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

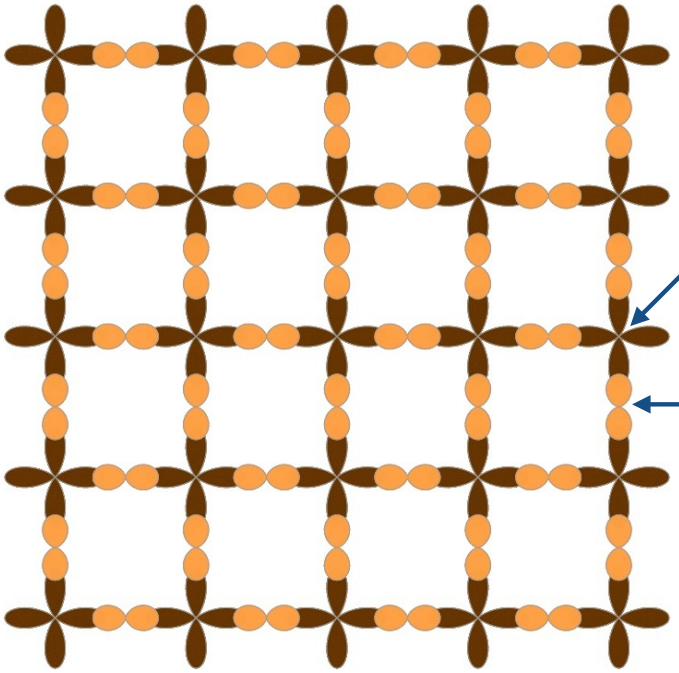
Correlated Systems with Multicomponent Local Hilbert Spaces
KITP, UC Santa Barbara
October 15, 2020

Subir Sachdev

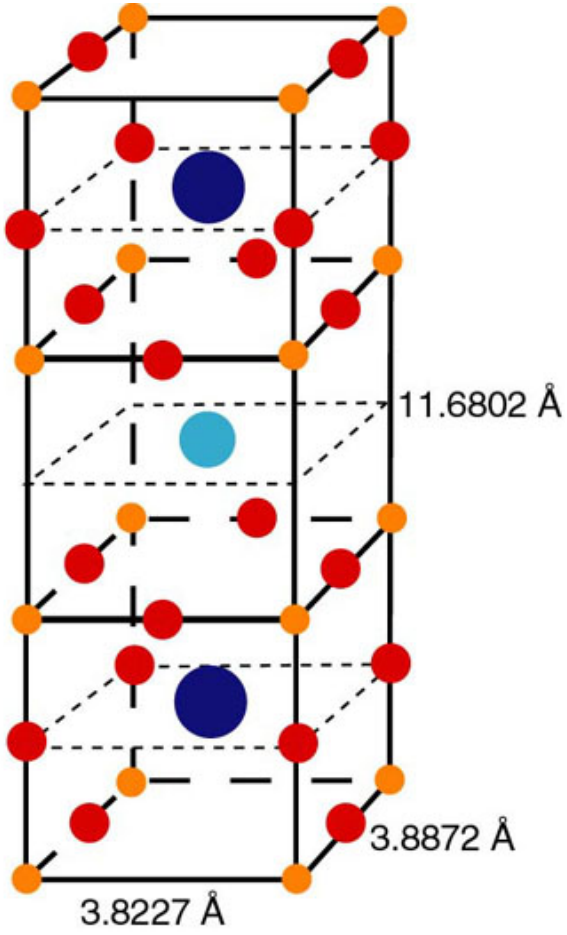
Talk online: sachdev.physics.harvard.edu

Yahui Zhang

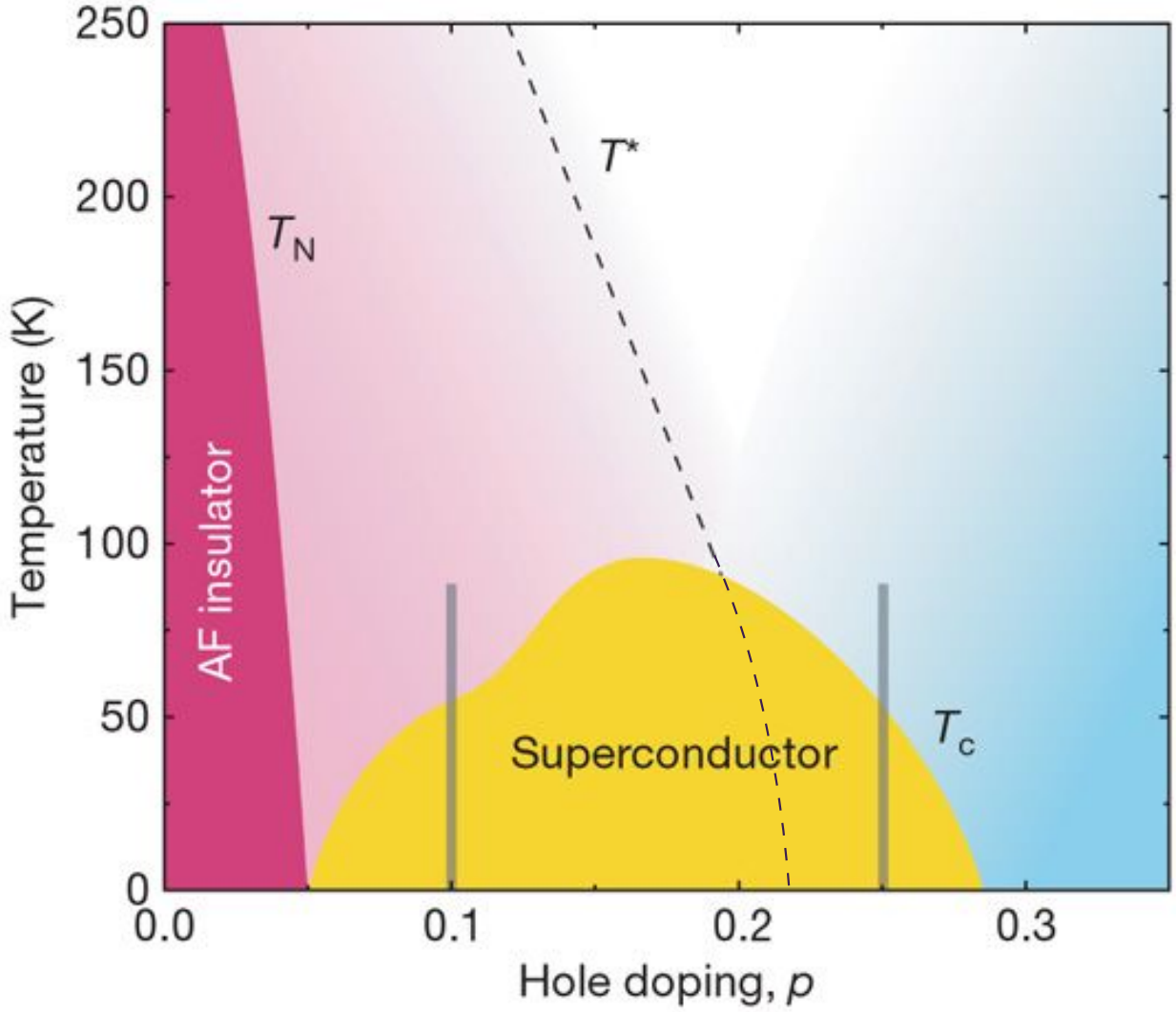
High temperature superconductors

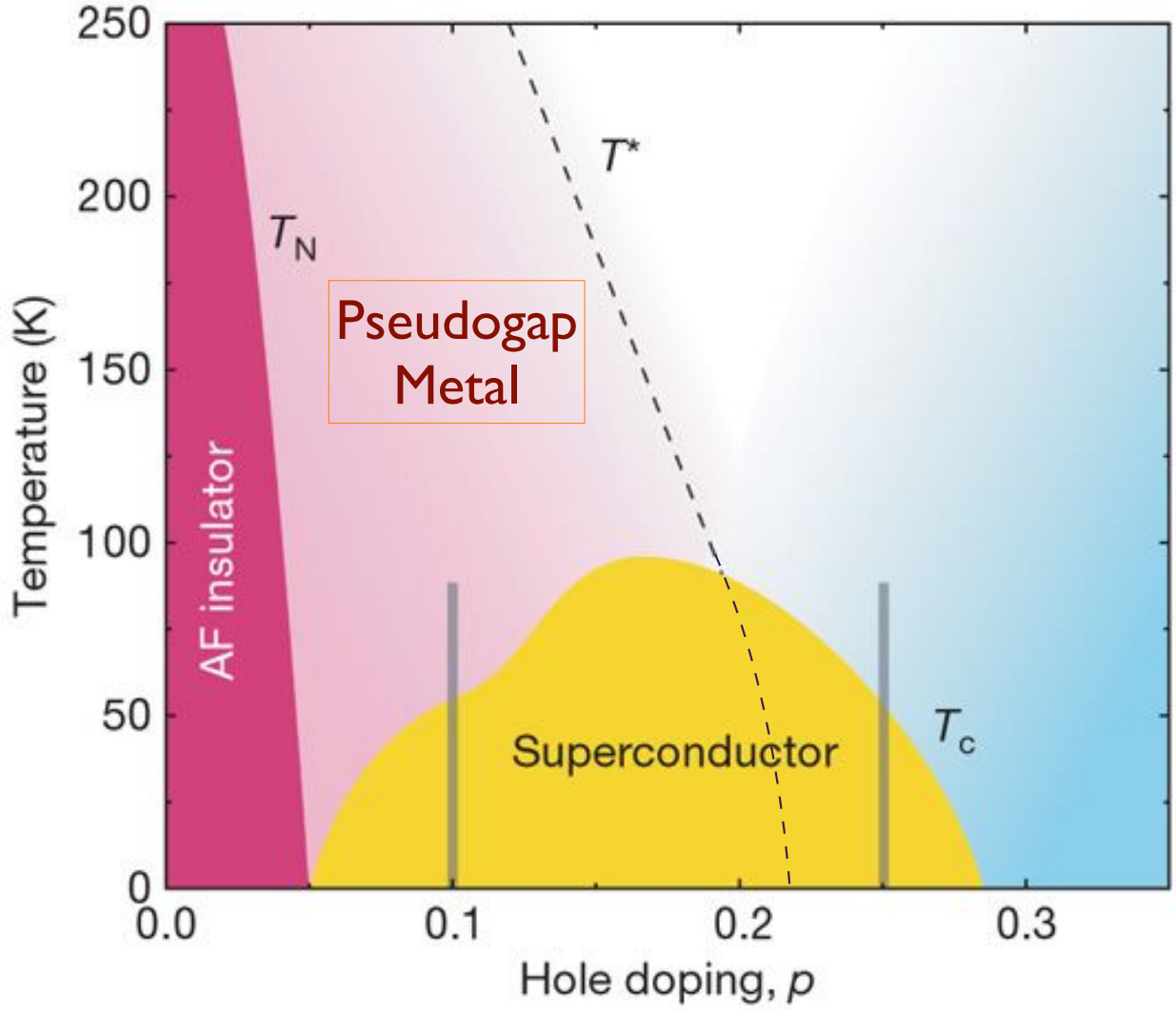


CuO_2 plane



$YBa_2Cu_3O_{6+x}$


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


250
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Hole doping, p
AF insulator
T_N
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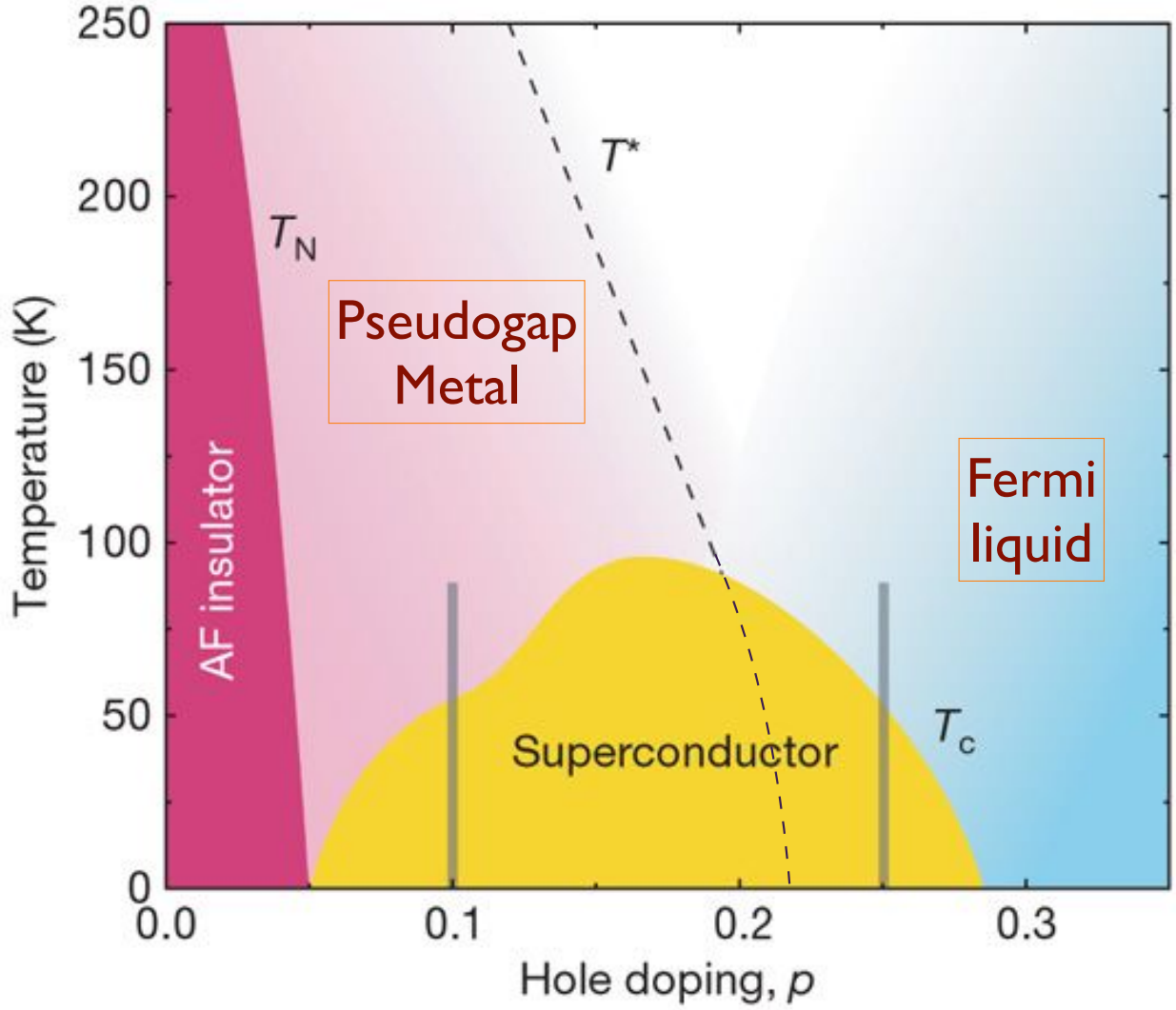
Pseudogap
Metal
Superconductor
T_c


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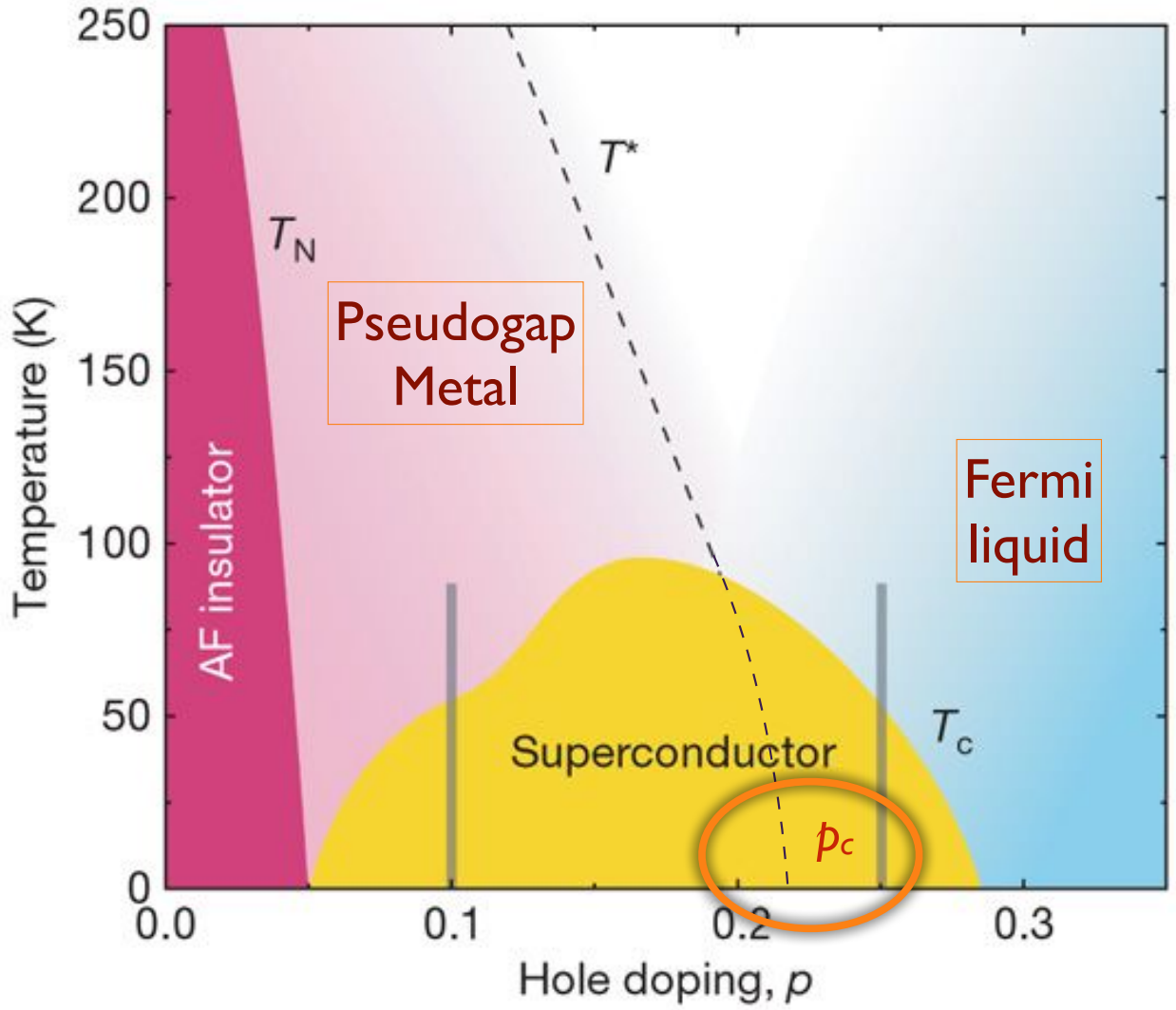
0.3
Hole doping, p
AF insulator
T_N
T^*
Pseudogap
Metal
Fermi
liquid
Superconductor
T_c


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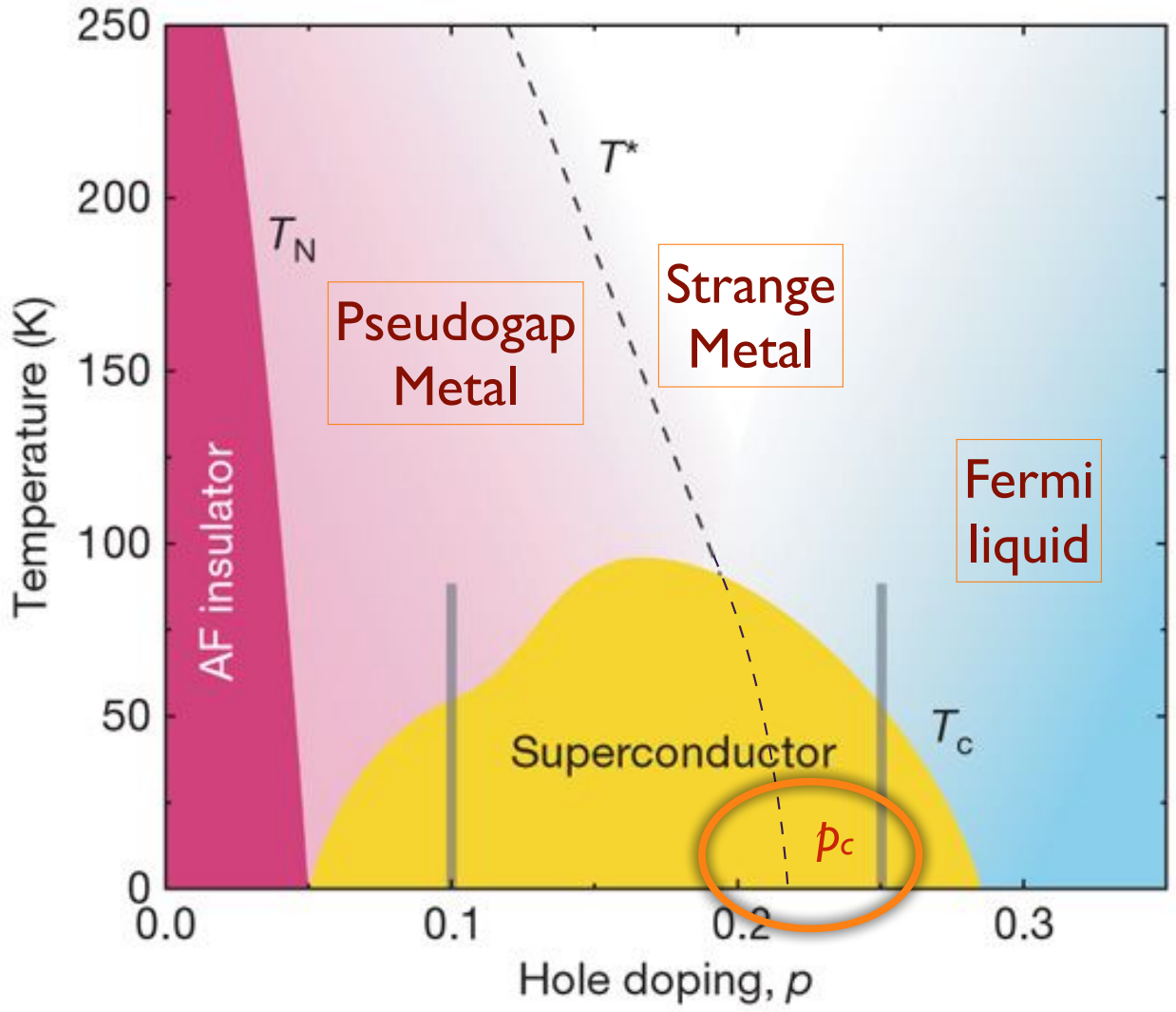
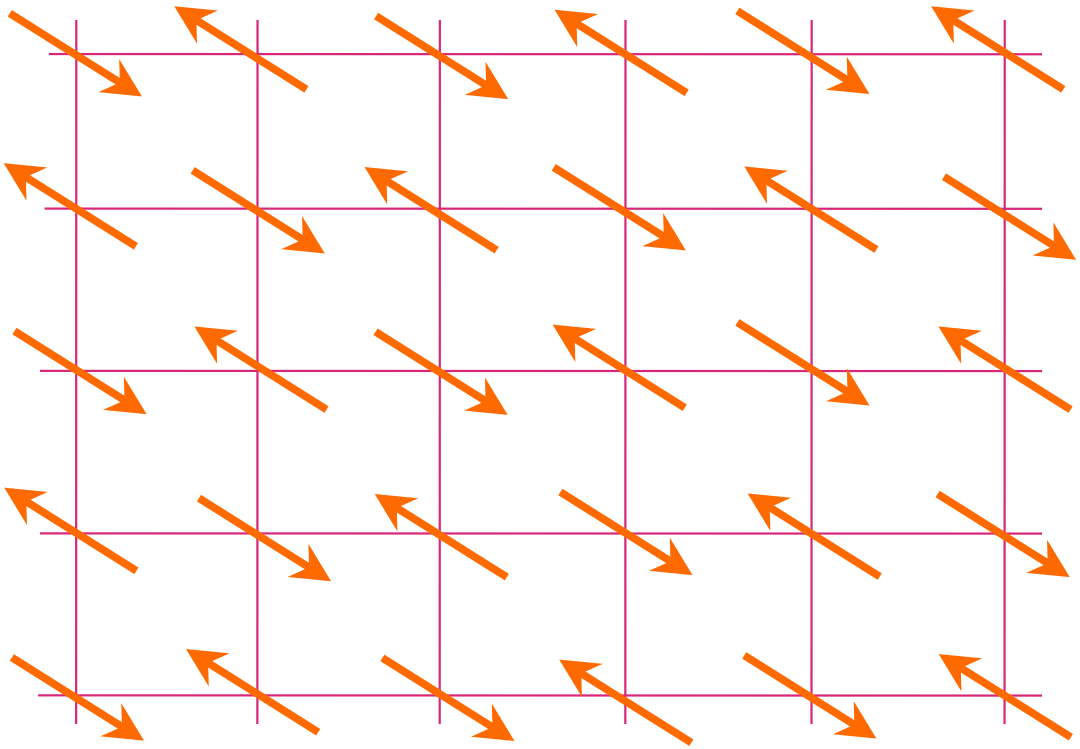
0
Temperature (K)
0.0
0.1
0.2
0.3
Hole doping, p
AF insulator
T_N
T^*
Pseudogap
Metal
Fermi
liquid
Superconductor
T_c
p_c


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

Insulating antiferromagnet



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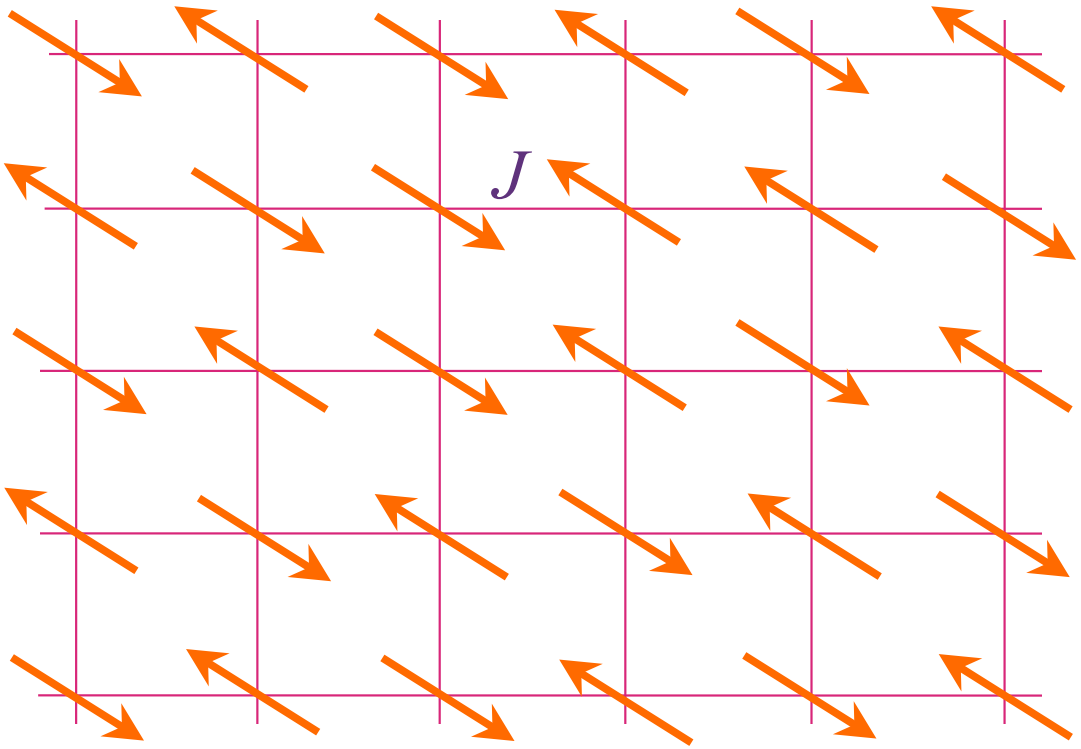

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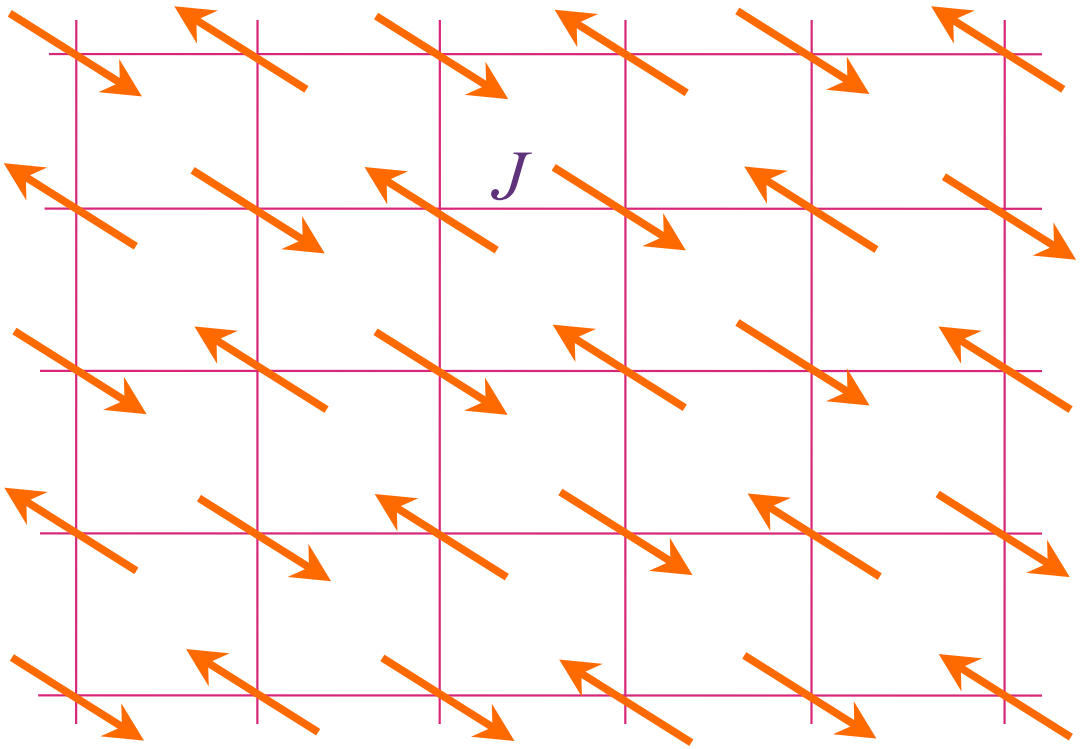
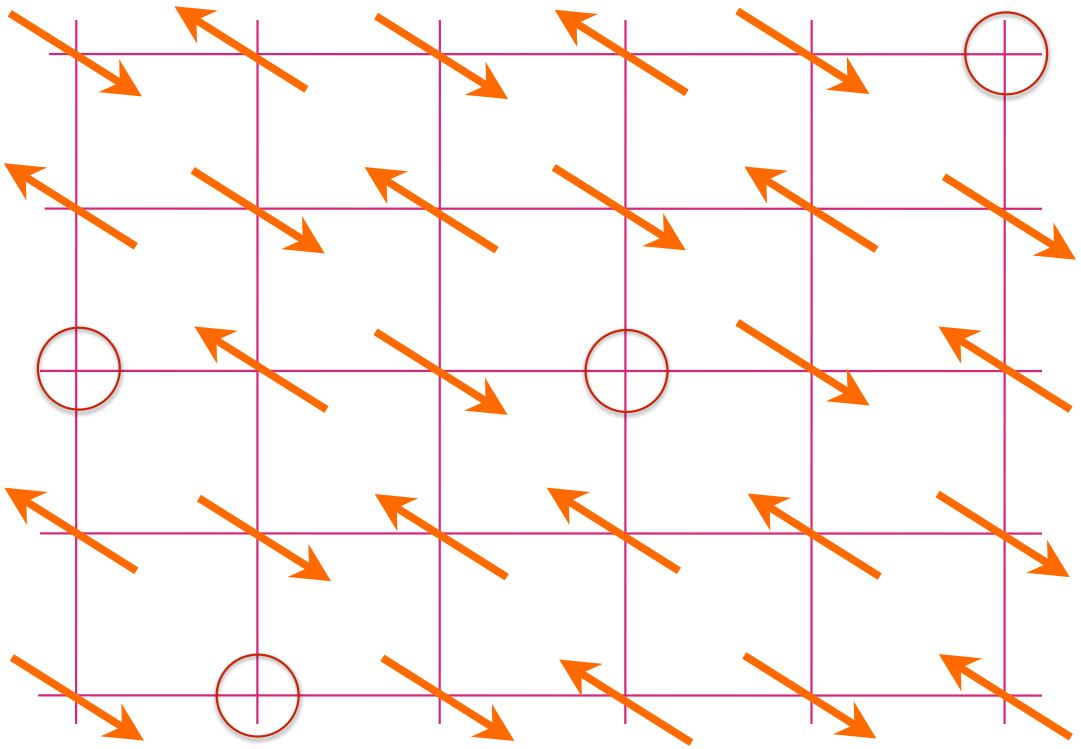


Antiferromagnet doped with hole density p



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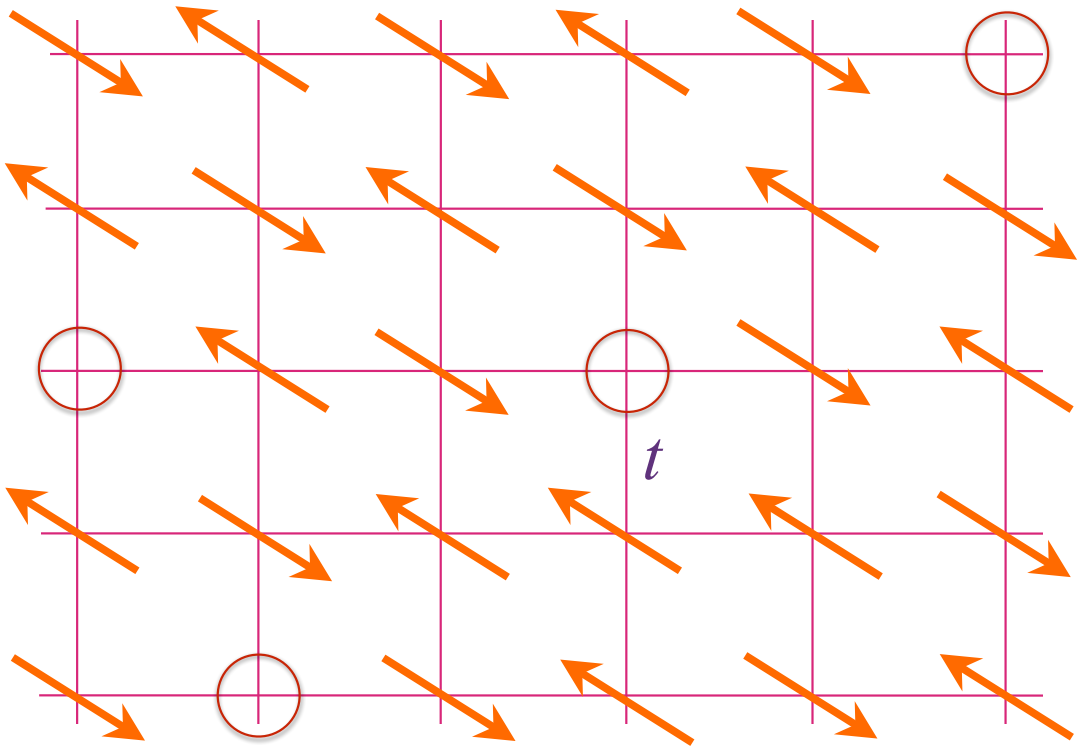

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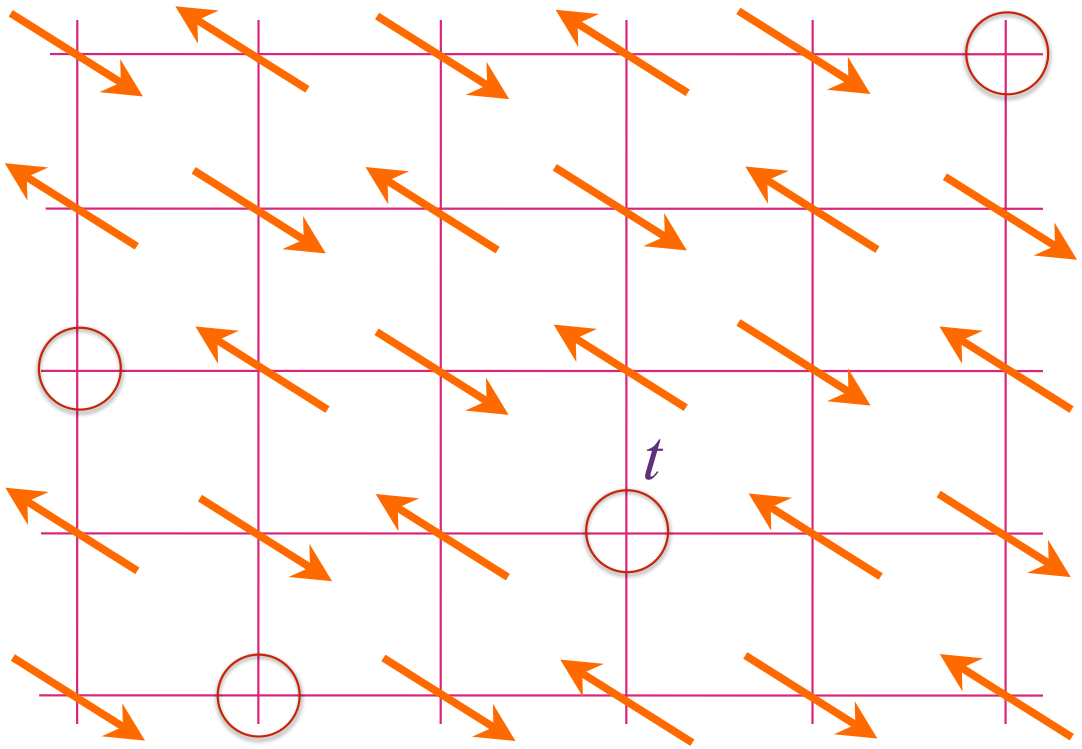
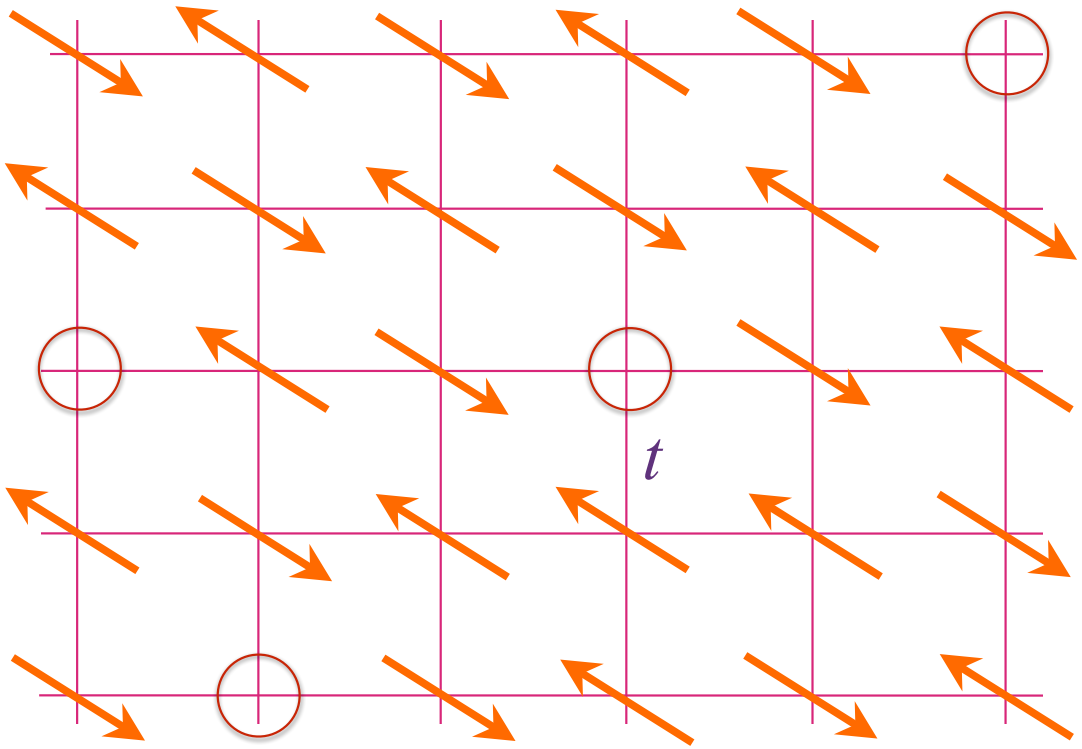
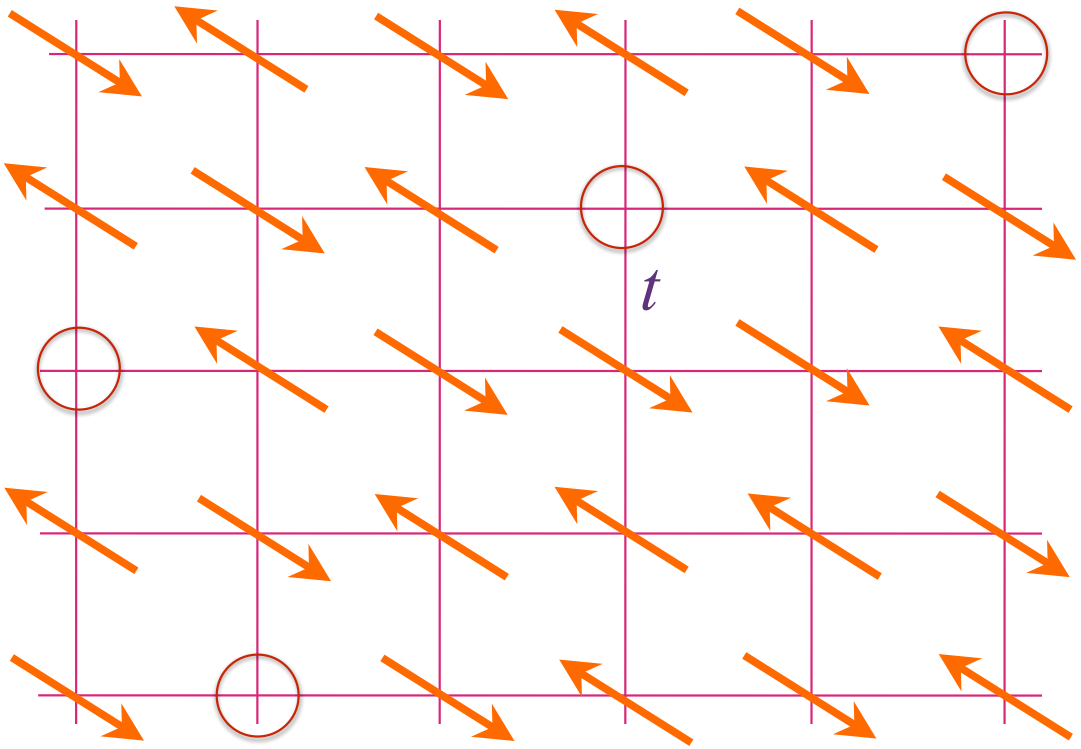


Antiferromagnet doped with hole density p



p mobile holes in a background of fluctuating spins

Antiferromagnet doped with hole density p



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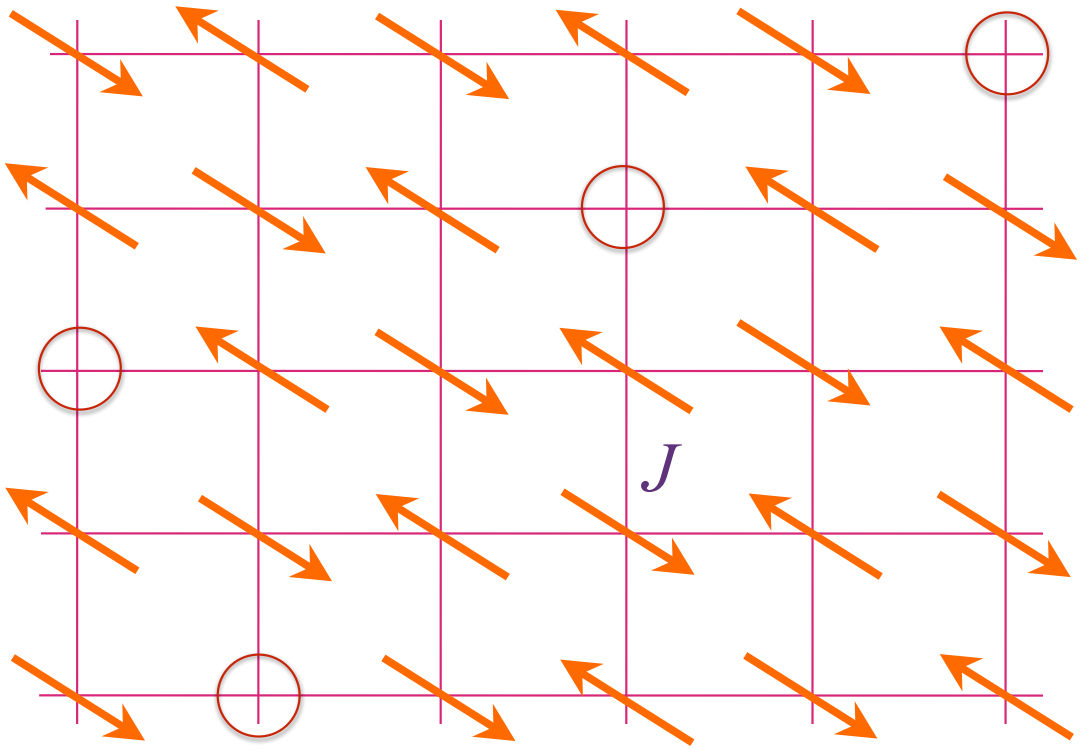

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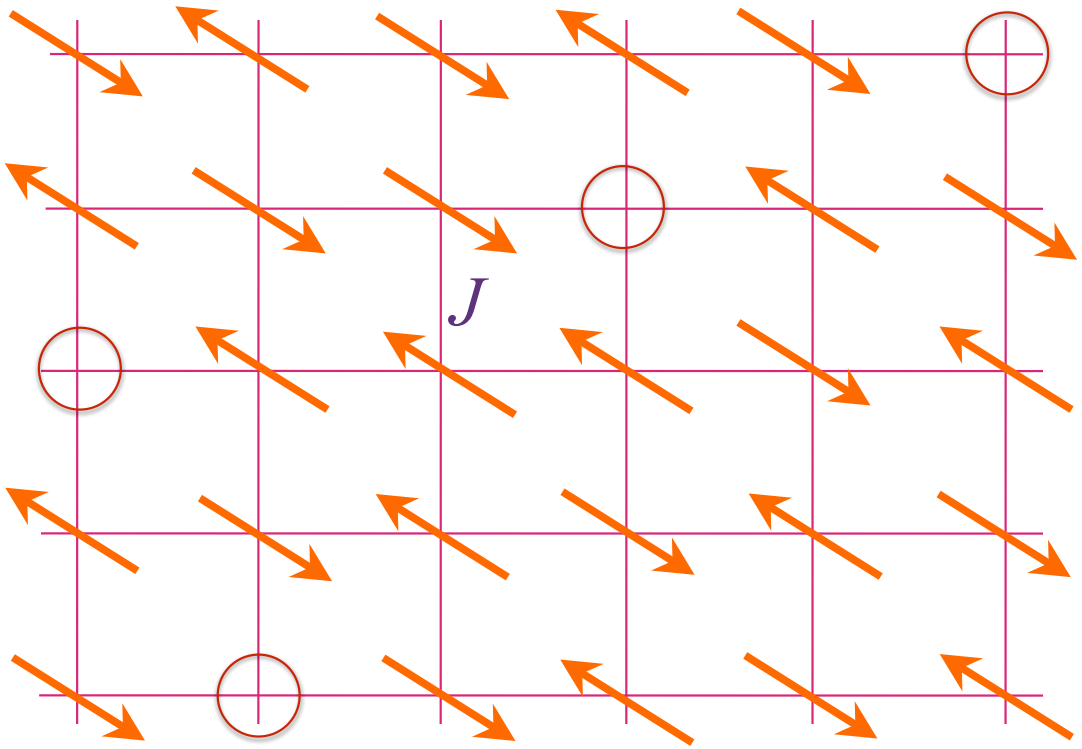
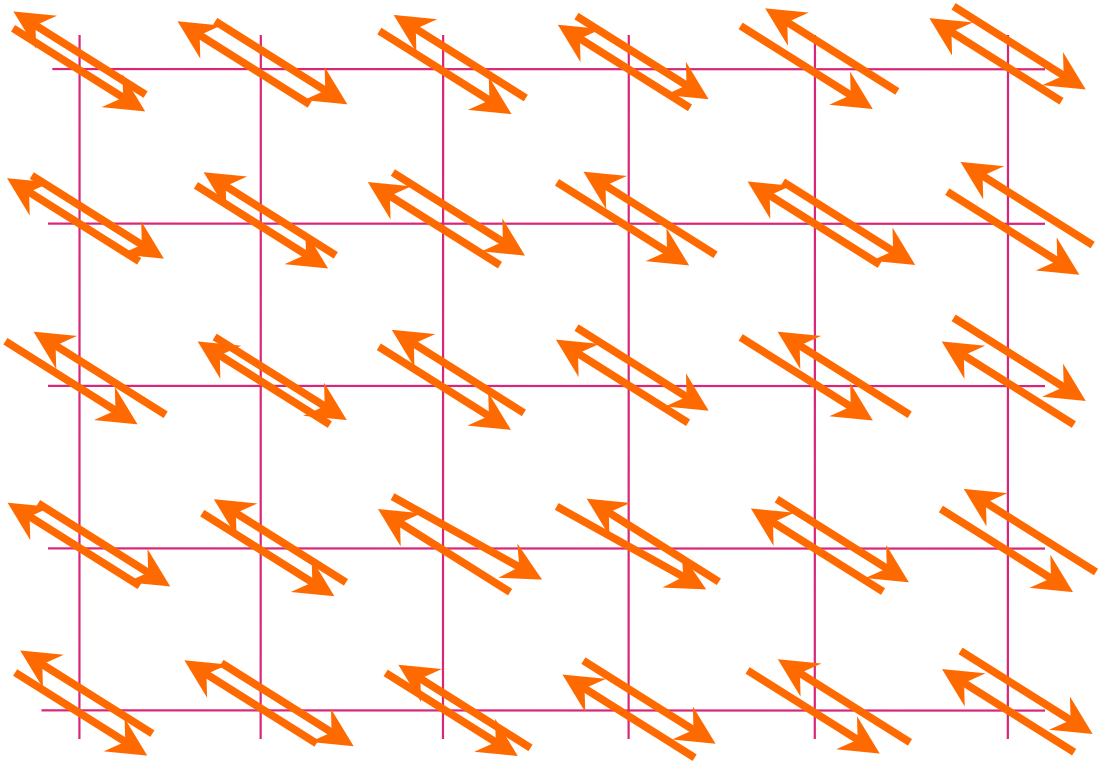


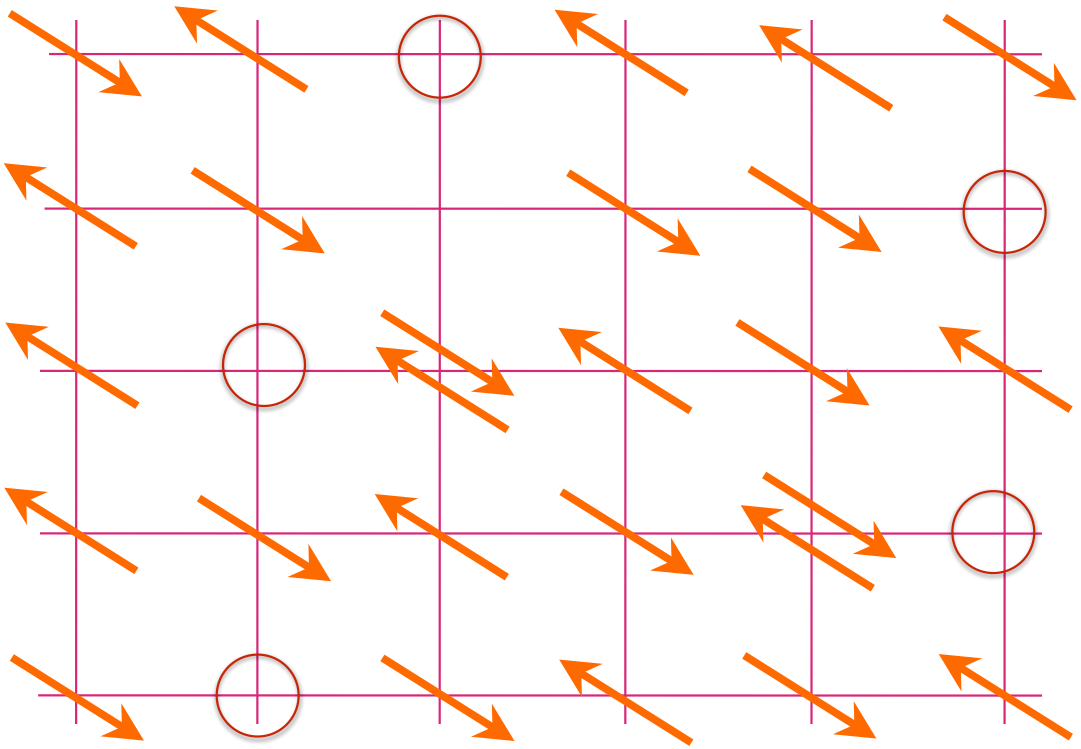
p mobile holes in a background of fluctuating spins

Momentum-space view at large p



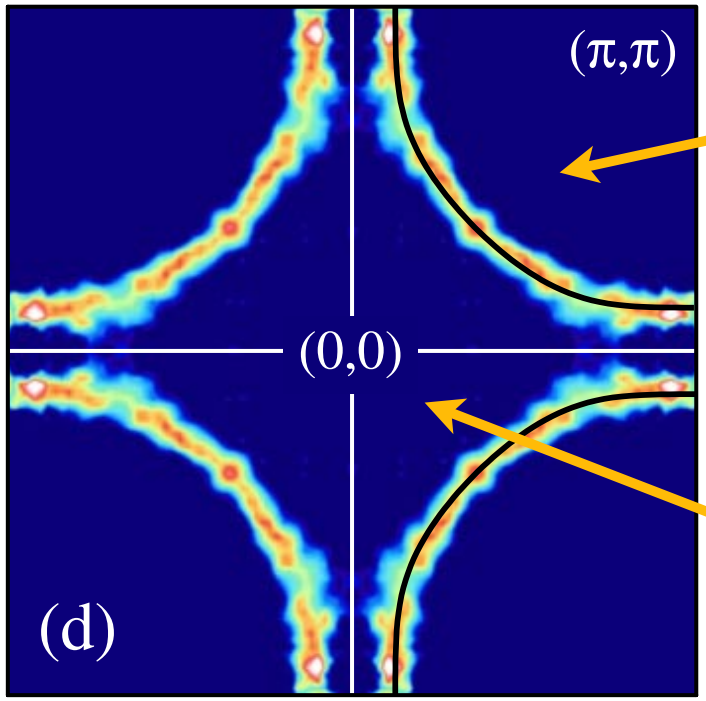
Filled Band

Momentum-space view at large p



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

Momentum-space view at large p



$1+p$ holes

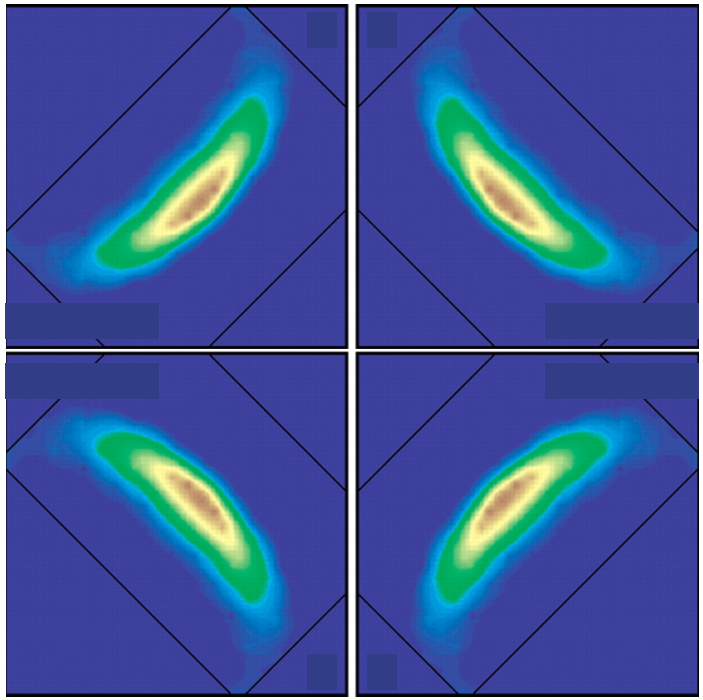
$1-p$ electrons

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

$1+p$ 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 $x = 0.10$

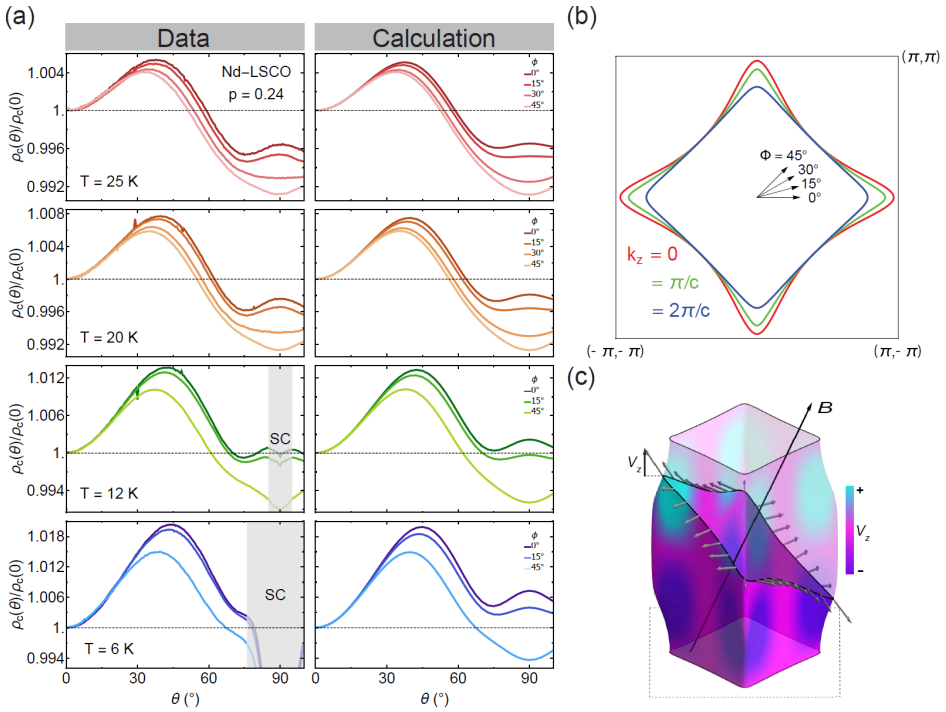
"Fermi arcs"

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)

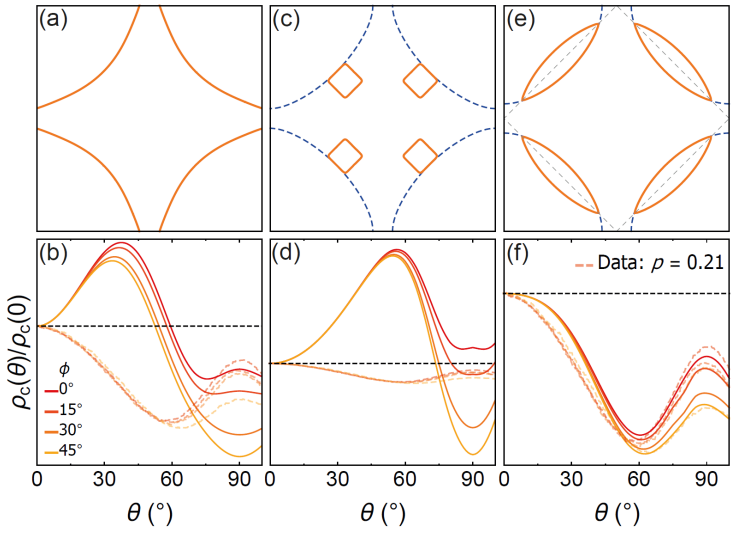
Fermi surface transformation at the pseudogap critical point of a cuprate superconductor

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

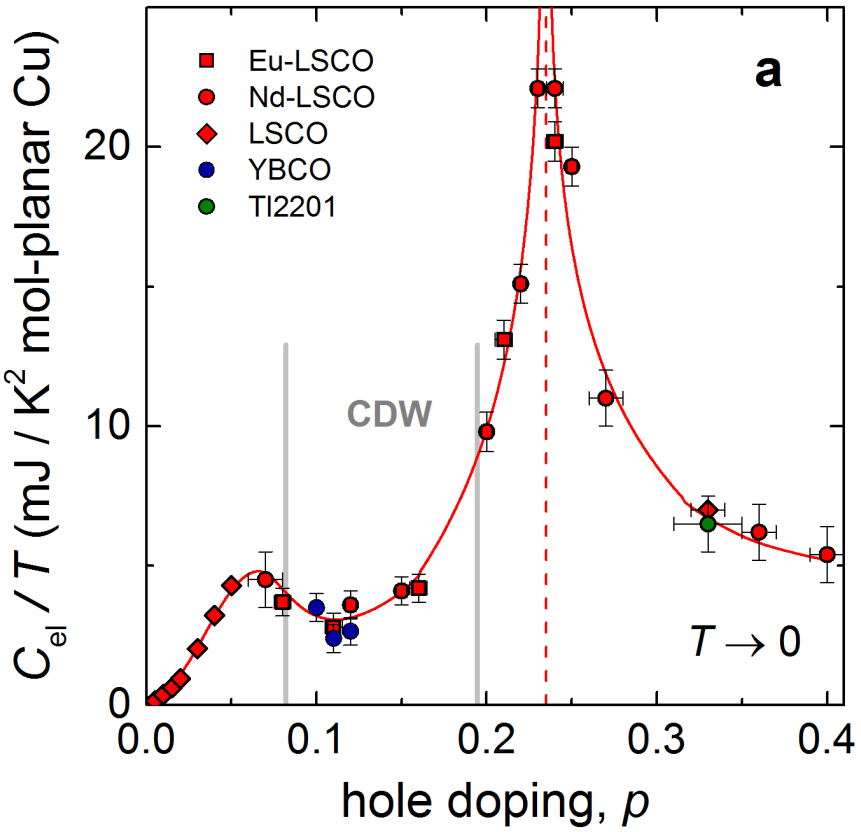


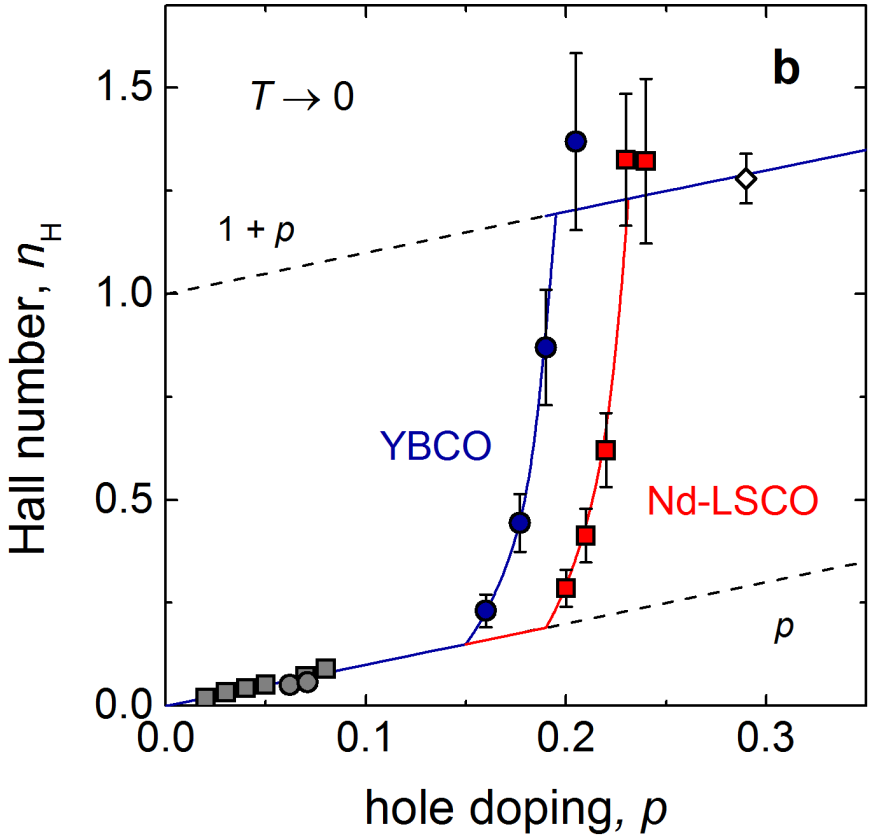
$p < p_c$ Reconstructed Fermi surface

Hole doped cuprates

The remarkable underlying ground states of cuprate superconductors

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

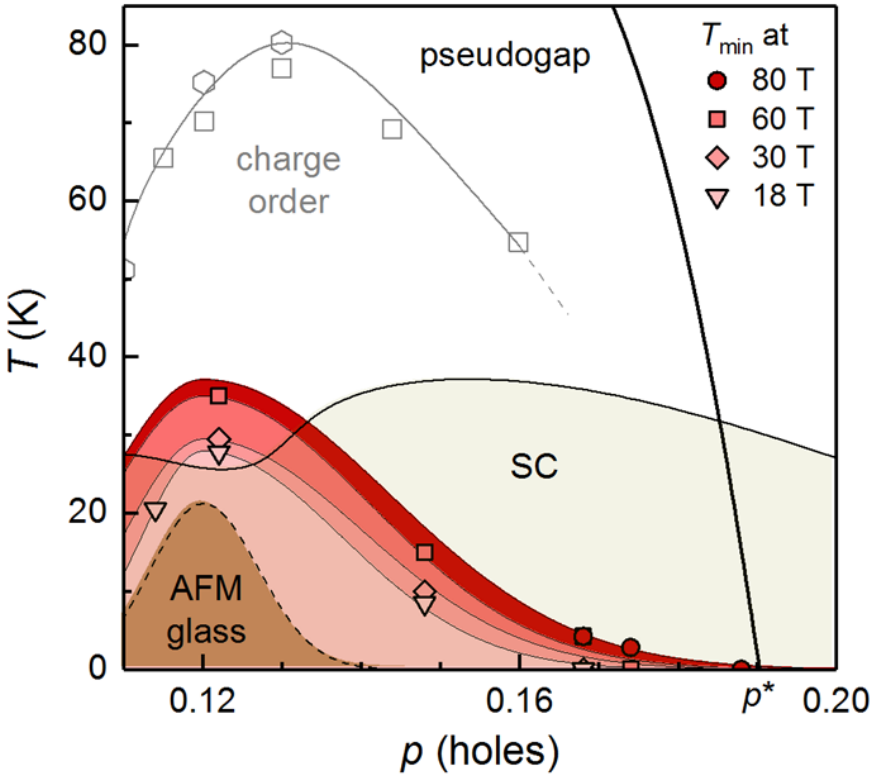




Hidden magnetism at the pseudogap critical point of a high temperature superconductor

Nature Physics **16**, 1064 (2020)

Mehdi Frachet[1]†, Igor Vinograd[1]†, Rui Zhou[1,2], Siham Benhabib[1], Shangfei Wu[1], Hadrien Mayaffre[1], Steffen Krämer[1], Sanath K. Ramakrishna[3], Arneil P. Reyes[3], Jérôme Debray[4], Tohru Kurosawa[5], Naoki Momono[6], Migaku Oda[5], Seiki Komiya[7], Shimpei Ono[7], Masafumi Horio[8], Johan Chang[8], Cyril Proust[1], David LeBoeuf[1*], Marc-Henri Julien[1*]



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

Temperature – doping phase diagram representing T_{min}, the temperature of the minimum in the sound velocity, at different fields. Since superconductivity precludes the observation of T_{min} in zero-field, the dashed line (brown area) represents the extrapolated $T_{min}(B=0)$. While not exactly equal to the freezing temperature T_f (see Fig. 2), T_{min} is closely tied to T_f 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. FL*-FL transition: ancilla qubits and ghost Fermi surfaces*

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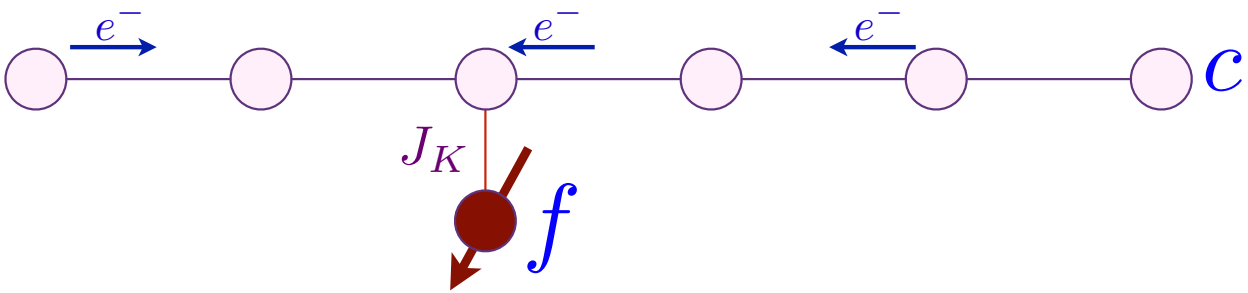
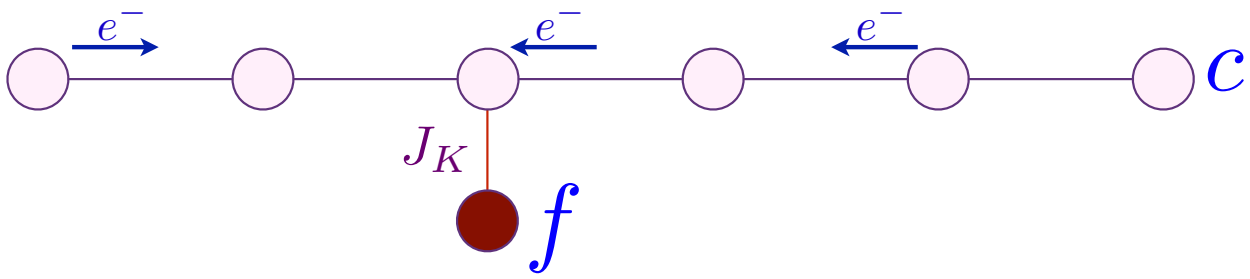
Kondo model

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



Kondo model

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

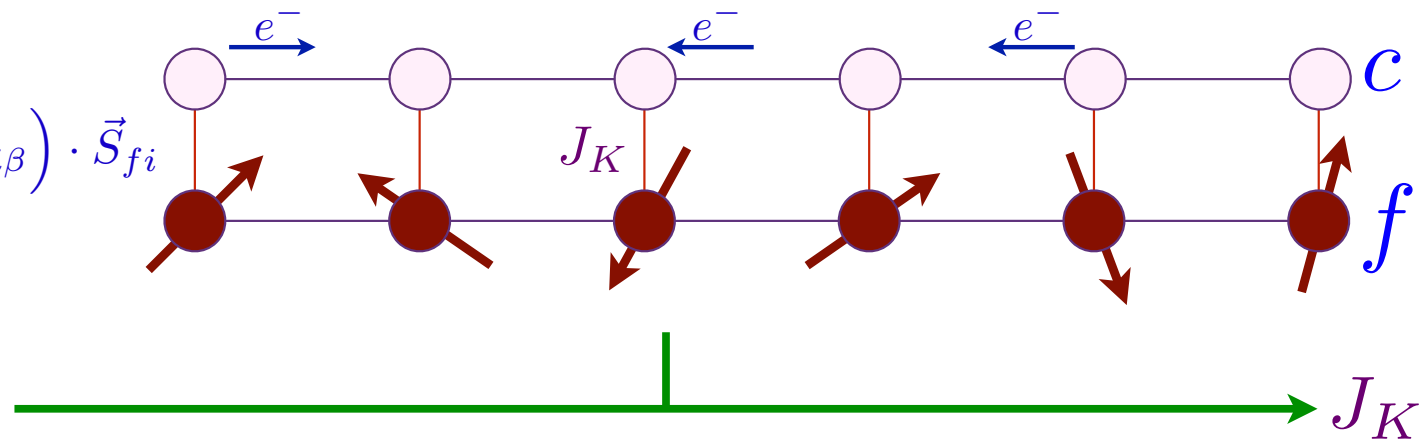


The c electrons 'Kondo screen' the f spin at low energies:
The f electron 'dissolves' into the Fermi sea.

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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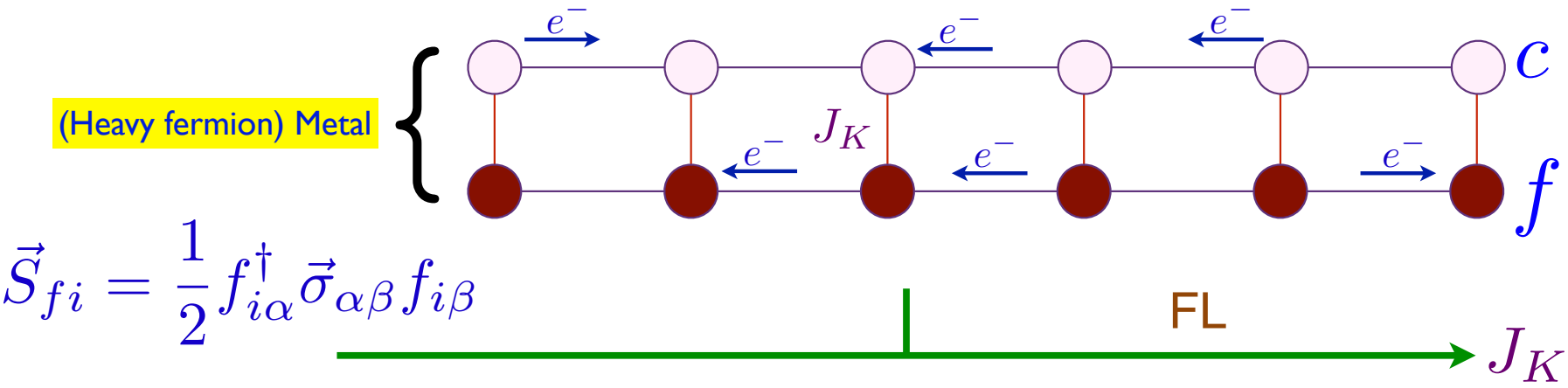

The c electrons 'Kondo screen' the f spins in the FL phase:
The f electrons 'dissolve' into the Fermi sea.

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

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

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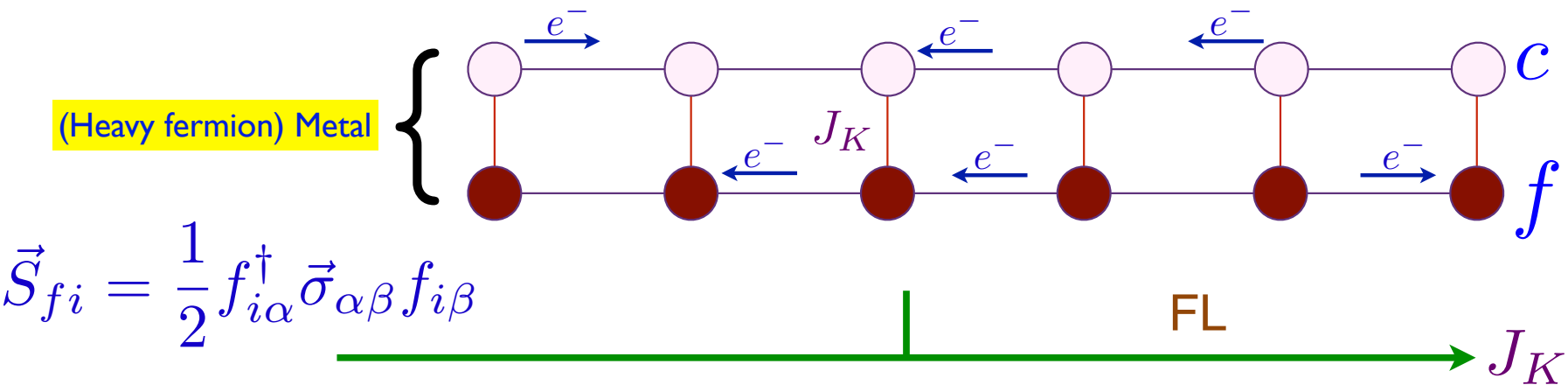

The c electrons 'Kondo screen' the f spins in the FL phase:
The f electrons 'dissolve' into the Fermi sea.
The Fermi surface is large: encloses volume of $1 + p$ electrons.

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

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

Kondo lattice of f electron spins coupled
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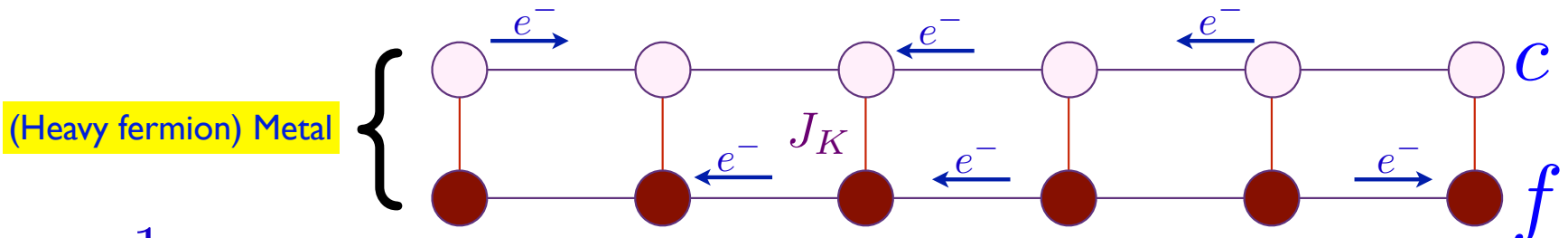

$$\vec{S}_{fi} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

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

The 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.

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

Kondo lattice of f electron spins coupled
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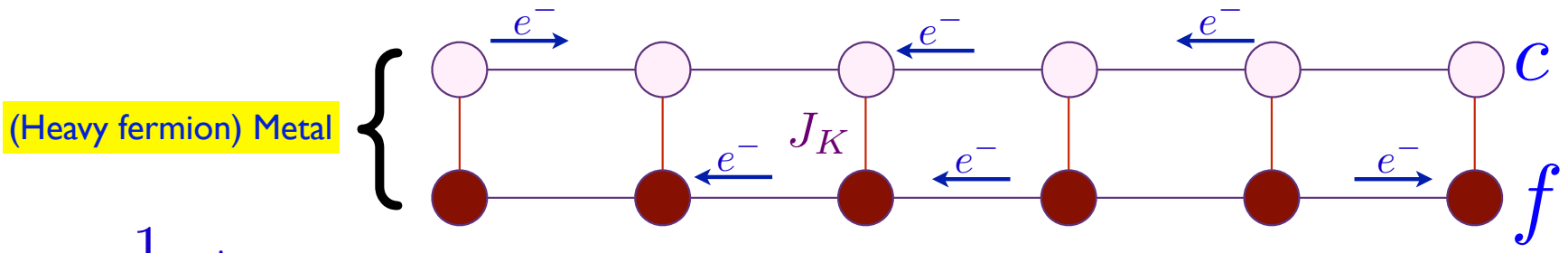

$$\vec{S}_{fi} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

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

Large Fermi surface of size $1 + p$

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

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

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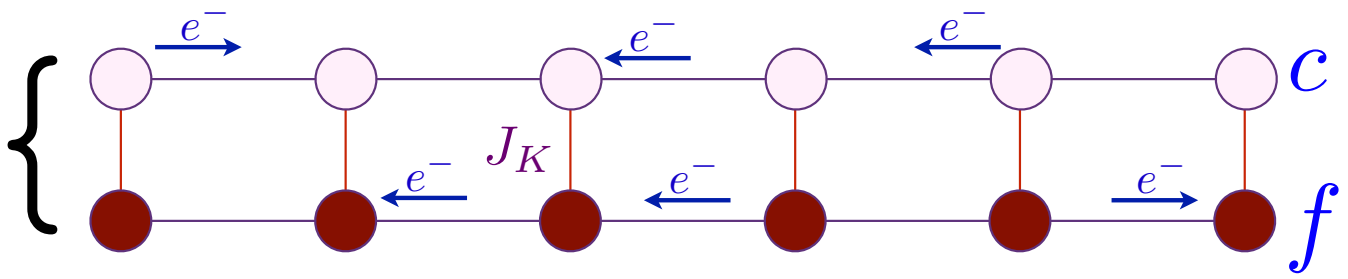

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Luttinger Theorem obeyed

Large Fermi surface of size $1 + p$

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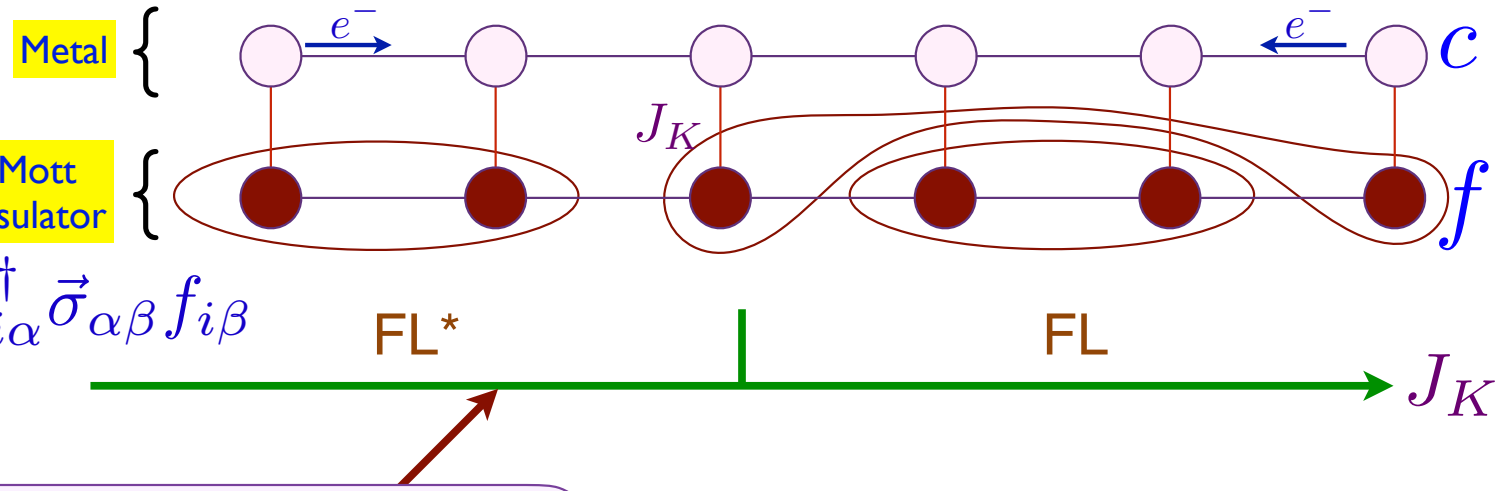

$$\vec{S}_{fi} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$

Small Fermi surface of size p

$|\Phi\rangle = |\text{Spin liquid insulator of } f\rangle$
$\otimes\, |\text{Slater determinant of } c\rangle$

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

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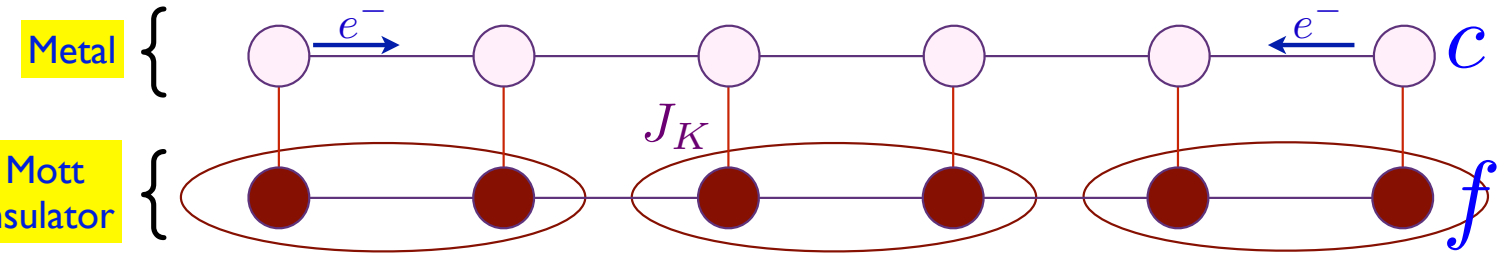

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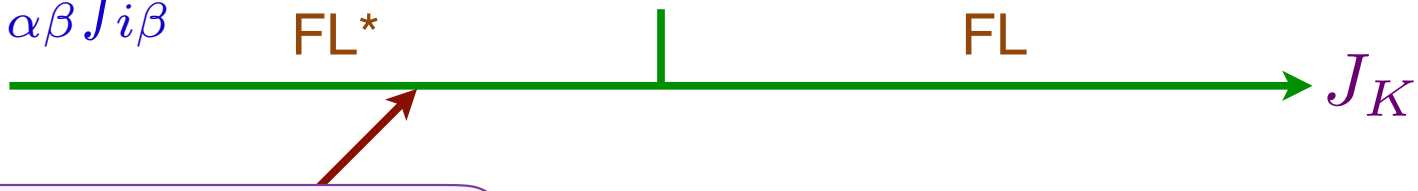

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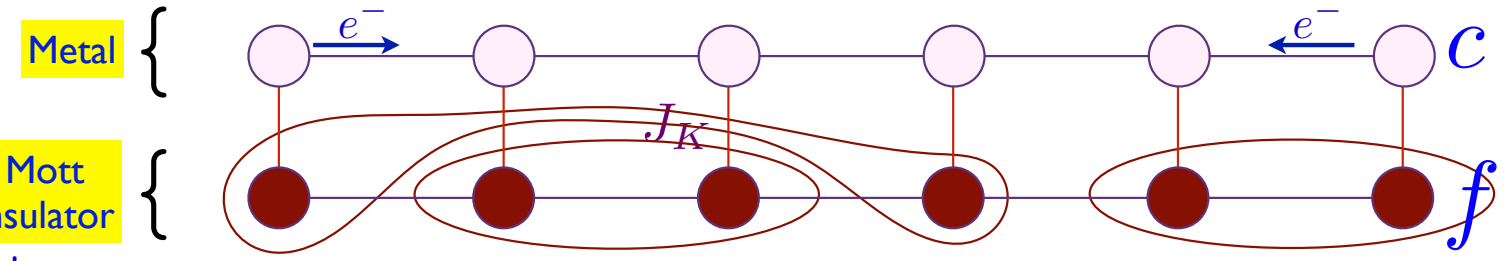
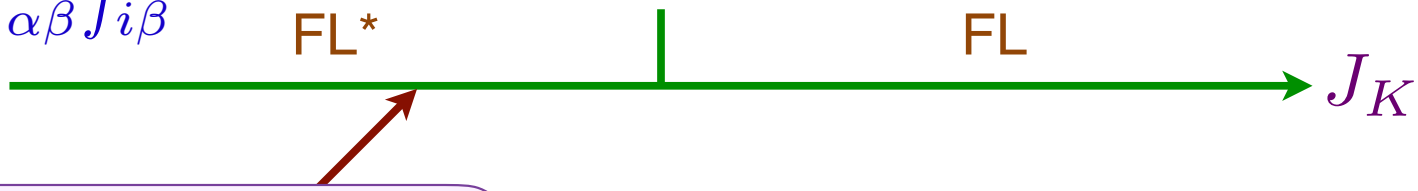


$$\vec{S}_{fi} = \frac{1}{2} f^\dagger_{i\alpha} \vec{\sigma}_{\alpha\beta} f_{i\beta}$$



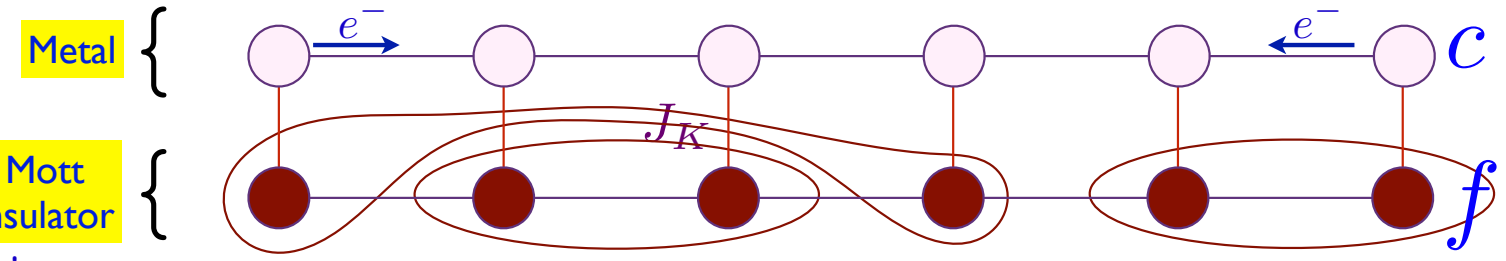
Small Fermi surface of size p

$|\Phi\rangle = |\text{Spin liquid insulator of } f\rangle$
$\otimes\, |\text{Slater determinant of } c\rangle$

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

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

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



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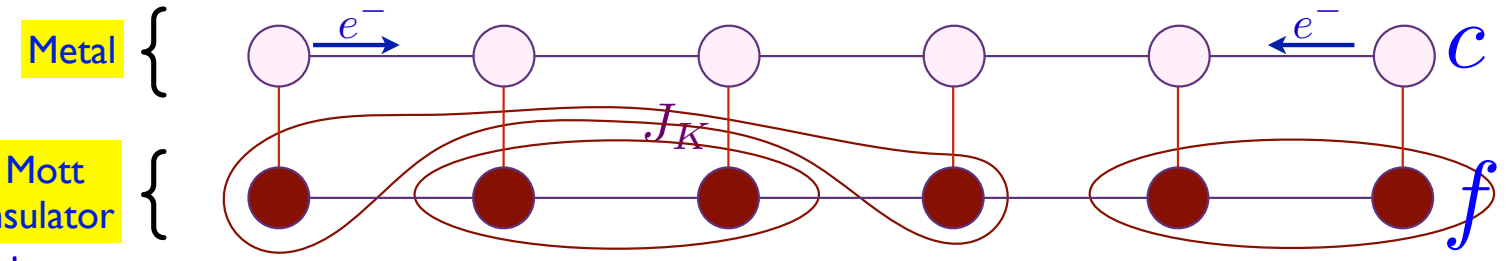
V.I. Anisimov, I.A. Nekrasov,
D.E. Kondakov, T.M. Rice & M. Sigrist,
EPJB **25**, 191 (2002)
L. de' Medici, A. Georges, S. Biermann,
PRB **72**, 205124 (2005)

Kondo-breakdown or 'selective Mott' transition



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Kondo-breakdown or 'selective Mott' transition

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

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

Small Fermi surface of size p

$|\Phi\rangle = |\text{Spin liquid insulator of } f\rangle$
$\otimes\, |\text{Slater determinant of } c\rangle$

Large Fermi surface of size $1+p$

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

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

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

Kondo lattice of f electron spins coupled
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Kondo-breakdown or 'selective Mott' transition

Shortcomings:

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

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

Kondo lattice of f electron spins coupled
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Metal-metal transitions in ***Kondo lattice*** models

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- No natural extension to the case where the non-FL state has magnetic order.
- No simple extension to one-band model.

1. Metal-metal transition in the Kondo Lattice

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

1. Metal-metal transition in the Kondo Lattice

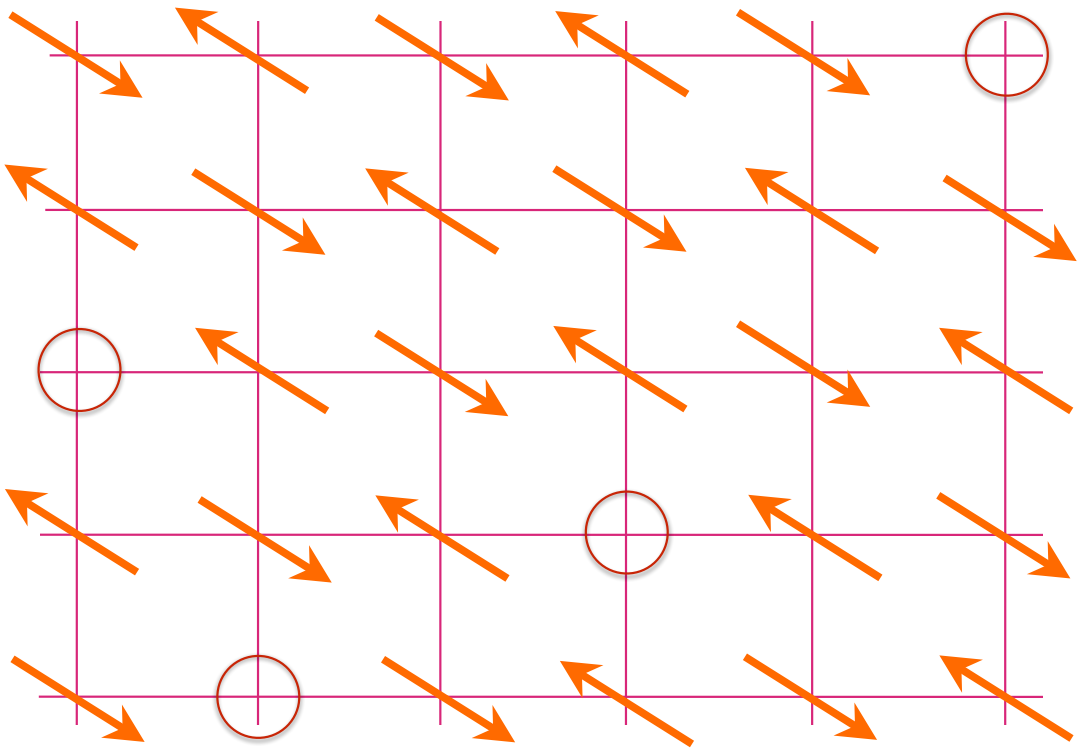
2. Metal-metal transition in a one-band model

   A. FL model of the pseudogap*

   B. FL-FL transition: ancilla qubits and ghost Fermi surfaces*

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

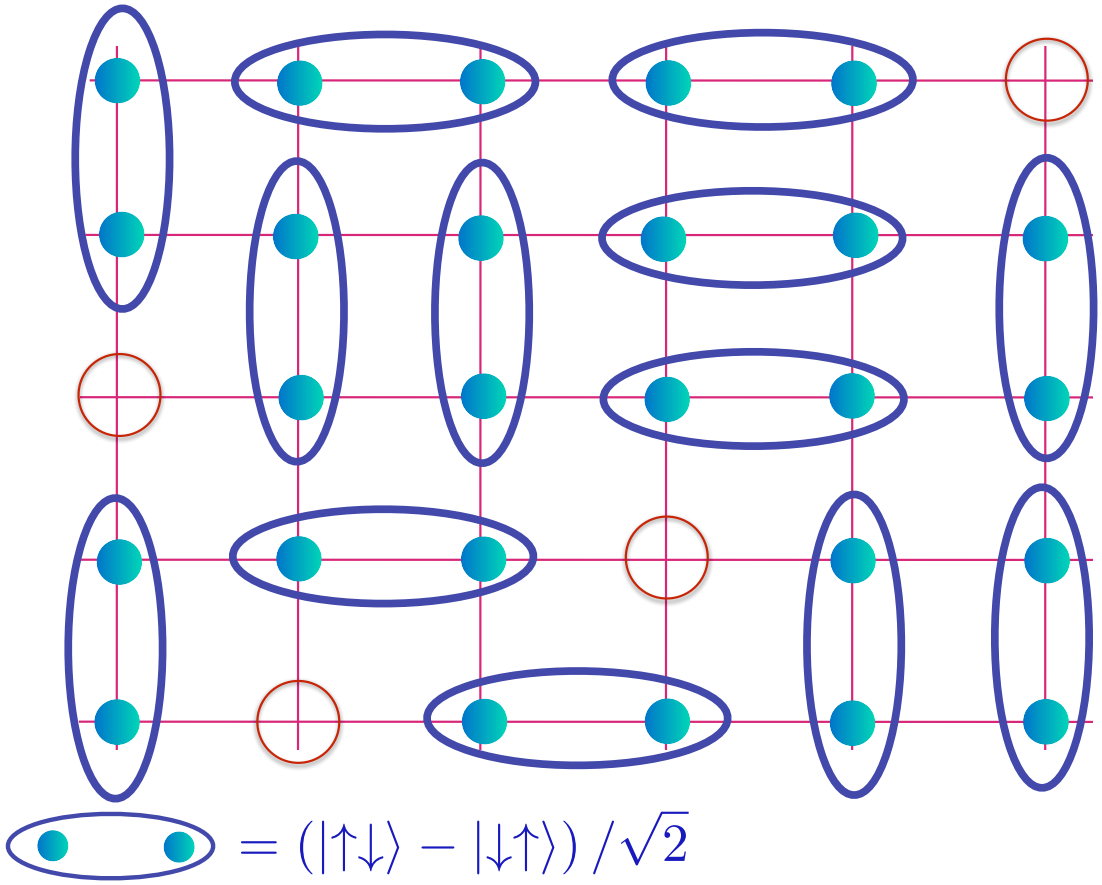
- Can realize the FL* state as a doped spin liquid in which spinons and holons bind to form 'electrons', which then form a small Fermi surface (X.-G. Wen and P. A. Lee, PRL **76**, 503 (1996)); but there is no complete description of this process, except in the very strong binding limit of dimer 'electrons'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



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

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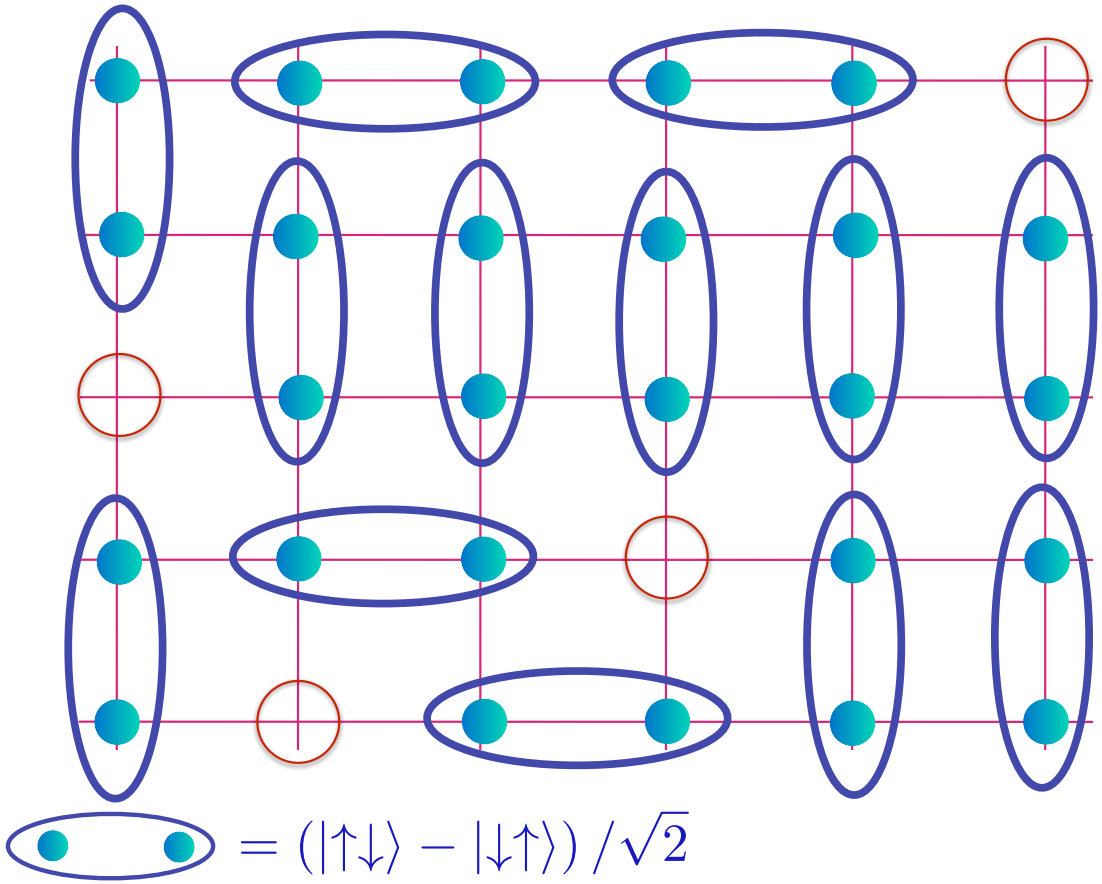

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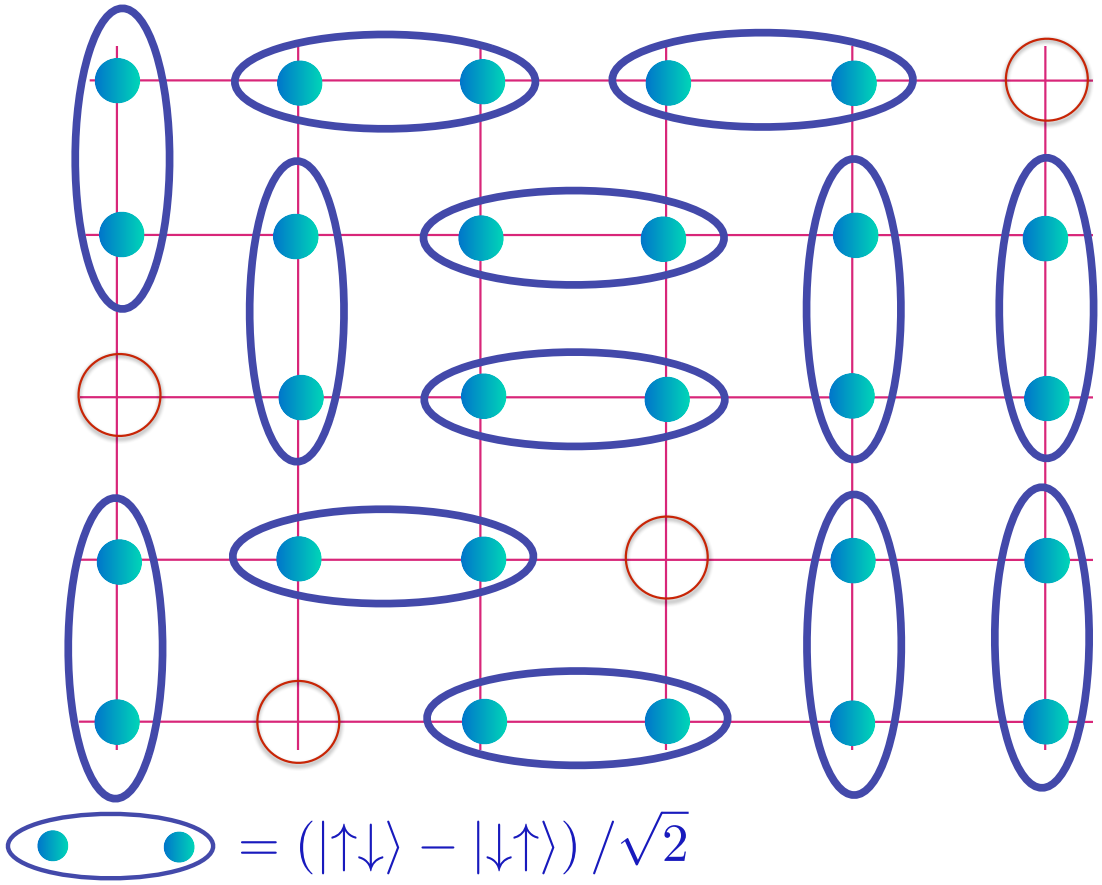

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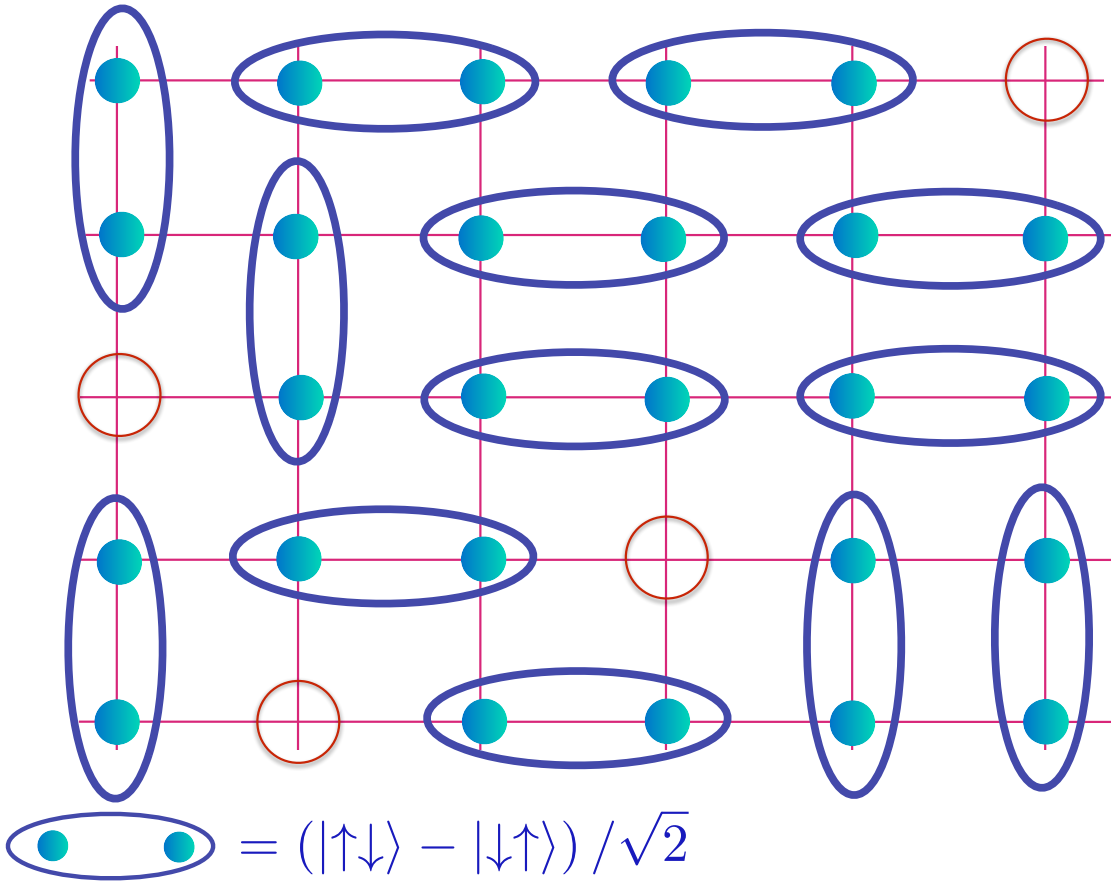

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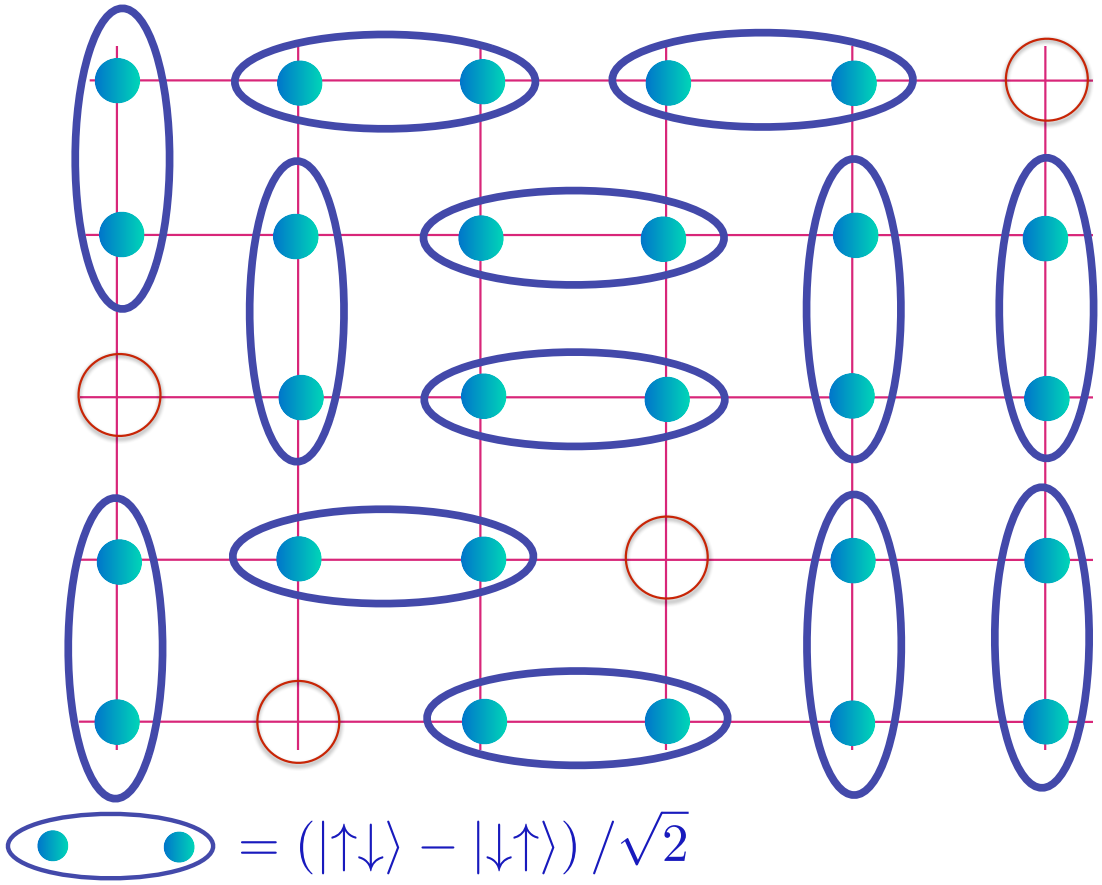

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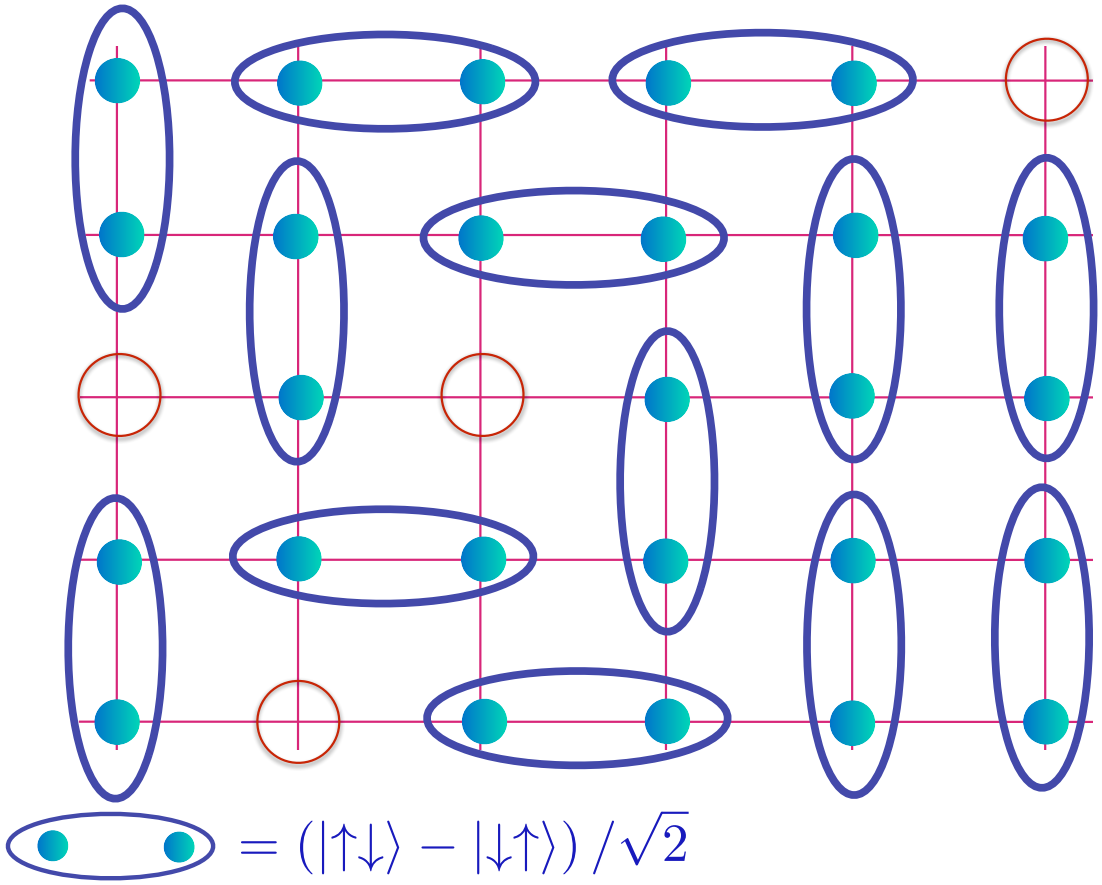

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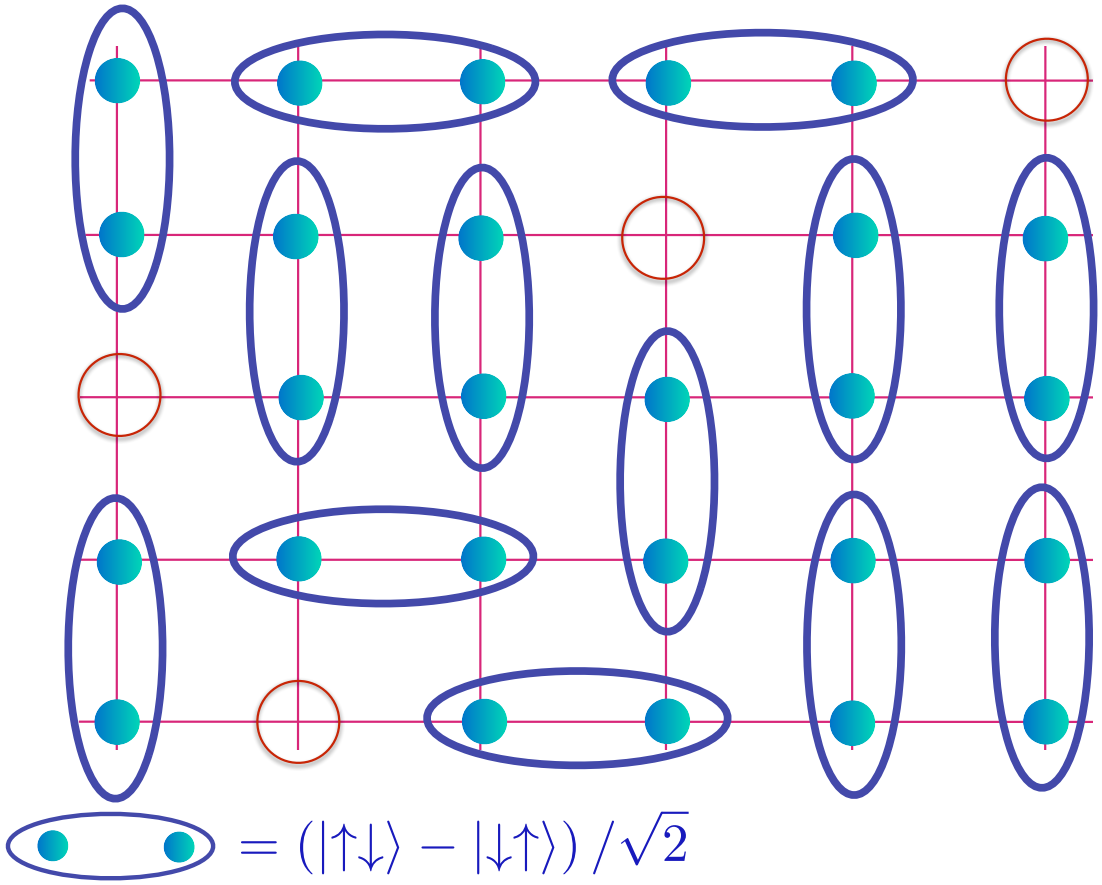

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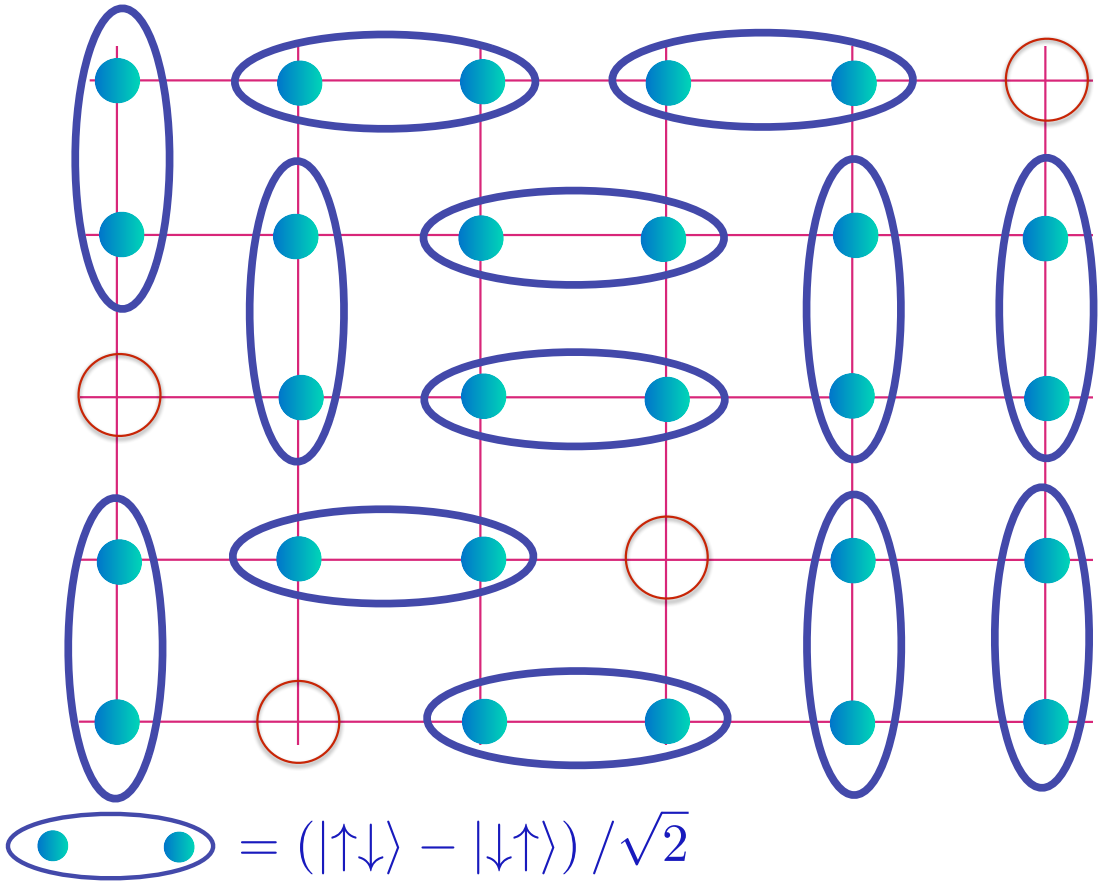

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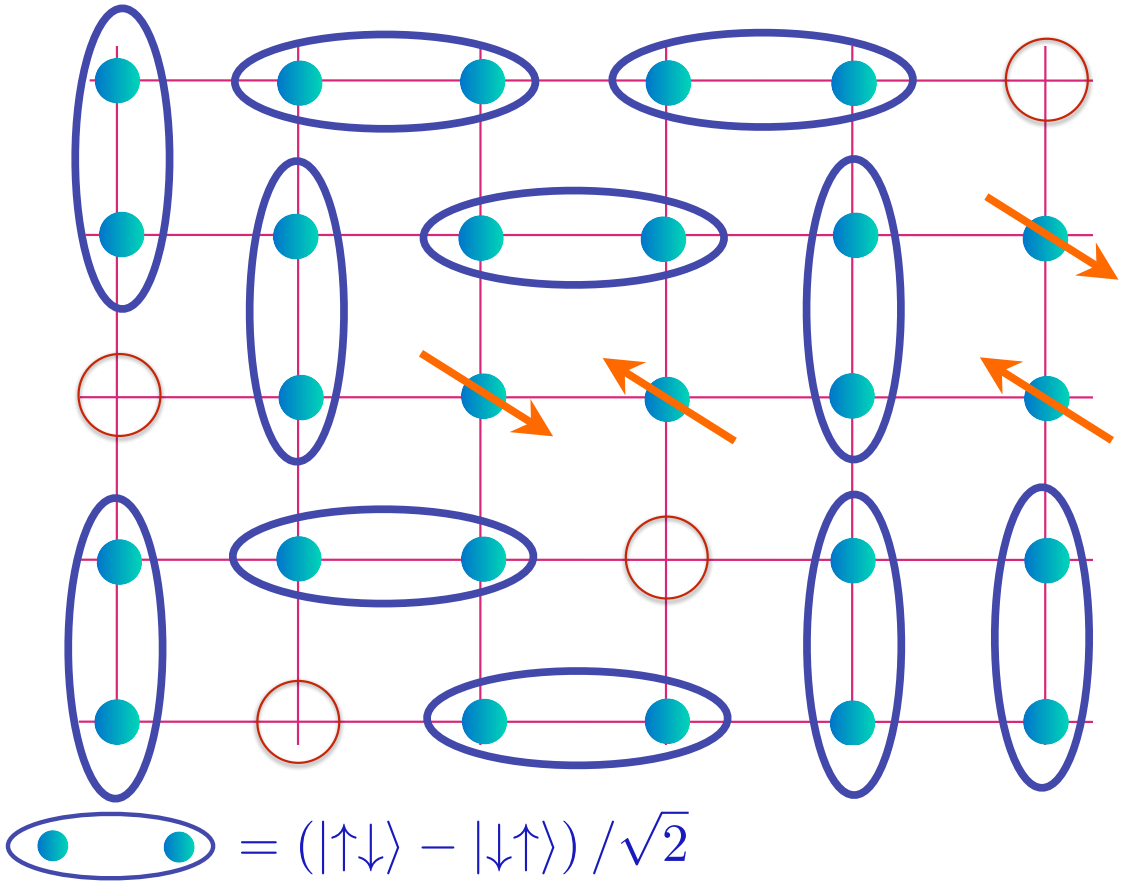

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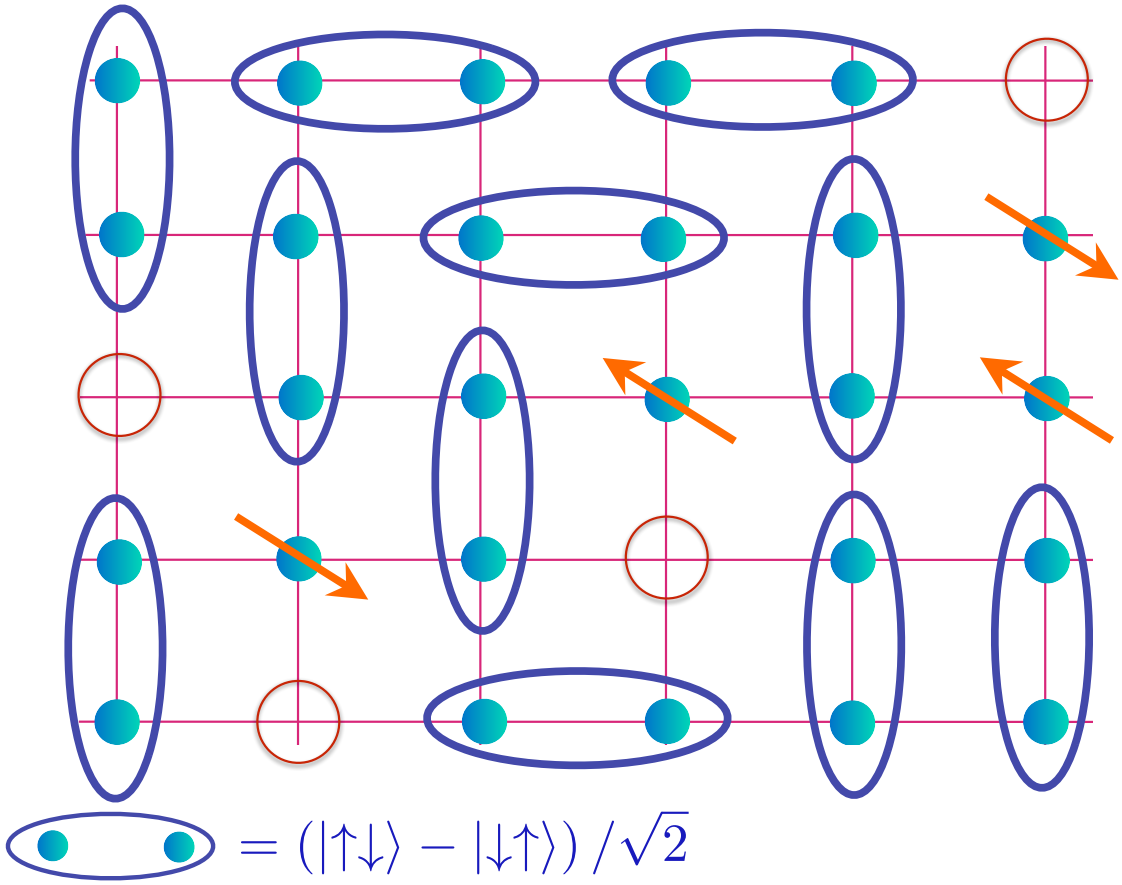

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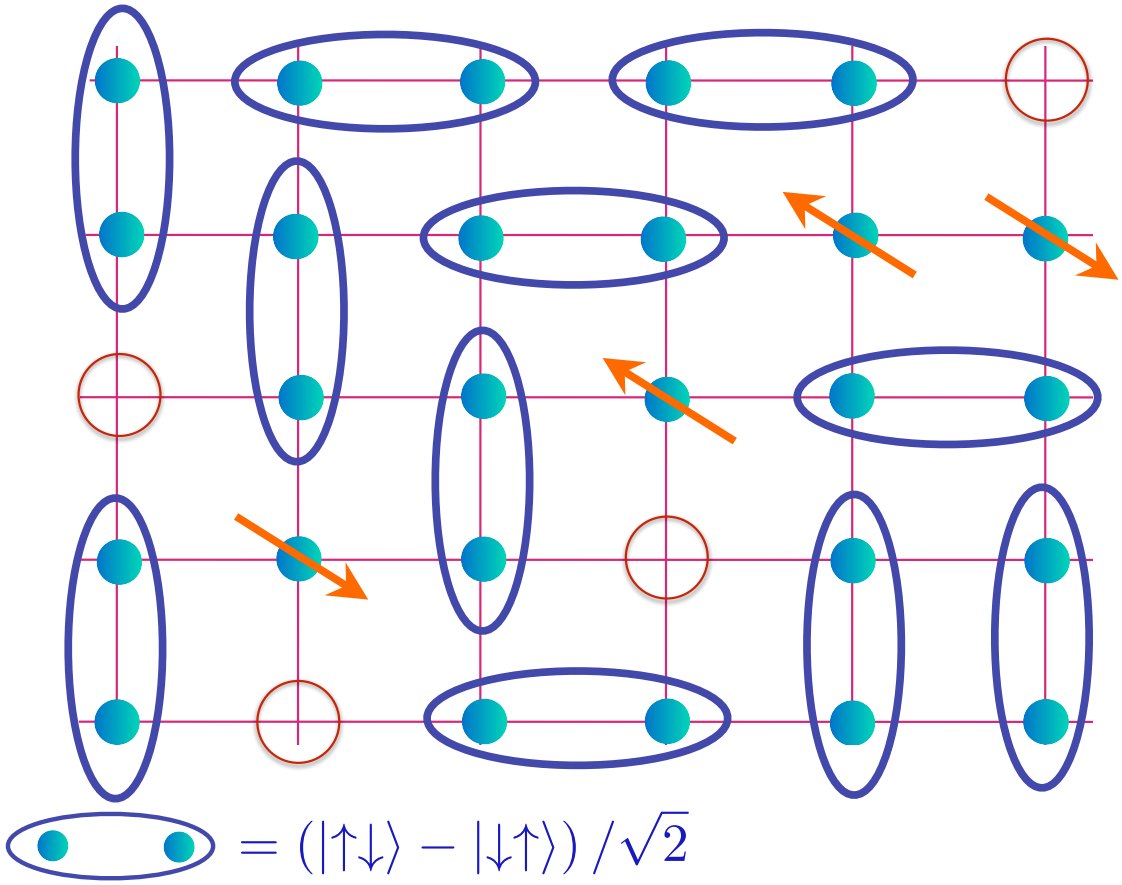

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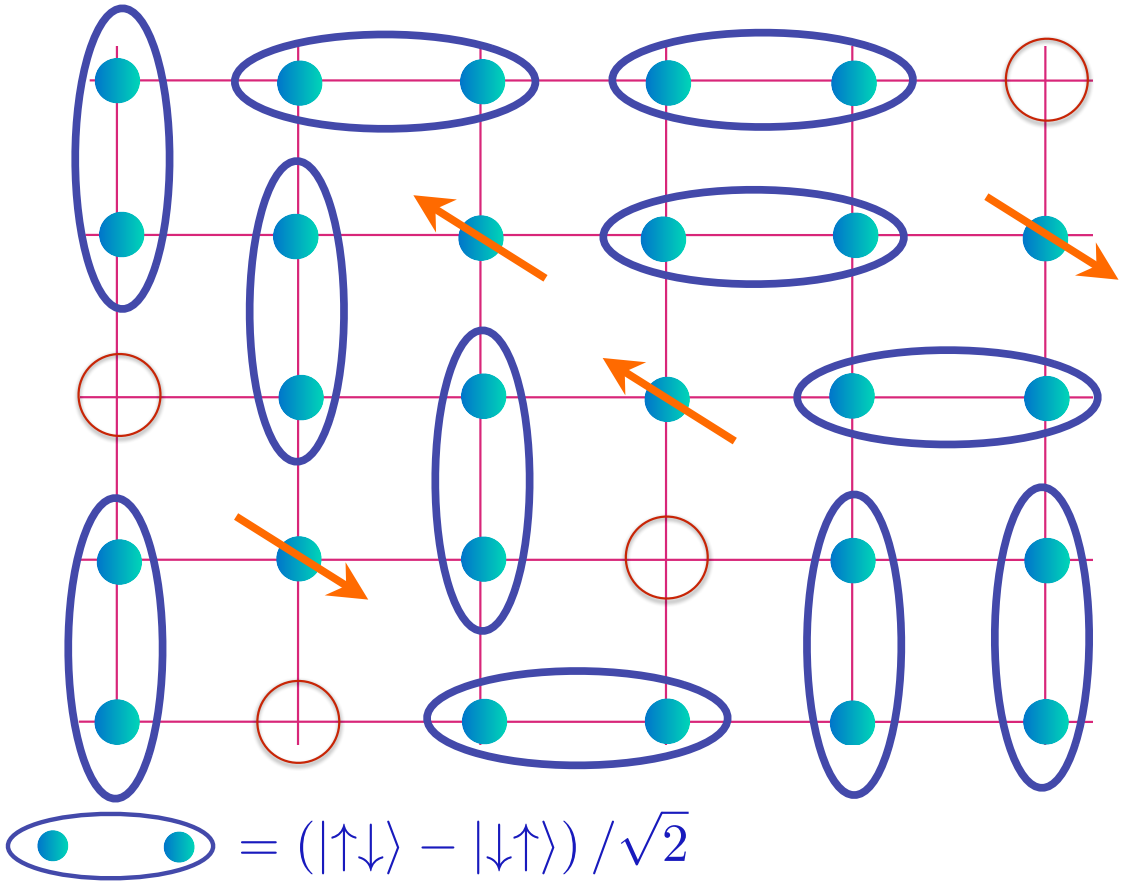

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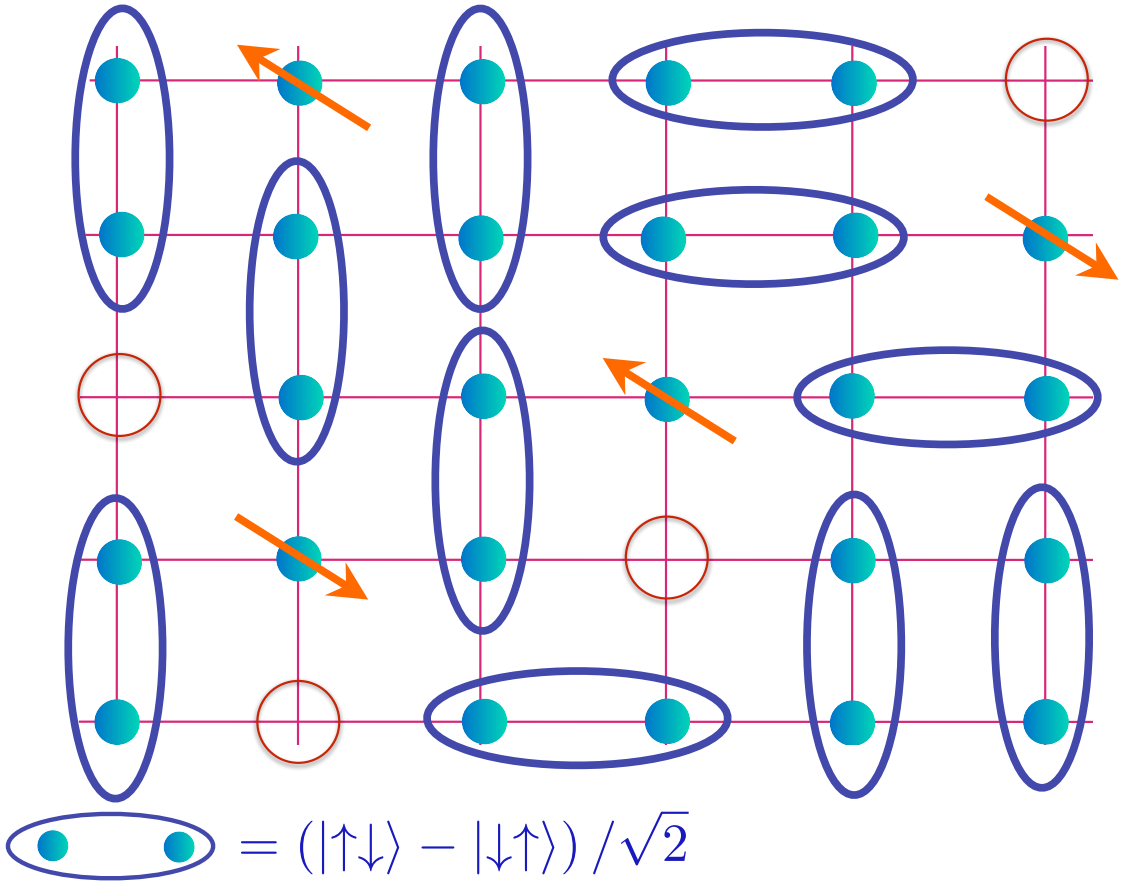

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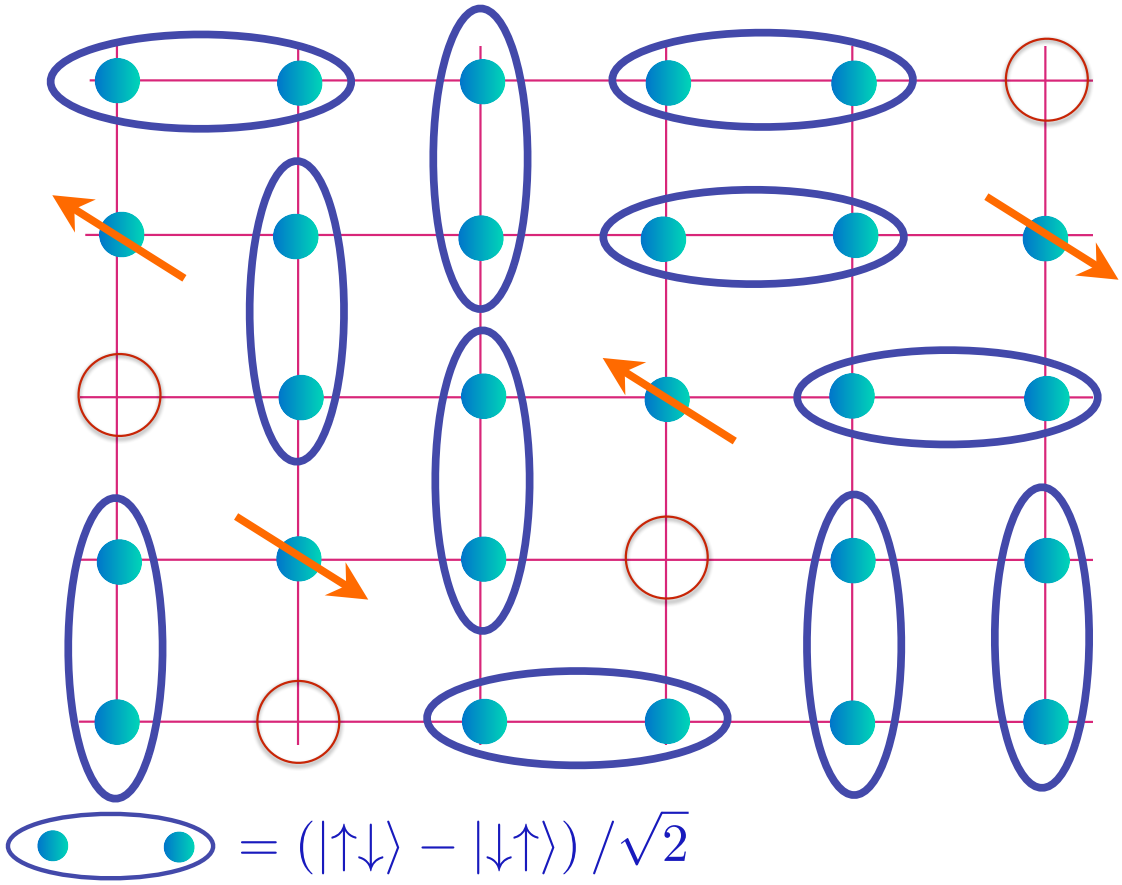

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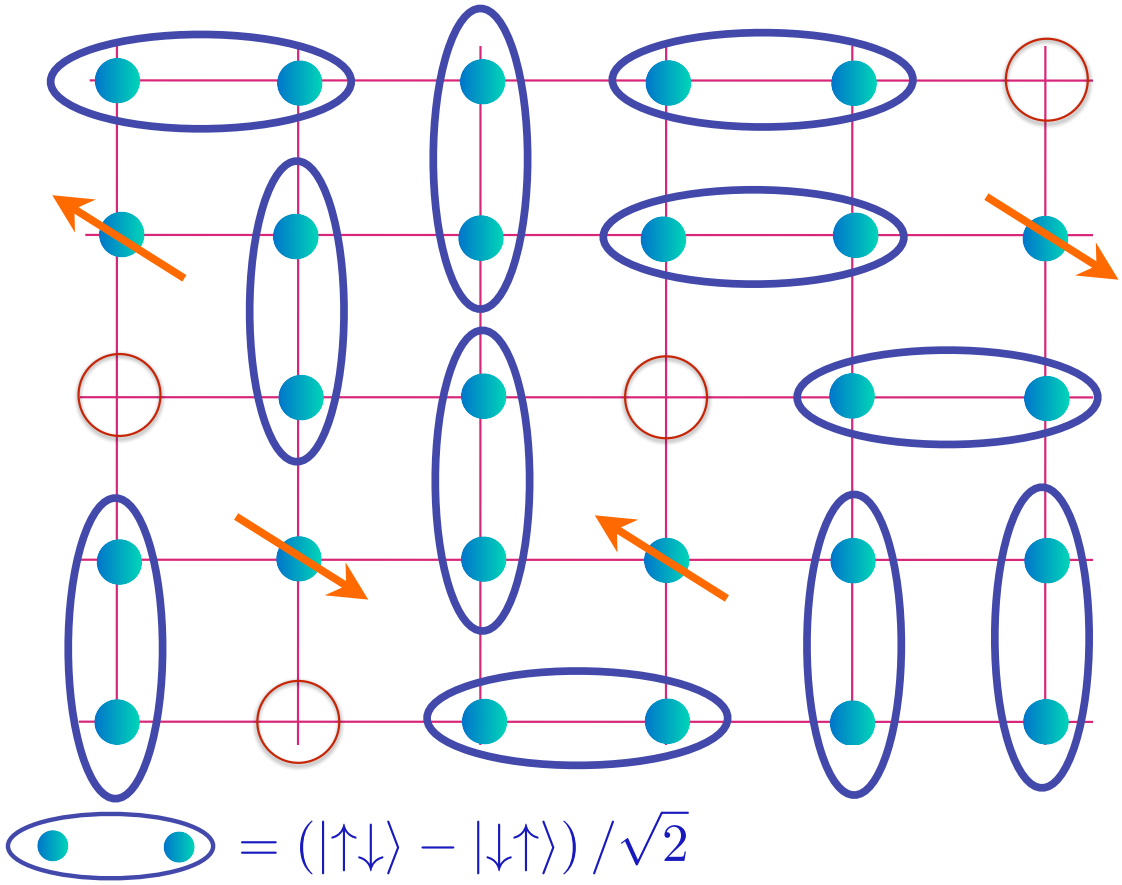

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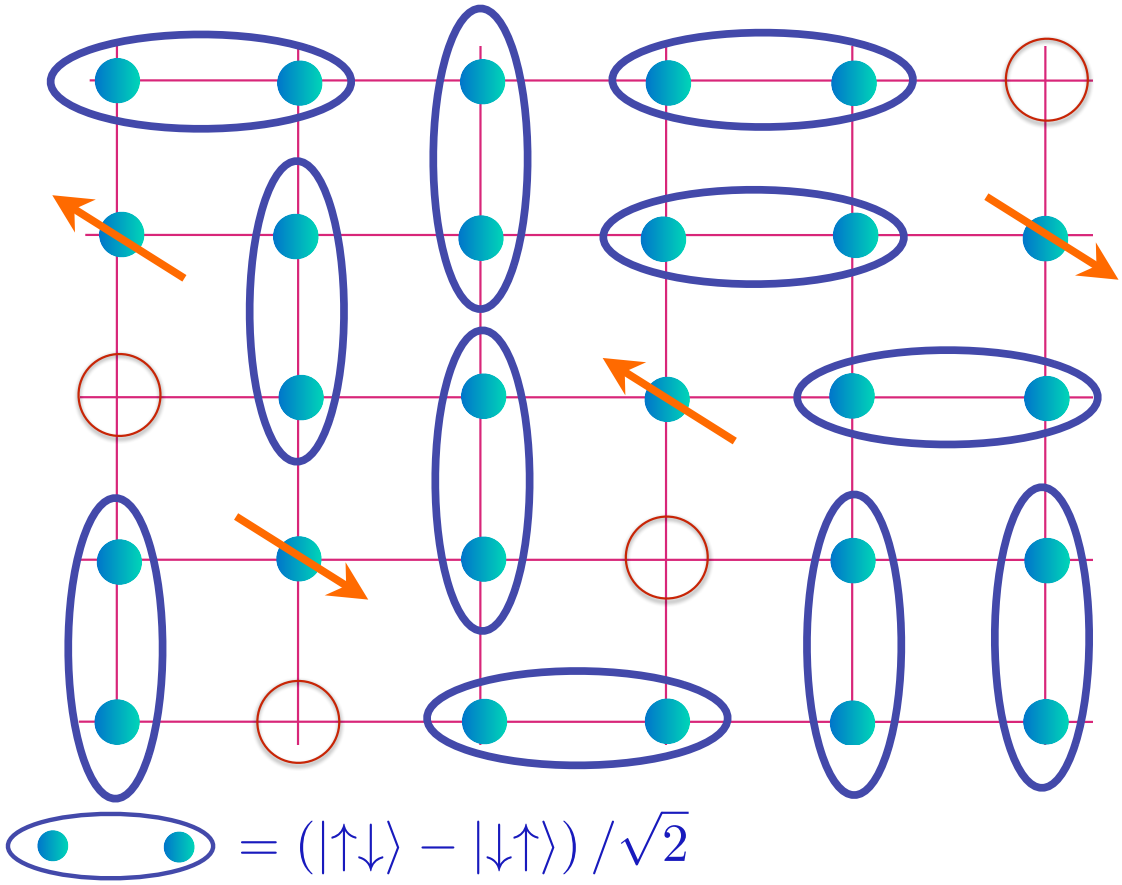

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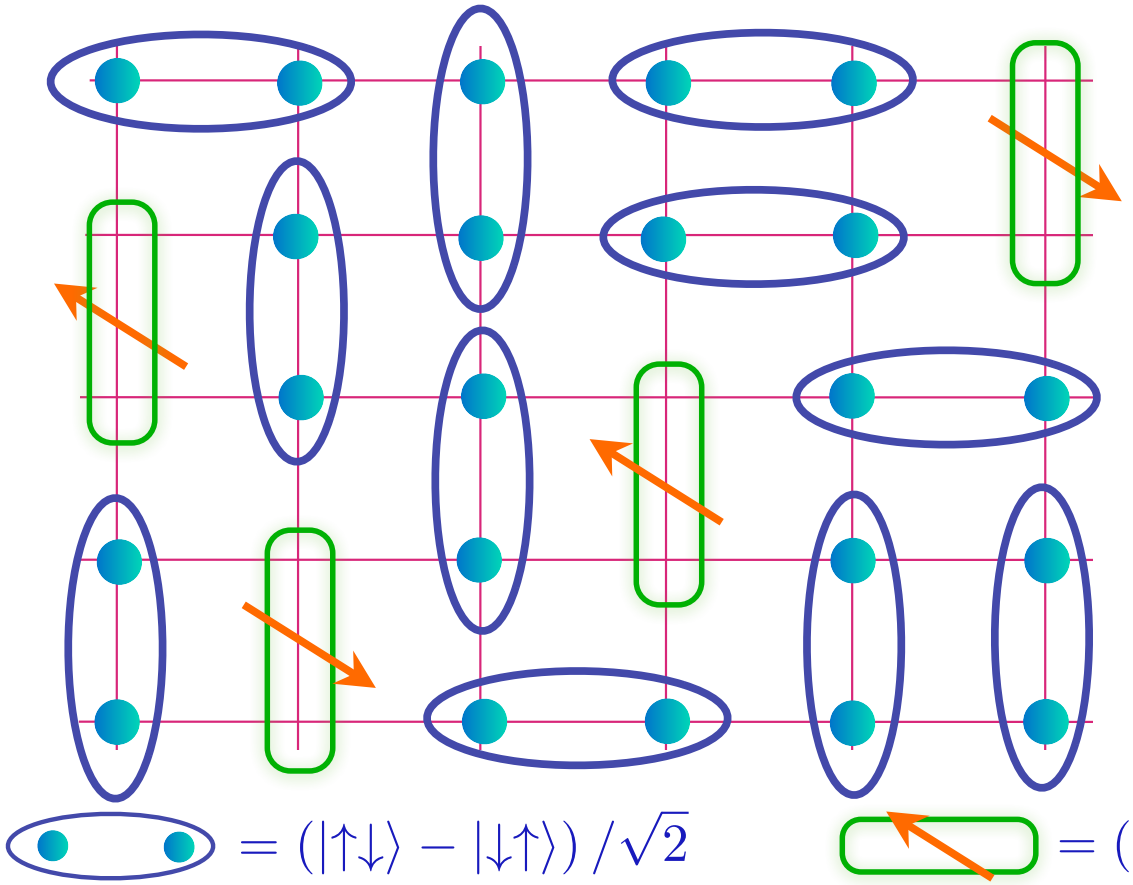

$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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

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

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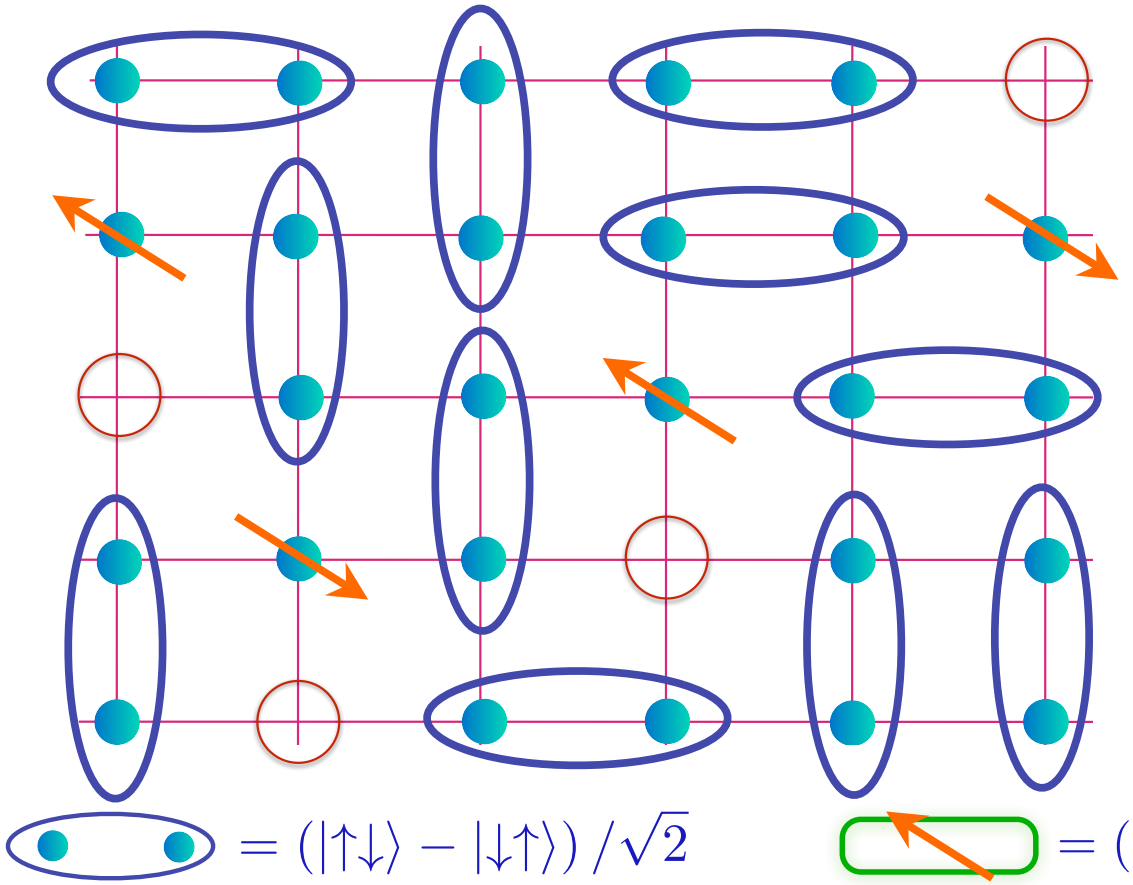

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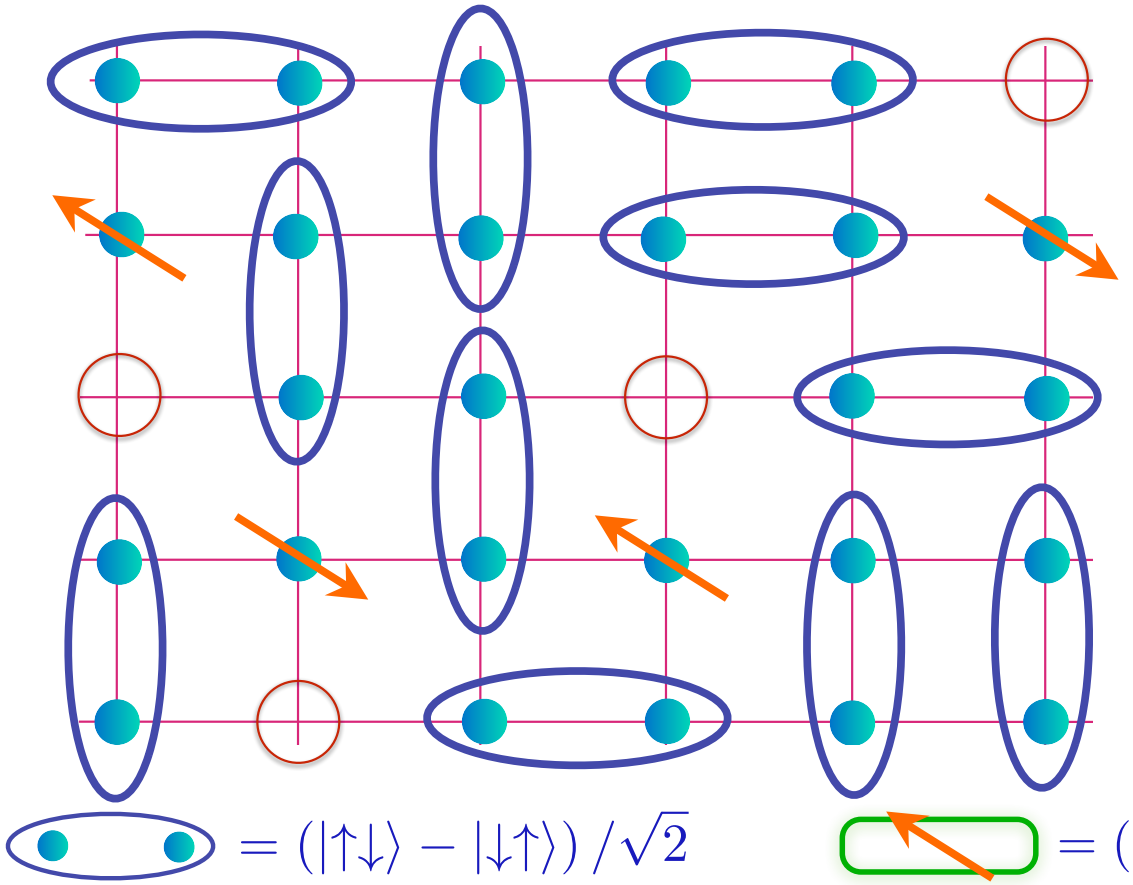

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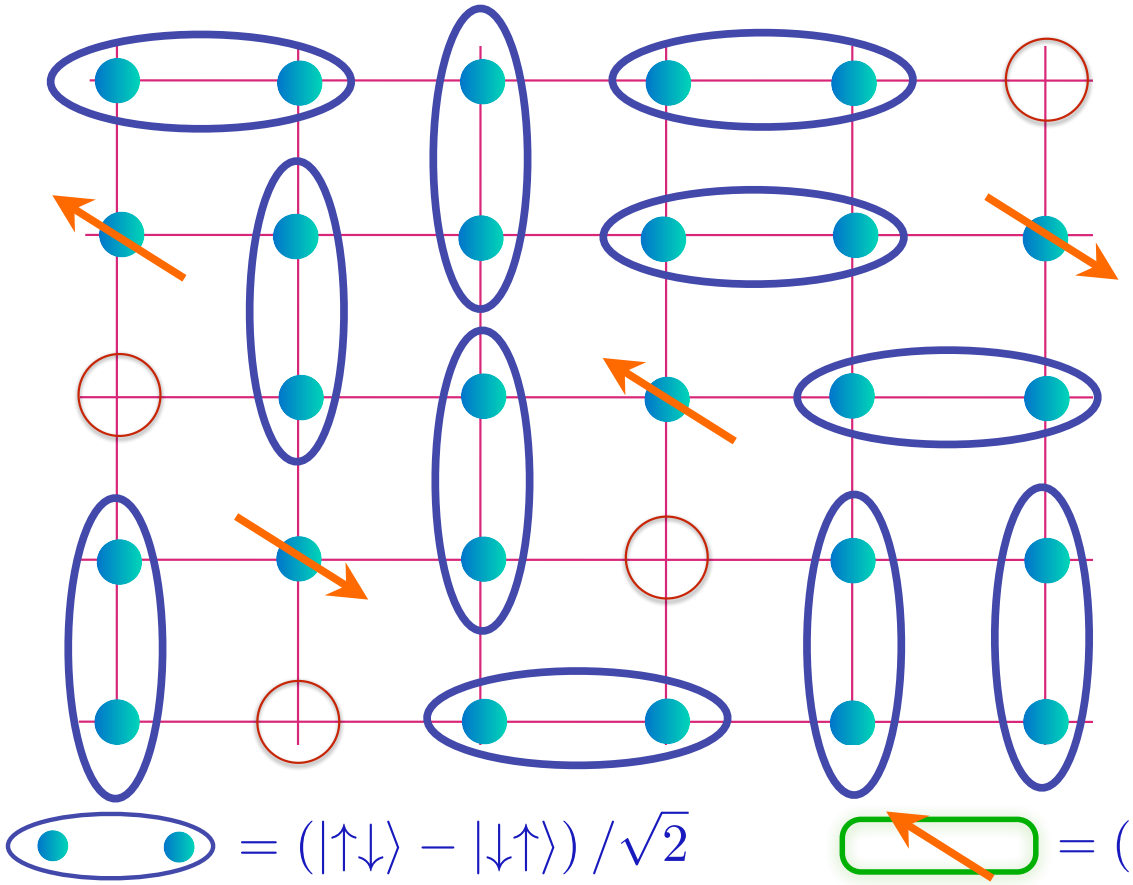

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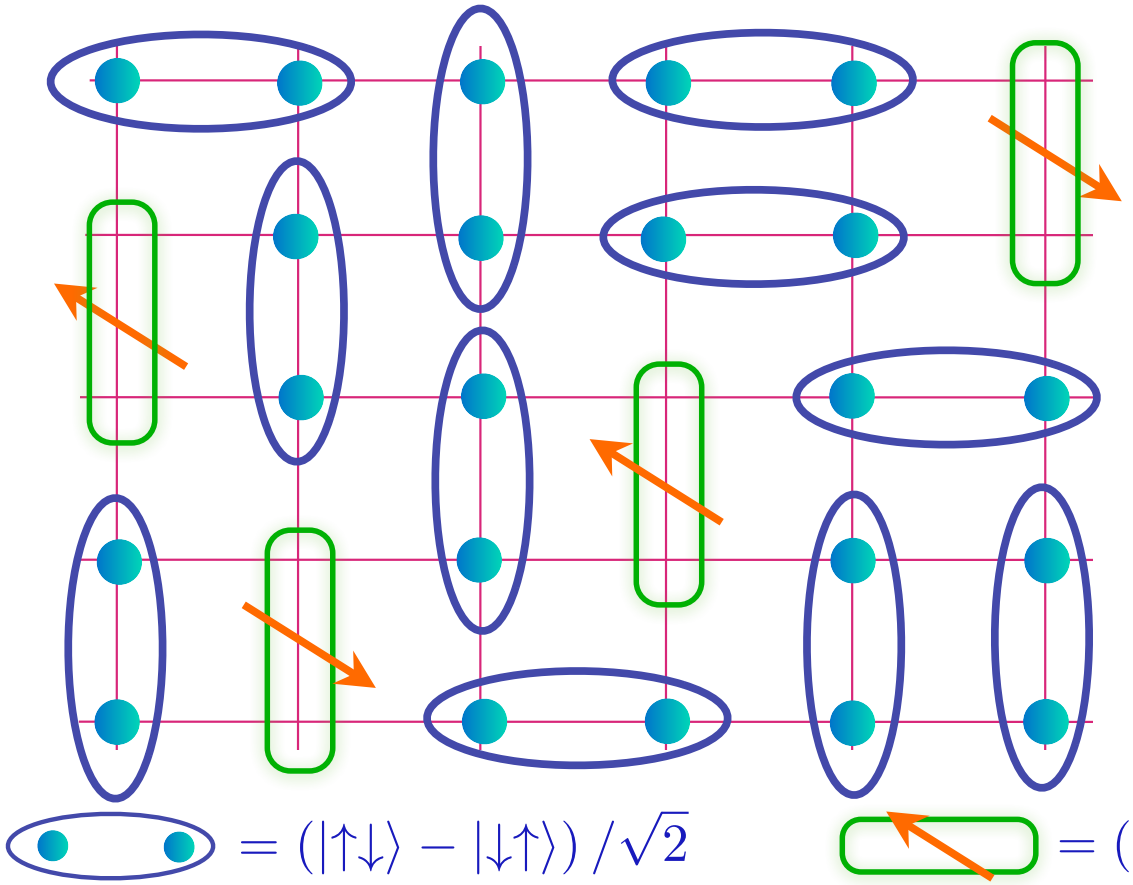

Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

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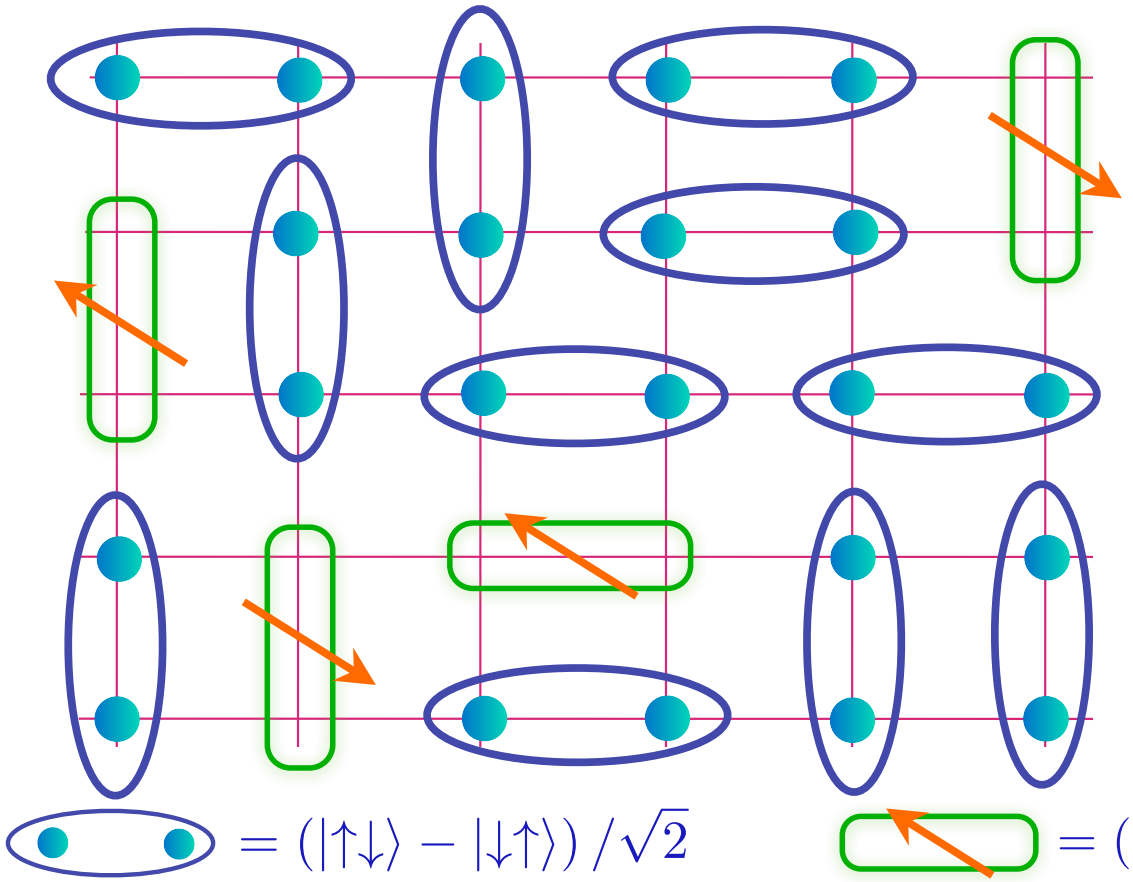

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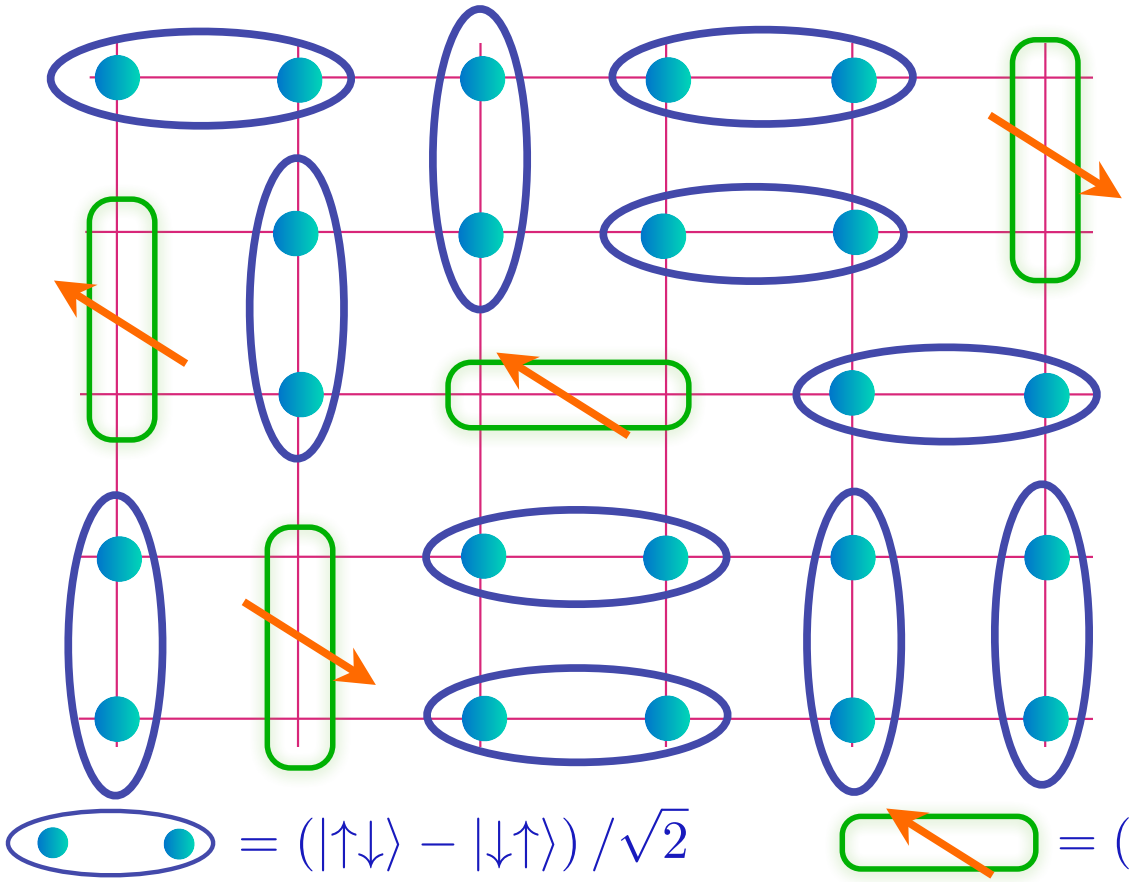

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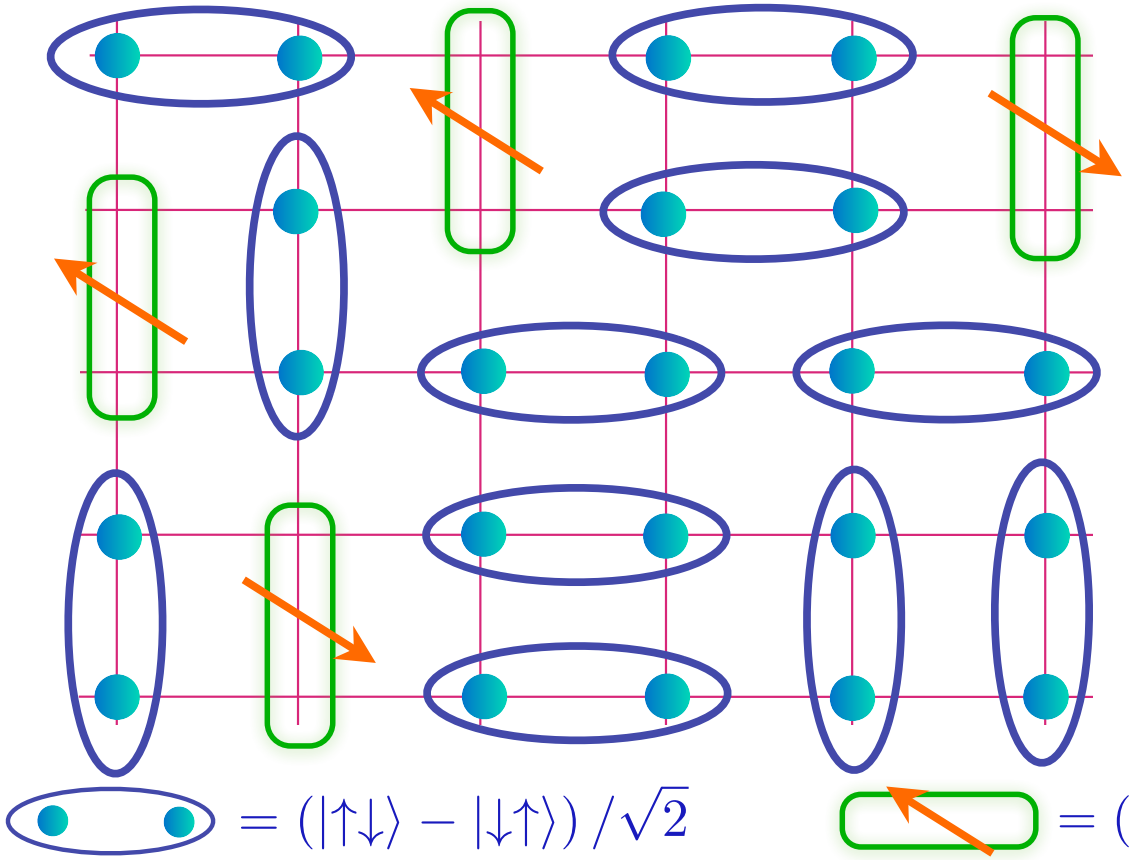

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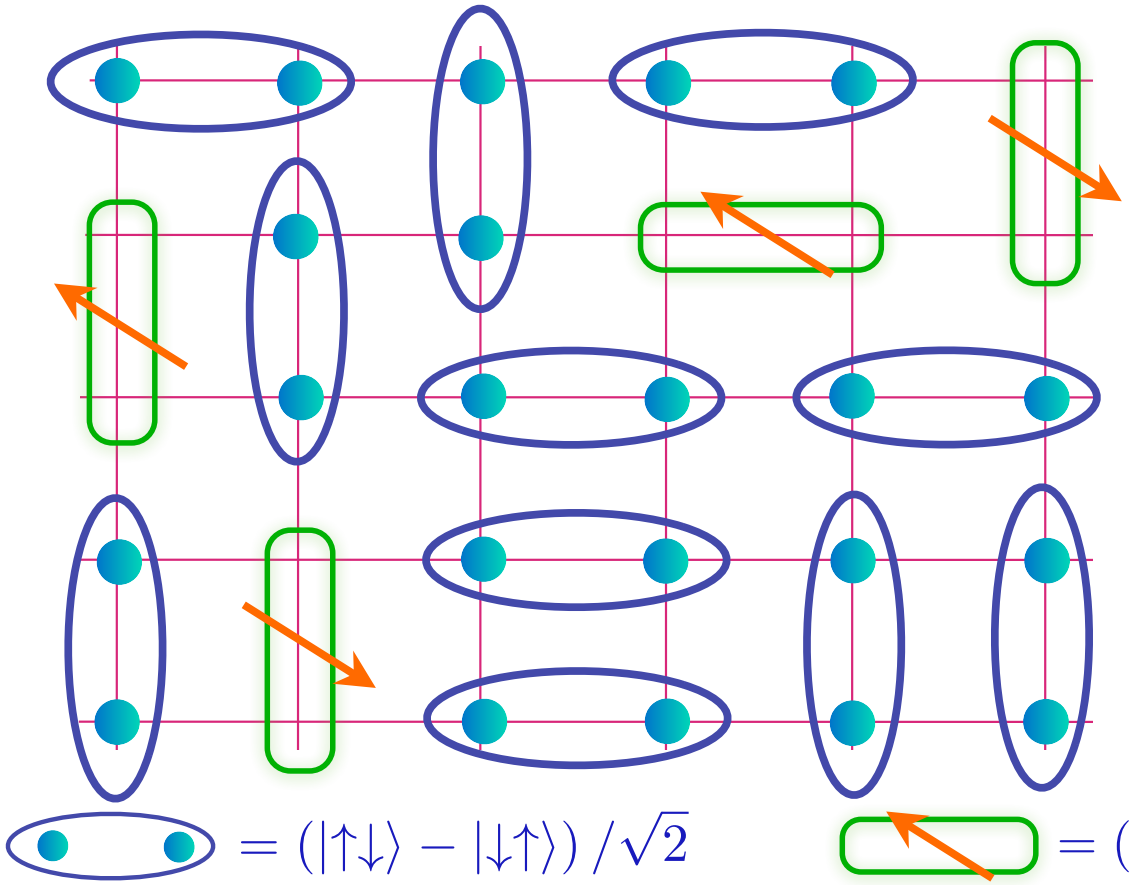

$= (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$

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

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

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

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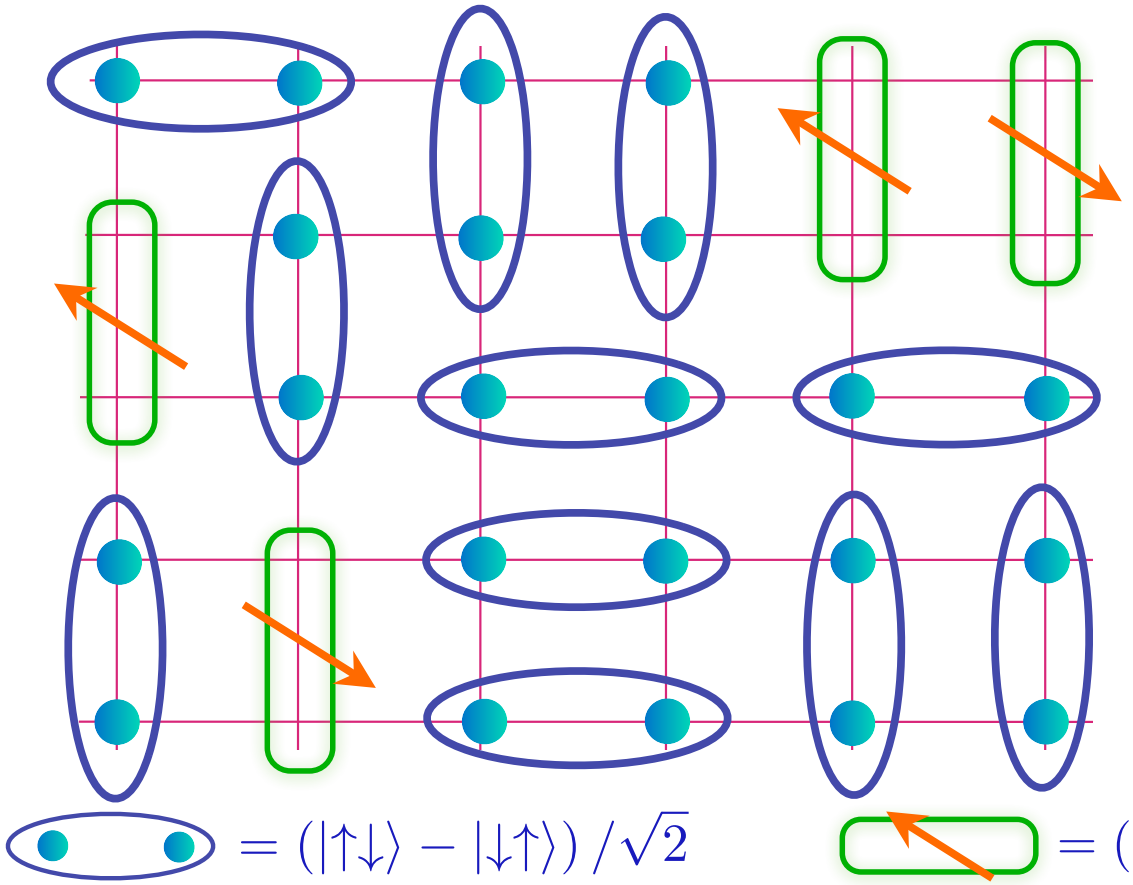

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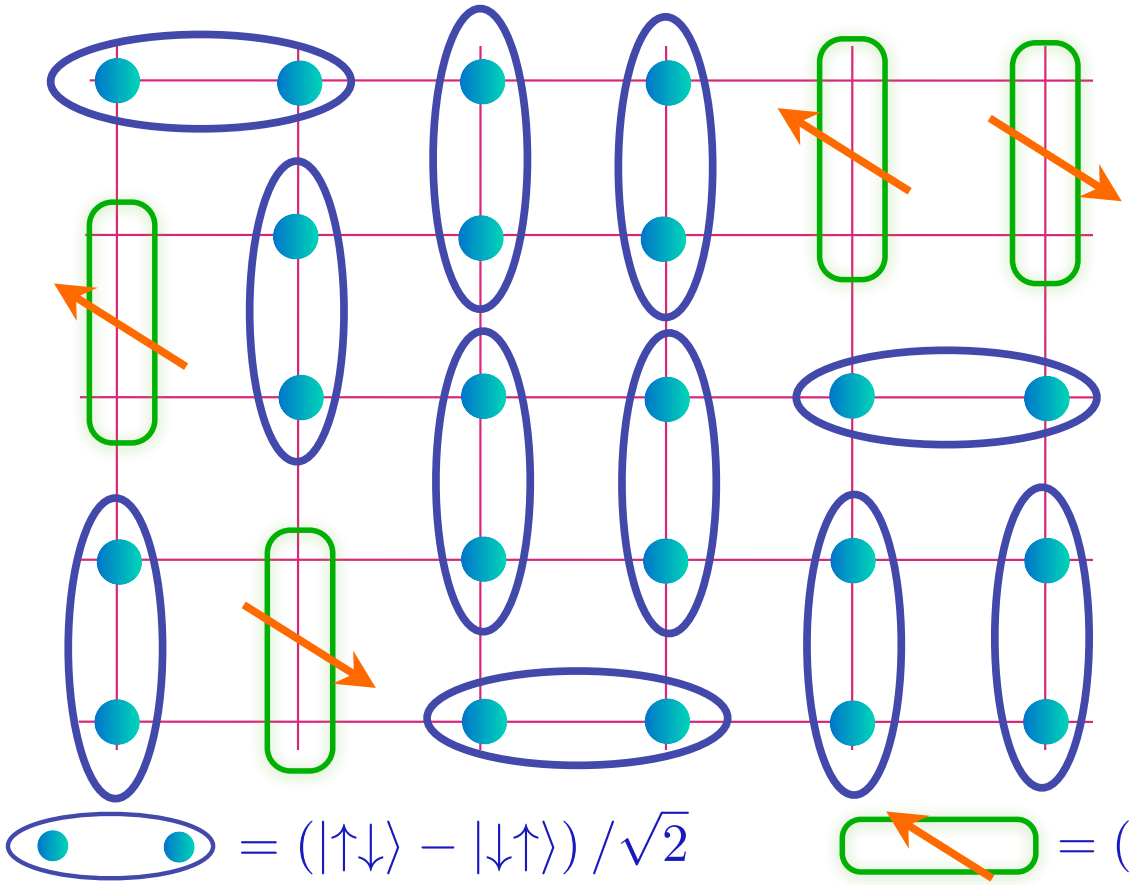

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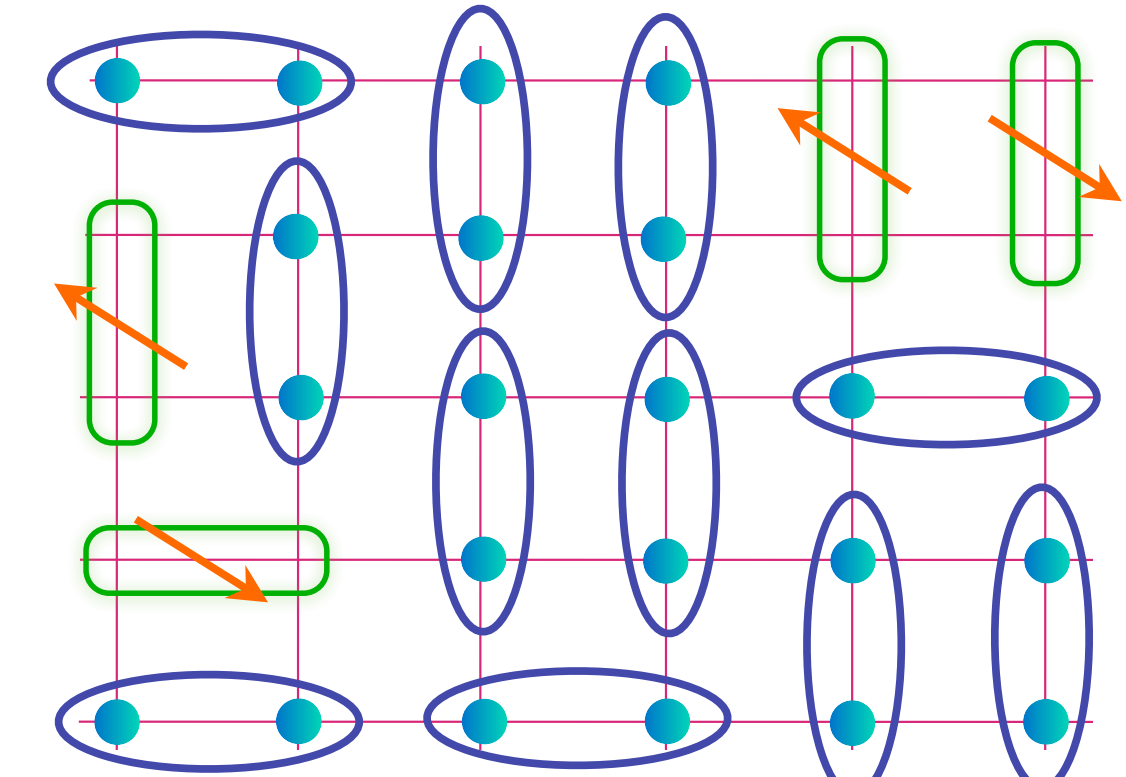

Metal with electron-like quasiparticles on a Fermi surface of size p, and emergent gauge fields

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

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

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 $SU(2)_S$ gauge theory, but some 'hand-waving' is required to produce the FL* Fermi surface.

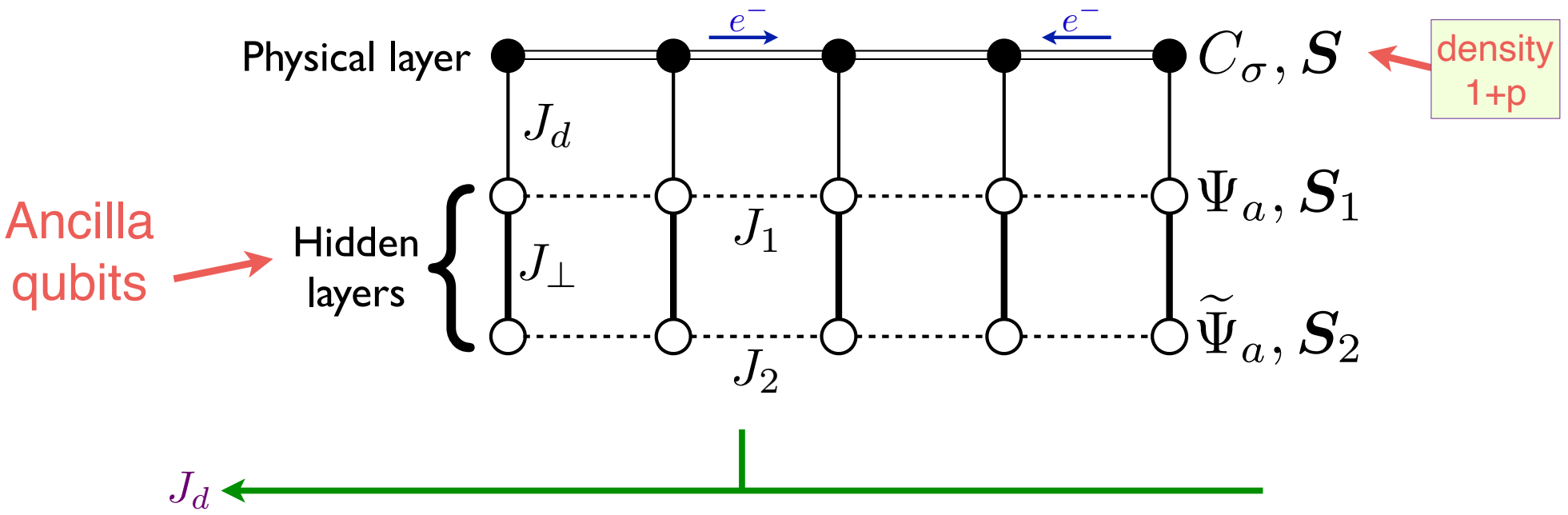
1. Metal-metal transition in the Kondo Lattice

2. Metal-metal transition in a one-band model

   A. FL model of the pseudogap*

   B. FL-FL transition: ancilla qubits and ghost Fermi surfaces*

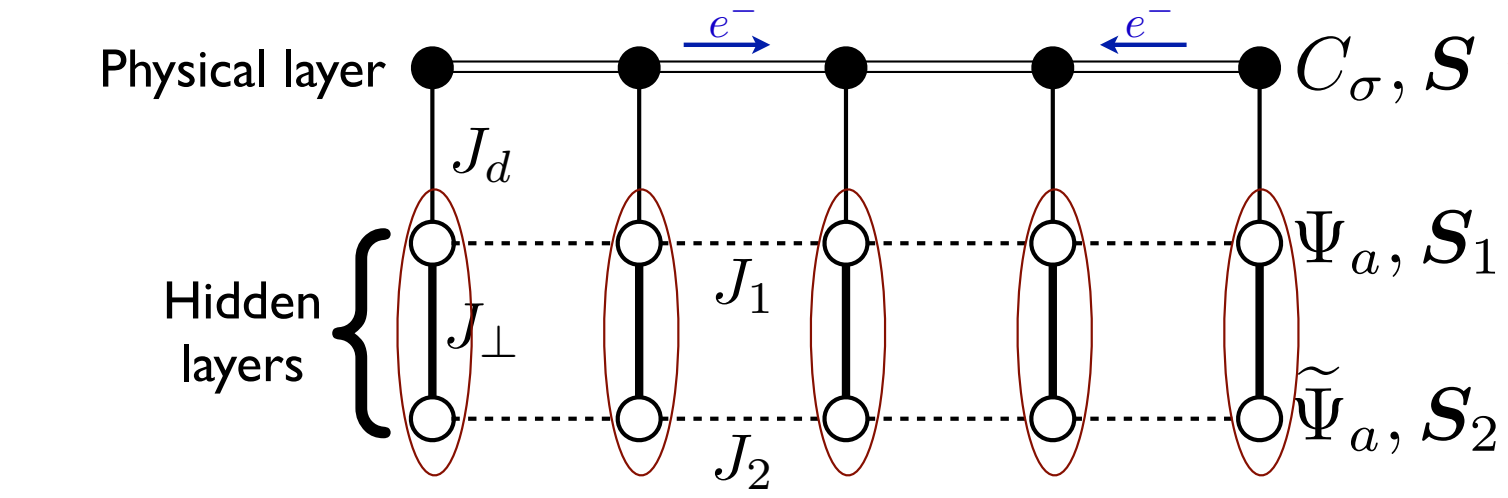
Metal-metal transitions in a ***one-band*** model

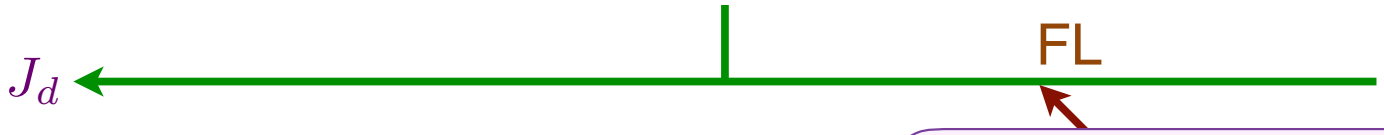


Ya-Hui Zhang

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

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





Large Fermi surface of size $1+p$

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

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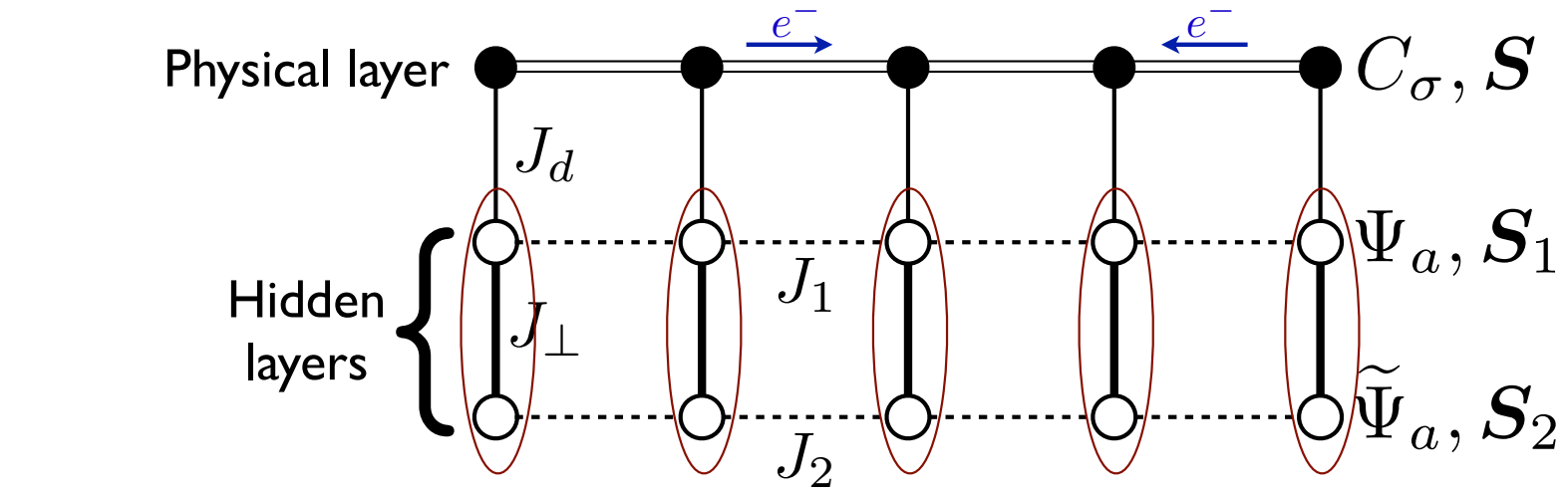

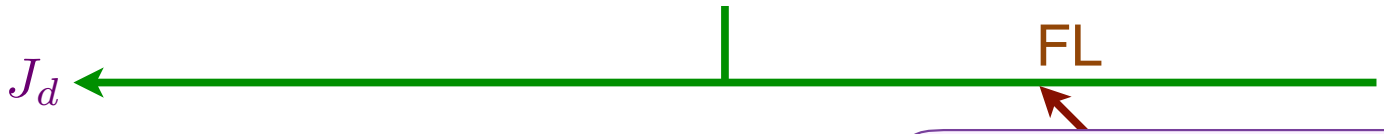

Luttinger Theorem obeyed

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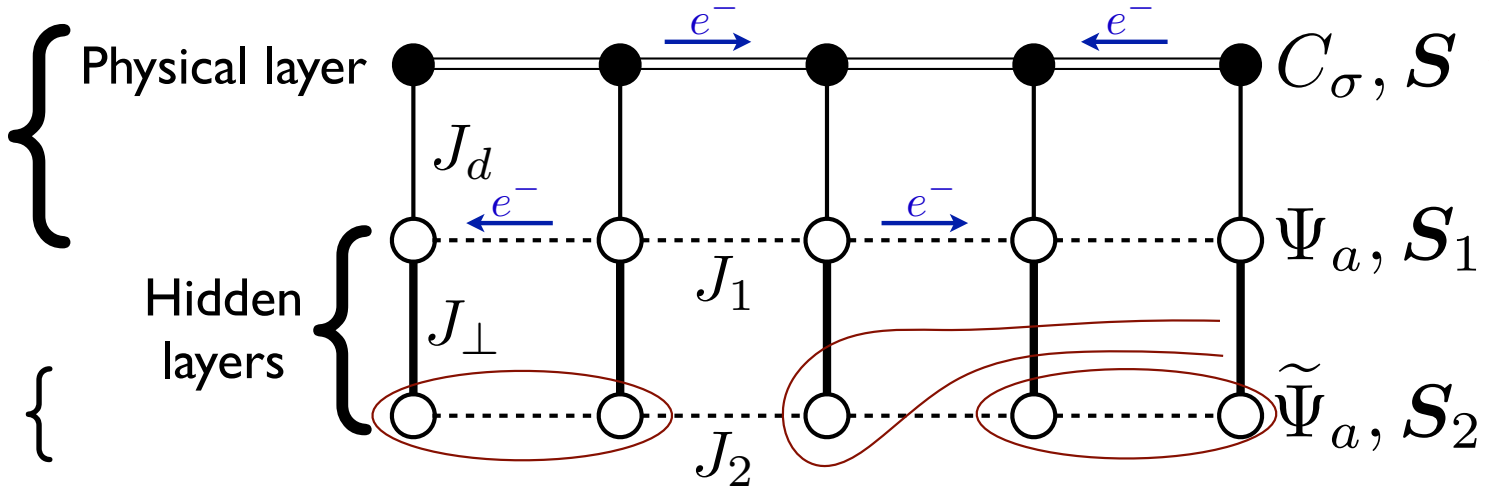
Metal-metal transitions in a ***one-band*** model

Metal.
Density
$2 + p \cong p$



Small Fermi surface of size p

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

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

Metal.
Density
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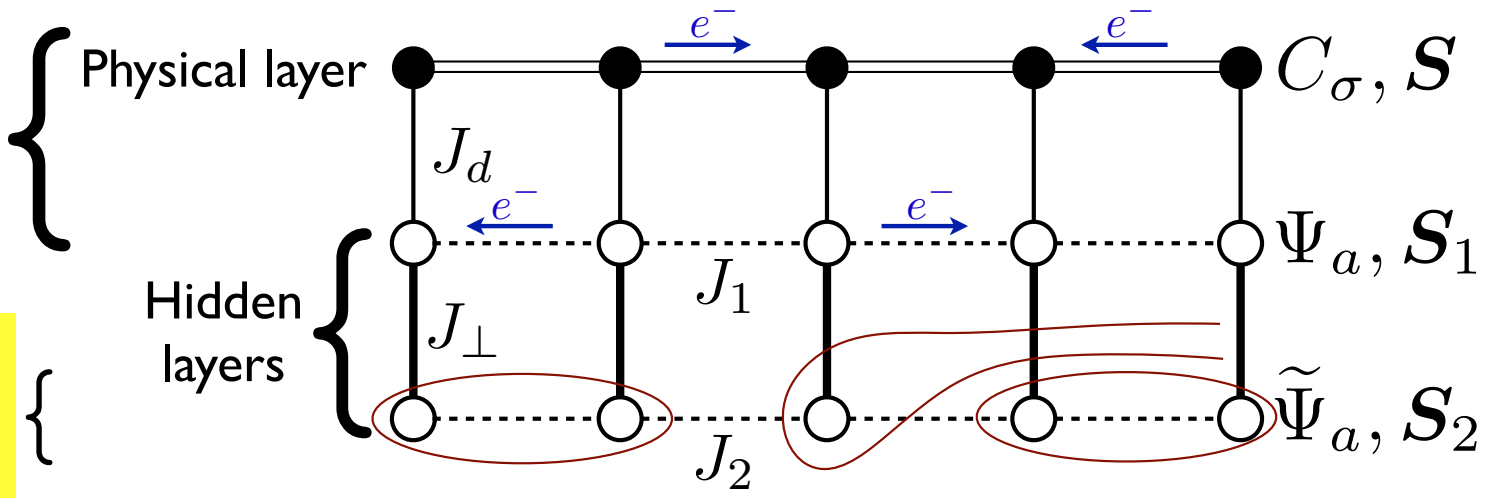
Mott insulator
Spin liquid
or AF order



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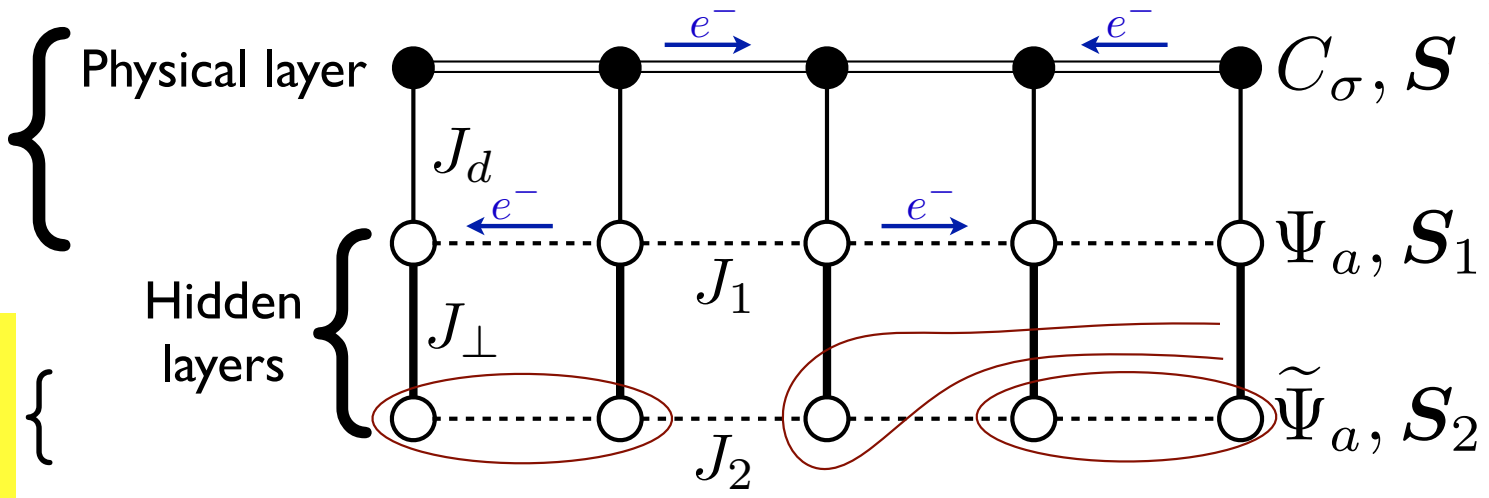

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Luttinger Theorem
violated;
OK, because of
topological order of $\tilde{\Psi}$

Ya-Hui Zhang

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

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

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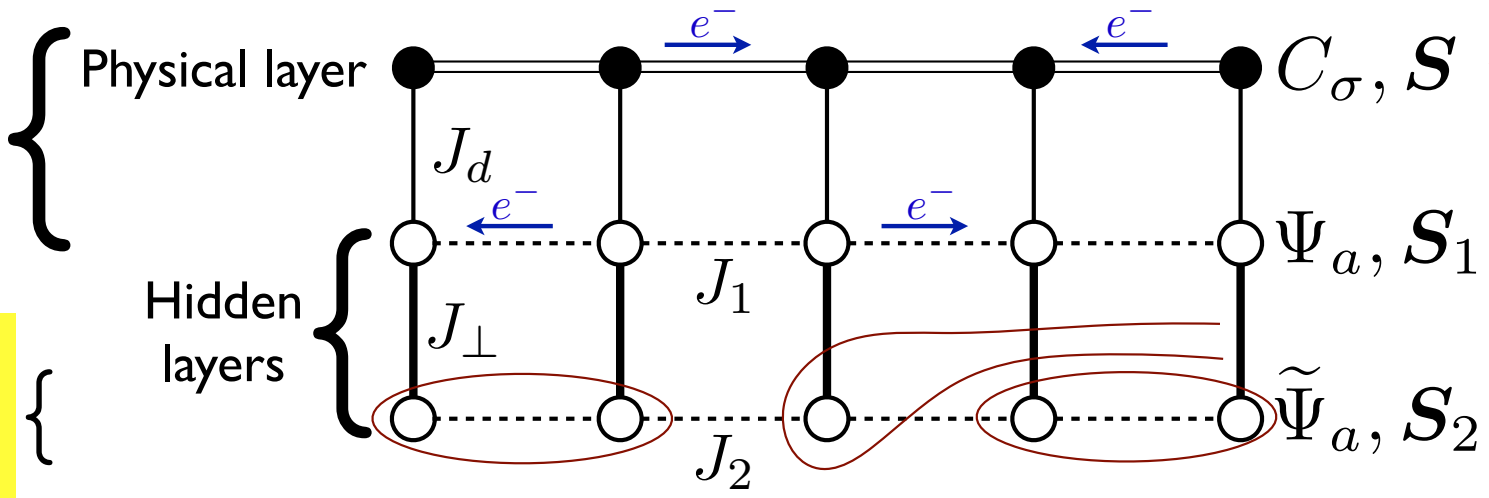

density
1+p

Mott insulator
Spin liquid
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Small Fermi surface of size p

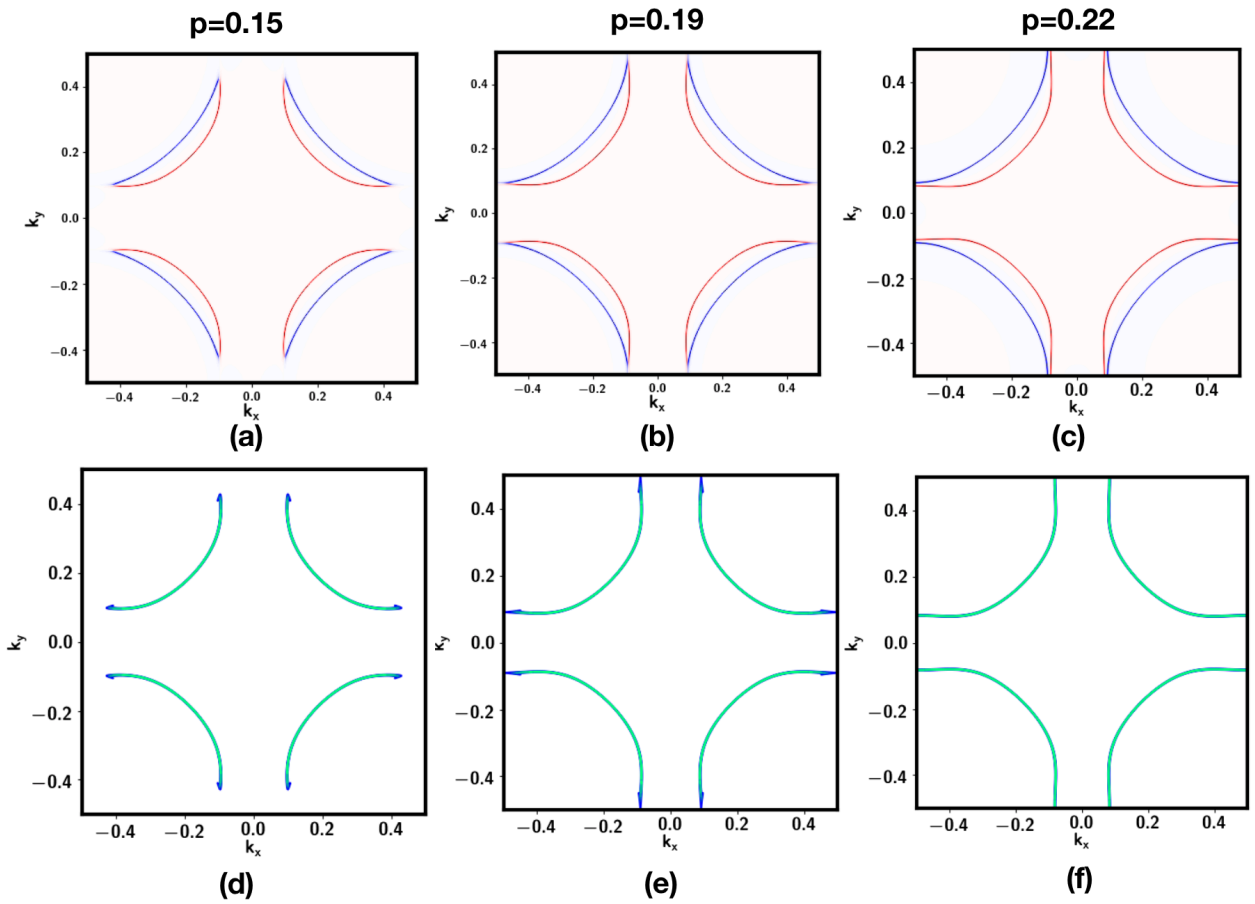
$$|\Phi\rangle = \Big[\text{Projection onto rung singlets of } \Psi, \widetilde{\Psi}\Big] \bowtie |\text{Slater determinant of } (C, \Psi)\rangle \otimes \Big|\text{Slater determinant of } \widetilde{\Psi}\Big\rangle$$

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

Ya-Hui Zhang

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

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



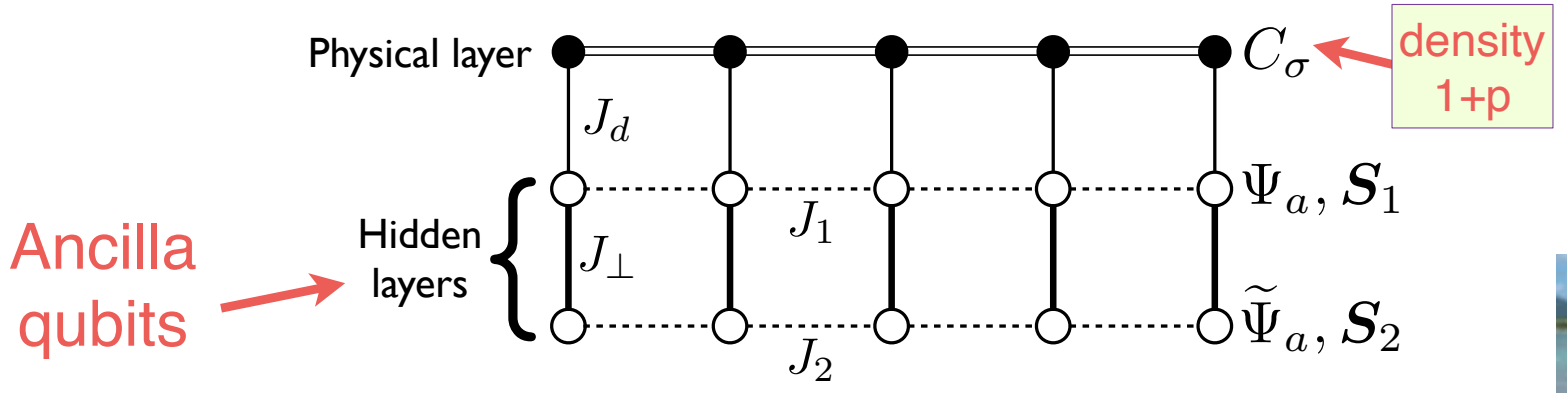
Zero frequency spectral density of electrons (red) and ghosts (blue)

"Fermi arc" spectral functions in the FL* phase

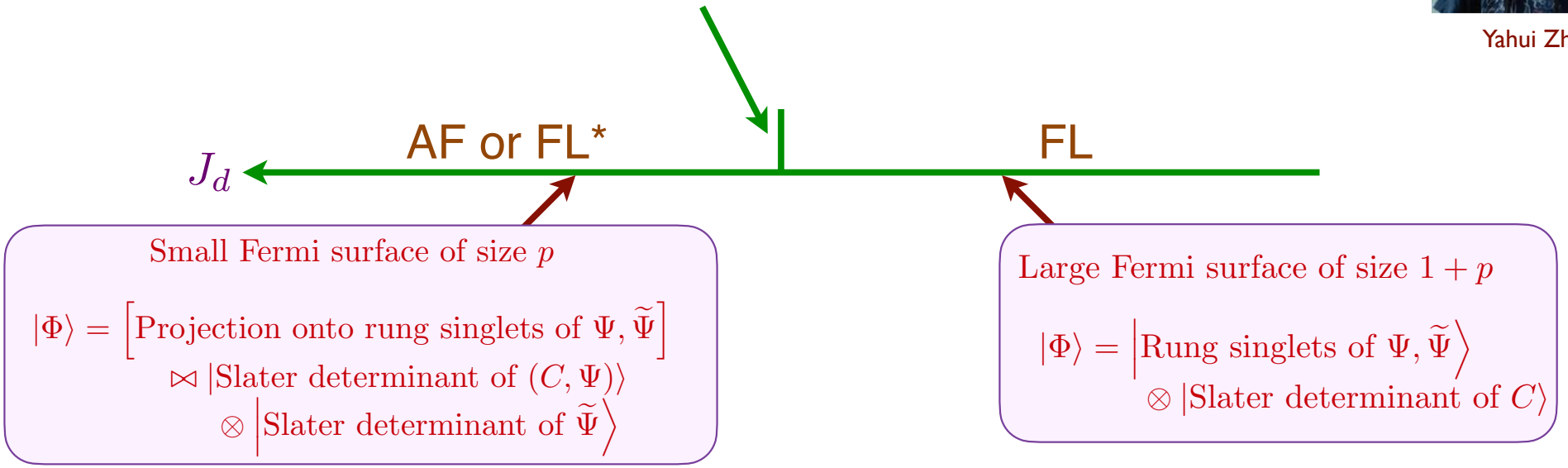
Ya-Hui Zhang

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

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



Yahui Zhang



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

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

Yahui Zhang

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)

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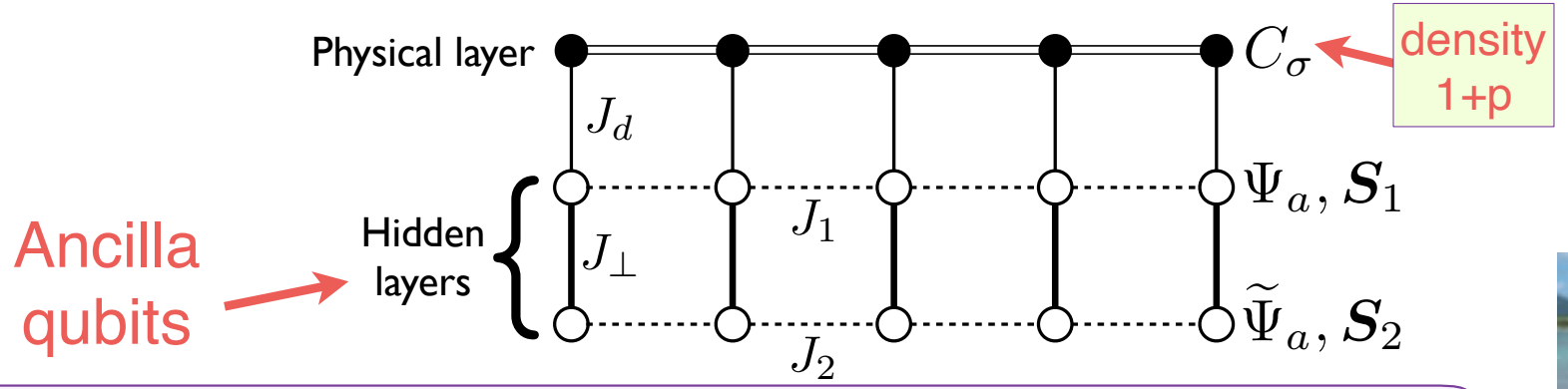
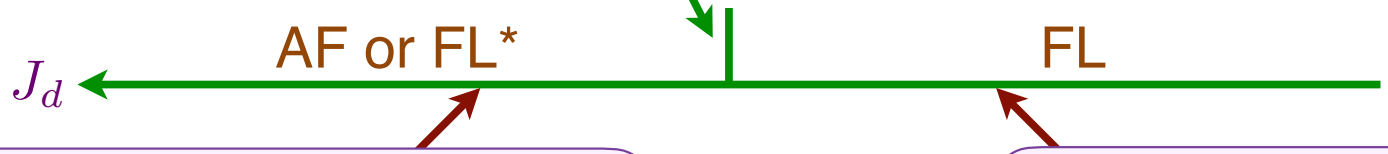


Yahui Zhang

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



Small Fermi surface of size p

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Large Fermi surface of size $1+p$

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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.

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

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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.

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).

See talk later today on random models:
Excitation spectra of quantum matter without quasiparticles
October 15, 2020, 2 PM (Eastern), Boston College
https://bccte.zoom.us/j/9901465258