A quantum dimer model for the pseudogap metal

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Subir Sachdev

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

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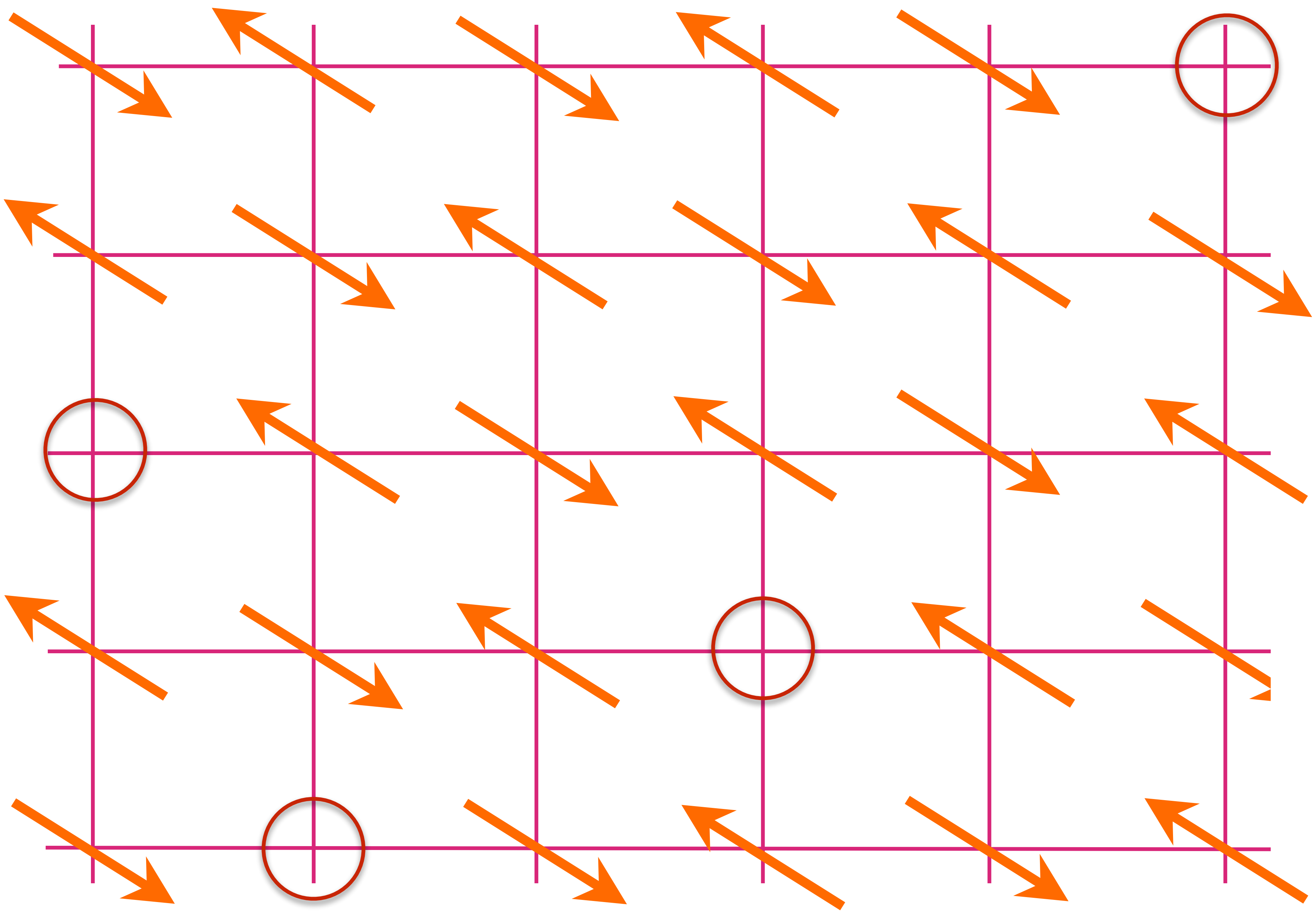
Talk online: sachdev.physics.harvard.edu

Andrea Allais

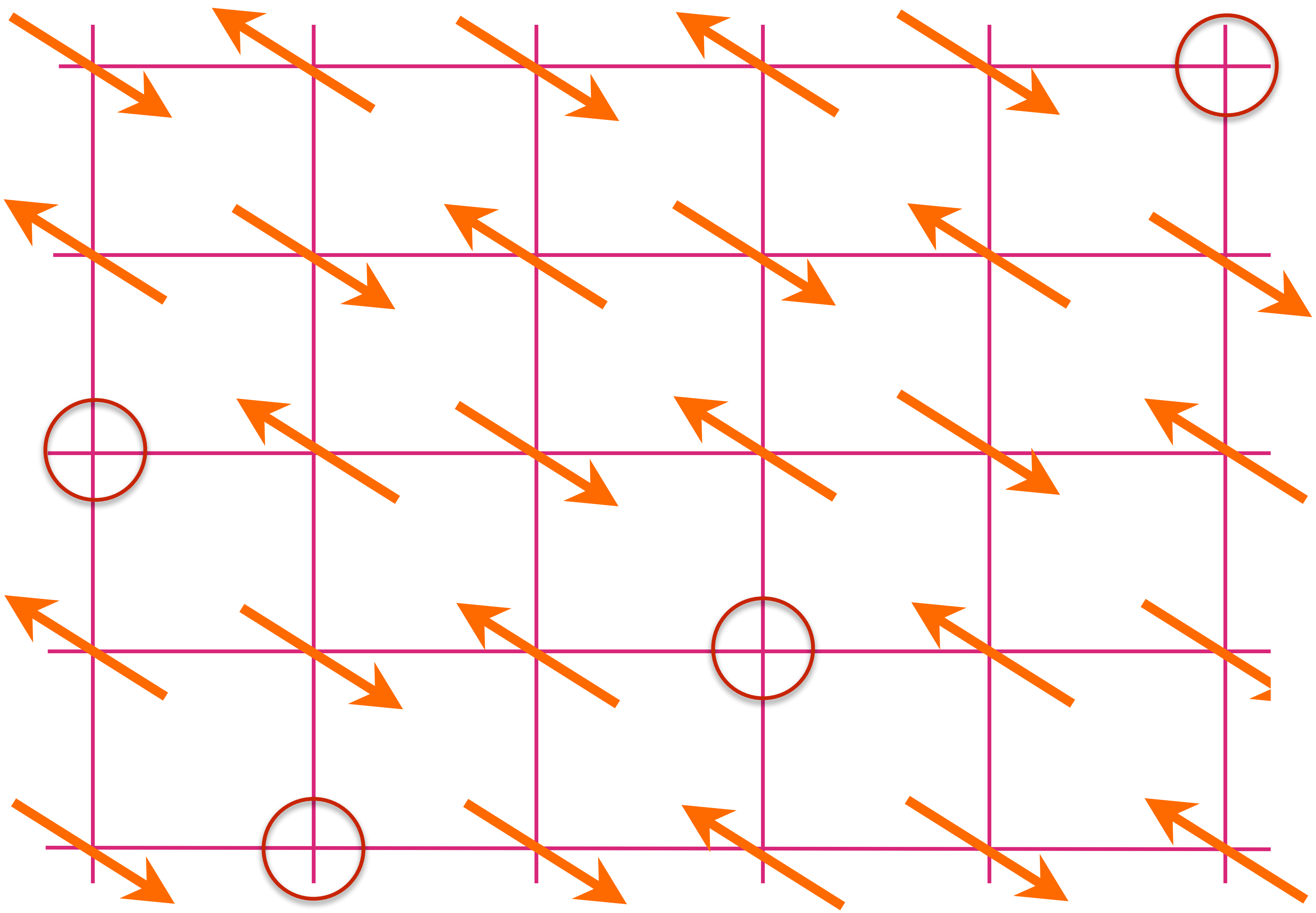
Debanjan Chowdhury

Alexandra Thomson

Matthias Punk (Innsbruck)

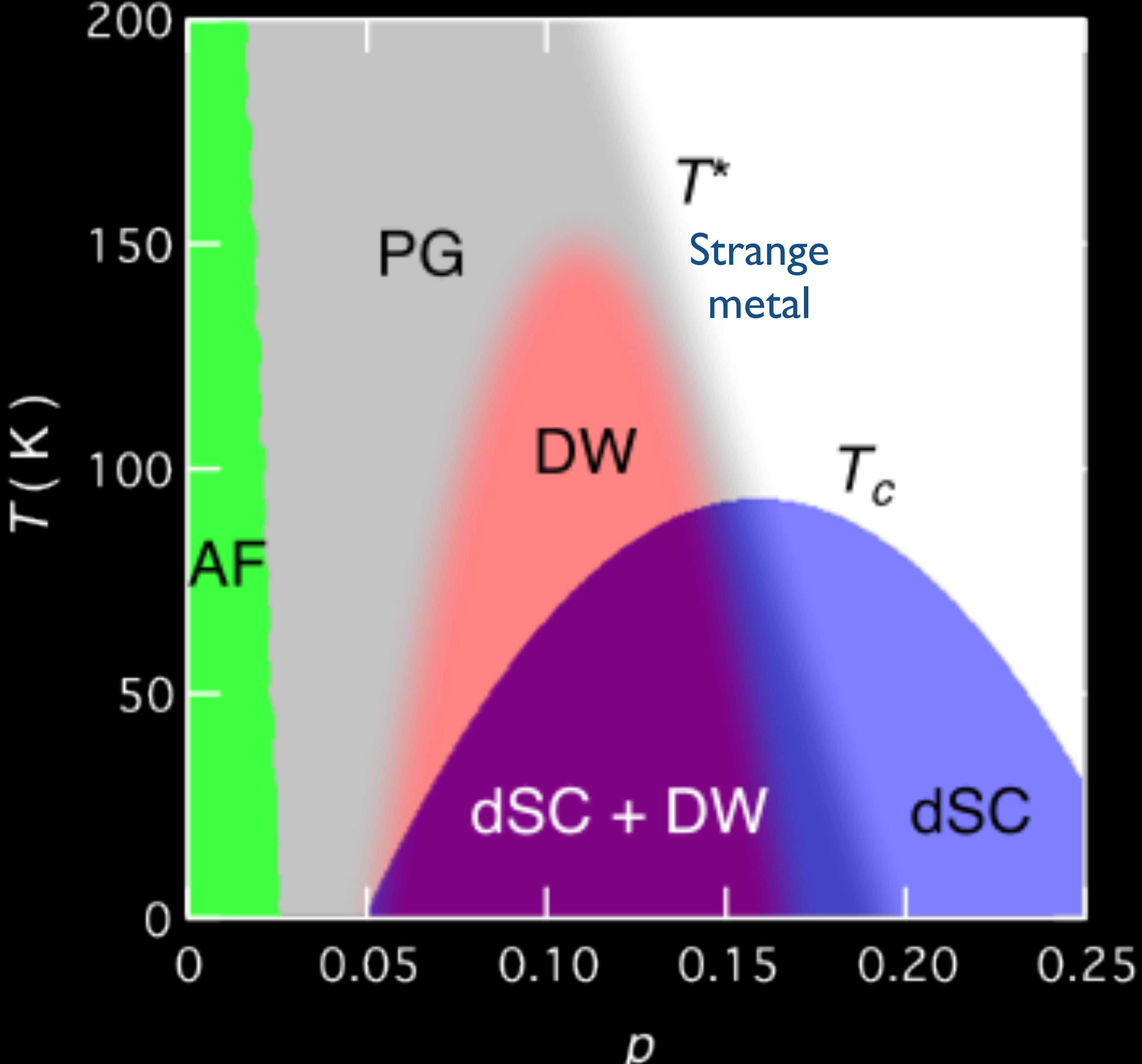


Anti-ferromagnet with p holes per square



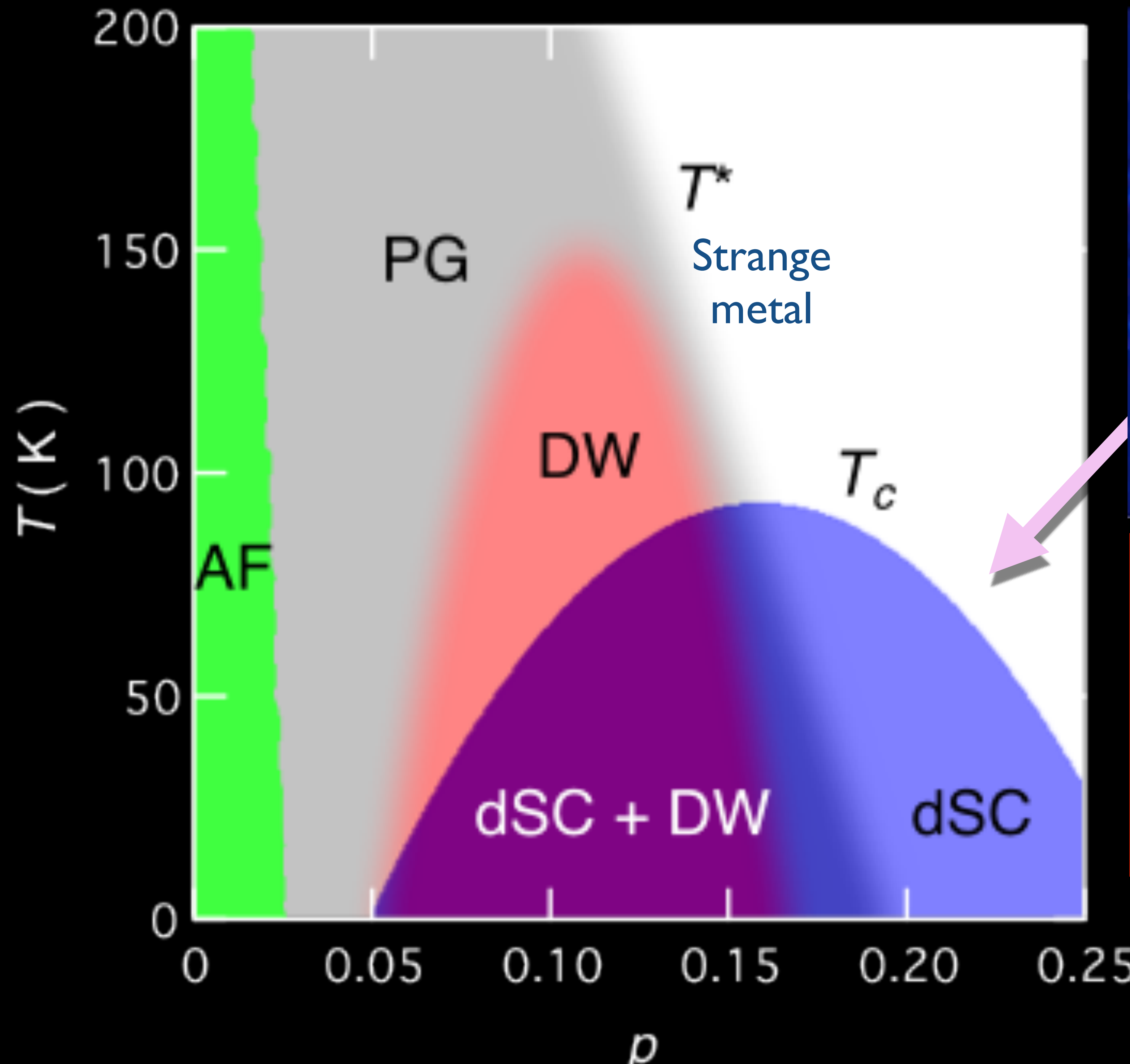
Anti-ferromagnet with p holes per square

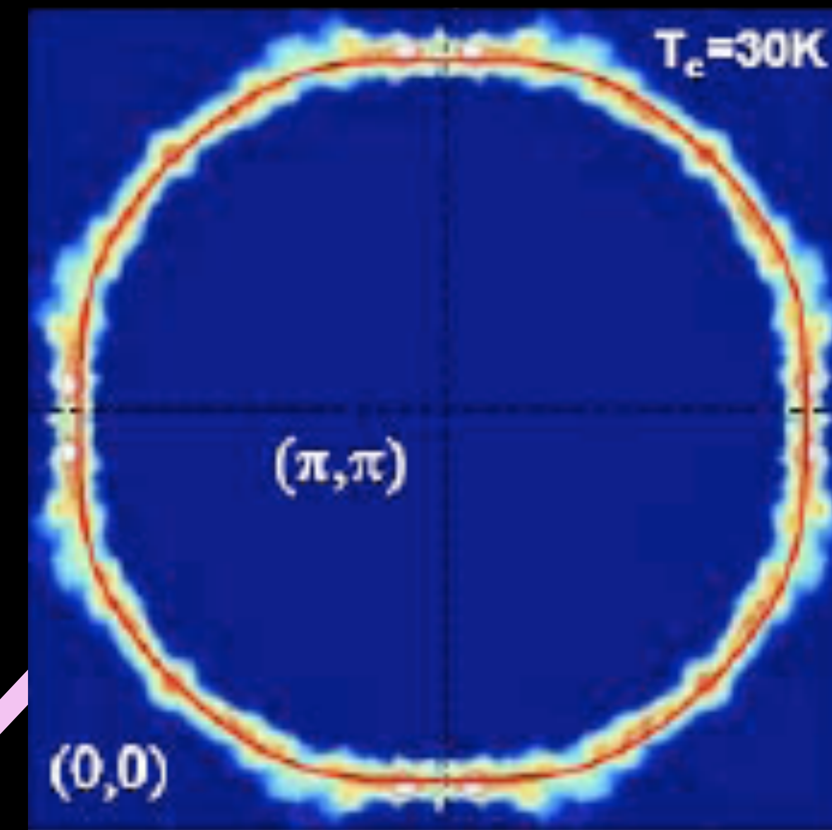
But relative to the band insulator, there are $1+p$ holes per square



200
150
100
50
0
T(K)
PG
T*
Strange
metal
DW
T_c
AF
dSC + DW
dSC
0
0.05
0.10
0.15
0.20
0.25
p

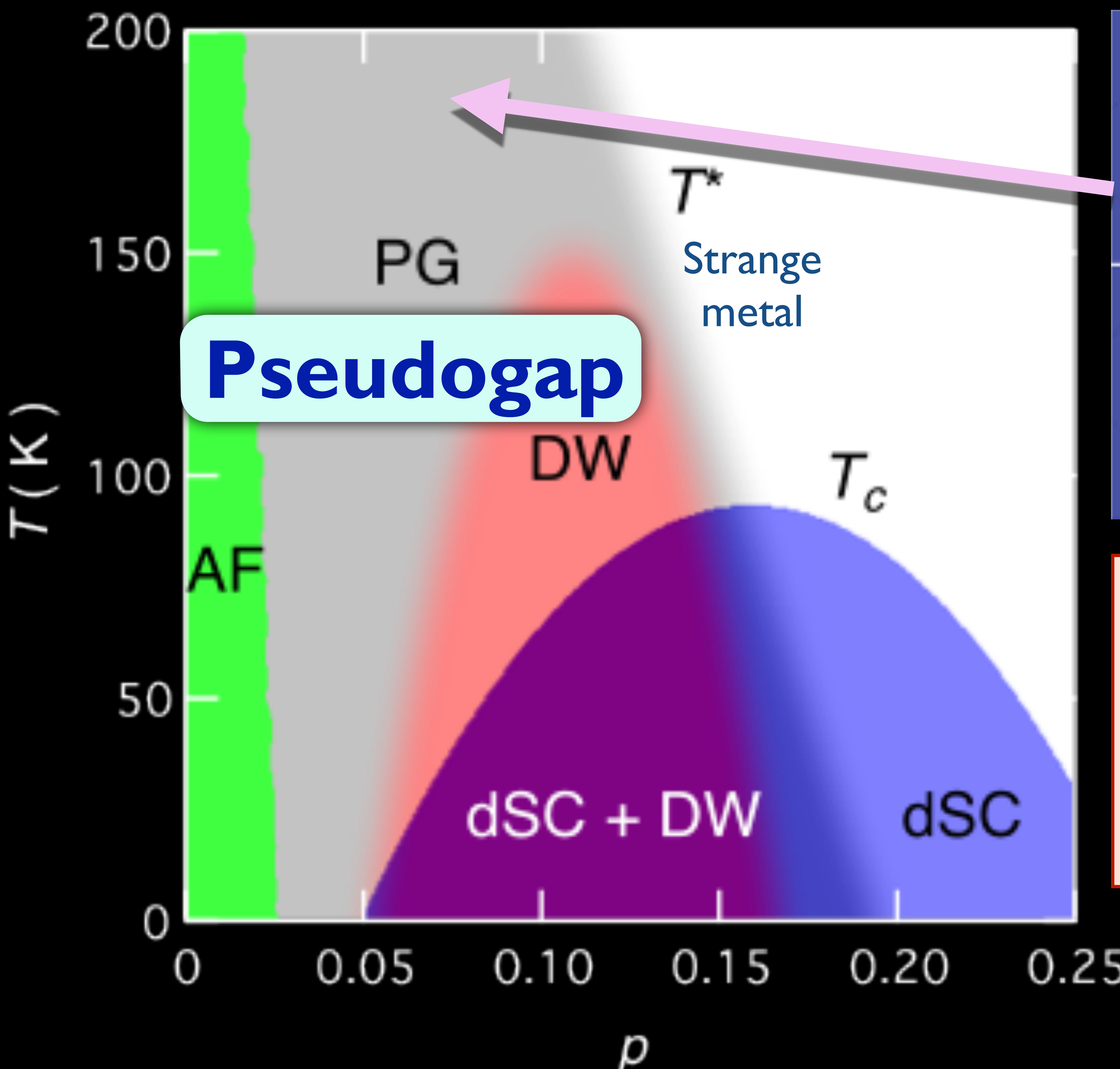
M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)

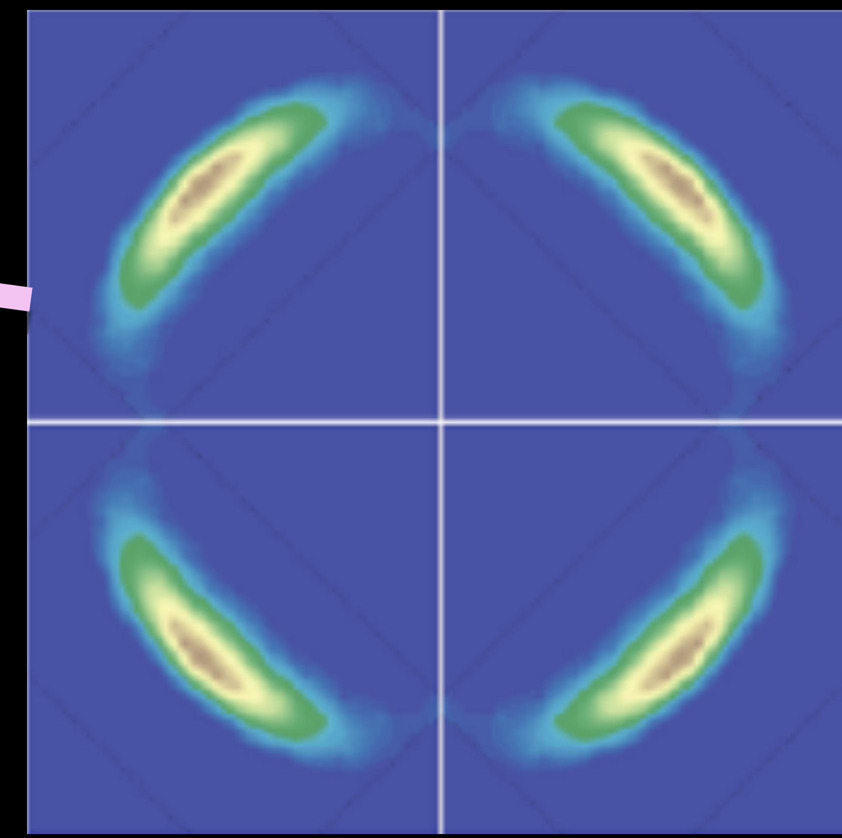




Fermi liquid:
Area enclosed
by Fermi surface
$=1+p$

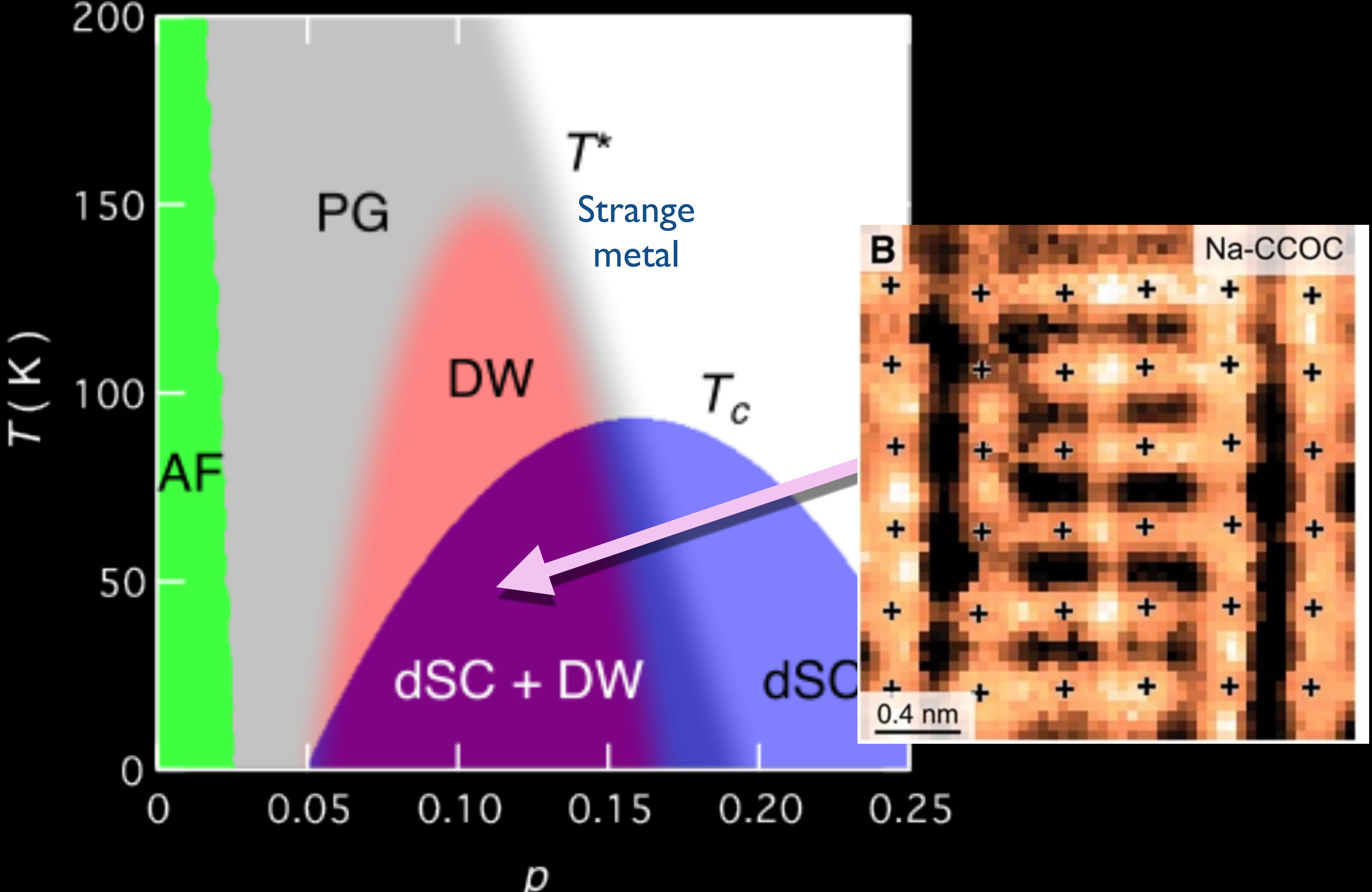
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)



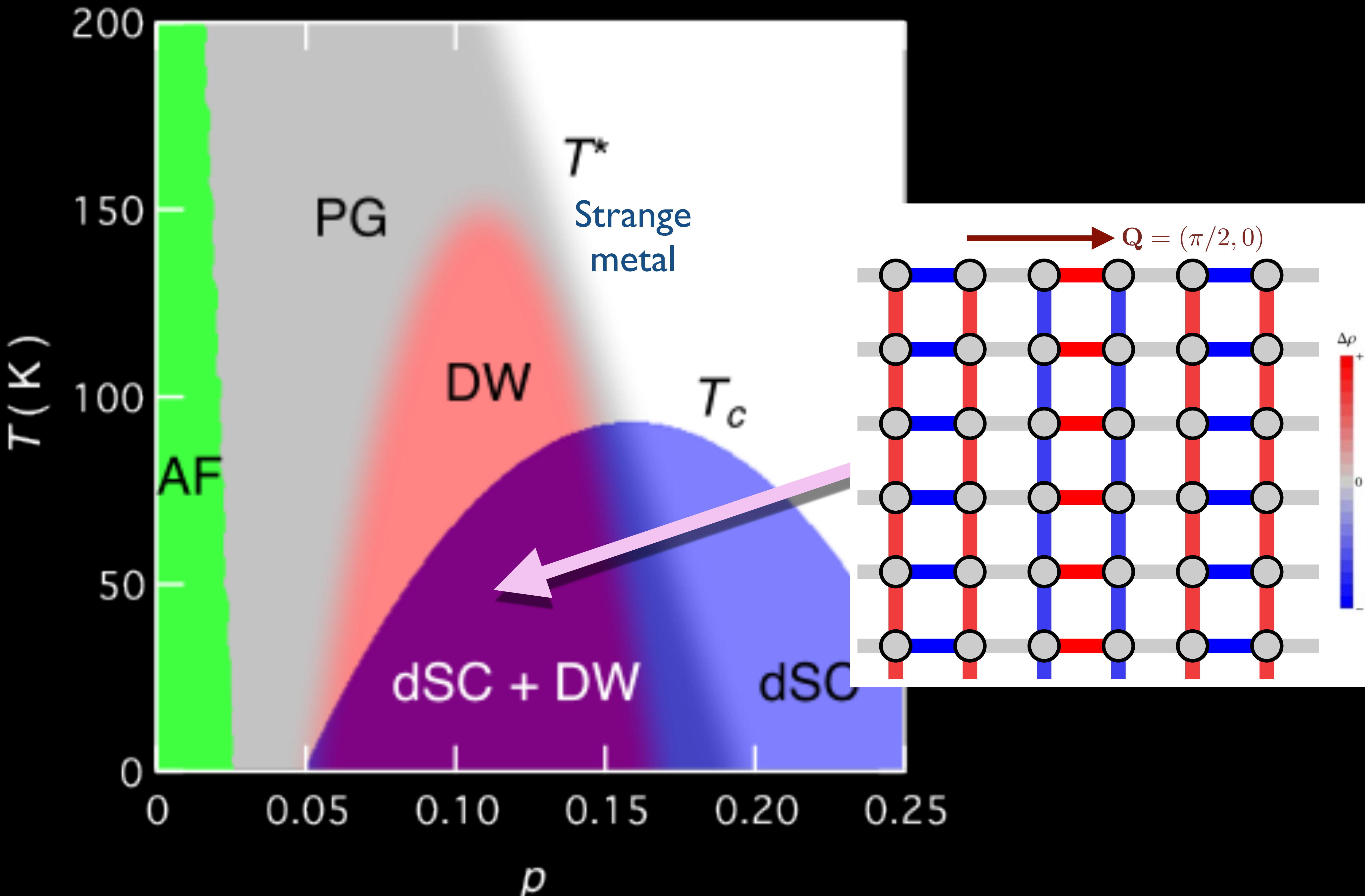


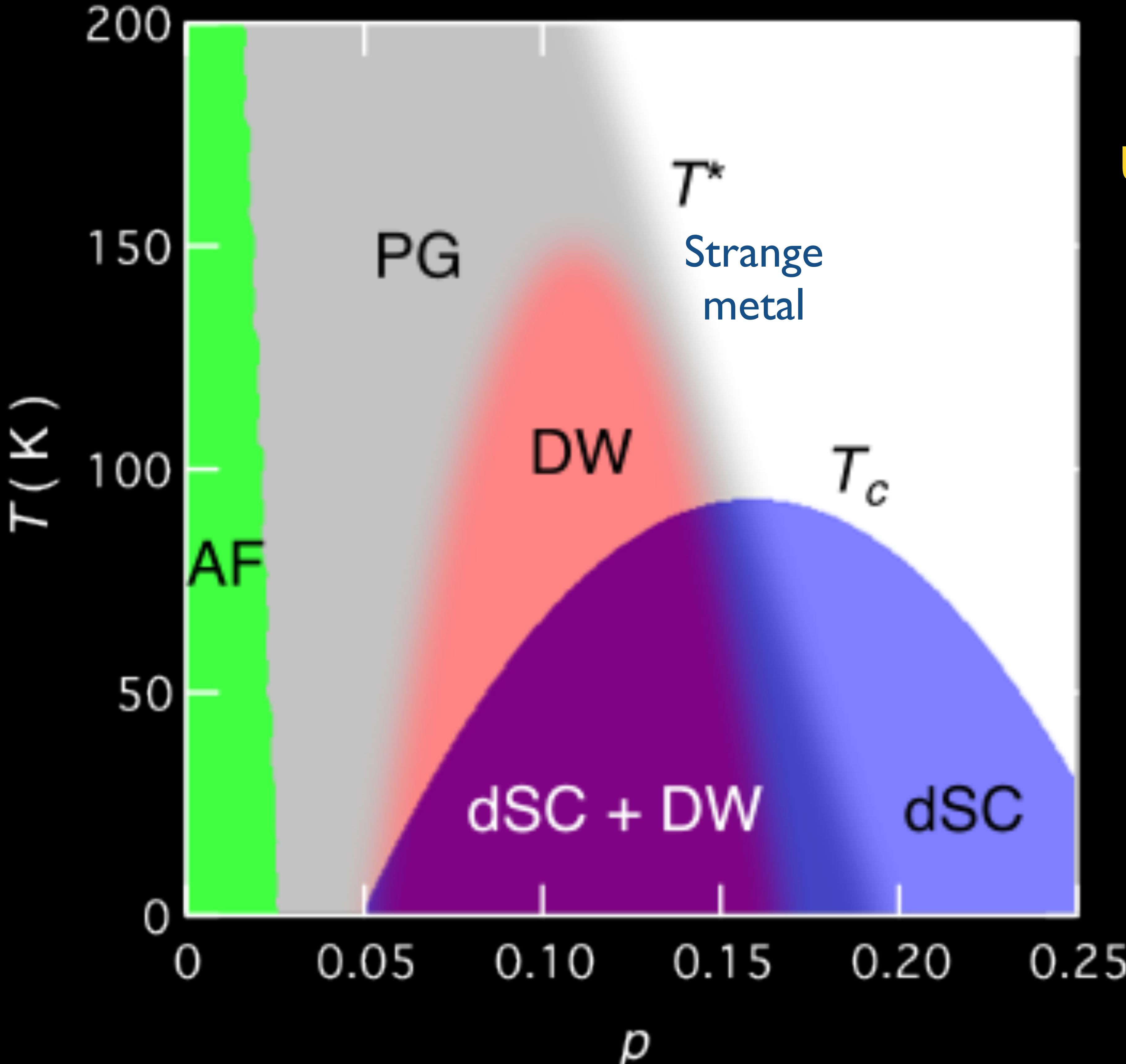
"Fermi arcs" at low p

Y. Kohsaka *et al.*, Science **315**, 1380 (2007)



M. A. Metlitski and S. Sachdev, Phys. Rev. B **82**, 075128 (2010).
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)





How do we understand the Fermi arc spectrum, and what is its relationship to the density wave (DW) order at lower *T* ?

Is the higher temperature pseudogap (with ``Fermi arc'' spectra) described by

(A) Thermal fluctuations of the low temperature orders (superconductivity, density wave, antiferromagnetism…)

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(A) Thermal fluctuations of the low temperature orders (superconductivity, density wave, antiferromagnetism…)

OR

(B) A new type of metal, which can be stable (in principle) as a quantum ground state

Reasons for working with option (B)

- Pseudogap appears already at high temperatures where there are no observed density wave correlations, and no pairing fluctuations.

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- Transport properties of metal in the pseudogap look like those of a Fermi liquid with fermionic carrier density p: this includes conductivity, Hall resistance, magnetoresistance, and optical conductivity.
  Ando PRL (2004); Chan PRL (2013); Mirzaei PNAS (2013)

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- No room for antinodal Fermi surfaces in high field, low T specific heat.

- Suppressed paramagnetic susceptibility at high fields and low T

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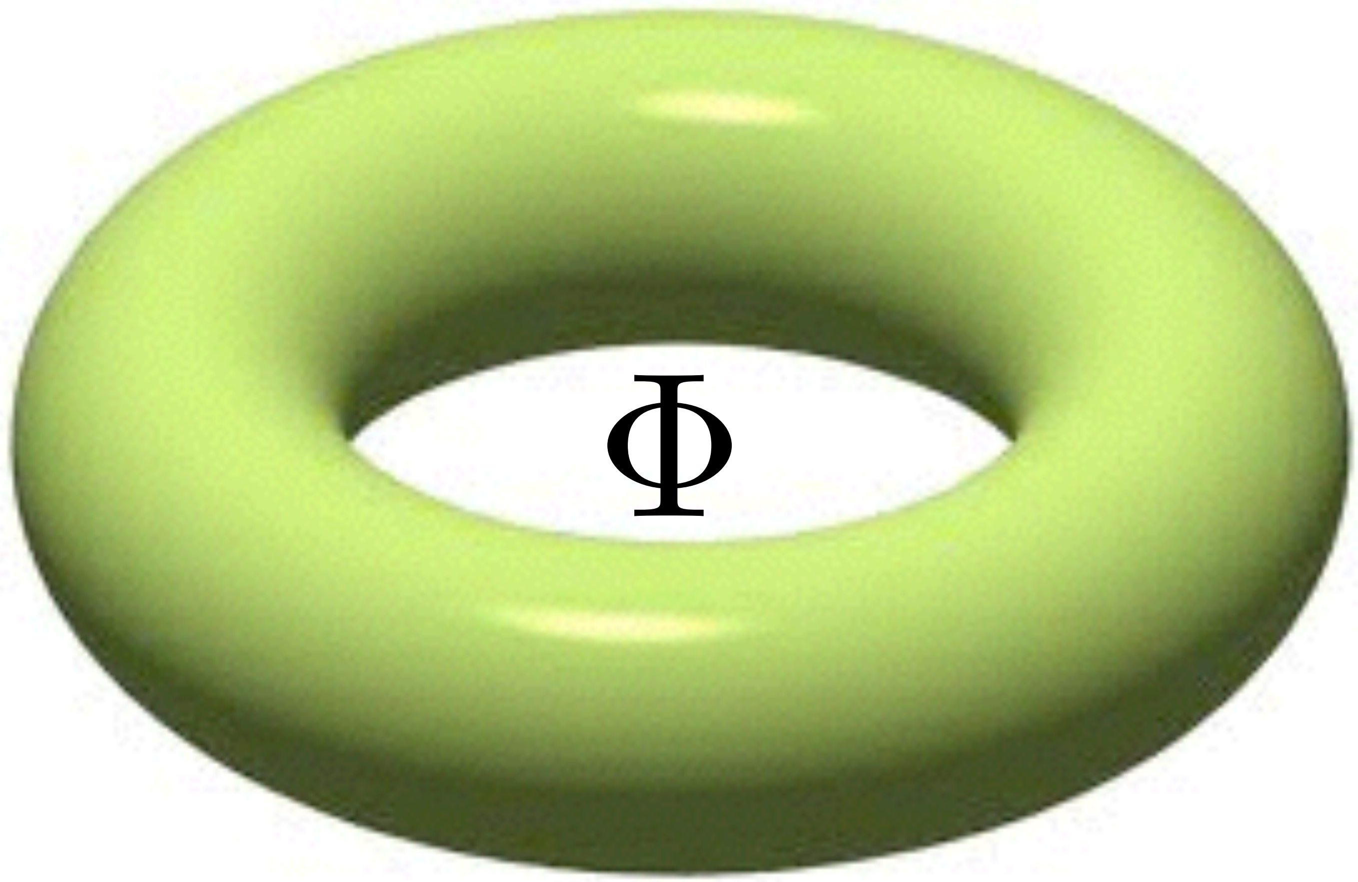
The Luttinger theorem for a Fermi liquid requires a Fermi surface of size $1+p$.

Answer: Yes.
There can be a Fermi surface of size p, but it must be accompanied by "topological order".

At $T=0$, such a metal must be separated from a Fermi liquid (with a Fermi surface of size $1+p$) by a quantum phase transition

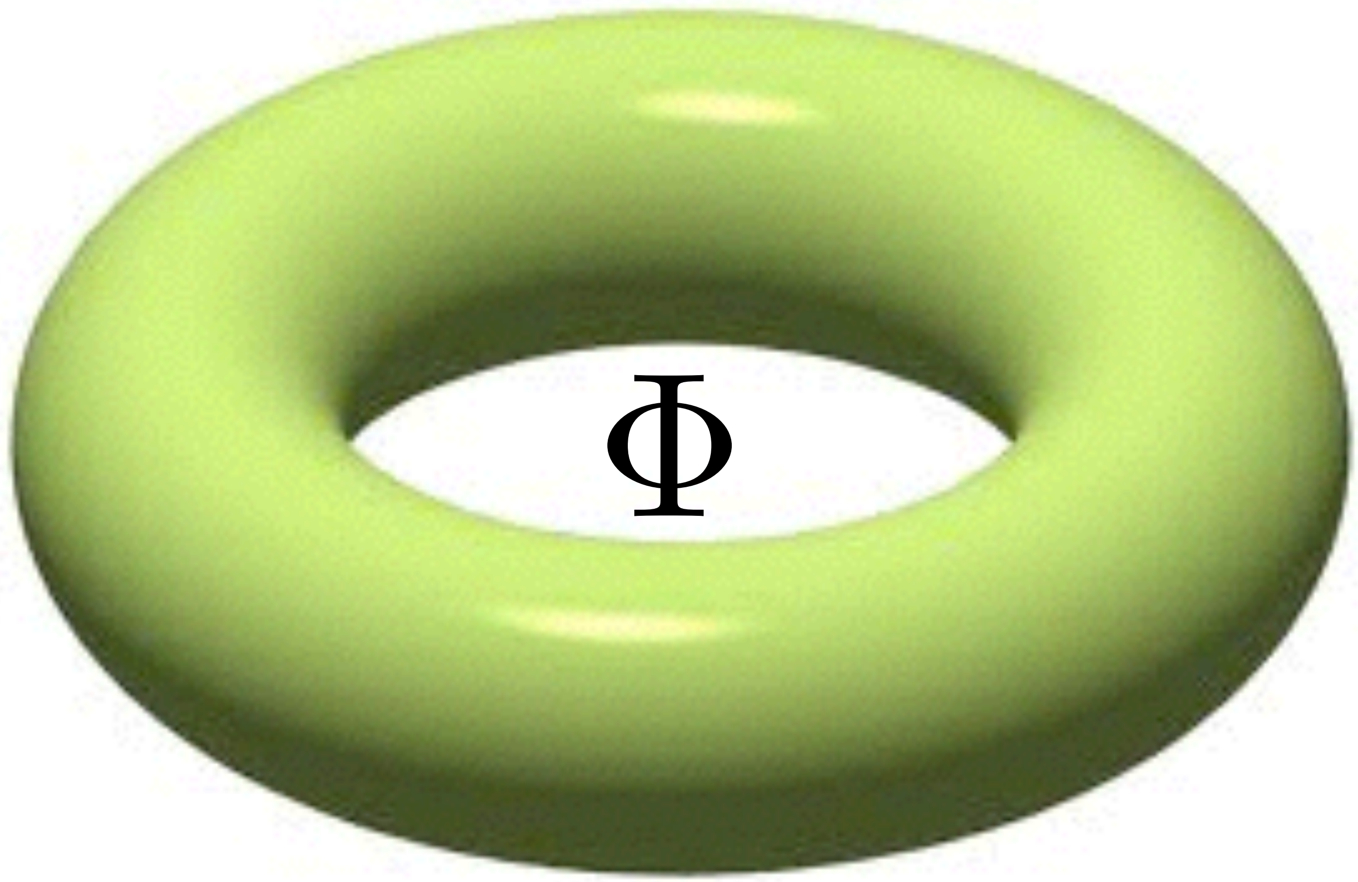
Topological argument



Put metal on a torus, adiabatically insert flux $\Phi = h/e$ through hole, and measure change in momentum. In a FL, we can assume the only low energy excitations are quasiparticles near the Fermi surface, and this leads to a non-perturbative proof of the Luttinger relation on the area enclosed by the Fermi surface.

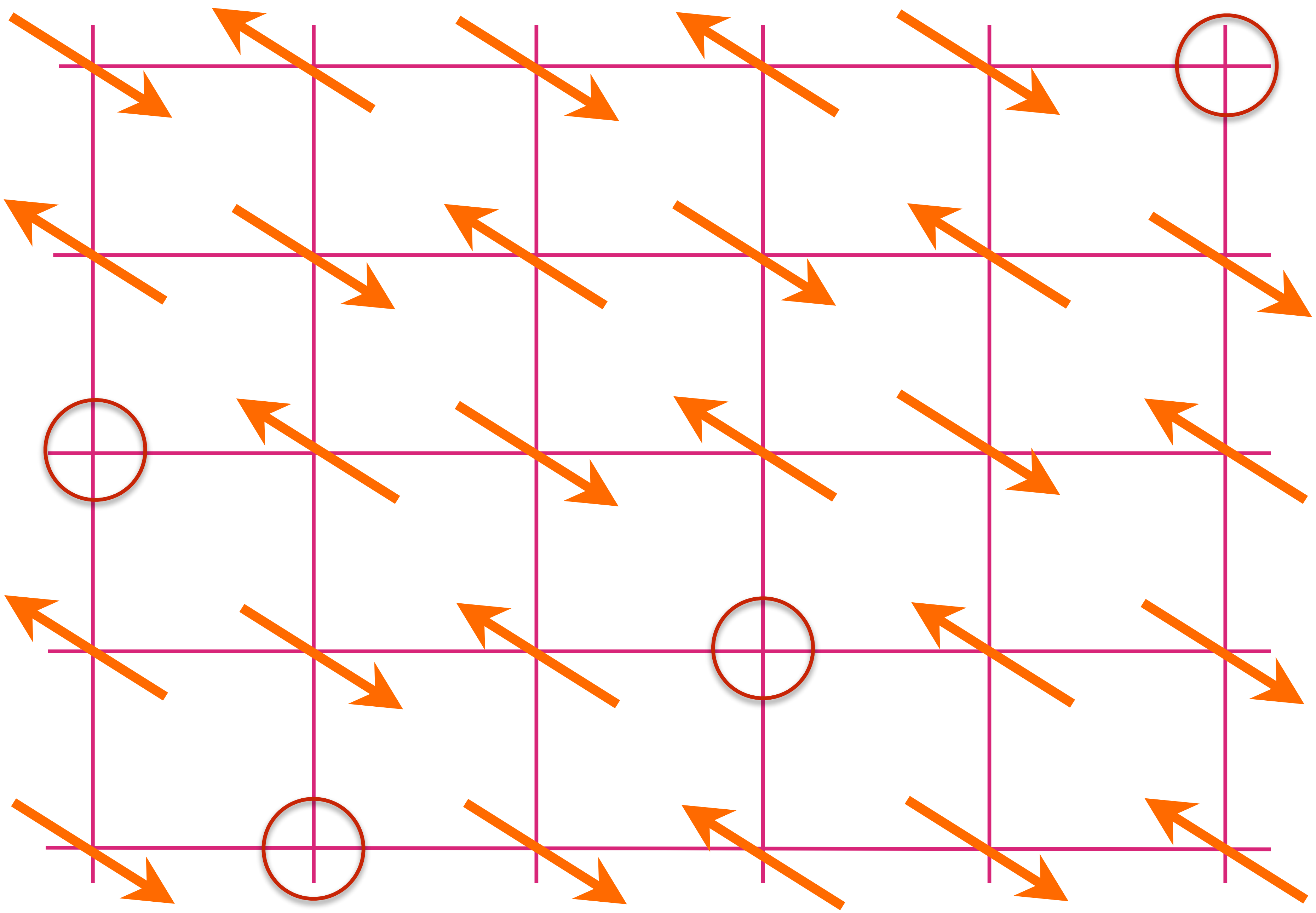
M. Oshikawa, *Phys. Rev. Lett.* **84**, 3370 (2000)

Topological argument



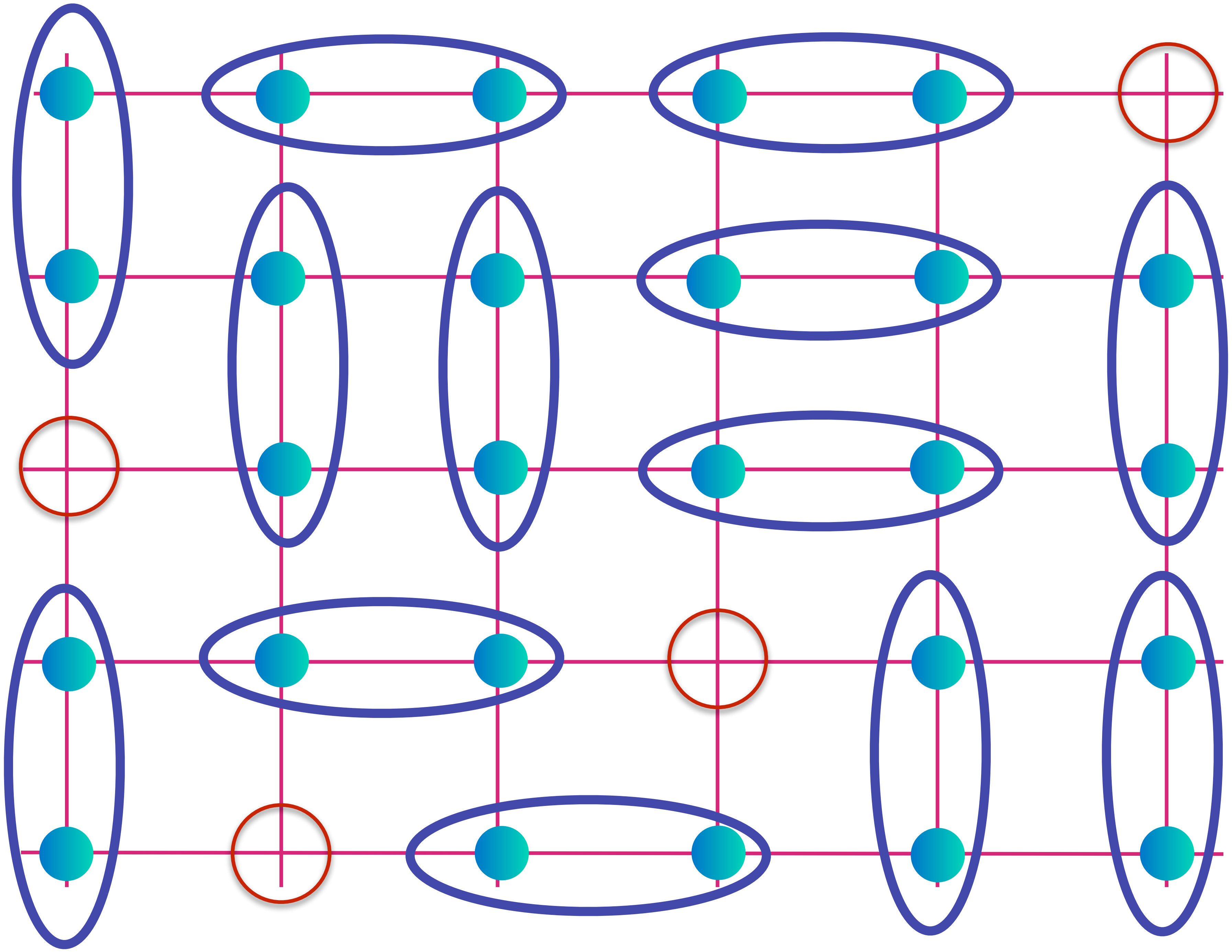
Violations of the Luttinger relation are possible in a fractionalized Fermi liquid (FL*) because there are "topological" low energy excitations associated with a flux of the emergent gauge field in the hole of the torus.

T. Senthil, M. Vojta, and S. Sachdev, *Phys. Rev. B* **69**, 035111 (2004)



Anti-ferromagnet with p holes per square

Note: relative to the fully-filled band insulator, there are $1+p$ holes per square

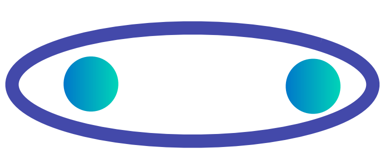


Spin liquid

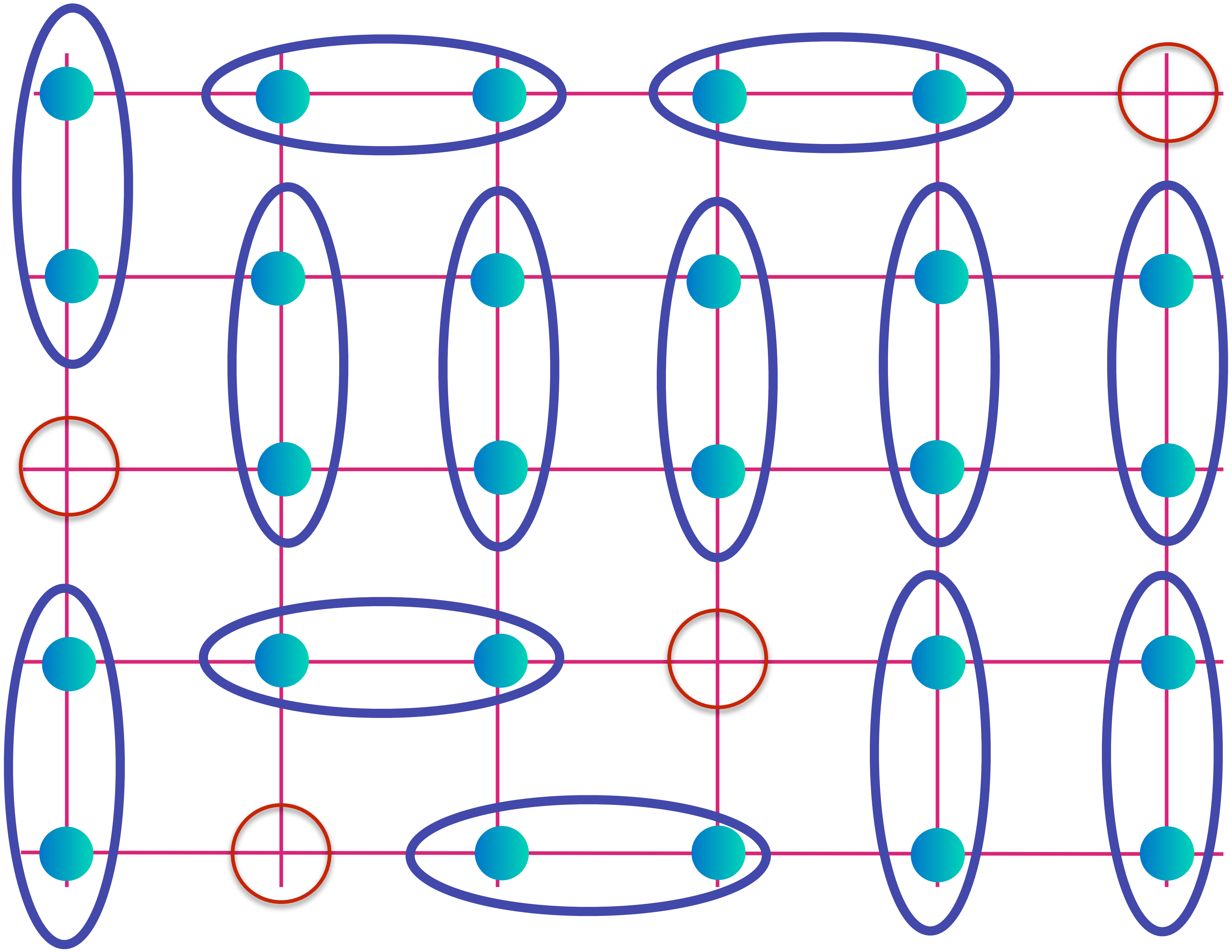
with emergent gauge field

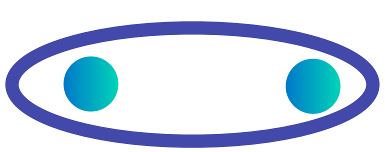
and

p "holons" (gauge-charged, spinless, charge +e quasiparticles) per square

 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Baskaran, Zou, Anderson, Fradkin, Kivelson…



 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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with emergent gauge field *and* *p* “holons" (gauge-charged, spinless, charge +e quasiparticles) per square

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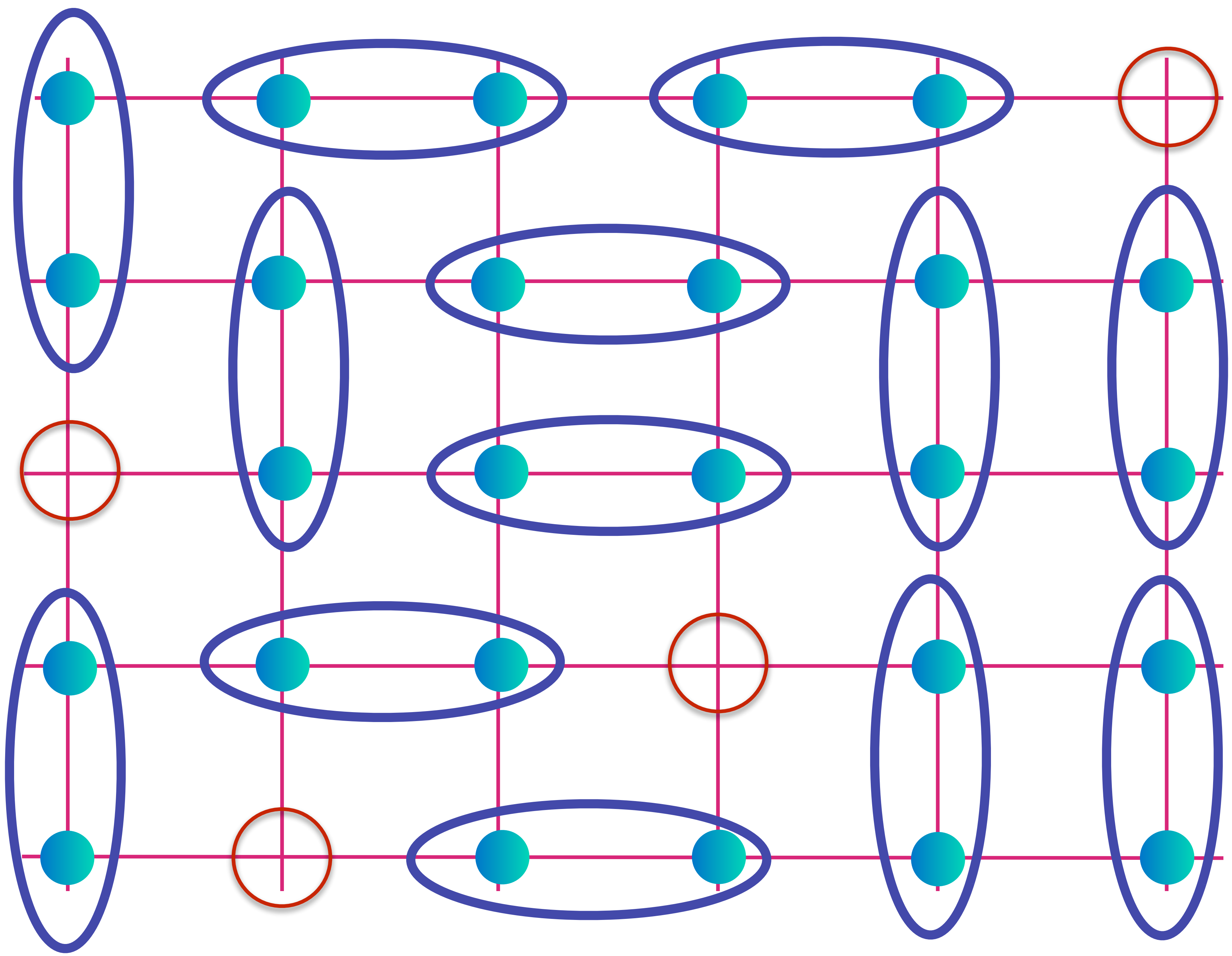

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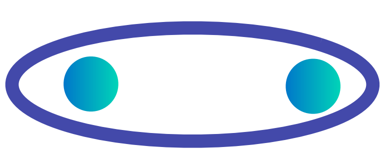 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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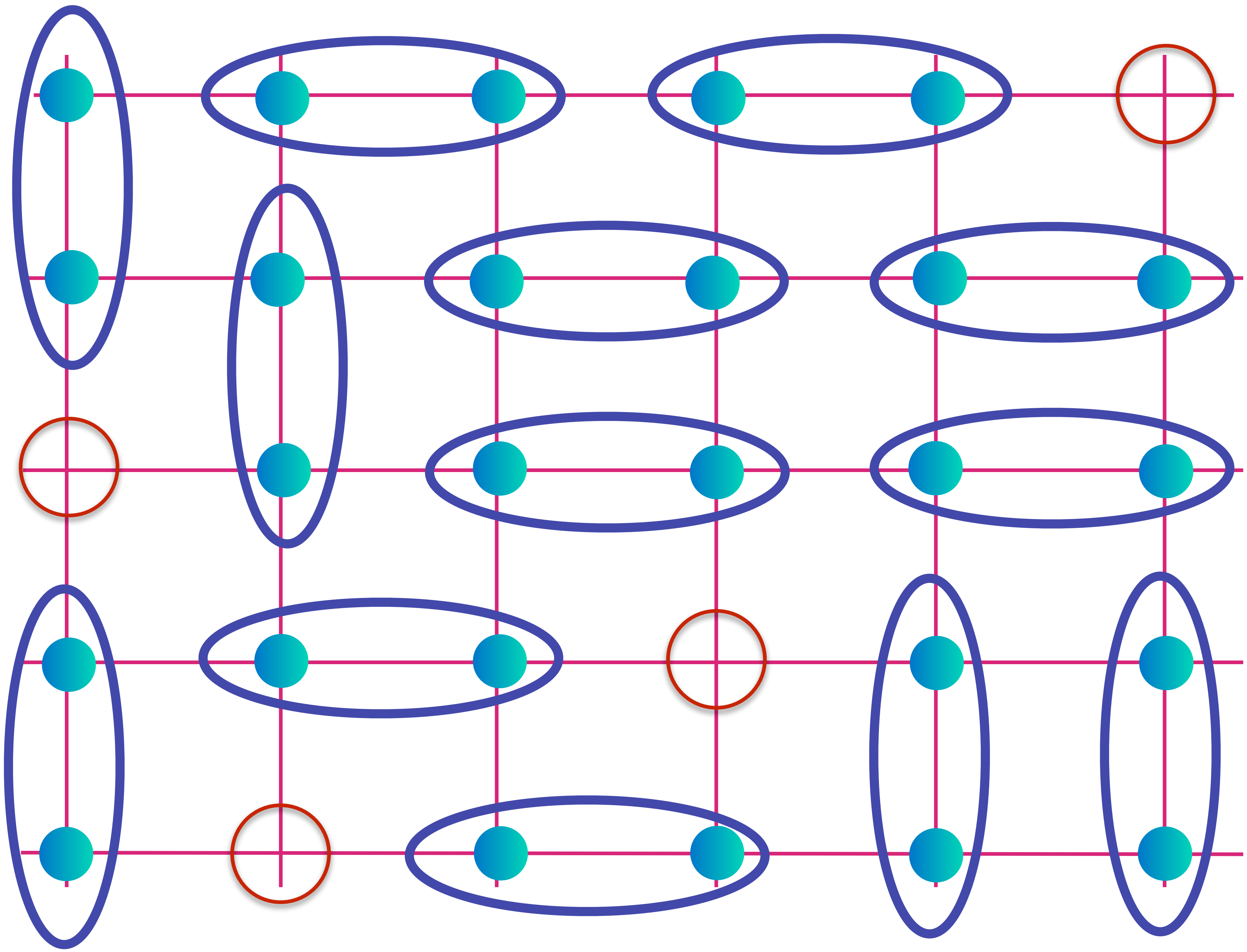

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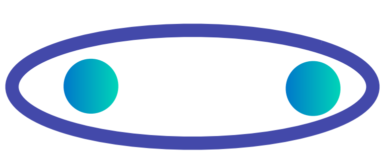 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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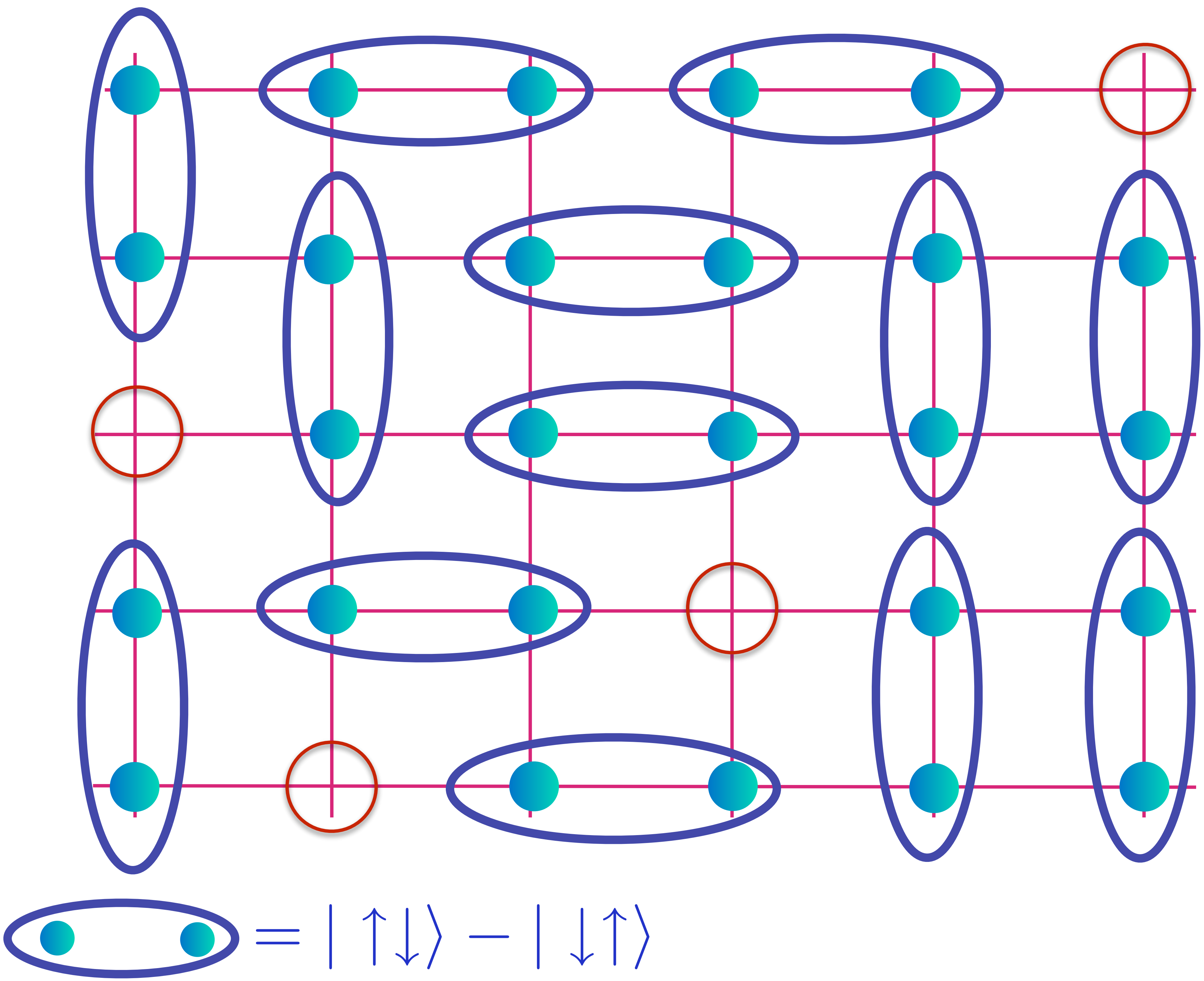

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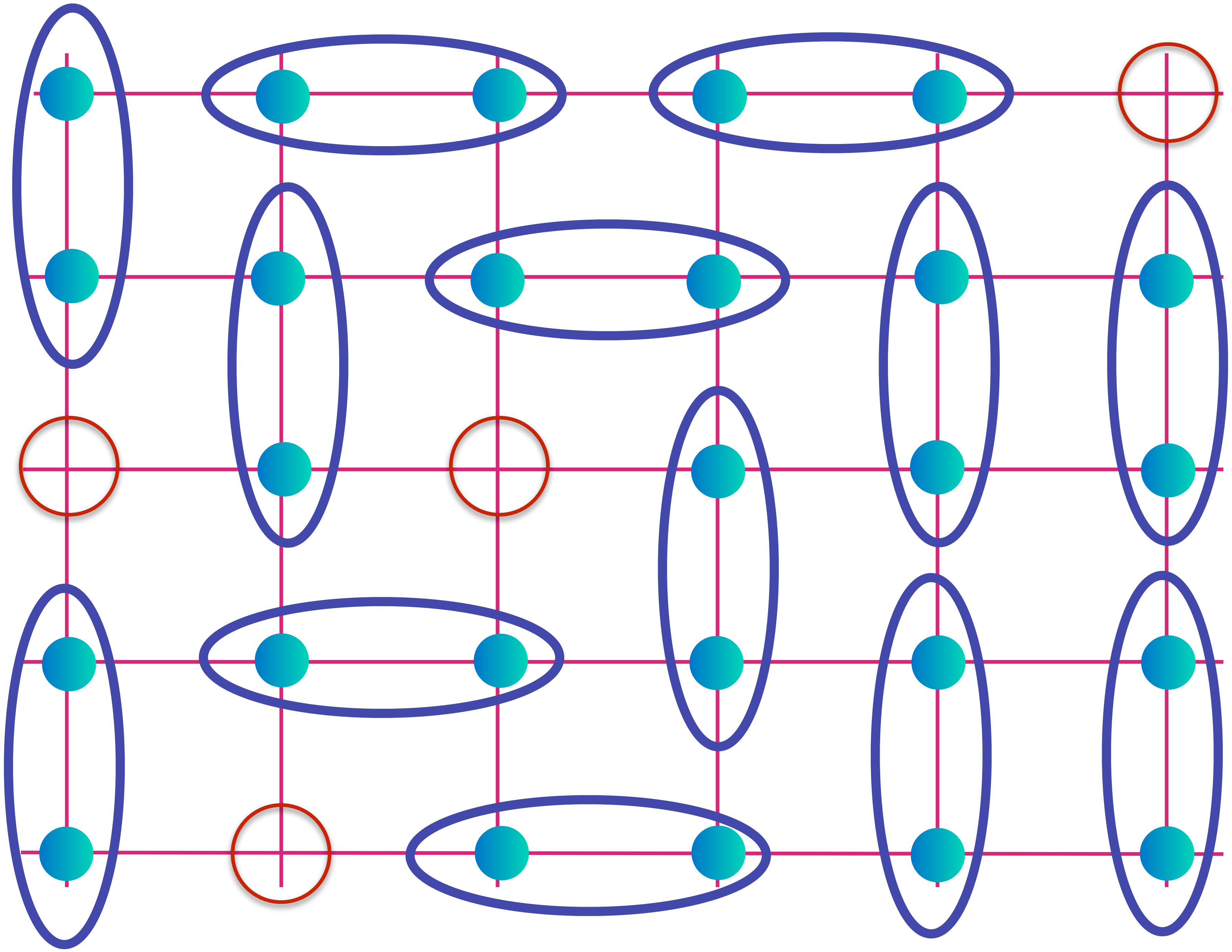

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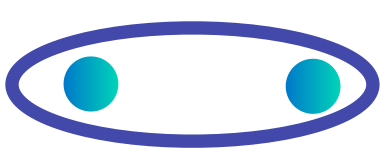 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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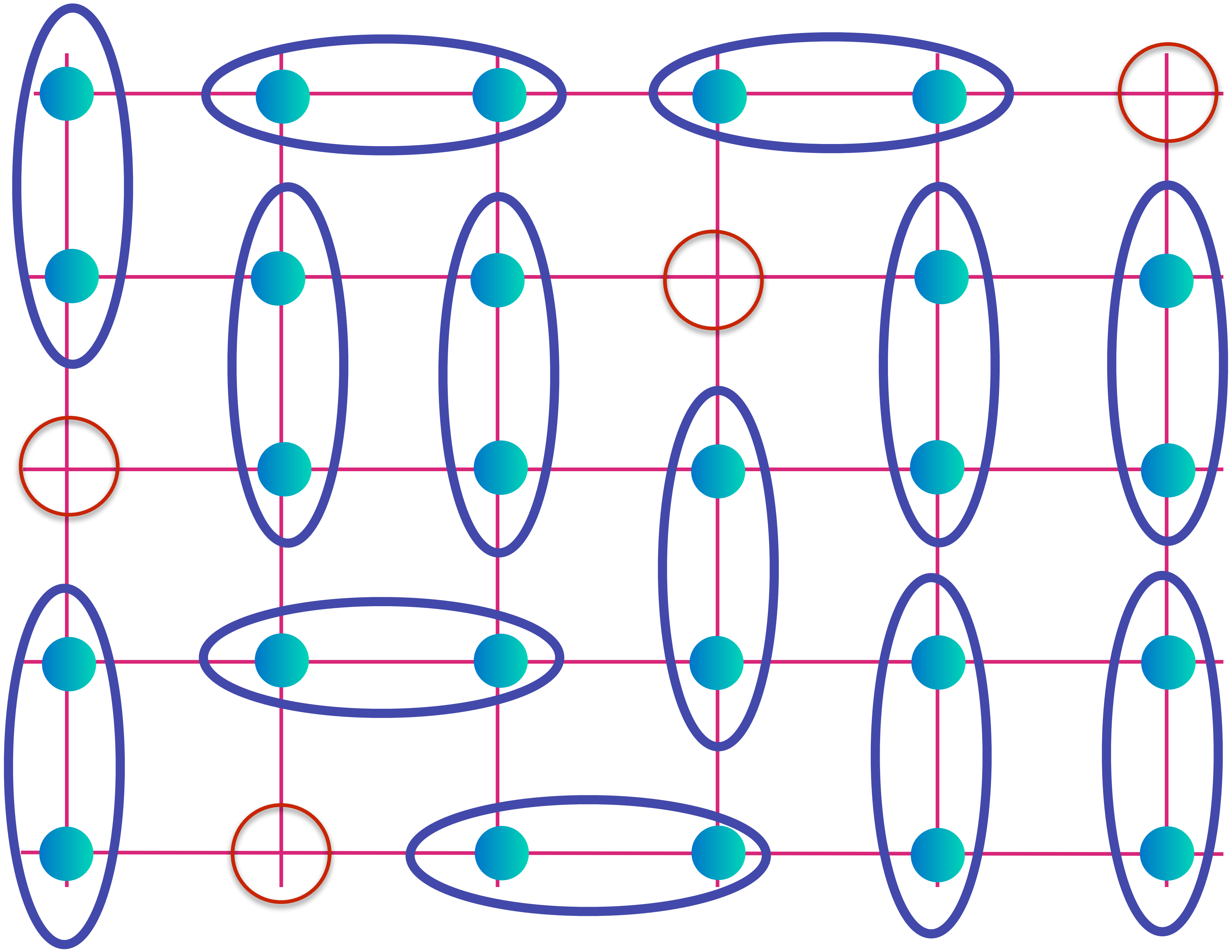

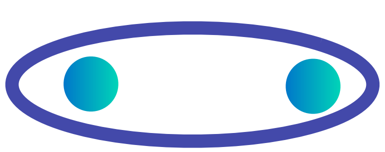 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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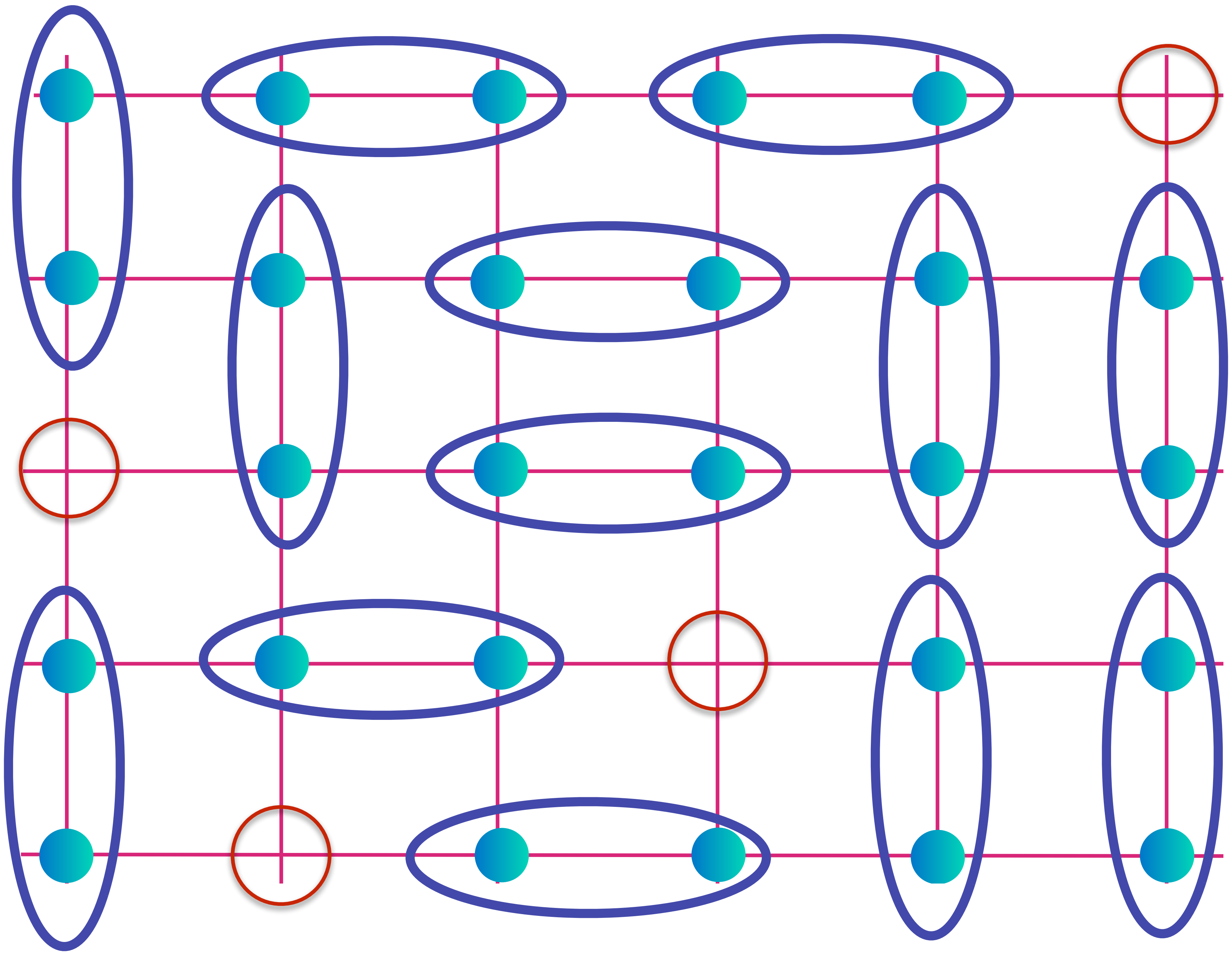

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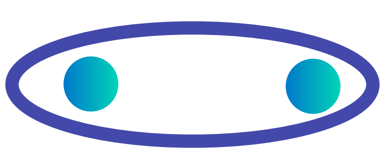
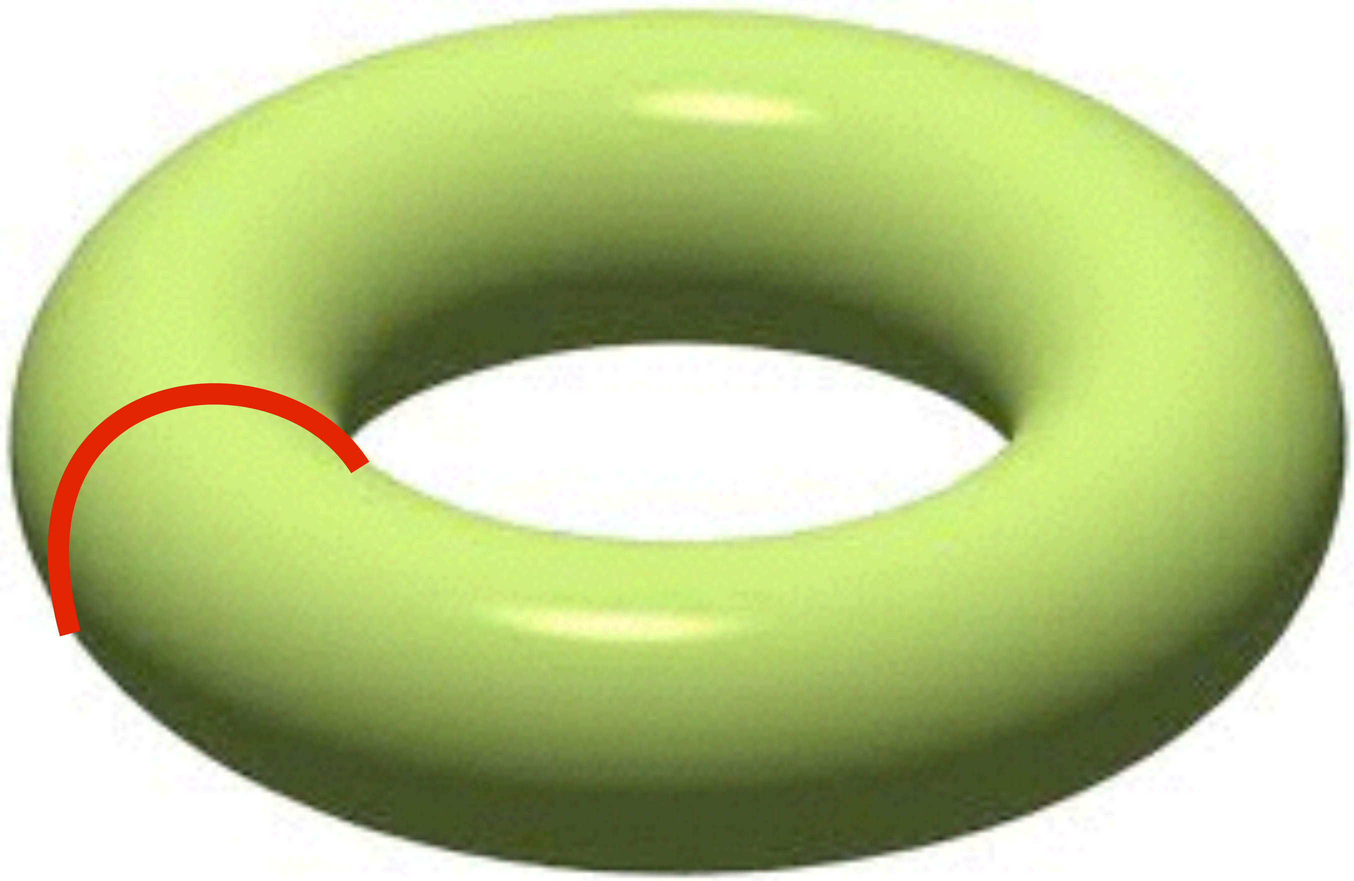
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

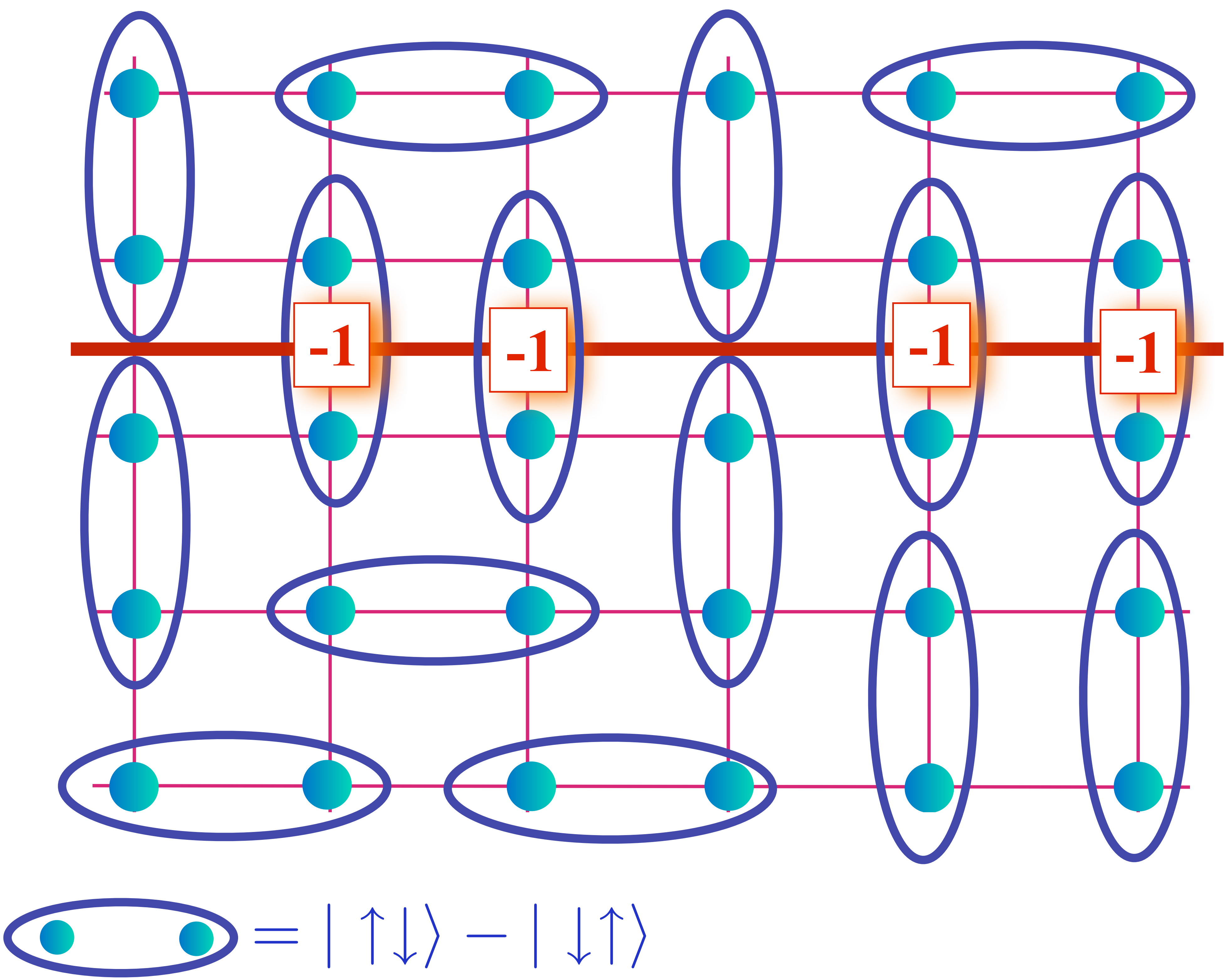
Baskaran, Zou, Anderson, Fradkin, Kivelson…

Spin liquid.
Place on a torus;



Spin liquid.

Place on a torus; to obtain "topological" states nearly degenerate with the ground state: change sign of every singlet bond across red line



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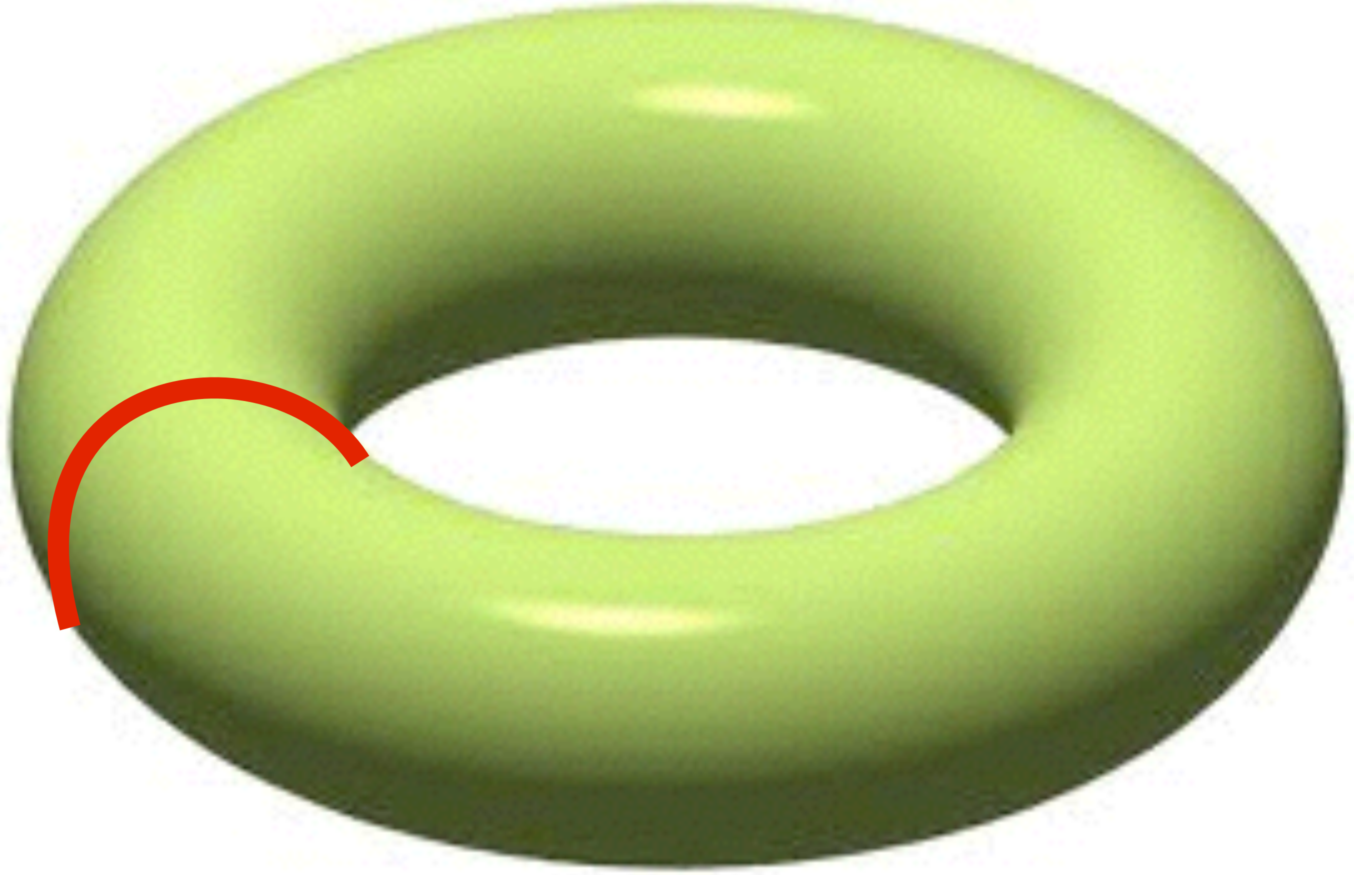
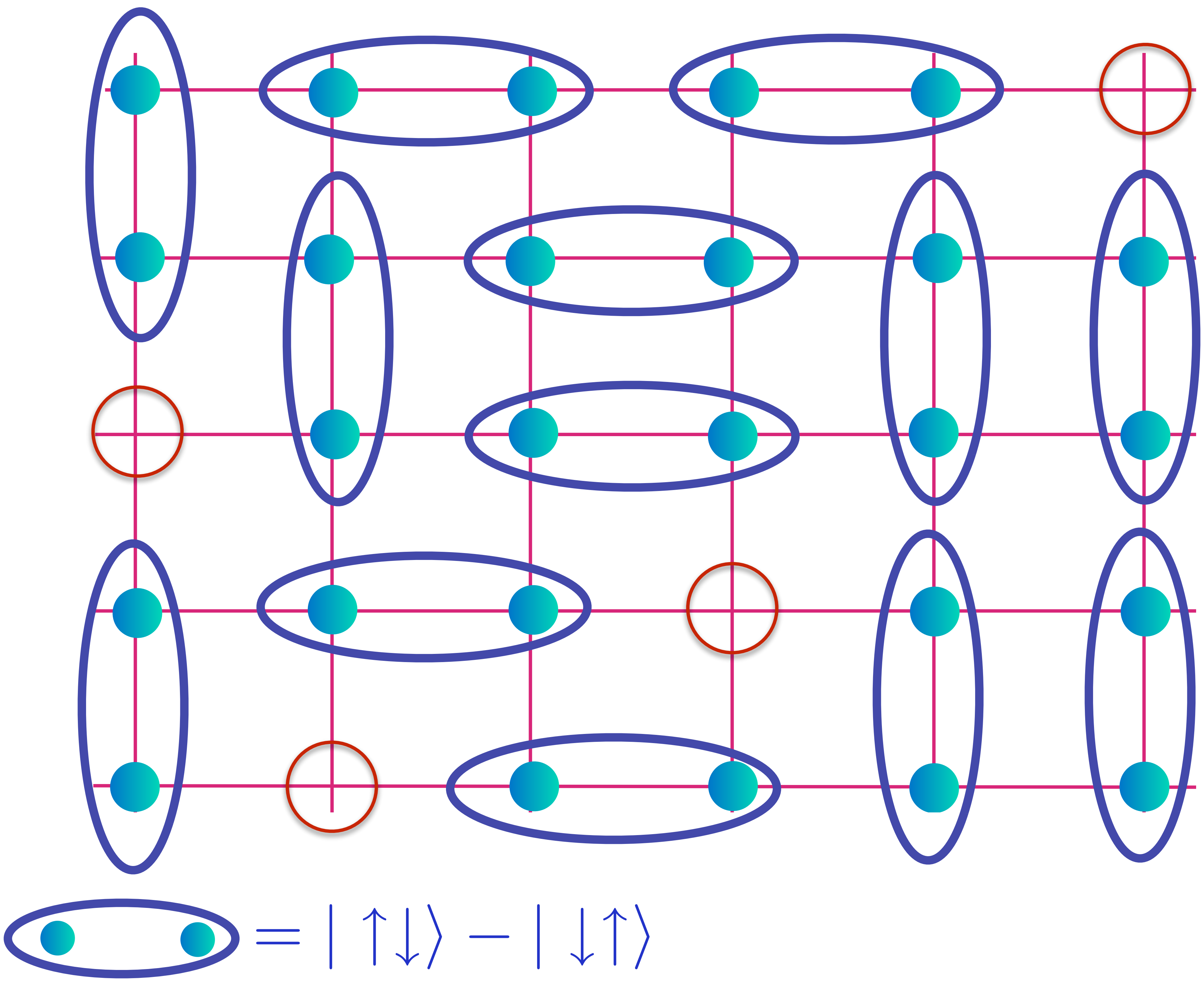


Spin liquid.

These "topological" states are needed to allow for Fermi surfaces of total size p (and not $1+p$)



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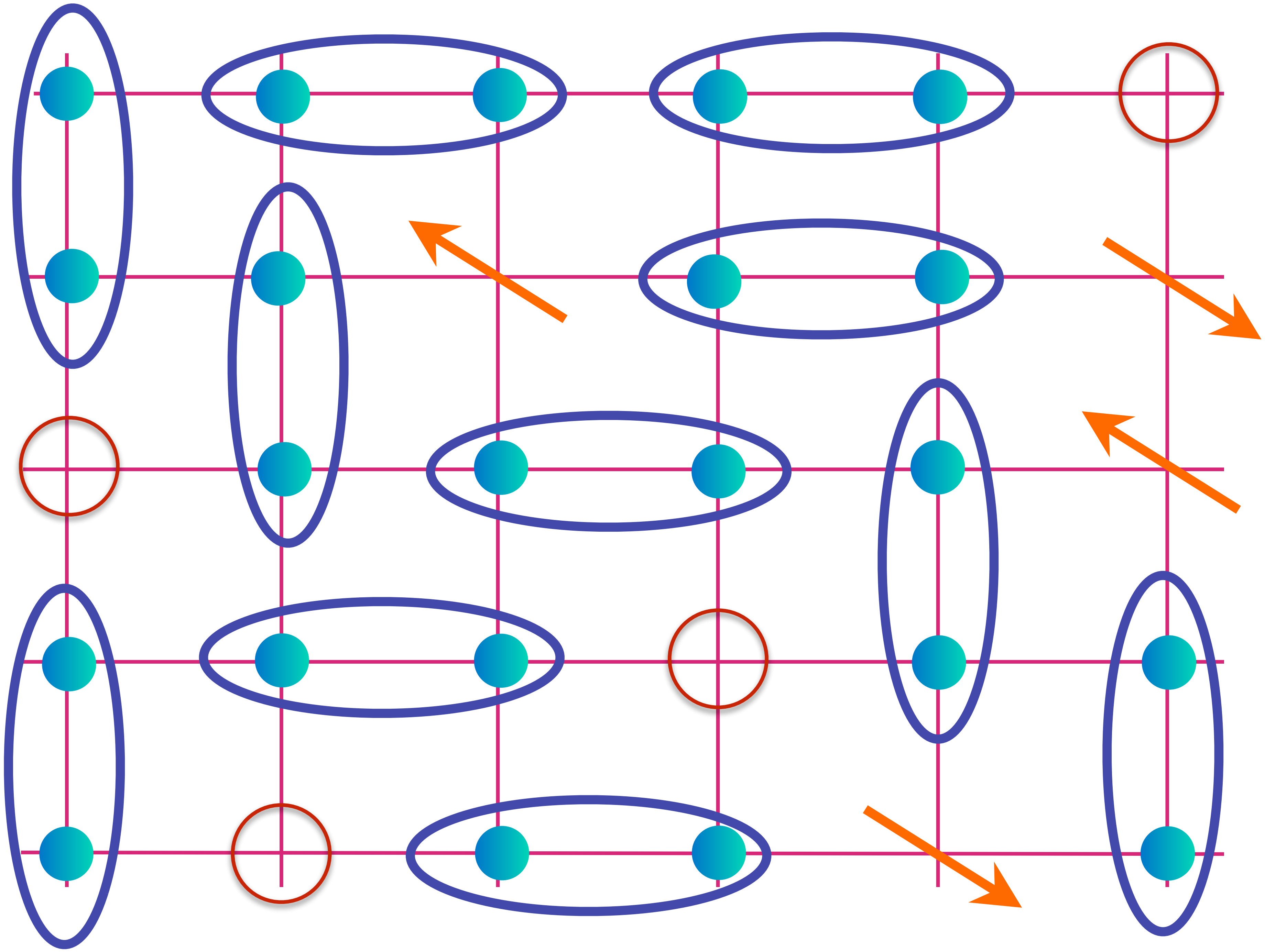
Baskaran, Zou, Anderson, Fradkin, Kivelson…

Gauge-charged, spin S=1/2, neutral “spinon” excitations



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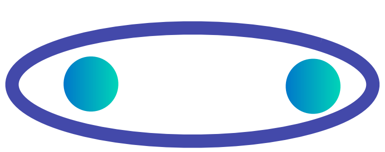
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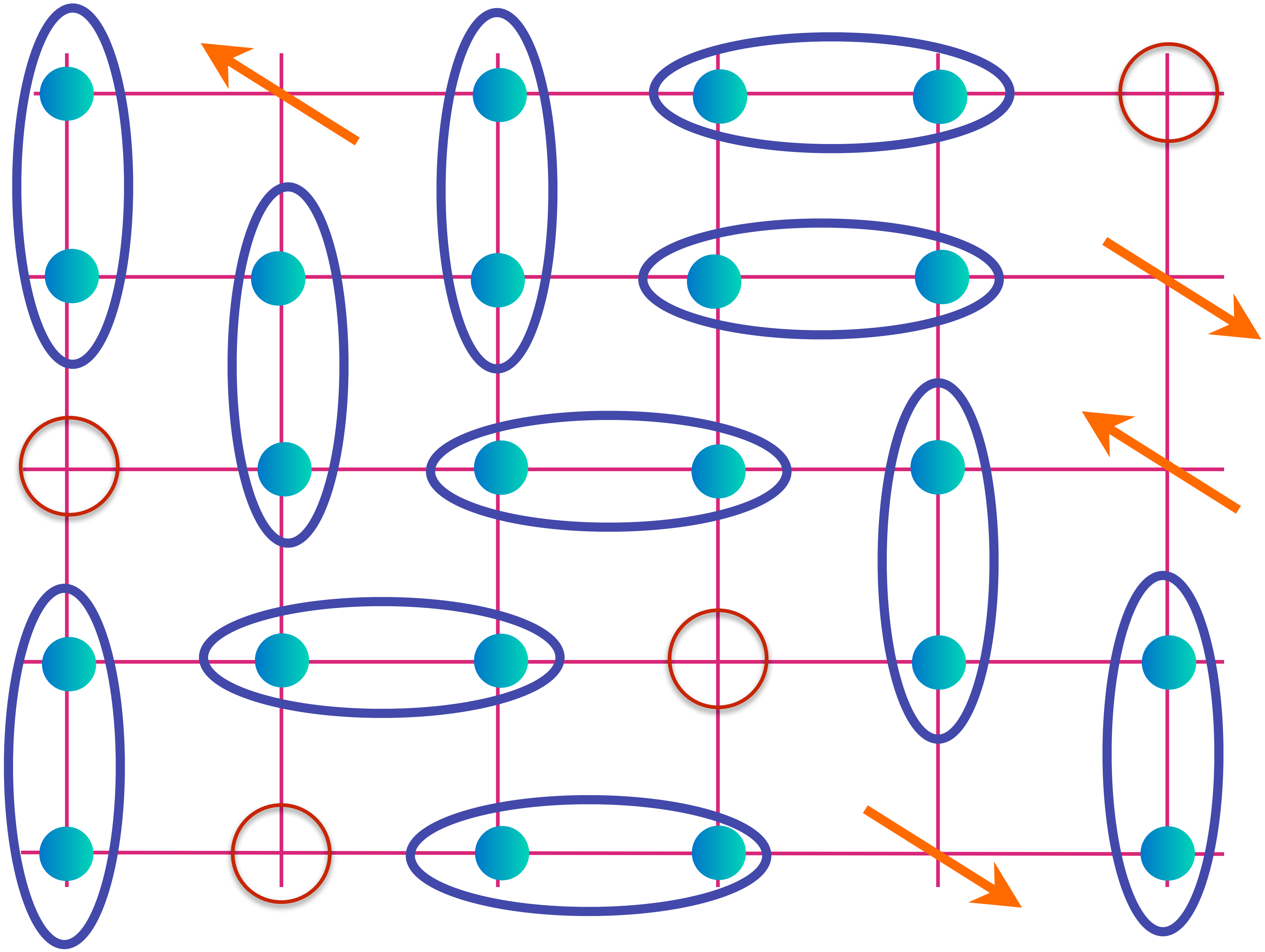

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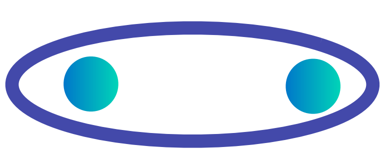
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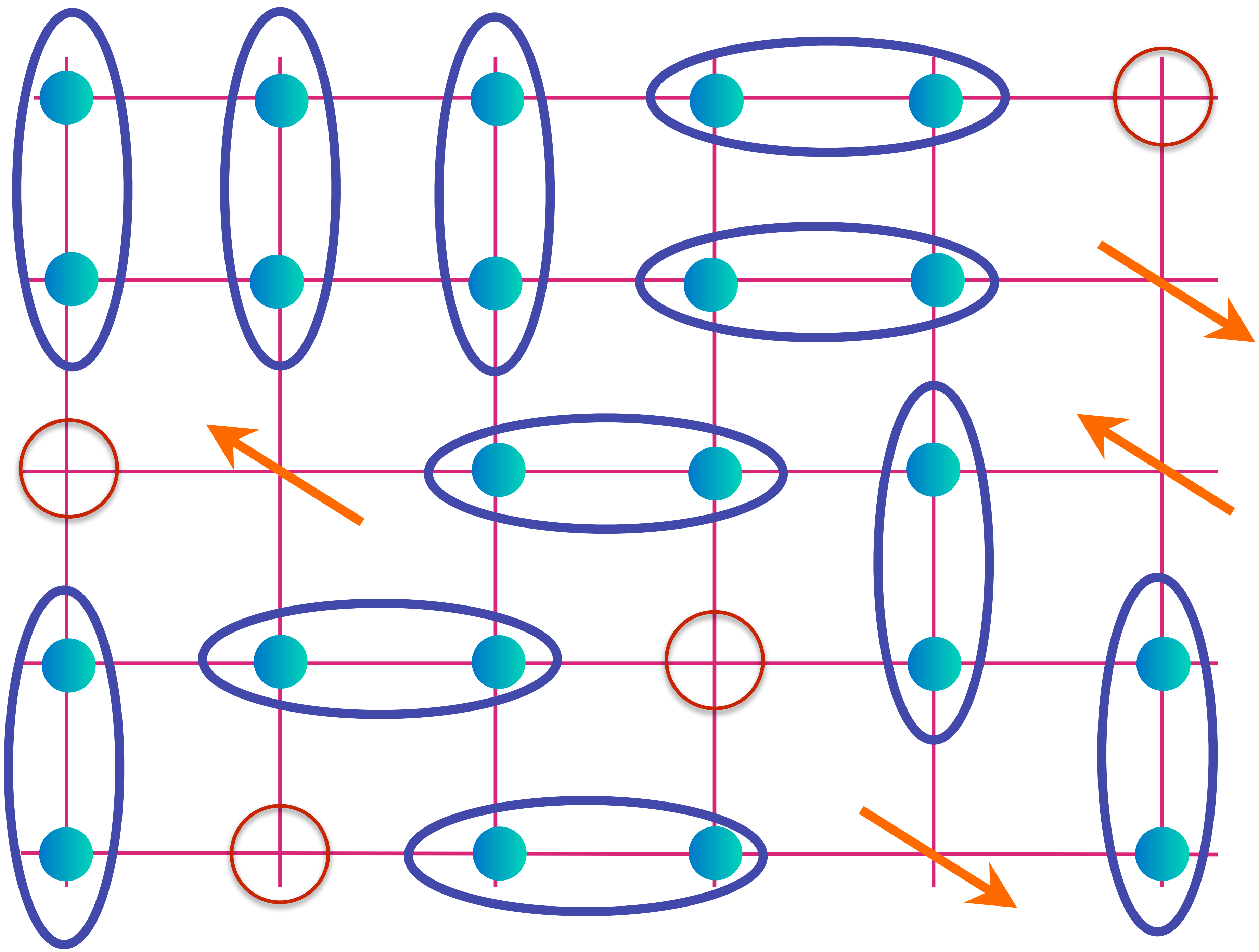

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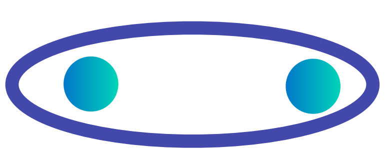 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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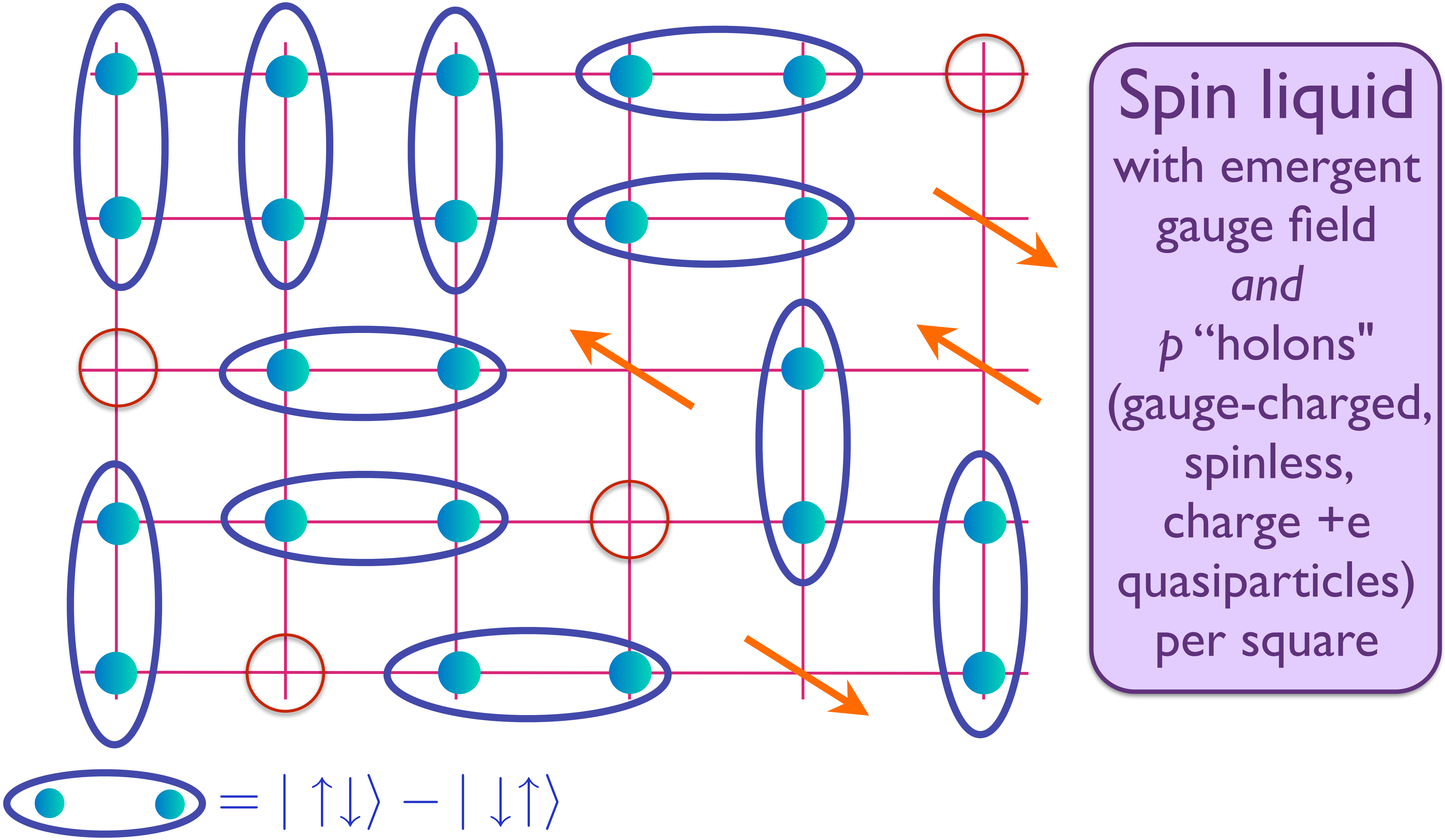

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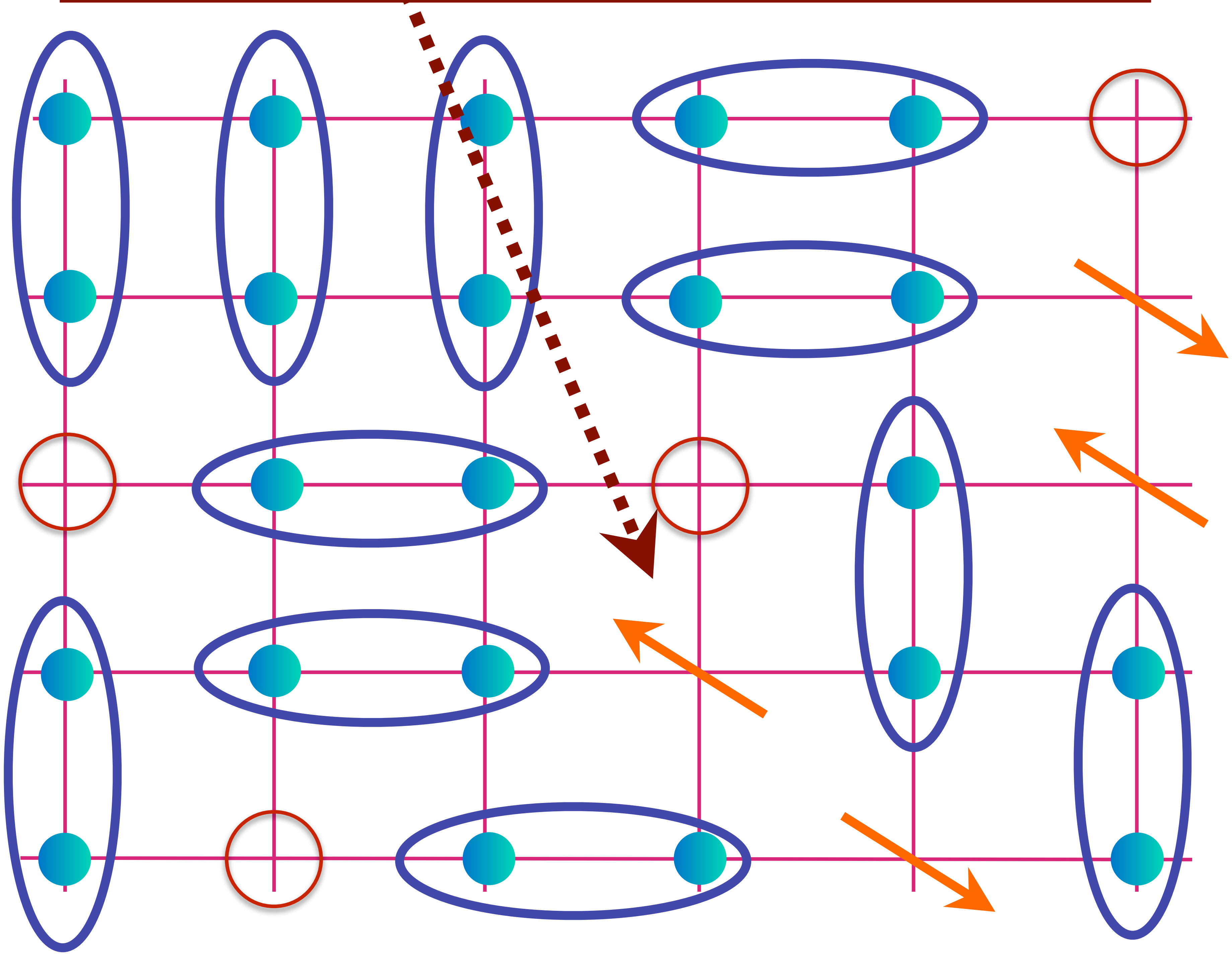
Nearest-neighbor hopping leads to attraction between holon and spinon, which can pay for the energy needed to create the spinon



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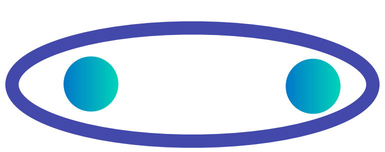 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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

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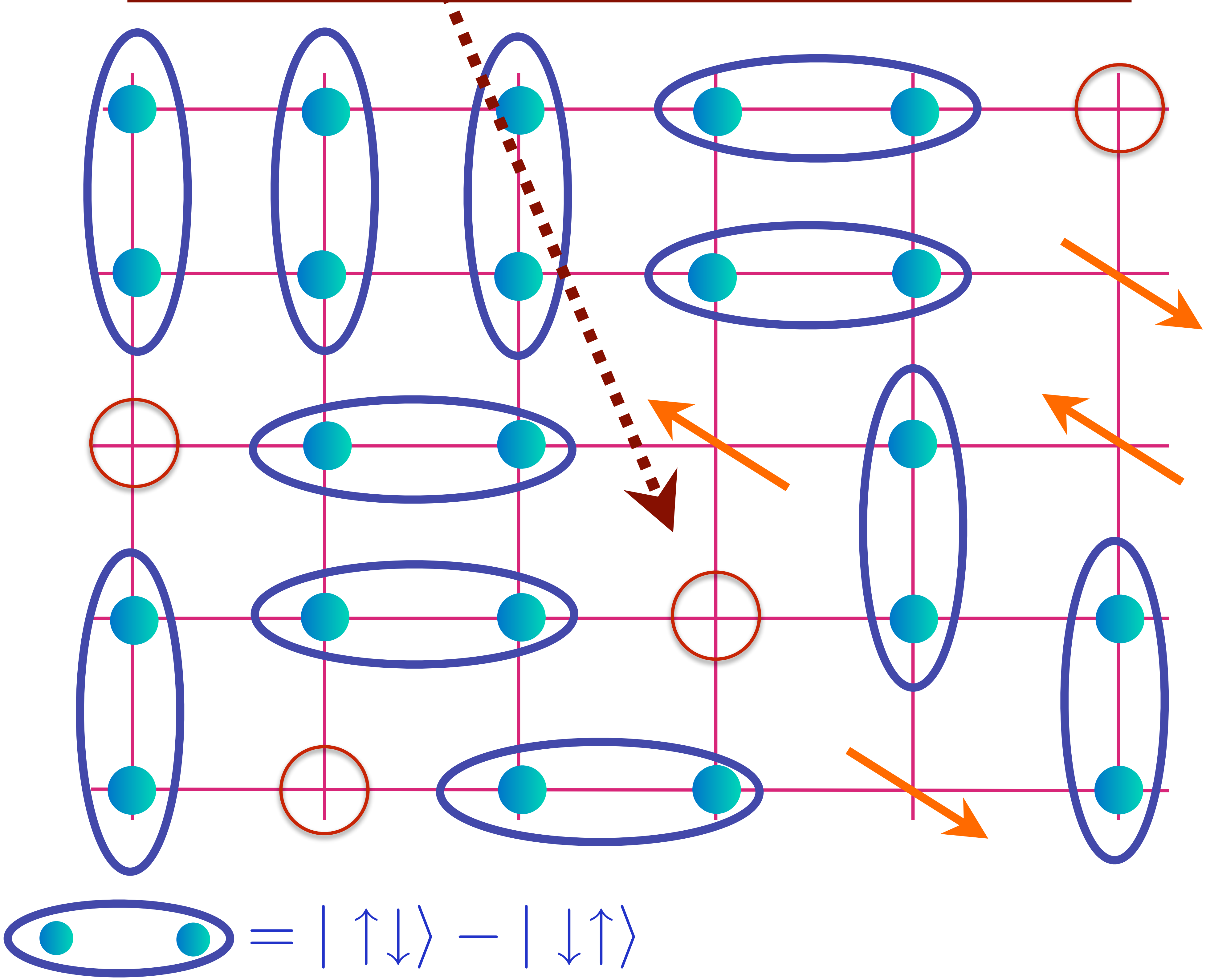

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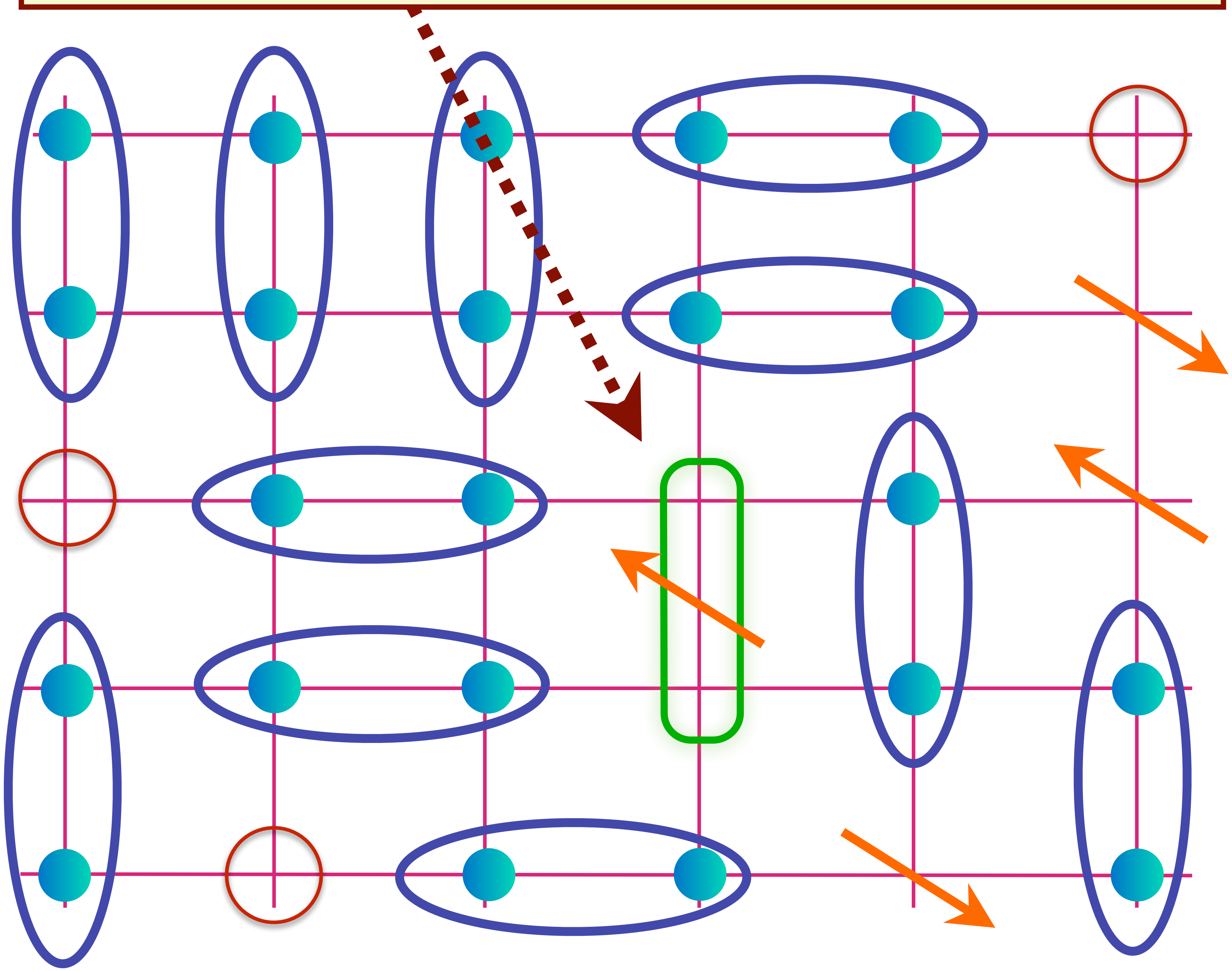
Spinon-holon bound state resides on a “bonding” orbital between two sites



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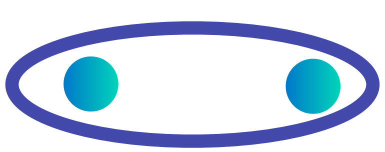 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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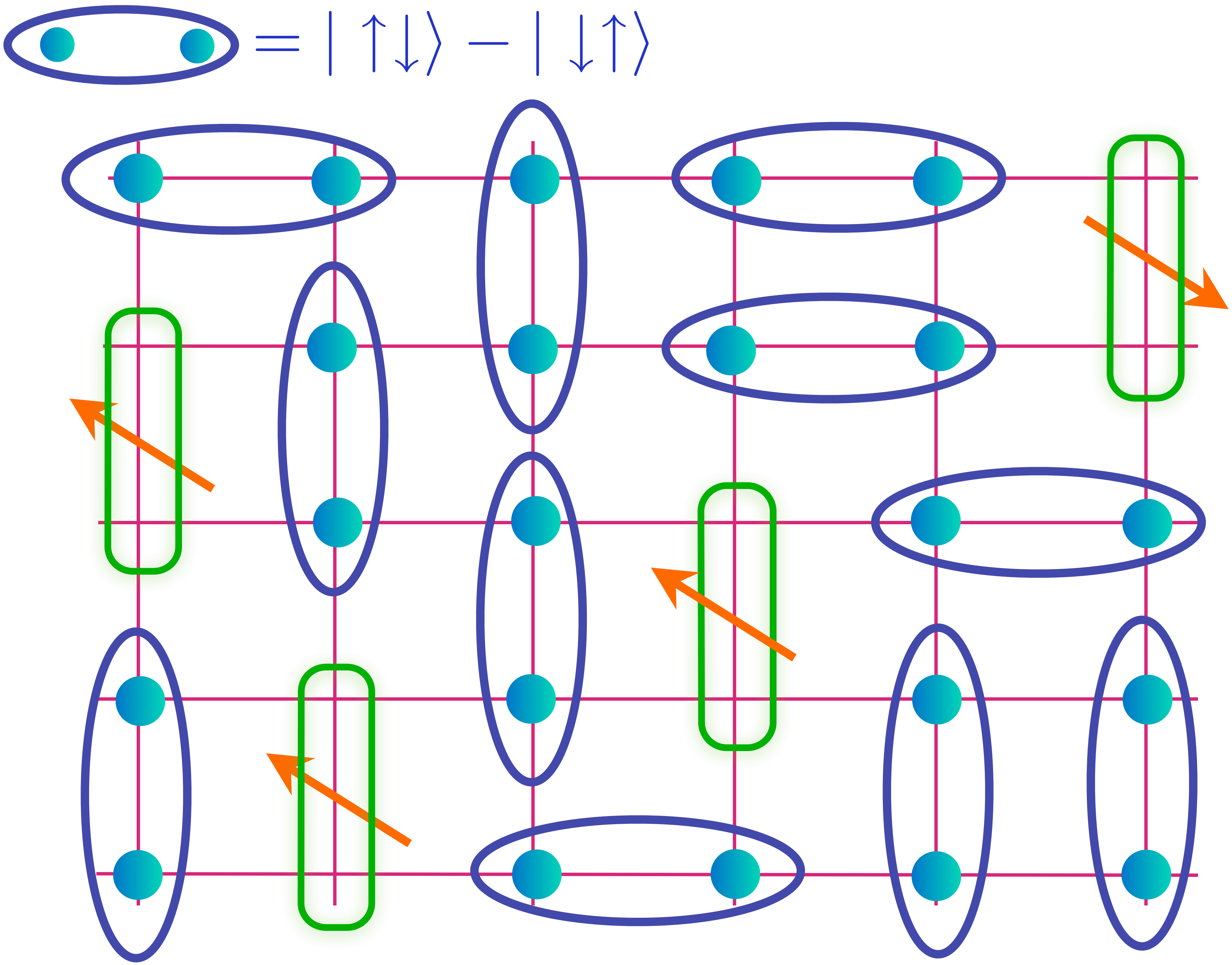
Fractionalized Fermi liquid (FL*)



Emergent gauge field *and* gauge-neutral, spin S=1/2, charge +e fermions of density p

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E. G. Moon and S. S. Phys. Rev. B **83**, 224508 (2011); M. Punk, A. Allais, and S. S., arXiv:1501.00978.

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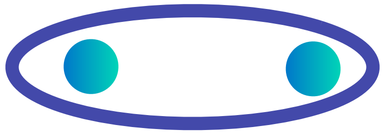
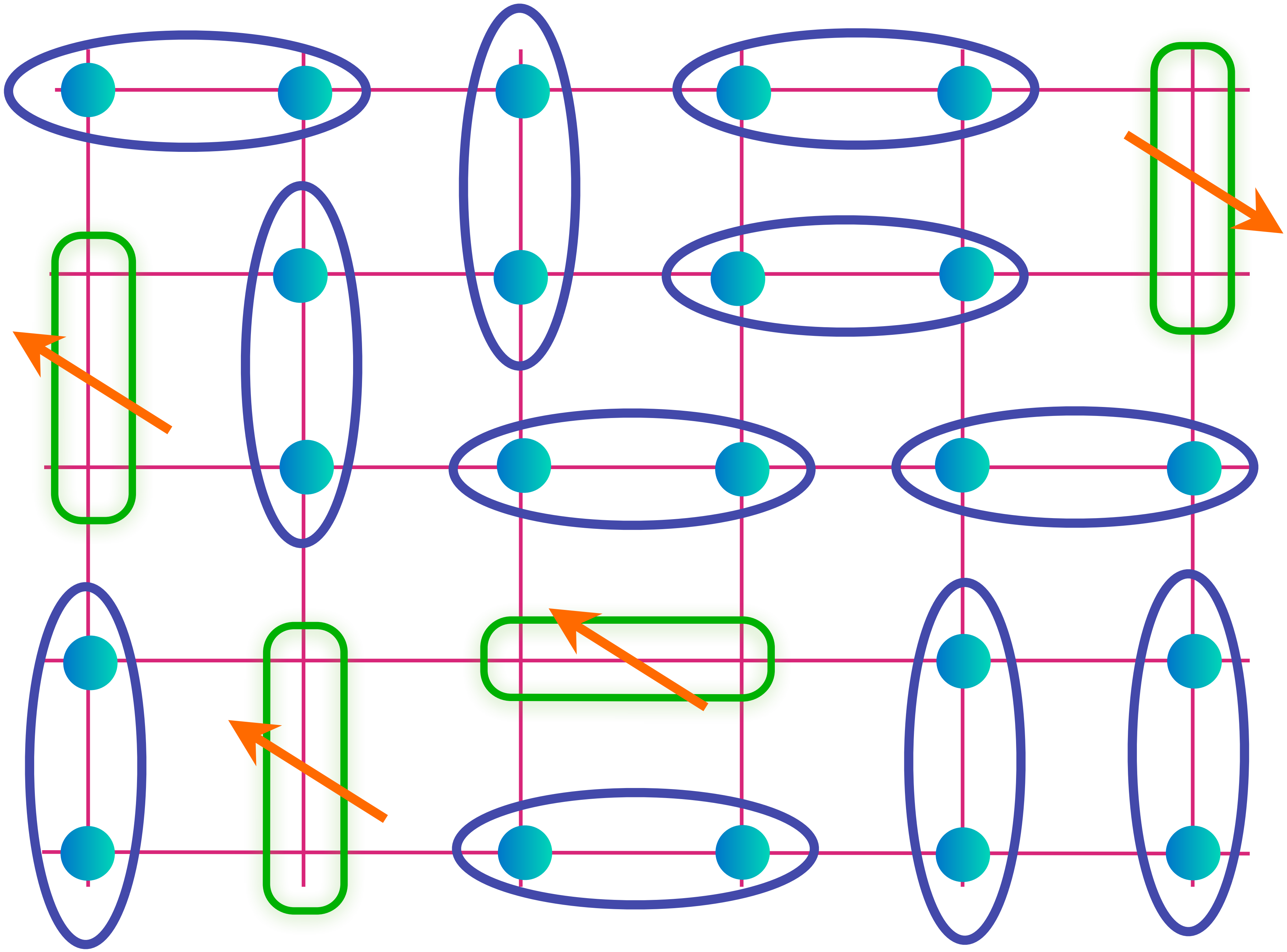
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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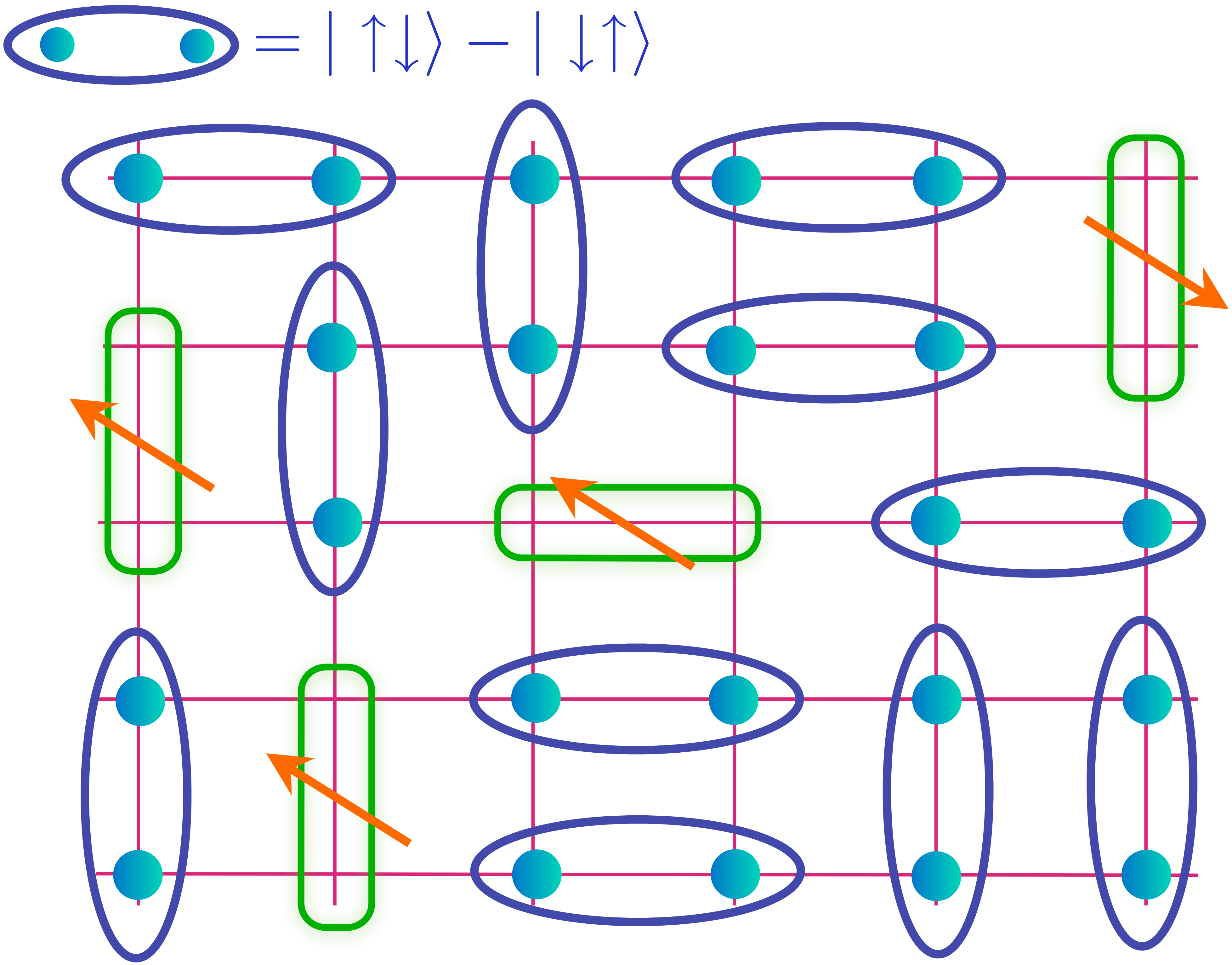
R. K. Kaul, A. Kolezhuk, M. Levin, S. S., and T. Senthil, *Phys. Rev. B* **75**, 235122 (2007)

E. G. Moon and S. S. Phys. Rev. B **83**, 224508 (2011); M. Punk, A. Allais, and S. S., arXiv:1501.00978.

Fractionalized Fermi liquid (FL*)



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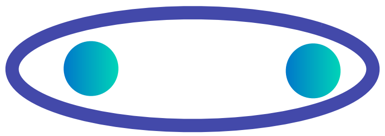
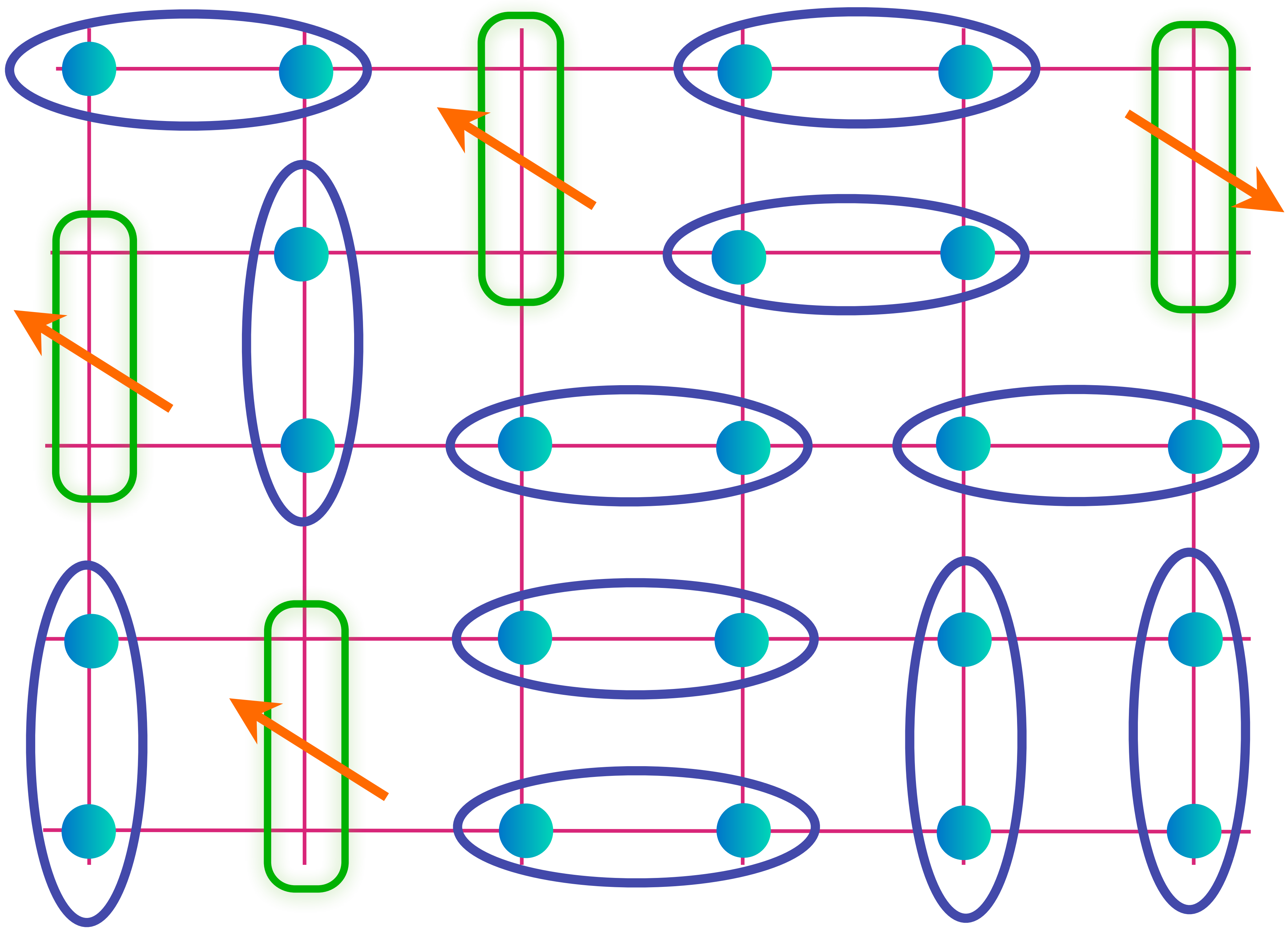
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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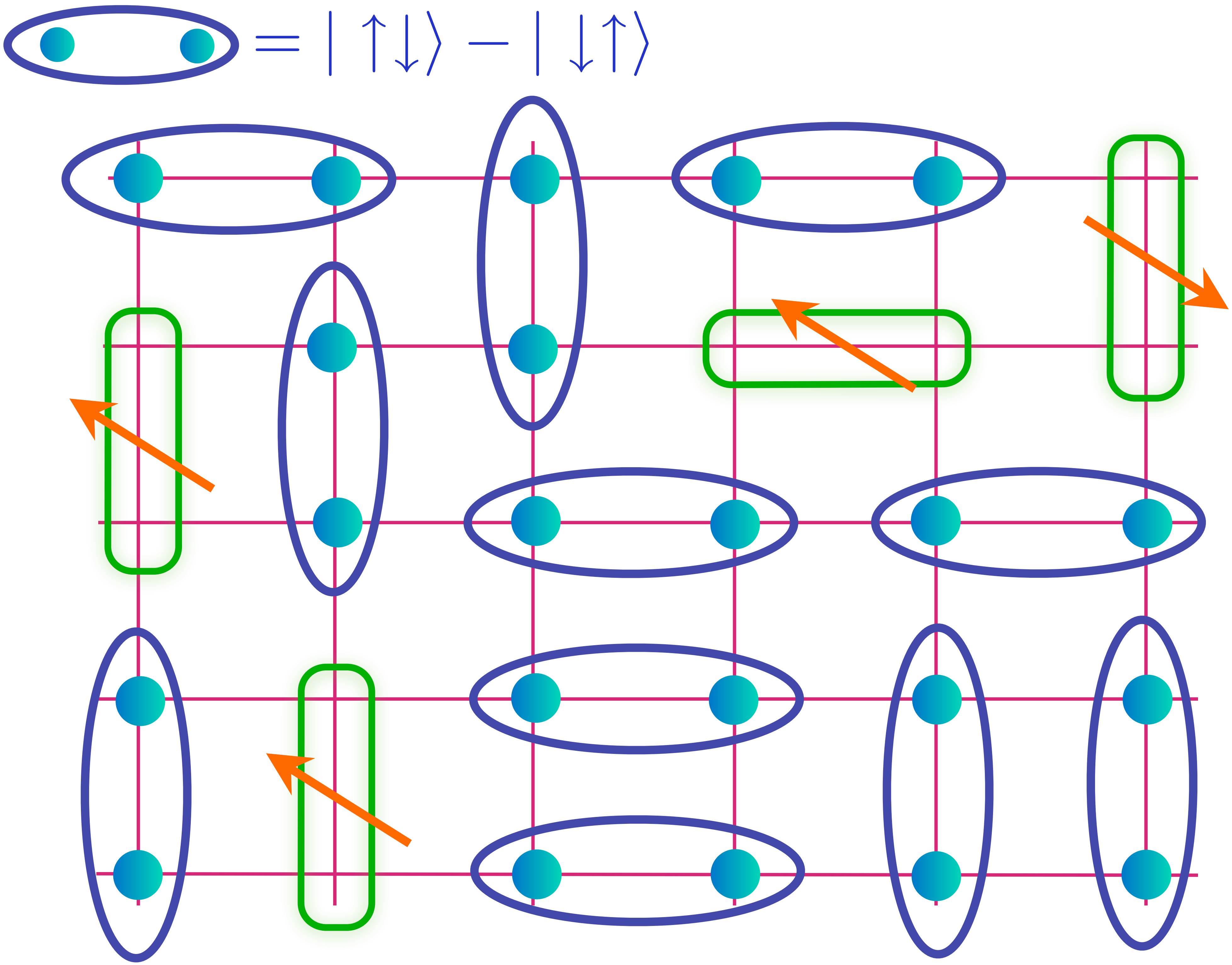

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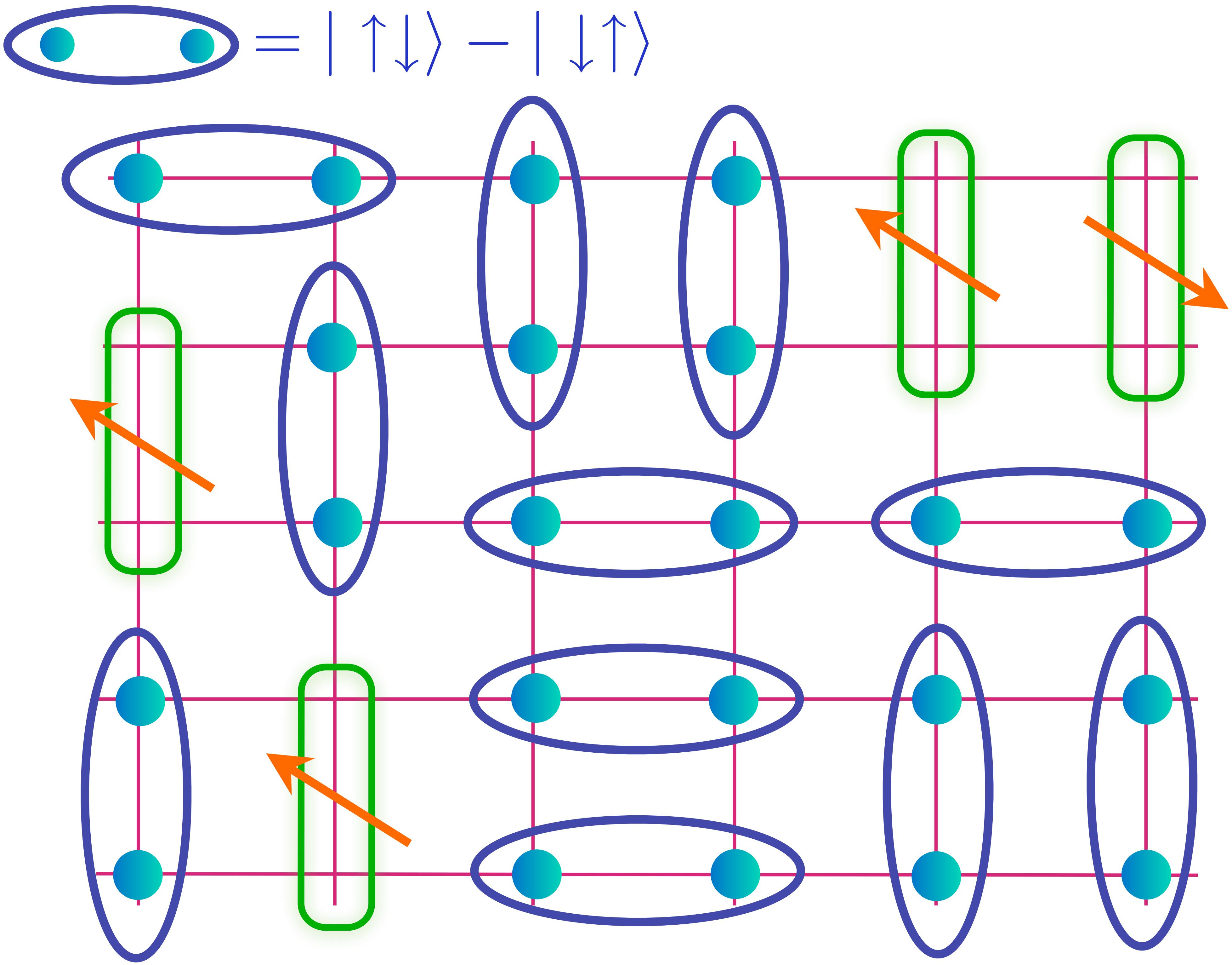

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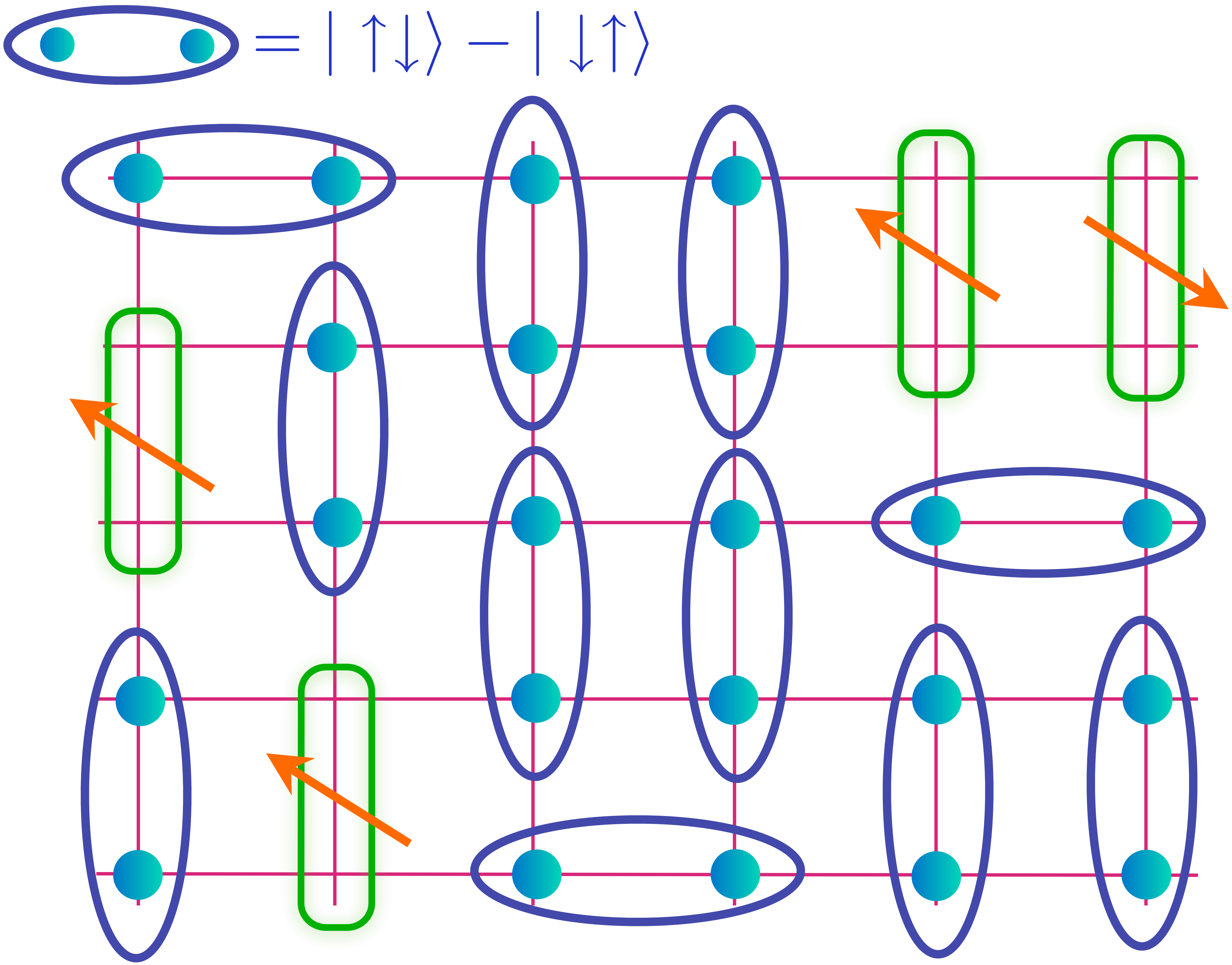

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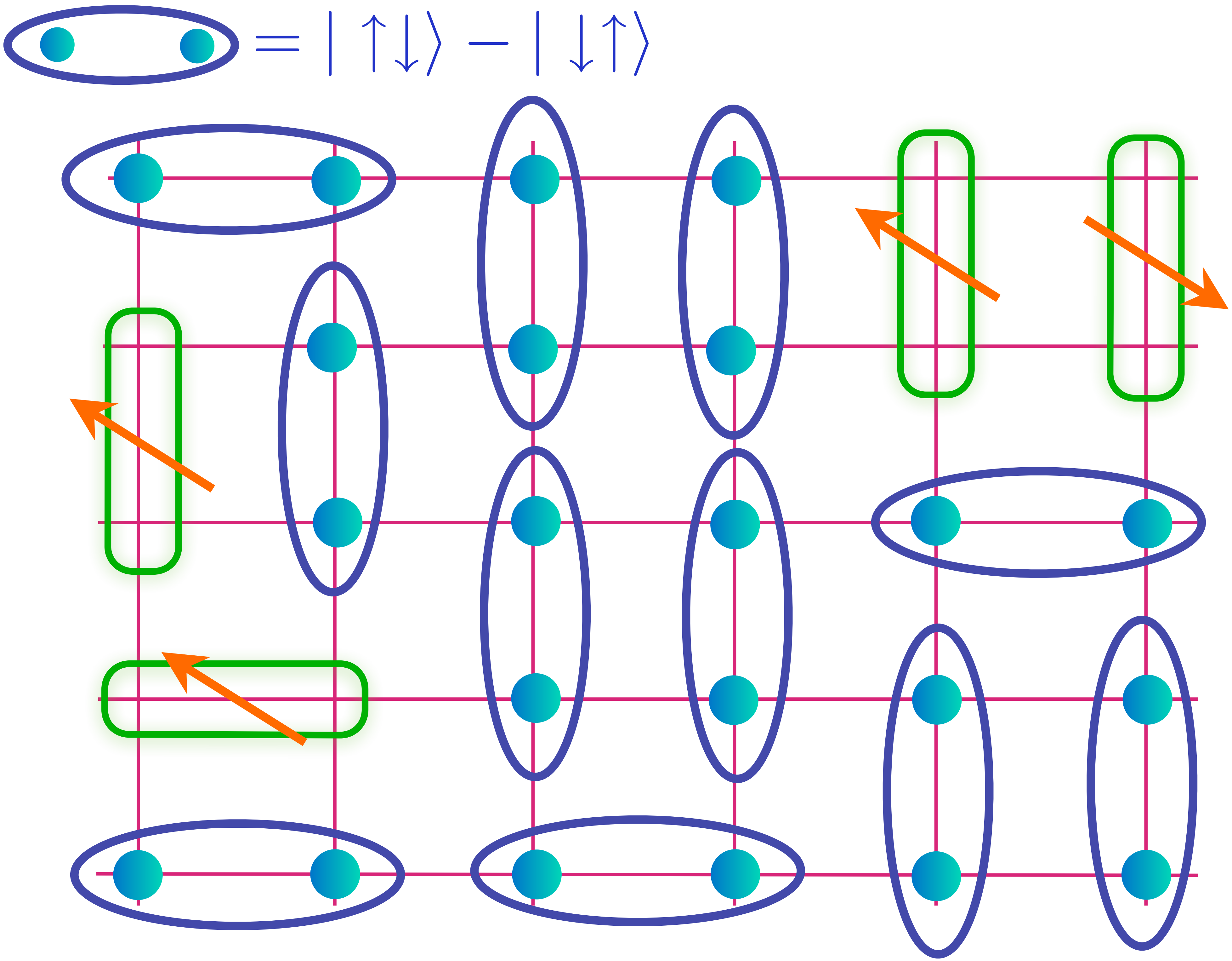

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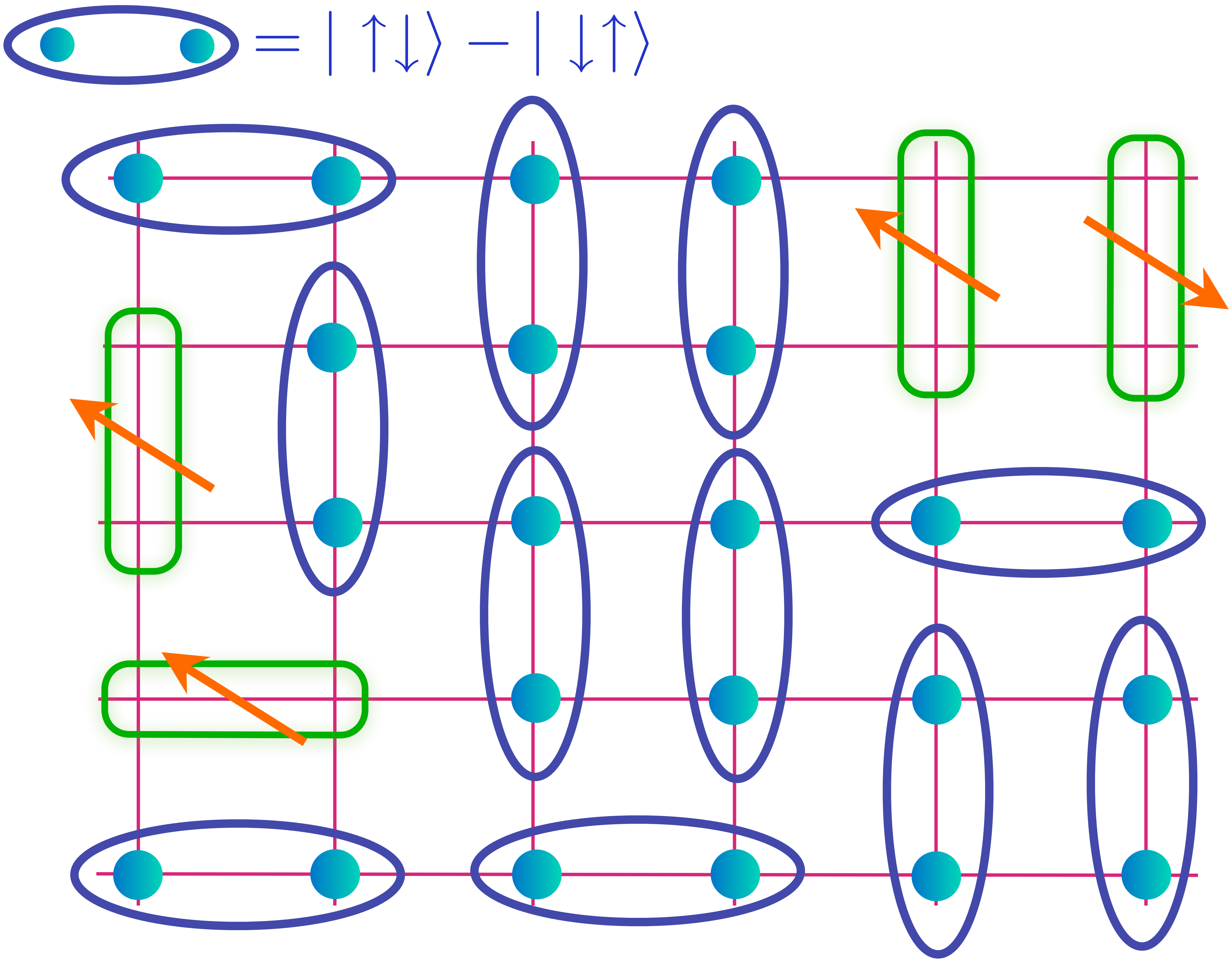

$$= | \uparrow\downarrow\rangle - | \downarrow\uparrow\rangle$$

Note: electron-like quasiparticle can only be a dimer because of spin-liquid background; it is not possible to have it on a single site

T. Senthil, S. S., M. Vojta *Phys. Rev. Lett.* **90**, 216403 (2003)

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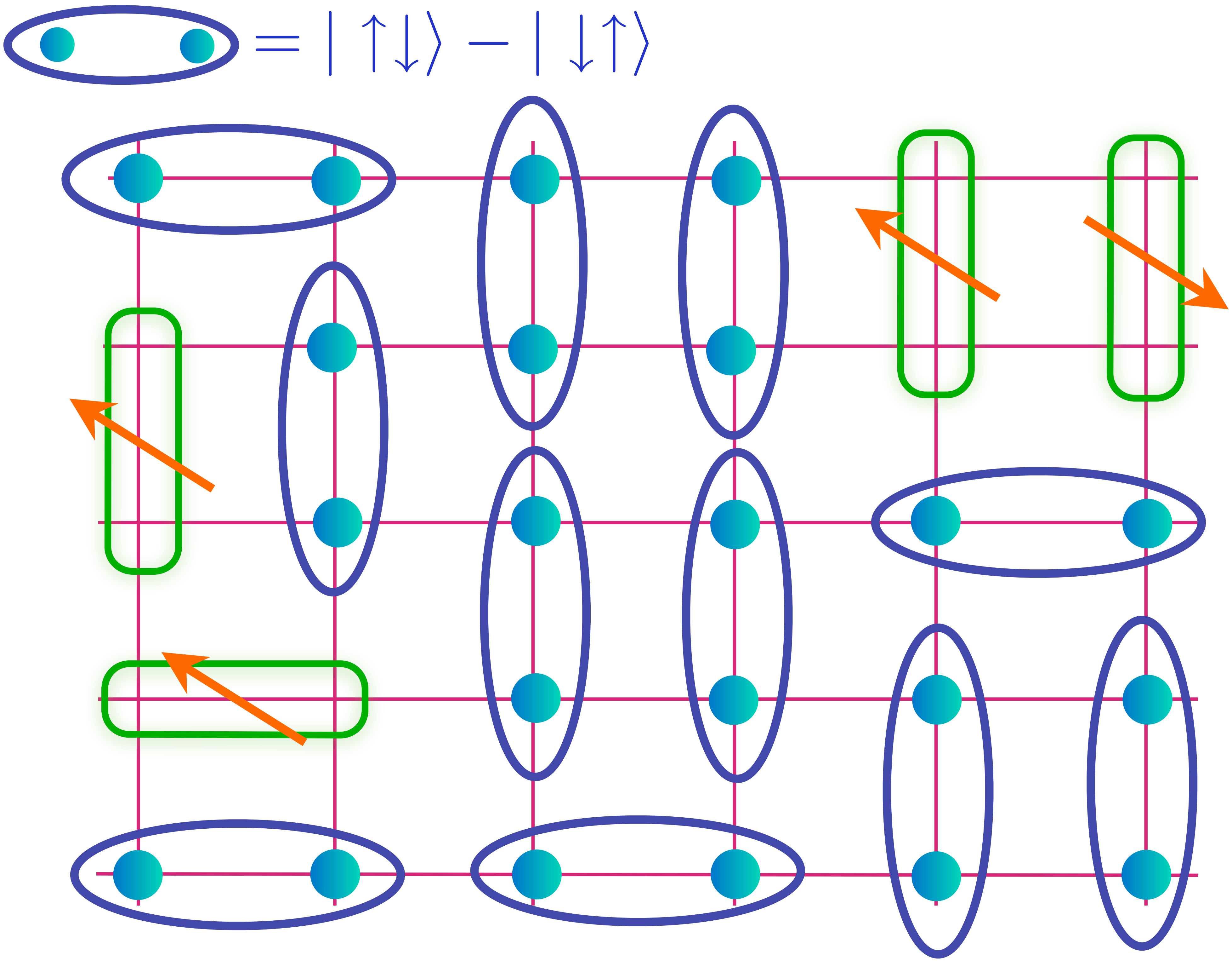


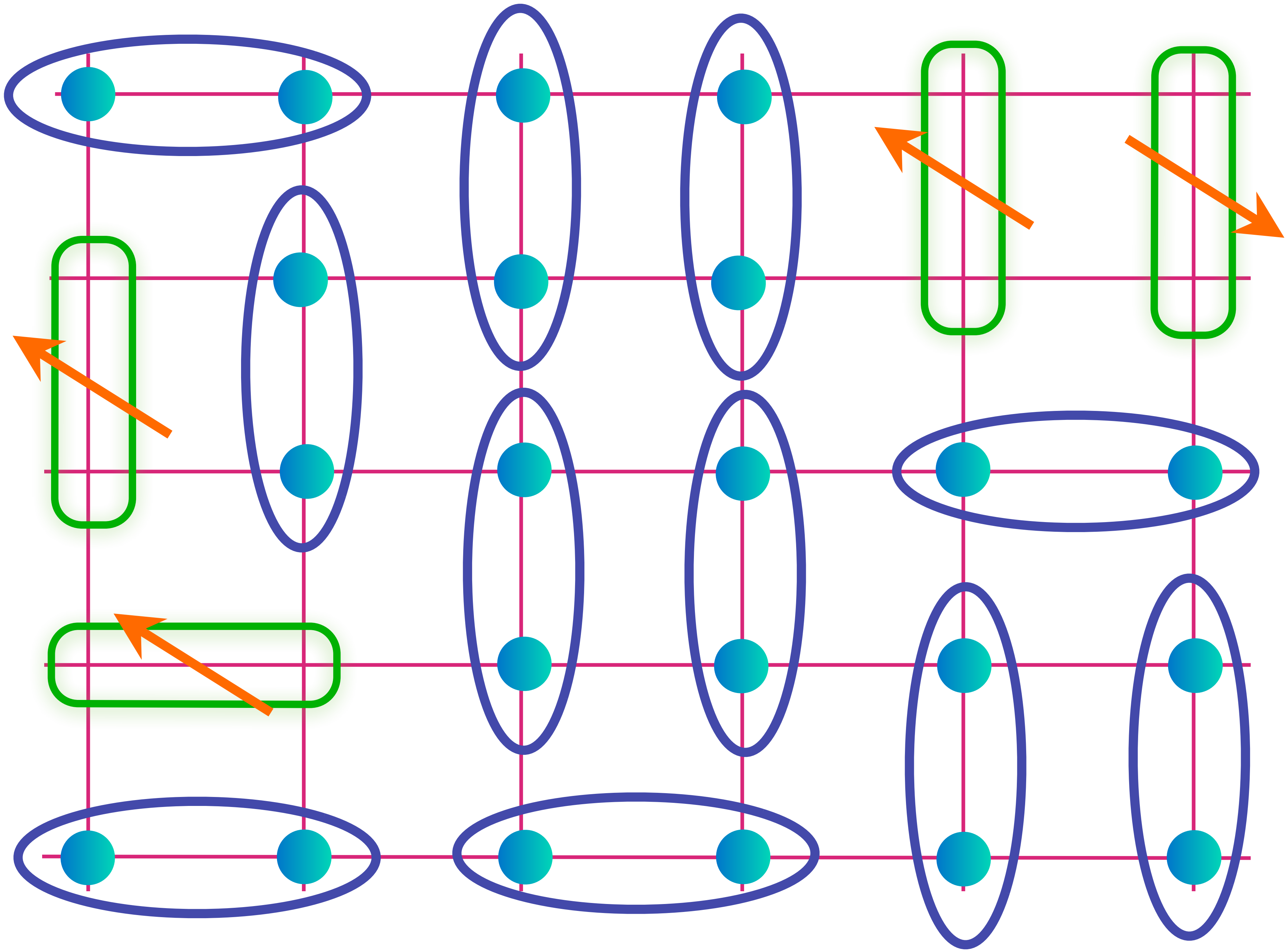
Realizes a metal with a Fermi surface of area p and "topological order"

T. Senthil, S. S., M. Vojta *Phys. Rev. Lett.* **90**, 216403 (2003)
R. K. Kaul, A. Kolezhuk, M. Levin, S. S., and T. Senthil, *Phys. Rev. B* **75**, 235122 (2007)
E. G. Moon and S. S. Phys. Rev. B **83**, 224508 (2011); M. Punk, A. Allais, and S. S., arXiv:1501.00978.

The high T pseudogap:

A quantum dimer model for a metal with topological order

Quantum dimer model with bosonic and fermionic dimers



M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978

Early discussion of a fermionic hole on a dimer

PHYSICAL REVIEW B VOLUME 38, NUMBER 16 1 DECEMBER 1988

Quasiparticles in the copper-oxygen planes of high-T_c superconductors: An exact solution for a ferromagnetic background

V. J. Emery
Brookhaven National Laboratory, Upton, New York 11973

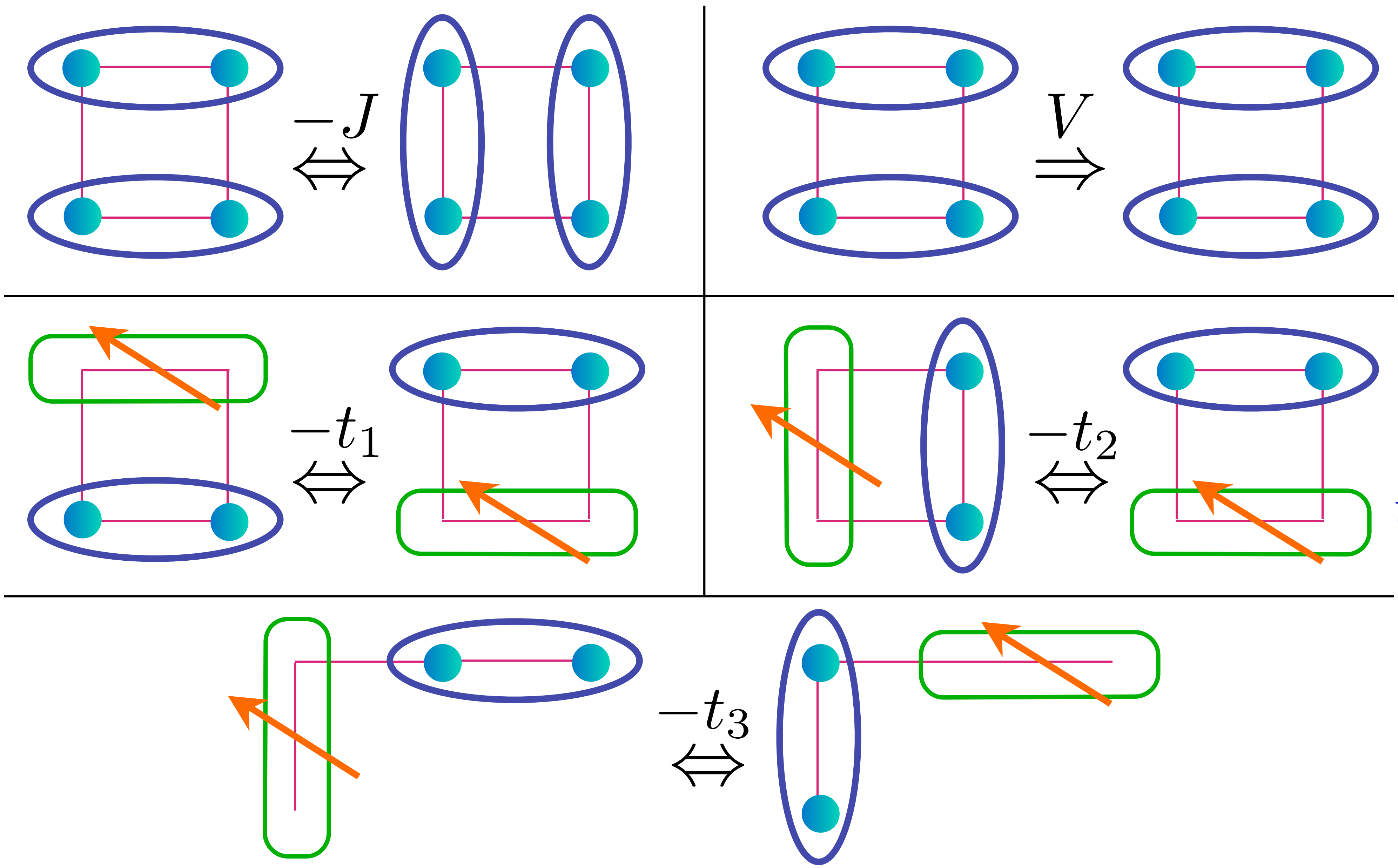
G. Reiter
Physics Department, University of Houston, Houston, Texas 77204-5504

(Received 22 July 1988)

A model for a mobile hole in the copper oxide planes of high-temperature superconductors is solved exactly. The hole moves on the oxygen atoms through a lattice of spins localized on the copper atoms. In order to obtain a solvable problem, it is assumed that the copper atoms provide a ferromagnetic background. The resulting quasiparticles have both charge and spin in contrast to the Cu-O singlets occurring in proposed effective single-band Hubbard models derived from the Cu-O network. Thus these two models of high-temperature superconductors may have different low-energy physics.

propose that the correct basis to describe the result is composed of a hole on a single O atom coupled to its two neighboring Cu atoms, i.e., basis states of the form $6^{-1/2}[2|\downarrow\uparrow\downarrow\rangle - |\uparrow\downarrow\downarrow\rangle - |\downarrow\downarrow\uparrow\rangle]$.

Quantum dimer model with bosonic and fermionic dimers



Connection to the t-t'-t''-J model:

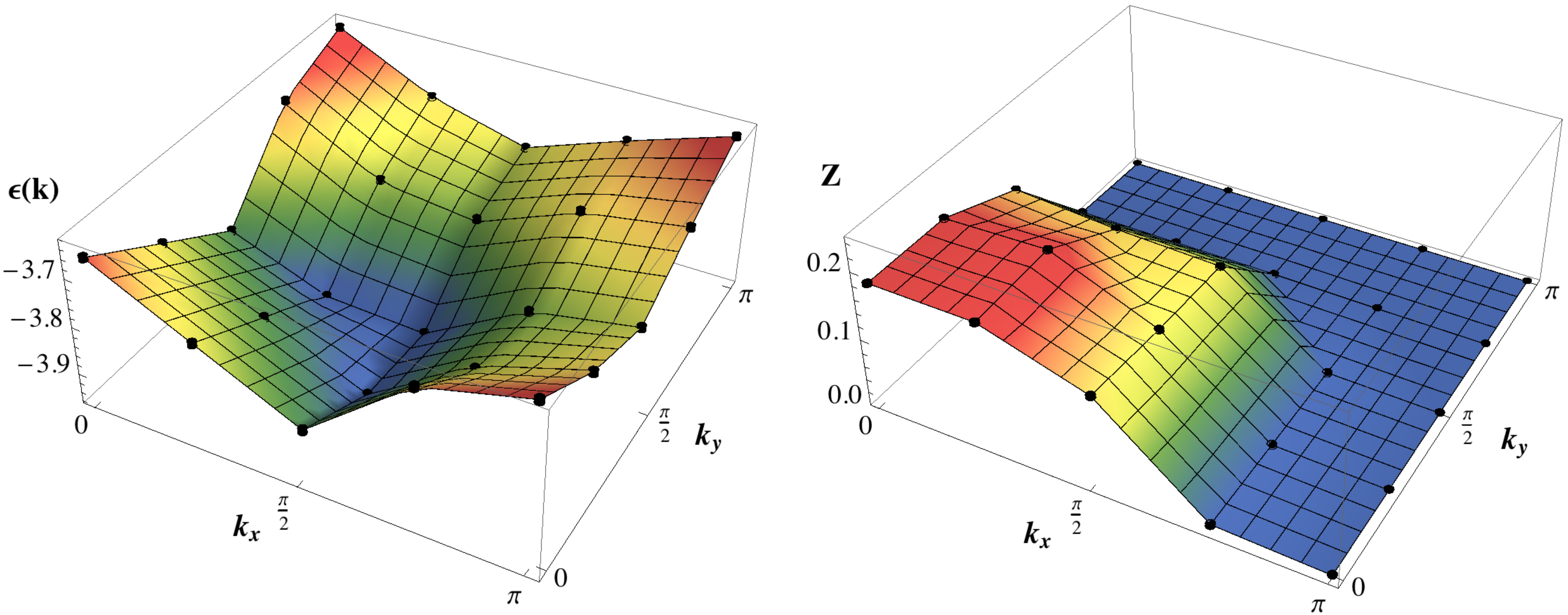
$$t_1 = -(t+t')/2$$

$$t_2 = (t-t')/2$$

$$t_3 = -(t+t'+t'')/4$$

M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978

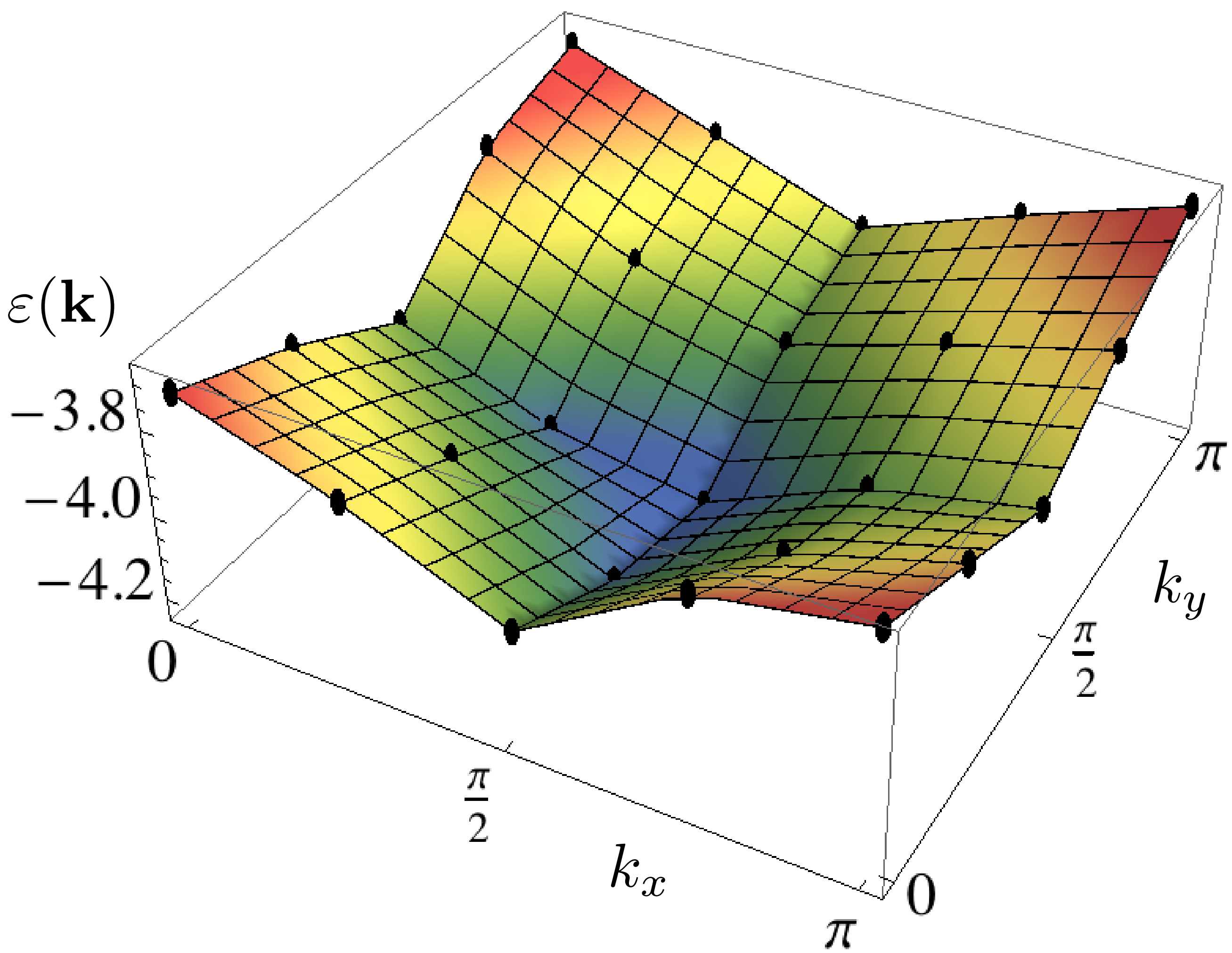
Quantum dimer model with bosonic and fermionic dimers

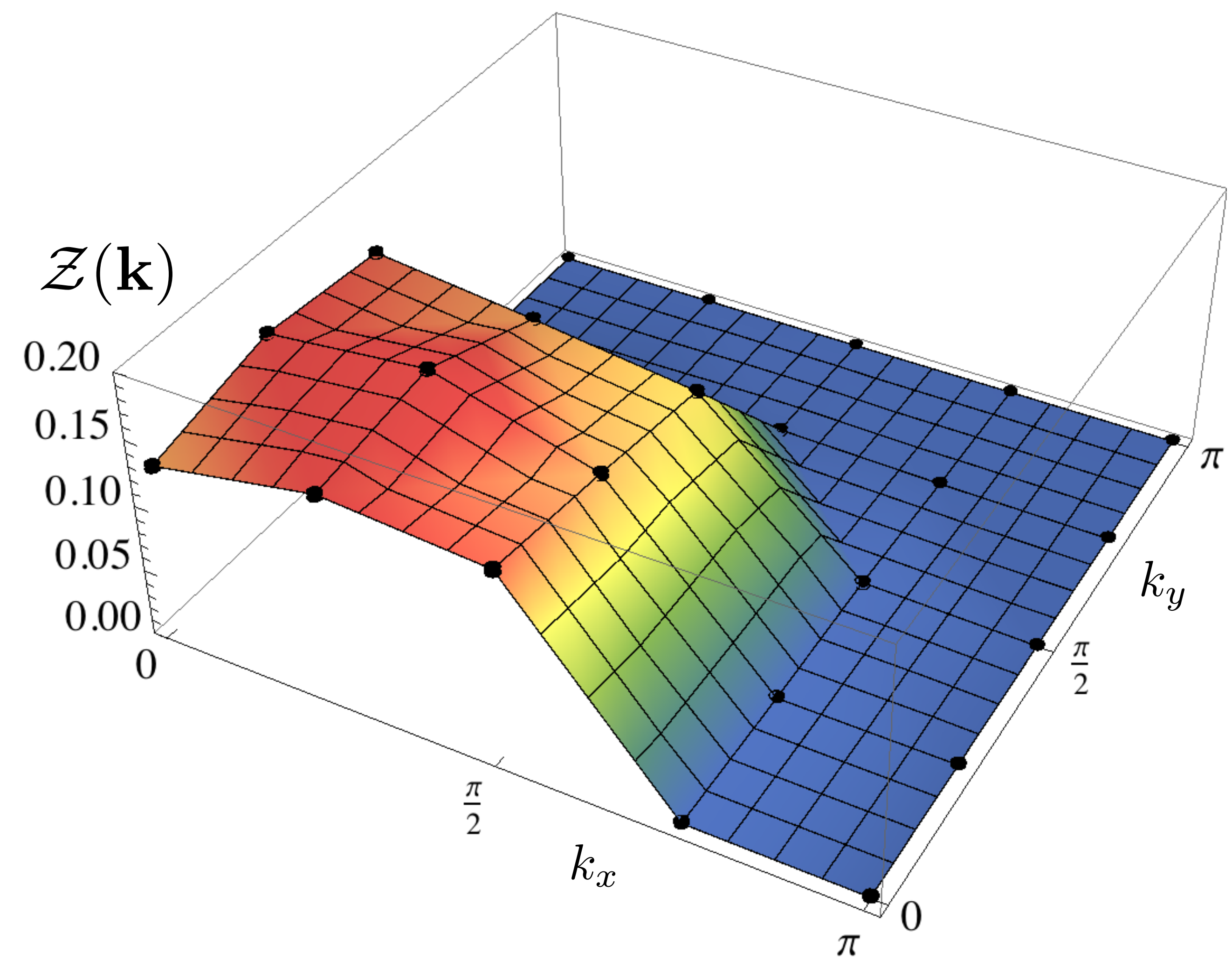


Dispersion and quasiparticle residue of a single fermionic dimer for $J = V = 1$, and hopping parameters obtained from the t-J model for the cuprates, $t_1 = -1.05$, $t_2 = 1.95$ and $t_3 = -0.6$, on a 8×8 lattice.

M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978

Quantum dimer model with bosonic and fermionic dimers

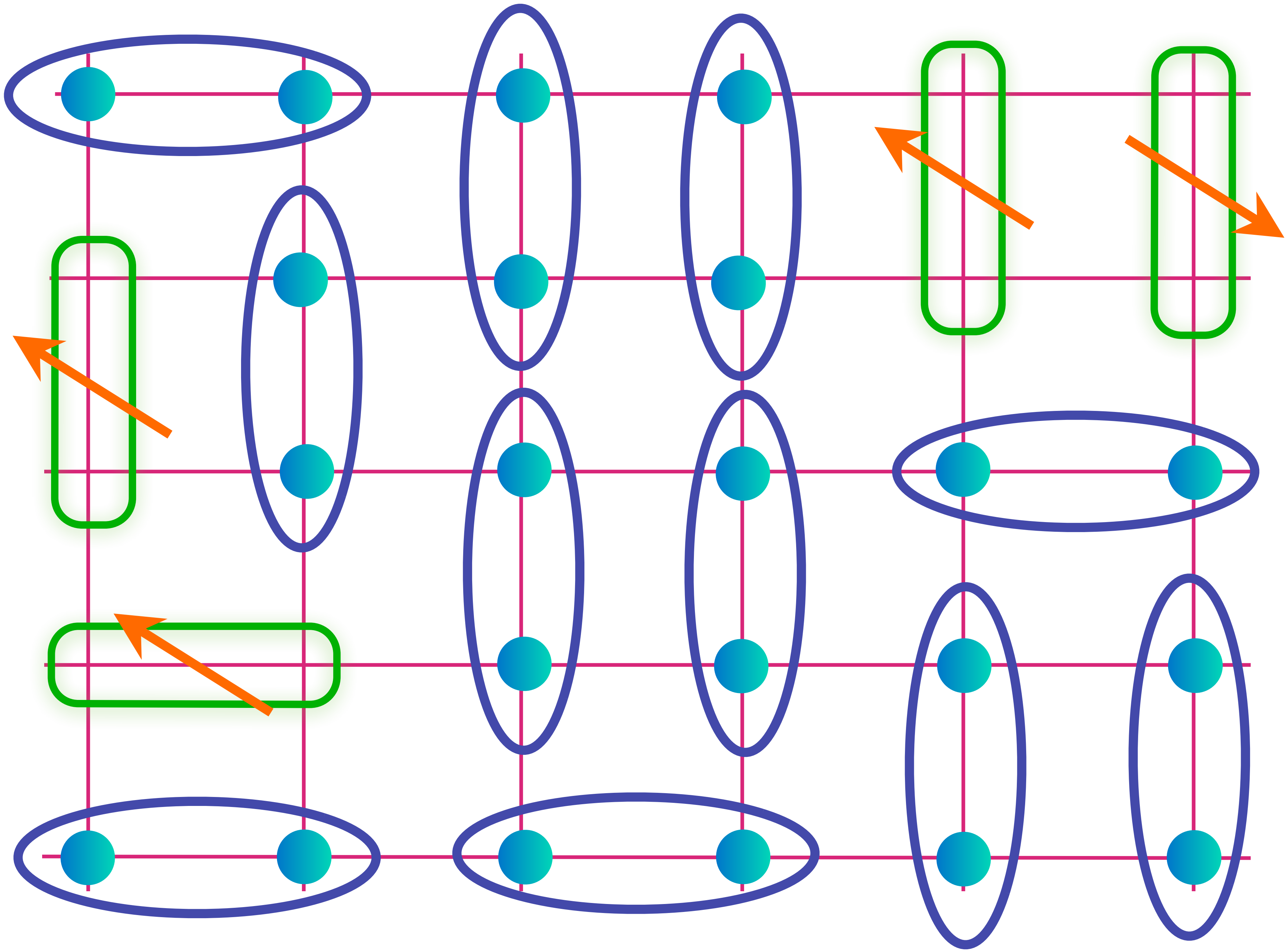




Dispersion and quasiparticle residue for $J = V = 1$, and hopping parameters $t_1 = 1$, $t_2 = 1$ and $t_3 = -1$, on a 8×8 lattice.

M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978

Quantum dimer model with bosonic and fermionic dimers



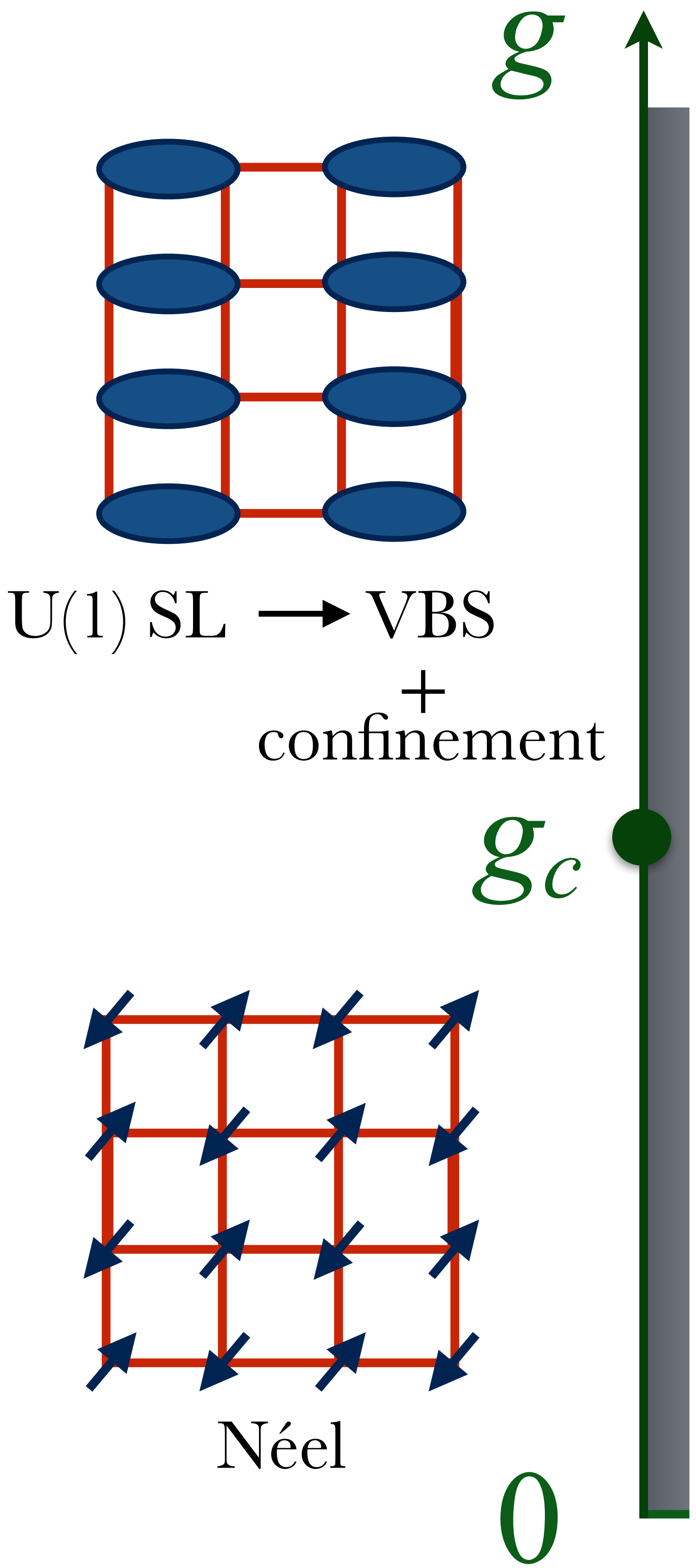
Dimer nature of charge carriers makes them "nematogens": the metallic state is likely to have nematic order/ correlations

M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978

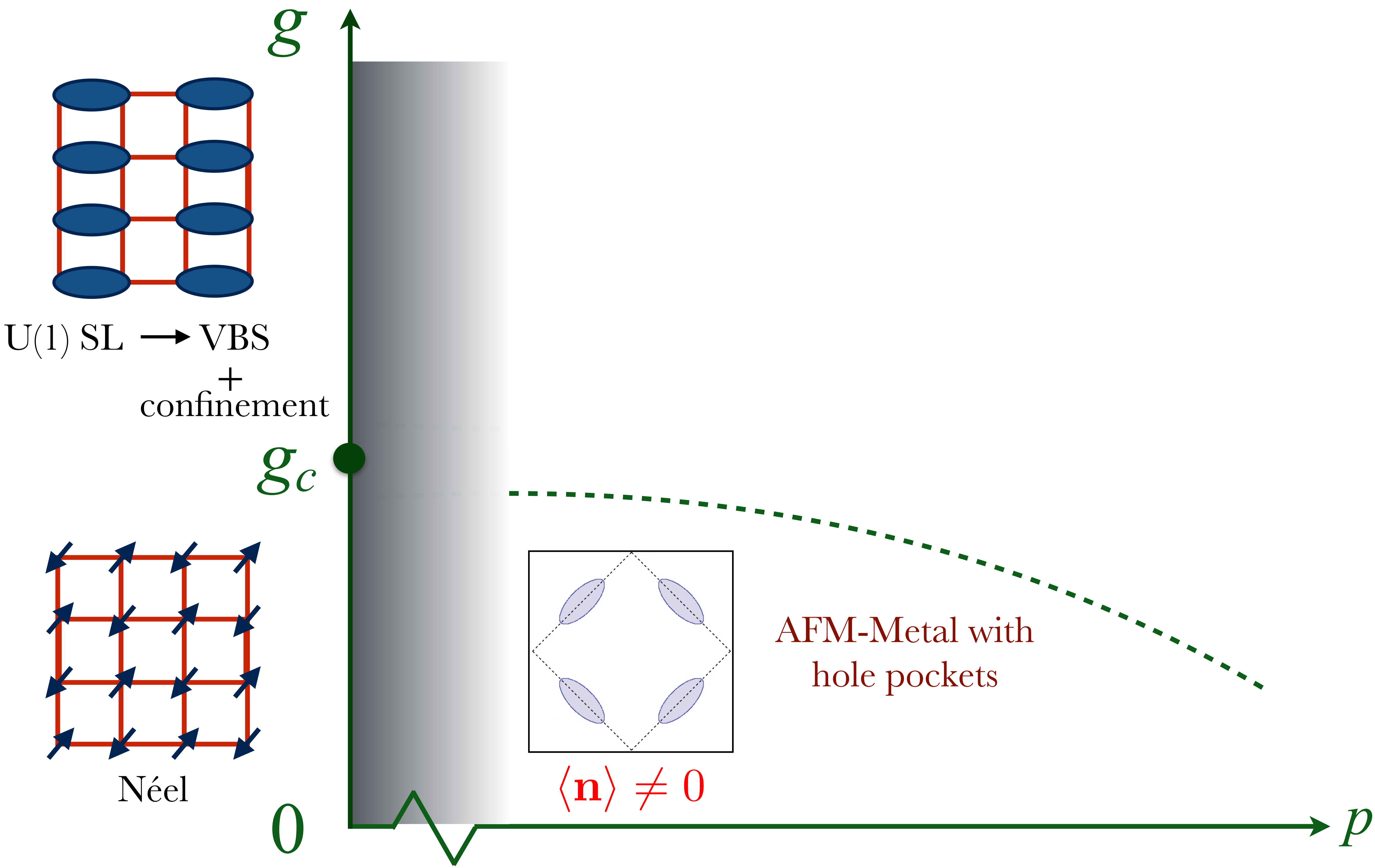
The high T pseudogap:

Doping deconfined quantum critical points in frustrated antiferromagnets

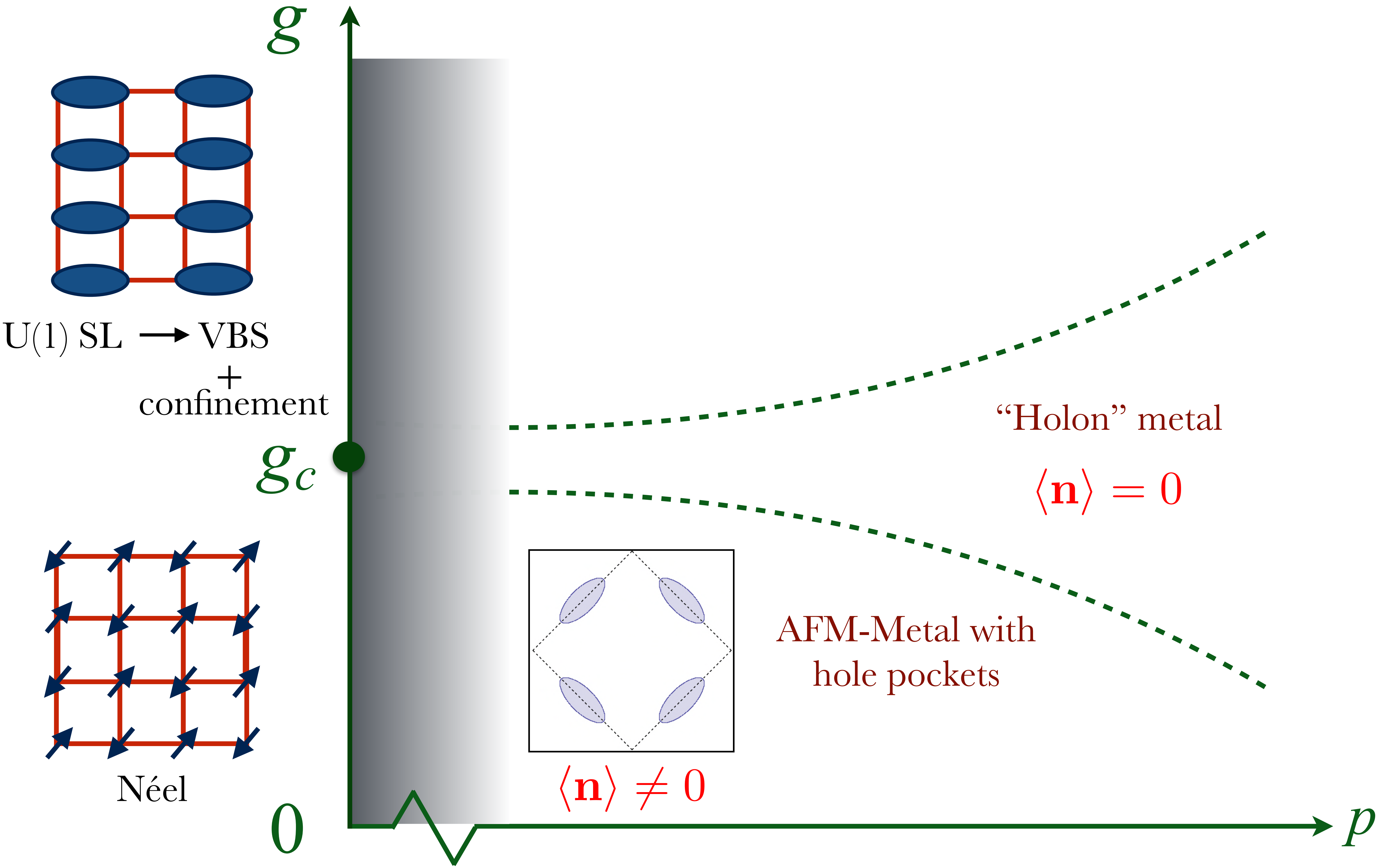
Deconfined criticality



Deconfined criticality



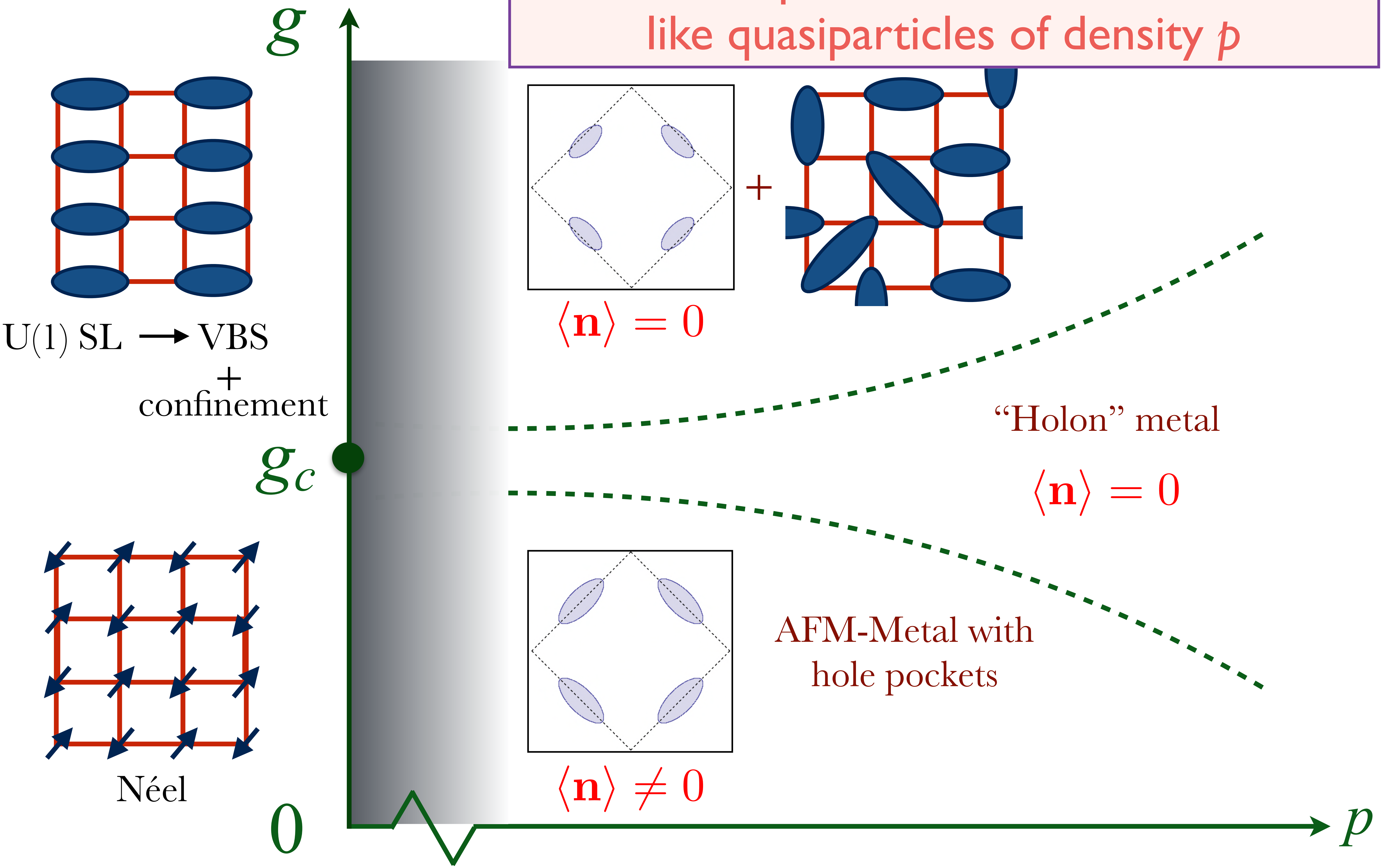
Deconfined criticality



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

Deconfined criticality

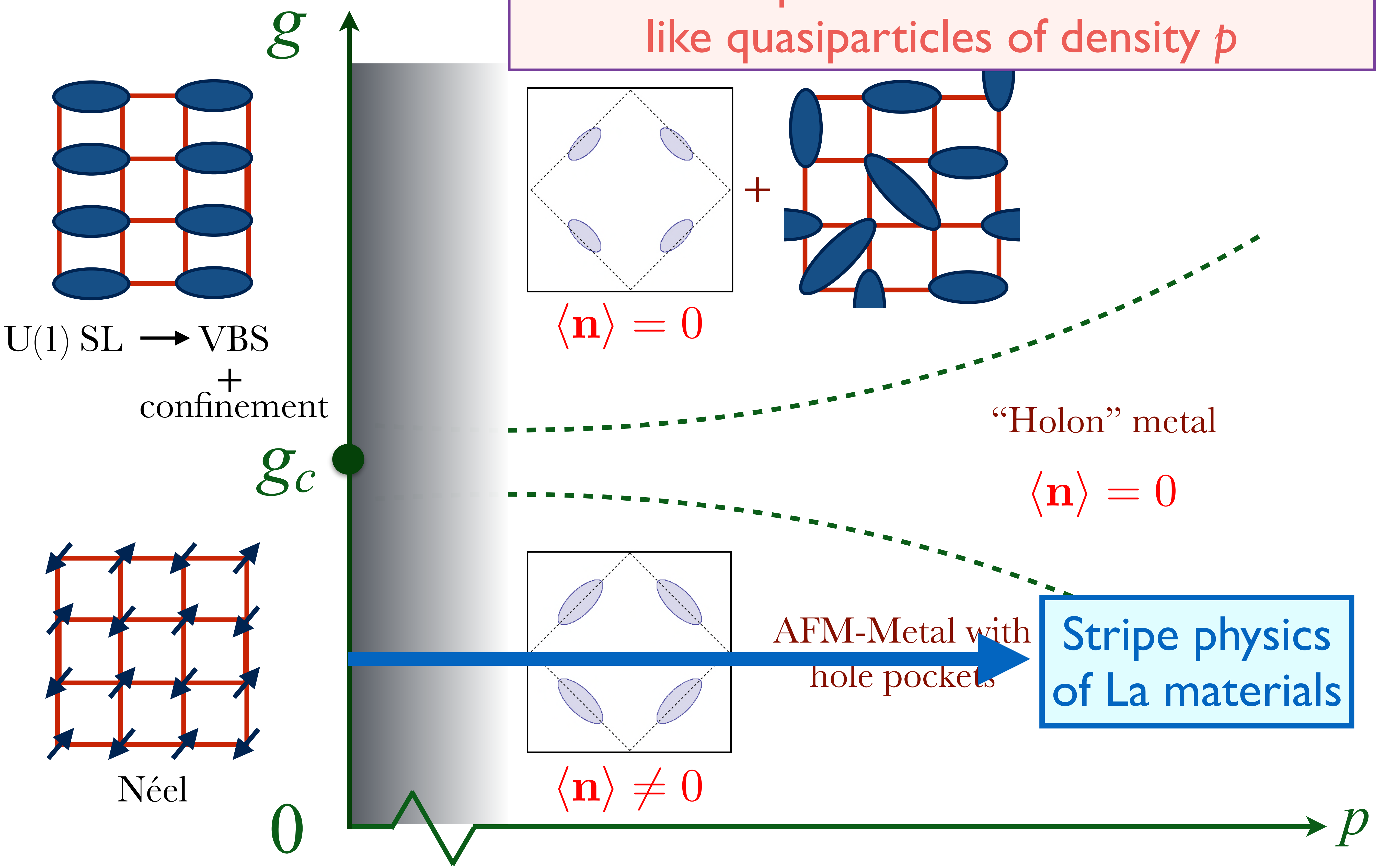
Holons and spinons bind to form electron-like quasiparticles of density p



R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, Phys. Rev. B **75** , 235122 (2007)
Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
D. Chowdhury and S. Sachdev, Phys. Rev. B **90**, 245136 (2014).

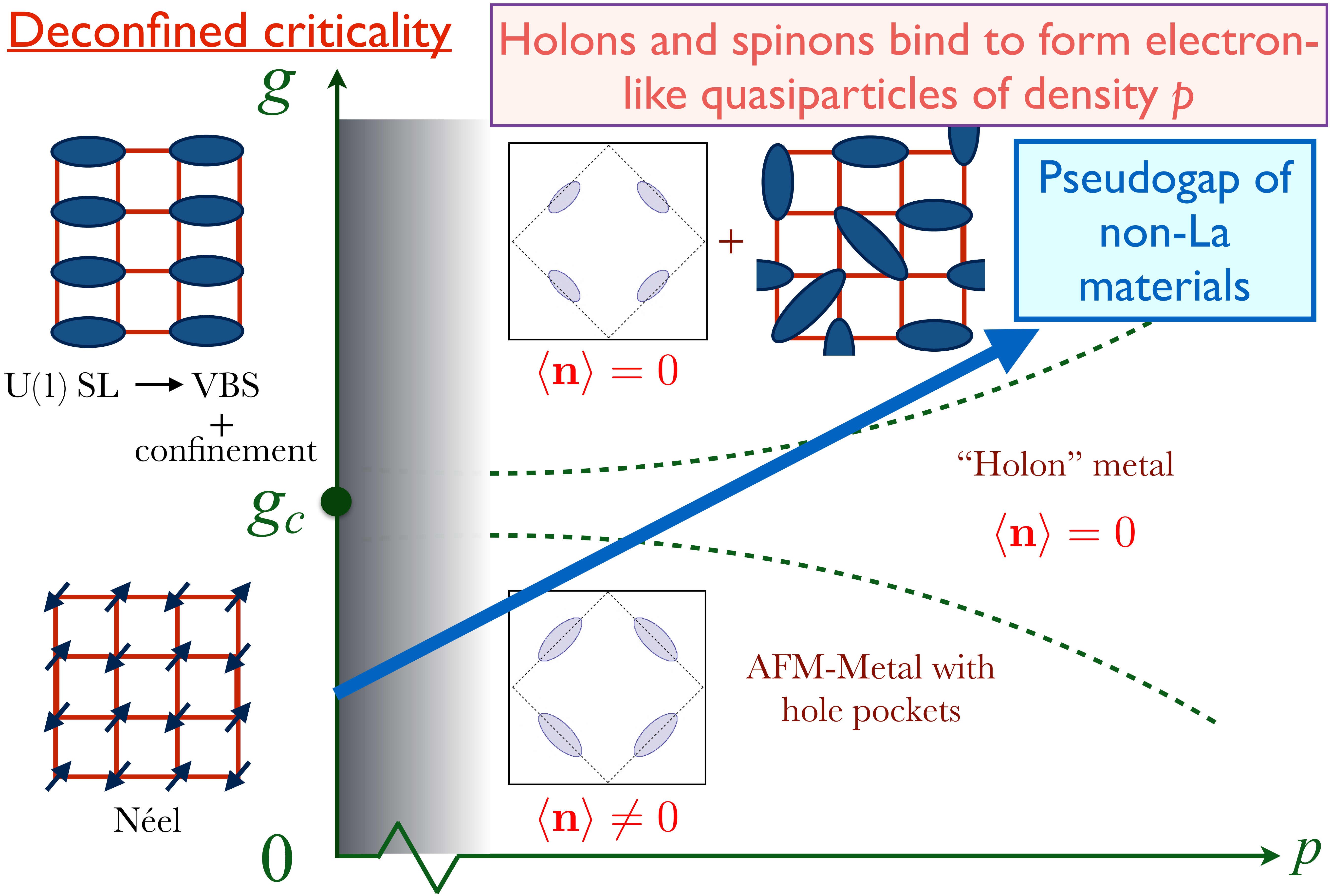
Deconfined criticality

Holons and spinons bind to form electron-like quasiparticles of density p

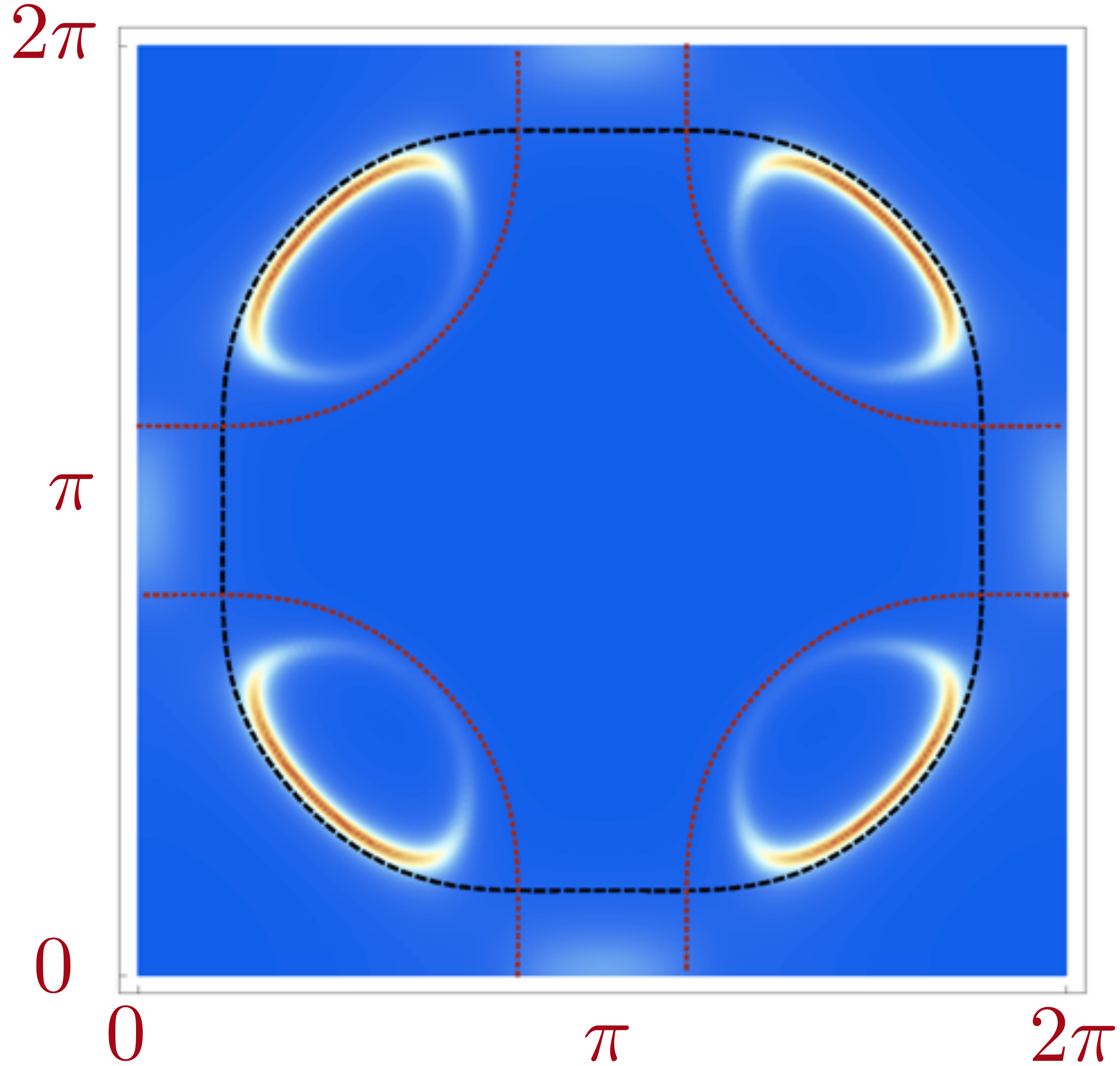


D. Chowdhury and S. Sachdev, Phys. Rev. B **90**, 245136 (2014)
A. Thomson and S. Sachdev, arXiv:1410.3483

Deconfined criticality



D. Chowdhury and S. Sachdev, Phys. Rev. B **90**, 245136 (2014)

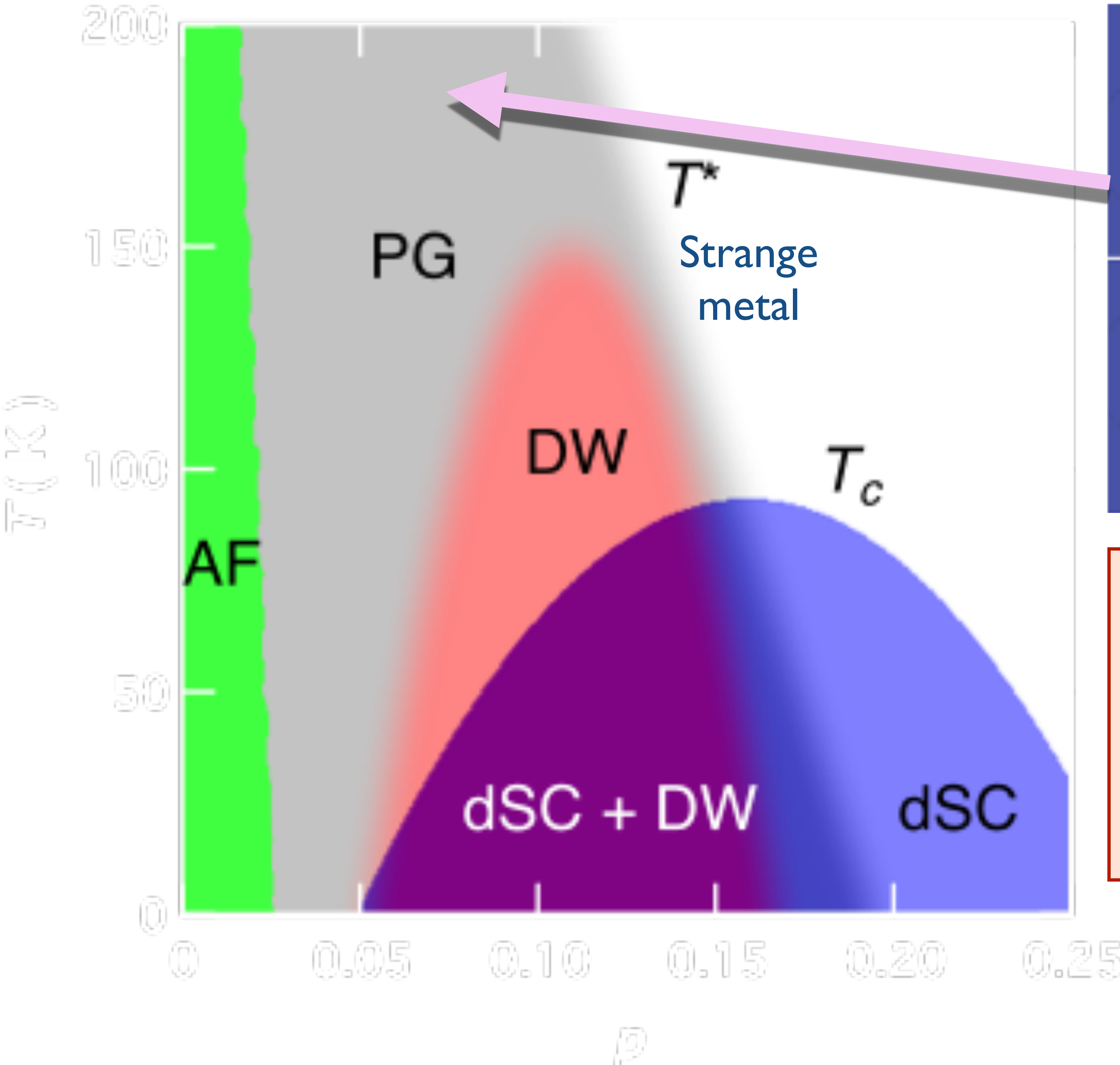


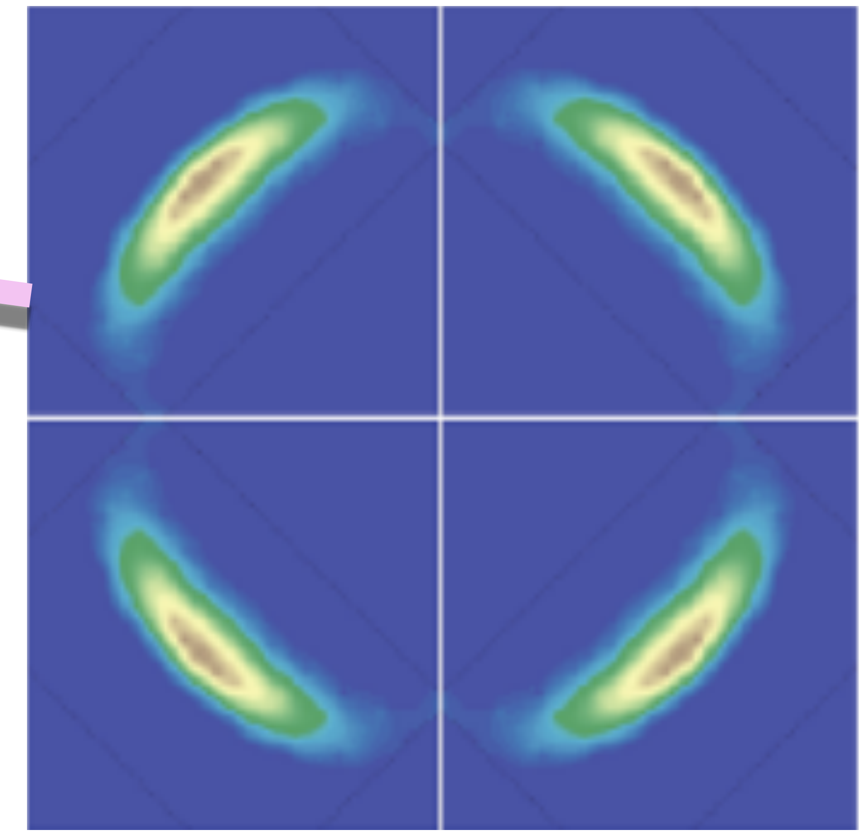
Electron spectral function of FL*

Semi-phenomenological theory of a FL* state with hole pockets of volume p, along with a background spin liquid with an emergent U(1) gauge field. Note that the quasiparticle excitations around the Fermi surface do not carry U(1) gauge charges.

Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978

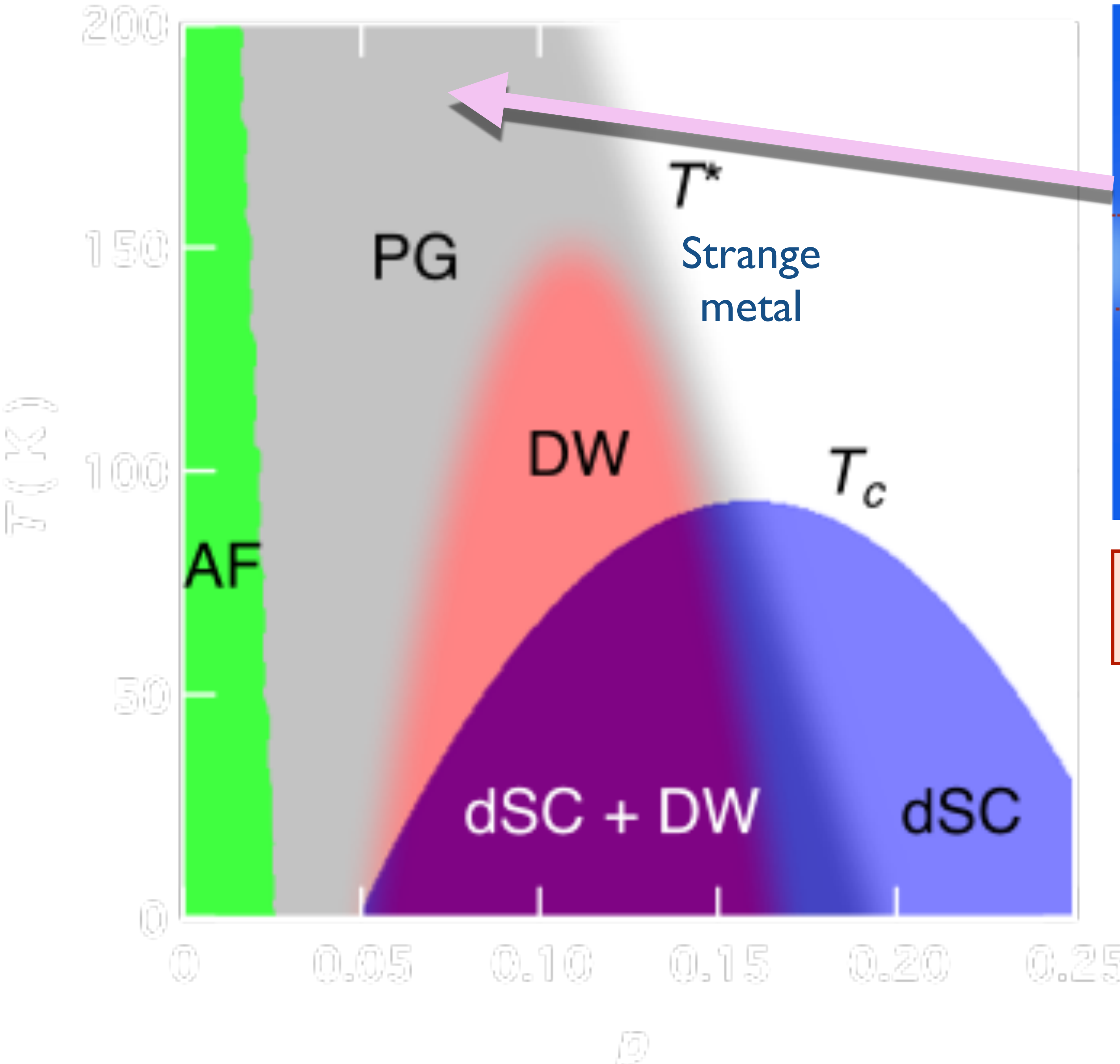
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)

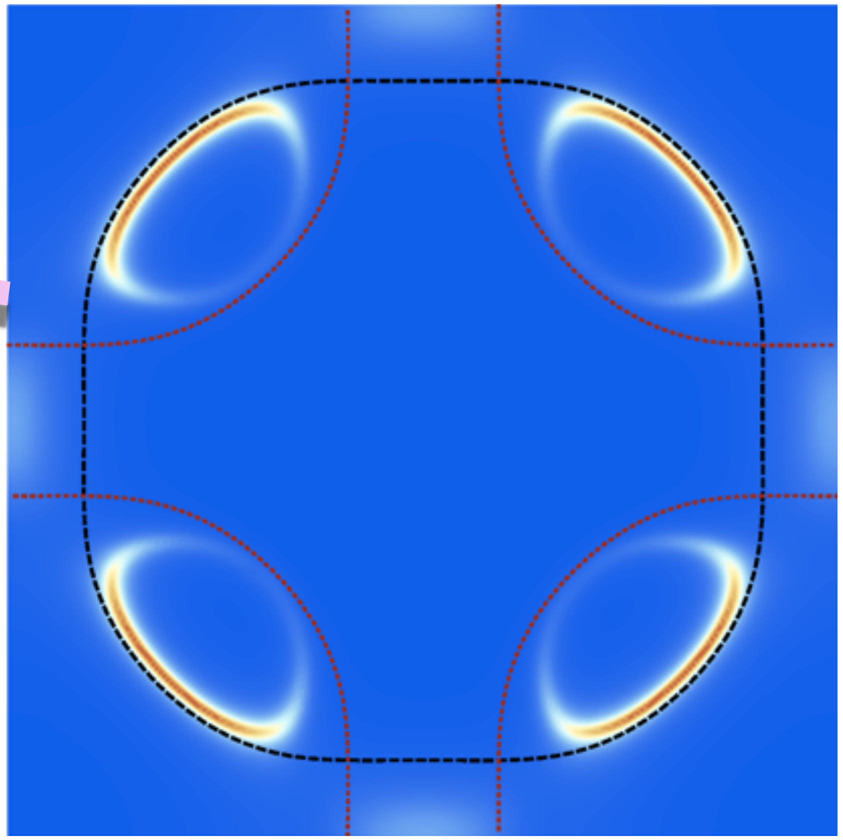




“Fermi arcs”
at
low p

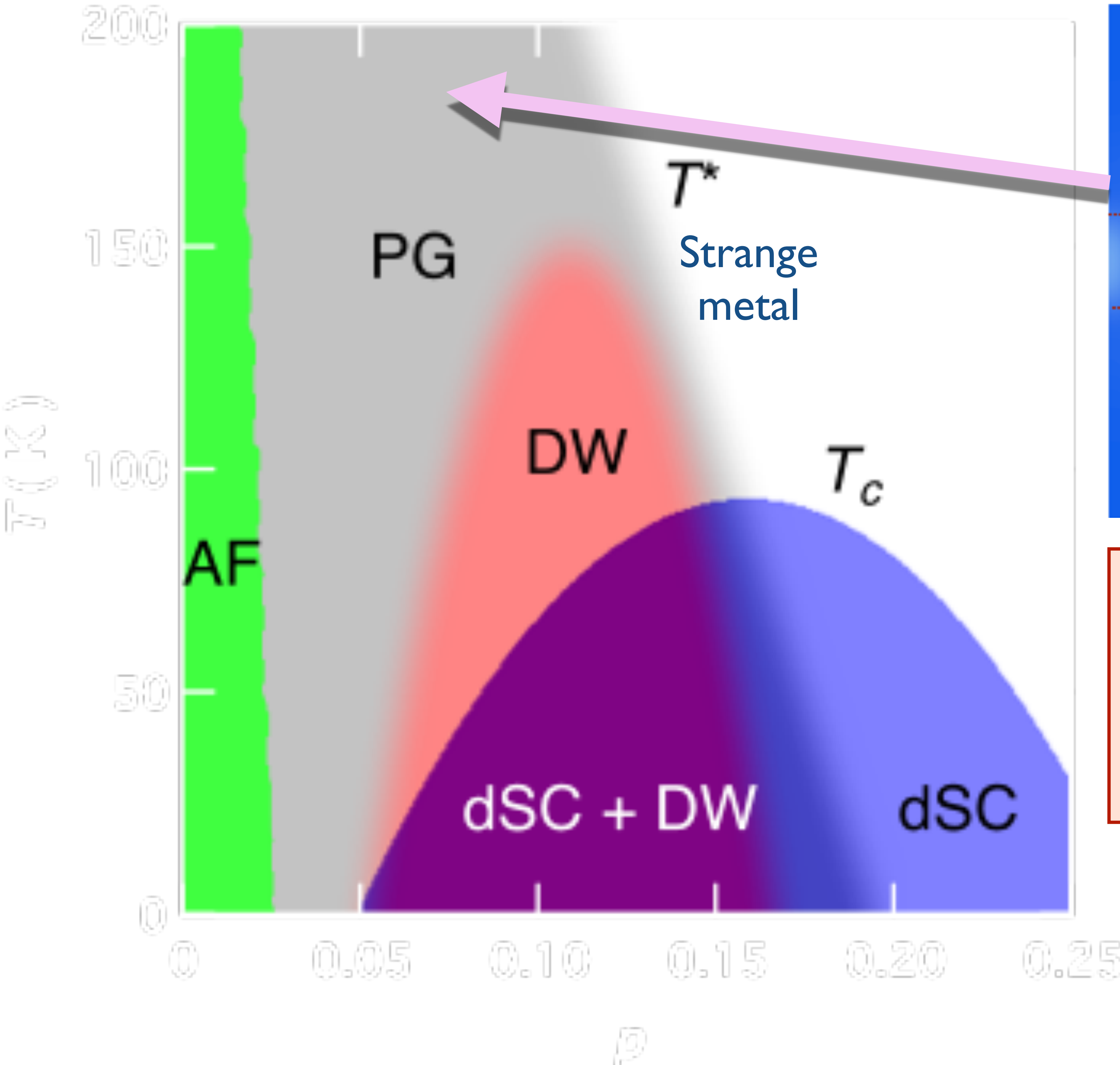
Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978

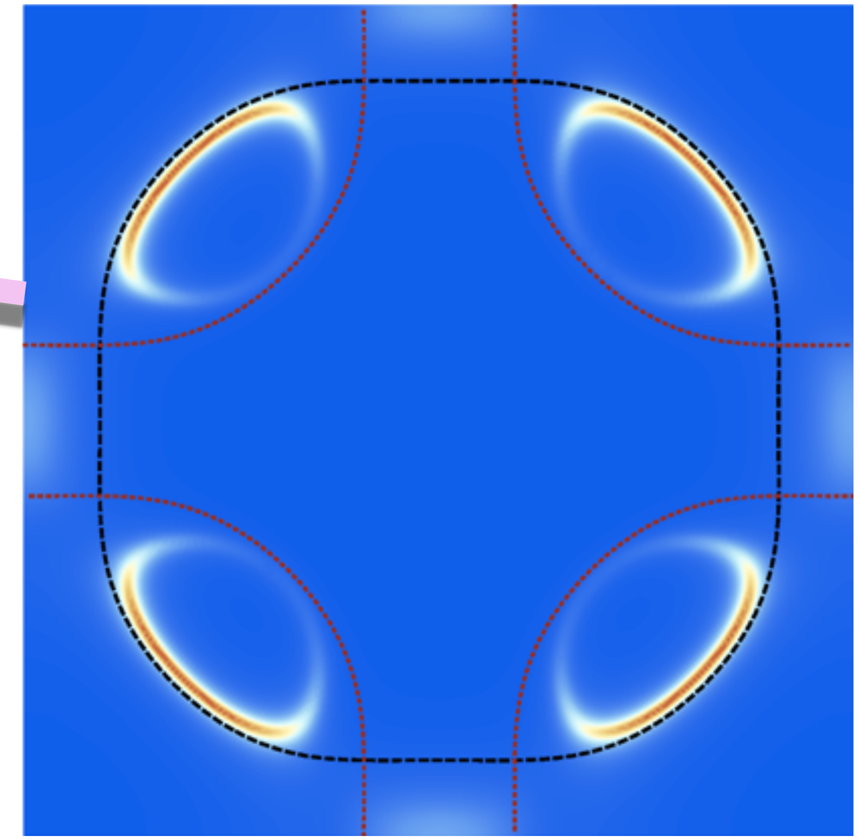




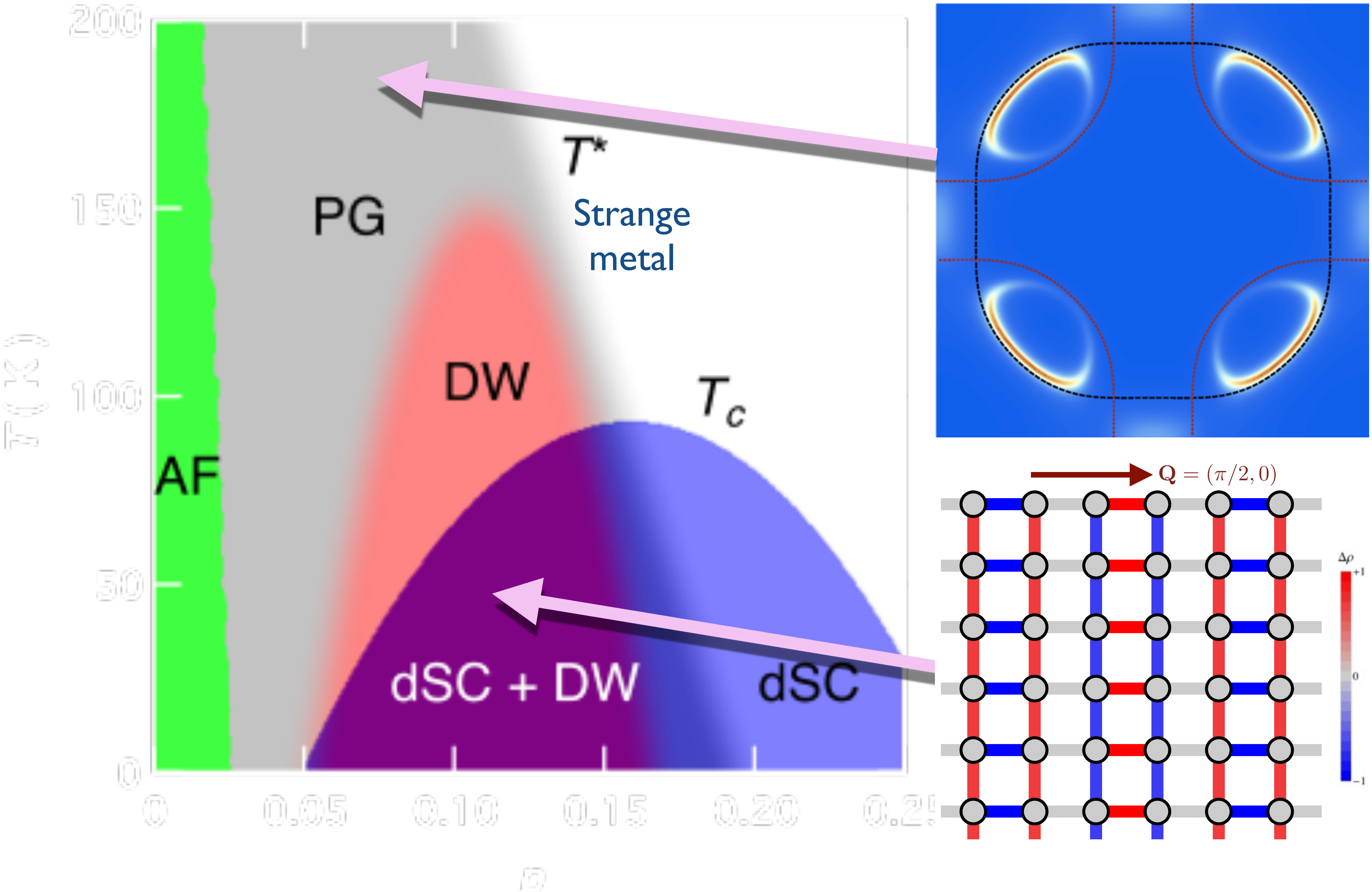
FL*.

Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978





FL*.
Expts to detect hole pockets ?

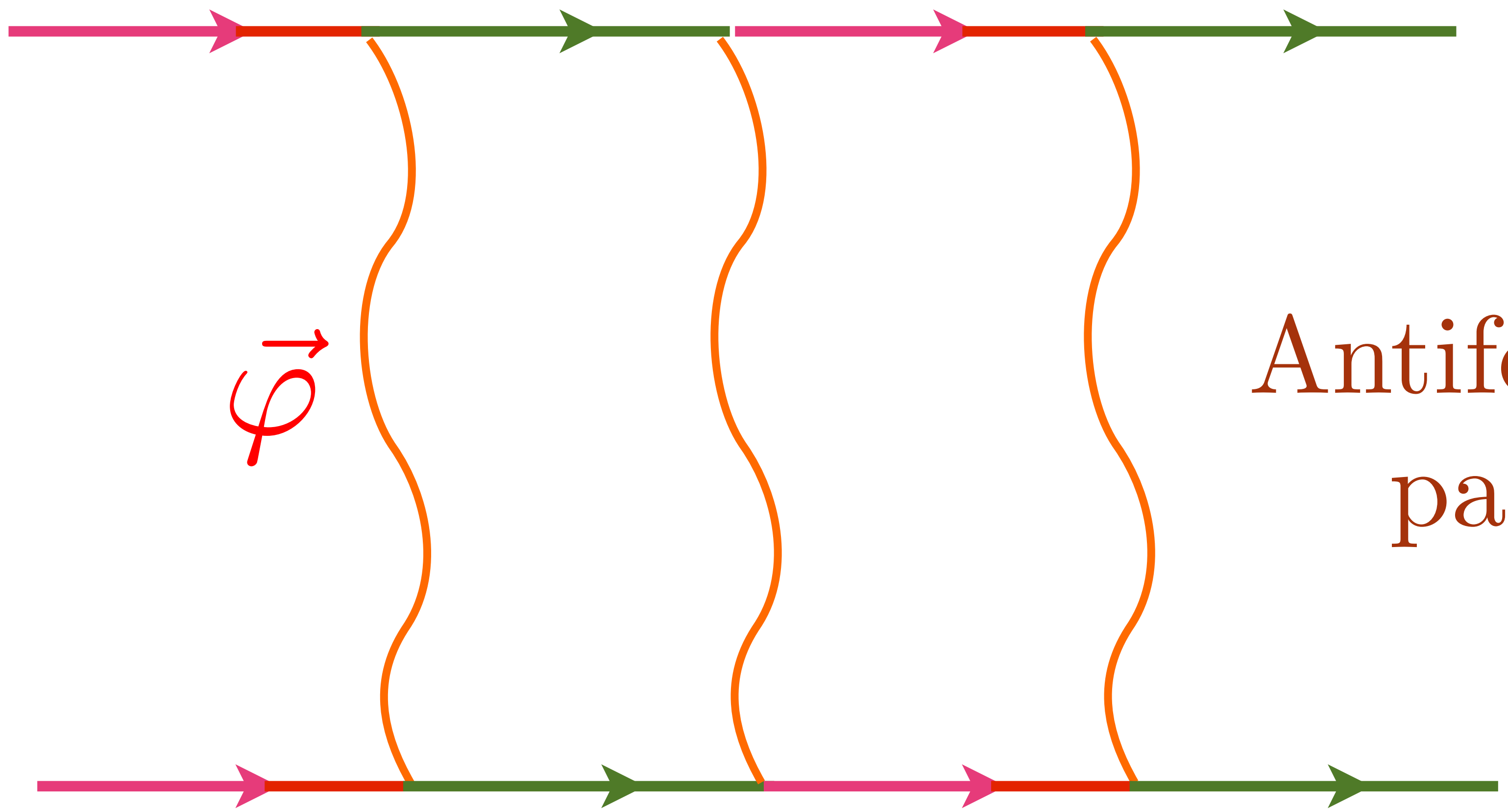


T(K)
200
150
100
50
0
0
0.05
0.10
0.15
0.20
p
AF
PG
T*
Strange metal
DW
T_c
dSC + DW
dSC
$\mathbf{Q} = (\pi/2, 0)$

Connecting high and low T

Density wave instabilities

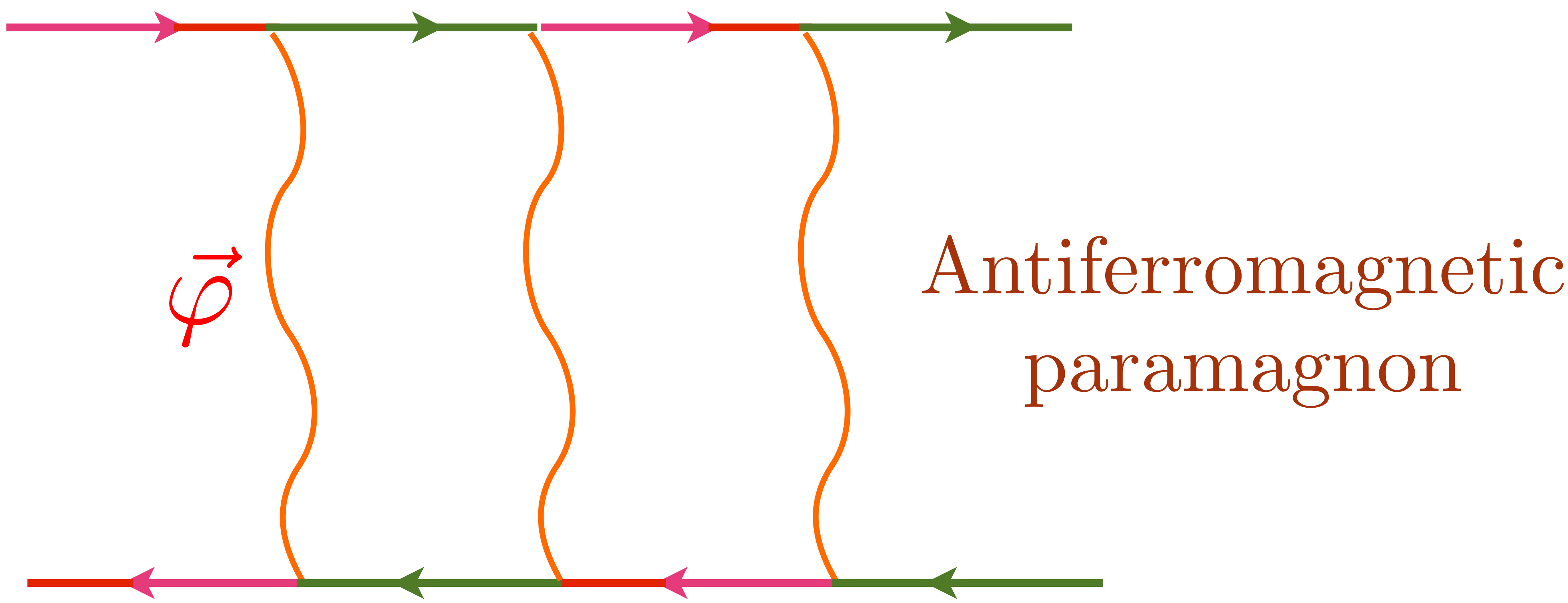
Pairing "glue" for d-wave superconductivity from antiferromagnetic fluctuations



$$\text{Leads to } \left\langle c^\dagger_{\mathbf{k}\alpha} c^\dagger_{-\mathbf{k}\beta} \right\rangle = \varepsilon_{\alpha\beta} \Delta(\cos k_x - \cos k_y)$$

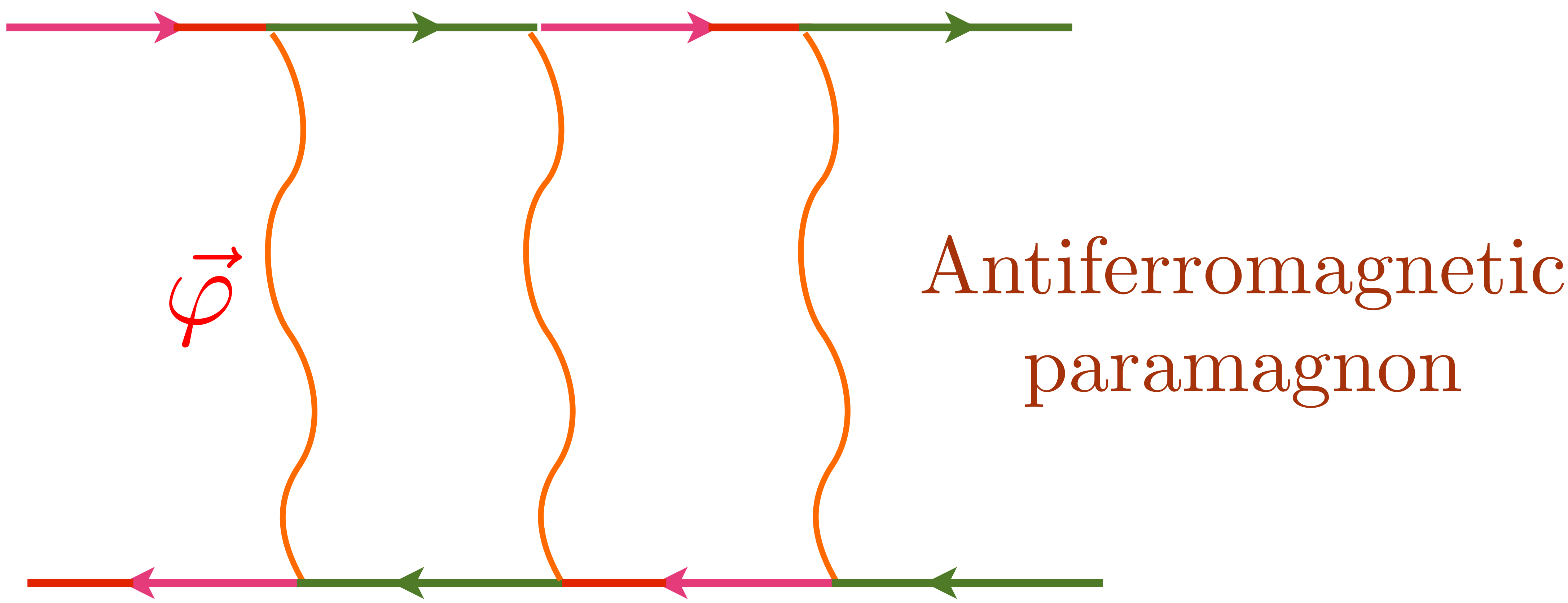
V. J. Emery, *J. Phys. (Paris) Colloq.* **44**, C3-977 (1983)
D.J. Scalapino, E. Loh, and J.E. Hirsch, *Phys. Rev. B* **34**, 8190 (1986)
K. Miyake, S. Schmitt-Rink, and C. M. Varma, *Phys. Rev. B* **34**, 6554 (1986)
P. Monthoux, A.V. Balatsky, and D. Pines, *Phys. Rev. Lett.* **67**, 3448 (1991)

Same glue can lead to "d-wave" particle-hole pairing



M. A. Metlitski and S. Sachdev, Phys. Rev. B **85**, 075127 (2010)
T. Holder and W. Metzner, Phys. Rev. B **85**, 165130 (2012)
M. Bejas, A. Greco, and H. Yamase, Phys. Rev. B **86**, 224509 (2012)
S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013)
K. B. Efetov, H. Meier, and C. Pépin, Nat. Phys. **9**, 442 (2013)
J. D. Sau and S. Sachdev, Phys. Rev. B **89**, 075129 (2014)
Y. Wang and A. V. Chubukov, Phys. Rev. B **90**, 035149 (2014)

Same glue can lead to "d-wave" particle-hole pairing

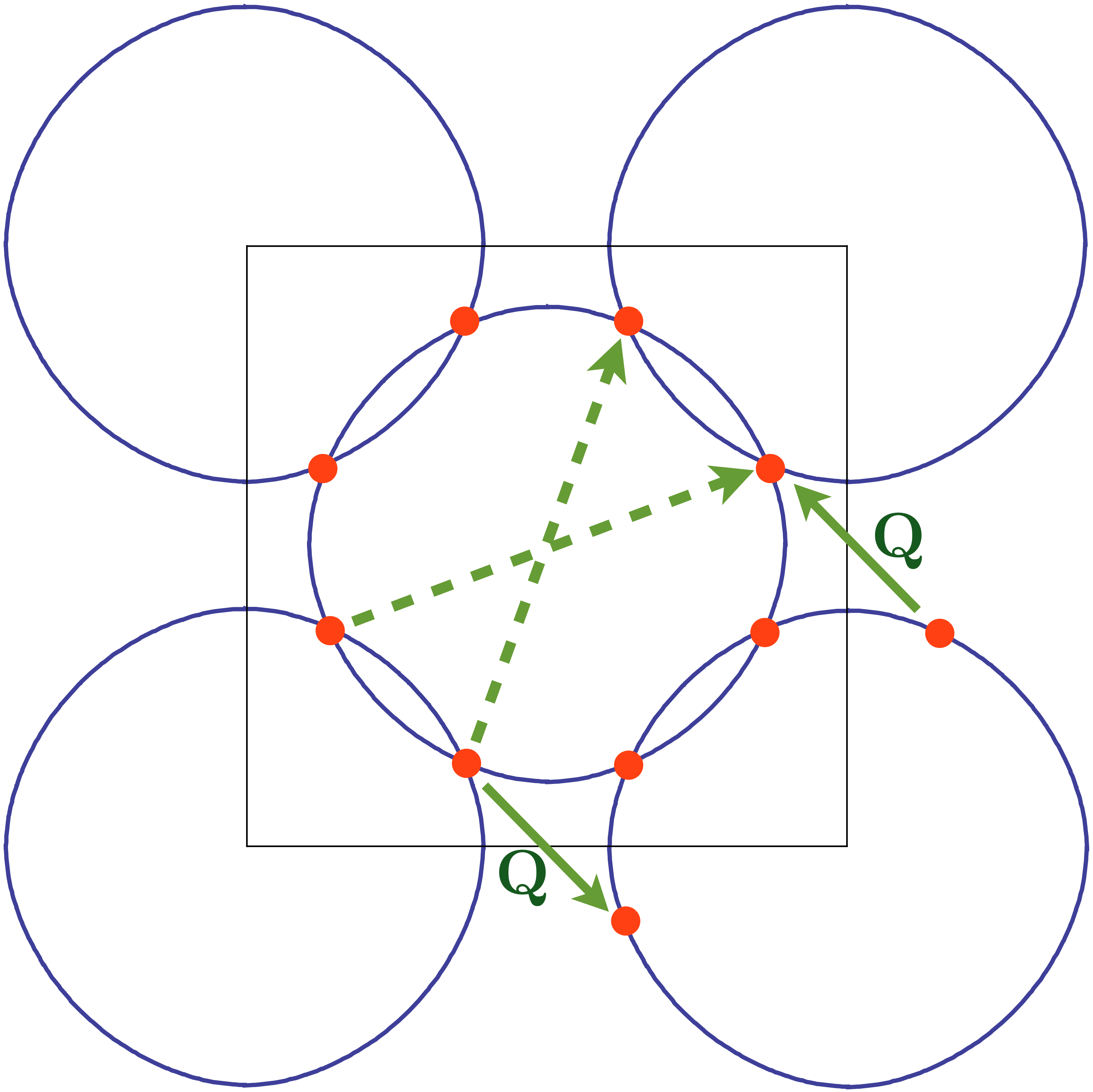


Leads to $\left\langle c^\dagger_{\mathbf{k}+\mathbf{Q}/2,\alpha} c_{\mathbf{k}-\mathbf{Q}/2,\alpha} \right\rangle =$

$\mathcal{P}_s + \mathcal{P}_{s'}(\cos k_x + \cos k_y) + \mathcal{P}_d(\cos k_x - \cos k_y)$

with $\mathcal{P}_d$ dominant.

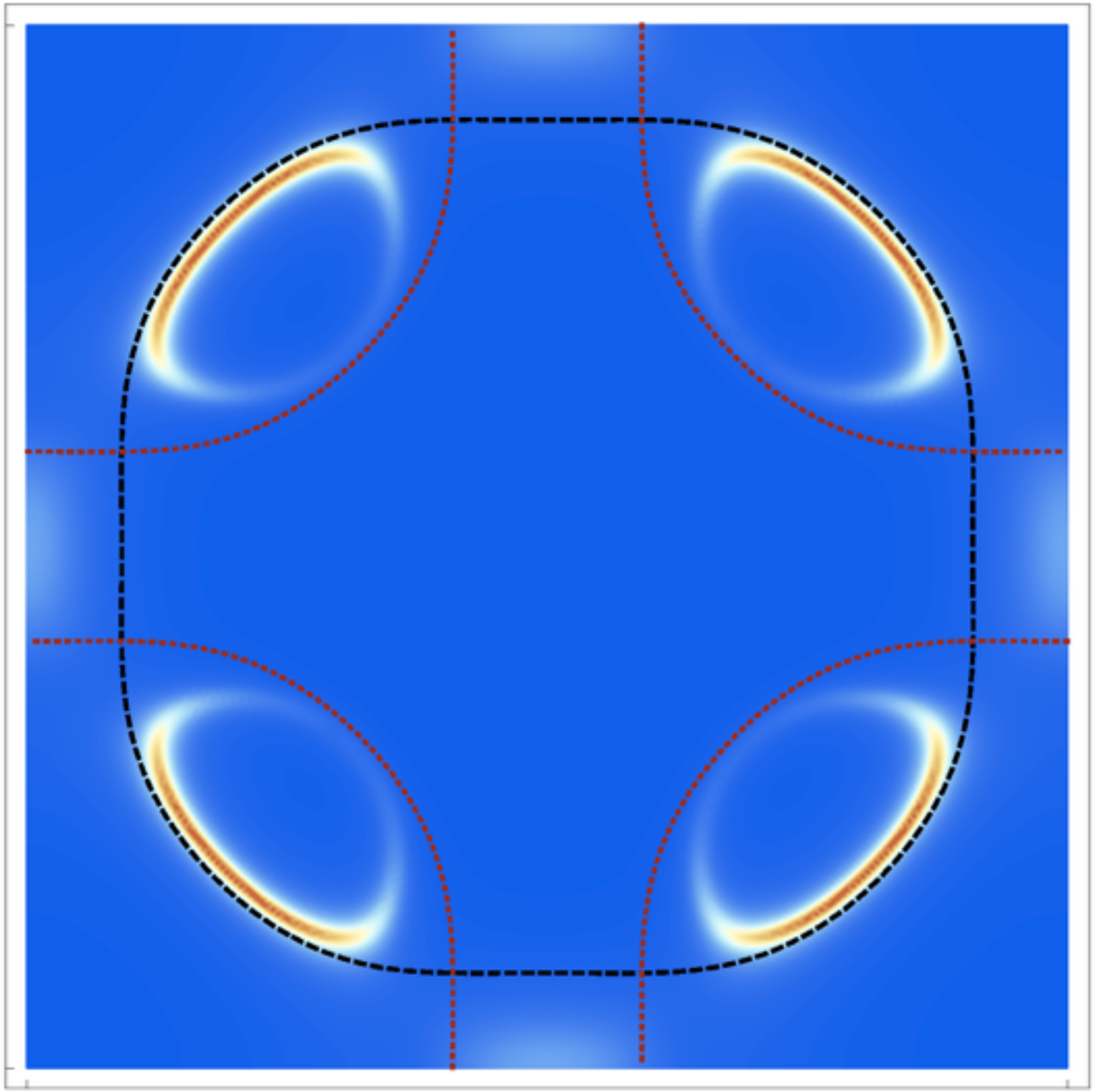
S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013)



Density wave instability of large Fermi surface leads to an incorrect "diagonal" wavevector

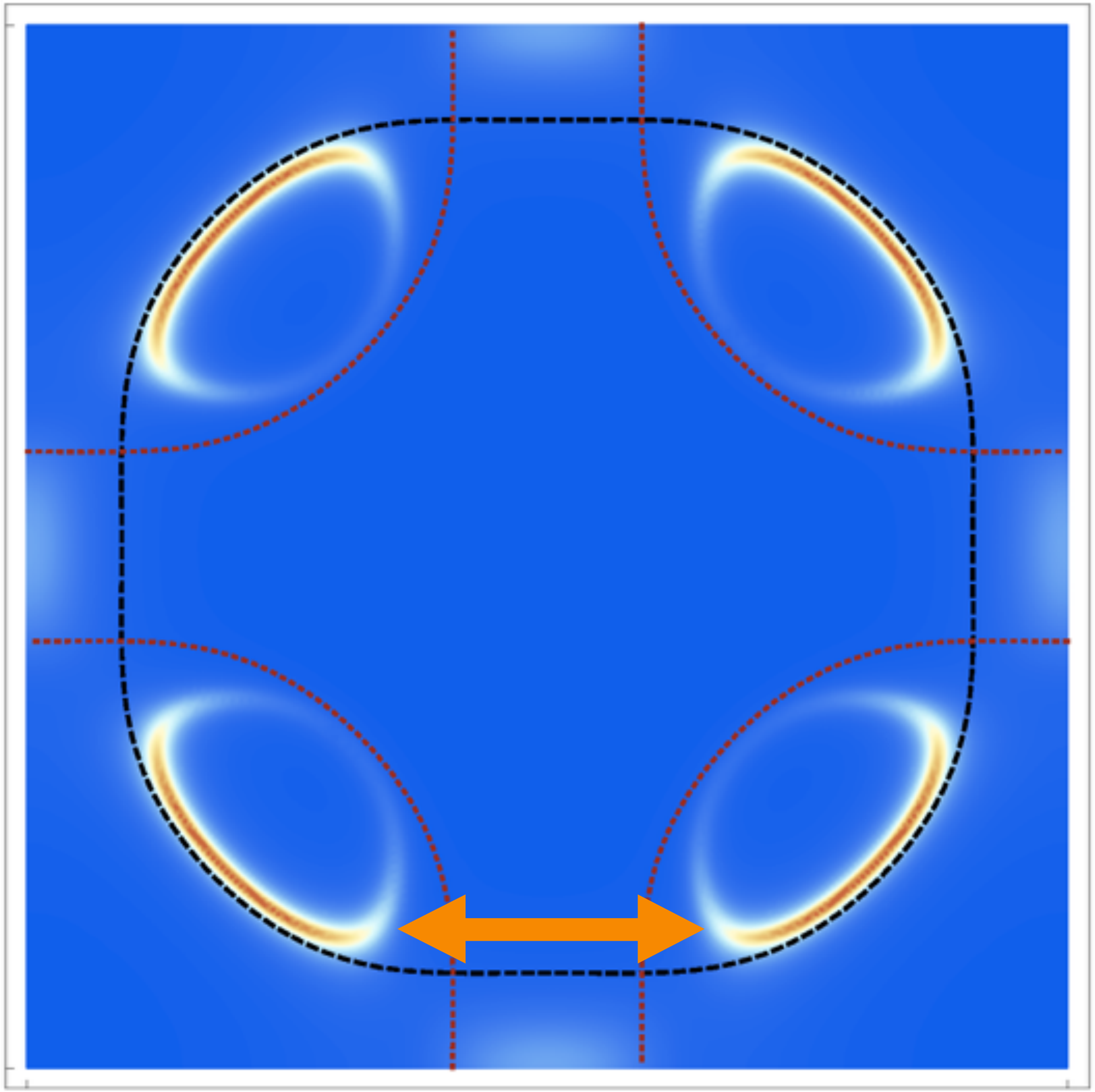
$$\left\langle c^\dagger_{\mathbf{k}-\mathbf{Q}/2,\alpha} c_{\mathbf{k}+\mathbf{Q}/2,\alpha} \right\rangle = \mathcal{P}_d(\cos k_x - \cos k_y)$$

M. A. Metlitski and S. Sachdev, *Phys. Rev. B* **85**, 075127 (2010)



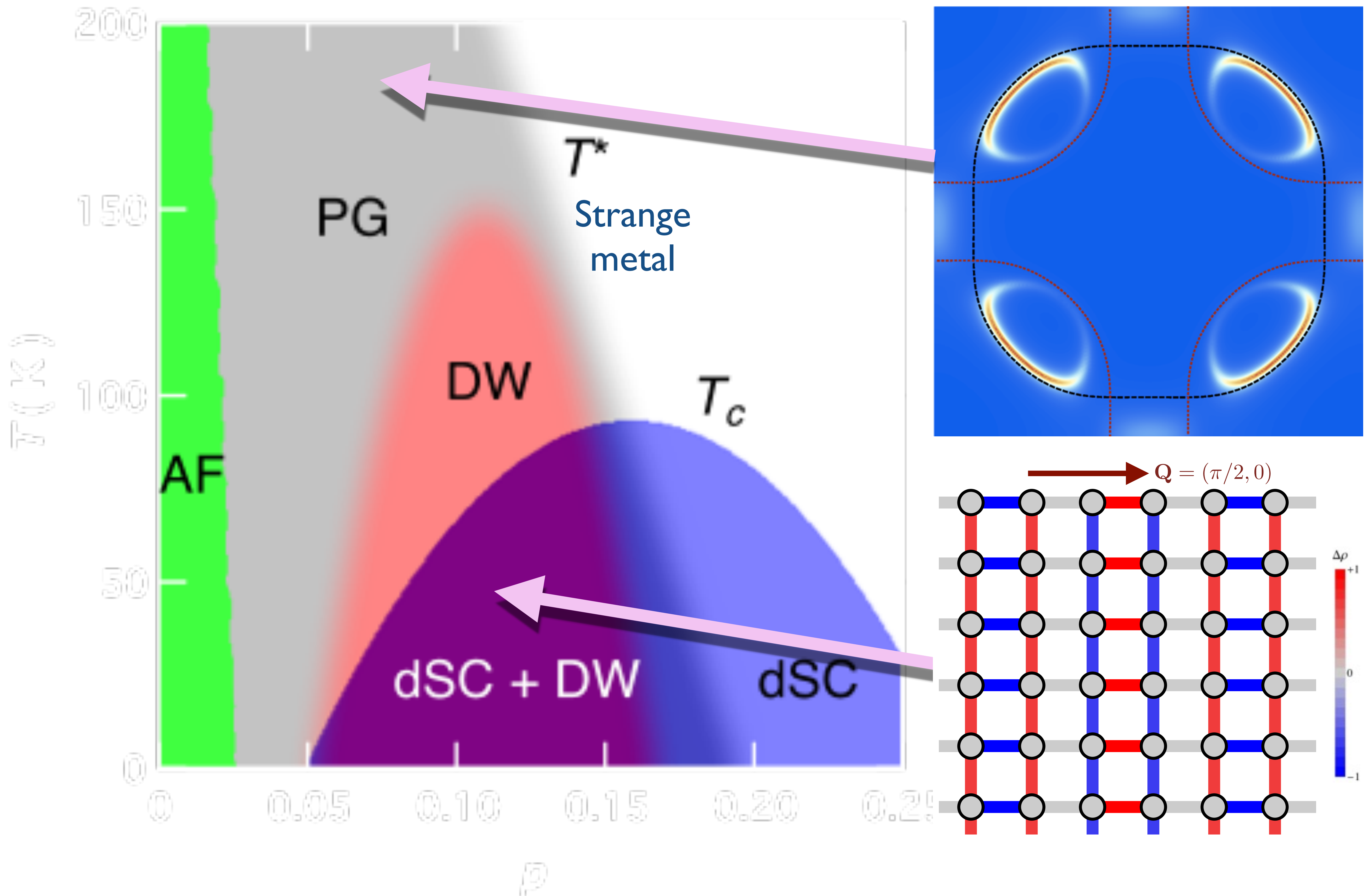
Fermi surface of FL*

Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)

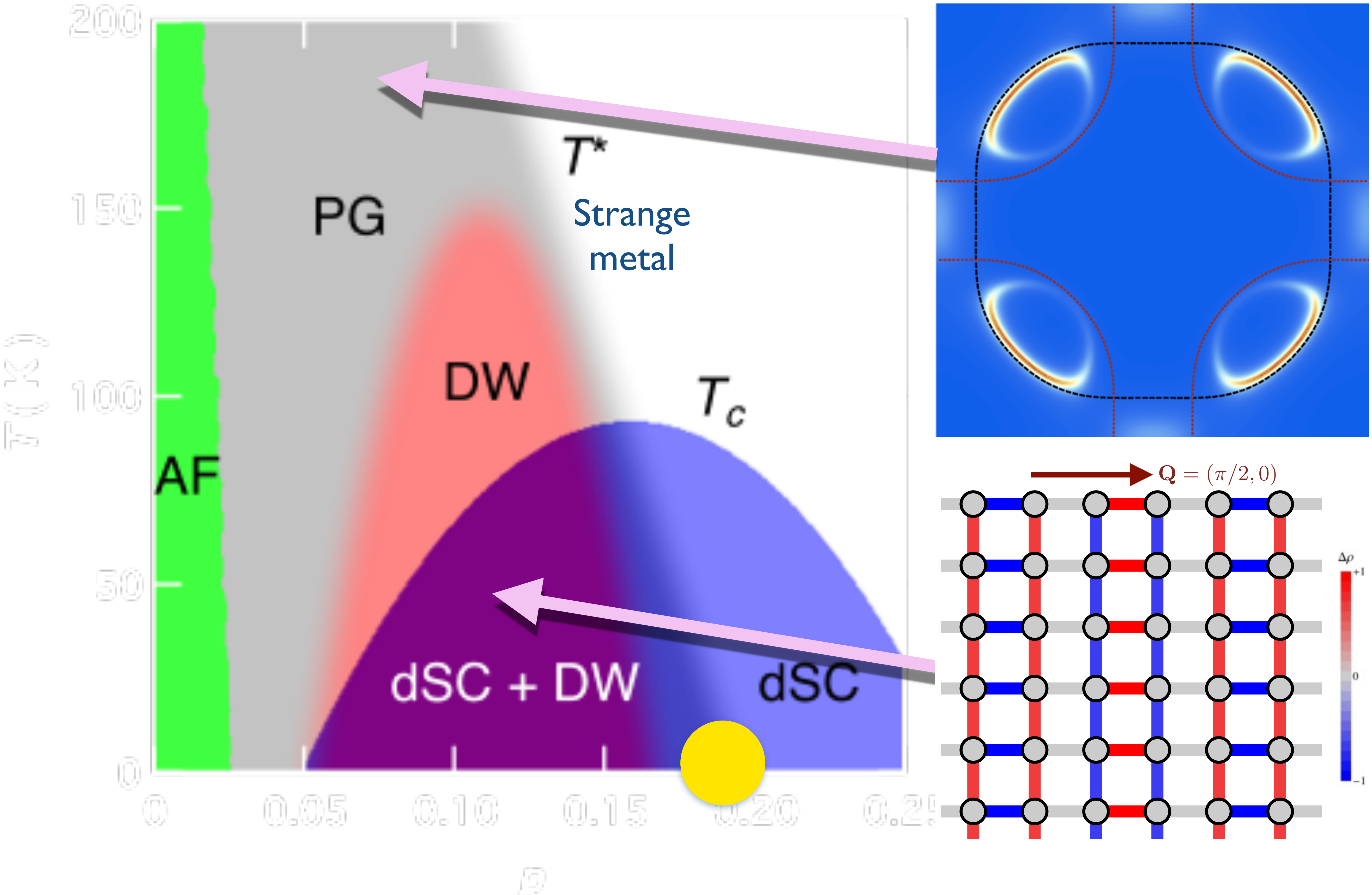


Density wave instability of FL* leads to the observed wavevector and form-factor

D. Chowdhury and S. Sachdev, Physical Review B **90**, 245136 (2014).



200
150
100
50
0
T (K)
PG
T*
Strange metal
DW
T_c
AF
dSC + DW
dSC
0
0.05
0.10
0.15
0.20
p
$\mathbf{Q} = (\pi/2, 0)$
$\Delta\rho$
+1
0
−1


200
150
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T (K)
0
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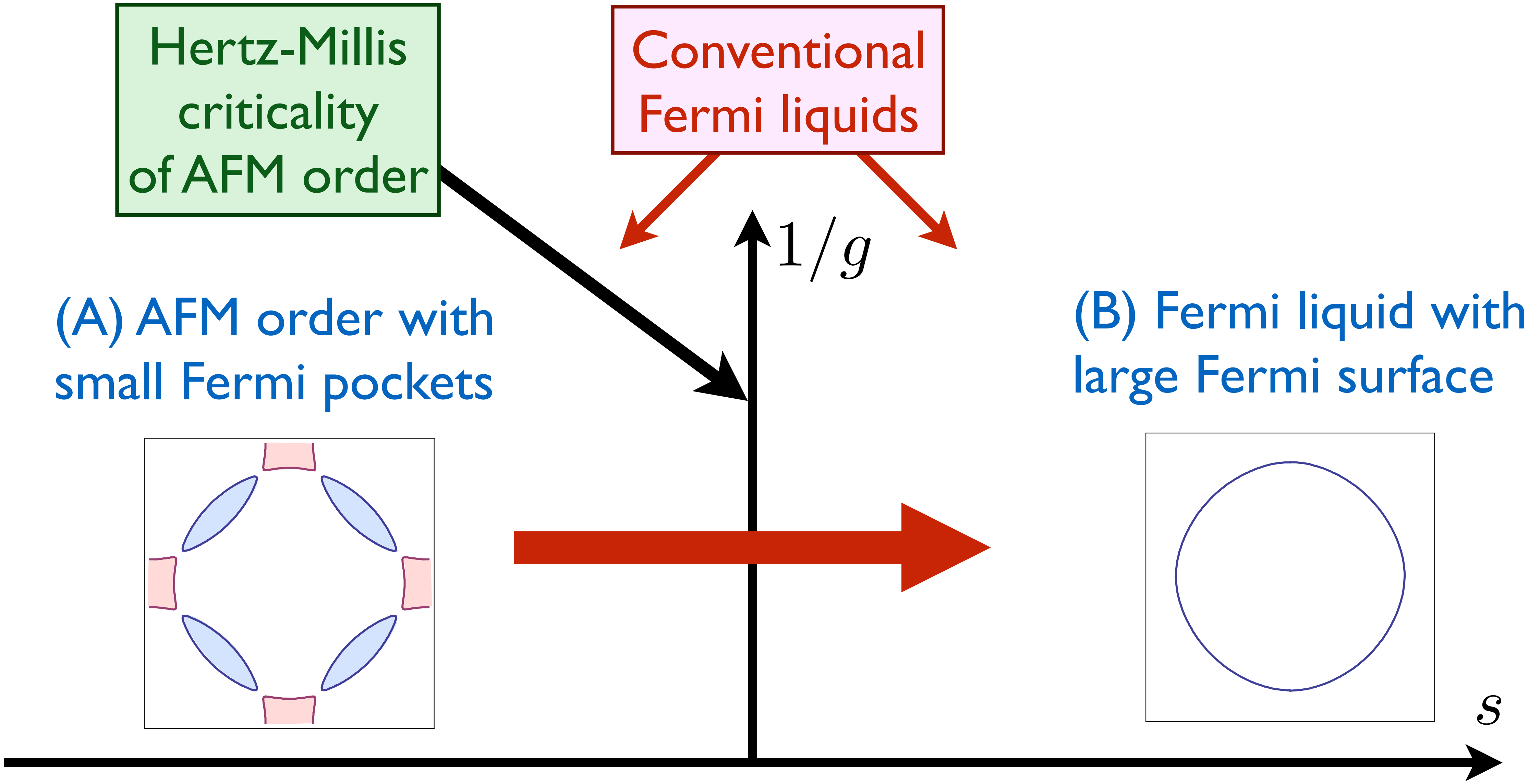
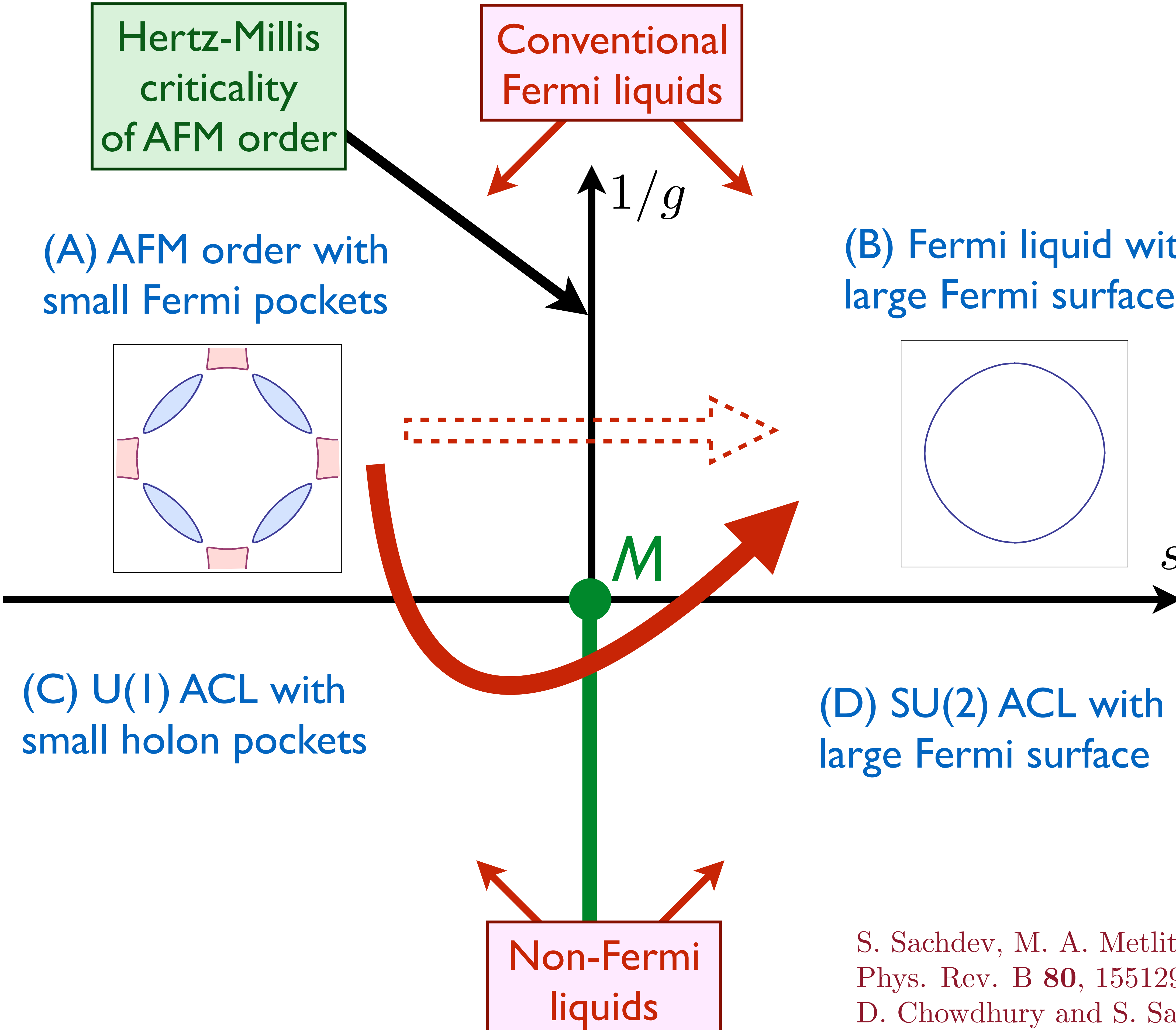
0.10
0.15
0.20
p
T*
PG
Strange metal
DW
T_c
AF
dSC + DW
dSC
$\mathbf{Q} = (\pi/2, 0)$
Δρ

Quantum critical point near optimal p

Higgs transition in a metal,
not directly involving any broken symmetry


Hertz-Millis criticality of AFM order
Conventional Fermi liquids
$1/g$
(A) AFM order with small Fermi pockets
(B) Fermi liquid with large Fermi surface
s



S. Sachdev, M. A. Metlitski, Y. Qi, and C. Xu,
Phys. Rev. B **80**, 155129 (2009)
D. Chowdhury and S. Sachdev,
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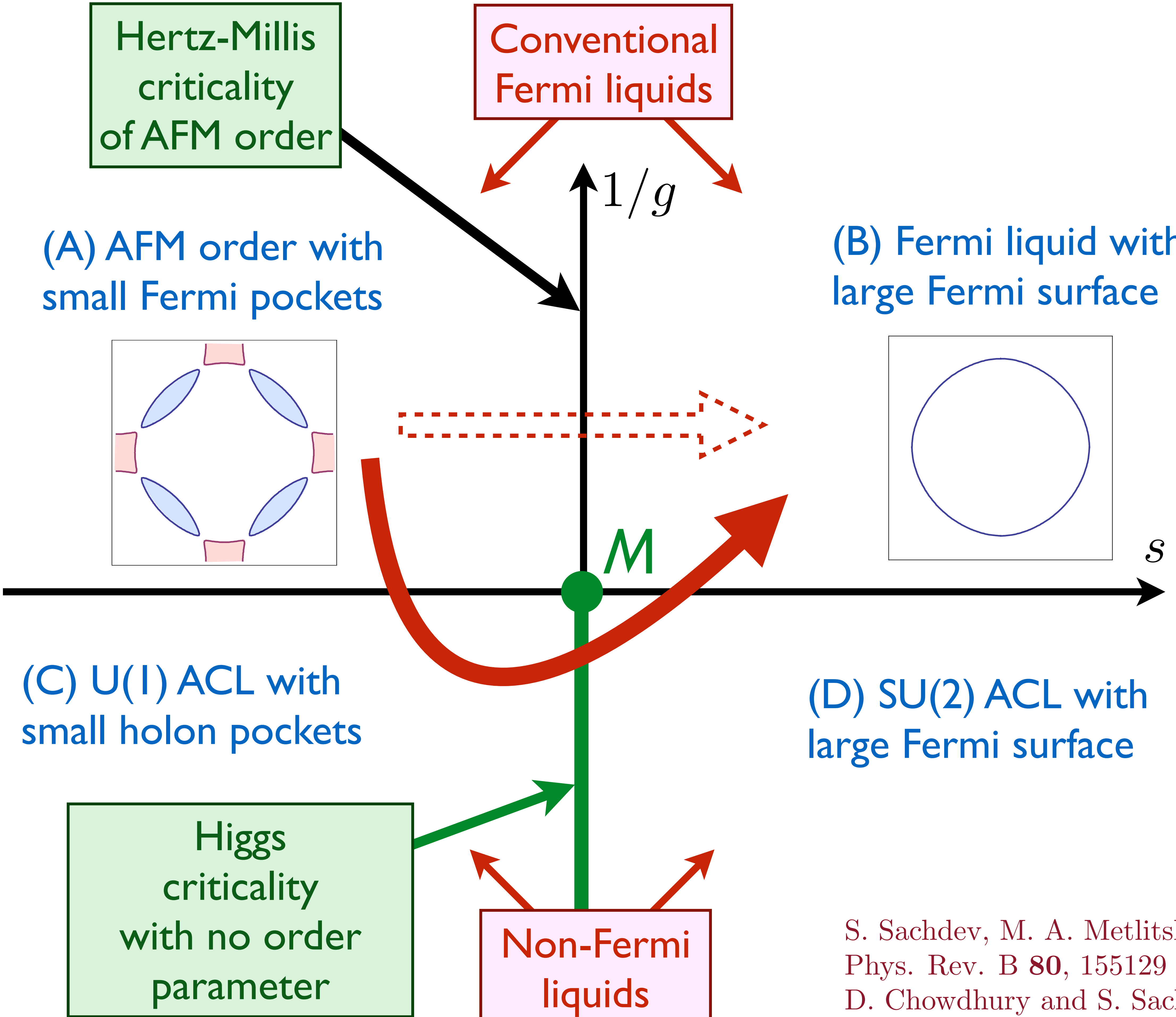

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Phys. Rev. B **80**, 155129 (2009)
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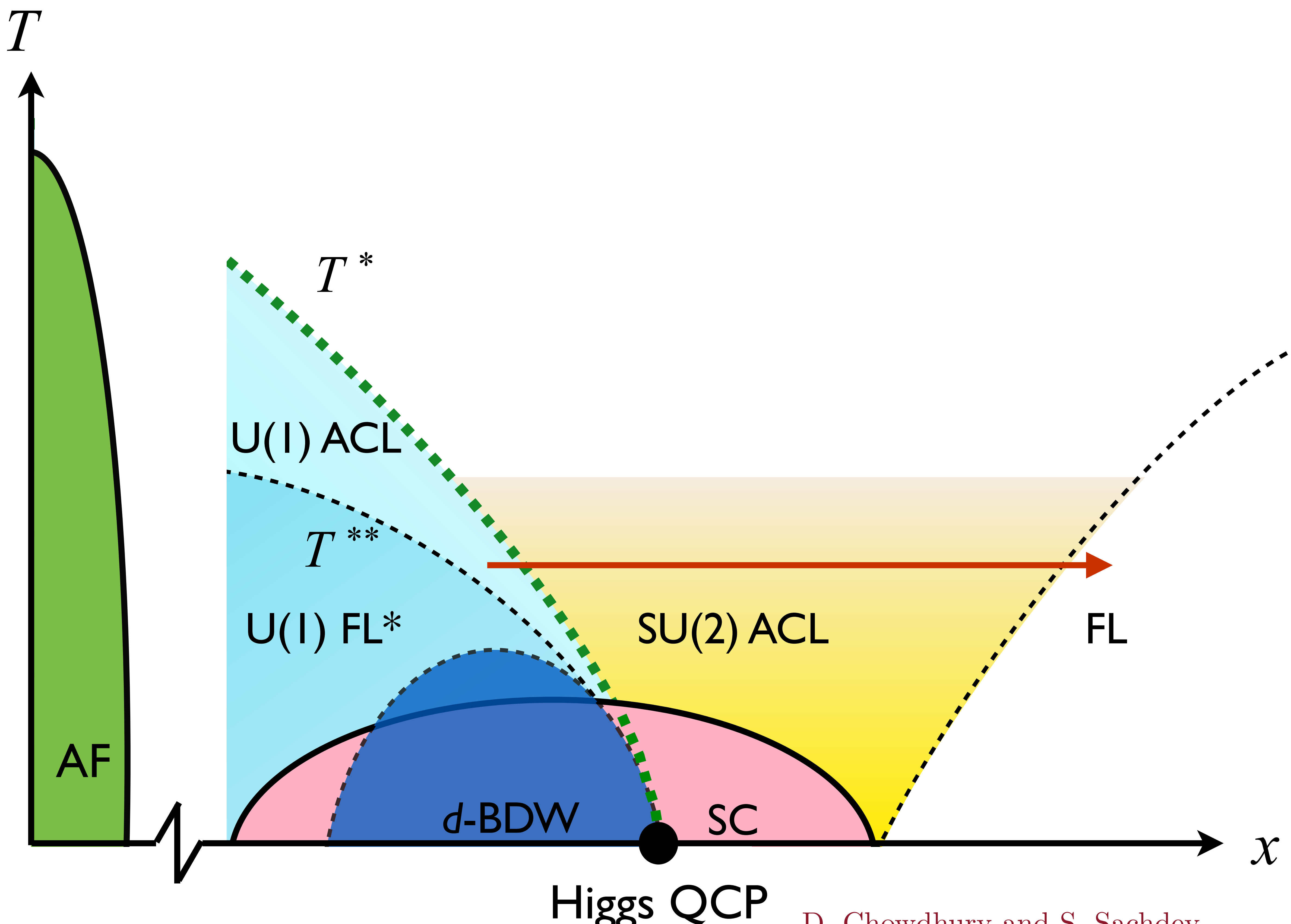
SU(2) gauge theory for underlying quantum critical point



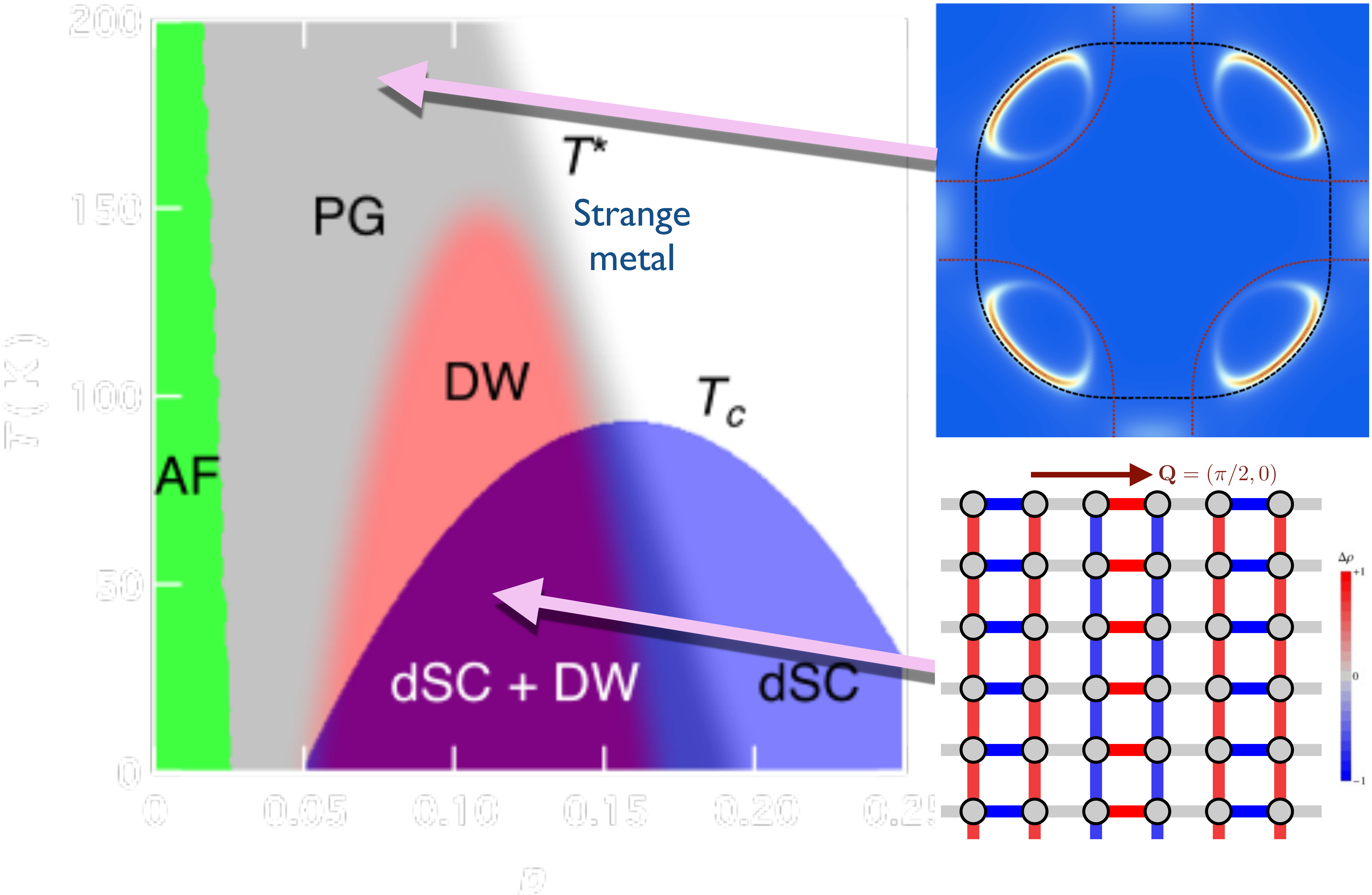
D. Chowdhury and S. Sachdev, Phys. Rev. B **91**, 115123 (2015).

Conclusions

1. Predicted *d*-form factor density wave order observed in the non-La hole-doped cuprate superconductors.

2. The "electron becomes a dimer" in the pseudogap metal: proposed a quantum dimer model.

3. Can we experimentally detect possible "topological order" in the pseudogap metal ?
(topological order is directly linked to Fermi surface size)



T*
PG
Strange
metal
DW
T_c
AF
dSC + DW
dSC
200
150
100
50
0
T (K)
0
0.05
0.10
0.15
0.20
p
Q = (π/2, 0)
Δρ
+1
0
−1