Fractionalization and emergent gauge fields in metals: application to $CeCoIn_5$ and the cuprates

KAIST, Korea
February 18, 2021

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Talk online: sachdev.physics.harvard.edu

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Yahui Zhang

Maria Tikhanovskaya

Alexander Nikolaenko

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.

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

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).

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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 $U_f = 0$.

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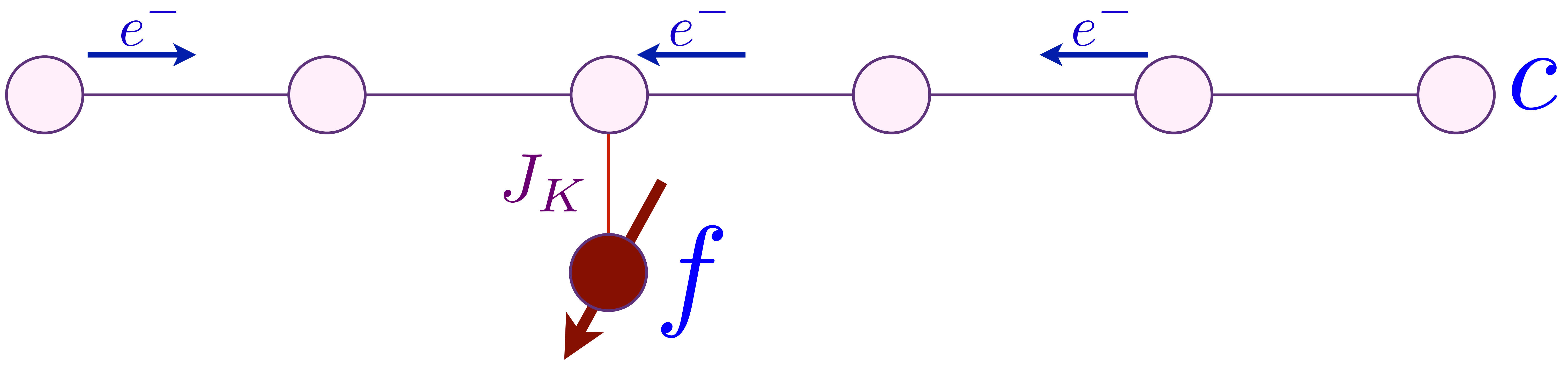
More recent proofs (Oshikawa; Else,Thorngren,Senthil) use an 'anomaly' associated with the combination of translations and the U(1) symmetry of electron number conservation, and can work directly with spin qubits.

Kondo model

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



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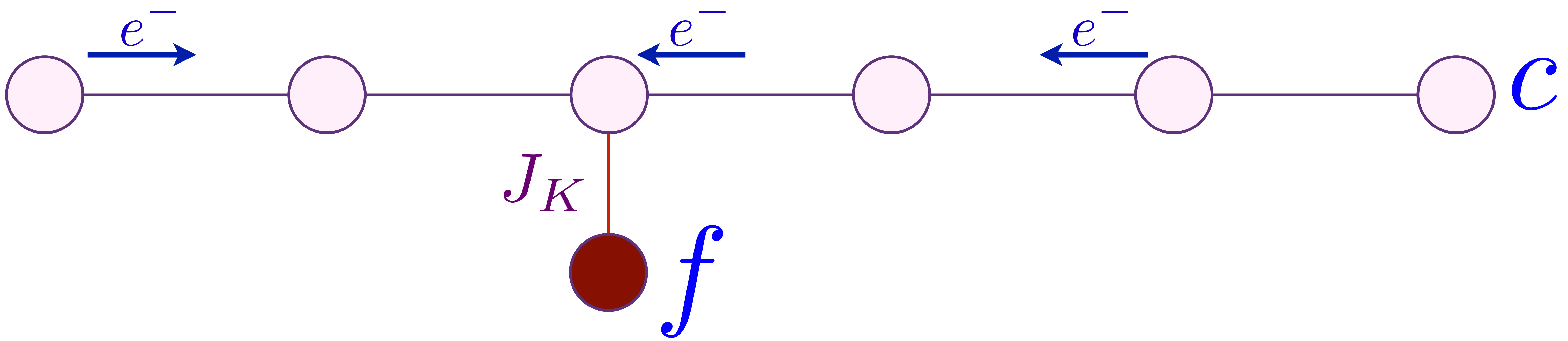
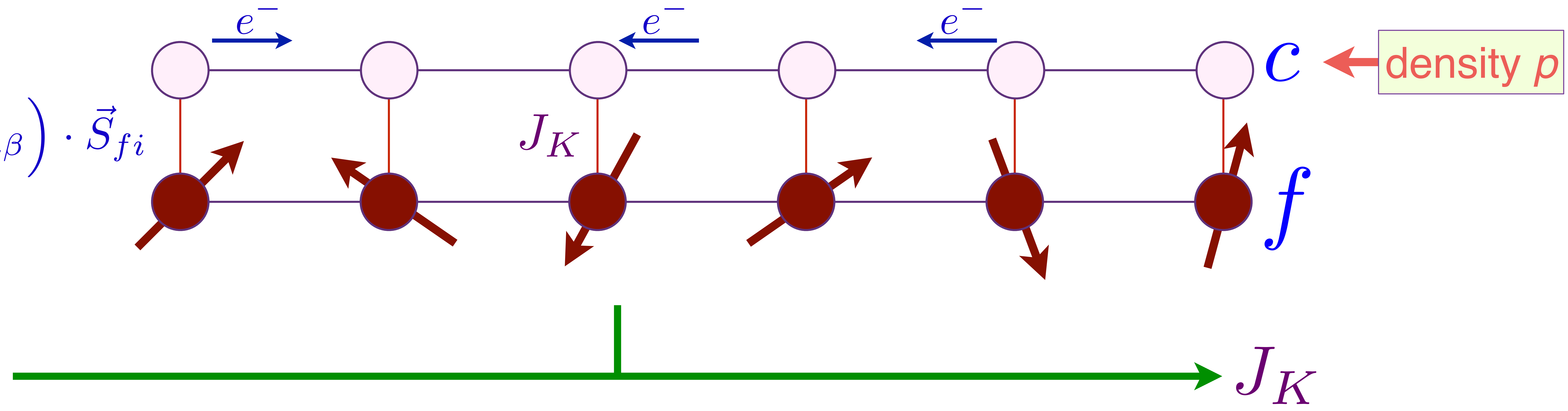


The c electrons ‘Kondo screen’ the f spin at low energies:
The f electron ‘dissolves’ into the Fermi sea.

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

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

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



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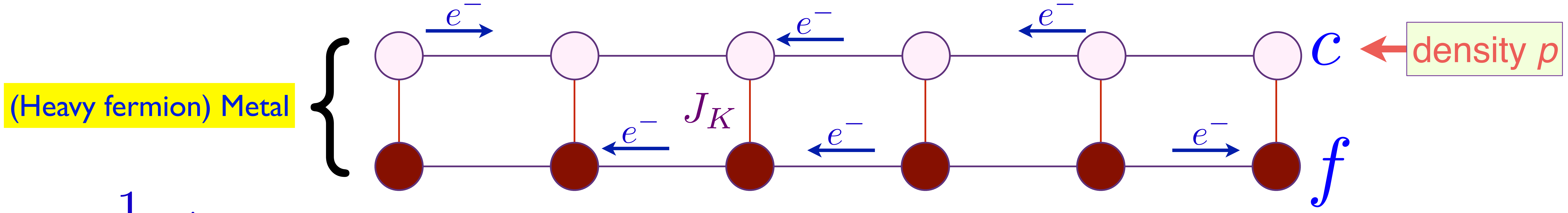
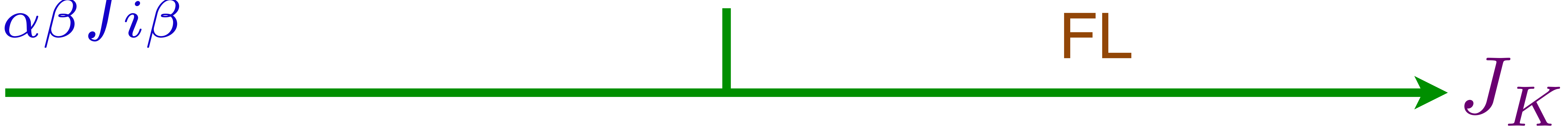


$$\vec{S}_{fi} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$



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

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

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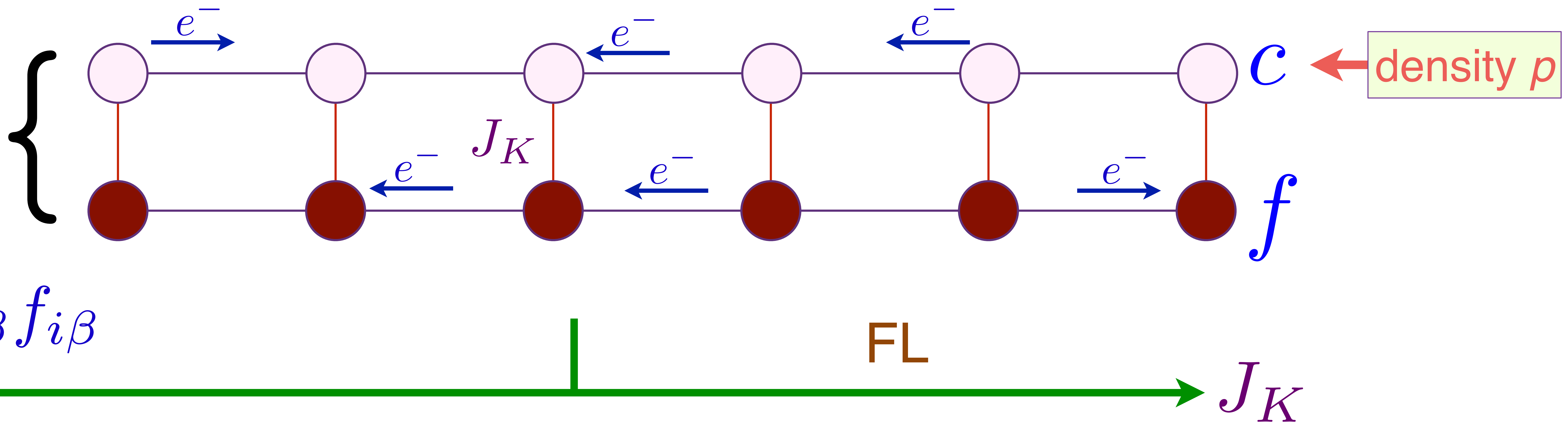
(Heavy fermion) Metal



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

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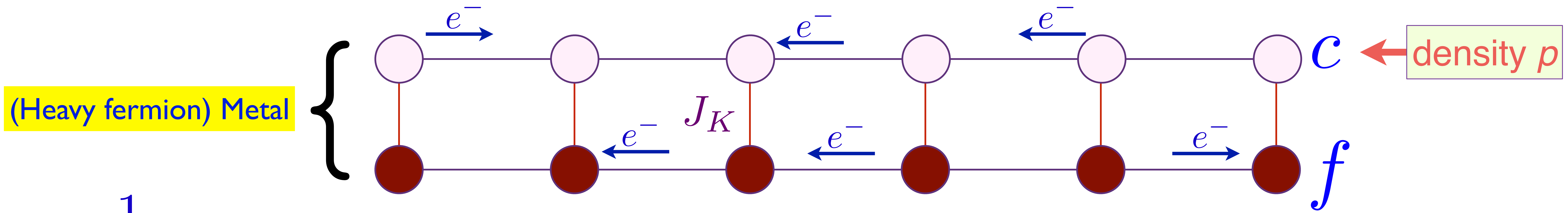

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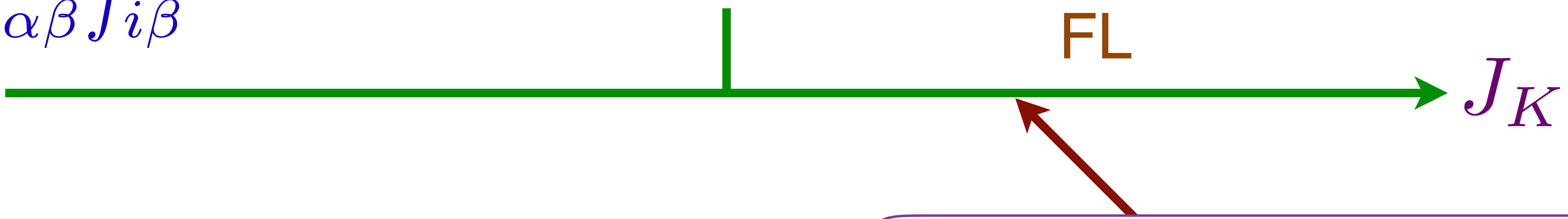

Large Fermi surface of size $1 + p$

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

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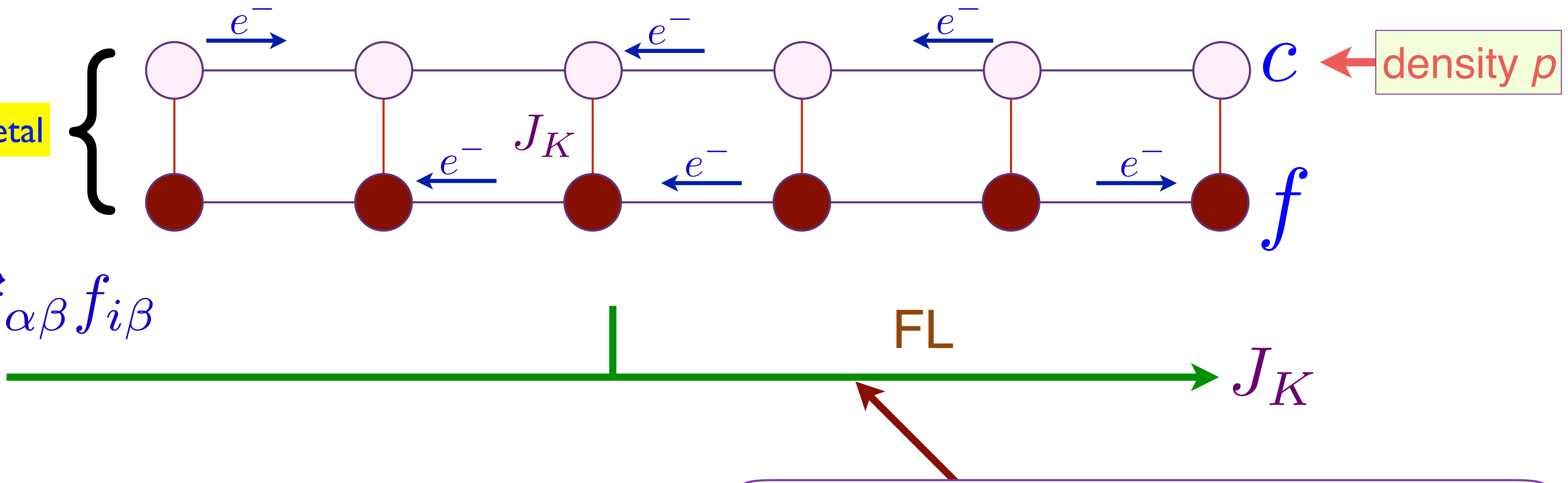

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Luttinger Theorem obeyed

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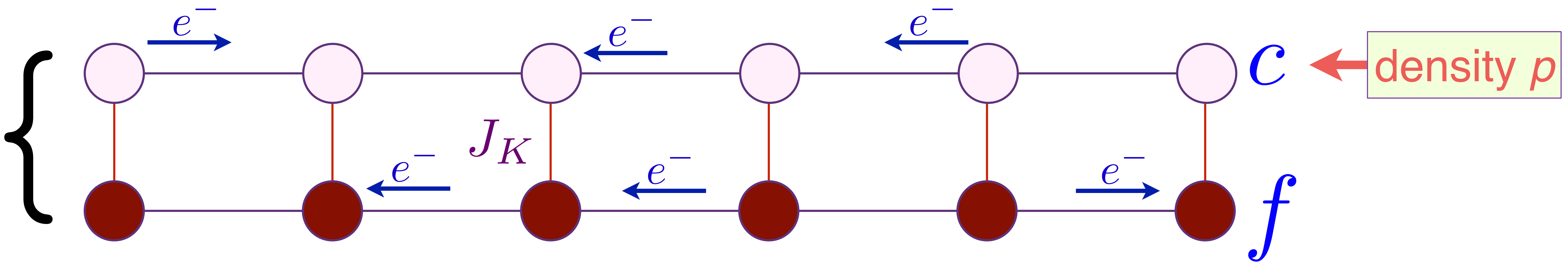

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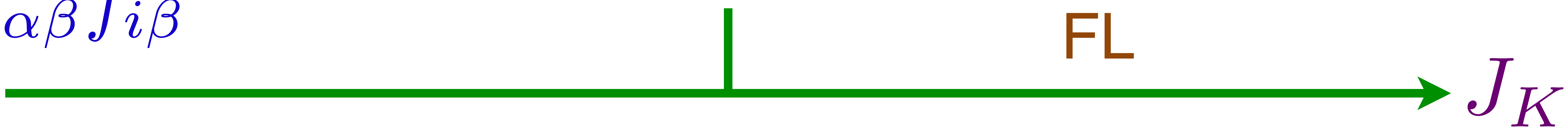

$$\langle c^\dagger_\alpha f_\alpha \rangle \neq 0$$

The Kondo lattice model has a gauge symmetry: $f_{i\alpha} \rightarrow e^{i\theta_i} f_{i\alpha}$
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 and* $CeCoIn_5$

2. Introduction to cuprates

Small to Large Fermi surface transition

3. Luttinger volume violation a one-band model

Ancilla qubits and ghost Fermi surfaces

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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)
A. Paramekanti and A. Vishwanath, PRB **70**, 245118 (2004)

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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.

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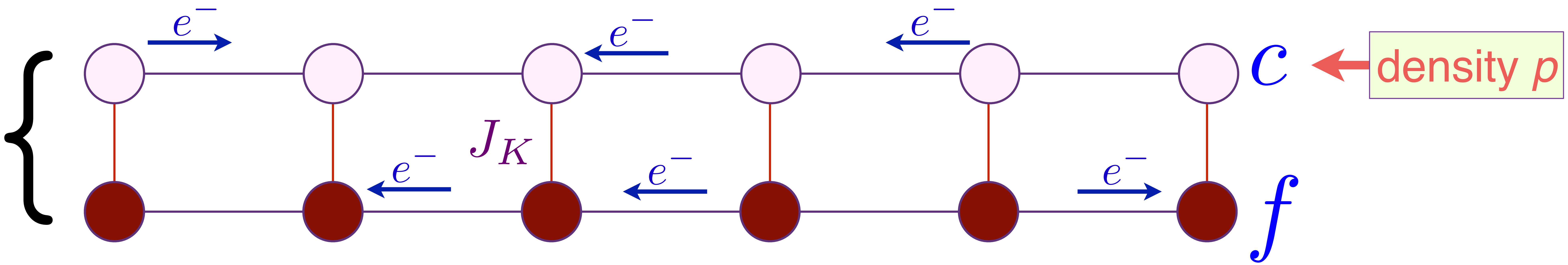

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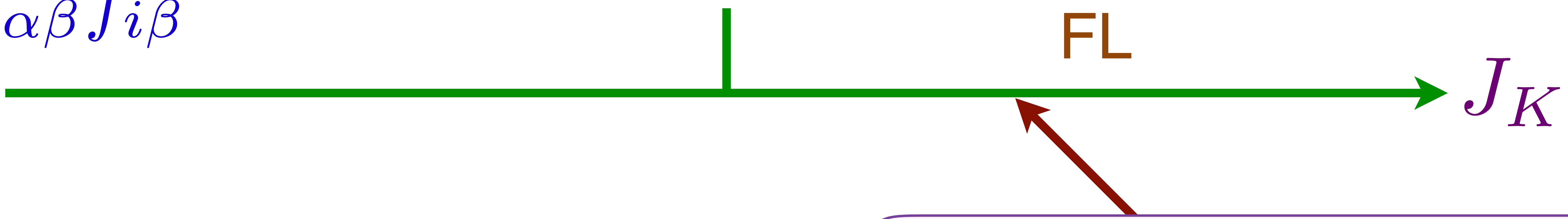

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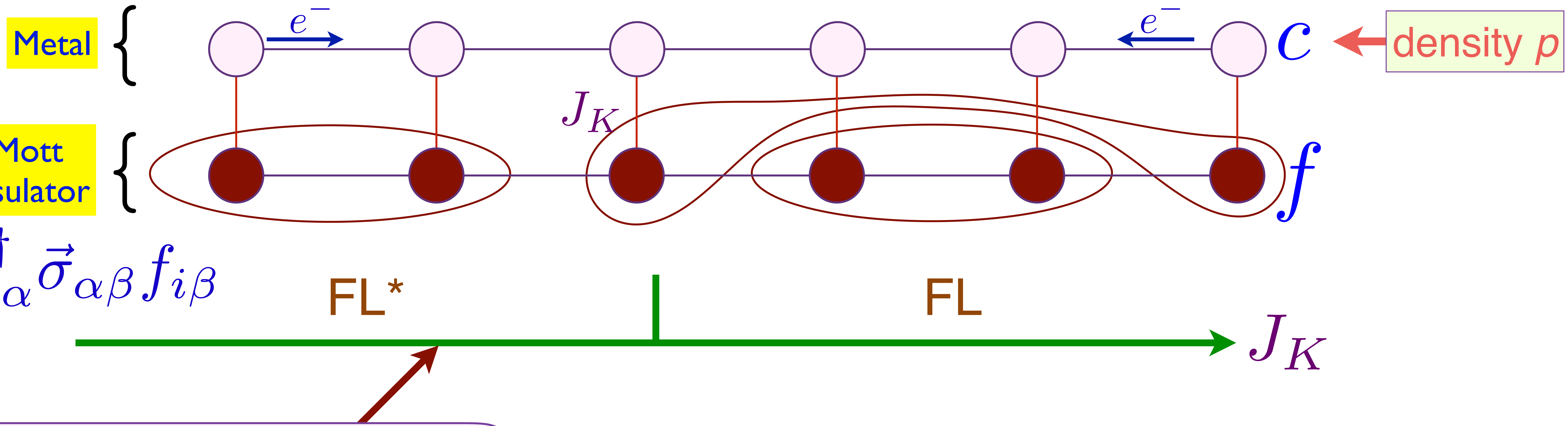

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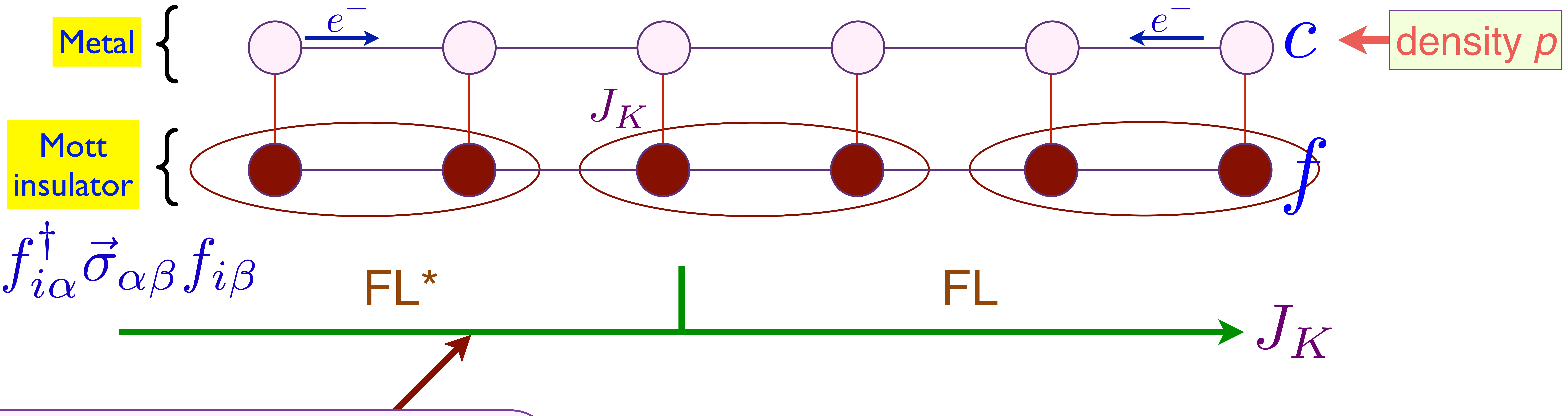

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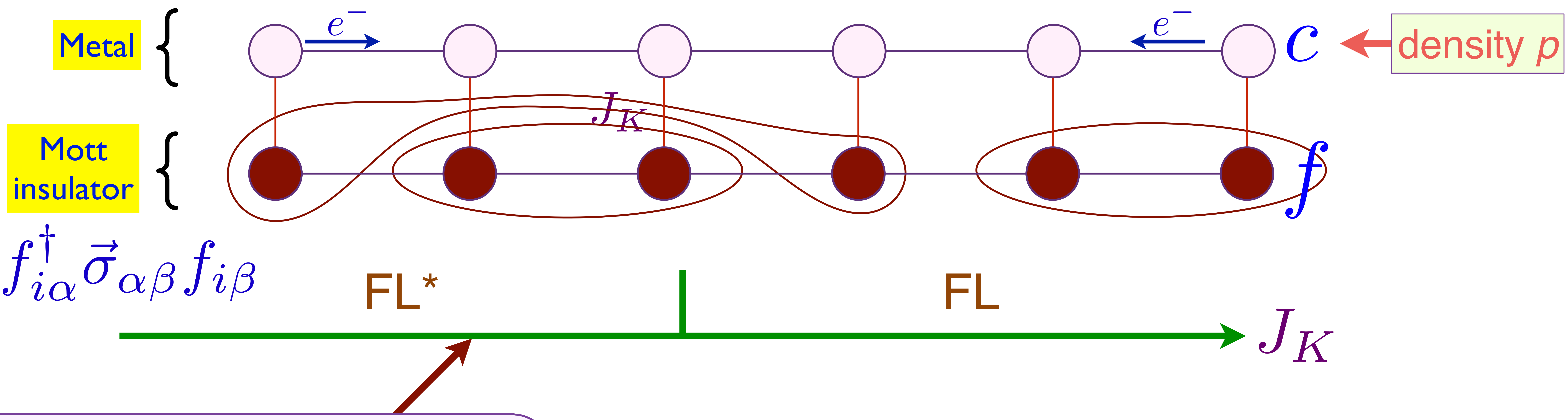

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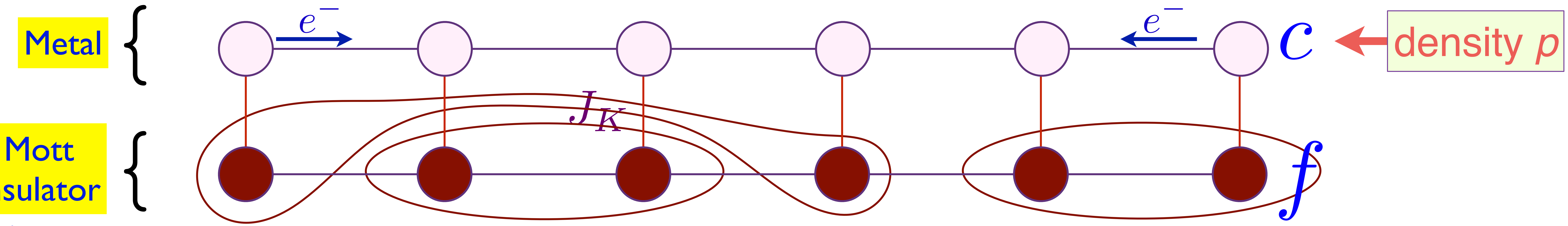

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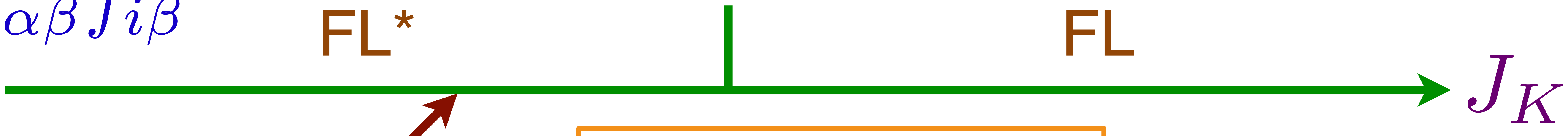

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Luttinger volume violation;
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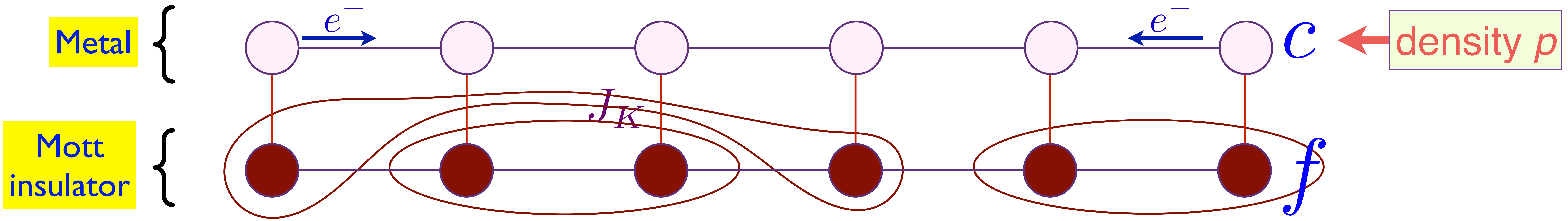
V.I. Anisimov, I.A. Nekrasov,
D.E. Kondakov, T.M. Rice & M. Sigrist,
EPJB **25**, 191 (2002)
L. de' Medici, A. Georges, S. Biermann,
PRB **72**, 205124 (2005)

Kondo-breakdown or 'selective Mott' transition



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

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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.

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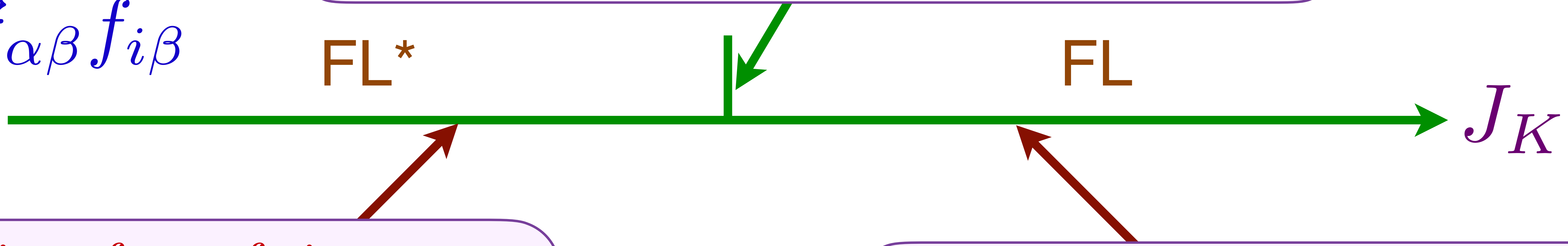

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Evidence for freezing of charge degrees of freedom across a critical point in $CeCoIn_5$

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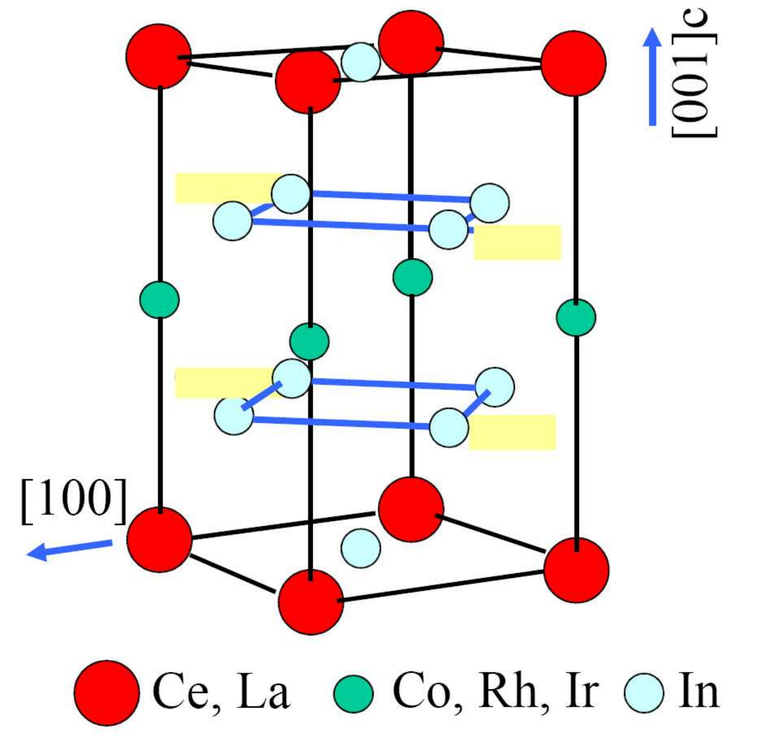

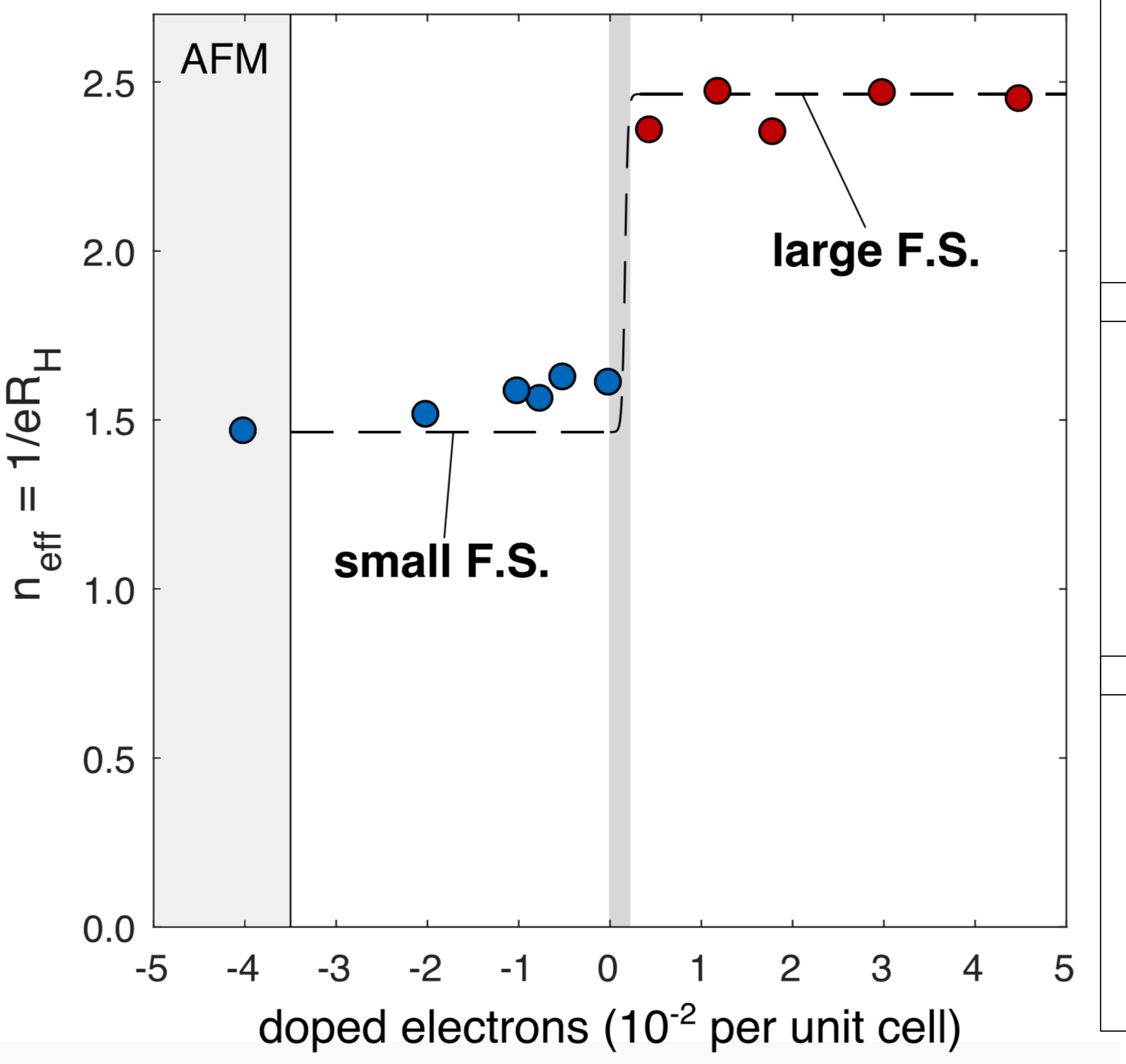

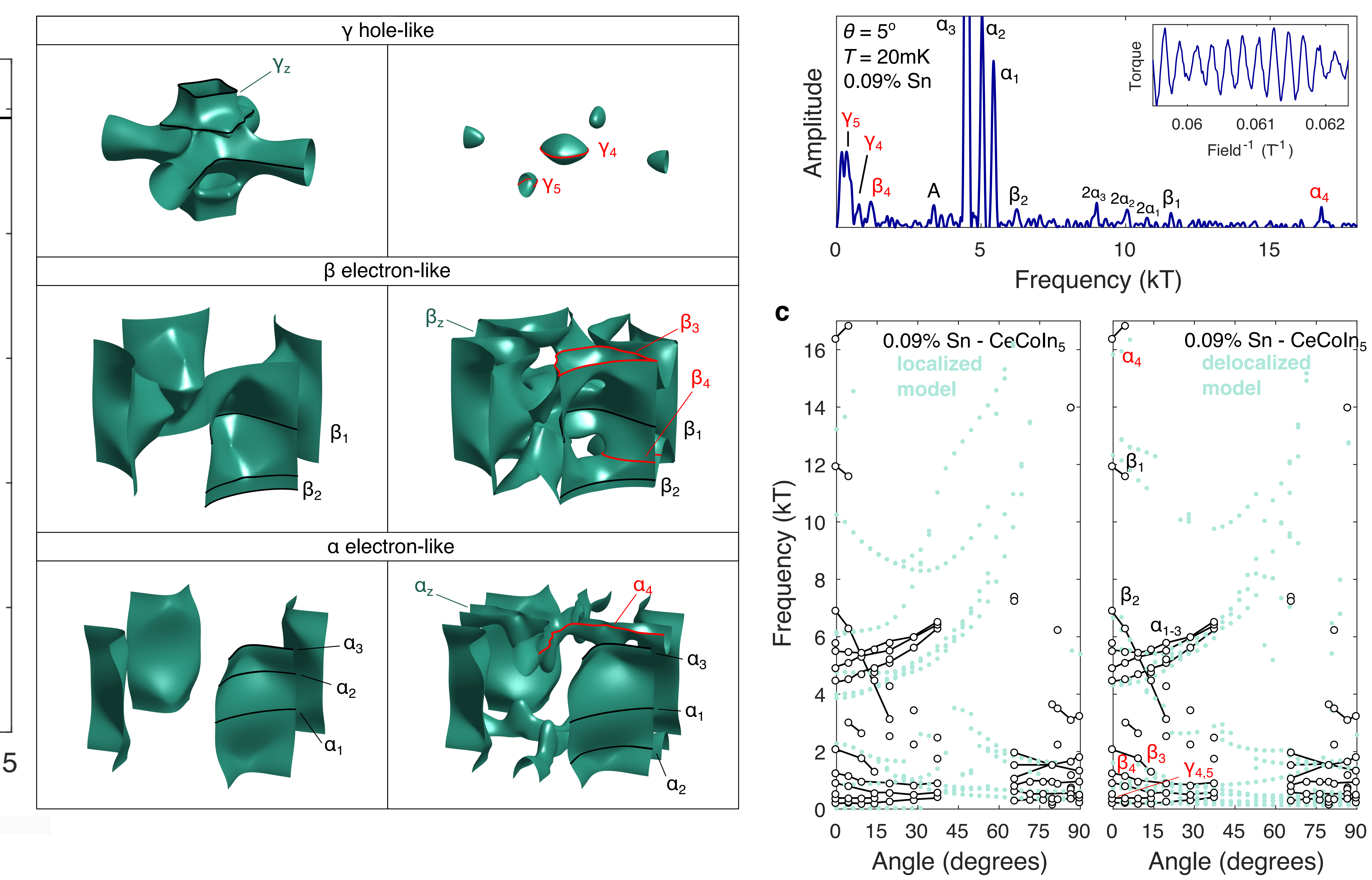

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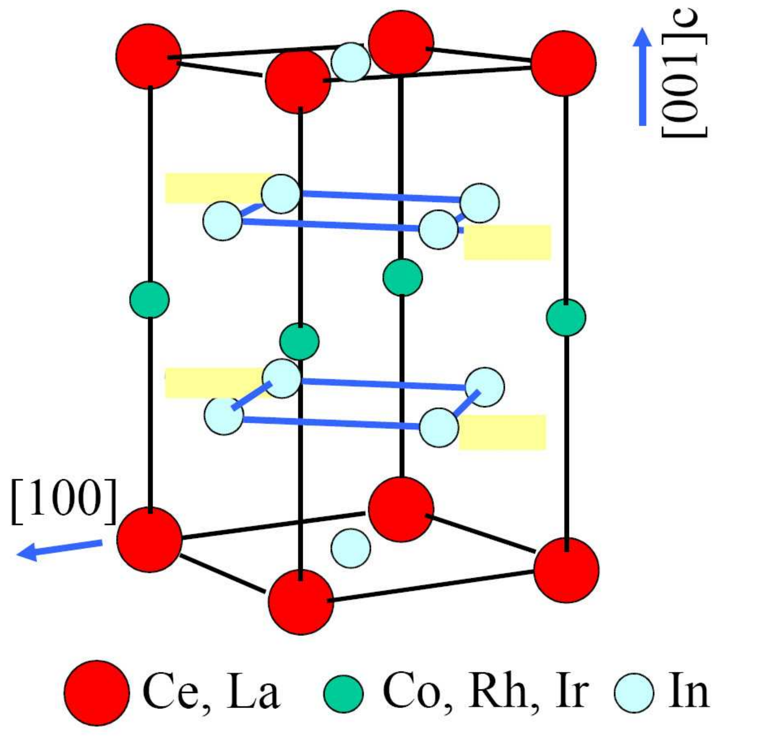

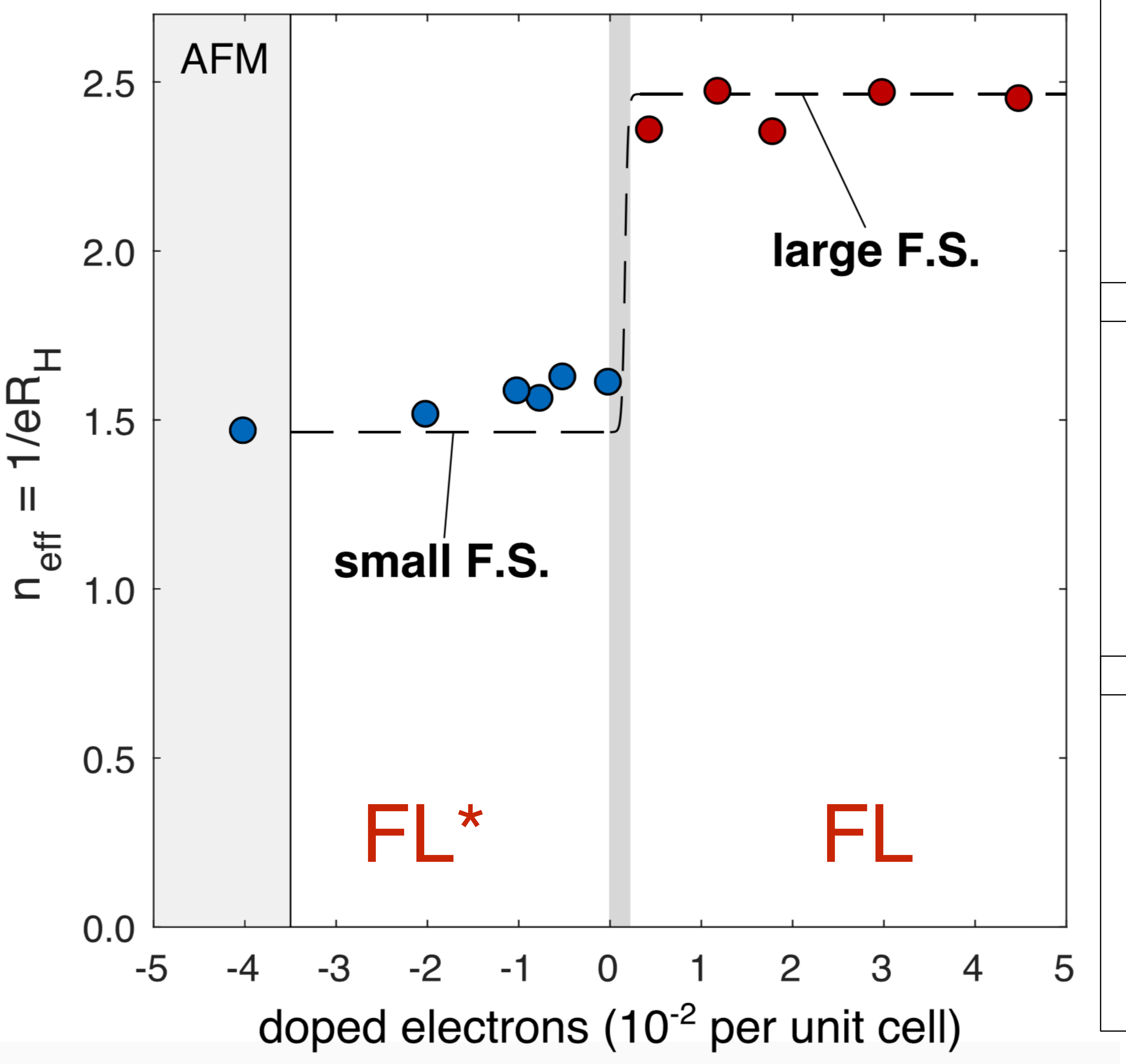

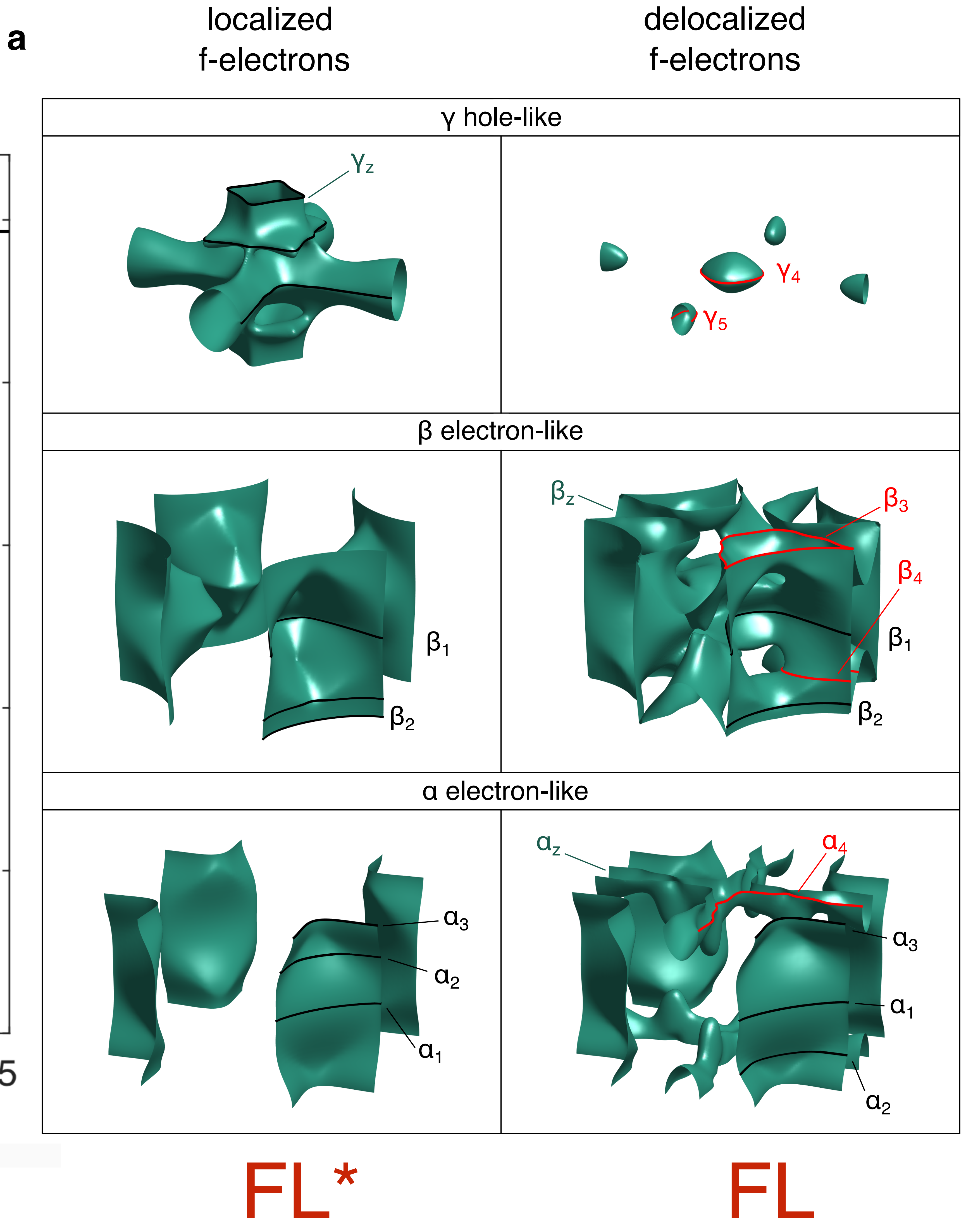

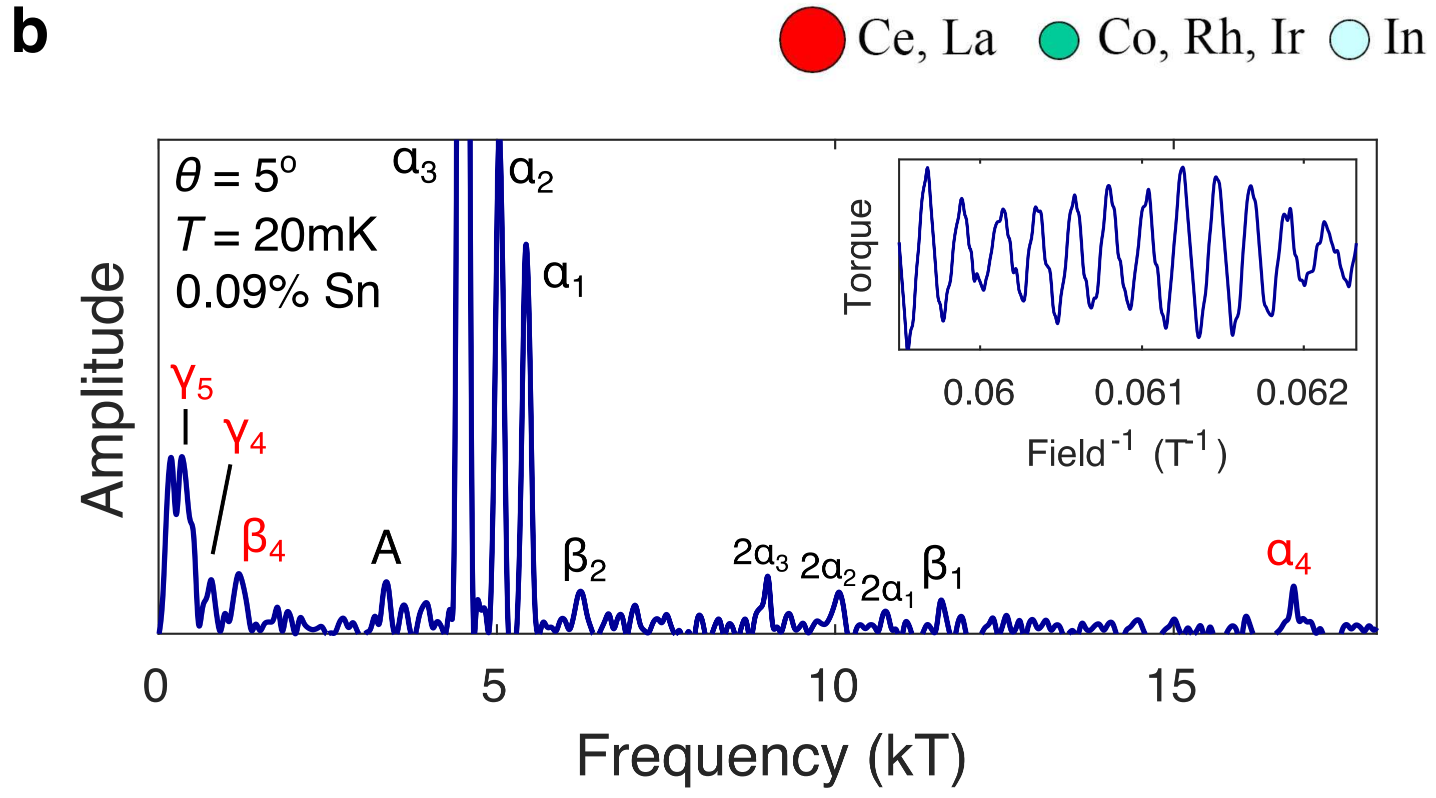

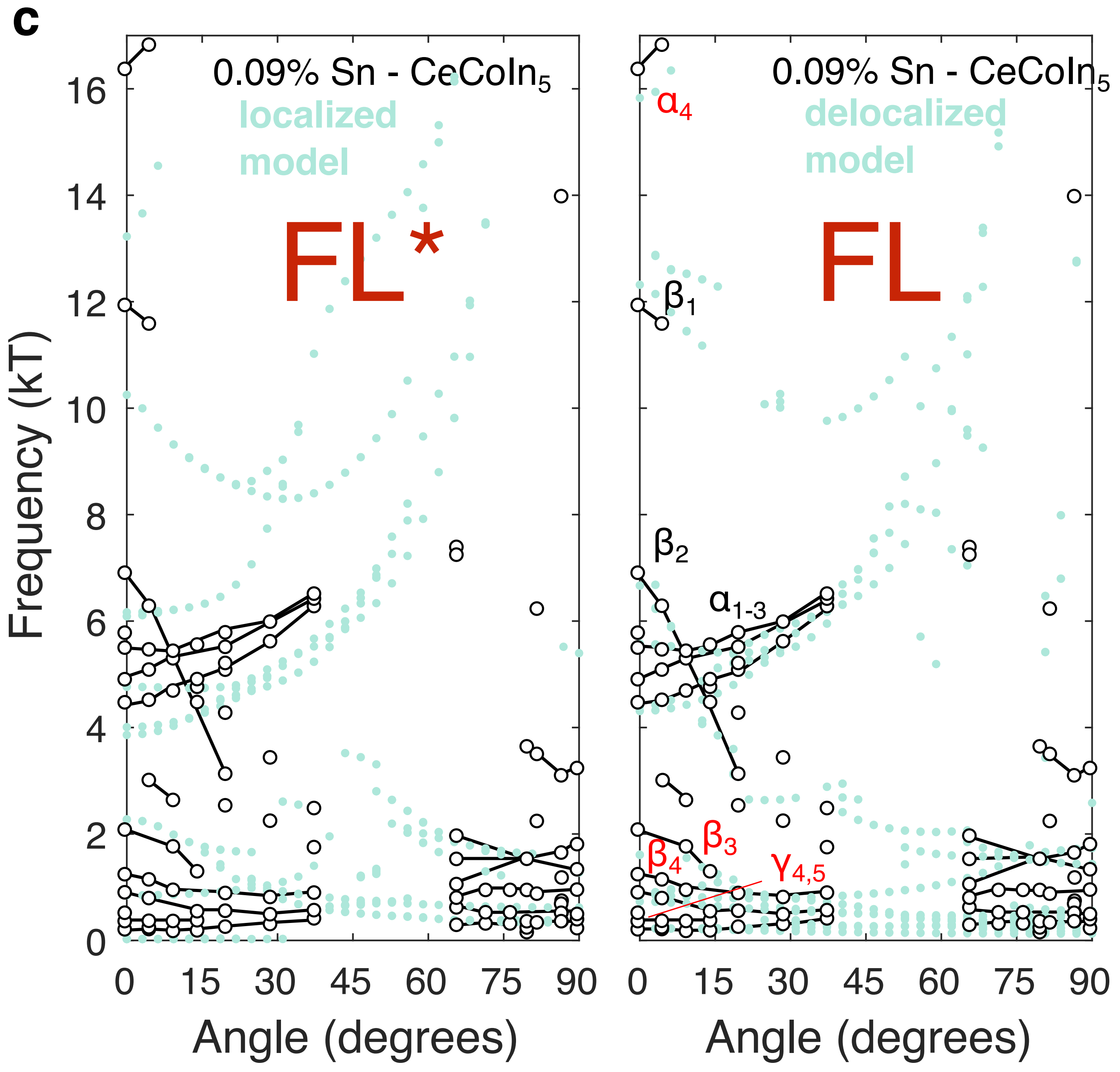

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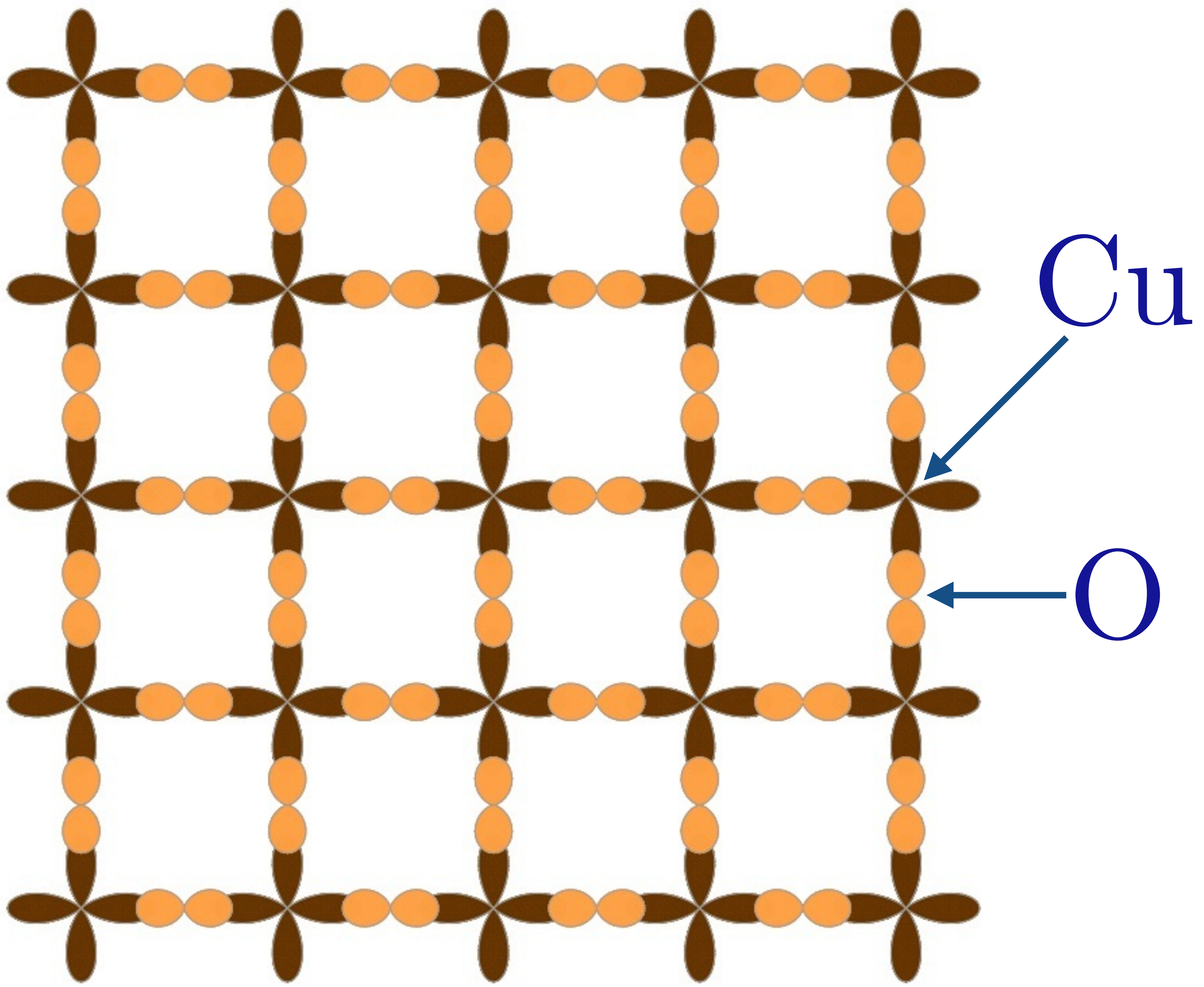
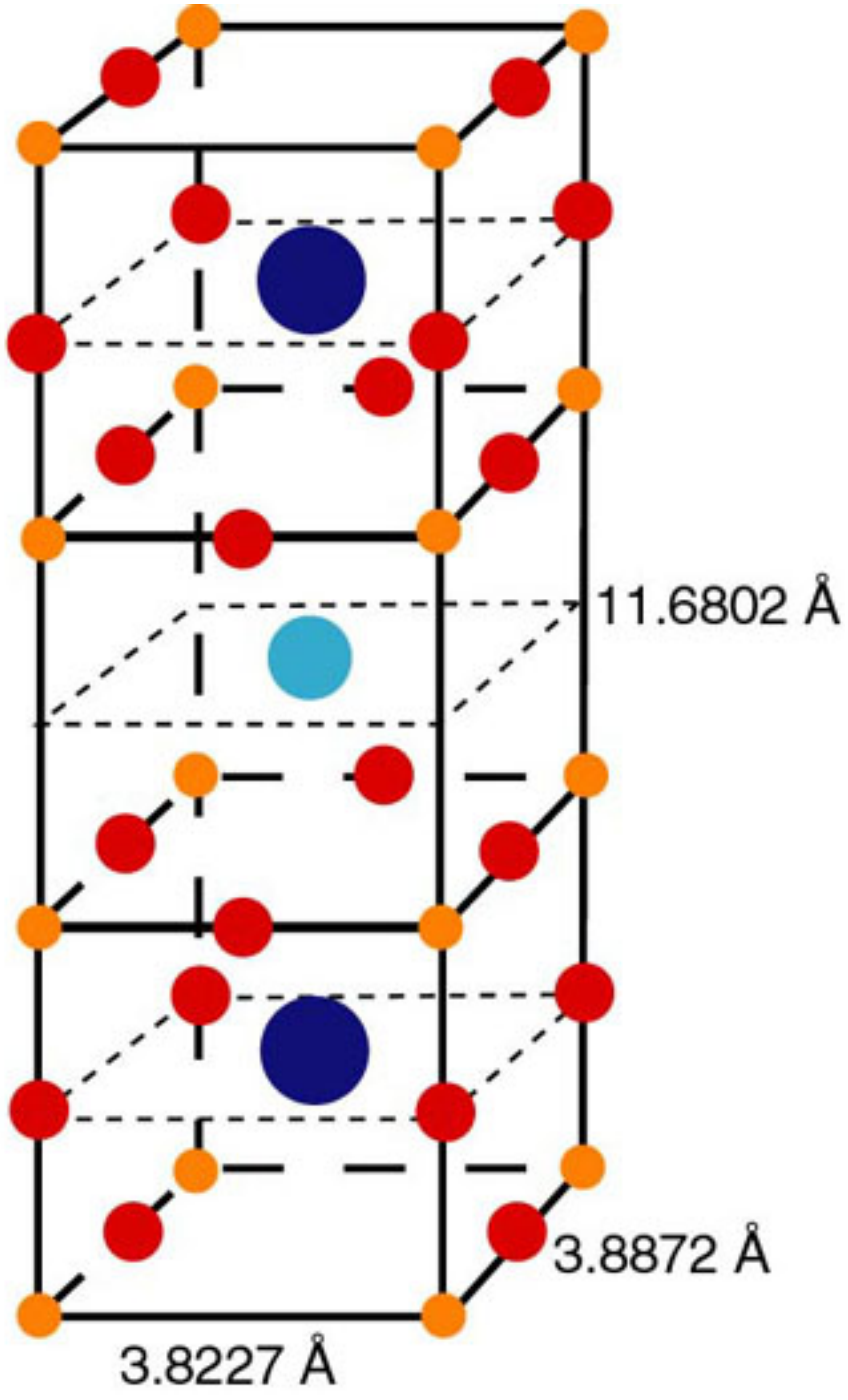
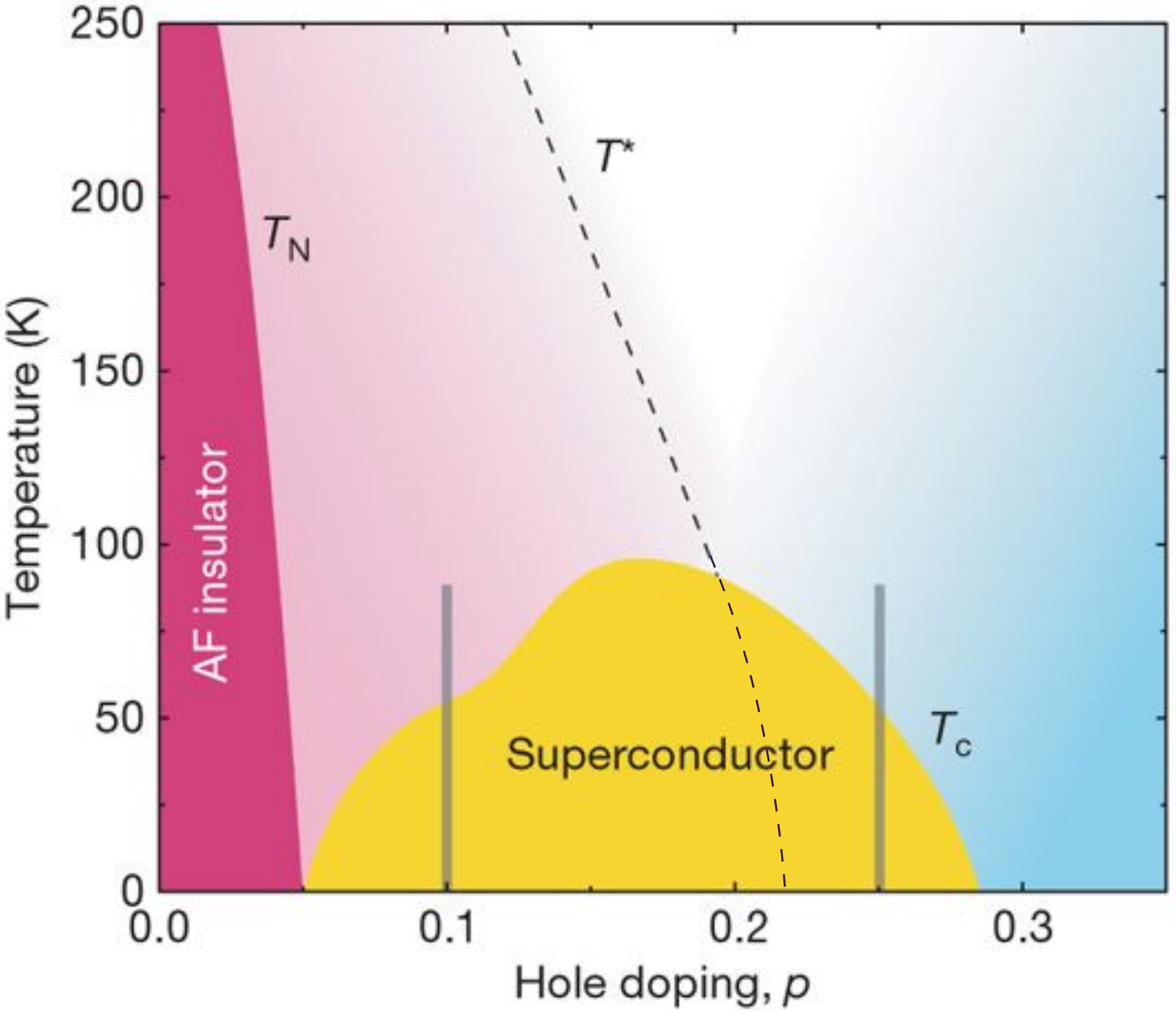
High temperature superconductors



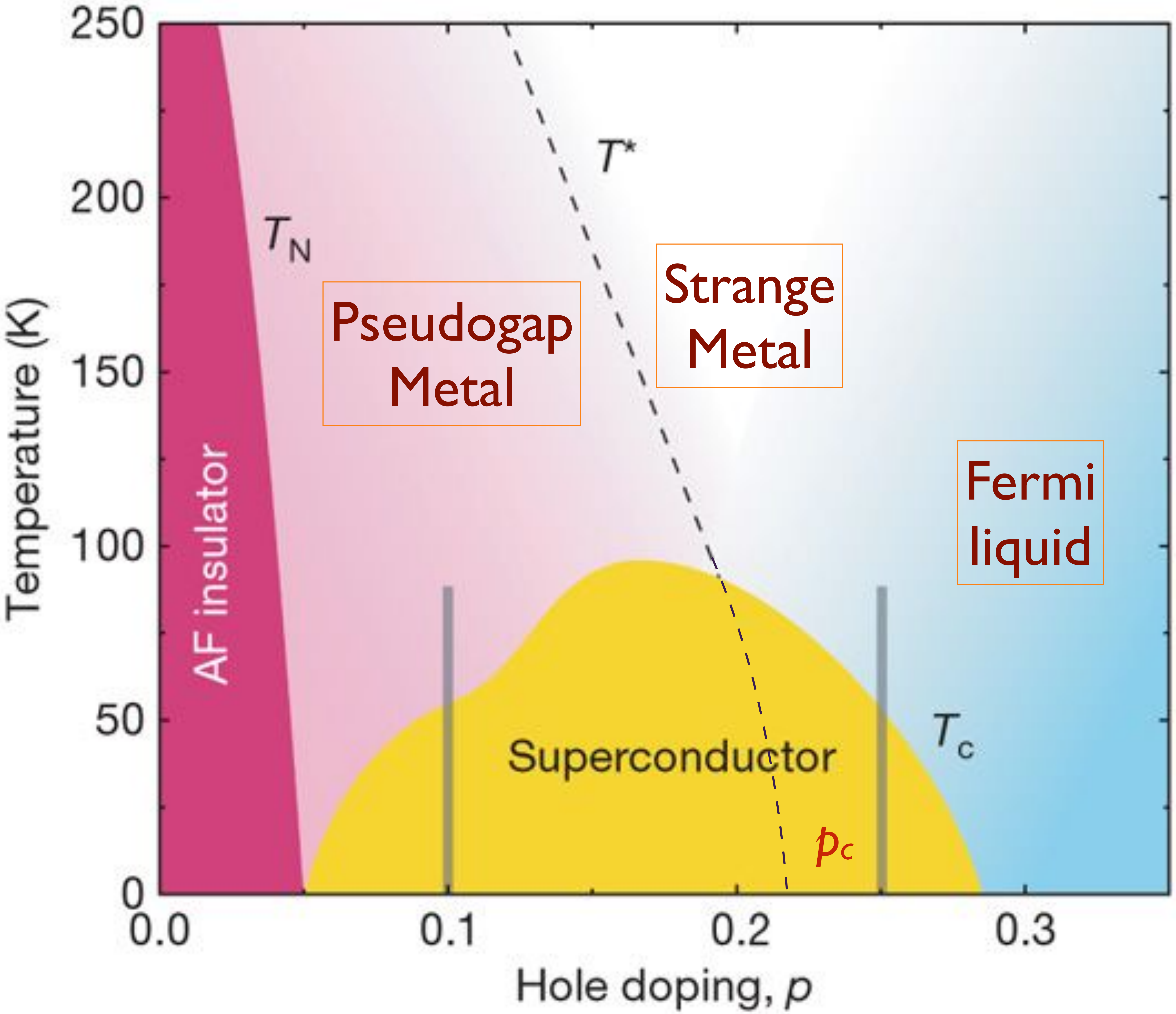
CuO_2 plane



$YBa_2Cu_3O_{6+x}$



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


250
200
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AF insulator
T N
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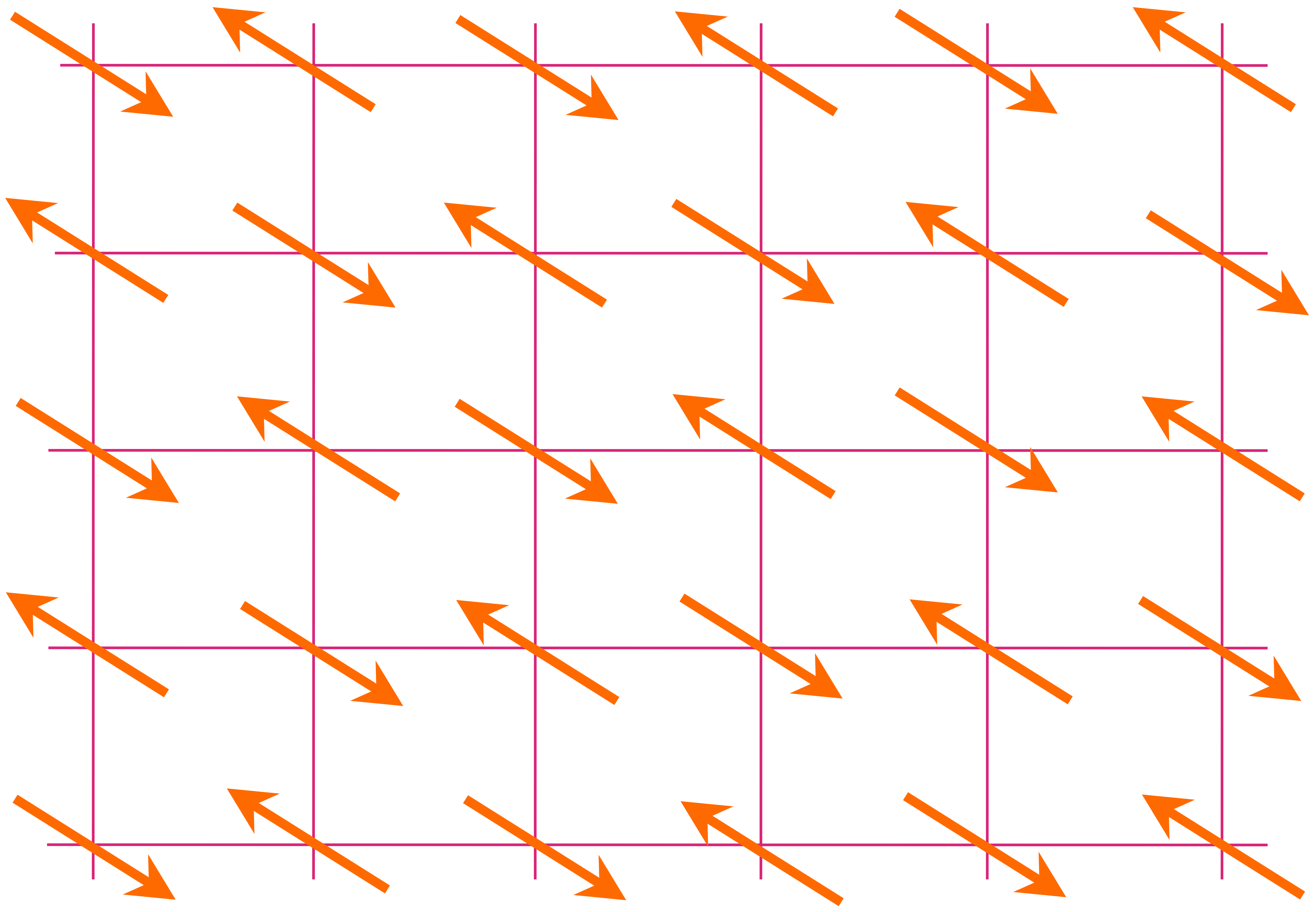
Strange Metal
Fermi liquid
Superconductor
T c
p c

Insulating antiferromagnet



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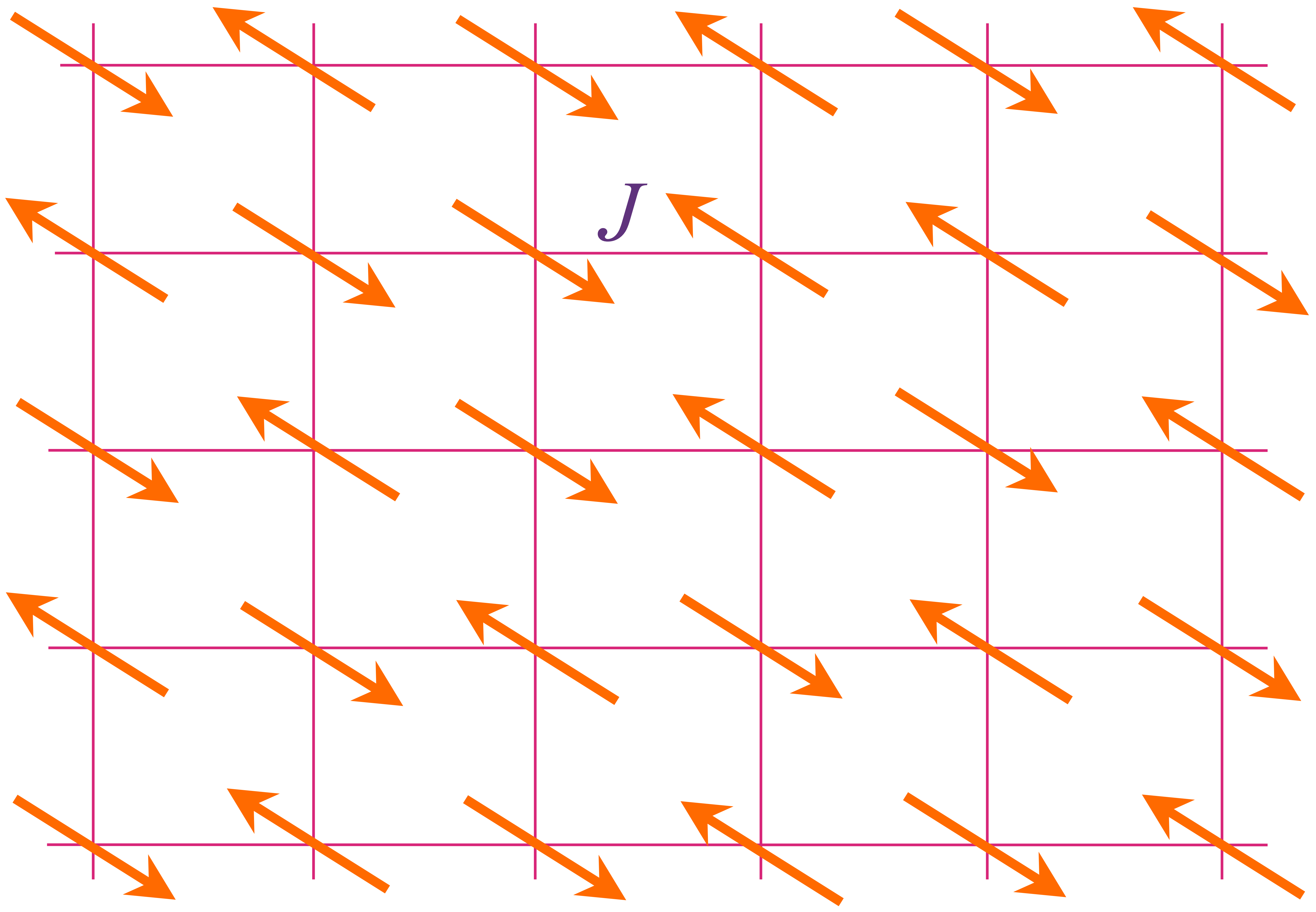
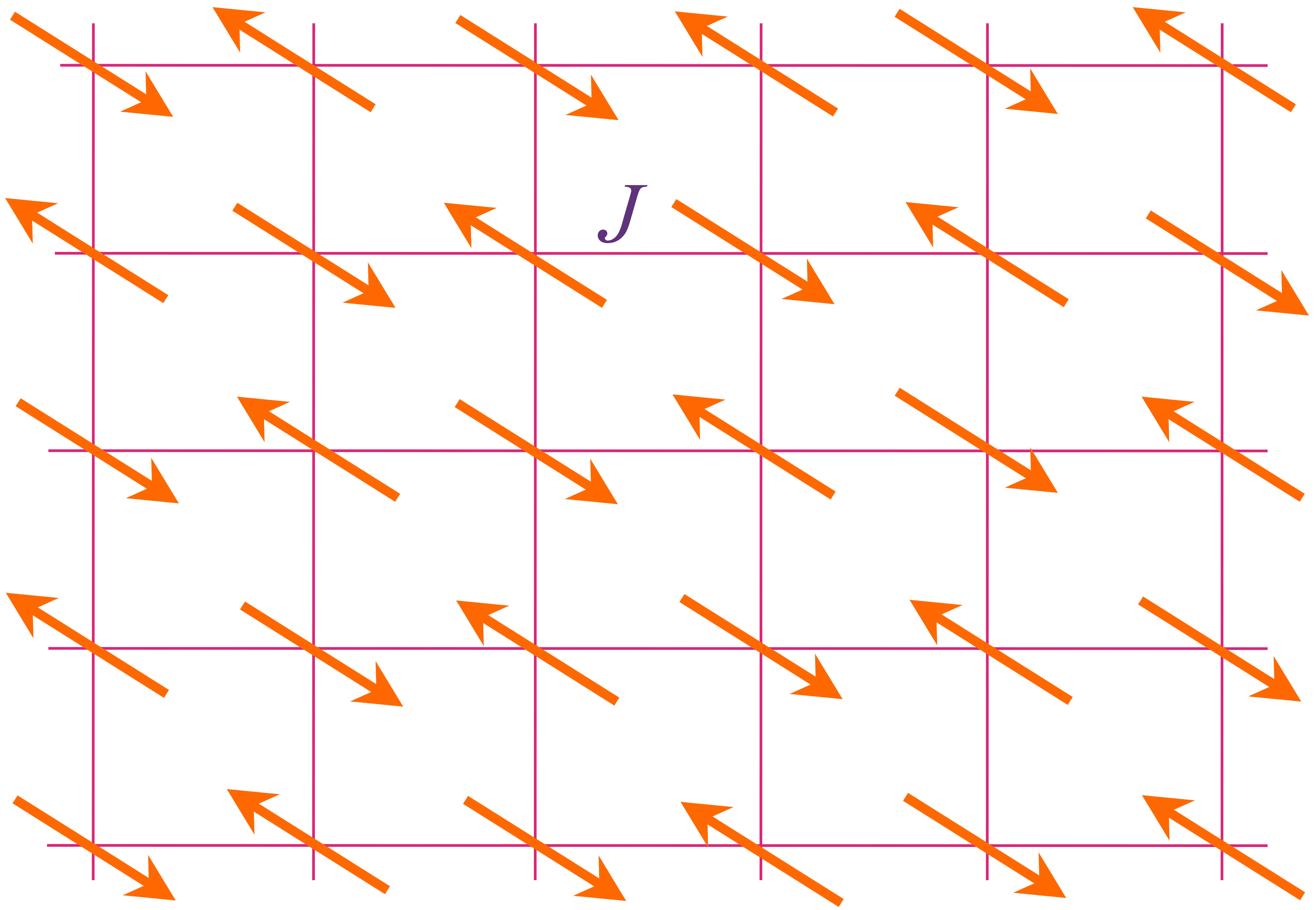
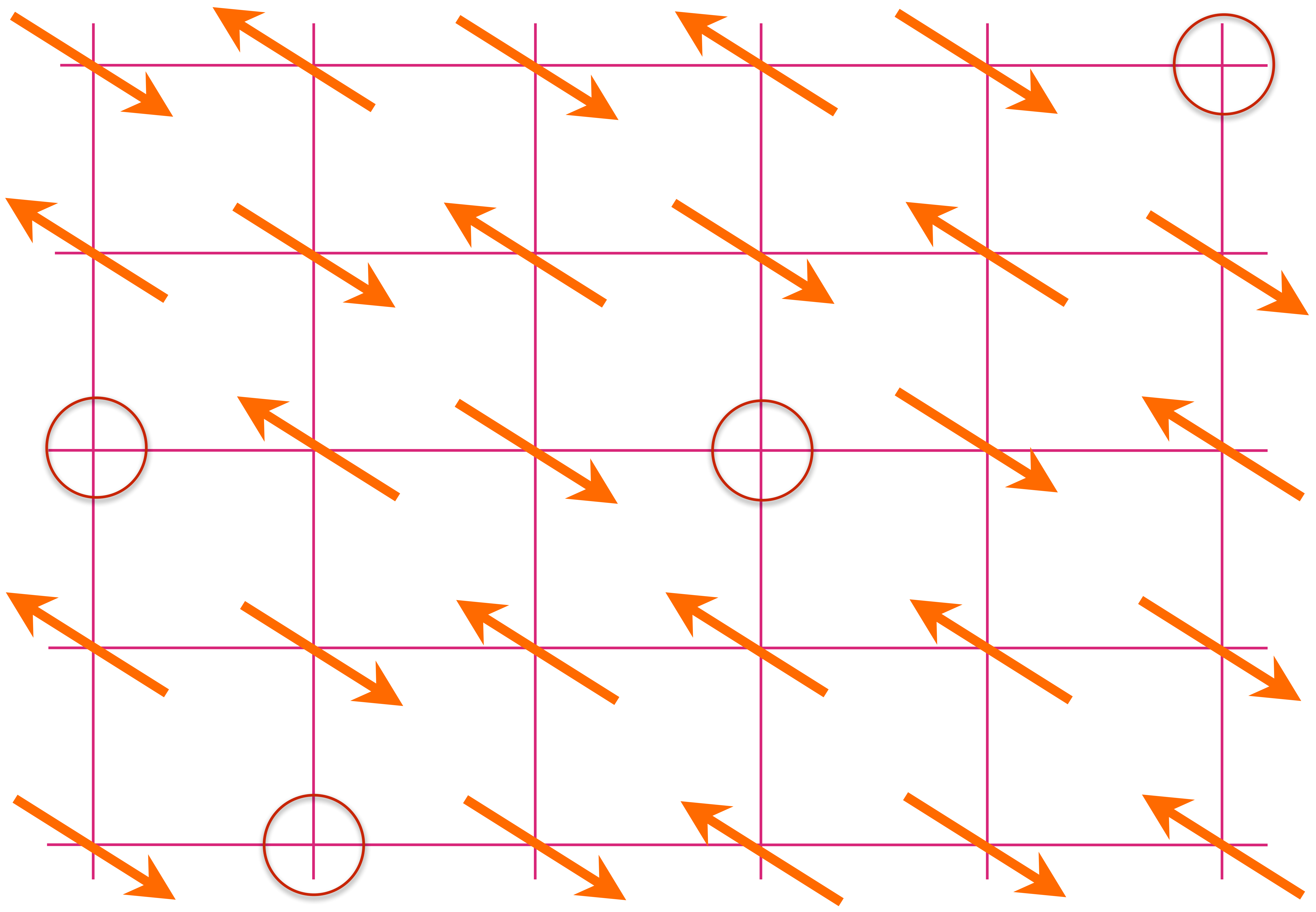


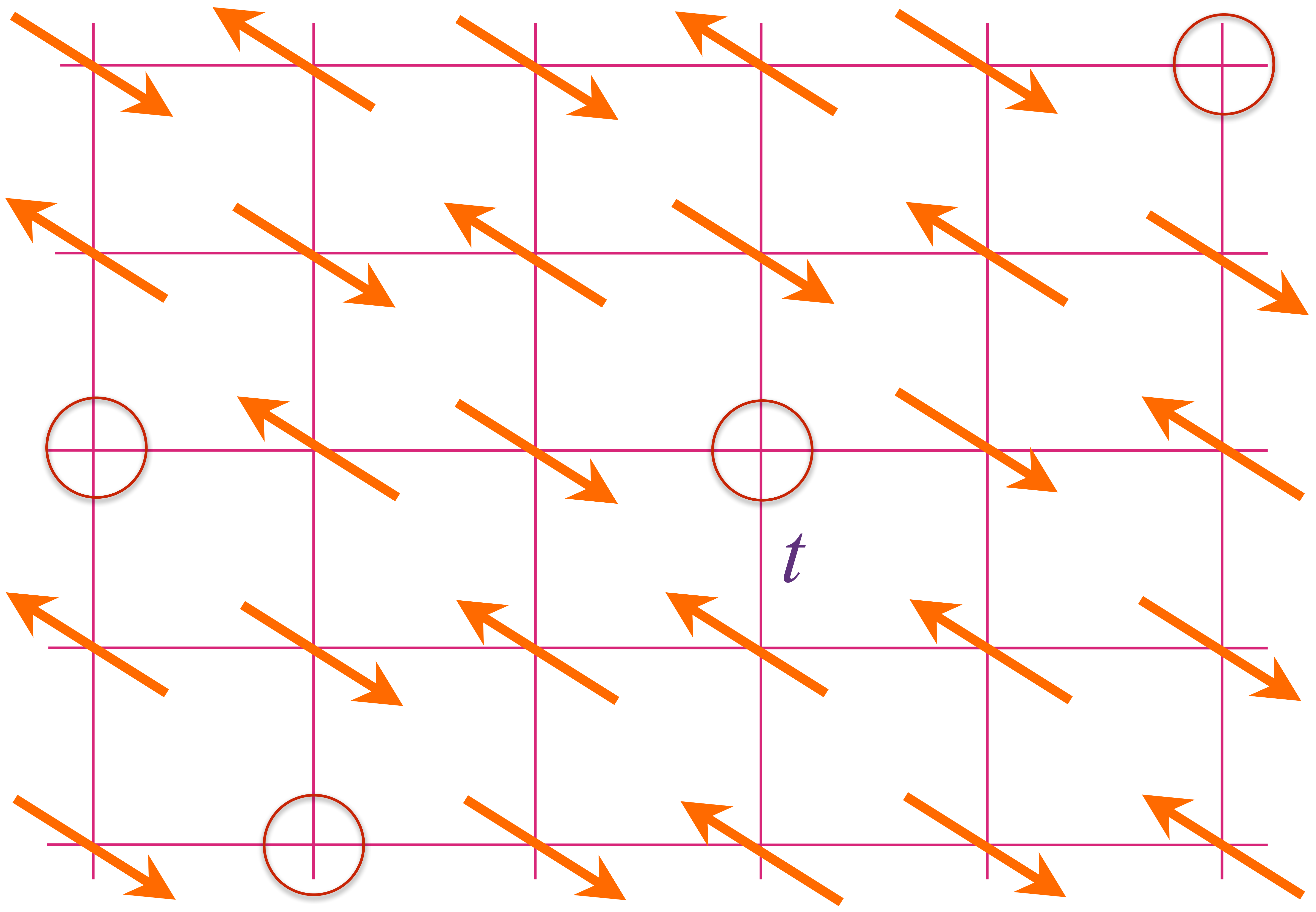
Insulating antiferromagnet



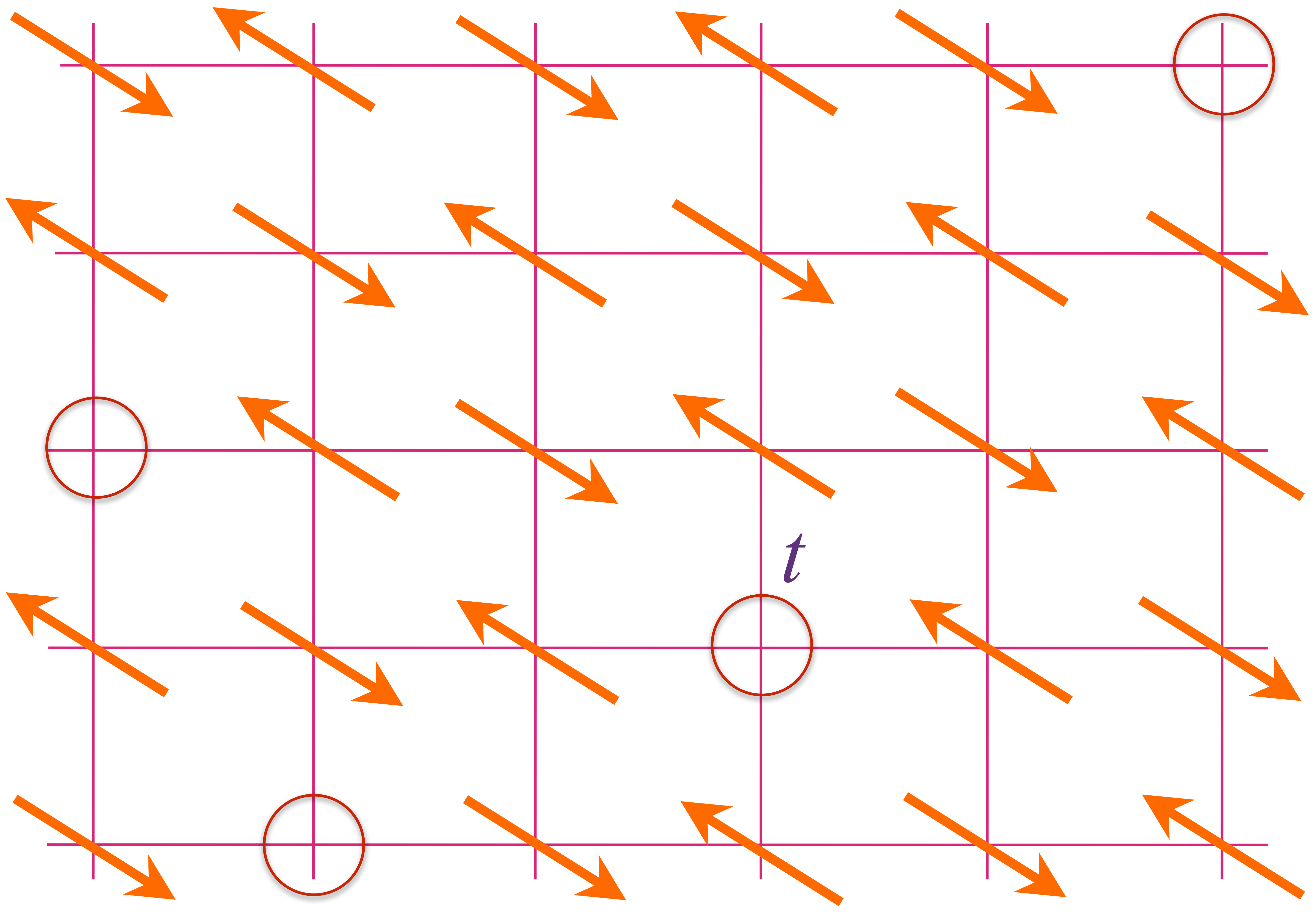
Antiferromagnet doped with hole density p



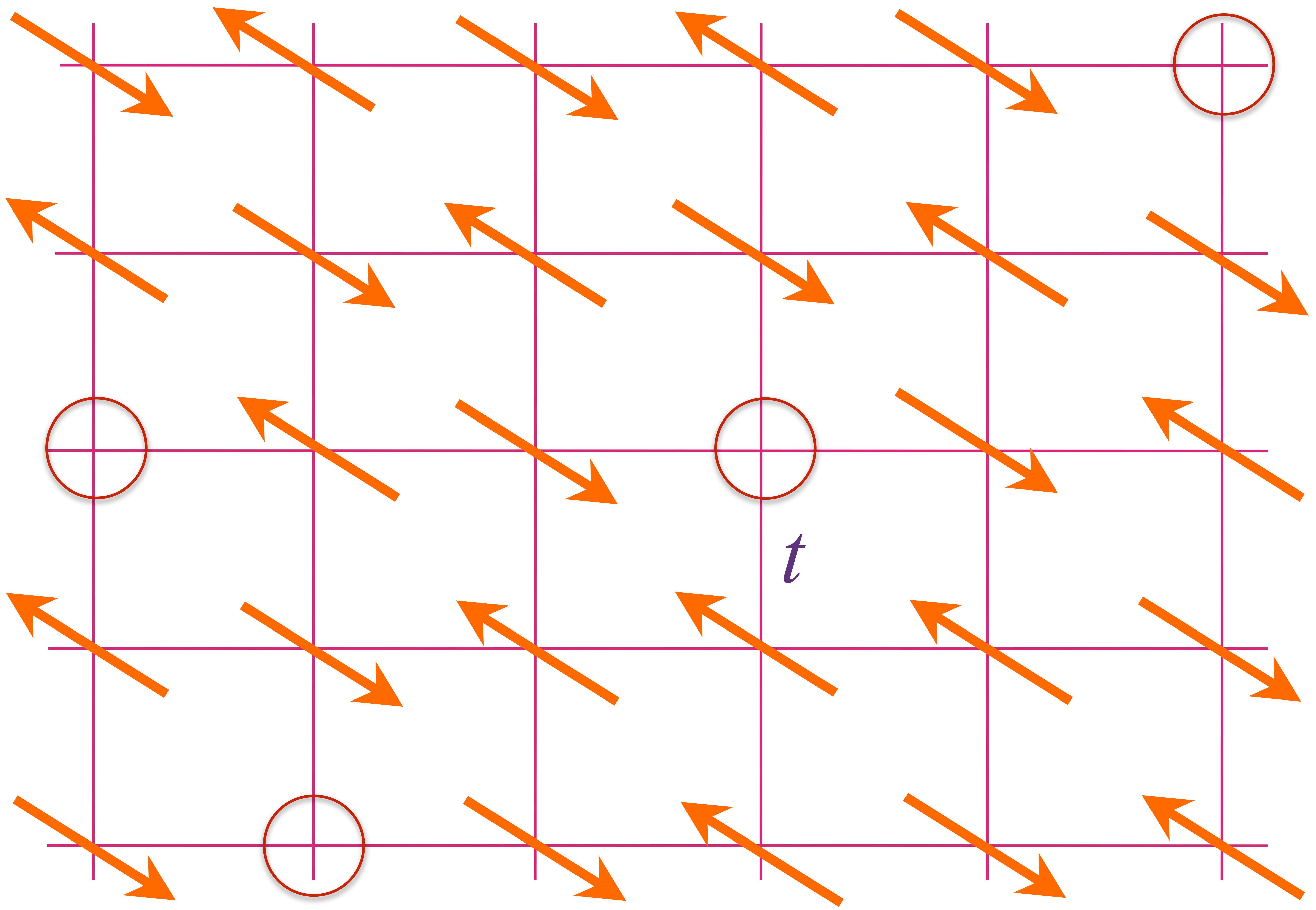
Antiferromagnet doped with hole density p



Antiferromagnet doped with hole density p

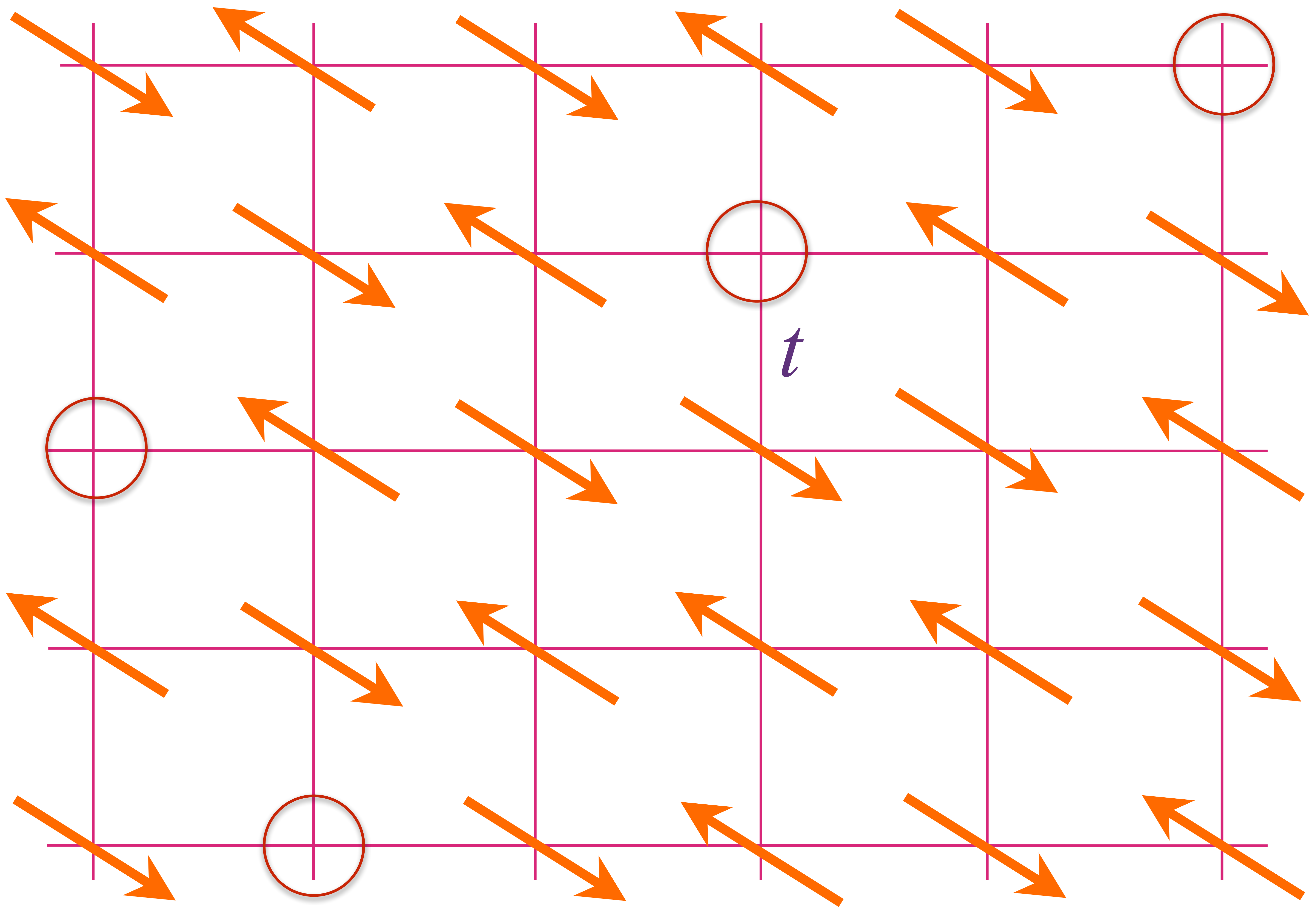


Antiferromagnet doped with hole density p



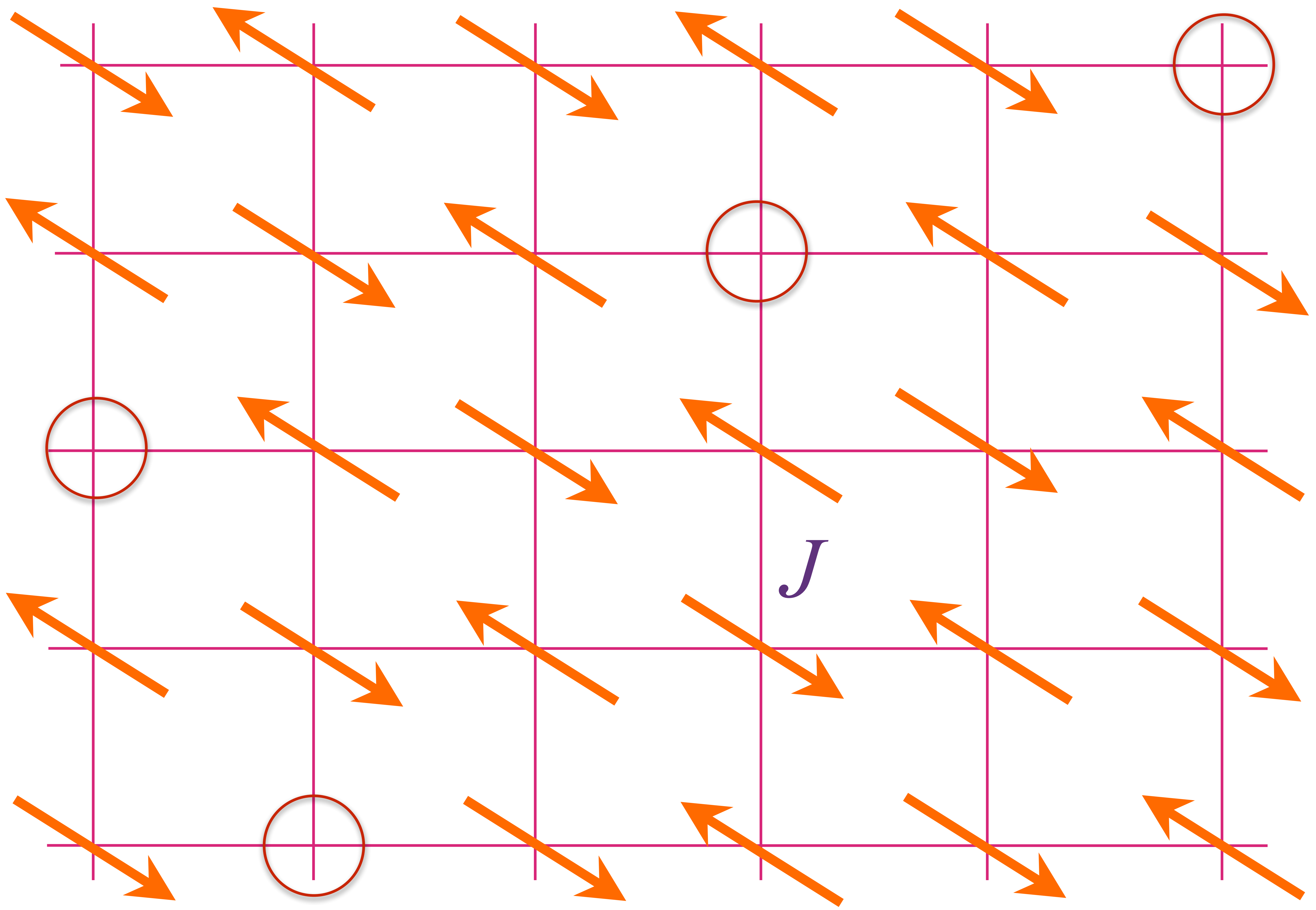
p mobile holes in a background of fluctuating spins

Antiferromagnet doped with hole density p



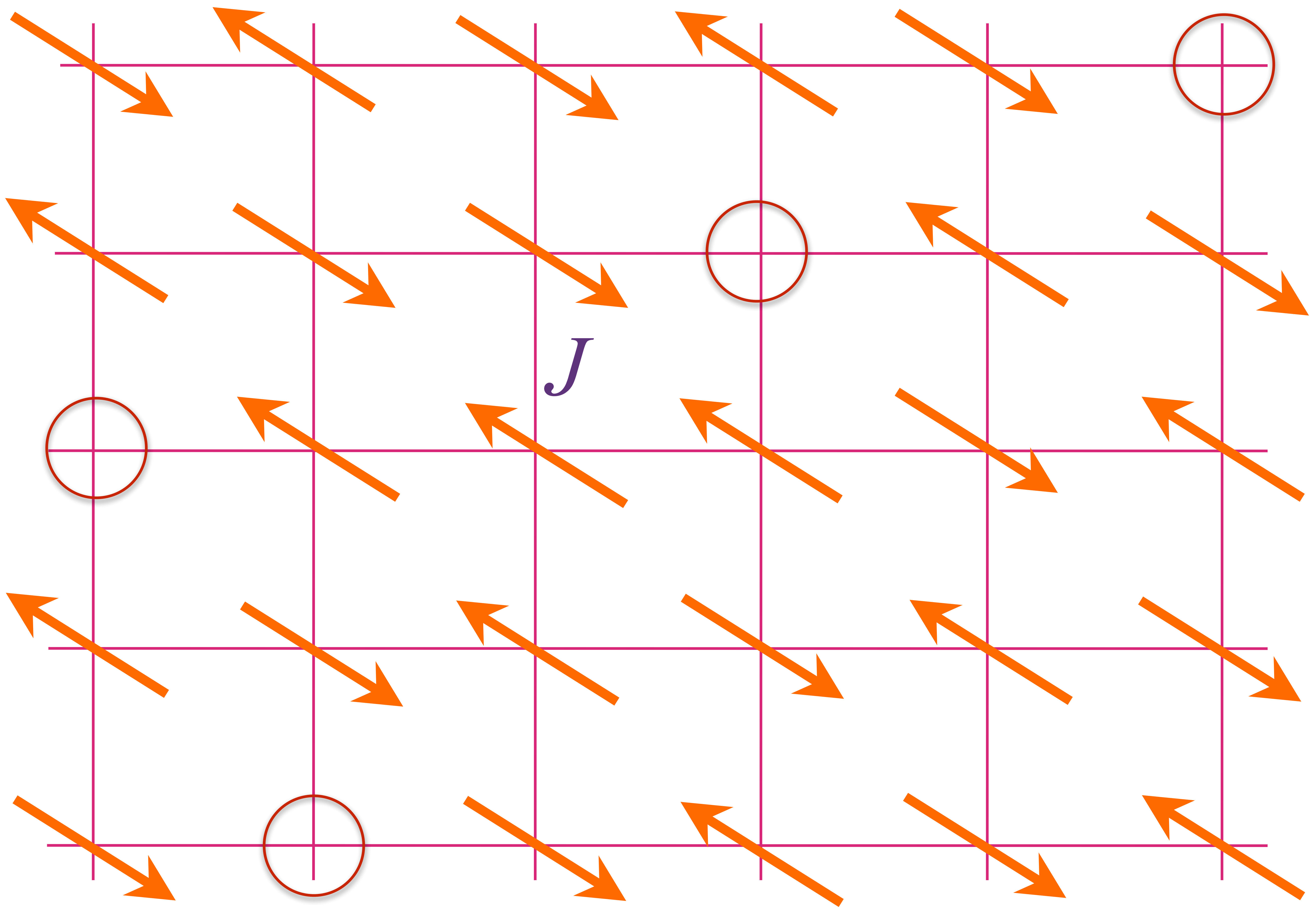
p mobile holes in a background of fluctuating spins

Antiferromagnet doped with hole density p



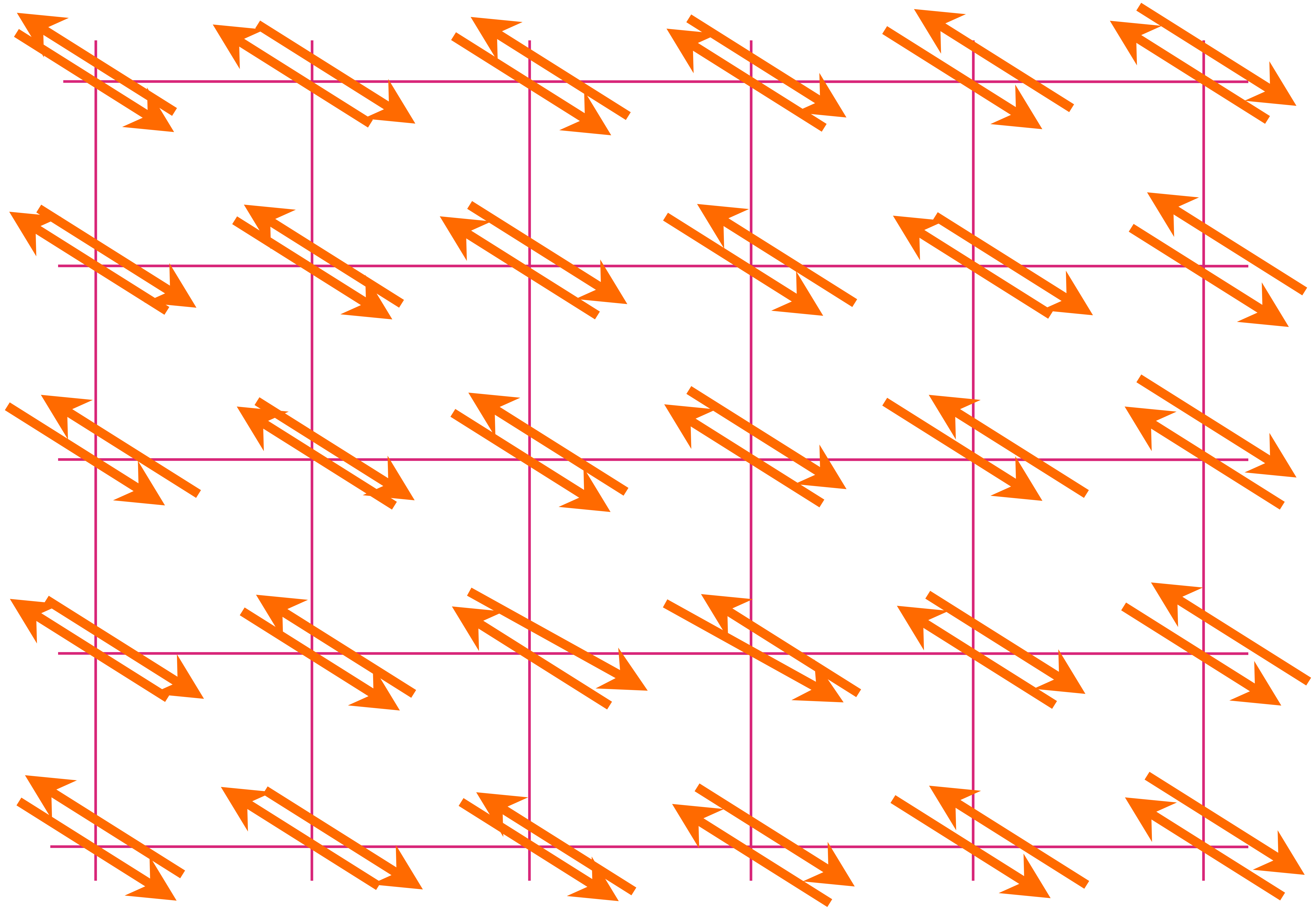
p mobile holes in a background of fluctuating spins

Antiferromagnet doped with hole density p



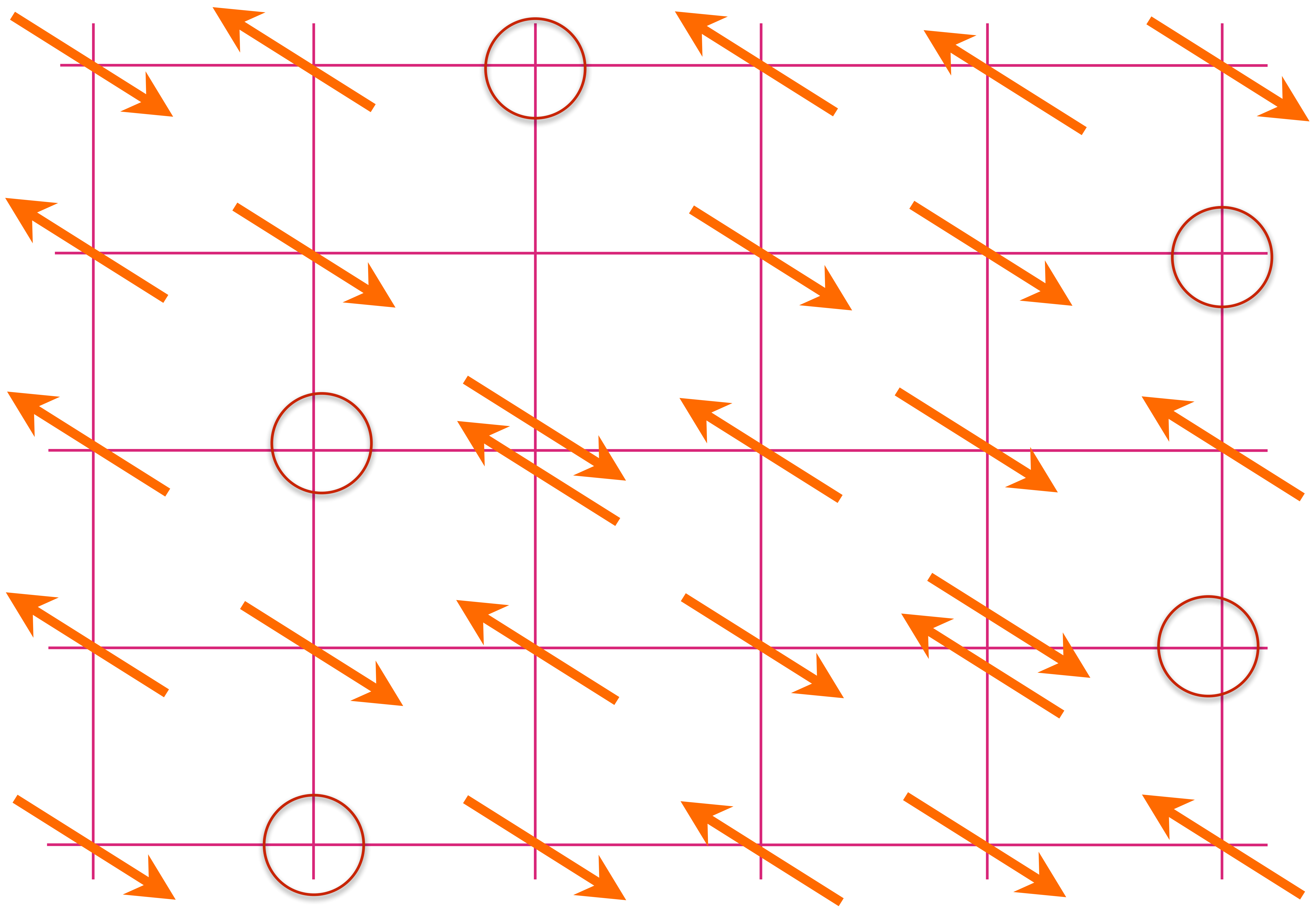
p mobile holes in a background of fluctuating spins

Momentum-space view at large p



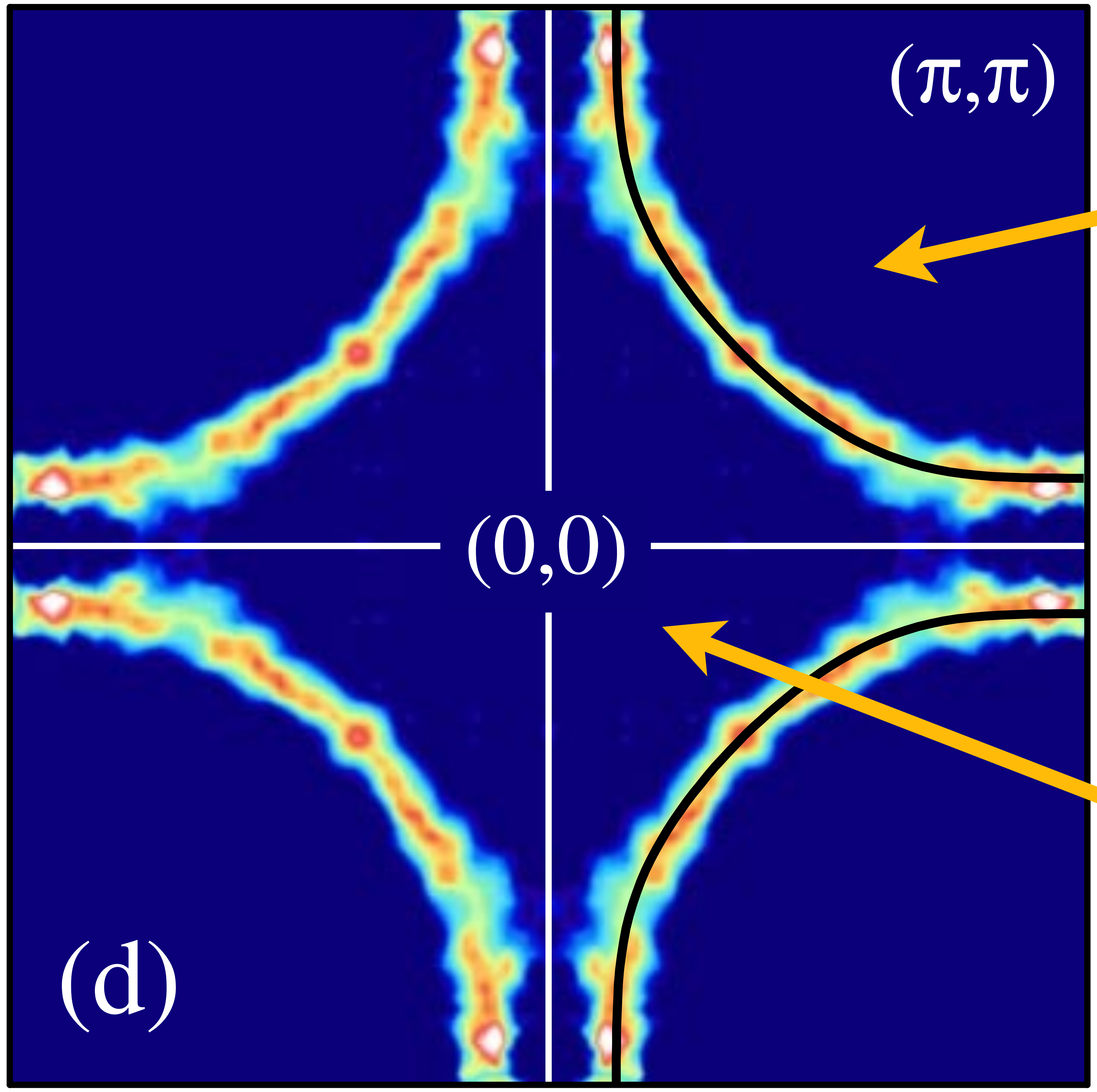
Filled Band

Momentum-space view at large p



$1\text{-}p$ mobile electrons =
$1+p$ mobile holes in a filled band

Momentum-space view at large p



$1+p$ holes

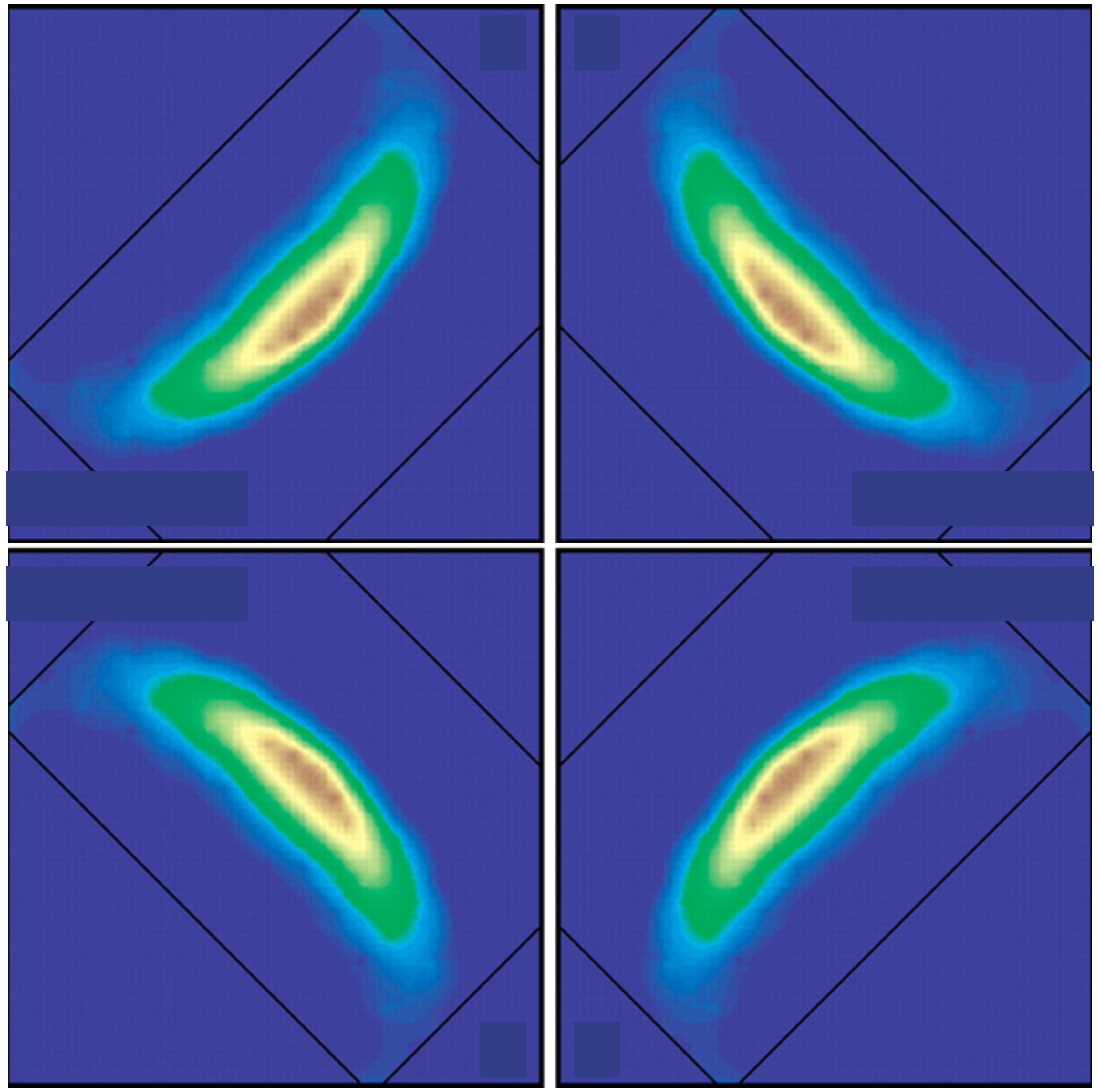
1-p electrons

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 $x = 0.10$

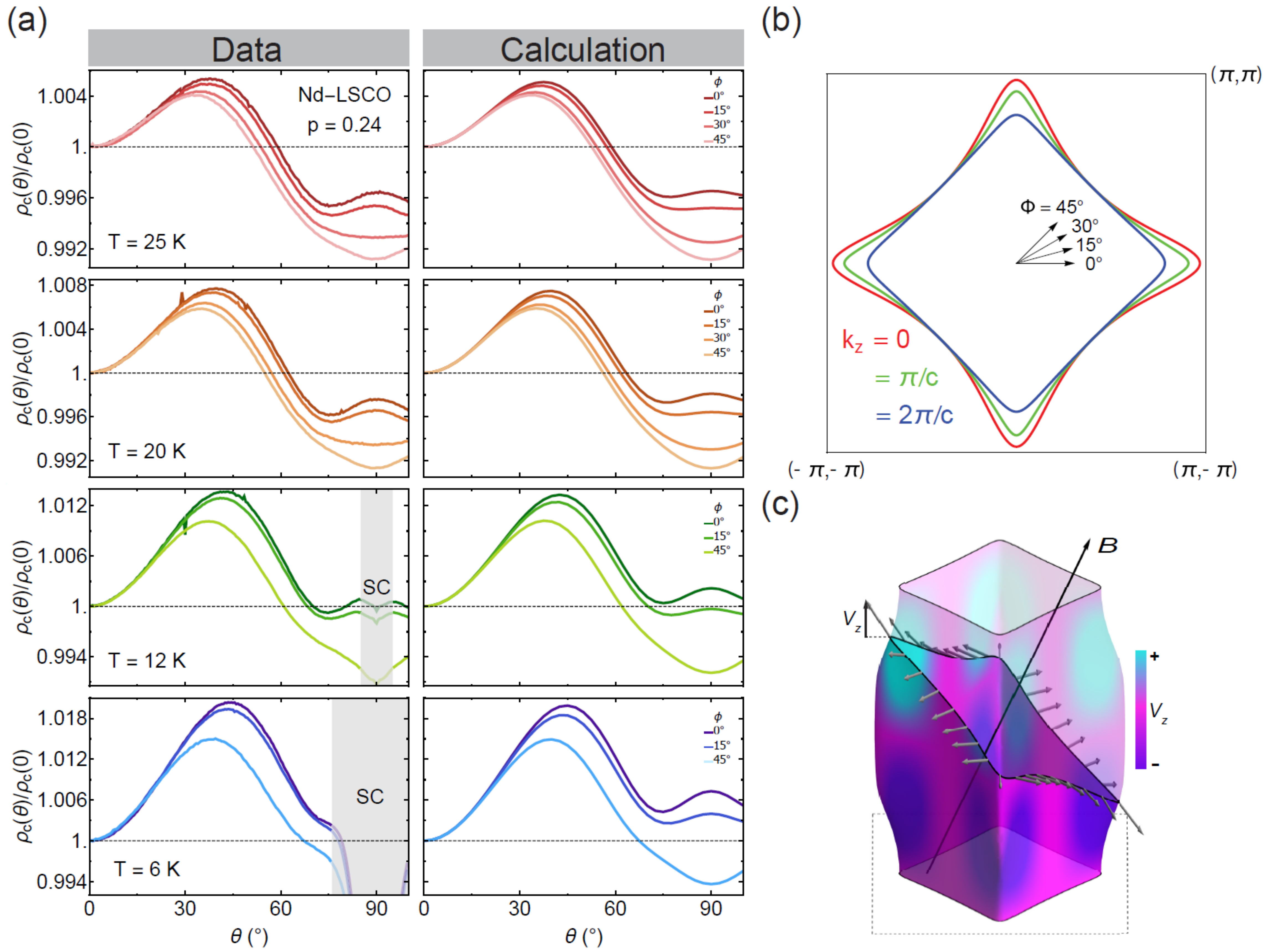
"Fermi arcs"

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)

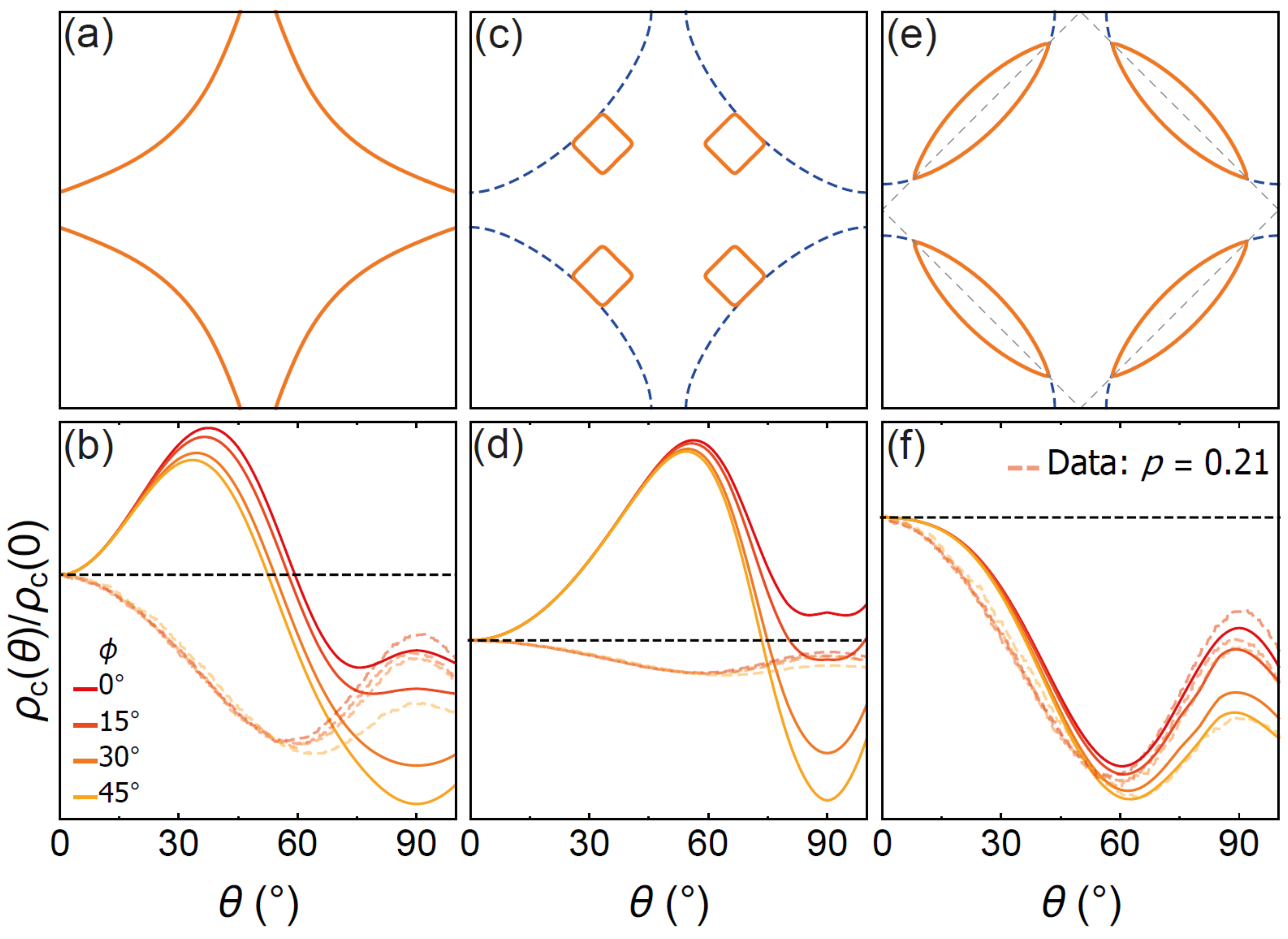
Fermi surface transformation at the pseudogap critical point of a cuprate superconductor

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

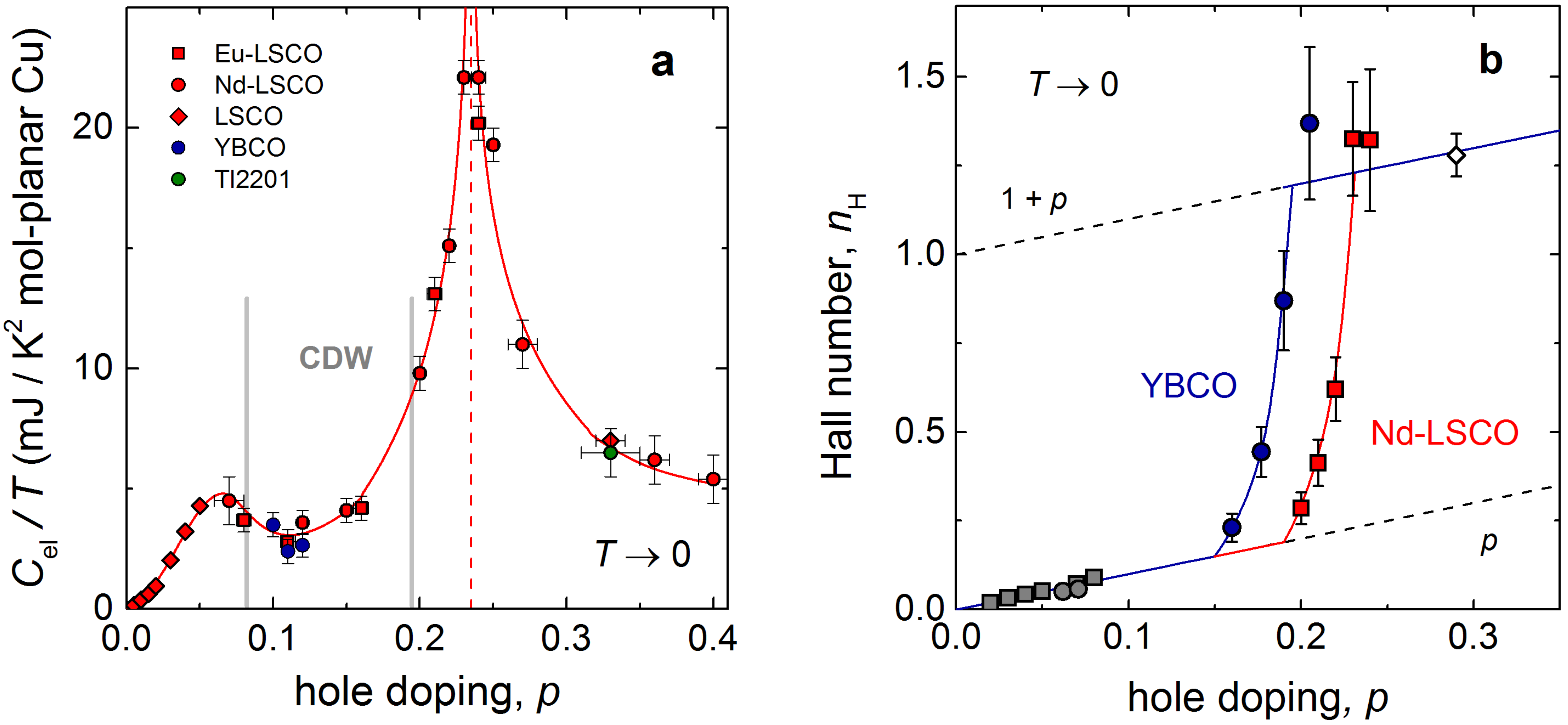


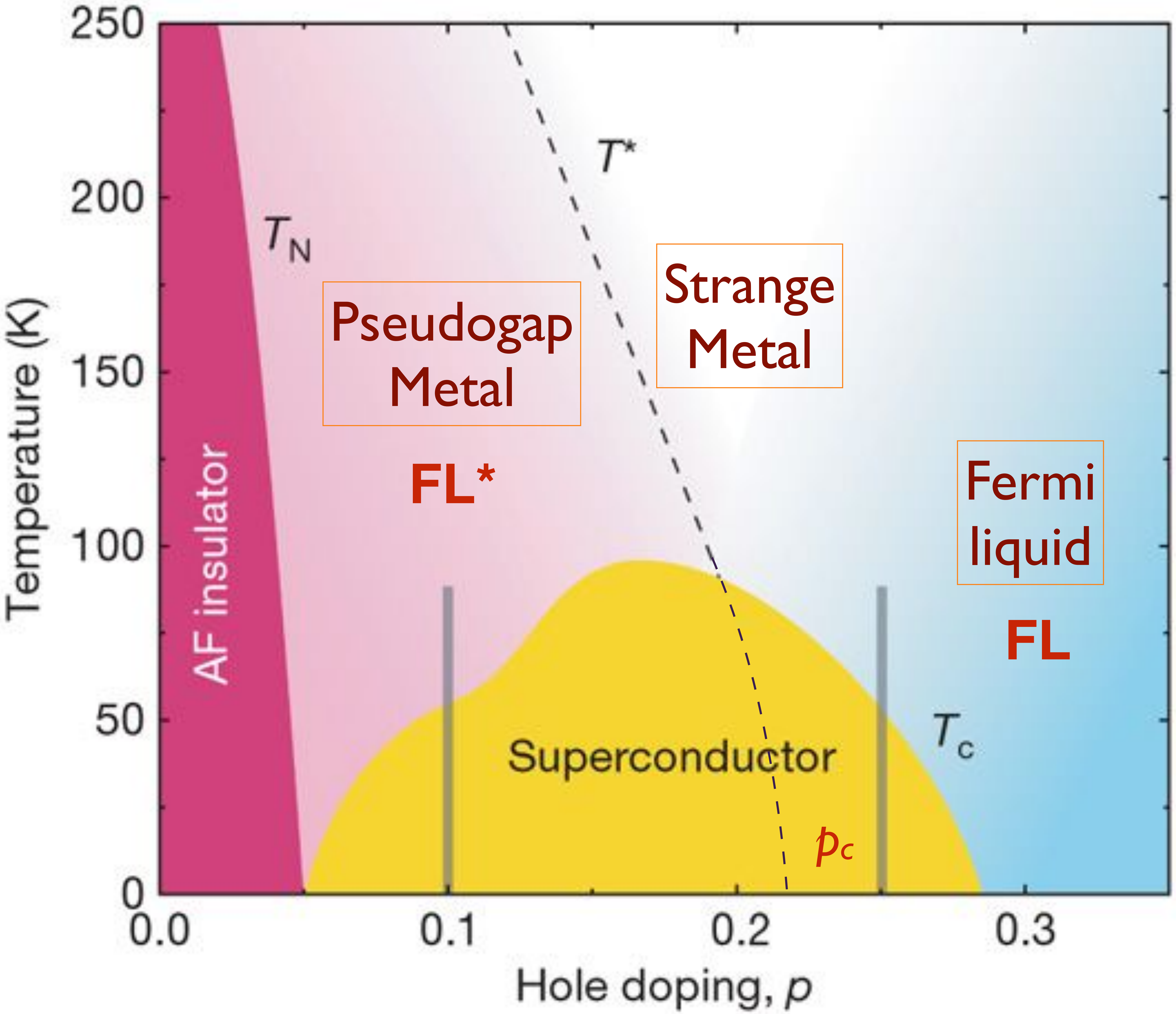
$p < p_c$ Reconstructed Fermi surface

Hole doped cuprates

The remarkable underlying ground states of cuprate superconductors

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





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
FL*
Strange
Metal
Fermi
liquid
FL
Superconductor
T_c
p_c

1. Luttinger volume violation in Kondo lattice models

The FL phase and $CeCoIn_5$*

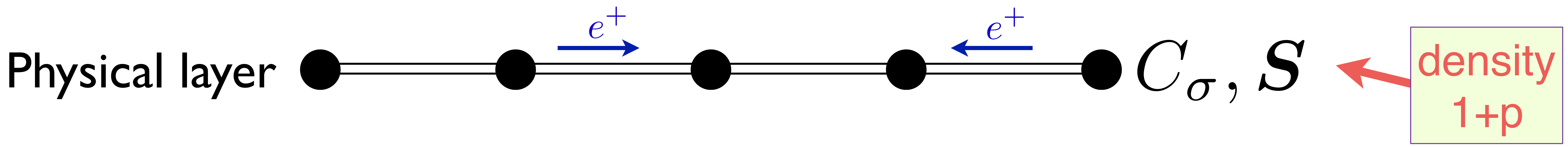
2. Introduction to cuprates

Small to Large Fermi surface transition

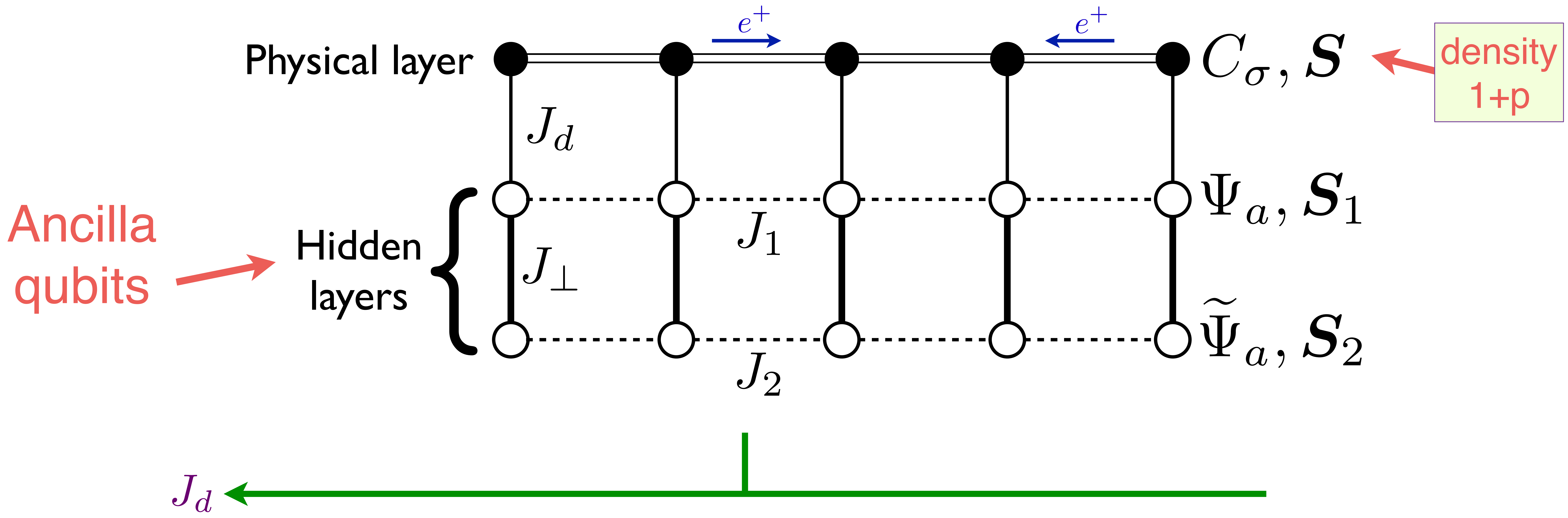
3. Luttinger volume violation a one-band model

Ancilla qubits and ghost Fermi surfaces

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



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

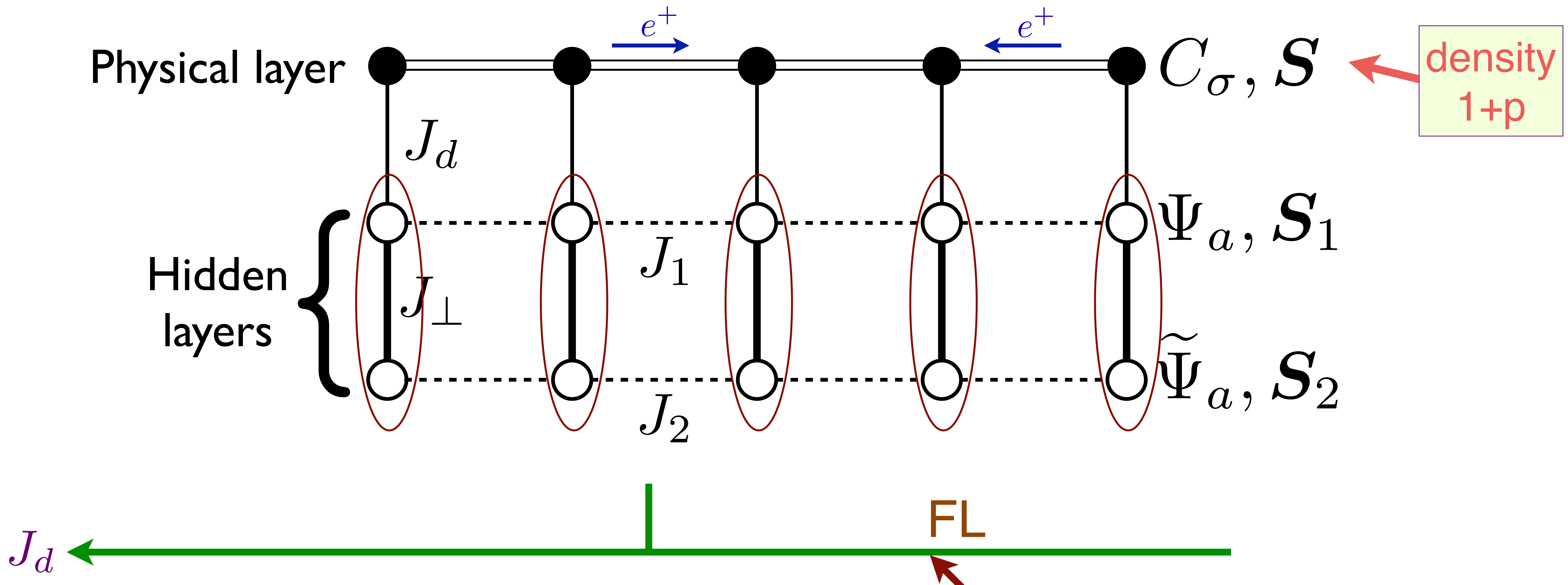


Ya-Hui Zhang

Precursor with one extra band of fermions in FL* phase:
Y. Qi and S. Sachdev, PRB **81**, 115129 (2010)
E. G. Moon and S. Sachdev, PRB **83**, 224508 (2011)

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

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

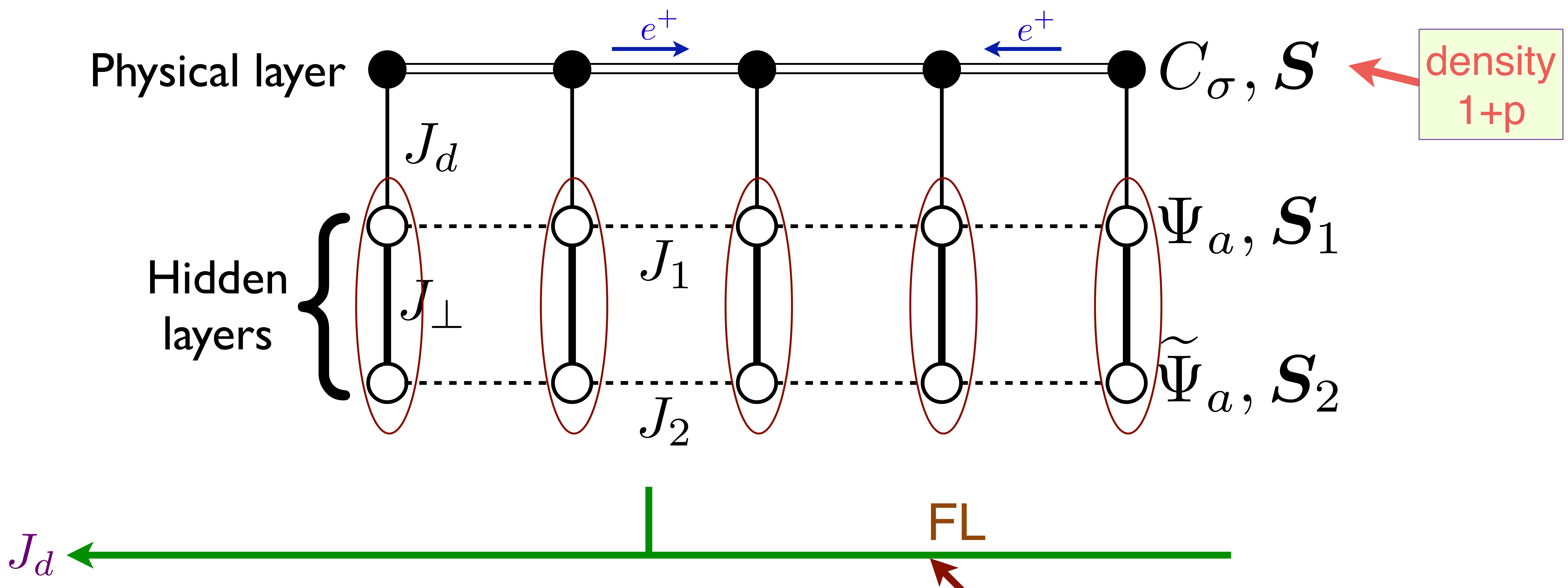


Large Fermi surface of size $1 + p$

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

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

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



Luttinger Theorem obeyed

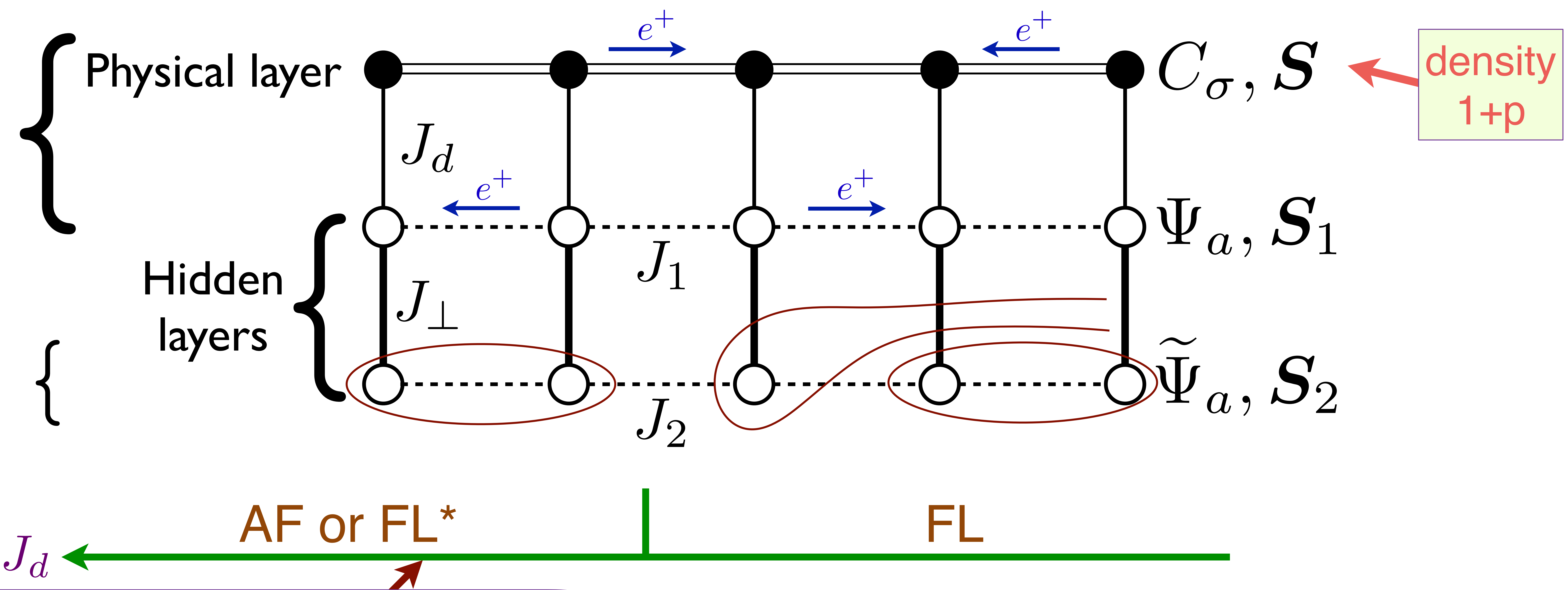
Large Fermi surface of size $1+p$

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

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

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

Metal.
Density
$2 + p \cong p$



Small Fermi surface of size p

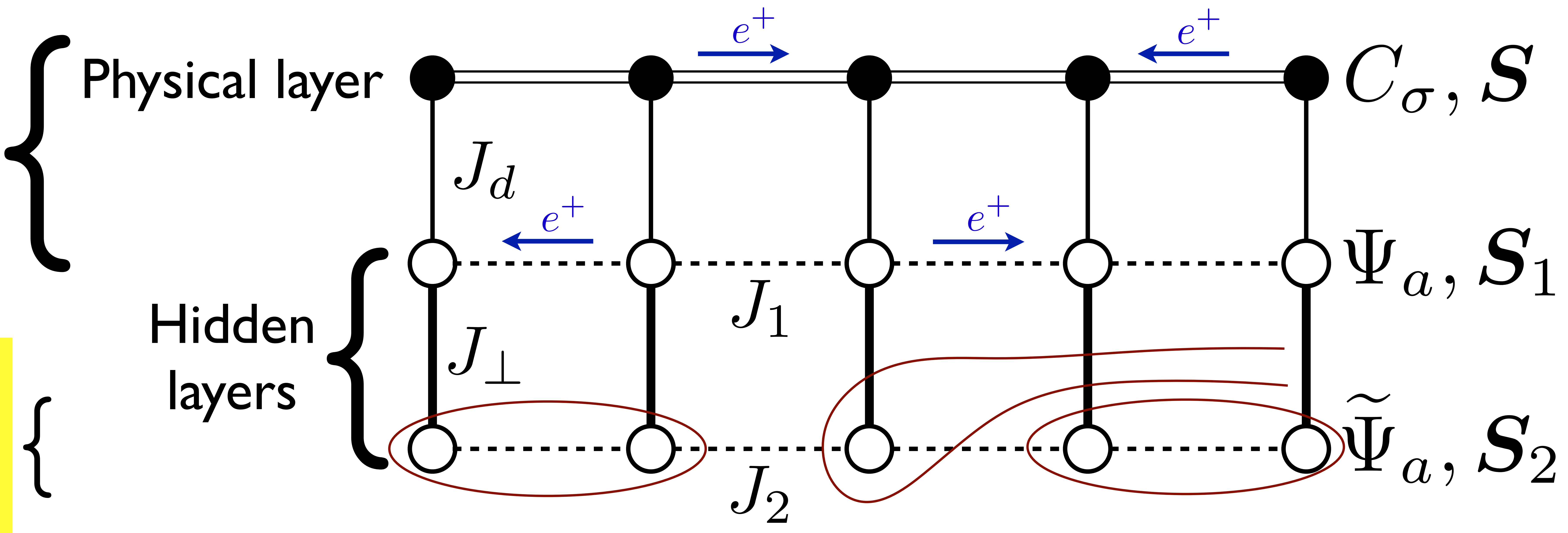
$$|\Phi\rangle = \left[\text{Projection onto rung singlets of } \Psi, \widetilde{\Psi}\right] \bowtie \left|\text{Slater determinant of } (C, \Psi)\right\rangle \otimes \left|\text{Slater determinant of } \widetilde{\Psi}\right\rangle$$

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

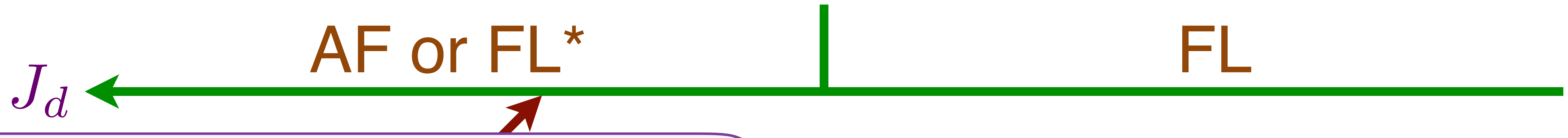
FL* and FL in a ***one-band*** model

Metal.
Density
$2 + p \cong p$

Mott insulator
Spin liquid
or AF order



density
1+p



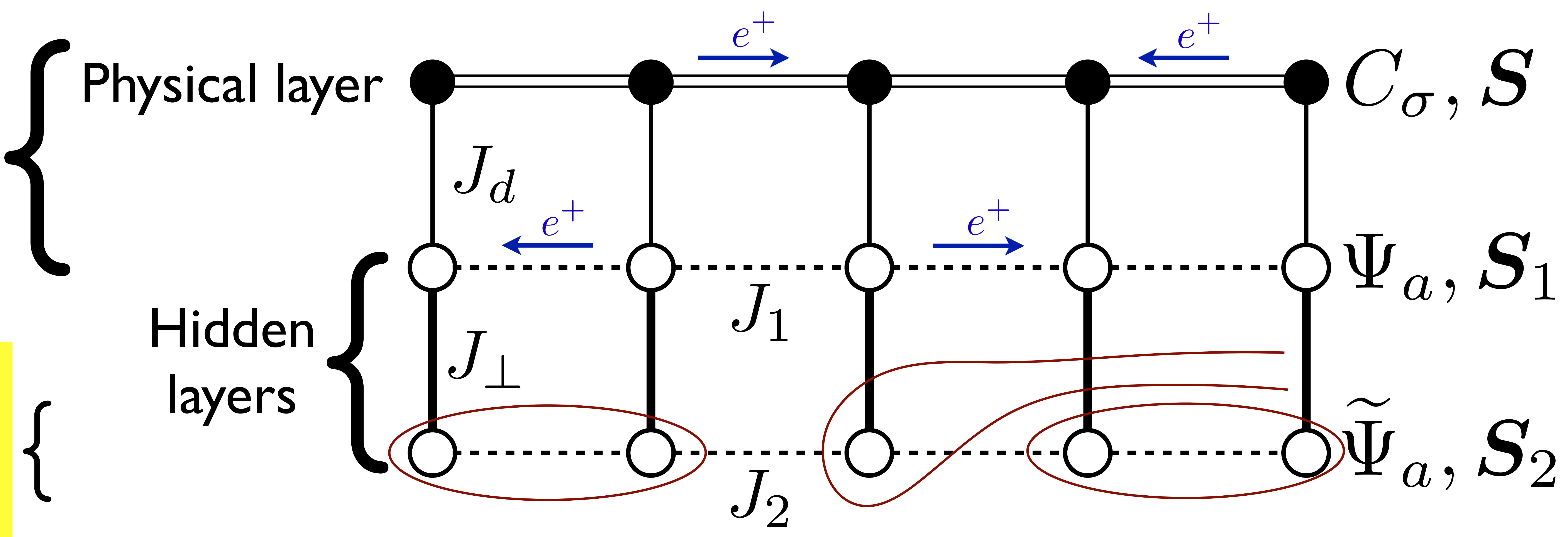
Small Fermi surface of size p

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

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

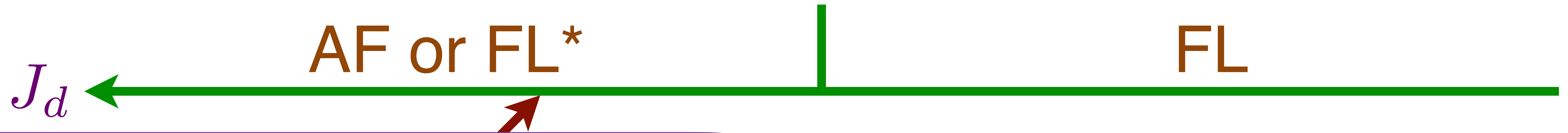
FL* and FL in a ***one-band*** model

Metal.
Density
$2 + p \cong p$



density
1+p

Mott insulator
Spin liquid
or AF order



Small Fermi surface of size p

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

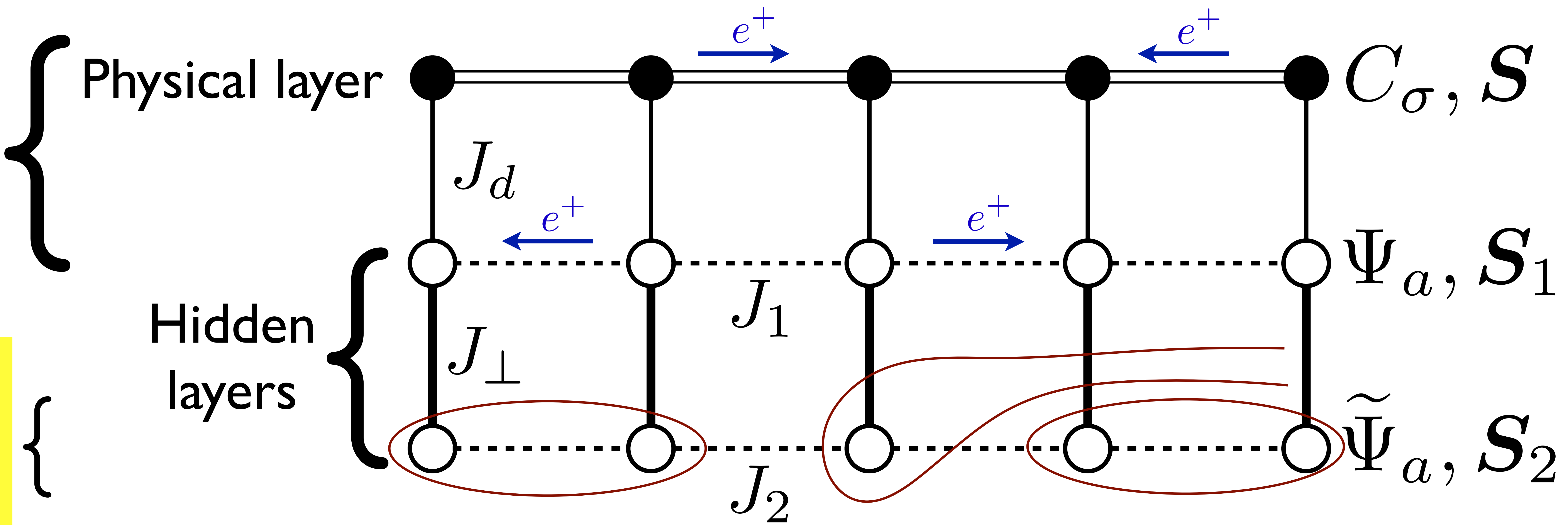
Luttinger Theorem
violated;
OK, because of
topological order of $\widetilde{\Psi}$

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

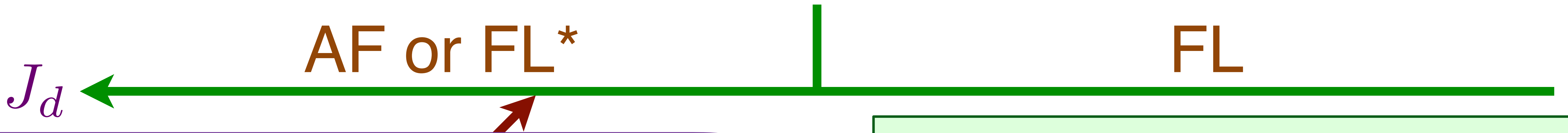
FL* and FL in a ***one-band*** model

Metal.
Density
$2 + p \cong p$

Mott insulator
Spin liquid
or AF order



density
1+p



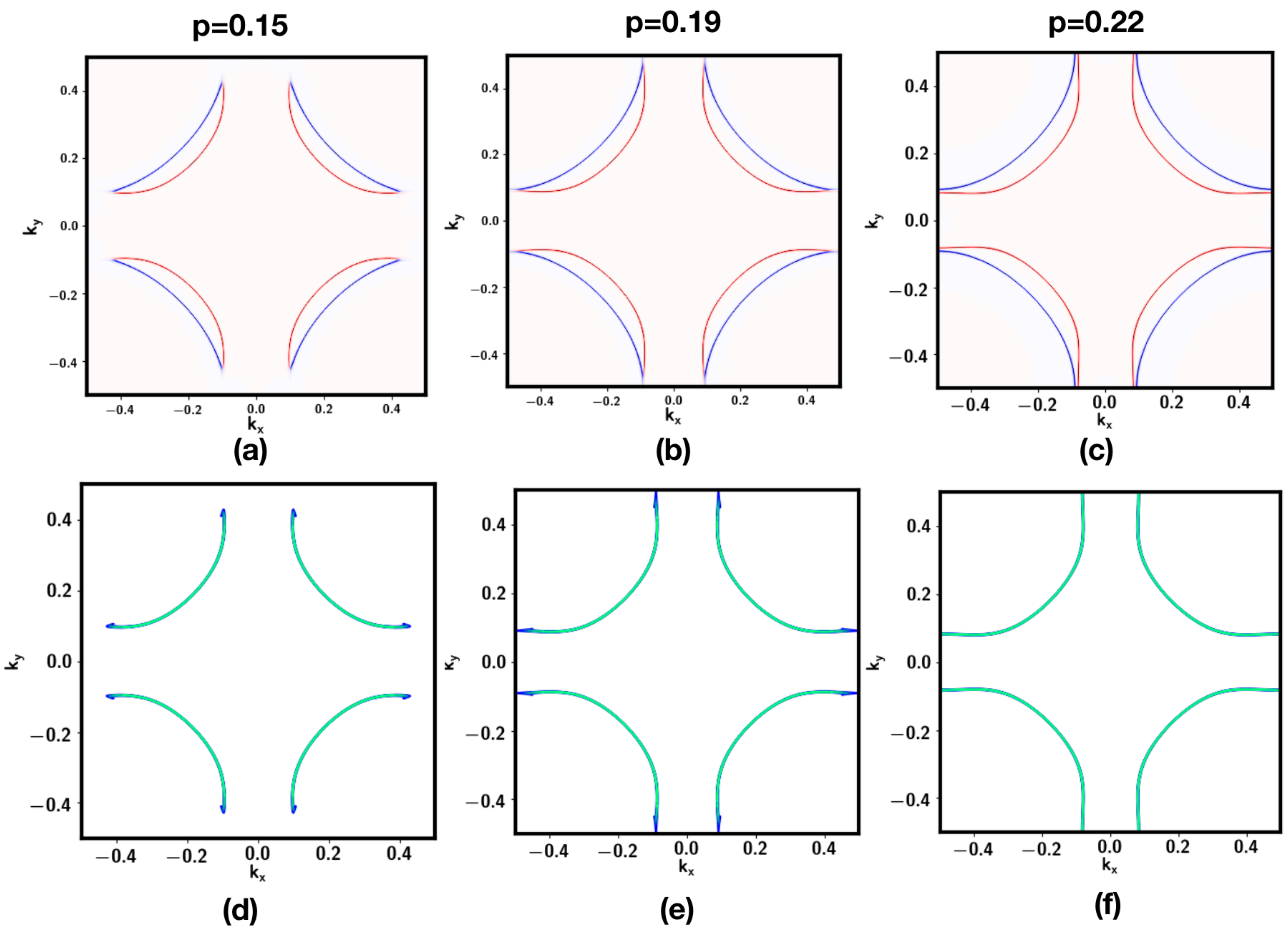
Small Fermi surface of size p

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

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, S. Sachdev, PRR **2**, 023172; PRB **102**, 155124 (2020)

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

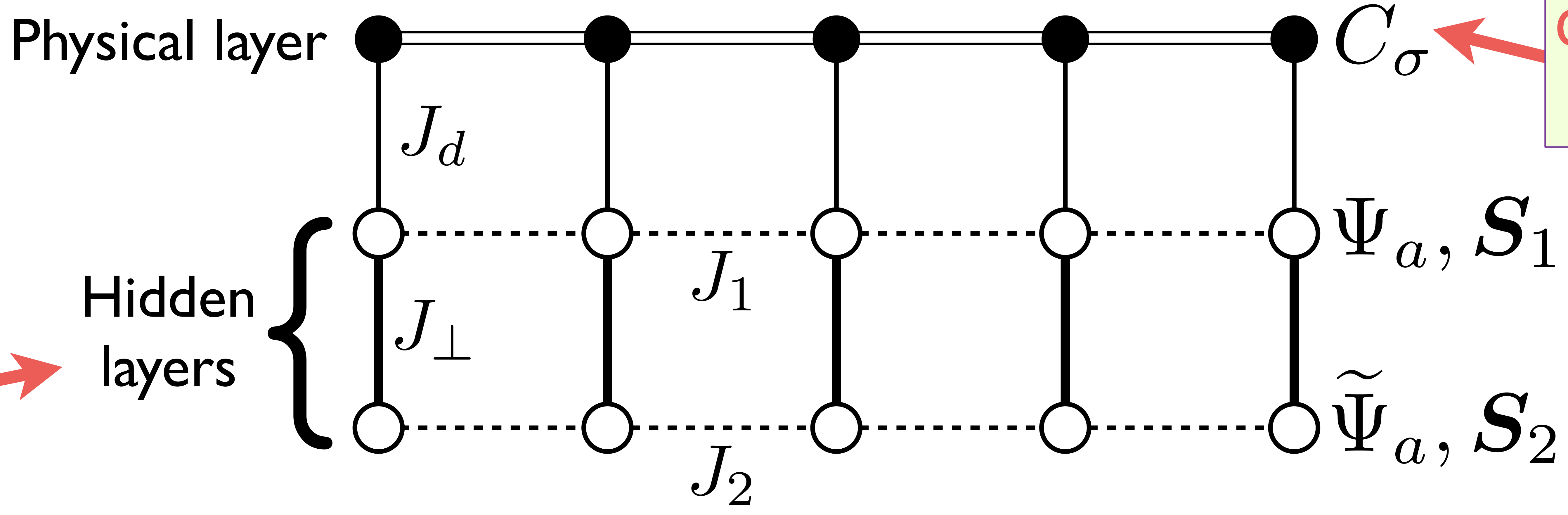


"Fermi arc" spectral functions in the FL* phase

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

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

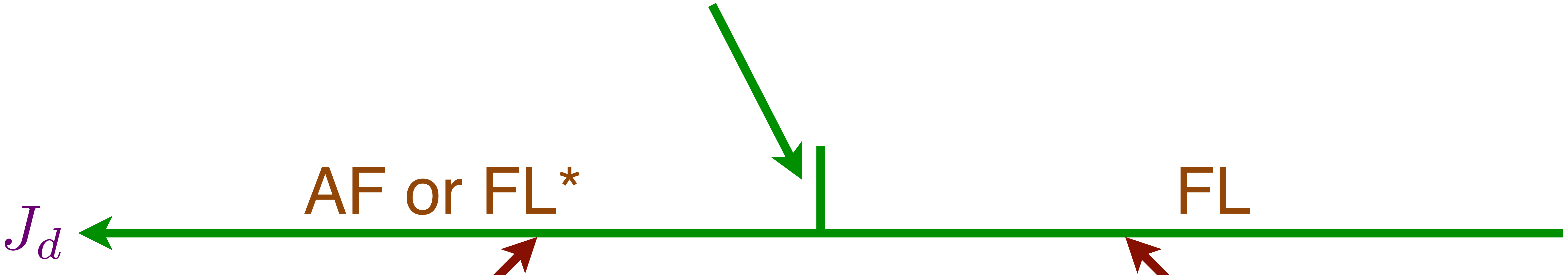
FL* and FL in a ***one-band*** model



density 1+p

Ancilla qubits

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:

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

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

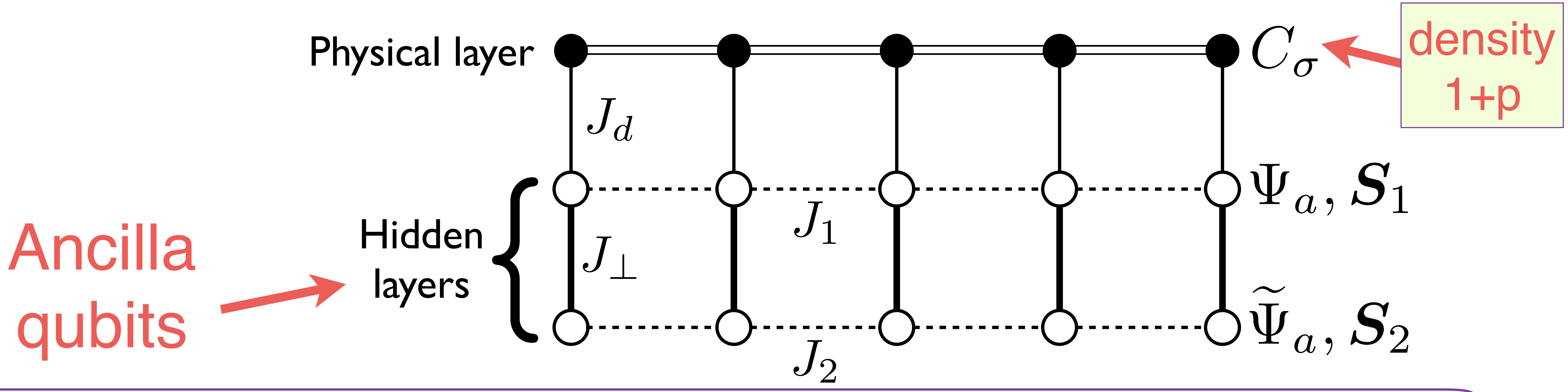
Local singlet formation ('antiferromagnetism') $\boldsymbol{S}_1 + \boldsymbol{S}_2 \approx 0$ leads to $\mathrm{SU}(2)_S$ gauge symmetry:

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

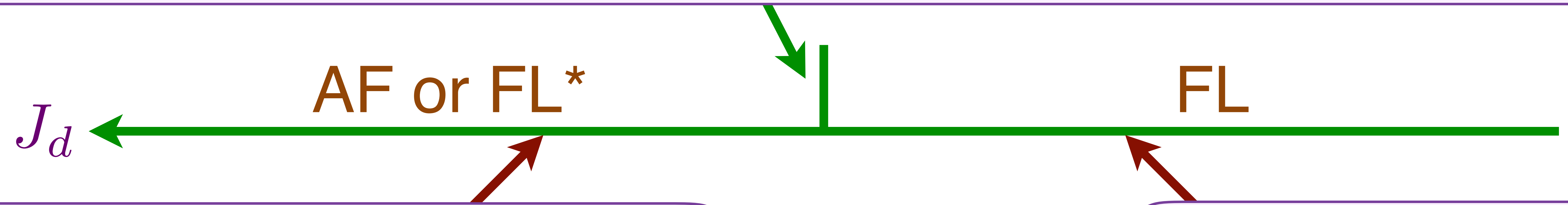
S. Sachdev, M.A. Metlitski, Yang Qi, and Cenke Xu, PRB **80**, 155129 (2009)
S. Sachdev, H. D. Scammell, M. S. Scheurer, and G. Tarnopolsky, PRB **99**, 054516 (2019)

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

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



$(\mathrm{U}(1)_S \times \mathrm{U}(1)_1)/Z_2$ 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.



Small Fermi surface of size p

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

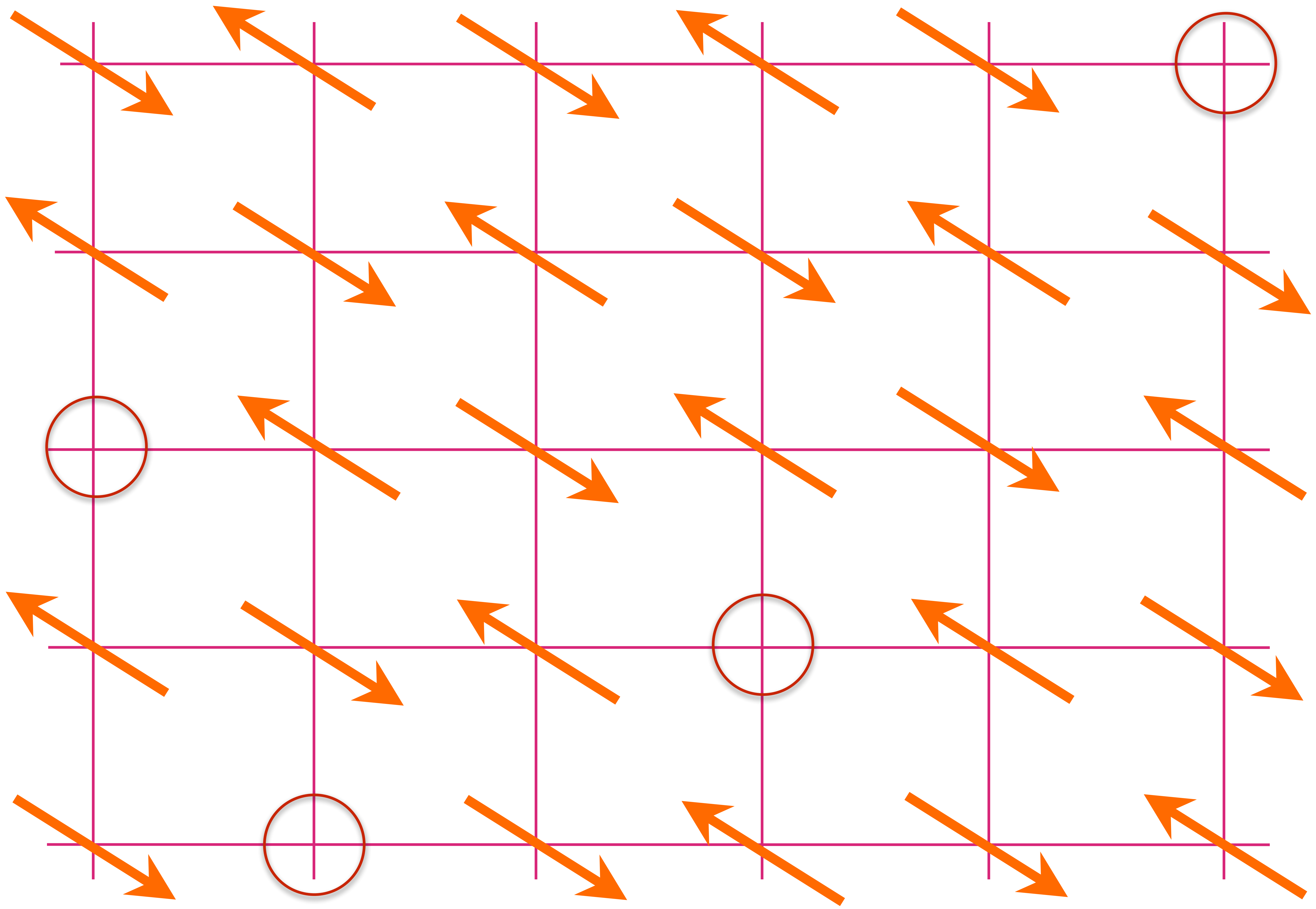
Large Fermi surface of size $1 + p$

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

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

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

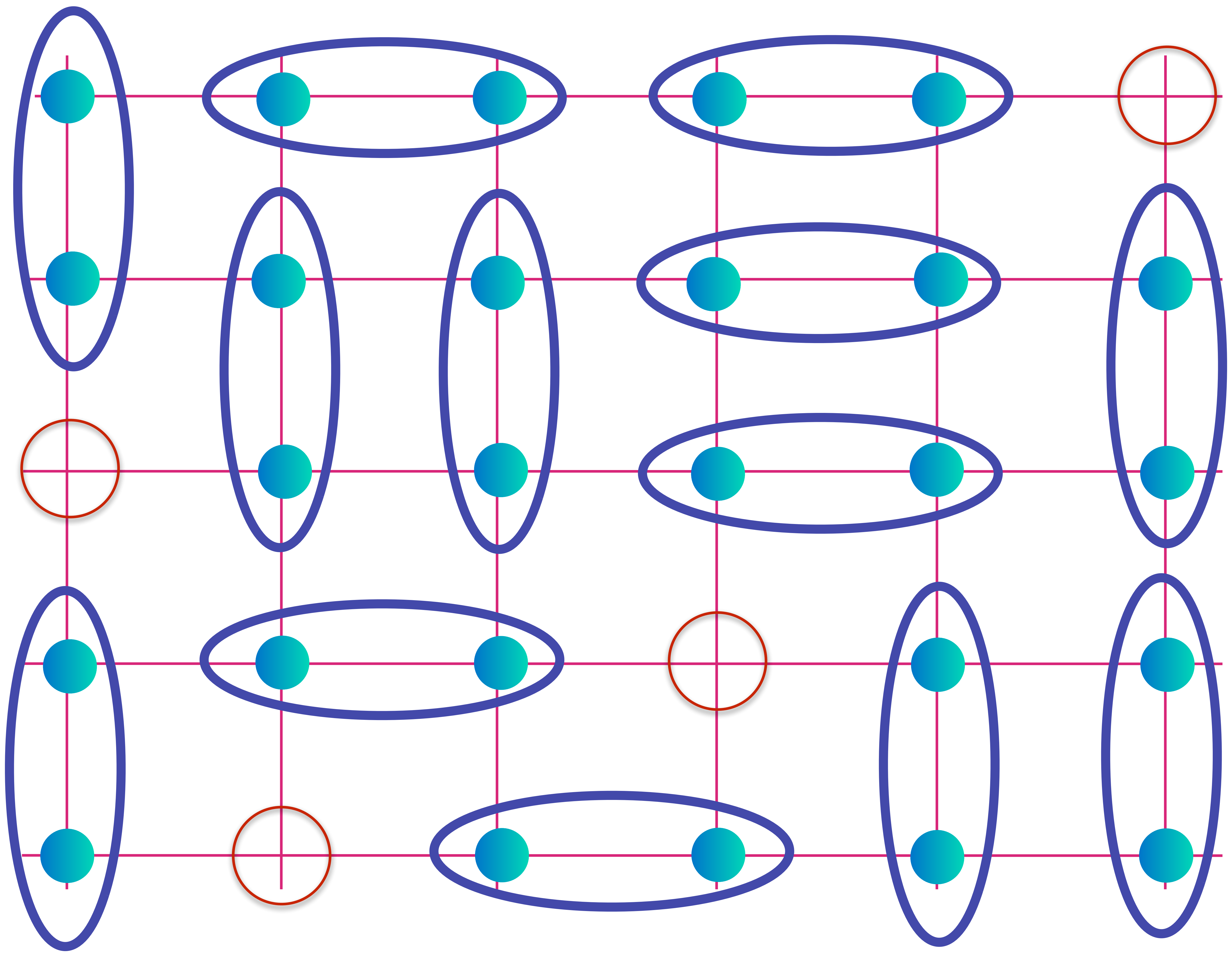
Earlier approach to FL* in a ***one-band*** model



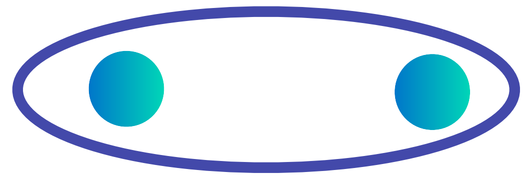
Anti-ferromagnet with p holes per square

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)

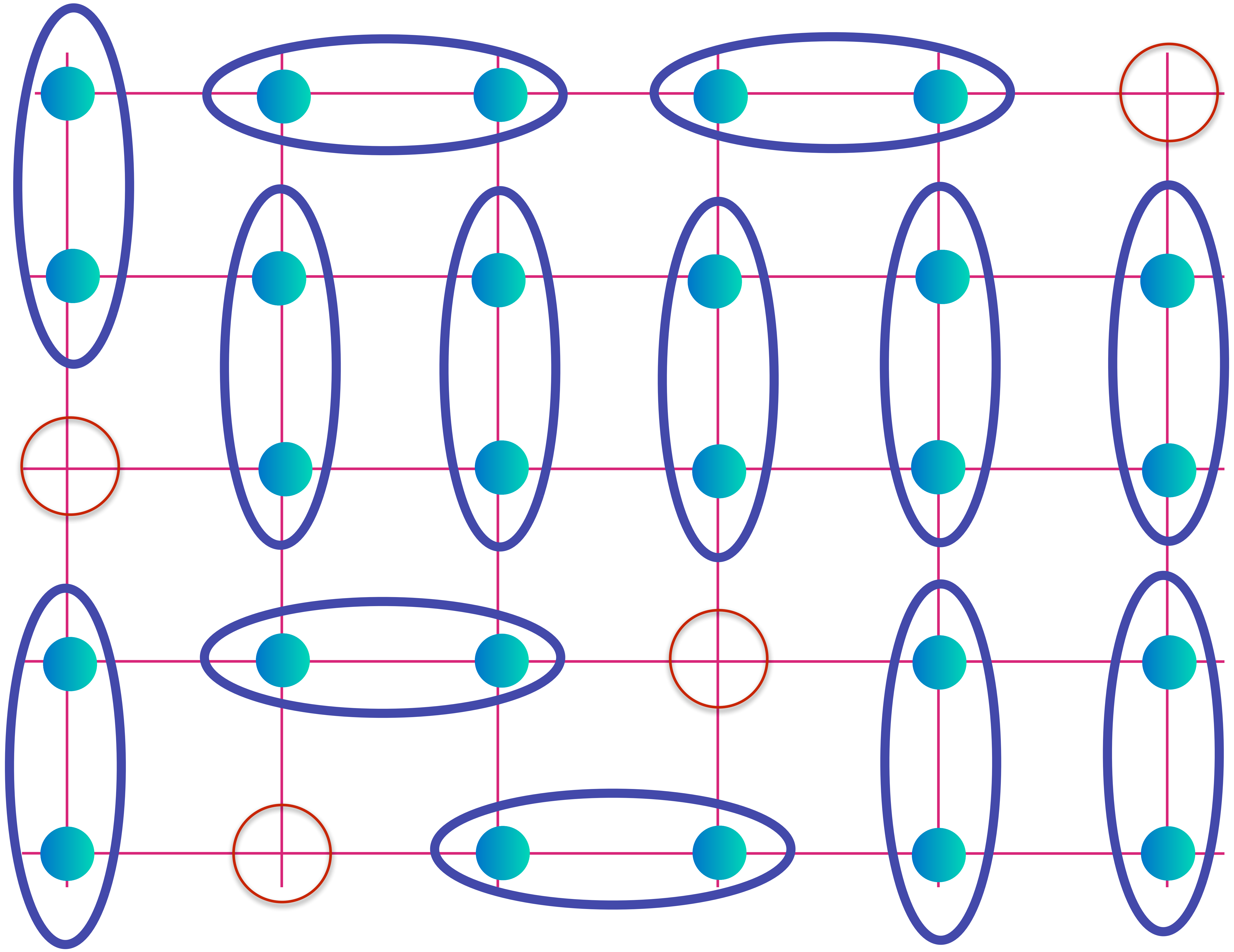


Spin liquid with density p of spinless, charge +e "holons".

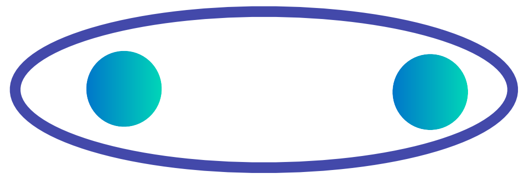
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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".

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

Holon metal

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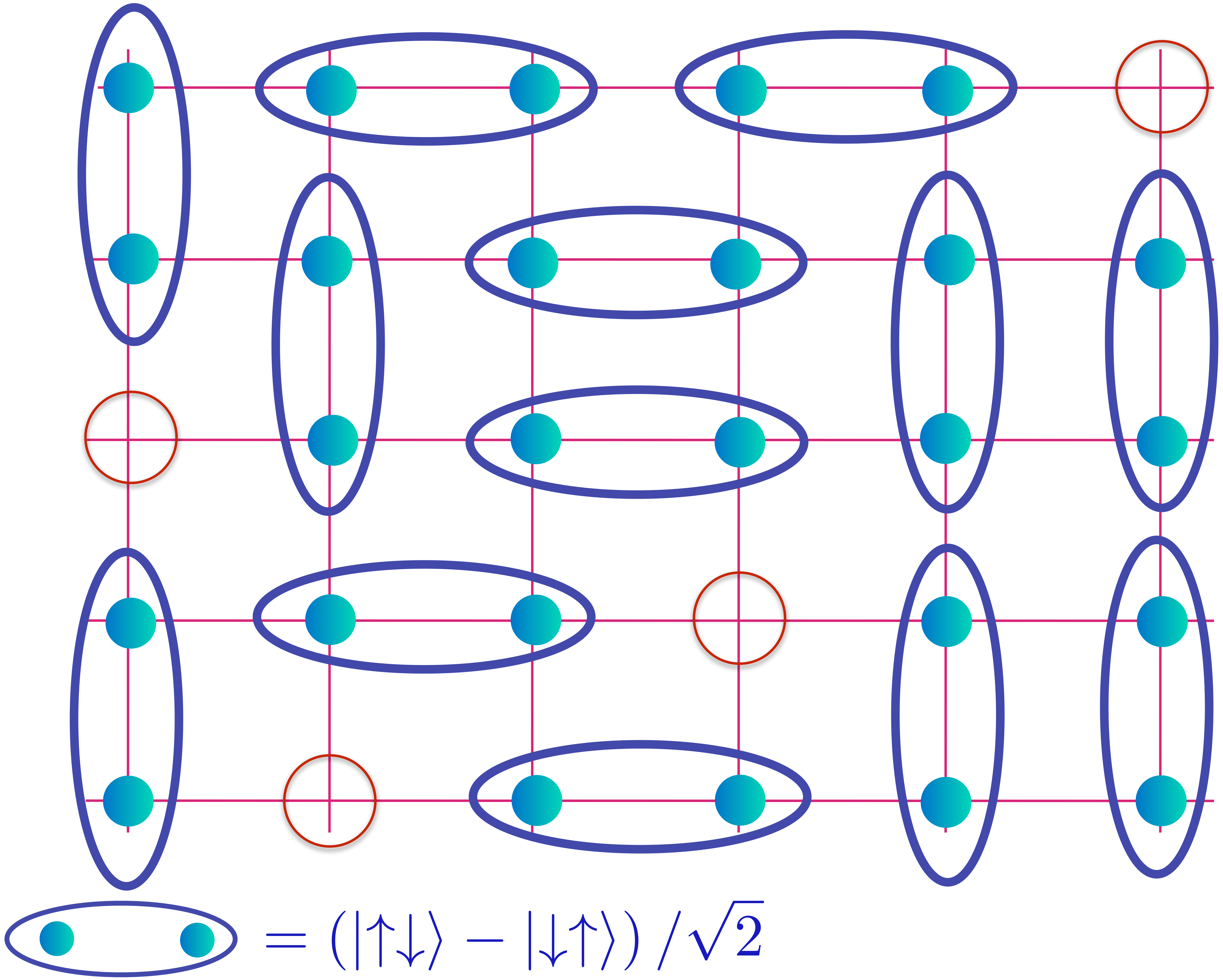

$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$$

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

Holon metal

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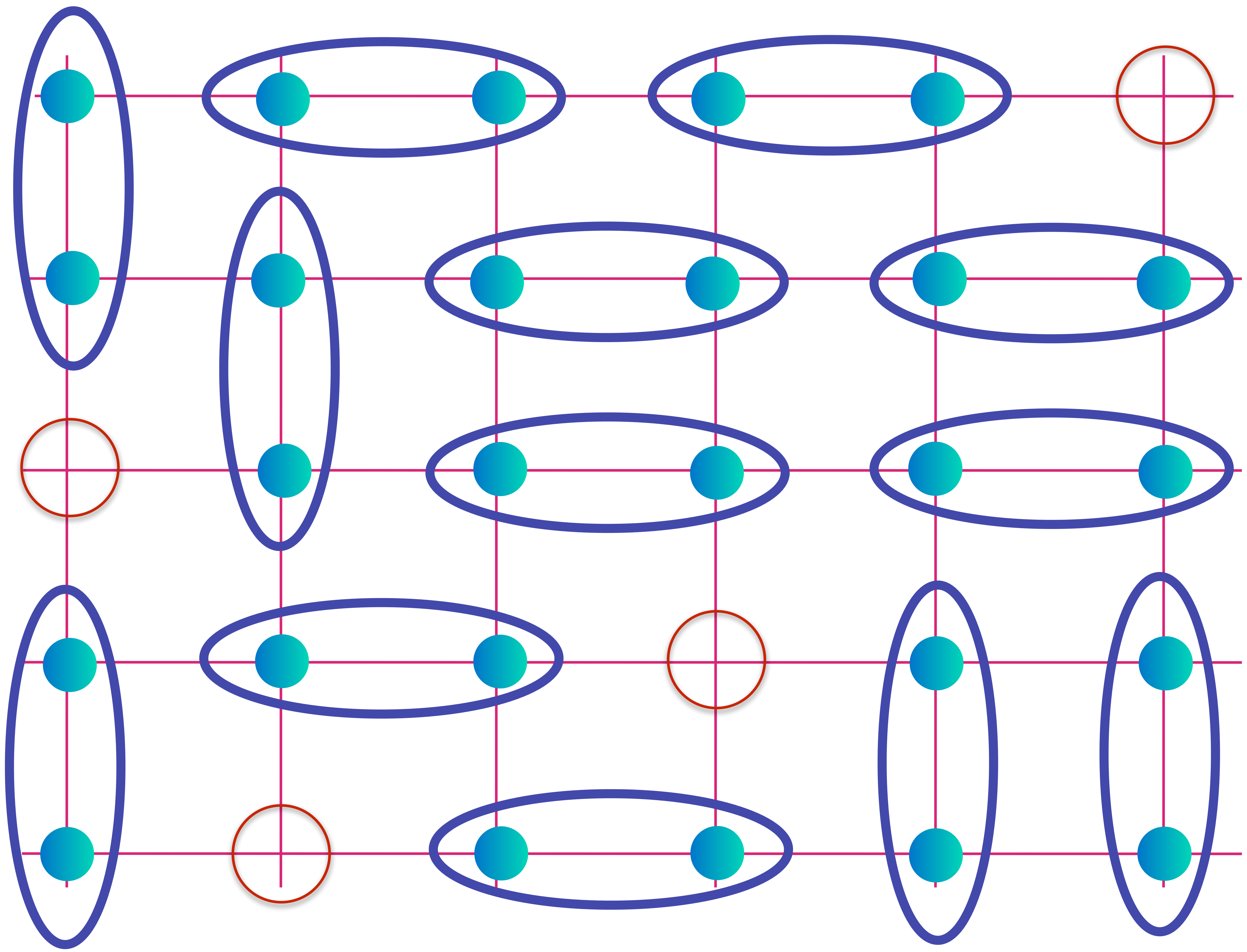
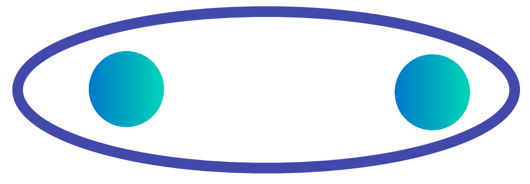
D. Rokhsar and S.A. Kivelson, PRL **61**, 2376 (1988)



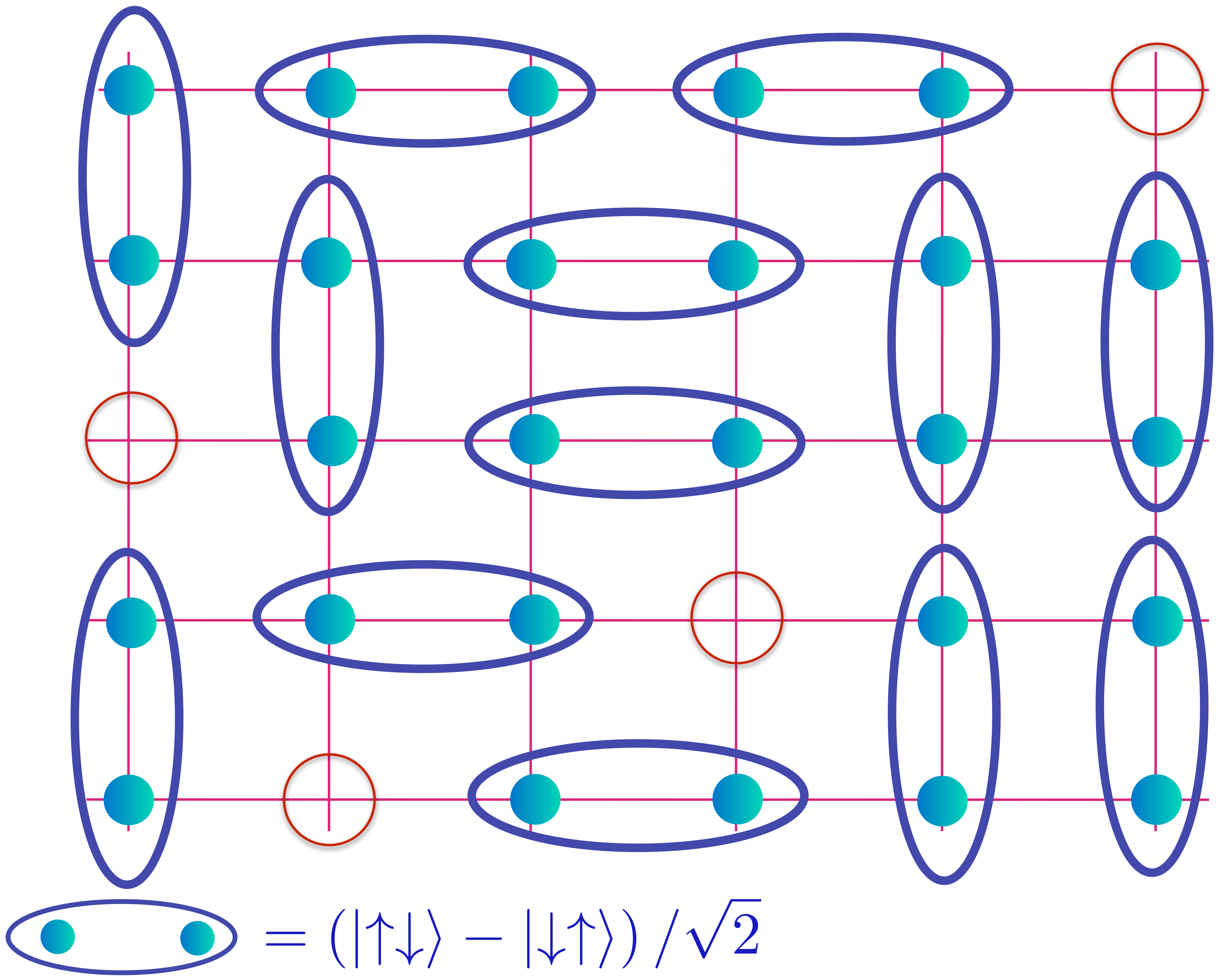
Spin liquid with density p of spinless, charge +e "holons".



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

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)

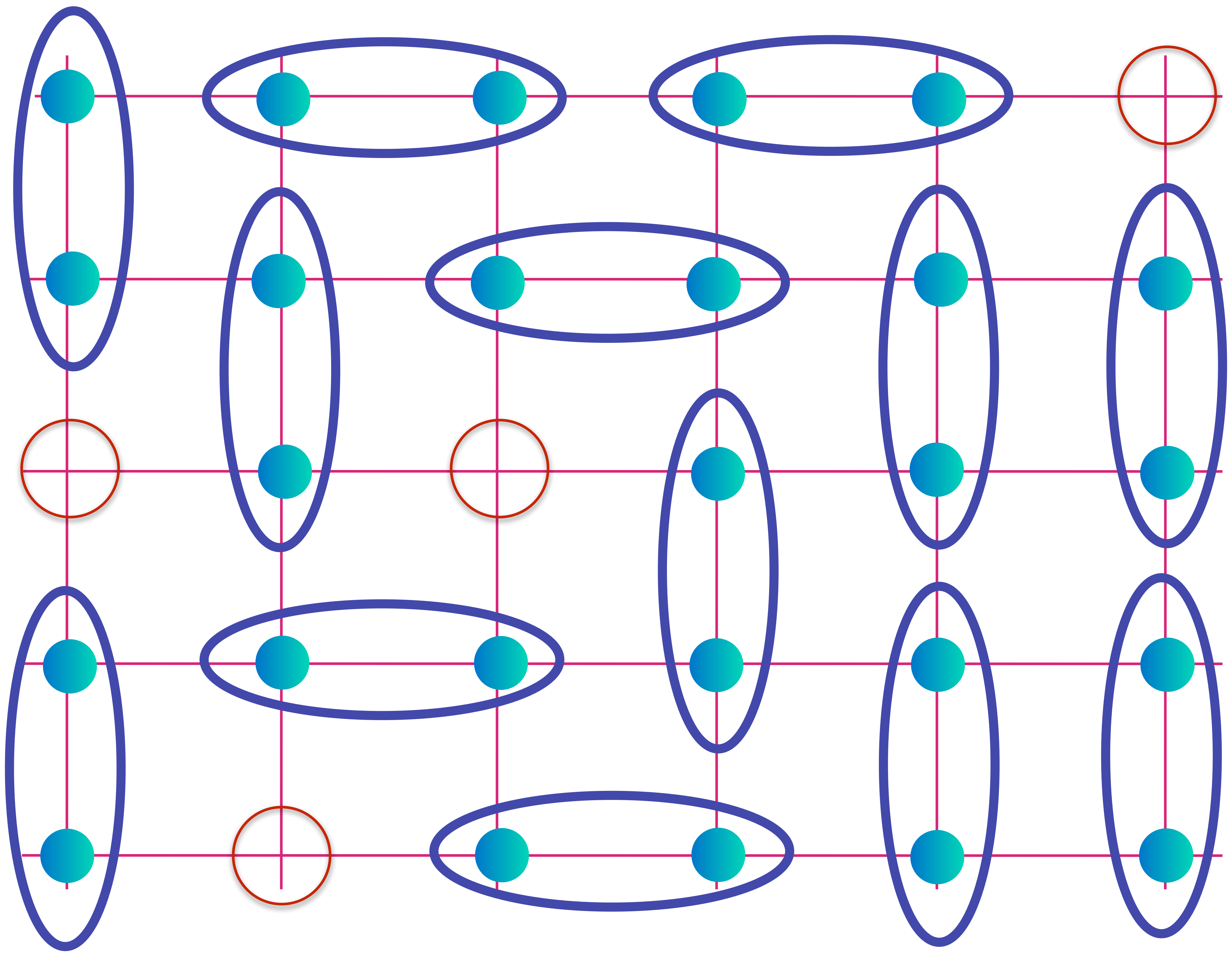


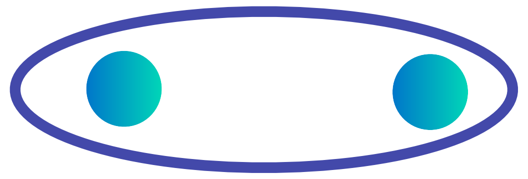
$$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$$

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

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

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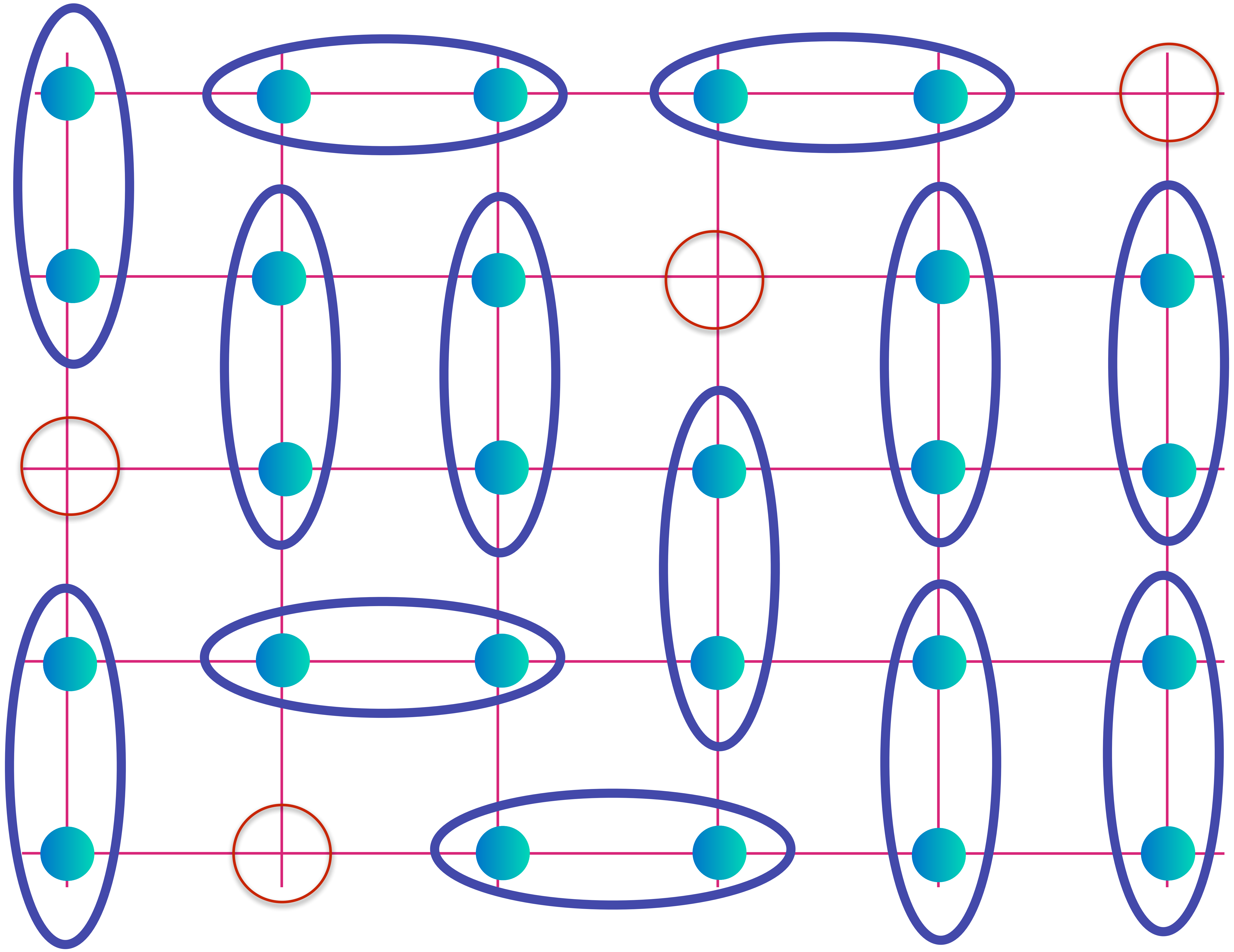

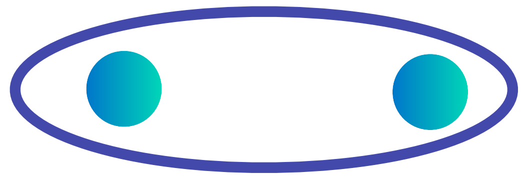 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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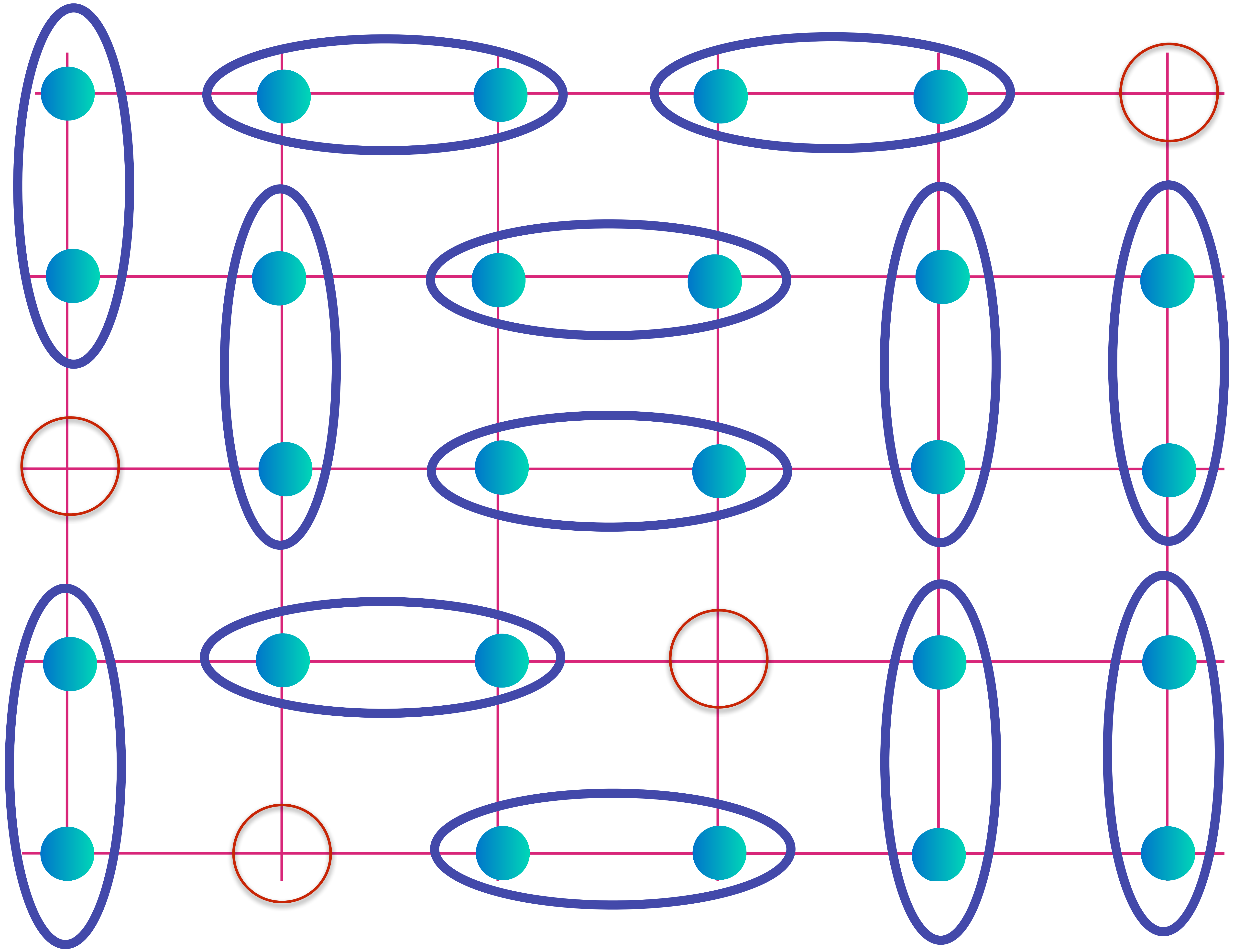

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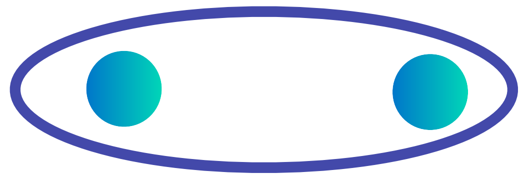 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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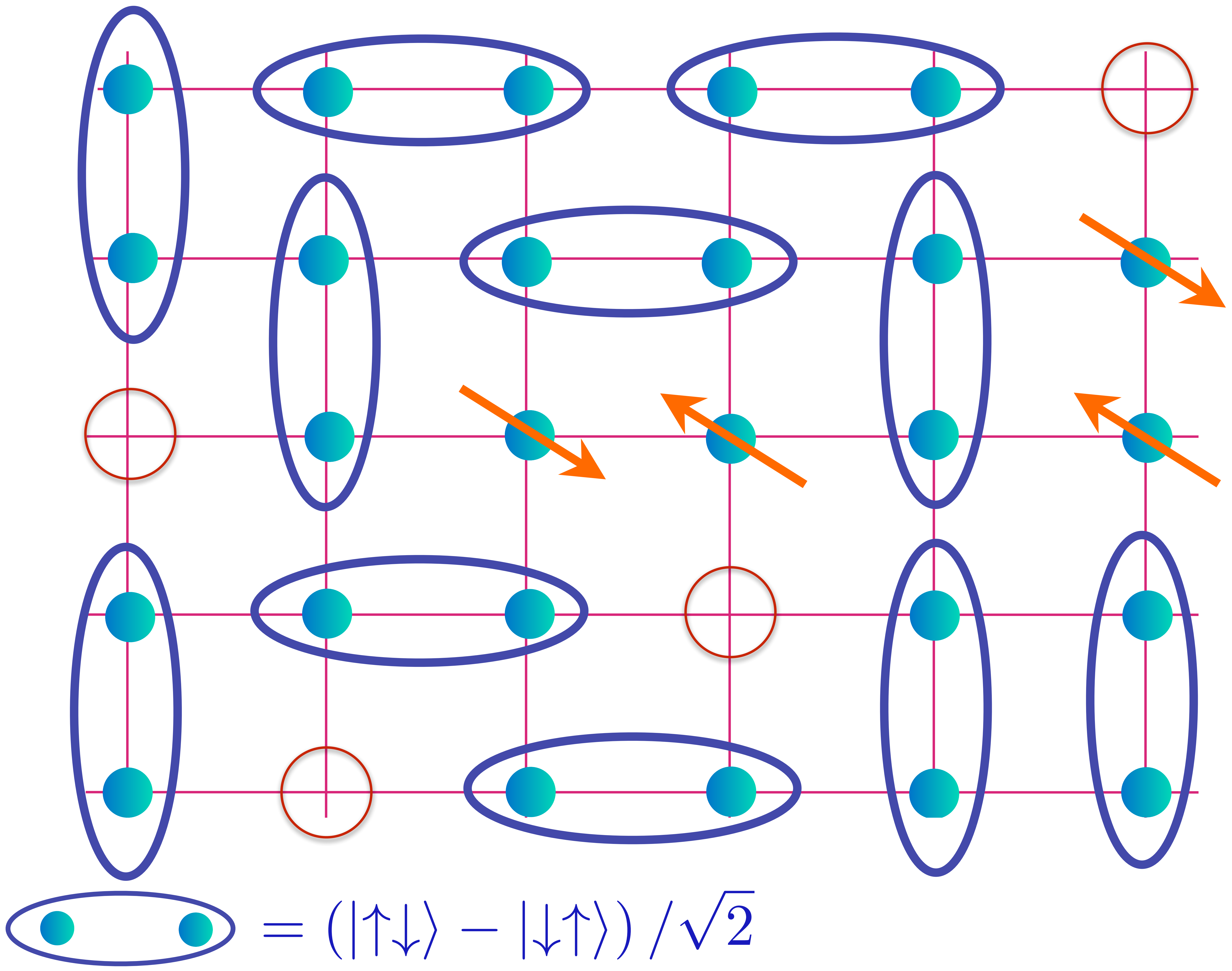

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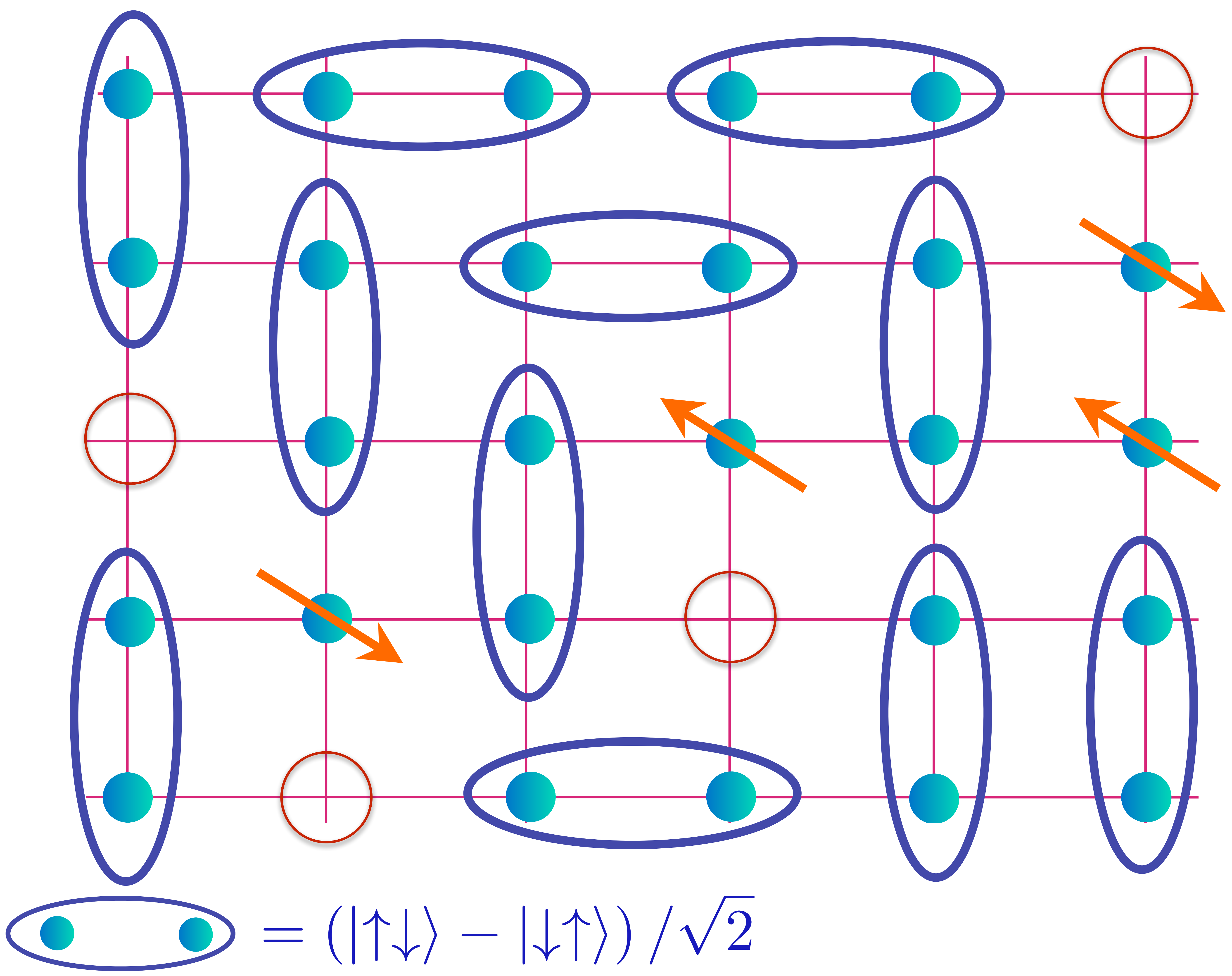

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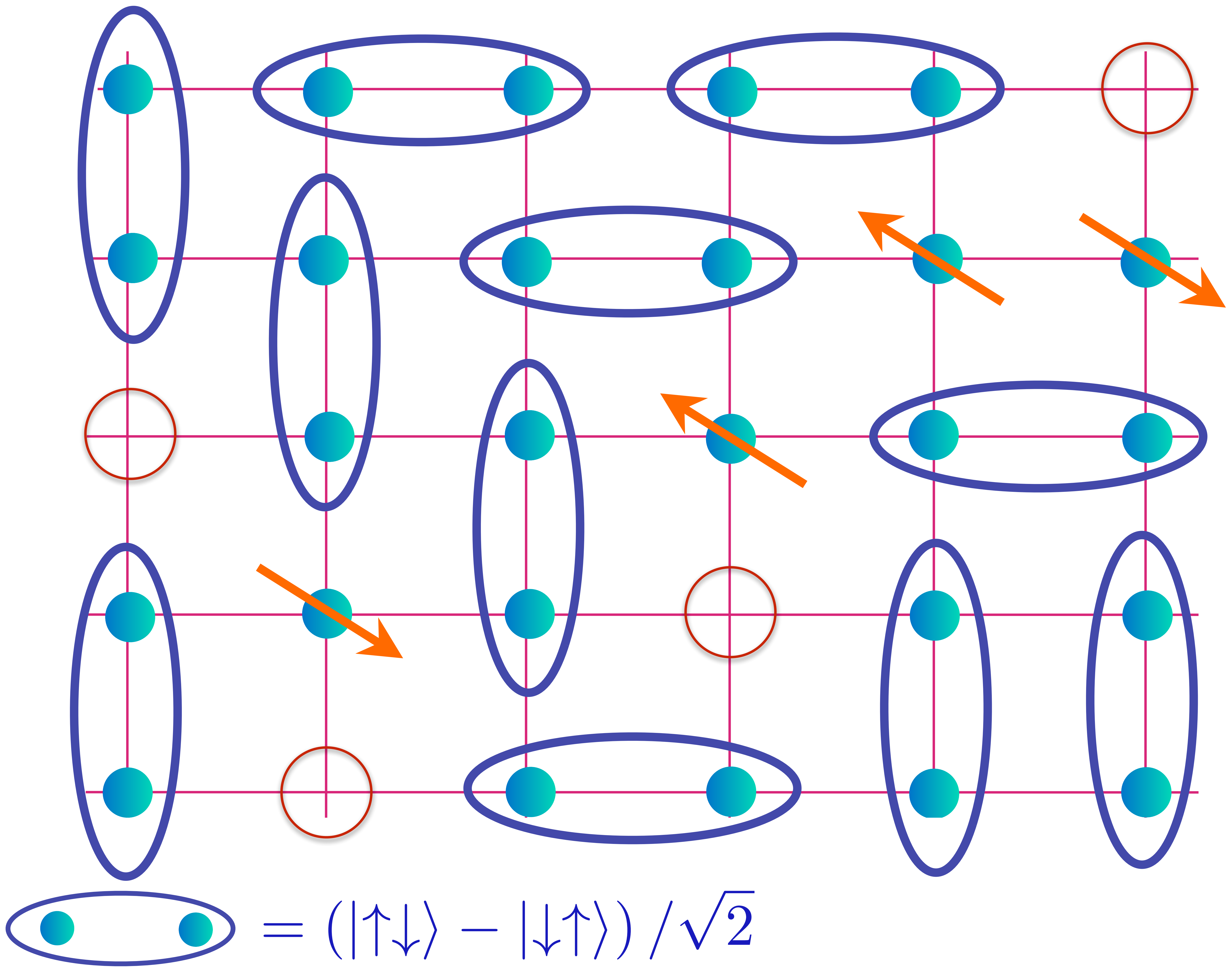

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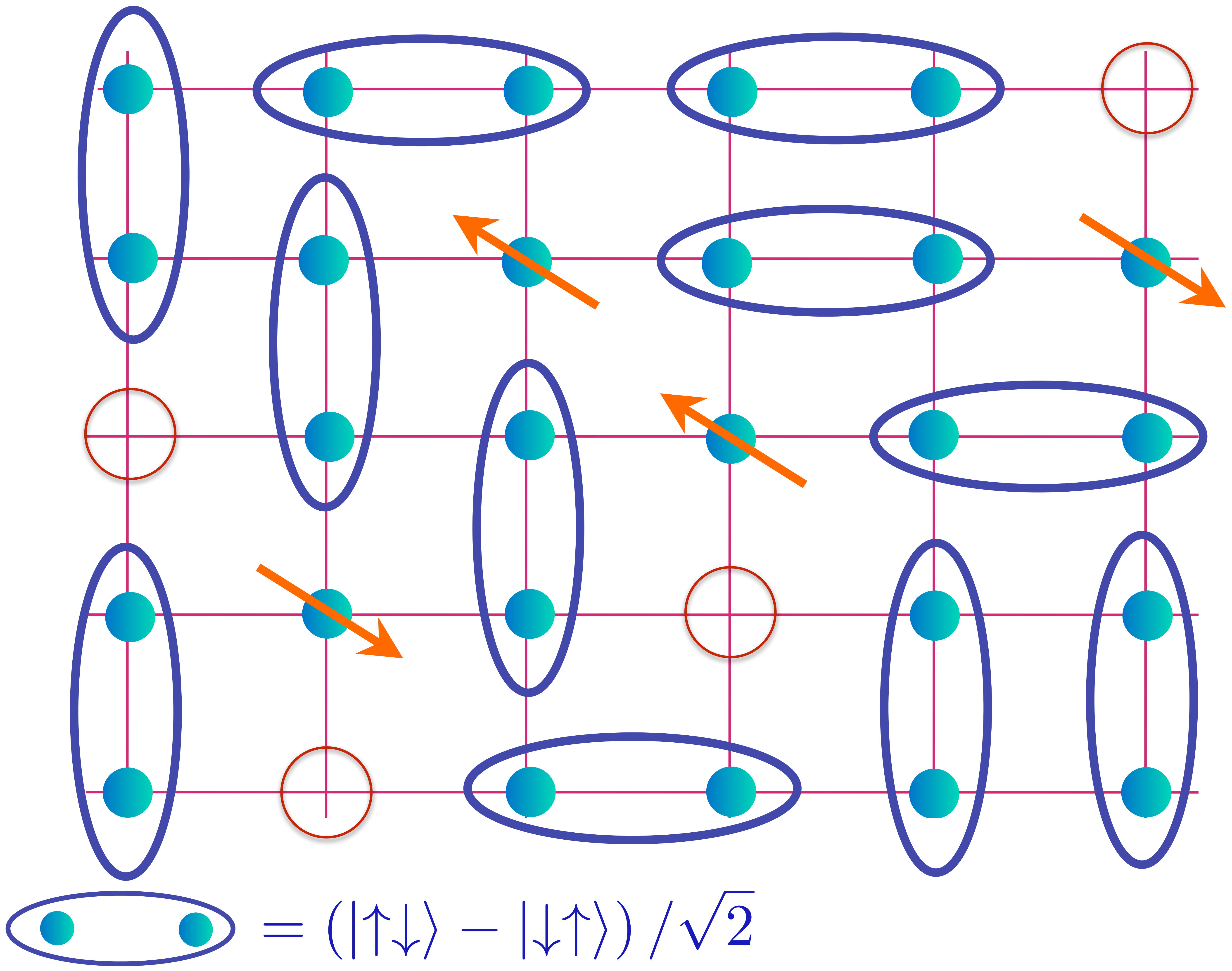

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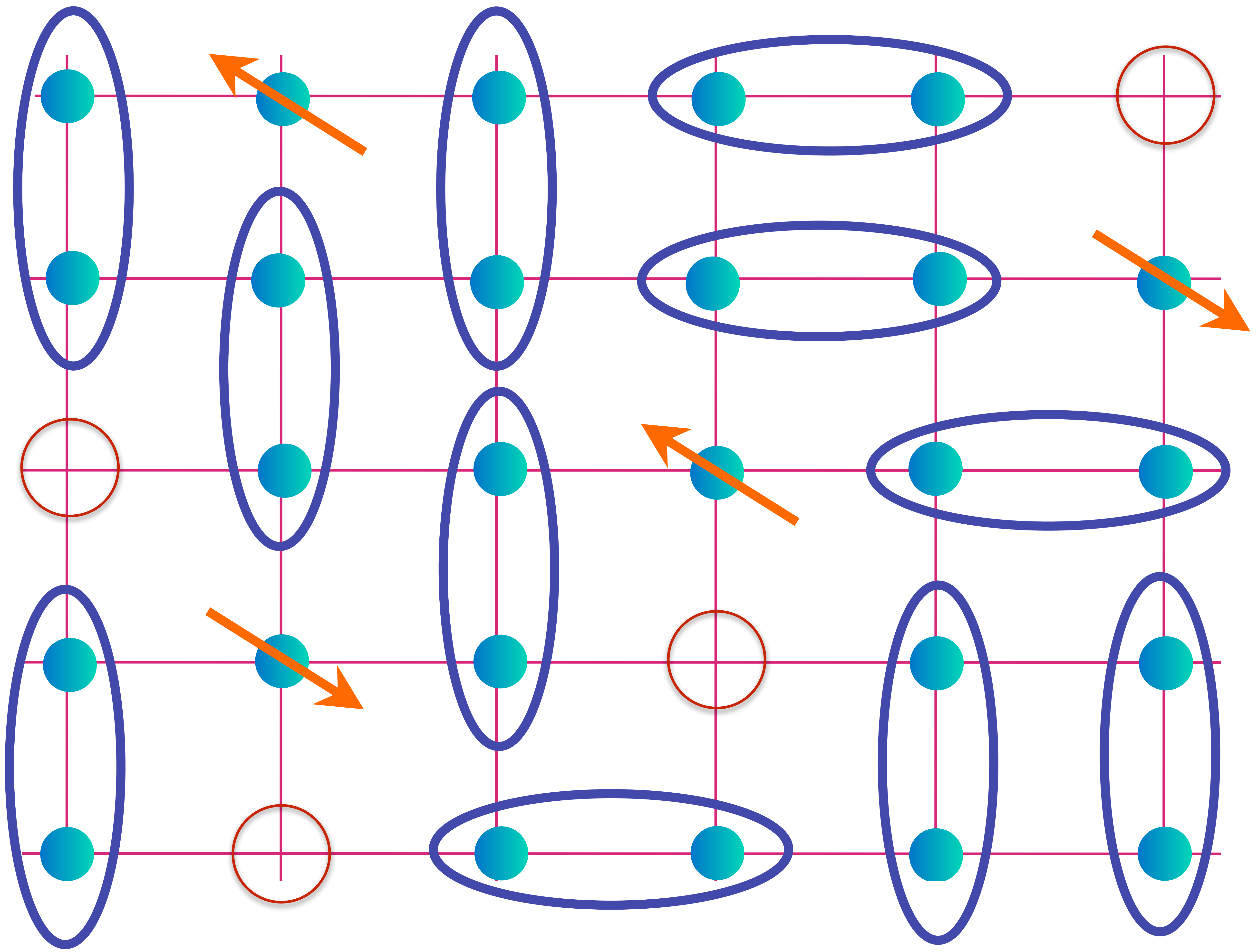

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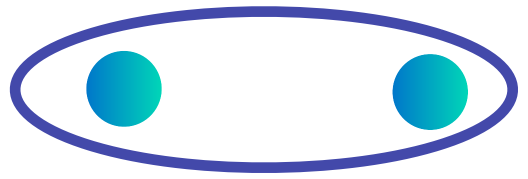 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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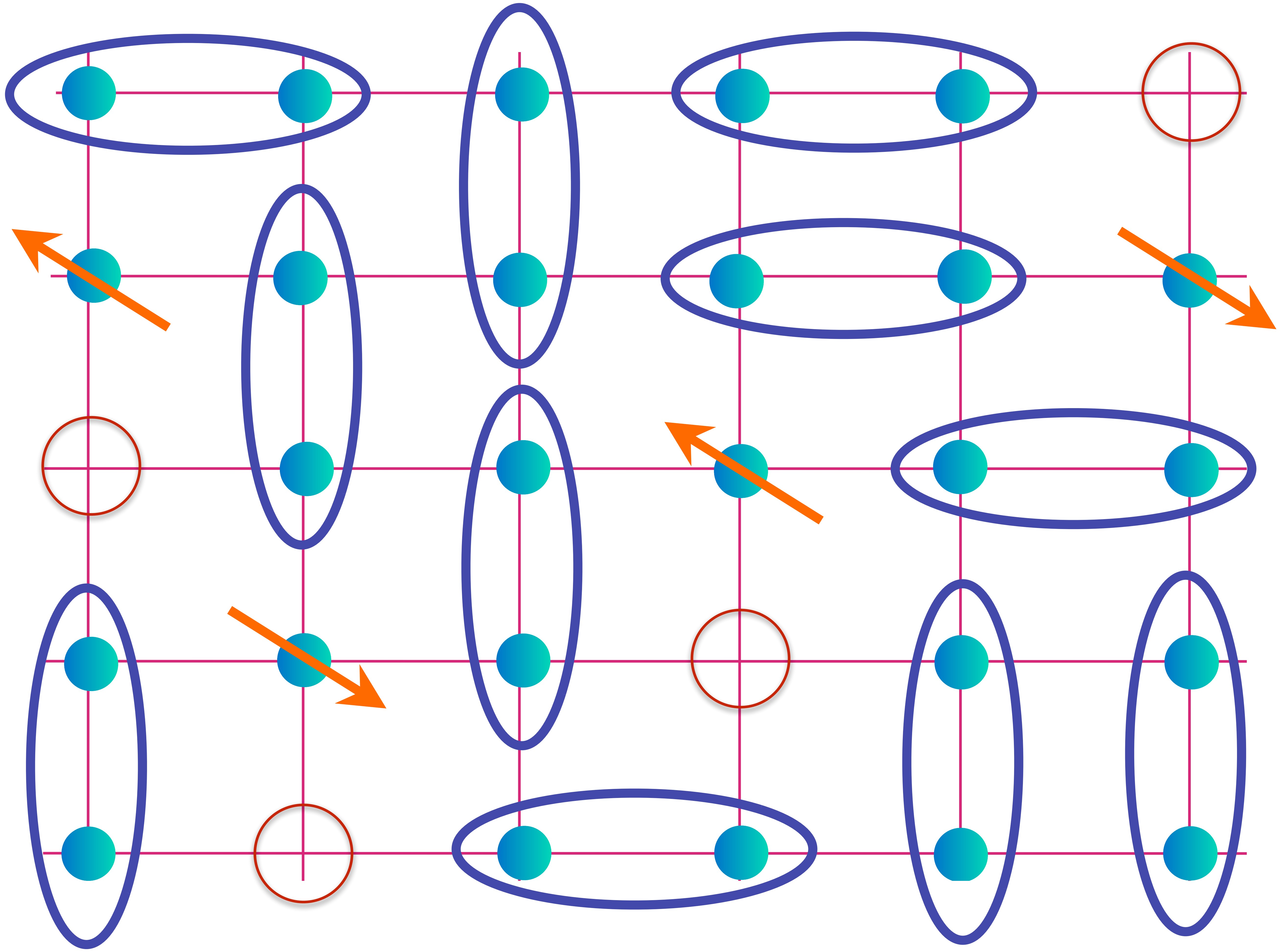

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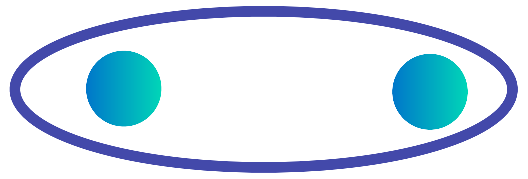

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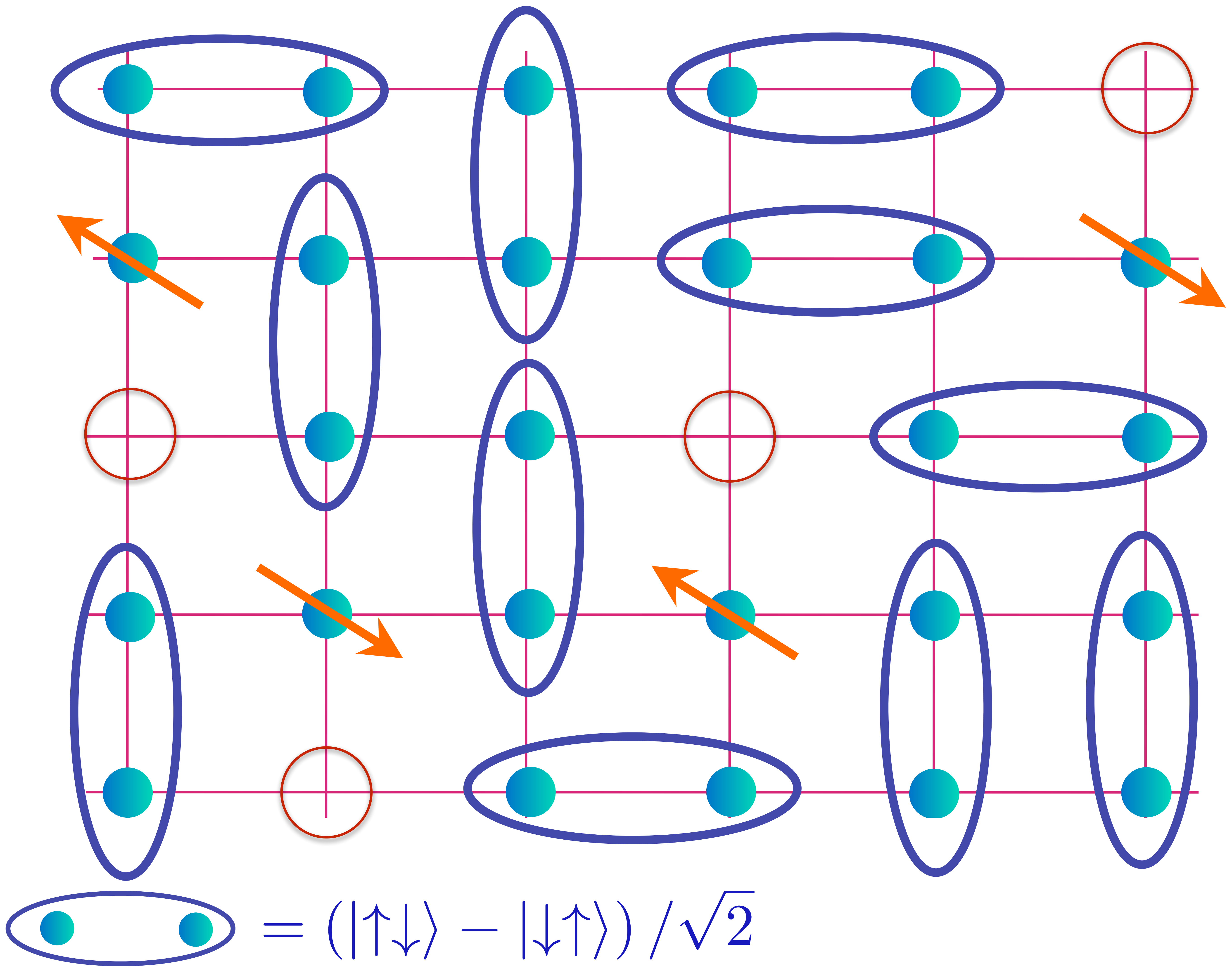

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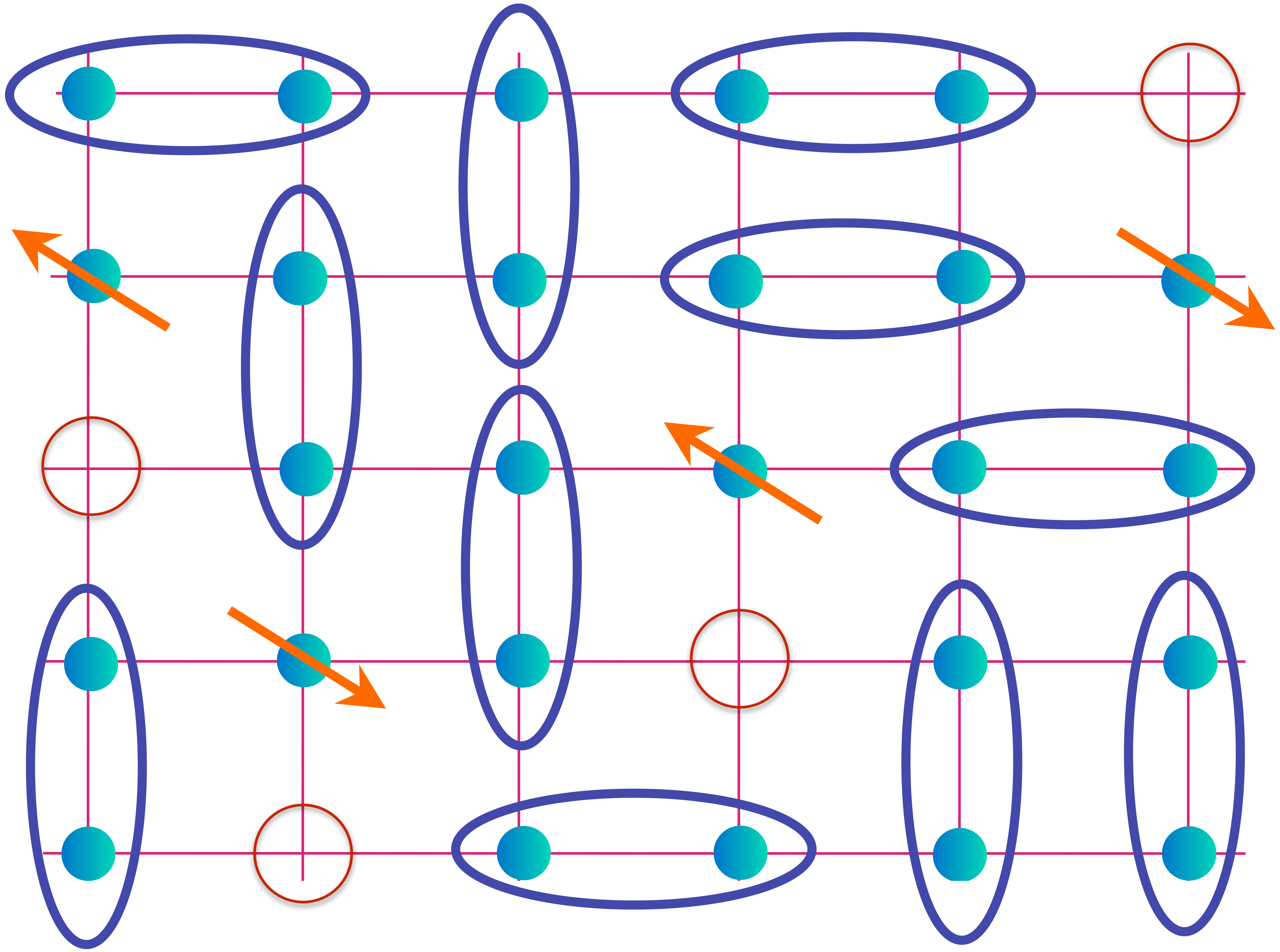

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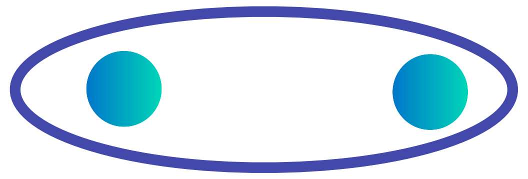 $= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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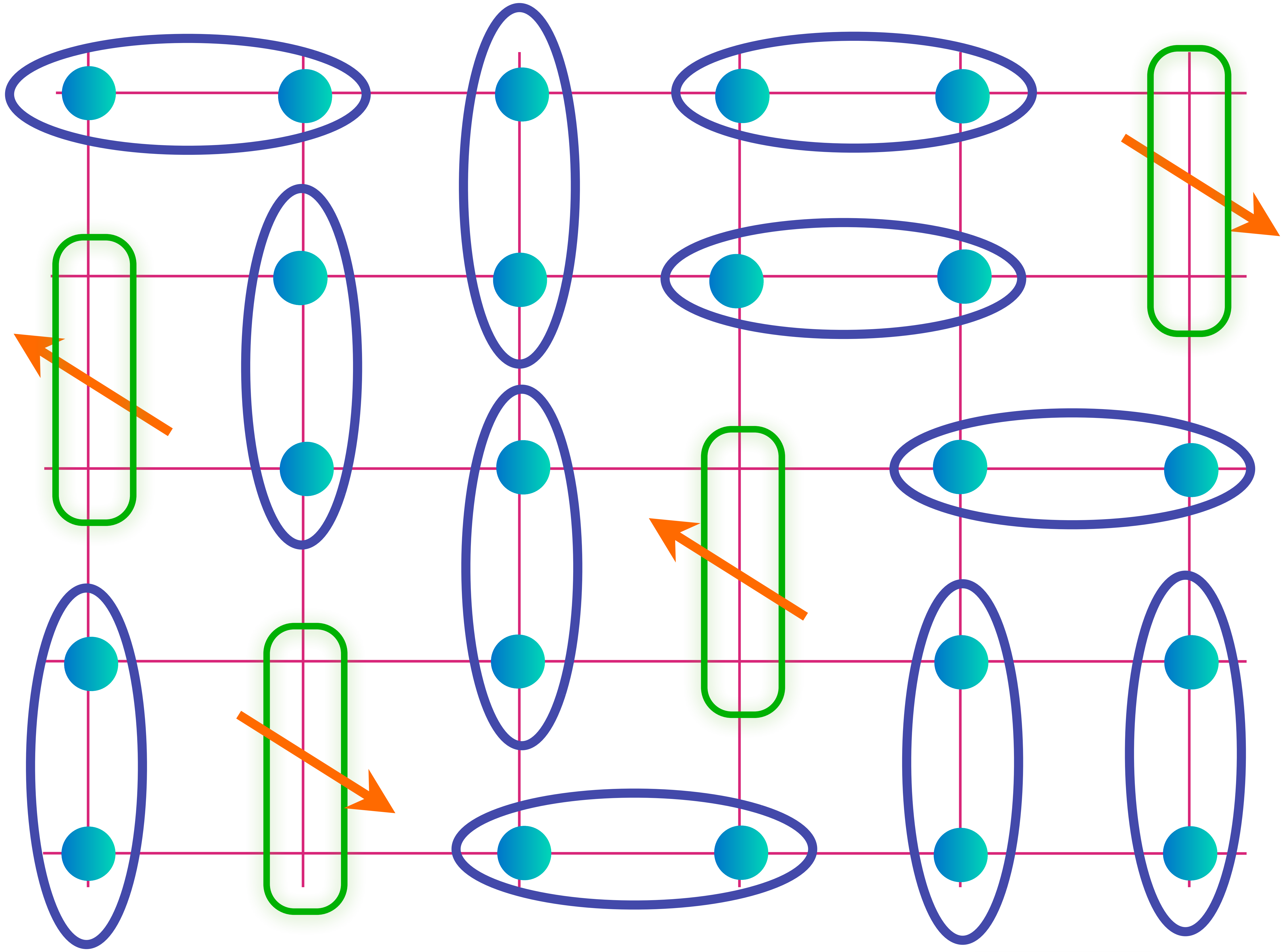
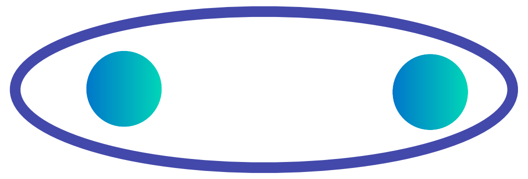
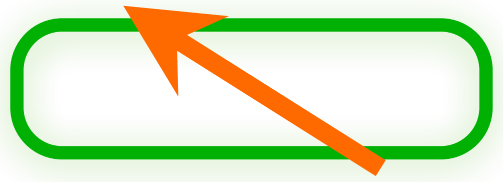


Each green "dimer" is a "bound state" of a vacancy and a free spin

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

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

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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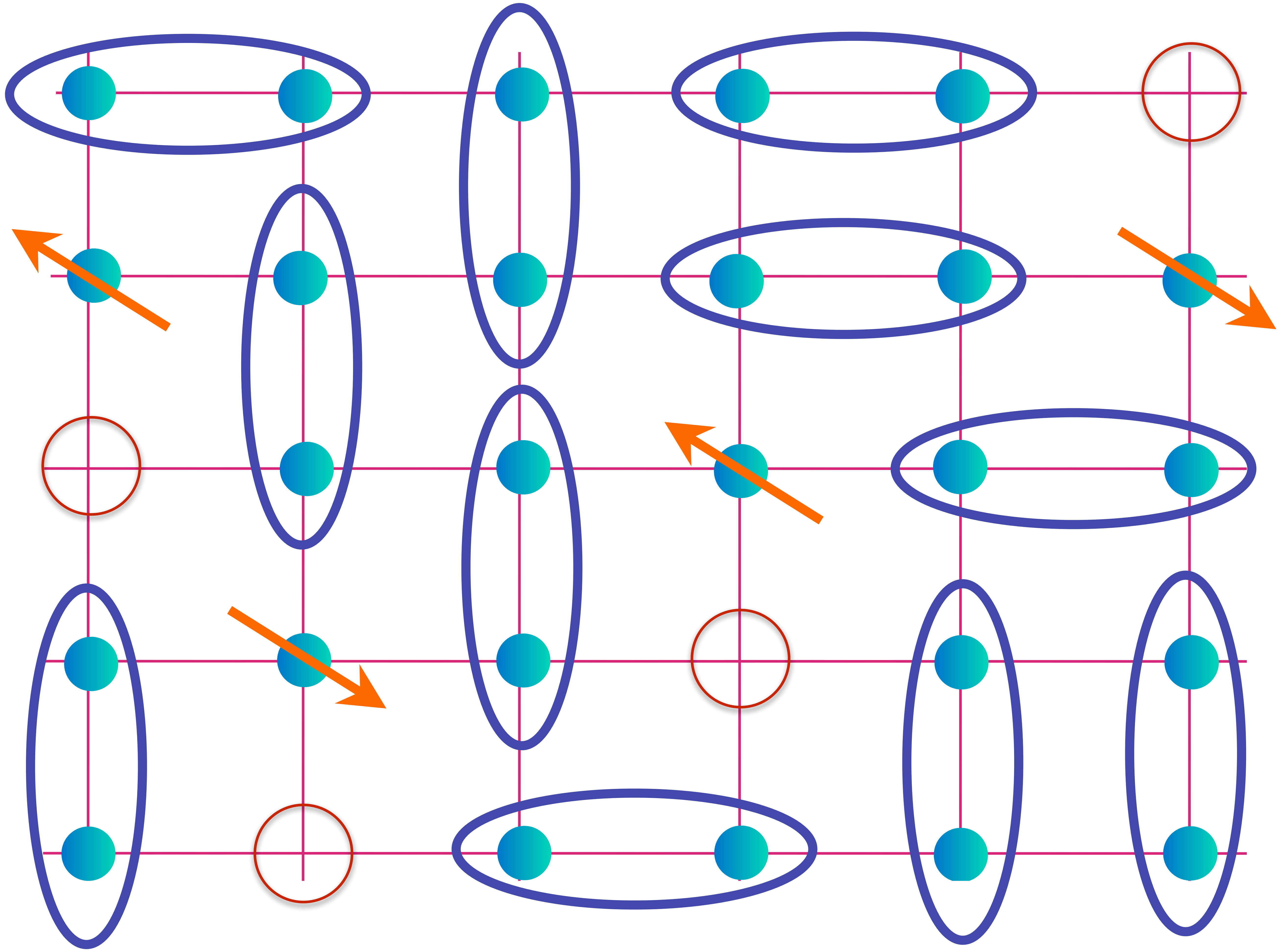

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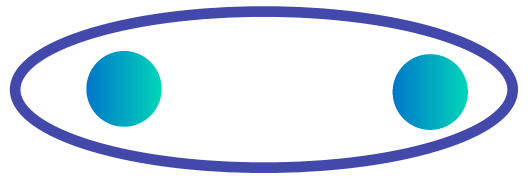
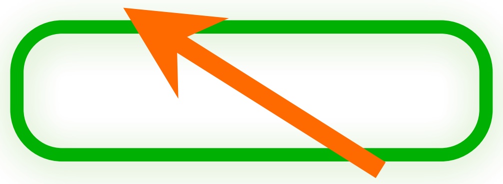
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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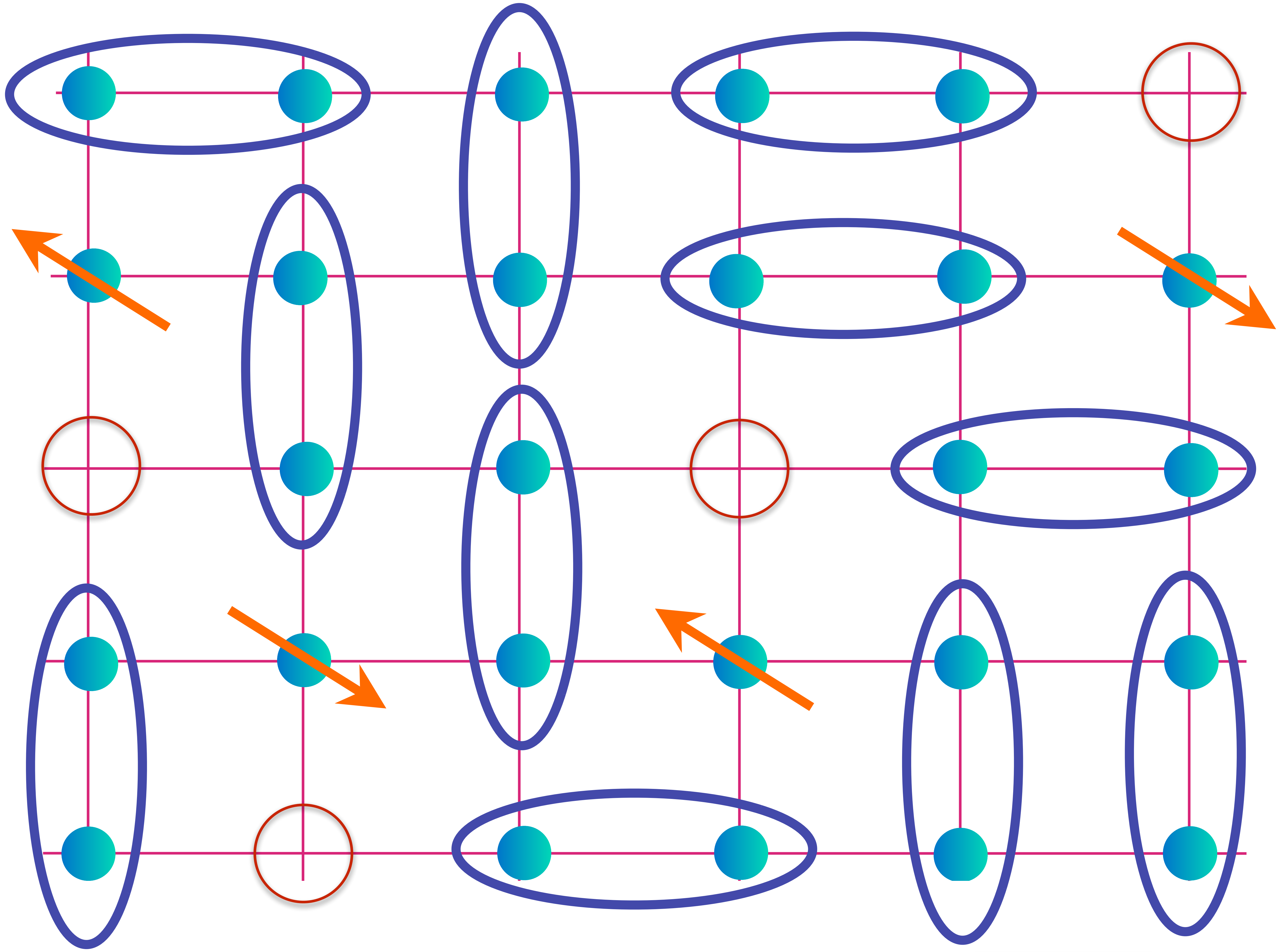

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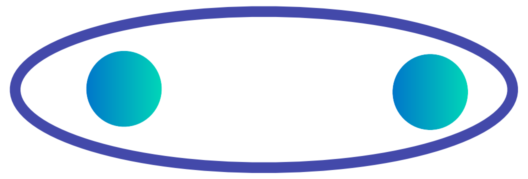
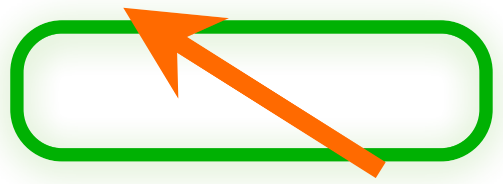
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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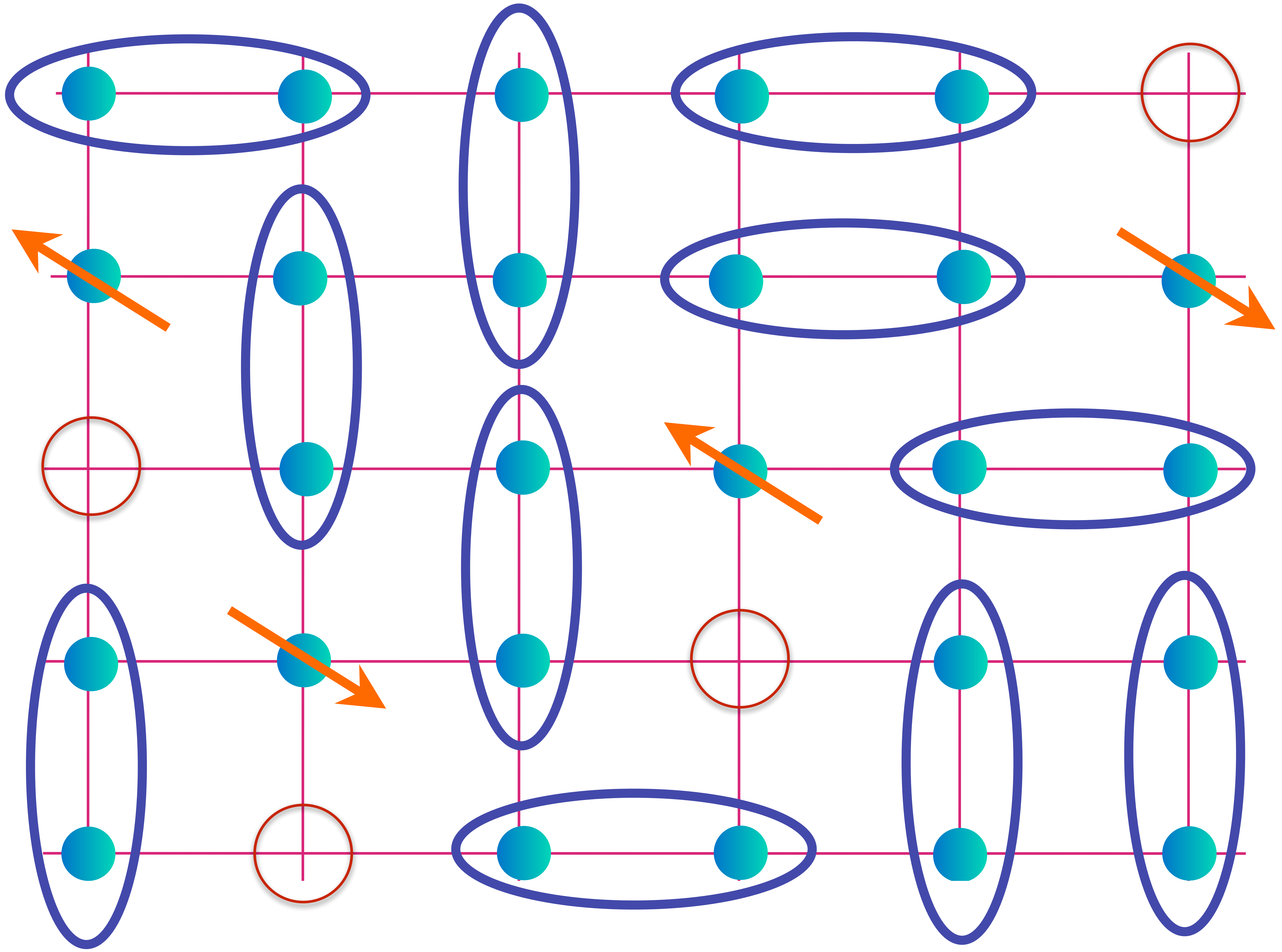

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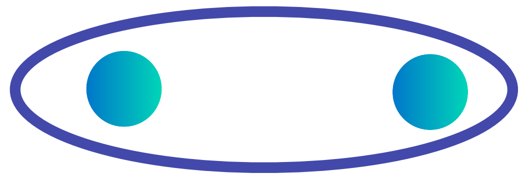
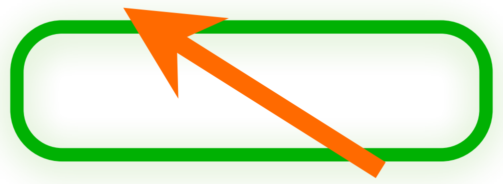
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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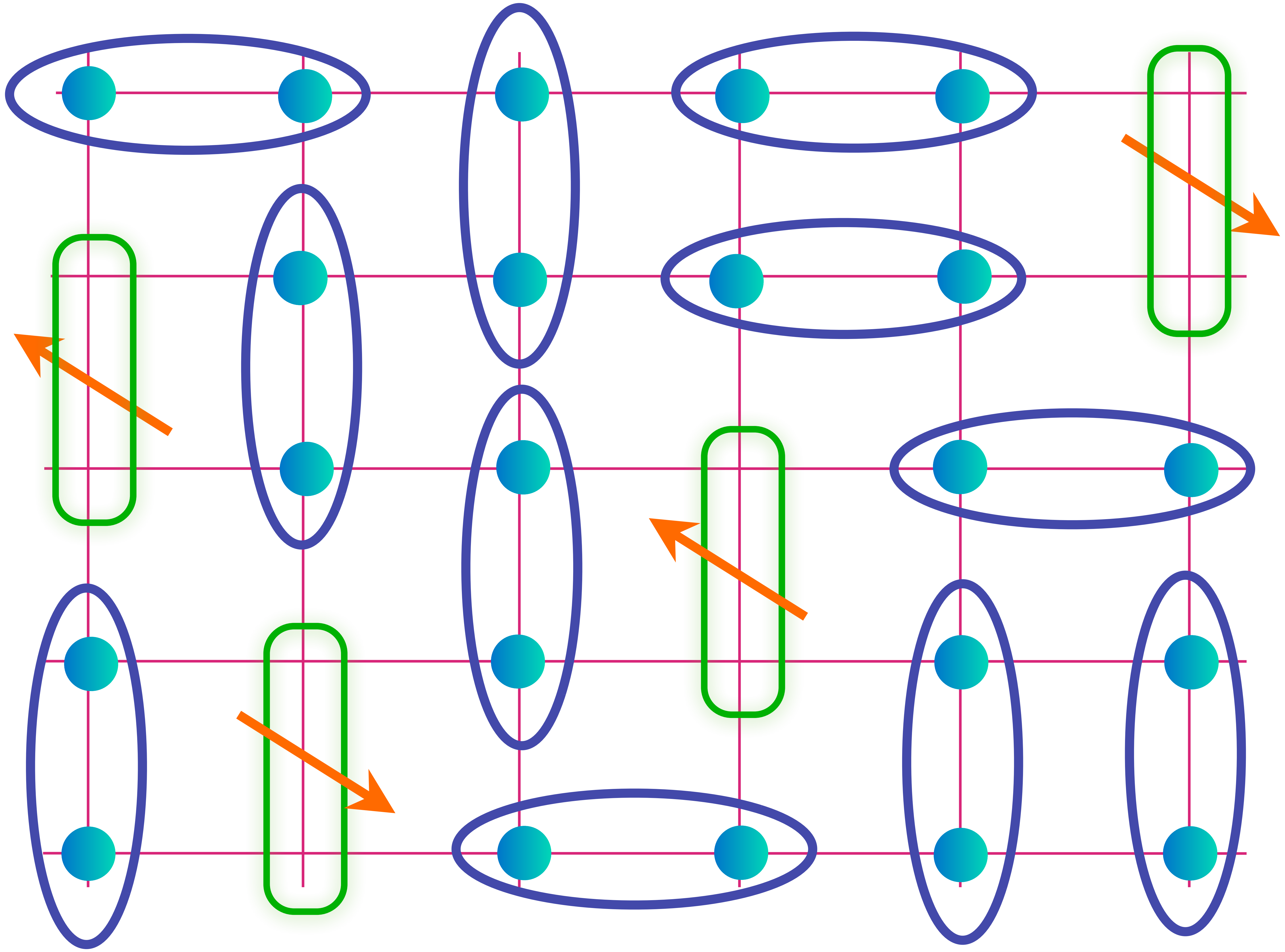
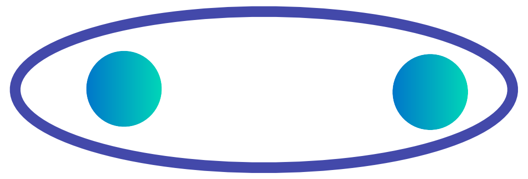
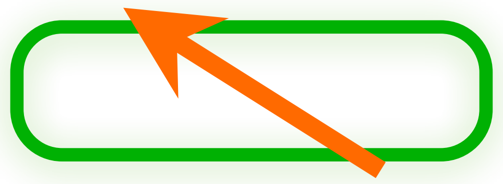


Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

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

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

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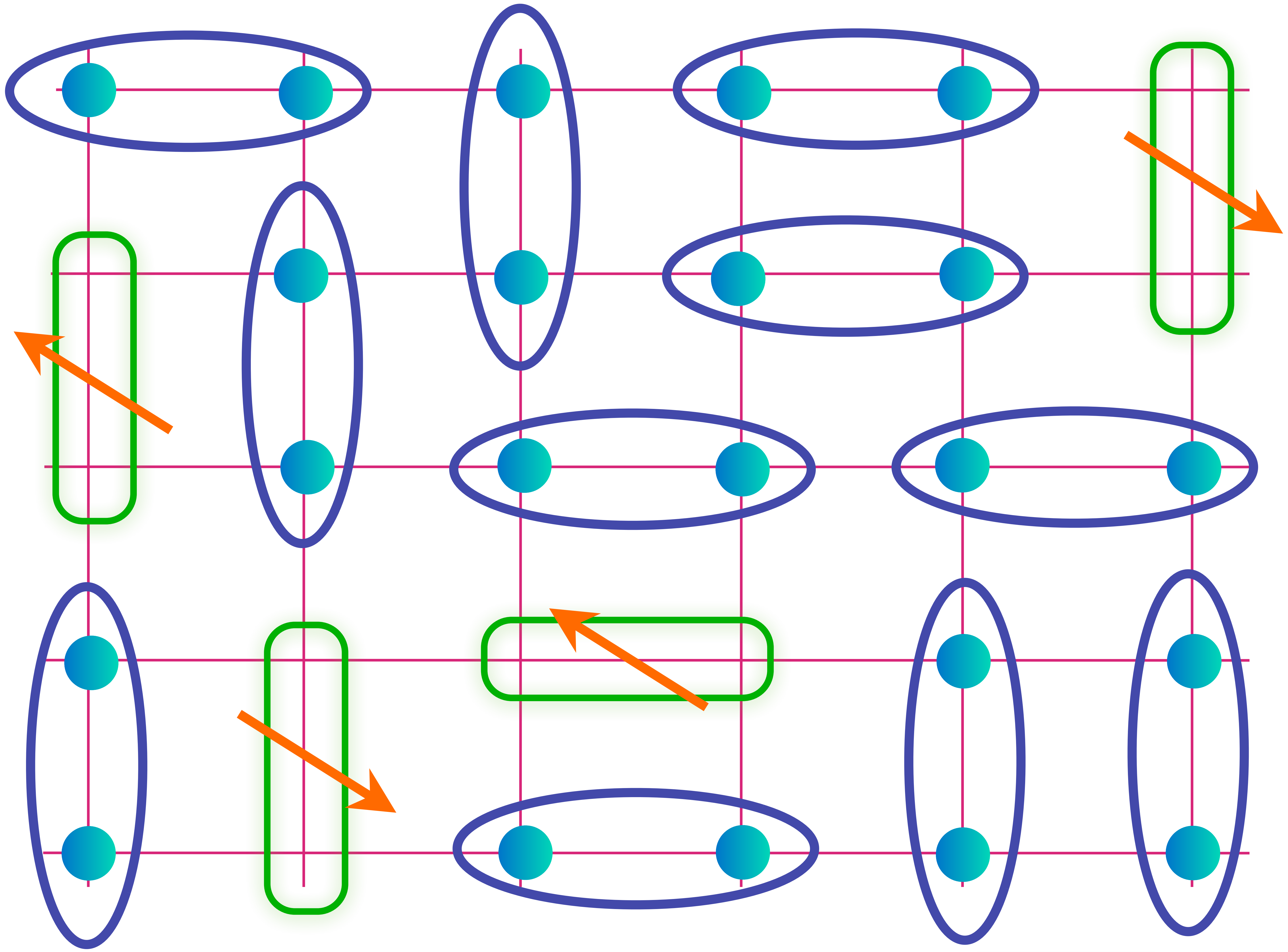

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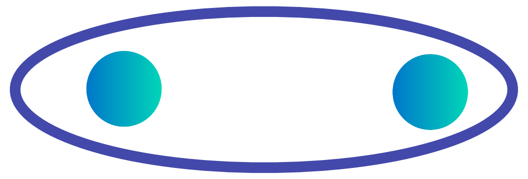
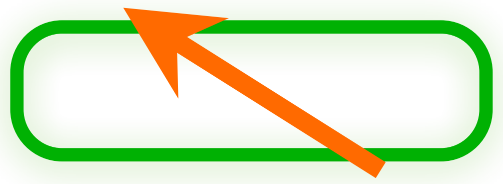
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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

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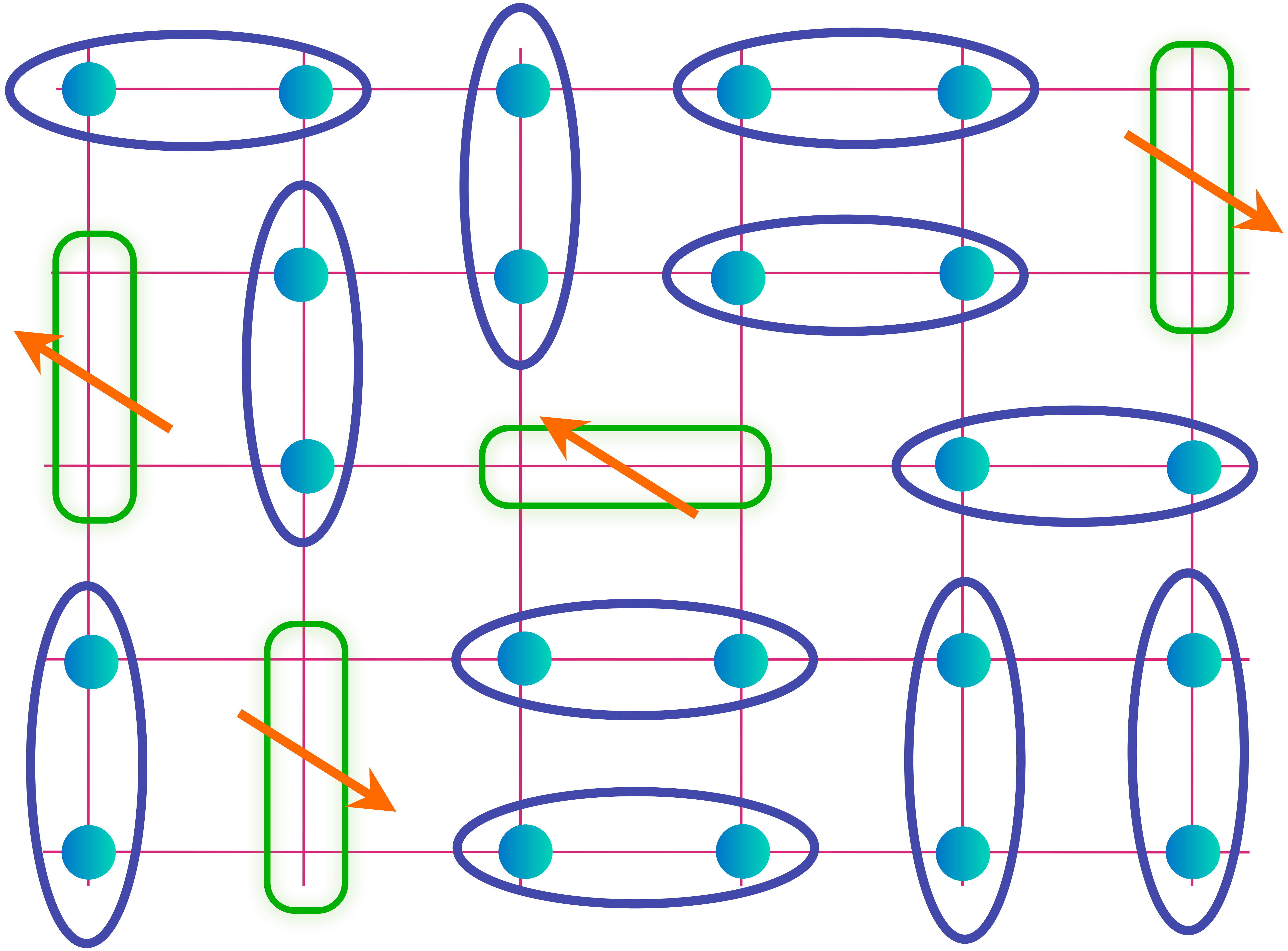

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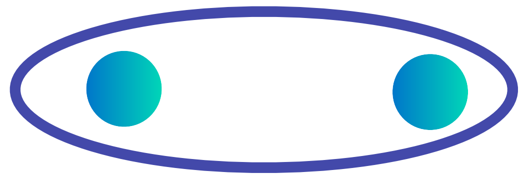

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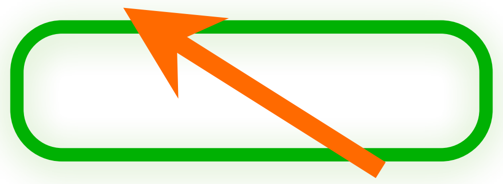

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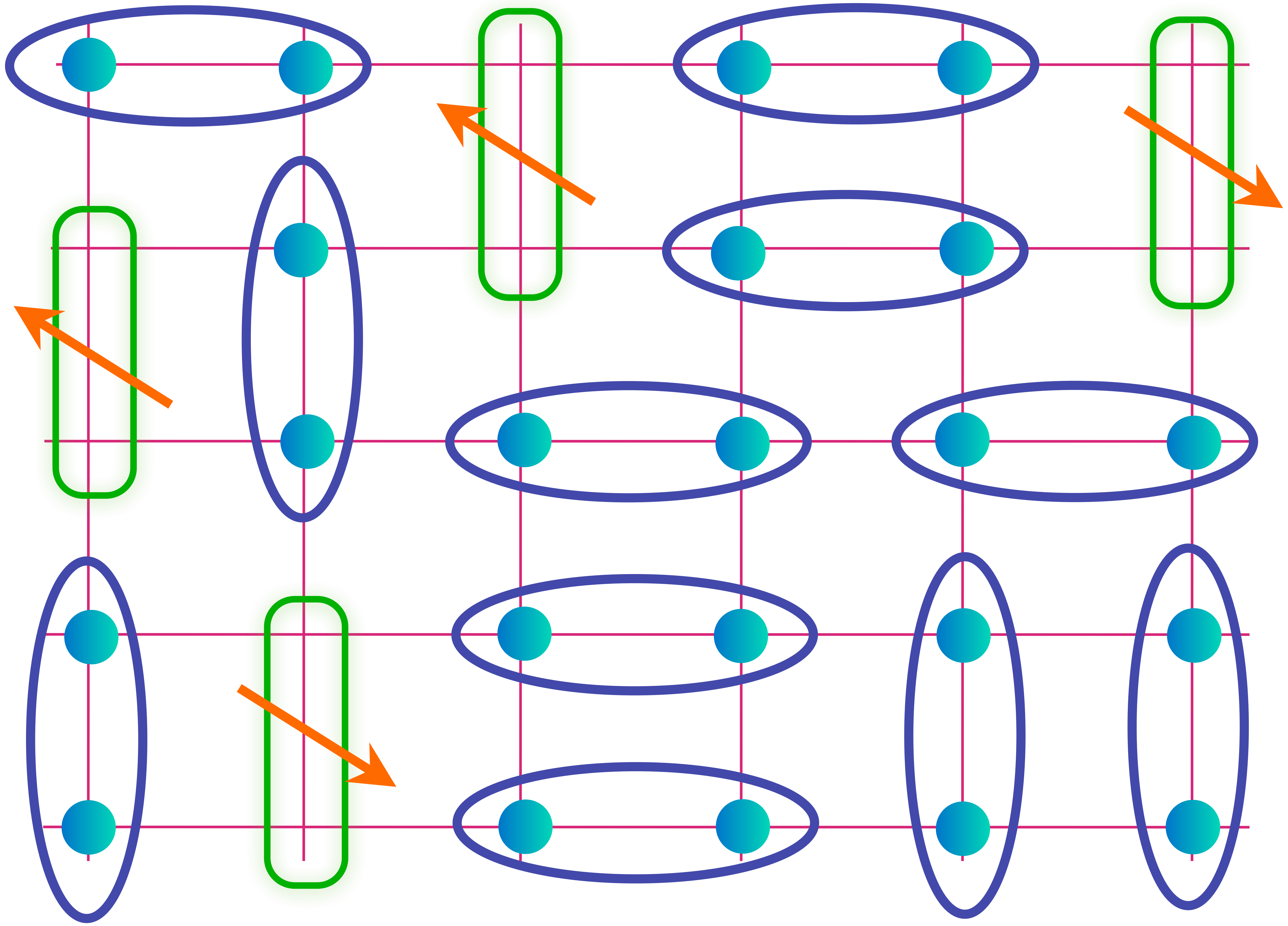

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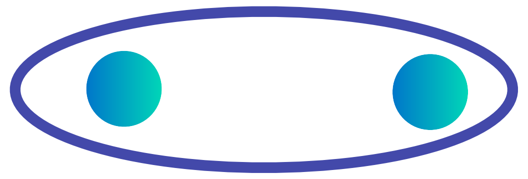

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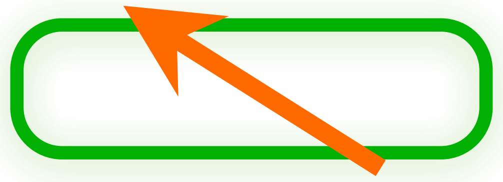

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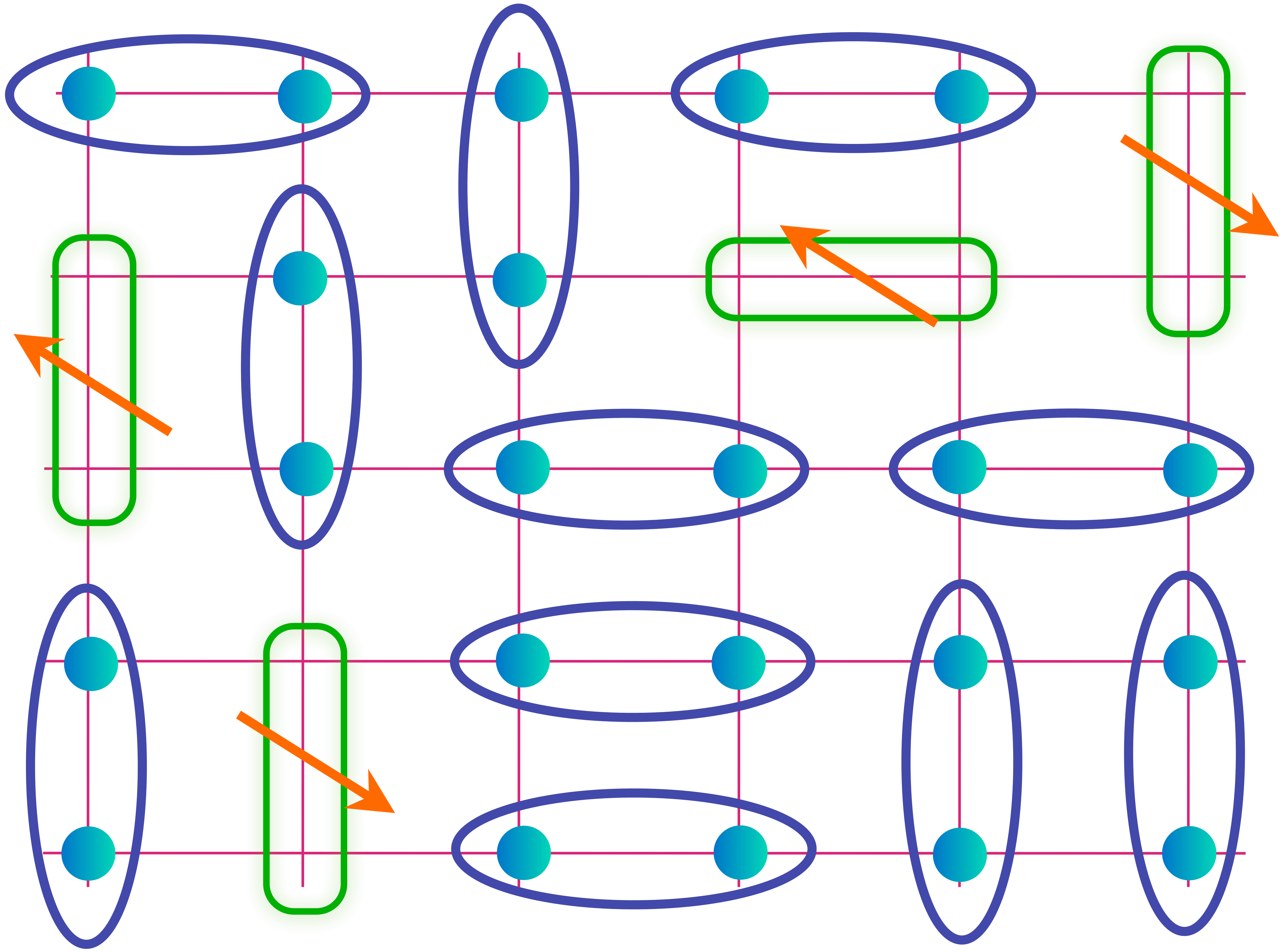

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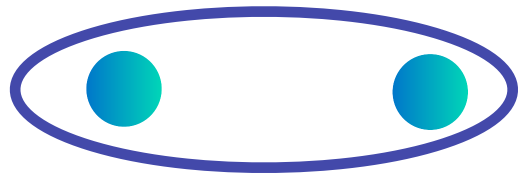
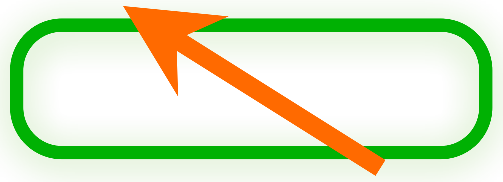
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$

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

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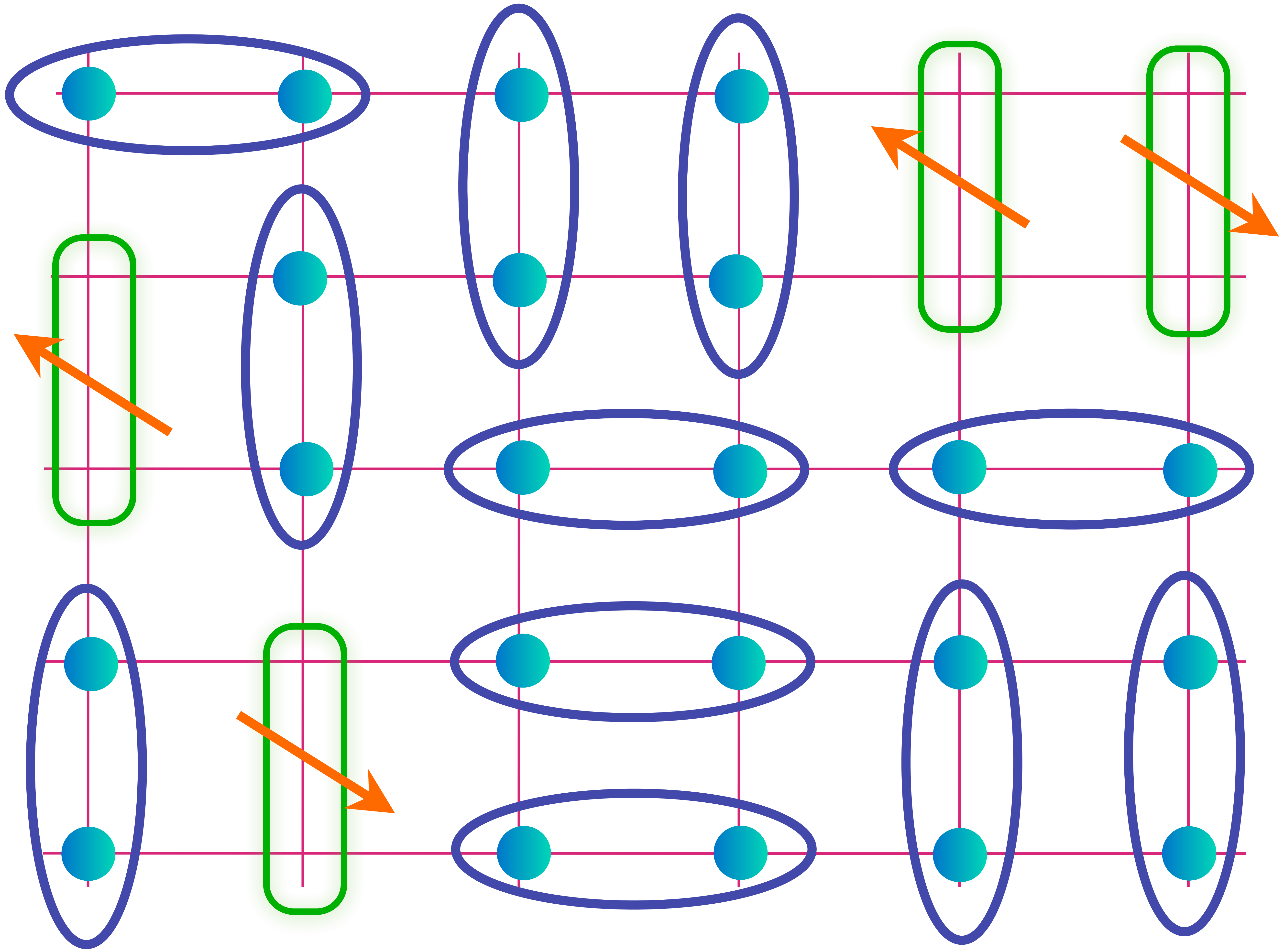
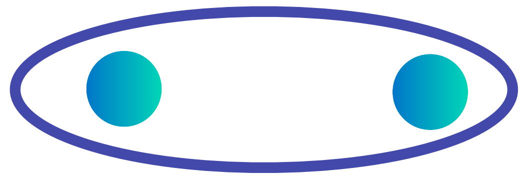
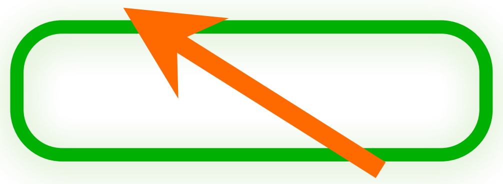


Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

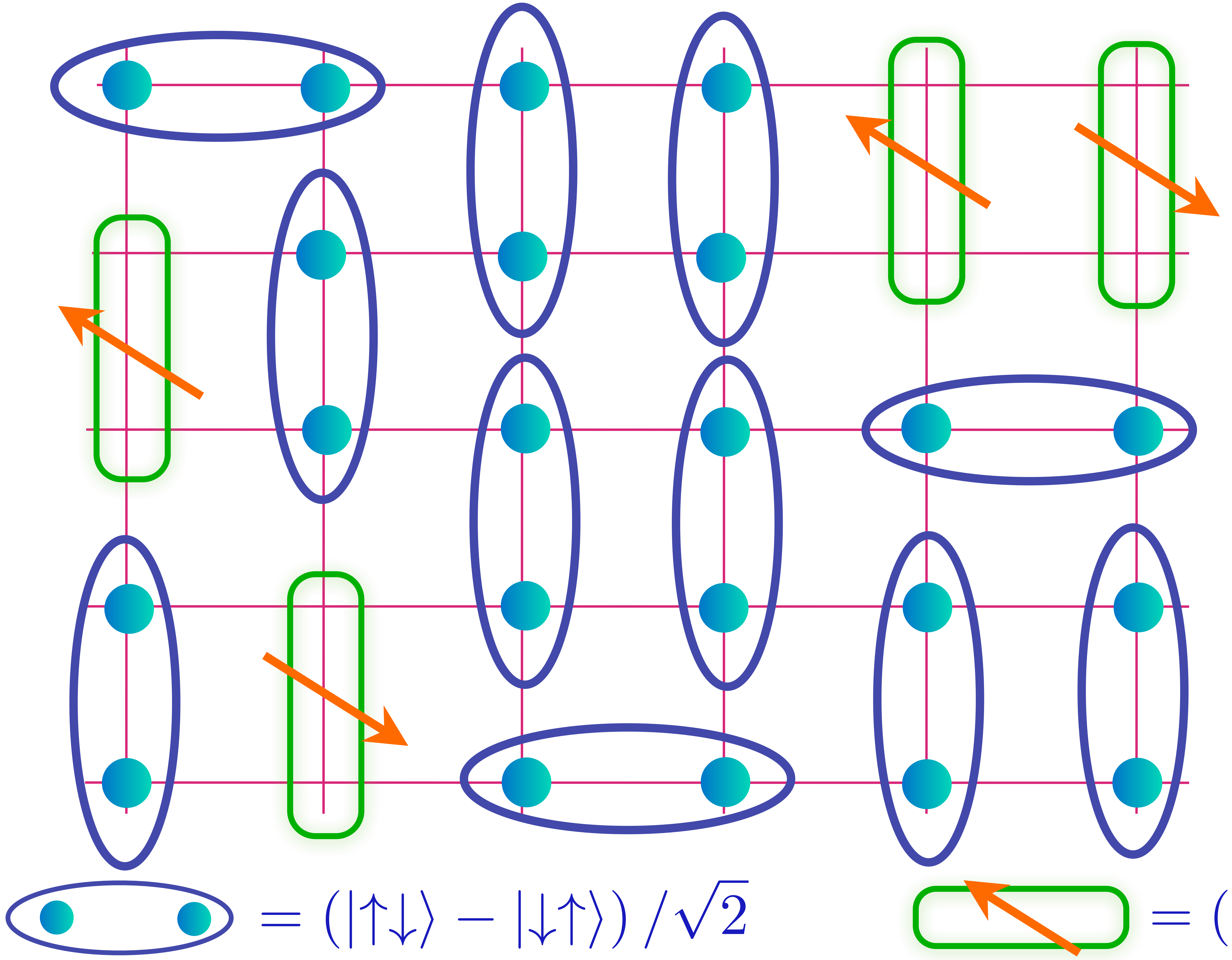
 $= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right) / \sqrt{2}$

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

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

Earlier approach to 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)



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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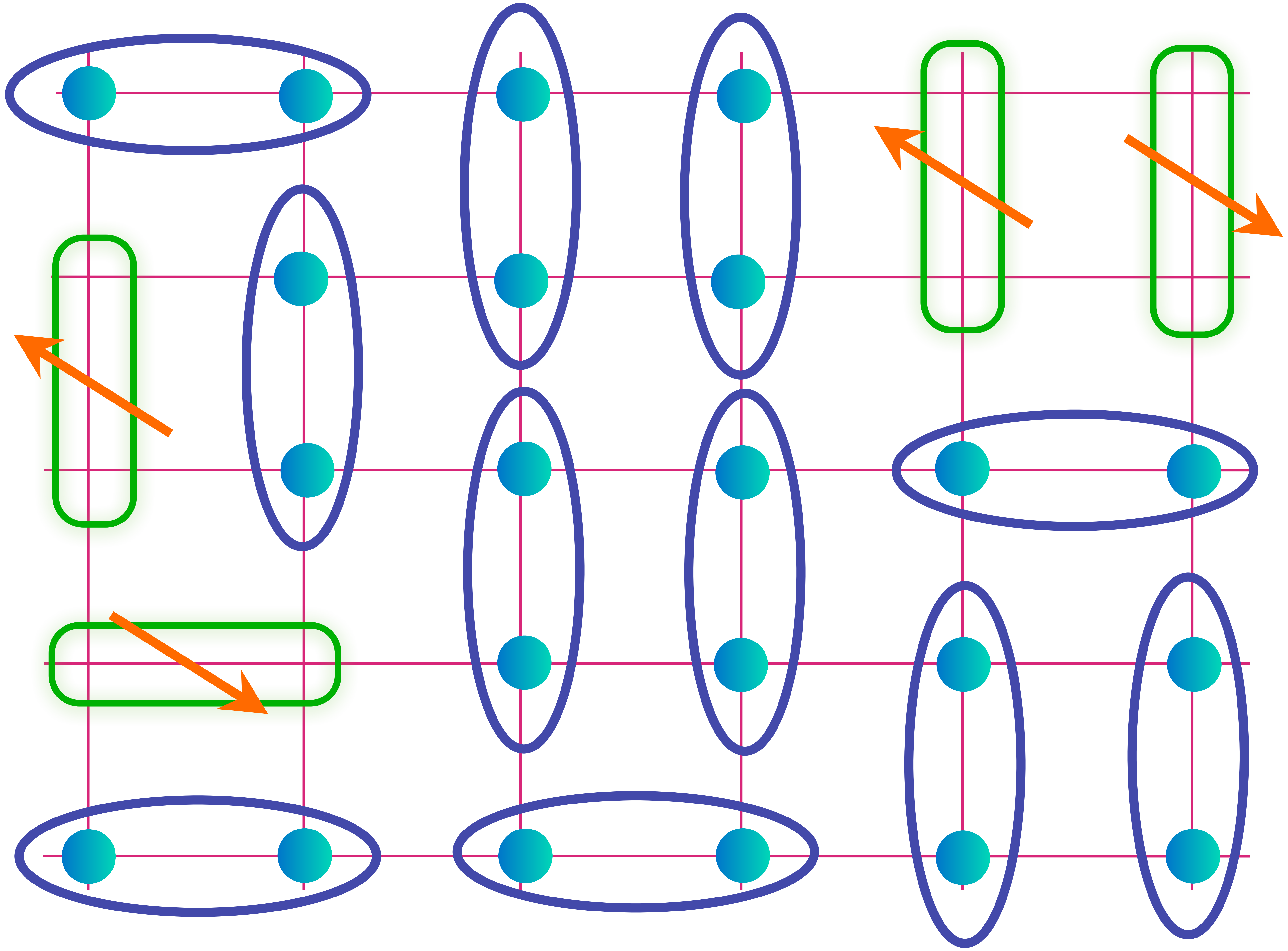

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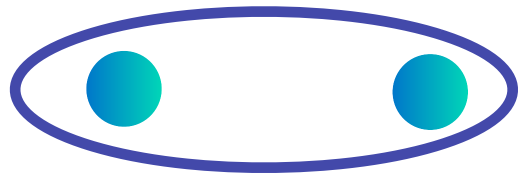
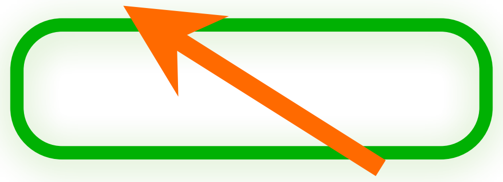


$= \left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)/\sqrt{2}$



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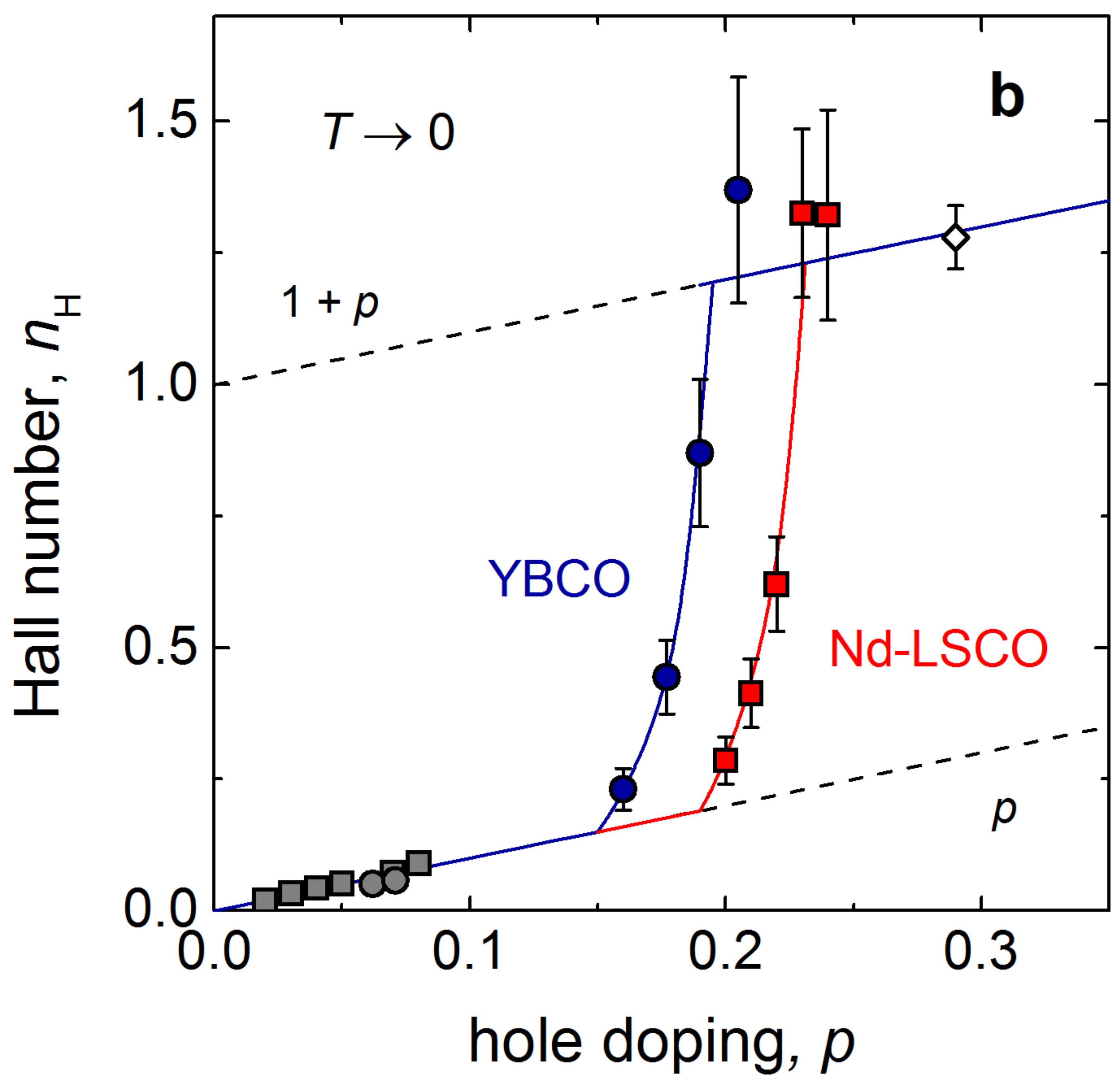
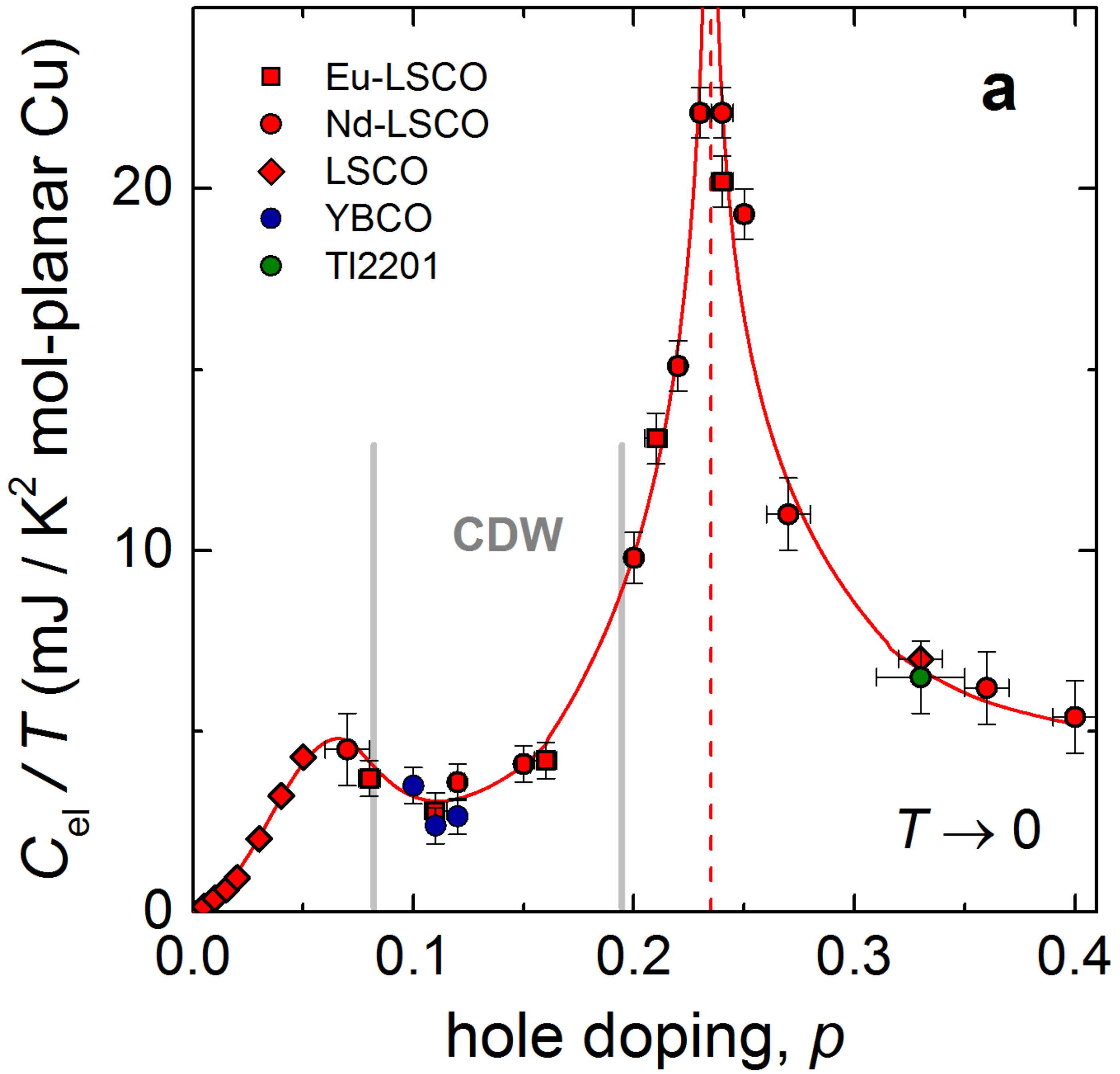
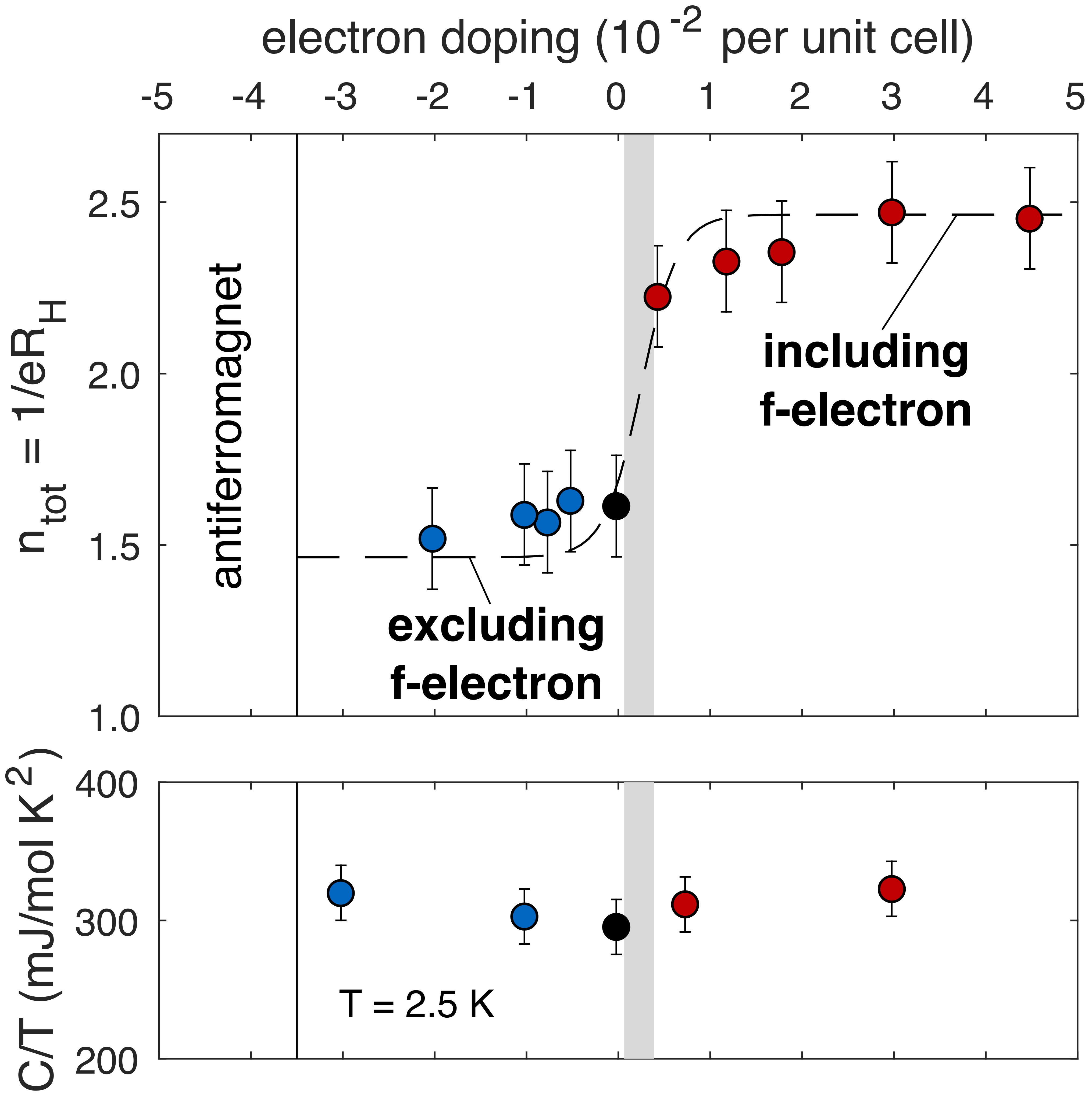
Cuprates





$CeCoIn_5$



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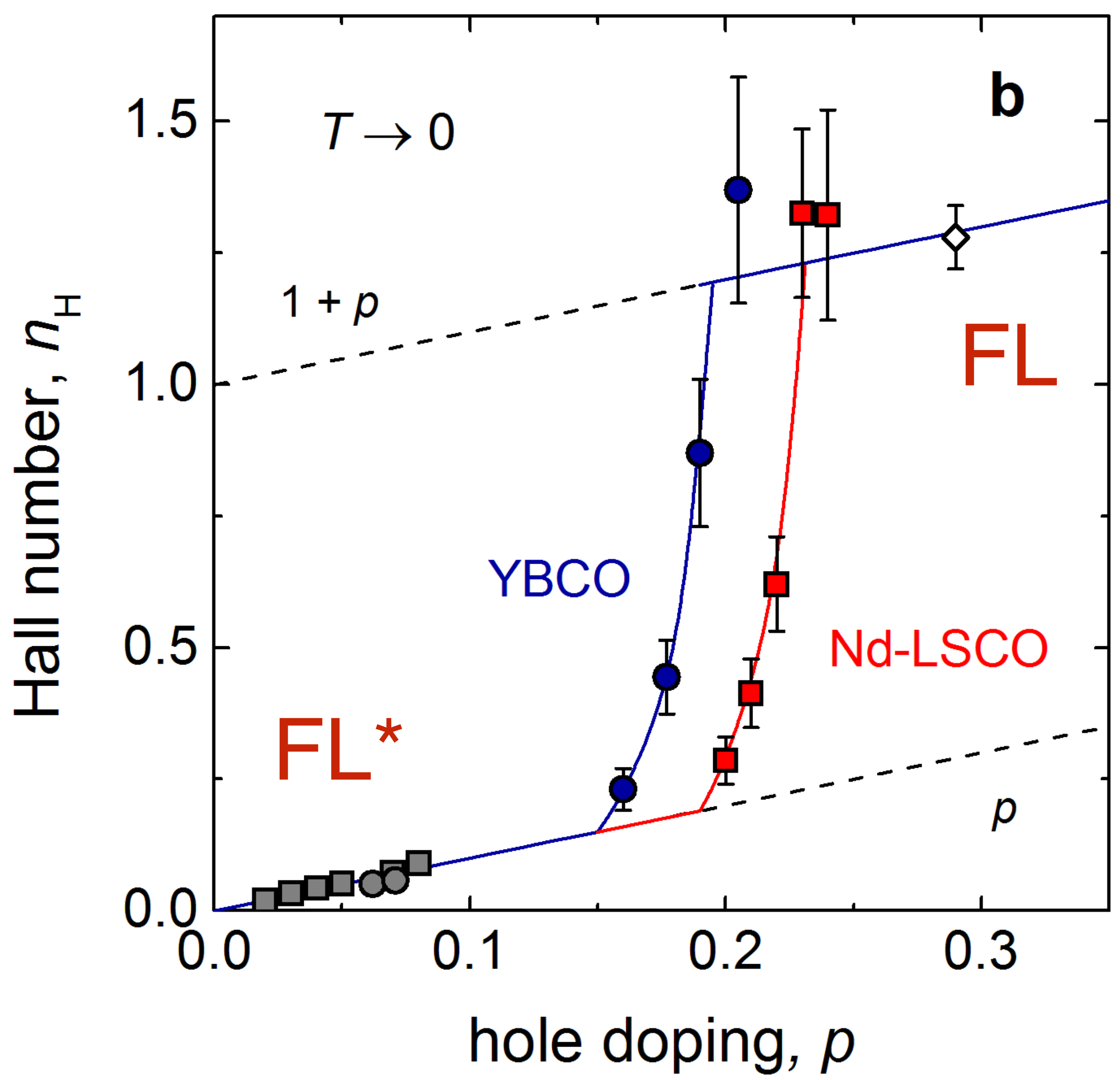

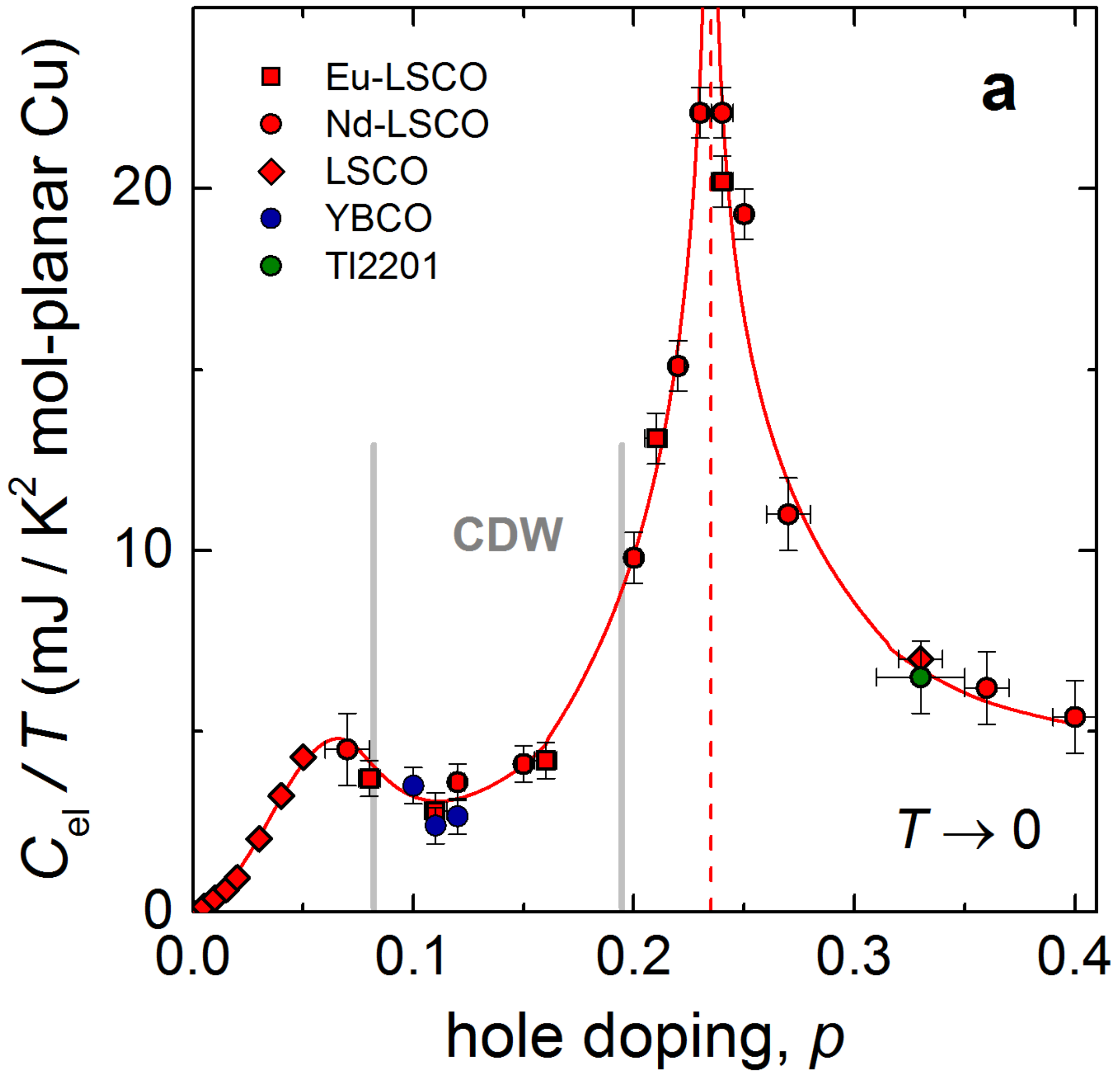

Evidence for
ghost Fermi surfaces
in the
FL*-FL transition
in a
single-band model ?

$CeCoIn_5$