Ancilla qubit wavefunctions for the pseudogap metal phase of the cuprates

Tensor Networks: From Simulations to Holography III
Perimeter Institute, Waterloo
November 16, 2020
Subir Sachdev

PHYSICS

VE RI TAS

HARVARD

Talk online: sachdev.physics.harvard.edu

Yahui Zhang

Luttinger theorem for Fermi liquids

Consider a general model of interacting electrons $c_\uparrow$, $c_\downarrow$ and $S = 1/2$ spins $\vec{S} = (1/2) f_\alpha^\dagger \sigma_{\alpha\beta} f_\beta$, $\sum_\alpha f_\alpha^\dagger f_\alpha = 1$.

$$c_\alpha c_\beta^\dagger + c_\beta^\dagger c_\alpha = \delta_{\alpha\beta}, \quad f_\alpha f_\beta^\dagger + f_\beta^\dagger f_\alpha = \delta_{\alpha\beta}, \quad c_\alpha f_\beta + f_\beta c_\alpha = 0$$

We can also think of the spins as qubits with $\vec{S} = (1/2)(X, Y, Z)$ the Pauli qubit operators.

$$\begin{aligned} H \quad = \quad & - \sum_{i \neq j} t_{ij} c_{i\alpha}^\dagger c_{j\alpha} - \mu \sum_i c_{i\alpha}^\dagger c_{i\alpha} + U \sum_i c_{i\uparrow}^\dagger c_{i\uparrow} c_{i\downarrow}^\dagger c_{i\downarrow} \\ & + \sum_{i<j} J_{ij} \vec{S}_i \cdot \vec{S}_j + \sum_i \frac{J_K}{2} \vec{S}_i \cdot c_{i\alpha}^\dagger \vec{\sigma}_{\alpha\beta} c_{i\beta} \ldots \end{aligned}$$

Luttinger theorem for Fermi liquids

Luttinger's theorem states that the momentum space volume enclosed by the Fermi surface (the location of a discontinuity in the electron distribution function) equals (1/2)(density of all electrons)$\times(2\pi)^d$ modulo the density contained in filled bands (which can accommodate 2 electrons per unit cell).

Luttinger theorem for Fermi liquids

Luttinger's theorem states that the momentum space volume enclosed by the Fermi surface (the location of a discontinuity in the electron distribution function) equals (1/2)(density of all electrons)$\times(2\pi)^d$ modulo the density contained in filled bands (which can accommodate 2 electrons per unit cell).

Note that each spin $\vec{S}_i$ is *included* as one electron in the electron density count.

Luttinger theorem for Fermi liquids

Luttinger's theorem states that the momentum space volume enclosed by the Fermi surface (the location of a discontinuity in the electron distribution function) equals (1/2)(density of all electrons)$\times(2\pi)^d$ modulo the density contained in filled bands (which can accommodate 2 electrons per unit cell).

Note that each spin $\vec{S}_i$ is *included* as one electron in the electron density count.

The traditional proofs rely upon a perturbative expansion about the free electron limit. In this proof we use the f_α representation of $\vec{S}$, and replace the constraint $\sum_\alpha f_\alpha^\dagger f_\alpha$ by an interaction $U_f f_\uparrow^\dagger f_\uparrow f_\downarrow^\dagger f_\downarrow$, and expand about $U_f = 0$.

Luttinger theorem for Fermi liquids

Luttinger's theorem states that the momentum space volume enclosed by the Fermi surface (the location of a discontinuity in the electron distribution function) equals (1/2)(density of all electrons)$\times(2\pi)^d$ modulo the density contained in filled bands (which can accommodate 2 electrons per unit cell).

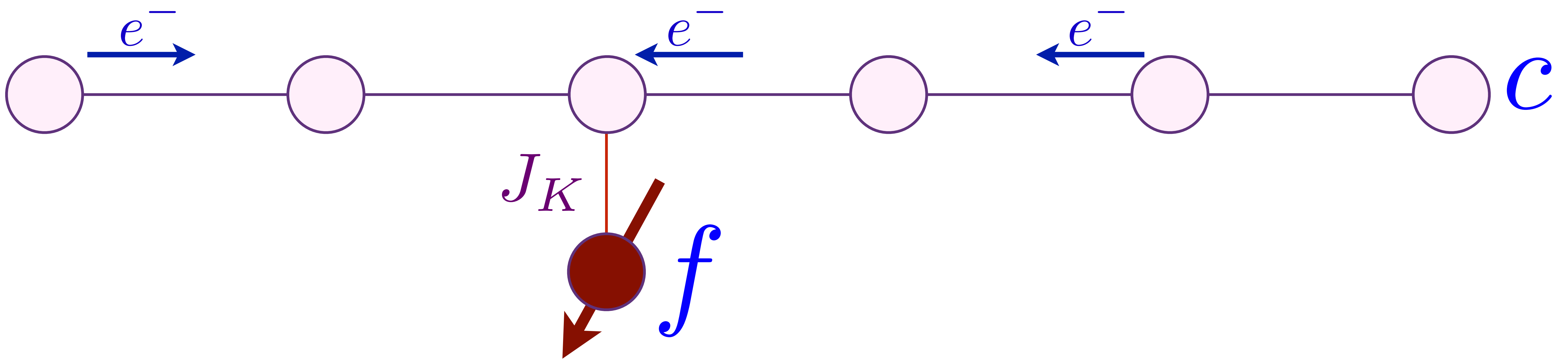
Note that each spin $\vec{S}_i$ is *included* as one electron in the electron density count.

The traditional proofs rely upon a perturbative expansion about the free electron limit. In this proof we use the f_α representation of $\vec{S}$, and replace the constraint $\sum_\alpha f_\alpha^\dagger f_\alpha$ by an interaction $U_f f_\uparrow^\dagger f_\uparrow f_\downarrow^\dagger f_\downarrow$, and expand about $U_f = 0$.

More recent proofs (Oshikawa; Else,Thorngren,Senthil) use an 'anomaly' associated with the combination of translations and the U(1) symmetry of electron number conservation, and can work directly with spin qubits.

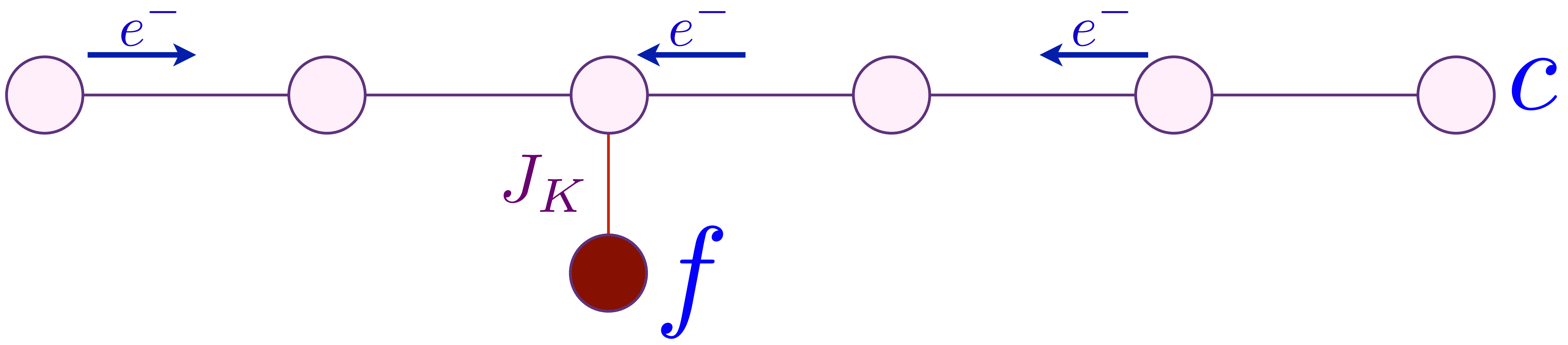
Kondo model

$$J_K \left(c^\dagger_{0\alpha} \vec{\sigma}_{\alpha\beta} c_{0\beta} \right) \cdot \vec{S}_f$$



Kondo model

$$J_K \left(c^\dagger_{0\alpha} \vec{\sigma}_{\alpha\beta} c_{0\beta} \right) \cdot \vec{S}_f$$

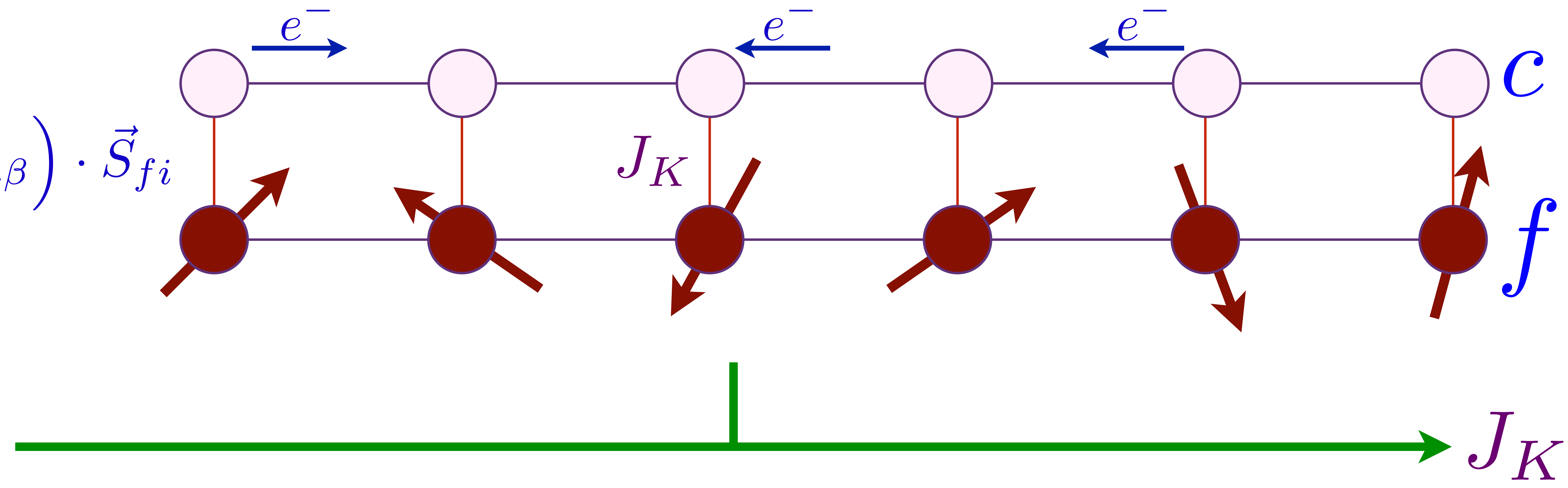


The c electrons ‘Kondo screen’ the f spin at low energies:
The f electron ‘dissolves’ into the Fermi sea.

Luttinger volume in ***Kondo lattice*** models

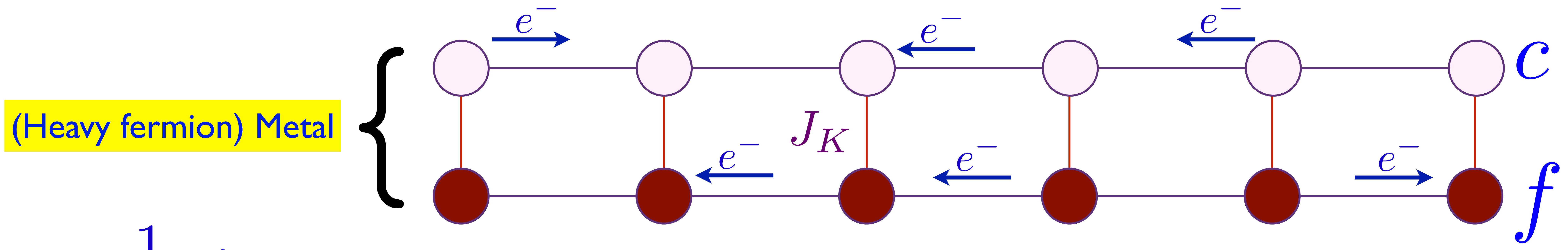
Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.

$$J_K \sum_i \left(c_{i\alpha}^\dagger \vec{\sigma}_{\alpha\beta} c_{i\beta} \right) \cdot \vec{S}_{fi}$$

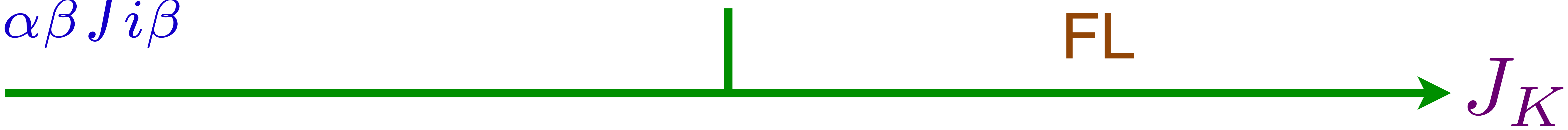


Luttinger volume in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.



$$\vec{S}_{fi} = \frac{1}{2} f_{i\alpha}^{\dagger} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

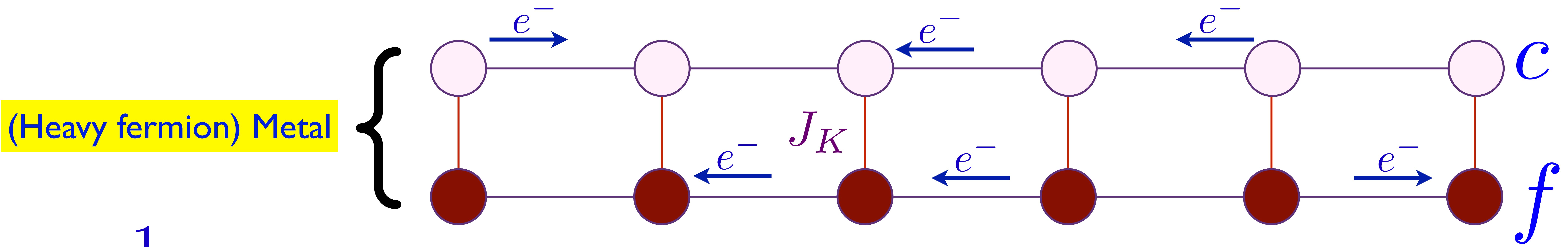


The c electrons 'Kondo screen' the f spins in the FL phase:
The f electrons 'dissolve' into the Fermi sea.

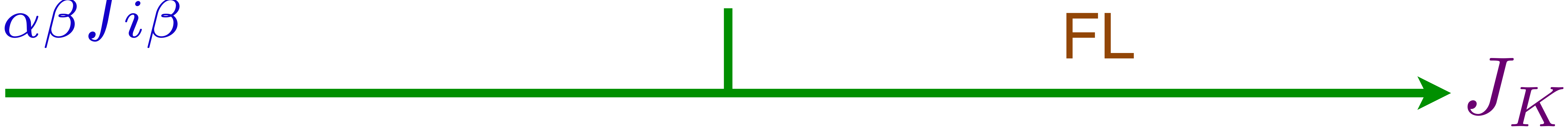
Varma, Coleman, Millis, P.A. Lee, Q. Si, Auerbach, Levin….

Luttinger volume in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.



$$\vec{S}_{fi} = \frac{1}{2} f^{\dagger}_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

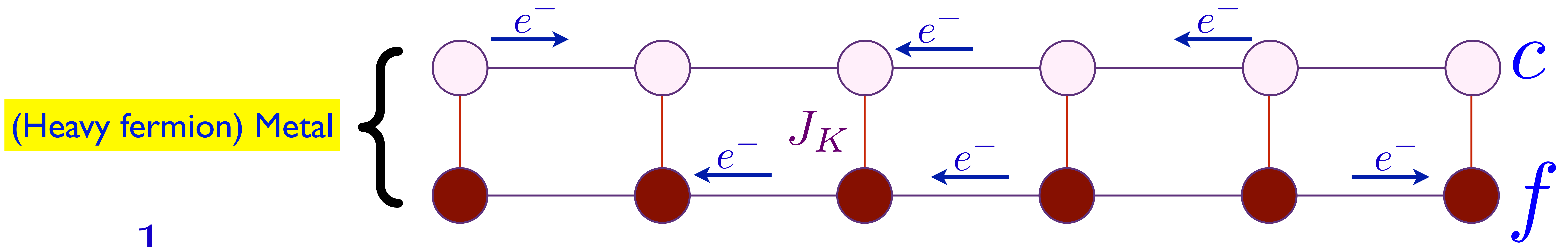


The c electrons 'Kondo screen' the f spins in the FL phase:
The f electrons 'dissolve' into the Fermi sea.
The Fermi surface is <u>large</u>: encloses volume of $1+p$ electrons.

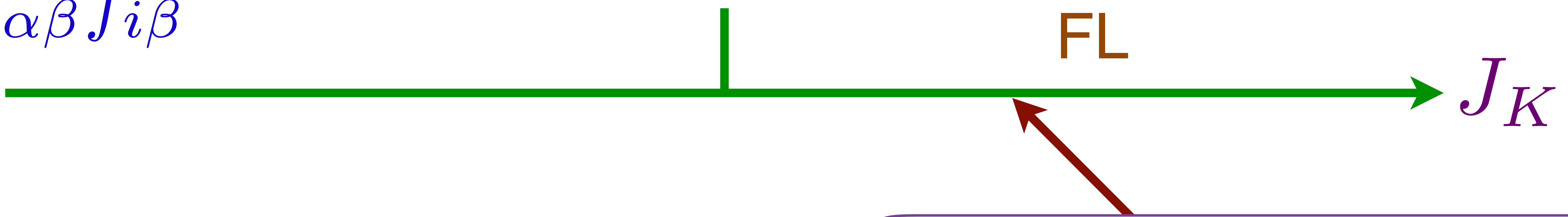
Varma, Coleman, Millis, P.A. Lee, Q. Si, Auerbach, Levin….

Luttinger volume in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.



$$\vec{S}_{fi} = \frac{1}{2} f^{\dagger}_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$



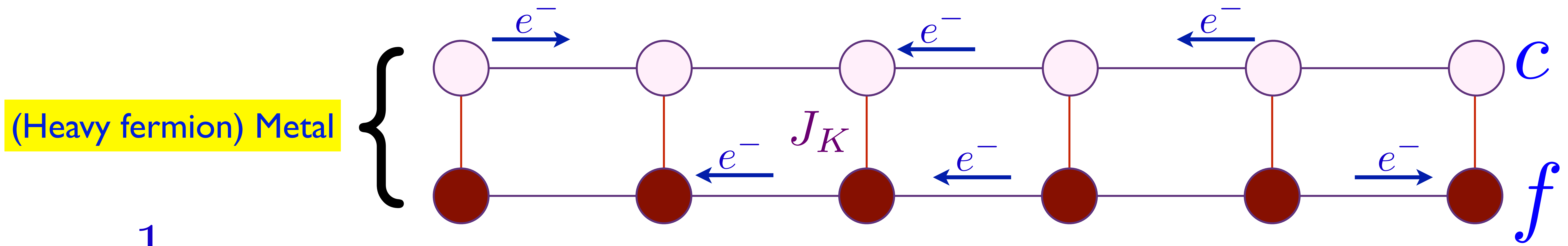
Large Fermi surface of size $1 + p$

$|\Phi\rangle = $ [Projection onto one f per site] $\bowtie$ $|$Slater determinant of $(c, f)\rangle$

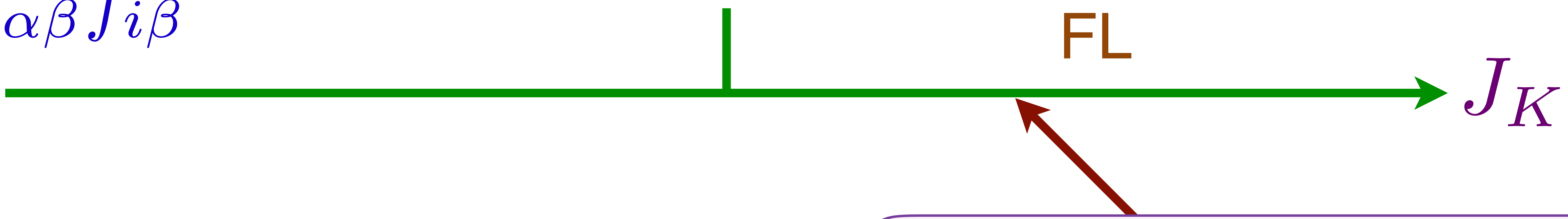
Varma, Coleman, Millis, P.A. Lee, Q. Si, Auerbach, Levin….

Luttinger volume in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.



$$\vec{S}_{fi} = \frac{1}{2} f^{\dagger}_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$



Luttinger Theorem obeyed

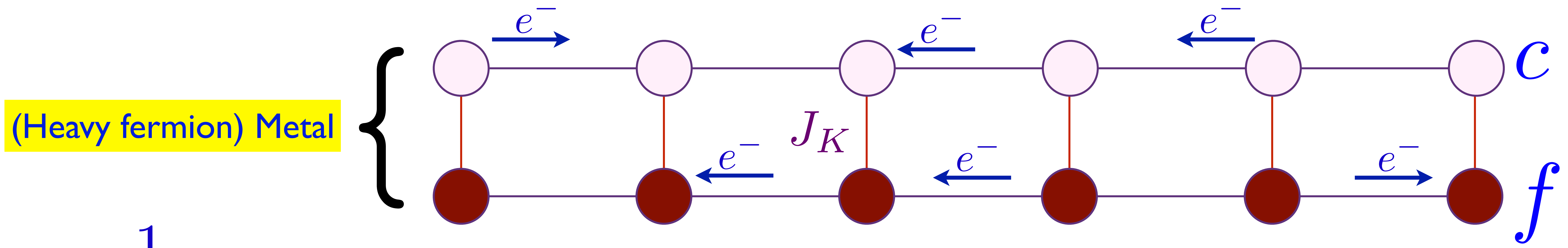
Large Fermi surface of size $1 + p$

$$|\Phi\rangle = [\text{Projection onto one } f \text{ per site}] \bowtie |\text{Slater determinant of } (c, f)\rangle$$

Varma, Coleman, Millis, P.A. Lee, Q. Si, Auerbach, Levin....

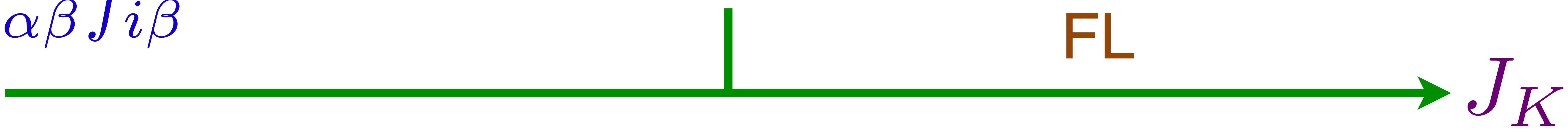
Luttinger volume in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.



$$\vec{S}_{fi} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

$$\langle c^\dagger_\alpha f_\alpha \rangle \neq 0$$



The Kondo lattice model has a gauge symmetry: $f_{i\alpha} \to e^{i\theta_i} f_{i\alpha}$
This gauge symmetry is fully broken by a Higgs condensate $\langle c^\dagger_\alpha f_\alpha \rangle$ in the FL phase.

1. Luttinger volume violation in Kondo lattice models

   The FL phase*

2. Introduction to cuprates

   The pseudogap metal

3. Luttinger volume violation a one-band model

   Ancilla qubits and ghost Fermi surfaces

1. Luttinger volume violation in Kondo lattice models

   The FL phase*

2. Introduction to cuprates

   The pseudogap metal

3. Luttinger volume violation a one-band model

   Ancilla qubits and ghost Fermi surfaces

Luttinger volume violation

The Luttinger volume can be violated in a metal when there is 'bulk topological order' *i.e.* excitations associated with fractionalization and emergent gauge fields.

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

Luttinger volume violation

The Luttinger volume can be violated in a metal when there is 'bulk topological order' *i.e.* excitations associated with fractionalization and emergent gauge fields.

The 'anomaly' associated with the global U(1)$\times$translational symmetries can be satisfied by a contribution from the emergent gauge fluxes.

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

Luttinger volume violation

The Luttinger volume can be violated in a metal when there is 'bulk topological order' *i.e.* excitations associated with fractionalization and emergent gauge fields.

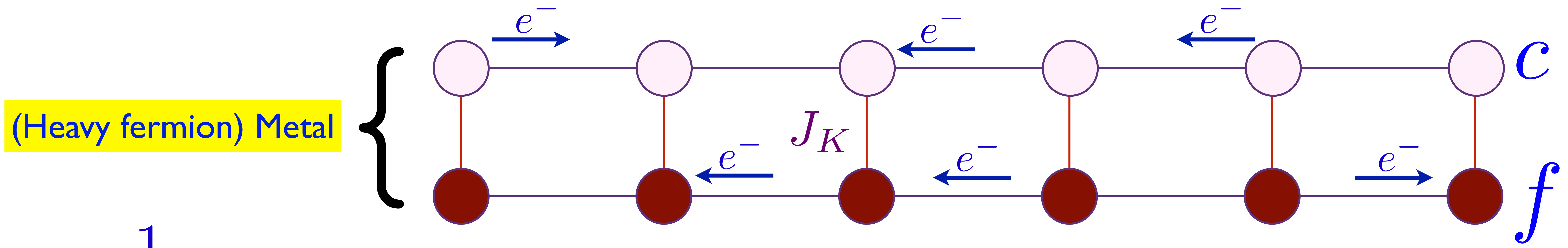
The 'anomaly' associated with the global U(1)$\times$translational symmetries can be satisfied by a contribution from the emergent gauge fluxes.

In this manner with obtain the FL* phase: a metallic phase with a Fermi surface of Fermi-liquid-like electronic quasiparticles, enclosing a non-Luttinger volume.

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

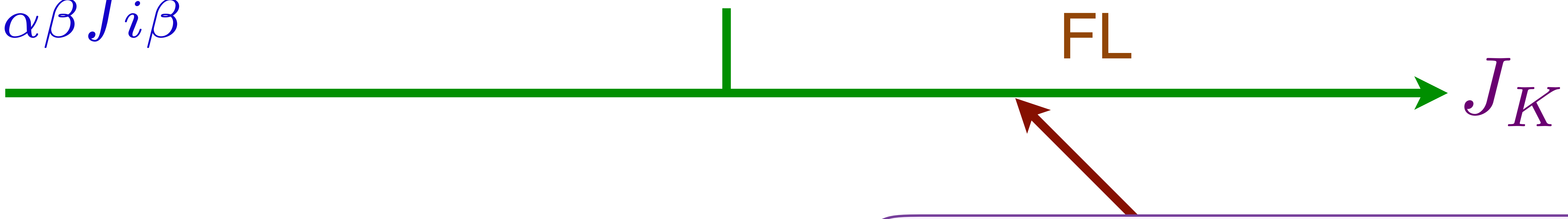
Luttinger volume in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.



$$\vec{S}_{fi} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

$$\langle c^\dagger_\alpha f_\alpha \rangle \neq 0$$



Luttinger volume obeyed

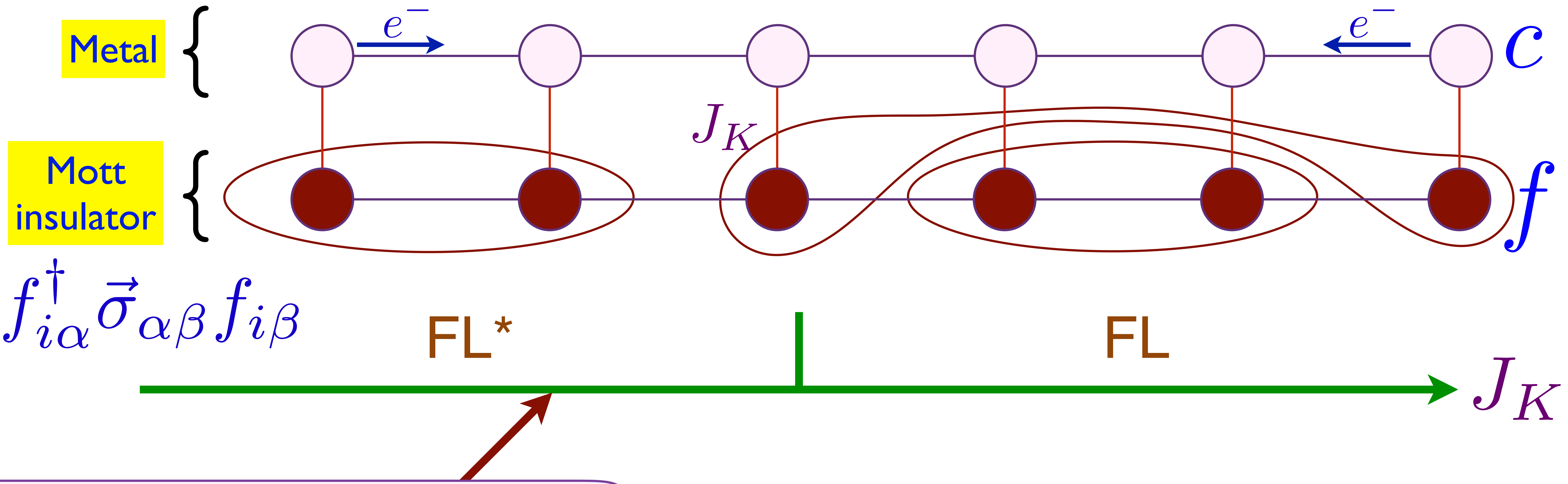
Large Fermi surface of size $1 + p$

$$|\Phi\rangle = [\text{Projection onto one } f \text{ per site}] \bowtie |\text{Slater determinant of } (c, f)\rangle$$

Varma, Coleman, Millis, P.A. Lee, Q. Si, Auerbach, Levin….

FL* phase in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.



$$\vec{S}_{fi} = \frac{1}{2} f^{\dagger}_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

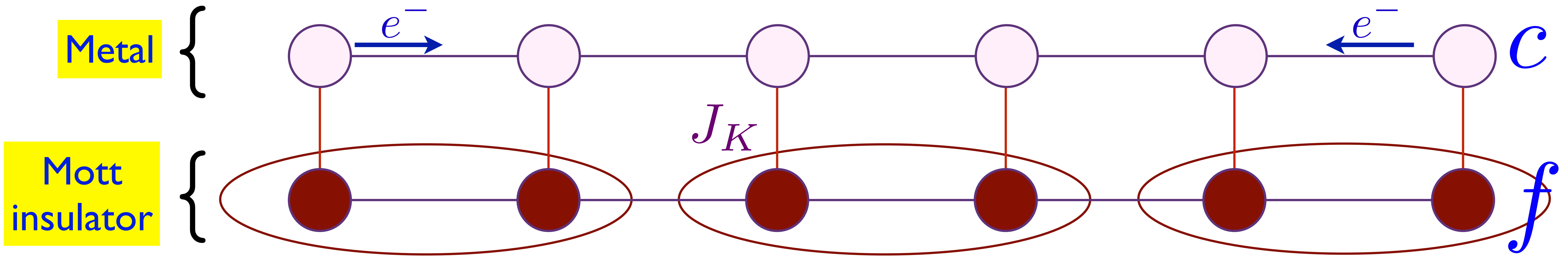
Small Fermi surface of size p

$|\Phi\rangle =$ [Projection onto one f per site]
$\bowtie$ |Slater determinant of $f\rangle$
$\otimes$ |Slater determinant of $c\rangle$

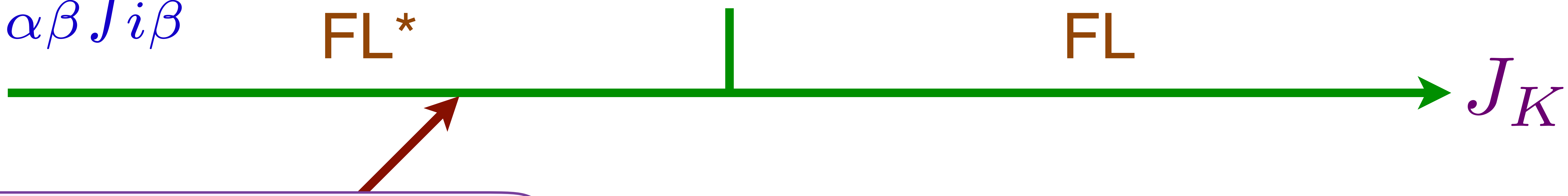
S. Burdin, D. R. Grempel, and A. Georges, PRB **66**, 045111 (2002)
T. Senthil, M. Vojta, and S. Sachdev, PRB **69**, 035111 (2004)

FL* phase in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.



$$\vec{S}_{fi} = \frac{1}{2} f_{i\alpha}^{\dagger} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$



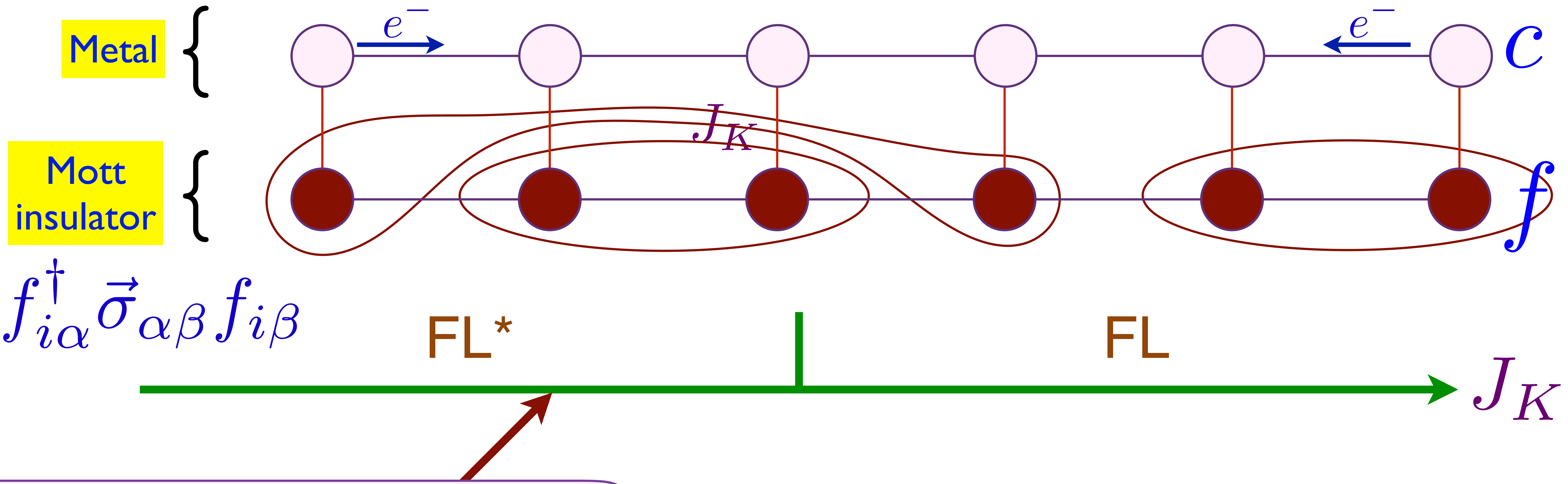
Small Fermi surface of size p

$$|\Phi\rangle = [\text{Projection onto one } f \text{ per site}] \bowtie |\text{Slater determinant of } f\rangle \otimes |\text{Slater determinant of } c\rangle$$

S. Burdin, D. R. Grempel, and A. Georges, PRB **66**, 045111 (2002)
T. Senthil, M. Vojta, and S. Sachdev, PRB **69**, 035111 (2004)

FL* phase in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.



$$\vec{S}_{fi} = \frac{1}{2} f_{i\alpha}^{\dagger} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

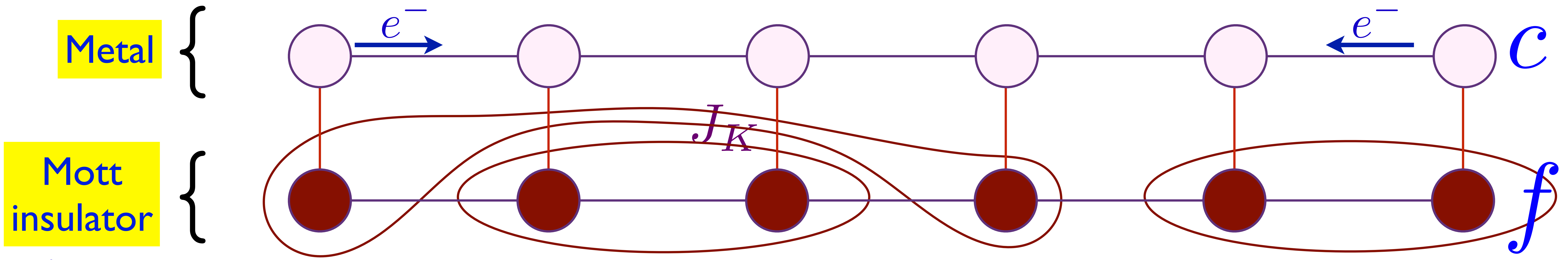
Small Fermi surface of size p

$$|\Phi\rangle = [\text{Projection onto one } f \text{ per site}] \bowtie |\text{Slater determinant of } f\rangle \otimes |\text{Slater determinant of } c\rangle$$

S. Burdin, D. R. Grempel, and A. Georges, PRB **66**, 045111 (2002)
T. Senthil, M. Vojta, and S. Sachdev, PRB **69**, 035111 (2004)

FL* phase in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.



$$\vec{S}_{fi} = \frac{1}{2} f_{i\alpha}^{\dagger} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

Small Fermi surface of size p

$$|\Phi\rangle = [\text{Projection onto one } f \text{ per site}] \bowtie |\text{Slater determinant of } f\rangle \otimes |\text{Slater determinant of } c\rangle$$

Luttinger volume violation;
OK, because of topological order of *f* spins

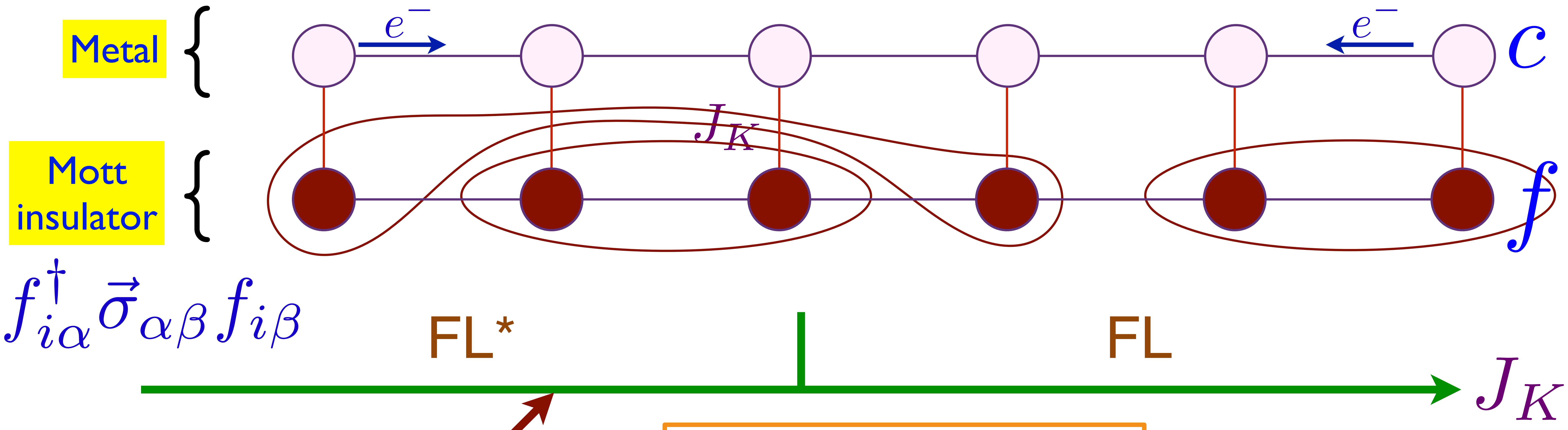
T. Senthil, M. Vojta, and S. Sachdev, PRB **69**, 035111 (2004)

FL* phase in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled to a conduction band of c electrons of density p.

V.I. Anisimov, I.A. Nekrasov, D.E. Kondakov, T.M. Rice & M. Sigrist, EPJB **25**, 191 (2002)
L. de' Medici, A. Georges, S. Biermann, PRB **72**, 205124 (2005)

Kondo-breakdown or 'selective Mott' transition



$$\vec{S}_{fi} = \frac{1}{2} f_{i\alpha}^{\dagger} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

Small Fermi surface of size p

$$|\Phi\rangle = [\text{Projection onto one } f \text{ per site}] \bowtie |\text{Slater determinant of } f\rangle \otimes |\text{Slater determinant of } c\rangle$$

Luttinger volume violation;
OK, because of topological order of *f* spins

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

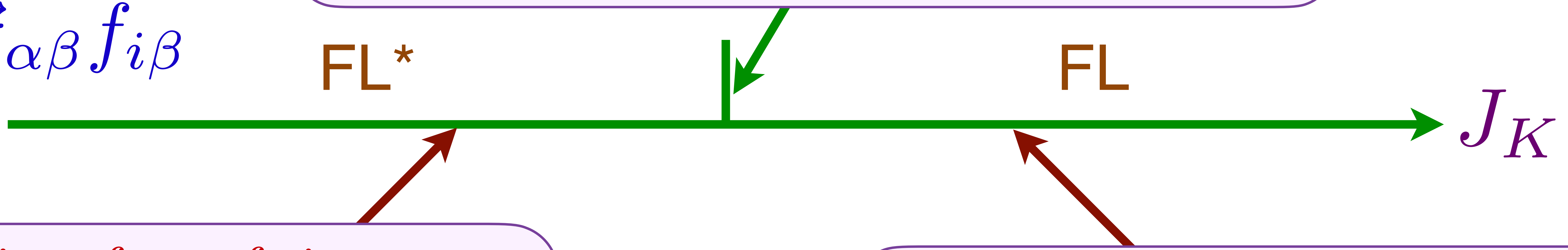
Metal-metal transitions in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.

Kondo-breakdown or 'selective Mott' transition

U(1) gauge theory of a
'hybridization-Higgs' boson $b \sim f_\alpha^\dagger c_\alpha$
which condenses on the
'Large Fermi surface' side.

$$\vec{S}_{fi} = \frac{1}{2} f_{i\alpha}^\dagger \vec{\sigma}_{\alpha\beta} f_{i\beta}$$



Small Fermi surface of size p

$$|\Phi\rangle = [\text{Projection onto one } f \text{ per site}] \bowtie |\text{Slater determinant of } f\rangle \otimes |\text{Slater determinant of } c\rangle$$

Large Fermi surface of size $1 + p$

$$|\Phi\rangle = [\text{Projection onto one } f \text{ per site}] \bowtie |\text{Slater determinant of } (c, f)\rangle$$

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

Metal-metal transitions in *Kondo lattice* models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.

Kondo-breakdown or 'selective Mott' transition

Shortcomings:

- Only works well for a particular spin liquid in the f band: the spinon Fermi surface with a trivial PSG.

Metal-metal transitions in *Kondo lattice* models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.

Kondo-breakdown or ‘selective Mott’ transition

Shortcomings:

- Only works well for a particular spin liquid in the f band: the spinon Fermi surface with a trivial PSG.
- No natural extension to the case where the non-FL state has magnetic order.

Metal-metal transitions in ***Kondo lattice*** models

Kondo lattice of f electron spins coupled
to a conduction band of c electrons of density p.

Kondo-breakdown or 'selective Mott' transition

Shortcomings:

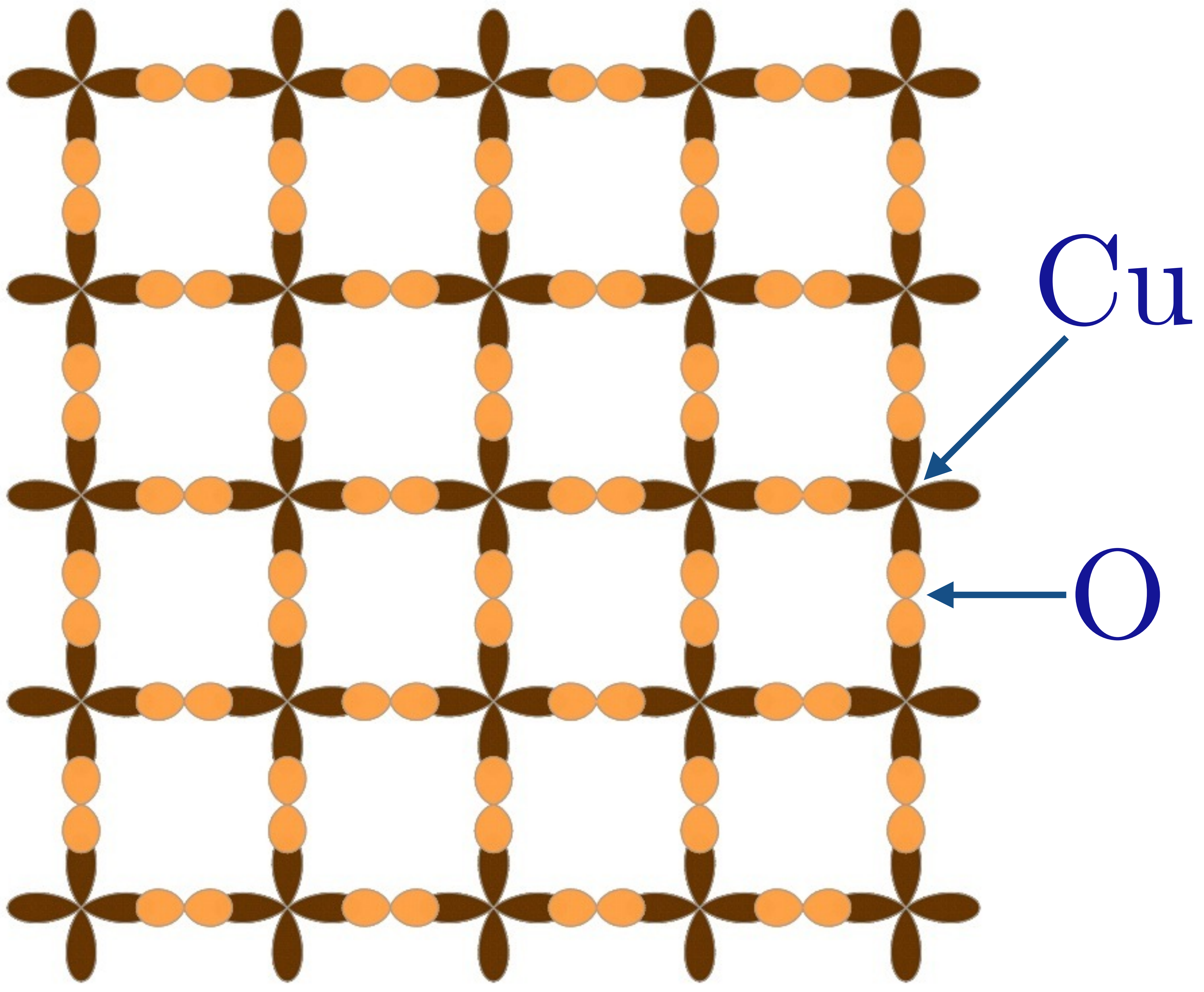
- Only works well for a particular spin liquid in the f band: the spinon Fermi surface with a trivial PSG.
- No natural extension to the case where the non-FL state has magnetic order.
- No simple extension to one-band model.

1. Luttinger volume violation in Kondo lattice models
   The FL phase*

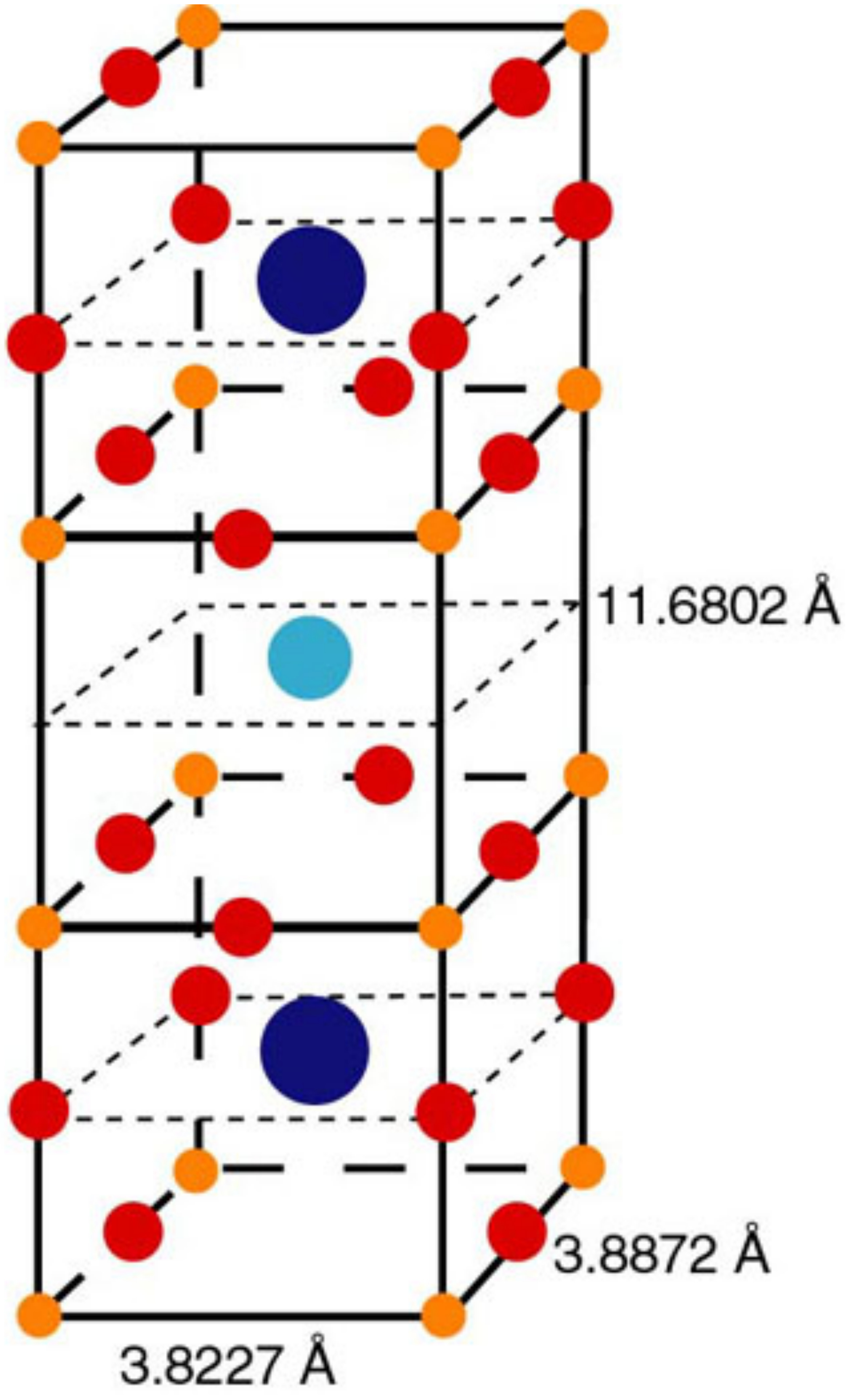
2. Introduction to cuprates
   The pseudogap metal

3. Luttinger volume violation a one-band model
   Ancilla qubits and ghost Fermi surfaces

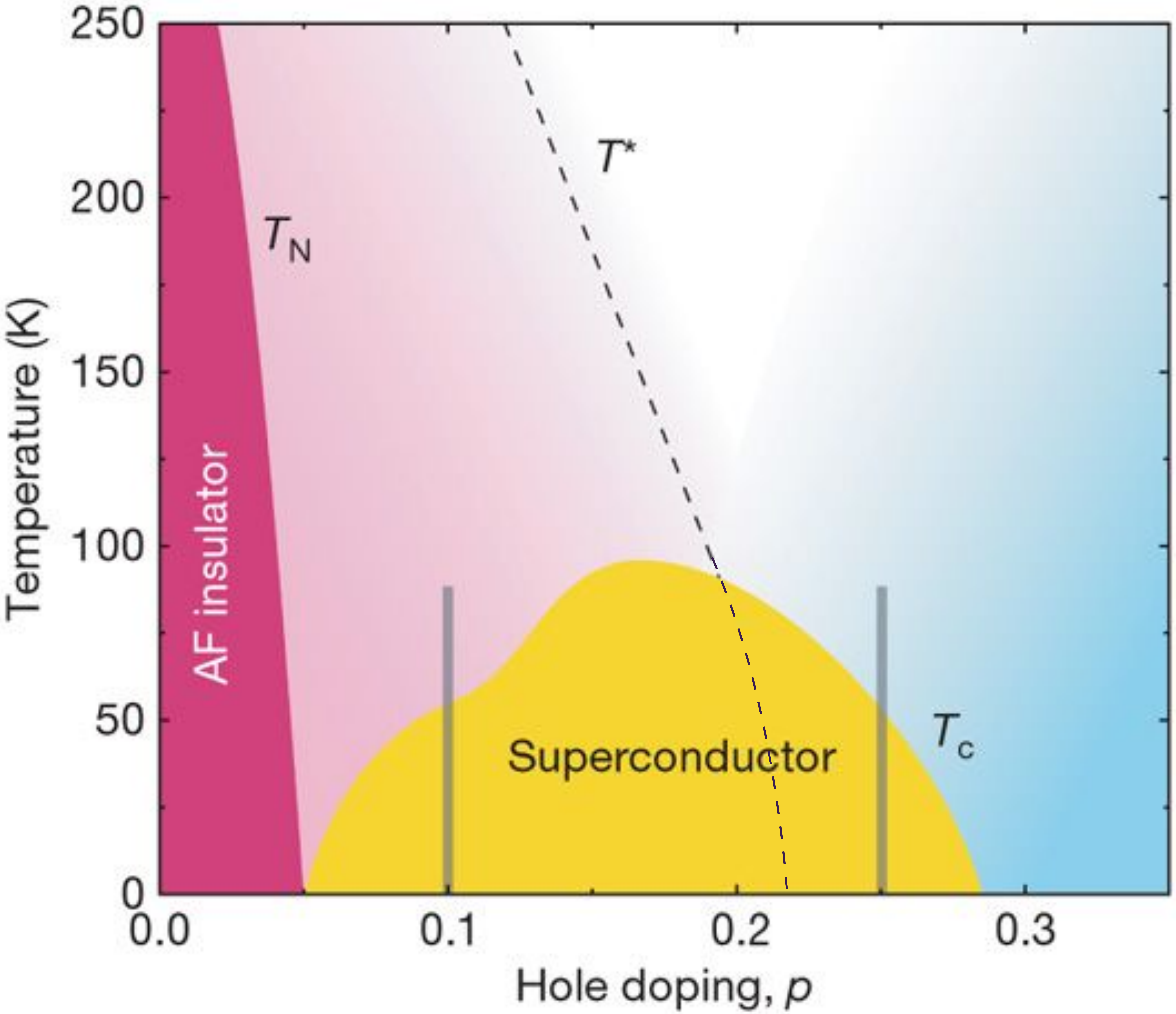
High temperature superconductors



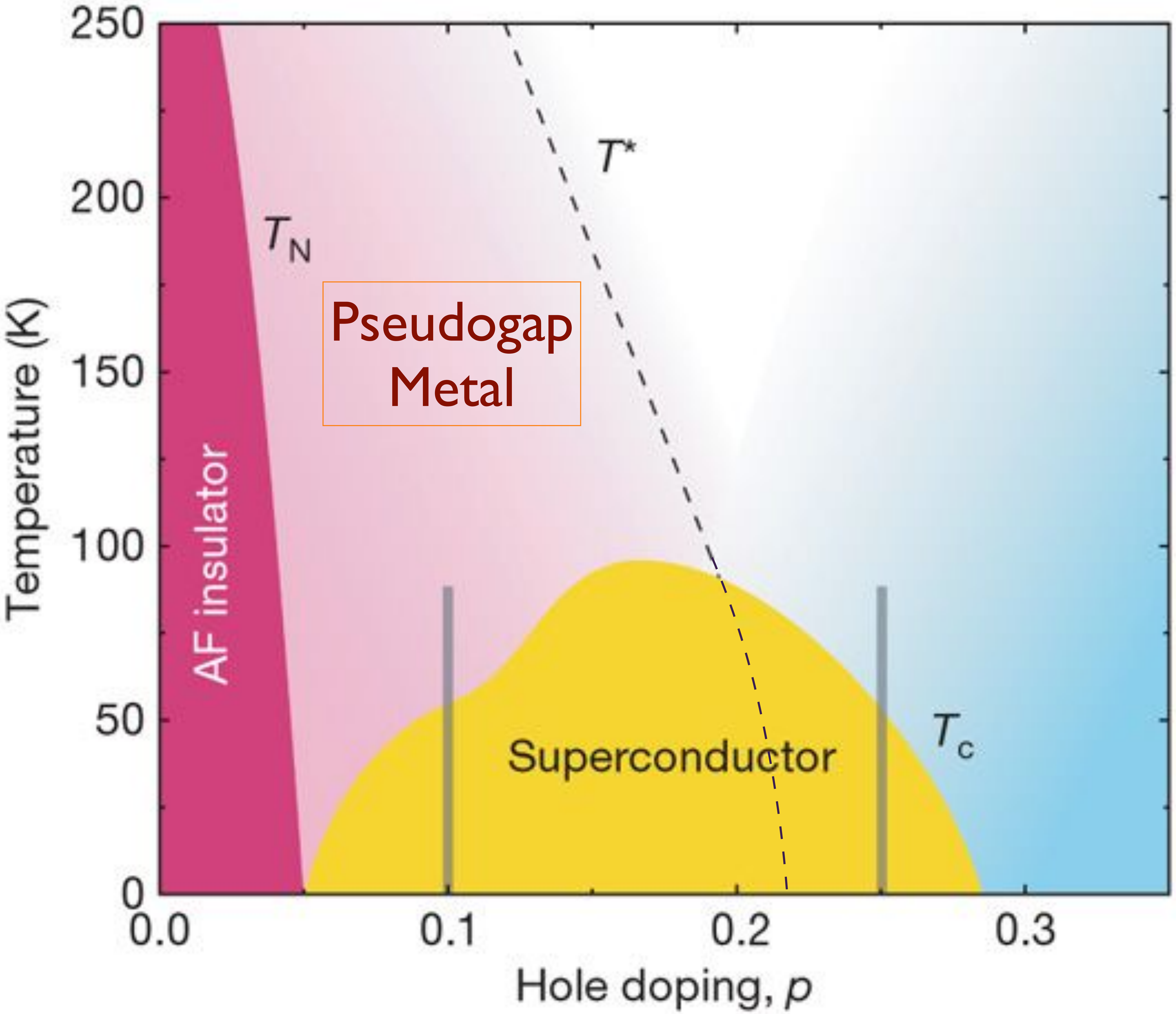
CuO_2 plane

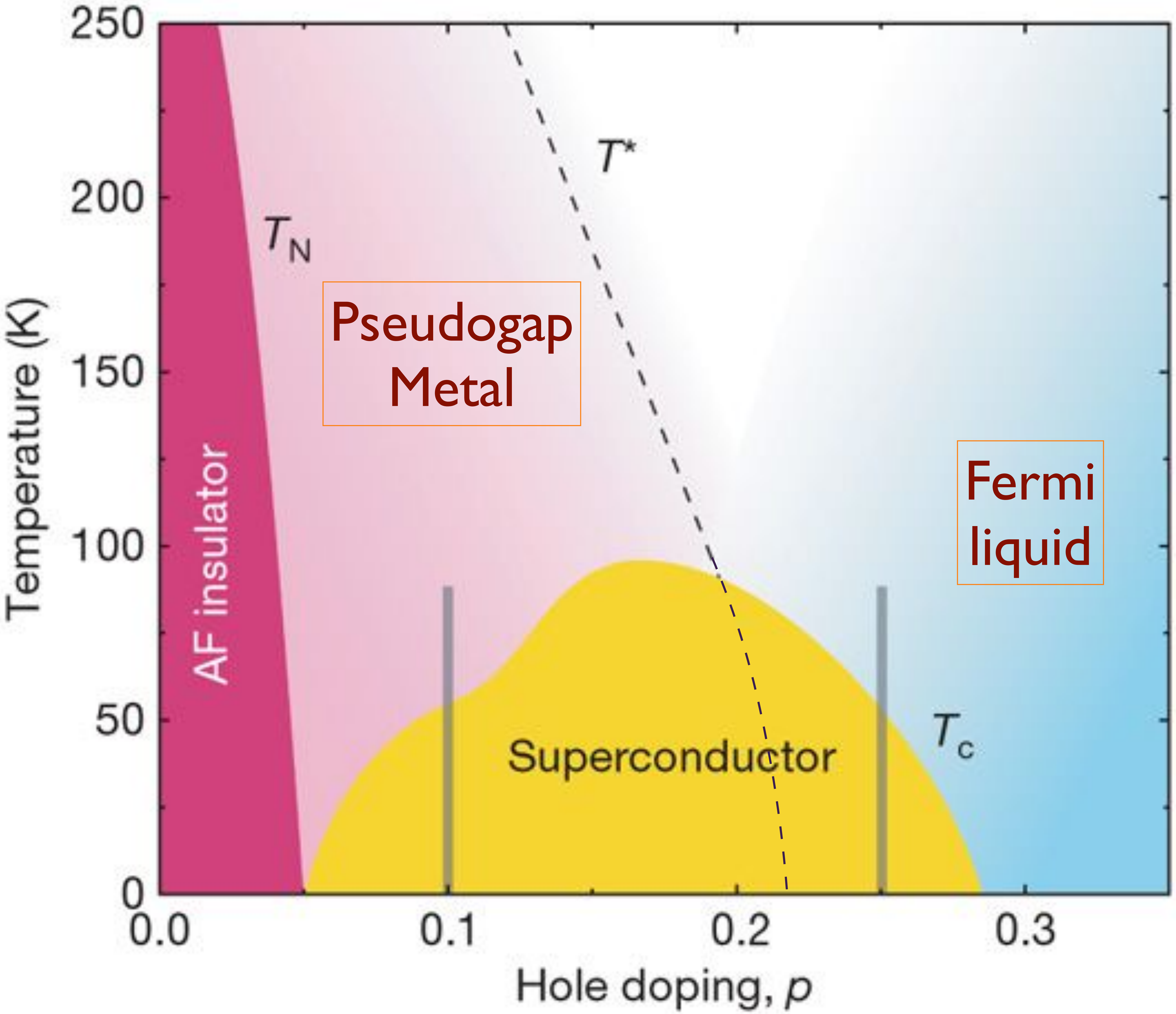


$YBa_2Cu_3O_{6+x}$

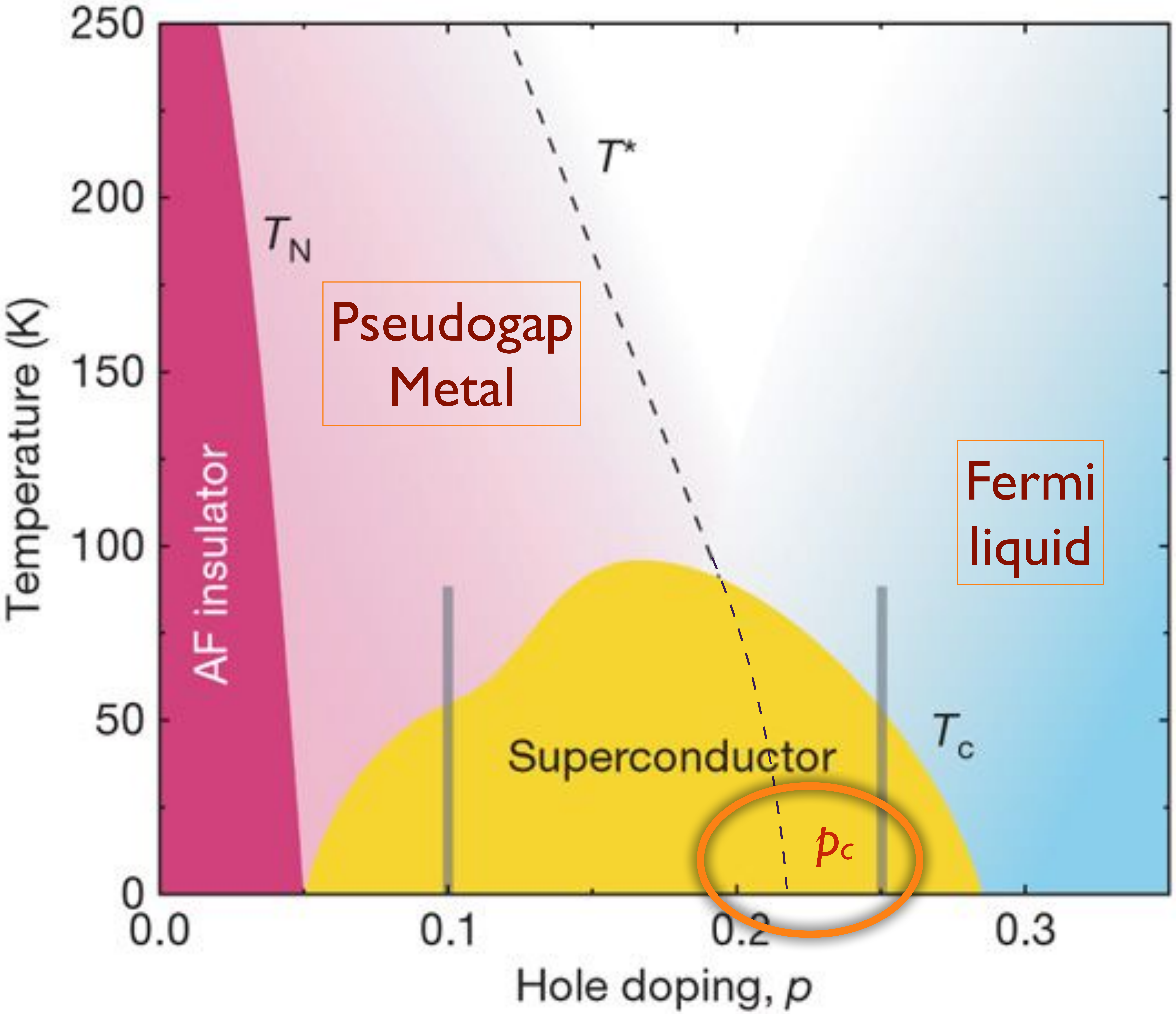


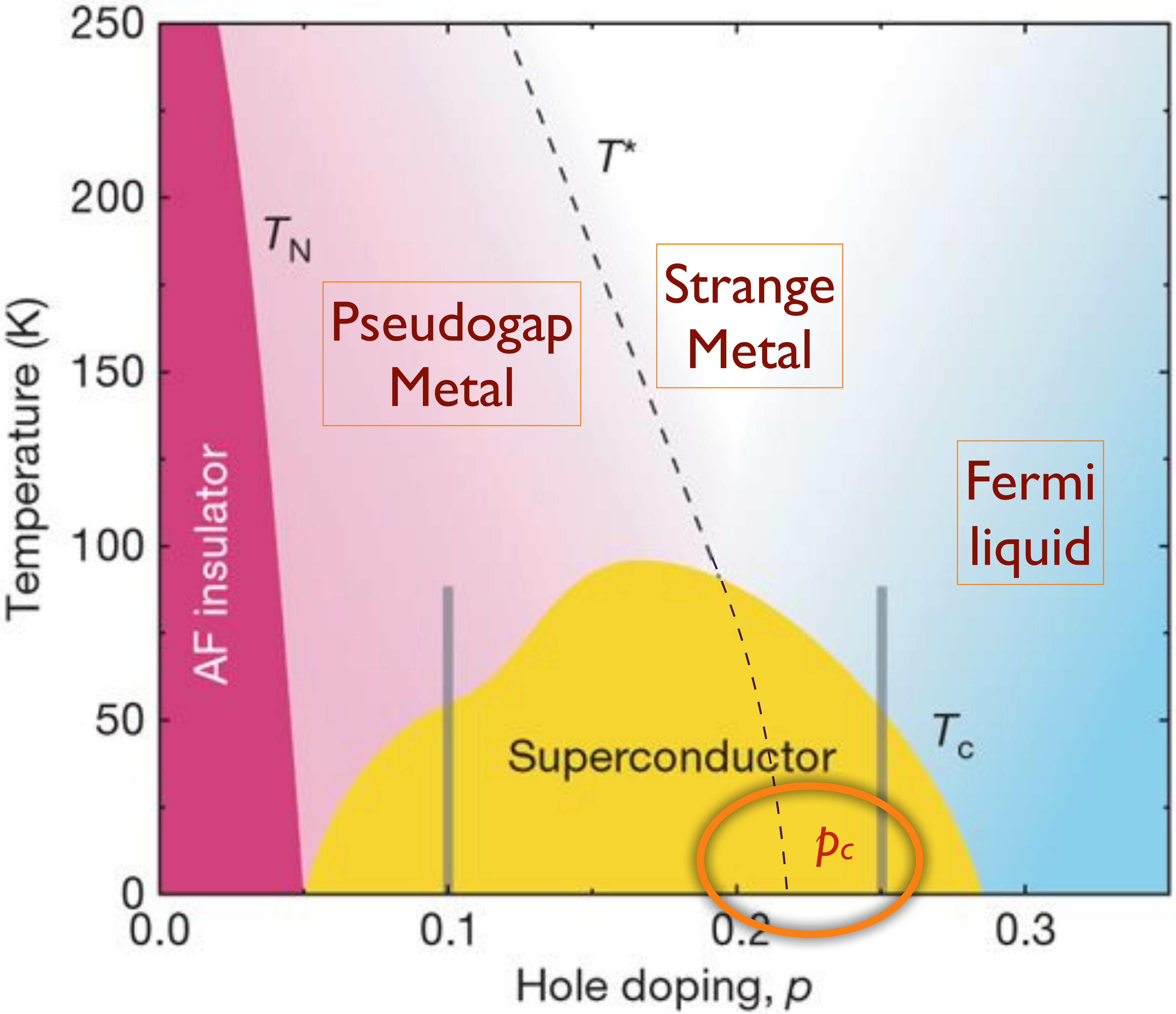
250
200
150
100
50
0
0.0
0.1
0.2
0.3
Temperature (K)
Hole doping, p
AF insulator
T_N
T*
Superconductor
T_C


Pseudogap
Metal
AF insulator
Superconductor
T_N
T^*
T_c
Temperature (K)
Hole doping, p
250
200
150
100
50
0
0.0
0.1
0.2
0.3

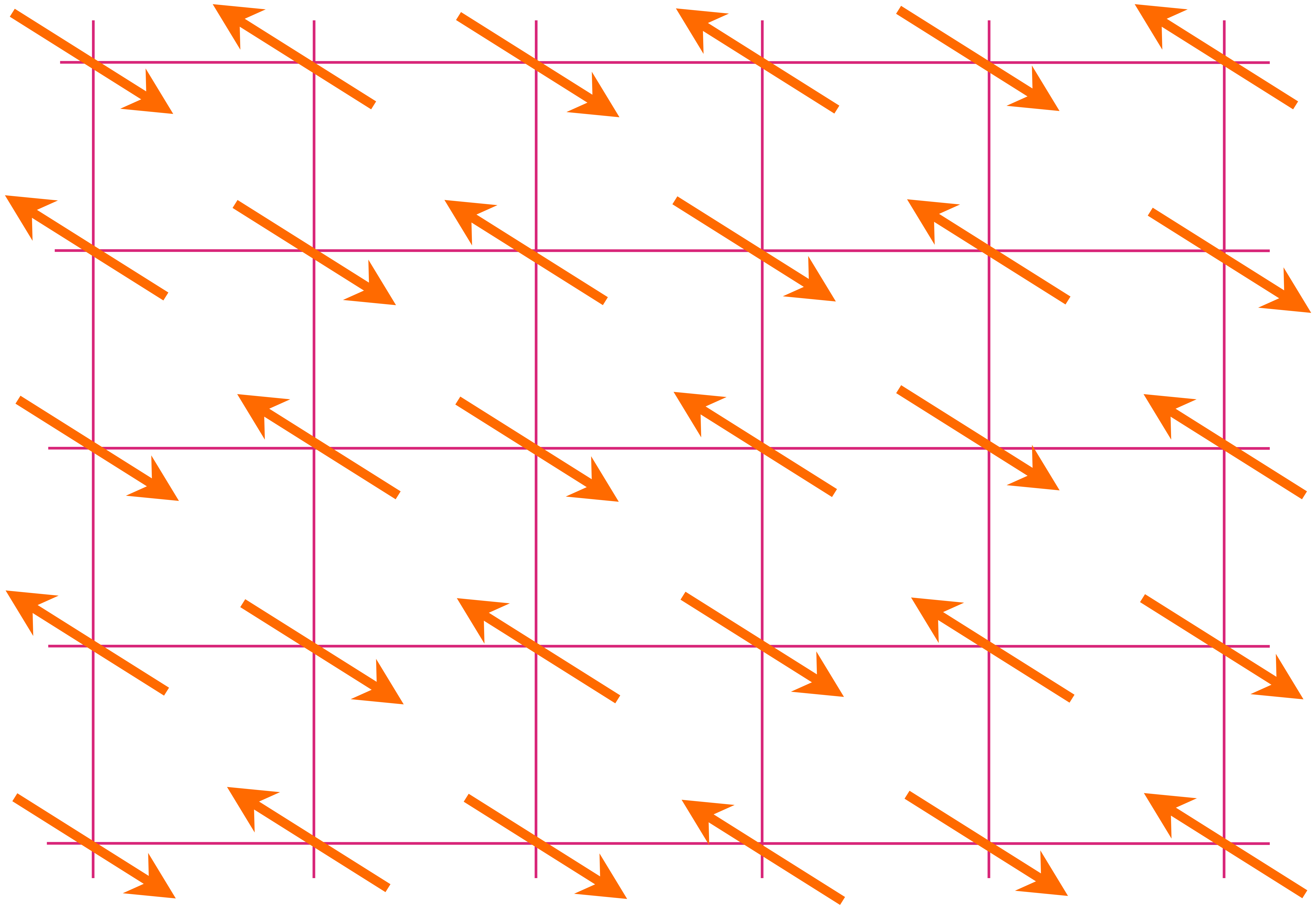


250
200
150
100
50
0
0.0
0.1
0.2
0.3
Temperature (K)
Hole doping, p
AF insulator
T_N
T*
Pseudogap Metal
Fermi liquid
Superconductor
T_c

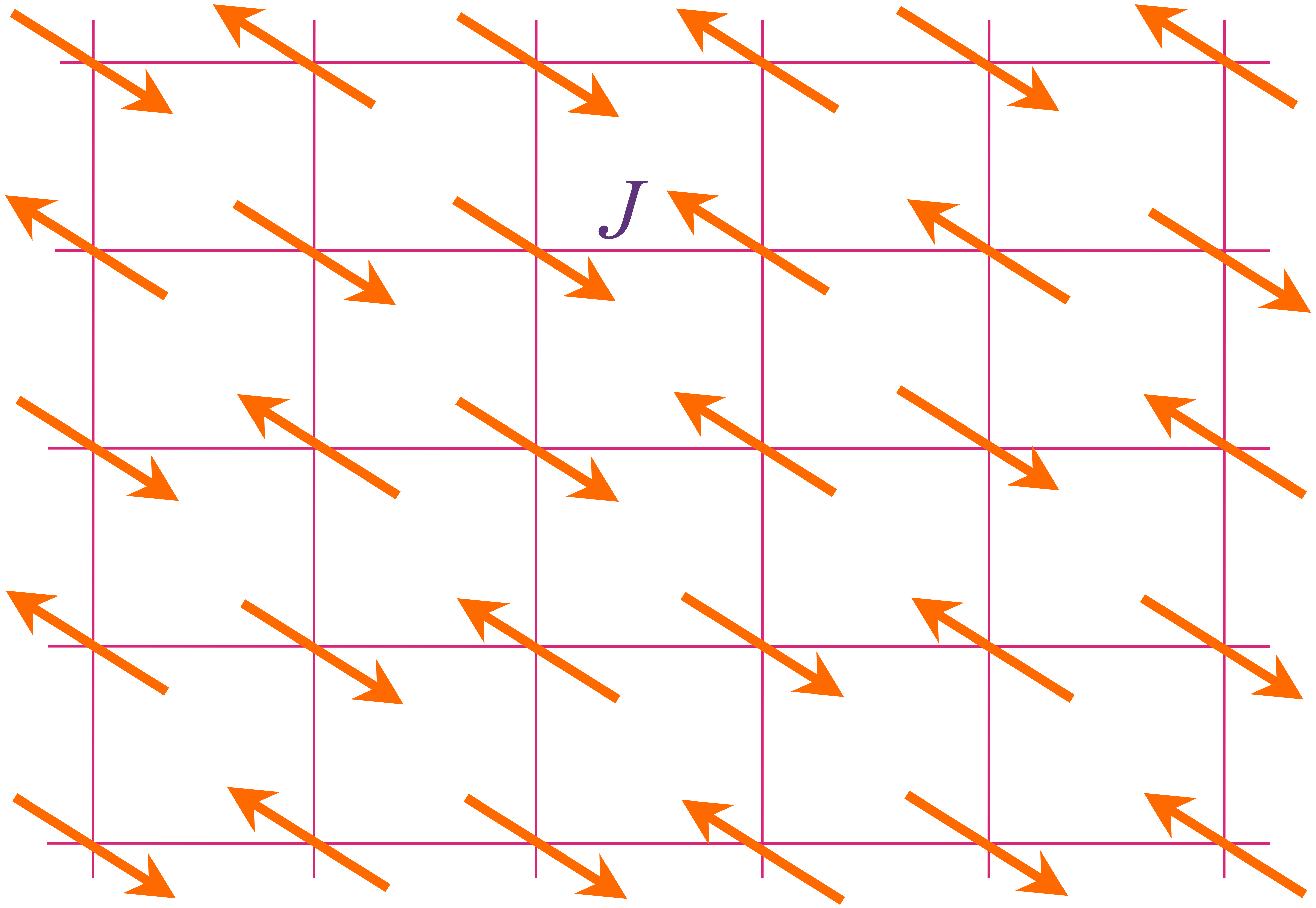

250
200
150
100
50
0
0.0
0.1
0.2
0.3
Temperature (K)
Hole doping, p
AF insulator
T_N
Pseudogap
Metal
T*
Fermi
liquid
Superconductor
T_c
p_c


250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
AF insulator
T_N
T*
Pseudogap Metal
Strange Metal
Fermi liquid
Superconductor
T_c
p_c

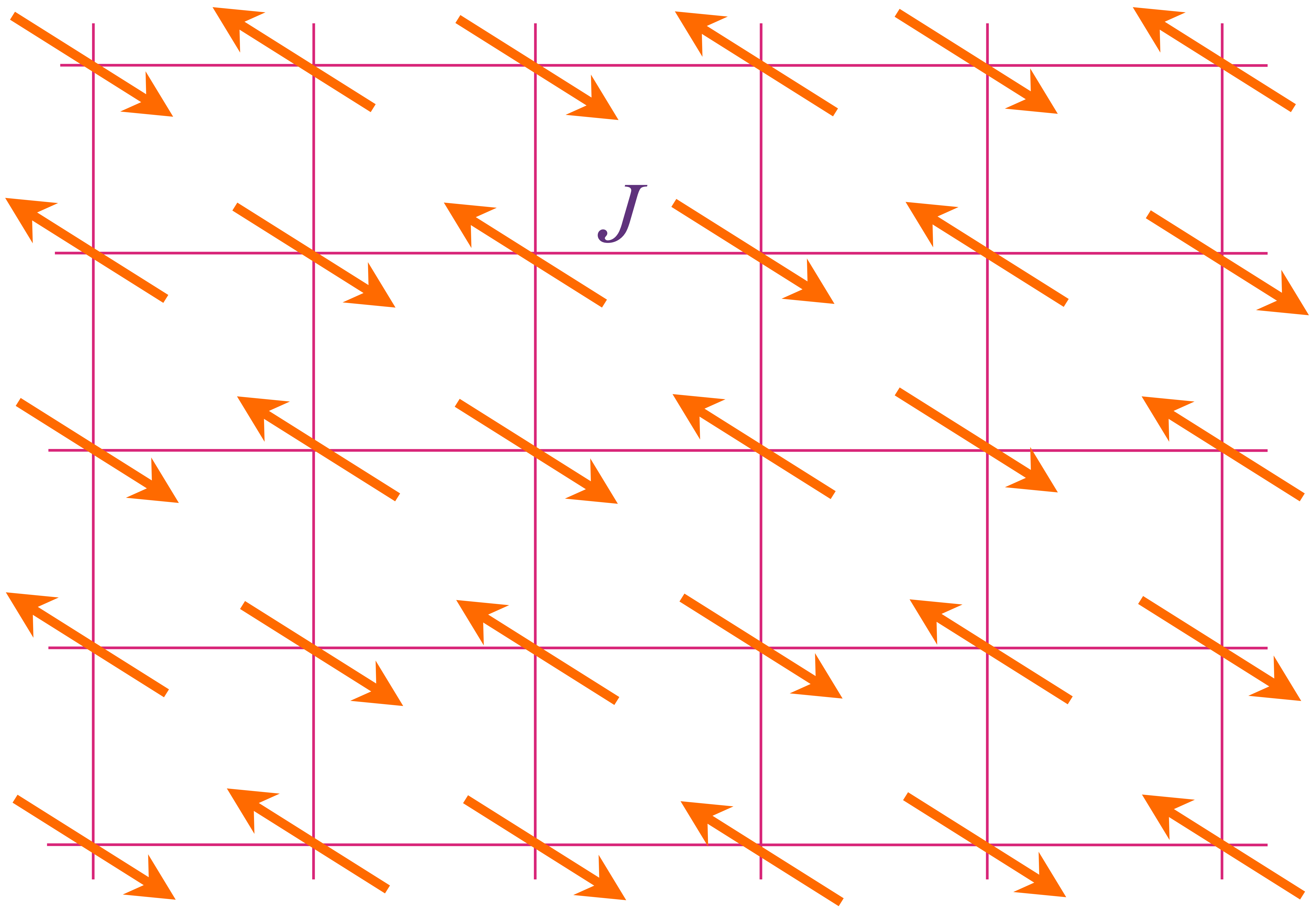
Insulating antiferromagnet



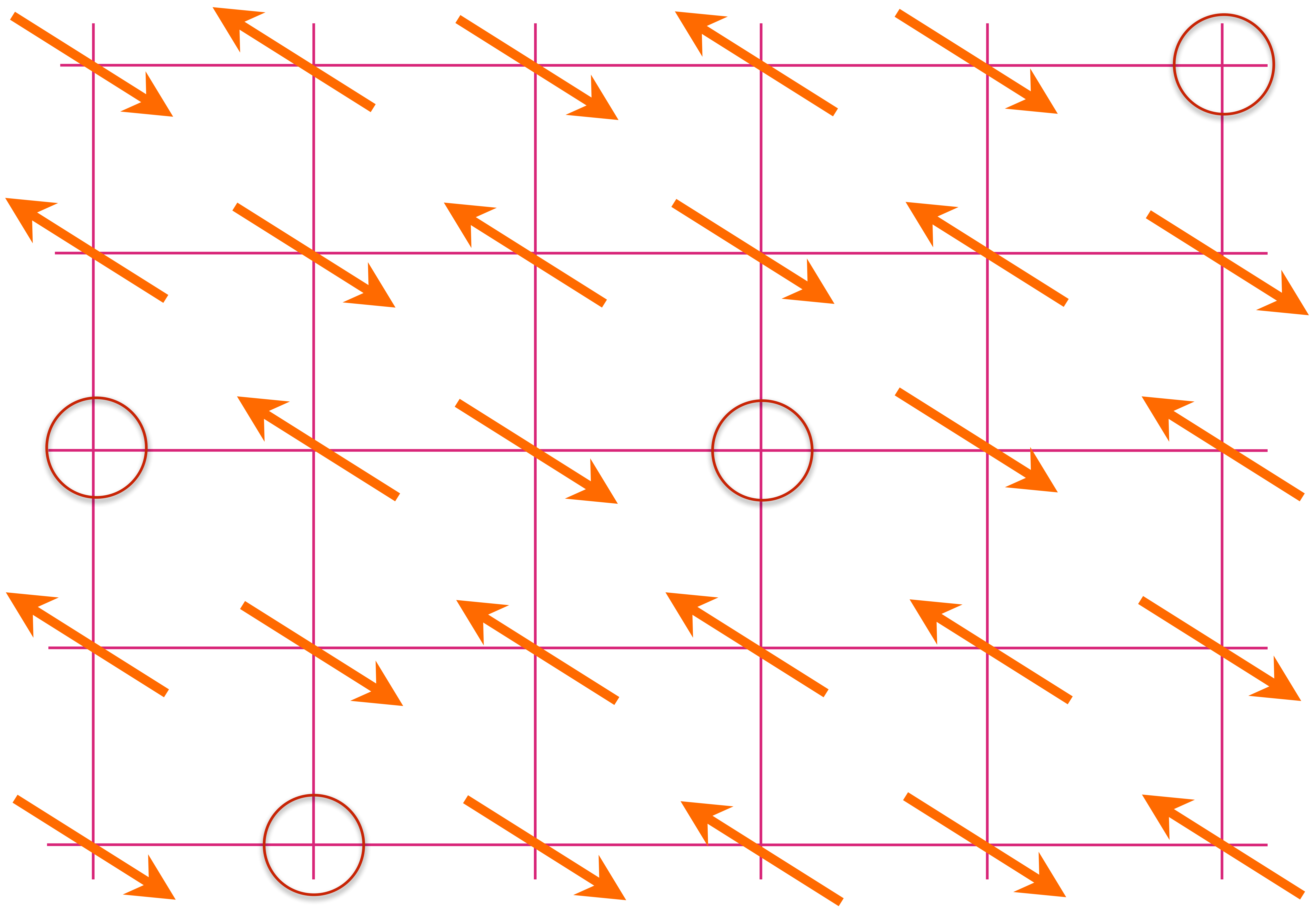
Insulating antiferromagnet



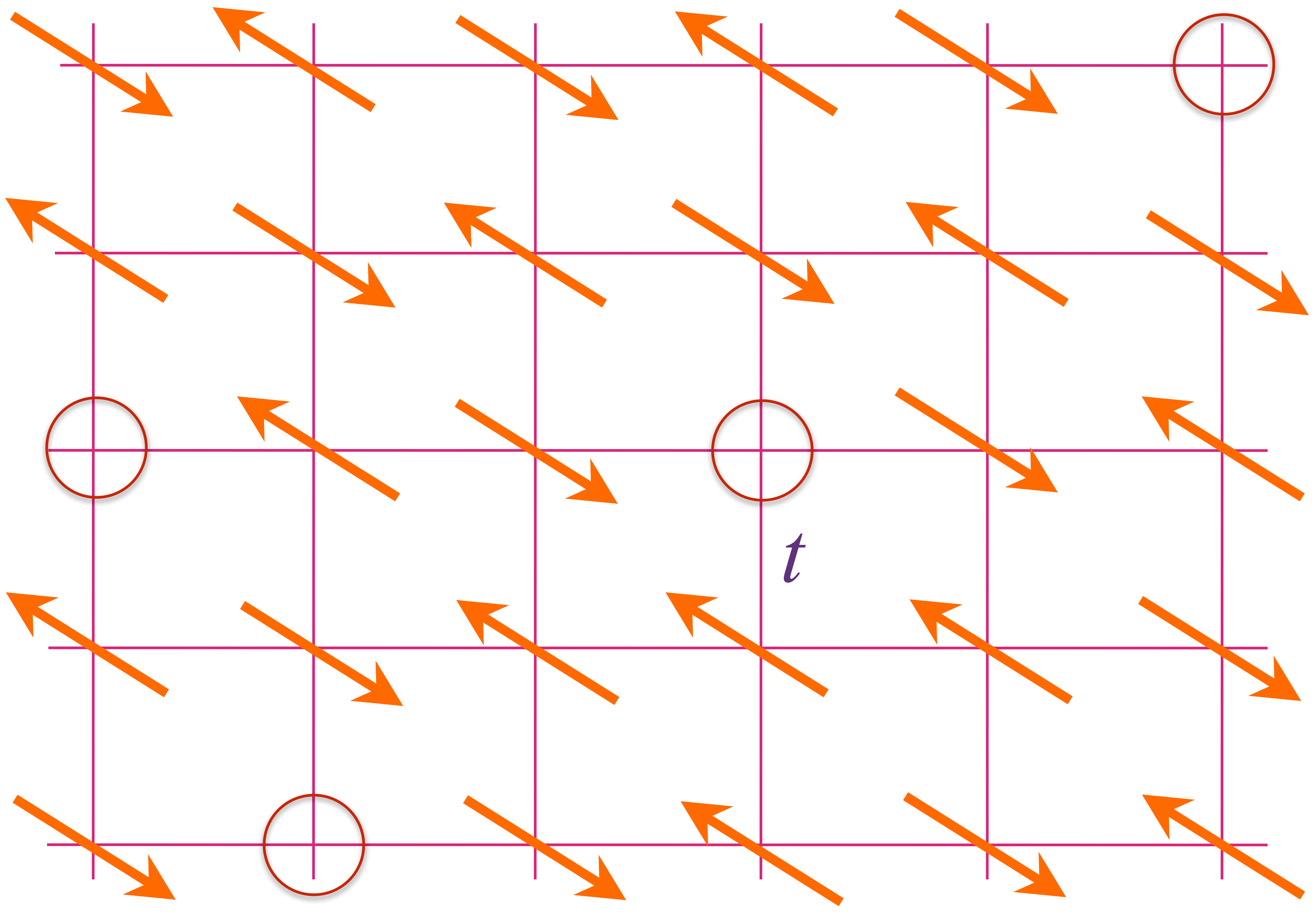
Insulating antiferromagnet



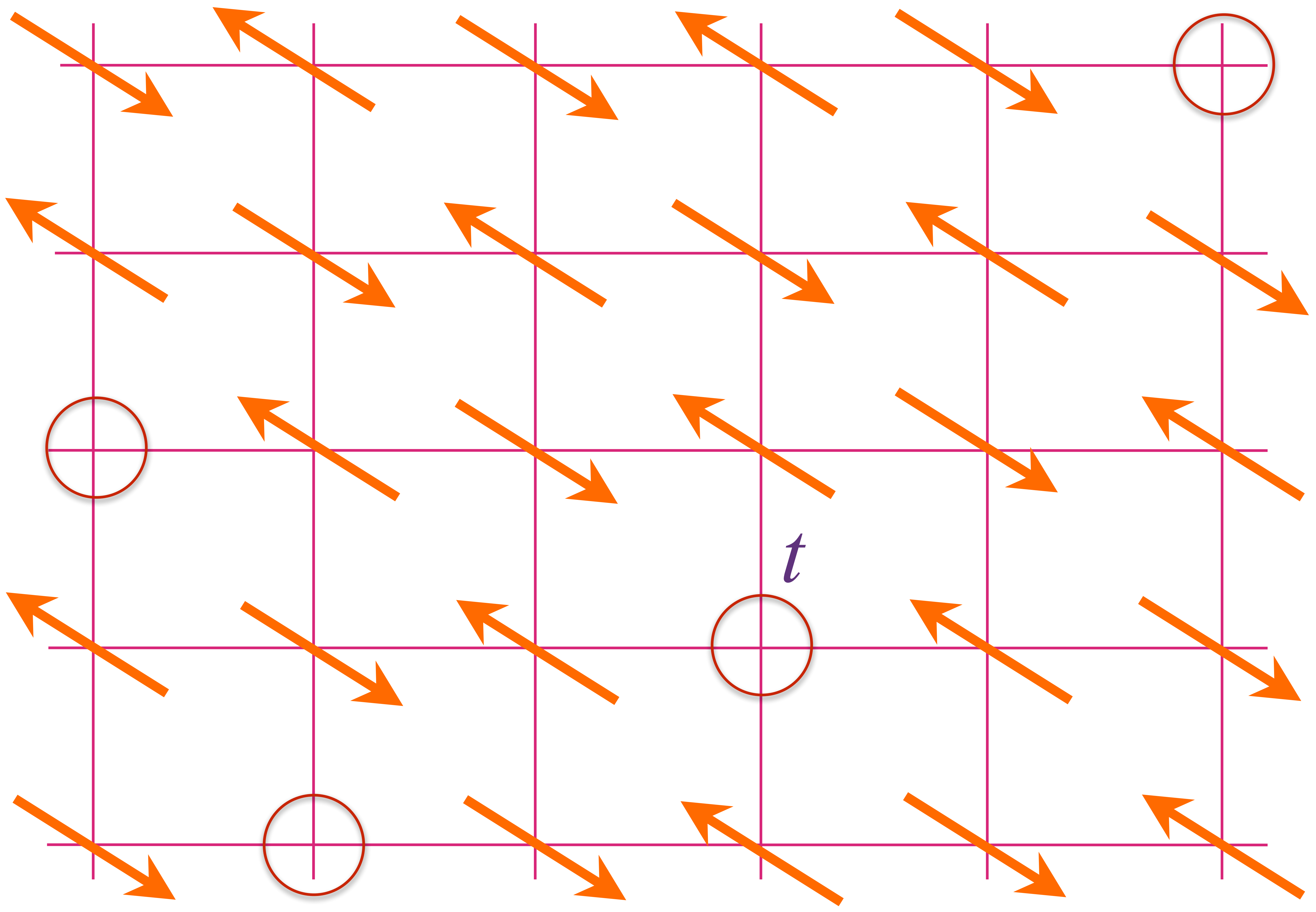
Antiferromagnet doped with hole density p



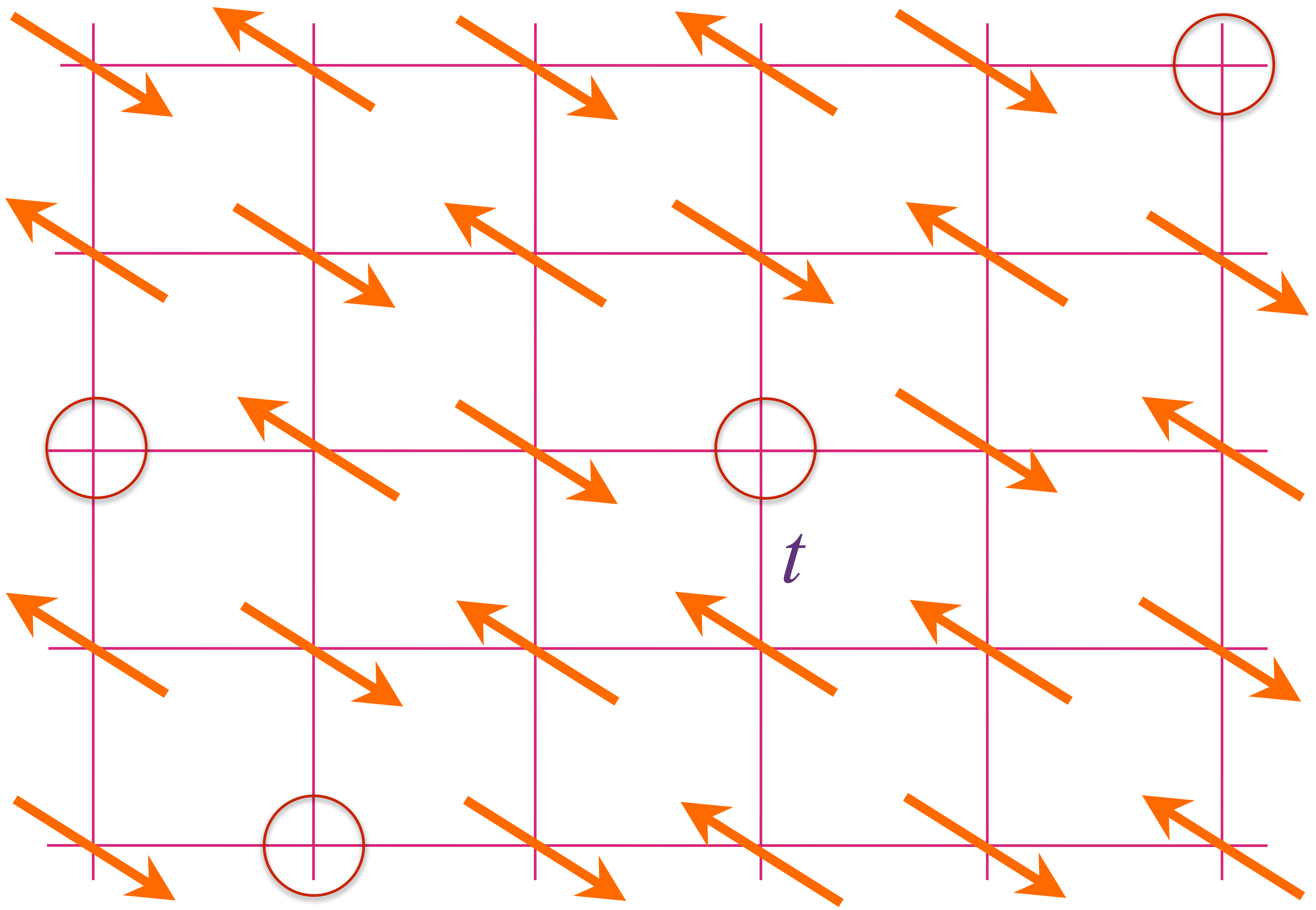
Antiferromagnet doped with hole density p



Antiferromagnet doped with hole density p

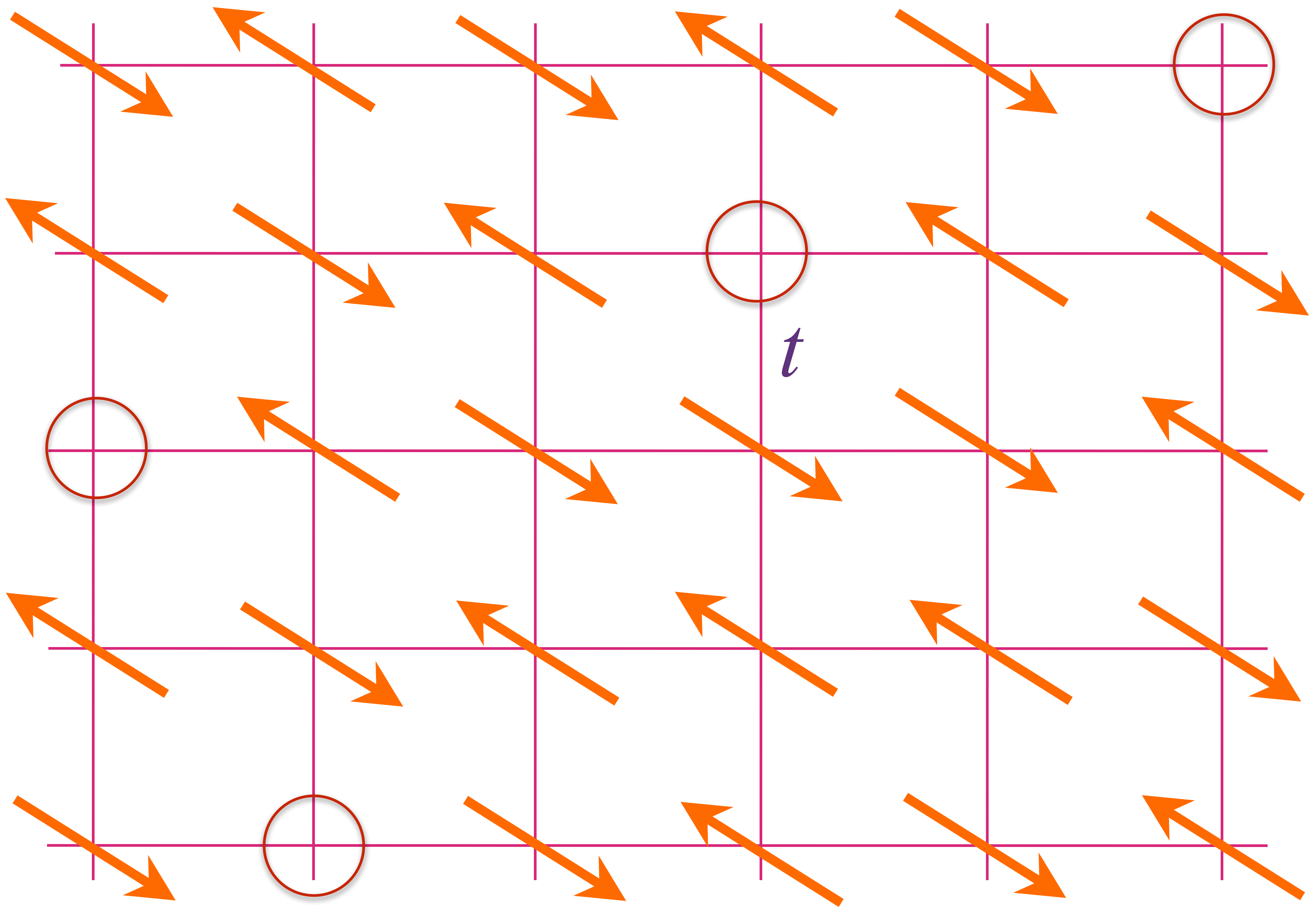


Antiferromagnet doped with hole density p



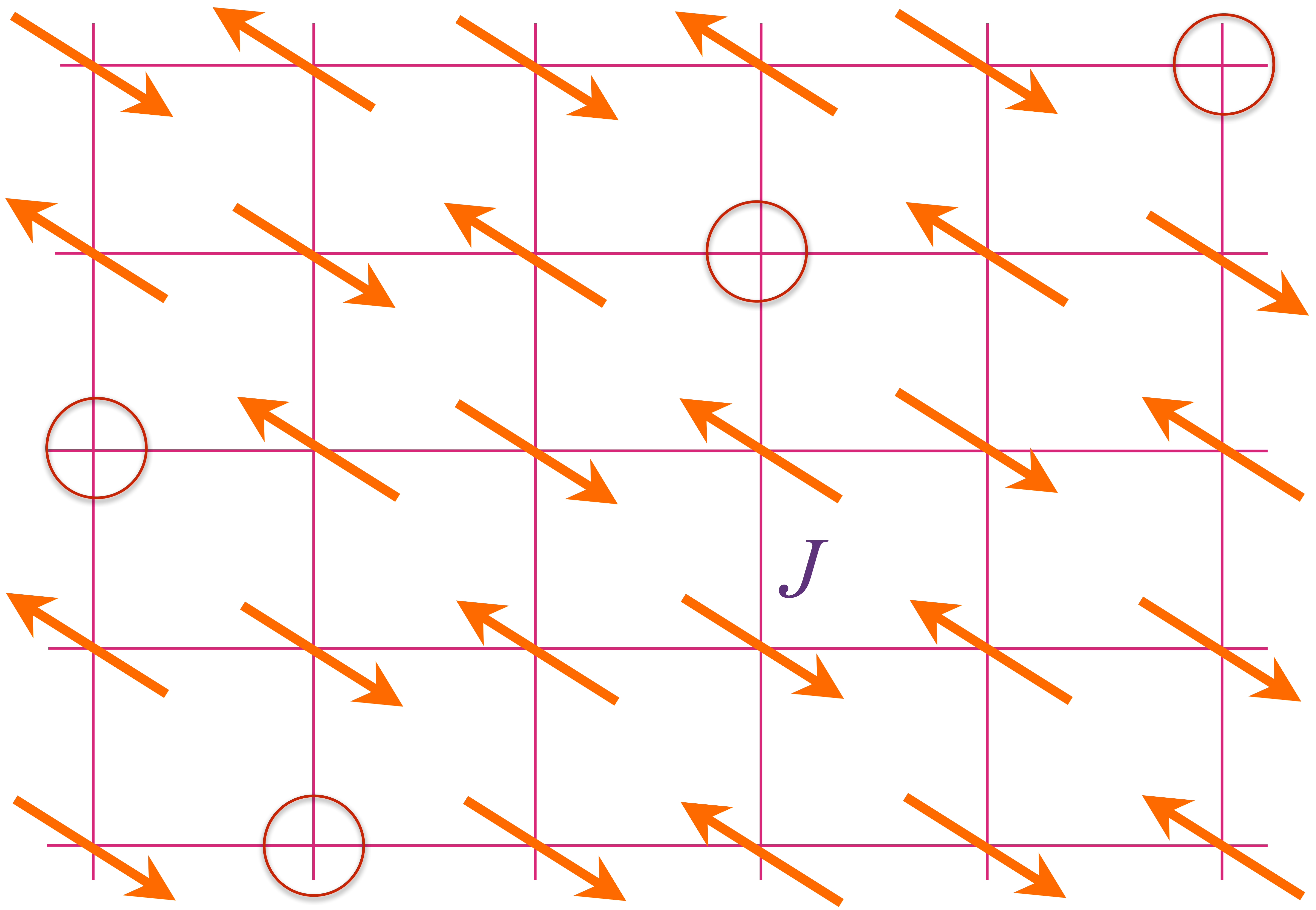
p mobile holes in a background of fluctuating spins

Antiferromagnet doped with hole density p



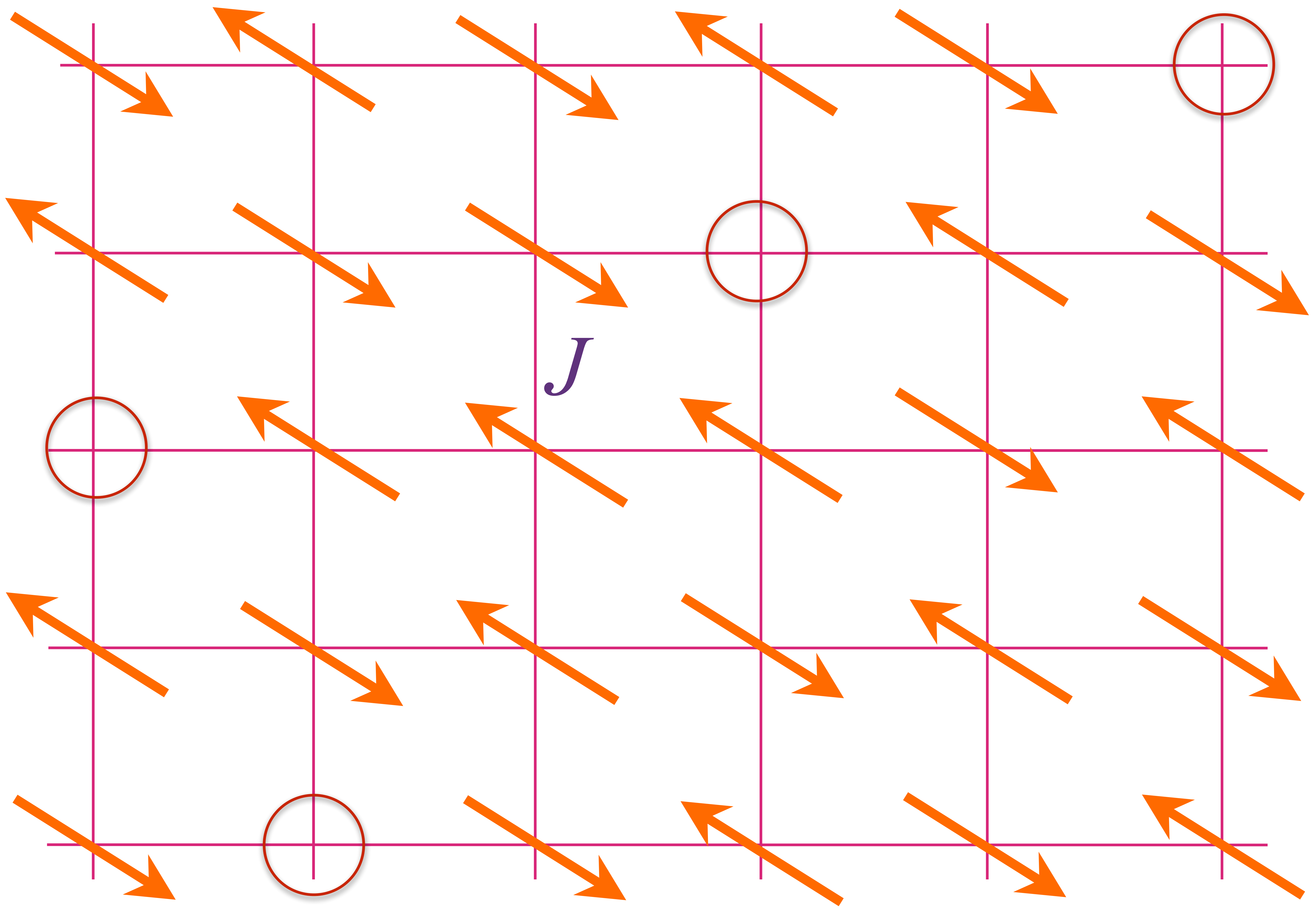
p mobile holes in a background of fluctuating spins

Antiferromagnet doped with hole density p



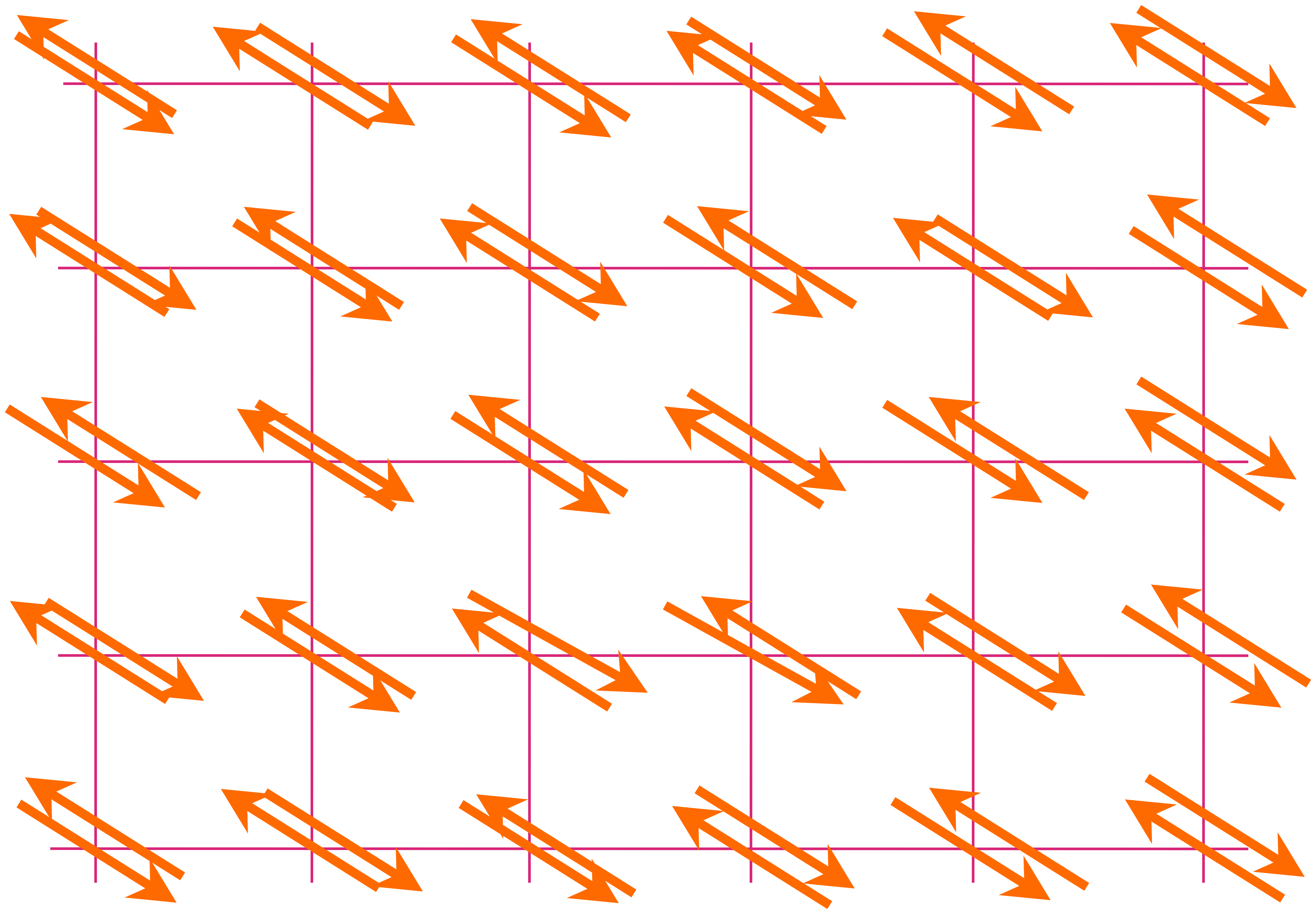
p mobile holes in a background of fluctuating spins

Antiferromagnet doped with hole density p



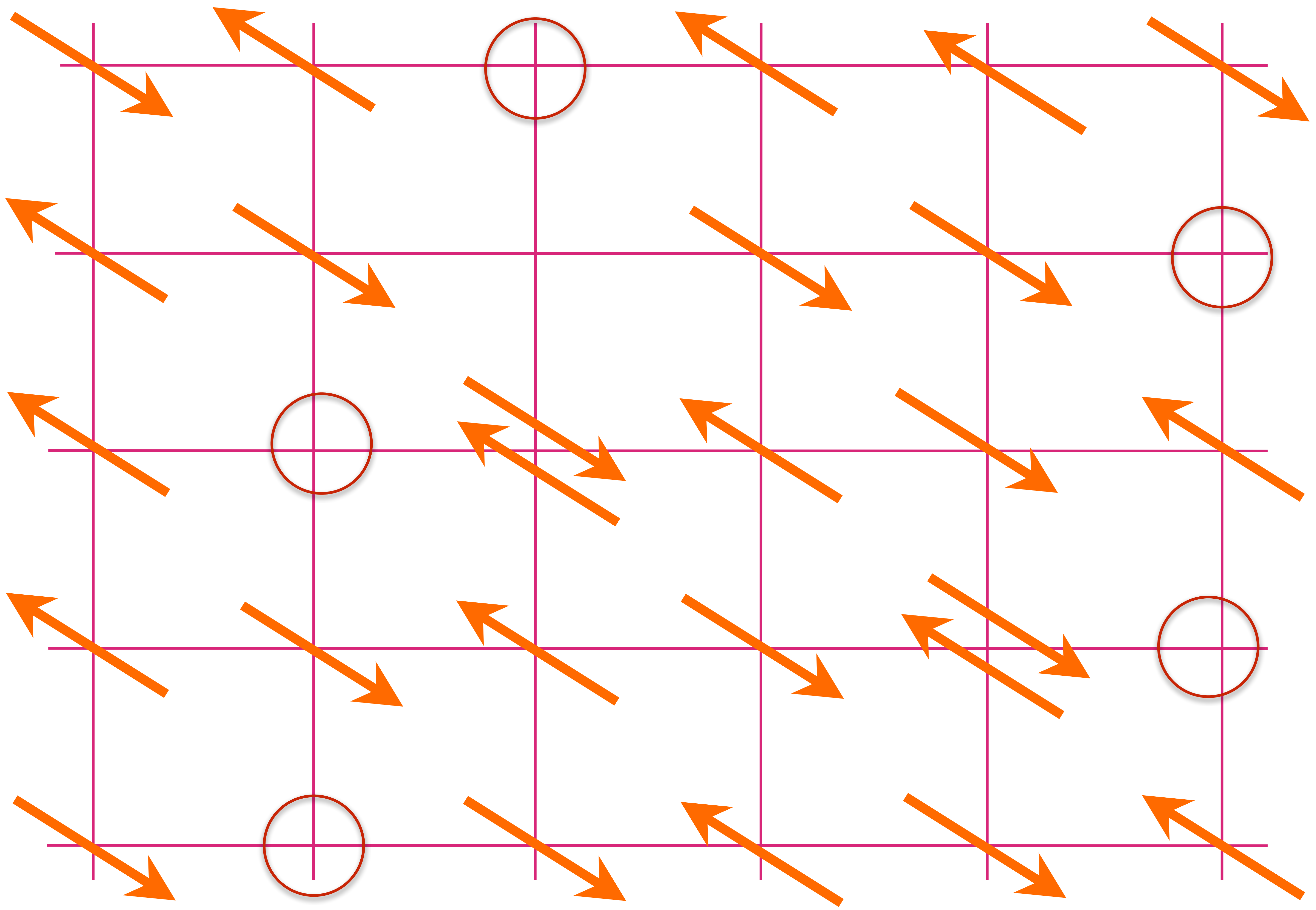
p mobile holes in a background of fluctuating spins

Momentum-space view at large p



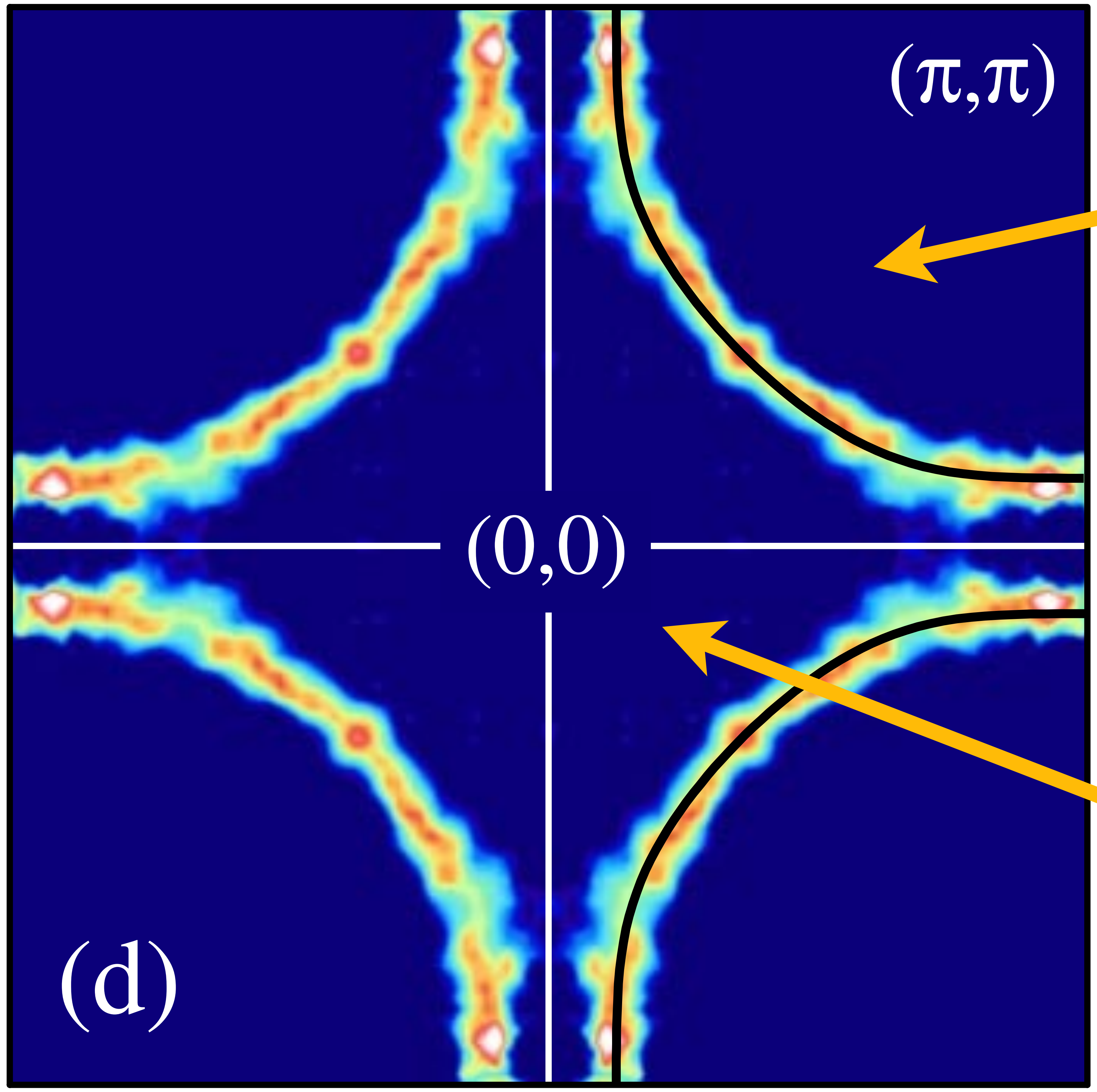
Filled Band

Momentum-space view at large p



1-p mobile electrons =
$1+p$ mobile holes in a filled band

Momentum-space view at large p



$1+p$ holes

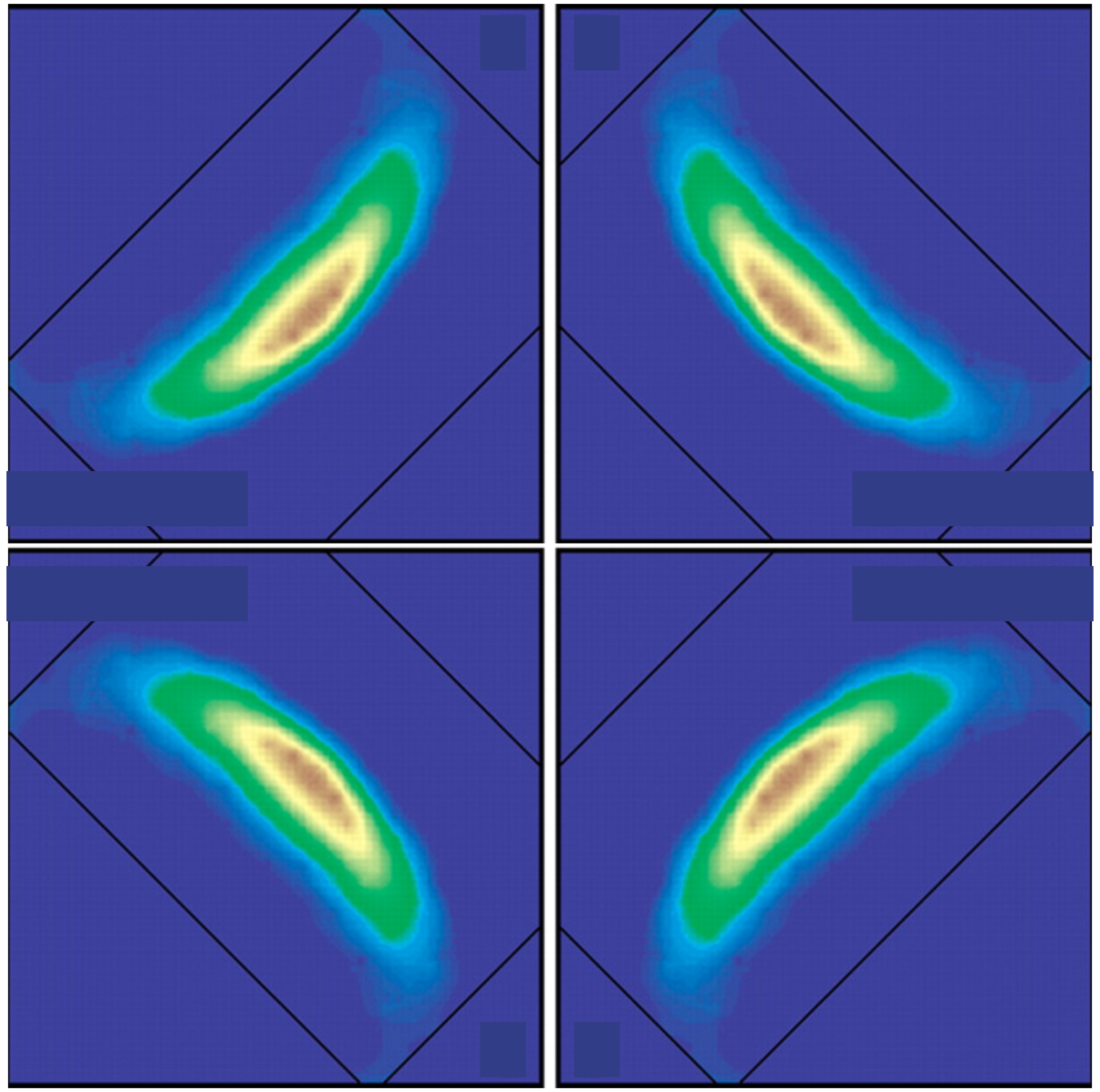
1-p electrons

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

$1+p$ mobile holes in a filled band

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)

Momentum-space view at small p



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

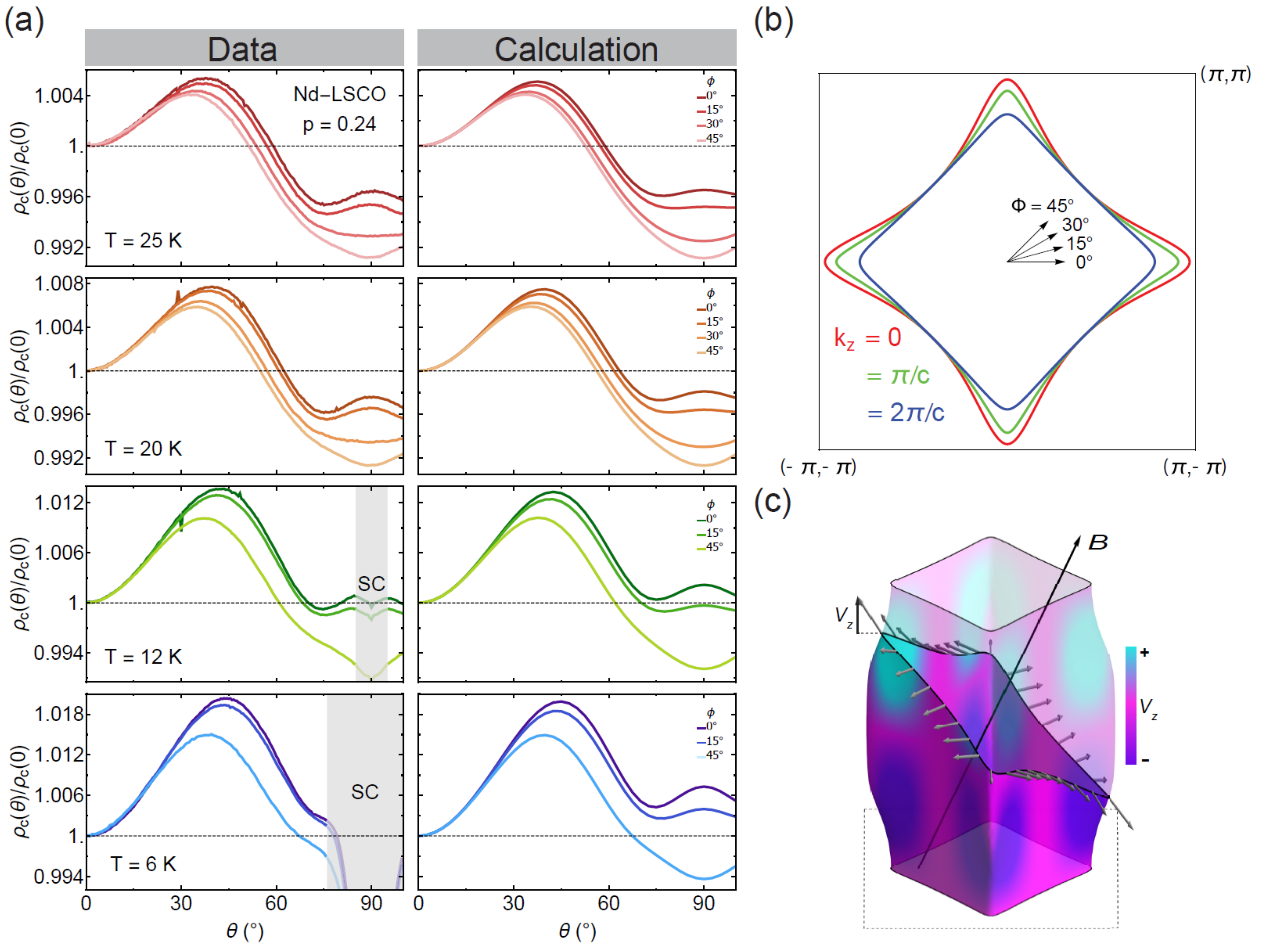
“Fermi arcs”

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)

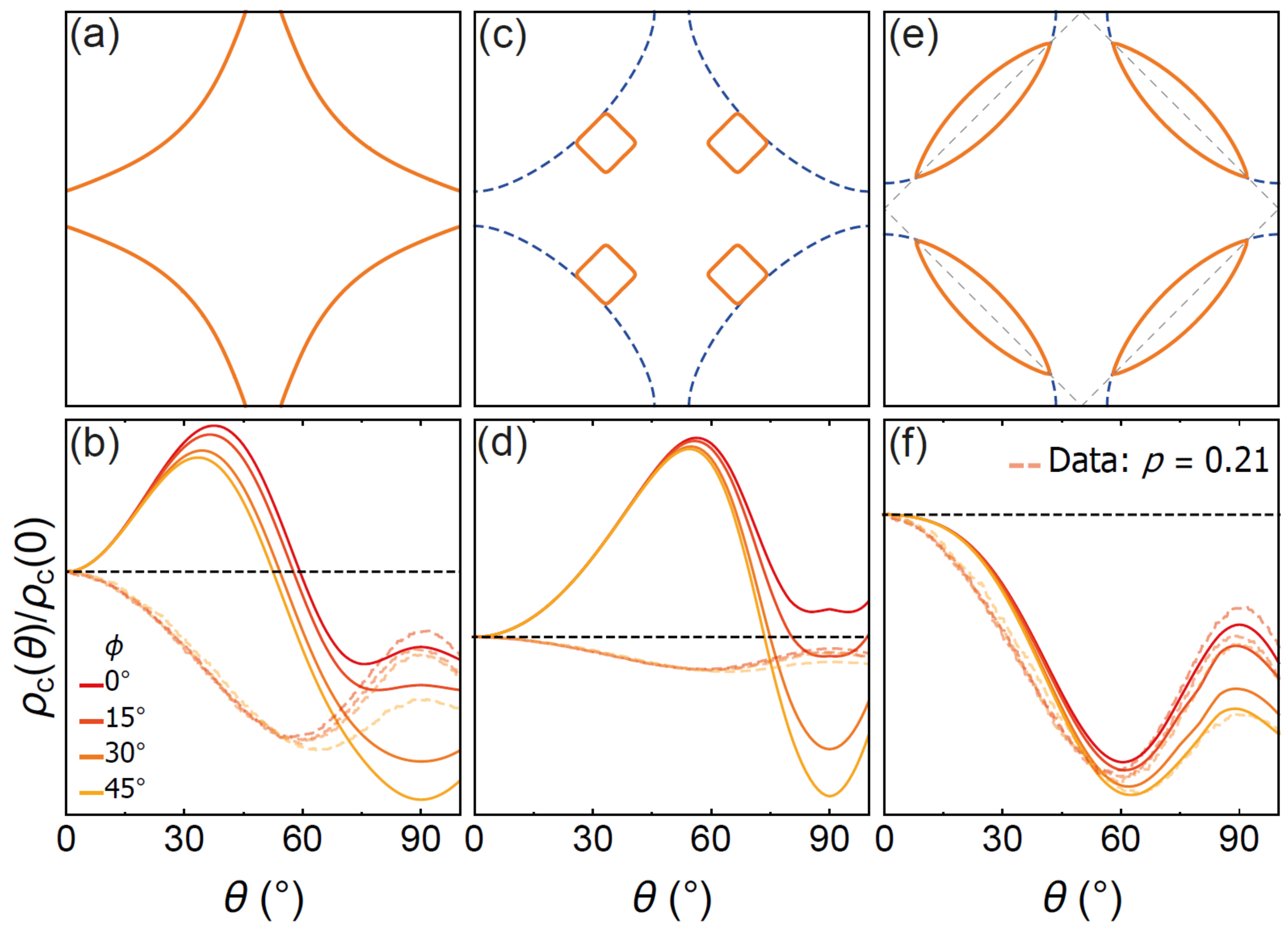
Fermi surface transformation at the pseudogap critical point of a cuprate superconductor

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, arXiv:2004.01725

We use angle-dependent magnetoresistance (ADMR) to measure the Fermi surface of the cuprate $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$. Above the critical doping p*—outside of the pseudogap phase—we find a Fermi surface that is in quantitative agreement with angle-resolved photoemission. Below p*, however, the ADMR is qualitatively different, revealing a clear change in Fermi surface topology. We find that our data is most consistent with a Fermi surface that has been reconstructed by a Q = (π,π) wavevector. While static Q = (π,π) antiferromagnetism is not found at these dopings, our results suggest that this wavevector is a fundamental organizing principle of the pseudogap phase.



$p > p_c$ Large Fermi surface

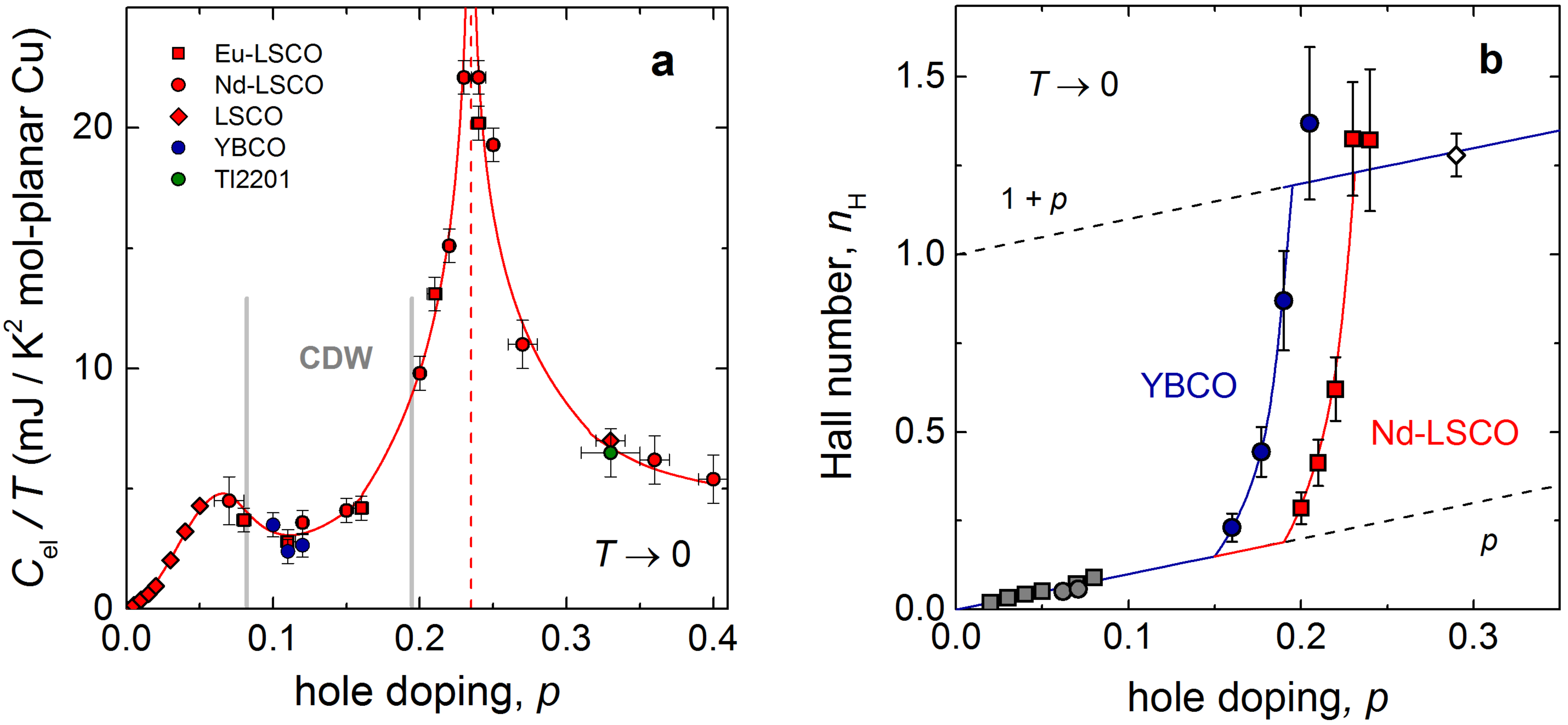


$p < p_c$ Reconstructed Fermi surface

Hole doped cuprates

The remarkable underlying ground states of cuprate superconductors

Cyril Proust and Louis Taillefer, Annual Review Condensed Matter Physics **10,** 409 (2019)



1. Luttinger volume violation in Kondo lattice models

   The FL phase*

2. Introduction to cuprates

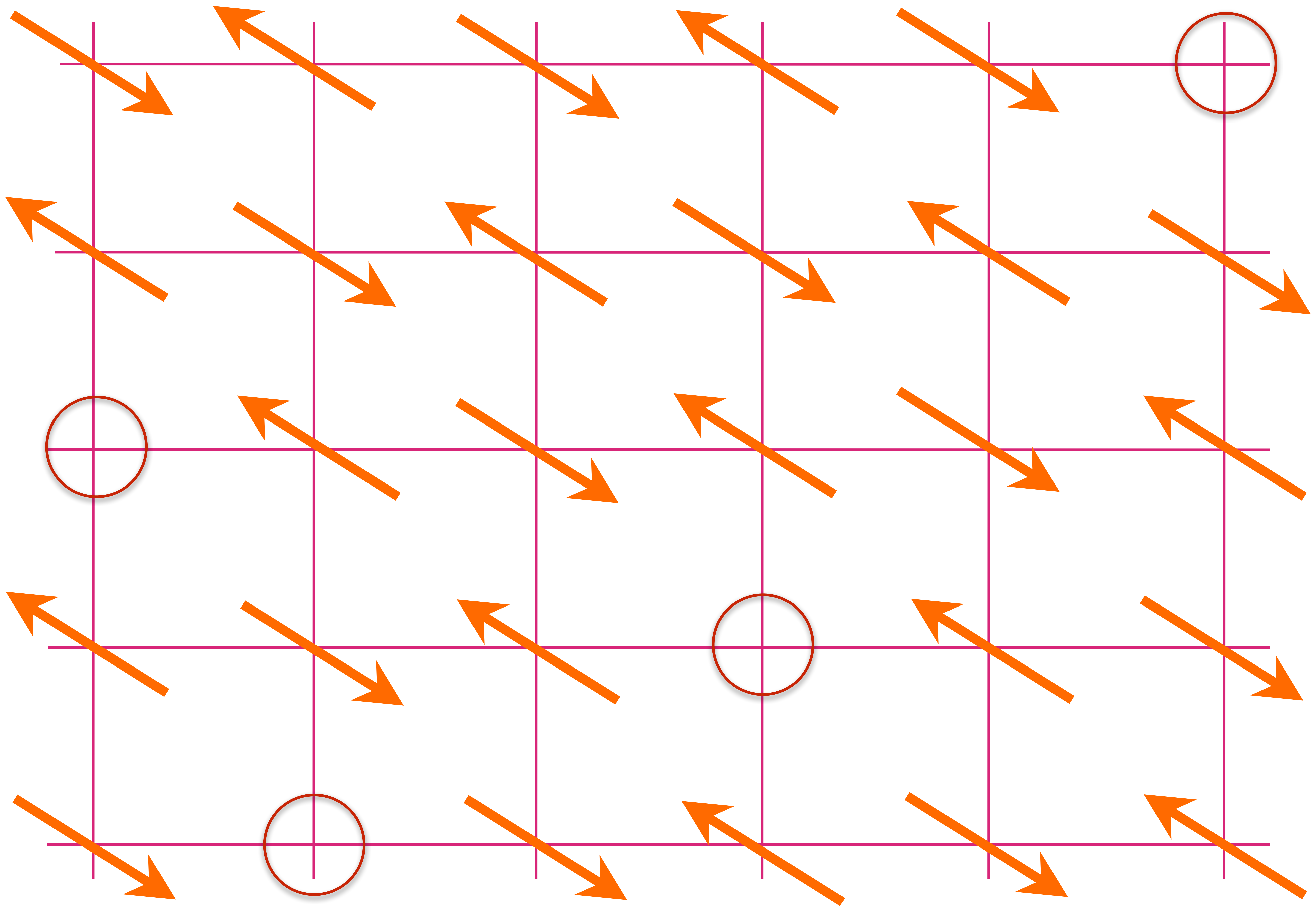
   The pseudogap metal

3. Luttinger volume violation a one-band model

   Ancilla qubits and ghost Fermi surfaces

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

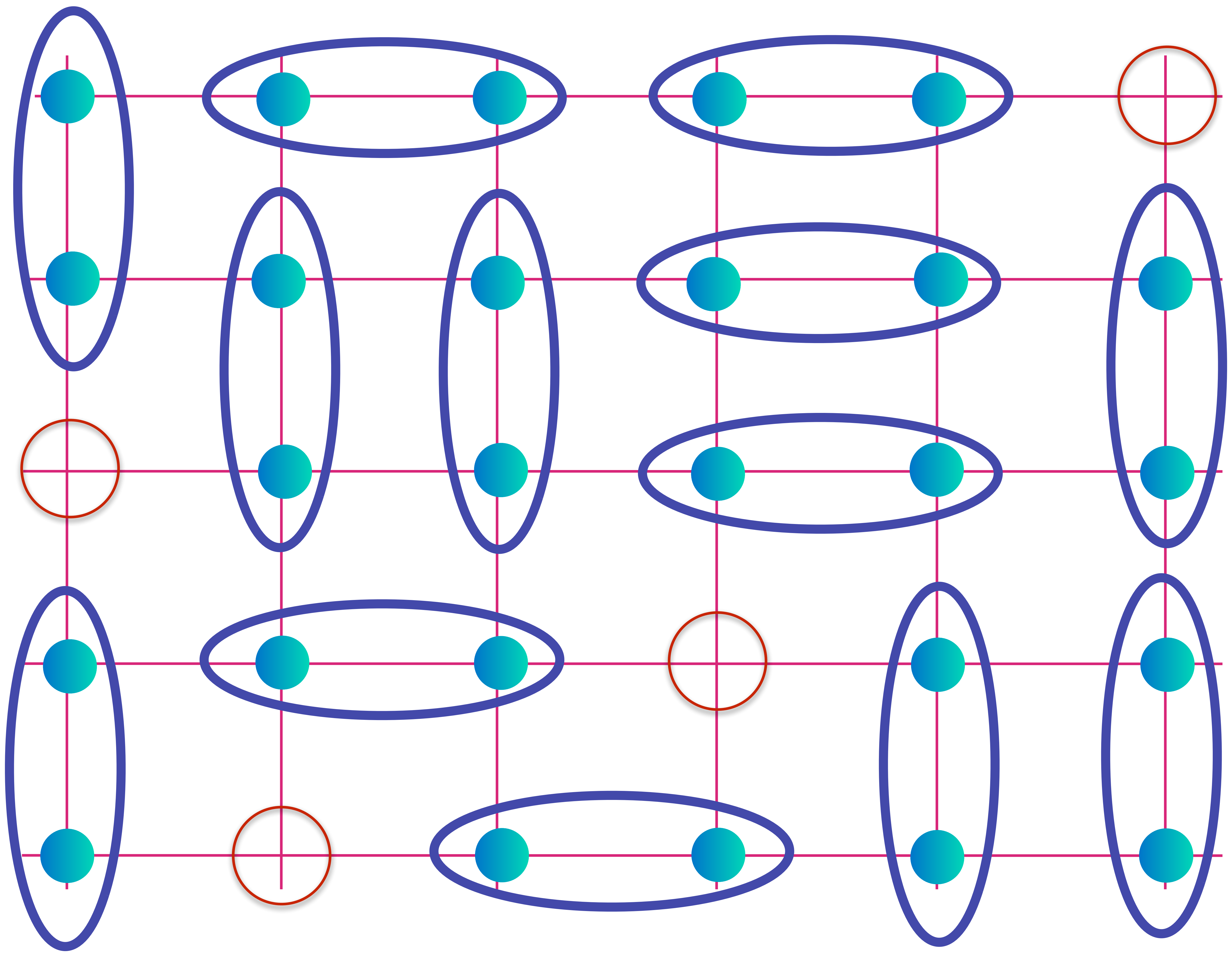
- Can realize the FL* state as a doped spin liquid in which spinons and holons bind to form 'electrons', which then form a small Fermi surface (X.-G. Wen and P. A. Lee, PRL **76**, 503 (1996)); but there is no complete description of this process, except in the very strong binding limit of dimer 'electrons' (M. Punk, A. Allais, and S. Sachdev,PNAS **112**, 9552 (2015)). This approach does not yield a theory of the transition to the FL state.



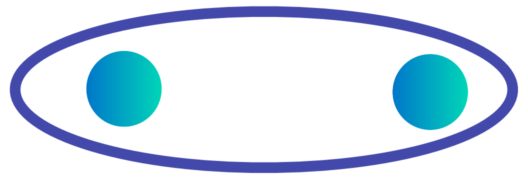
Anti-ferromagnet with p holes per square

Holon metal

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

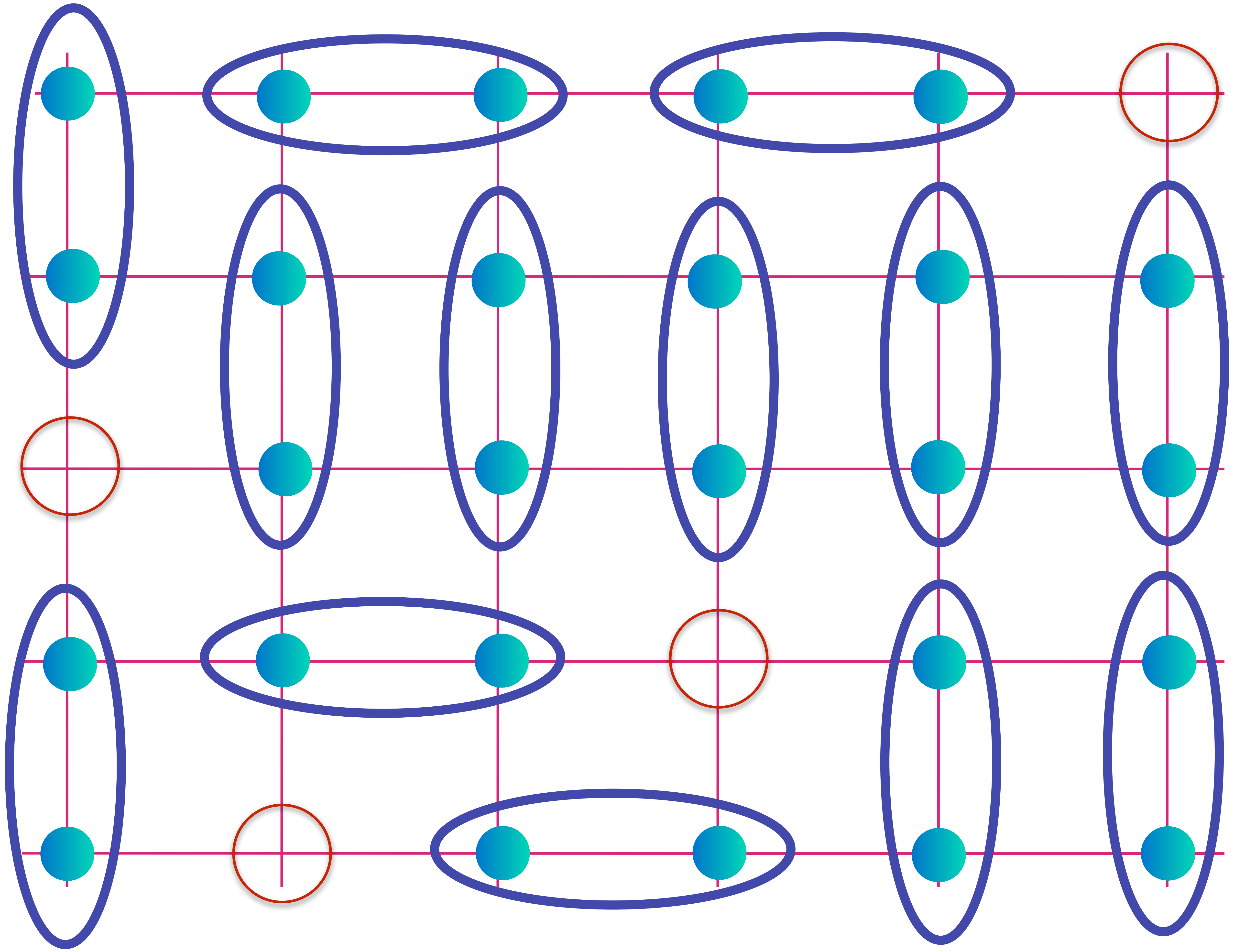


Spin liquid with density p of spinless, charge +e "holons".

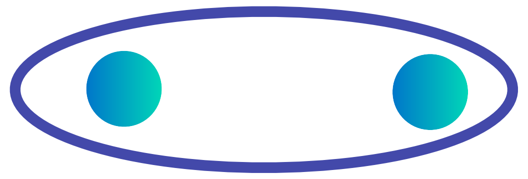
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

Holon metal

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

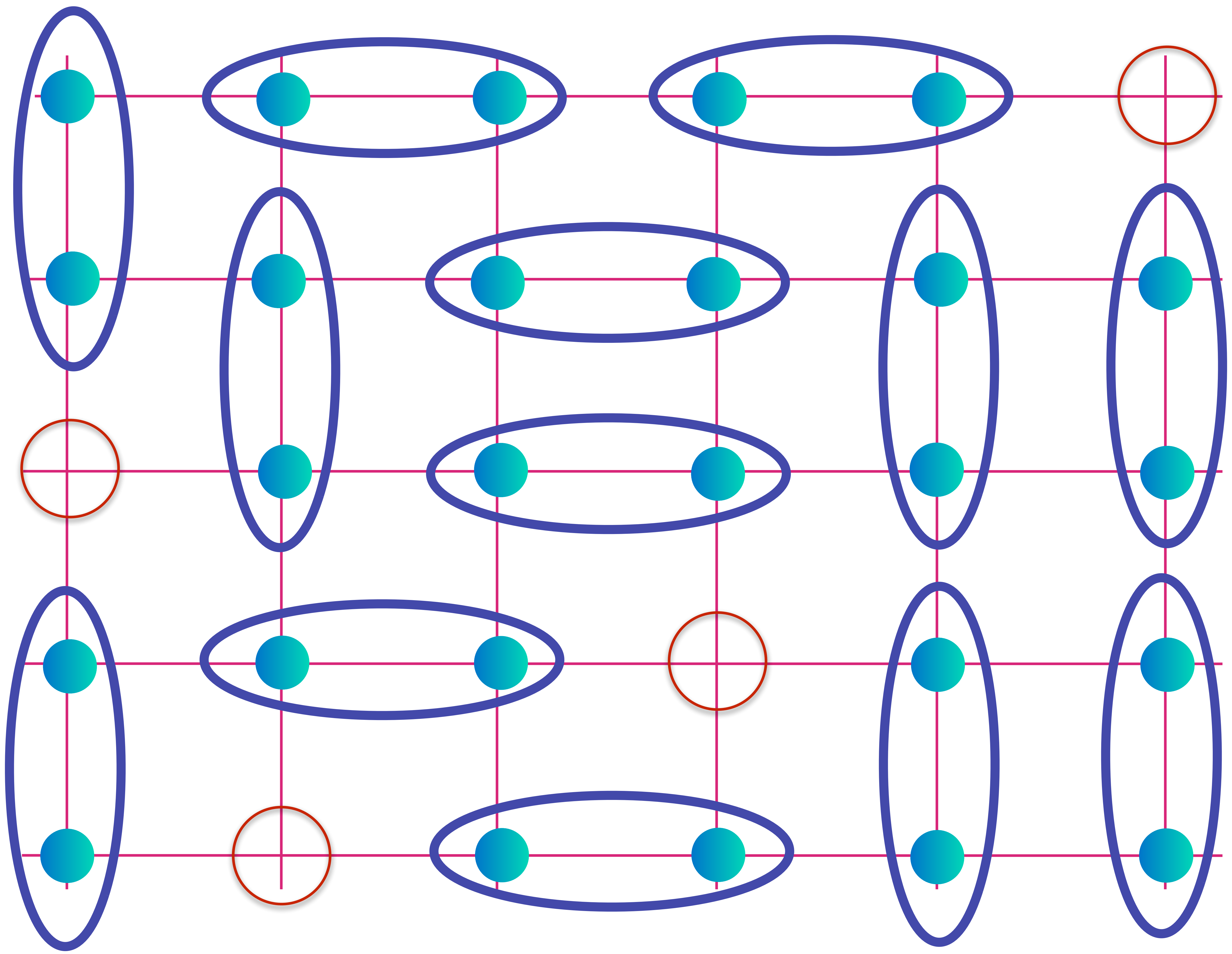


Spin liquid with density p of spinless, charge +e "holons".

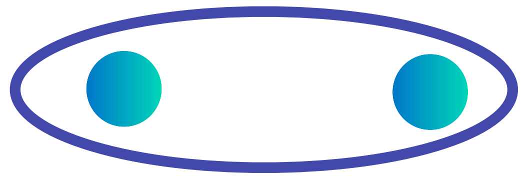
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

Holon metal

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

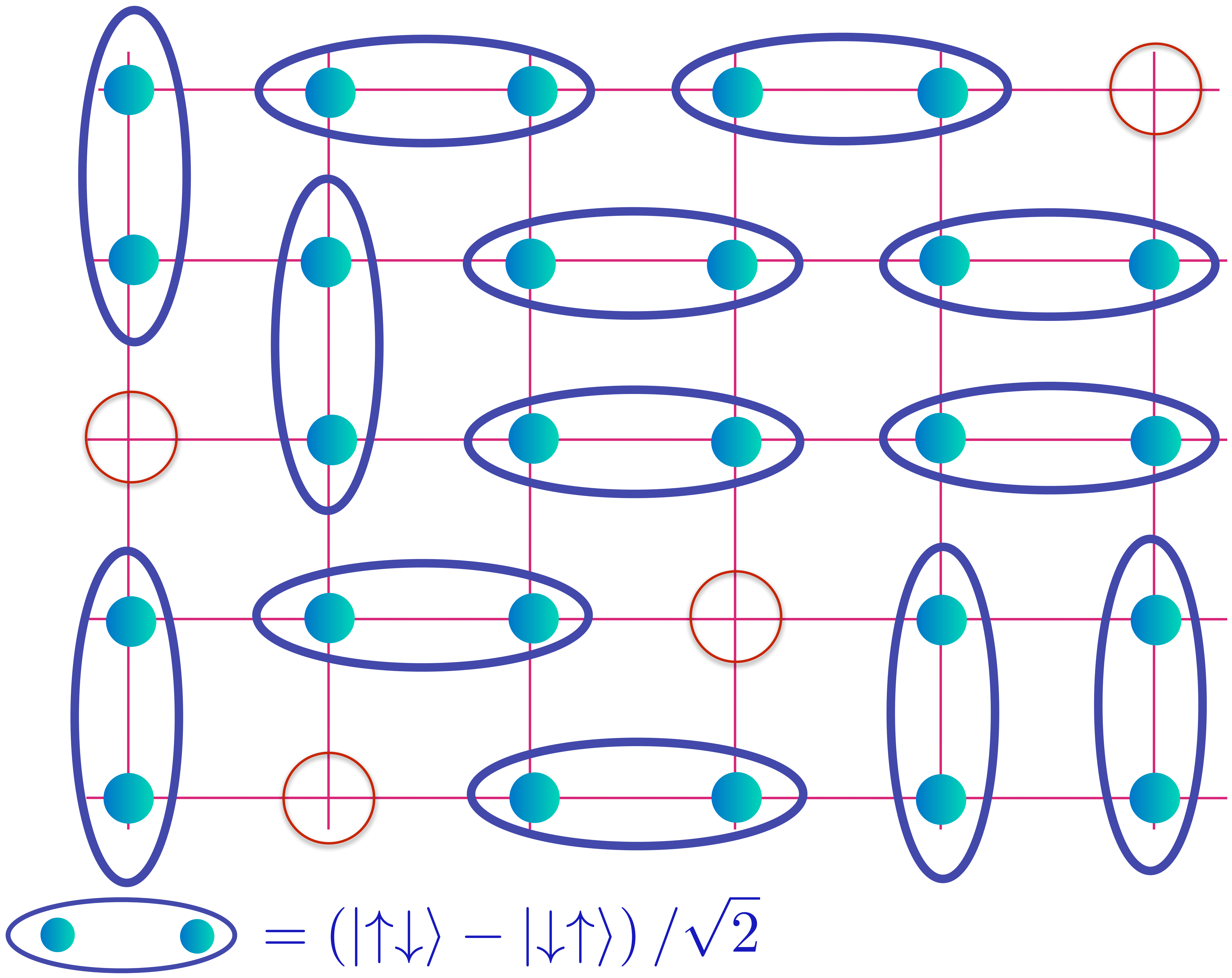


Spin liquid with density p of spinless, charge +e “holons”.

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

Holon metal

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

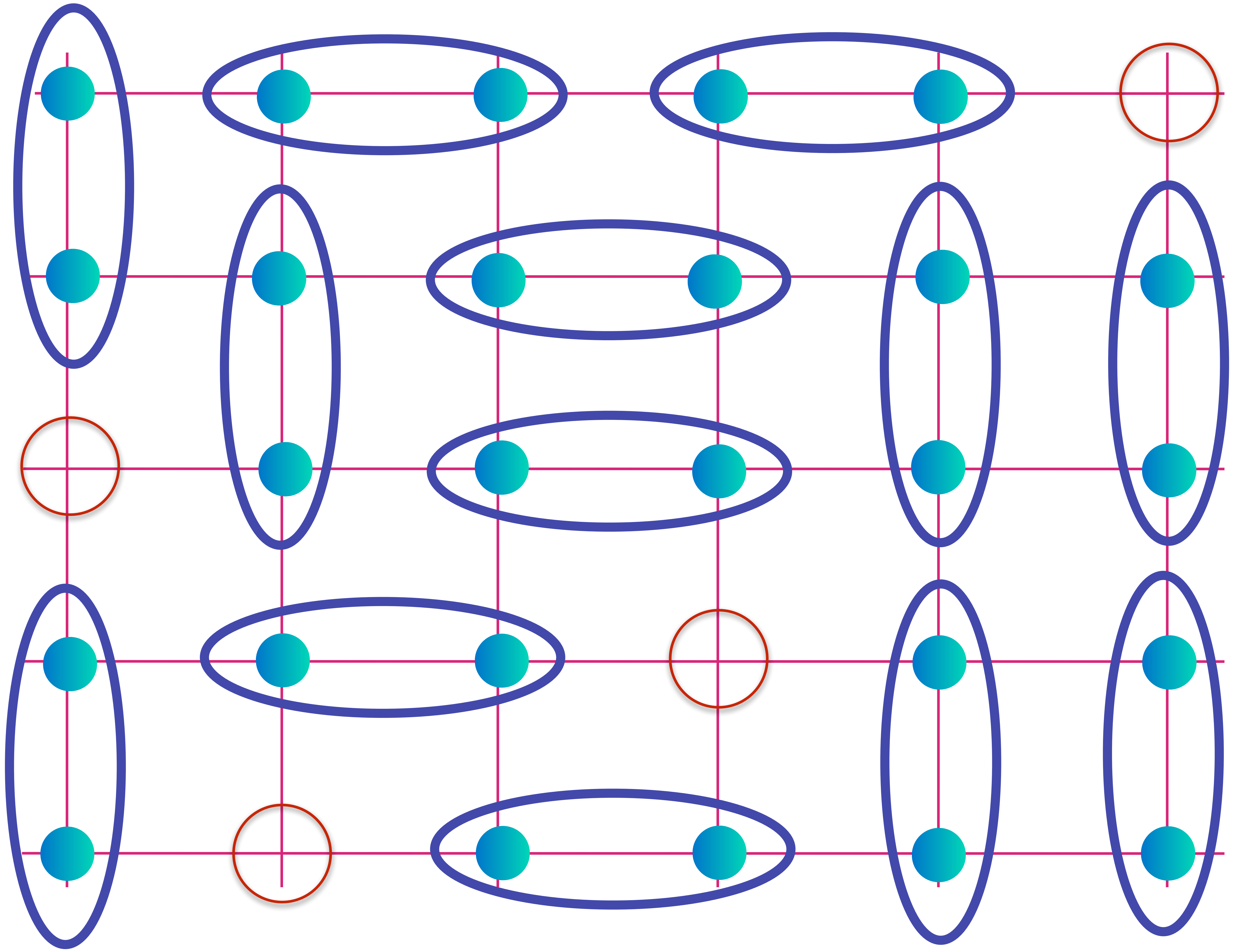


$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

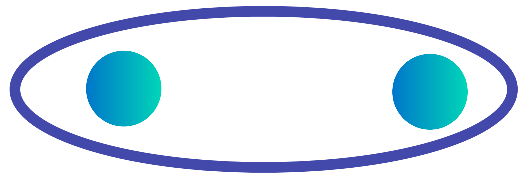
Spin liquid with density p of spinless, charge +e "holons".

Holon metal

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

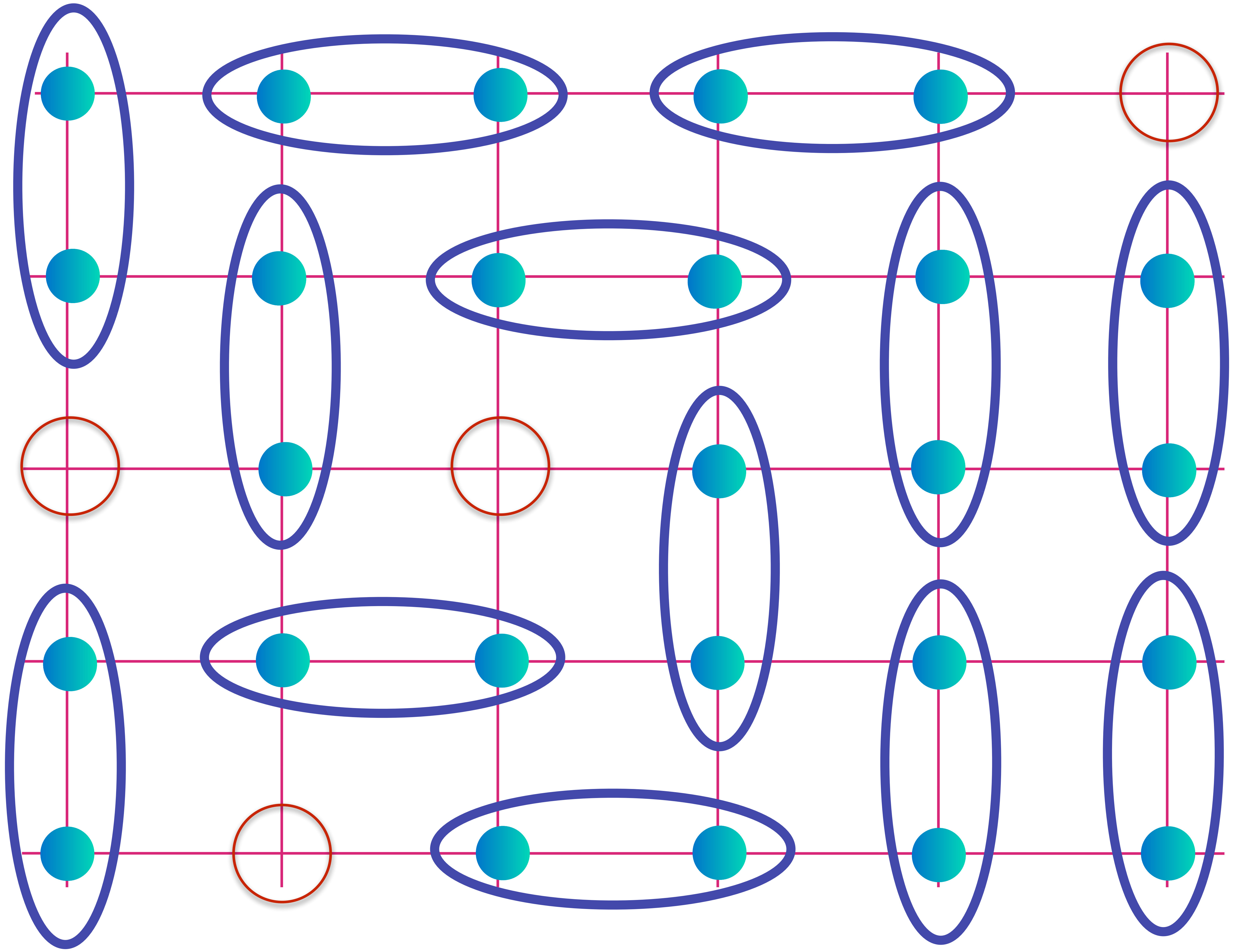


Spin liquid with density p of spinless, charge +e "holons".

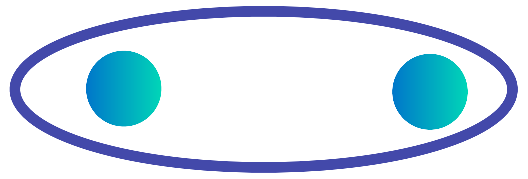
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

Holon metal

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

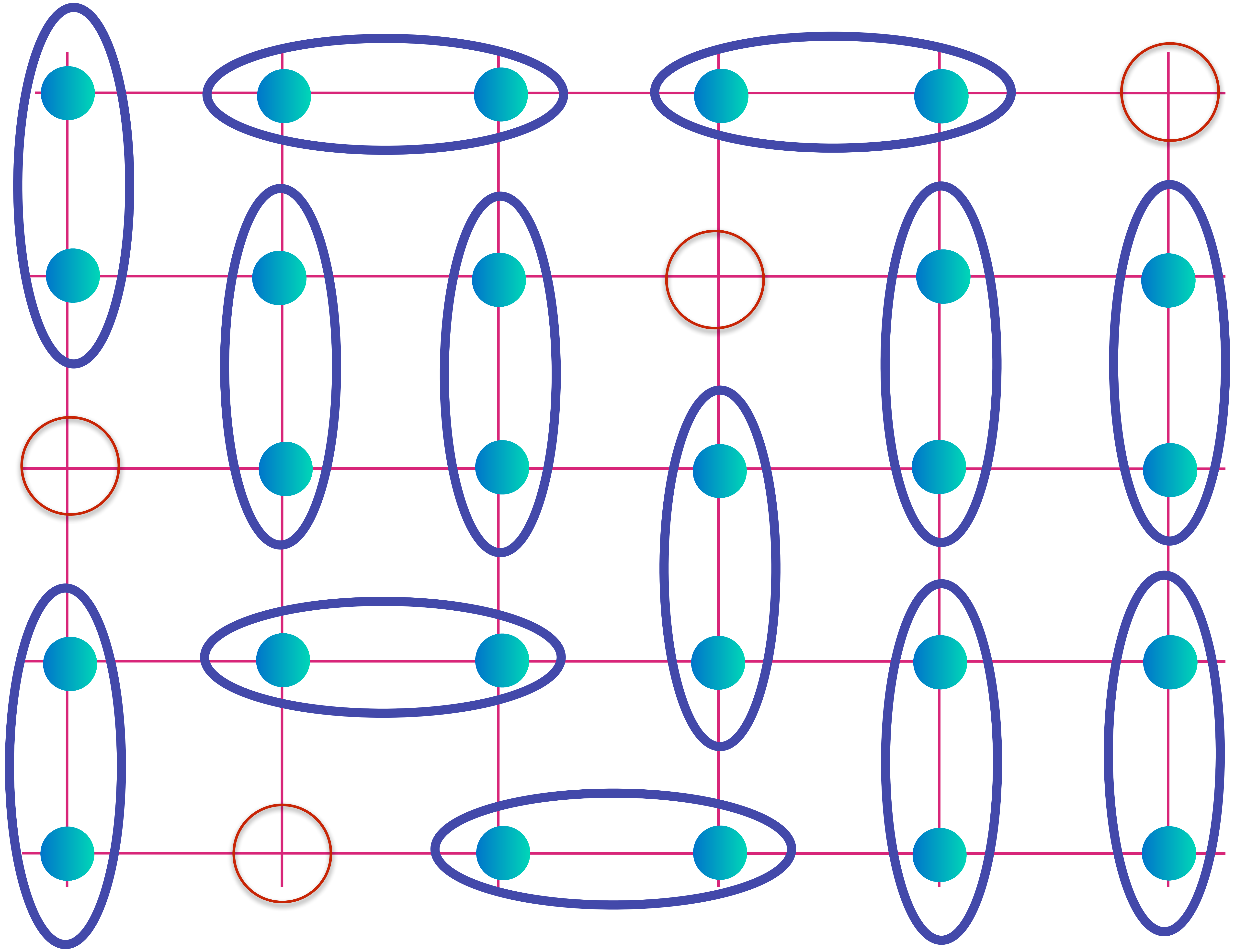


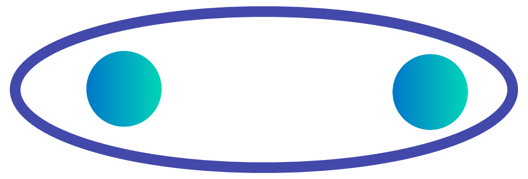
Spin liquid with density p of spinless, charge +e “holons”.

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

Holon metal

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



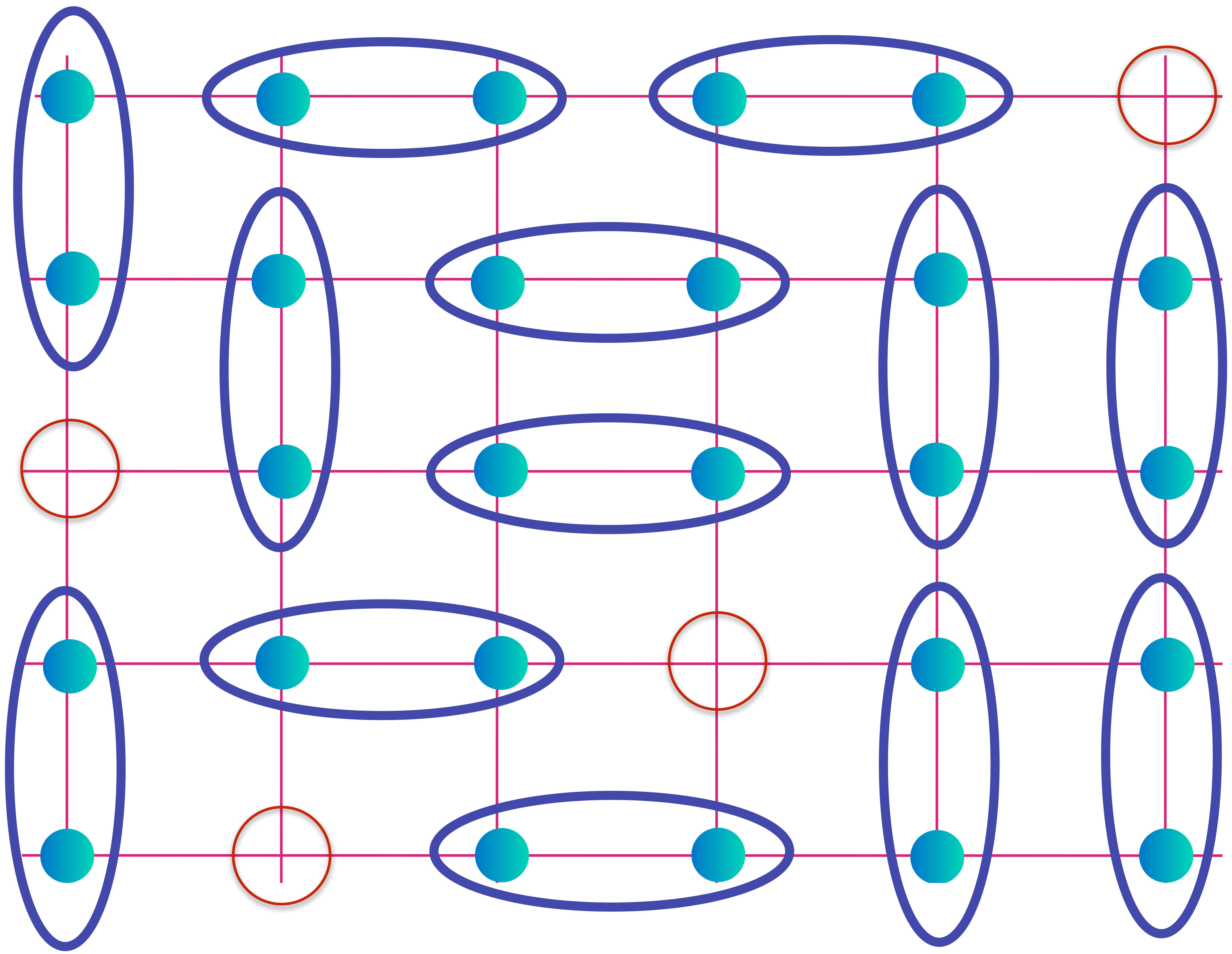


$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

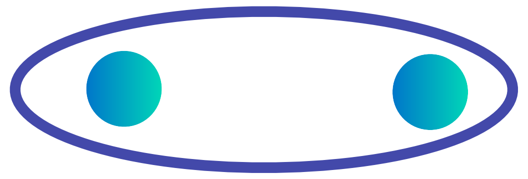
Spin liquid with density p of spinless, charge +e "holons".

Holon metal

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



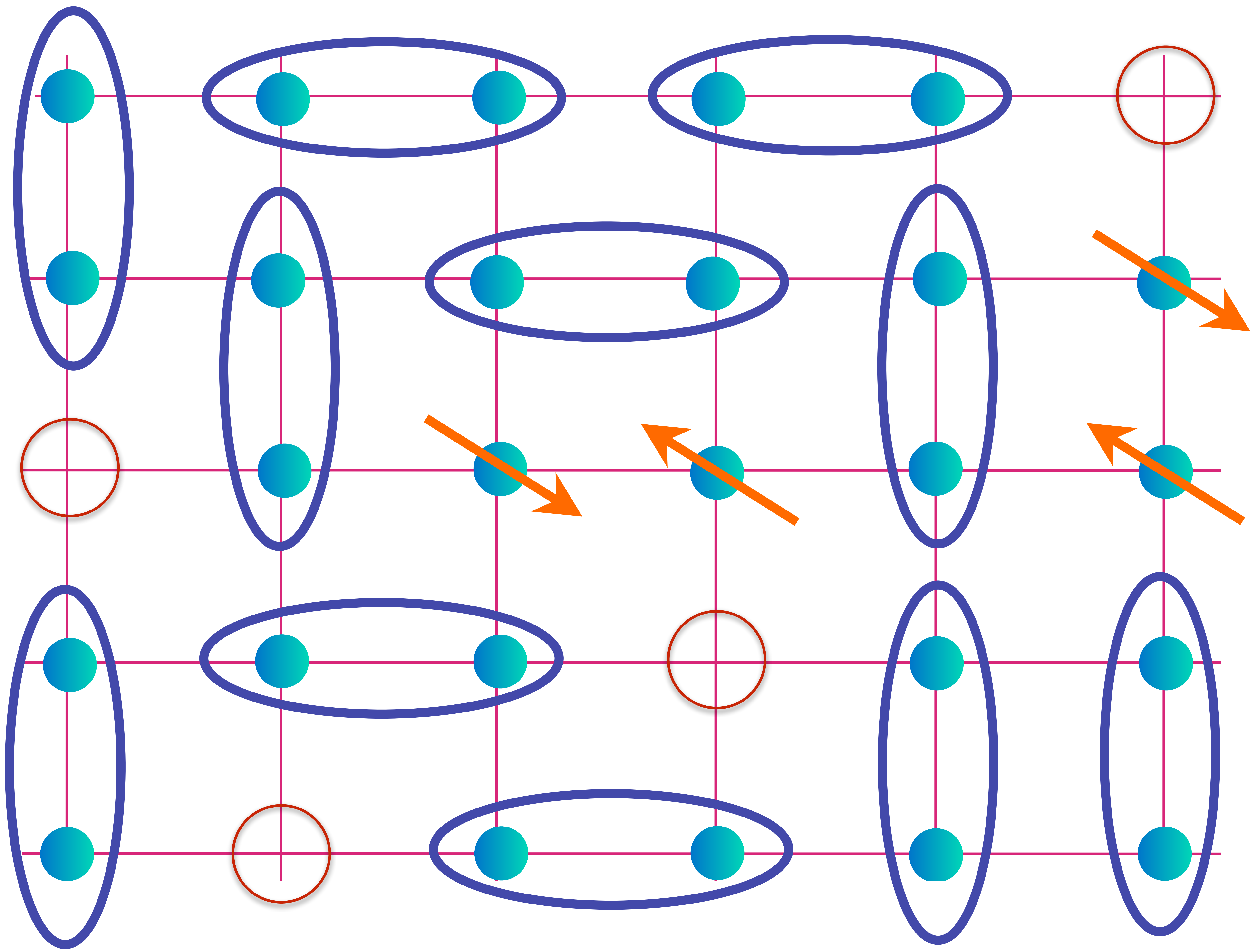
Spin liquid with density p of spinless, charge +e "holons".



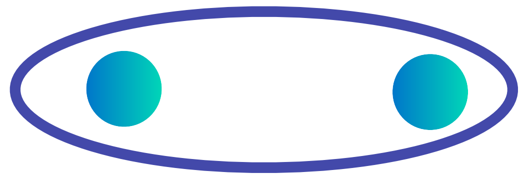
$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

Holon metal

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



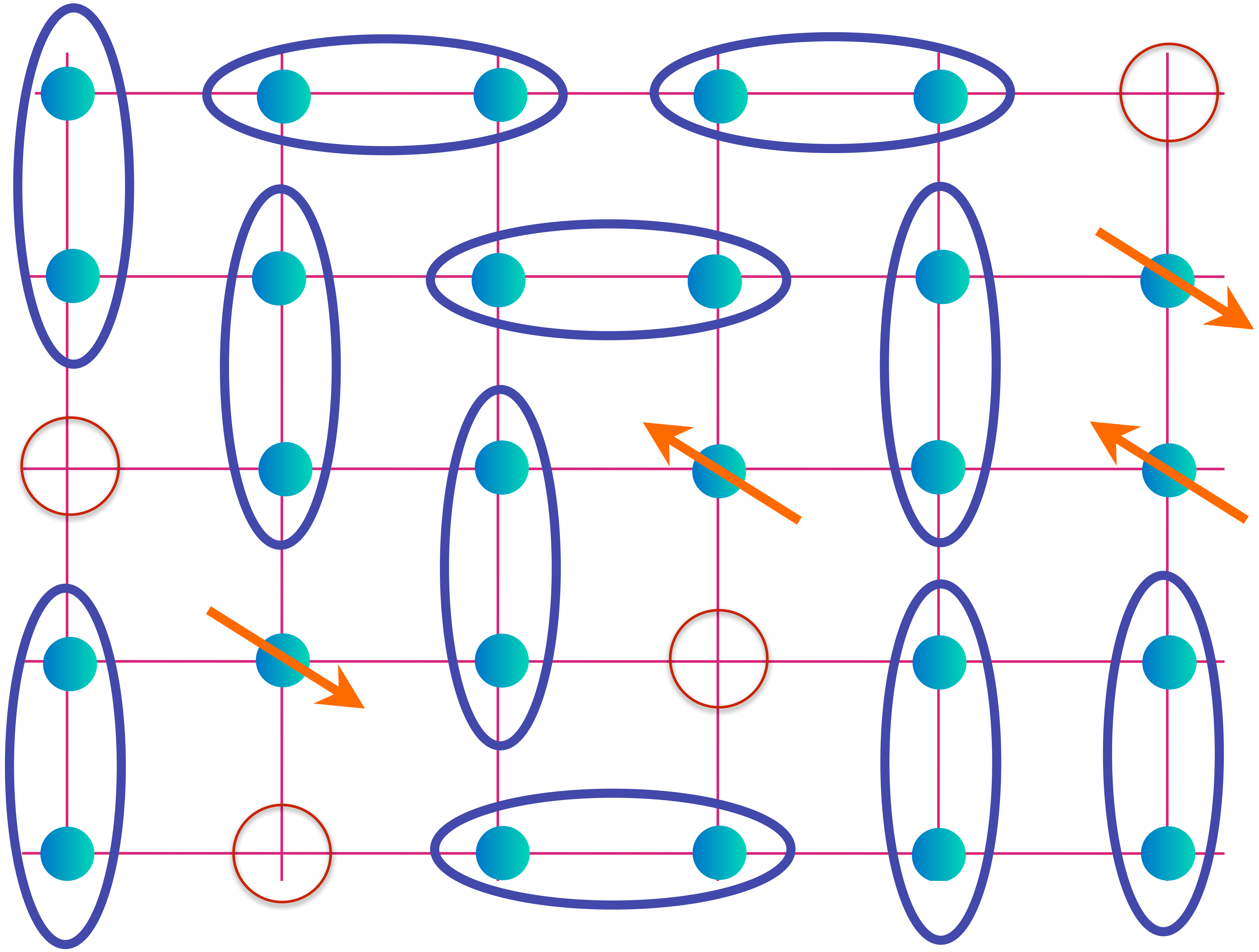
Spin liquid with density p of spinless, charge +e "holons" and charge 0, spin-1/2 "spinons".



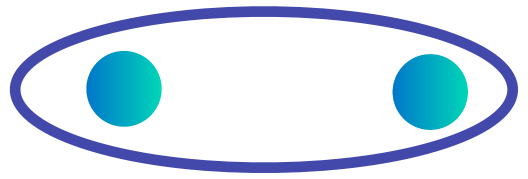
$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$$

Holon metal

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

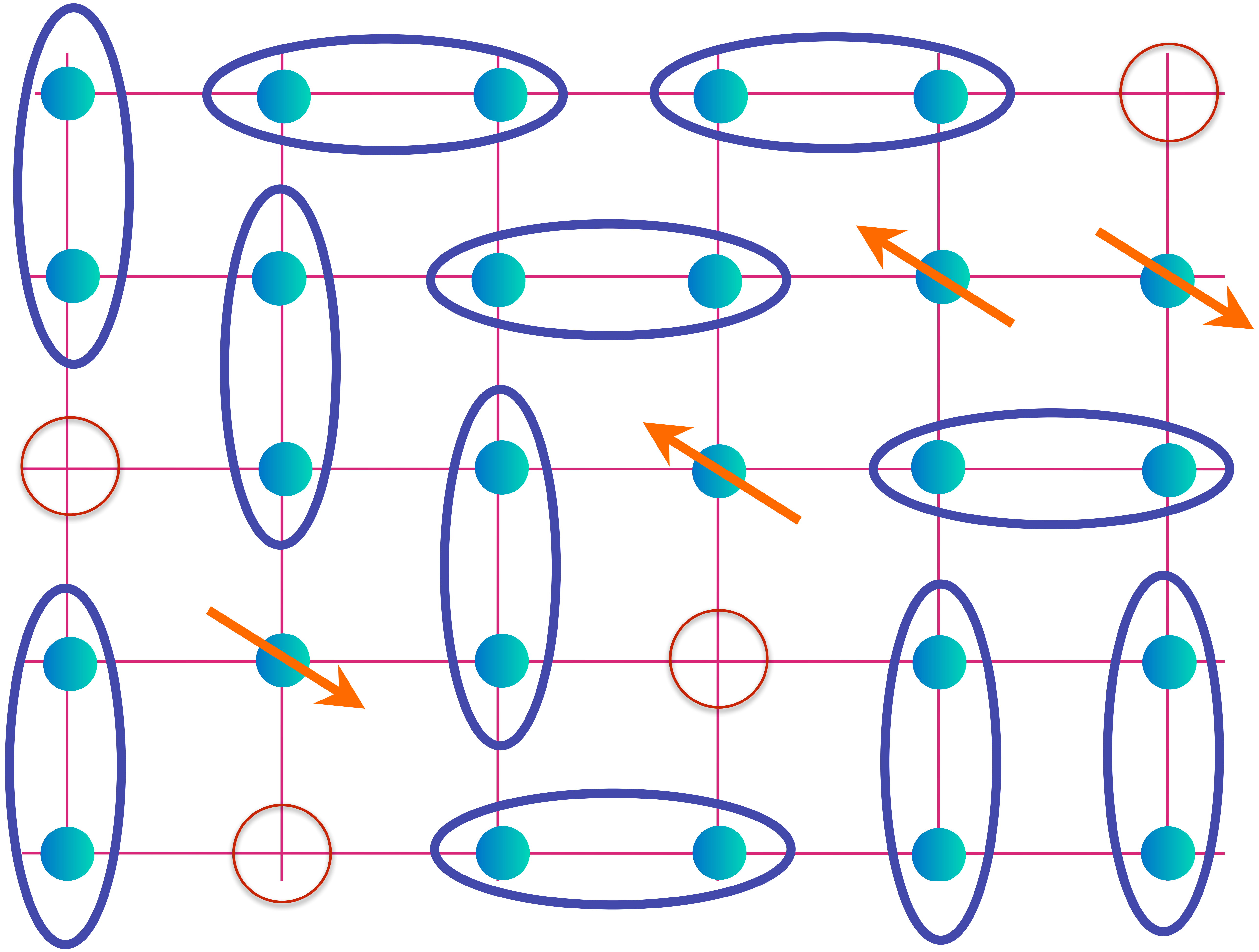


Spin liquid with density p of spinless, charge +e "holons" and charge 0, spin-1/2 "spinons".

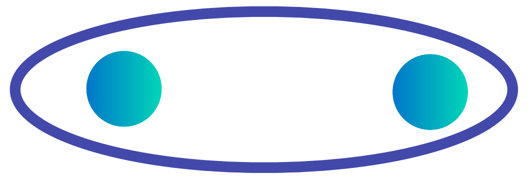
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right) / \sqrt{2}$

Holon metal

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



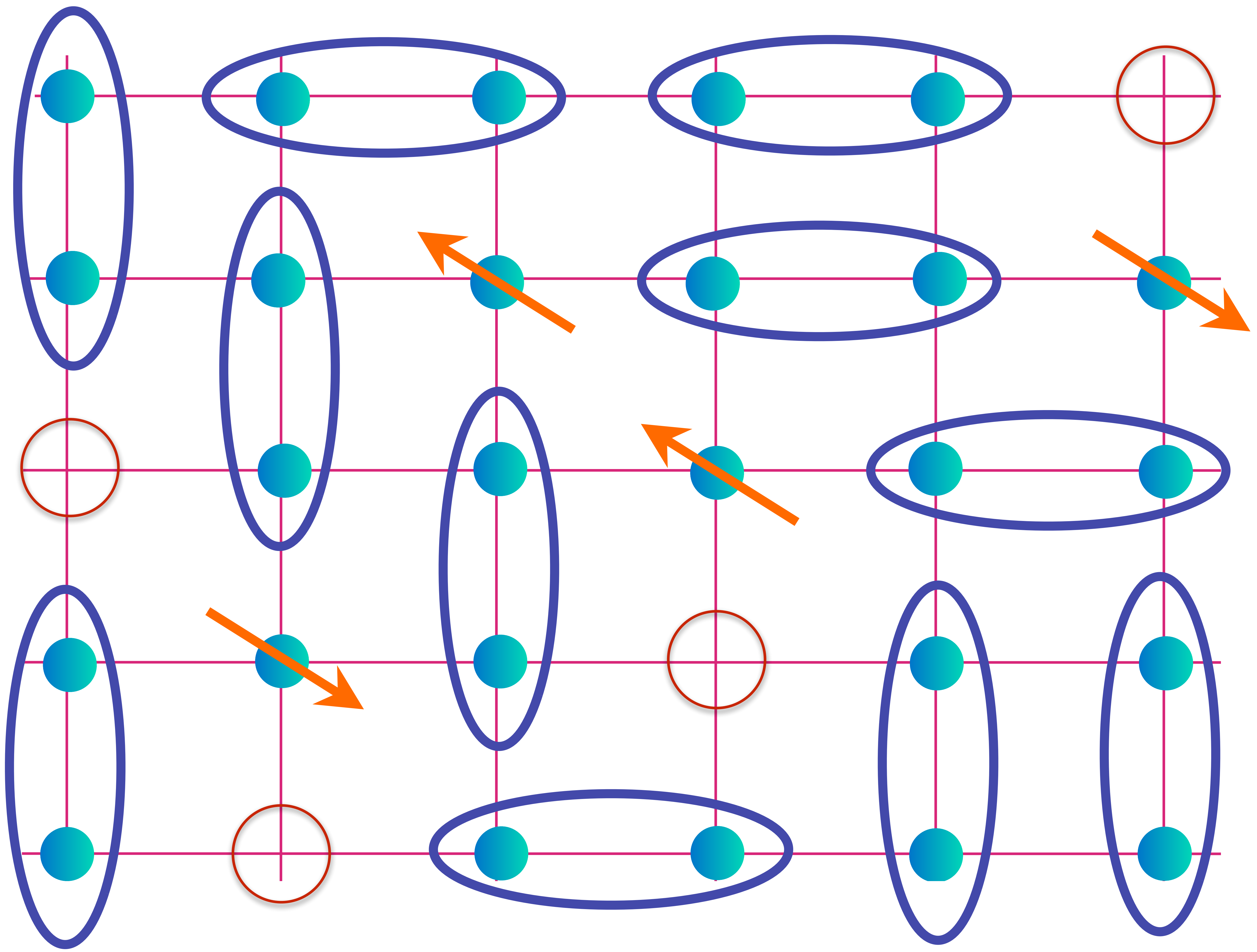
Spin liquid with density p of spinless, charge +e "holons" and charge 0, spin-1/2 "spinons".

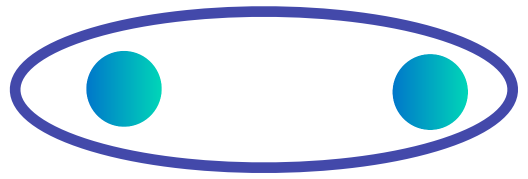


$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$$

Holon metal

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



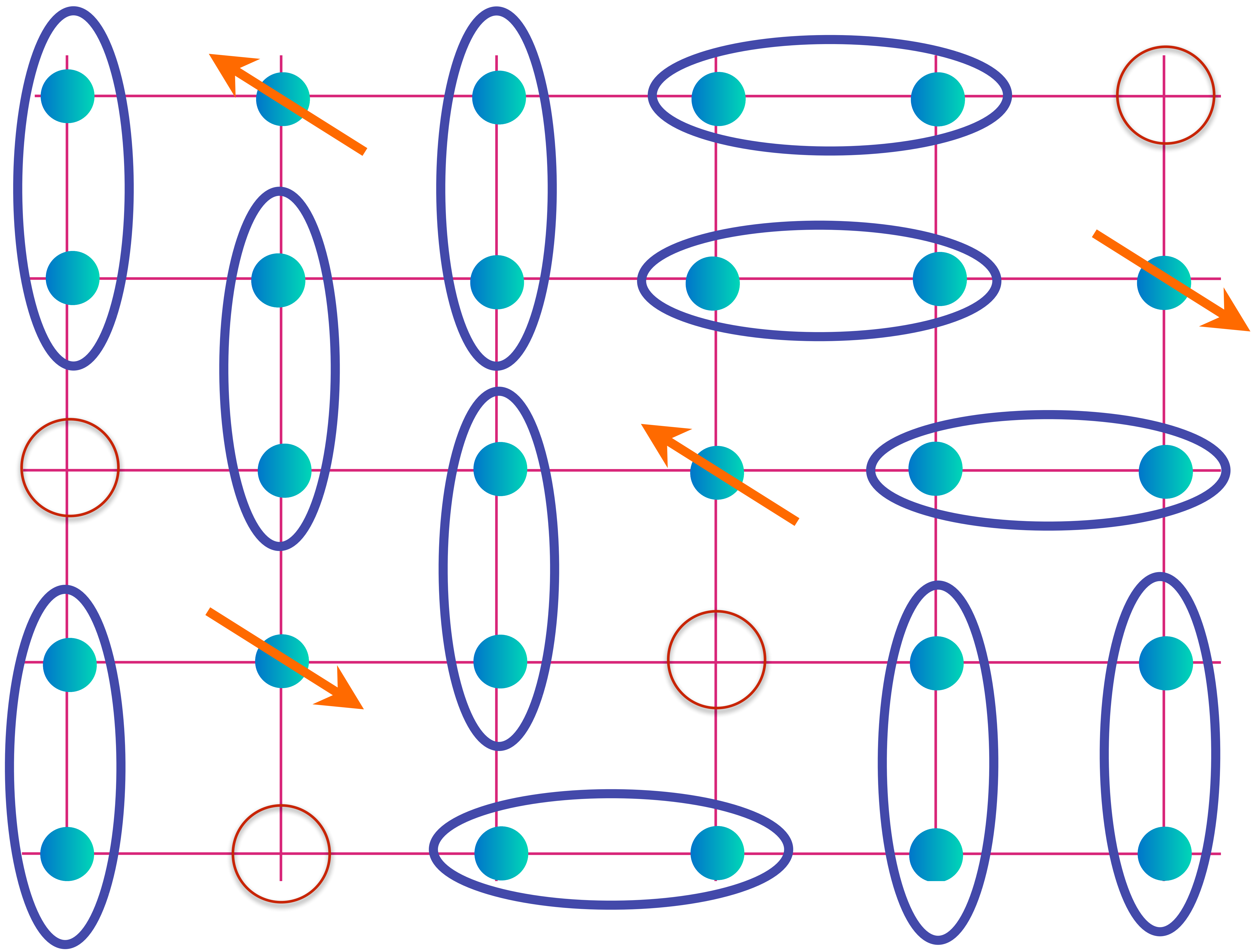


$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

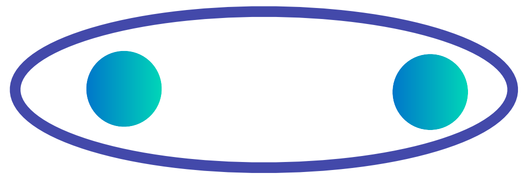
Spin liquid with density p of spinless, charge +e "holons" and charge 0, spin-1/2 "spinons".

Holon metal

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

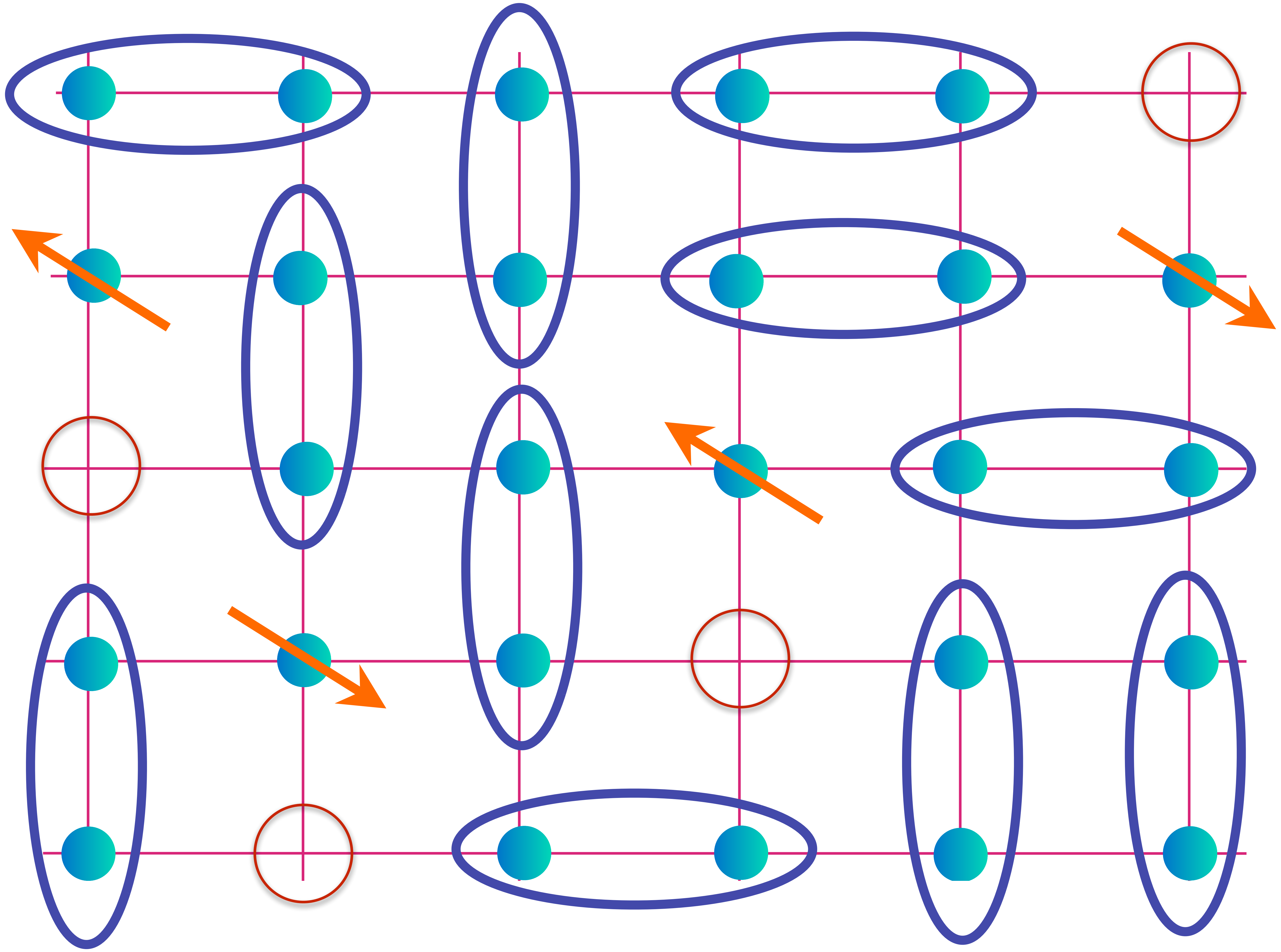


Spin liquid with density p of spinless, charge +e "holons" and charge 0, spin-1/2 "spinons".

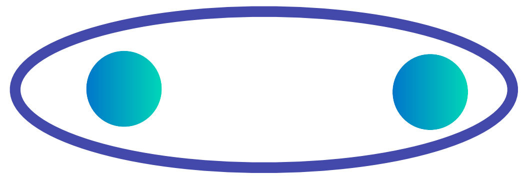
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

Holon metal

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

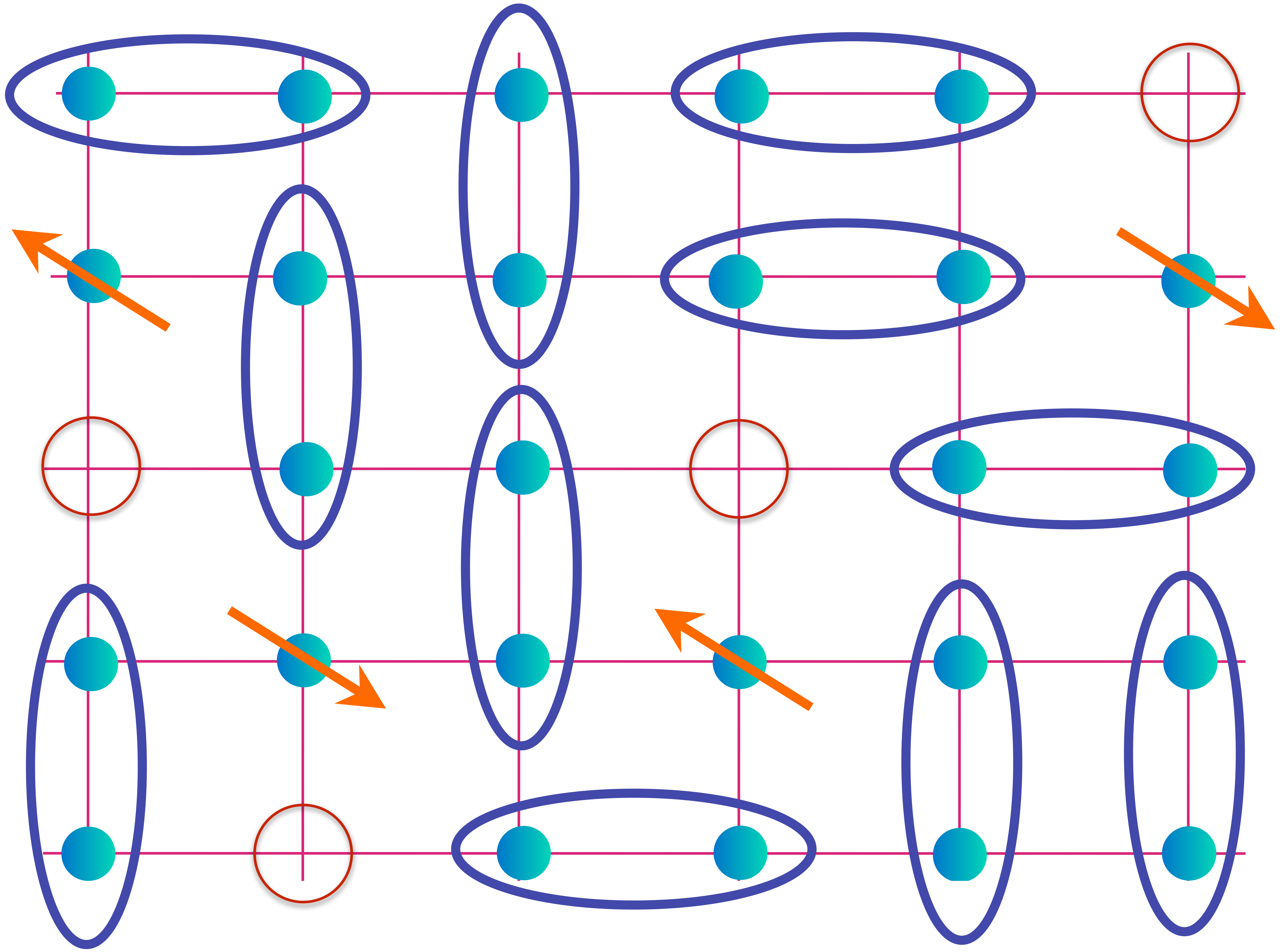


Spin liquid with density p of spinless, charge +e "holons" and charge 0, spin-1/2 "spinons".

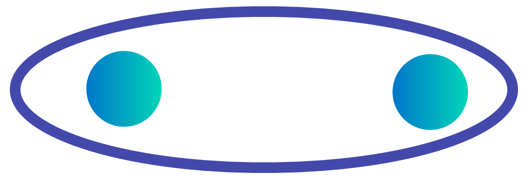
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

Holon metal

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

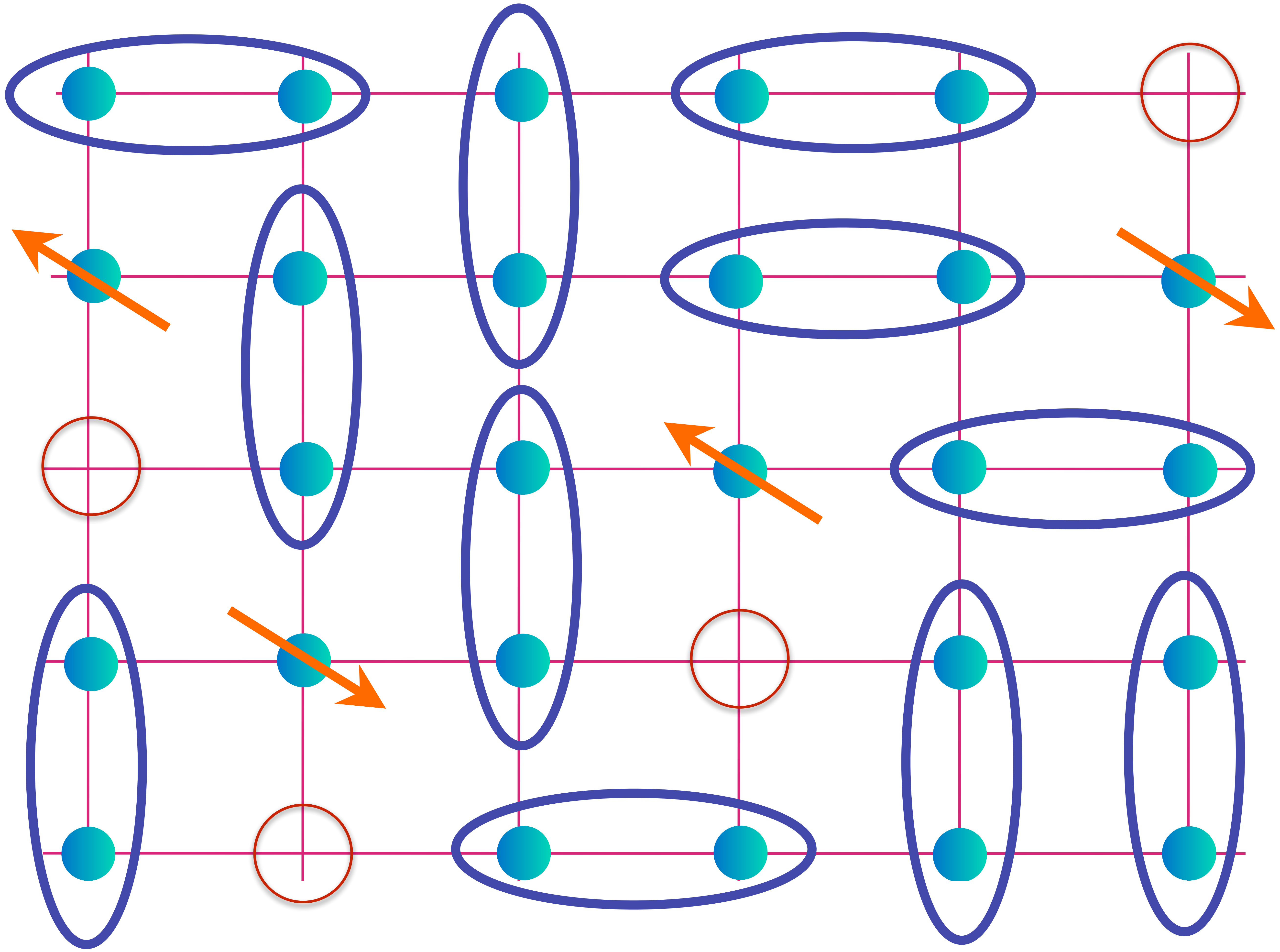


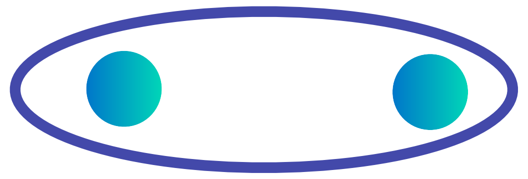
Spin liquid with density p of spinless, charge +e "holons" and charge 0, spin-1/2 "spinons".

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

Holon metal

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

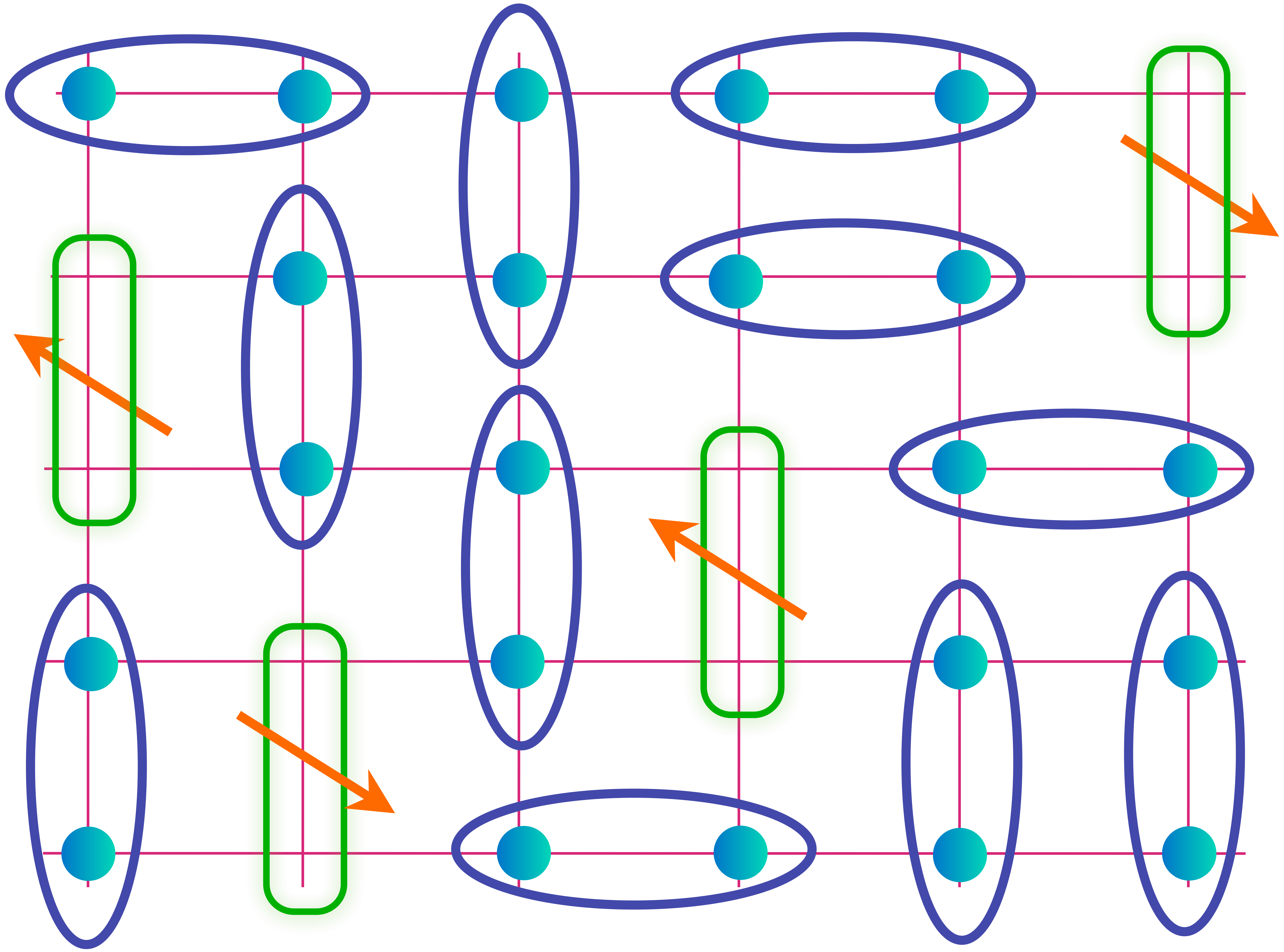


 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

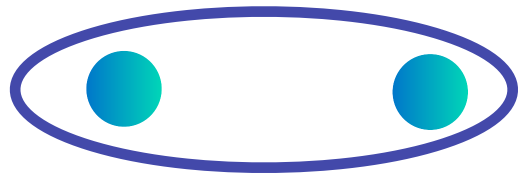
Spin liquid
with density
p of spinless,
charge +e
"holons" and
charge 0, spin-1/2
"spinons".

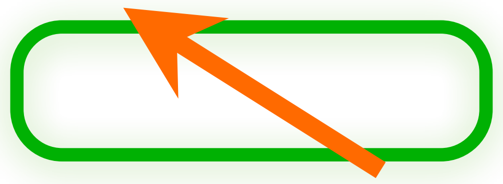
FL*

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

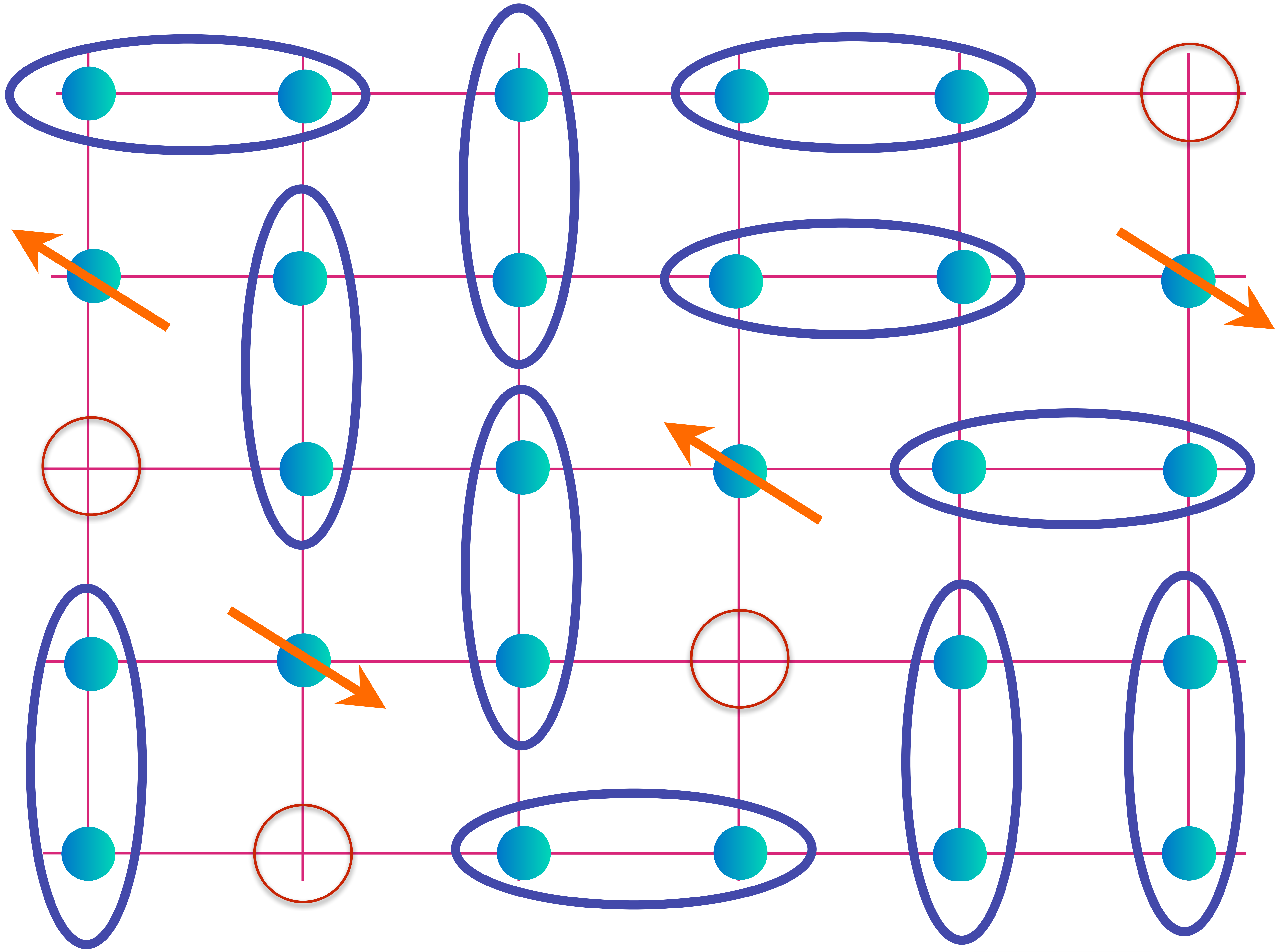
 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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

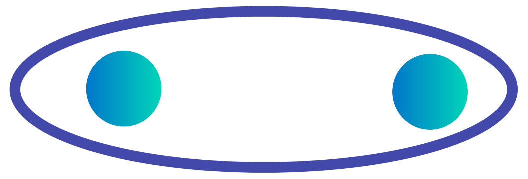
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

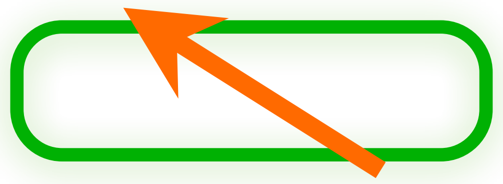
FL*

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

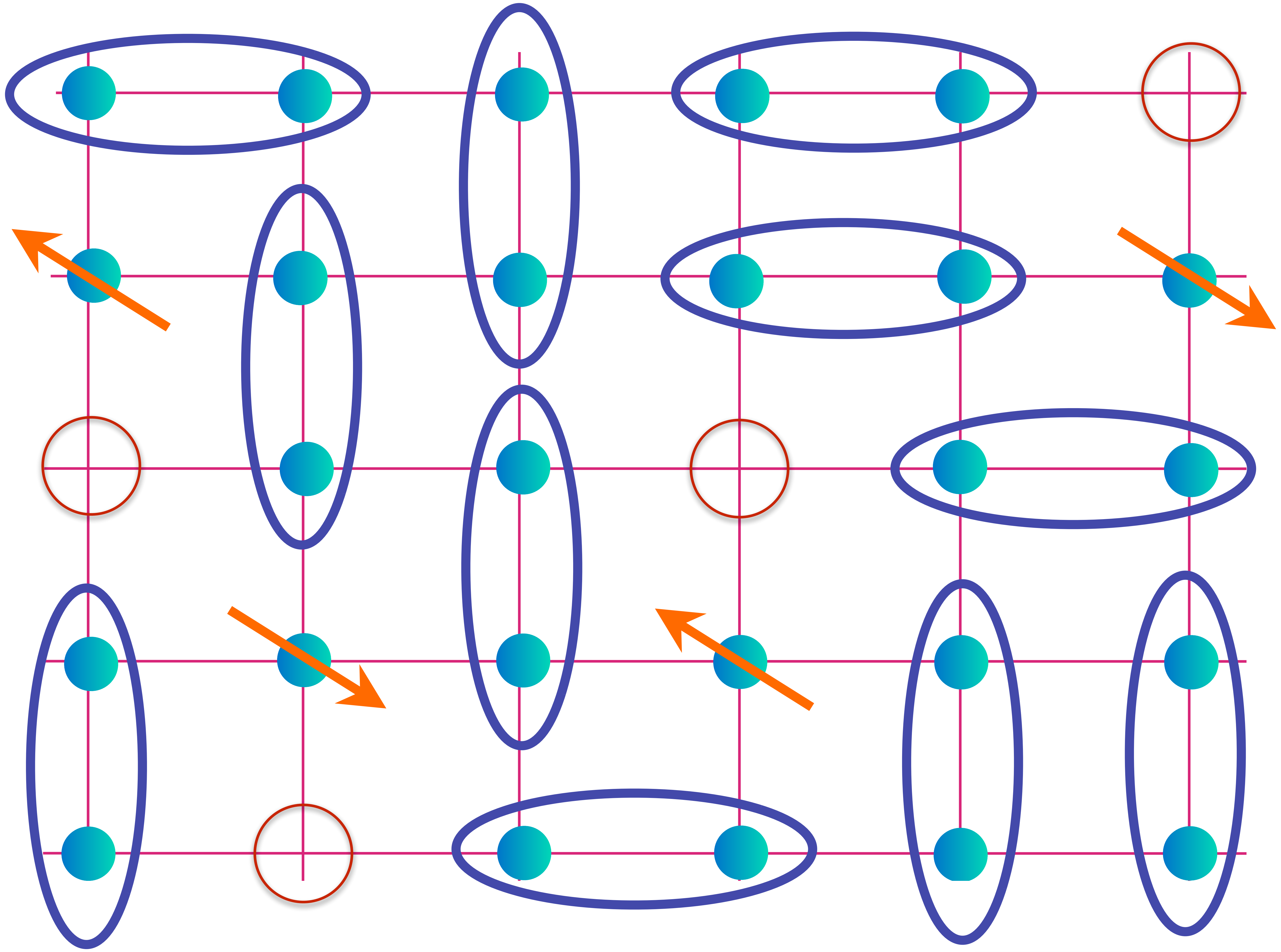
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

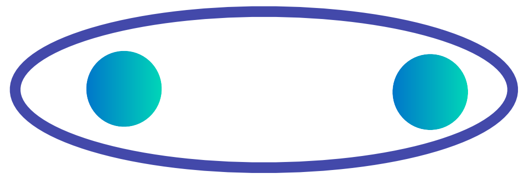
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

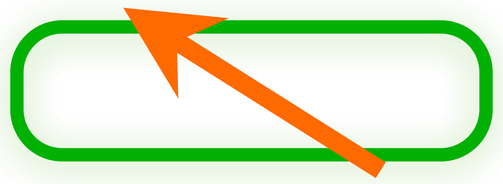
FL*

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

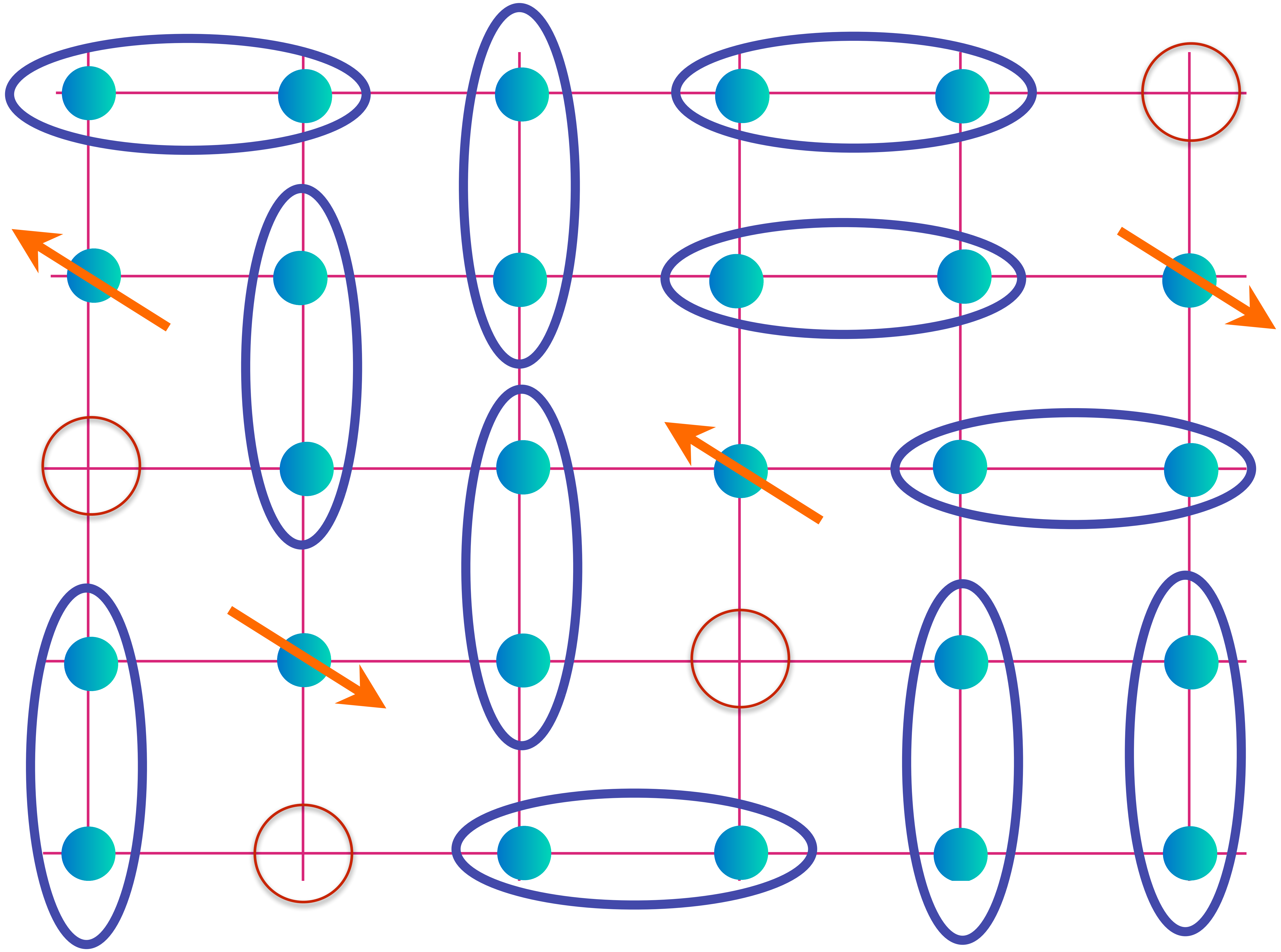
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

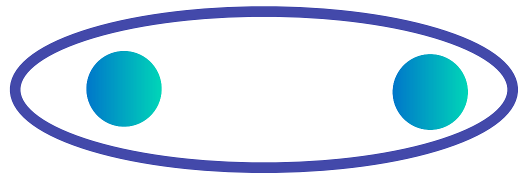
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

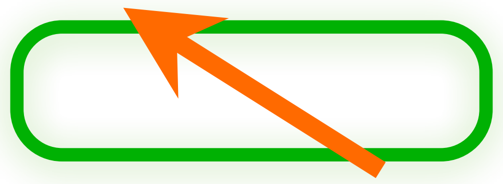
FL*

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

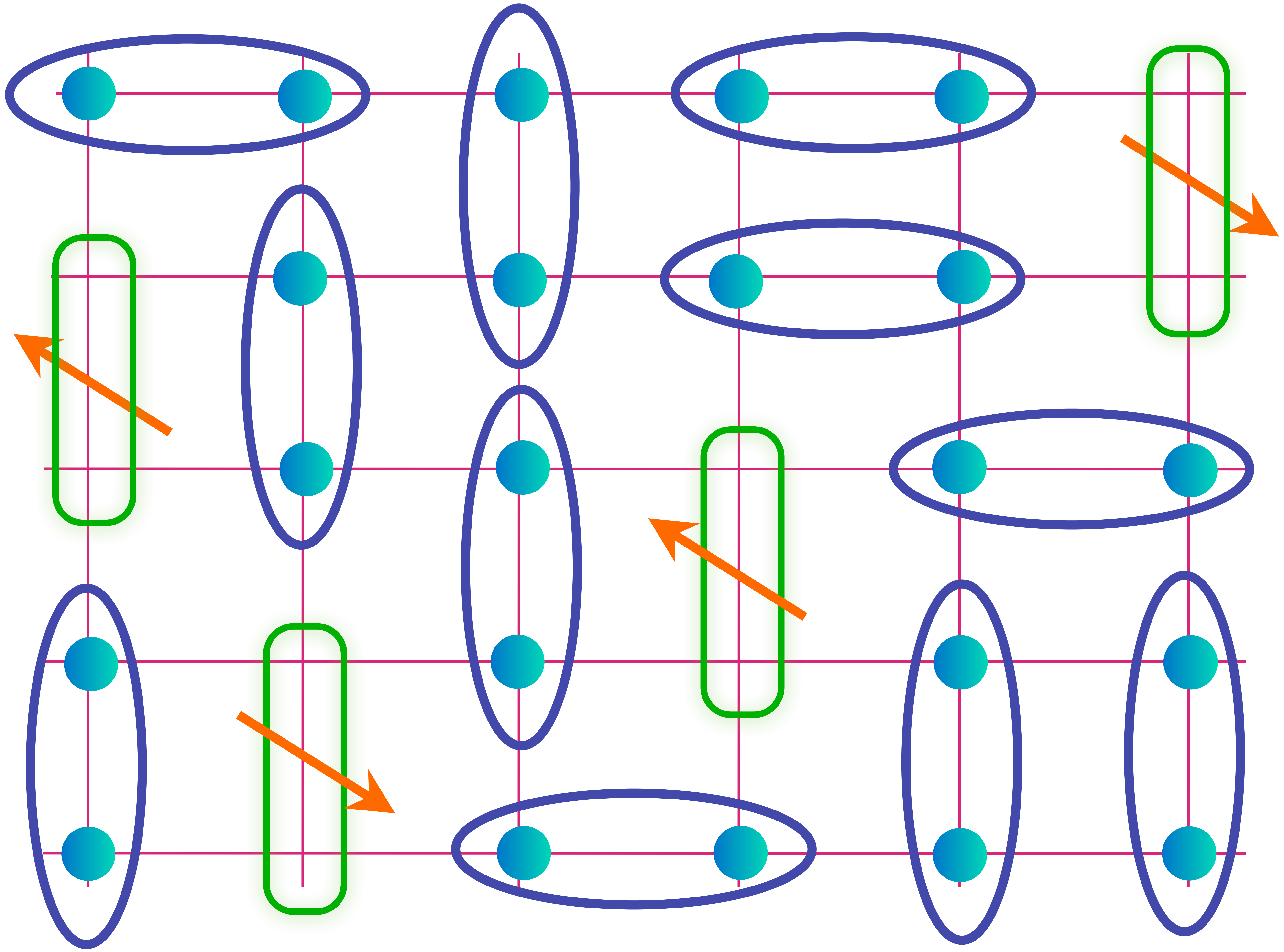
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

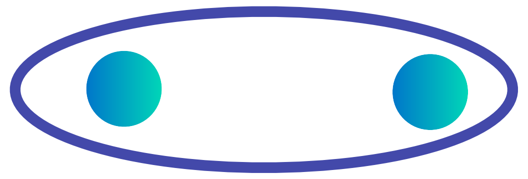
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

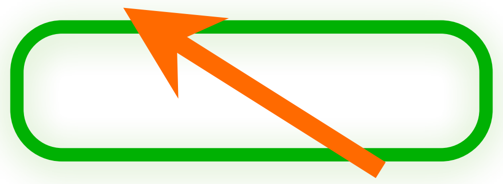
FL*

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)



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

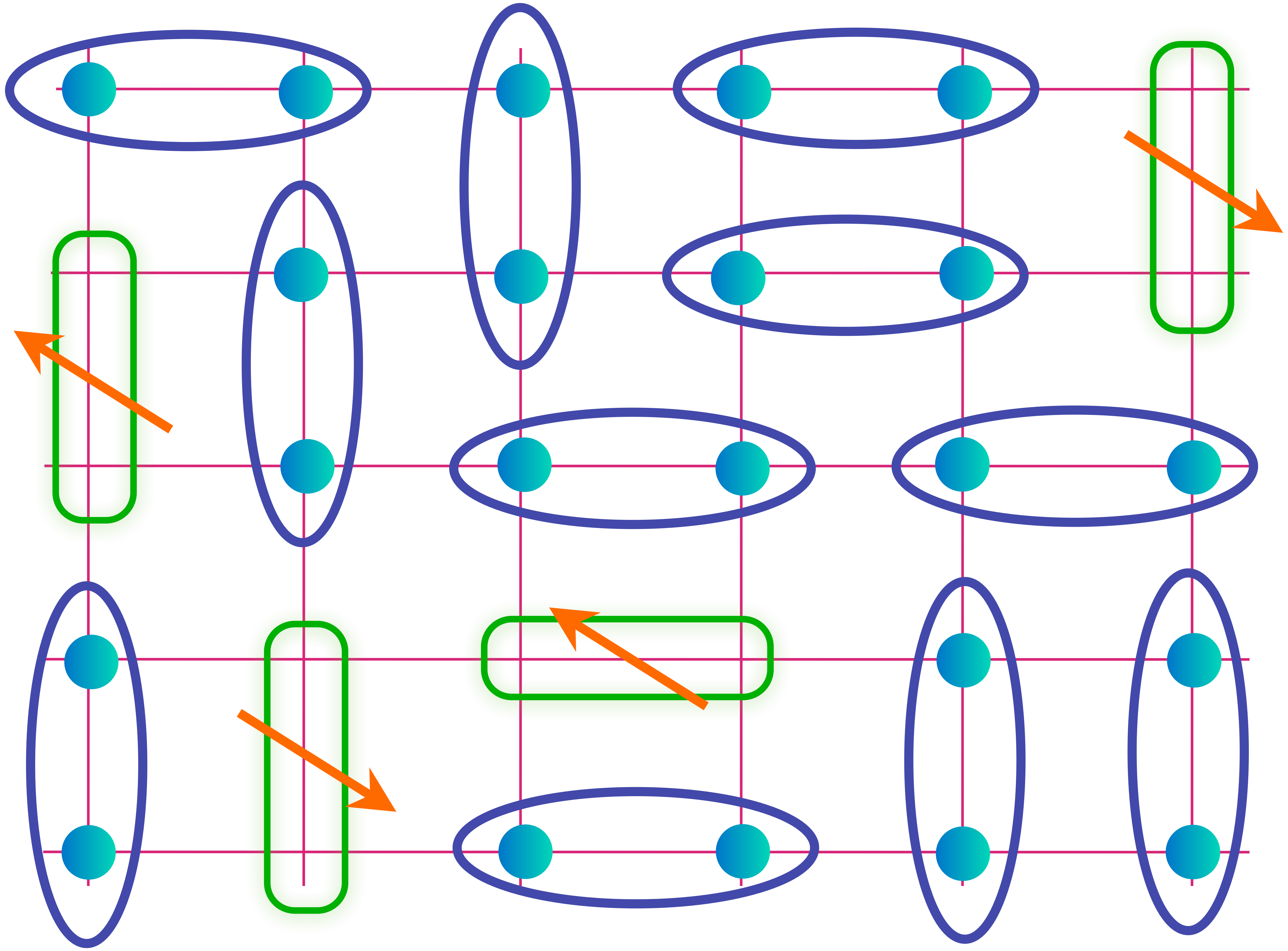
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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

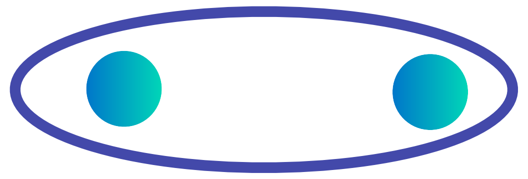
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

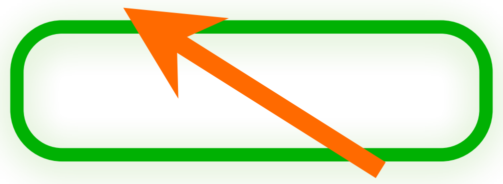
FL*

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)



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

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

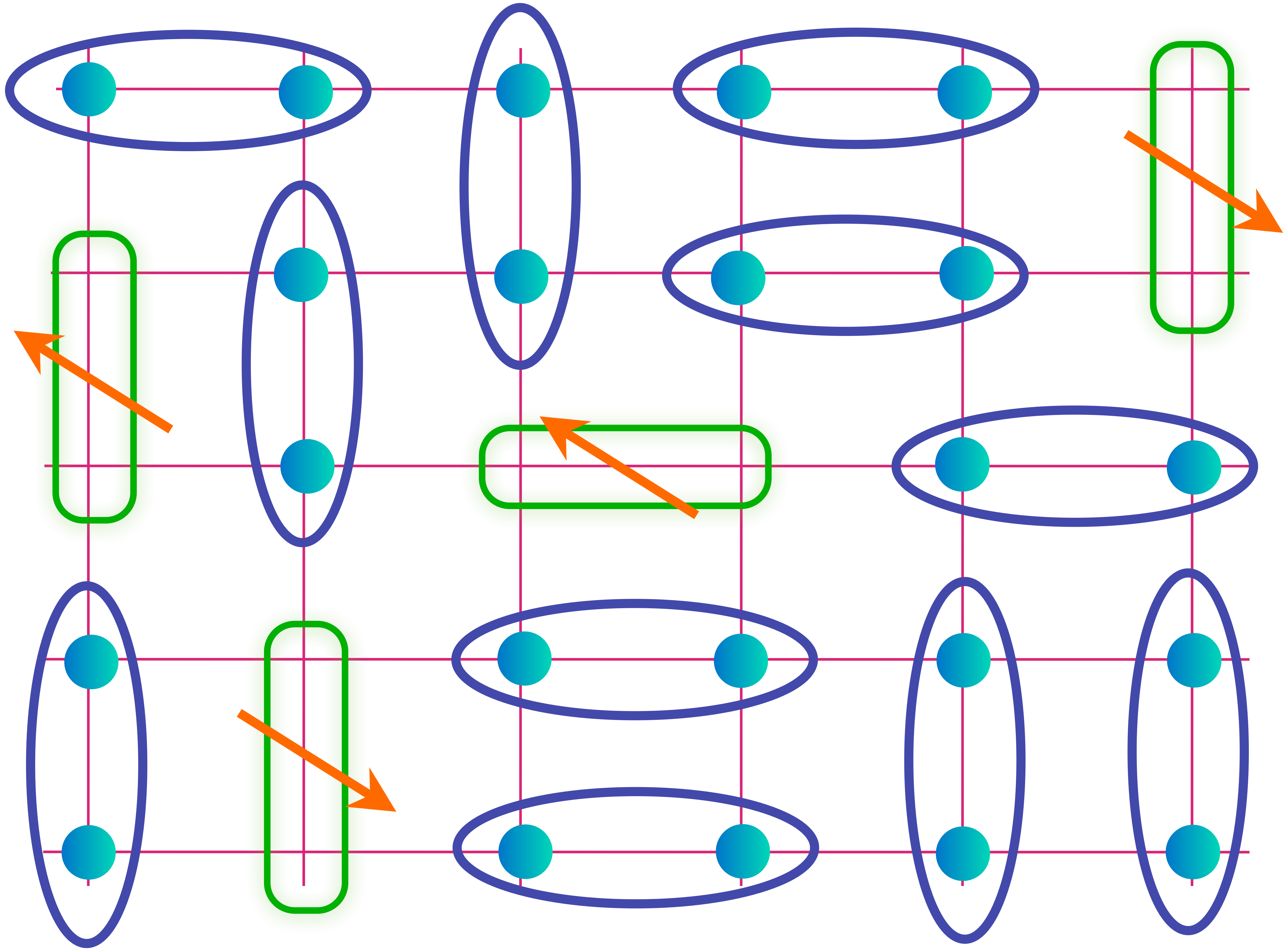
 $= \left(|\uparrow \circ\rangle + |\circ \uparrow\rangle\right)/\sqrt{2}$

M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

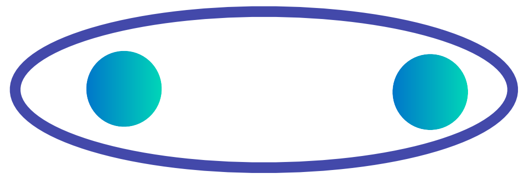
FL*

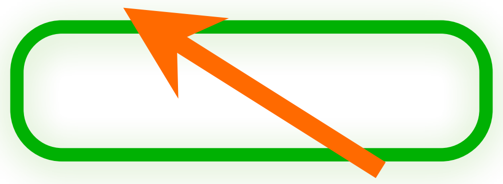
S. Sachdev PRB **49**, 6770 (1994); X.-G. Wen and P.A. Lee PRL **76**, 503 (1996)

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



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

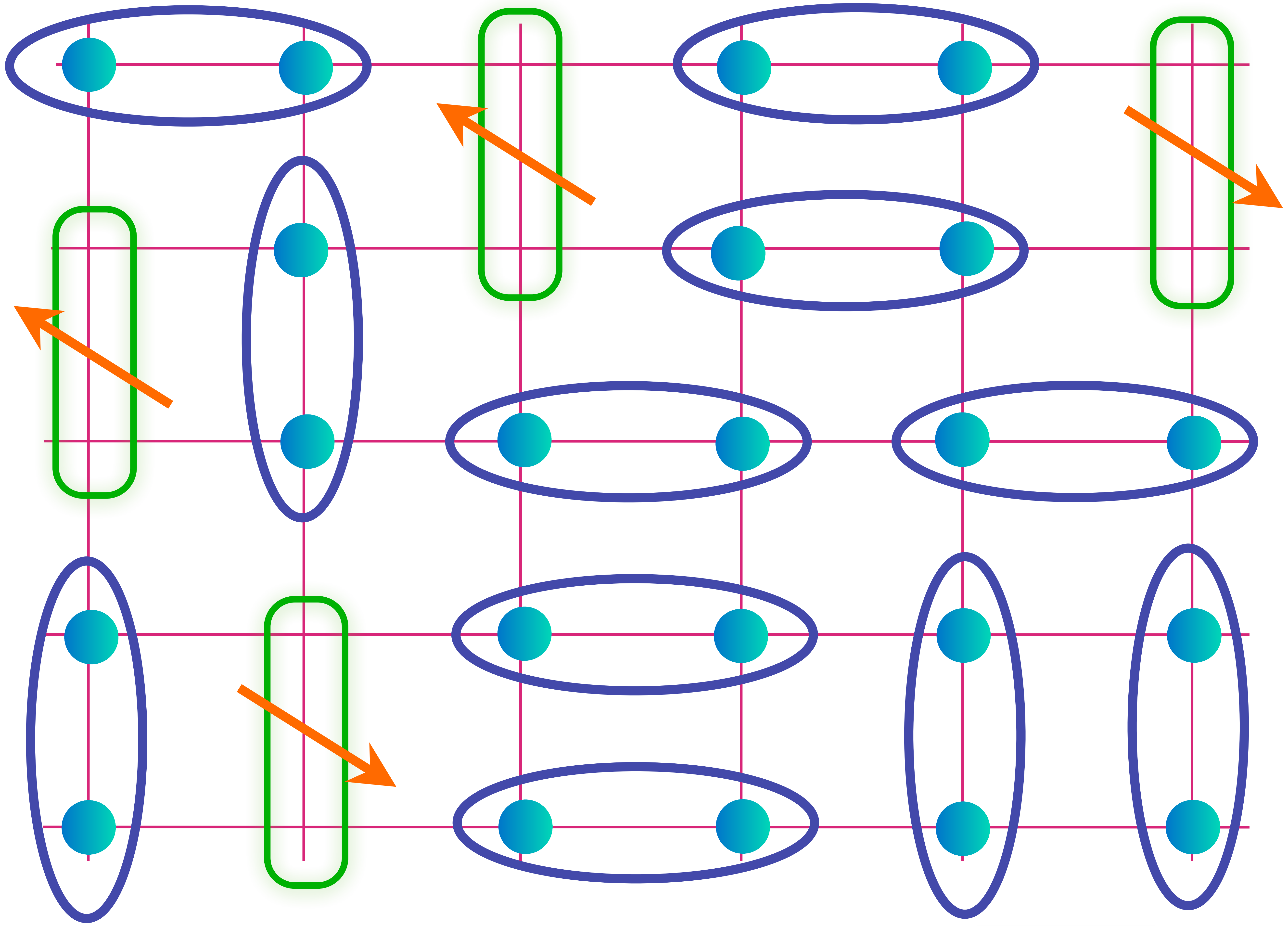
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

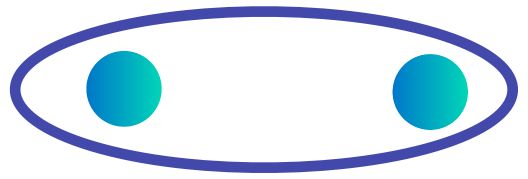
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

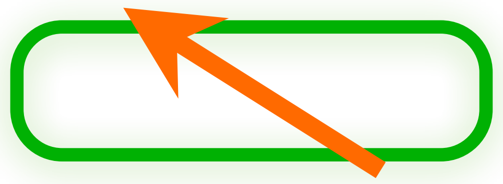
FL*

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)



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

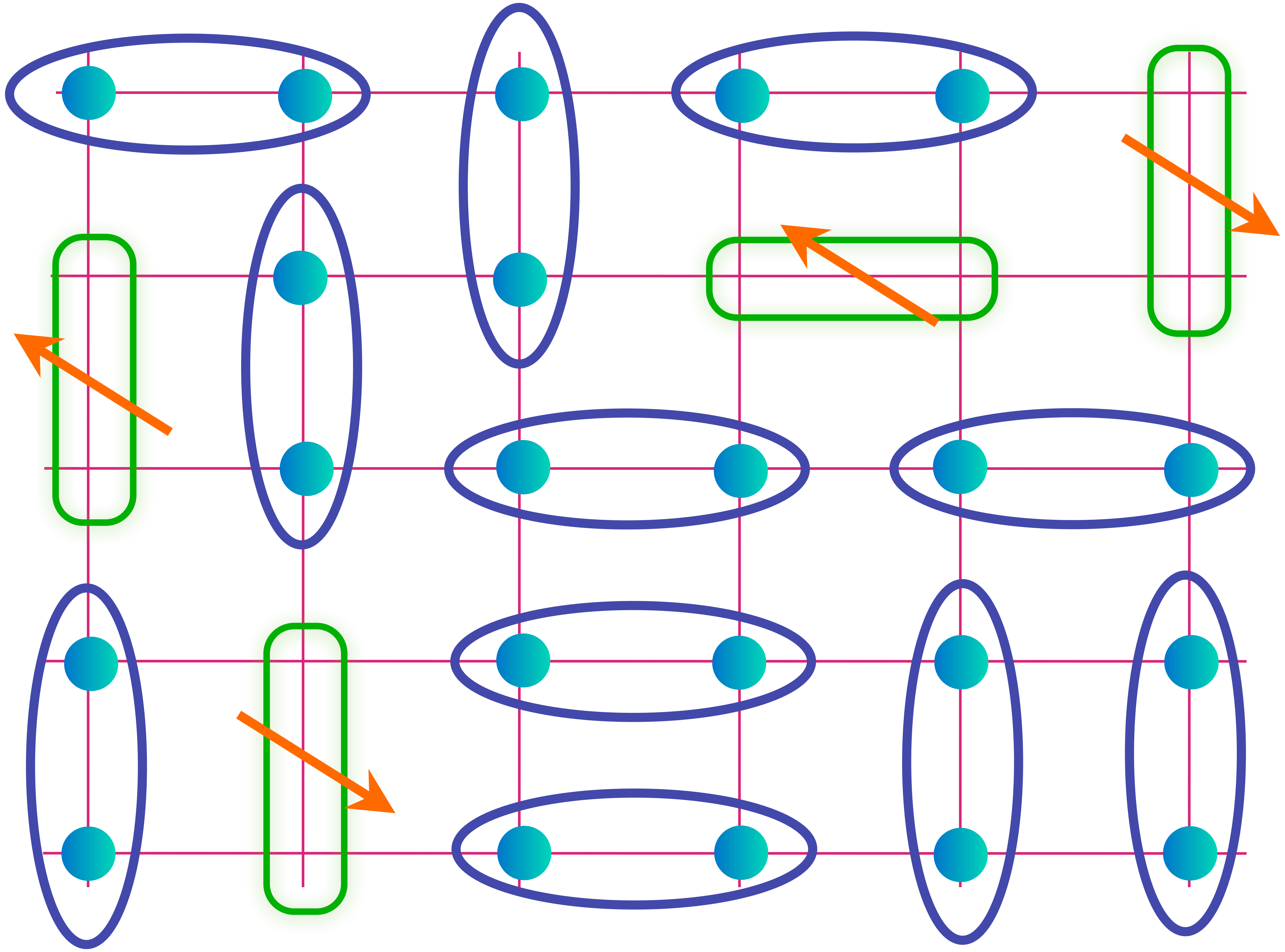
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

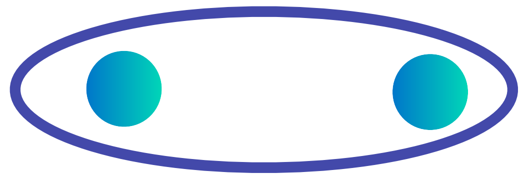
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

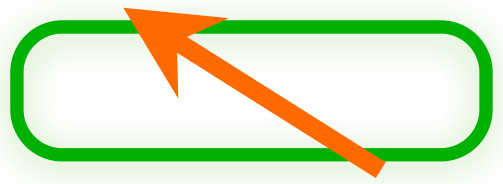
FL*

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)



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

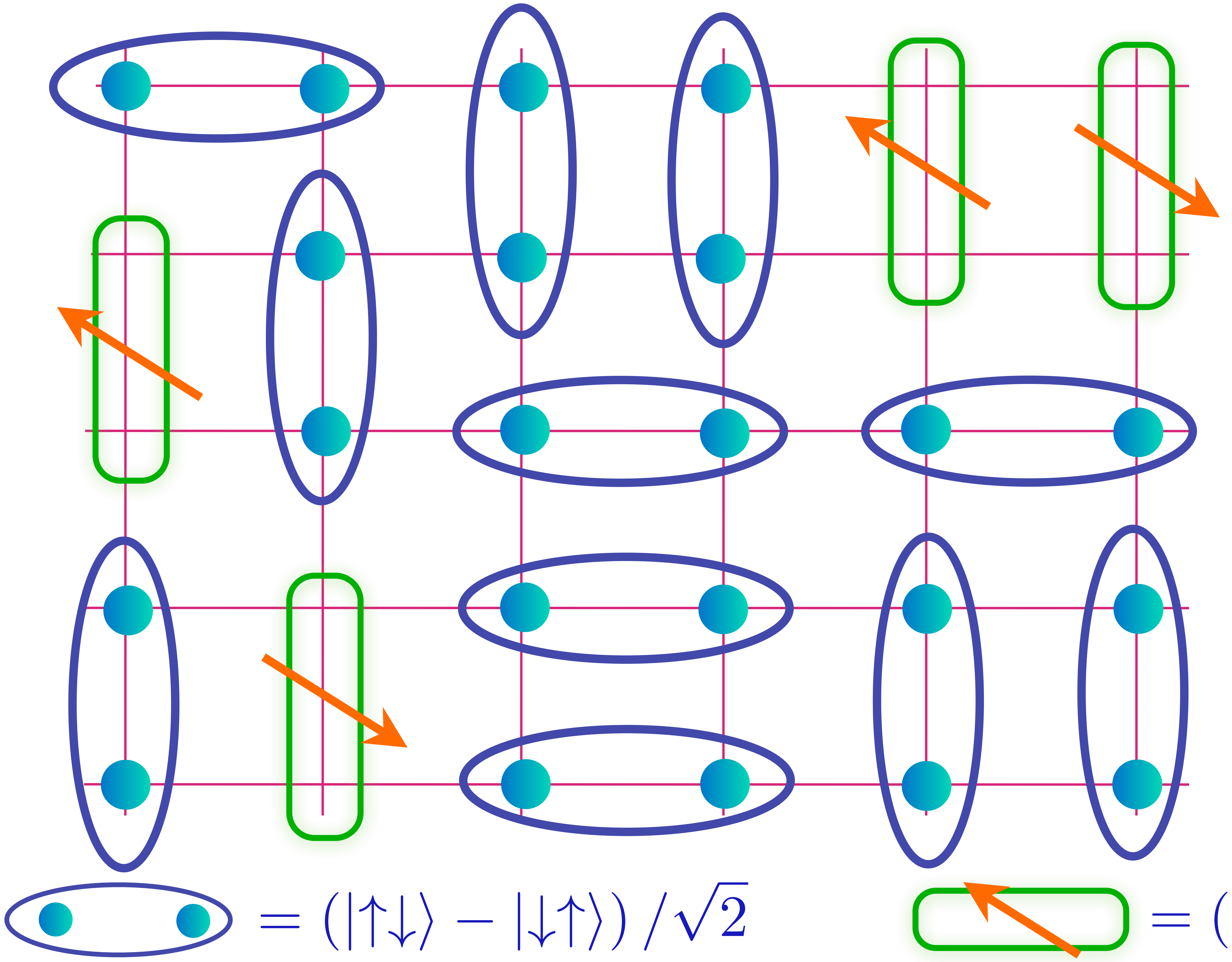
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

FL*

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)



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

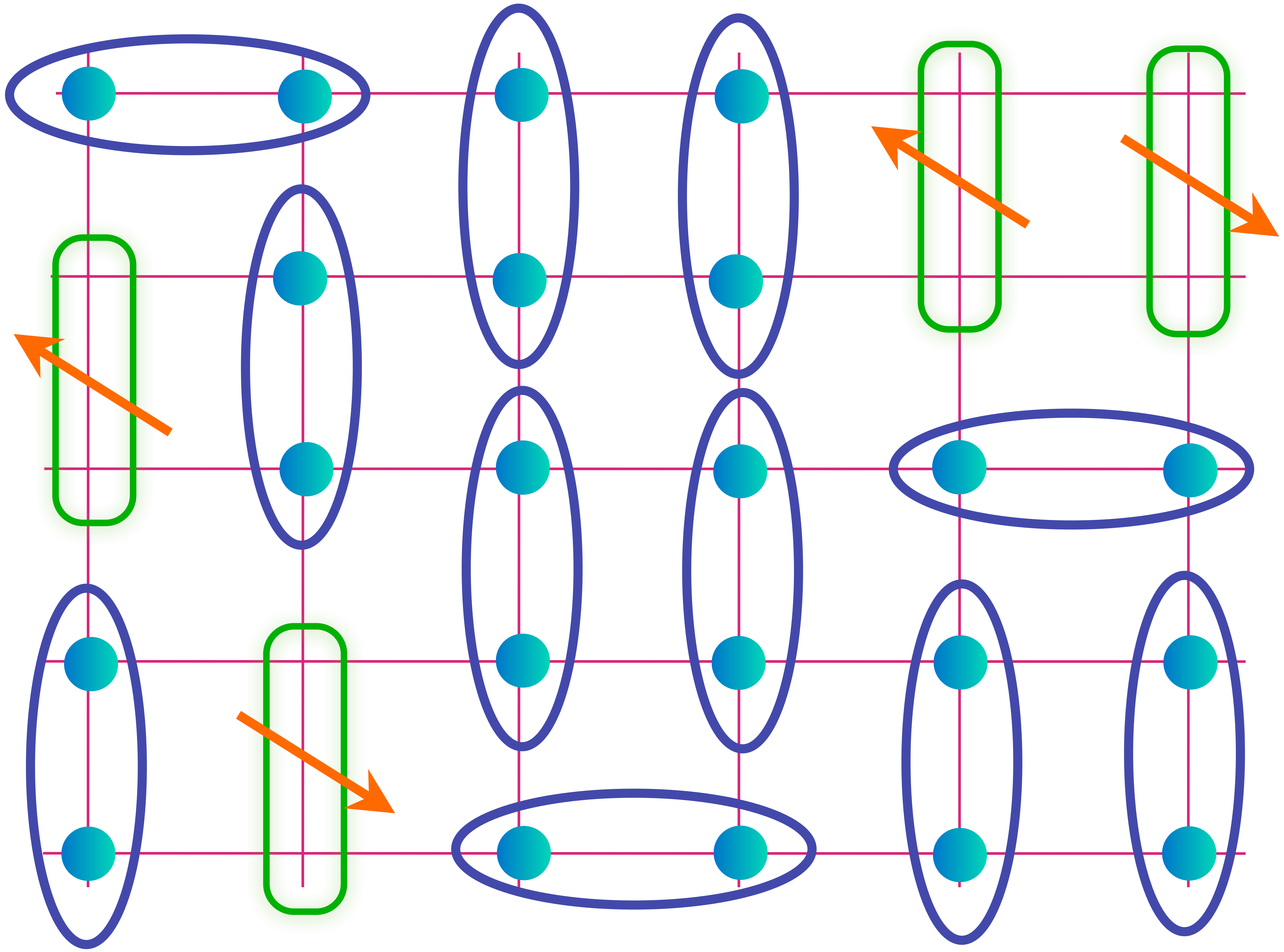
$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

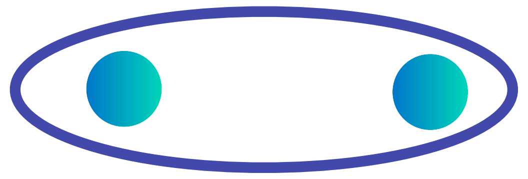
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

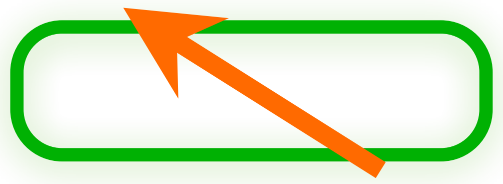
FL*

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)



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

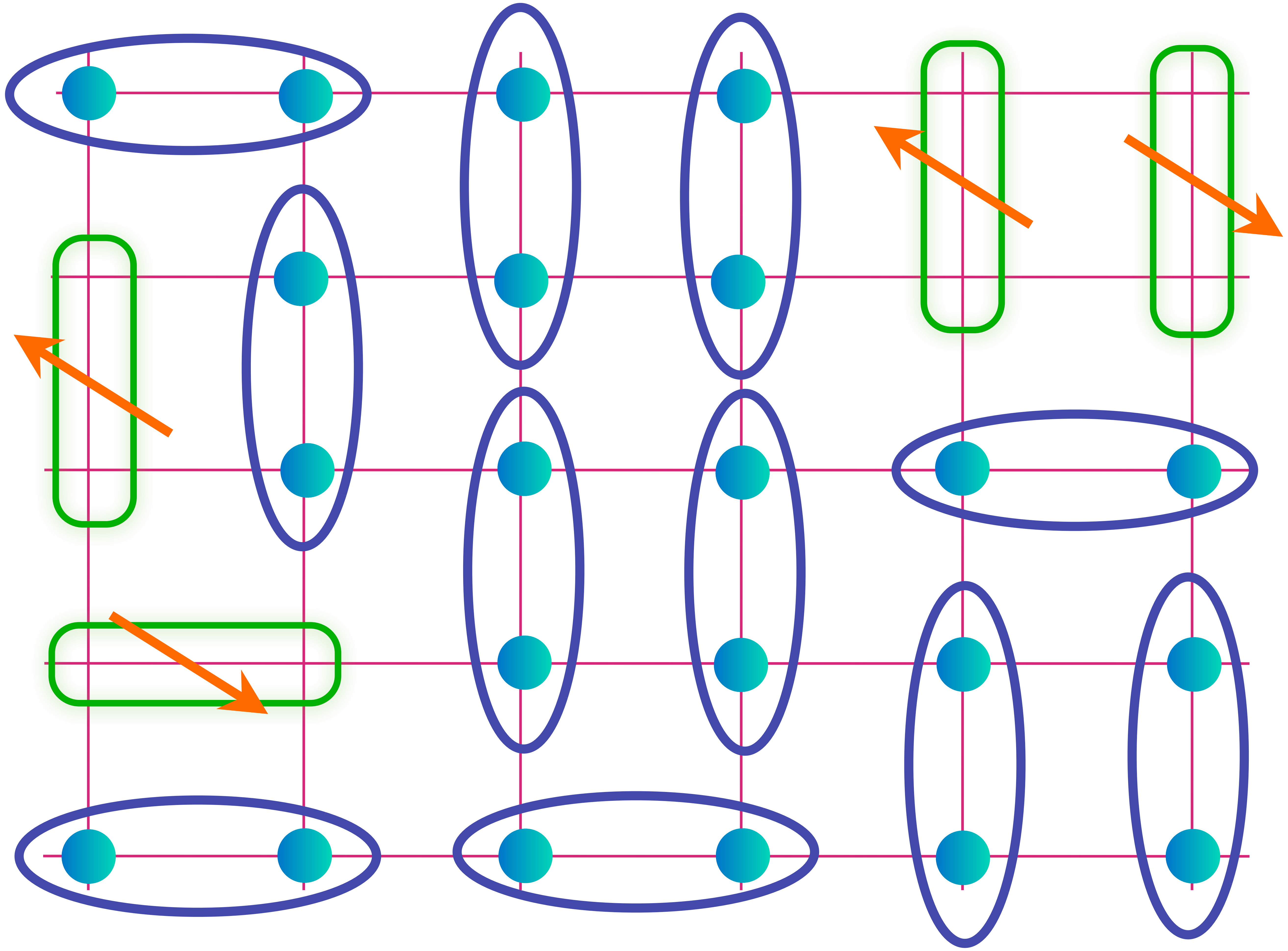
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

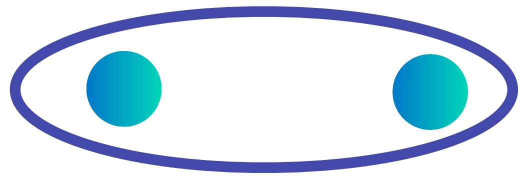
M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

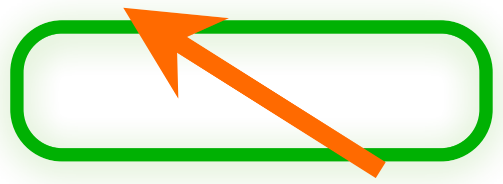
FL*

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)



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

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

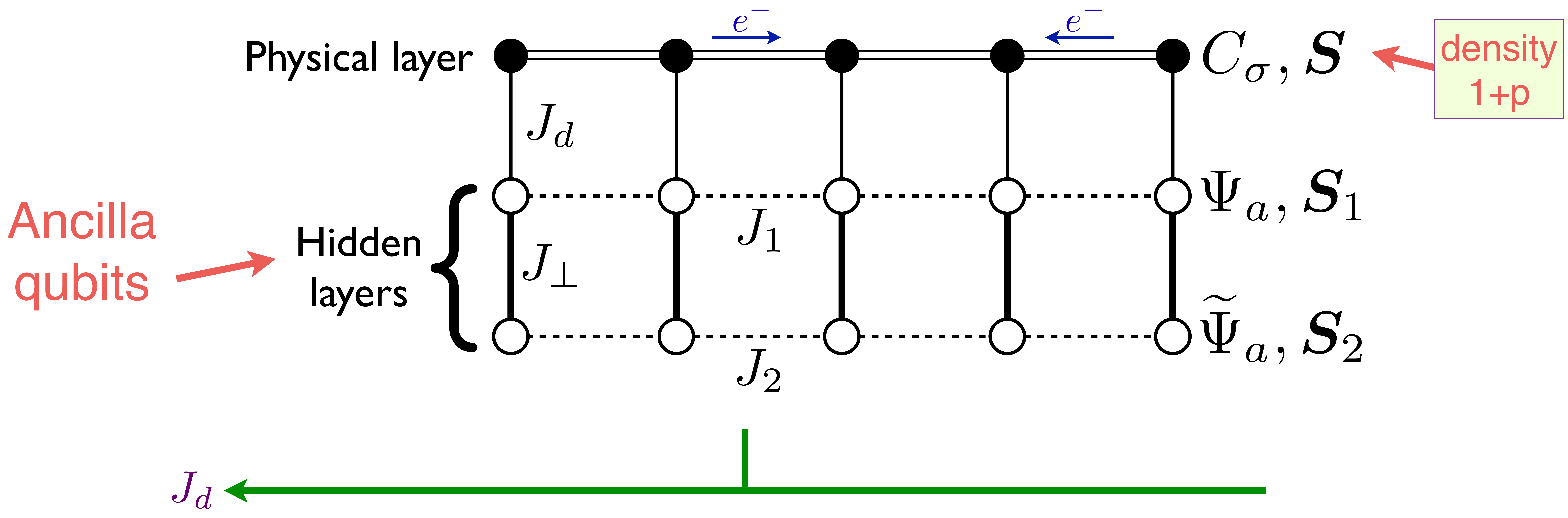
 $= (|\uparrow \circ\rangle + |\circ \uparrow\rangle) / \sqrt{2}$

M. Punk, A. Allais, and S. Sachdev, PNAS **112**, 9552 (2015)

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

- Can realize the FL* state as a doped spin liquid in which spinons and holons bind to form 'electrons', which then form a small Fermi surface (X.-G. Wen and P. A. Lee, PRL **76**, 503 (1996)); but there is no complete description of this process, except in the very strong binding limit of dimer 'electrons' (M. Punk, A. Allais, and S. Sachdev,PNAS **112**, 9552 (2015)). This approach does not yield a theory of the transition to the FL state.

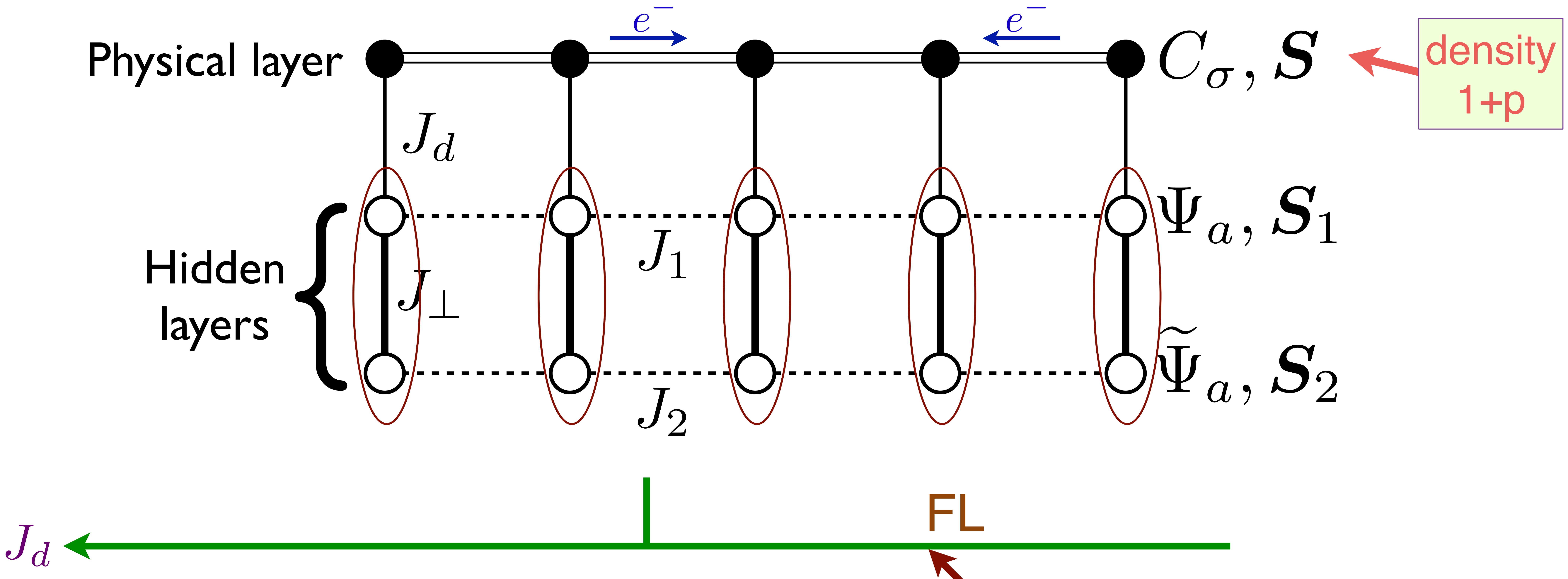
FL* and FL in a ***one-band*** model



Ya-Hui Zhang

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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



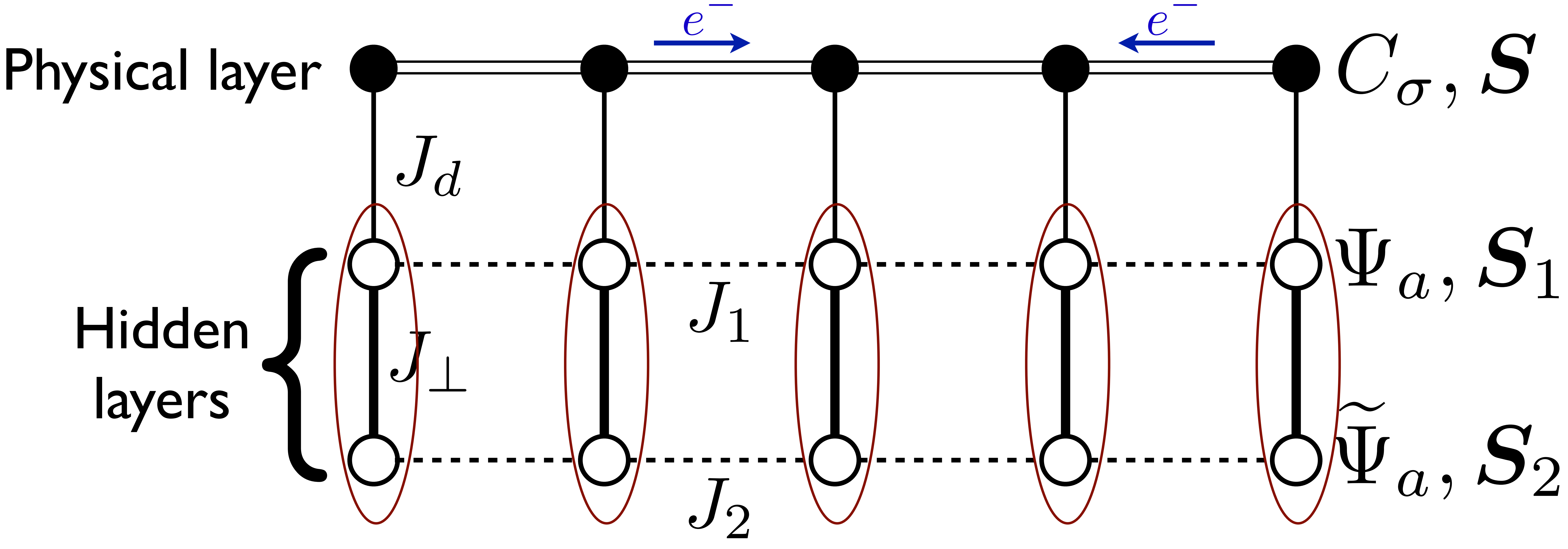
Large Fermi surface of size $1 + p$

$$|\Phi\rangle = \left| \text{Rung singlets of } \Psi, \widetilde{\Psi} \right\rangle \otimes \left| \text{Slater determinant of } C \right\rangle$$

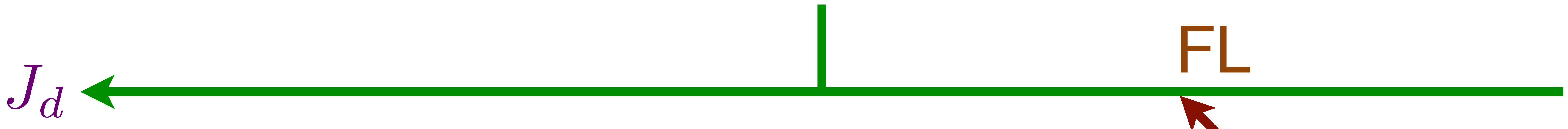
Ya-Hui Zhang

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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



density 1+p



Luttinger Theorem obeyed

Large Fermi surface of size $1+p$

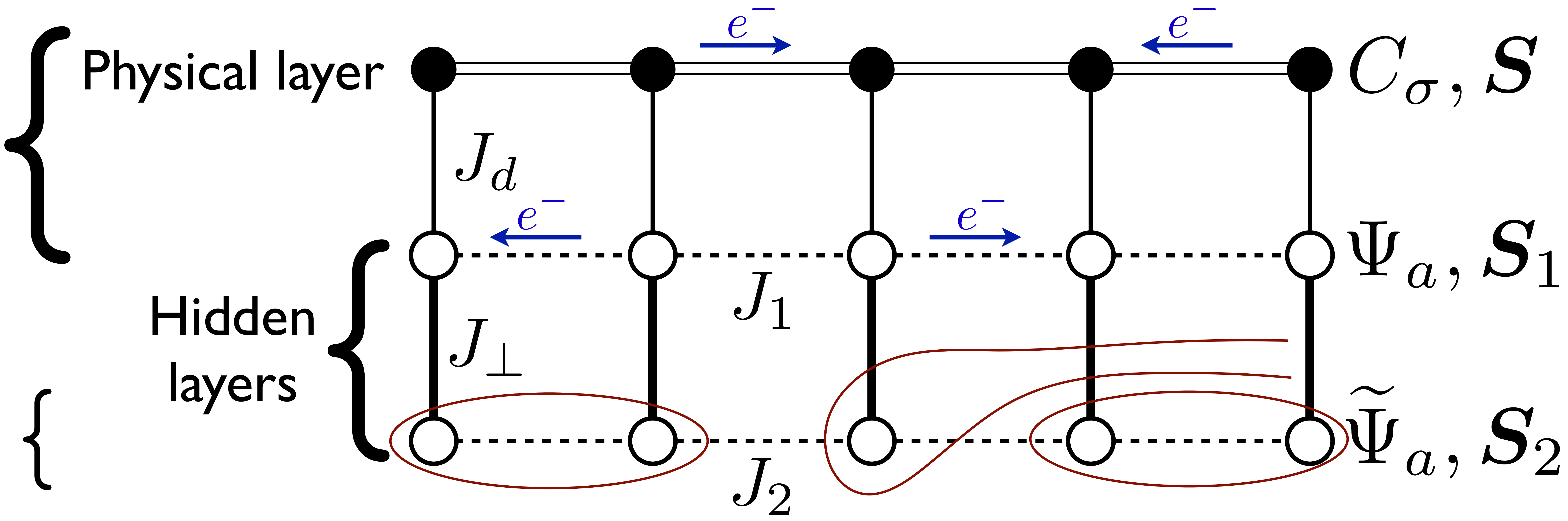
$$|\Phi\rangle = \left|\text{Rung singlets of } \Psi, \widetilde{\Psi}\right\rangle \otimes |\text{Slater determinant of } C\rangle$$

Ya-Hui Zhang

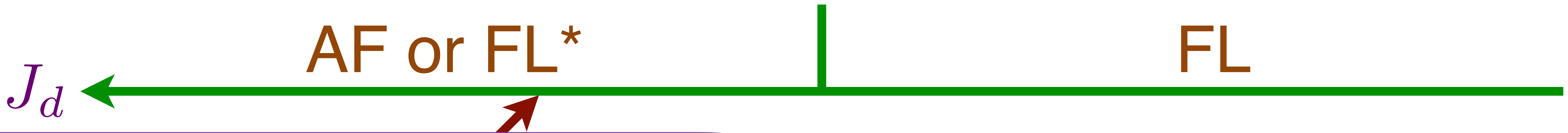
Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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

Metal.
Density
$2 + p \cong p$



density
1+p



Small Fermi surface of size p

$$|\Phi\rangle = \left[\text{Projection onto rung singlets of } \Psi, \widetilde{\Psi}\right] \bowtie \left|\text{Slater determinant of } (C, \Psi)\right\rangle \otimes \left|\text{Slater determinant of } \widetilde{\Psi}\right\rangle$$

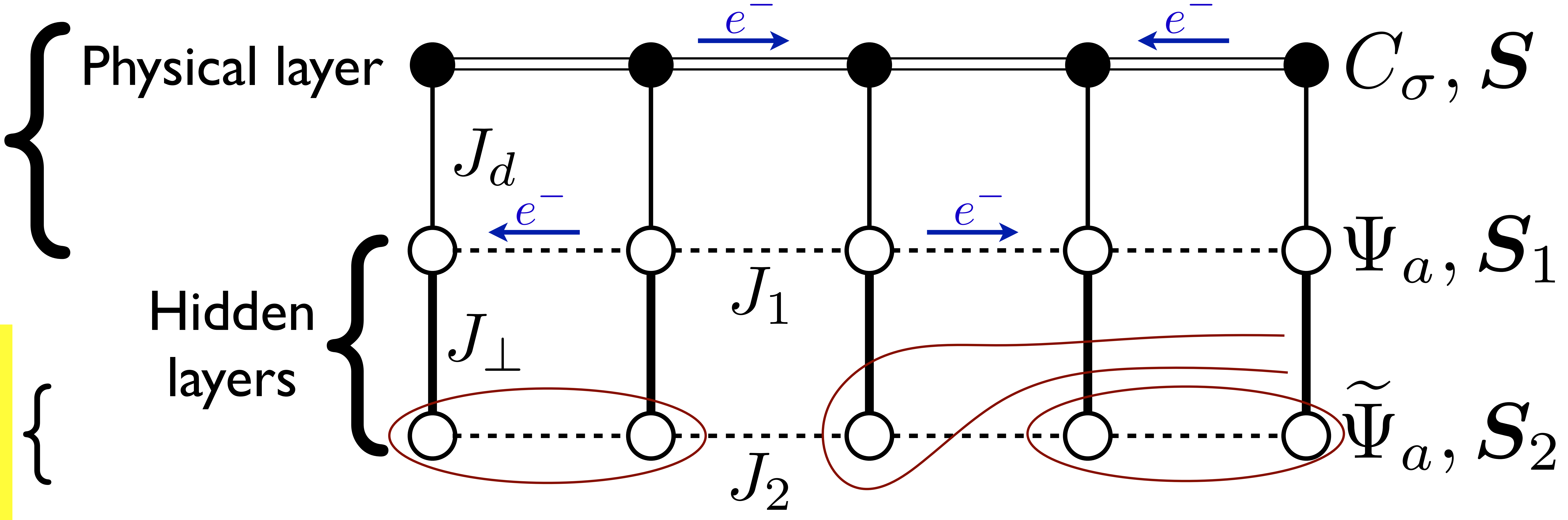
Ya-Hui Zhang

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

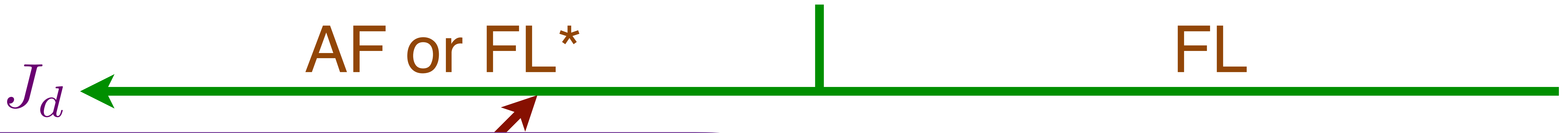
FL* and FL in a ***one-band*** model

Metal.
Density
$2 + p \cong p$

Mott insulator
Spin liquid
or AF order



density
1+p



Small Fermi surface of size p

$$|\Phi\rangle = \left[\text{Projection onto rung singlets of } \Psi, \widetilde{\Psi}\right] \bowtie \left|\text{Slater determinant of } (C, \Psi)\right\rangle \otimes \left|\text{Slater determinant of } \widetilde{\Psi}\right\rangle$$

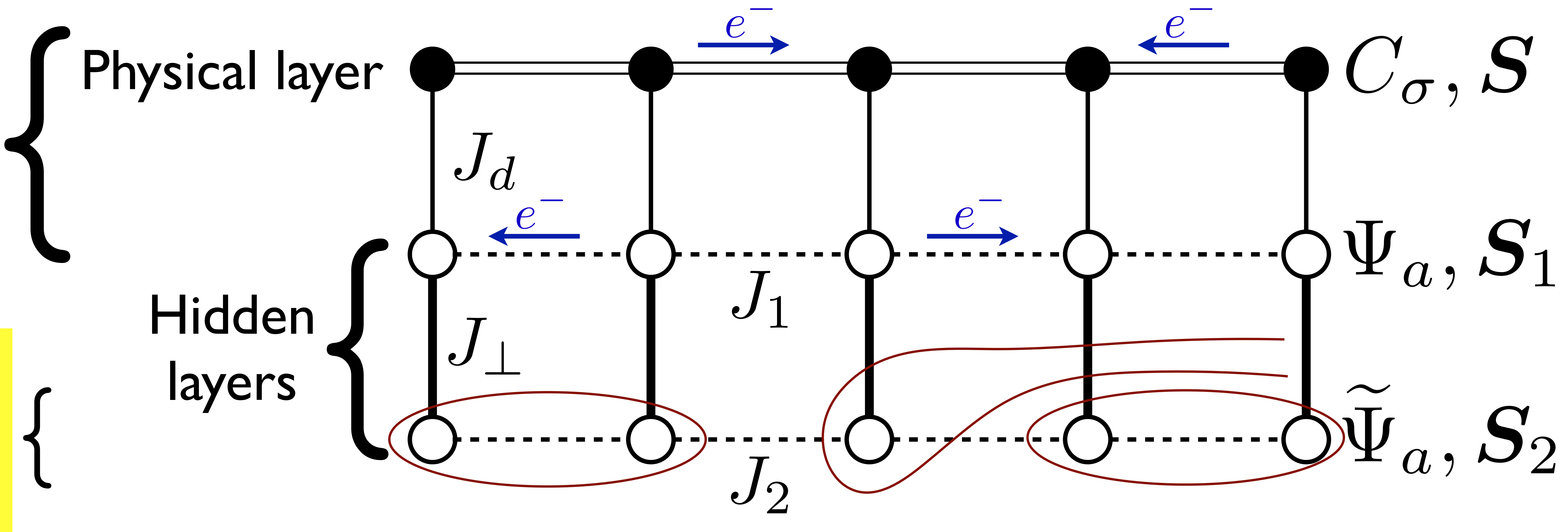
Ya-Hui Zhang

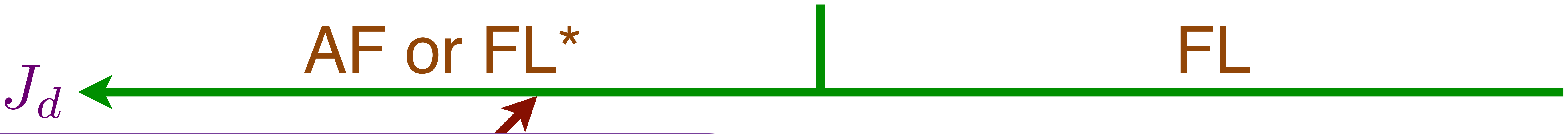
Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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

Metal.
Density
$2 + p \cong p$

Mott insulator
Spin liquid
or AF order





Small Fermi surface of size p

$$|\Phi\rangle = \left[\text{Projection onto rung singlets of } \Psi, \widetilde{\Psi}\right] \ltimes |\text{Slater determinant of } (C, \Psi)\rangle \otimes \left|\text{Slater determinant of } \widetilde{\Psi}\right\rangle$$

Luttinger Theorem violated;
OK, because of topological order of $\widetilde{\Psi}$

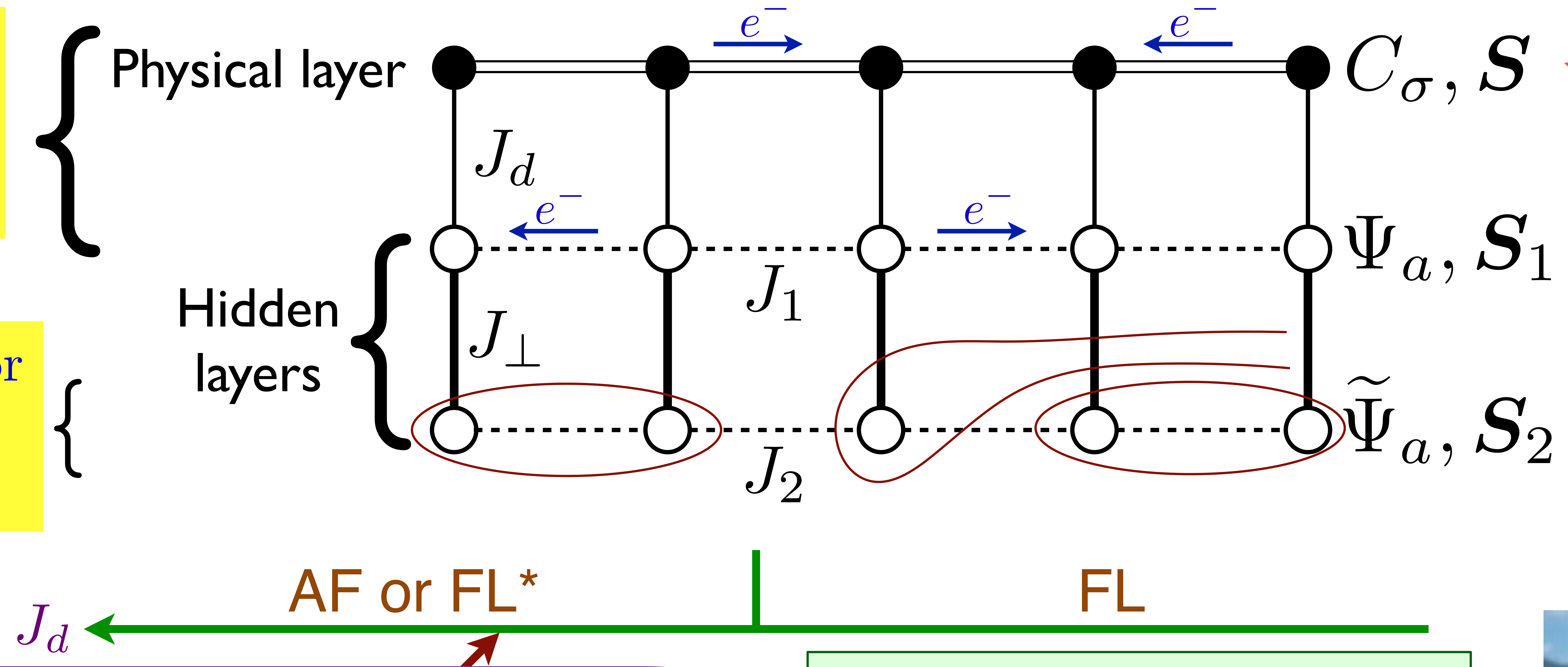
Ya-Hui Zhang

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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

Metal.
Density
$2 + p \cong p$

Mott insulator
Spin liquid
or AF order



density
1+p

Small Fermi surface of size p

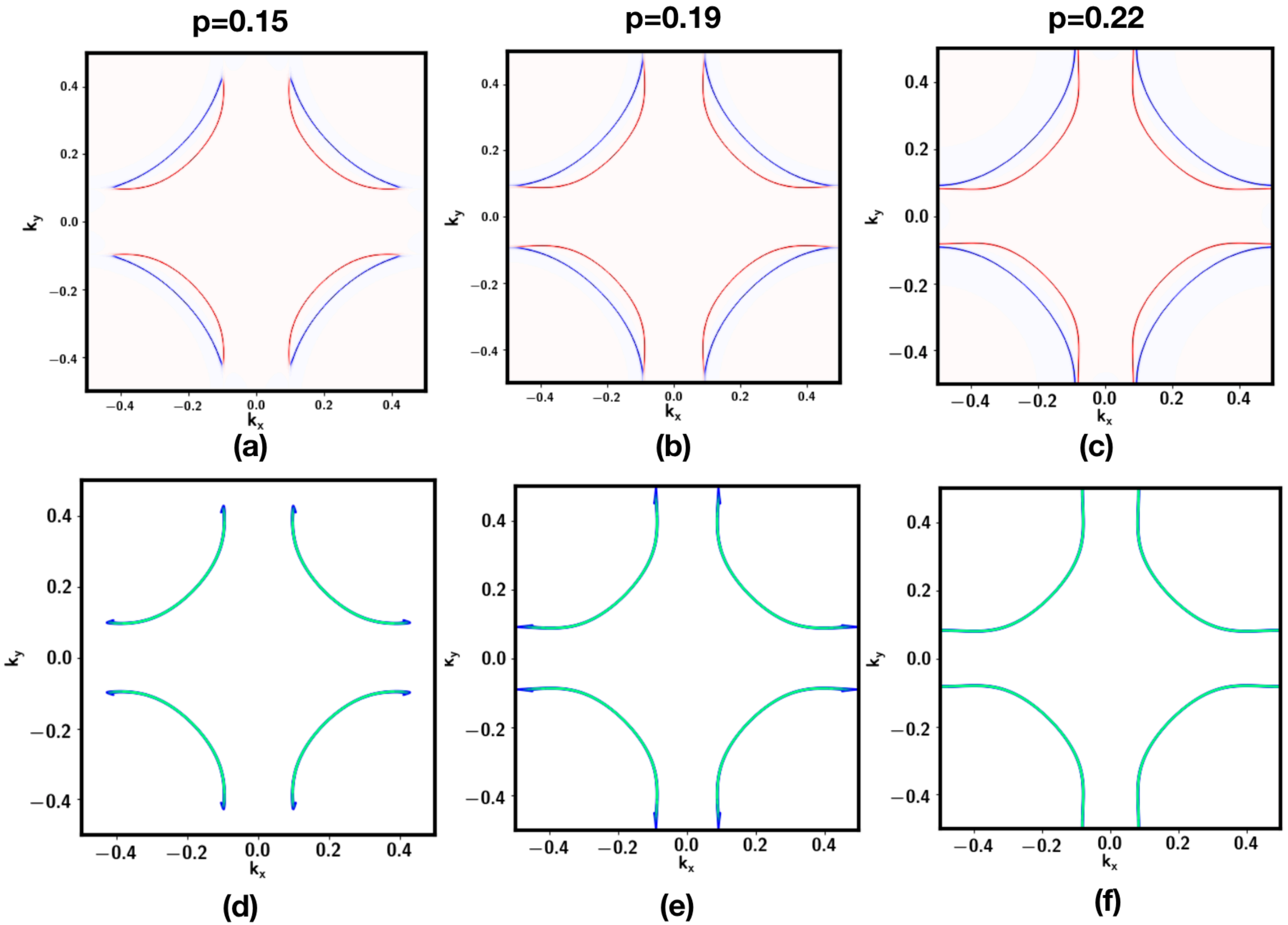
$$|\Phi\rangle = \left[\text{Projection onto rung singlets of } \Psi, \widetilde{\Psi}\right] \bowtie \left|\text{Slater determinant of } (C, \Psi)\right\rangle \otimes \left|\text{Slater determinant of } \widetilde{\Psi}\right\rangle$$

Similar to a selective Mott transition in hidden layer 1: Ψ fermions are insulating in FL phase, and metallic in FL* phase.

Ya-Hui Zhang

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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



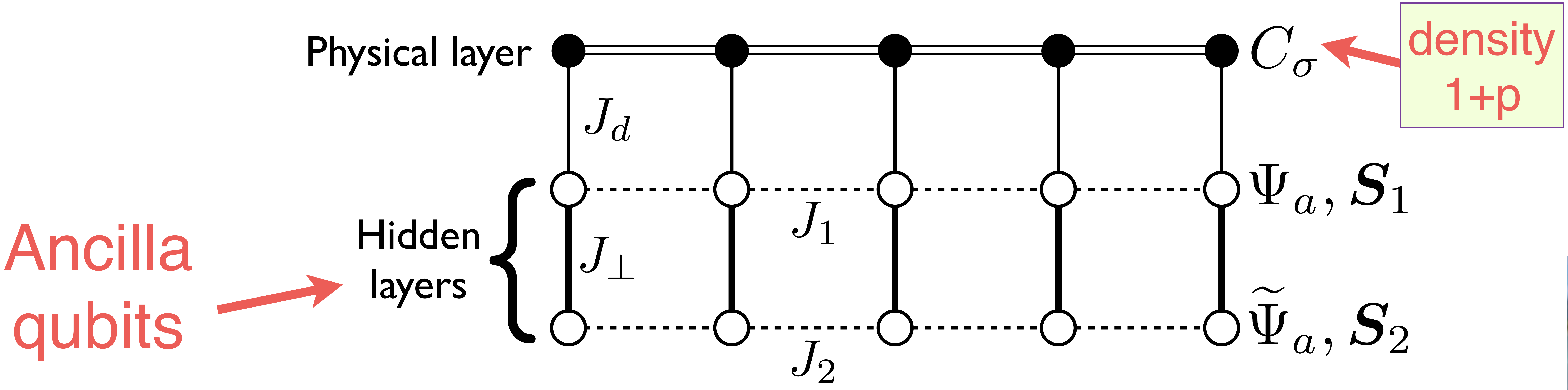
Zero frequency spectral density of electrons (red) and ghosts (blue)

"Fermi arc" spectral functions in the FL* phase

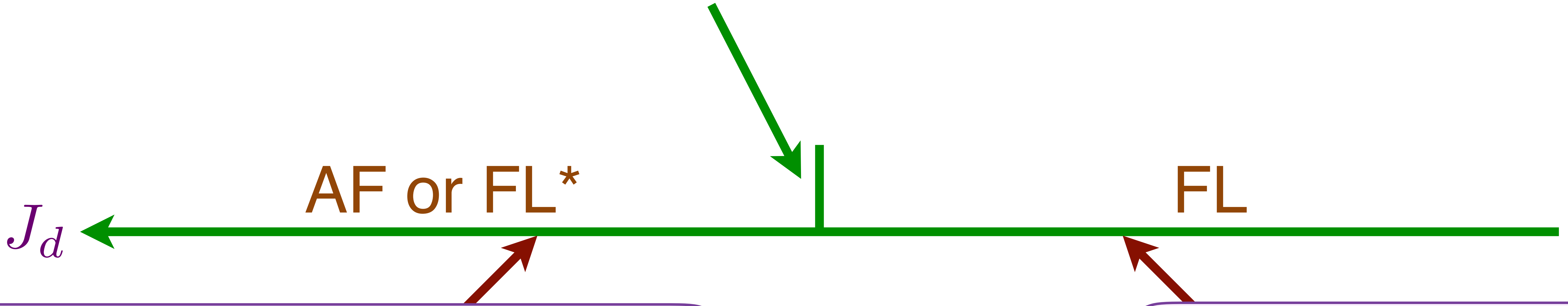
Ya-Hui Zhang

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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



Yahui Zhang



Small Fermi surface of size p

$$|\Phi\rangle = \left[\text{Projection onto rung singlets of } \Psi, \widetilde{\Psi}\right] \bowtie |\text{Slater determinant of } (C, \Psi)\rangle \otimes \left|\text{Slater determinant of } \widetilde{\Psi}\right\rangle$$

Large Fermi surface of size $1+p$

$$|\Phi\rangle = \left|\text{Rung singlets of } \Psi, \widetilde{\Psi}\right\rangle \otimes |\text{Slater determinant of } C\rangle$$

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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

Write fermion operators as 2×2 matrices

$$\boldsymbol{\Psi} = \begin{pmatrix} \Psi_\uparrow & -\Psi_\downarrow^\dagger \\ \Psi_\downarrow & \Psi_\uparrow^\dagger \end{pmatrix} \quad , \quad \widetilde{\boldsymbol{\Psi}} = \begin{pmatrix} \widetilde{\Psi}_\uparrow & -\widetilde{\Psi}_\downarrow^\dagger \\ \widetilde{\Psi}_\downarrow & \widetilde{\Psi}_\uparrow^\dagger \end{pmatrix}$$

Yahui Zhang

Single occupancy constraints of $\boldsymbol{\Psi}$, $\widetilde{\boldsymbol{\Psi}}$ leads to $\mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2$ gauge symmetry:

$$\mathrm{SU}(2)_1 : \quad \boldsymbol{\Psi} \rightarrow \boldsymbol{\Psi} U_1 \quad , \quad \widetilde{\boldsymbol{\Psi}} \rightarrow \widetilde{\boldsymbol{\Psi}}$$
$$\mathrm{SU}(2)_2 : \quad \boldsymbol{\Psi} \rightarrow \boldsymbol{\Psi} \quad , \quad \widetilde{\boldsymbol{\Psi}} \rightarrow \widetilde{\boldsymbol{\Psi}} U_2$$

P.A. Lee, N. Nagaosa, and X.-G. Wen, RMP **78**, 17 (2006)

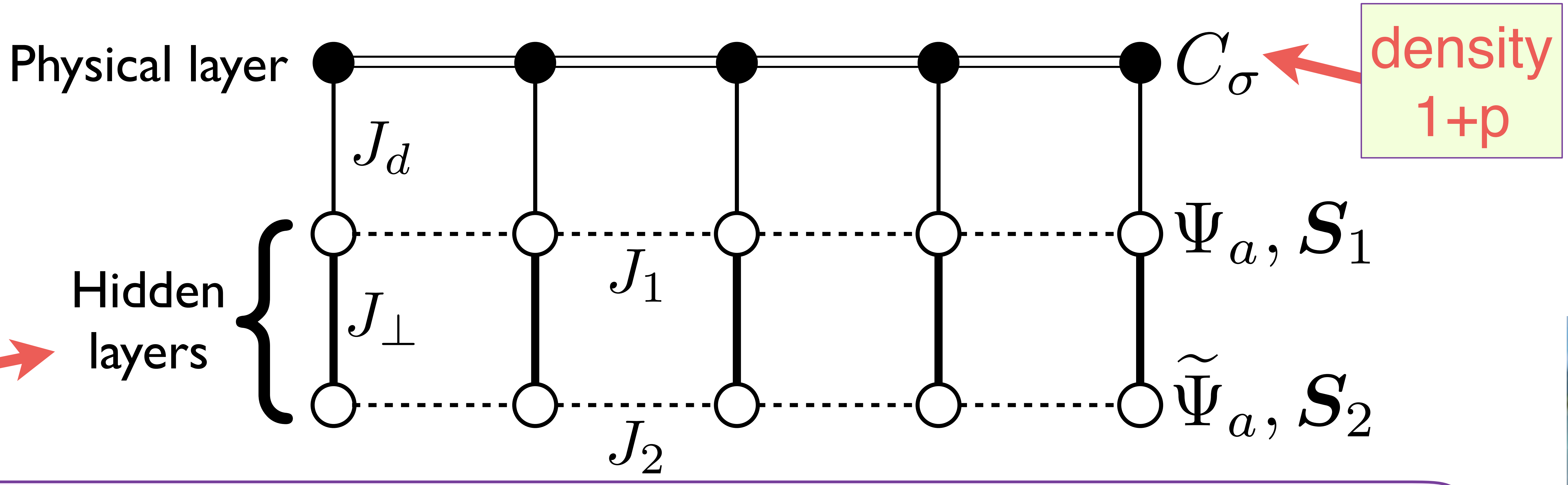
Local singlet formation ('antiferromagnetism') $\boldsymbol{S}_1 + \boldsymbol{S}_2 \approx 0$ leads to $\mathrm{SU}(2)_S$ gauge symmetry:

$$\mathrm{SU}(2)_S : \quad \boldsymbol{\Psi} \rightarrow U_S \boldsymbol{\Psi} \quad , \quad \widetilde{\boldsymbol{\Psi}} \rightarrow U_S \widetilde{\boldsymbol{\Psi}}$$

S. Sachdev, M.A. Metlitski, Yang Qi, and Cenke Xu, PRB **80**, 155129 (2009)
S. Sachdev, H. D. Scammell, M. S. Scheurer, and G. Tarnopolsky, PRB **99**, 054516 (2019)

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

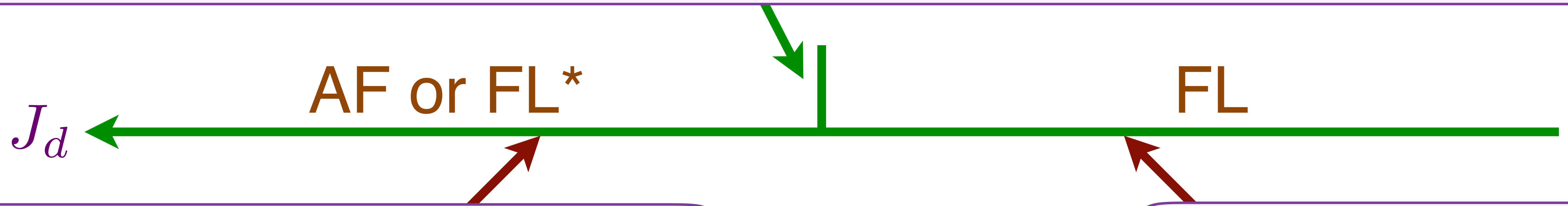
Metal-metal transitions in a ***one-band*** model



Ancilla qubits

$(\mathrm{U}(1)_S \times \mathrm{U}(1)_1)/Z_2$ or $(\mathrm{SU}(2)_S \times \mathrm{U}(1)_1)/Z_2$ gauge theory of a Ψ ghost Fermi surface and a 'hybridization-Higgs' boson $\sim C_\sigma^\dagger \Psi_a$ which condenses on the 'Small Fermi surface' side.

Yahui Zhang



Small Fermi surface of size p

$$|\Phi\rangle = \left[\text{Projection onto rung singlets of } \Psi, \widetilde{\Psi}\right] \bowtie |\text{Slater determinant of } (C, \Psi)\rangle \otimes \left|\text{Slater determinant of } \widetilde{\Psi}\right\rangle$$

Large Fermi surface of size $1+p$

$$|\Phi\rangle = \left|\text{Rung singlets of } \Psi, \widetilde{\Psi}\right\rangle \otimes |\text{Slater determinant of } C\rangle$$

See also Liujun Zou, D. Chowdhury, PRR **2**, 023344 (2020)

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

Ancilla qubit theory of FL* and FL phases in a one-band model

- FL* as the pseudogap metal with carrier density p. Variants of the theory can have broken symmetries (*e.g.* antiferromagnetism) without fractionalization in the pseudogap metal.

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

Ancilla qubit theory of FL* and FL phases in a one-band model

- FL* as the pseudogap metal with carrier density p. Variants of the theory can have broken symmetries (*e.g.* antiferromagnetism) without fractionalization in the pseudogap metal.

- Ghost fermions, carrying neither spin nor charge, emerge as additional low energy excitations near the critical point to the FL phase. While the ancilla qubits are gauged away as 'fake' in the UV theory, the ghost fermions are physical excitations in the IR theory, which can be detected by thermal probes.

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

Ancilla qubit theory of FL* and FL phases in a one-band model

- FL* as the pseudogap metal with carrier density p. Variants of the theory can have broken symmetries (*e.g.* antiferromagnetism) without fractionalization in the pseudogap metal.

- Ghost fermions, carrying neither spin nor charge, emerge as additional low energy excitations near the critical point to the FL phase. While the ancilla qubits are gauged away as 'fake' in the UV theory, the ghost fermions are physical excitations in the IR theory, which can be detected by thermal probes.

- The ghost fermions are coupled to 2 gauge fields: the first arising from the no double occupancy constraint, and the second from transforming to a rotating reference frame in spin space. These gauge fields lead respectively to repulsive and attractive interactions between the ghost fermions.

See also Liujun Zou, D. Chowdhury, PRR **2**, 023344 (2020)

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

Ancilla qubits for the cuprates

- By introducing a double layer of ancilla qubits, we are able to describe a FL* phase in a single band model: some of the electrons localize into an insulator of spins, while the others form a Luttinger-volume-violating Fermi surface.

Ancilla qubits for the cuprates

- By introducing a double layer of ancilla qubits, we are able to describe a FL* phase in a single band model: some of the electrons localize into an insulator of spins, while the others form a Luttinger-volume-violating Fermi surface.

- A metal-metal quantum phase transition with a change in carrier density from p in a FL* phase, to $1 + p$ in a FL phase.

Ancilla qubits for the cuprates

- By introducing a double layer of ancilla qubits, we are able to describe a FL* phase in a single band model: some of the electrons localize into an insulator of spins, while the others form a Luttinger-volume-violating Fermi surface.

- A metal-metal quantum phase transition with a change in carrier density from p in a FL* phase, to $1 + p$ in a FL phase.

- Fractionalization of the electron in the critical regime.

Ancilla qubits for the cuprates

- By introducing a double layer of ancilla qubits, we are able to describe a FL* phase in a single band model: some of the electrons localize into an insulator of spins, while the others form a Luttinger-volume-violating Fermi surface.

- A metal-metal quantum phase transition with a change in carrier density from p in a FL* phase, to $1 + p$ in a FL phase.

- Fractionalization of the electron in the critical regime.

- Unexpectedly large low-T entropy near the critical point.

Ancilla qubits for the cuprates

- By introducing a double layer of ancilla qubits, we are able to describe a FL* phase in a single band model: some of the electrons localize into an insulator of spins, while the others form a Luttinger-volume-violating Fermi surface.

- A metal-metal quantum phase transition with a change in carrier density from p in a FL* phase, to $1 + p$ in a FL phase.

- Fractionalization of the electron in the critical regime.

- Unexpectedly large low-T entropy near the critical point.

- It would be interesting to use PEPS/tensor-network technology to compute properties of the ancilla wavefunctions for FL*!