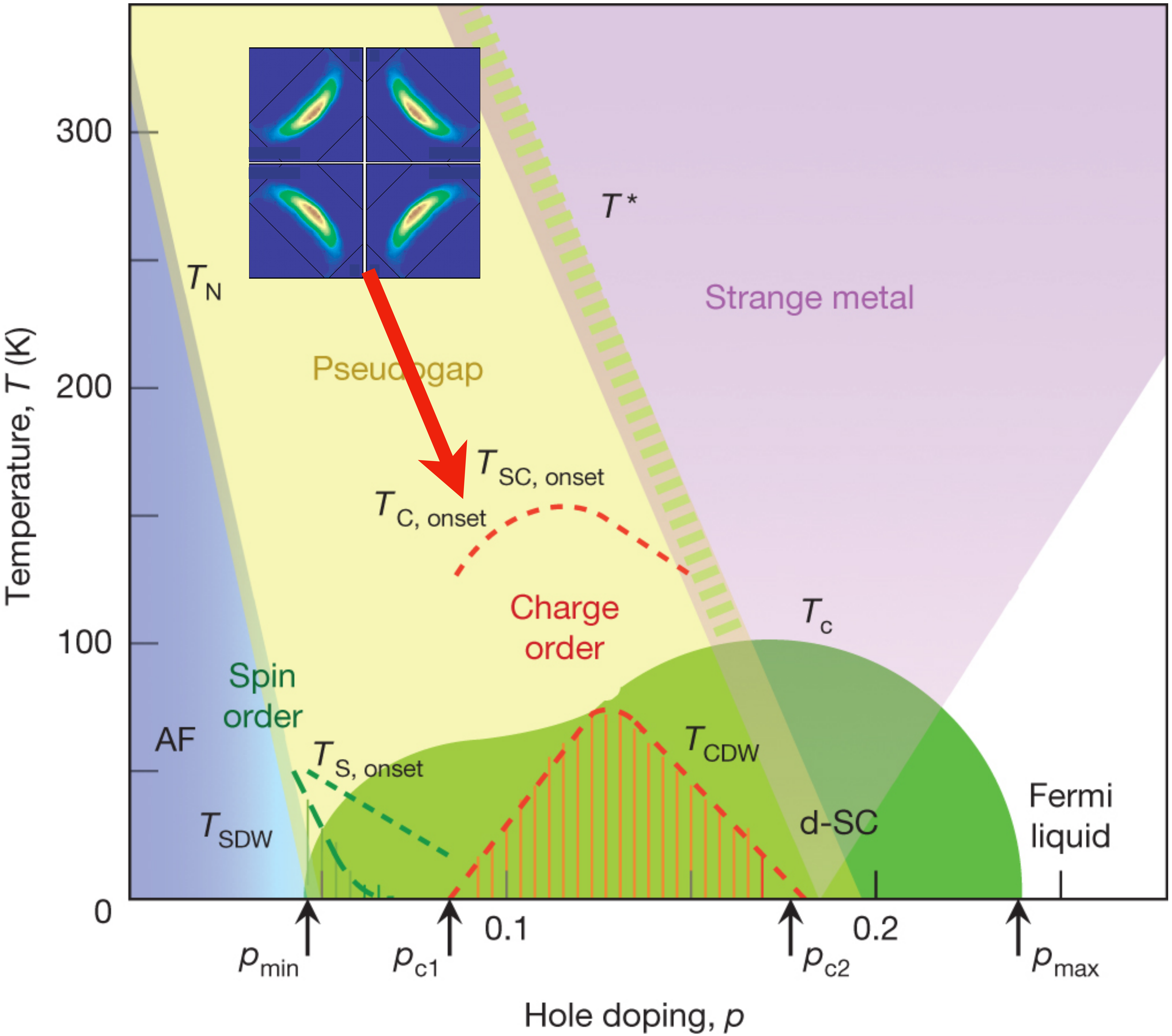
T. Senthil, M. Vojta, and S. S., PRB **69**, 035111 (2004)

B Keimer, S.A. Kivelson, M.R. Norman, S. Uchida, **J. Zaanen**, *Nature* **518**, 179 (2015)



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 ...

B Keimer, S.A. Kivelson, M.R. Norman, S. Uchida, **J. Zaanen**, *Nature* **518**, 179 (2015)



The onset of conventional order is a *confinement transition* for the emergent gauge theory describing the fractionalized excitations of the spin liquid in the FL* state.

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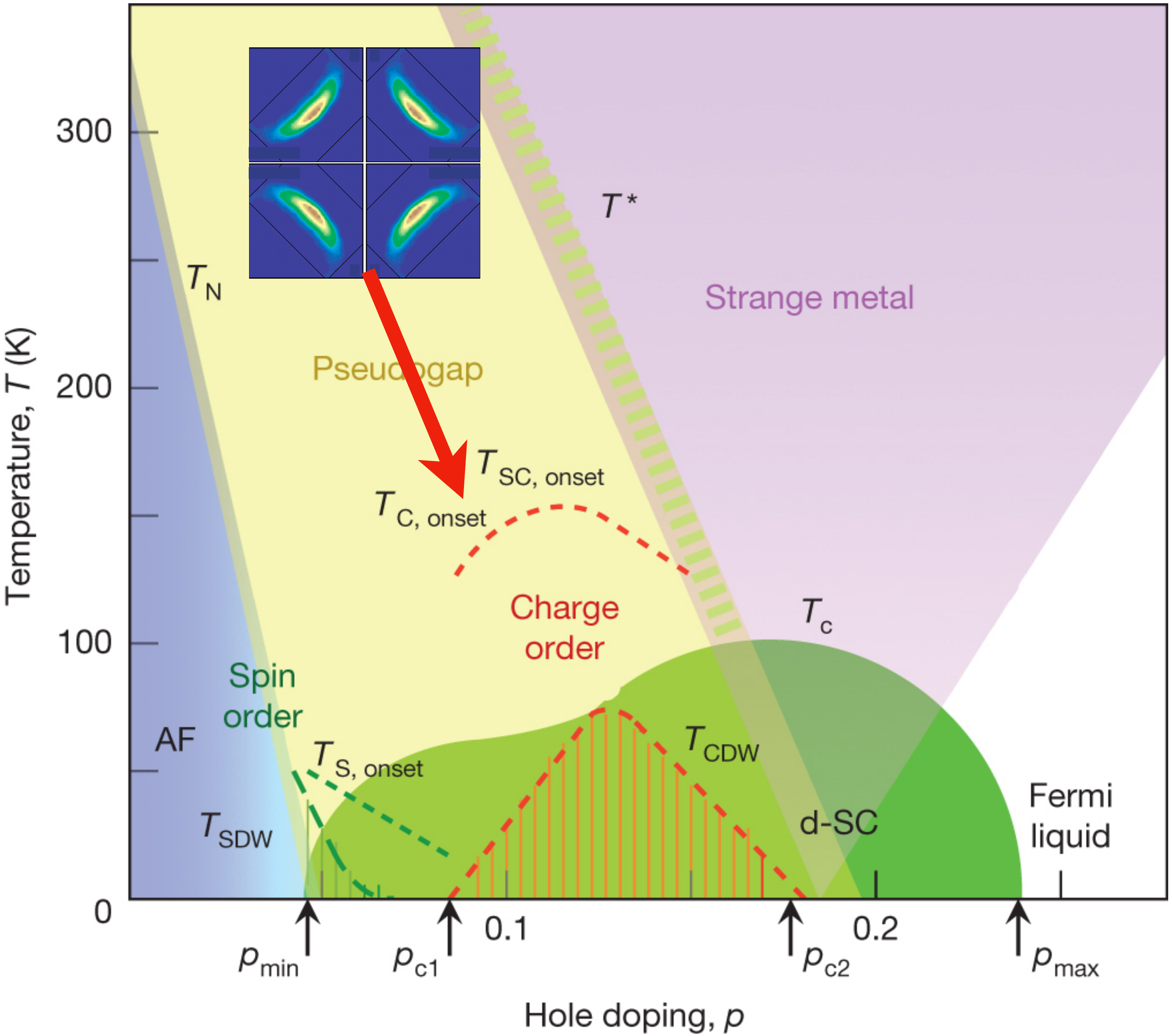

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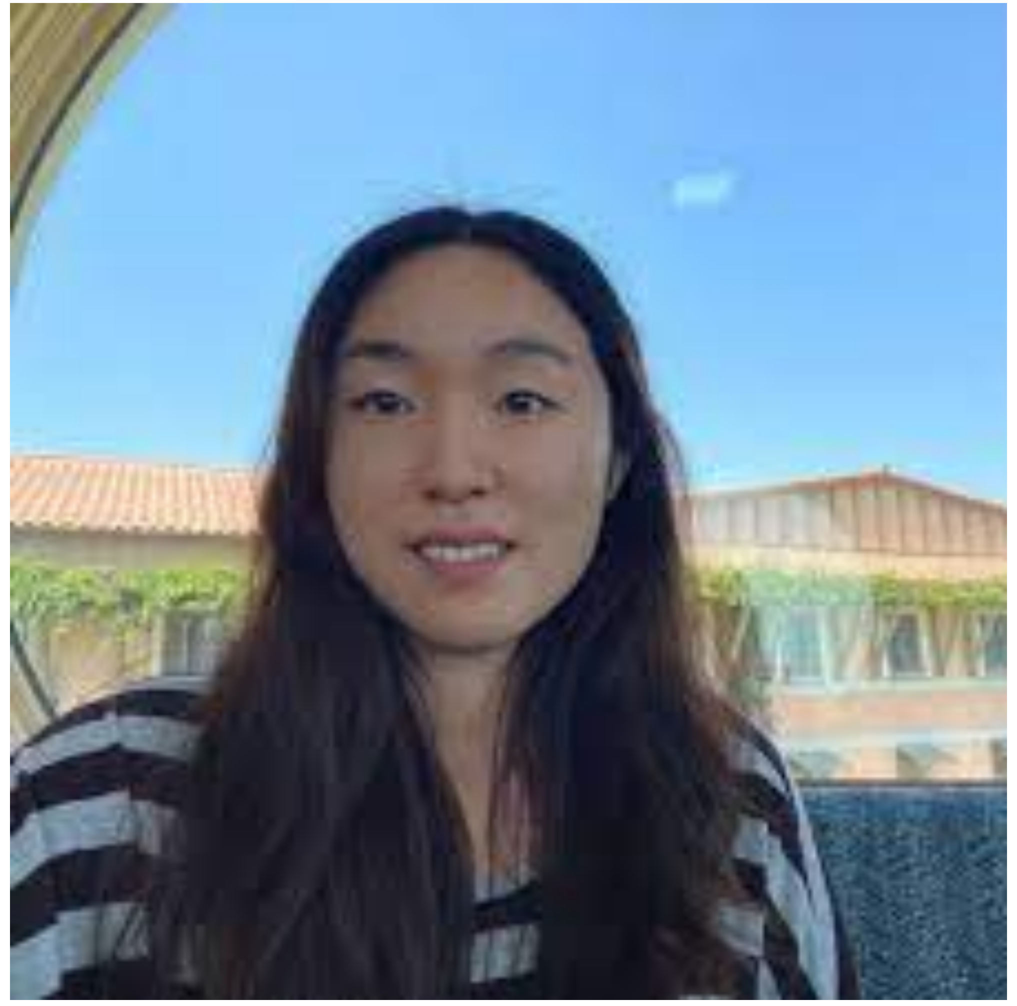
But which spin liquid?

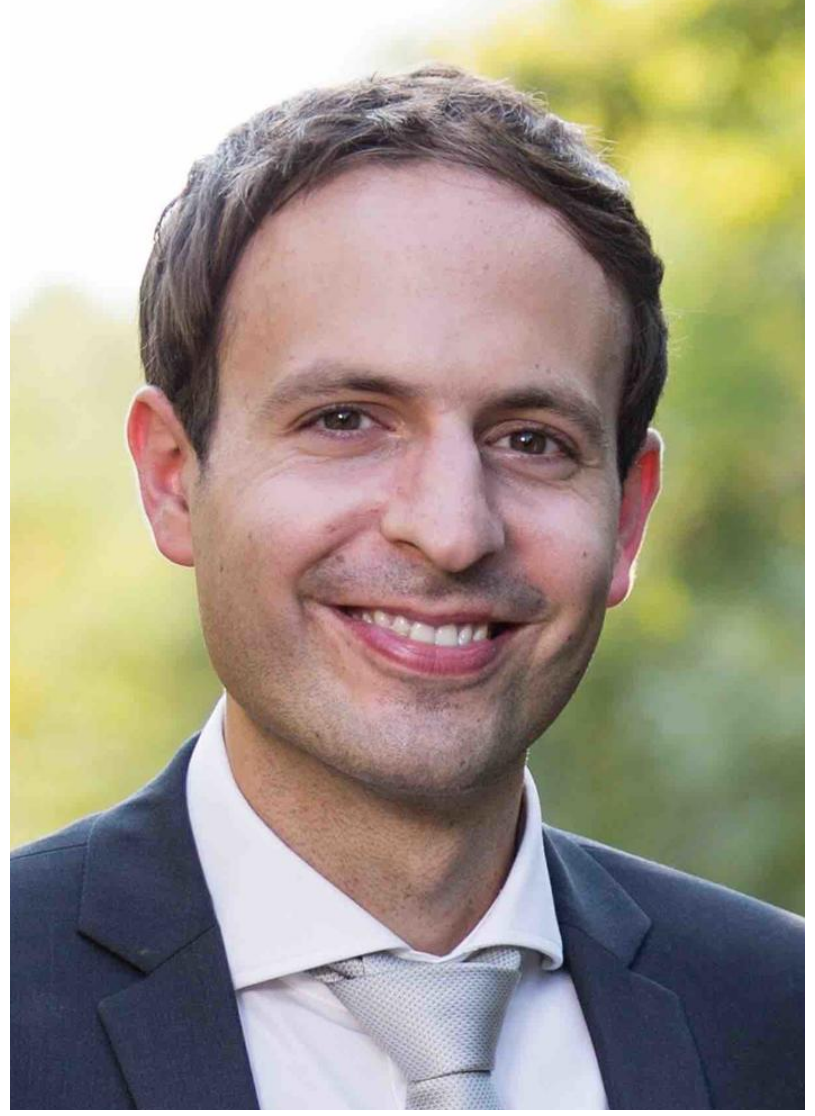
A spin liquid which is ultimately IR-unstable to confinement

Maine Christos

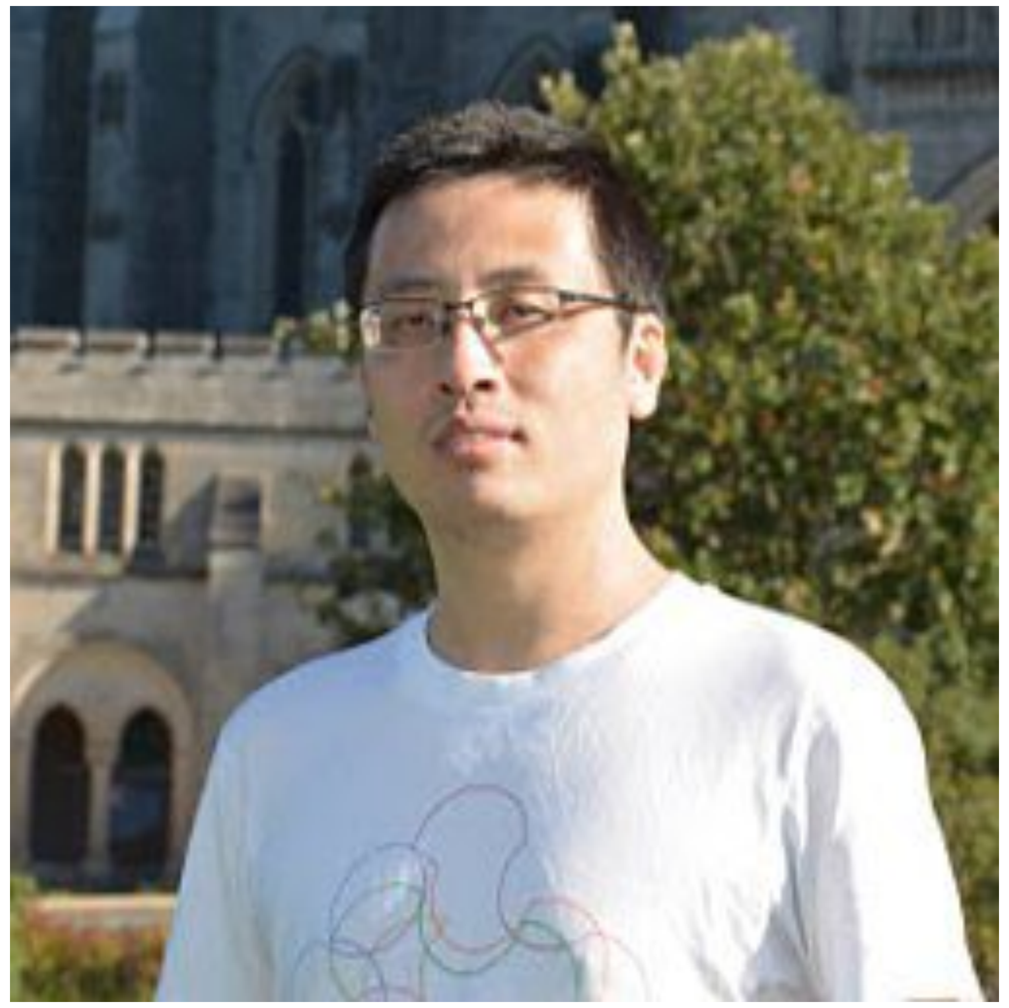


Zhu-Xi Luo
→GA Tech

Henry
Shackleton



Mathias Scheurer
Innsbruck→Stuttgart



Ya-Hui Zhang
Johns Hopkins

Alexander
Nikolaenko

Darshan Joshi
TIFR Hyderabad

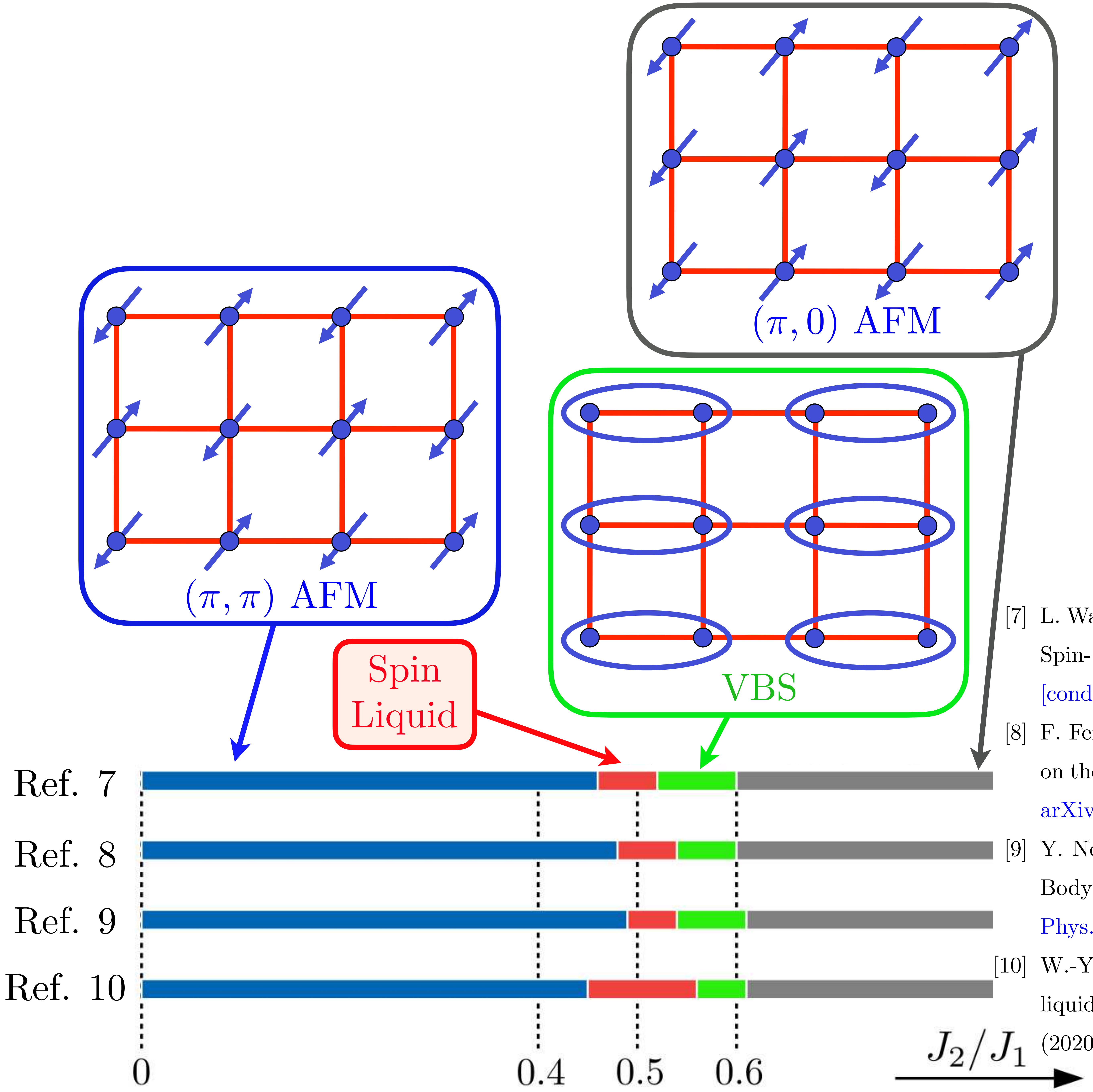
Jonas von Milczewski

1. The π-flux spin liquid

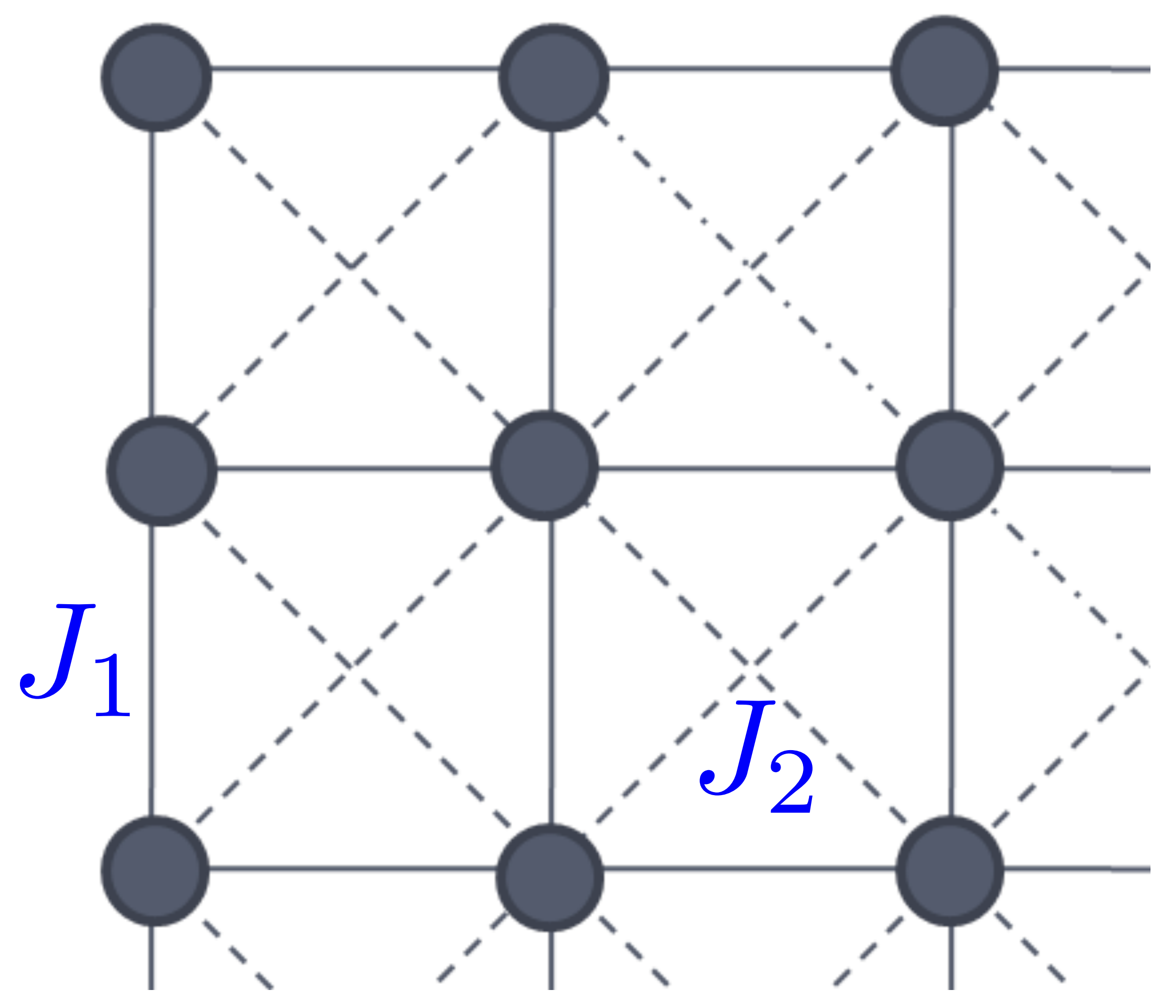
2. Doping the π-flux spin liquid: FL*

3. Confinement transitions of π-flux-FL*

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



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



[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].

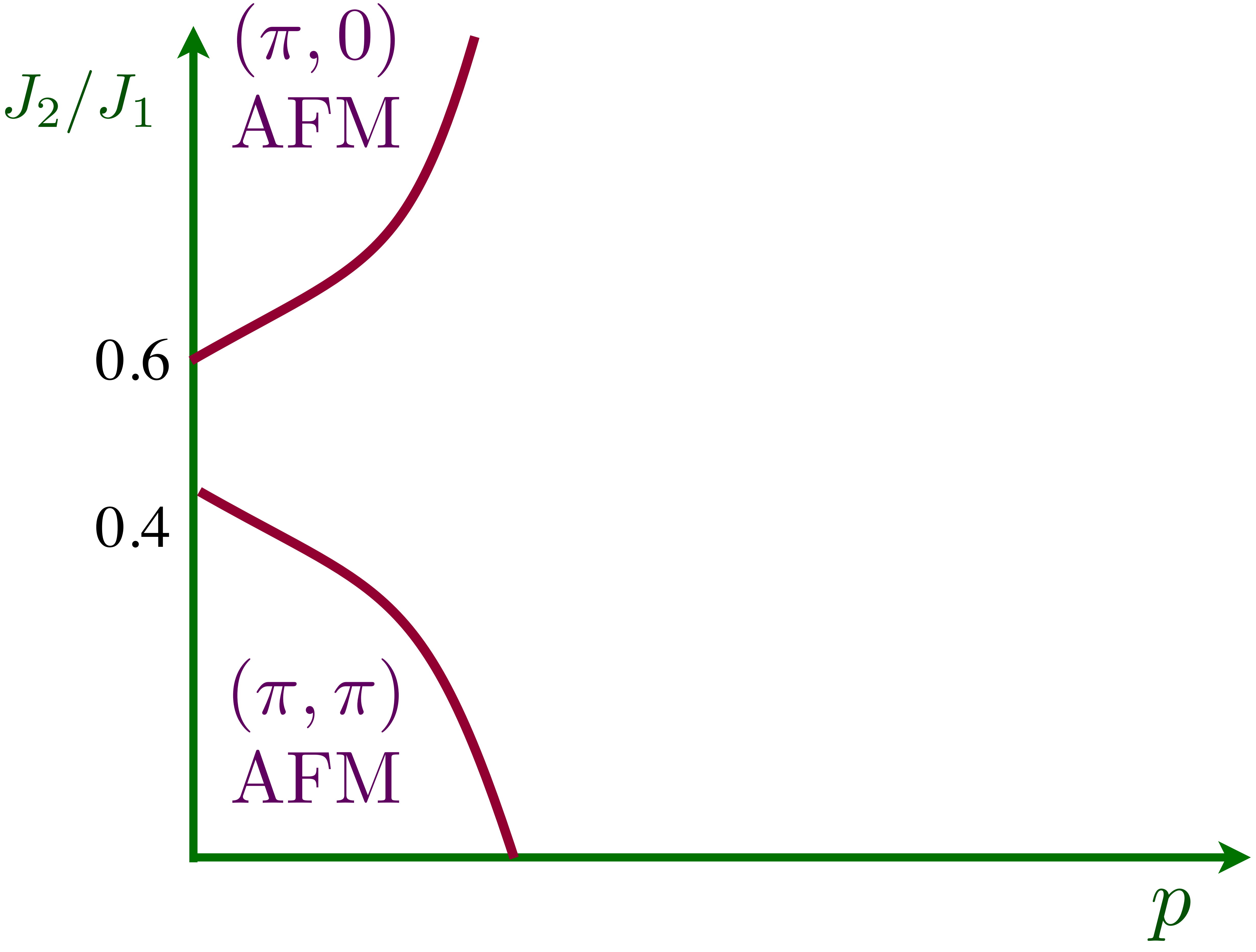
[9] Y. Nomura and M. Imada, "Dirac-Type Nodal Spin Liquid Revealed by Refined Quantum Many-Body Solver Using Neural-Network Wave Function, Correlation Ratio, and Level Spectroscopy," Phys. Rev. X **11**, 031034 (2021), arXiv:2005.14142 [cond-mat.str-el].

[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].

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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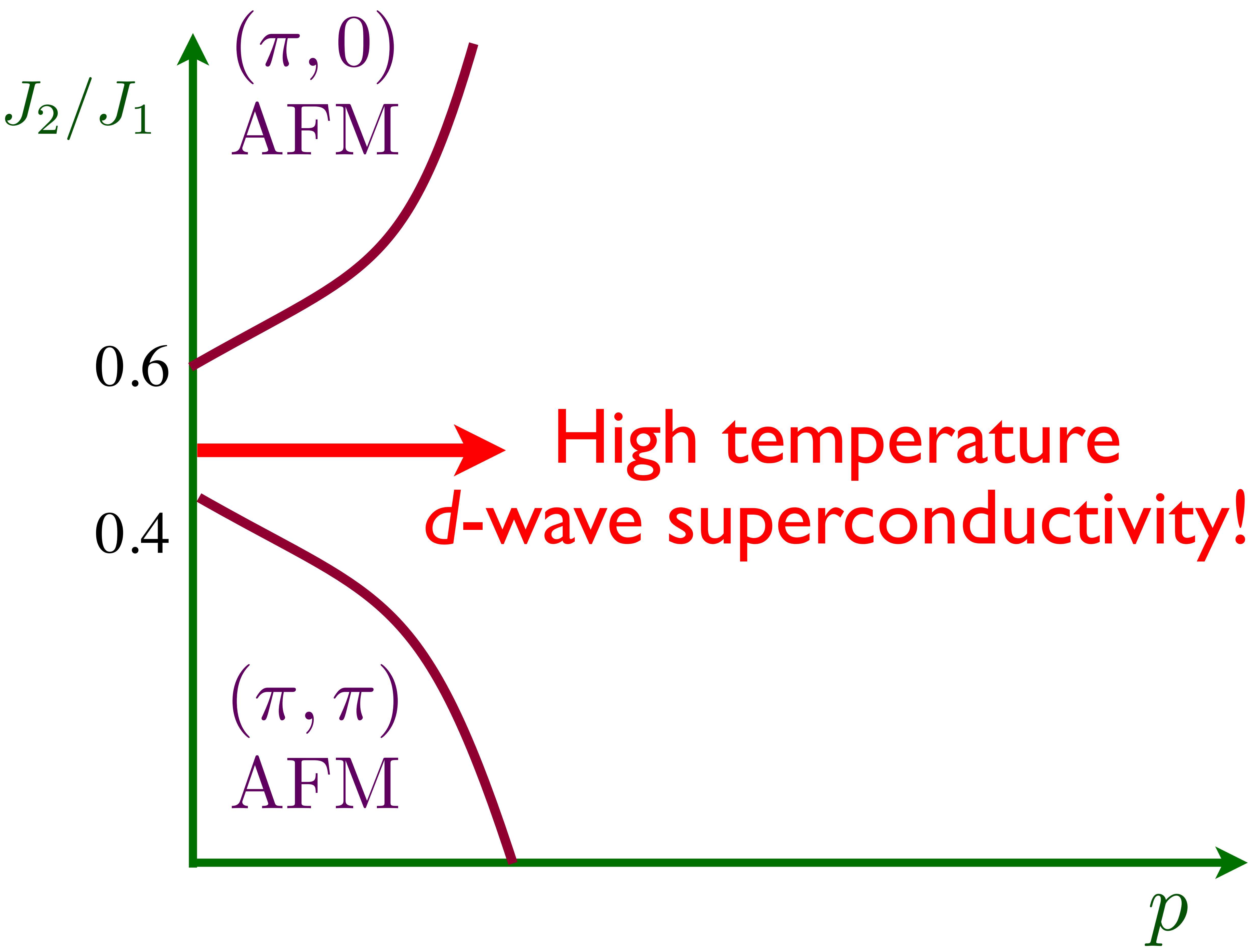

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Insulating S=1/2 antiferromagnet

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

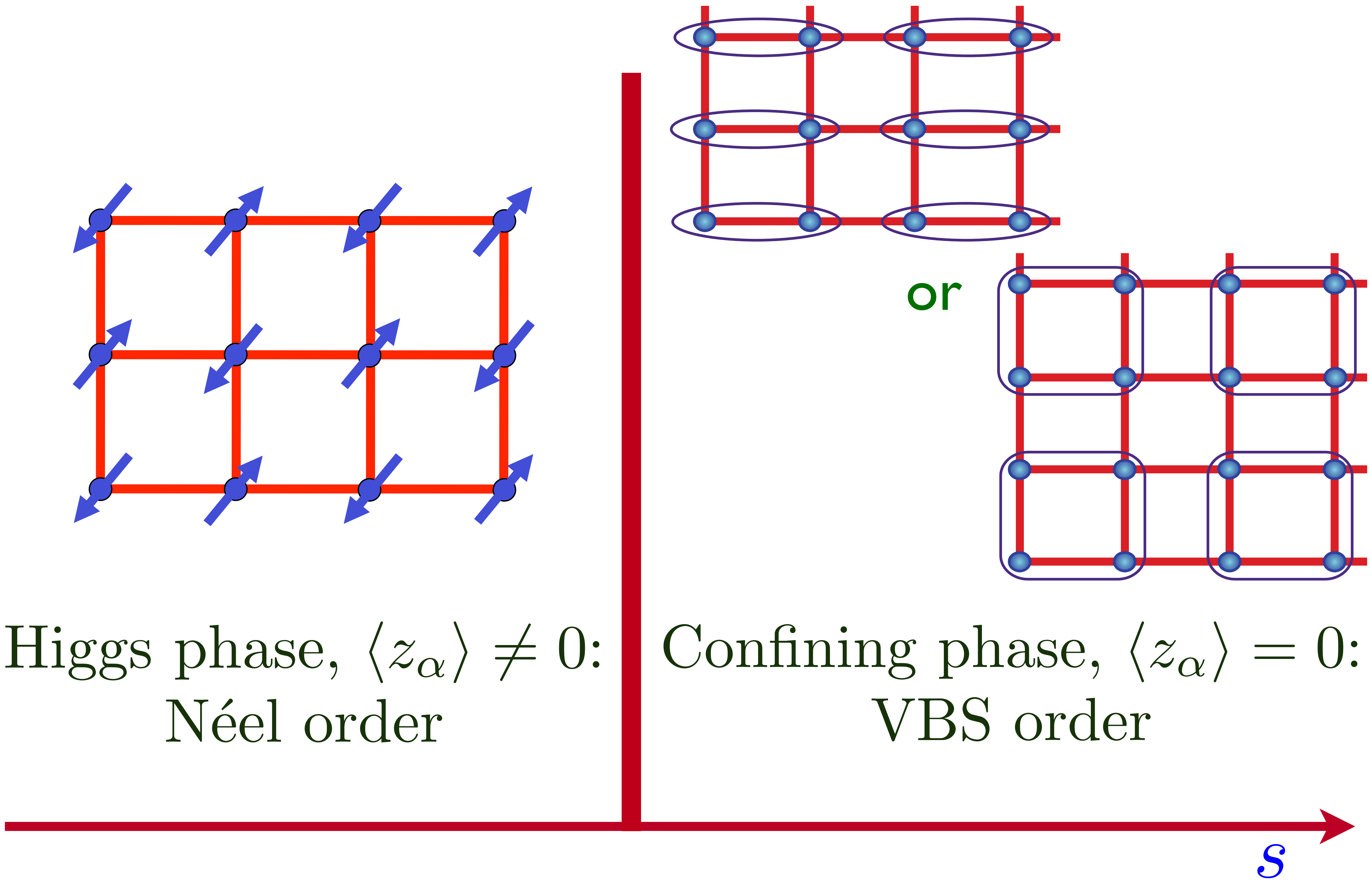
Schwinger bosons

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

Mean-field spin liquid
with gapped bosonic spinons.

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

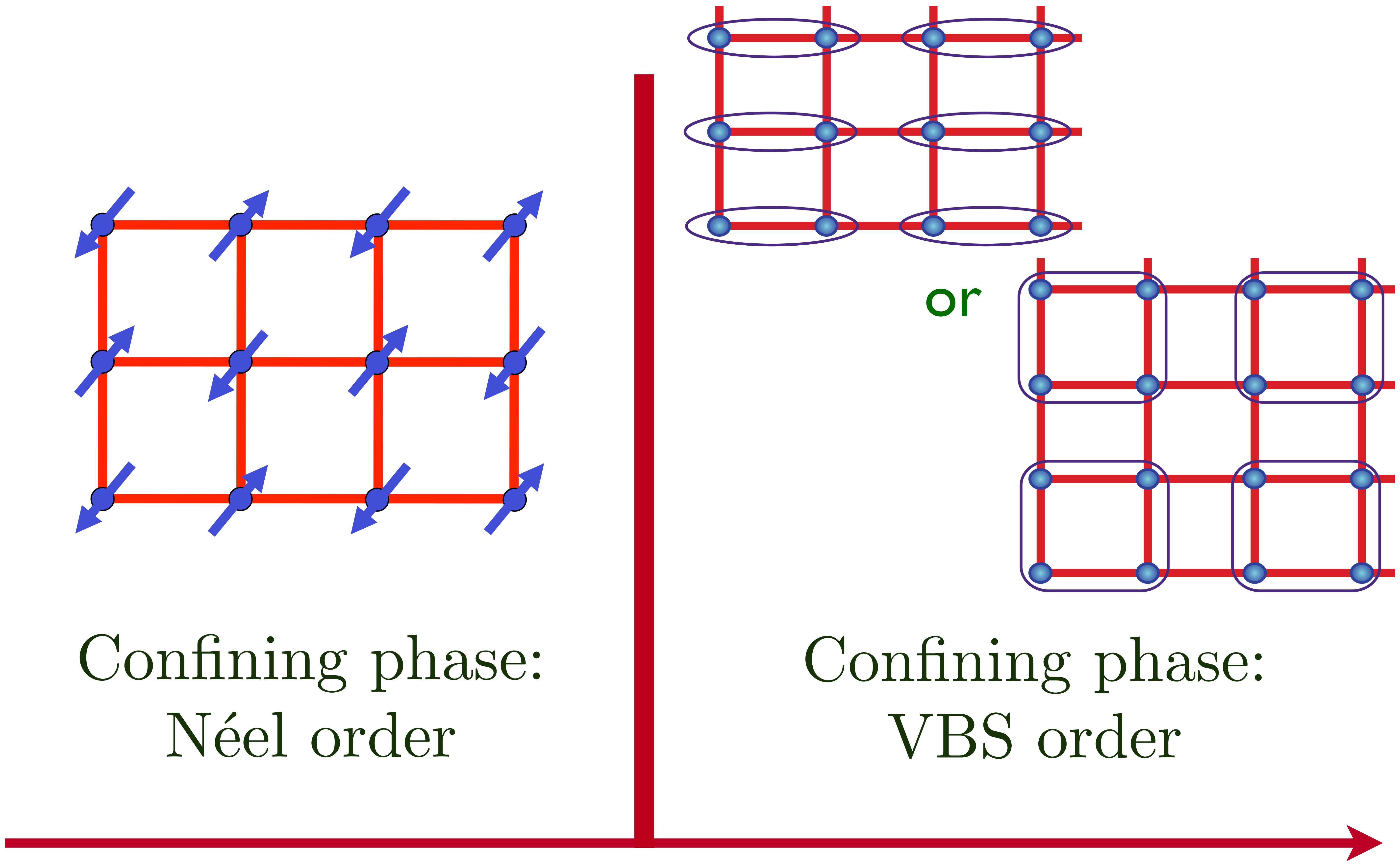
$$z_\alpha \sim b_{A\alpha} + \varepsilon_{\alpha\beta} b_{B\beta}$$



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

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

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

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

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)

Condensed Matter > Strongly Correlated Electrons

[Submitted on 28 Jun 2023]

The $\mathrm{SO}(5)$ Deconfined Phase Transition under the Fuzzy Sphere Microscope: Approximate Conformal Symmetry, Pseudo-Criticality, and Operator Spectrum

Zheng Zhou, Liangdong Hu, W. Zhu, Yin-Chen He

The deconfined quantum critical point (DQCP) is an example of phase transitions beyond the Landau symmetry breaking paradigm that attracts wide interest. However, its nature has not been settled after decades of study. In this paper, we apply the recently proposed fuzzy sphere regularization to study the $\mathrm{SO}(5)$ non-linear sigma model (NLσM) with a topological Wess-Zumino-Witten term, which serves as a dual description of the DQCP with an exact $\mathrm{SO}(5)$ symmetry. We demonstrate that the fuzzy sphere functions as a powerful microscope, magnifying and revealing a wealth of crucial information about the DQCP, ultimately paving the way towards its final answer. In particular, through exact diagonalization, we provide clear evidence that the DQCP exhibits approximate conformal symmetry. The evidence includes the existence of a conserved $\mathrm{SO}(5)$ symmetry

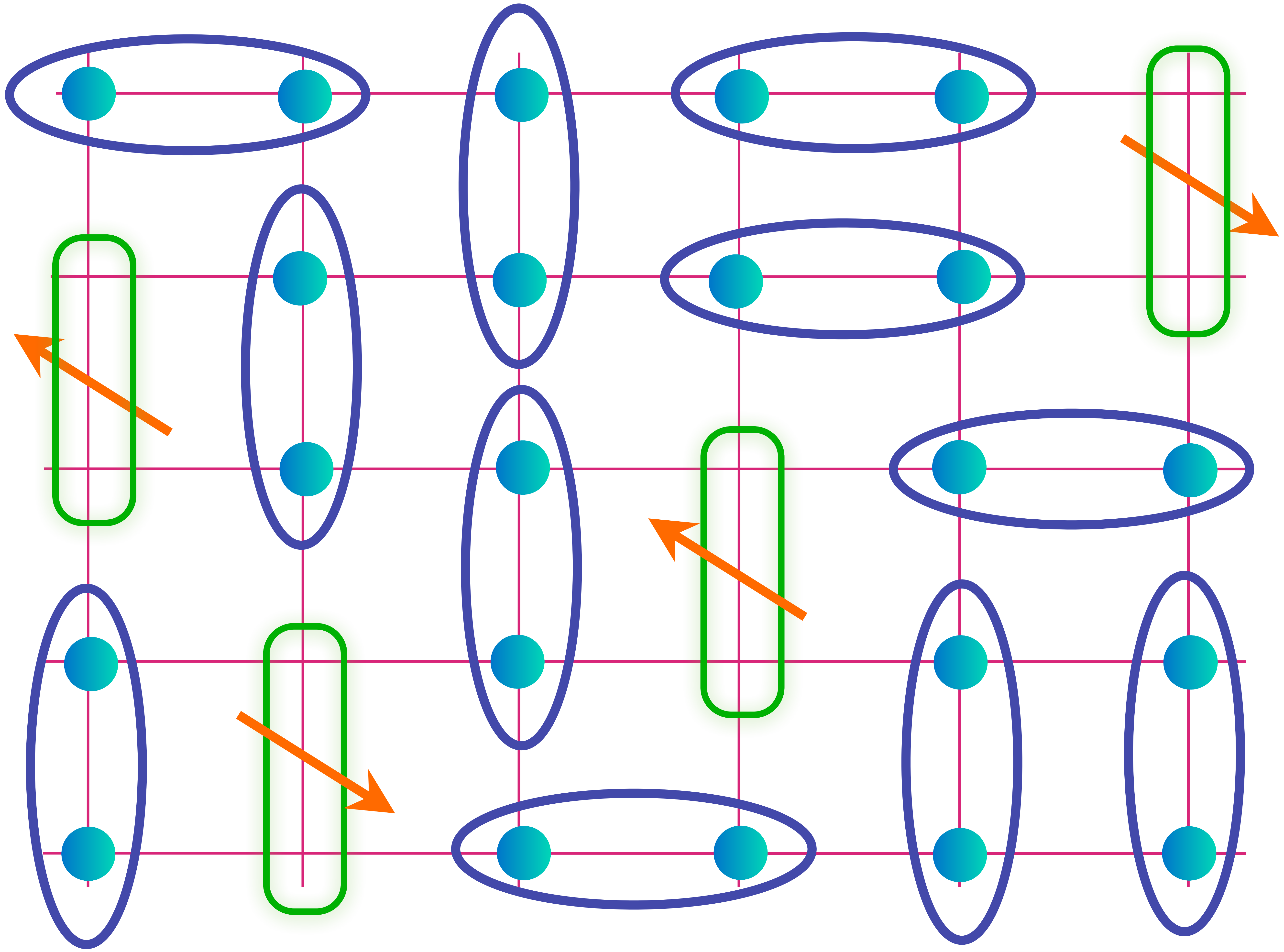
1. The π-flux spin liquid

2. Doping the π-flux spin liquid: FL*

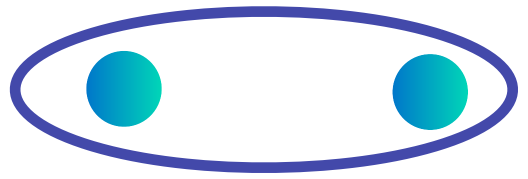
3. Confinement transitions of π-flux-FL*

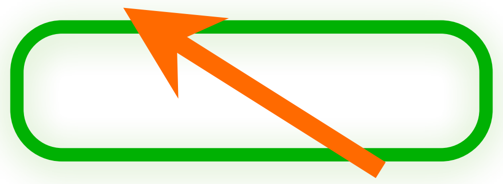
FL* in a ***one-band*** model

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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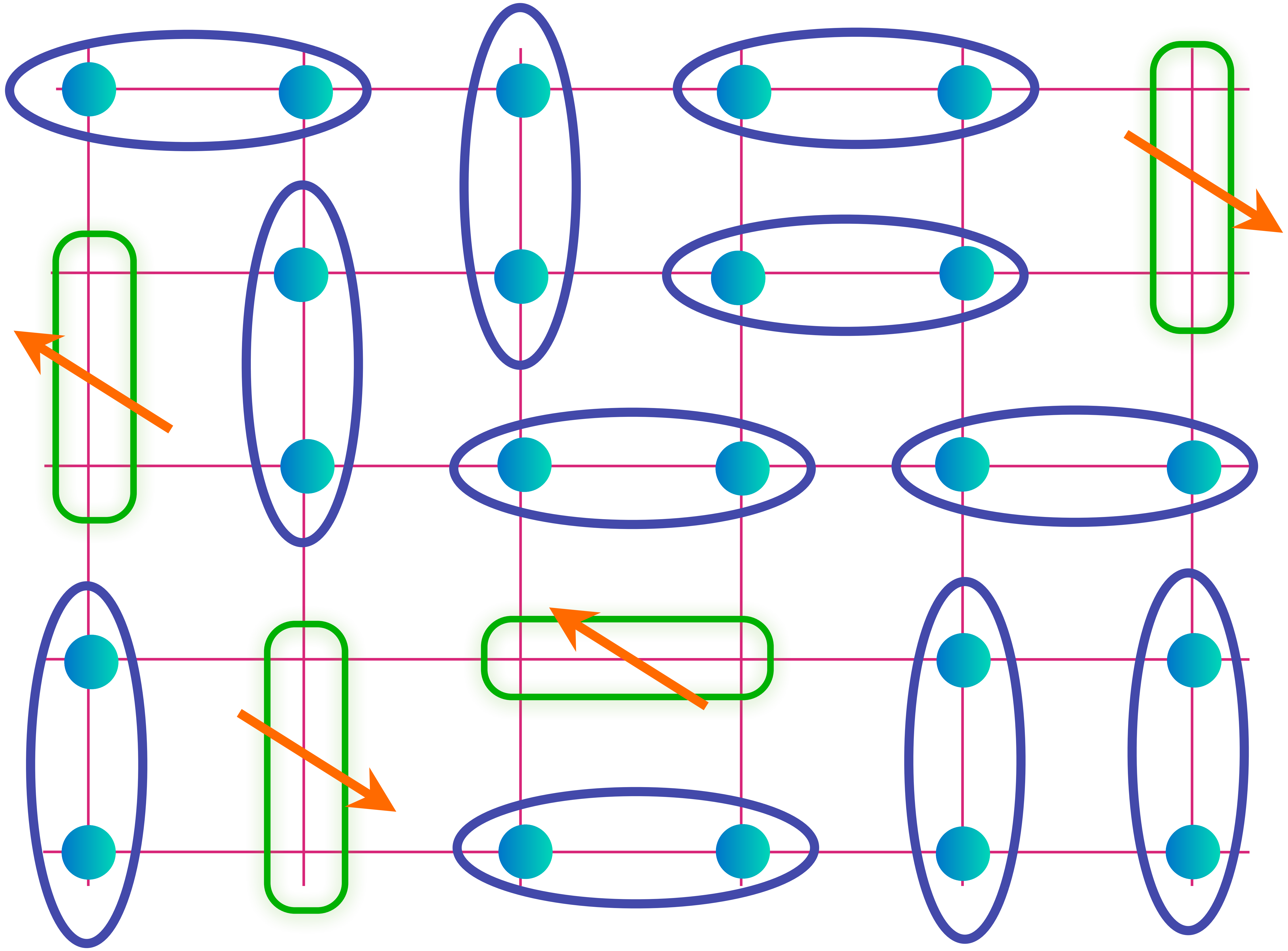
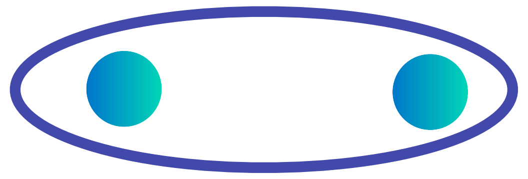
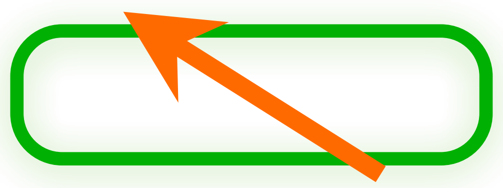


Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

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

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

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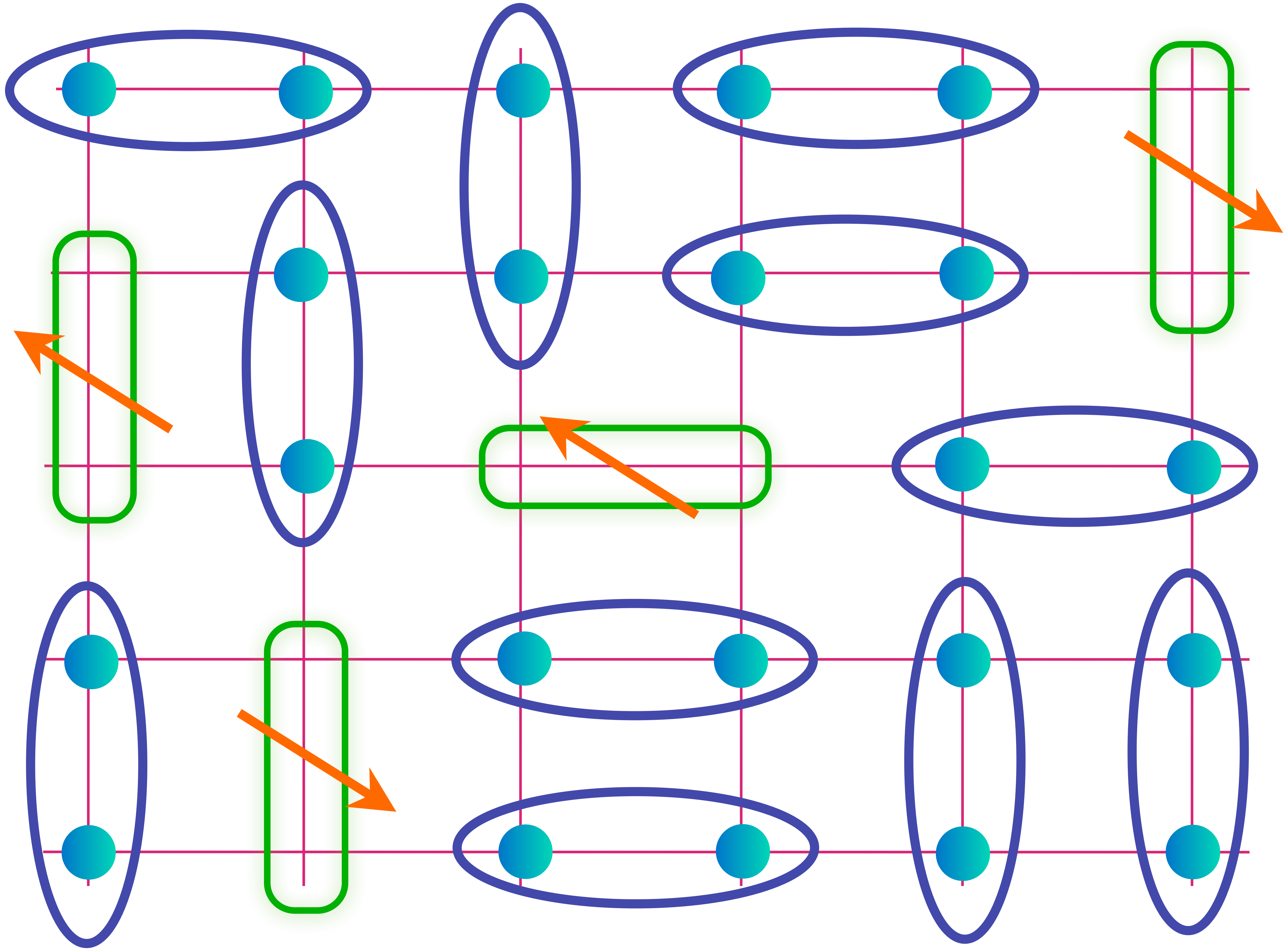

Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

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

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

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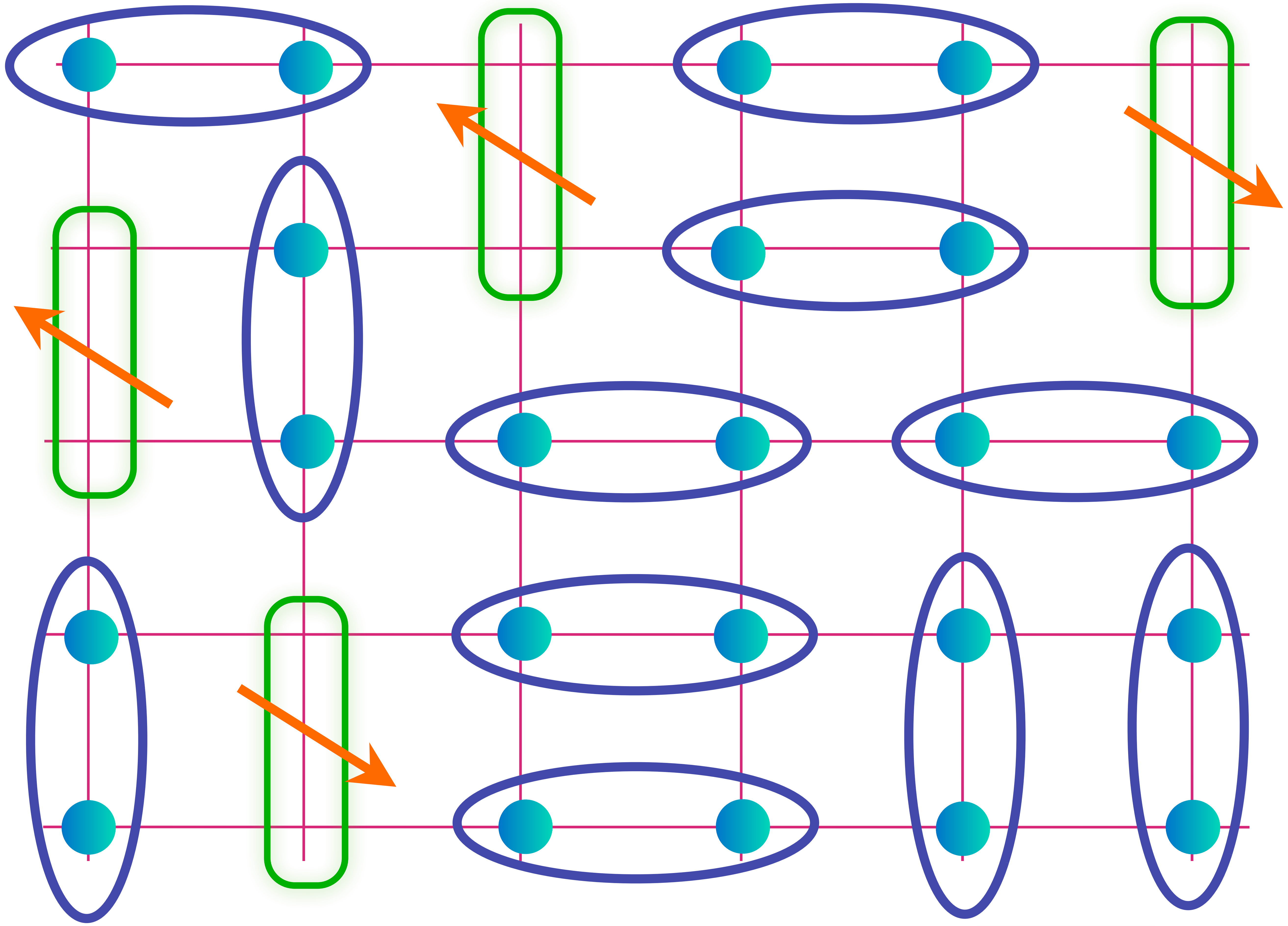

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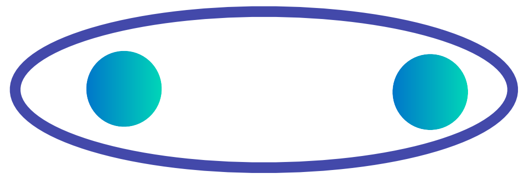
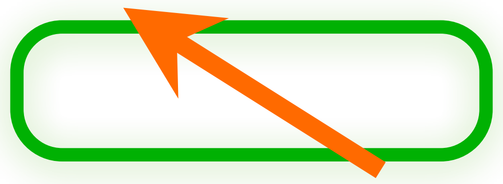


$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$



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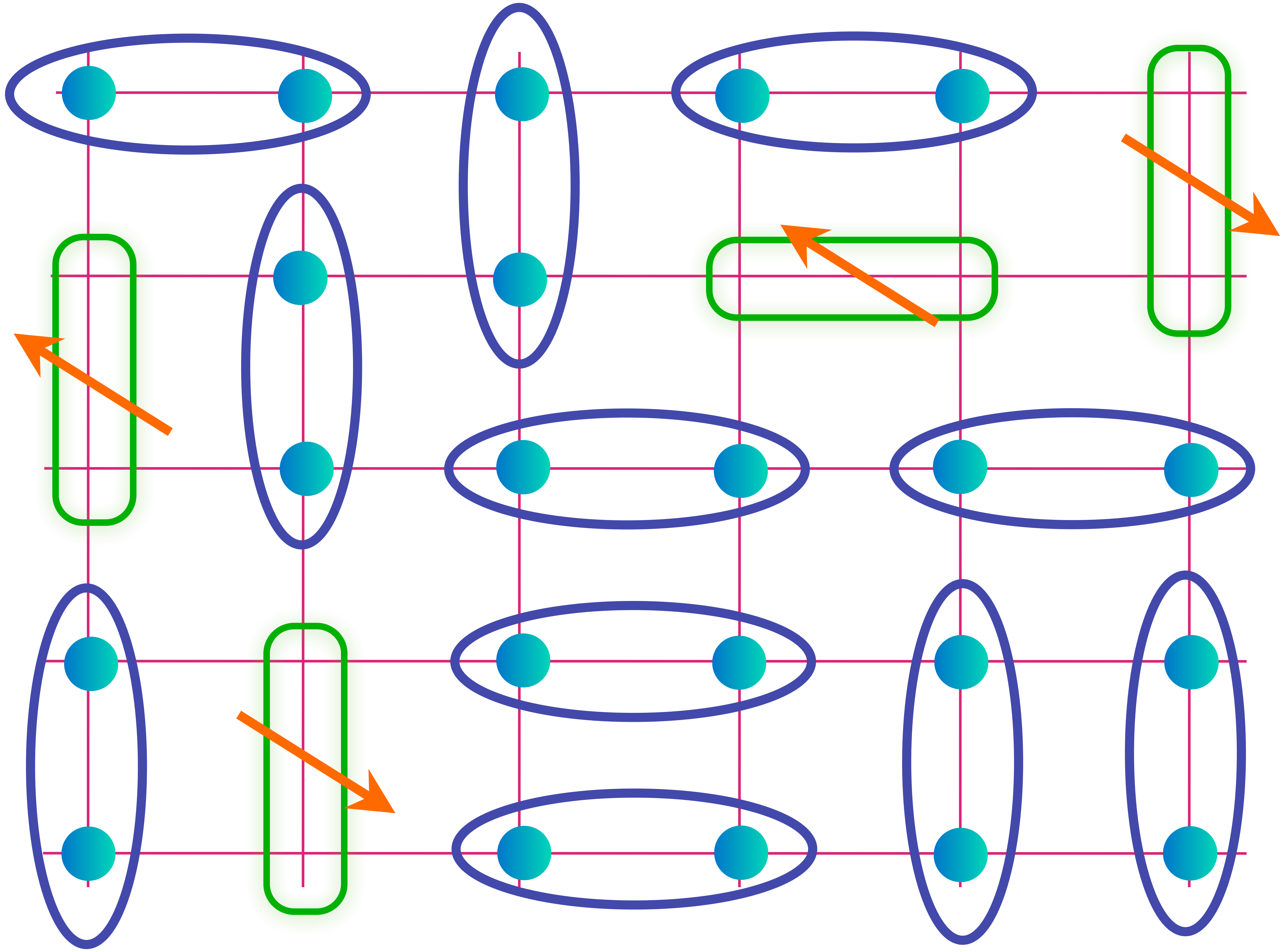

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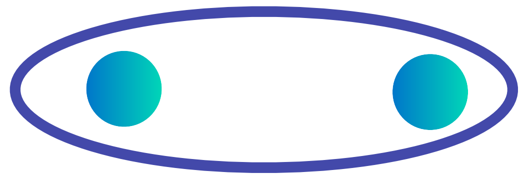
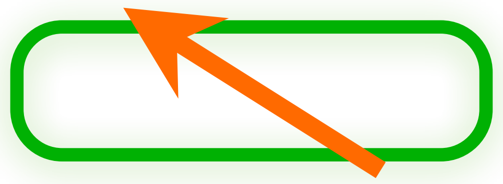
 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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

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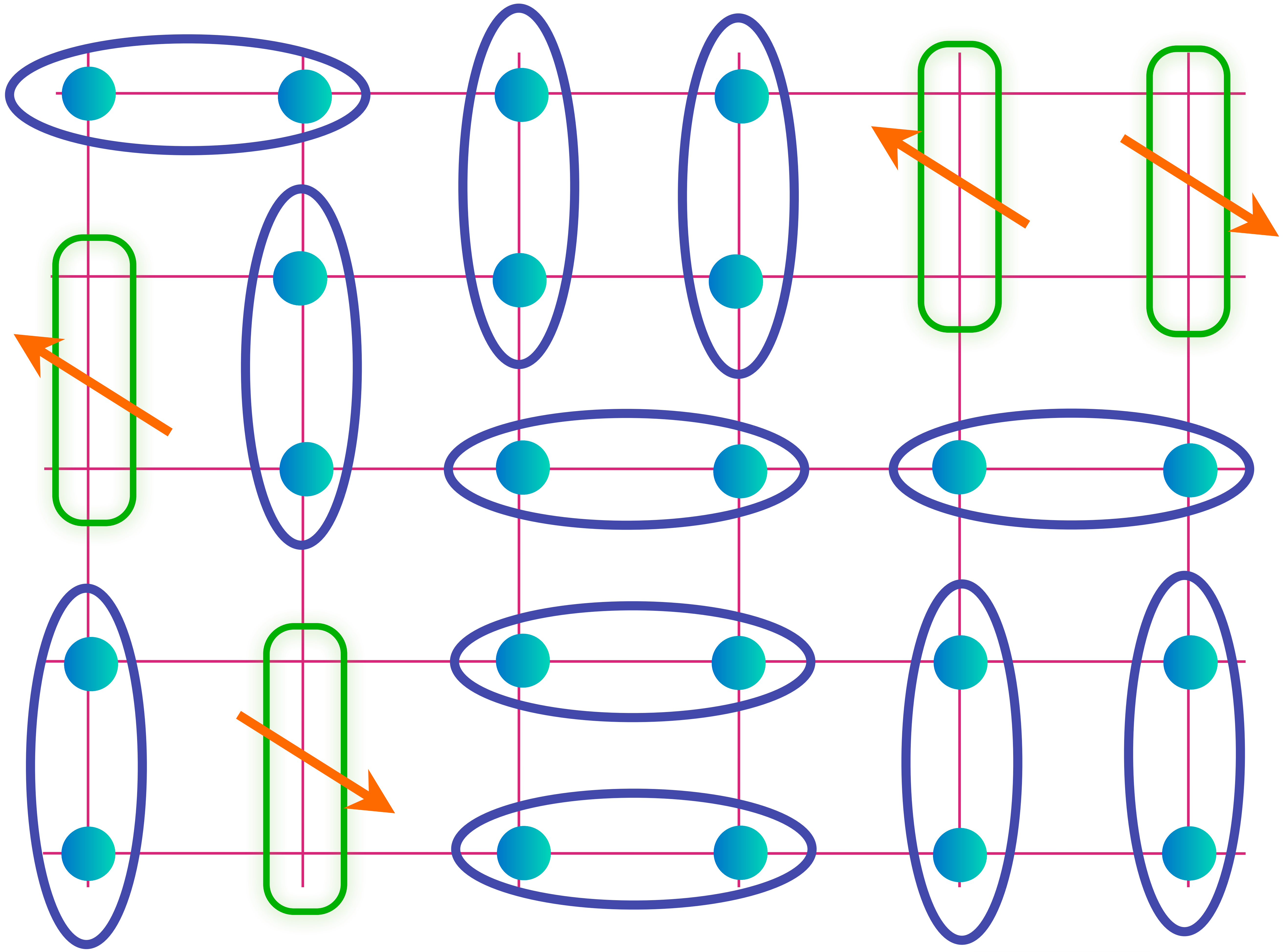
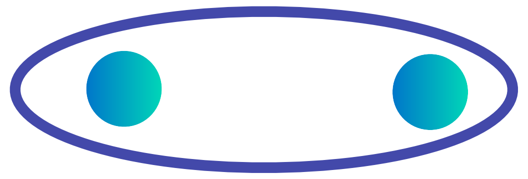
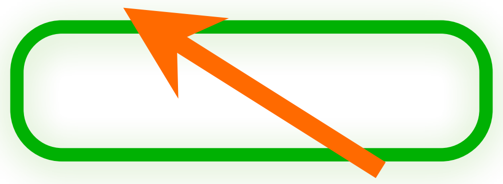


Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

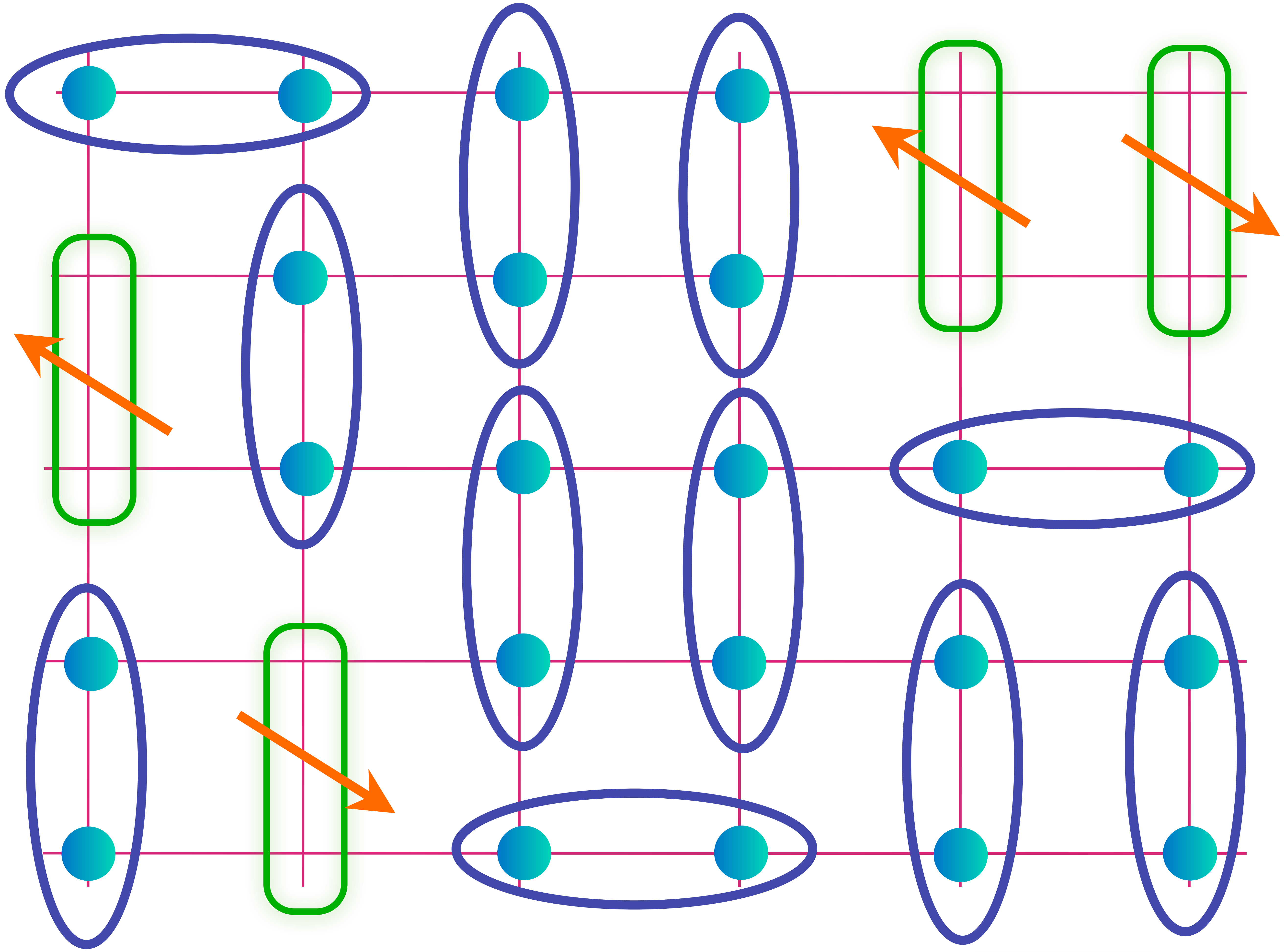
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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

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

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)



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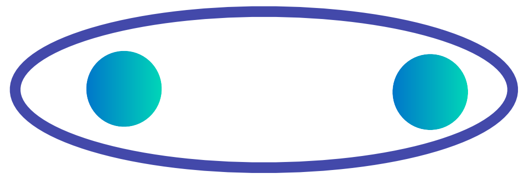
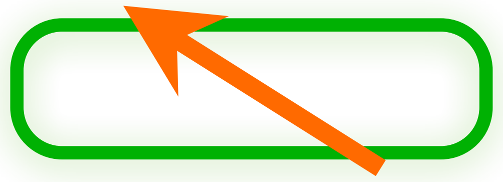
 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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

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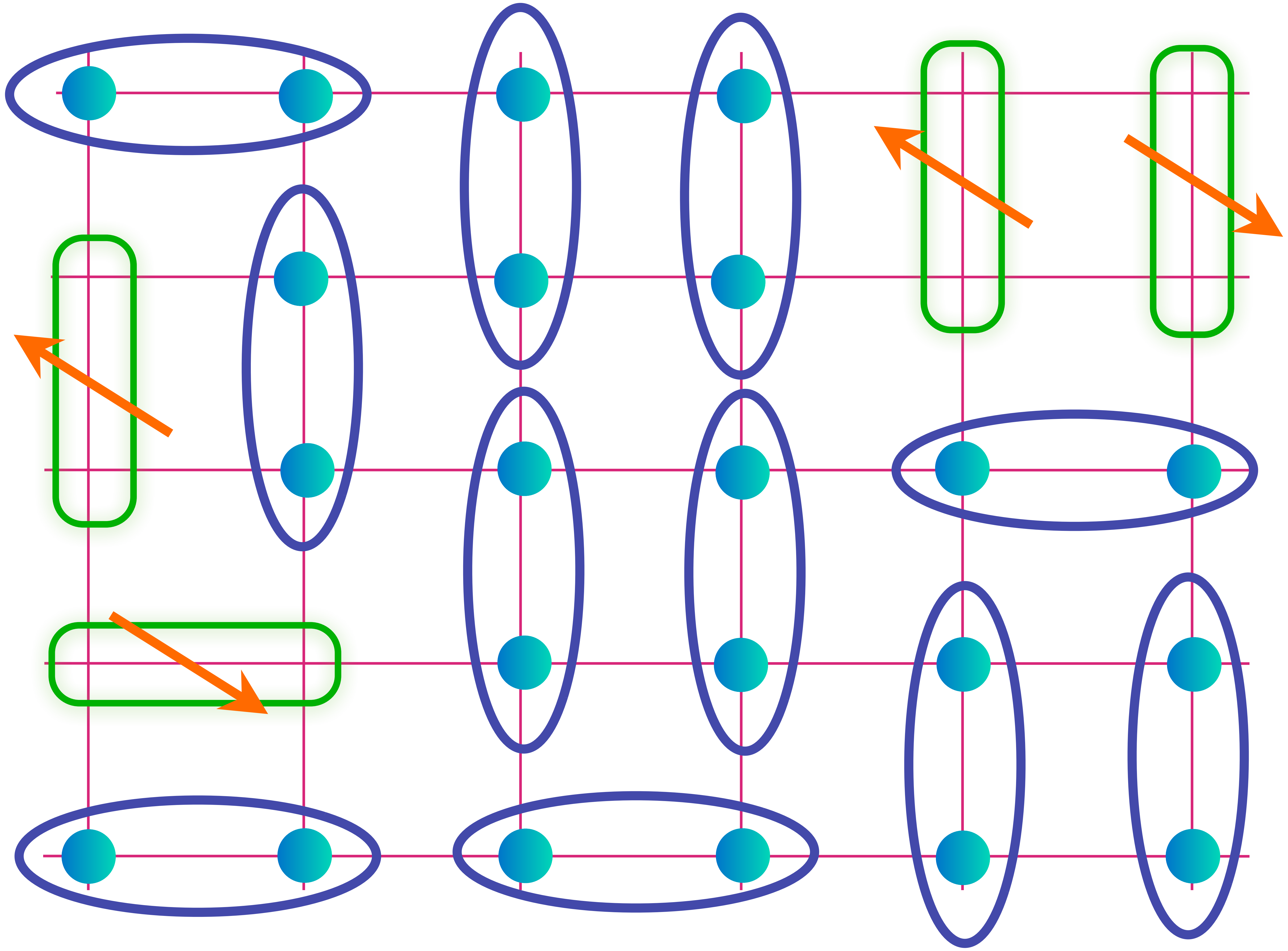

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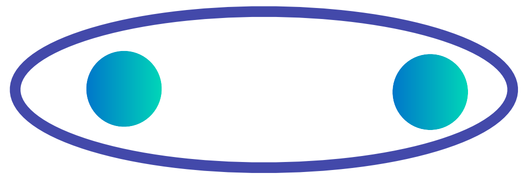
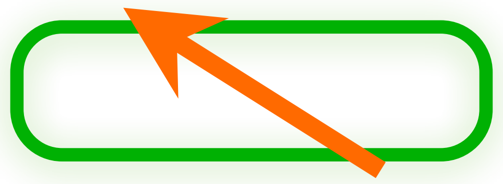
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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

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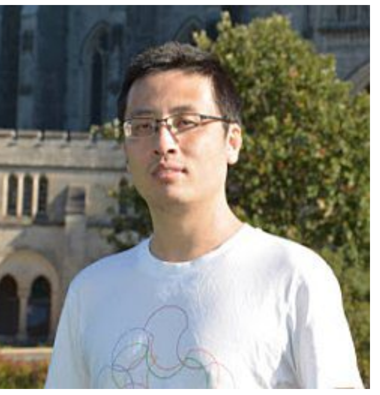


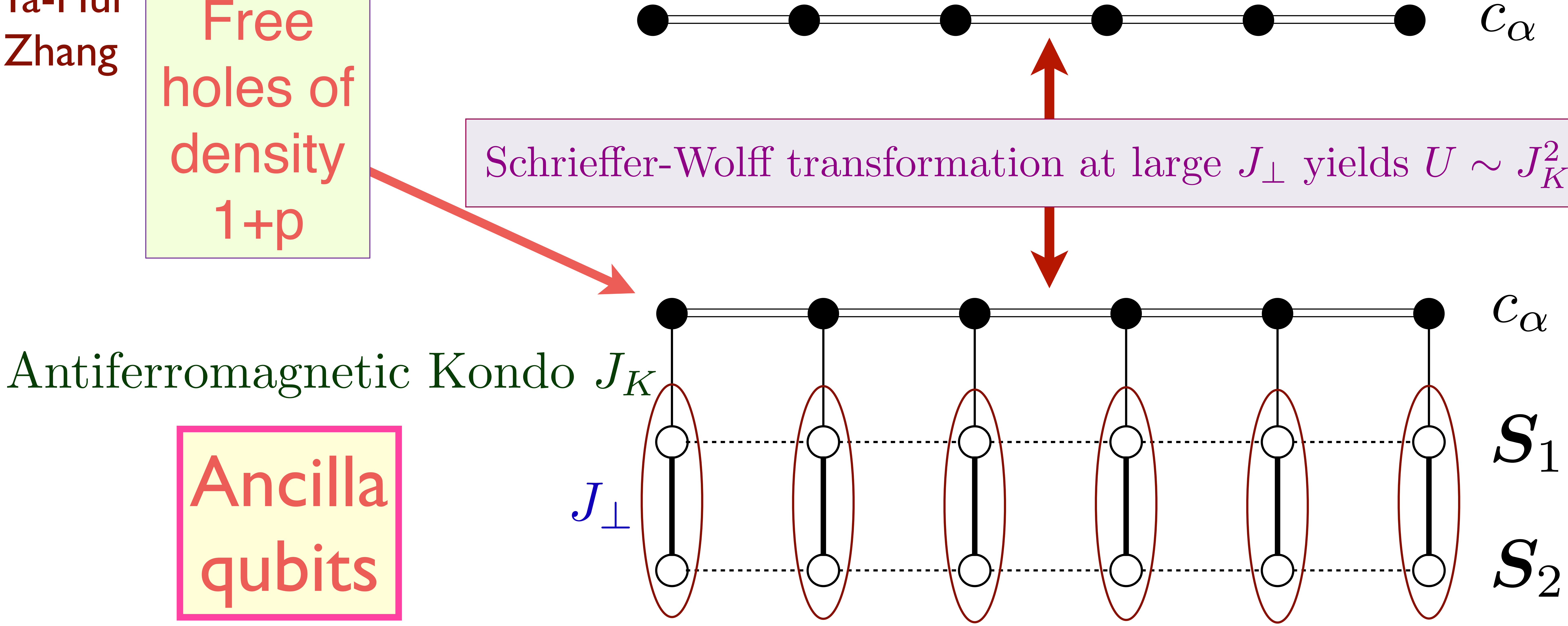
Ancilla theory of the Hubbard model

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

Free holes of density 1+p

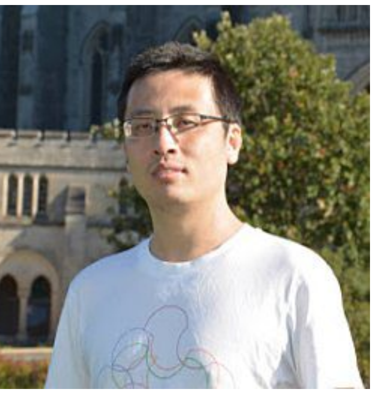
Hubbard model of hole density 1+p

Schrieffer-Wolff transformation at large $J_\perp$ yields $U \sim J_K^2/J_\perp$



Ancilla qubits

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



Ya-Hui Zhang

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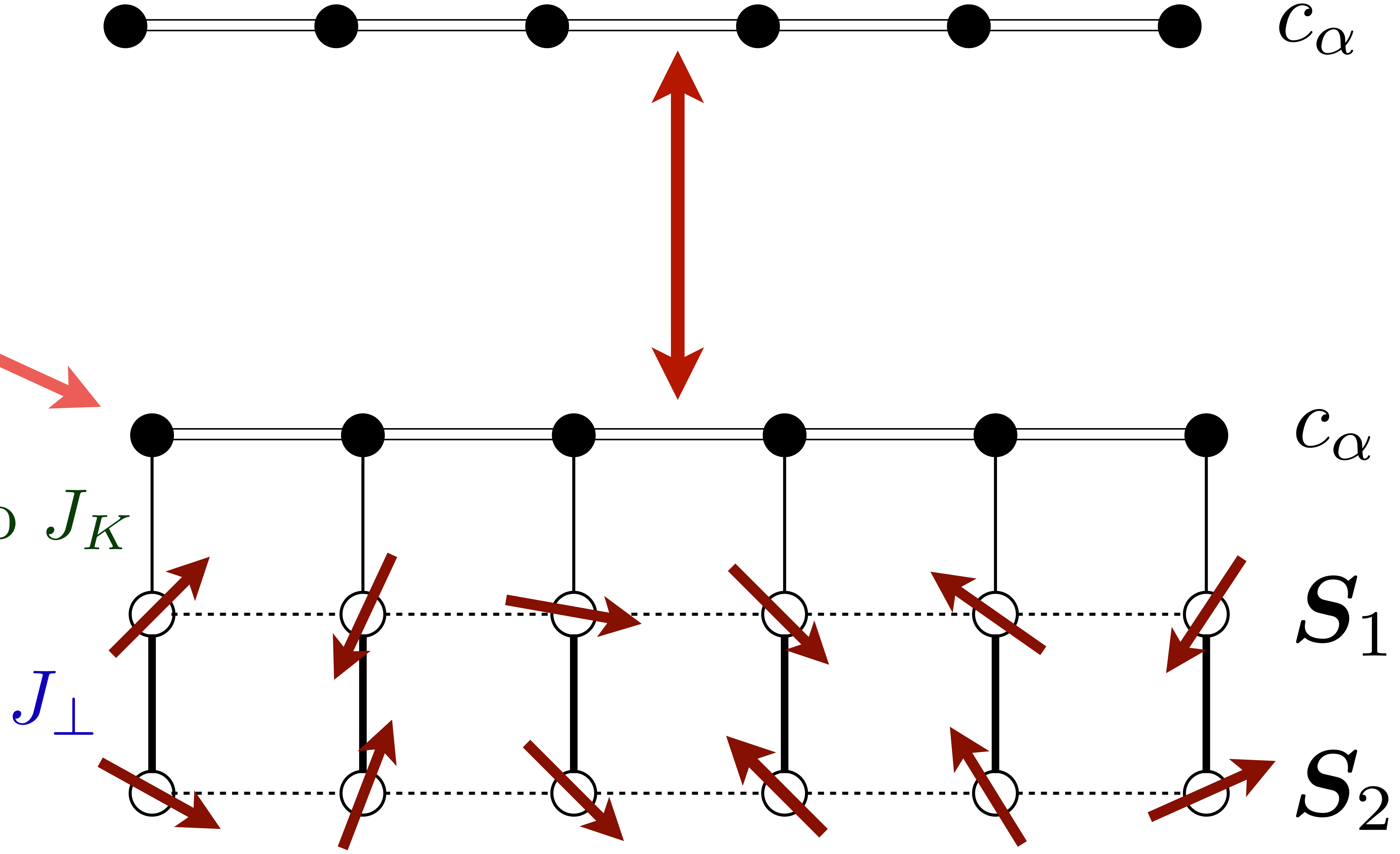
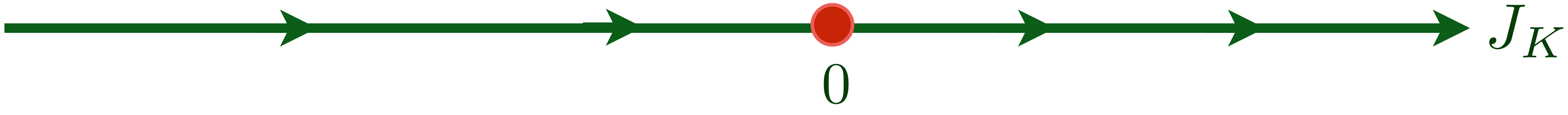


Antiferromagnetic Kondo J_K

Ferromagnetic Kondo $\widetilde{J}_K$

Ancilla qubits



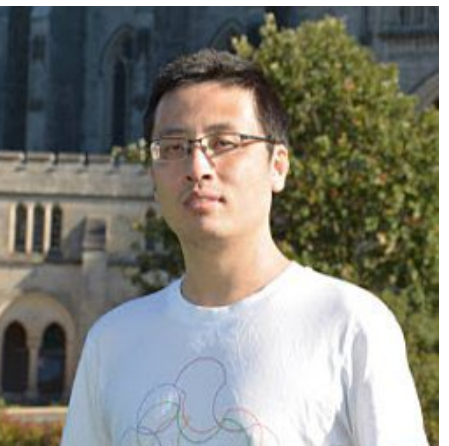
Kondo RG

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

Ancilla theory of the Hubbard model

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

Ya-Hui
Zhang

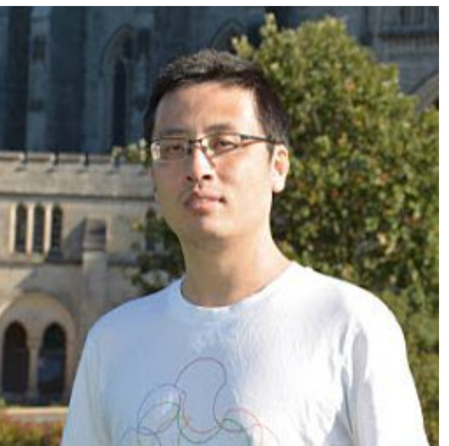


Ancilla theory of the Hubbard model

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

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

Ya-Hui Zhang



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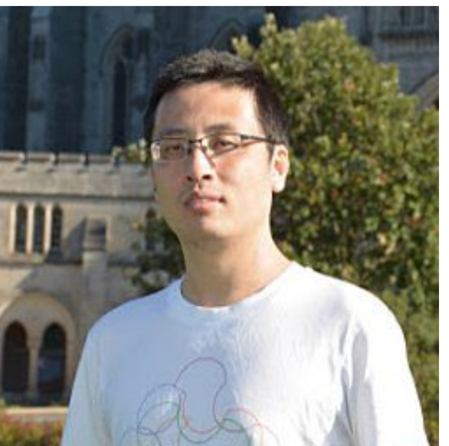

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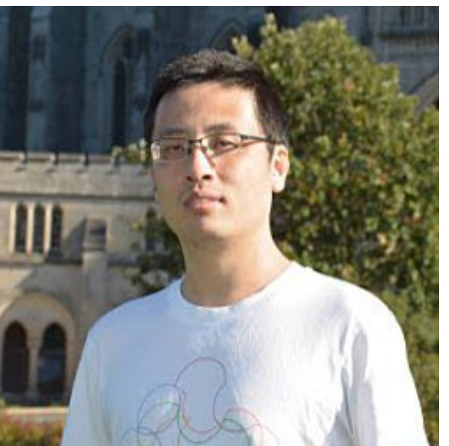

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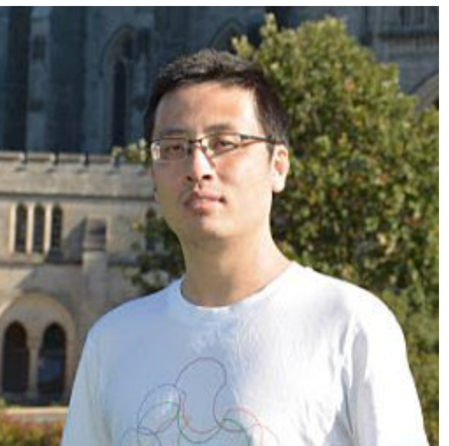


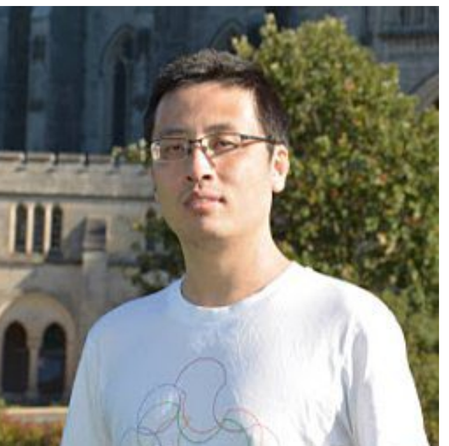
1. The π-flux spin liquid

2. Doping the π-flux spin liquid: FL*

3. Confinement transitions of π-flux-FL*

Ancilla theory of the Hubbard model

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



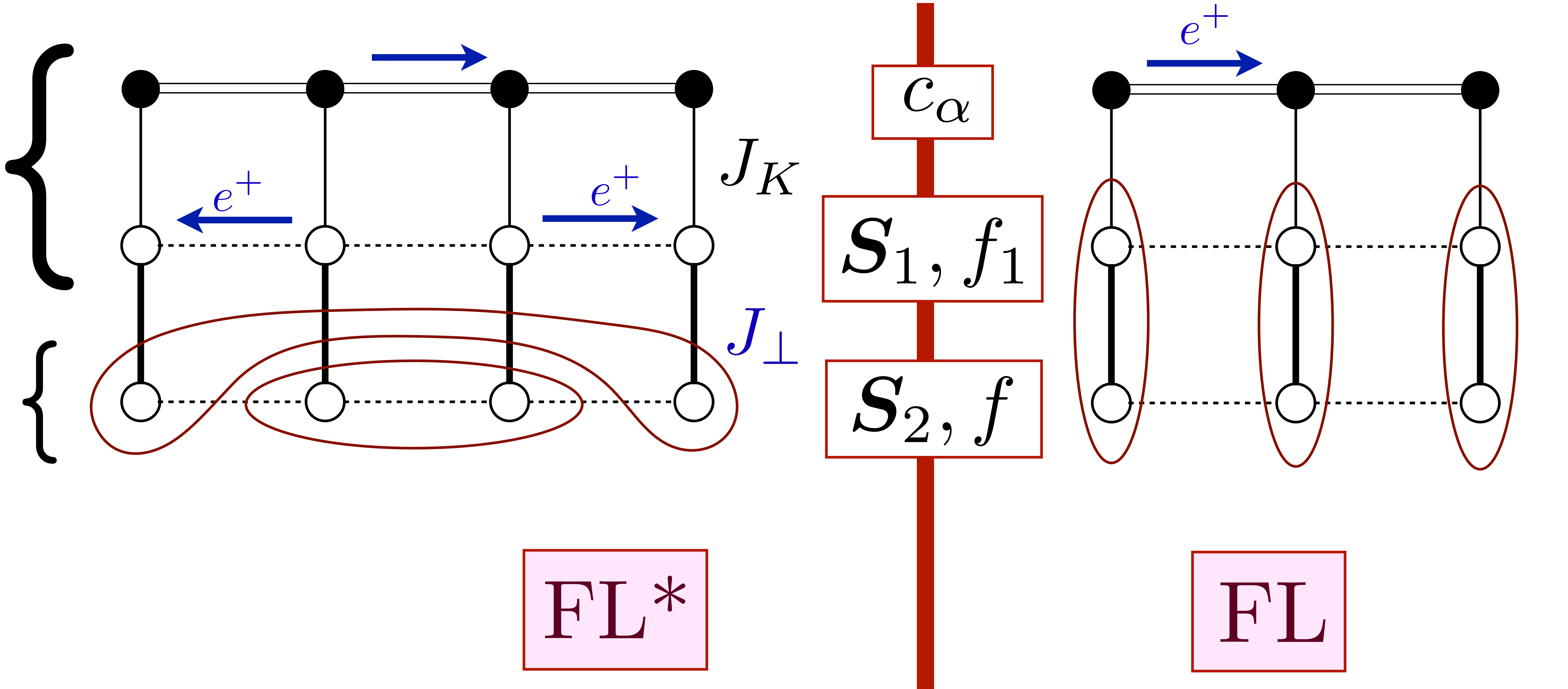
Ya-Hui Zhang

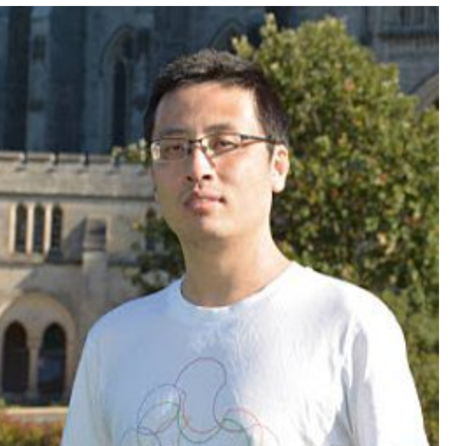
Ancilla theory of the Hubbard model

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

Higgs field 1
$\Phi \sim c_\alpha^\dagger f_{1\alpha}$
$\langle \Phi \rangle \neq 0$

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





Ya-Hui Zhang

Ancilla theory of the Hubbard model

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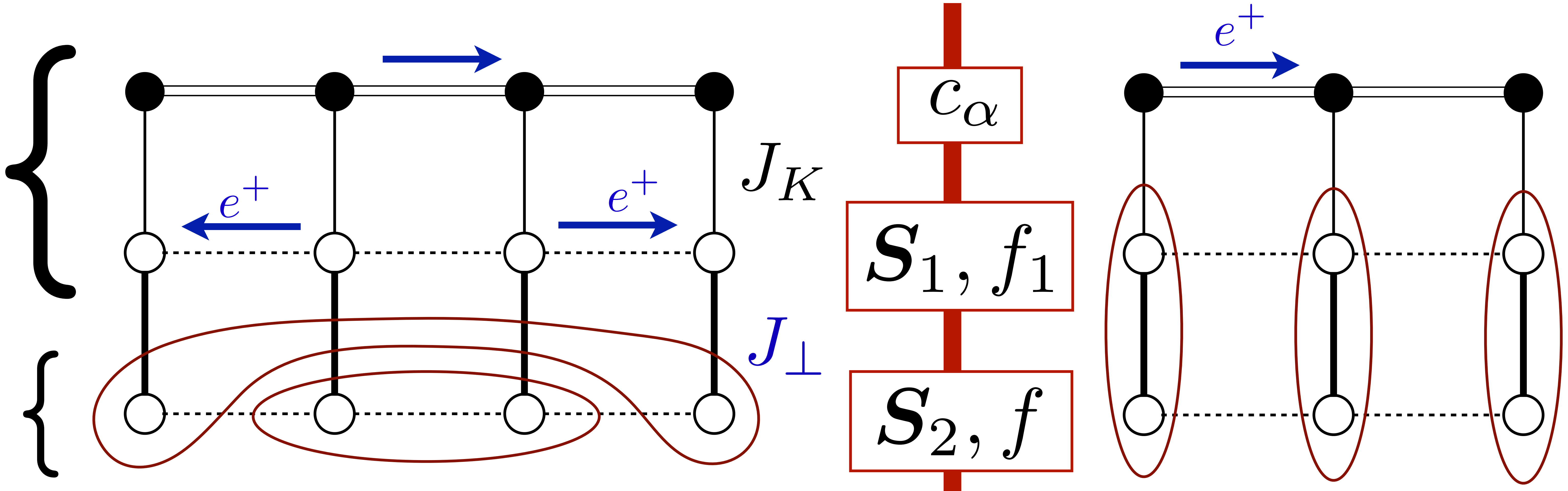
π-flux spin liquid of f_α with $\mathrm{SU}(2)_N$ gauge field



FL*

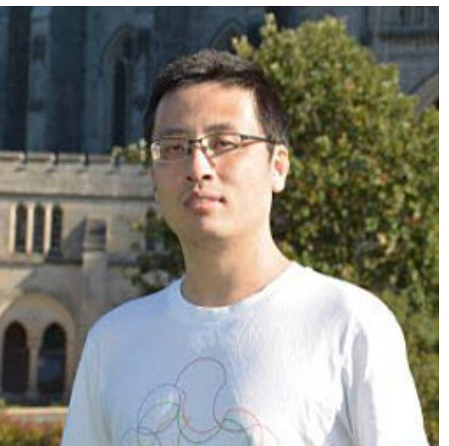
FL

Higgs field 2
Charge e, $\mathrm{SU}(2)_N$ fundamental

$$B \sim \begin{pmatrix} f_{1\alpha}^\dagger f_\alpha \\ \varepsilon_{\alpha\beta} f_{1\alpha}^\dagger f_\beta^\dagger \end{pmatrix}$$

J_K

doping p



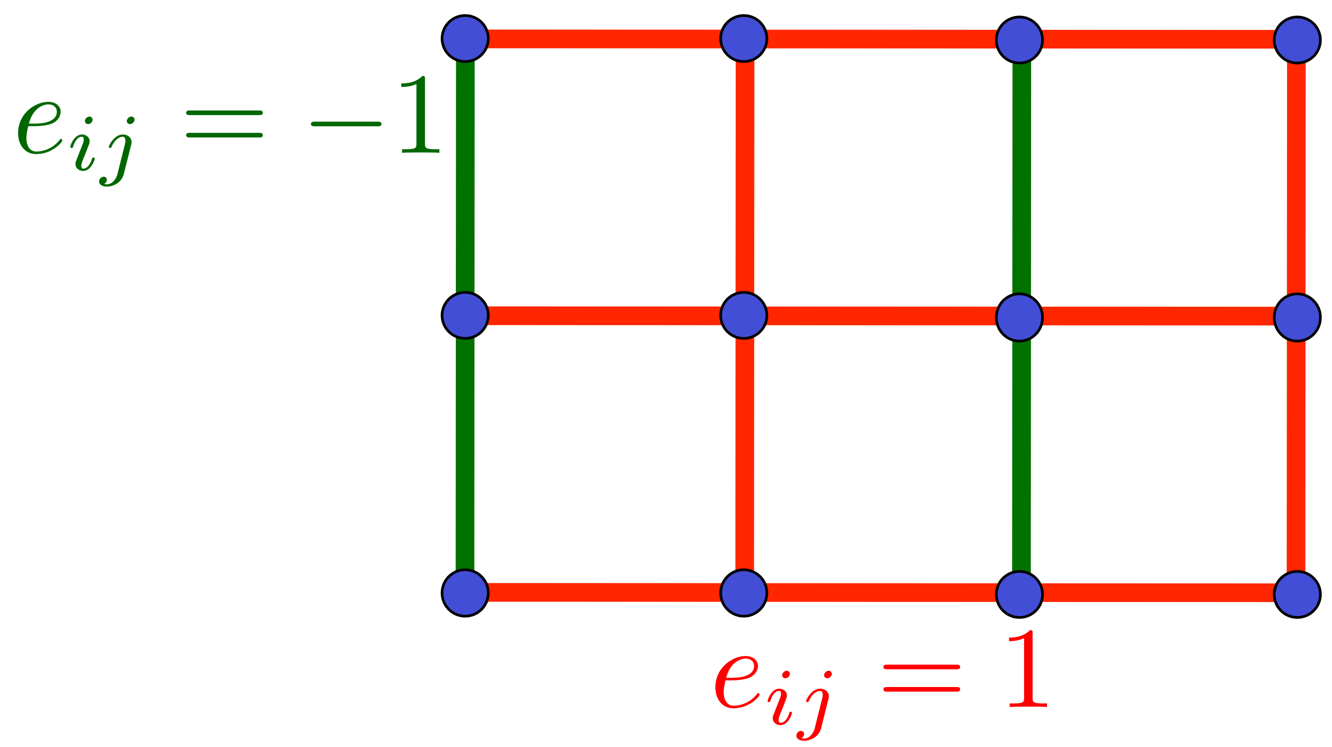
Ya-Hui Zhang

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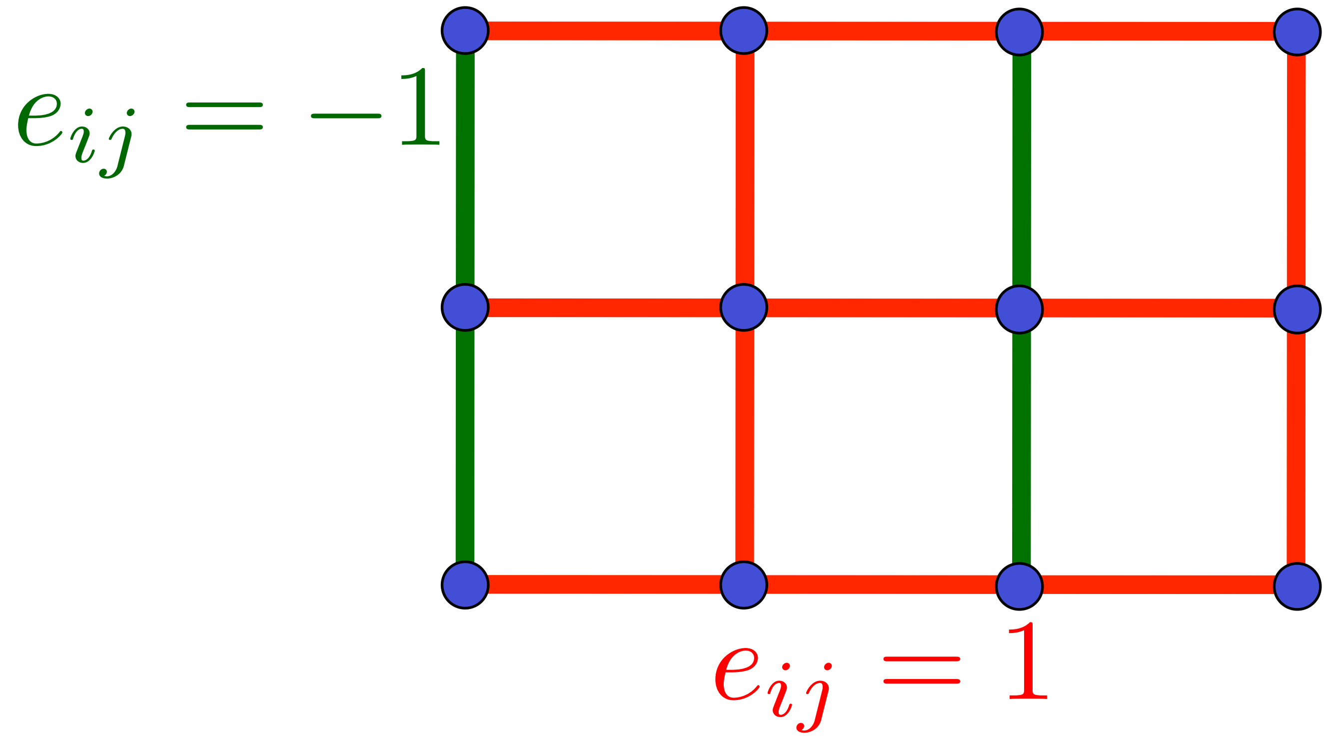
$$H_f = iJ \sum_{\langle ij \rangle} e_{ij} \left(f_{i\alpha}^\dagger f_{j\alpha} - f_{j\alpha}^\dagger f_{i\alpha} \right) = iJ \sum_{\langle ij \rangle} e_{ij} \left(\Psi_i^\dagger U_{ij} \Psi_j - \Psi_j^\dagger U_{ji} \Psi_i \right) ; \quad \Psi_i = \begin{pmatrix} f_{i\uparrow} \\ f_{i\downarrow}^\dagger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

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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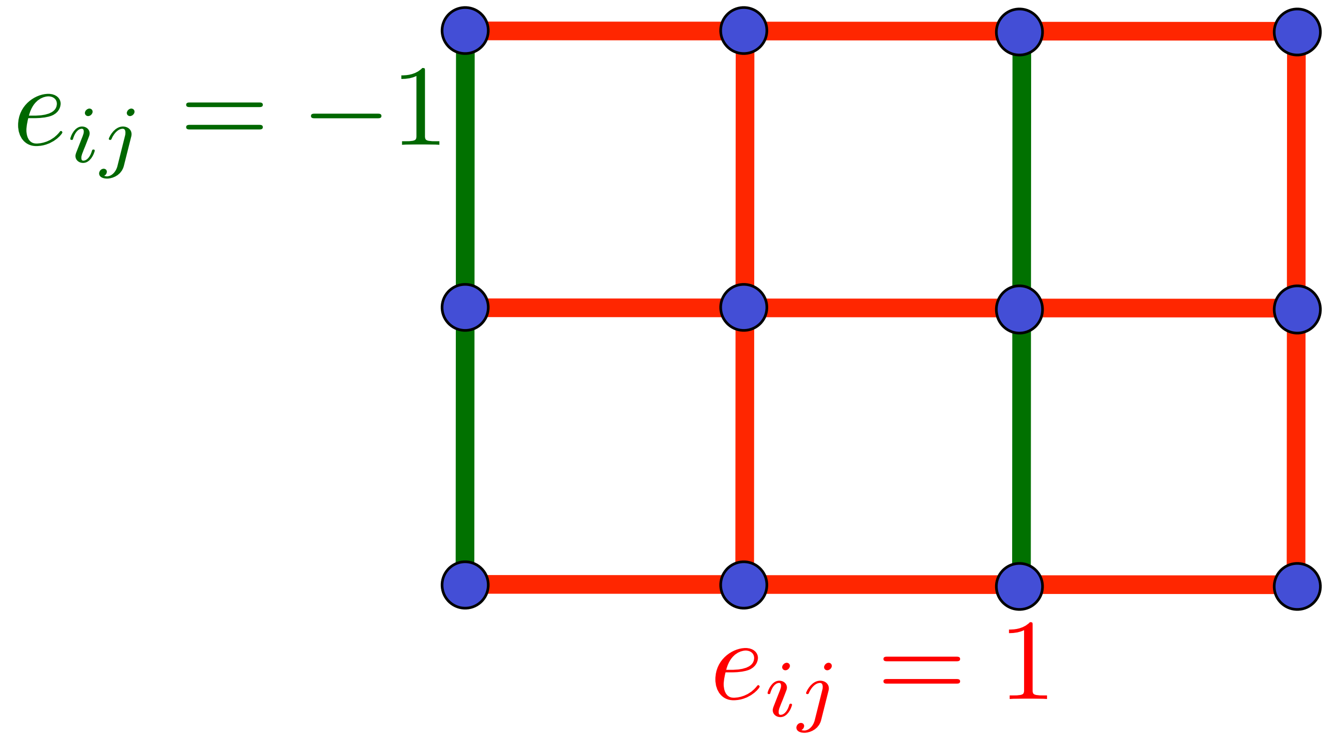


- The nearest-neighbor effective Hamiltonian for charge e, SU(2)$_N$ fundamental boson B_i is constrained by the fact that the composite of B_i and Ψ_i is an electron:

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

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

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

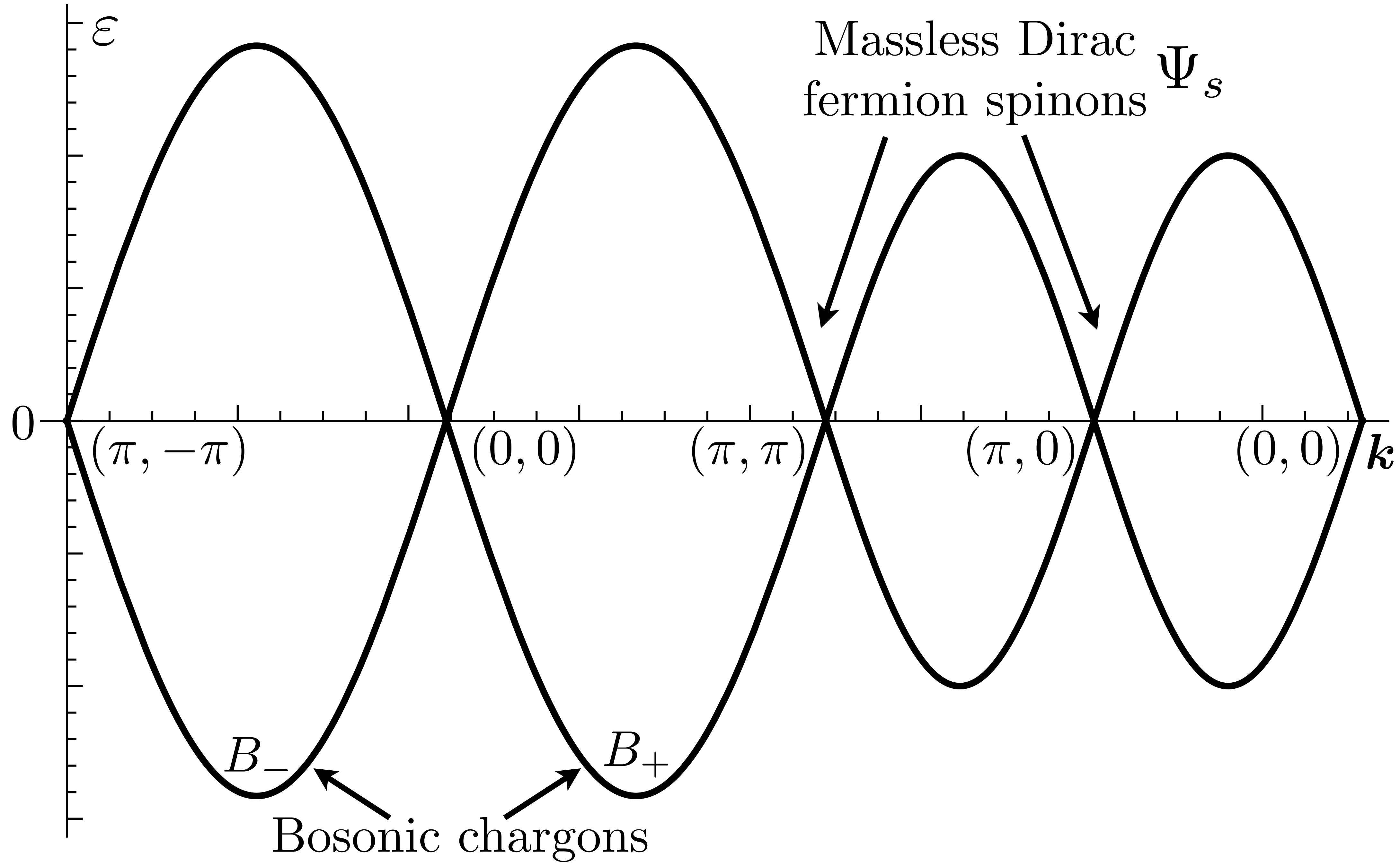
site charge density: $\left\langle c_{\boldsymbol{i}\alpha}^\dagger c_{\boldsymbol{i}\alpha} \right\rangle \sim \rho_{\boldsymbol{i}} = B_{\boldsymbol{i}}^\dagger B_{\boldsymbol{i}}$

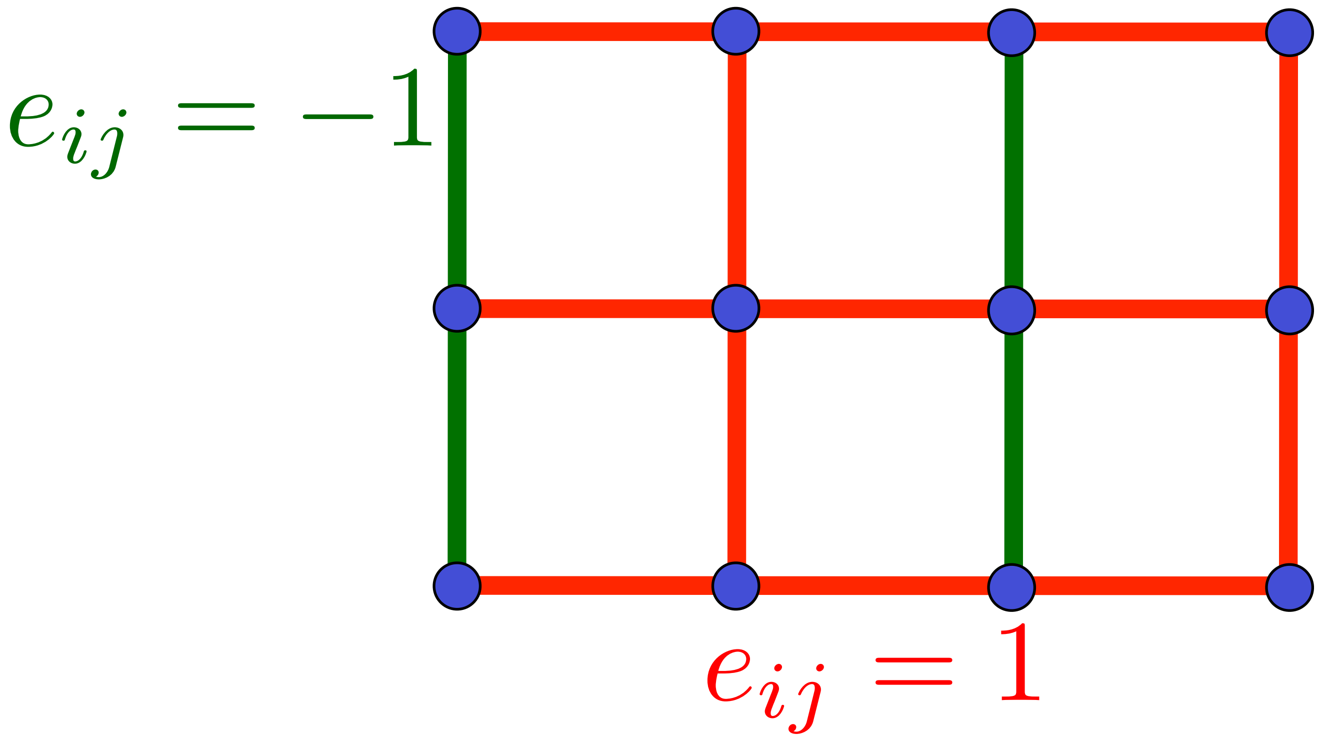
bond density: $\left\langle c_{\boldsymbol{i}\alpha}^\dagger c_{\boldsymbol{j}\alpha} + c_{\boldsymbol{j}\alpha}^\dagger c_{\boldsymbol{i}\alpha} \right\rangle \sim Q_{\boldsymbol{ij}} = Q_{\boldsymbol{ji}} = \mathrm{Im}\left(B_{\boldsymbol{i}}^\dagger e_{\boldsymbol{ij}} U_{\boldsymbol{ij}} B_{\boldsymbol{j}}\right)$

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

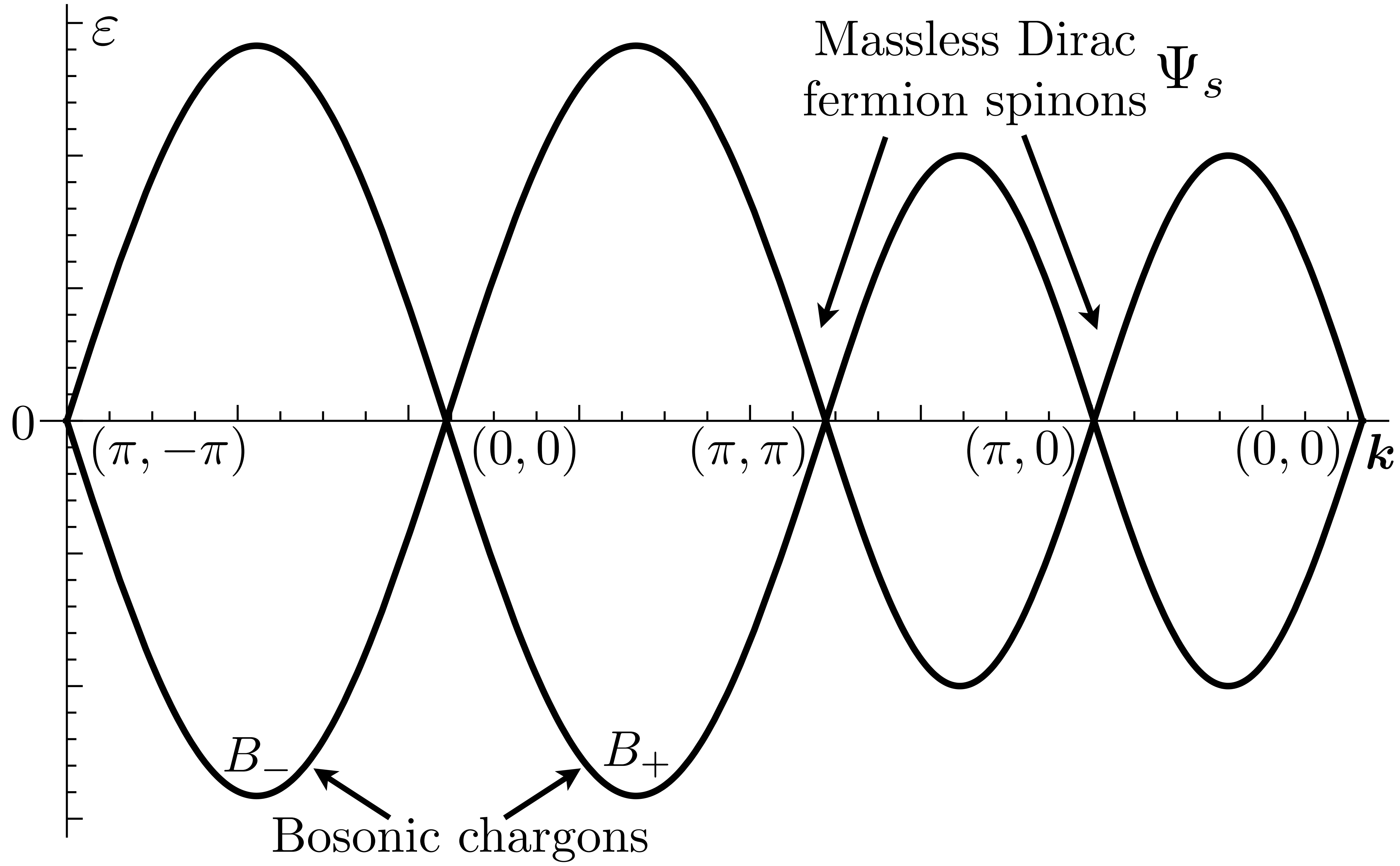
Pairing: $\langle \varepsilon_{\alpha\beta} c_{i\alpha} c_{j\beta} \rangle \sim \Delta_{\boldsymbol{ij}} = \Delta_{\boldsymbol{ji}} = \varepsilon_{ab} B_{a\boldsymbol{i}} e_{\boldsymbol{ij}} U_{\boldsymbol{ij}} B_{b\boldsymbol{j}}$.

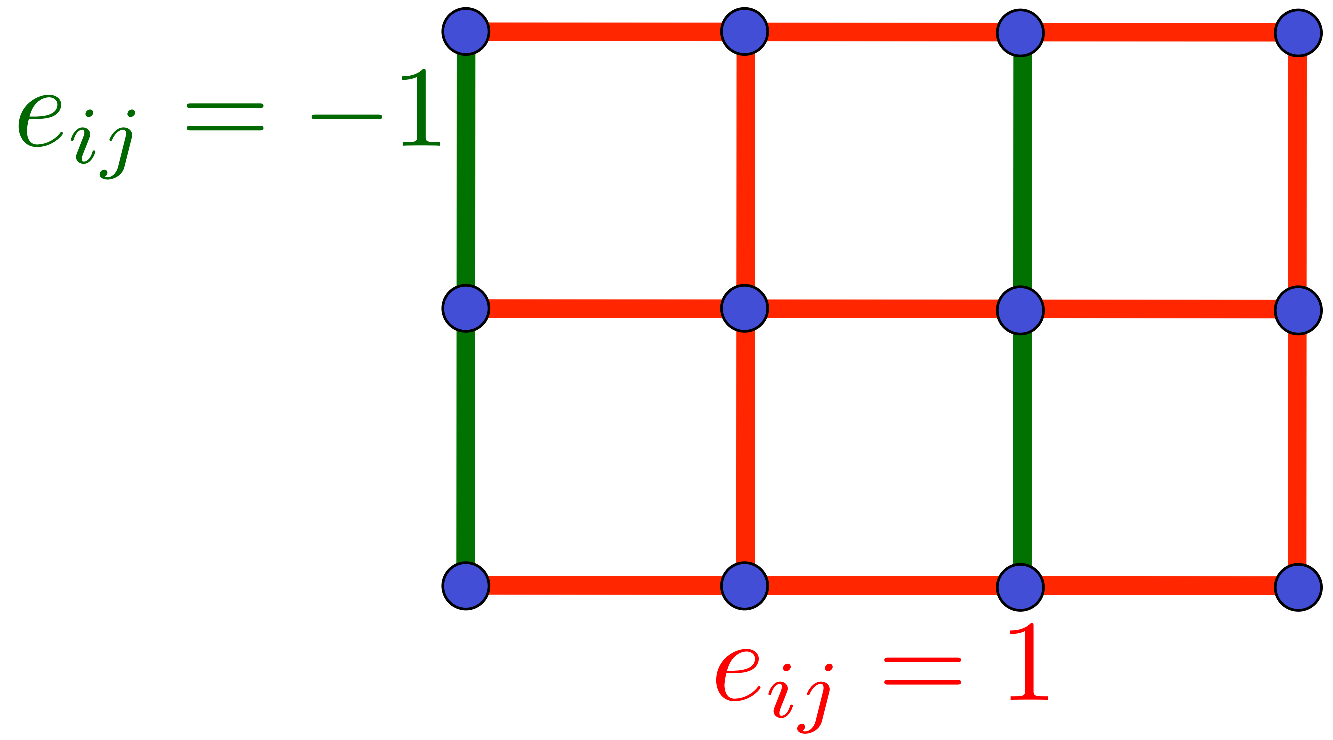
Confinement of SU(2)$_N$ gauge theory by charge fluctuations





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





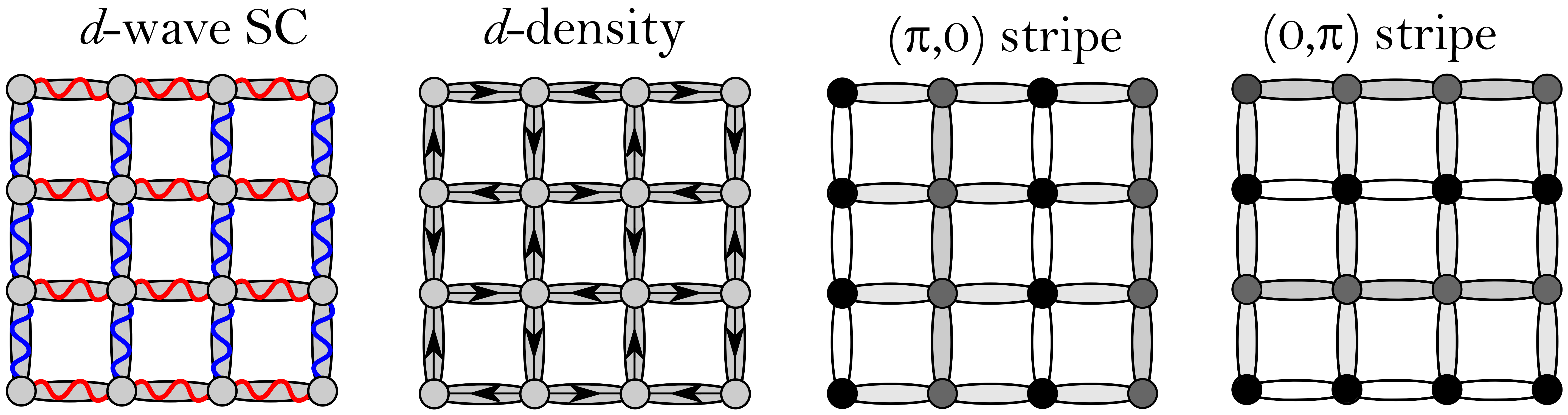
$SU(2)_N$ gauge-invariant and $SU(2)$ spin invariant order parameters of Higgs phases:

$$x\text{-CDW}: \quad \rho_{(\pi,0)} = B^*_{a+}B_{a+} - B^*_{a-}B_{a-}$$

$$y\text{-CDW}: \quad \rho_{(0,\pi)} = B^*_{a+}B_{a-} + B^*_{a-}B_{a+}$$

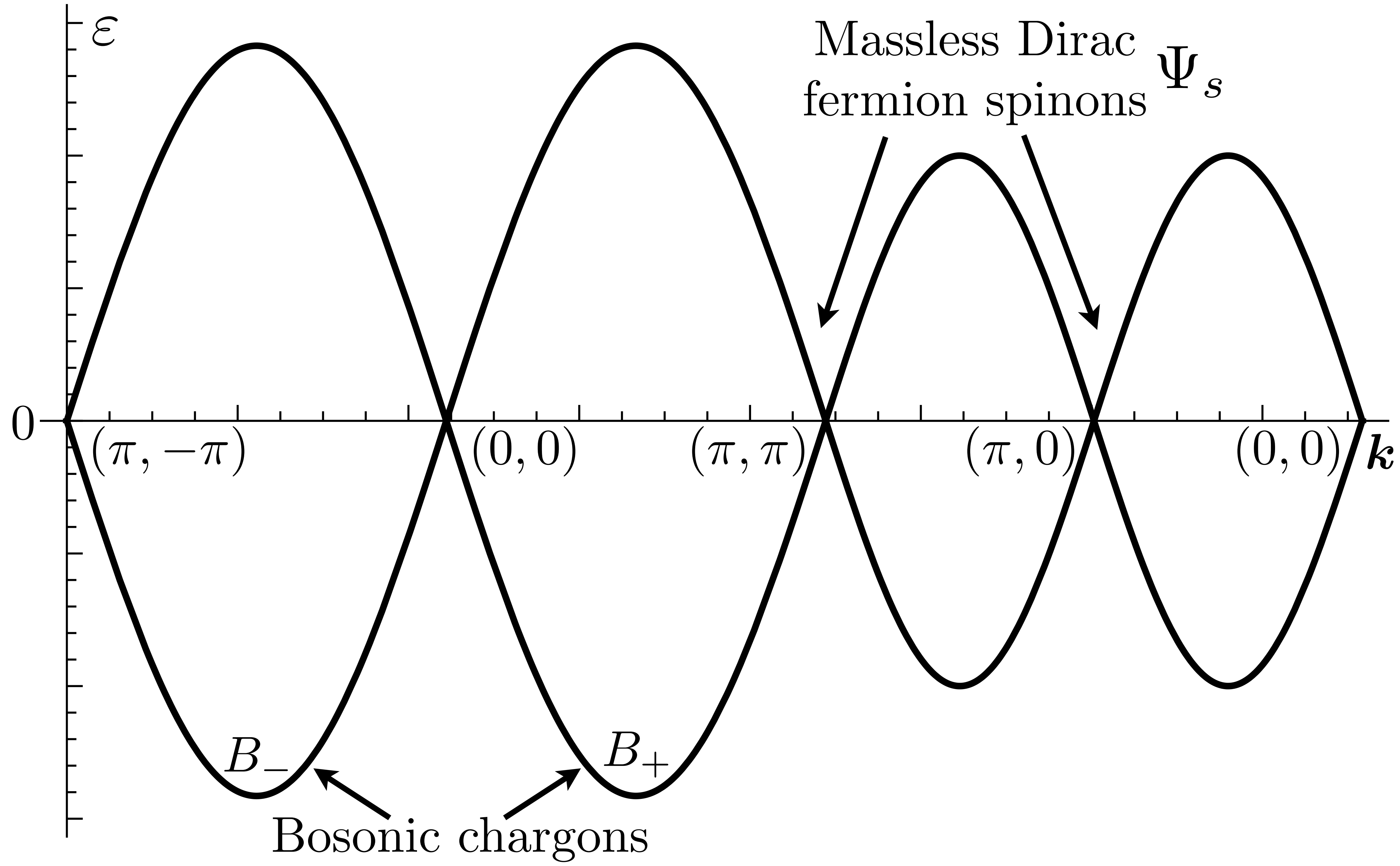
$$d\text{-density wave}: \quad D = i\left(B^*_{a+}B_{a-} - B^*_{a-}B_{a+}\right)$$

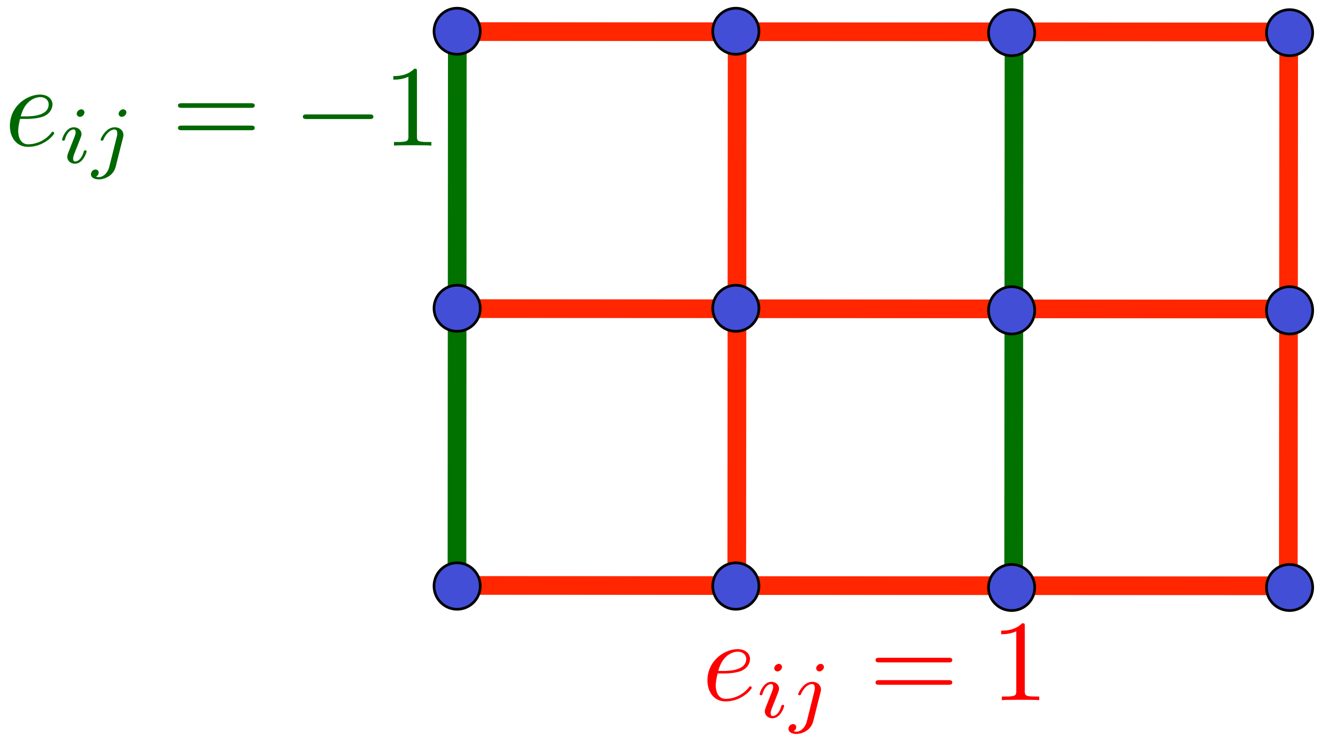
$$d\text{-wave superconductor}: \quad \Delta = \varepsilon_{ab}B_{a+}B_{b-}$$



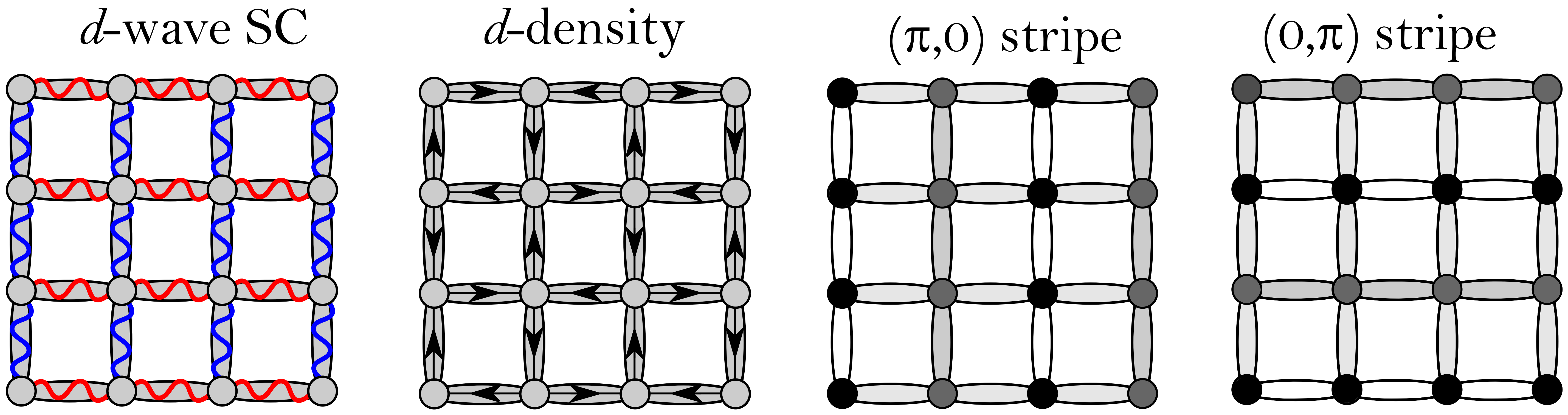
The $\mathcal{O}(B^2_{a\pm})$ terms in the energy have a $SO(5)_b$ rotation symmetry between these orders.

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

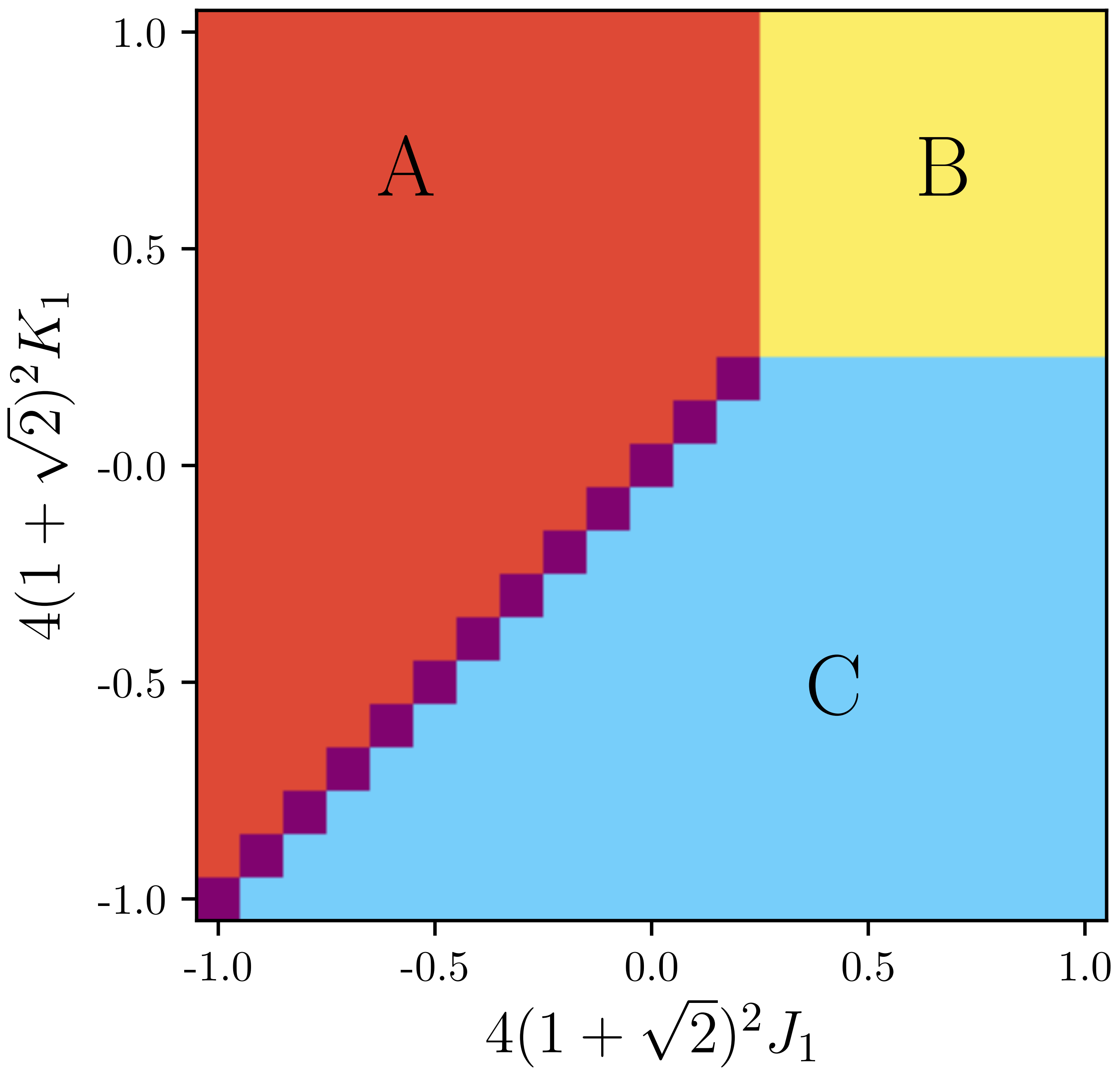




The B_{av}
($a \to$ SU(2)$_N$ gauge, $v \to$ valley)
are the "square roots" of
conventional
d-wave superconductor,
charge density wave,
pair density wave
...

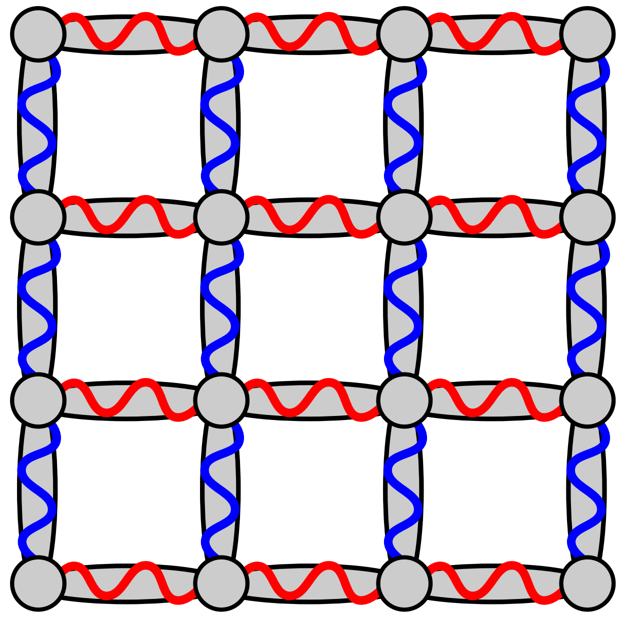


Confinement of SU(2)$_N$ gauge theory by charge fluctuations

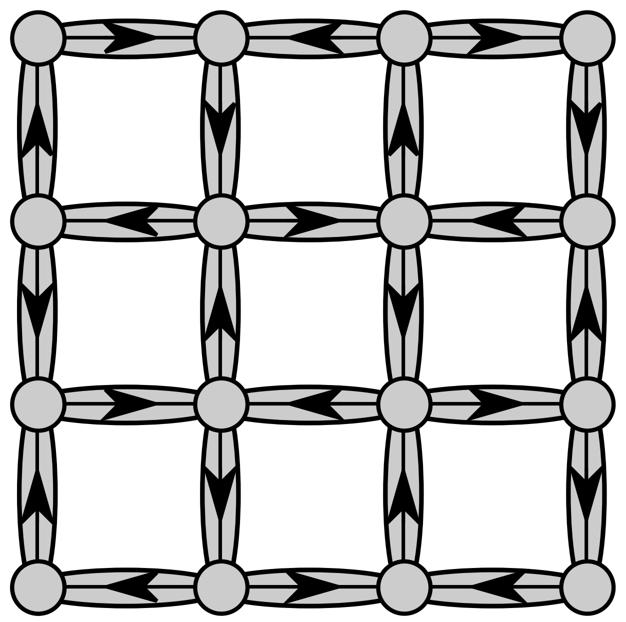


$$\langle B \rangle \neq 0$$

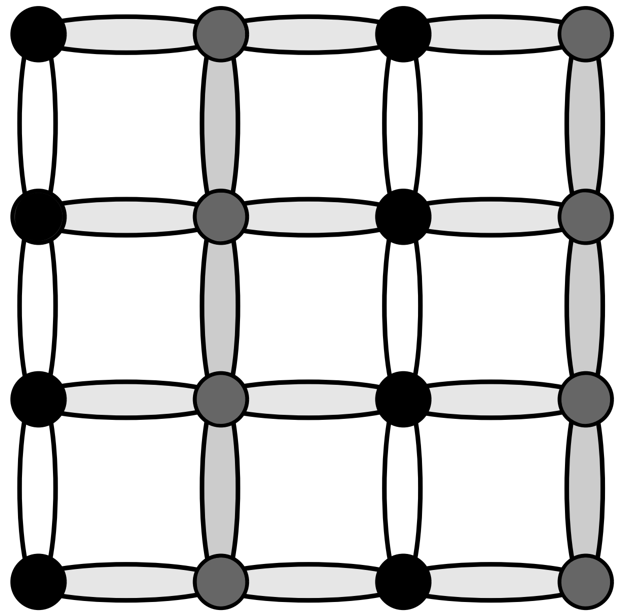
Phase B
d-wave SC



Phase C
d-density



Phase A
(π,0) stripe



Phase A
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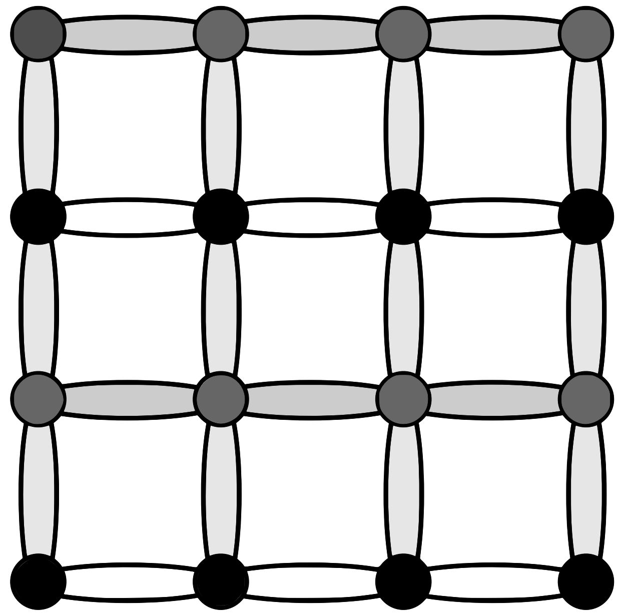
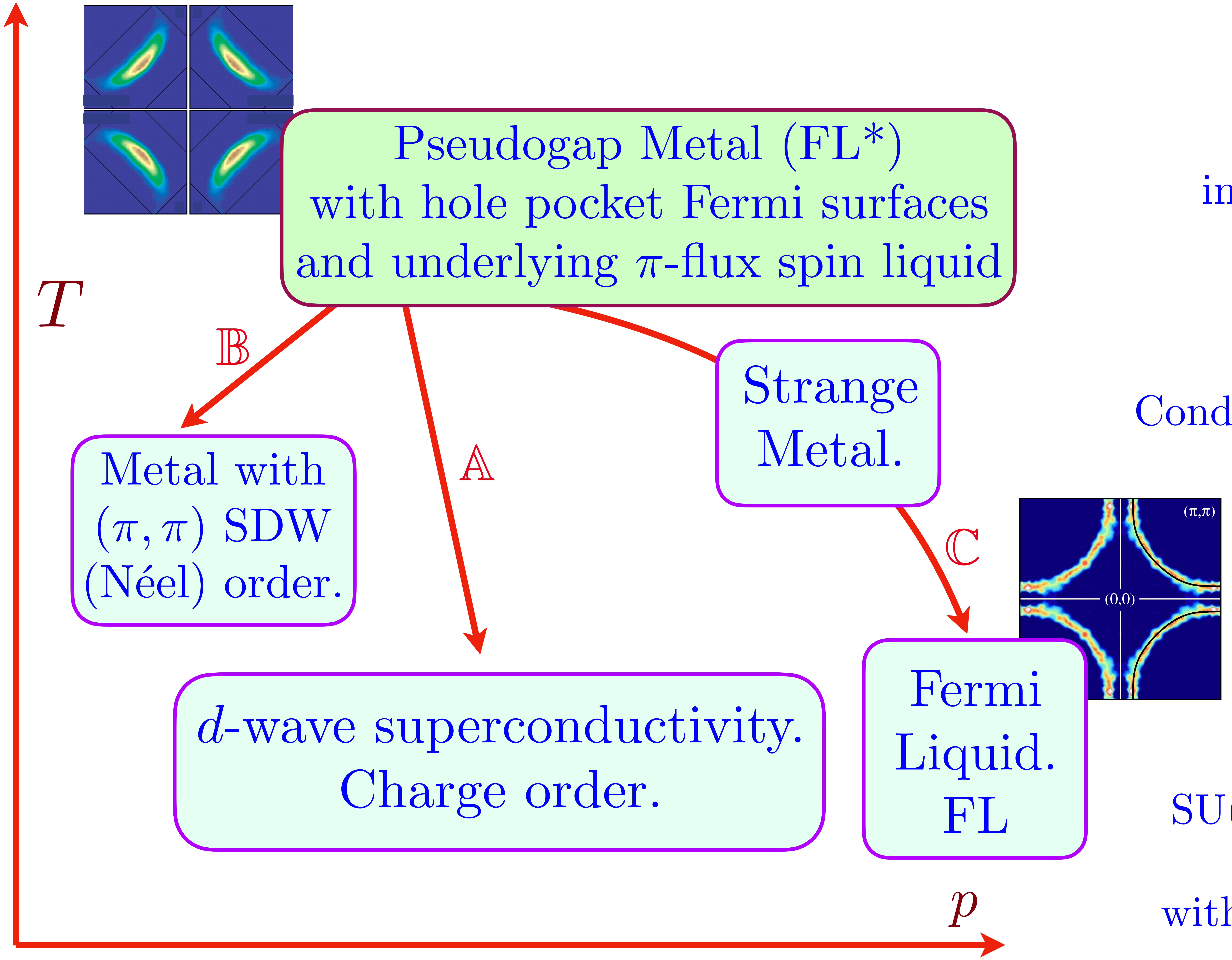


Global phase diagram of SU(2)$_N$ gauge theory

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



<u>Arrow 𝔸</u>

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

<u>Arrow 𝔹</u>

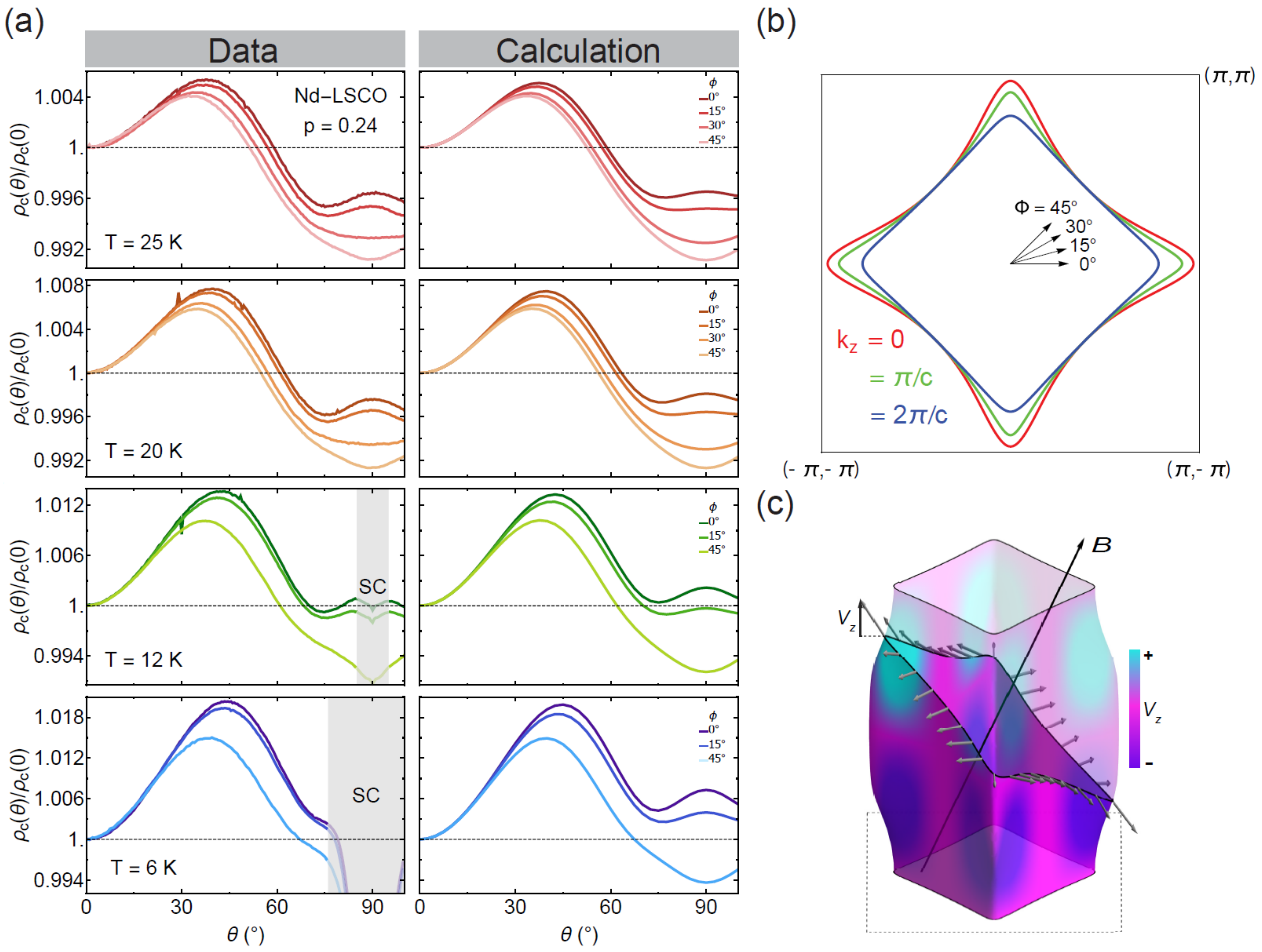
Condensation of z_α in dual $\mathbb{CP}^1$
U(1) gauge theory.

<u>Arrow ℂ</u>

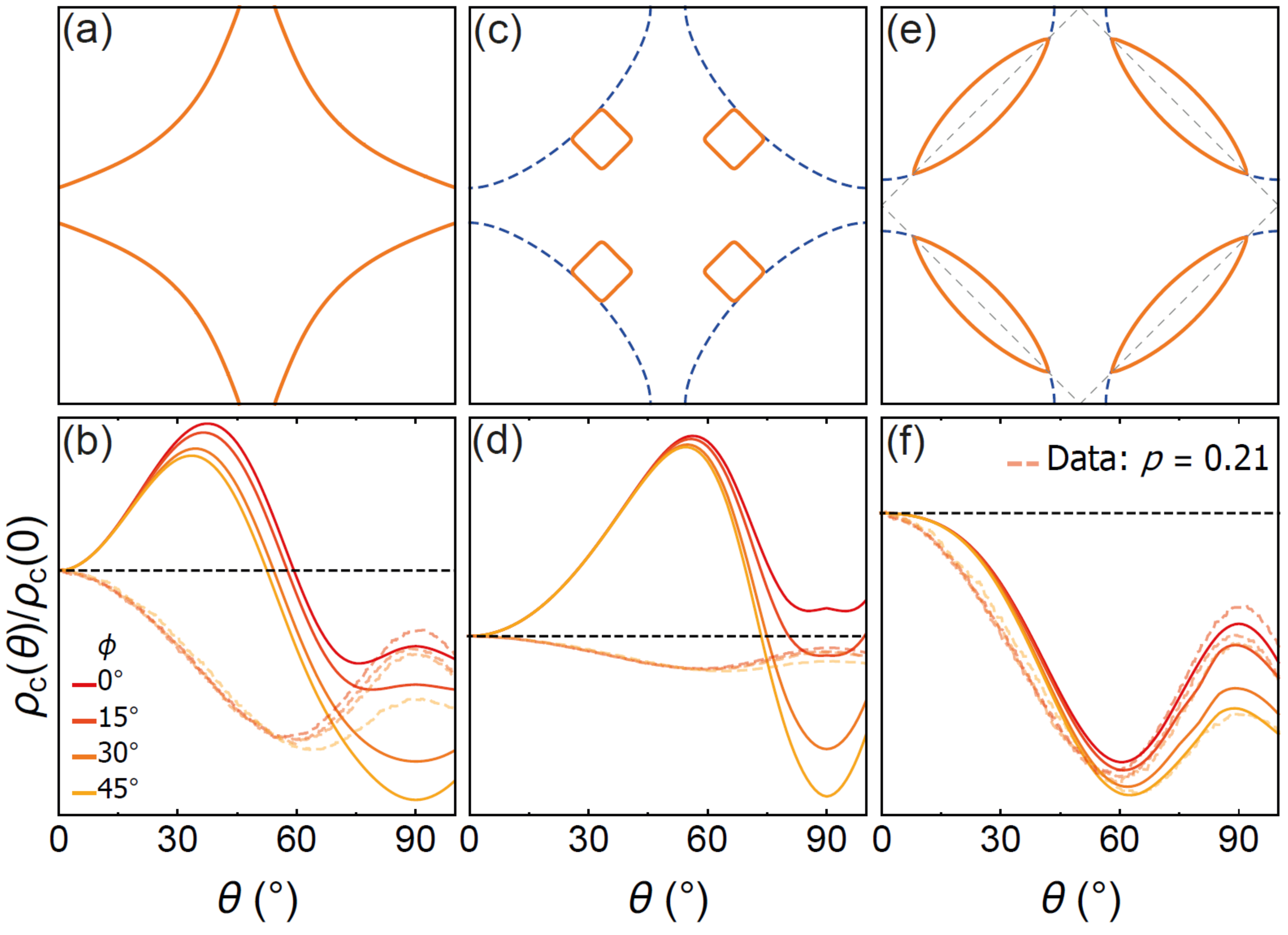
$SU(2)_s \times U(1)_a$ gauge theory
in ancilla model
with Higgs field $H_{\alpha a} \sim c_\alpha^\dagger f_{1a}$

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



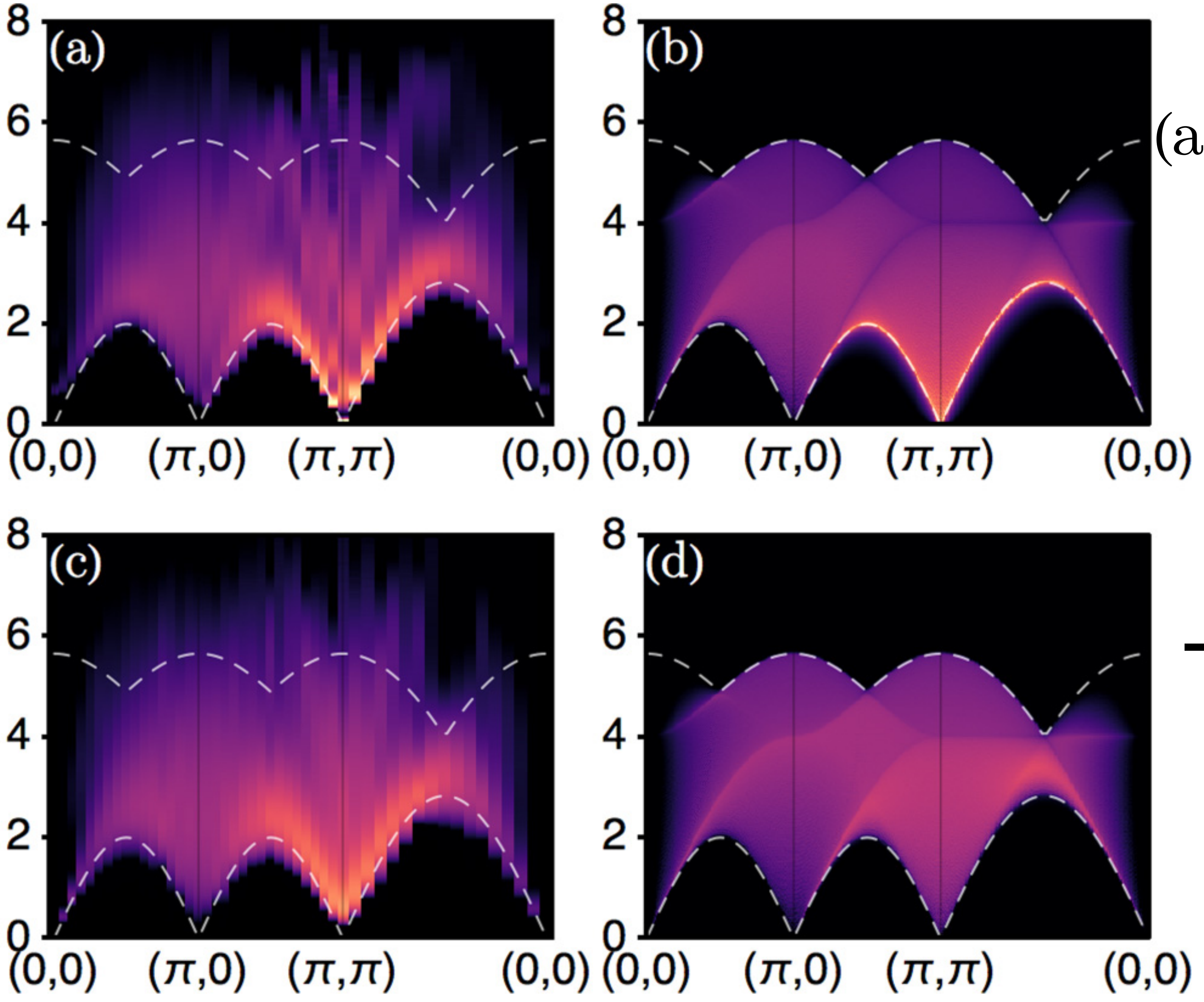
$p < p_c$ Reconstructed Fermi surface

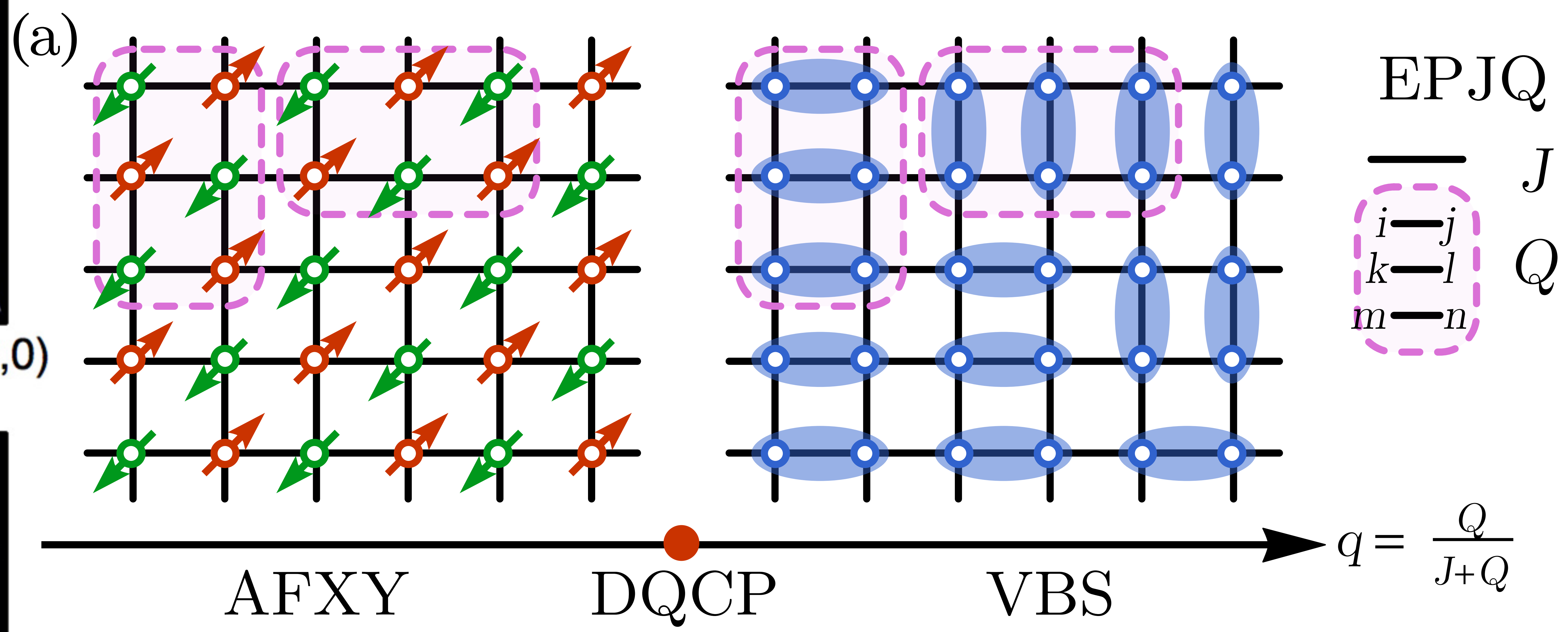
QMC

Free fermion spinons in π-flux

XX

ZZ

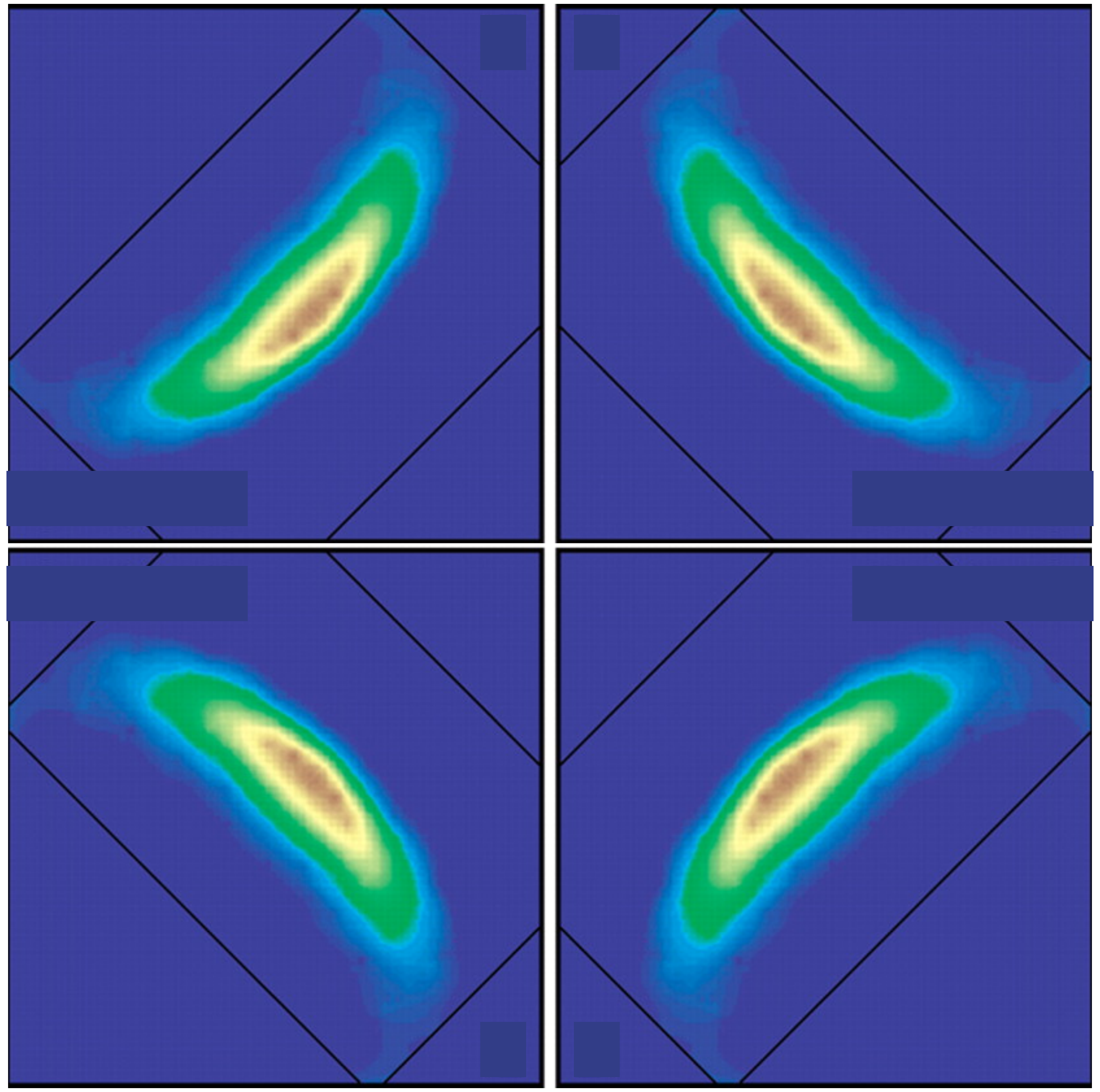




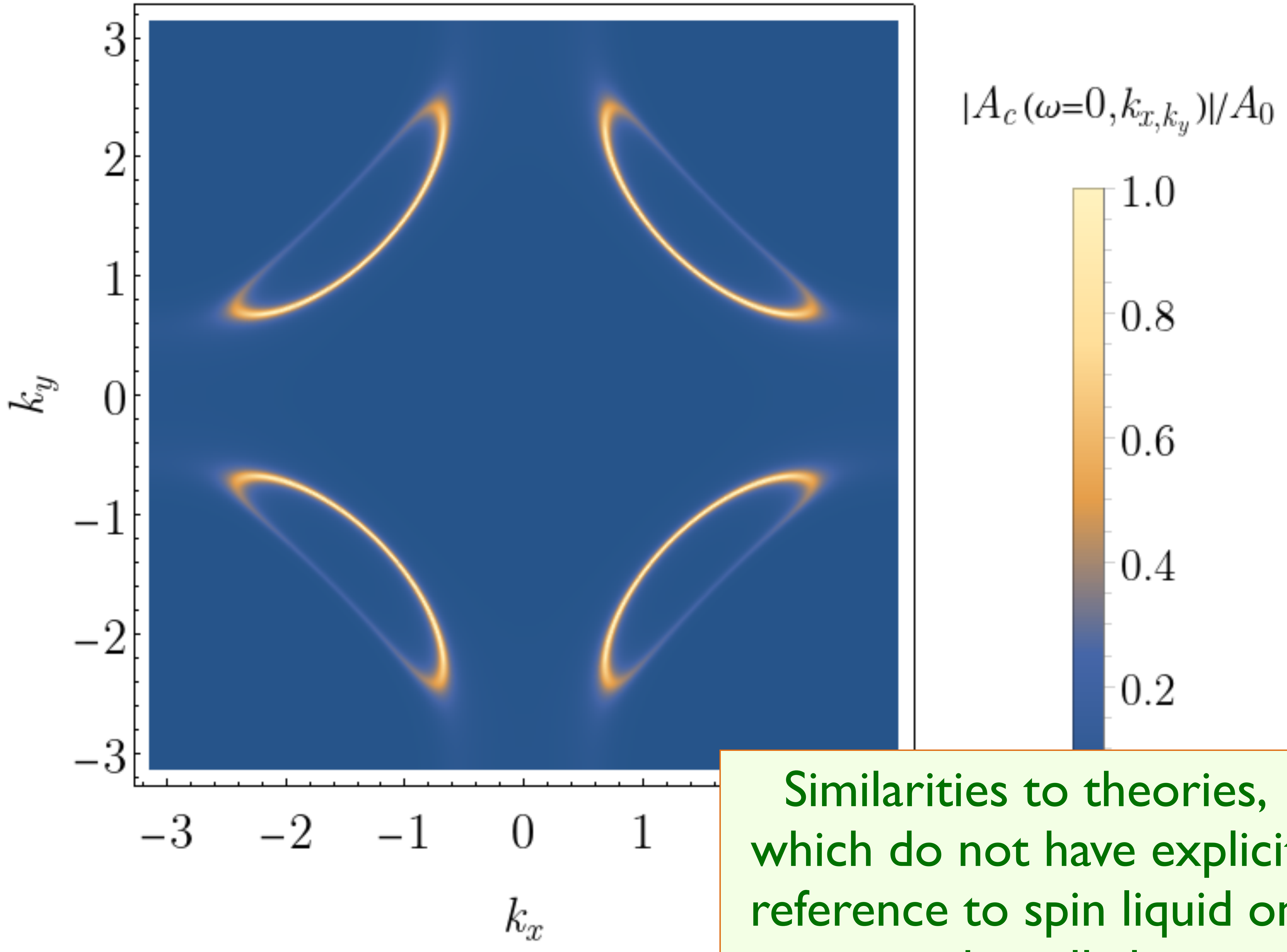
Nvsen Ma, Guang-Yu Sun, Yi-Zhuang You, Cenke Xu, Ashvin Vishwanath, Anders W. Sandvik, and Zi Yang Meng, PRB **98**, 174421 (2018)

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"

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)

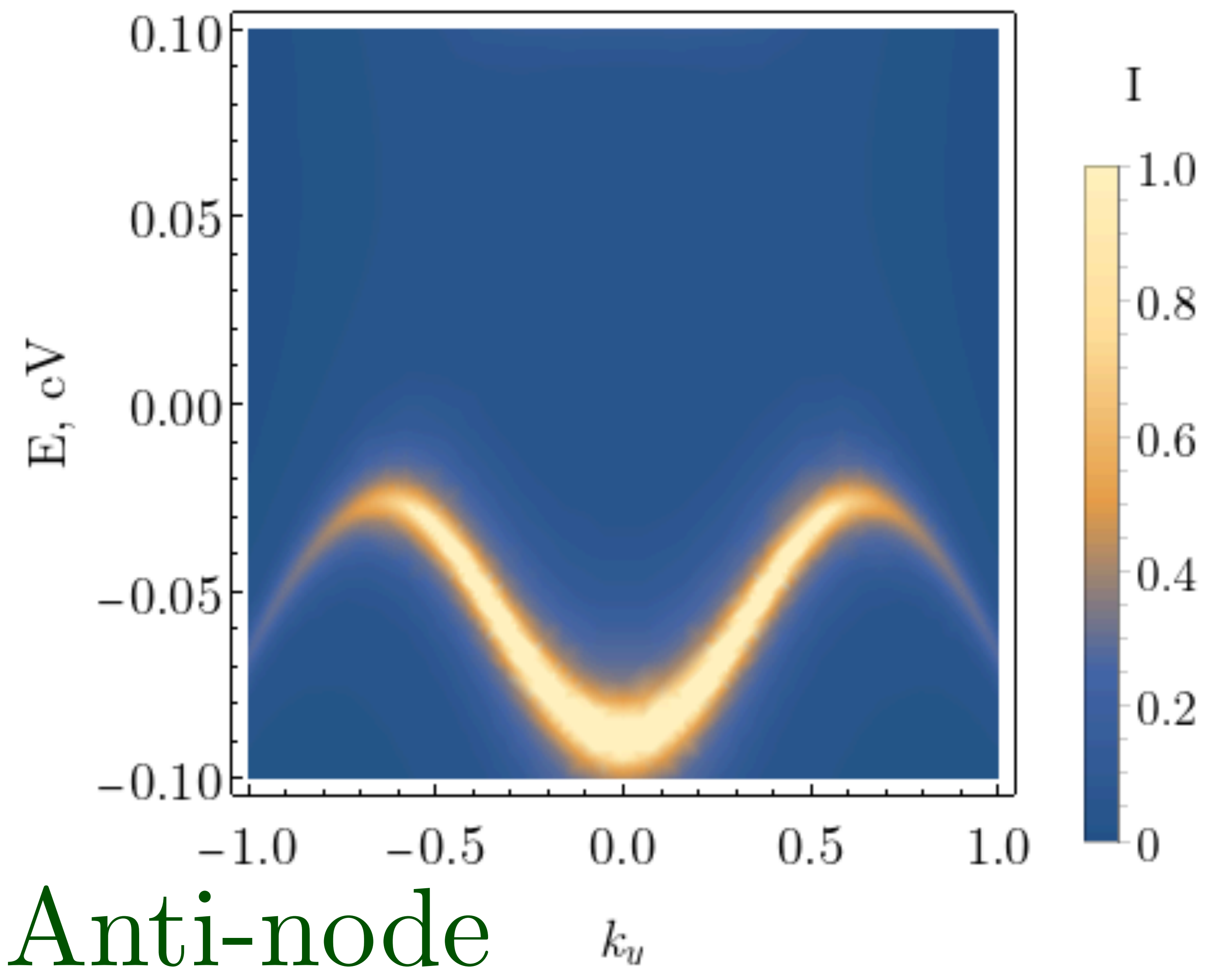
Similarities to theories, which do not have explicit reference to spin liquid on second ancilla layer

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

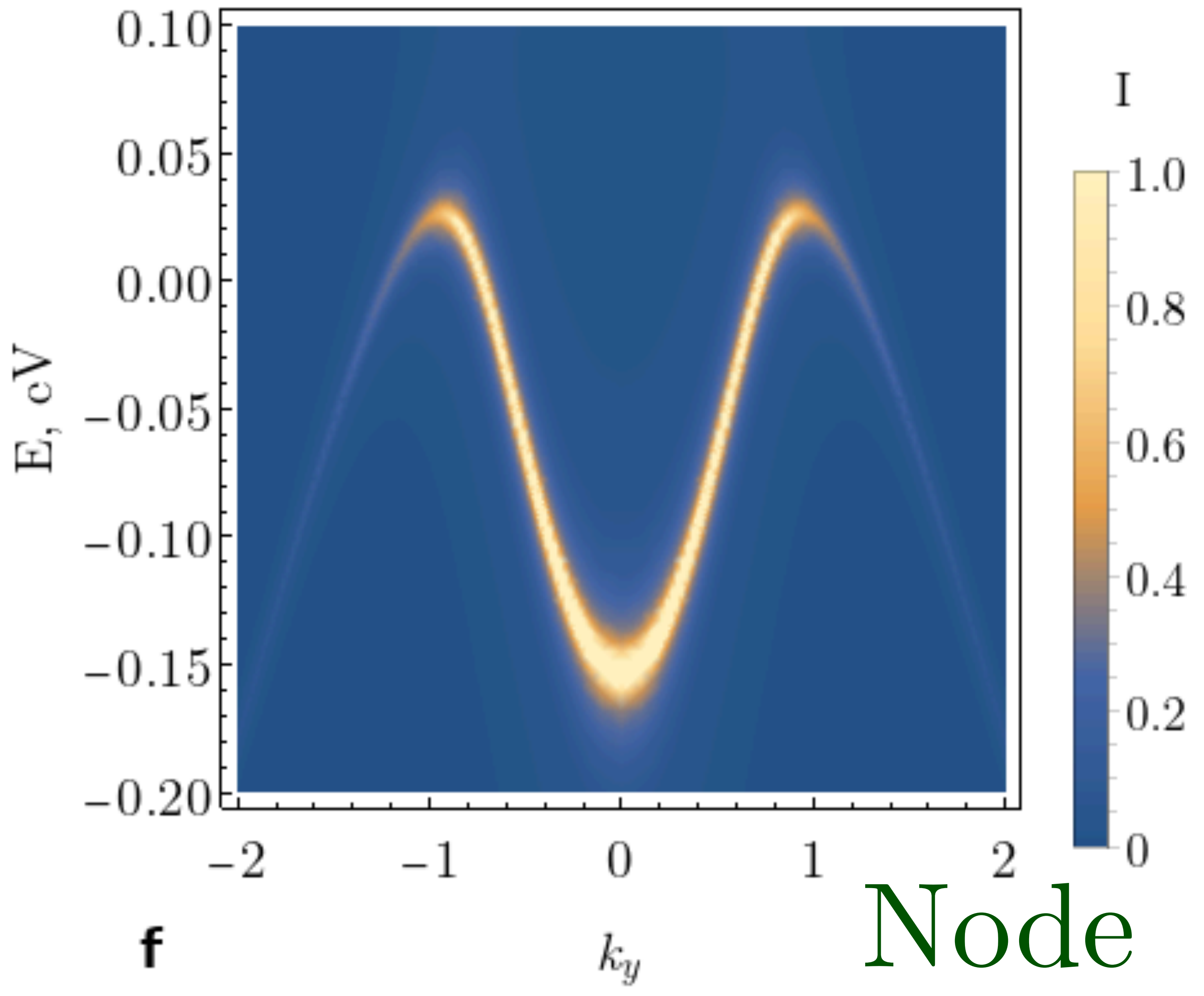
E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, and S. S., PRB **105**, 075146 (2022)

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

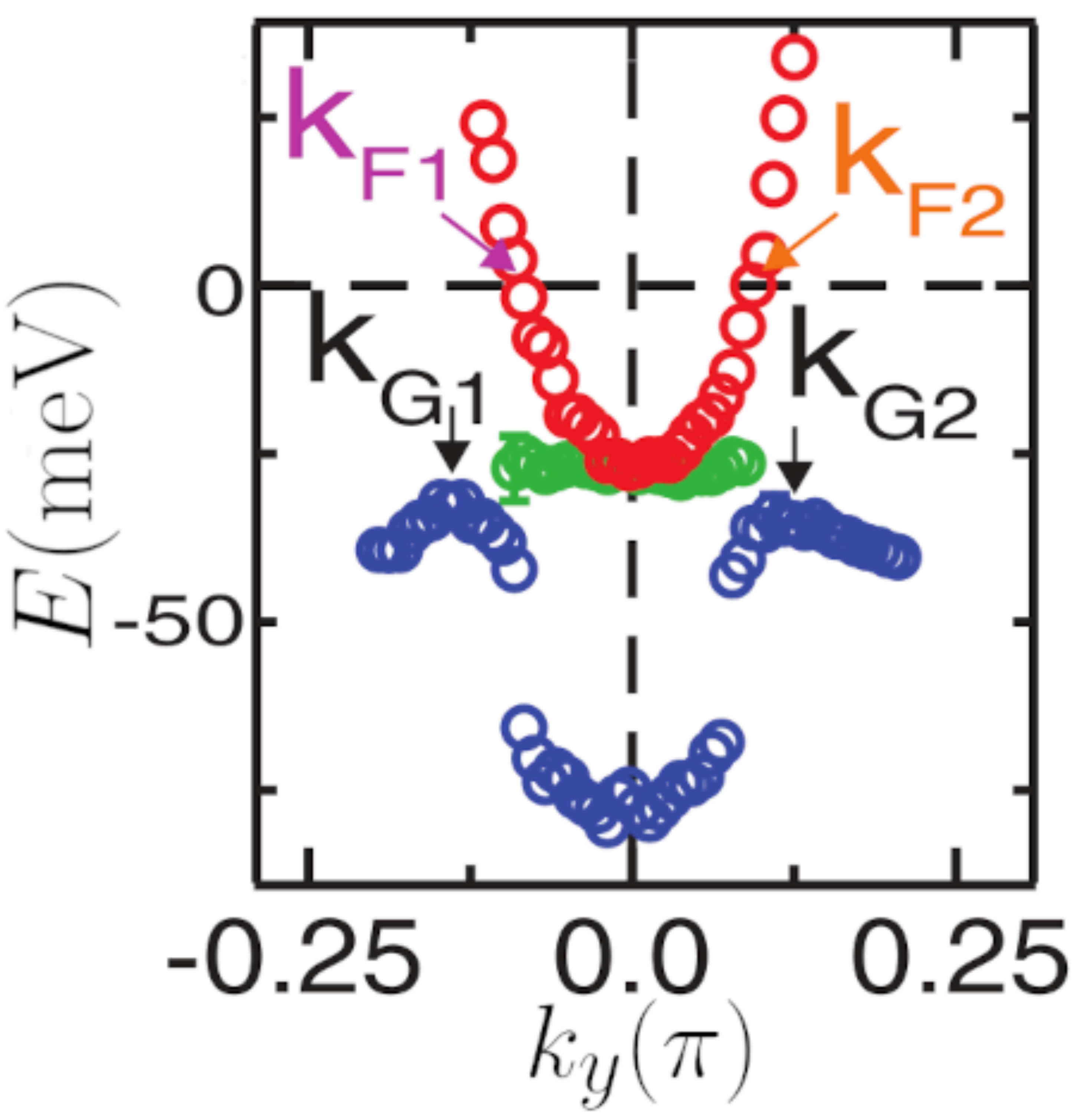
Second ancilla layer is needed to describe MDC and EDC

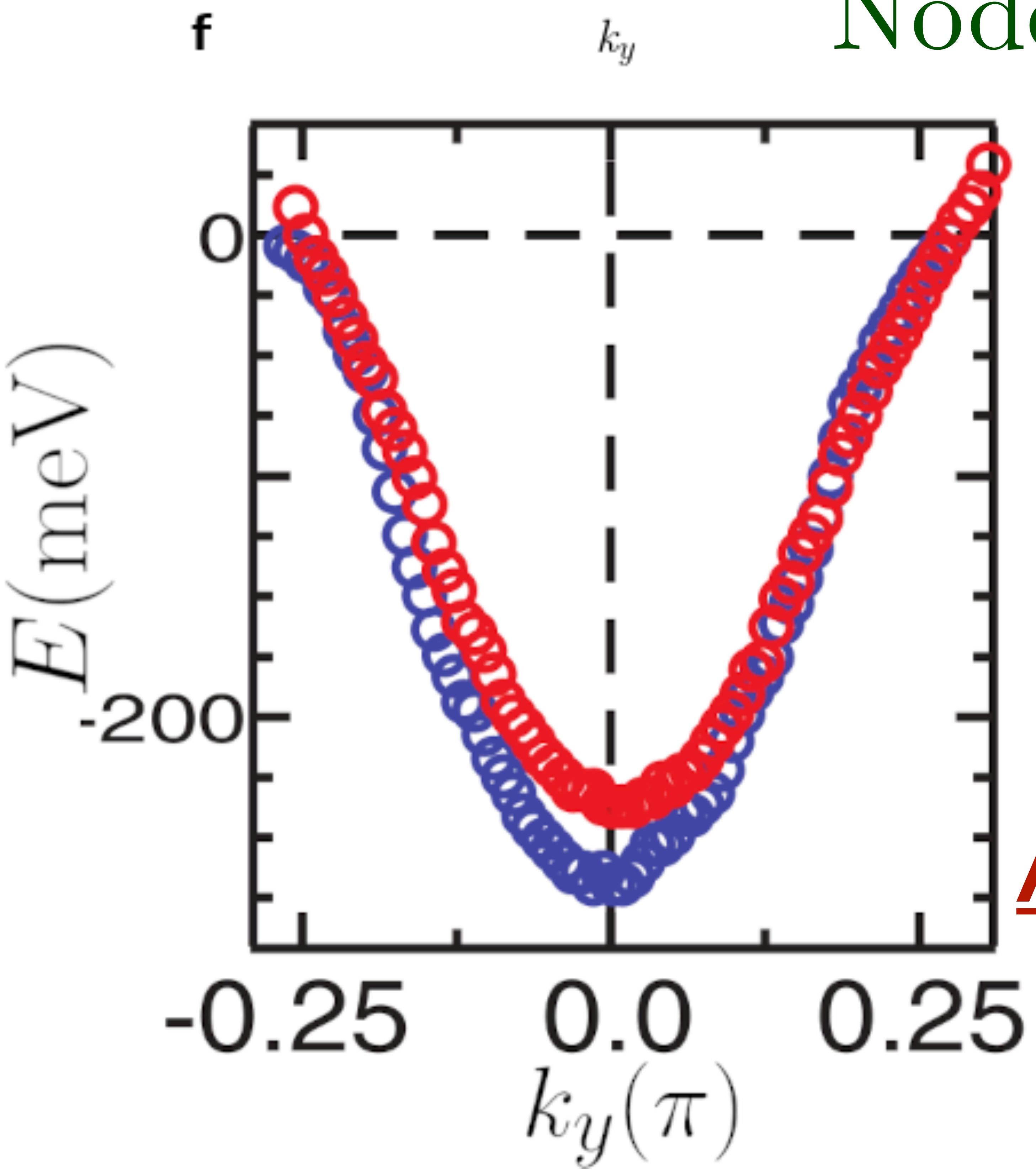


Anti-node



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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S. Sakai, Y. Motome, M. Imada, PRL **102**, 056404 (2009)

Unified SU(2)xU(1) gauge theory of spinons, electrons and Higgs bosons:
uncanny similarities to the Salam-Weinberg-Glashow theory of weak interactions

- The electromagnetic U(1) is effectively global, because $\alpha \ll 1$.

- 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

- The Higgs sector has a boson B_i which is fundamental of SU(2)

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

- 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 $B_i = (B_{1i}, B_{2i})$:

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