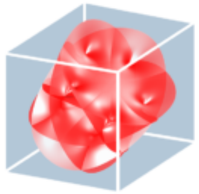
Metal-to-metal quantum phase transitions not described by symmetry breaking orders

Strongly Correlated Quantum Materials
and High Temperature Superconductors



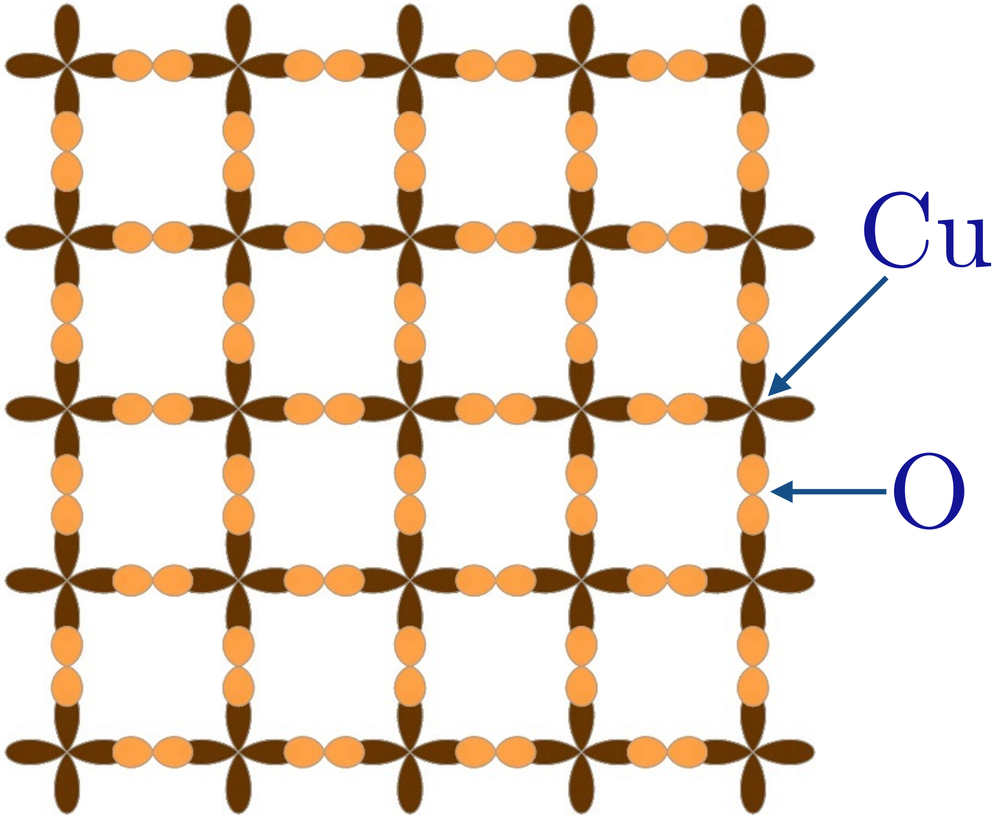
HARVARD UNIVERSITY
CENTER OF MATHEMATICAL
SCIENCES AND APPLICATIONS

September 2, 2020

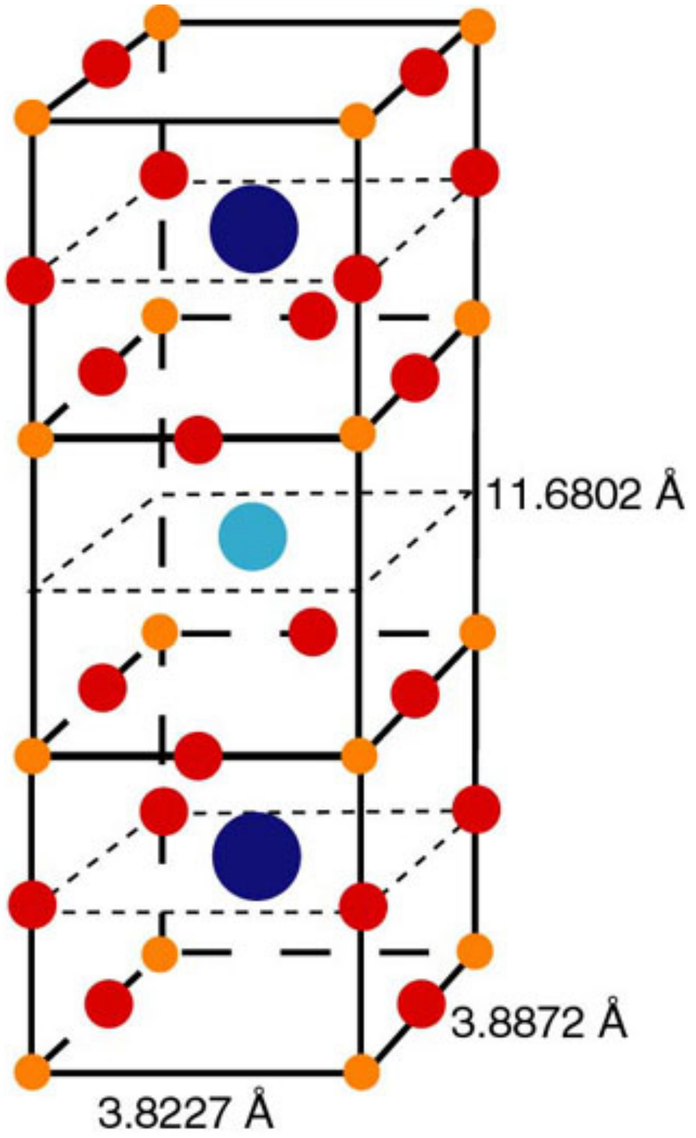
Subir Sachdev

Talk online: sachdev.physics.harvard.edu

High temperature superconductors

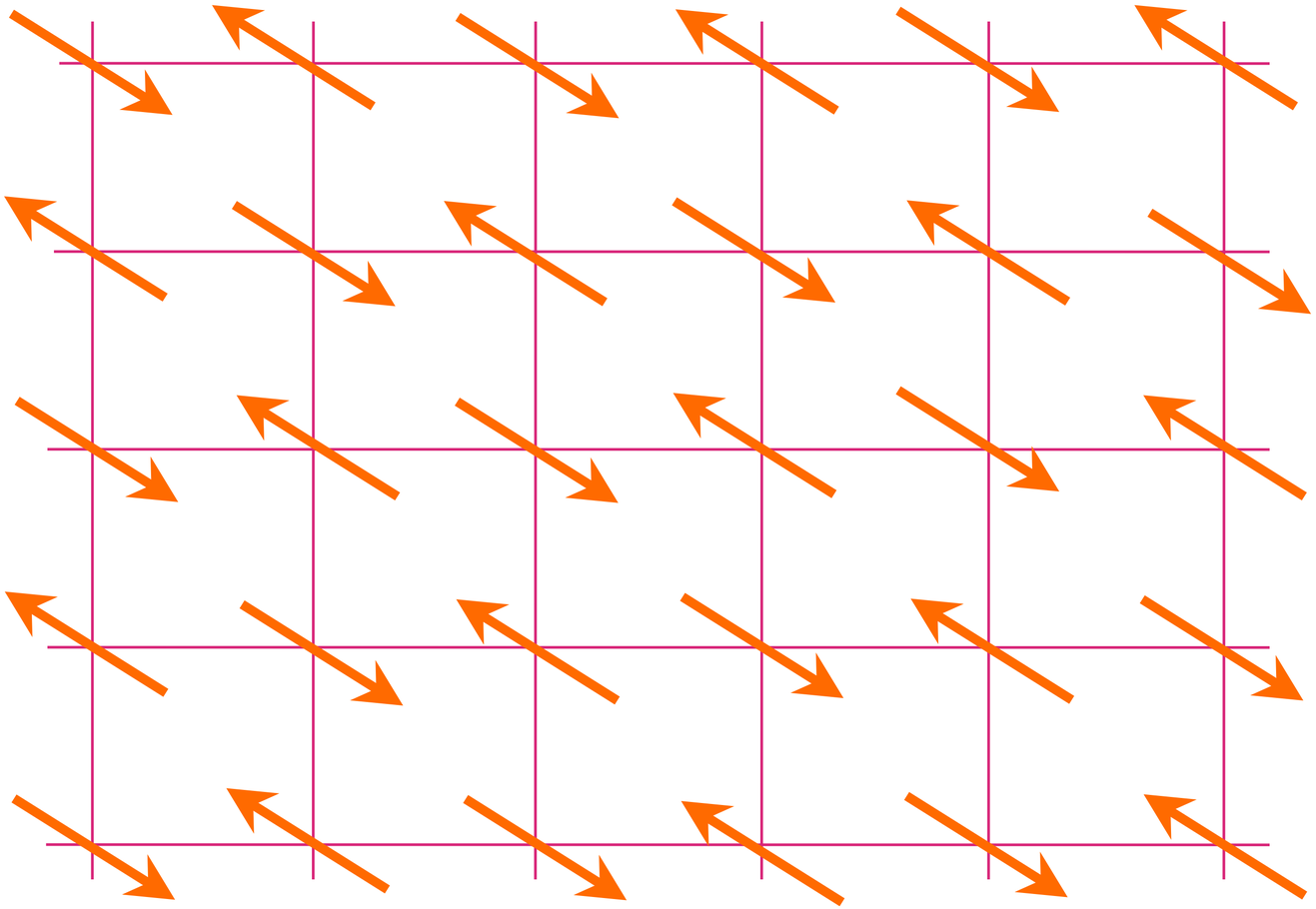


CuO_2 plane



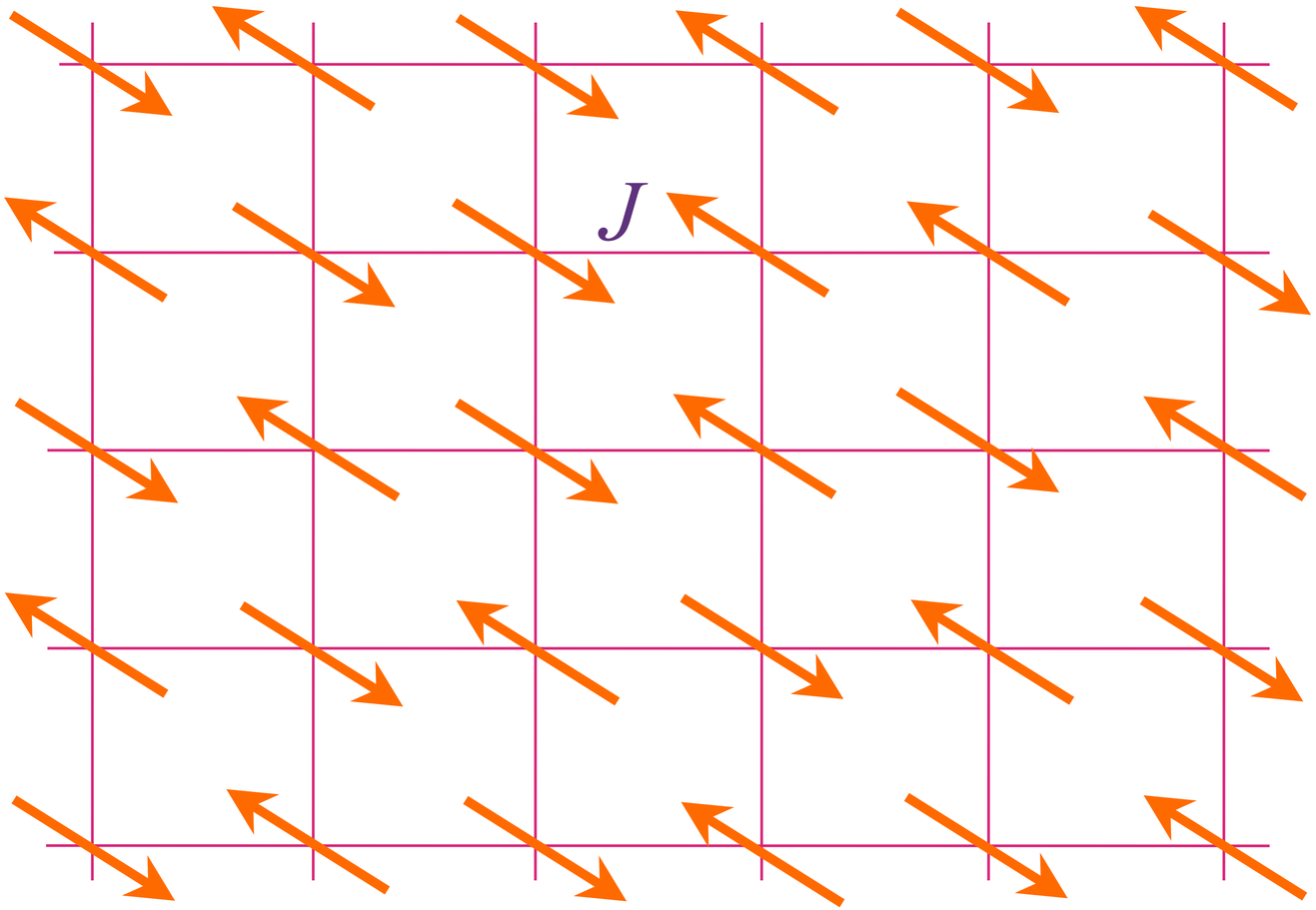
$YBa_2Cu_3O_{6+x}$

Insulating antiferromagnet



$$H = J \sum_{\langle ij \rangle} \Big[X_i X_j + Y_i Y_j + Z_i Z_j \Big]$$

Insulating antiferromagnet



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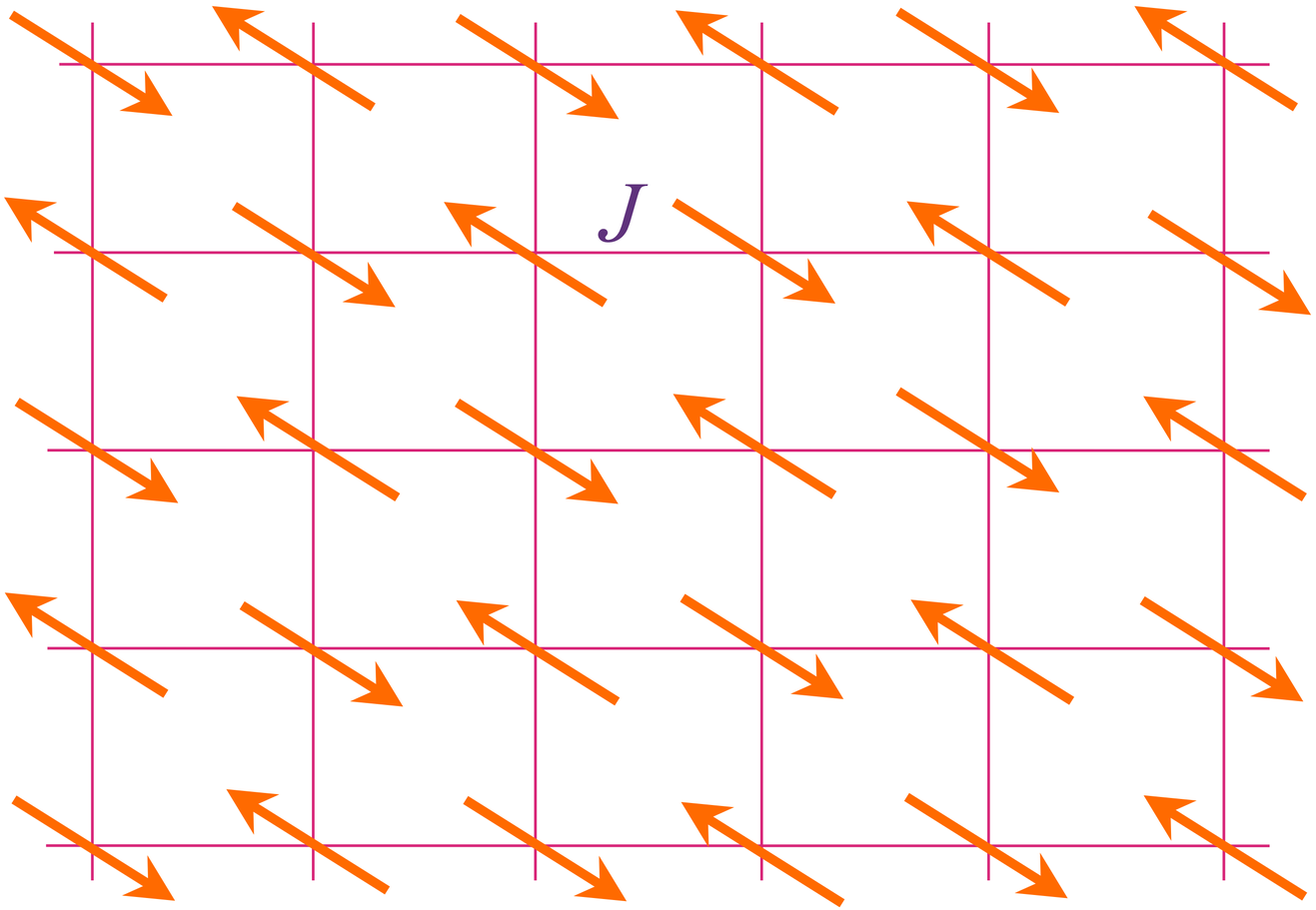
Insulating antiferromagnet



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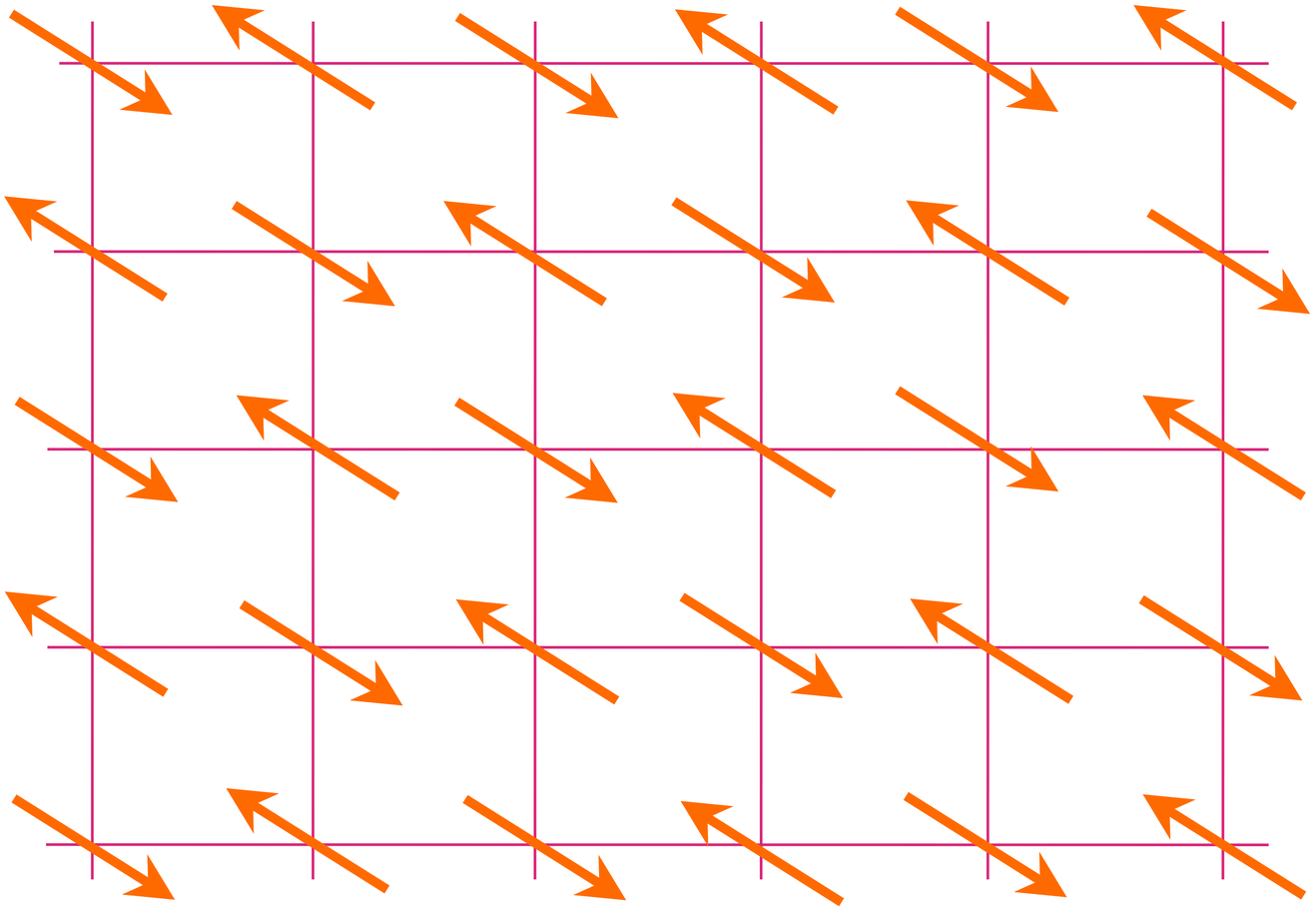
Insulating antiferromagnet



$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$

$$\alpha = \uparrow, \downarrow$$

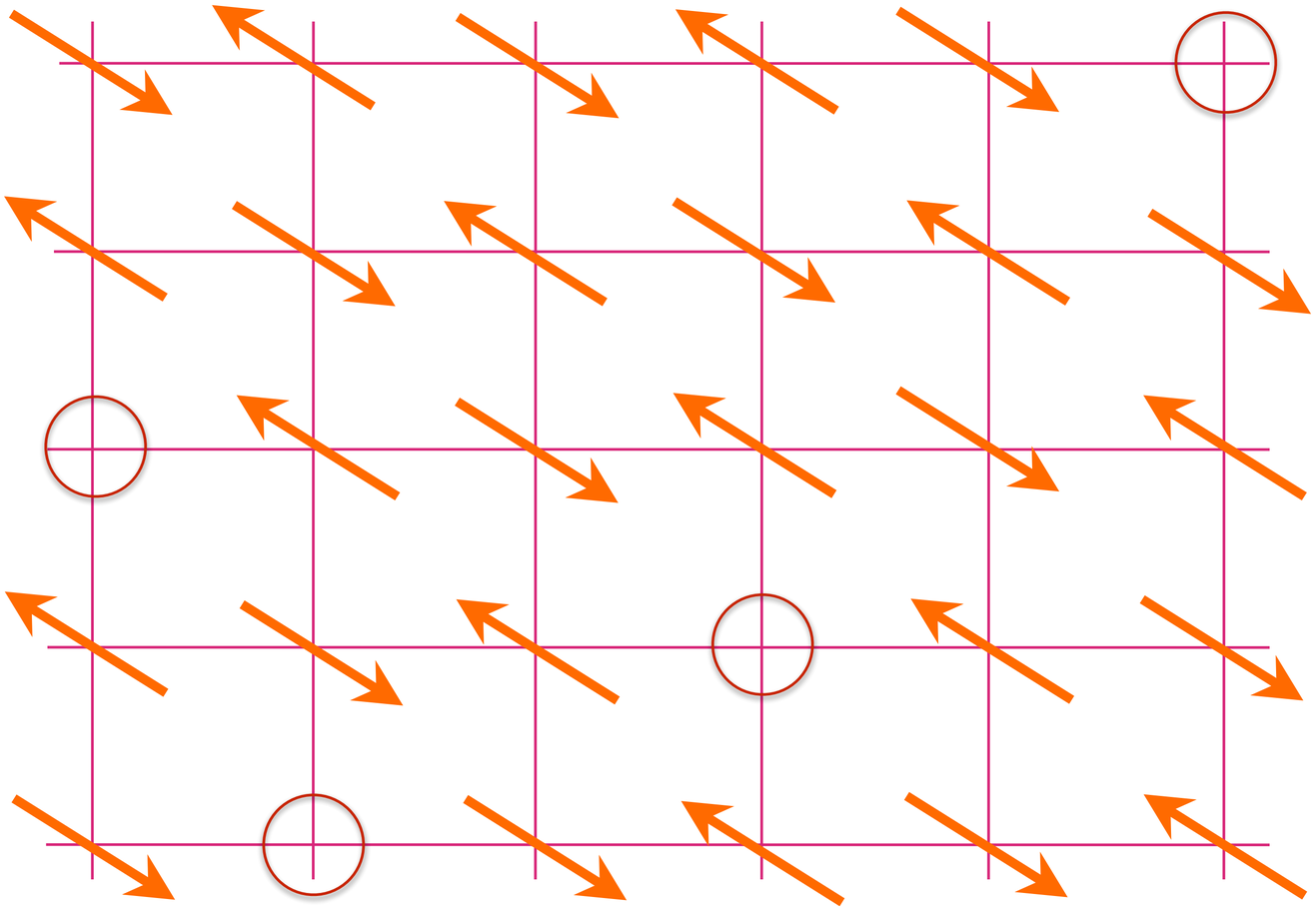
$$\{c_{i\alpha}, c^\dagger_{j\beta}\} = \delta_{ij}\delta_{\alpha\beta},$$

$$\{c_{i\alpha}, c_{j\beta}\} = 0$$

$$\sum_\alpha c^\dagger_{i\alpha} c_{i\alpha} = 1$$

$$\vec{S}_i = \frac{1}{2} c^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} c_{i\beta}$$

Antiferromagnet doped with hole density p



$$H = J \sum_{\langle ij \rangle} \vec{S}_i \cdot \vec{S}_j$$

$$-t \sum_{\langle ij \rangle} c^\dagger_{i\alpha} c_{j\alpha} + \text{H.c.}$$

$$\sum_\alpha c^\dagger_{i\alpha} c_{i\alpha} \leq 1$$

$$\frac{1}{N} \sum_{i\alpha} c^\dagger_{i\alpha} c_{i\alpha} = 1 - p$$

$$\alpha = \uparrow, \downarrow \quad , \quad \{c_{i\alpha}, c^\dagger_{j\beta}\} = \delta_{ij}\delta_{\alpha\beta},$$

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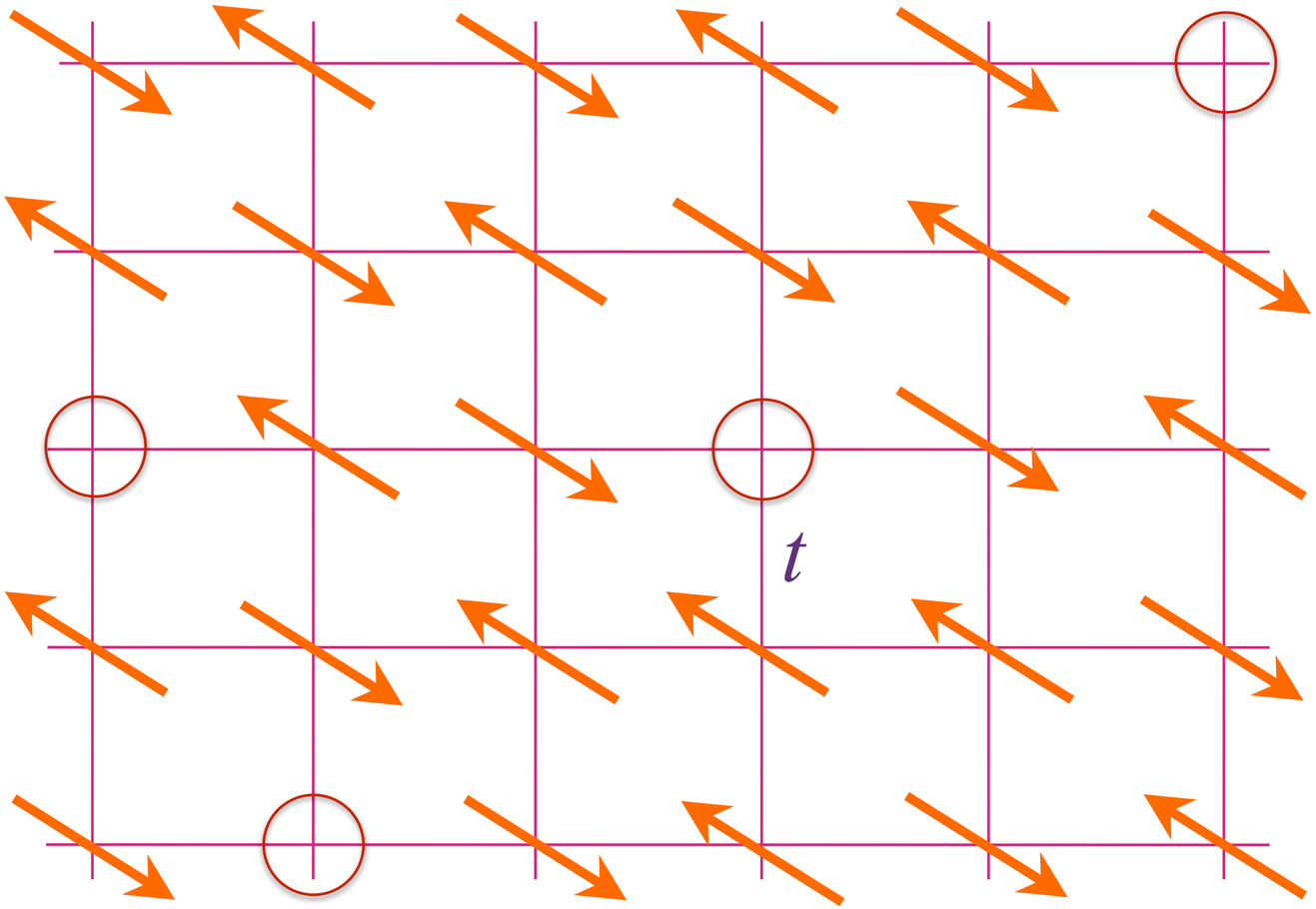
Antiferromagnet doped with hole density p



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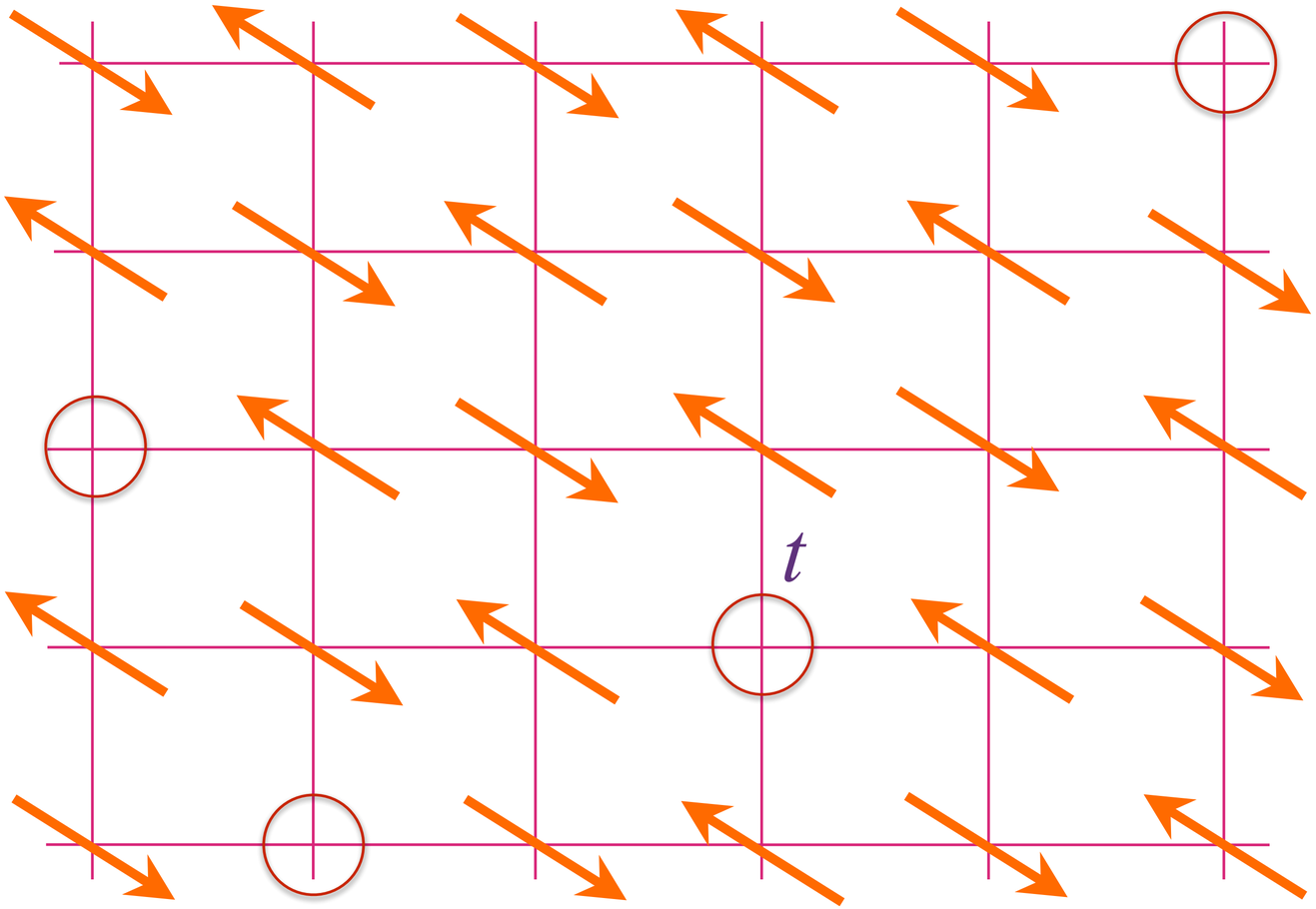
Antiferromagnet doped with hole density p



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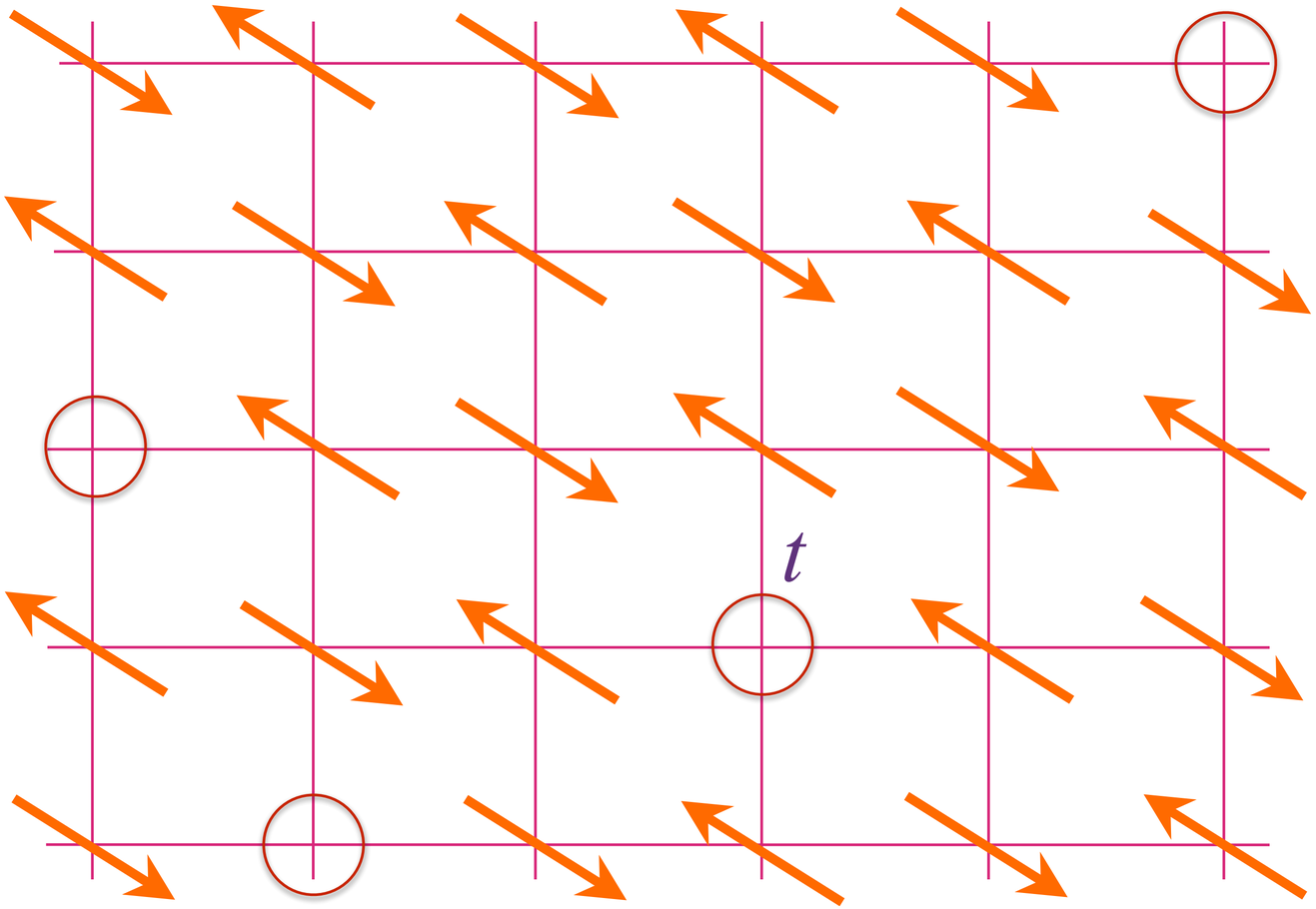
Antiferromagnet doped with hole density p



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Complete mathematical definition of the high-T_c problem !

$$\alpha = \uparrow, \downarrow \quad , \quad \{c_{i\alpha}, c^\dagger_{j\beta}\} = \delta_{ij}\delta_{\alpha\beta},$$

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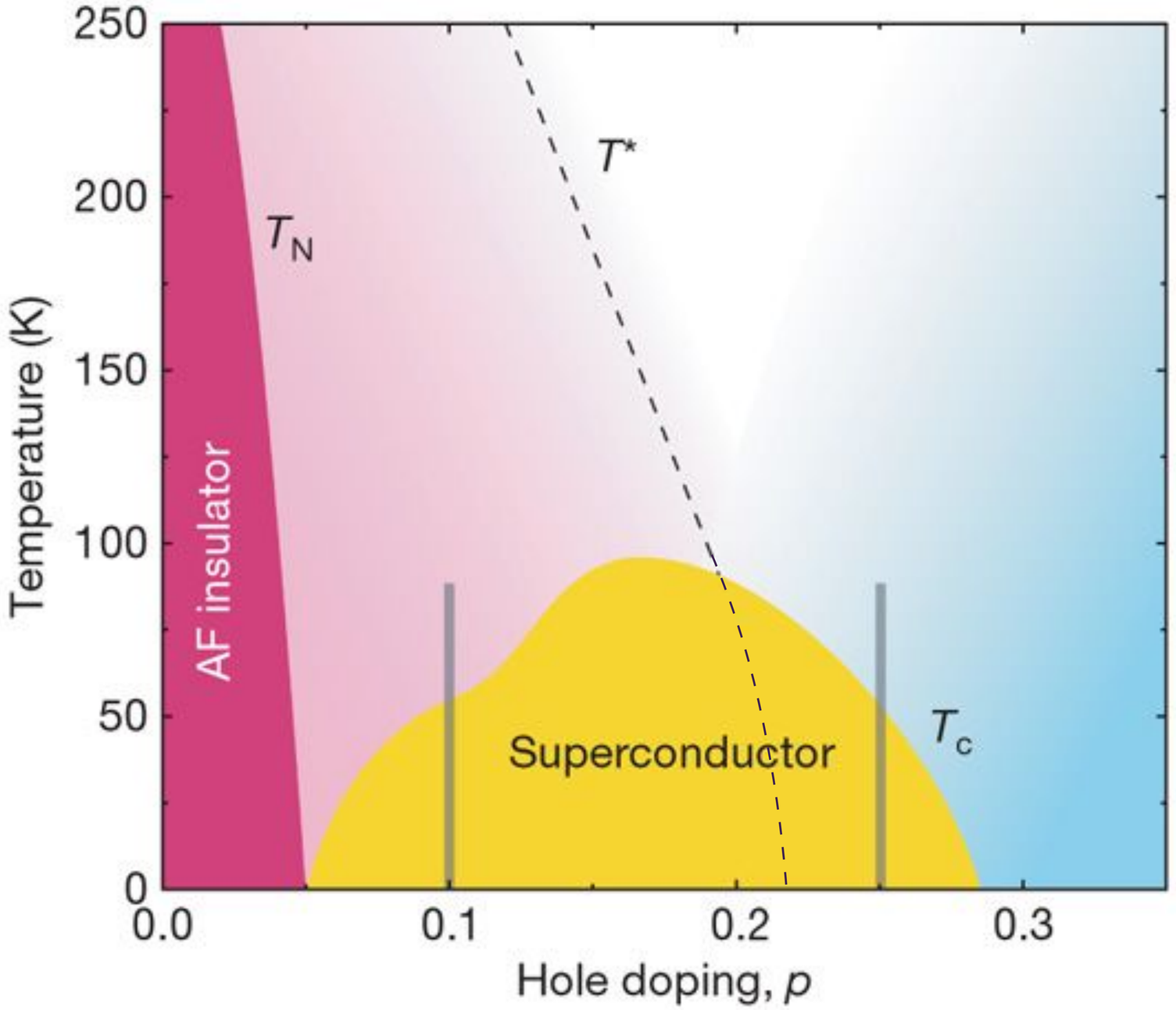
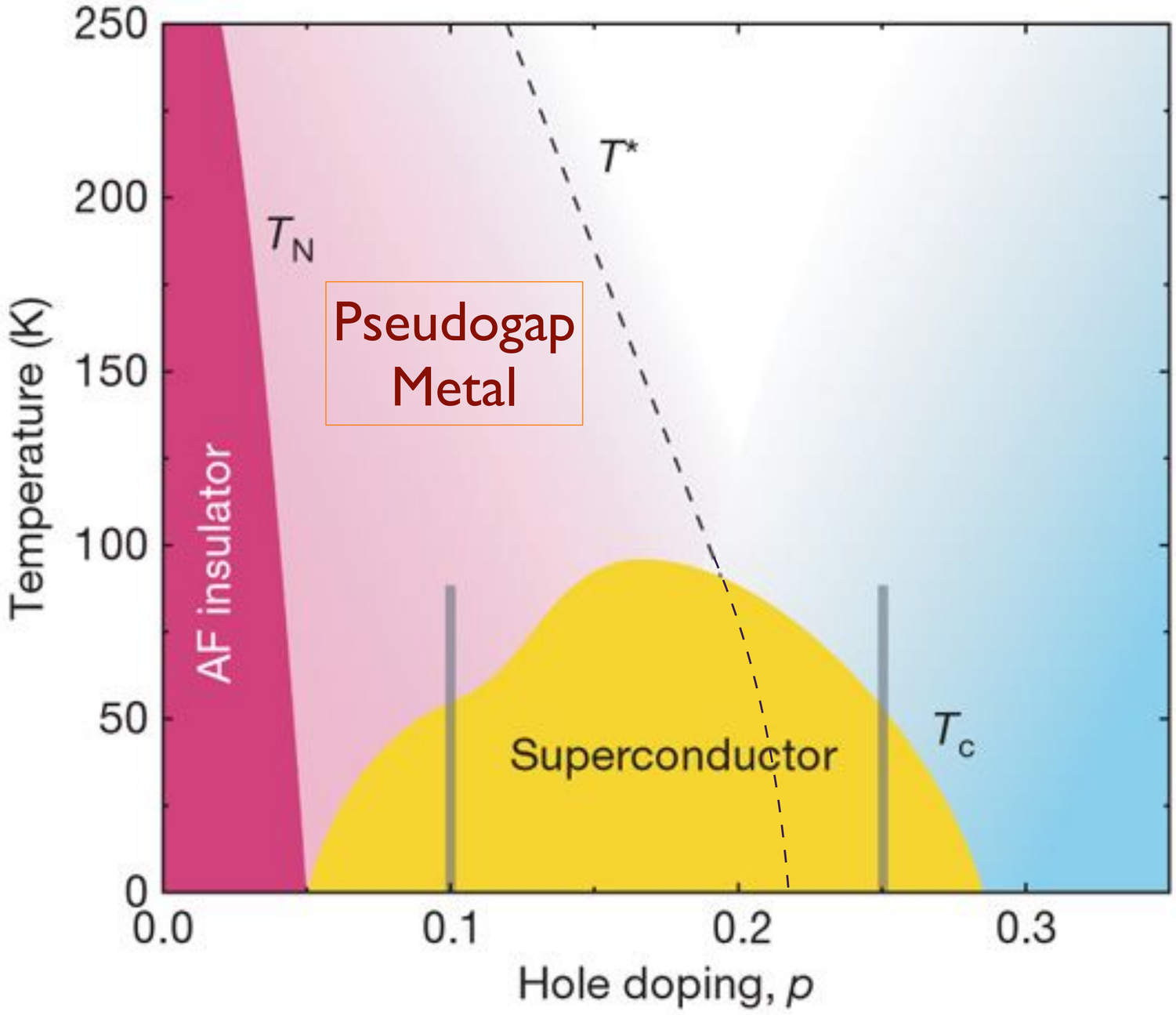
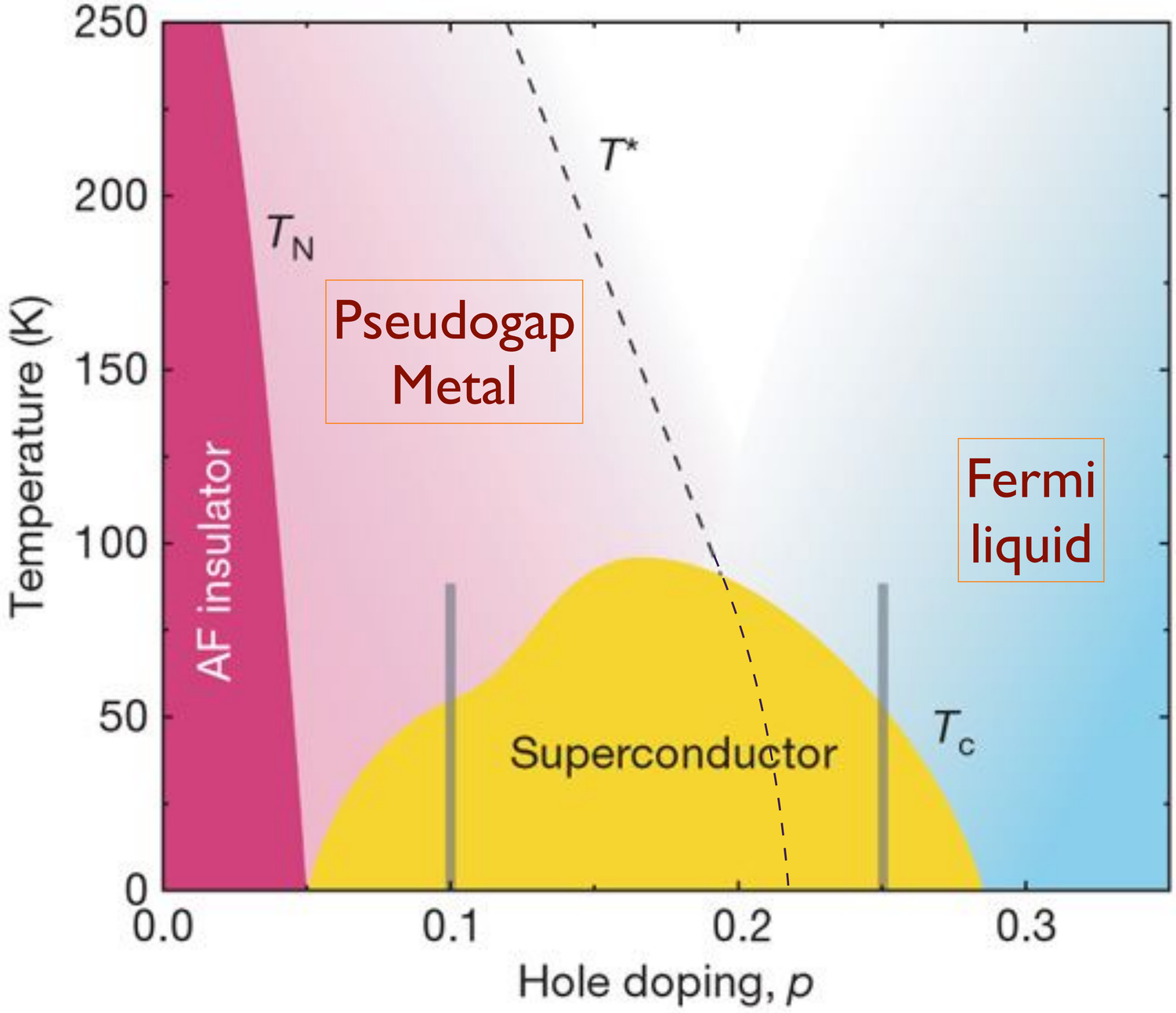
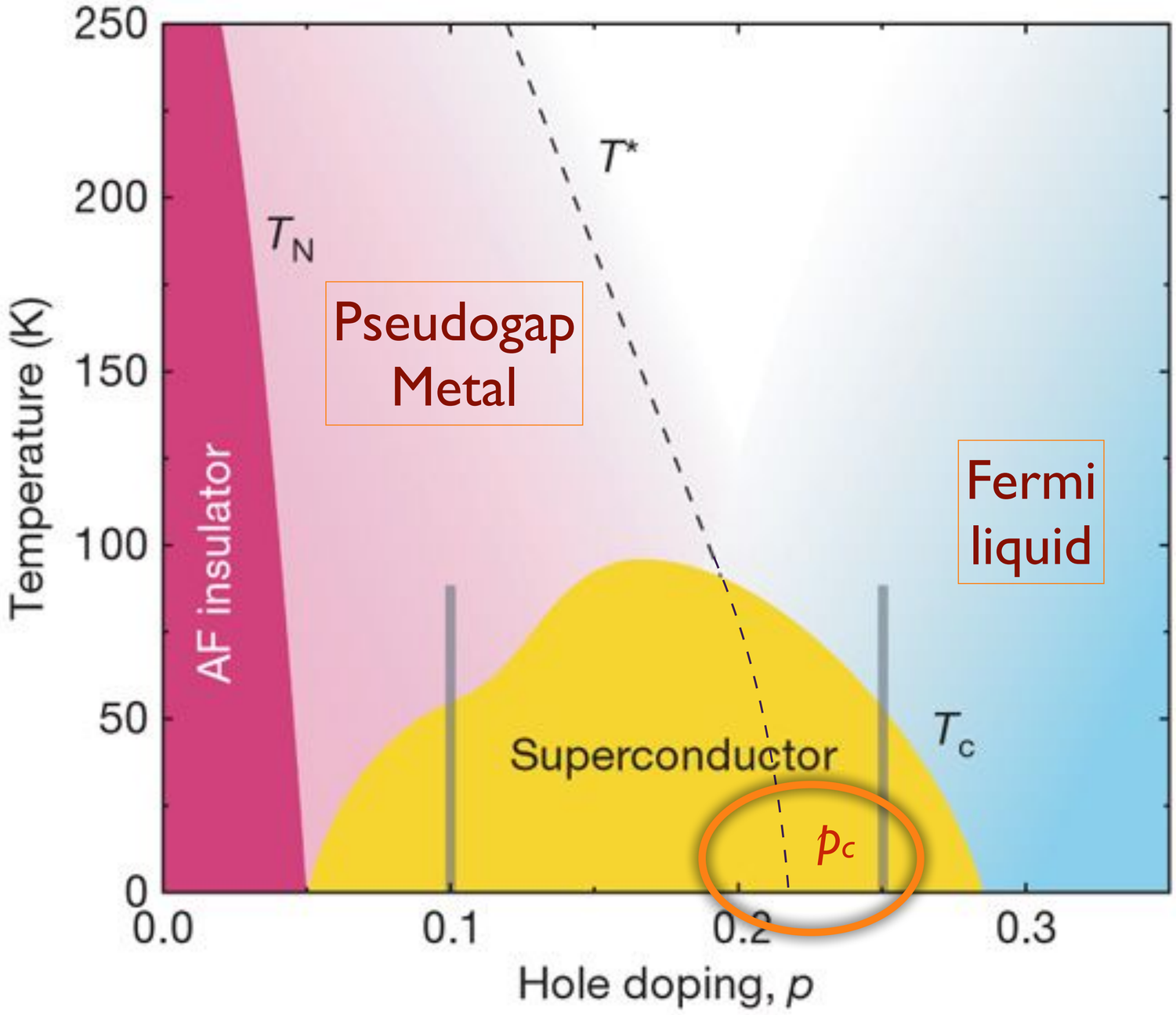

250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
AF insulator
T_N
T^*
Superconductor
T_c


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
Superconductor
T_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
Fermi
liquid
Superconductor
T_c


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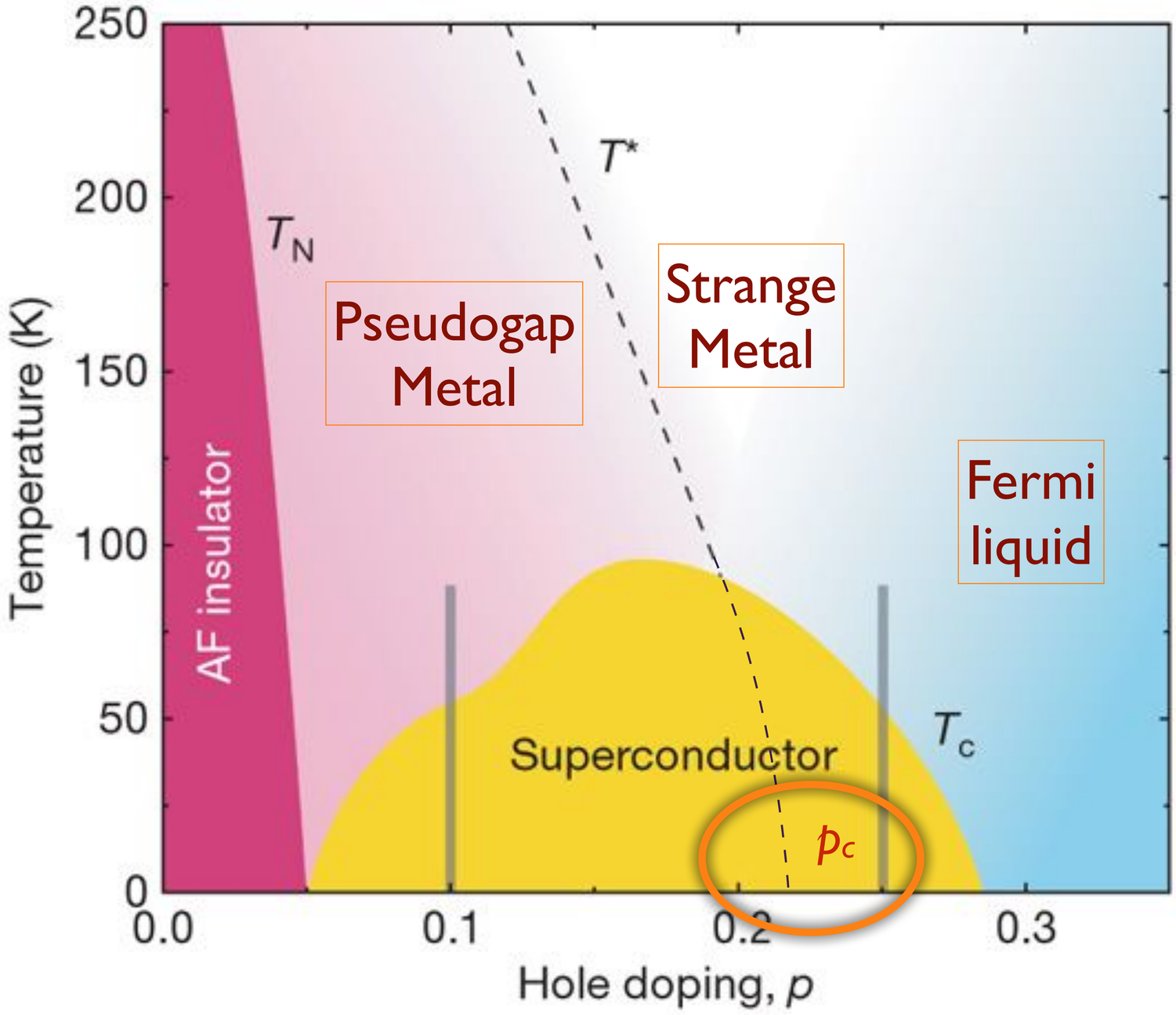
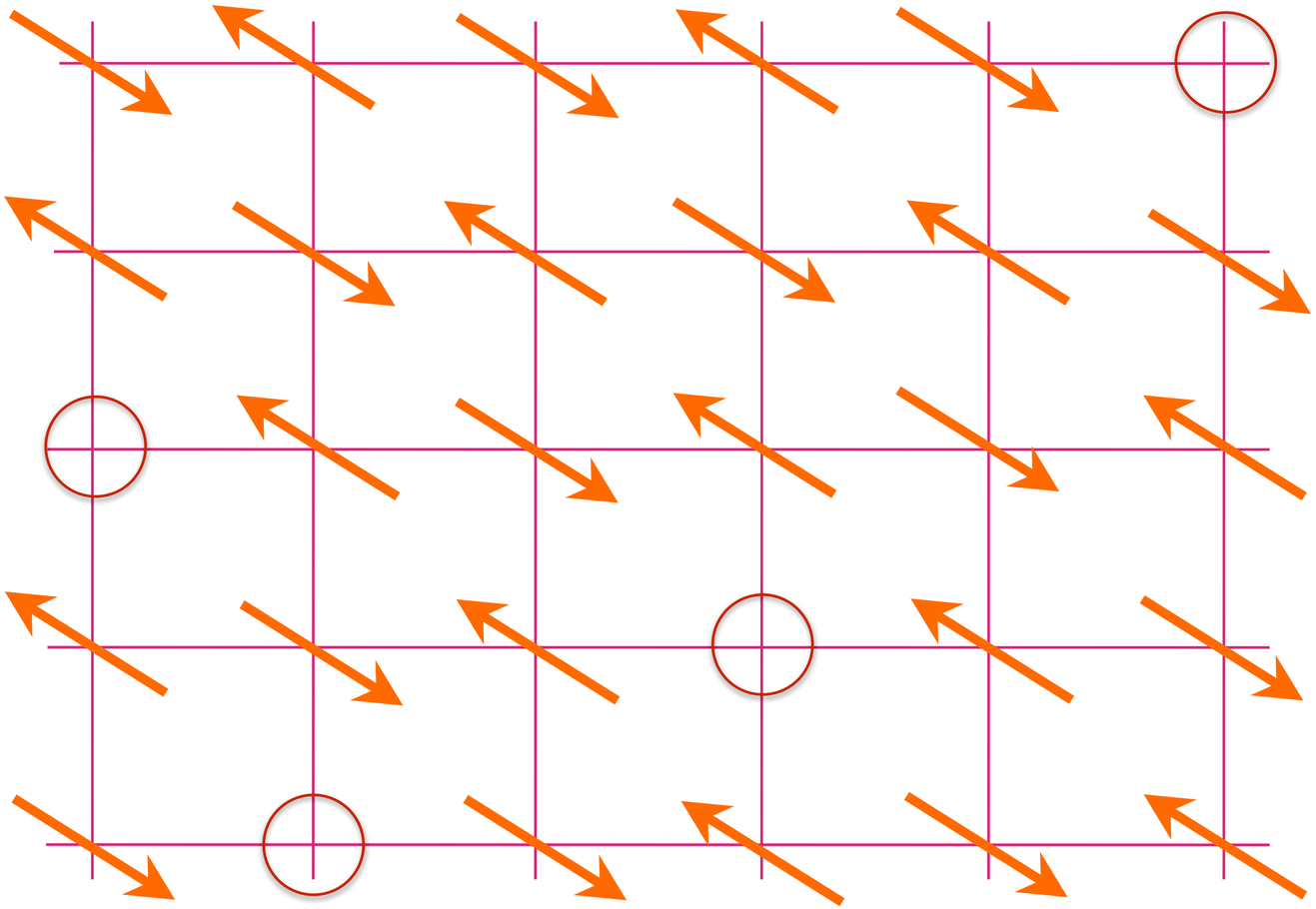
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
AF insulator
T_N
T^*
Pseudogap
Metal
Fermi
liquid
Superconductor
T_c
p_c

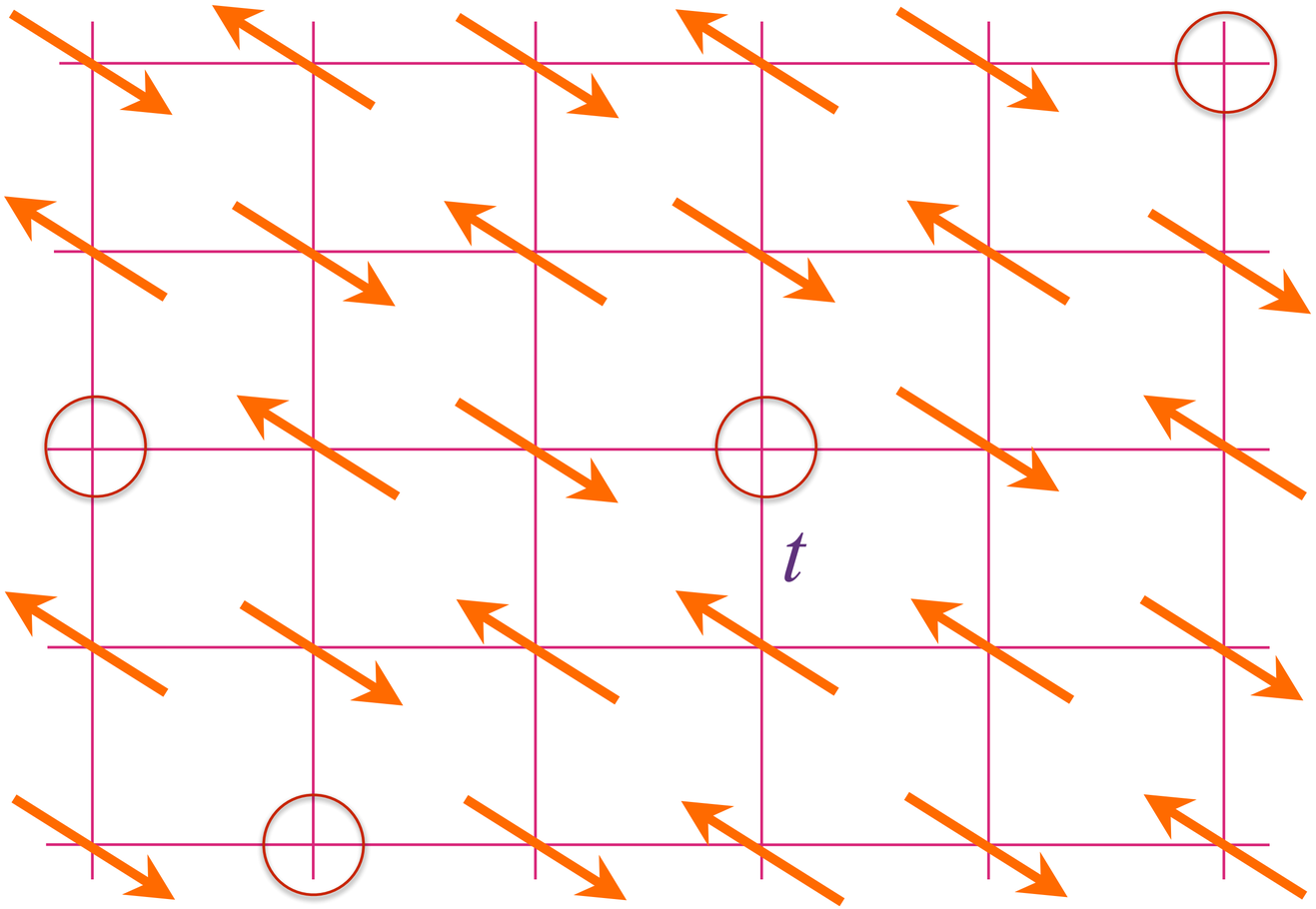

250
200
150
100
50
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
AF insulator
T_N
T^*
Pseudogap Metal
Strange Metal
Fermi liquid
Superconductor
T_c
p_c

Real-space view at small p



p mobile holes in a background of fluctuating spins

Real-space view at small p



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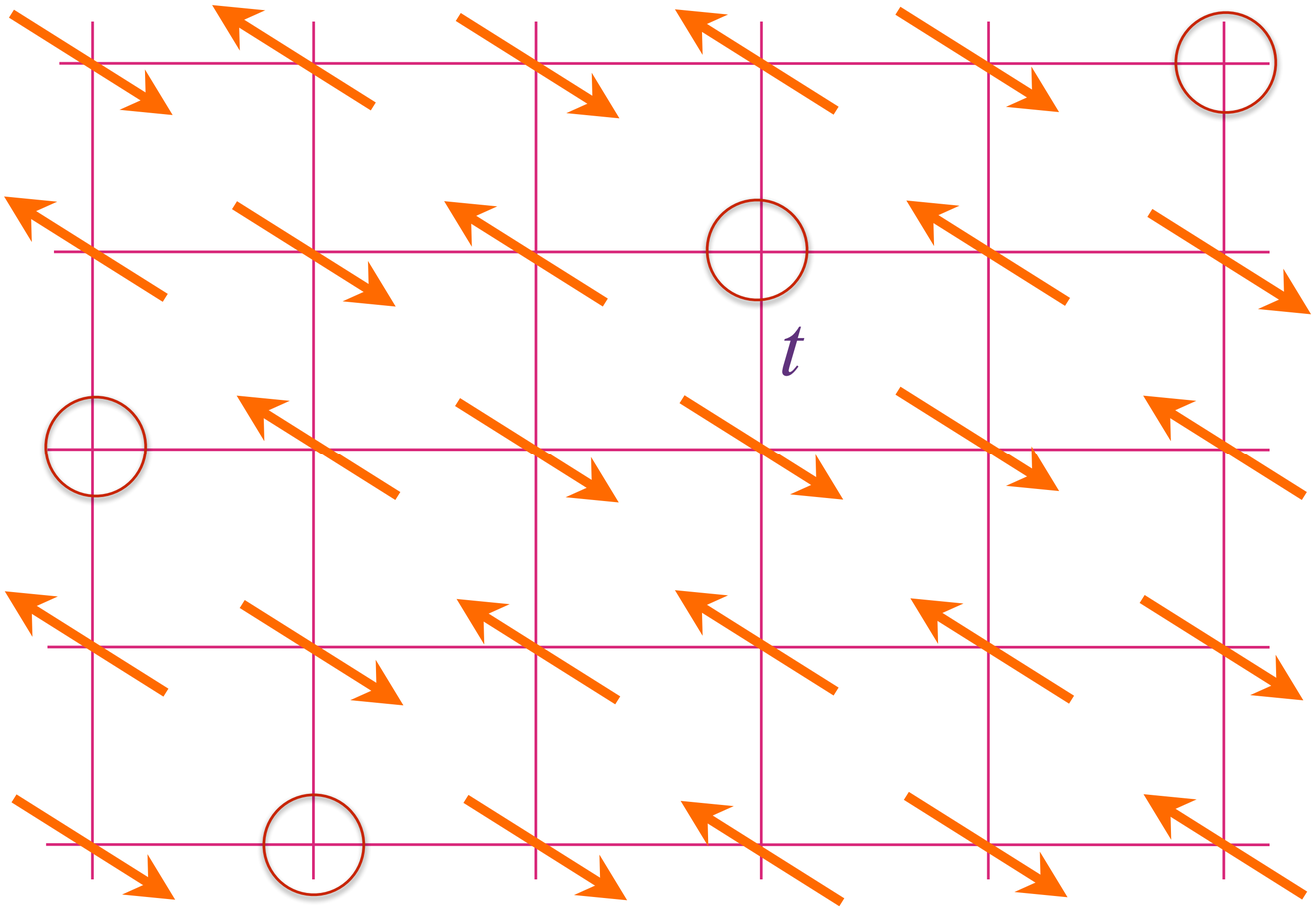
Real-space view at small p



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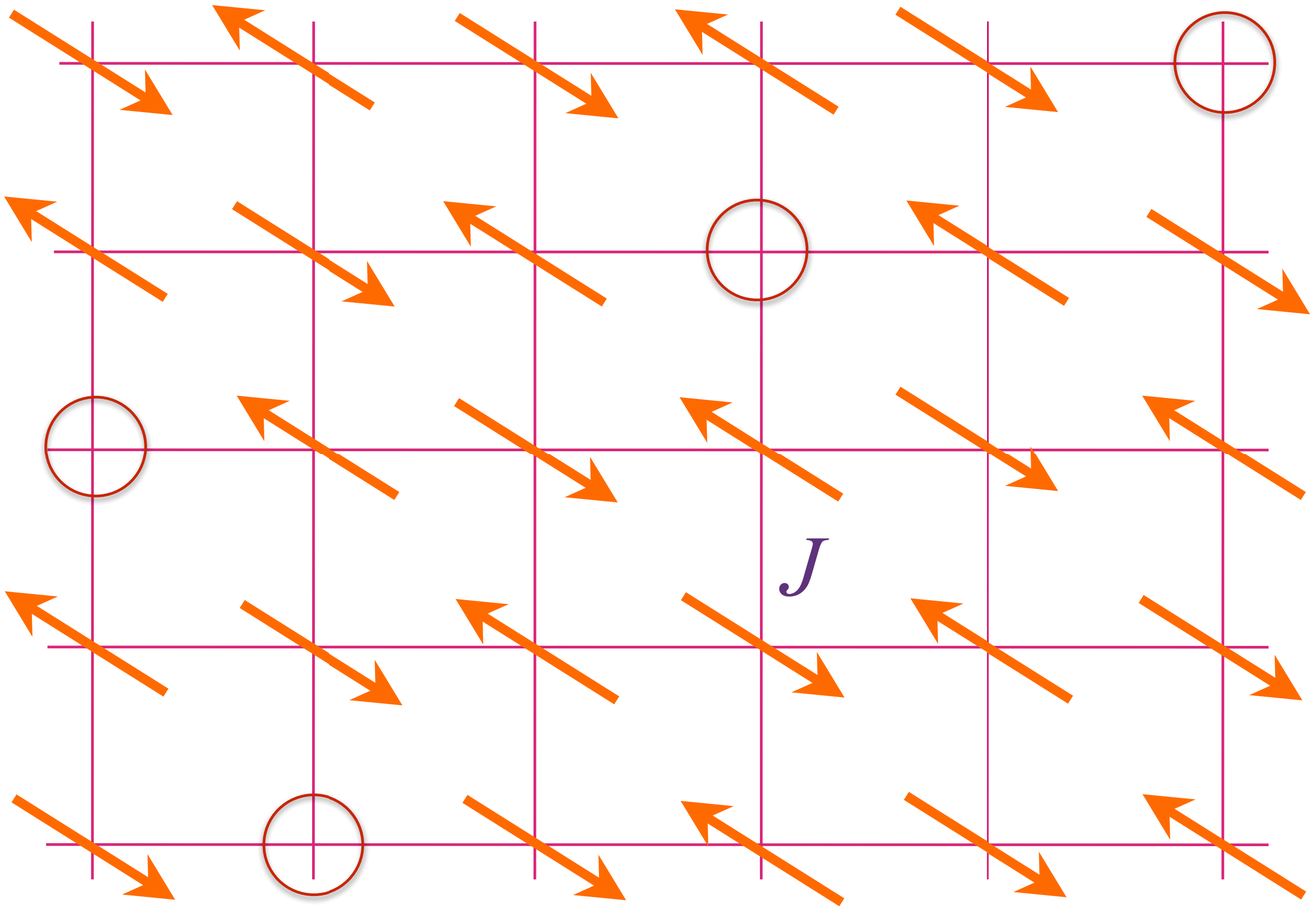
Real-space view at small p



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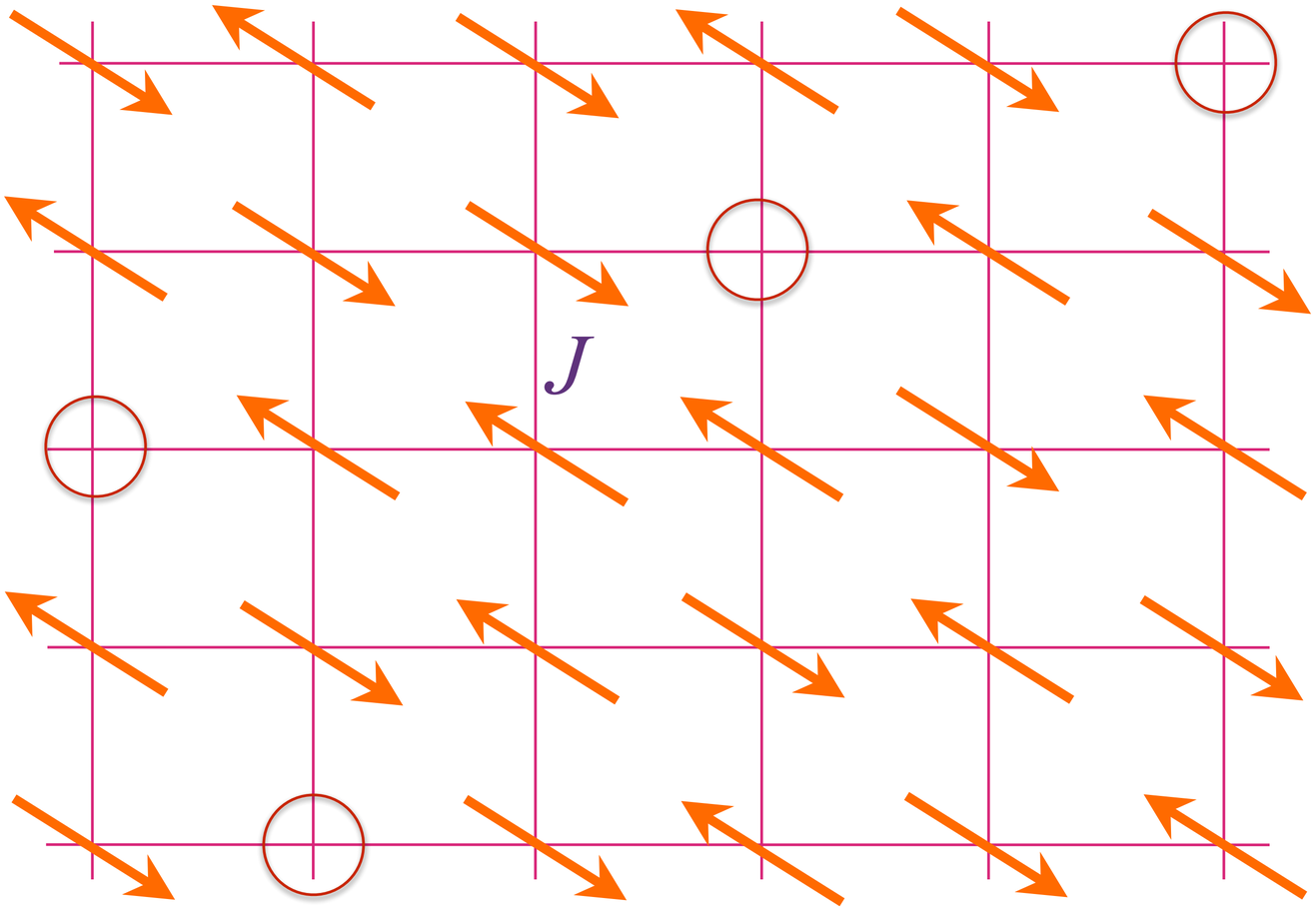
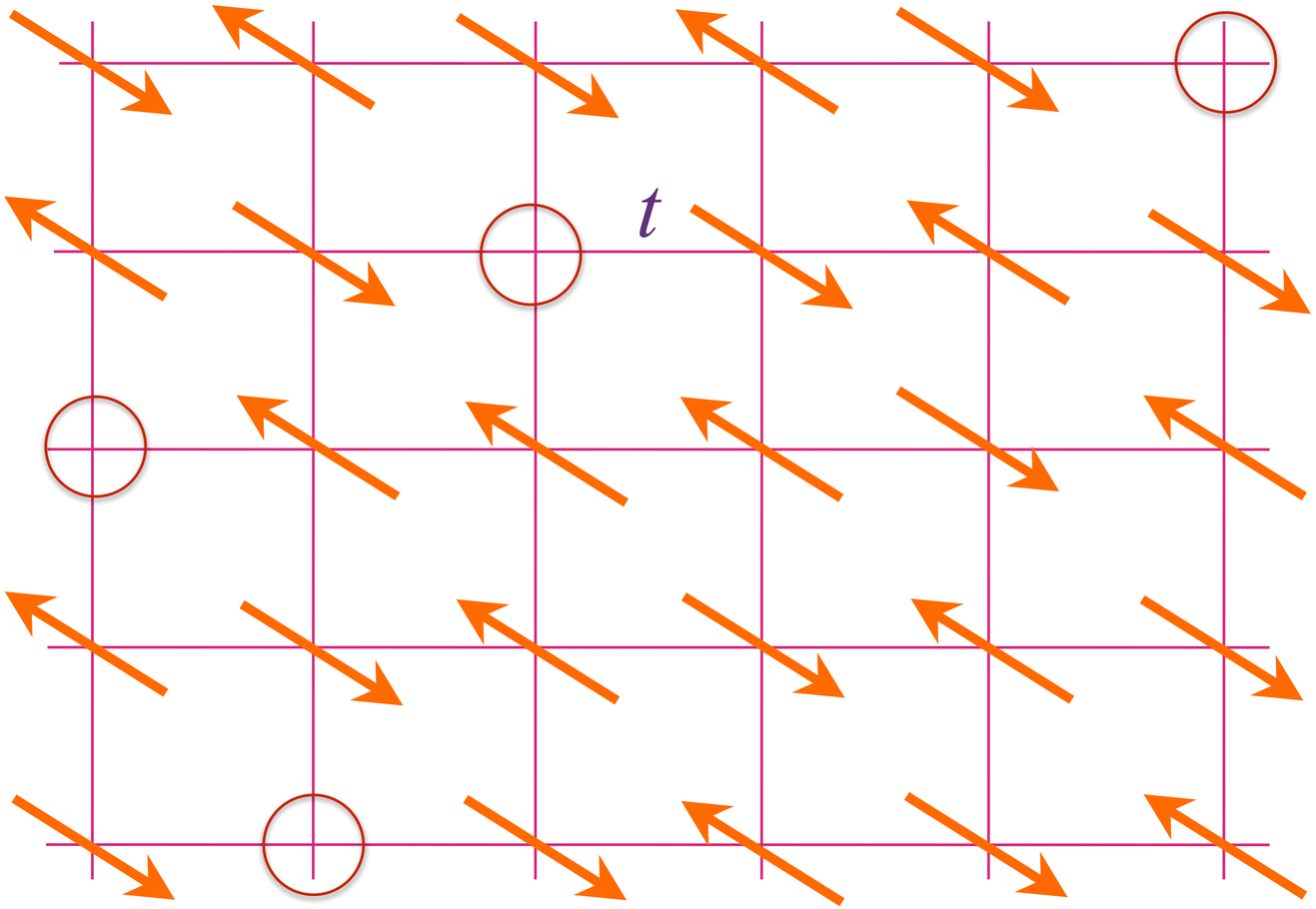
Real-space view at small p



p mobile holes in a background of fluctuating spins

Real-space view at small p



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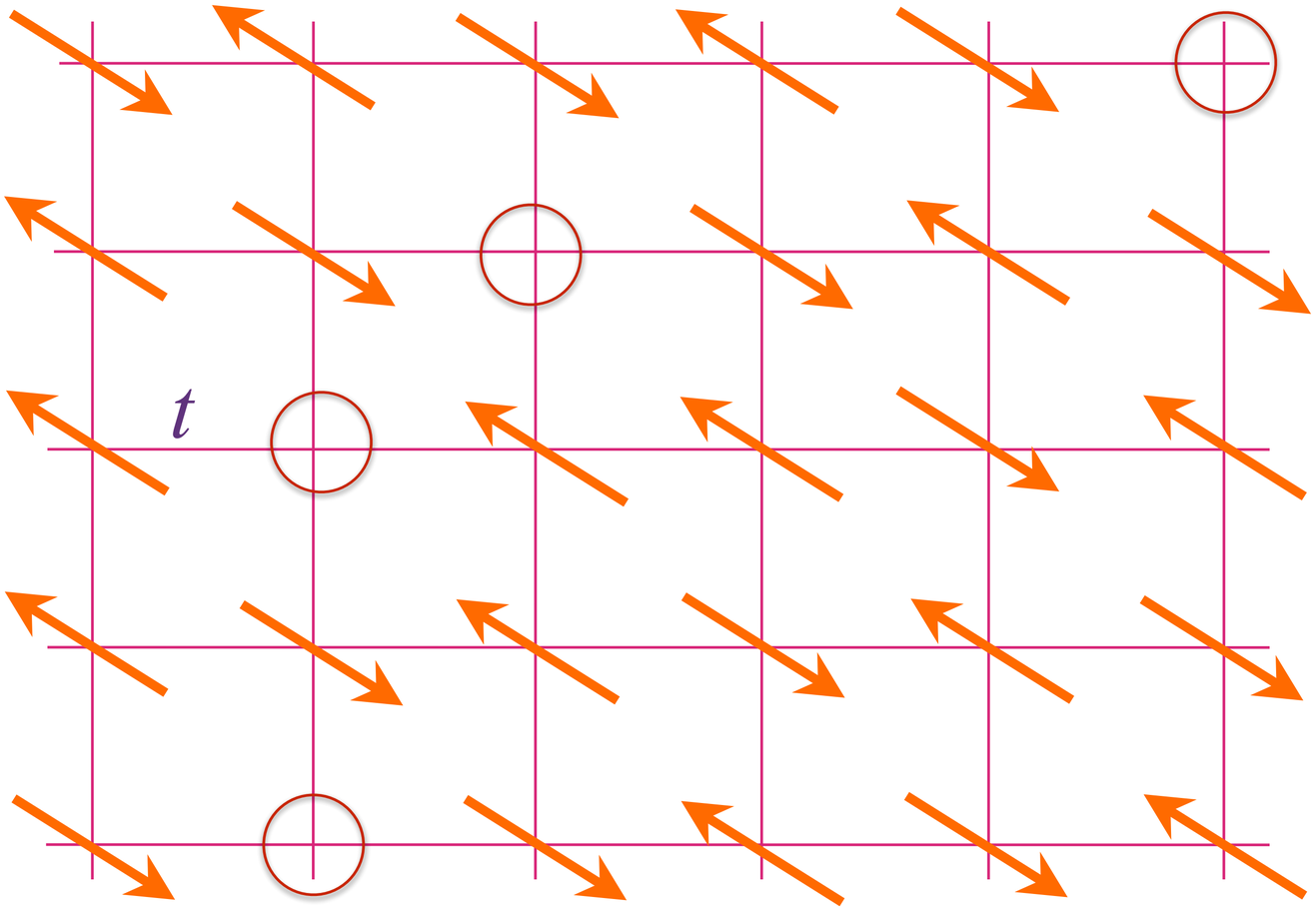
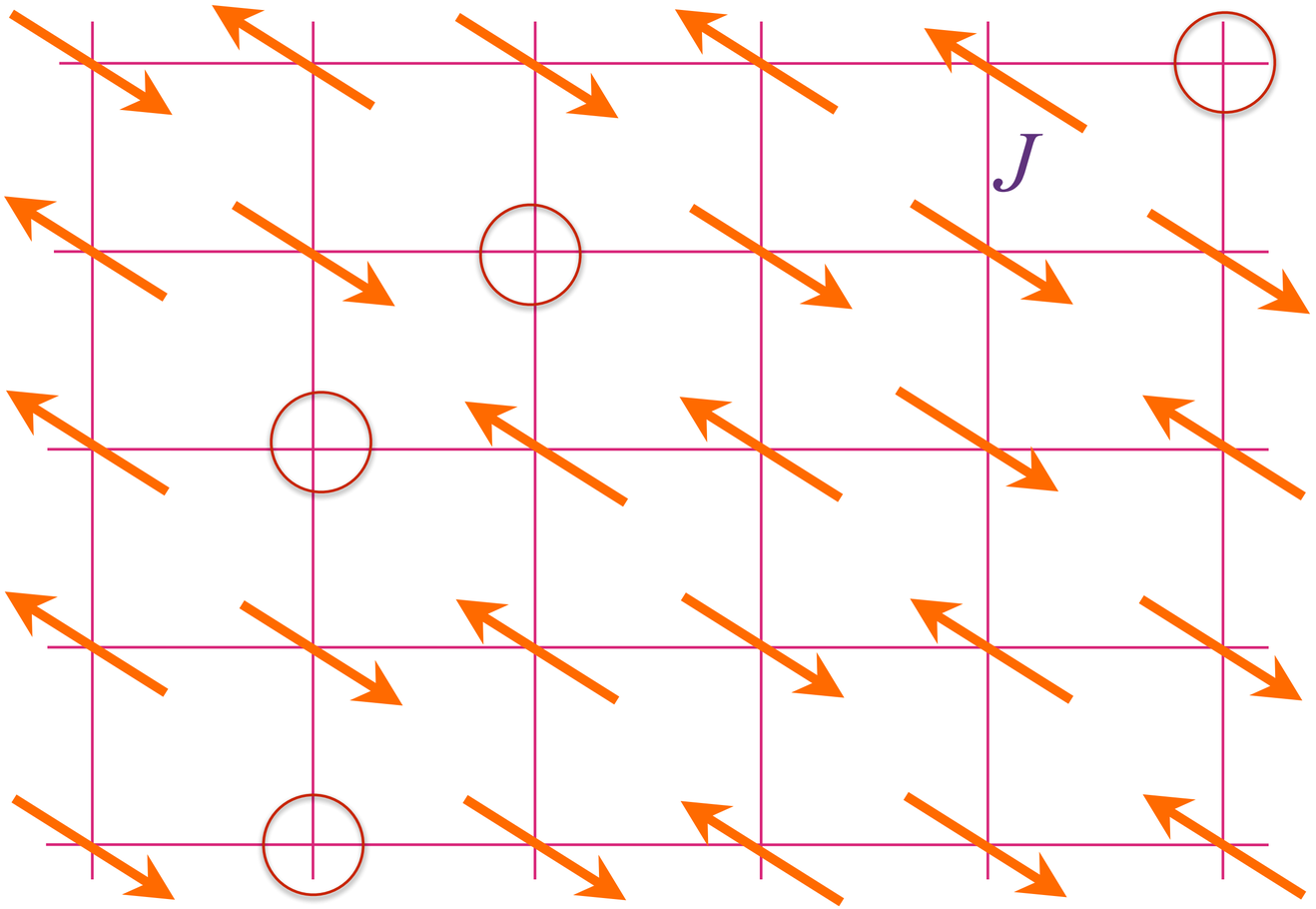
Real-space view at small p



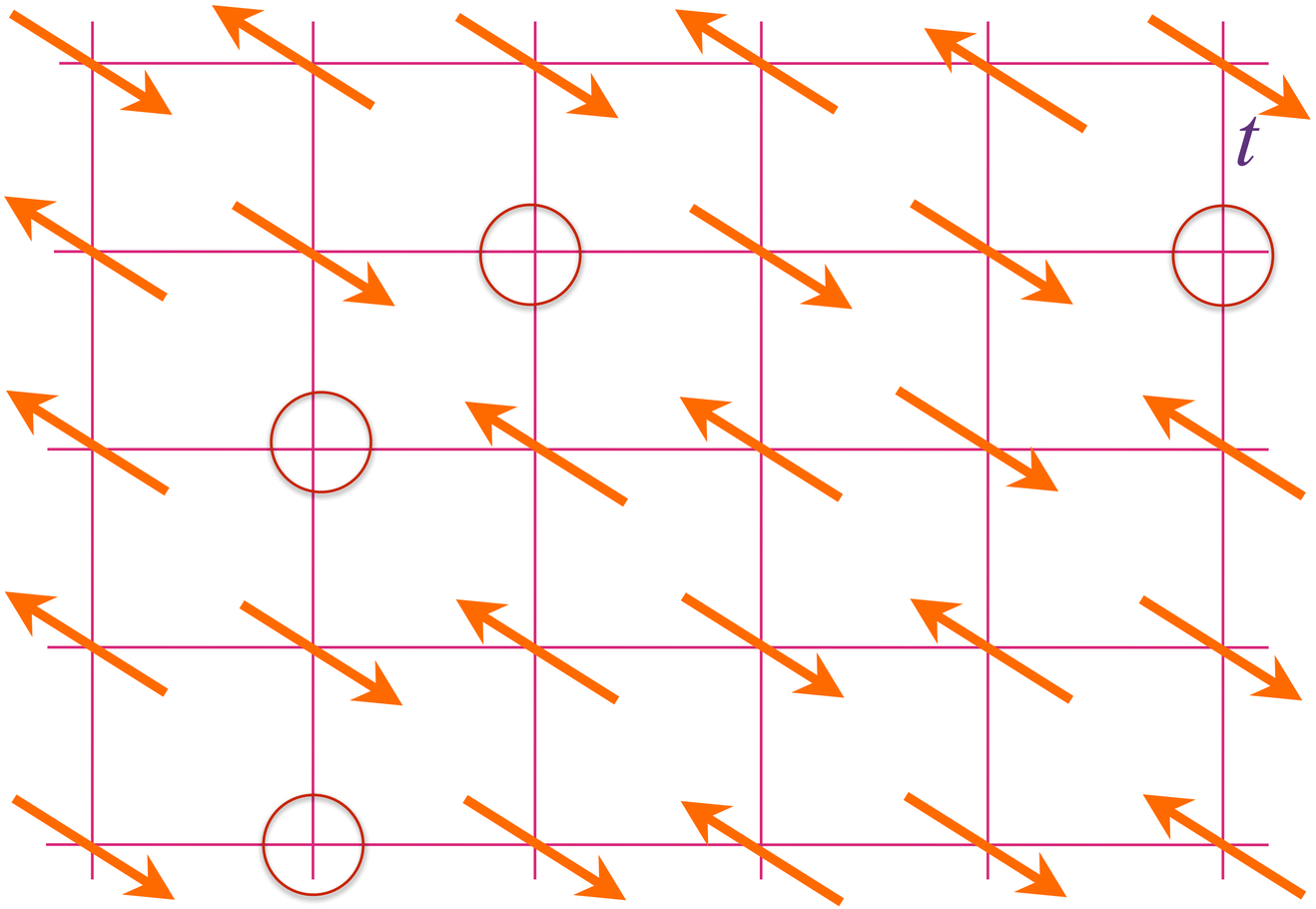
p mobile holes in a background of fluctuating spins

Real-space view at small p



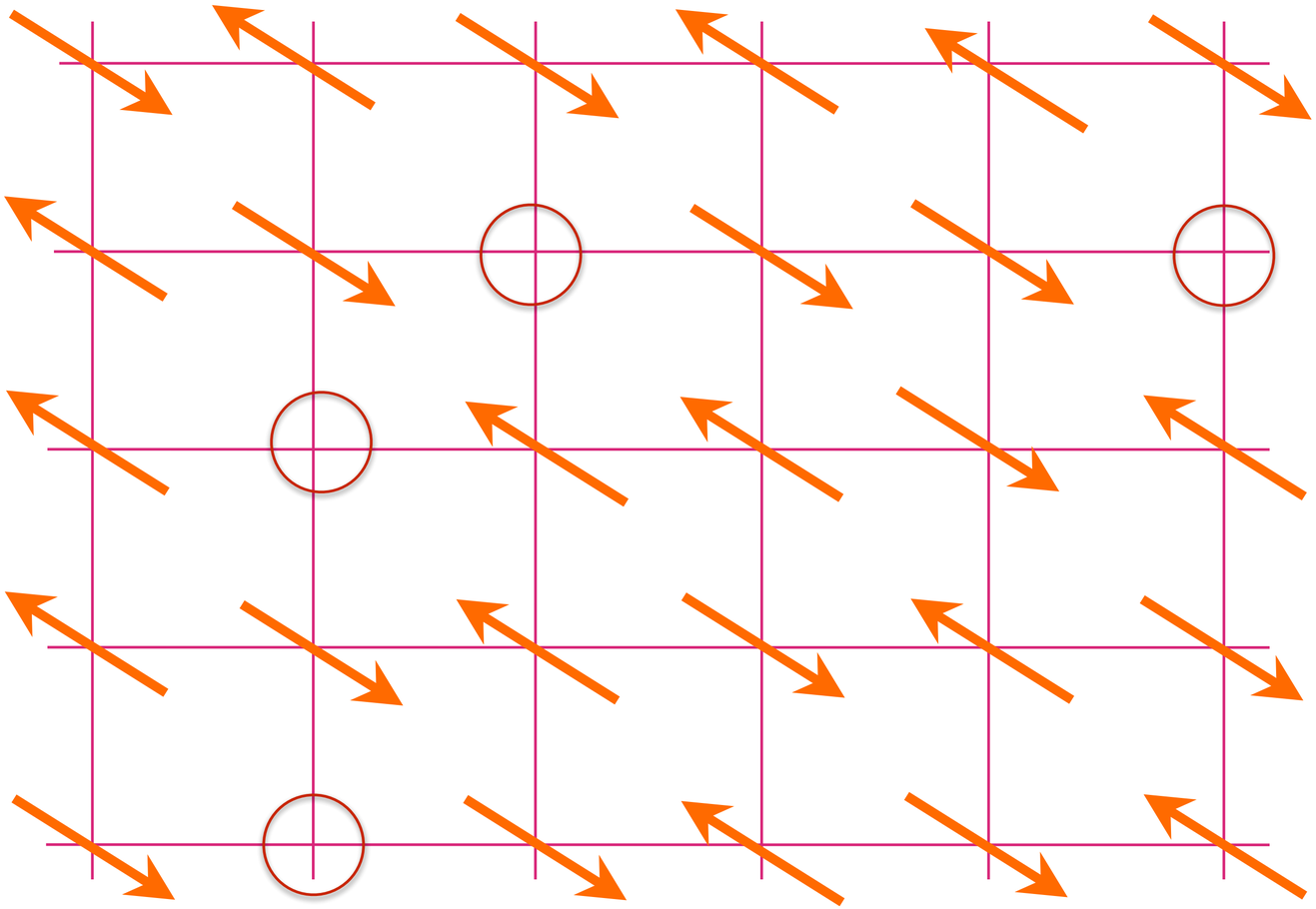
p mobile holes in a background of fluctuating spins

Real-space view at small p



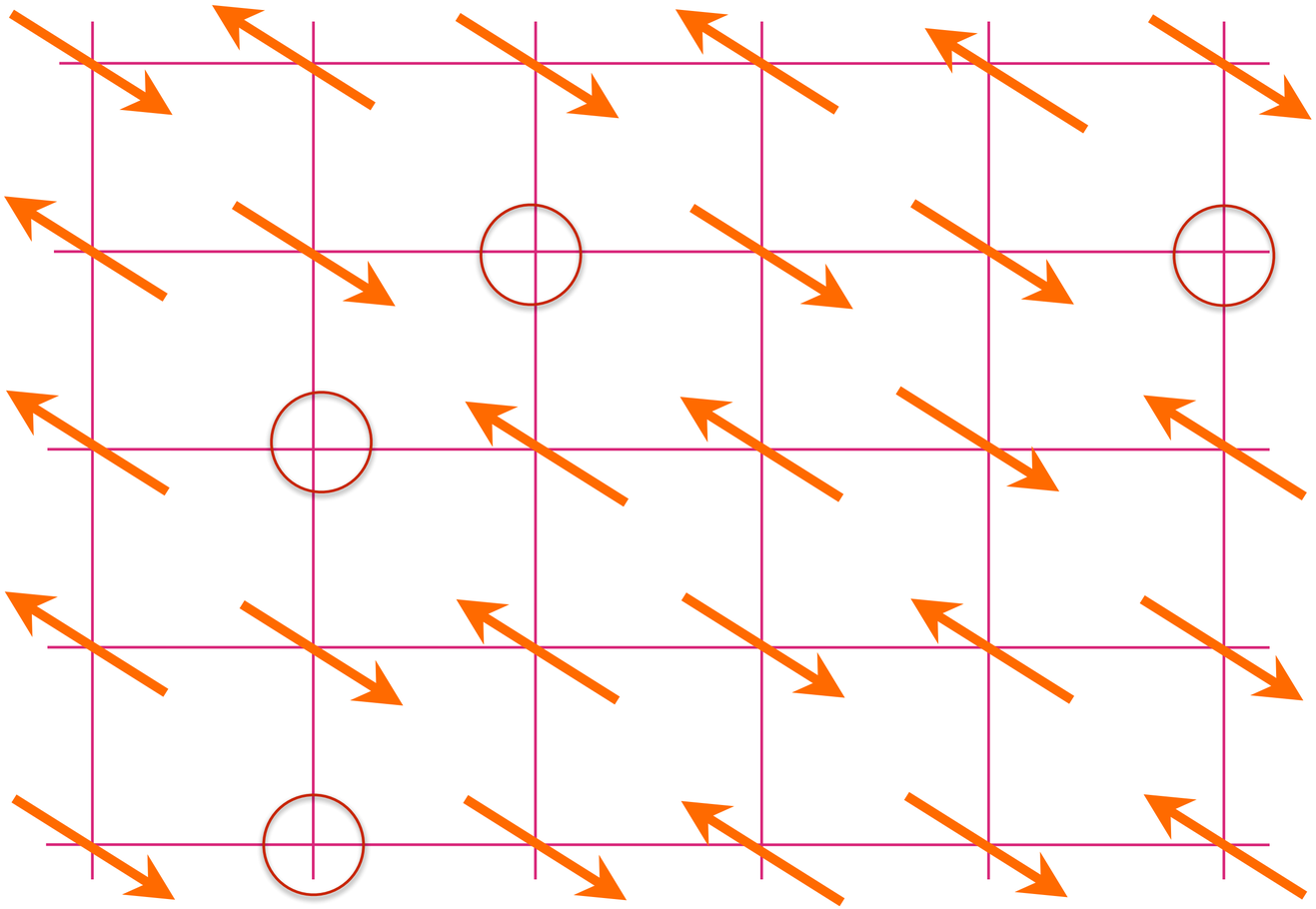
p mobile holes in a background of fluctuating spins

Momentum-space view at large p



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

Momentum-space view at large p



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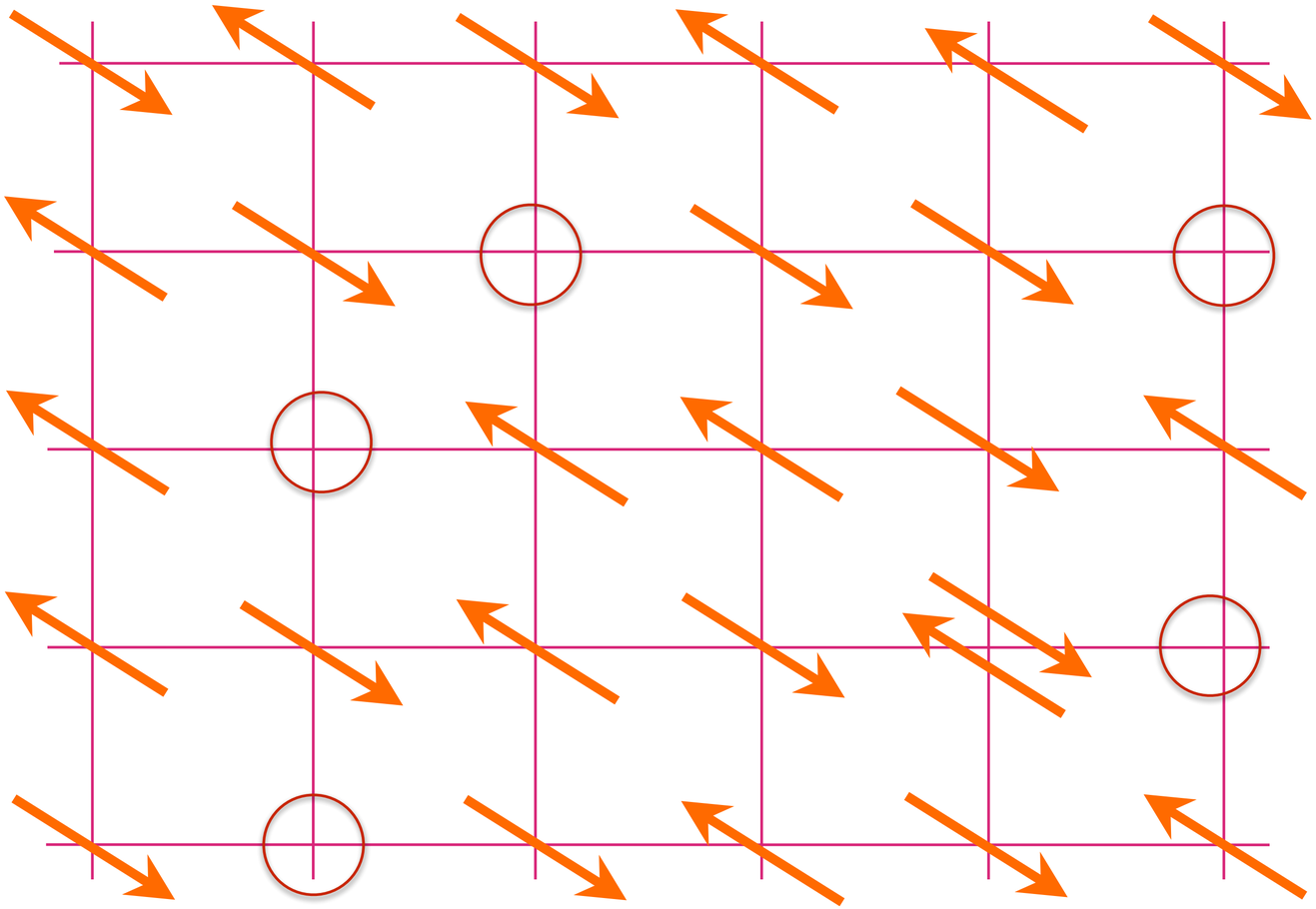
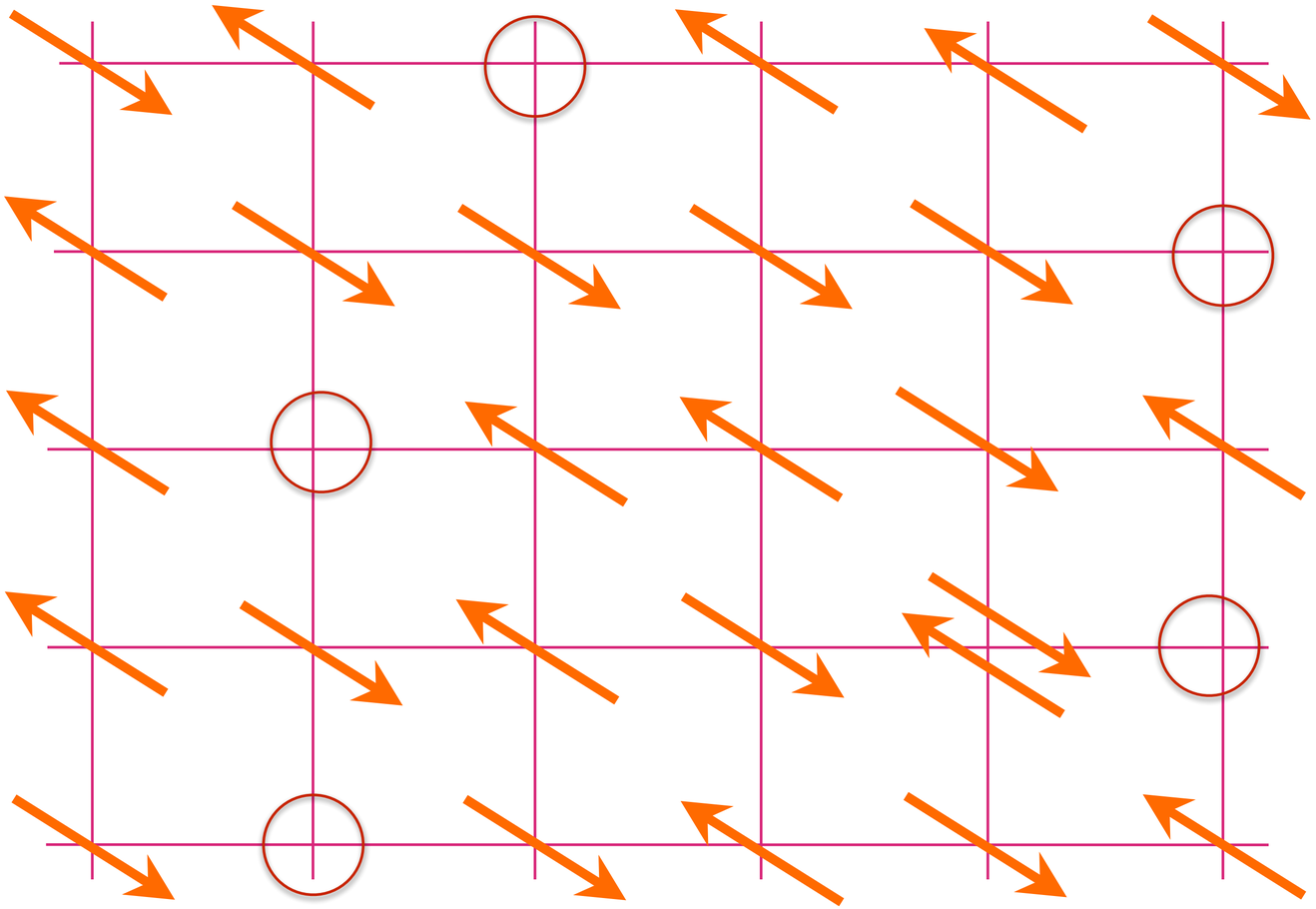
Momentum-space view at large p



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

Momentum-space view at large p



1-p mobile electrons =
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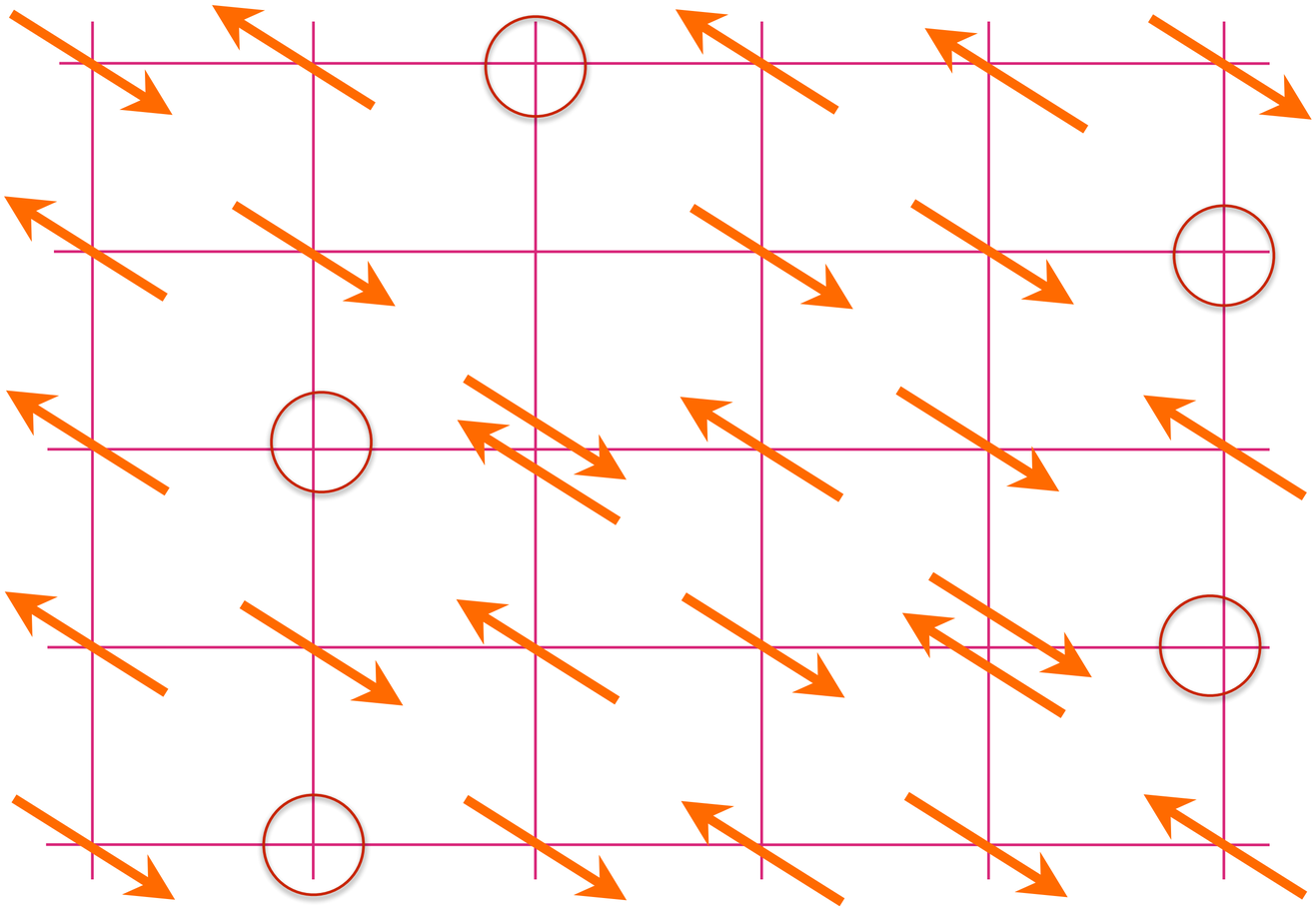
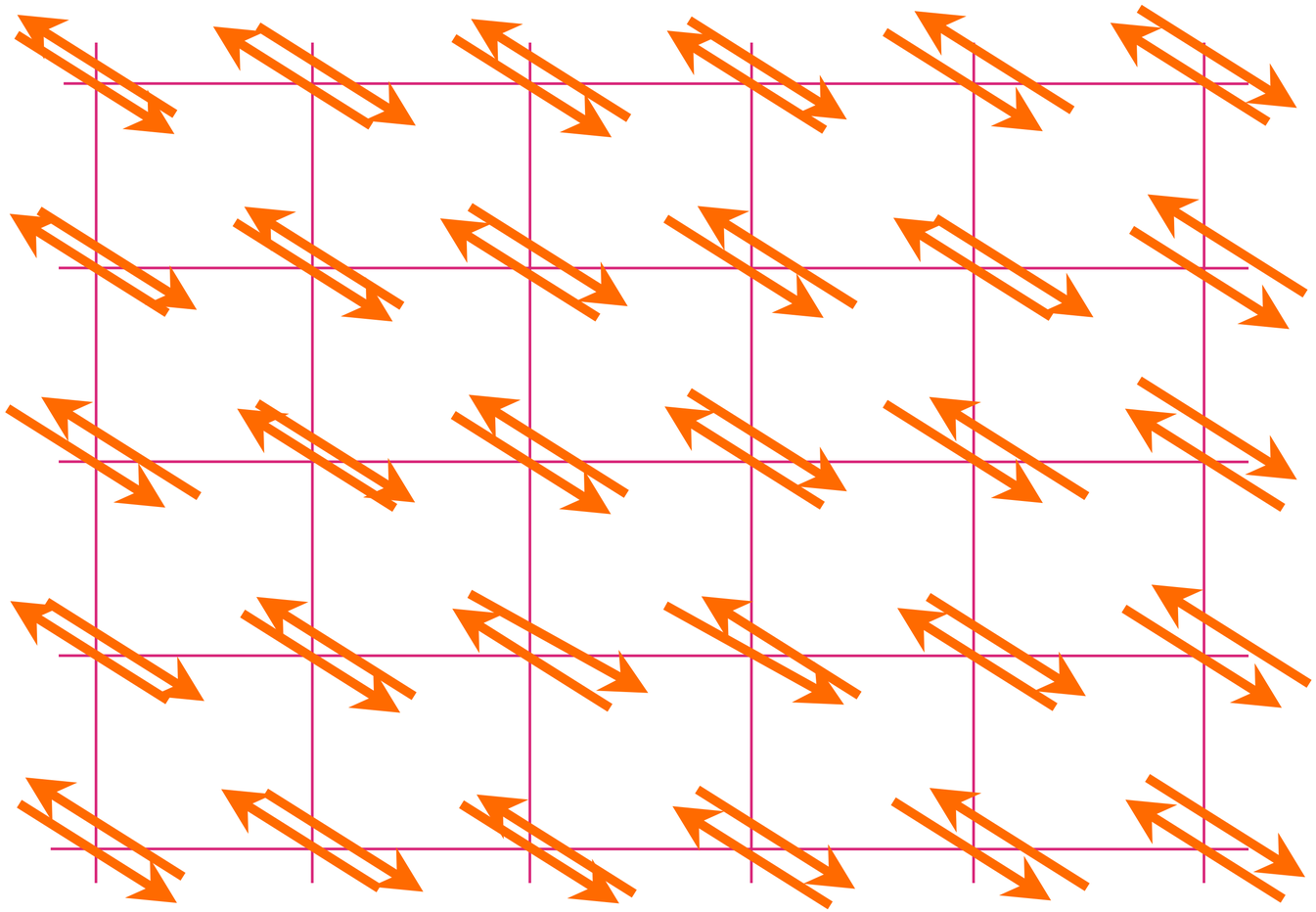
Momentum-space view at large p



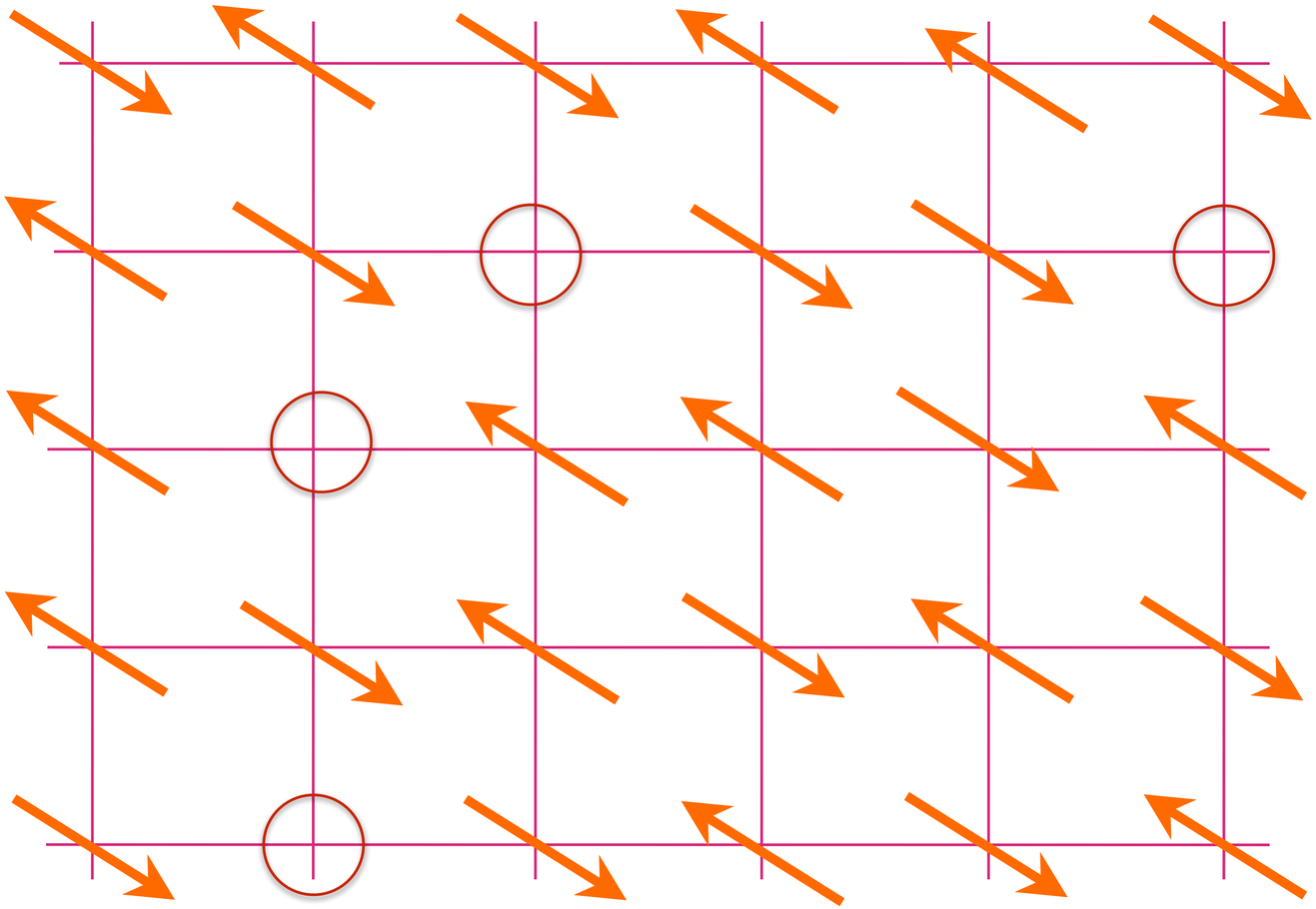
1-p mobile electrons =
1+p mobile holes in a filled band

Momentum-space view at large p



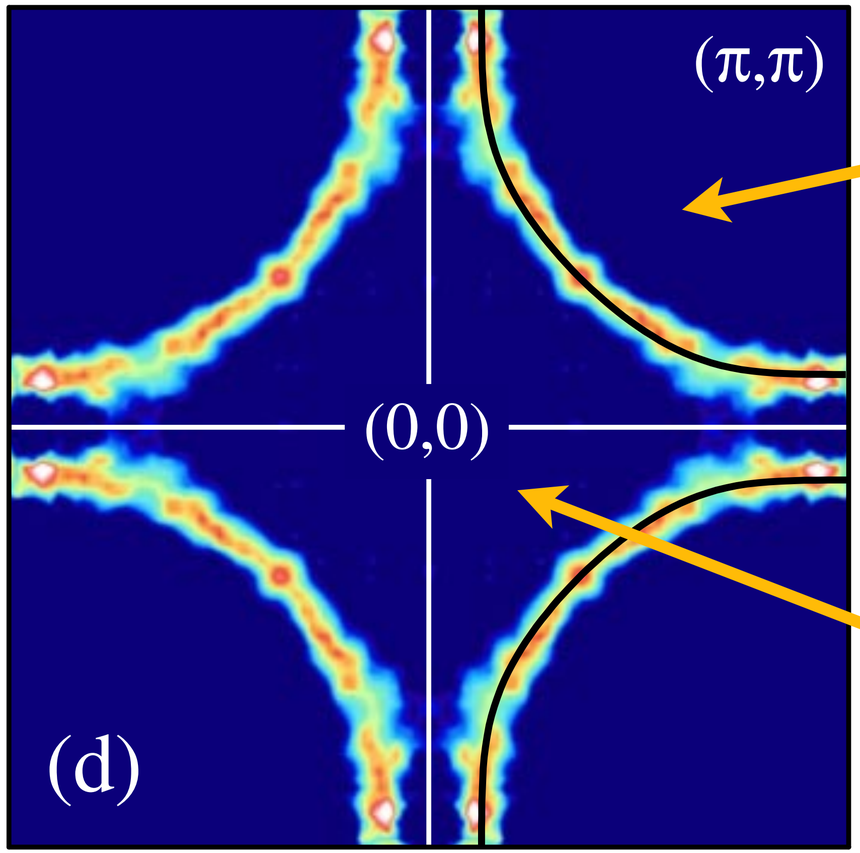
Filled Band

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

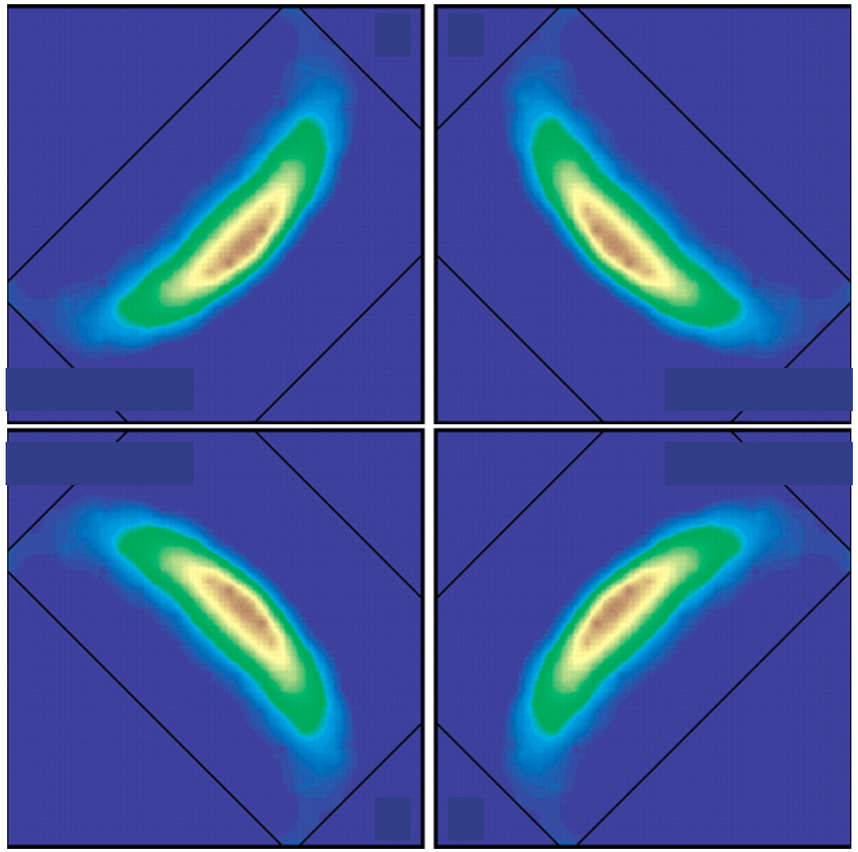
$1-p$ electrons

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

$1+p$ 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 $x = 0.10$

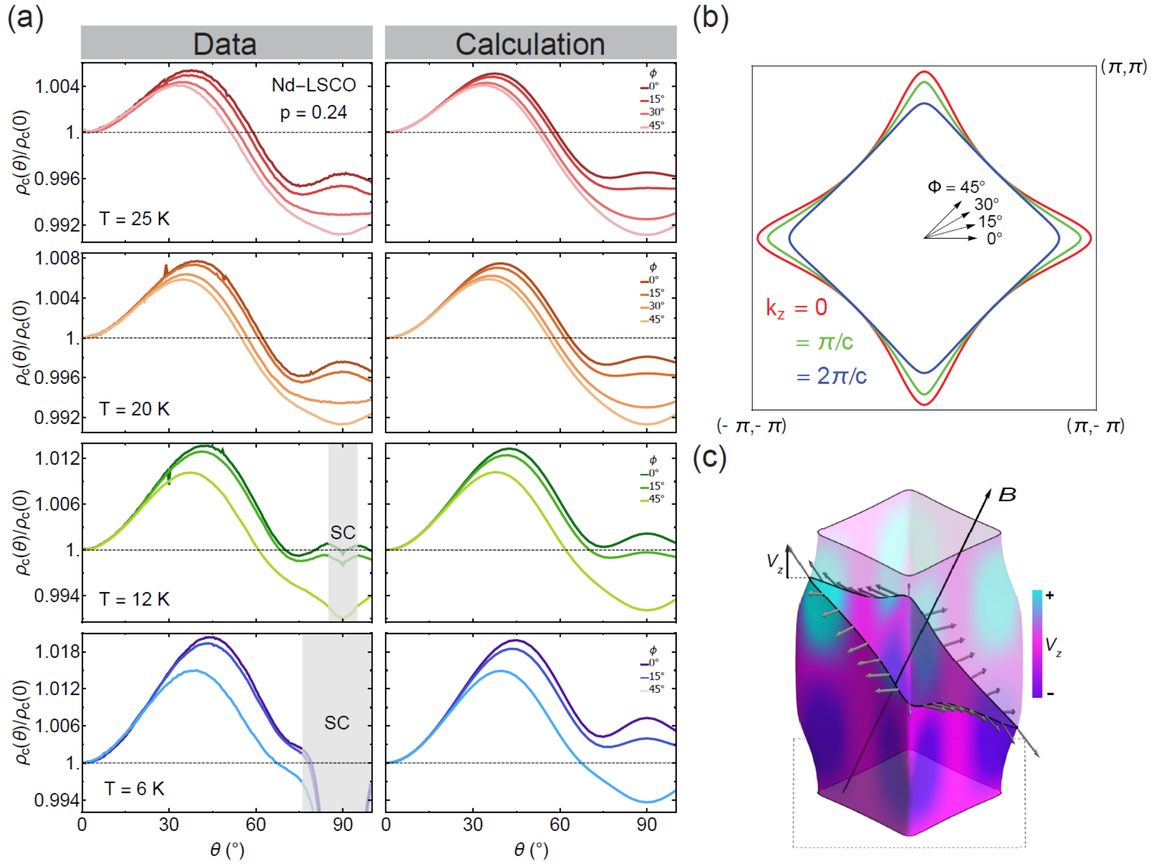
"Fermi arcs"

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)

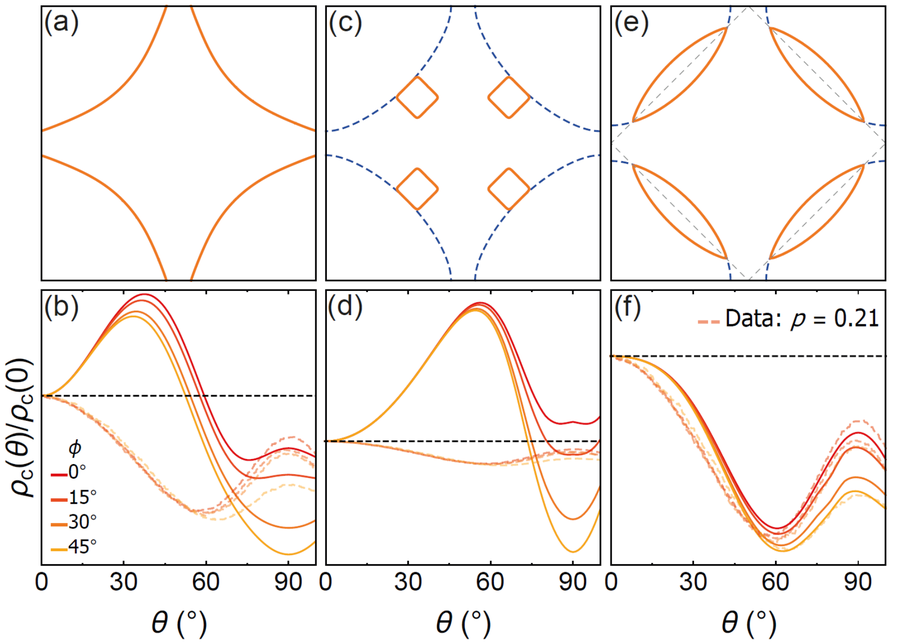
Fermi surface transformation at the pseudogap critical point of a cuprate superconductor

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

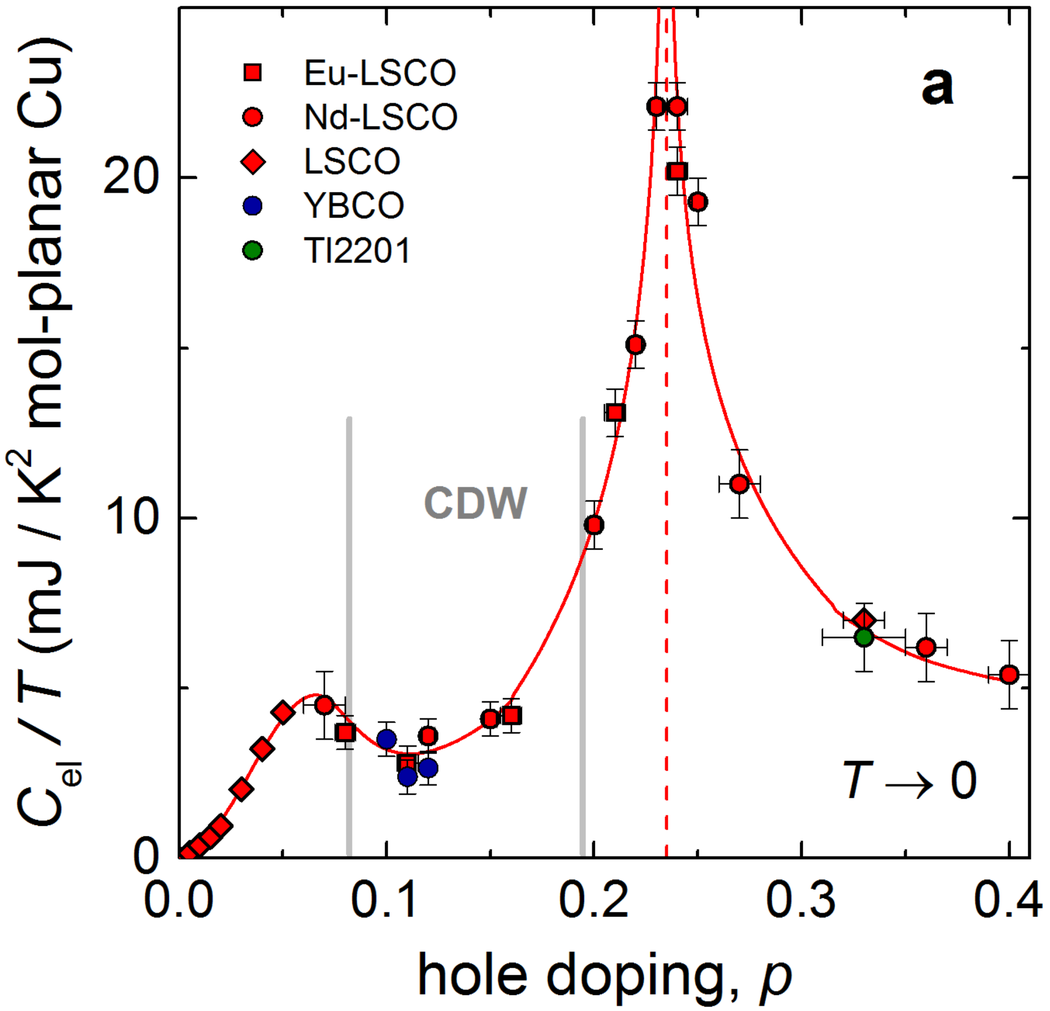


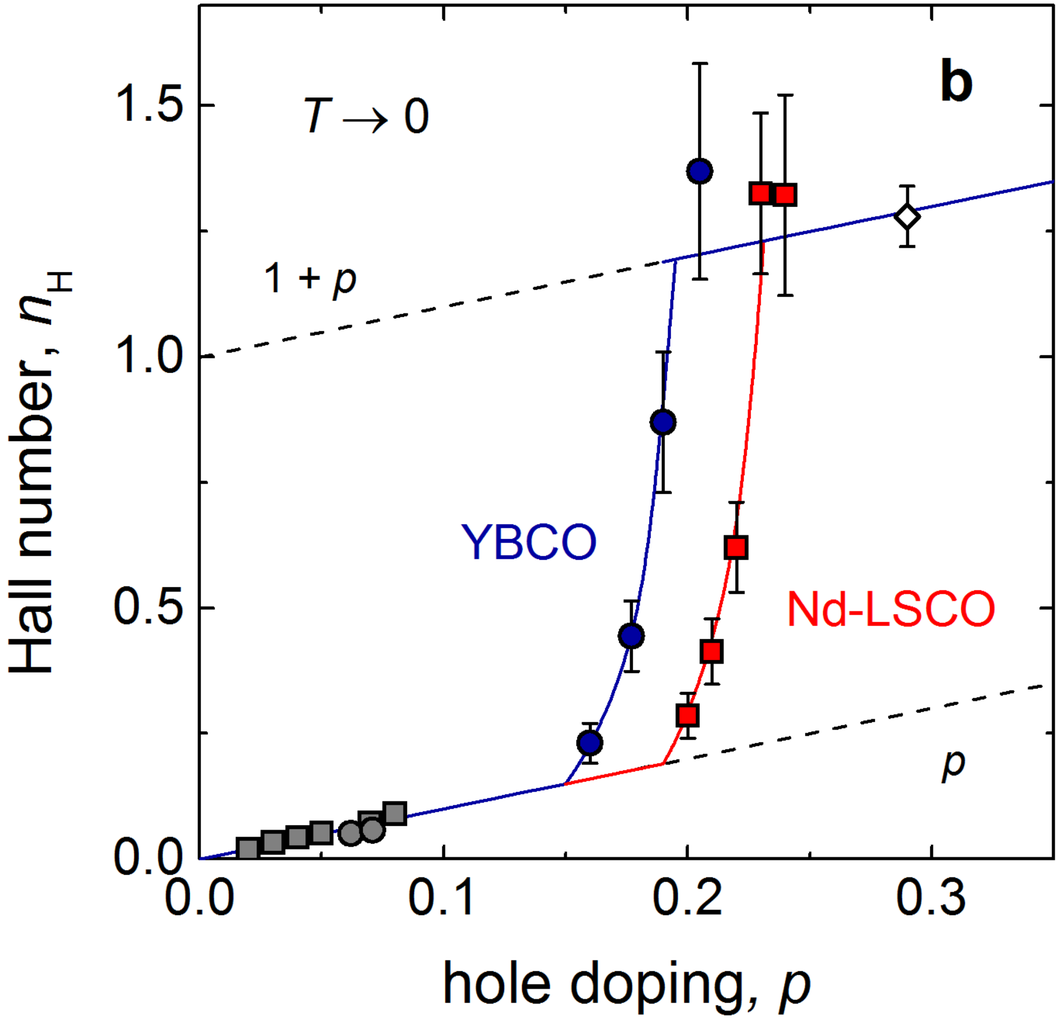
$p < p_c$ Reconstructed Fermi surface

Hole doped cuprates

The remarkable underlying ground states of cuprate superconductors

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





Hidden magnetism at the pseudogap critical point of a high temperature superconductor

Nature Physics doi: 10.1038/s41567-020-0950-5

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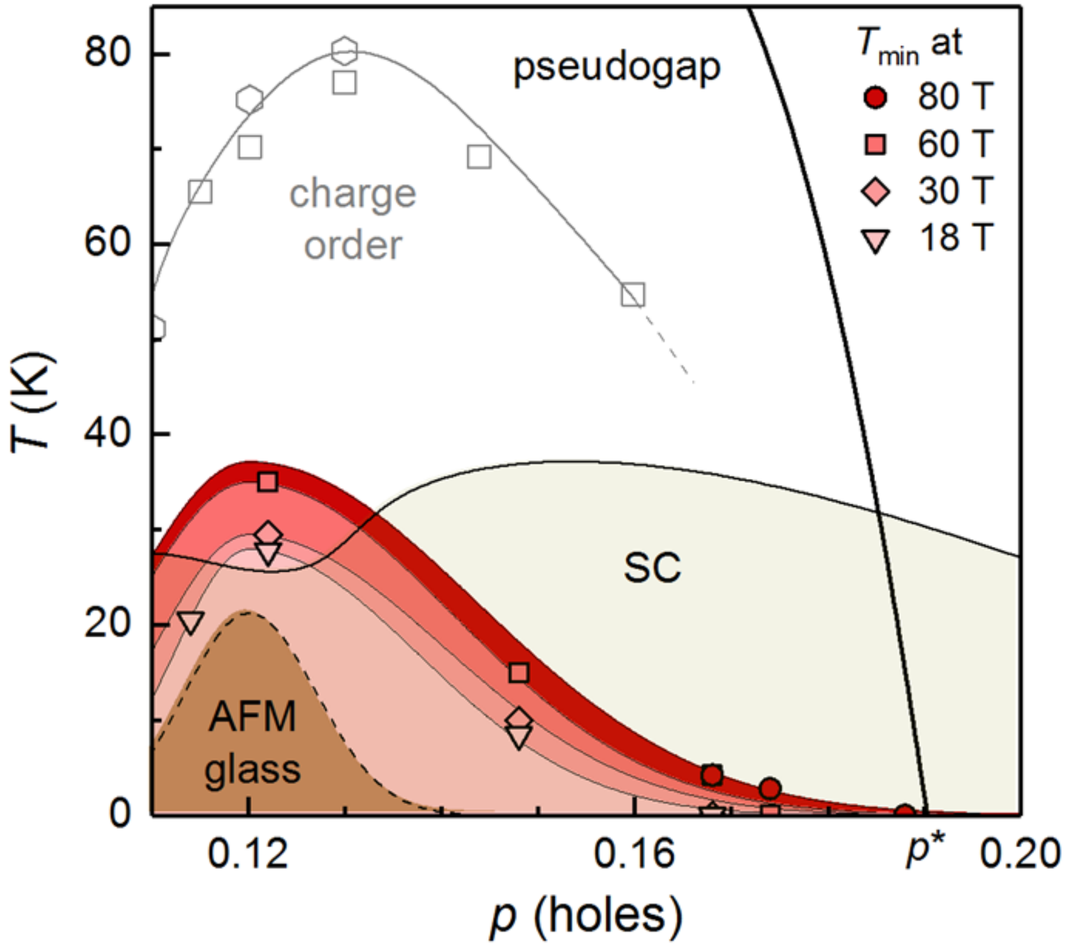

Quasi-static magnetism in the pseudogap state of La2-xSrxCuO4.

Temperature – doping phase diagram representing Tmin, the temperature of the minimum in the sound velocity, at different fields. Since superconductivity precludes the observation of Tmin in zero-field, the dashed line (brown area) represents the extrapolated Tmin(B=0). While not exactly equal to the freezing temperature Tf (see Fig. 2), Tmin is closely tied to Tf and so is expected to have the same doping dependence, including a peak around p = 0.12 in zero/low fields (ref. 2). Onset temperatures of charge order are from ref. 33 (squares) and 35 (hexagons).

1. Metal-metal transition in the Kondo Lattice

2. Metal-metal transition in a one-band model
   - *A. FL* model of the pseudogap*
   - *B. Ancilla qubits and ghost Fermi surfaces*

3. Random *J* model (insulator)
   - *RG analysis and exact exponent*

4. Random t-*J* model (metals)
   - *Numerics, RG analysis and exact exponents*

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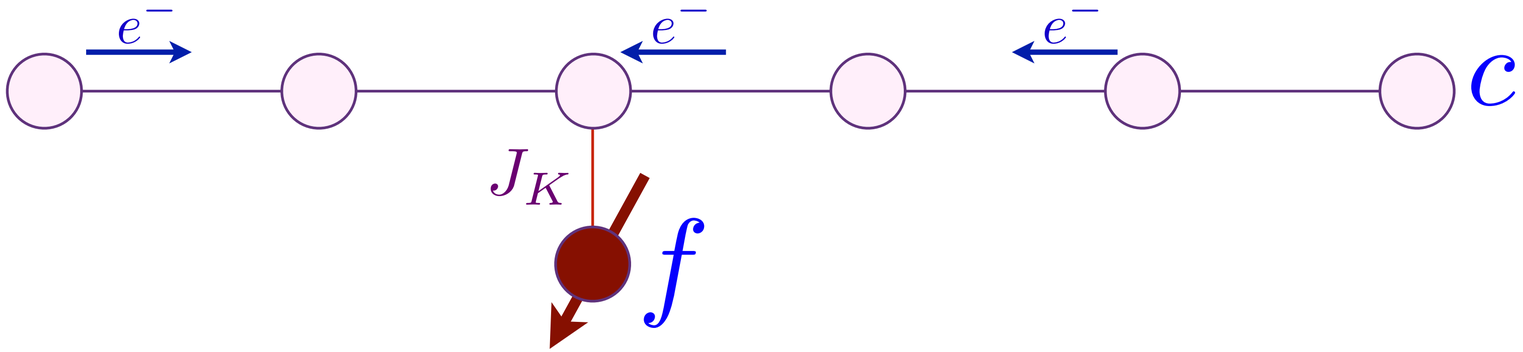
Kondo model

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



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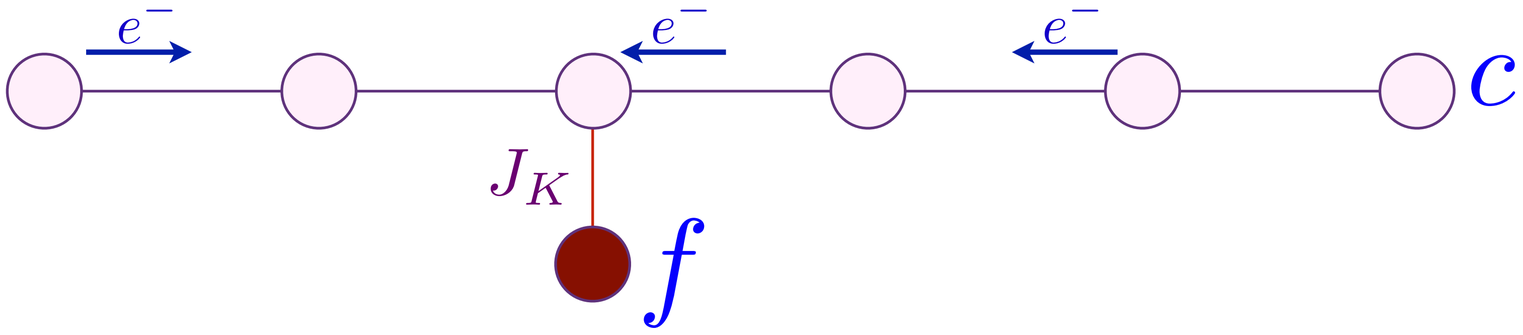
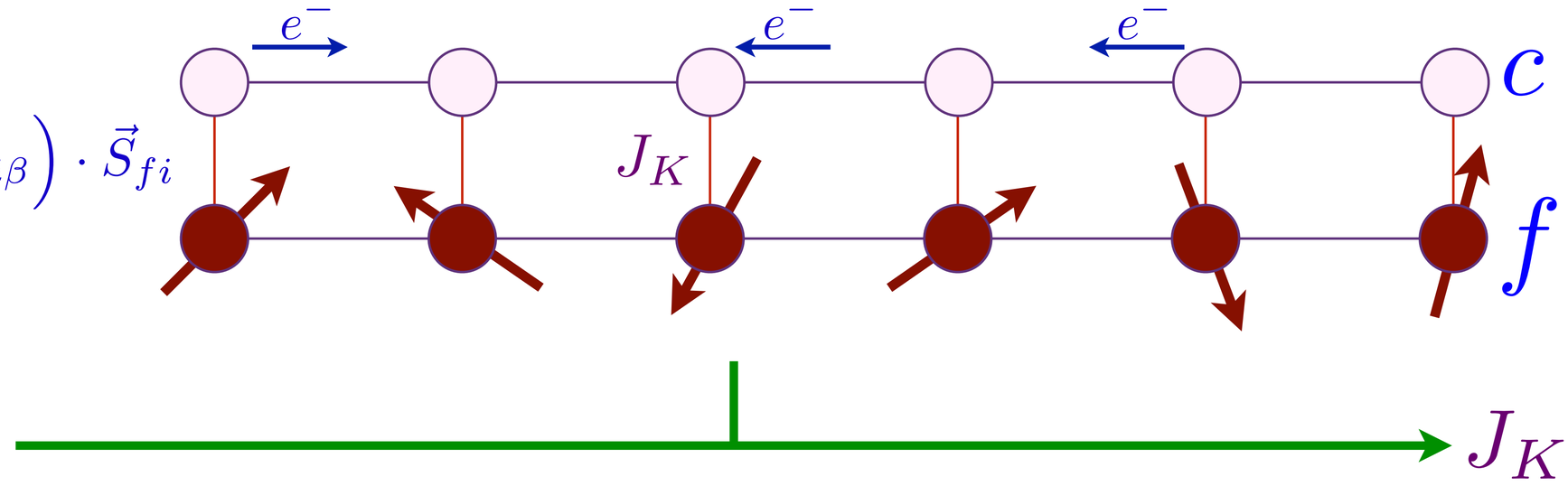


The c electrons 'Kondo screen' the f spin at low energies:
The f electron 'dissolves' into the Fermi sea.

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

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

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



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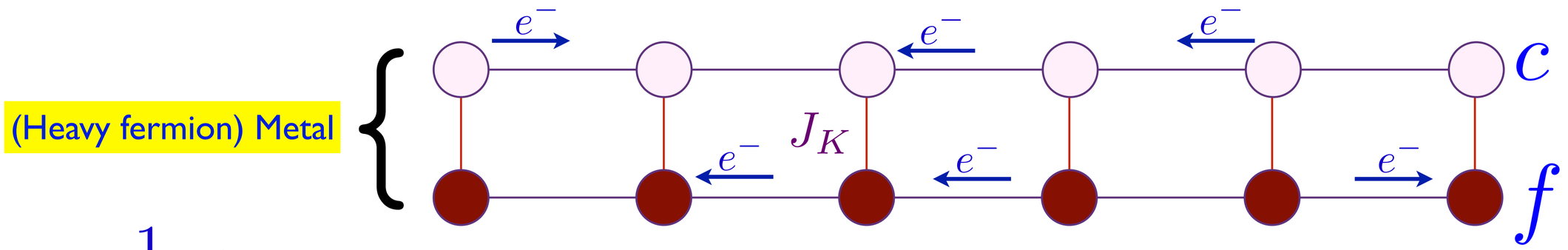
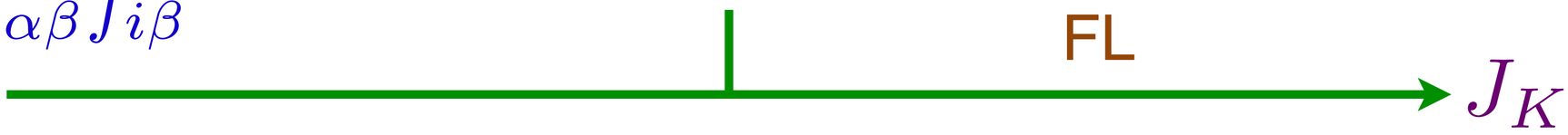


$$\vec{S}_{fi} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

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



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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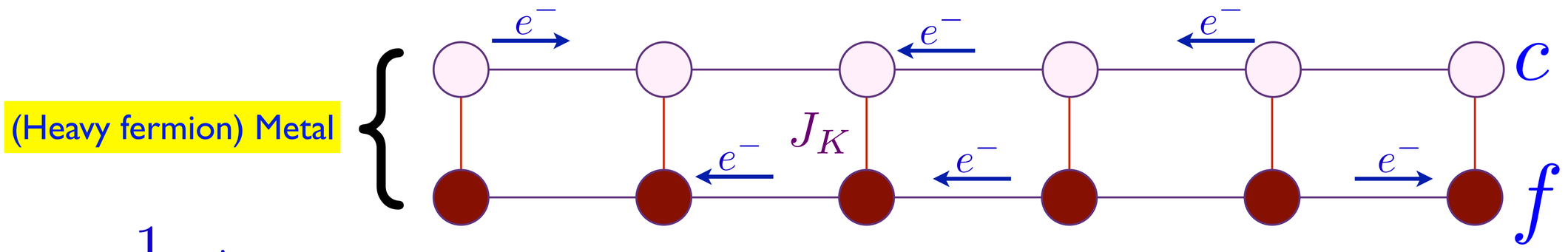

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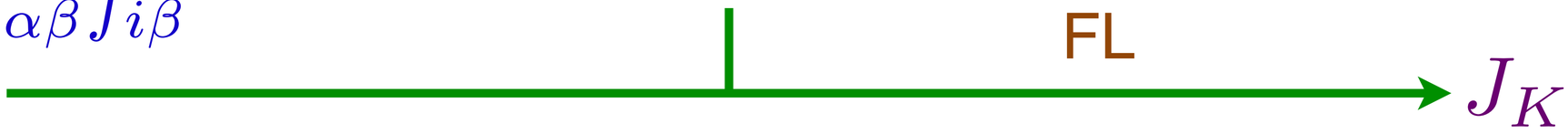

The Kondo lattice model has a gauge symmetry: $f_{i\alpha} \to e^{i\theta_i} f_{i\alpha}$
This gauge symmetry is fully broken by a Higgs condensate $\langle c^\dagger_\alpha f_\alpha \rangle$ in the FL phase.

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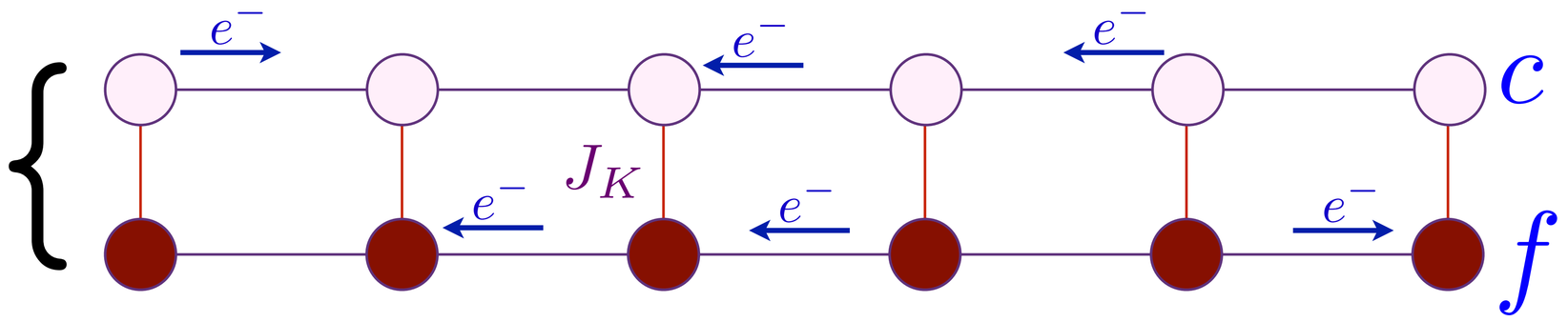
(Heavy fermion) Metal



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

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Large Fermi surface of size $1 + p$

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

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

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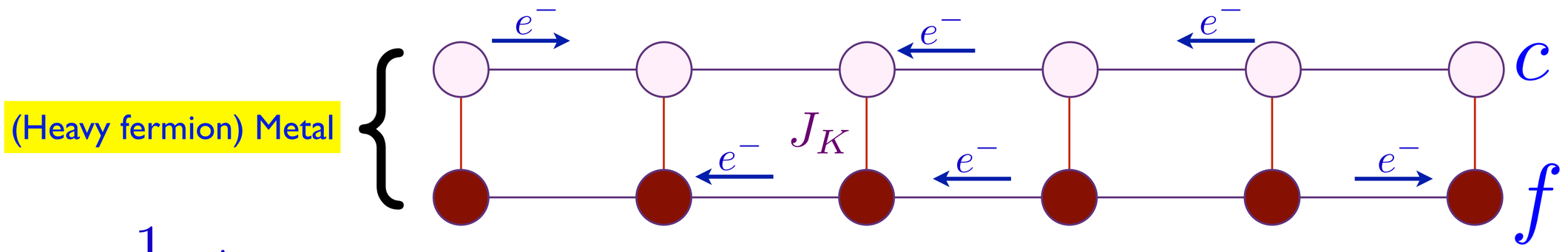

$$\vec{S}_{fi} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

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Luttinger Theorem obeyed

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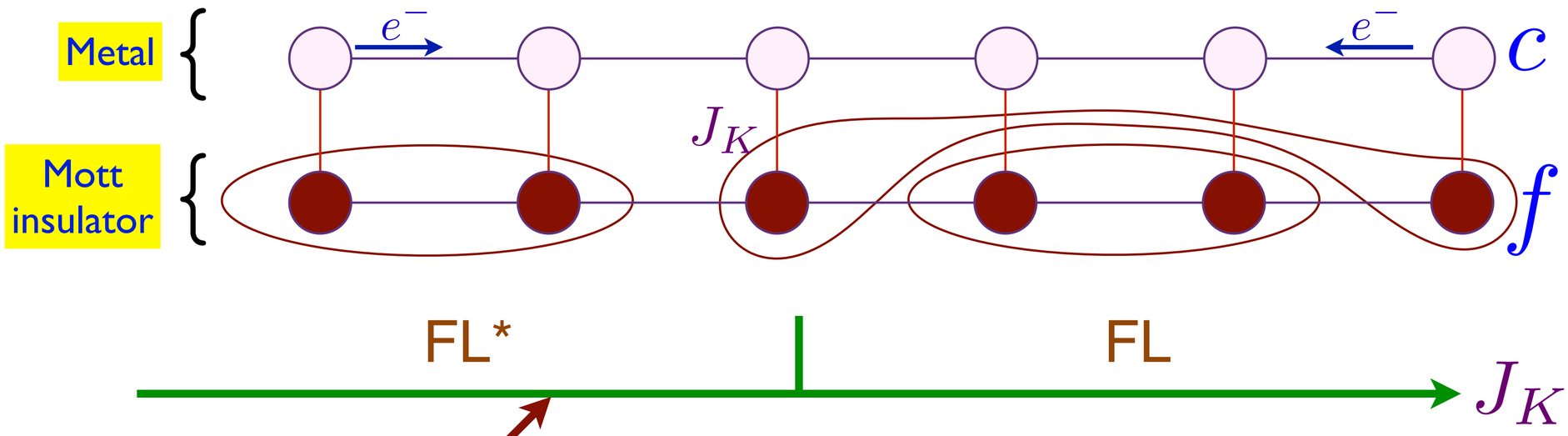
Kondo-breakdown or 'selective Mott' transition



Small Fermi surface of size p

$|\Phi\rangle = |\text{Spin liquid insulator of } f\rangle$
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S. Burdin, D. R. Grempel, and A. Georges, PRB **66**, 045111 (2002)

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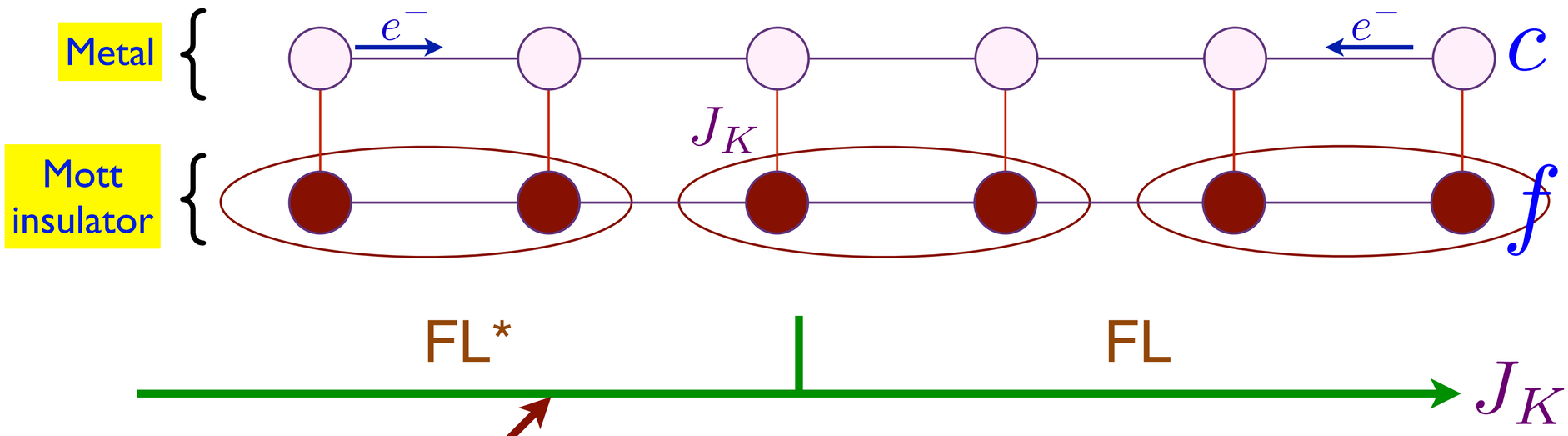

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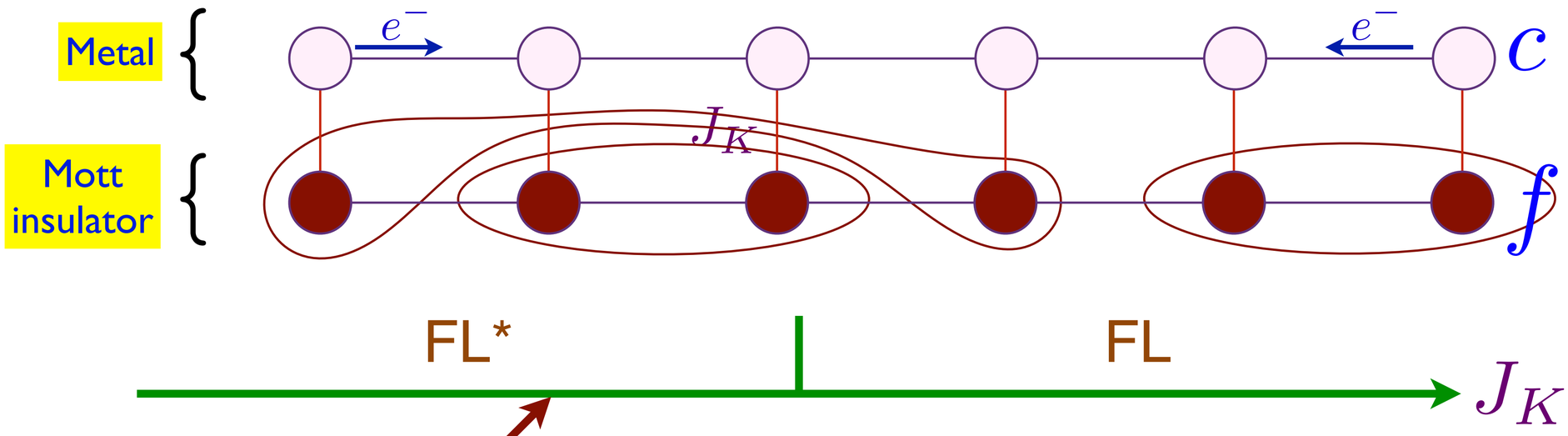

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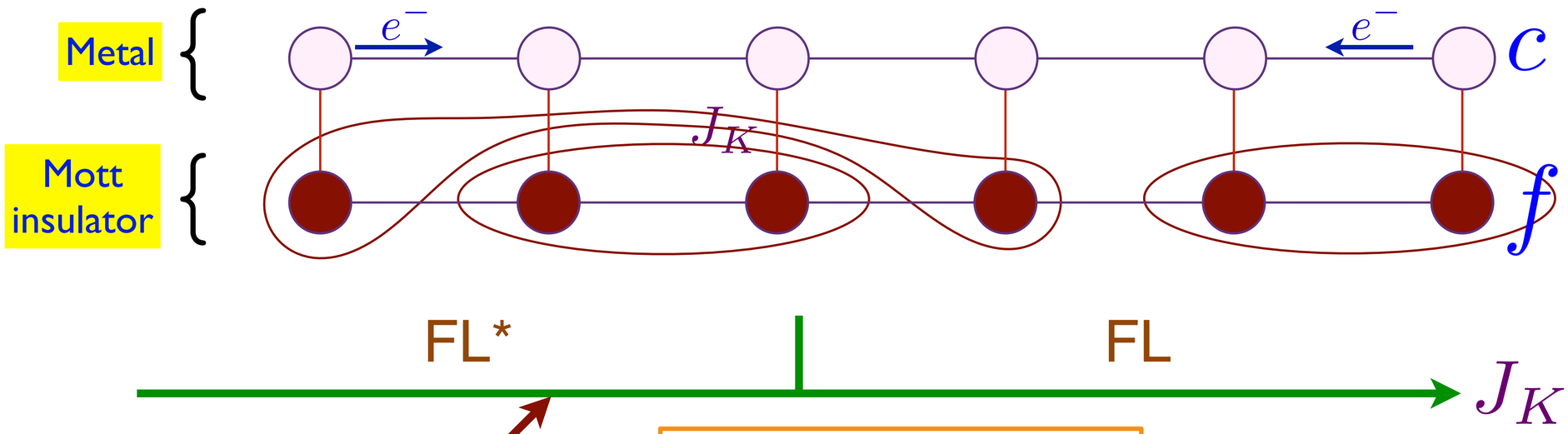

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Luttinger Theorem violated; OK, because of topological order of *f* spins

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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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Shortcomings:

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- No simple extension to one-band model.

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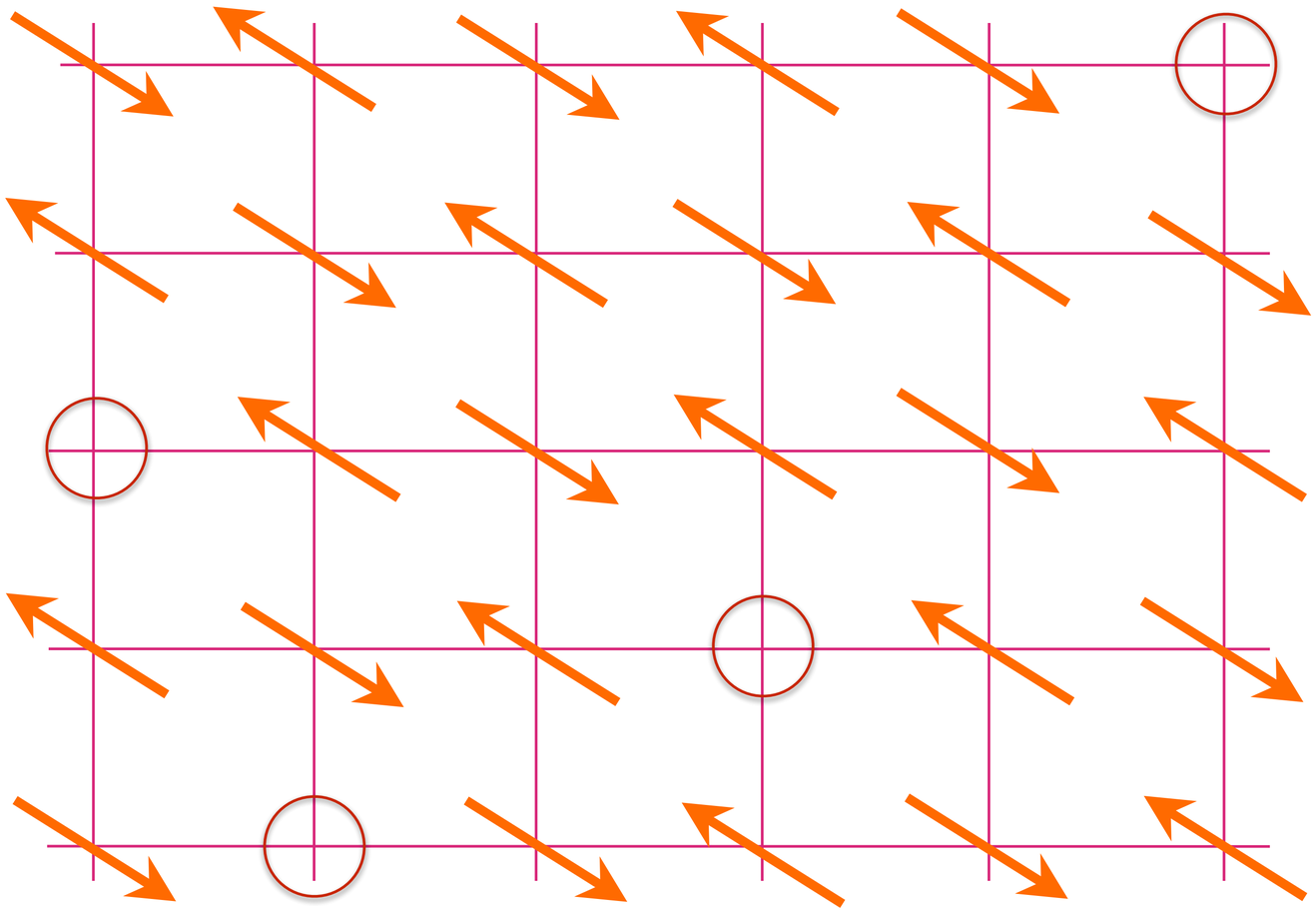
Metal-metal transitions in a ***one-band*** model

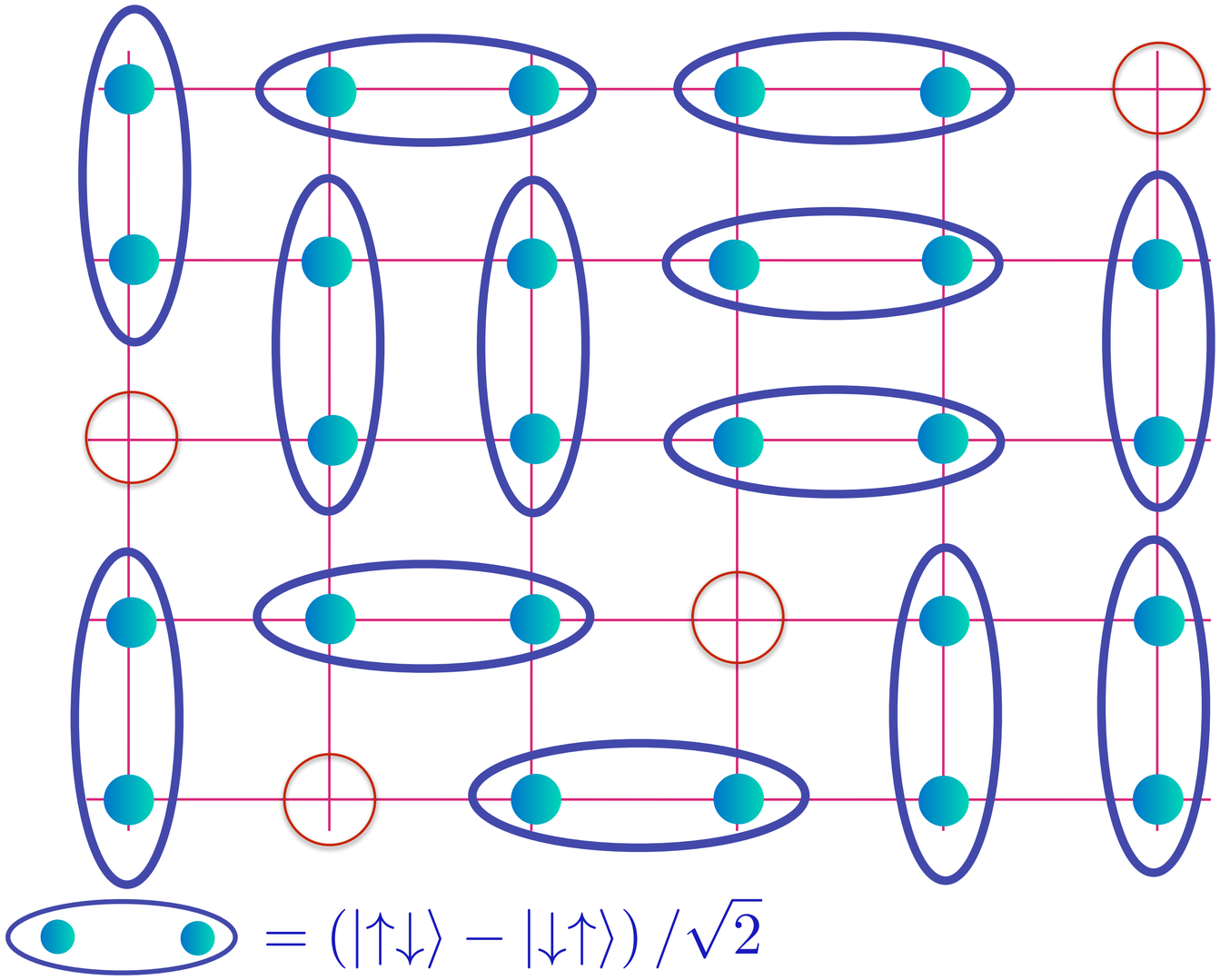
- Can realize the FL* state as a doped spin liquid in which spinons and holons bind to form 'electrons', which then form a small Fermi surface (X.-G. Wen and P. A. Lee, PRL **76**, 503 (1996)); but there is no complete description of this process, except in the very strong binding limit of dimer 'electrons' (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)



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

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

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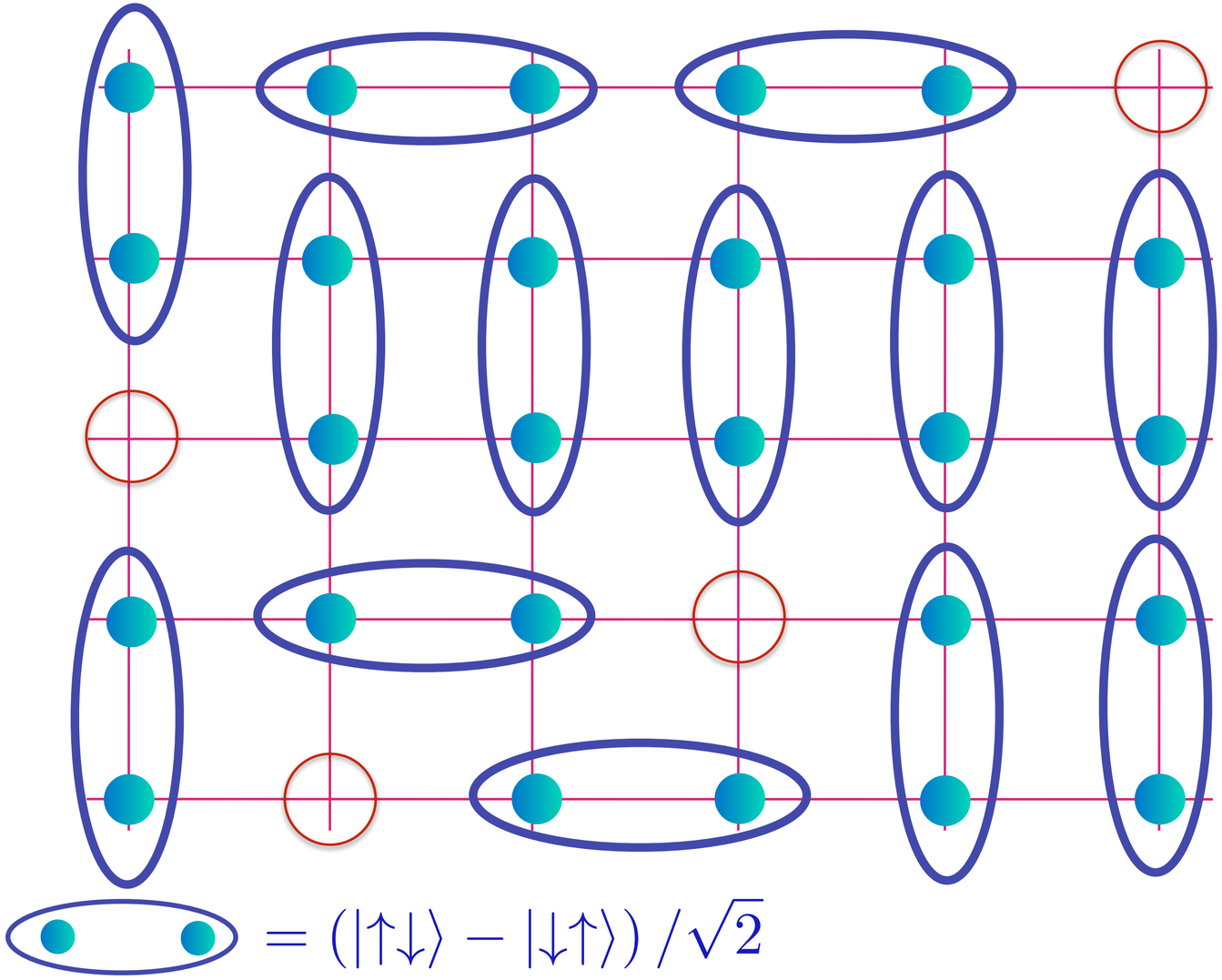

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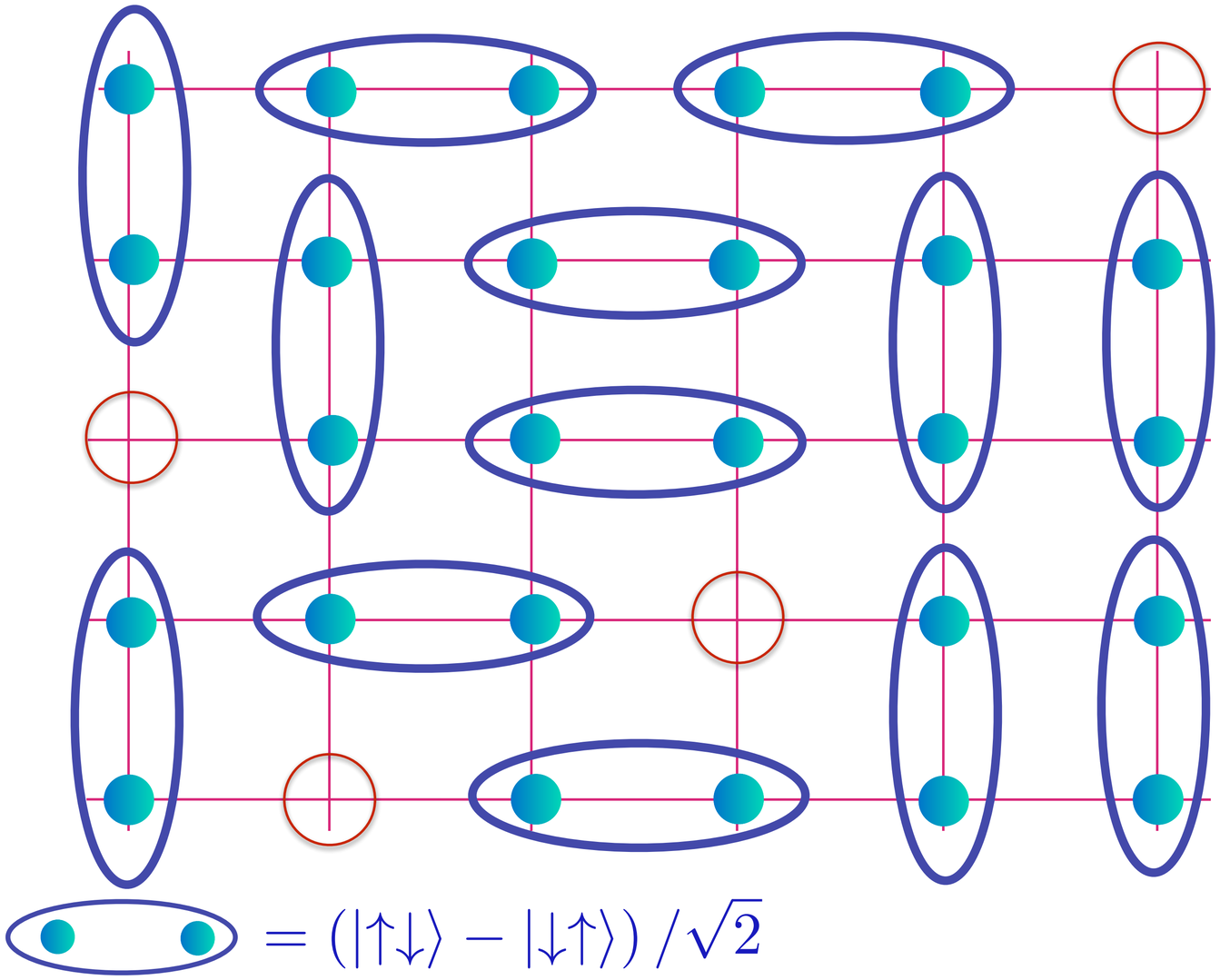

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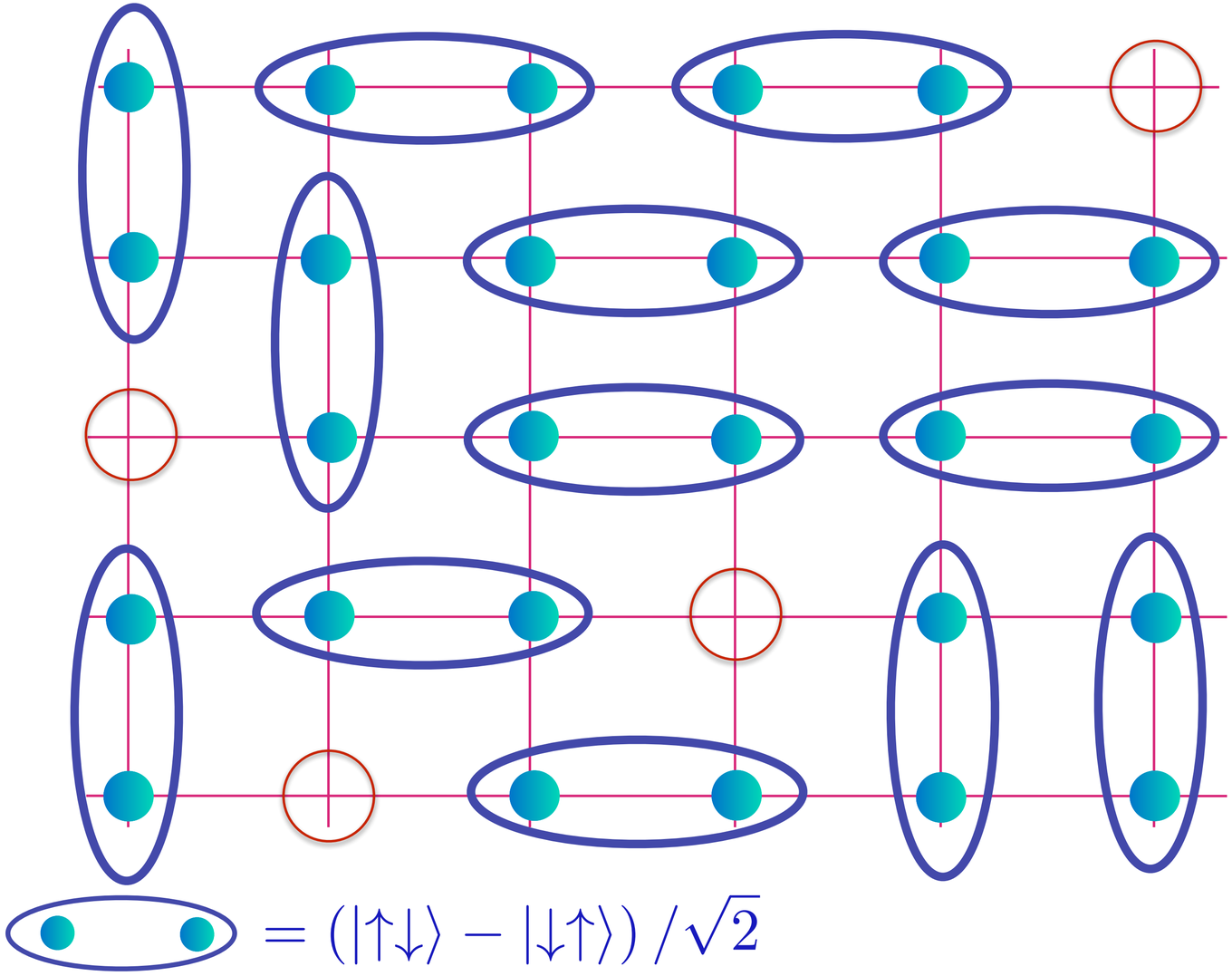

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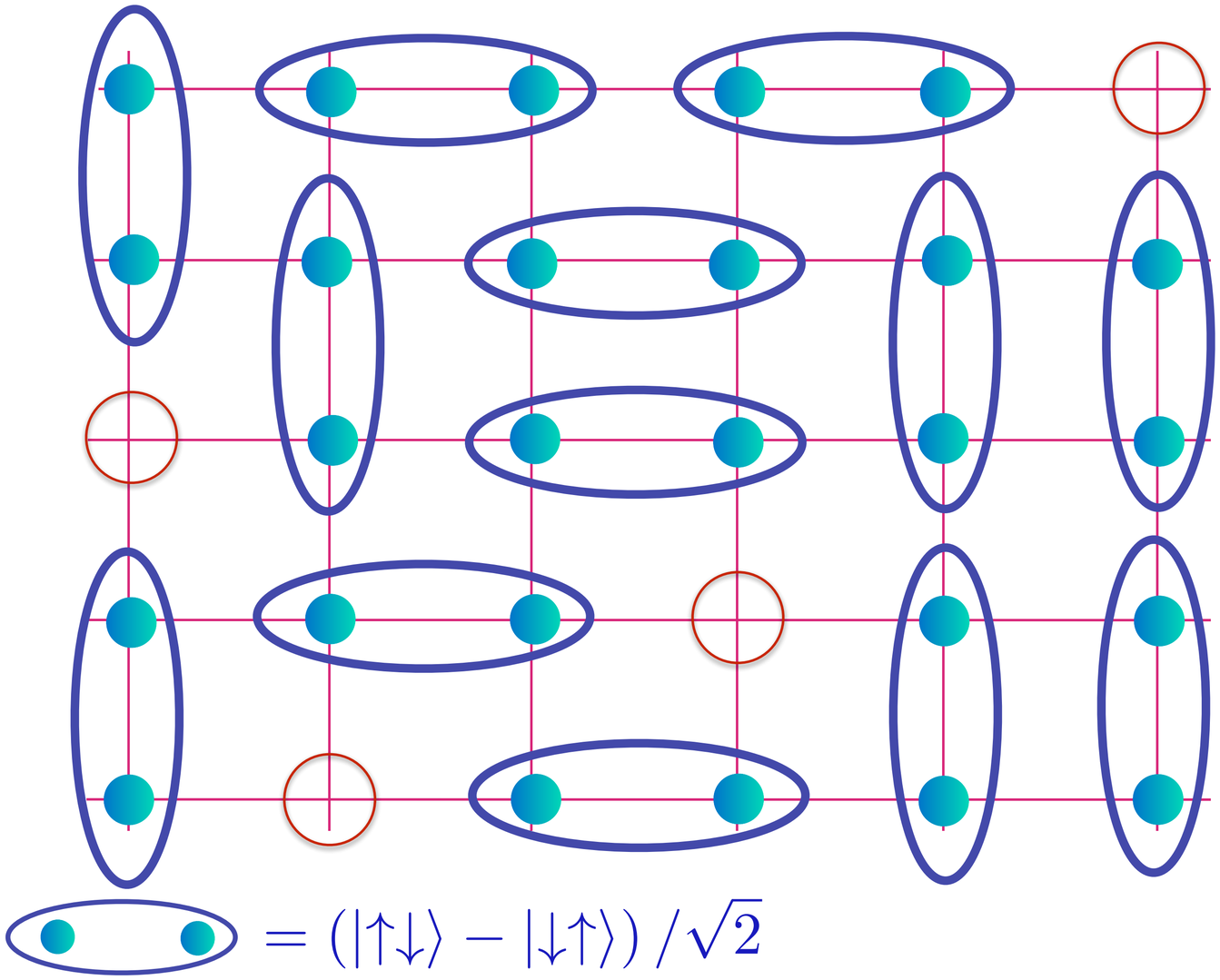

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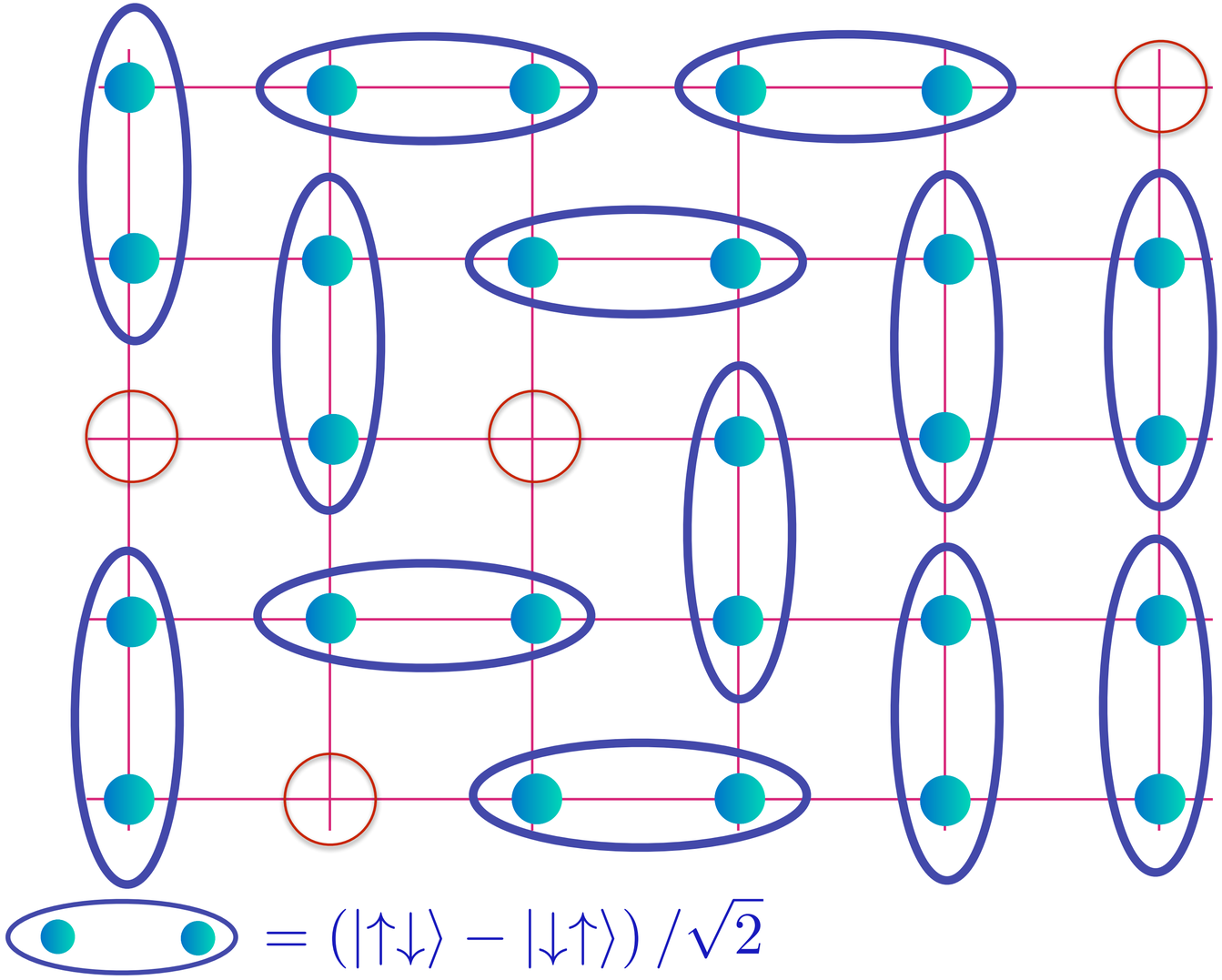

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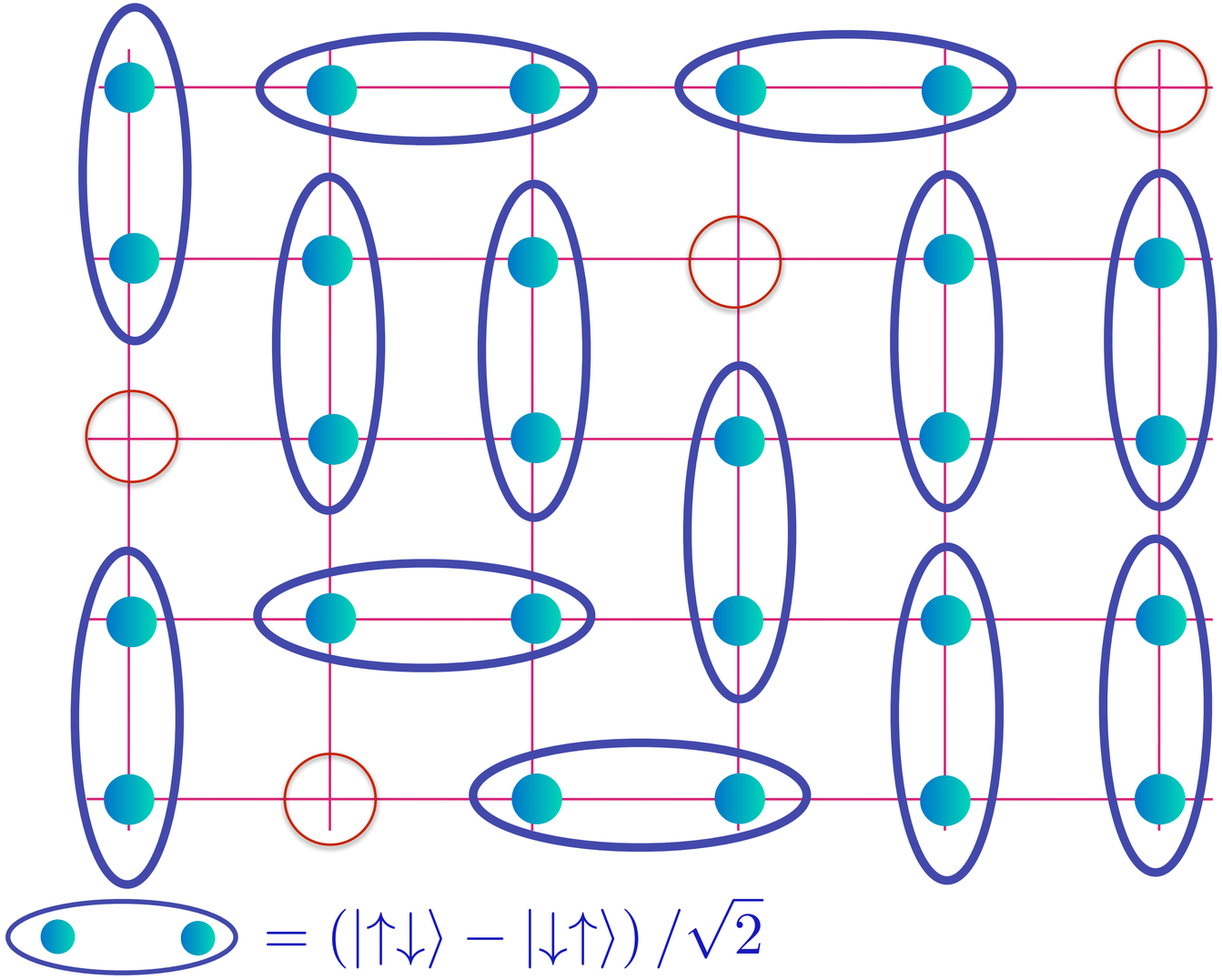

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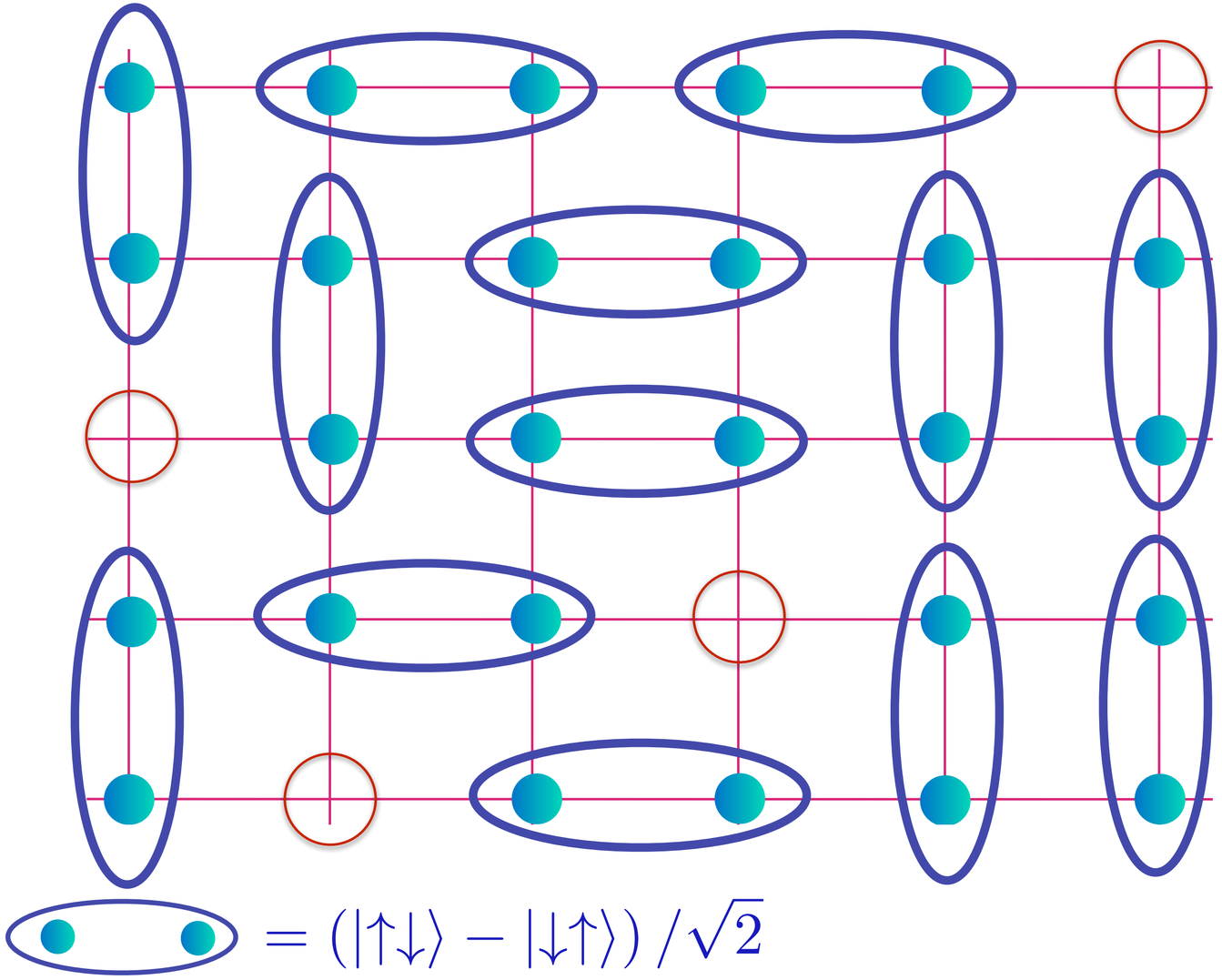

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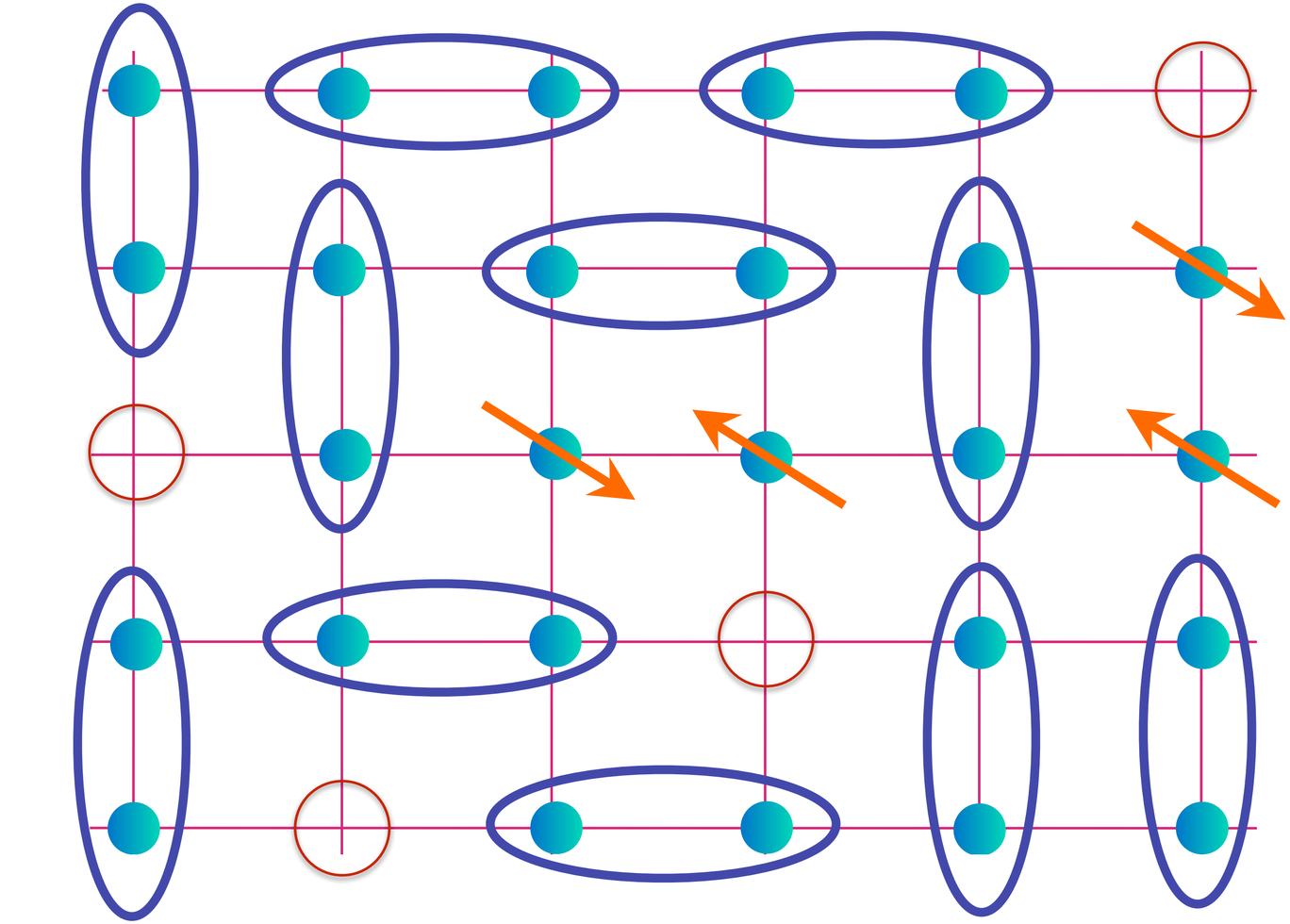

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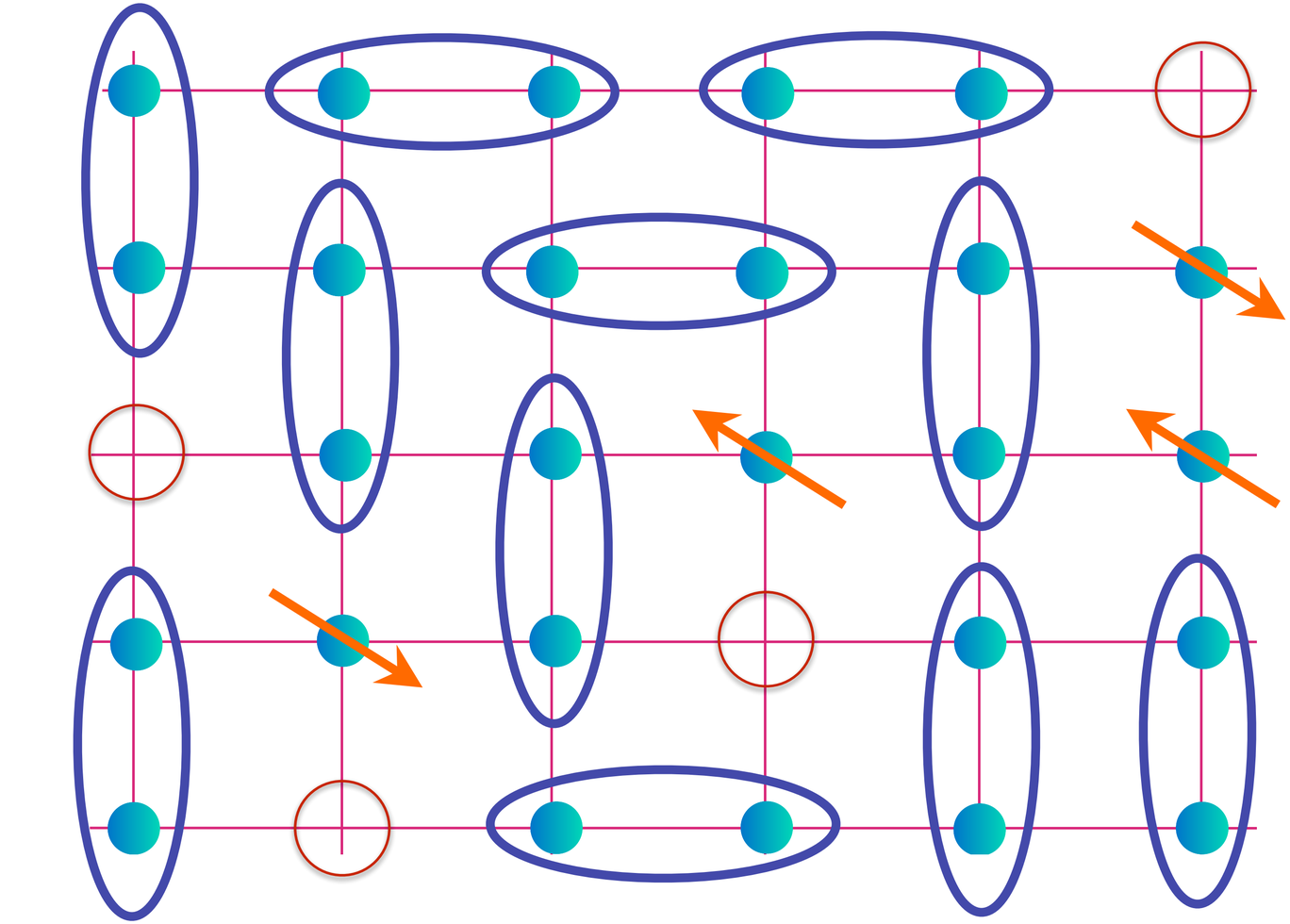

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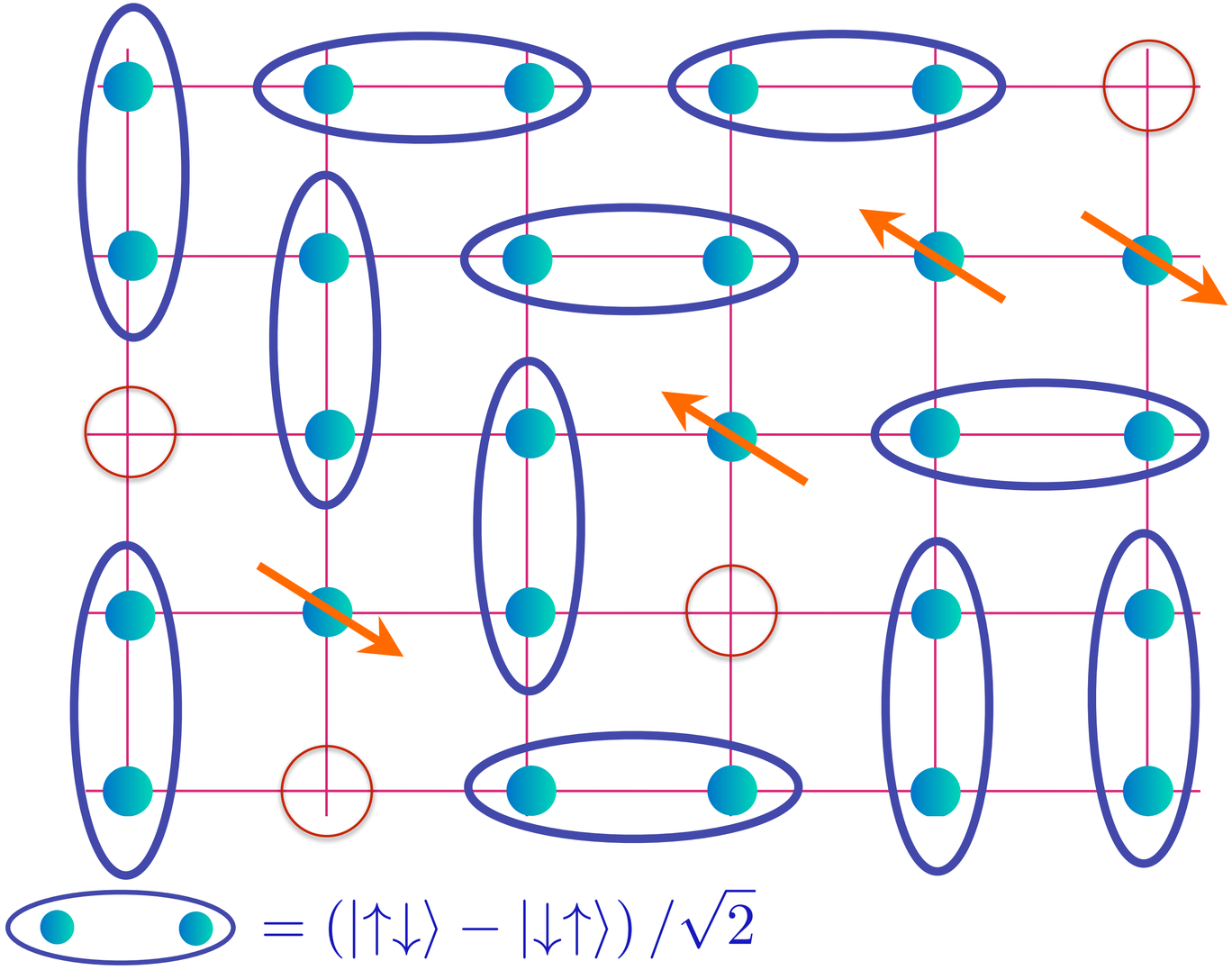

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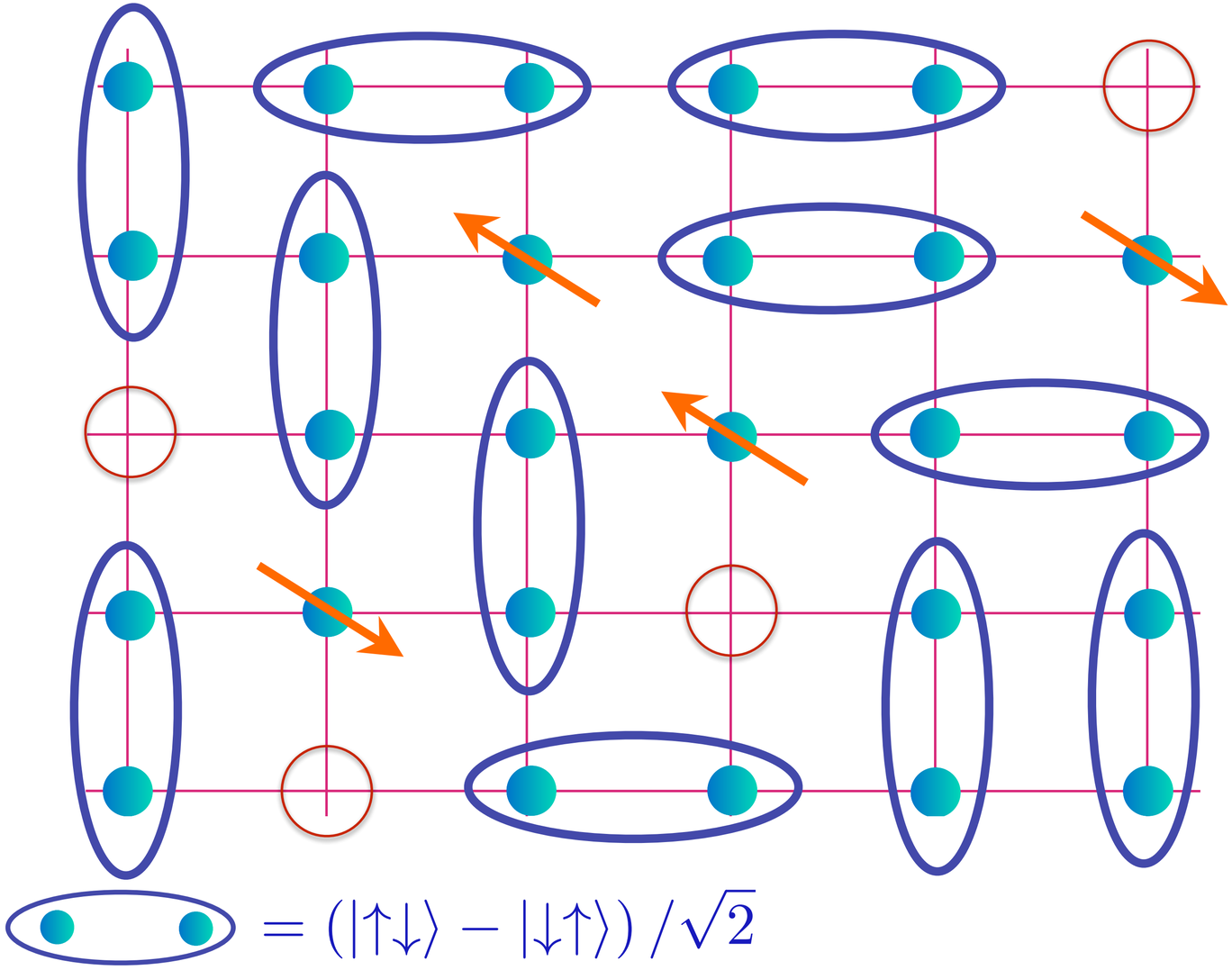

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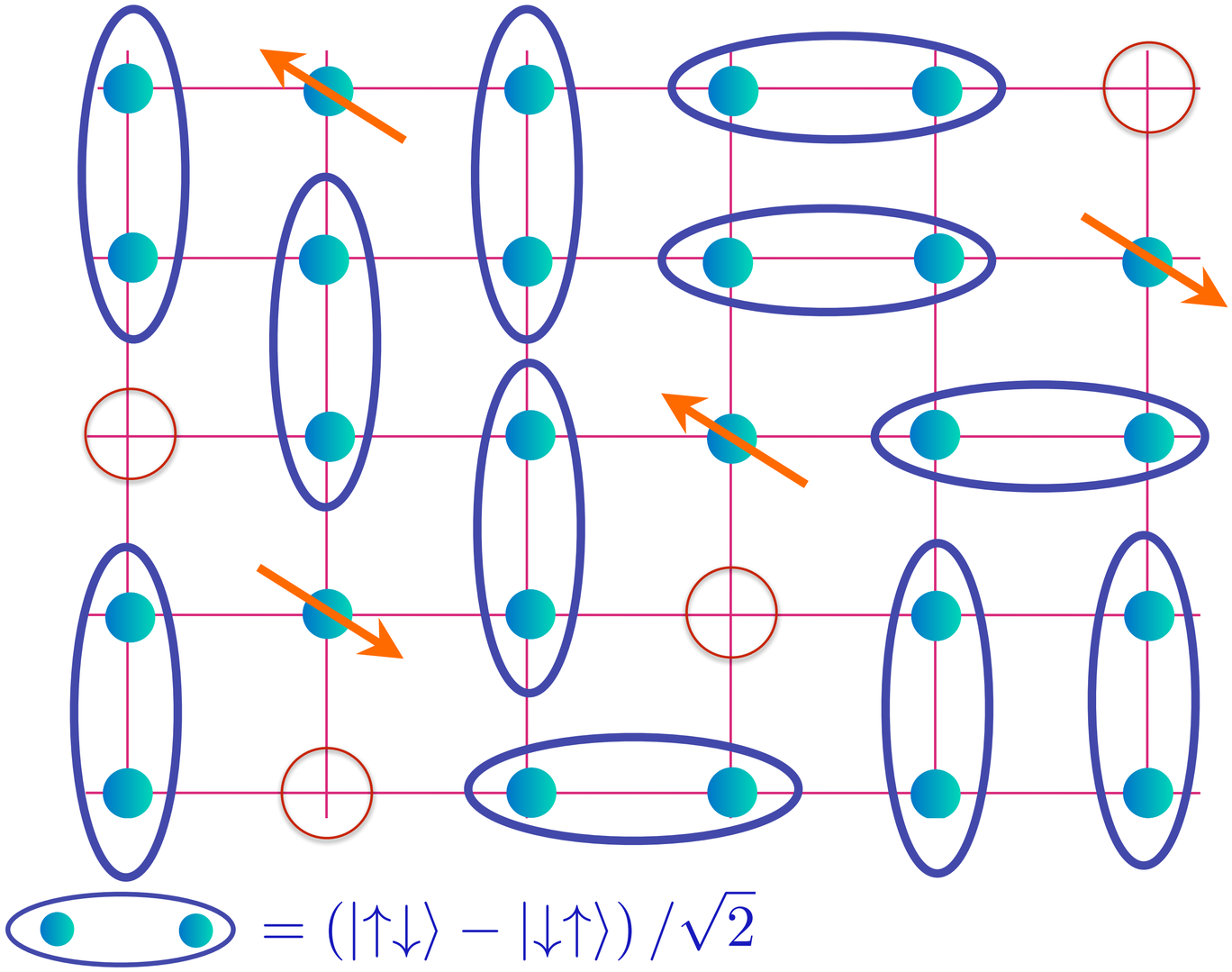

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Spin liquid with density p of spinless, charge +e "holons" and charge 0, spin-1/2 "spinons".

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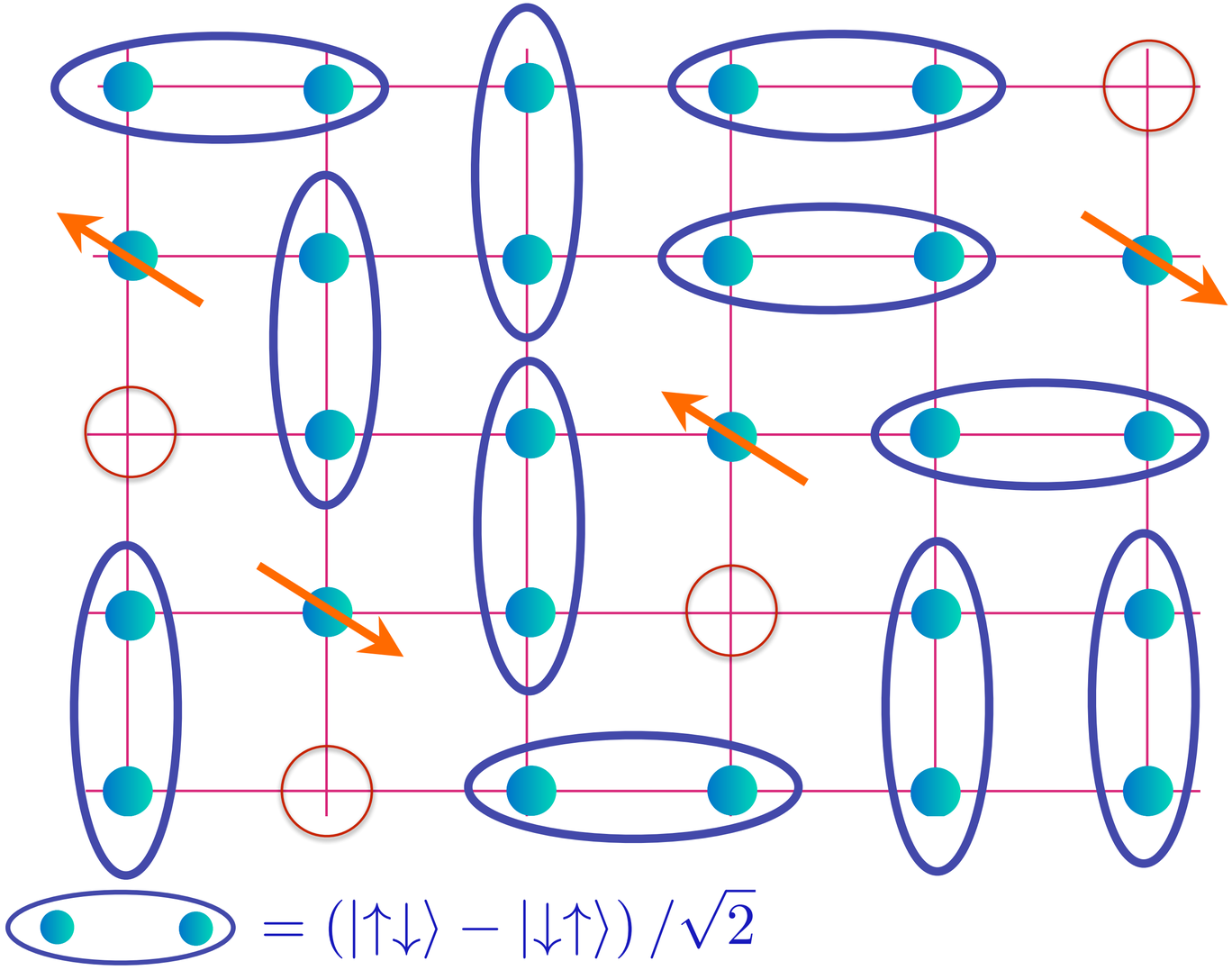

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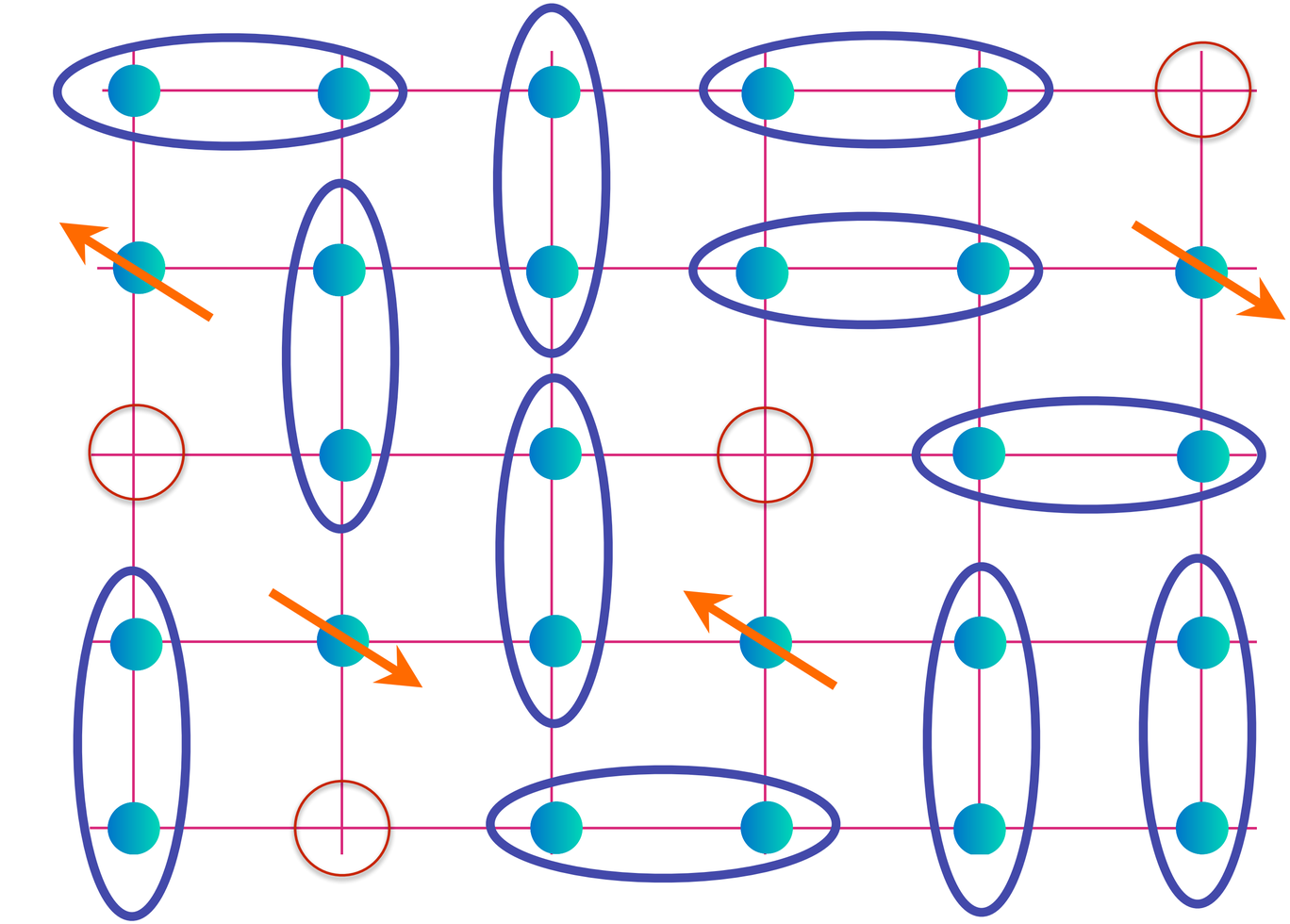

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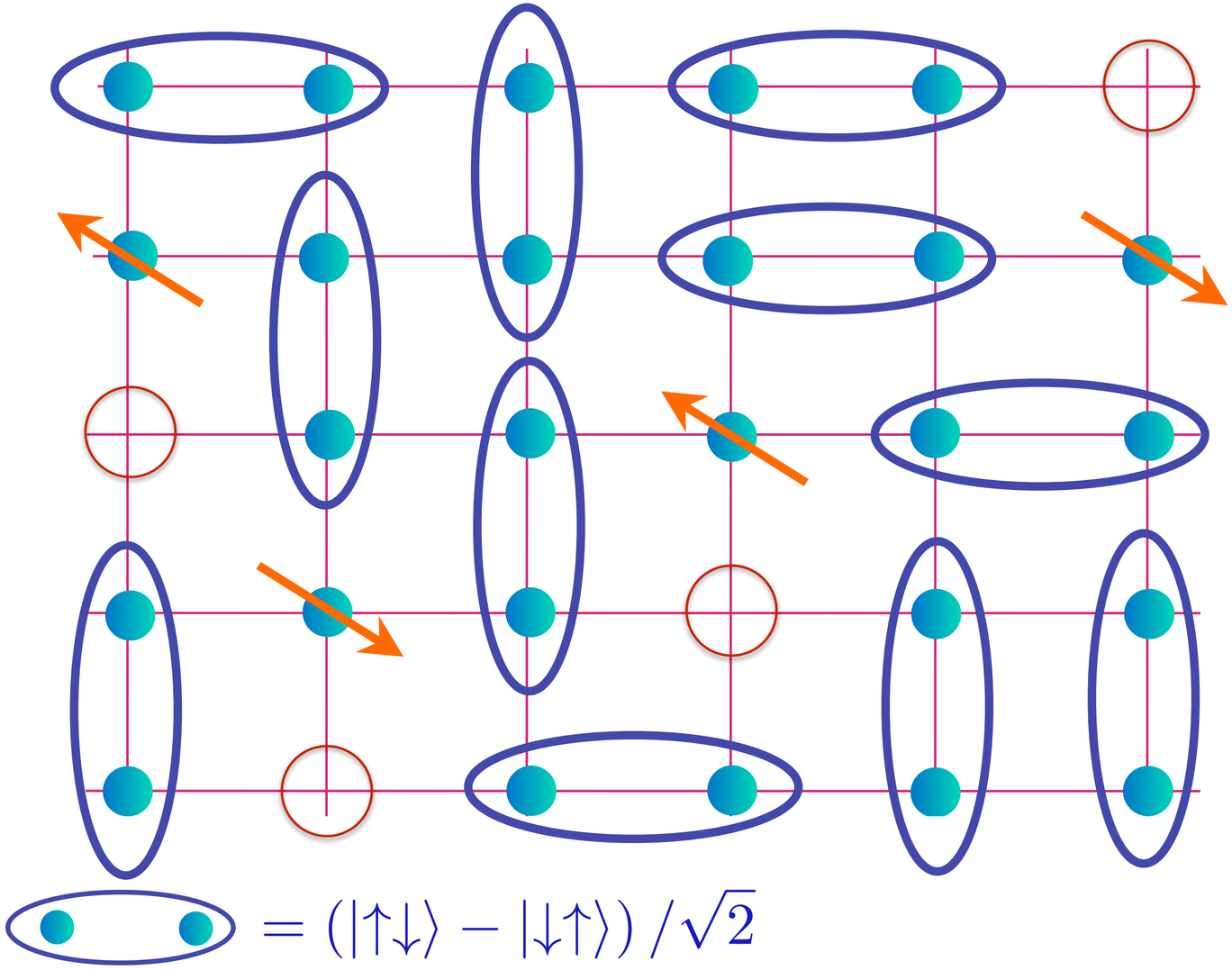

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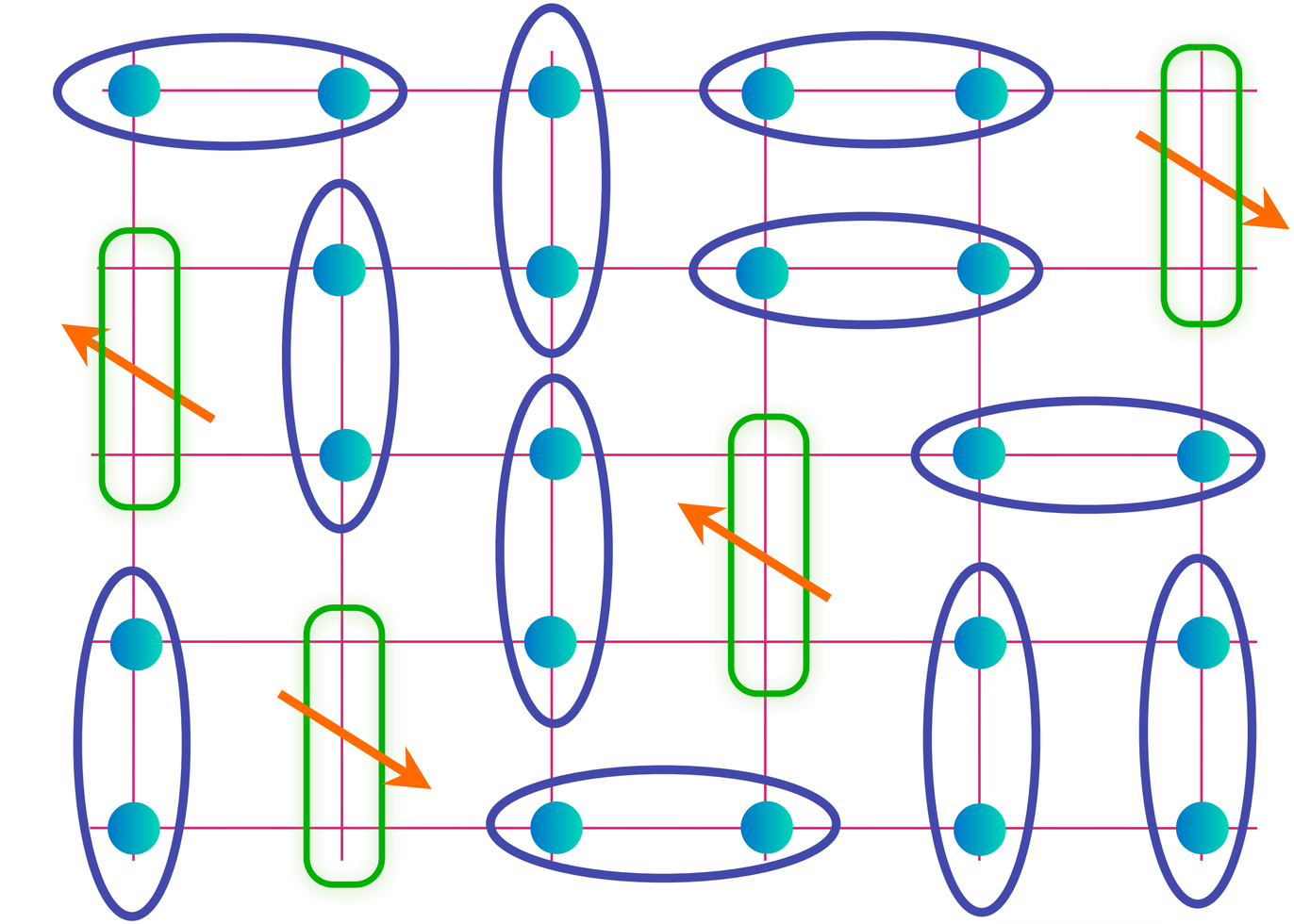

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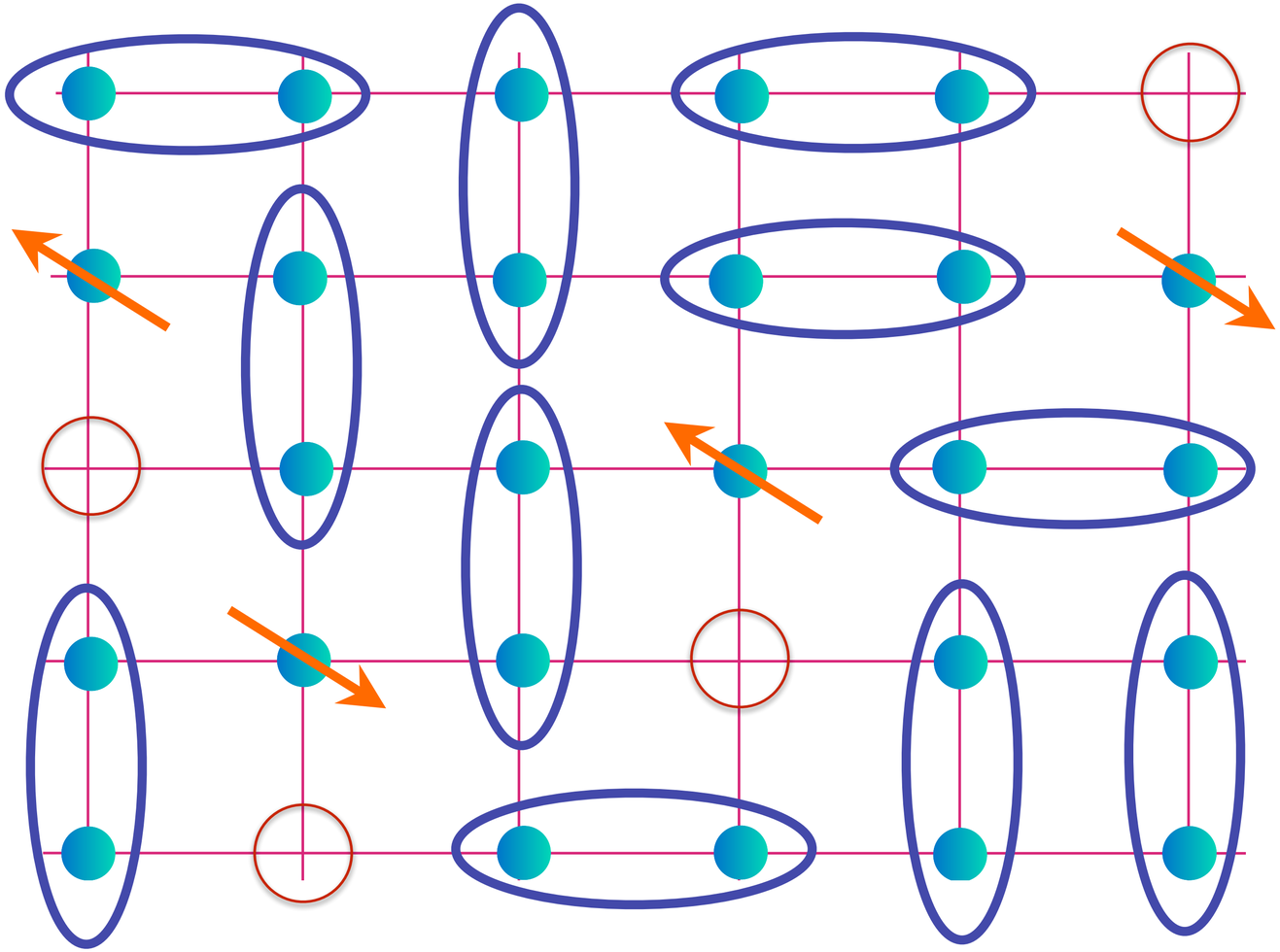

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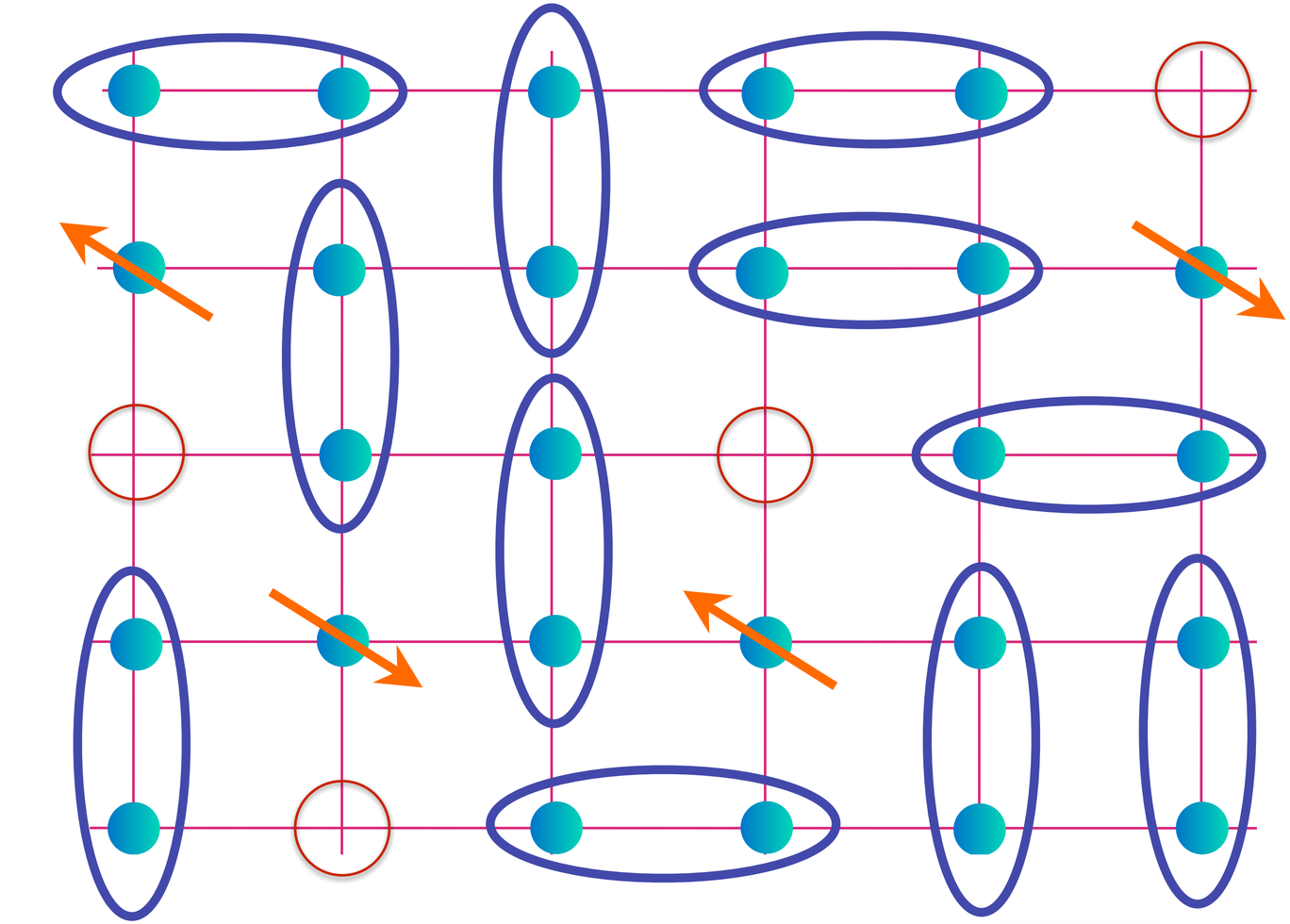

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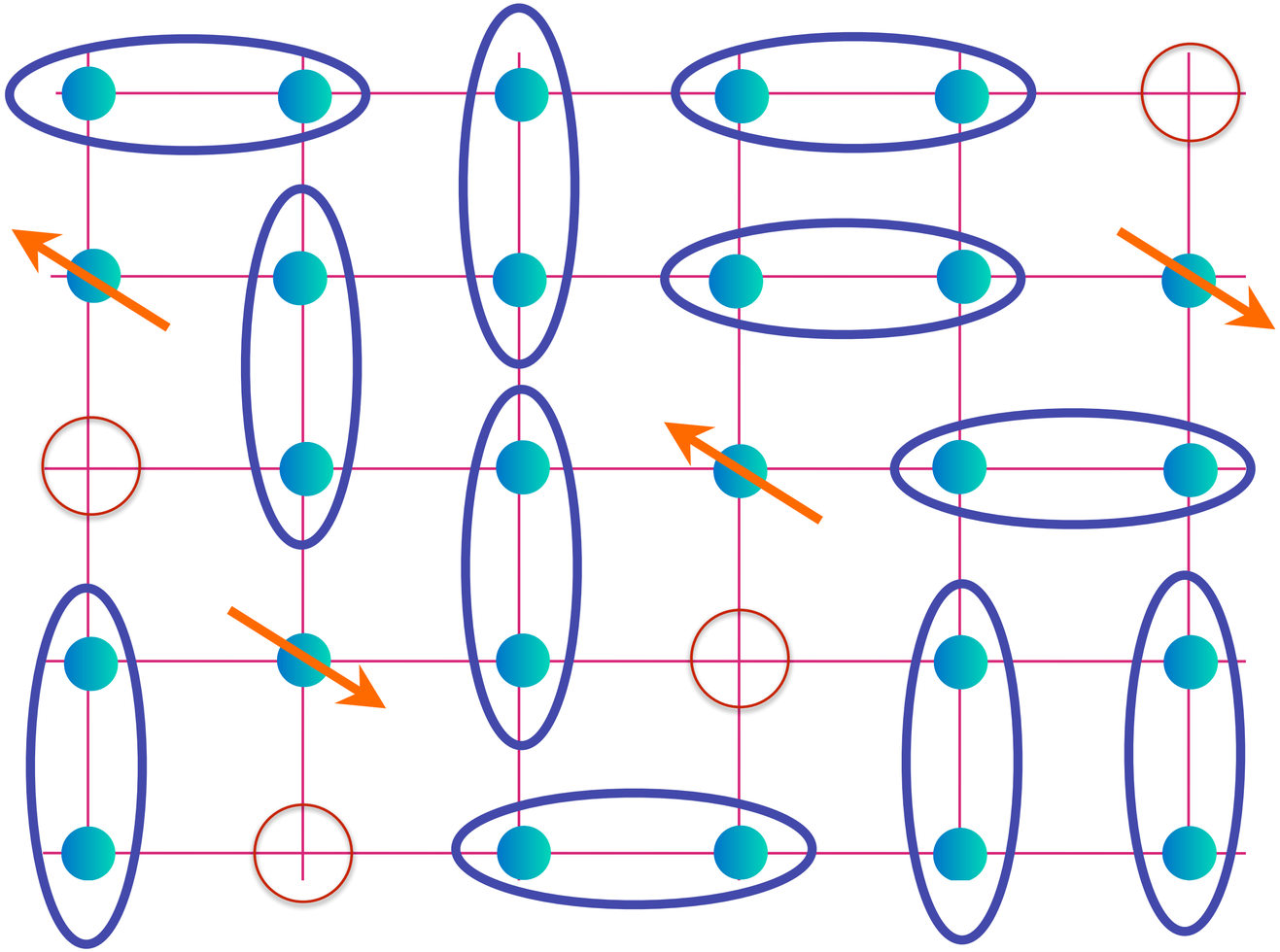

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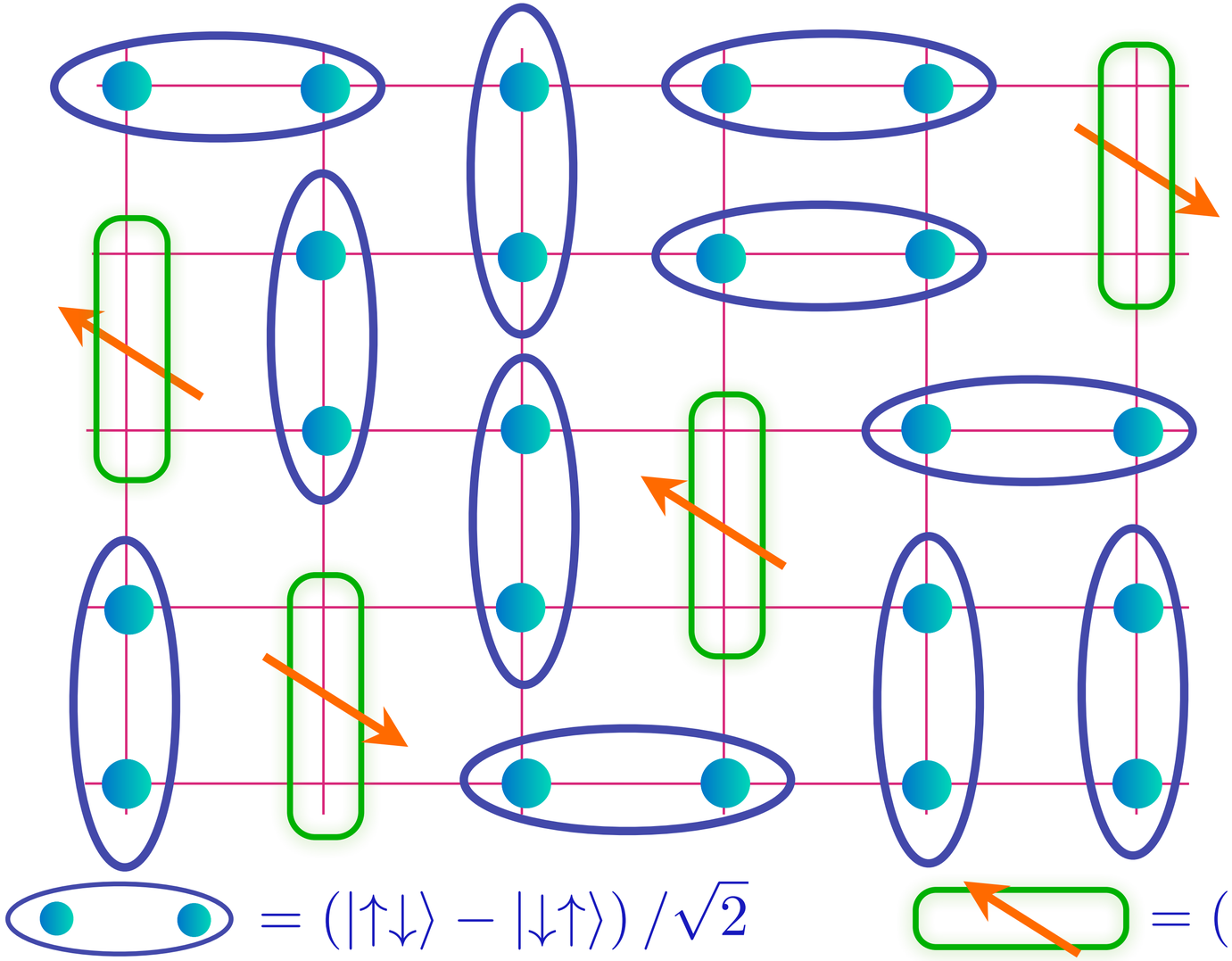

Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

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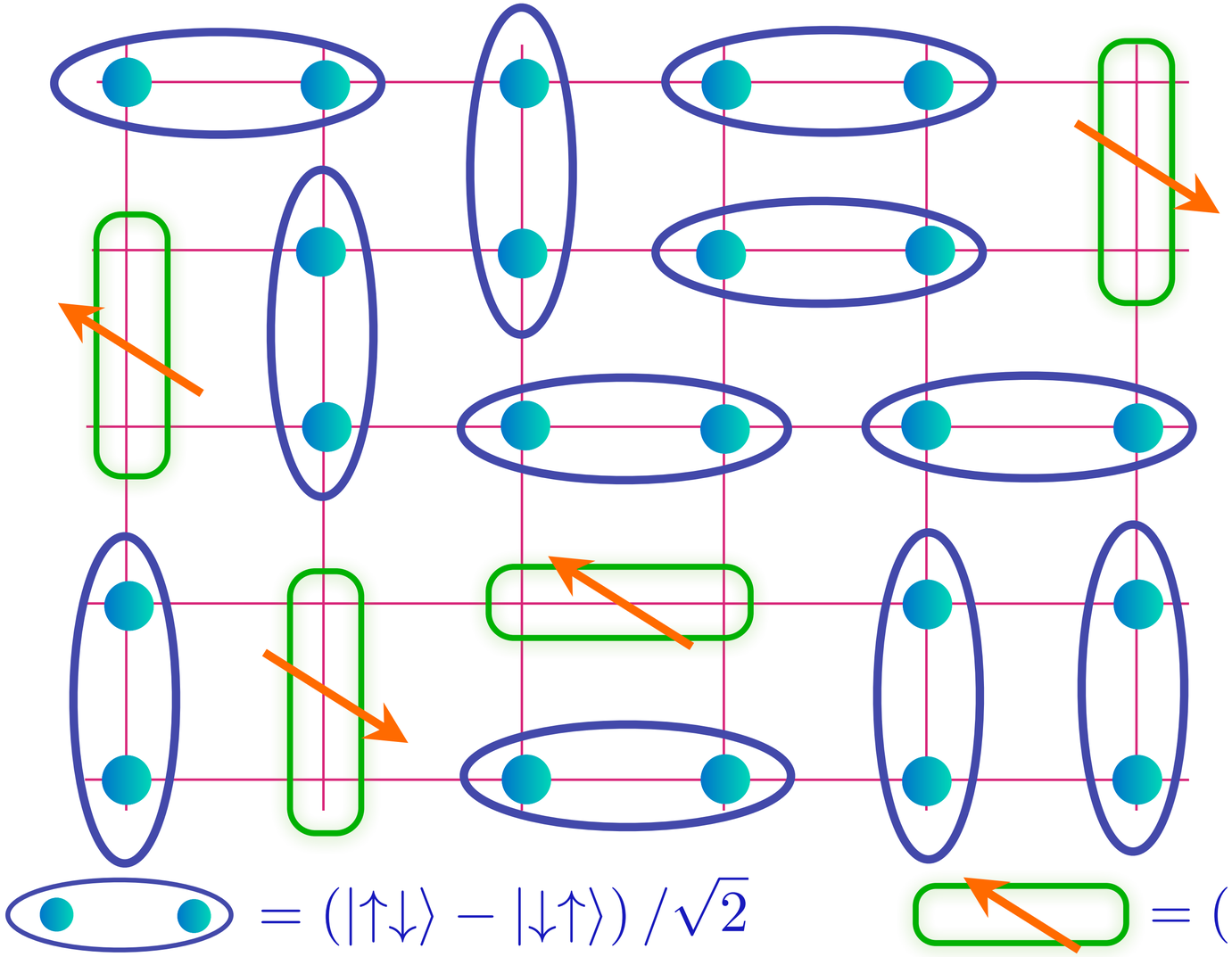

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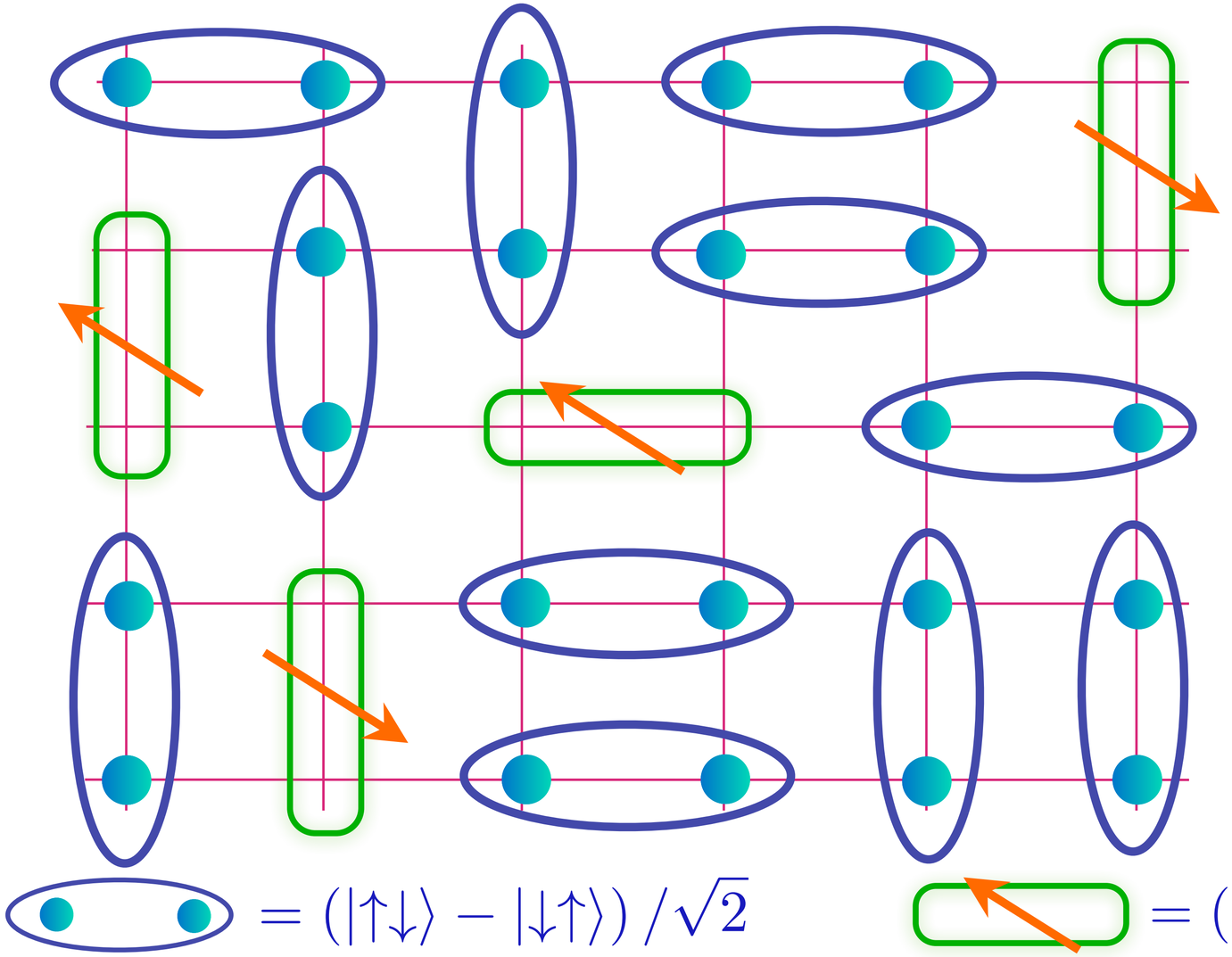

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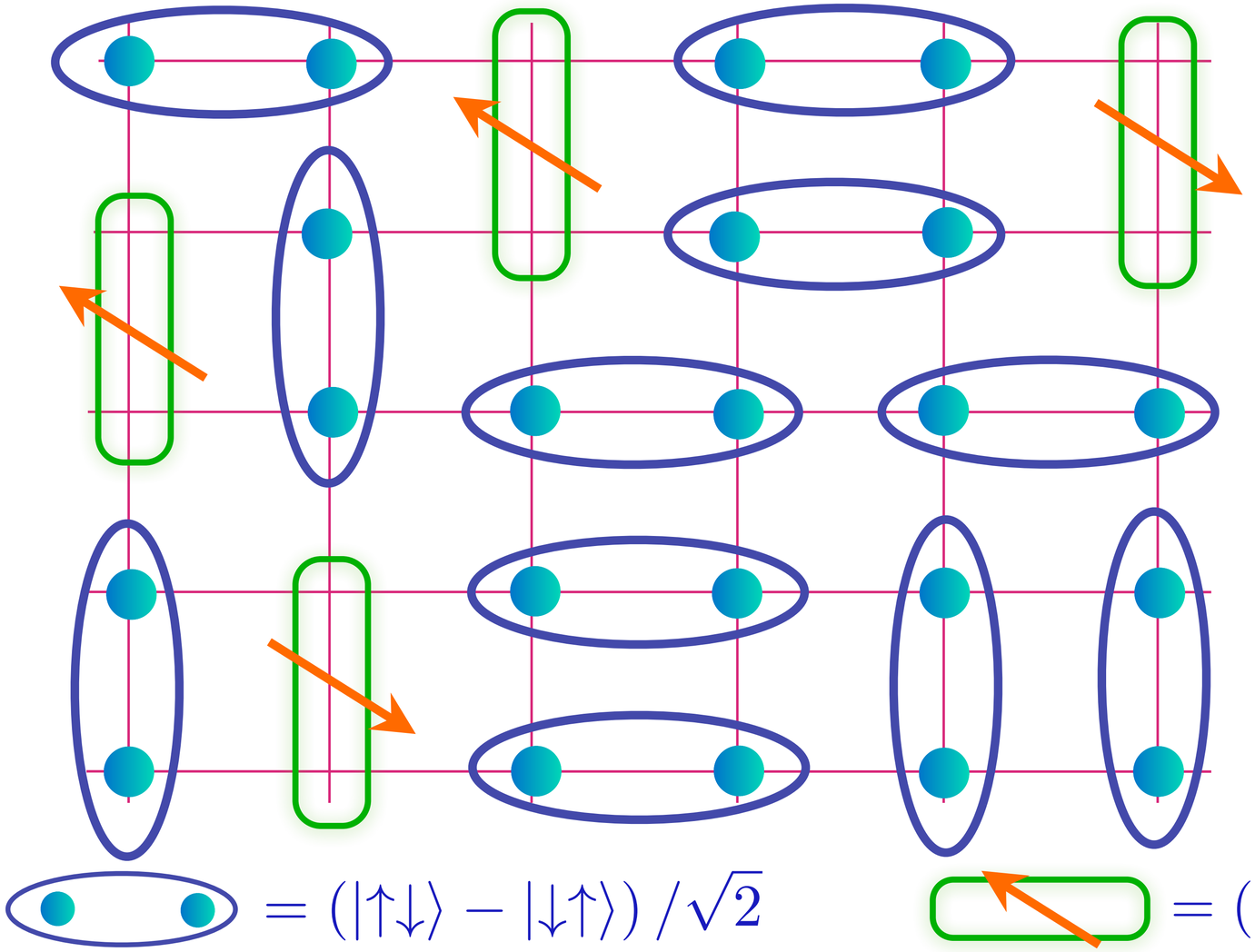

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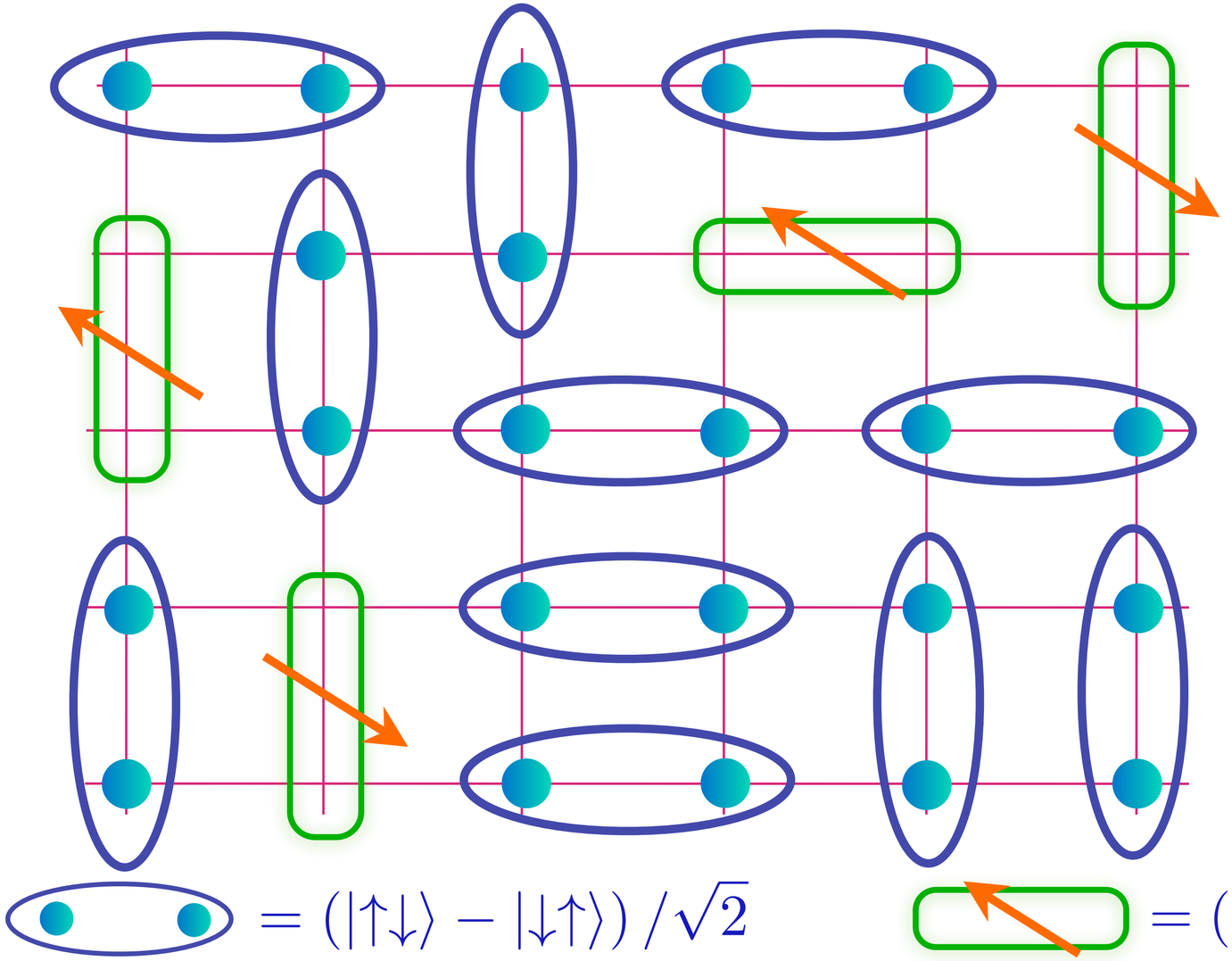

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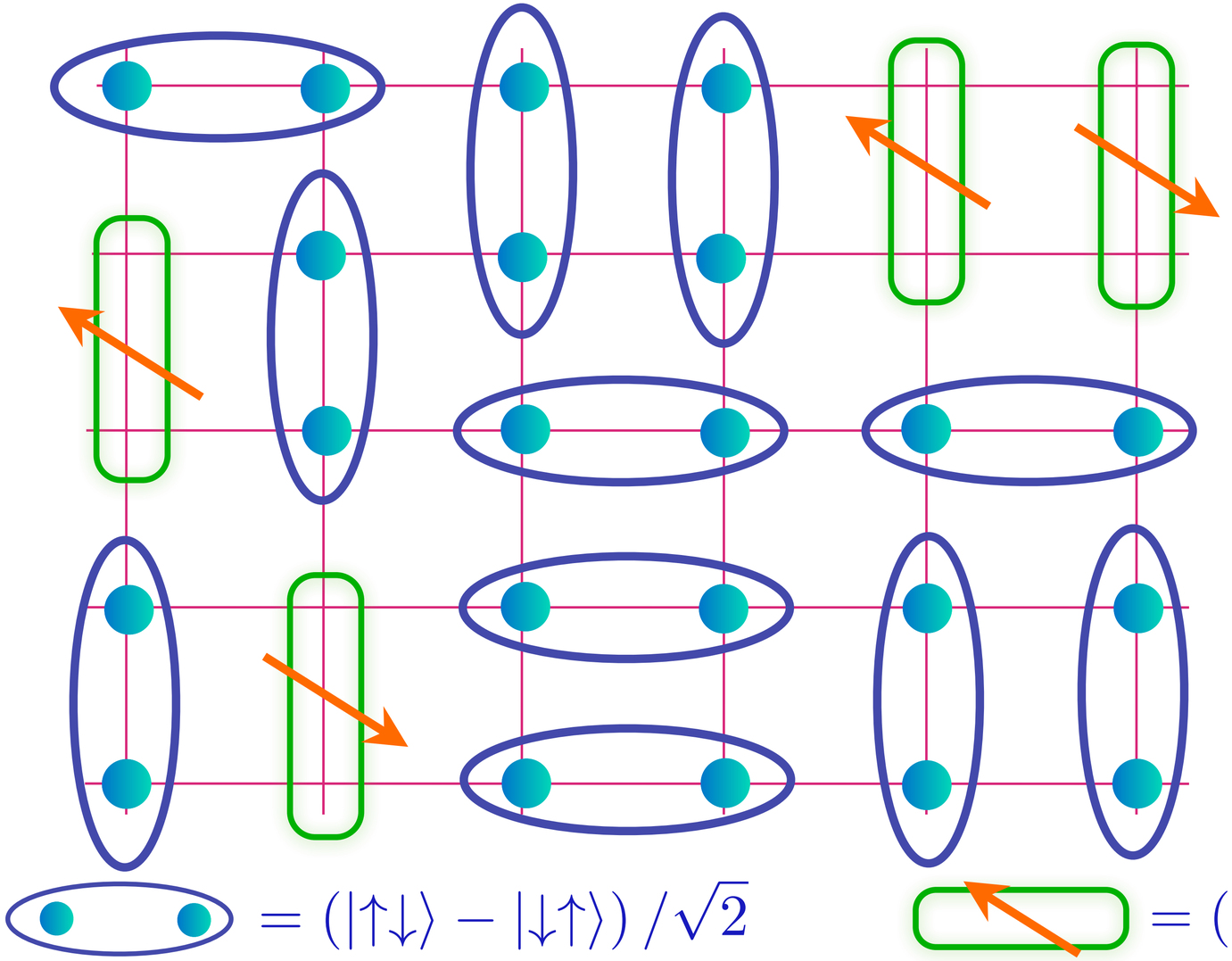

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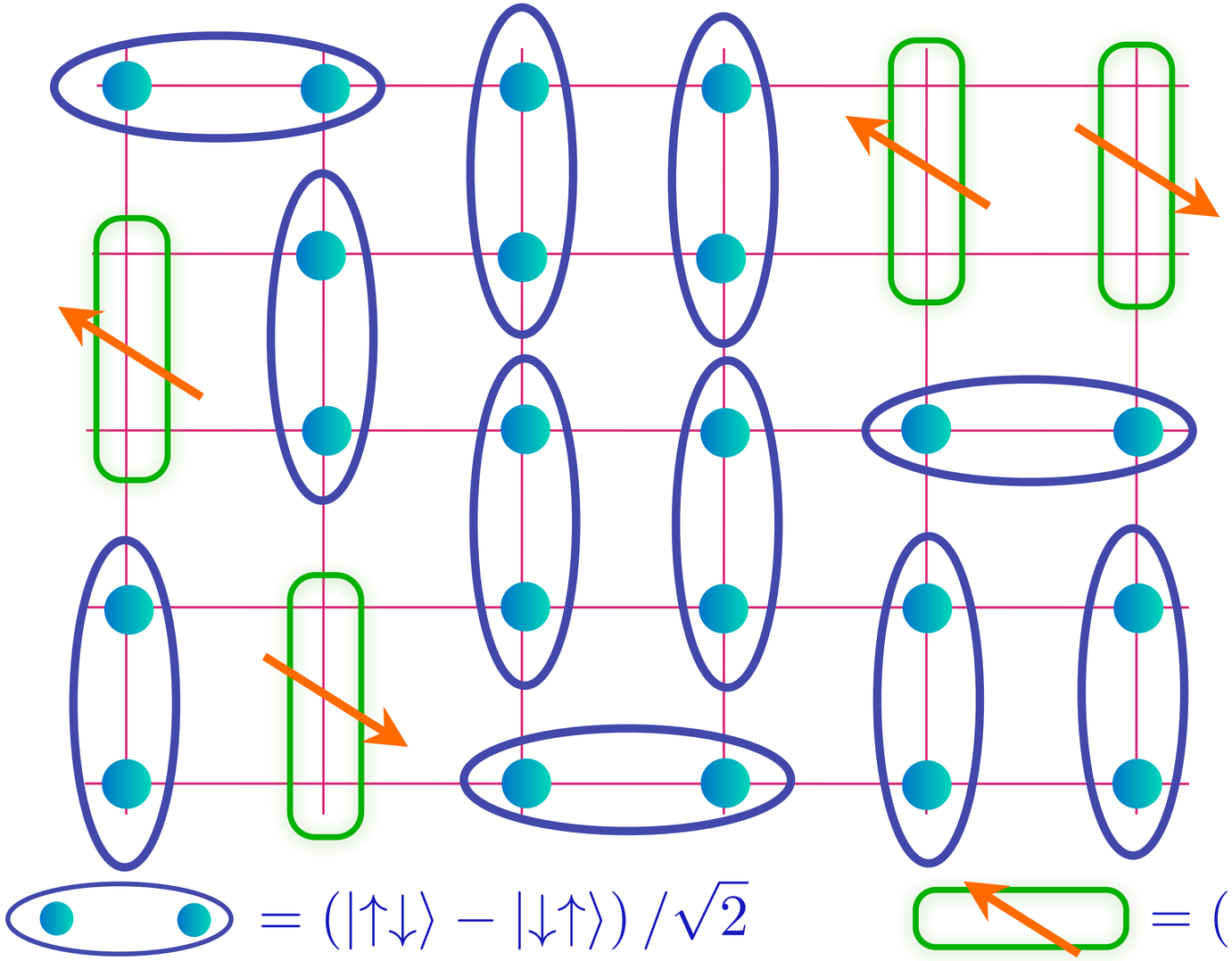

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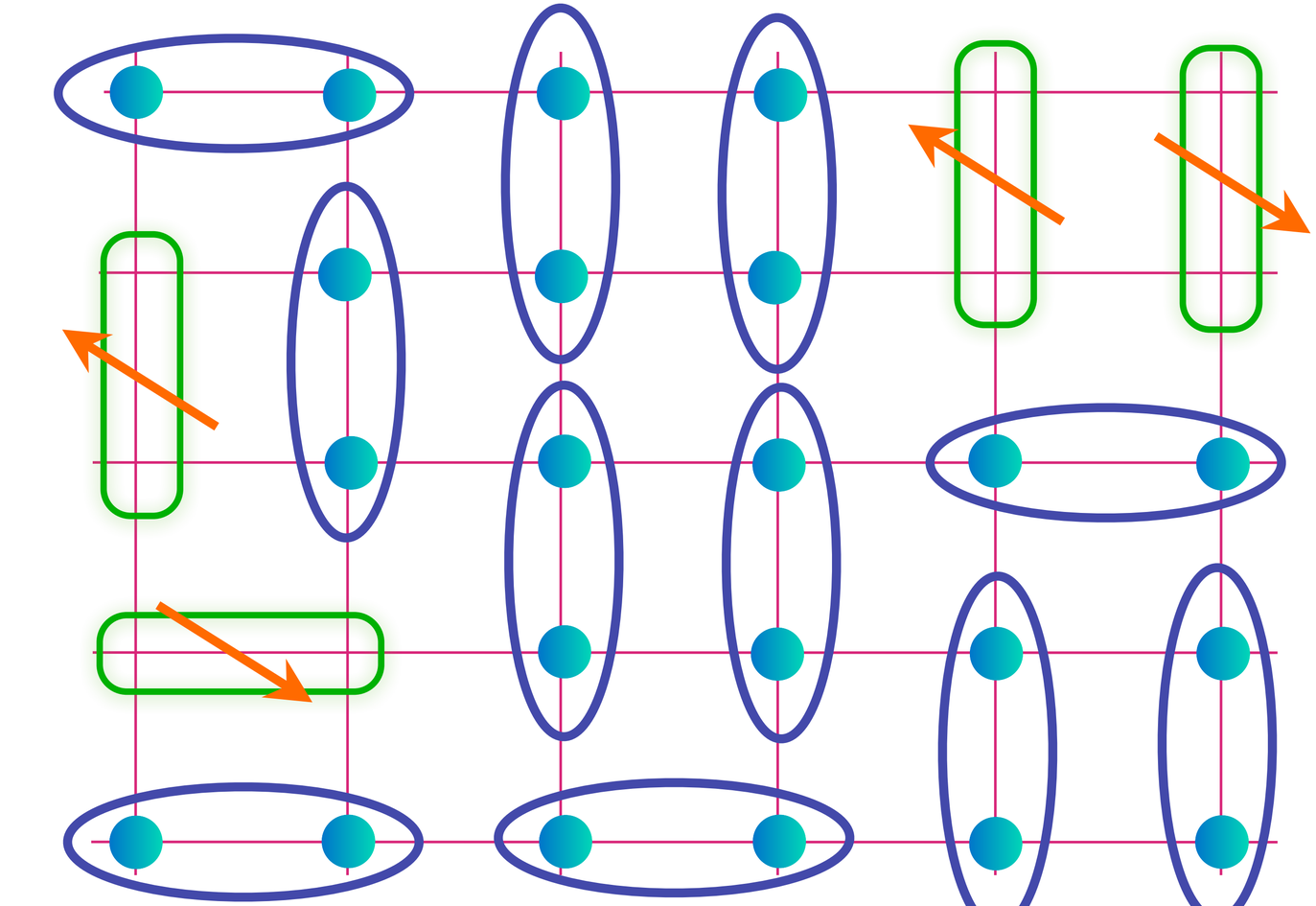

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Metal-metal transitions in a ***one-band*** model

- 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.

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- There is a proposal (S. Sachdev, H. D. Scammell, M. S. Scheurer, and G. Tarnopolsky, PRB **99**, 054516 (2019)) for a transition from FL* to FL using a $\mathrm{SU}(2)_S$ gauge theory, but some 'hand-waving' is required to produce the FL* Fermi surface.

1. Metal-metal transition in the Kondo Lattice

2. Metal-metal transition in a one-band model
   - *A. FL* model of the pseudogap*
   - *B. Ancilla qubits and ghost Fermi surfaces*

3. Random *J* model (insulator)
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4. Random t-*J* model (metals)
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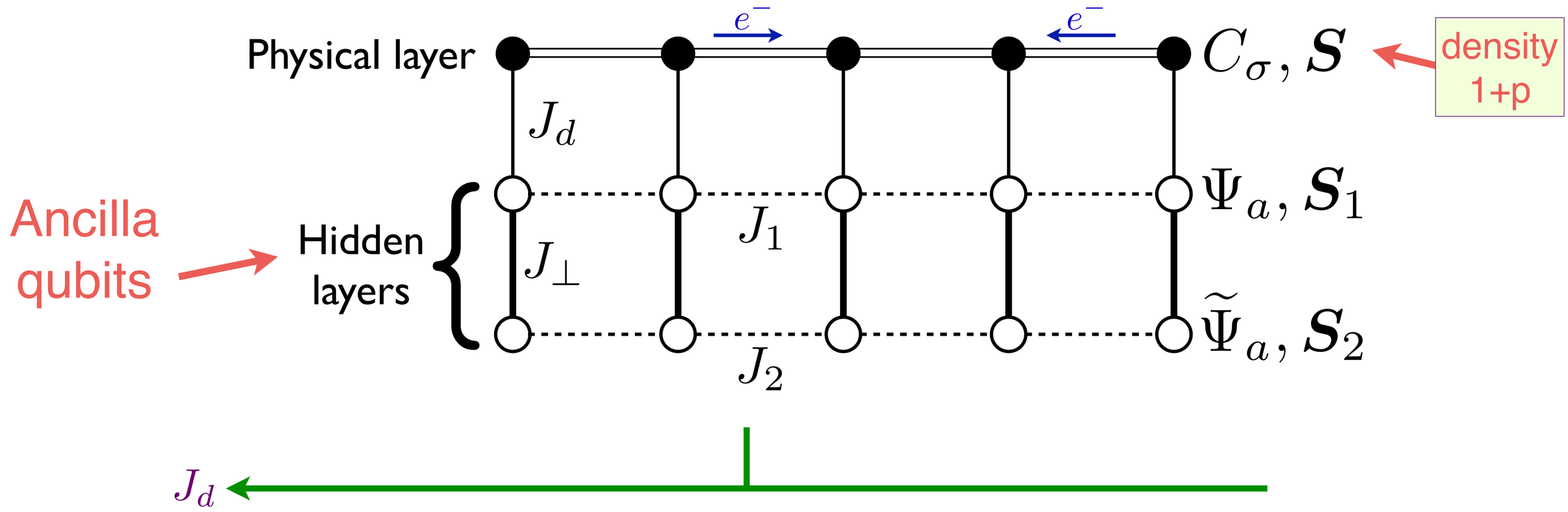

Ya-Hui Zhang

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172 (2020); arXiv:2006.01140.

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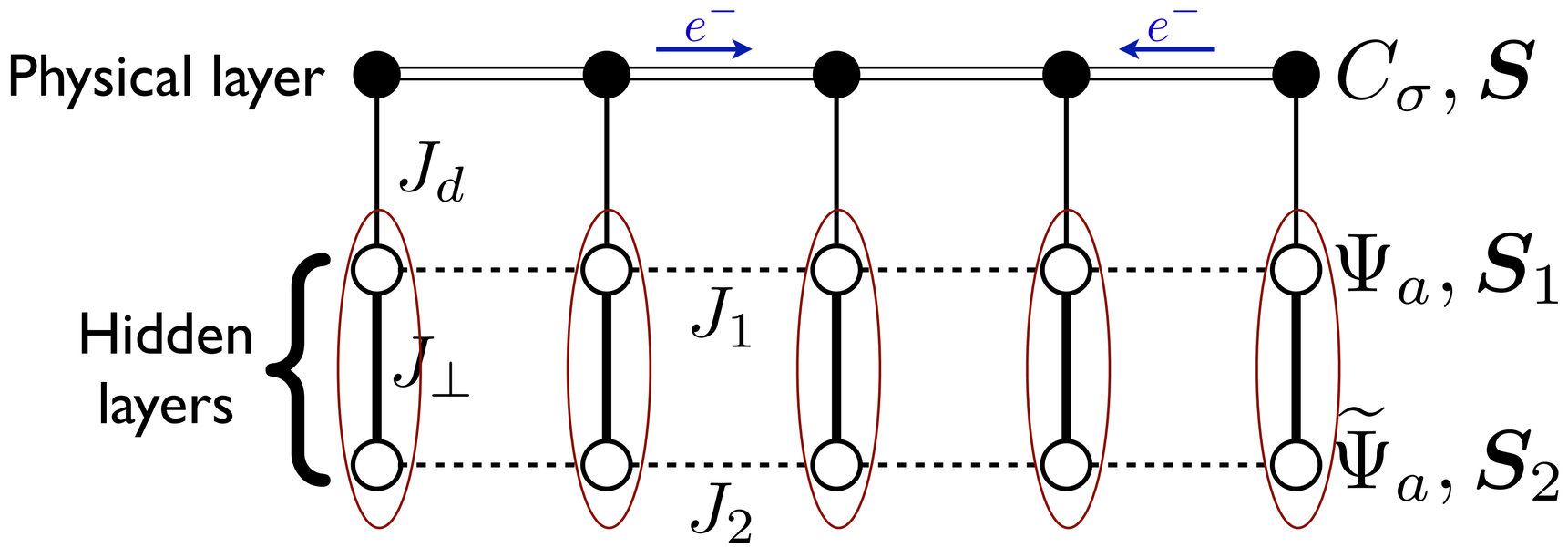

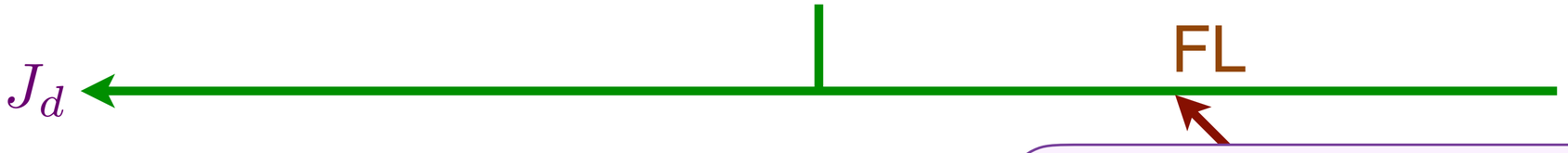

Large Fermi surface of size $1+p$

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

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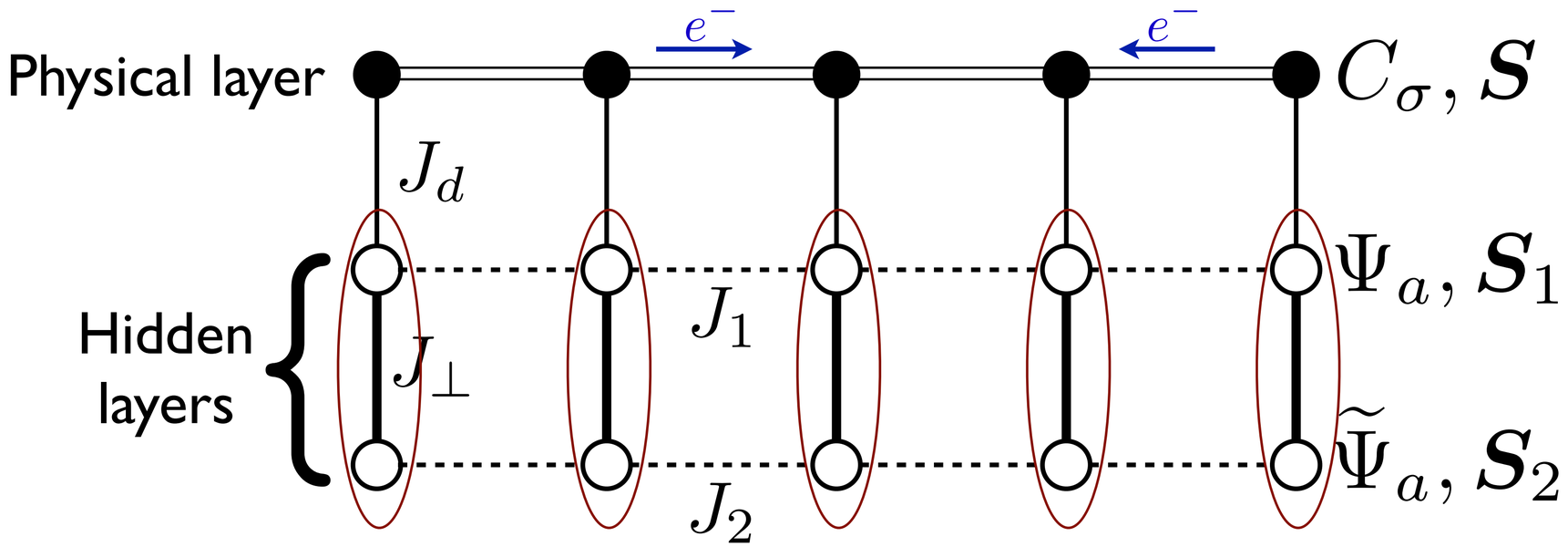

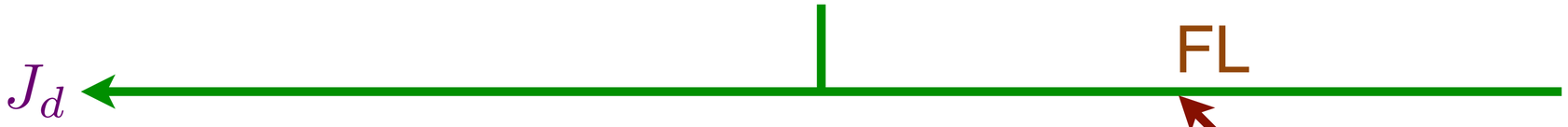

Luttinger Theorem obeyed

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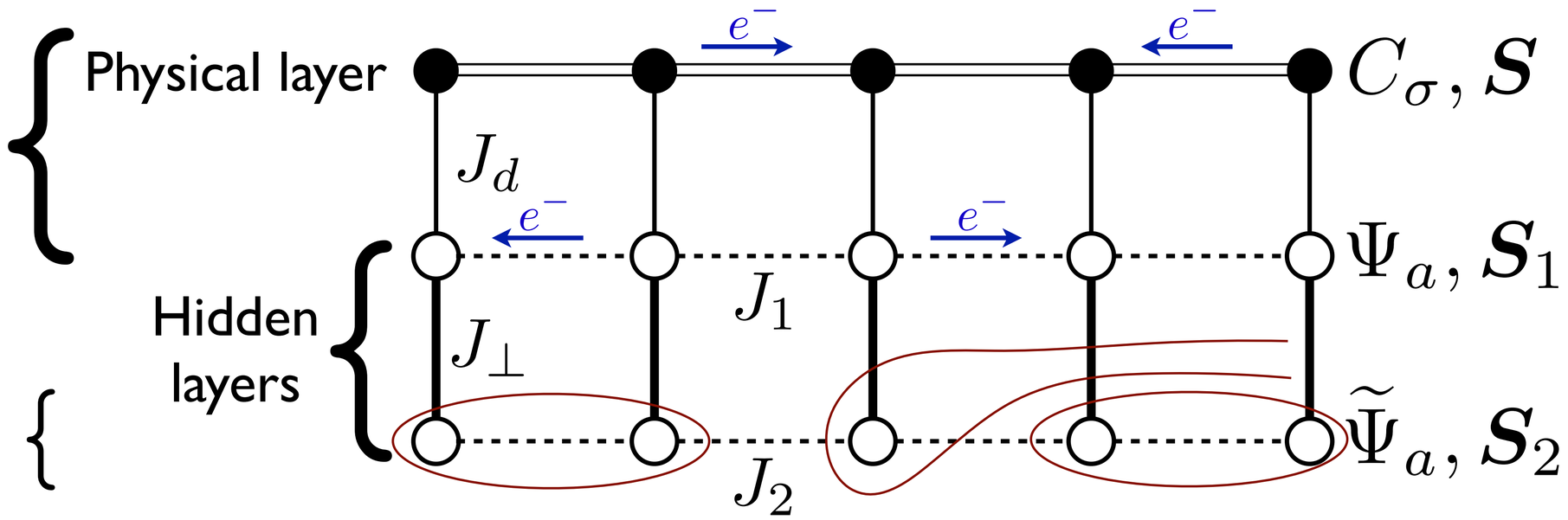
Metal-metal transitions in a ***one-band*** model

Metal.
Density
$2 + p \cong p$



density
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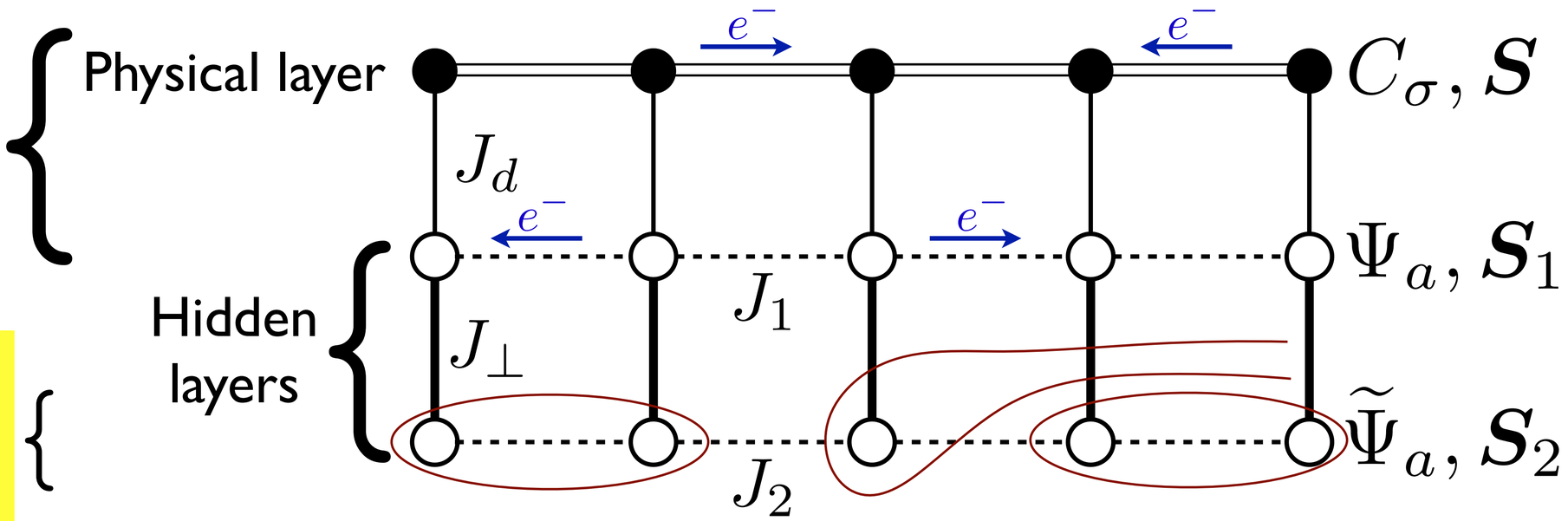

density
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Mott insulator
Spin liquid
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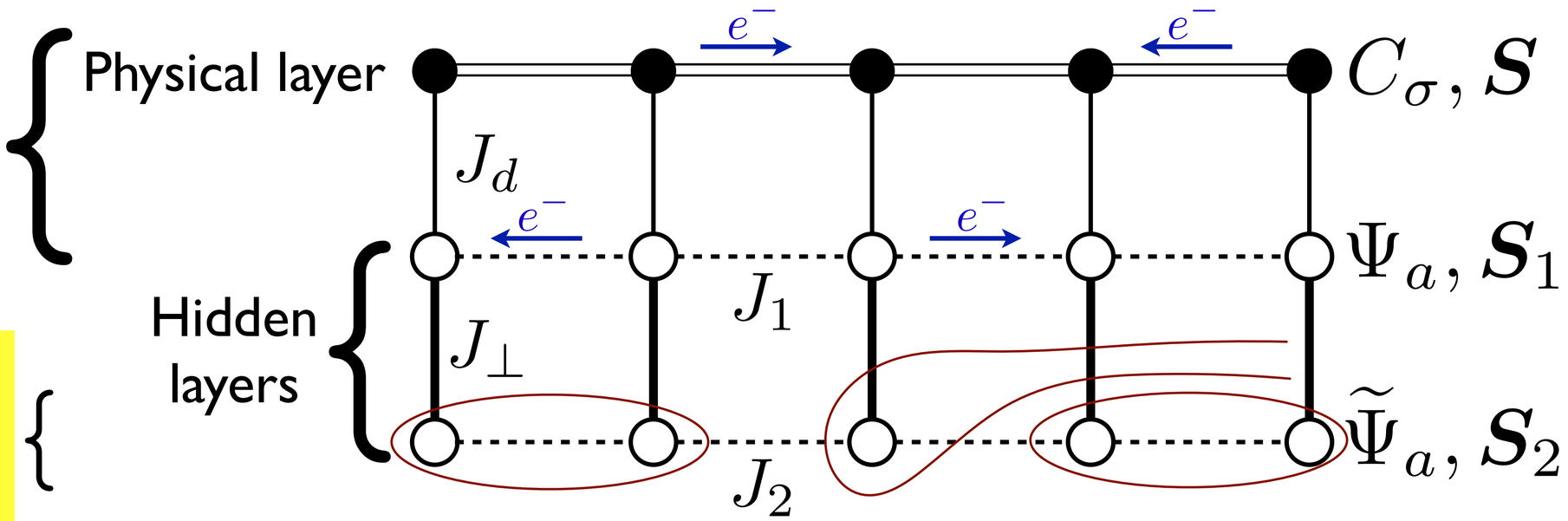

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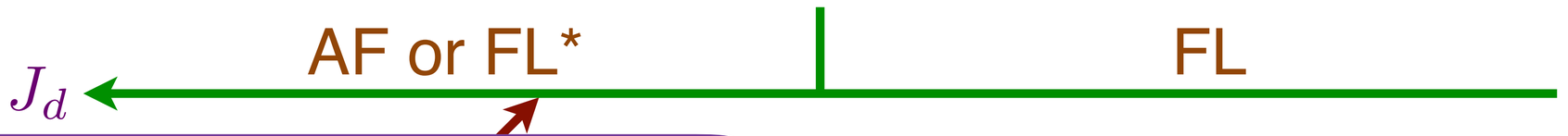

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Luttinger Theorem
violated;
OK, because of
topological order of $\widetilde{\Psi}$

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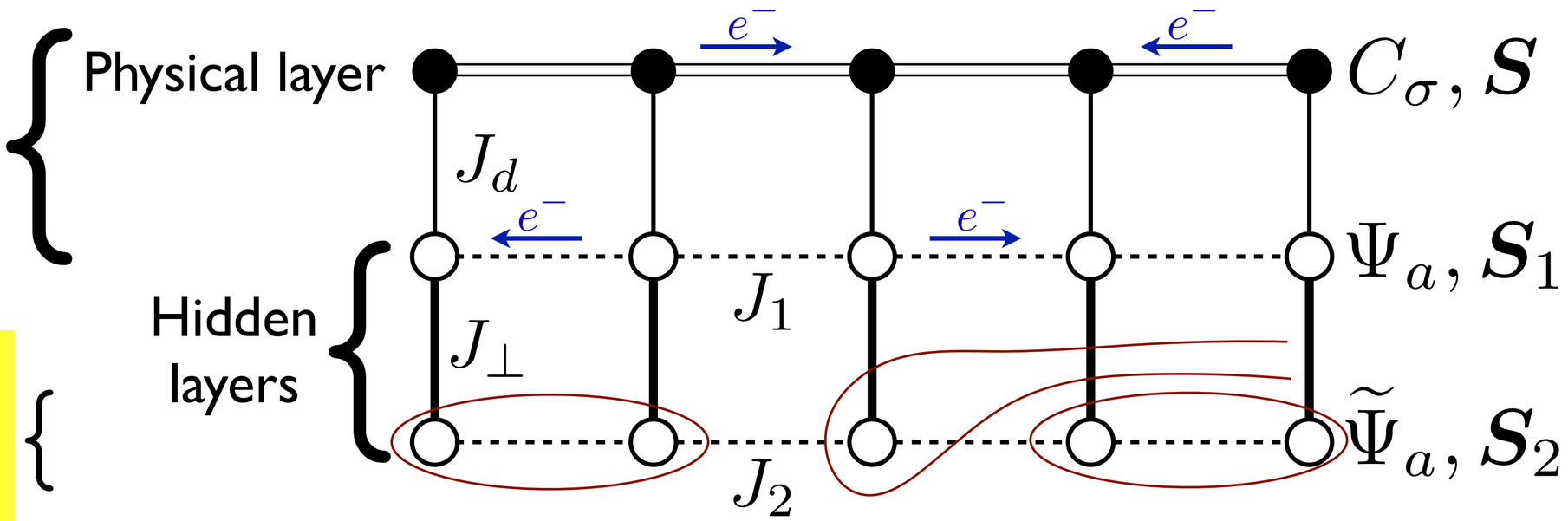

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Similar to a selective Mott transition in hidden layer 1:
Ψ fermions are insulating in FL phase,
and metallic in FL* phase.

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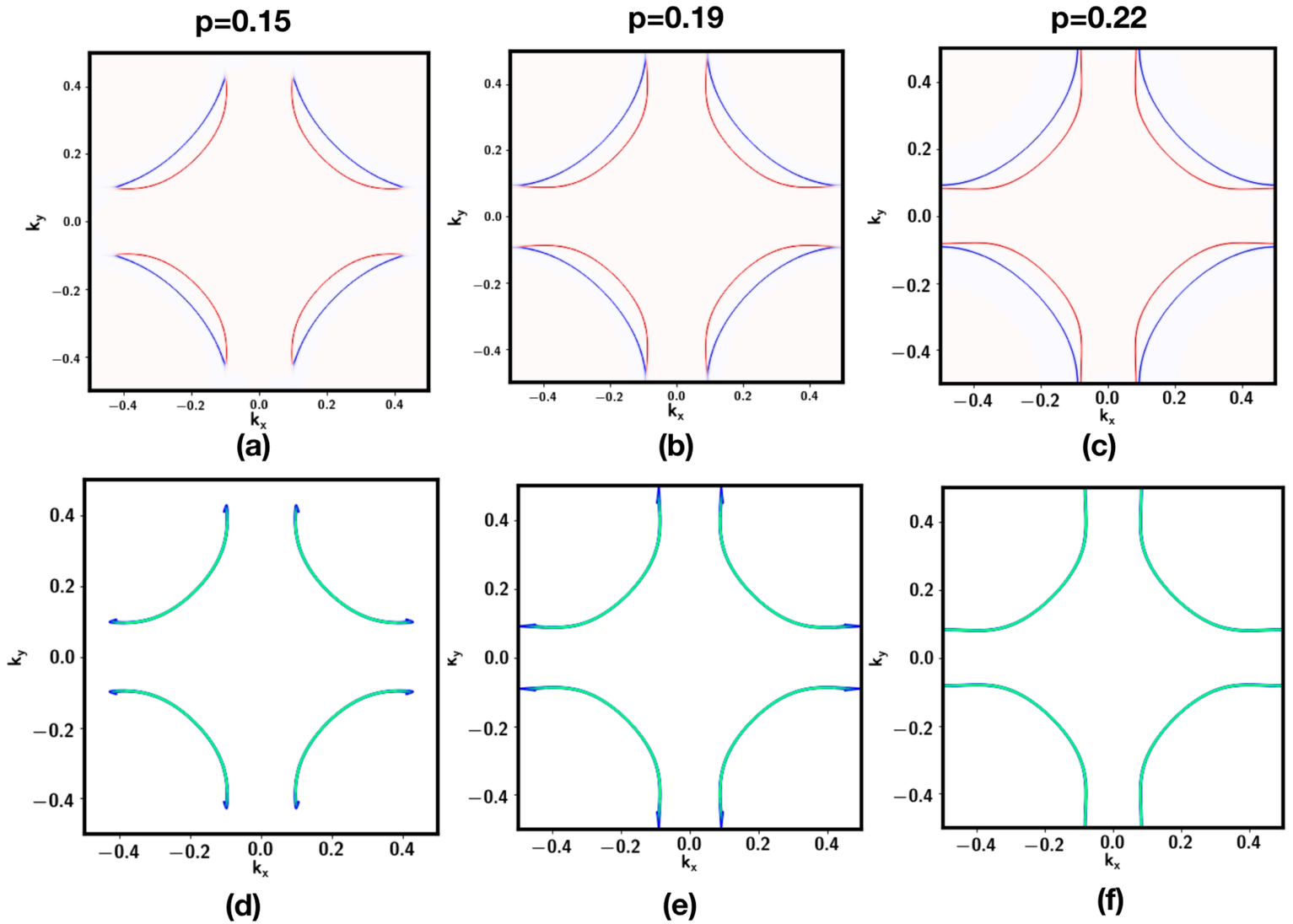

"Fermi arc" spectral functions in the FL* phase

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

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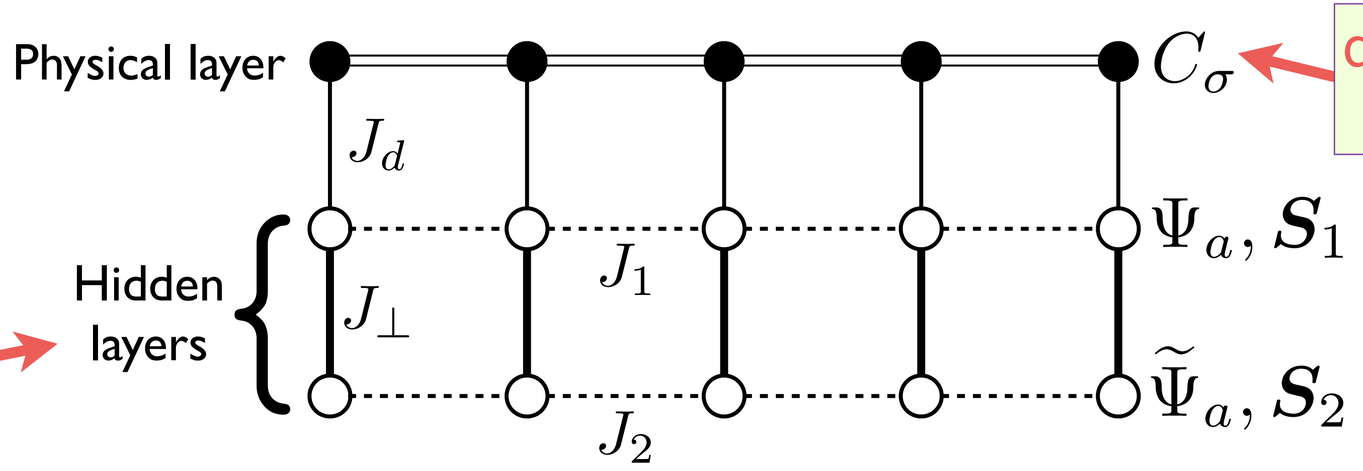
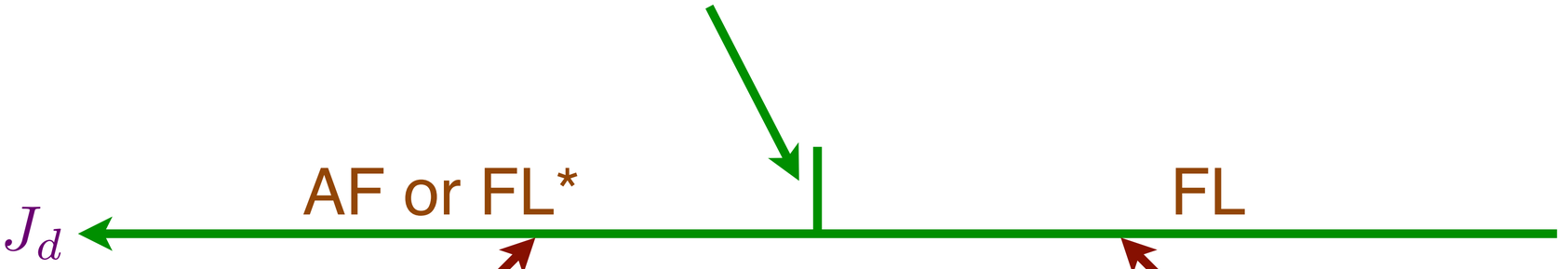
Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172 (2020); arXiv:2006.01140.

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



Yahui Zhang



Small Fermi surface of size p

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

Large Fermi surface of size $1+p$

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Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172 (2020); arXiv:2006.01140.

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

Write fermion operators as 2×2 matrices

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

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

$$\begin{aligned} \mathrm{SU}(2)_1 : \quad & \mathbf{\Psi} \to \mathbf{\Psi} U_1 \quad , \quad \widetilde{\mathbf{\Psi}} \to \widetilde{\mathbf{\Psi}} \\ \mathrm{SU}(2)_2 : \quad & \mathbf{\Psi} \to \mathbf{\Psi} \quad , \quad \widetilde{\mathbf{\Psi}} \to \widetilde{\mathbf{\Psi}} U_2 \end{aligned}$$

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

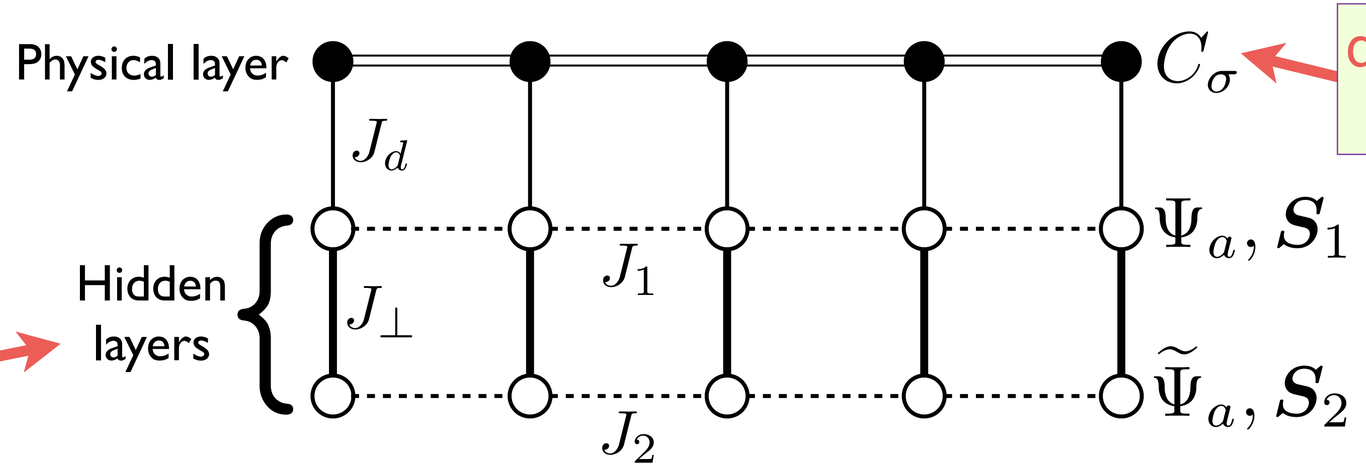
Local singlet formation ('antiferromagnetism') $\boldsymbol{S}_1 + \boldsymbol{S}_2 \approx 0$ leads to $\mathrm{SU}(2)_S$ gauge symmetry:

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

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)

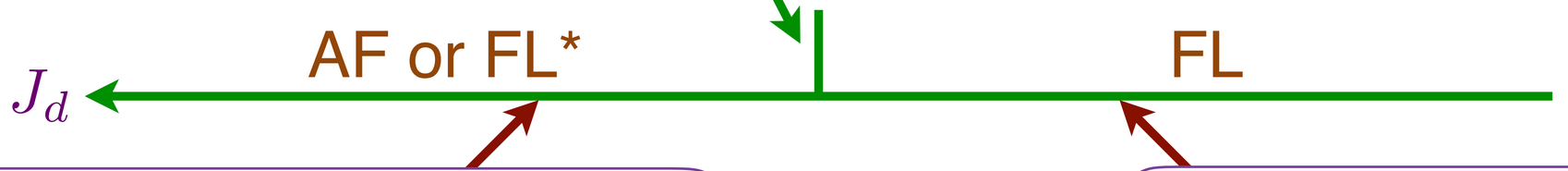
Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172 (2020); arXiv:2006.01140.

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



Yahui Zhang

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



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

Ya-Hui Zhang, S. Sachdev, PRR **2**, 023172 (2020); arXiv:2006.01140.

Ancilla qubit theory of metal-metal quantum phase transitions

- 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 (2020); arXiv:2006.01140.

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- 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 (2020); arXiv:2006.01140.

1. Metal-metal transition in the Kondo Lattice

2. Metal-metal transition in a one-band model
   - *A. FL* model of the pseudogap*
   - *B. Ancilla qubits and ghost Fermi surfaces*

3. Random *J* model (insulator)
   RG analysis and exact exponent

4. Random t-*J* model (metals)
   Numerics, RG analysis and exact exponents

Physical Review X
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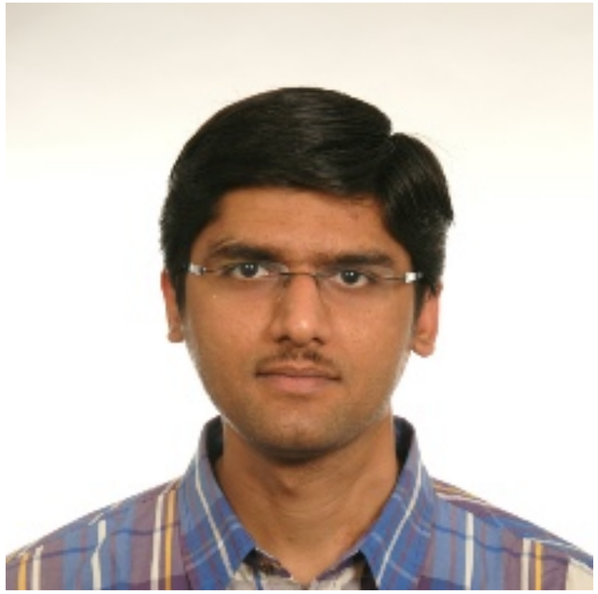
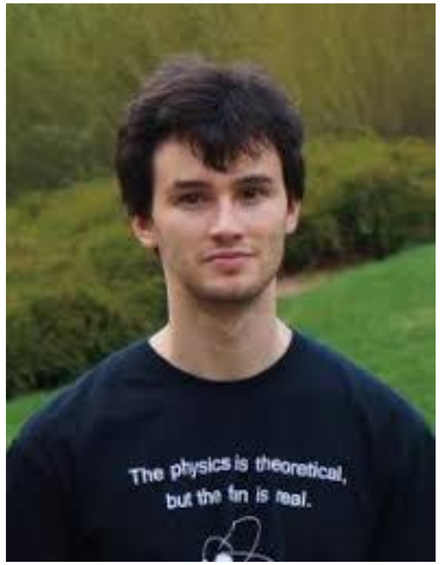


Darshan Joshi

Henry Shackleton

Chenyuan Li

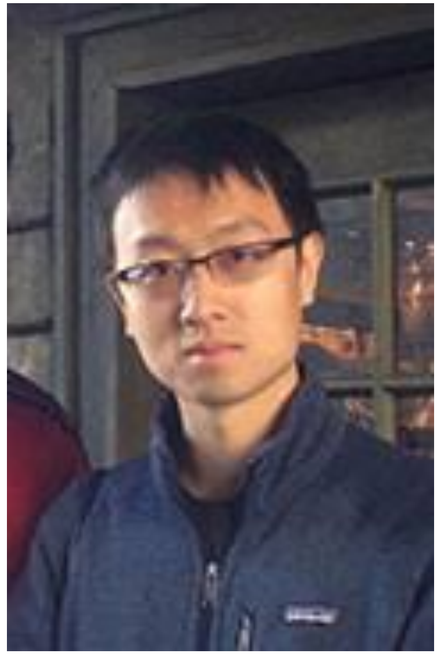


Grigory Tarnopolsky

Alexander Wietek

Antoine Georges

Annals of Physics,
418, 168202 (2020)



Haoyu Guo

Yingfeu Gu

Maria Tikhanovskaya

M. Tikhanovskaya, Haoyu Guo, Grigory Tarnopolsky, S. Sachdev, to appear

Random *t-J* model

$$H = -\frac{1}{\sqrt{N}} \sum_{i,j=1}^{N} t_{ij}\, c^{\dagger}_{i\alpha} c_{j\alpha} + \frac{1}{\sqrt{N}} \sum_{i<j=1}^{N} J_{ij}\, \vec{S}_i \cdot \vec{S}_j$$

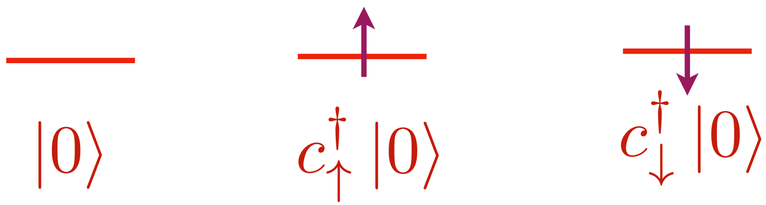
We consider the hole-doped case, with no double occupancy.

$$\alpha = \uparrow, \downarrow, \quad \{c_{i\alpha}, c^{\dagger}_{j\beta}\} = \delta_{ij}\delta_{\alpha\beta}, \quad \{c_{i\alpha}, c_{j\beta}\} = 0$$

$$\vec{S}_i = \frac{1}{2} c^{\dagger}_{i\alpha} \vec{\sigma}_{\alpha\beta} c_{i\beta}, \quad \sum_{\alpha} c^{\dagger}_{i\alpha} c_{i\alpha} \leq 1, \quad \frac{1}{N} \sum_{i\alpha} c^{\dagger}_{i\alpha} c_{i\alpha} = 1 - p$$

$$J_{ij} \text{ random}, \ \overline{J_{ij}} = 0, \ \overline{J^2_{ij}} = J^2$$

$$t_{ij} \text{ random}, \ \overline{t_{ij}} = 0, \ \overline{t^2_{ij}} = t^2$$



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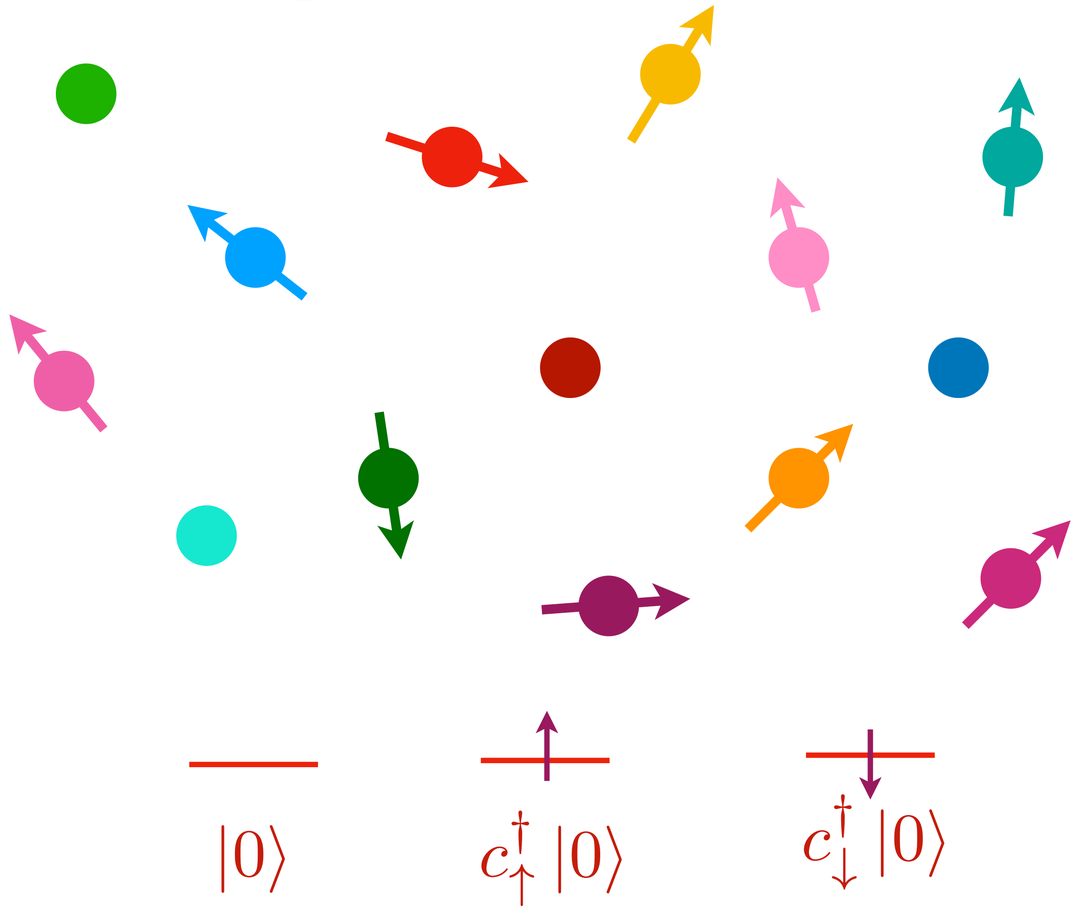

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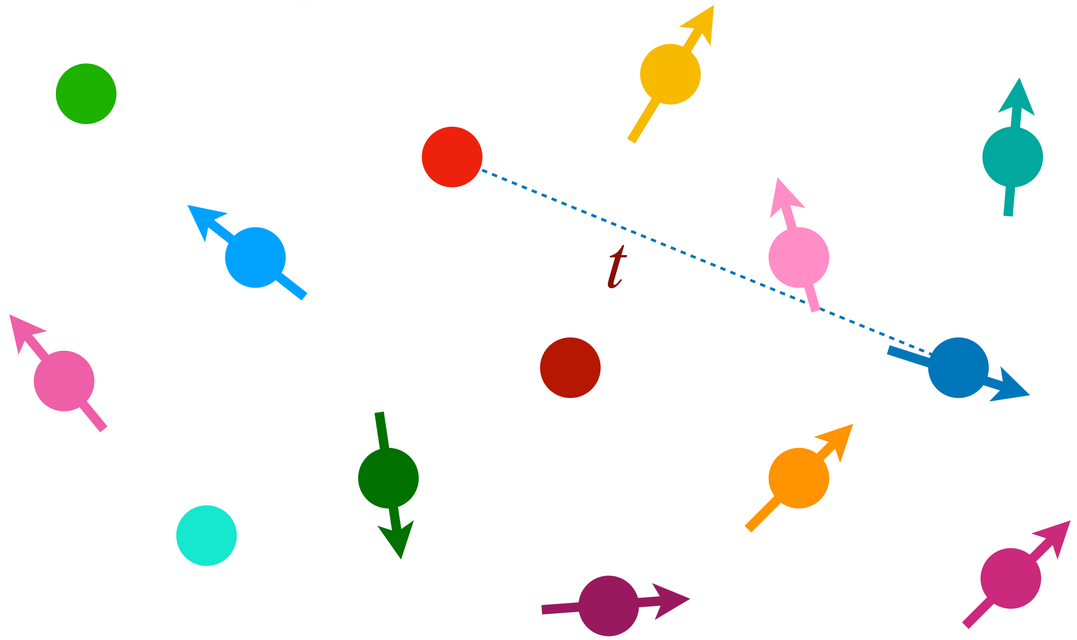

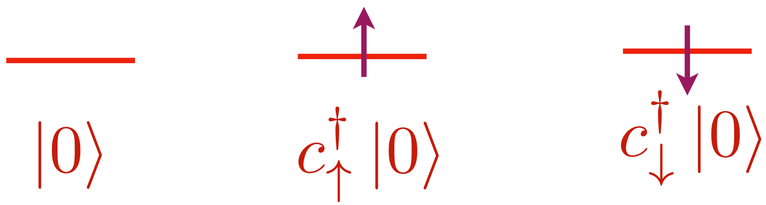

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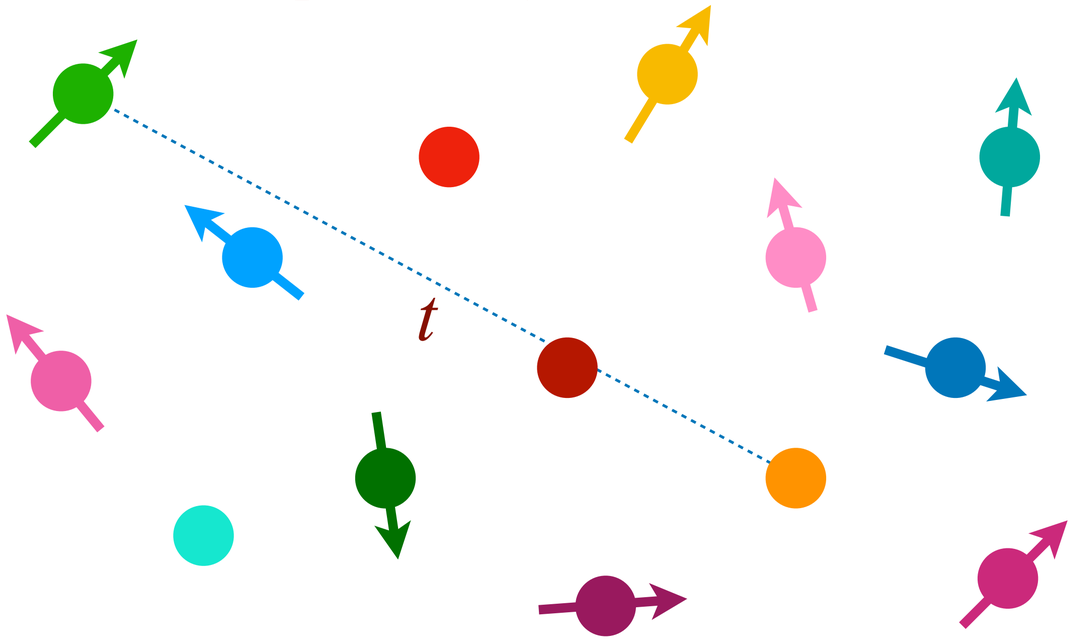

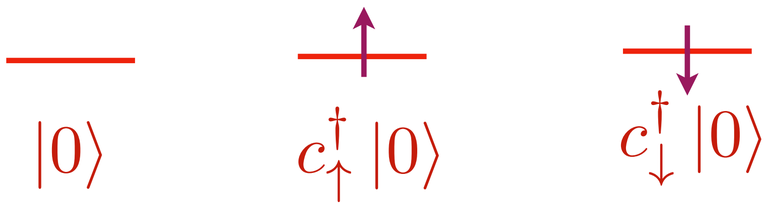

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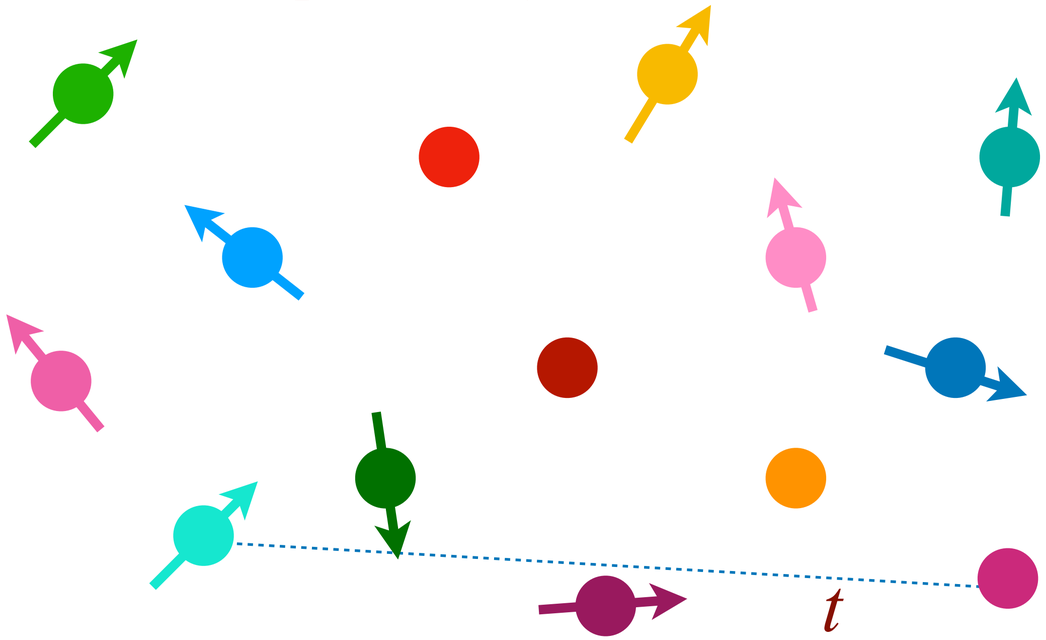

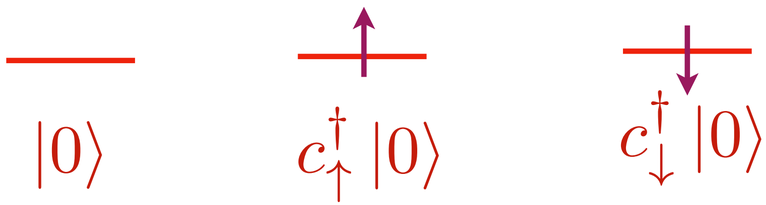

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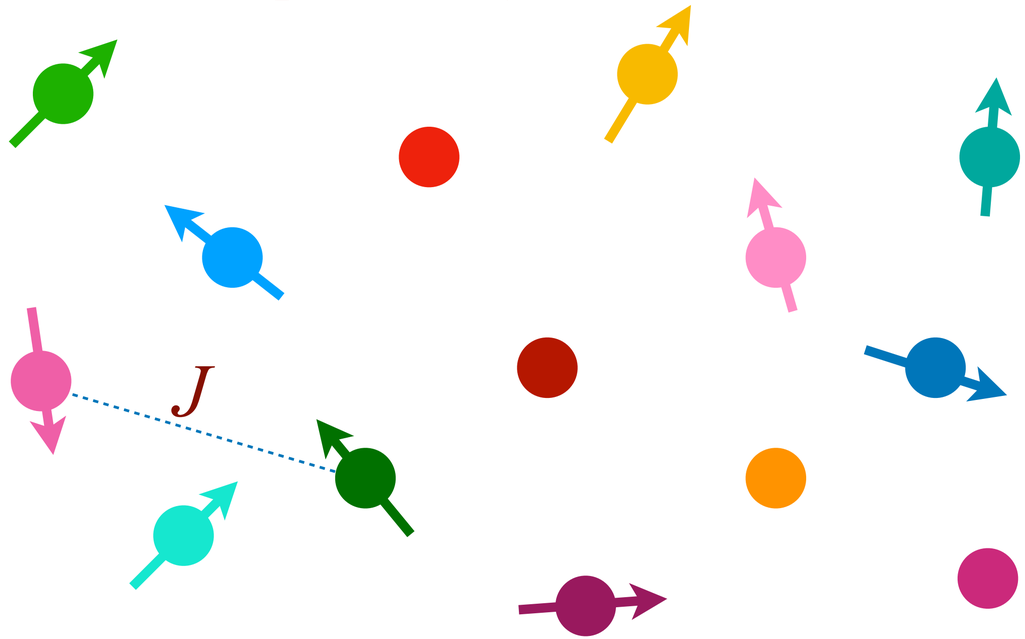

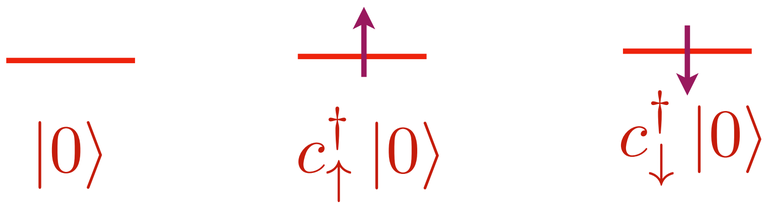

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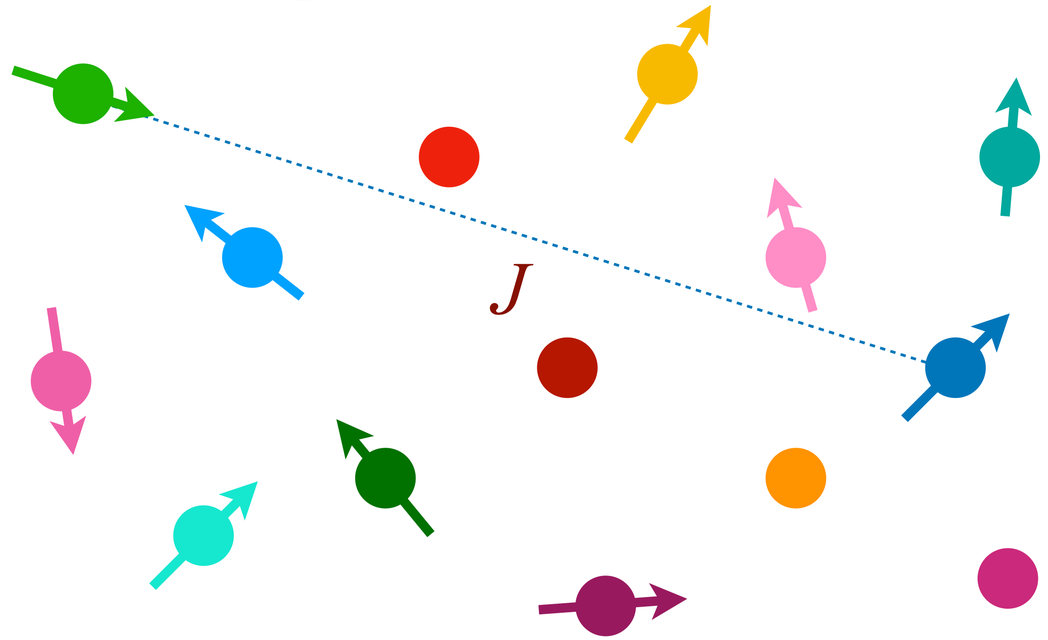

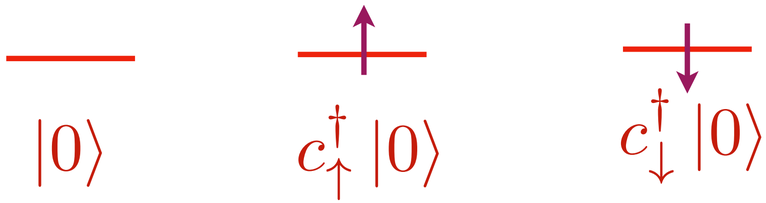

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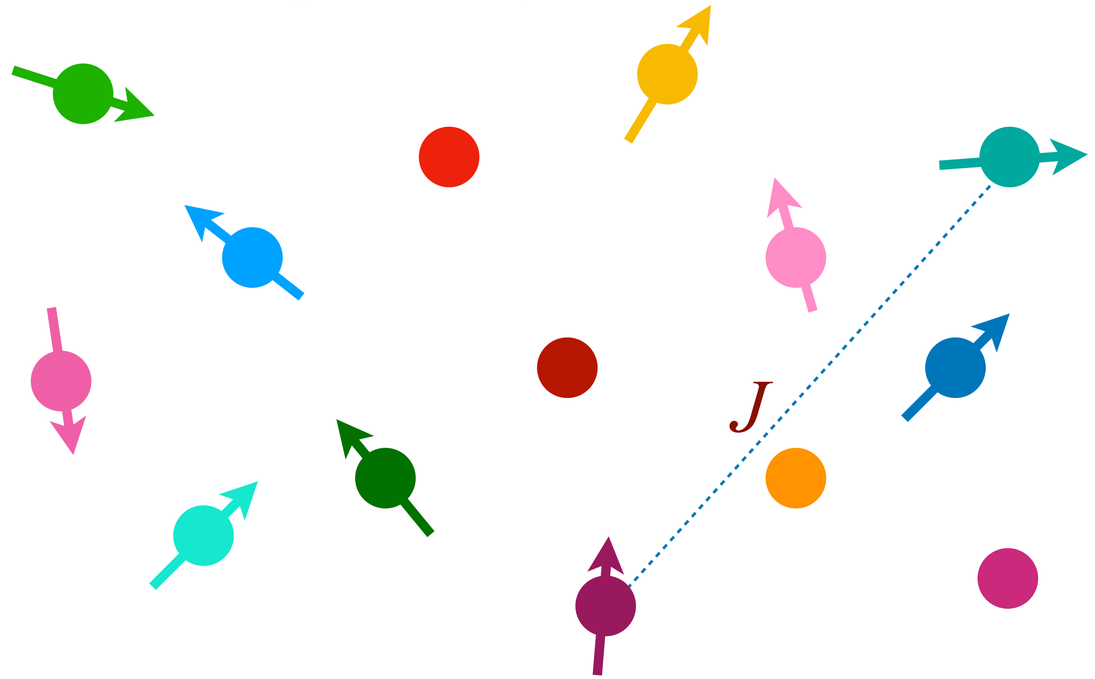
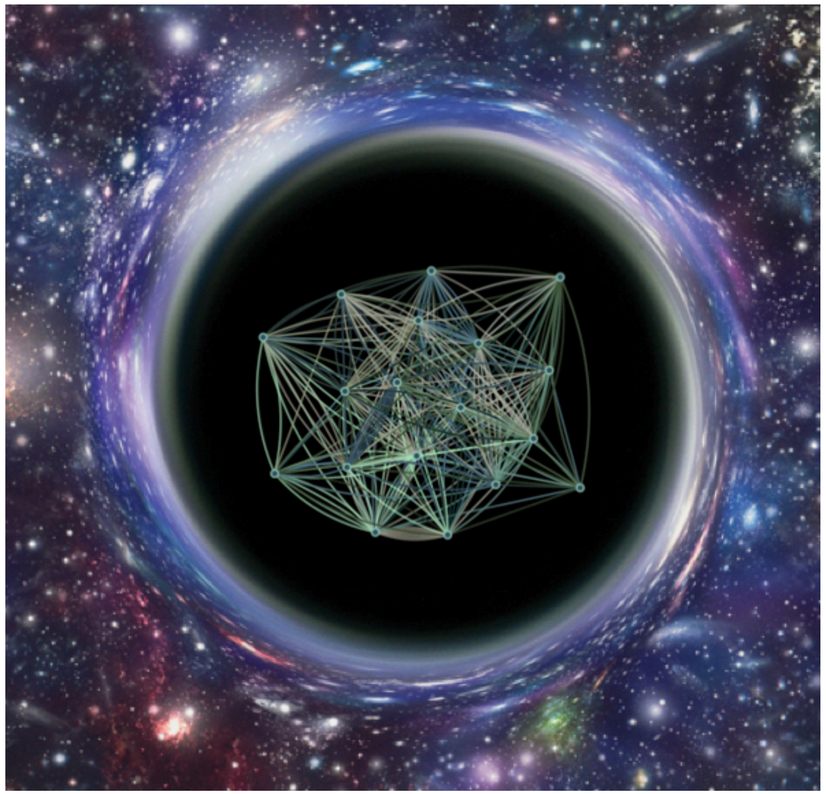


$|0\rangle$ $c_{\uparrow}^{\dagger}|0\rangle$ $c_{\downarrow}^{\dagger}|0\rangle$

- The t-J model with random and all-to-all hopping and exchange displays a phase diagram which captures many of the key characteristics of the cuprate phase diagram.

- It has an optimal doping metal-metal deconfined transition with SYK criticality.



Metal-metal quantum phase transitions

The ancilla qubit approach for non-random t-J models, and the random t-J model, have in common

- A metal-metal quantum phase transition with a change in carrier density from p to $1+p$.
- Fractionalization of the electron in the critical regime
- Unexpectedly large low T entropy near the critical point (from ghost fermions, or the SYK black hole entropy).