The remarkable non-superconducting states of the high temperature superconductors

University of California, Santa Barbara
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Subir Sachdev

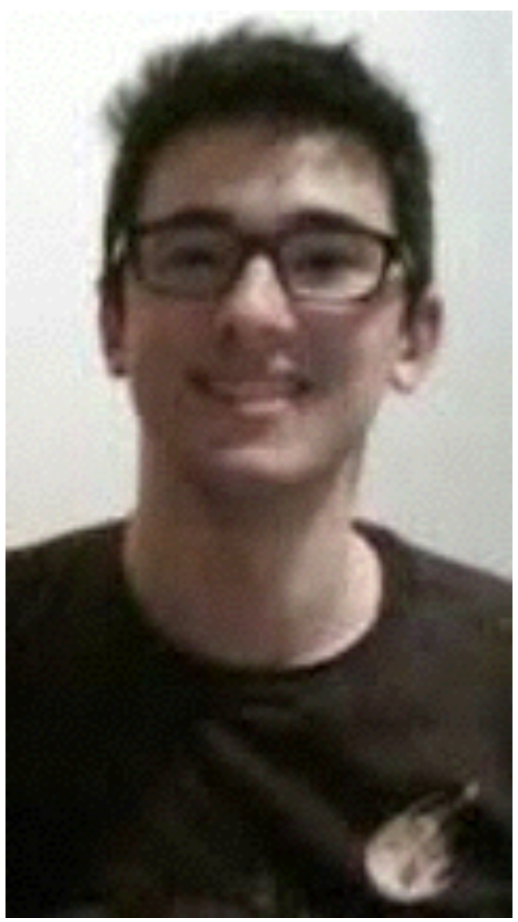
PERIMETER INSTITUTE FOR THEORETICAL PHYSICS
NSF
JOHN TEMPLETON FOUNDATION
PHYSICS HARVARD

Talk online: sachdev.physics.harvard.edu

Debanjan Chowdhury

Andrea Allais

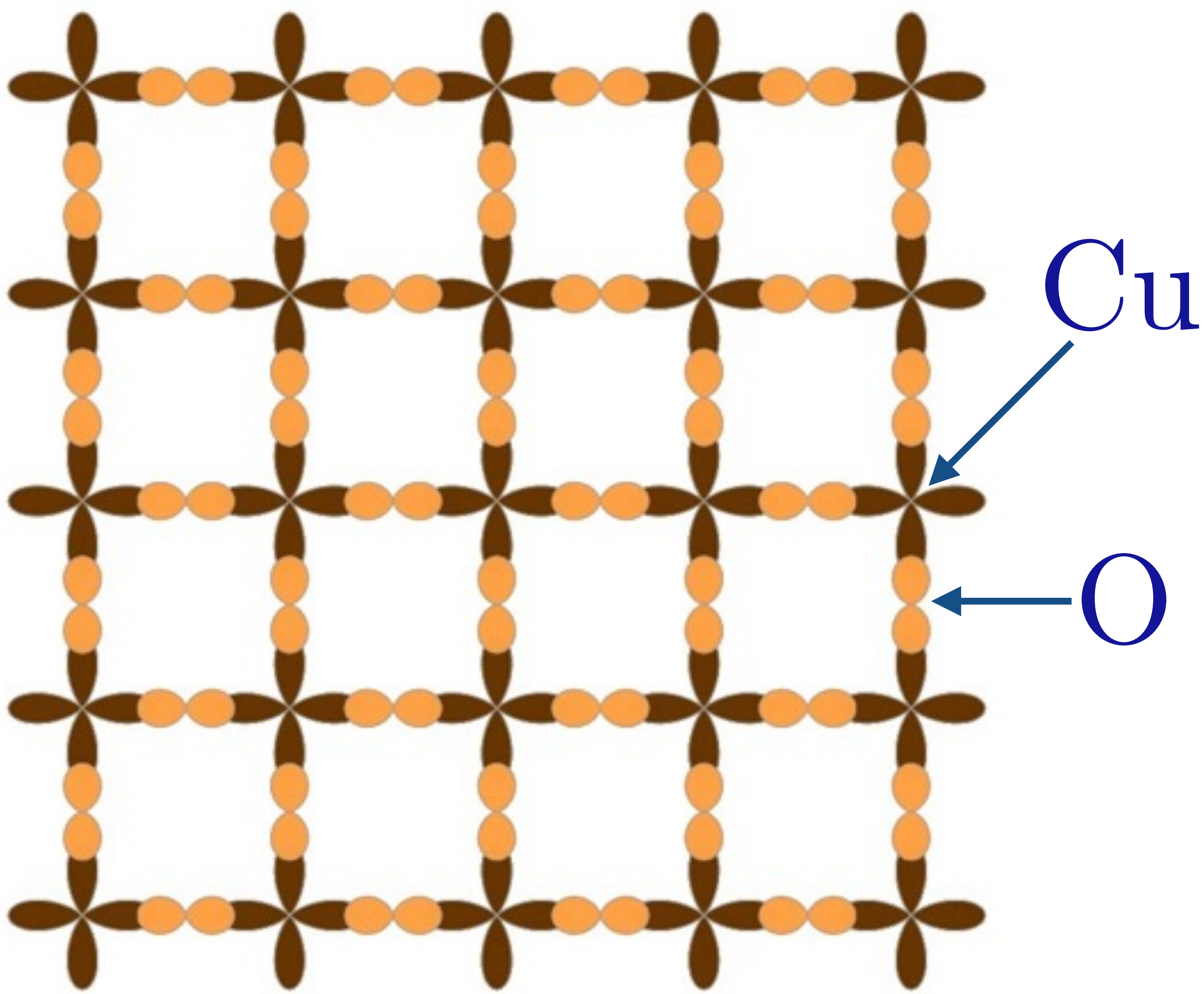
Matthias Punk (Innsbruck)



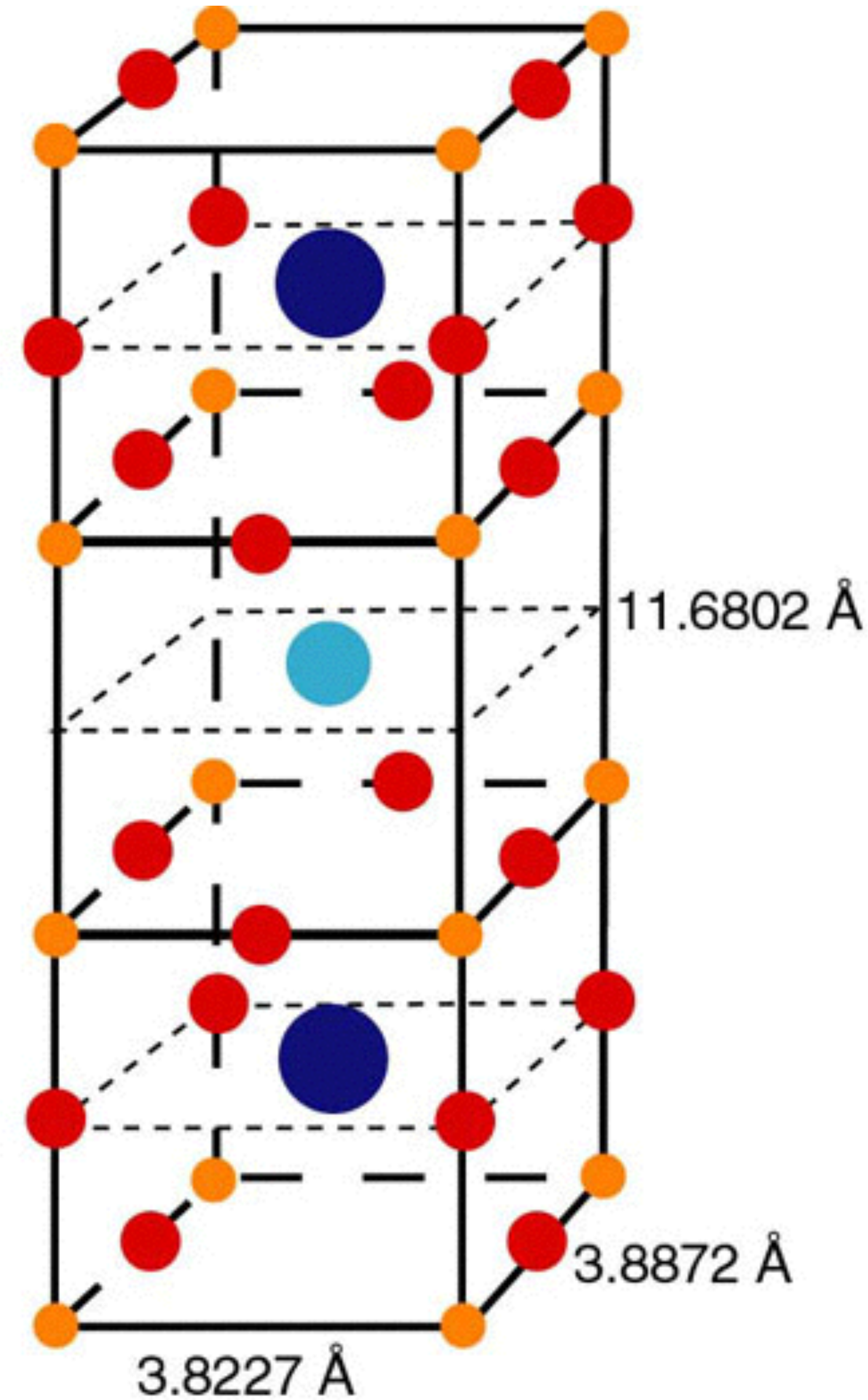
Andrew Lucas

Alexandra Thomson

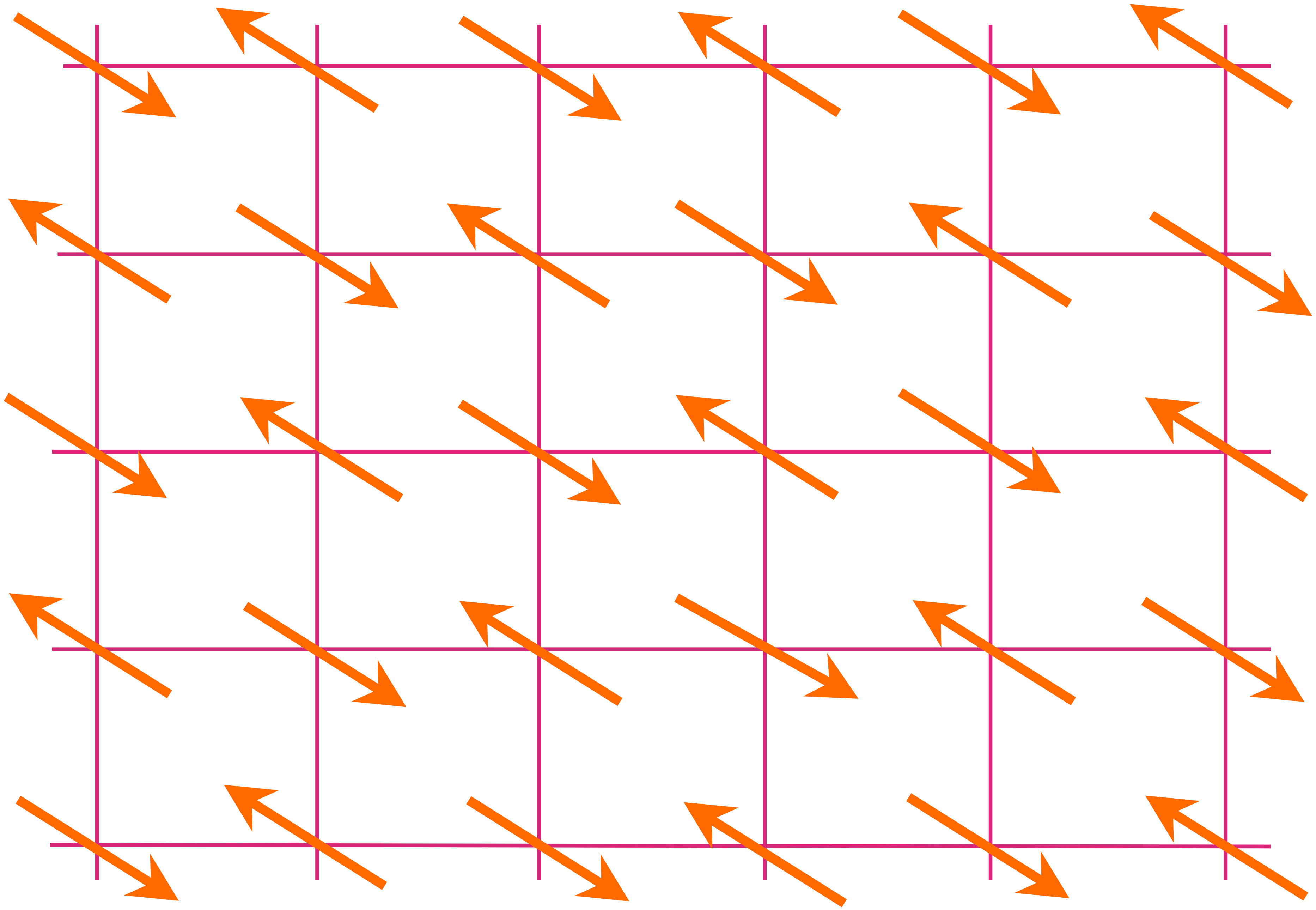
High temperature superconductors



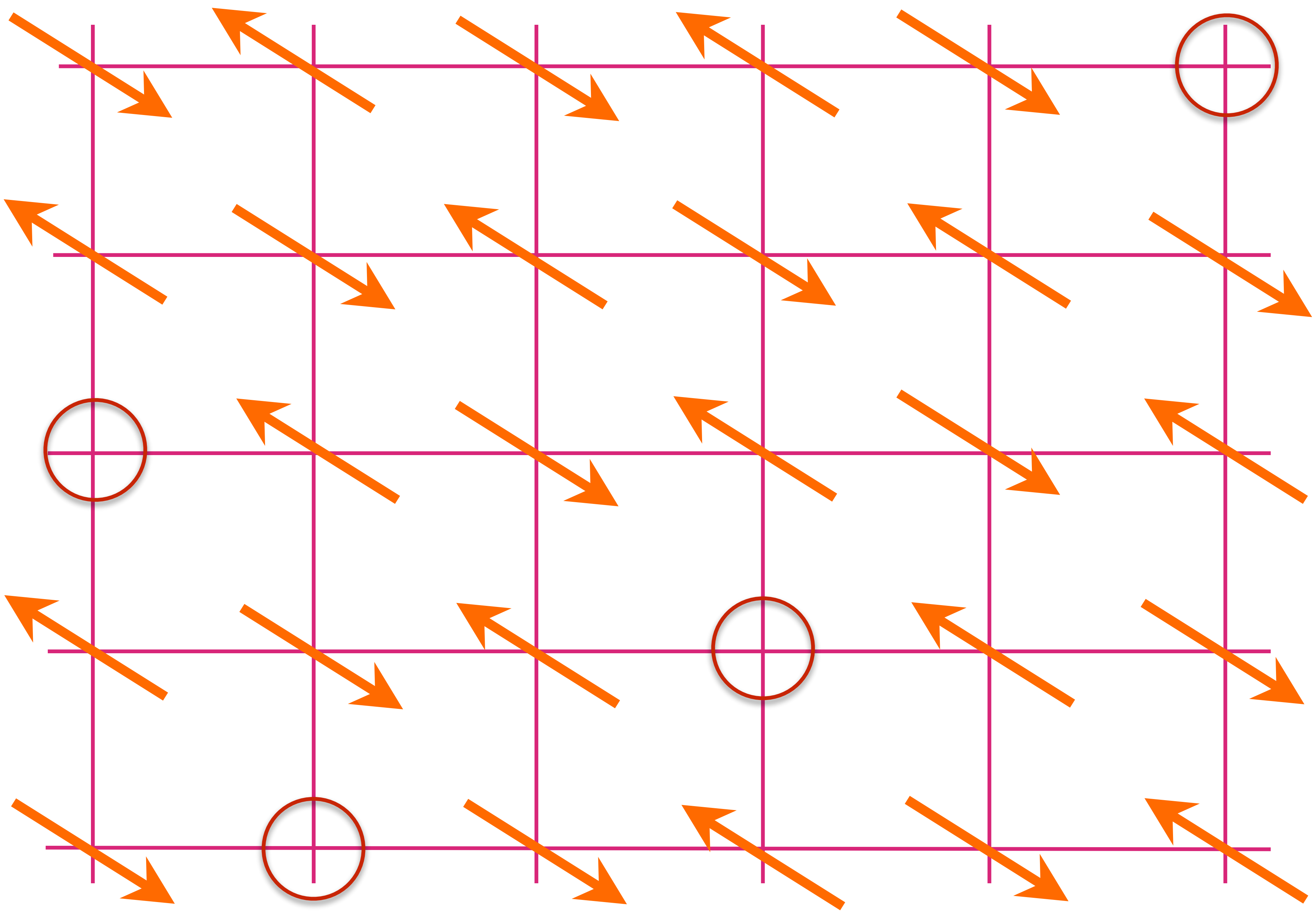
CuO_2 plane



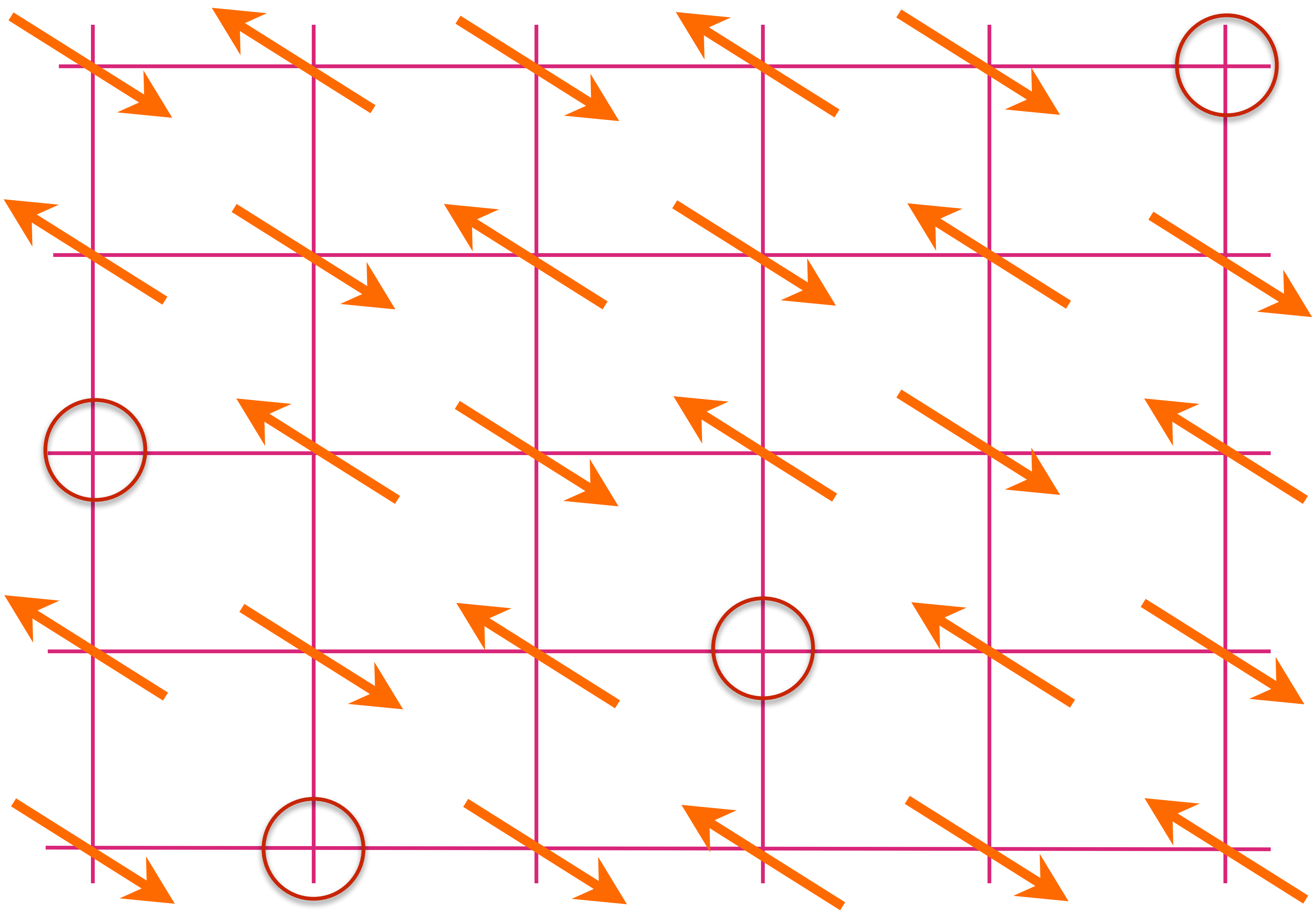
$YBa_2Cu_3O_{6+x}$



"Undoped" Anti-ferromagnet

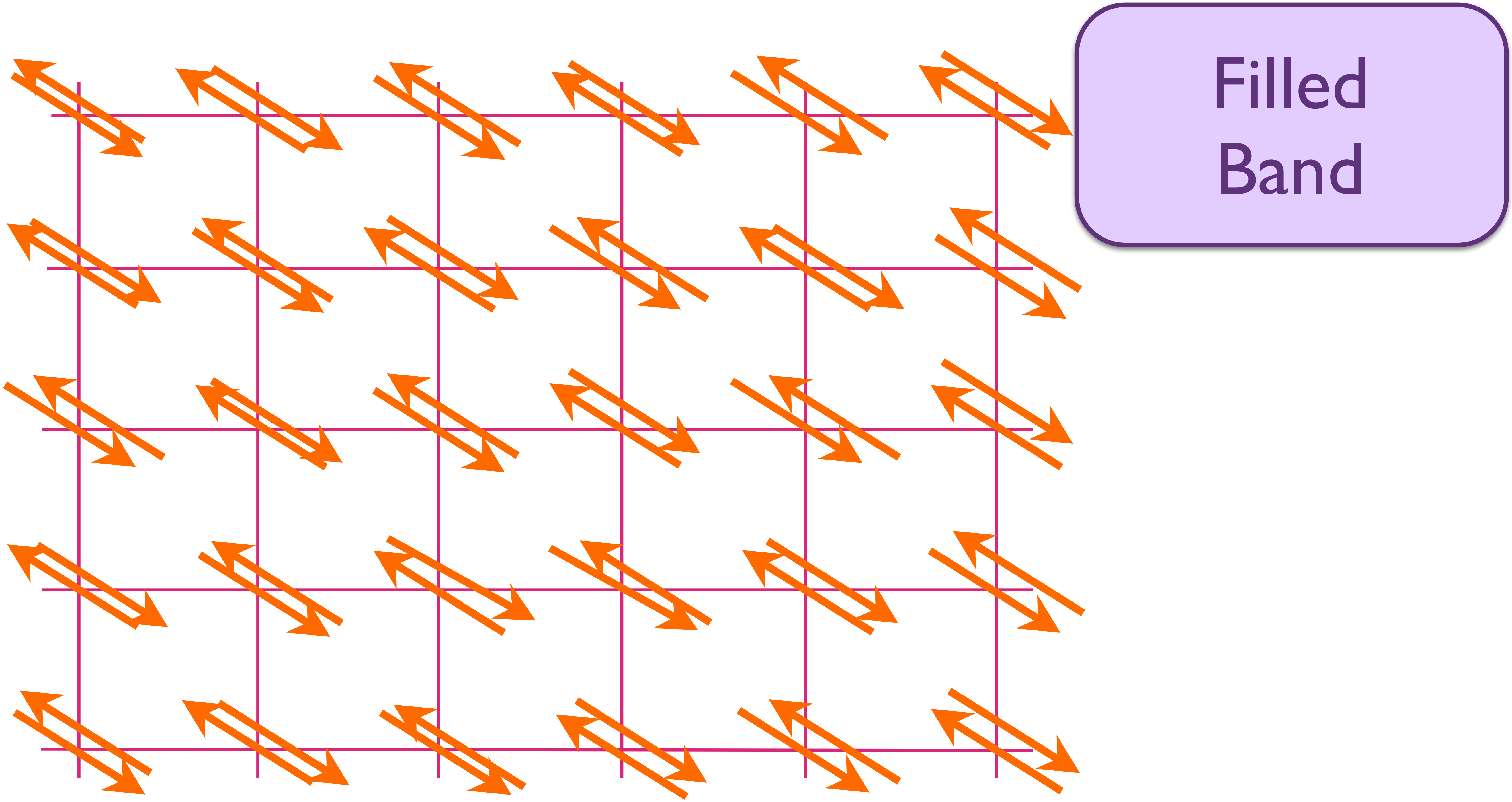


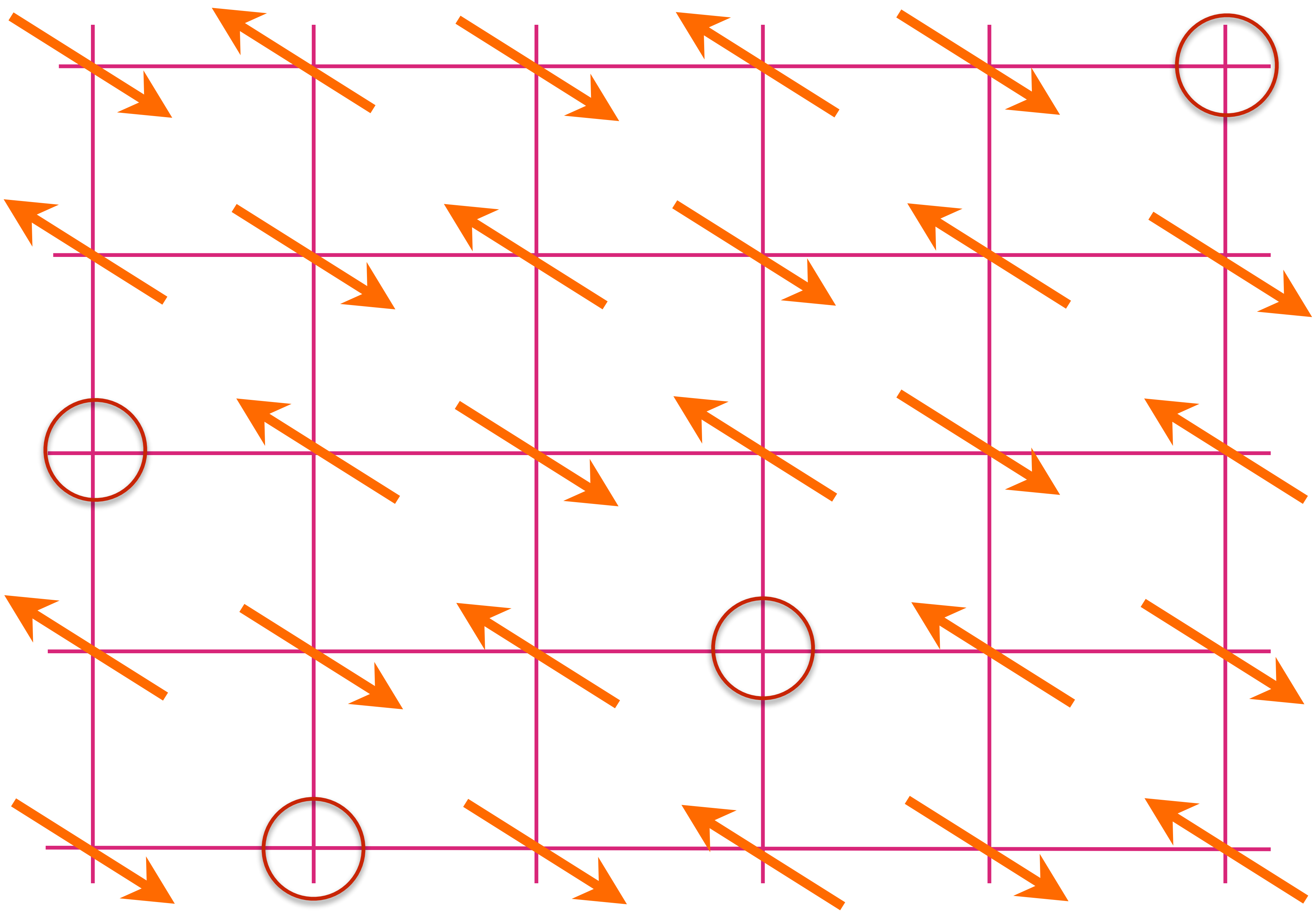
Anti-ferromagnet with p holes per square



Anti-ferromagnet with p holes per square

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


Filled Band



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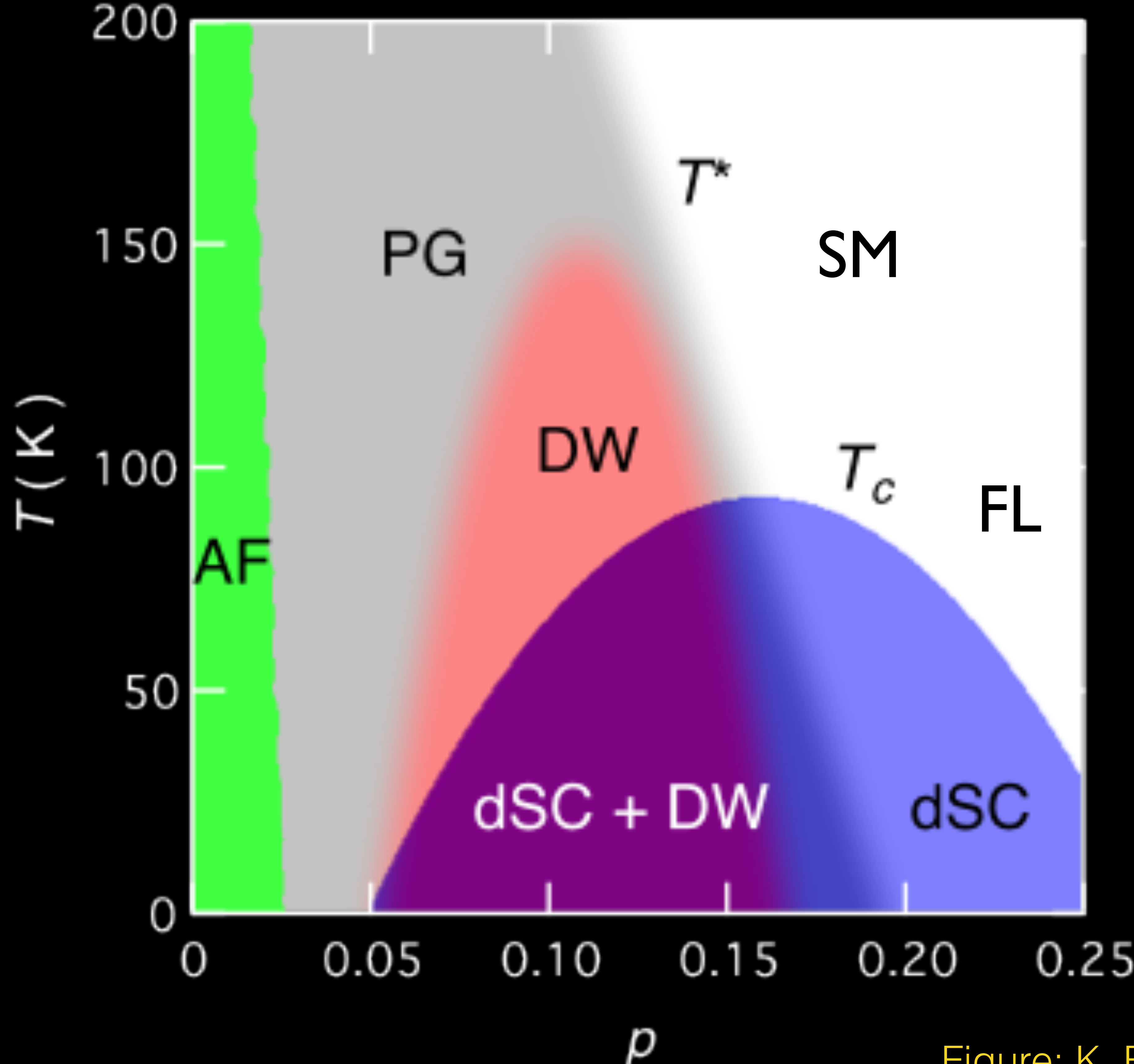


Figure: K. Fujita and J. C. Seamus Davis

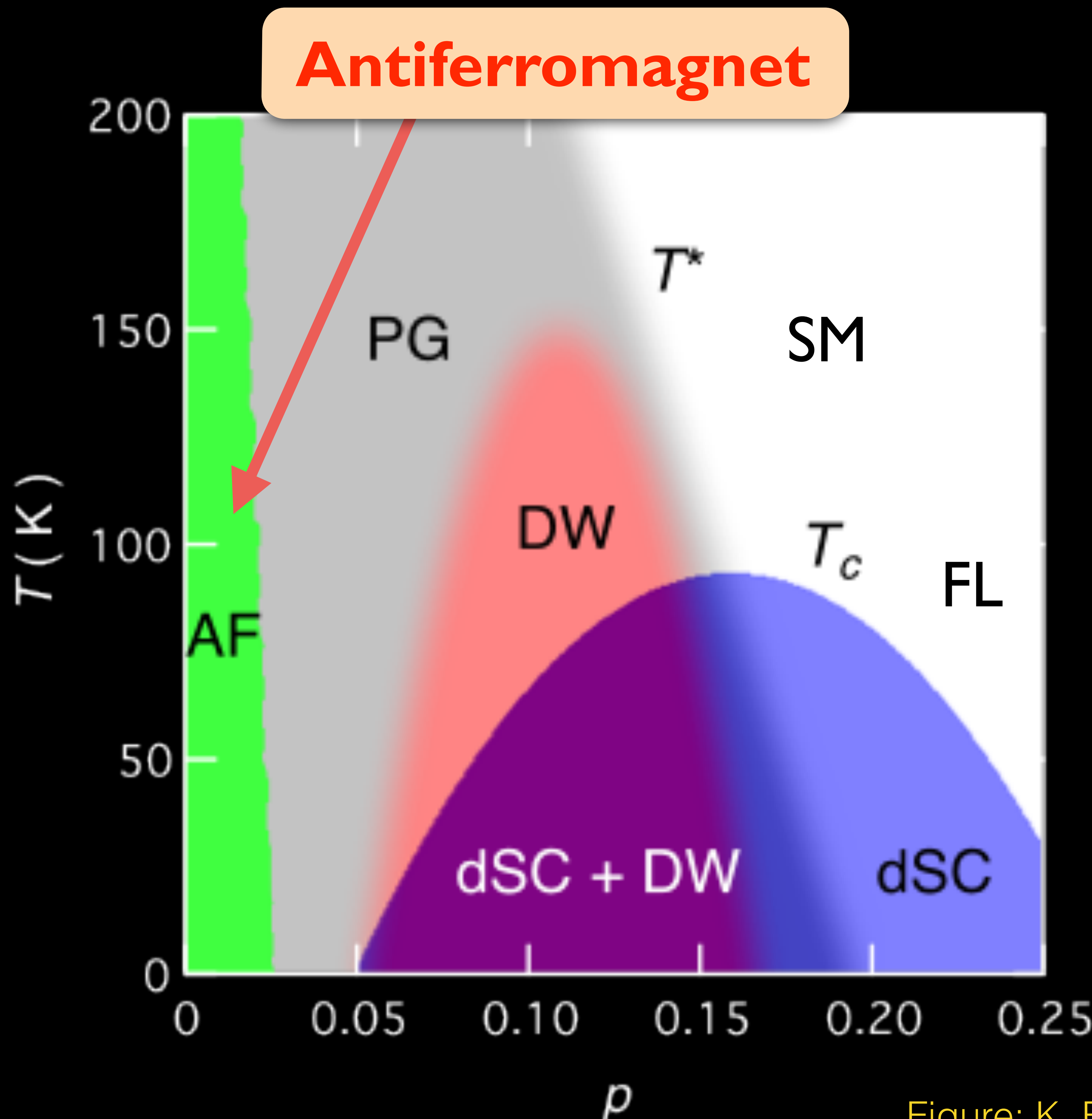


Figure: K. Fujita and J. C. Seamus Davis

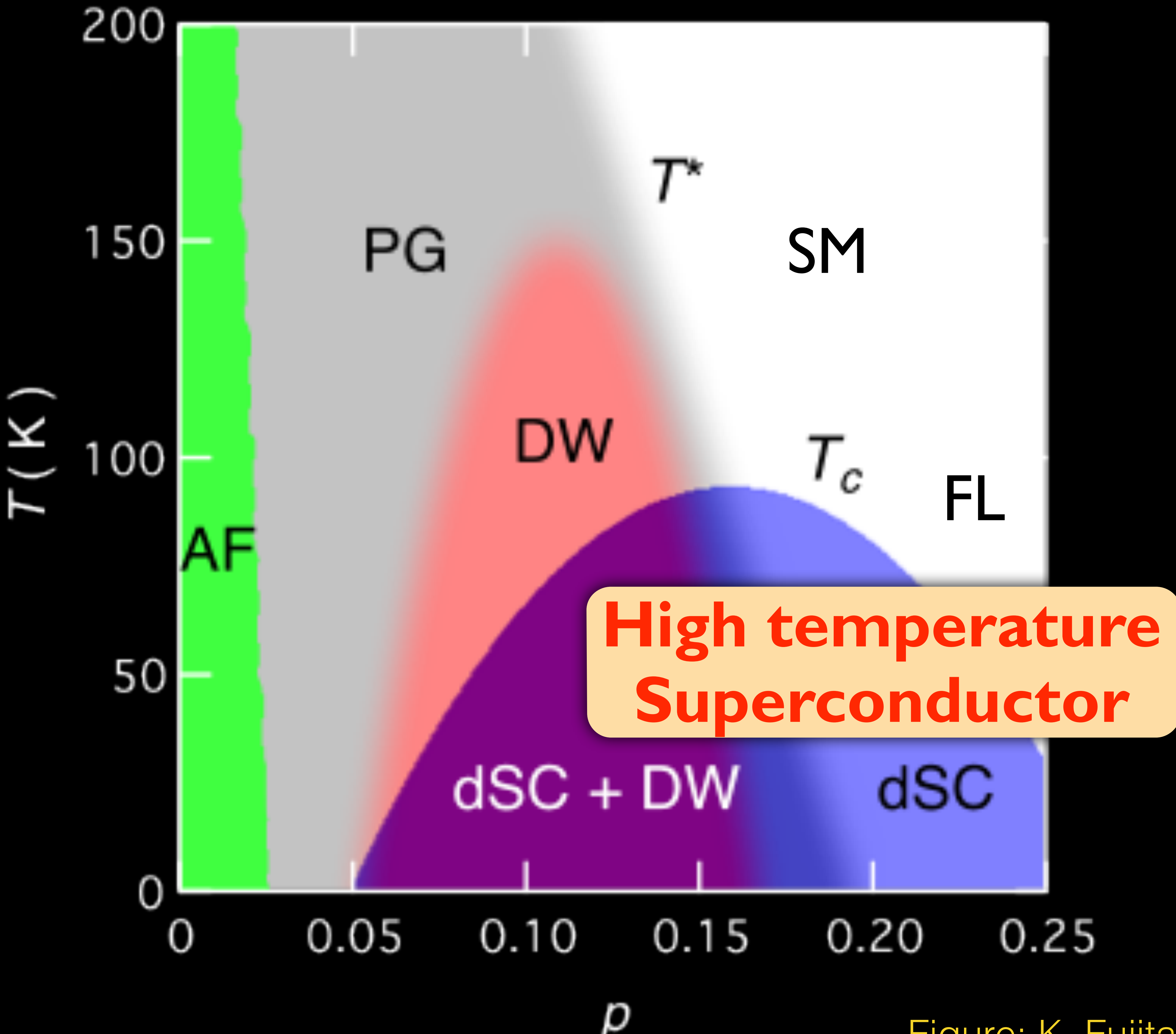
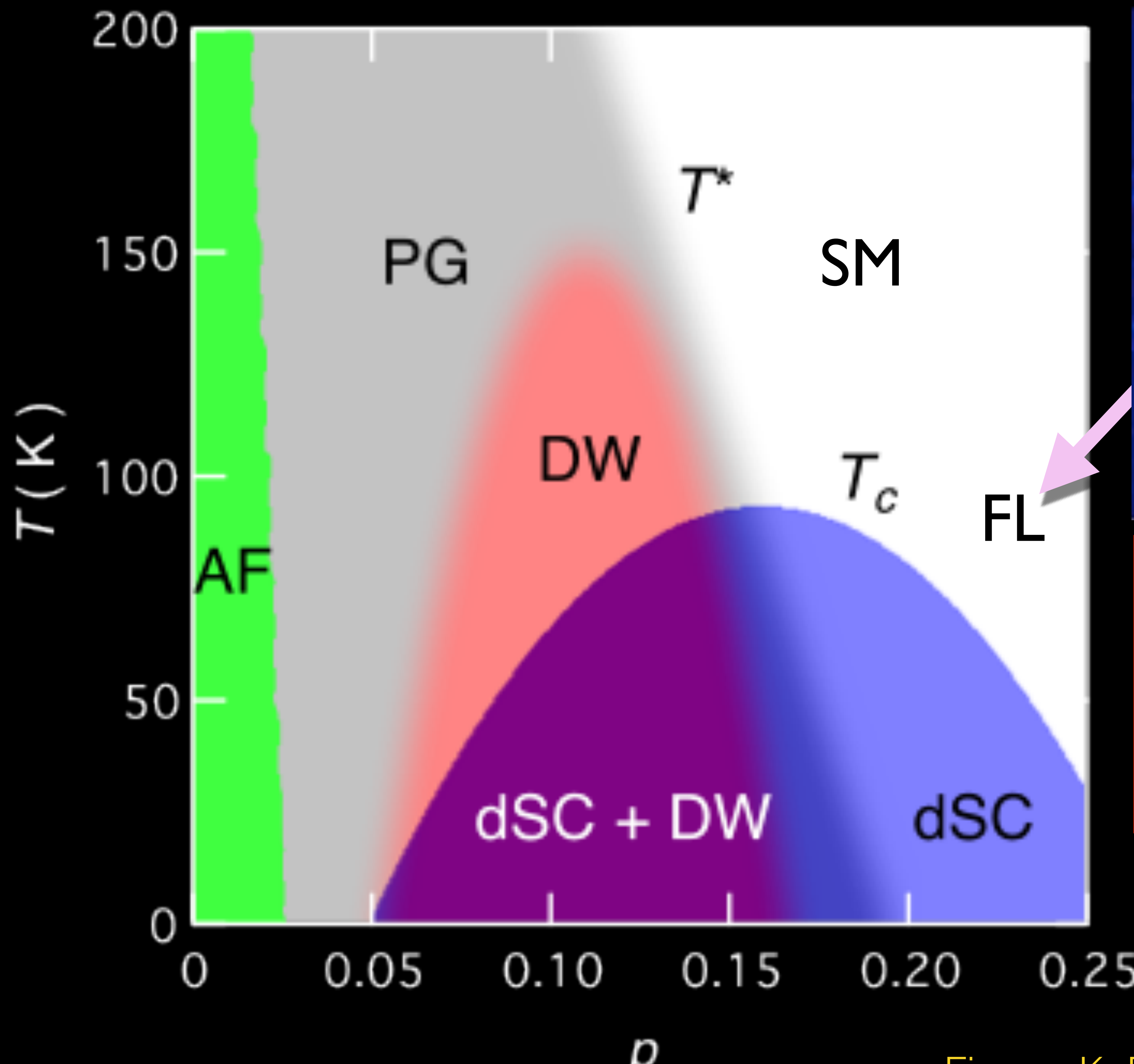
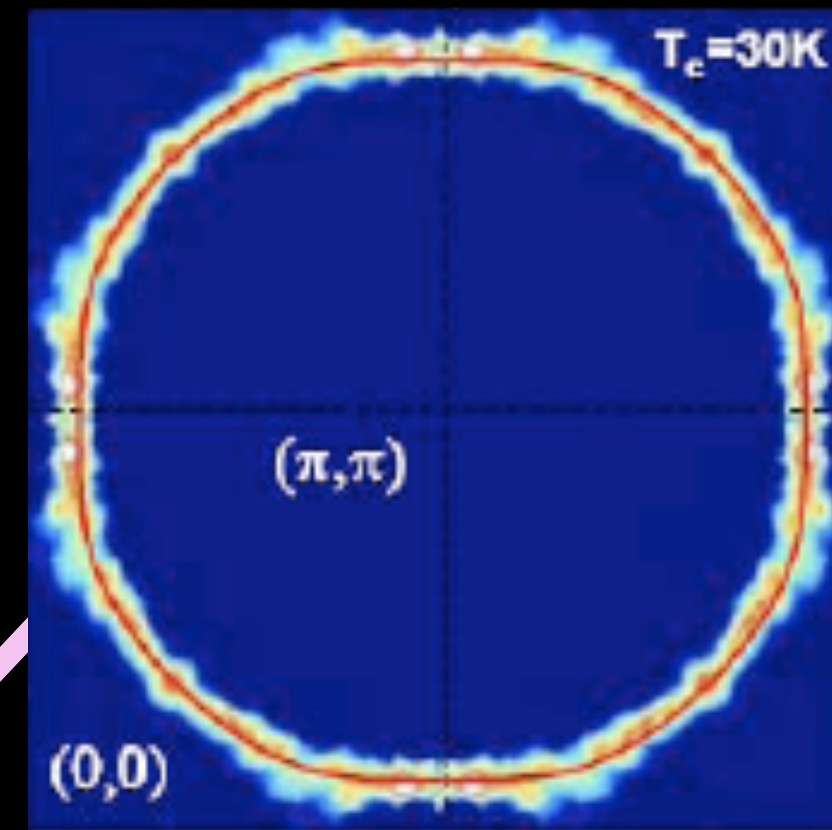


Figure: K. Fujita and J. C. Seamus Davis

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)



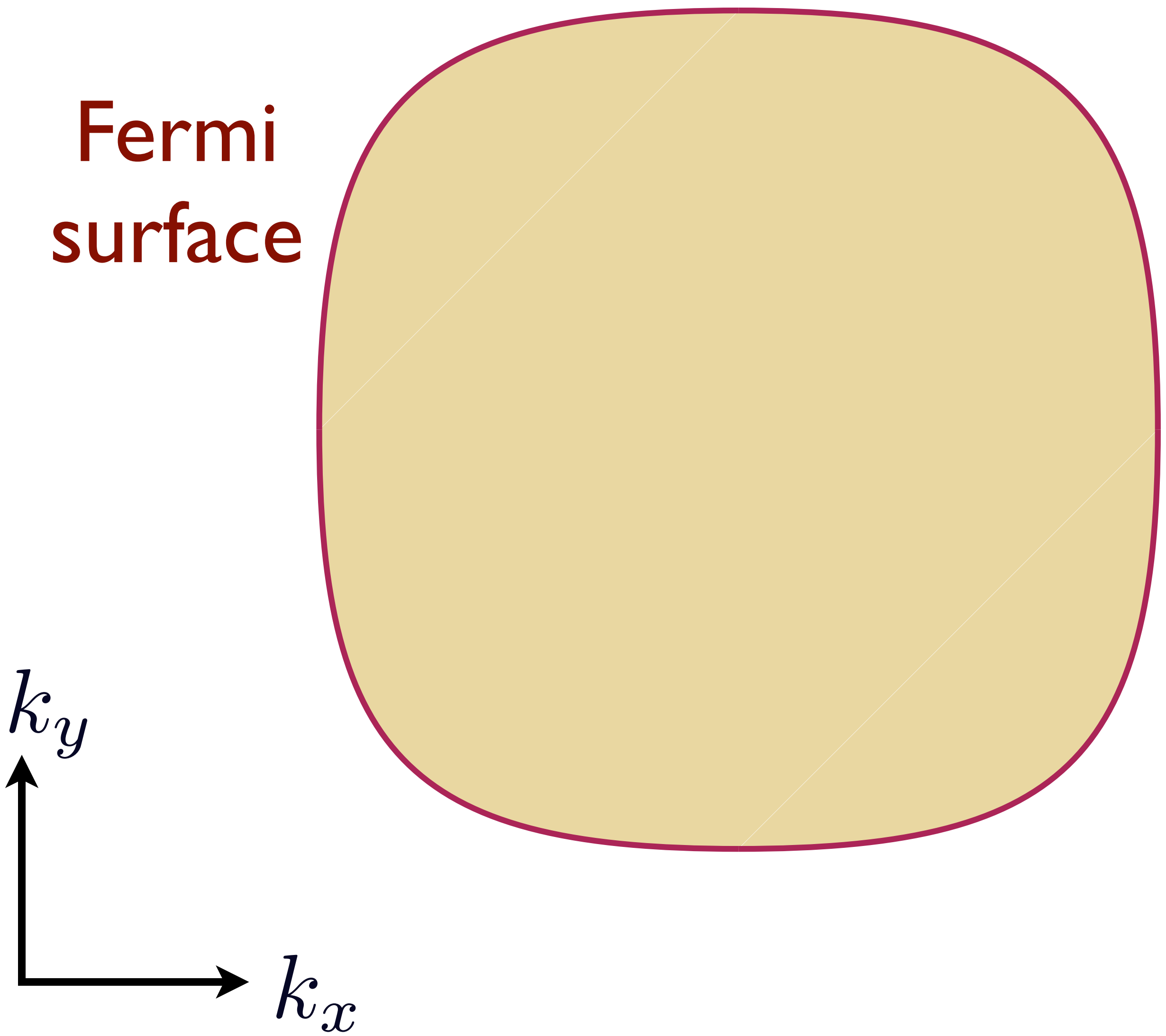


Conventional metal

Area enclosed by Fermi surface $=1+p$

Figure: K. Fujita and J. C. Seamus Davis

Fermi liquid (FL)



- Fermi surface separates empty and occupied states in momentum space.

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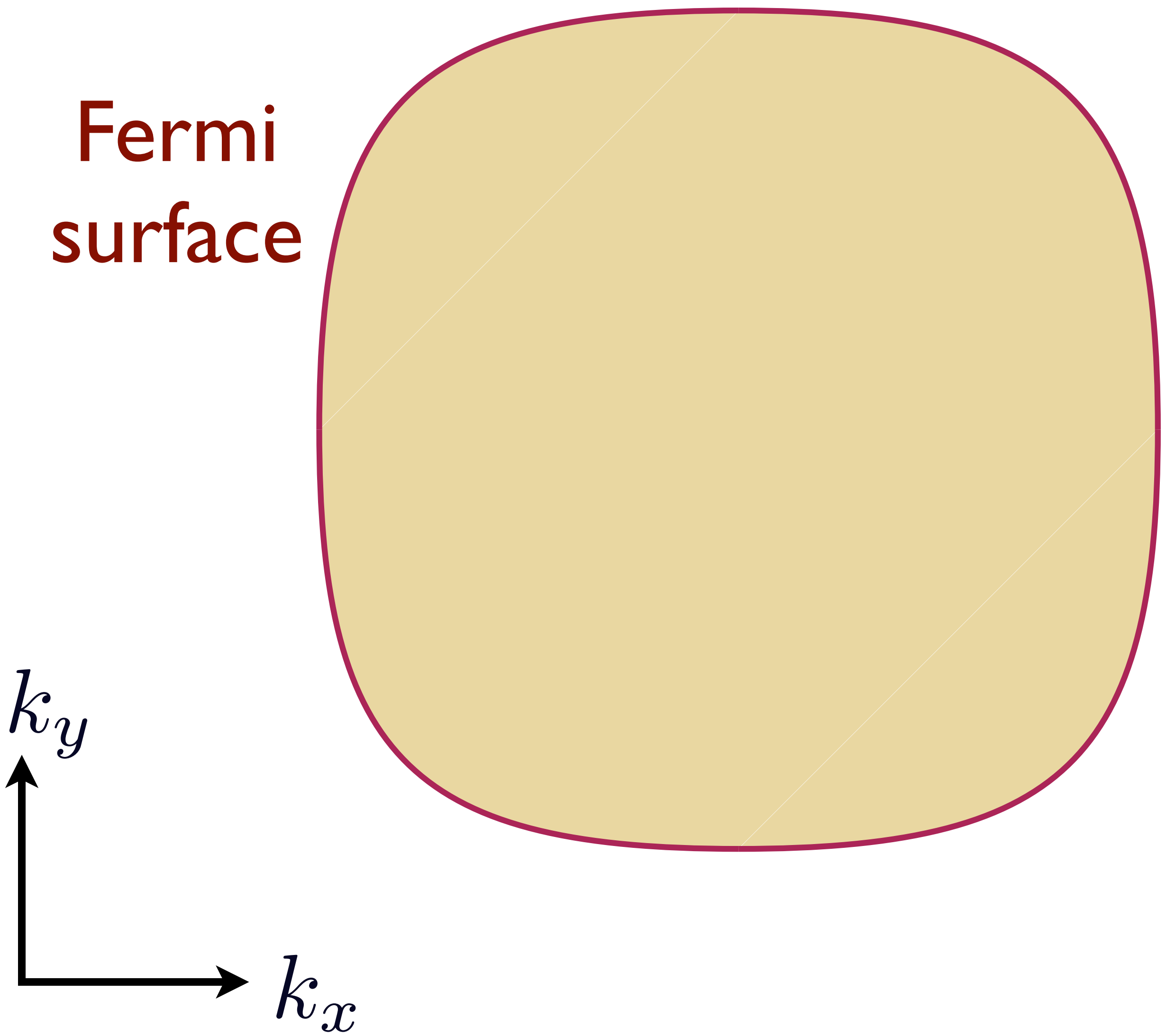

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- Long-lived electron-like quasiparticle excitations near the Fermi surface: lifetime of quasiparticles $\sim 1/T^2$.

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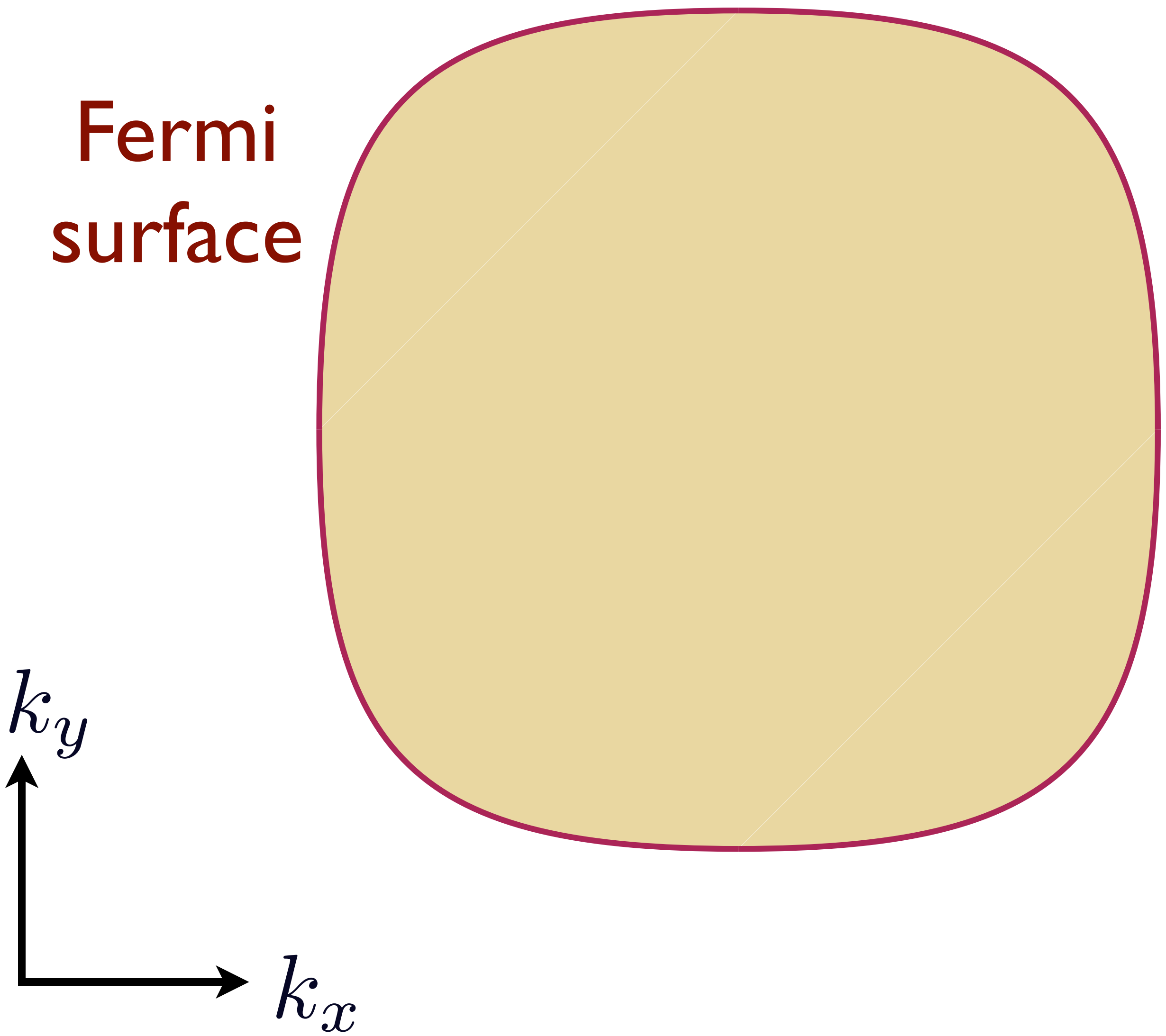


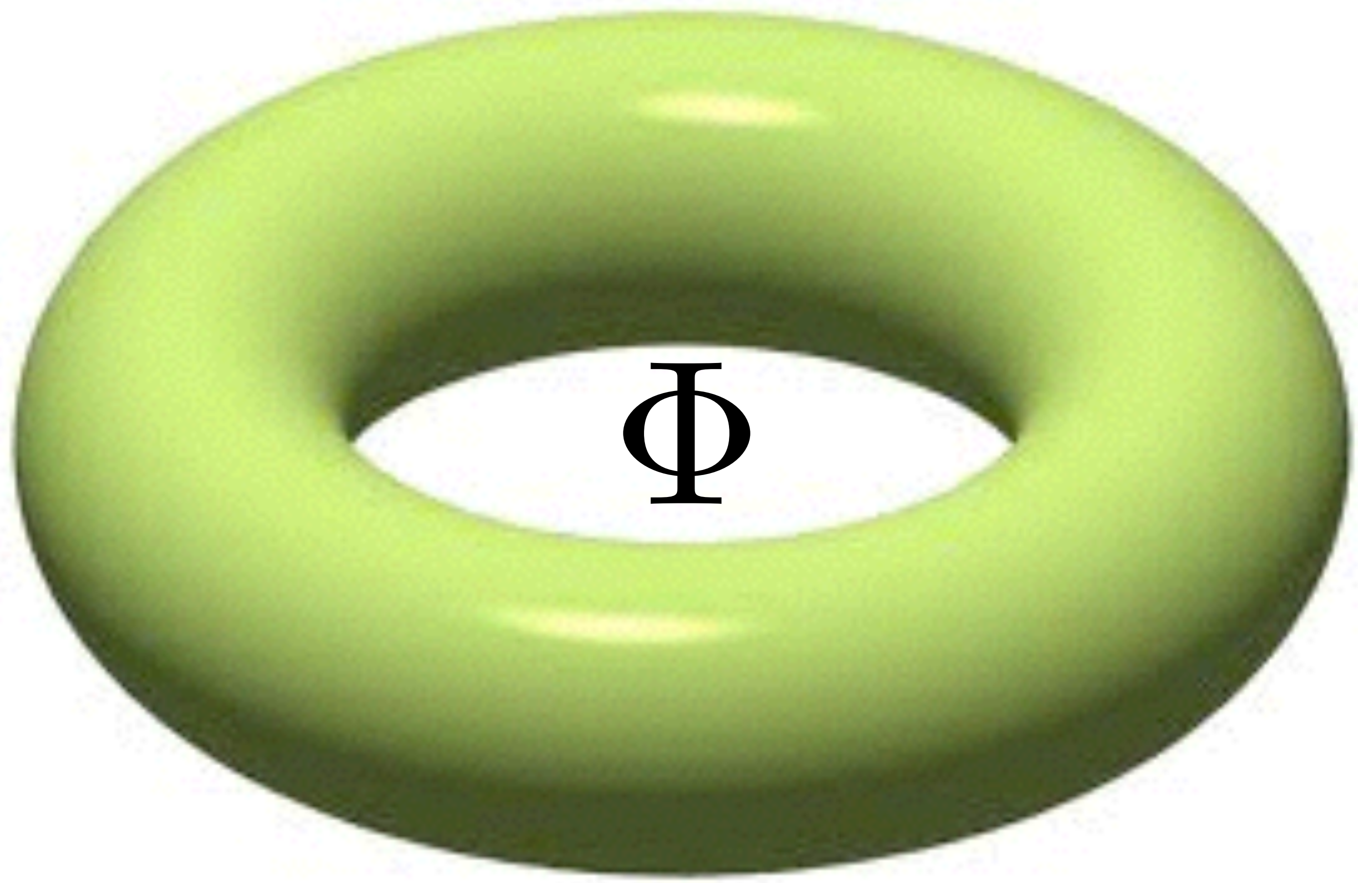
- Fermi surface separates empty and occupied states in momentum space.

- Long-lived electron-like quasiparticle excitations near the Fermi surface: lifetime of quasiparticles $\sim 1/T^2$.

- Area enclosed by Fermi surface = total density of electrons (mod 2) = $1 + p$.

Fermi liquid (FL)

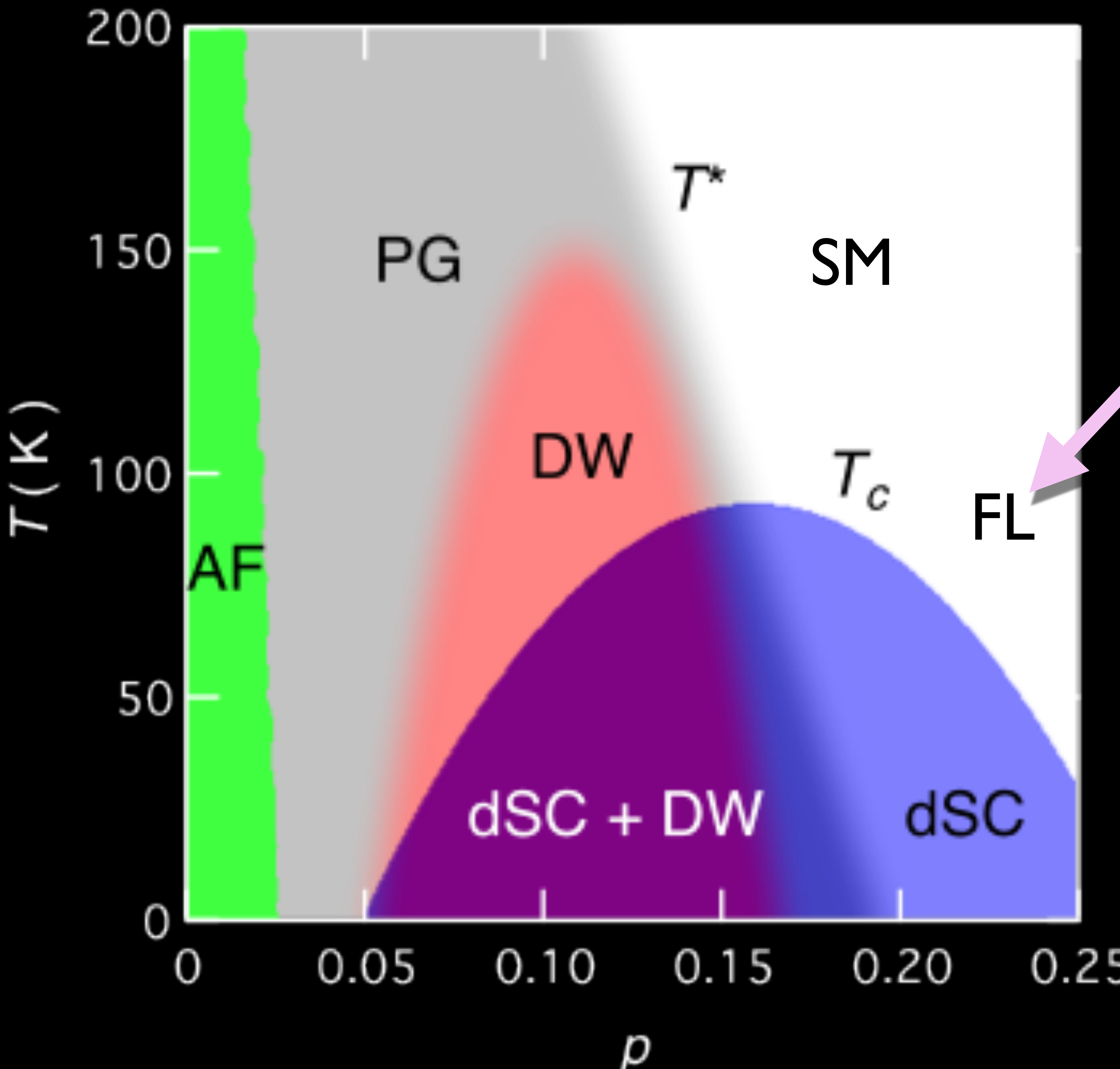
Topological argument for the area of Fermi surface

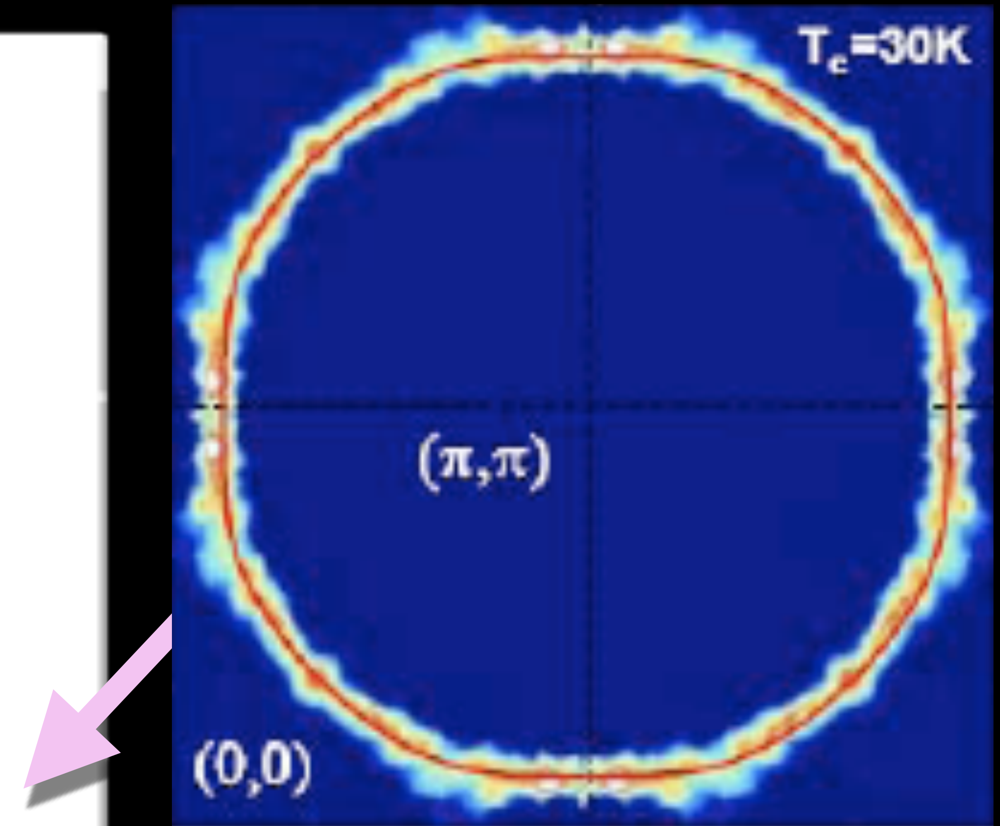


Put metal on a torus, adiabatically insert flux $\Phi = h/e$ through hole, and measure change in momentum. In a FL, we can assume the only low energy excitations are quasiparticles near the Fermi surface, and this leads to a non-perturbative proof of the Luttinger relation on the area enclosed by the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

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

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)

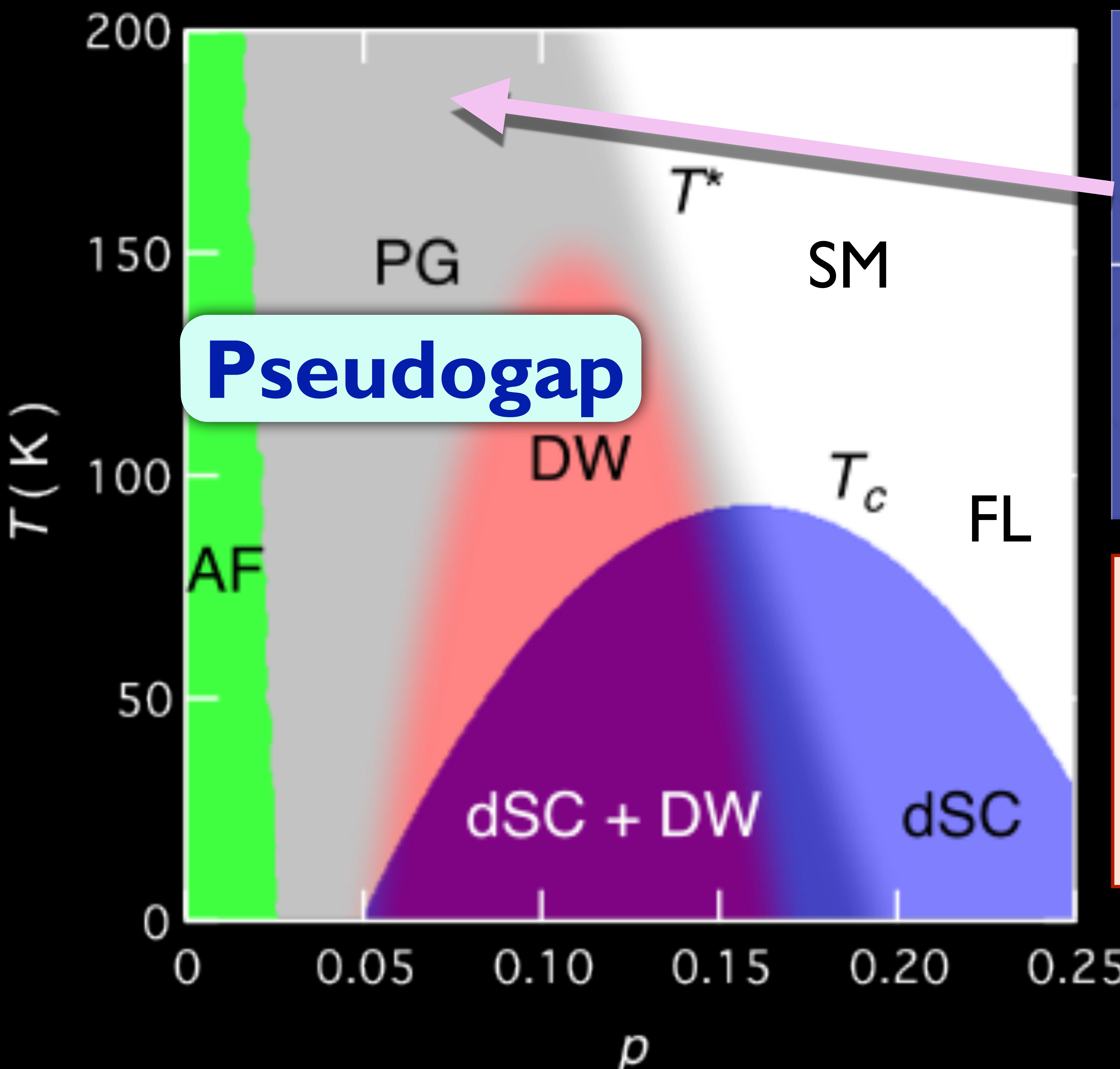


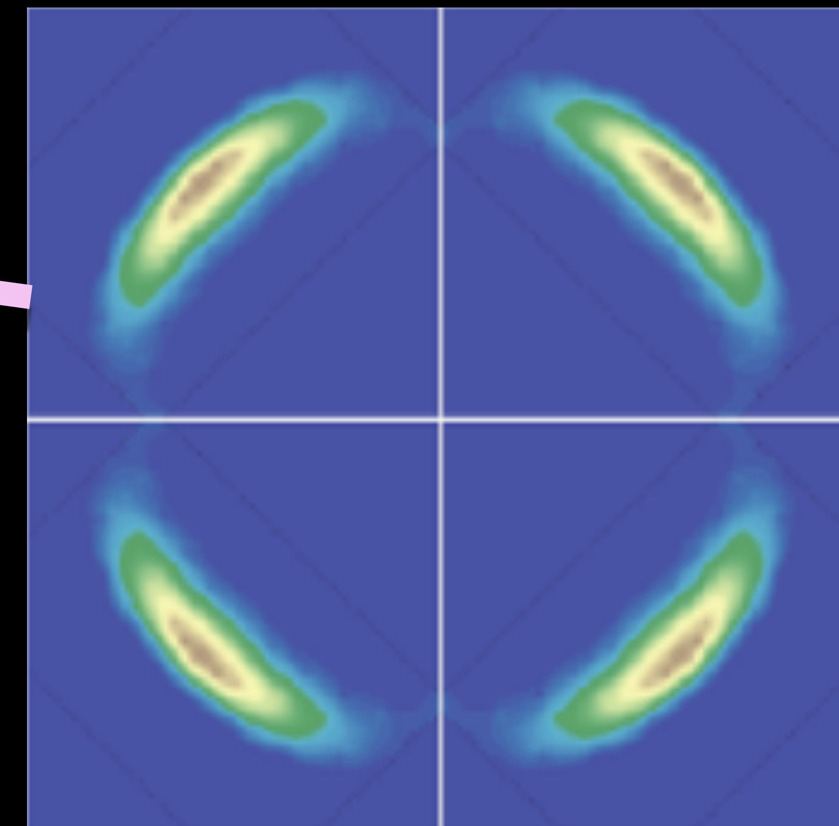


Conventional metal

Area enclosed by Fermi surface =1+p

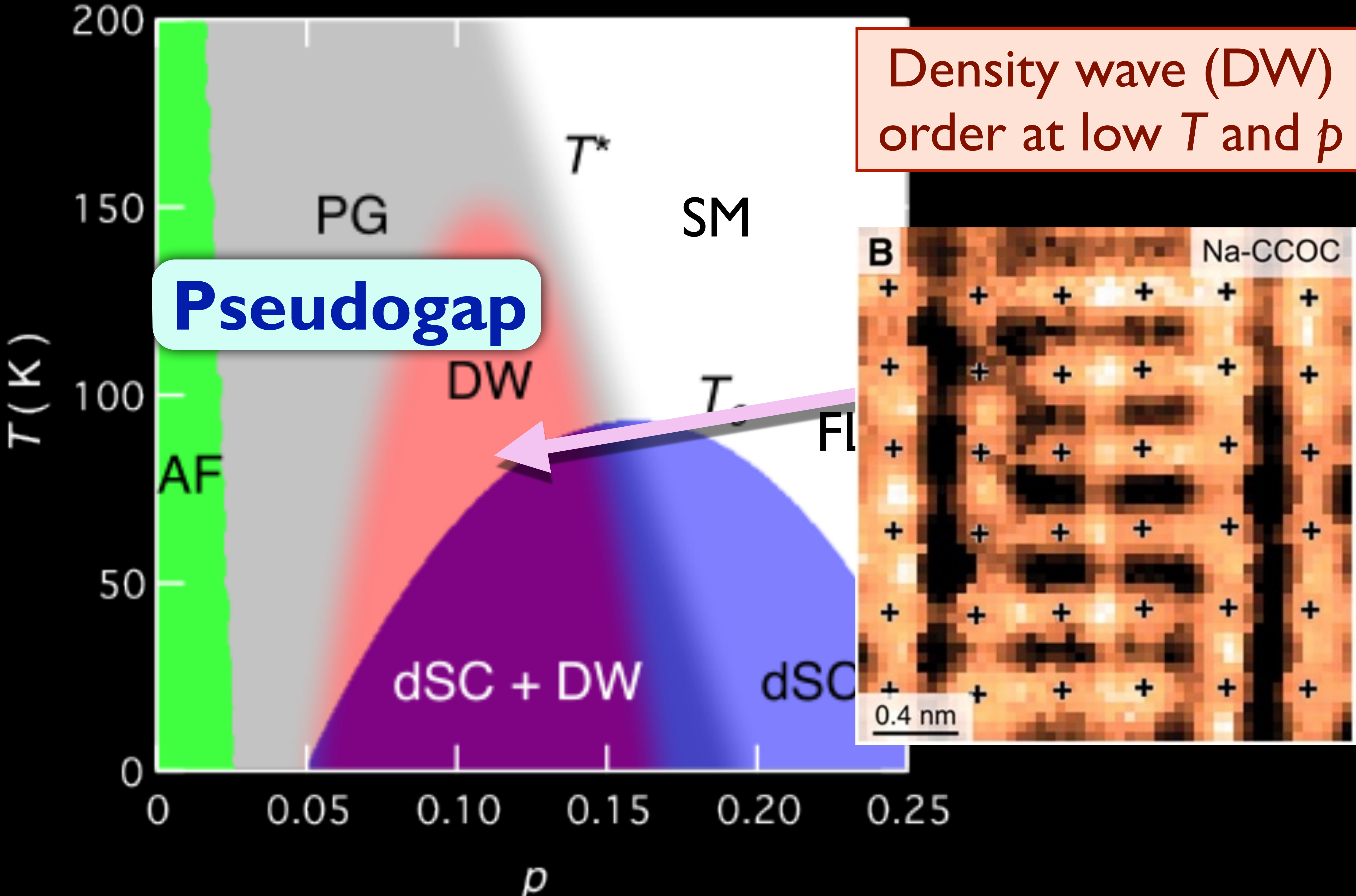
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)



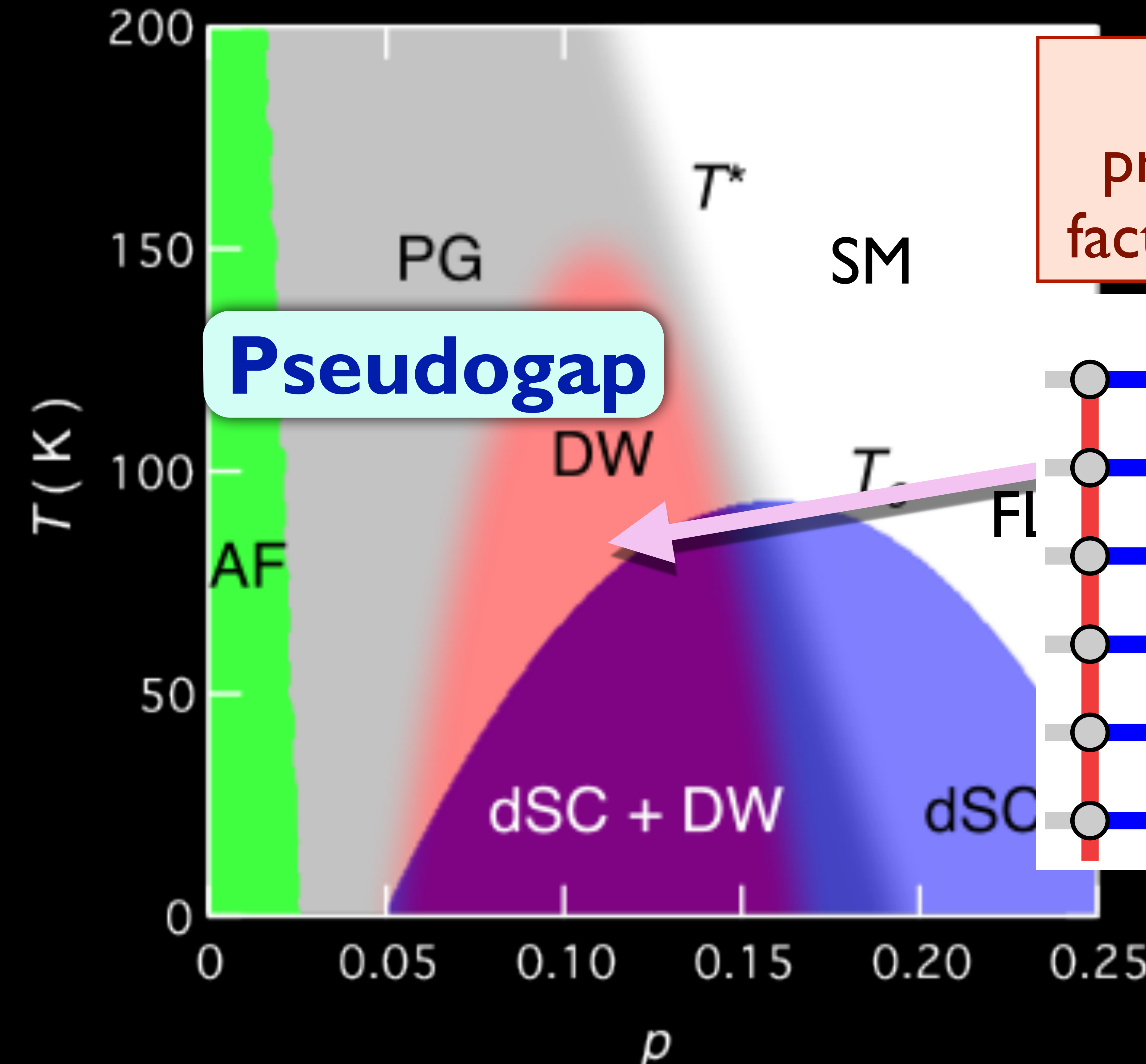


“Fermi arcs”
at
low p

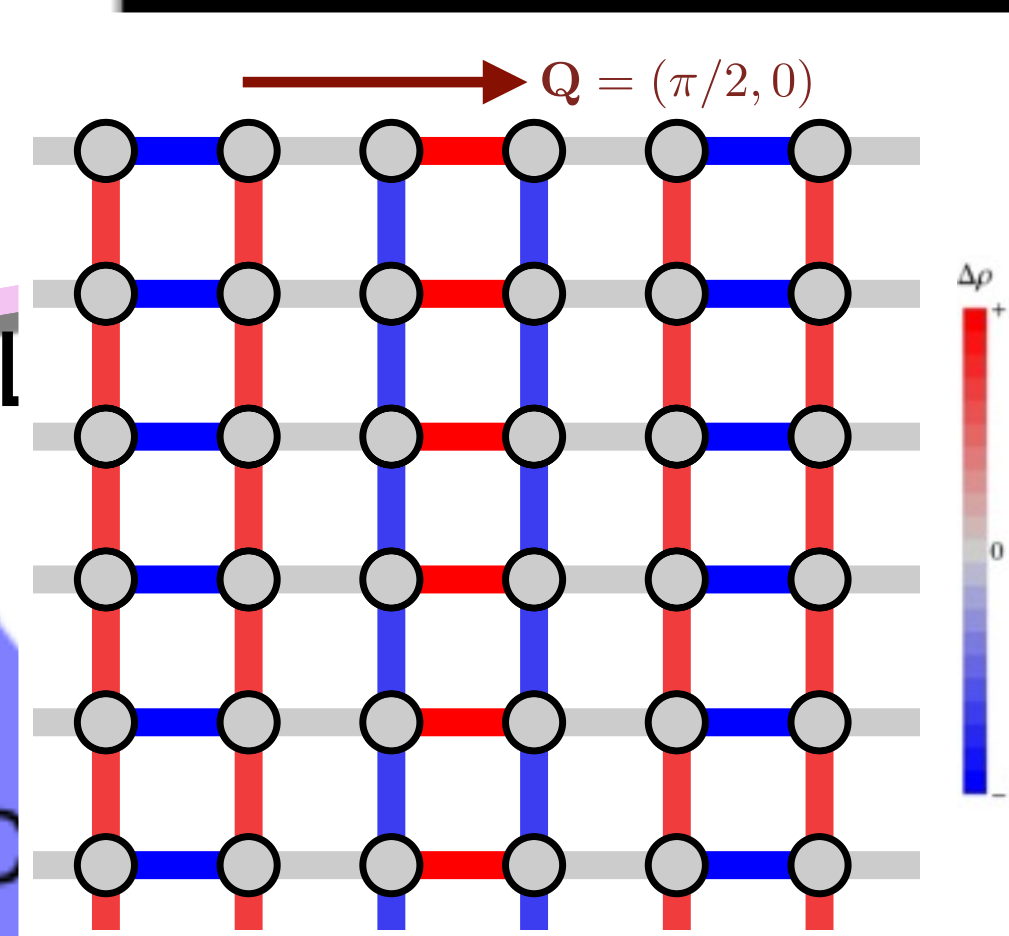
Y. Kohsaka *et al.*, Science **315**, 1380 (2007)

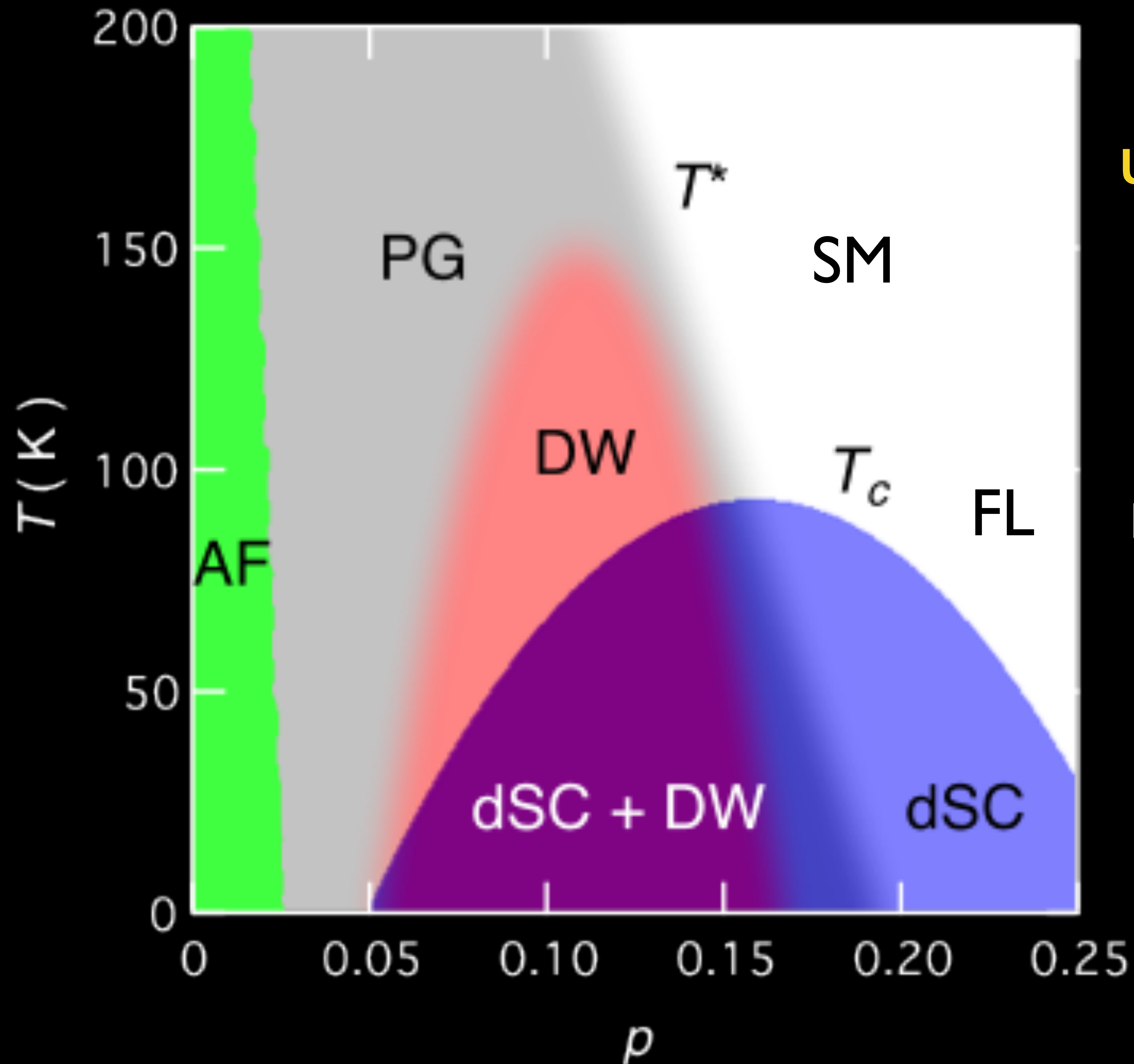


M. A. Metlitski and S. Sachdev, PRB **82**, 075128 (2010). S. Sachdev R. La Placa, PRL **111**, 027202 (2013).
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS **111**, E3026 (2014)



Identified as a predicted "*d*-form factor density wave"





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 (dSC), density wave (DW), antiferromagnetism (AF)…)

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OR

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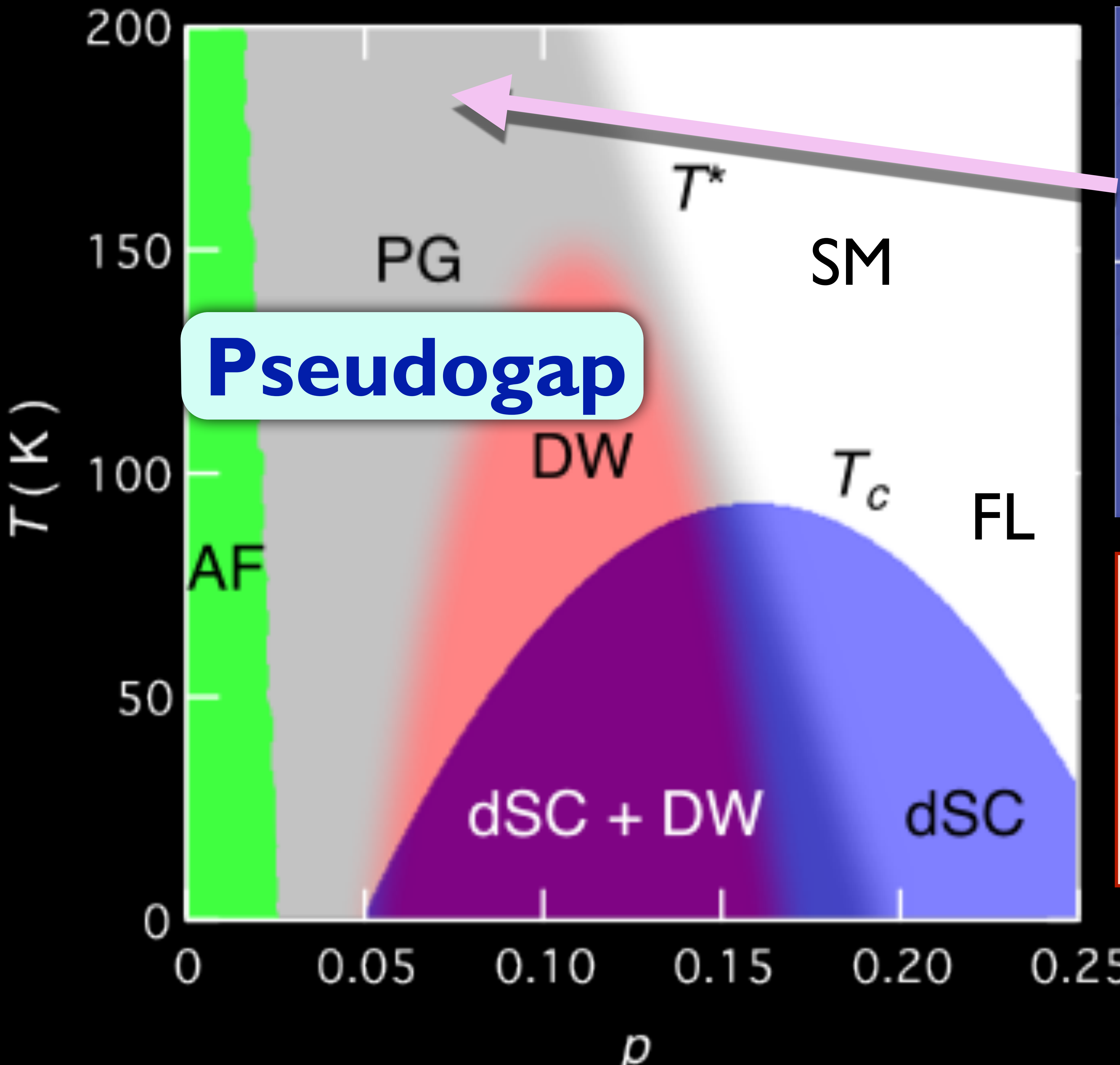
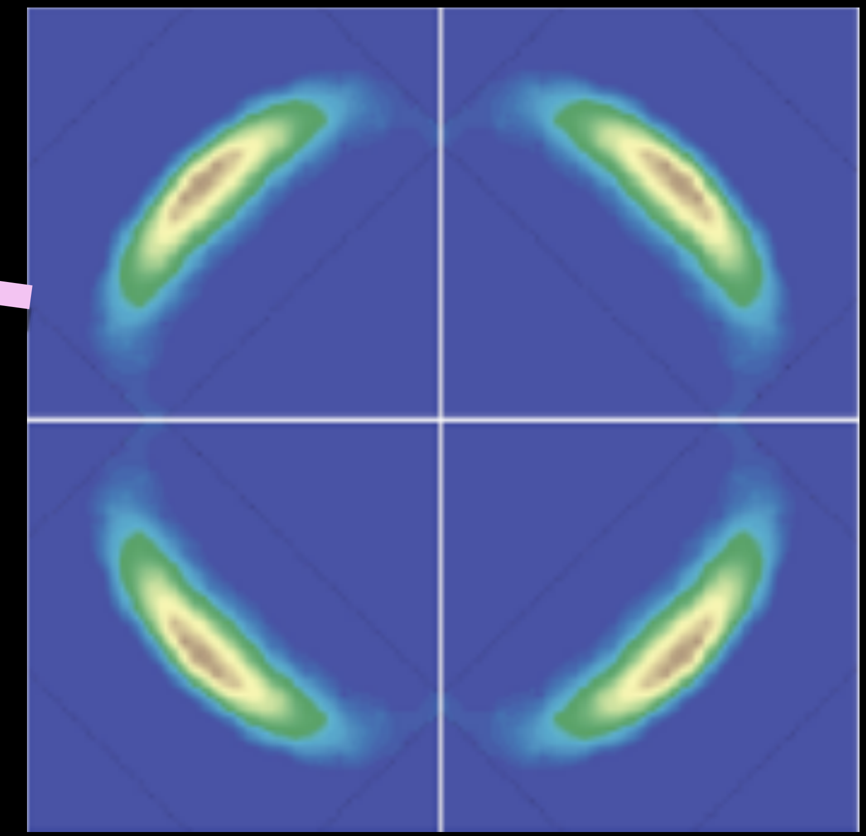
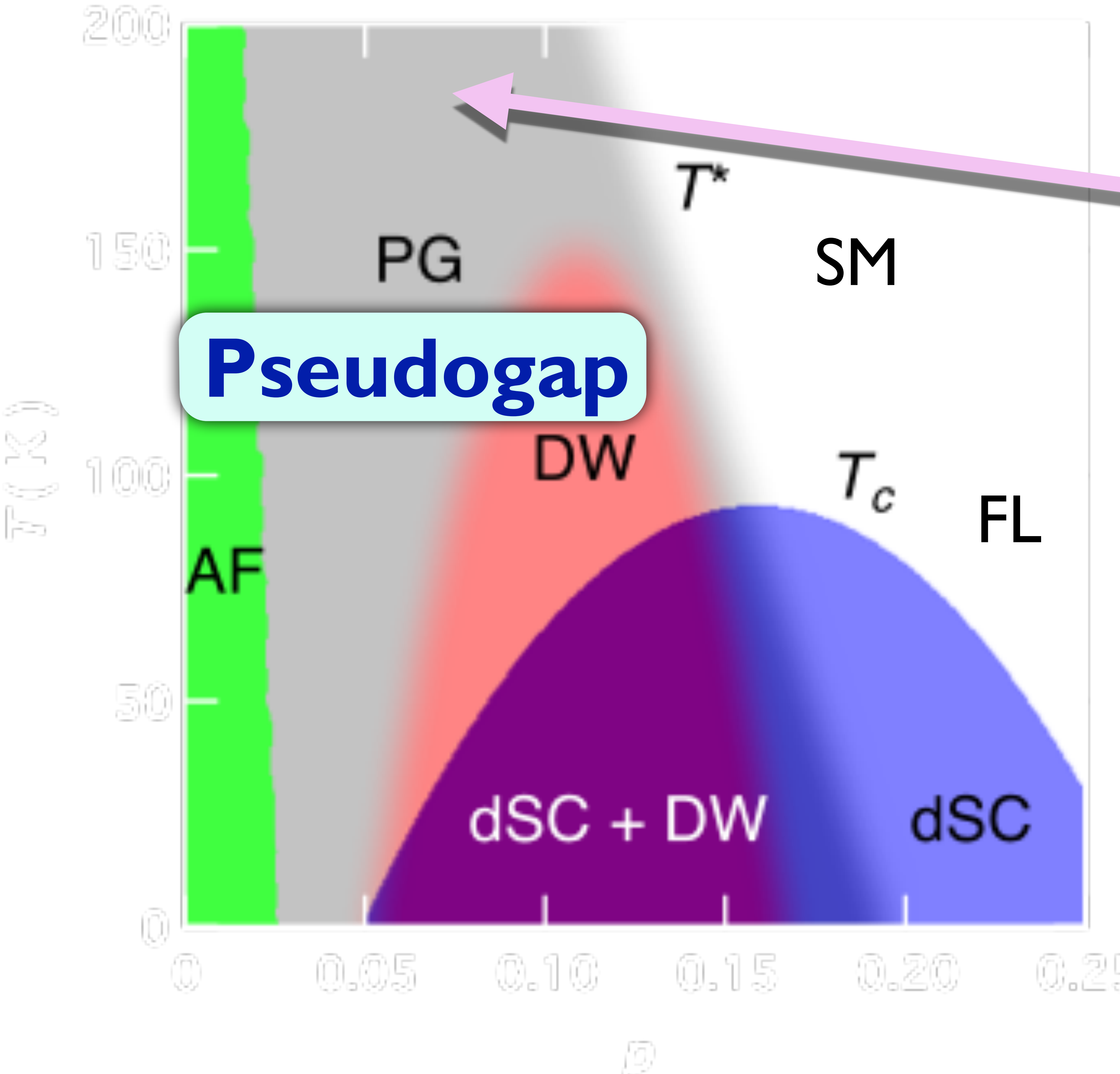
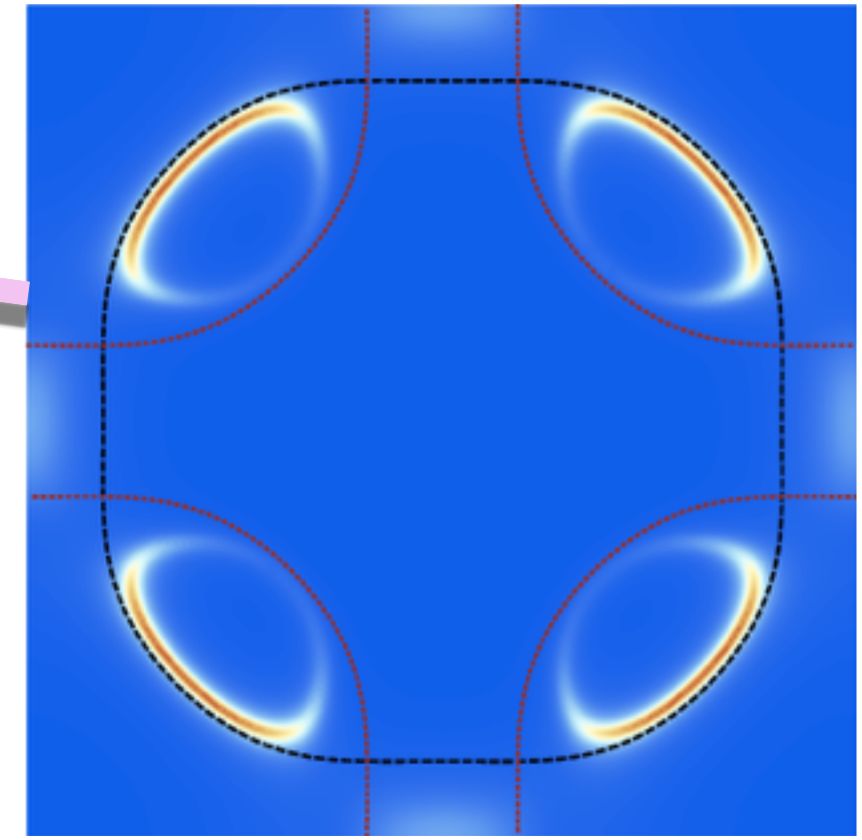




“Fermi arcs” at low p

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





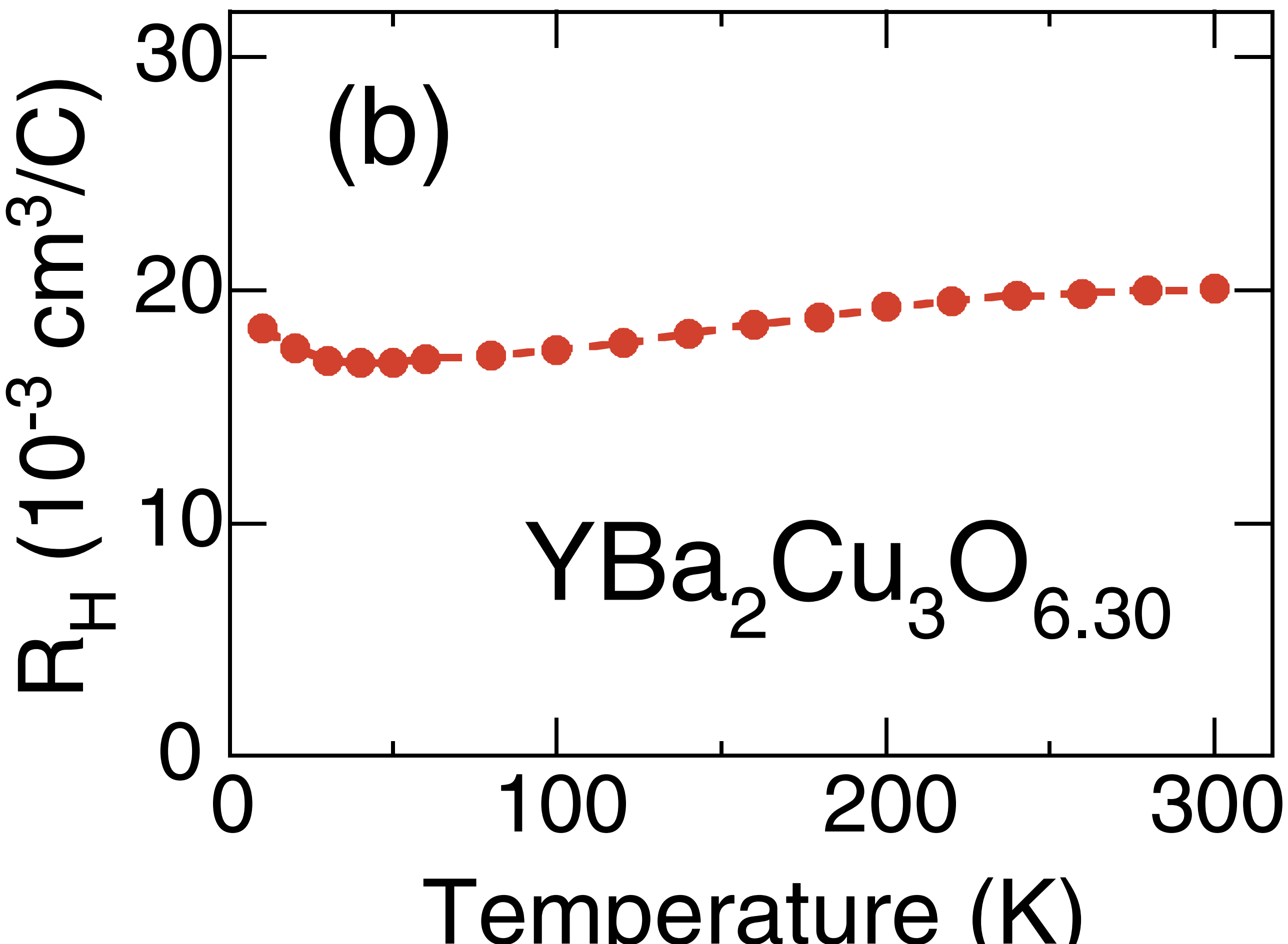
A new metal — a fractionalized Fermi liquid (FL*) — with electron-like quasiparticles on a Fermi surface of size p ?

Electrical and optical evidence for Fermi surface of long-lived quasiparticles of density *p*

Evolution of the Hall Coefficient and the Peculiar Electronic Structure of the Cuprate Superconductors

Yoichi Ando,* Y. Kurita,† Seiki Komiya, S. Ono, and Kouji Segawa

PRL **92**, 197001 (2004)



T-independent Hall effect in a magnetic field of fermions of charge +e and density *p*

Electrical and optical evidence for Fermi surface of long-lived quasiparticles of density p

Spectroscopic evidence for Fermi liquid-like energy and temperature dependence of the relaxation rate in the pseudogap phase of the cuprates

Seyed Iman Mirzaei[a], Damien Stricker[a], Jason N. Hancock[a,b], Christophe Berthod[a], Antoine Georges[a,c,d], Erik van Heumen[a,e], Mun K. Chan[f], Xudong Zhao[f,g], Yuan Li[h], Martin Greven[f], Neven Barišić[f,i,j], and Dirk van der Marel[a,1]

PNAS 110, 5774 (2013)

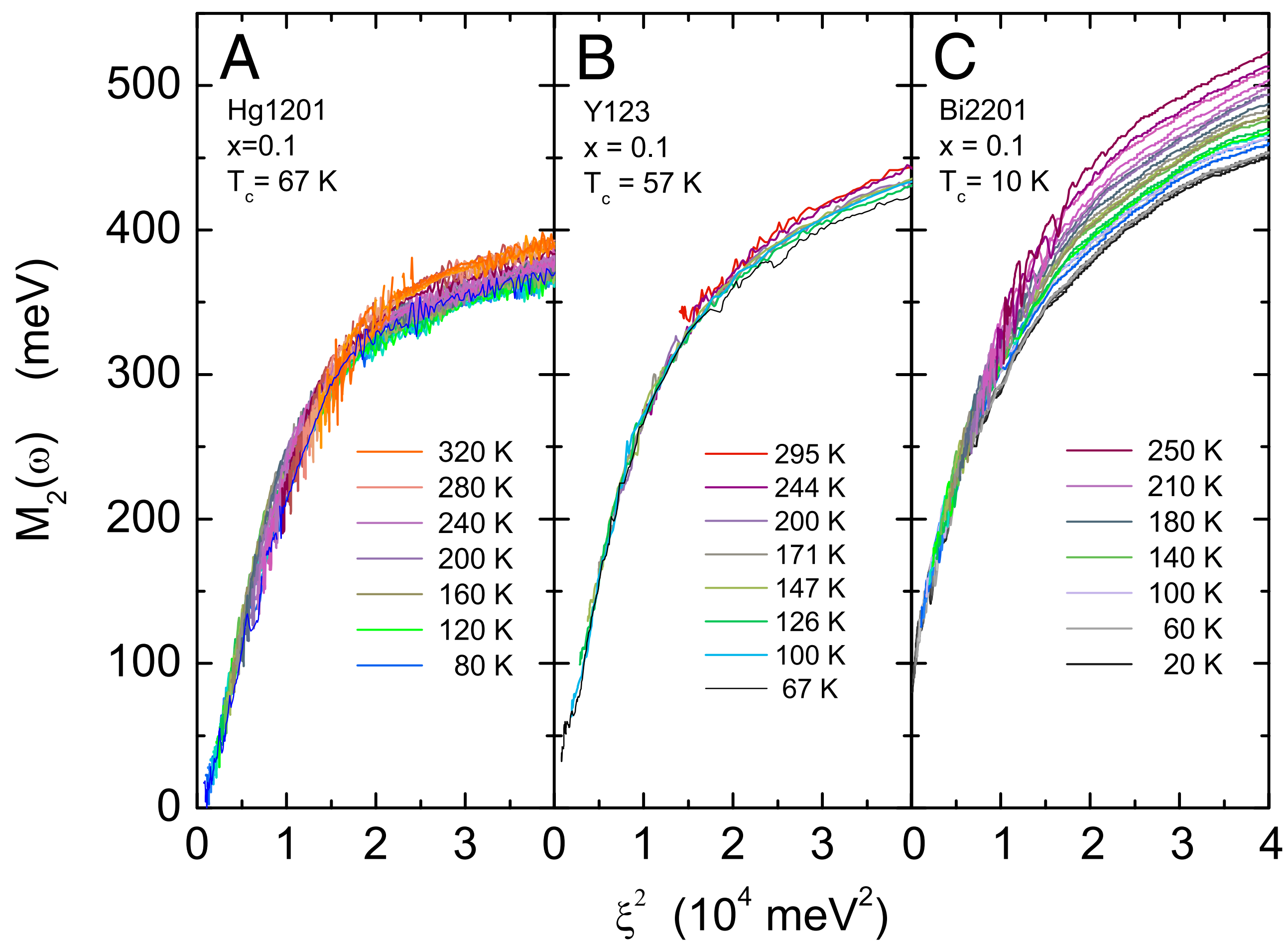


Fig. 6. Collapse of the frequency and temperature dependence of the relaxation rate of underdoped cuprate materials. Normal state $M_2(\omega, T)$ as a function of $\xi^2 \equiv (\hbar\omega)^2 + (p\pi k_B T)^2$

$$\sigma_{xx} \sim \frac{1}{(-i\omega + 1/\tau)}$$

$$\text{with } \frac{1}{\tau} \sim \omega^2 + T^2$$

Electrical and optical evidence for Fermi surface of long-lived quasiparticles of density *p*

In-Plane Magnetoresistance Obeys Kohler's Rule in the Pseudogap Phase of Cuprate Superconductors

M. K. Chan,[1,*] M. J. Veit,[1] C. J. Dorow,[1,†] Y. Ge,[1] Y. Li,[1] W. Tabis,[1,2] Y. Tang,[1] X. Zhao,[1,3]
N. Barišić,[1,4,5,‡] and M. Greven[1,§]

PRL **113**, 177005 (2014)

We report in-plane resistivity (ρ) and transverse magnetoresistance (MR) measurements for underdoped $HgBa_2CuO_{4+\delta}$ (Hg1201). Contrary to the long-standing view that Kohler's rule is strongly violated in underdoped cuprates, we find that it is in fact satisfied in the pseudogap phase of Hg1201. The transverse MR shows a quadratic field dependence, $\delta\rho/\rho_0 = aH^2$, with $a(T) \propto T^{-4}$. In combination with the observed $\rho \propto T^2$ dependence, this is consistent with a single Fermi-liquid quasiparticle scattering rate. We show that this behavior is typically masked in cuprates with lower structural symmetry or strong disorder effects.

$$\rho_{xx} \sim \frac{1}{\tau}(1 + aH^2\tau^2 + \ldots)$$

$$\text{with } \frac{1}{\tau} \sim T^2$$

Can we have a metal with no broken translational symmetry, and with long-lived electron-like quasiparticles on a Fermi surface of size p ?

Can we have a metal with no broken translational symmetry, and with long-lived electron-like quasiparticles on a Fermi surface of size p ?

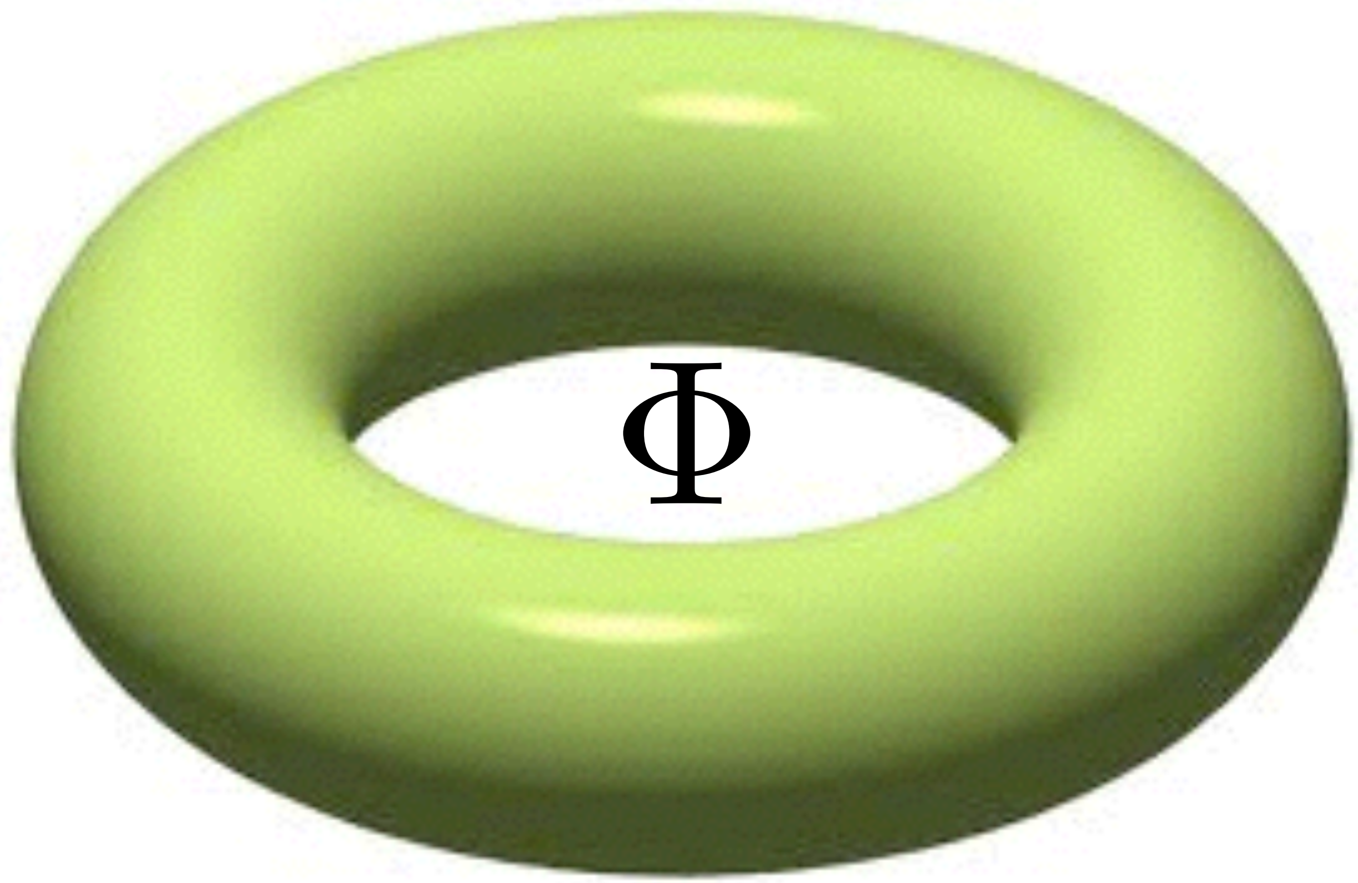
Answer: **Yes.**

There can be a Fermi surface of size p,
but it must be accompanied by
topological order, in a "fractionalized Fermi liquid".

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

Fermi liquid (FL)

Topological argument for the area of Fermi surface



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)

Fractionalized Fermi liquid (FL*)

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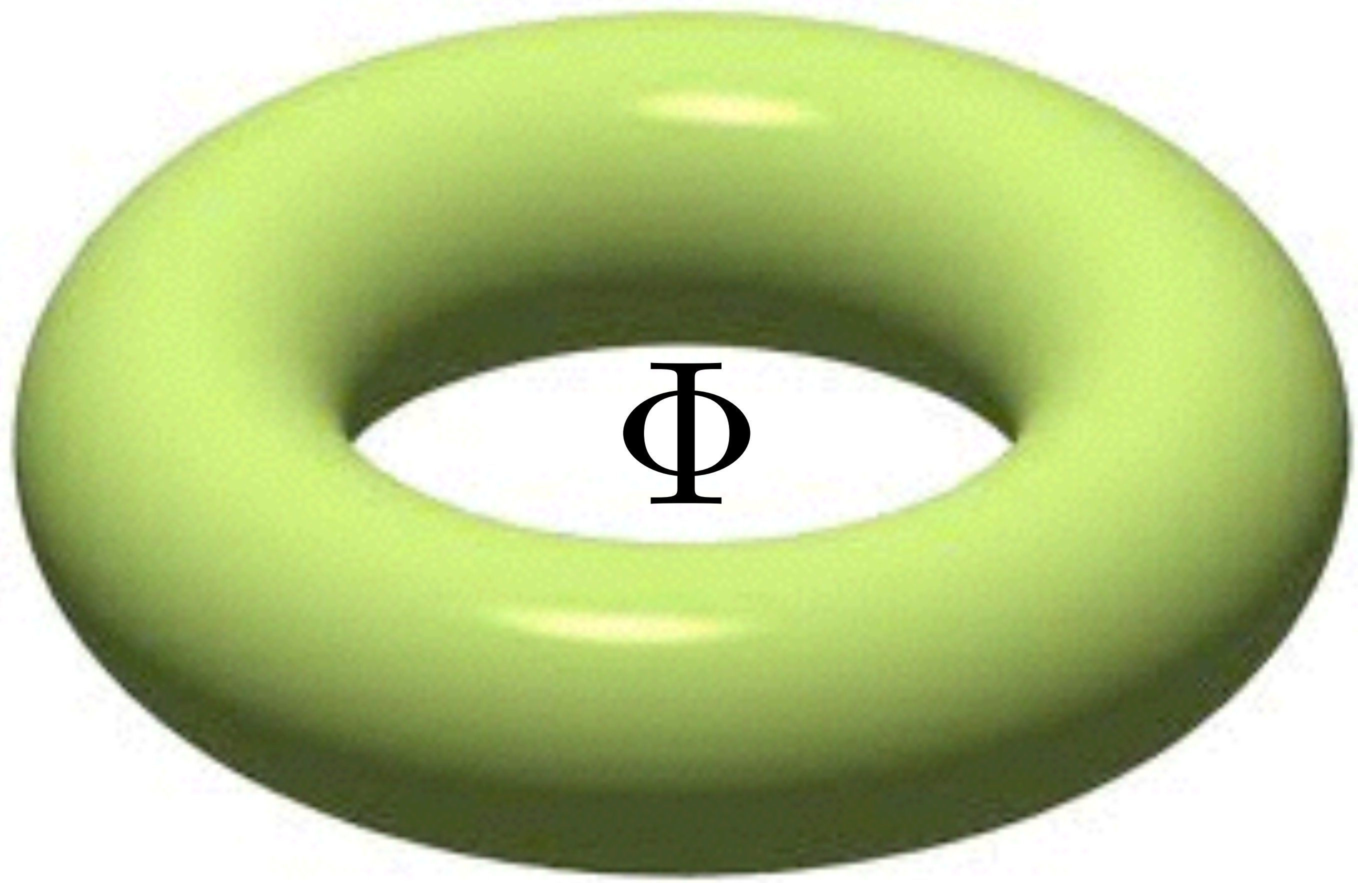
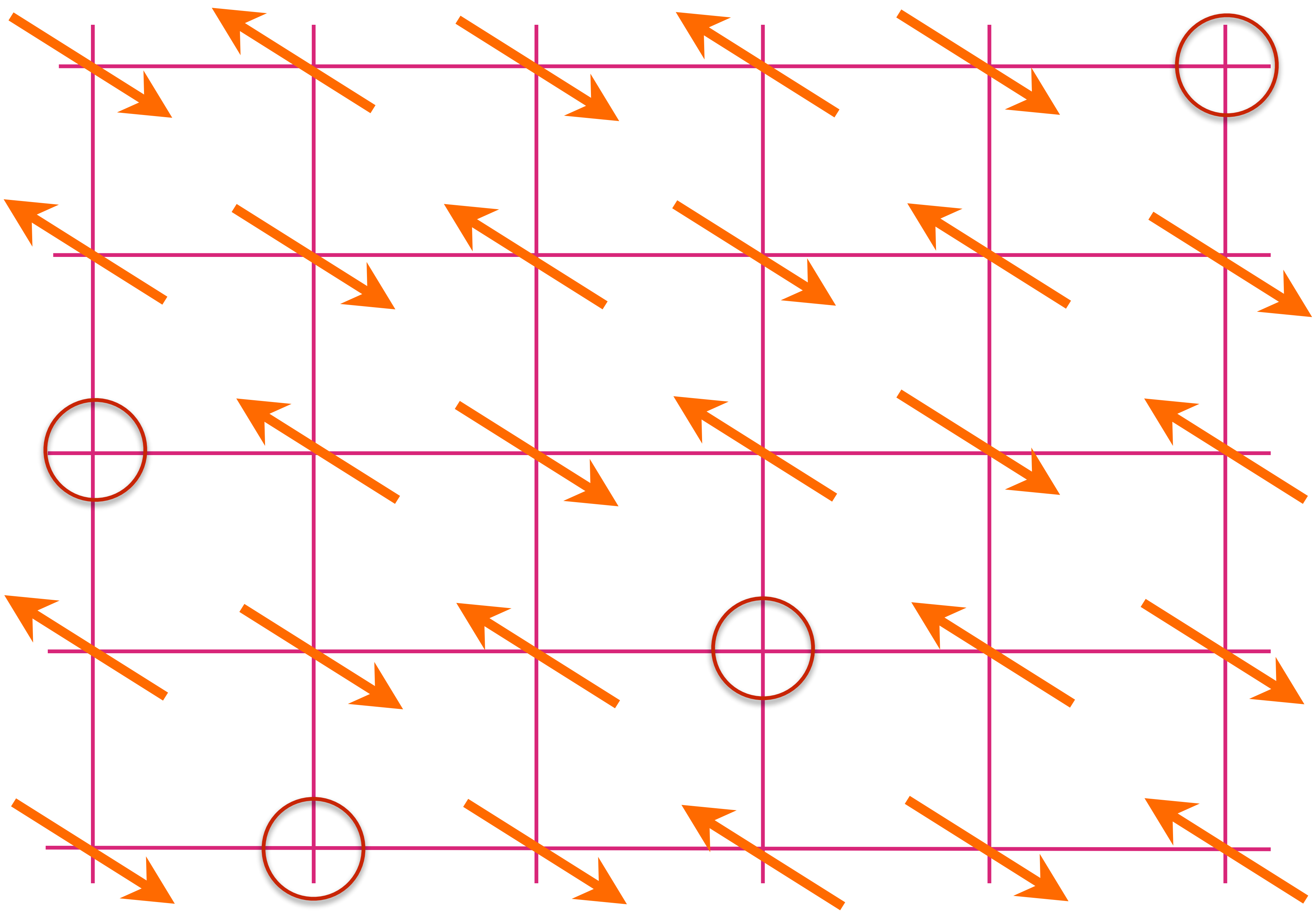


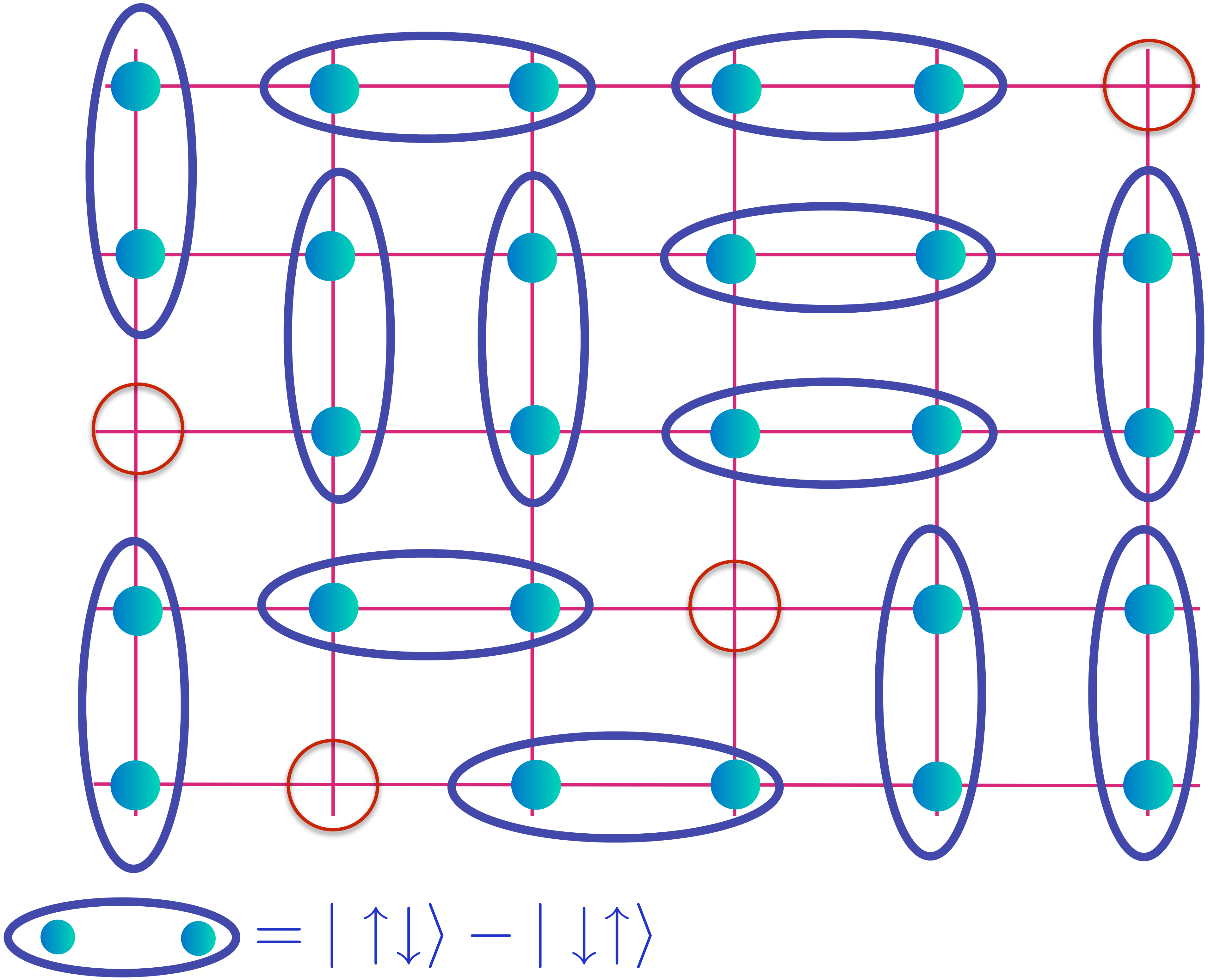
Violations of the Luttinger relation are possible in a fractionalized Fermi liquid (FL*) because there are "topological" low energy excitations associated with a flux of the emergent gauge field in the hole of the torus.

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



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

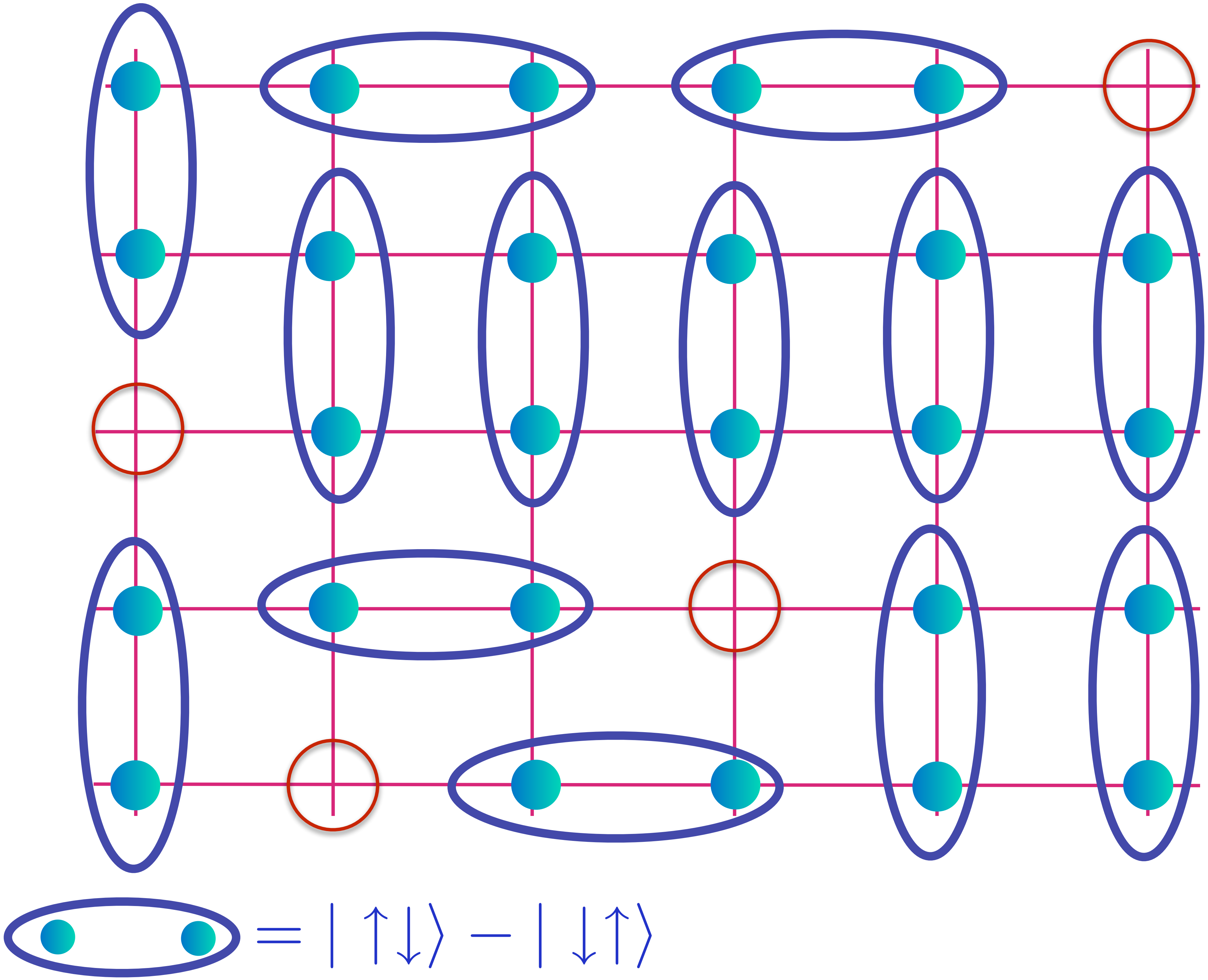
Spin liquid

with emergent gauge field

and

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

Baskaran, Anderson, Fradkin, Kivelson…



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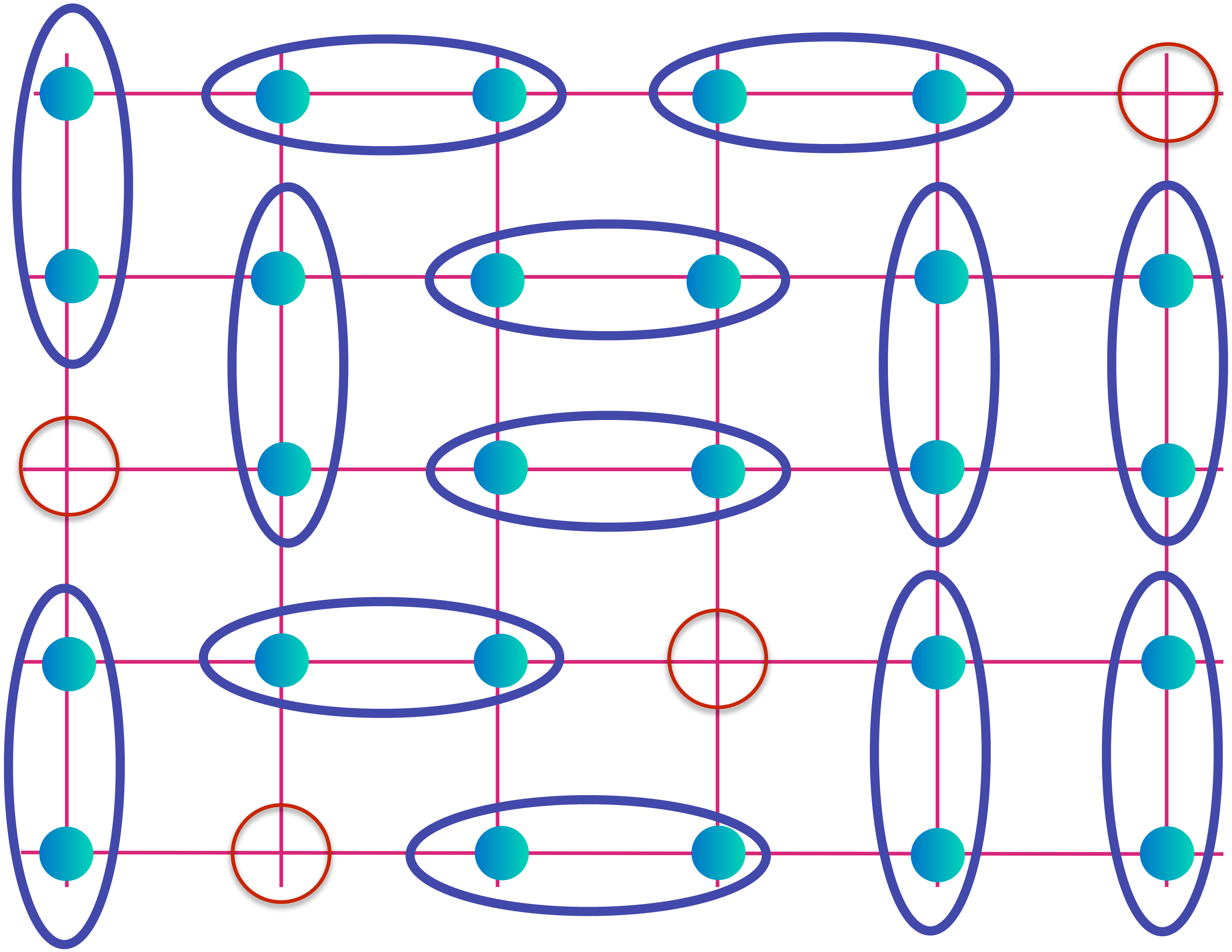

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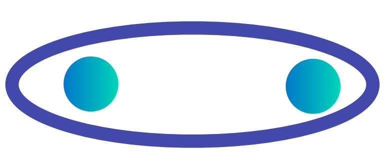 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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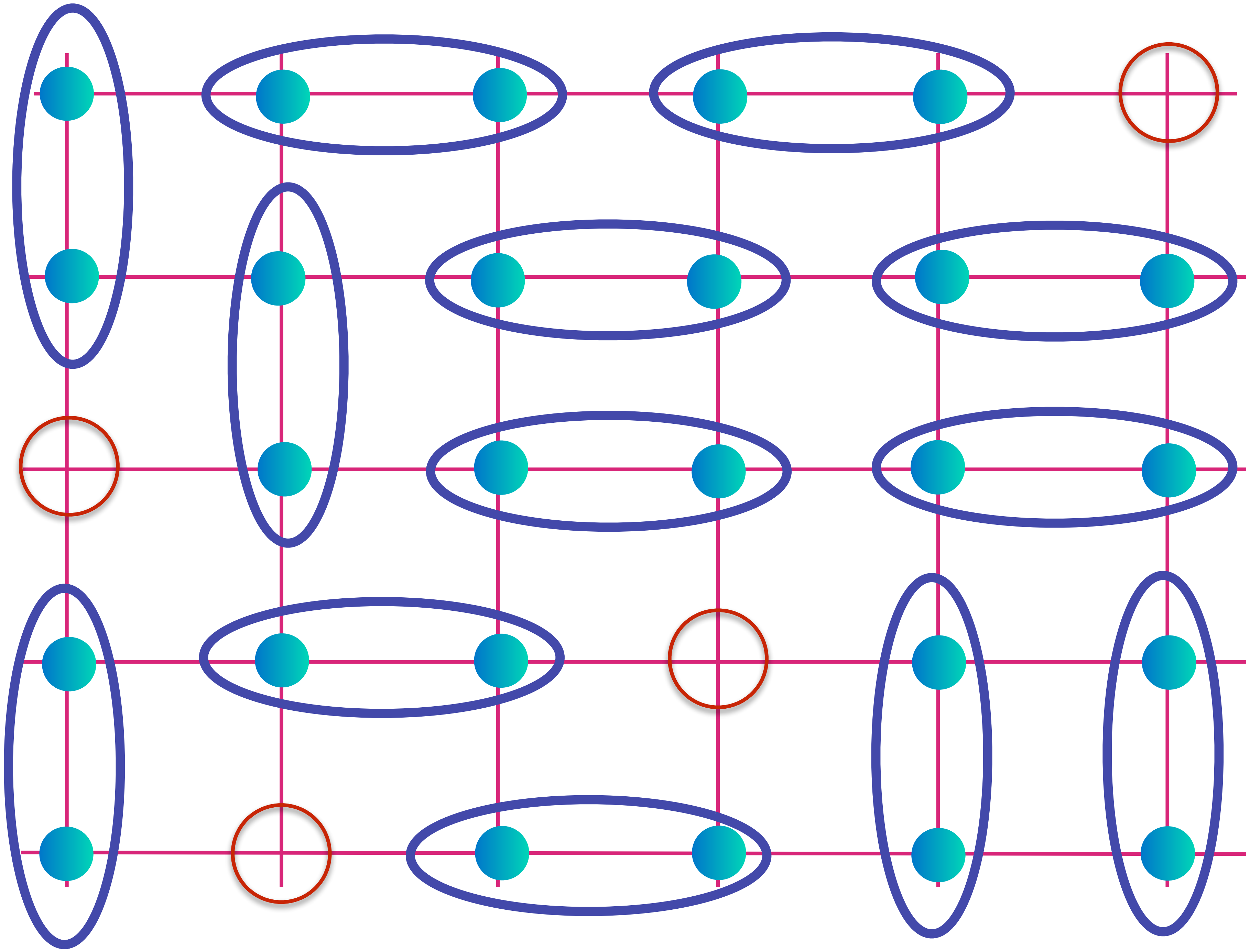

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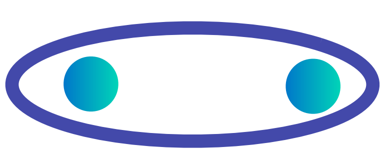 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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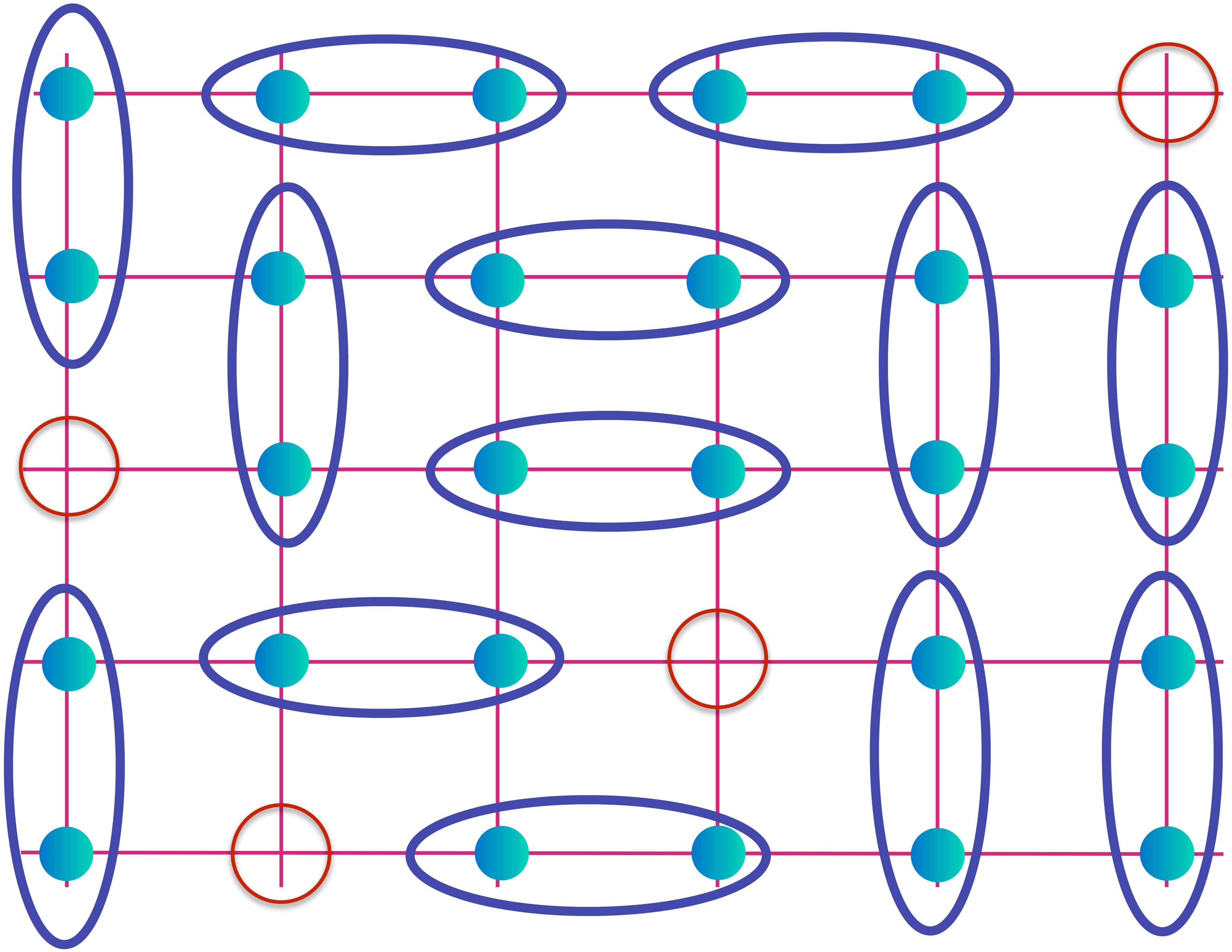
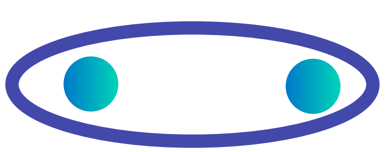
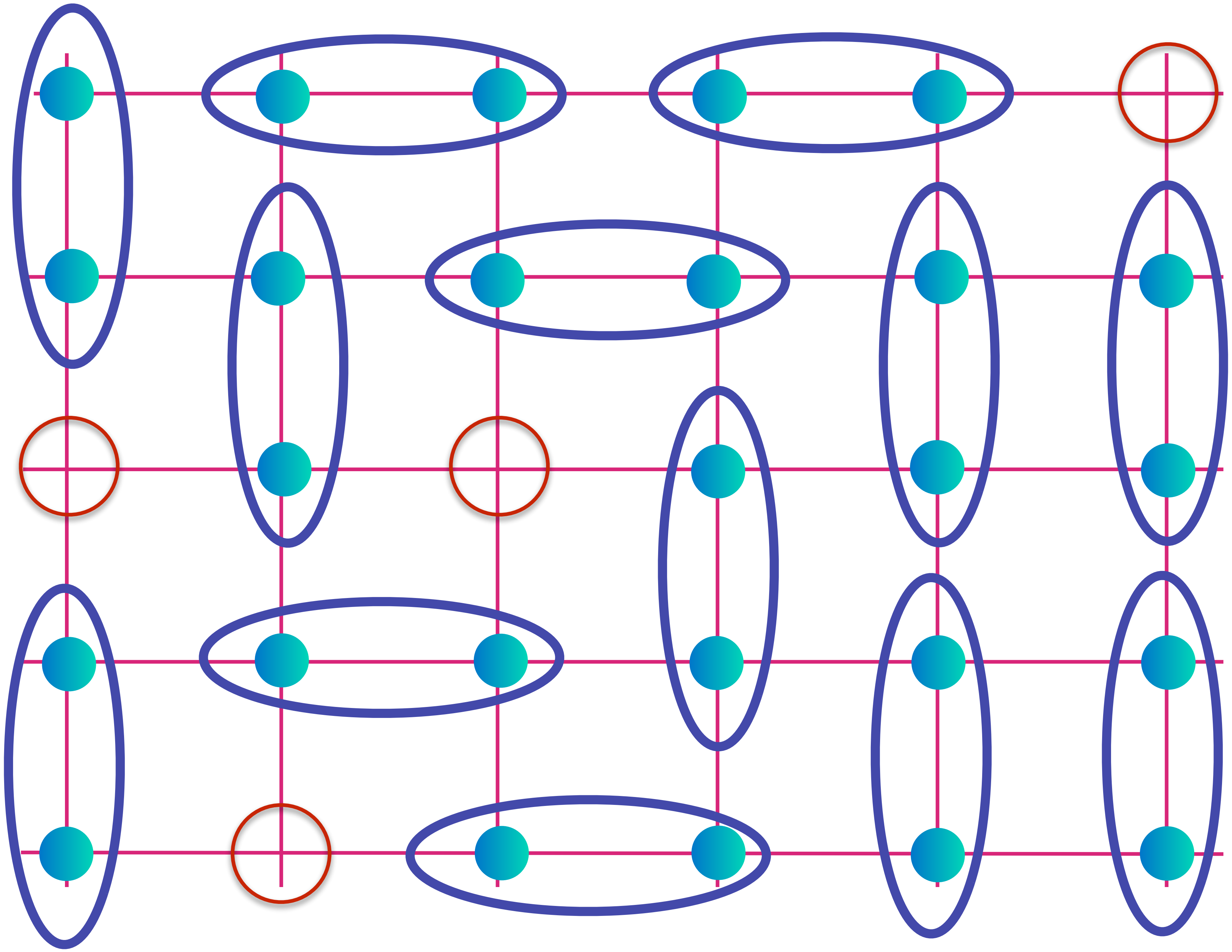


 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Spin liquid

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

Baskaran, Anderson, Fradkin, Kivelson…



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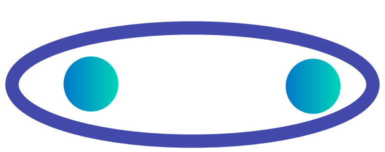

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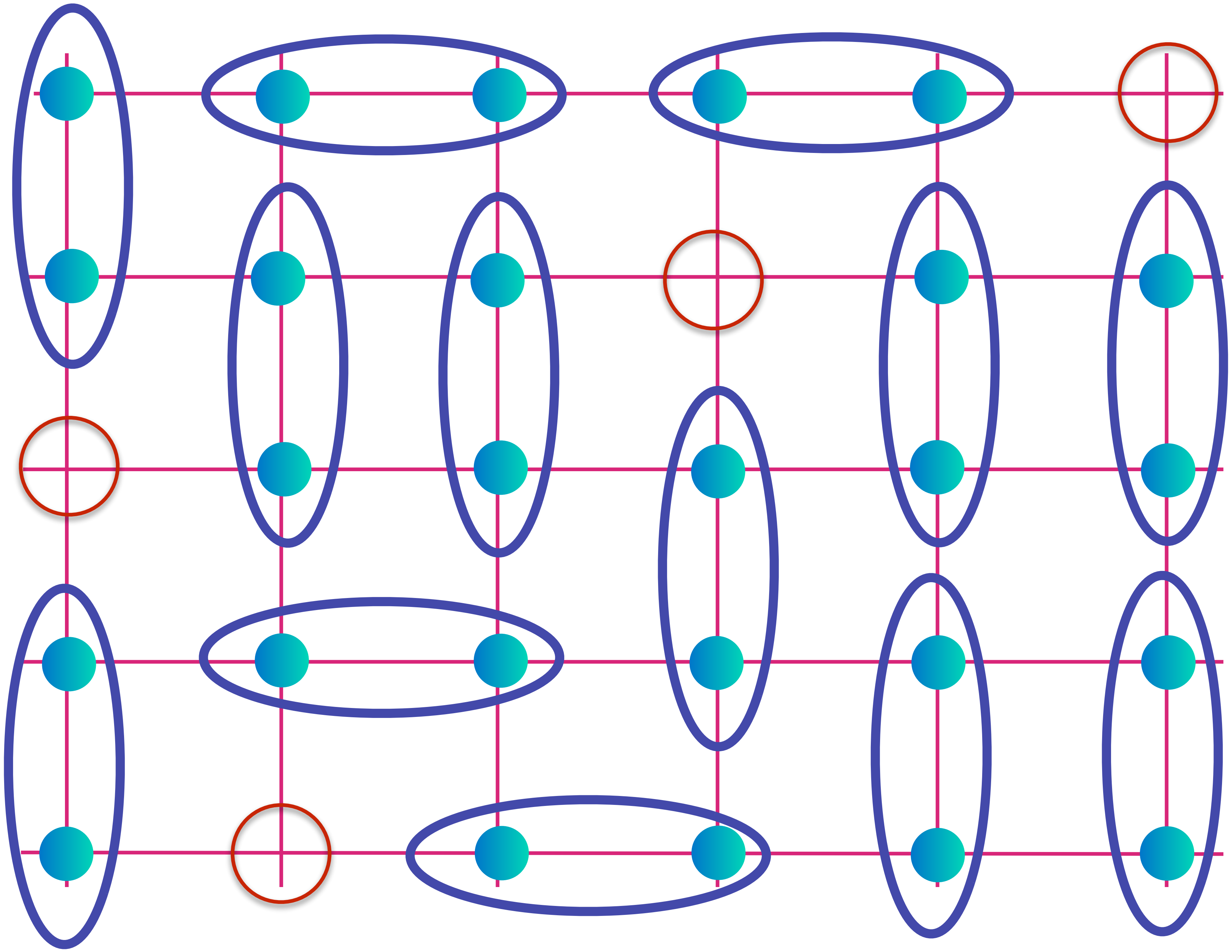
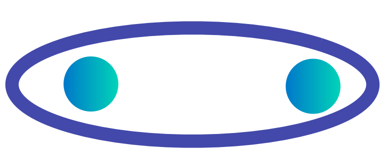


Spin liquid
with emergent gauge field *and* *p* “holons" (gauge-charged, spinless, charge +e quasiparticles) per square

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

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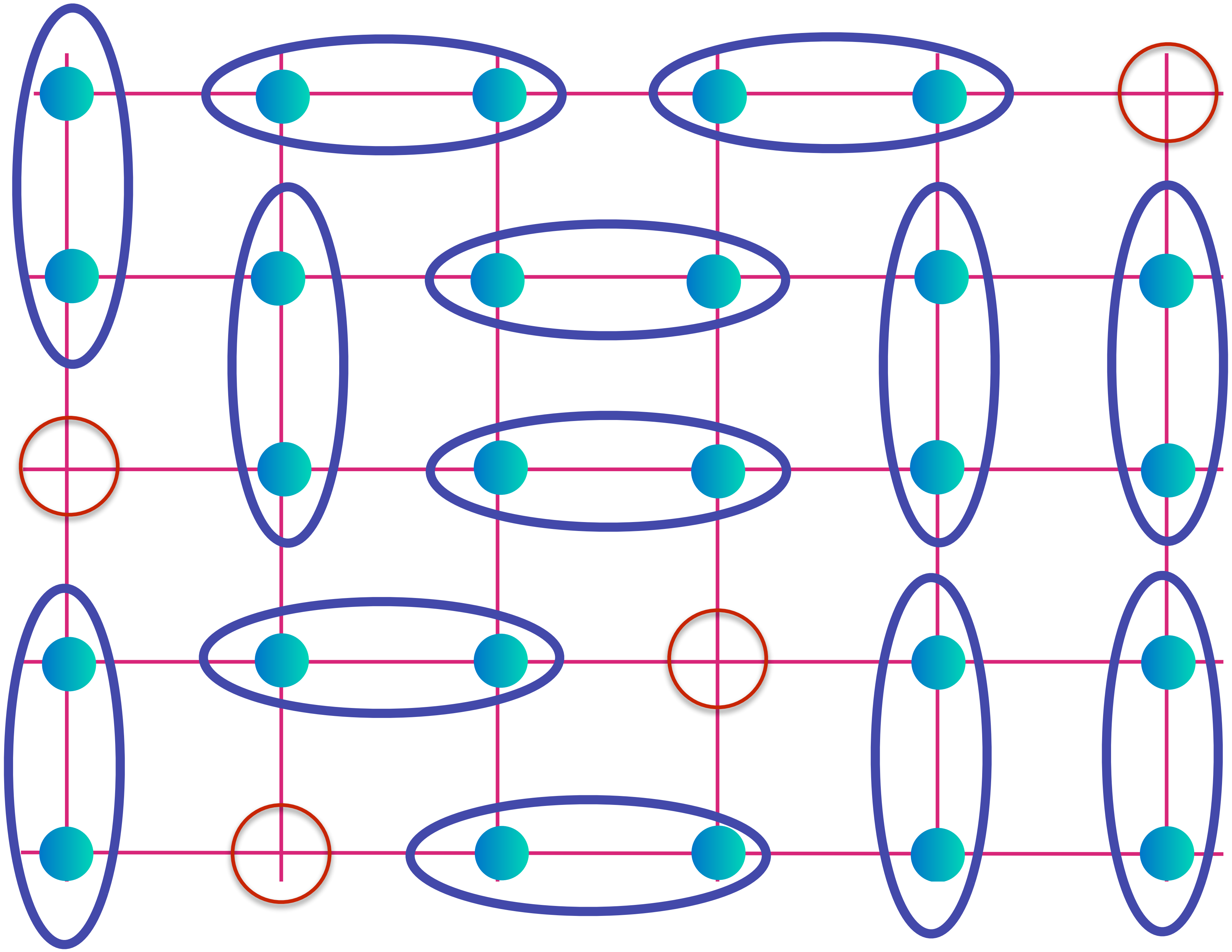

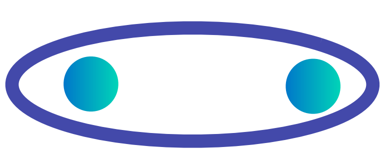

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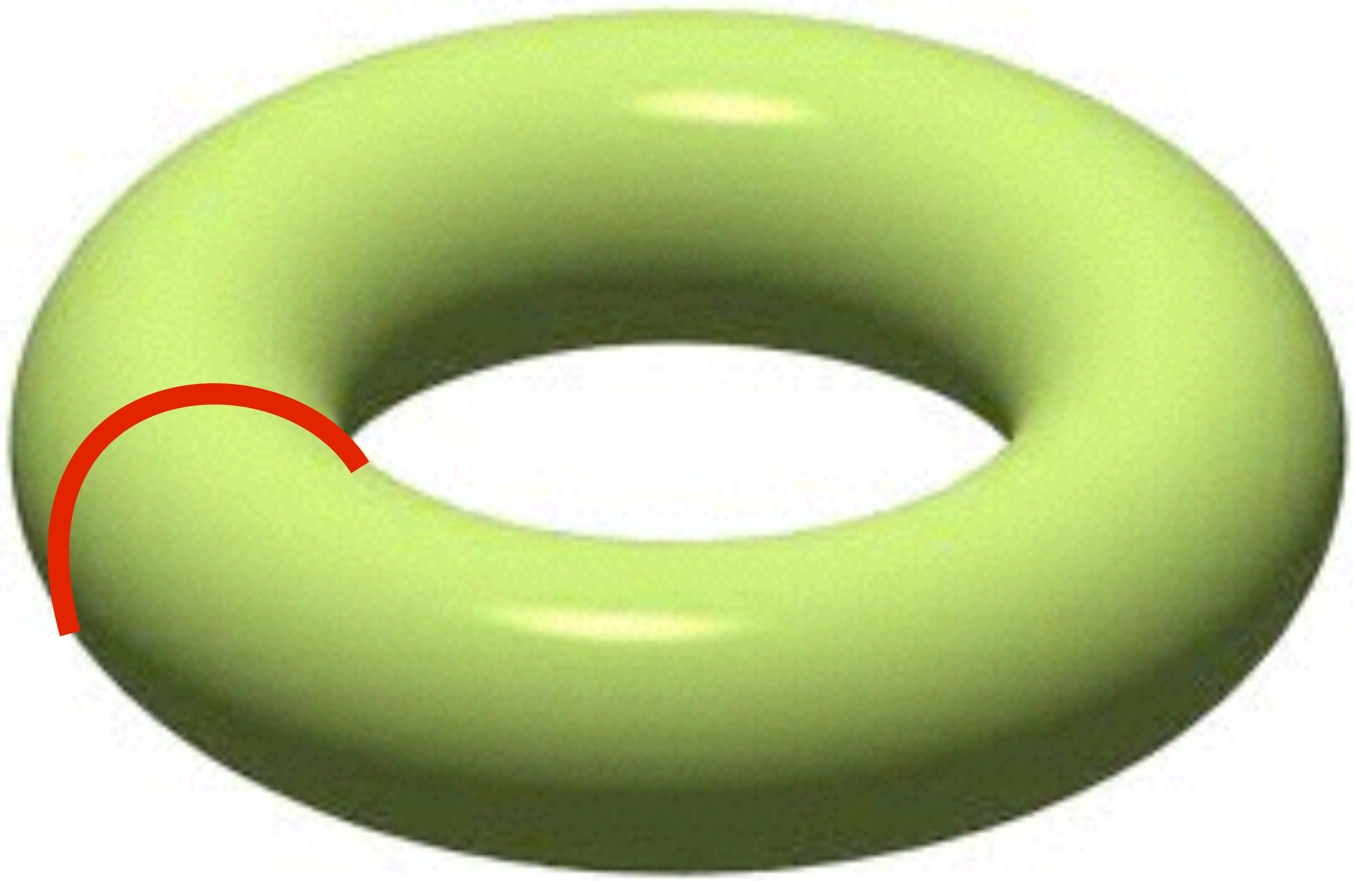
p “holons" (gauge-charged, spinless, charge +e quasiparticles) per square

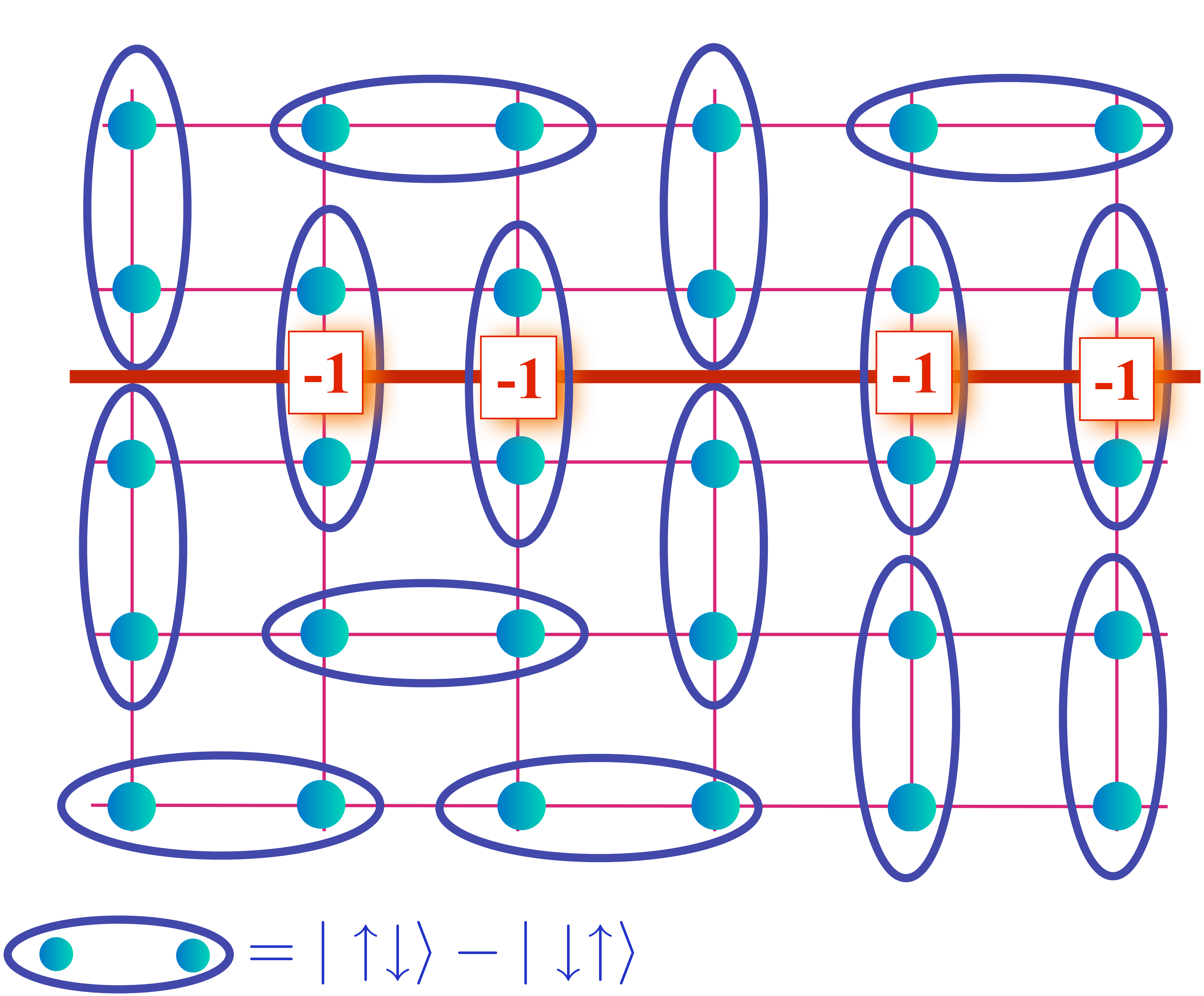
Baskaran, Anderson, Fradkin, Kivelson…

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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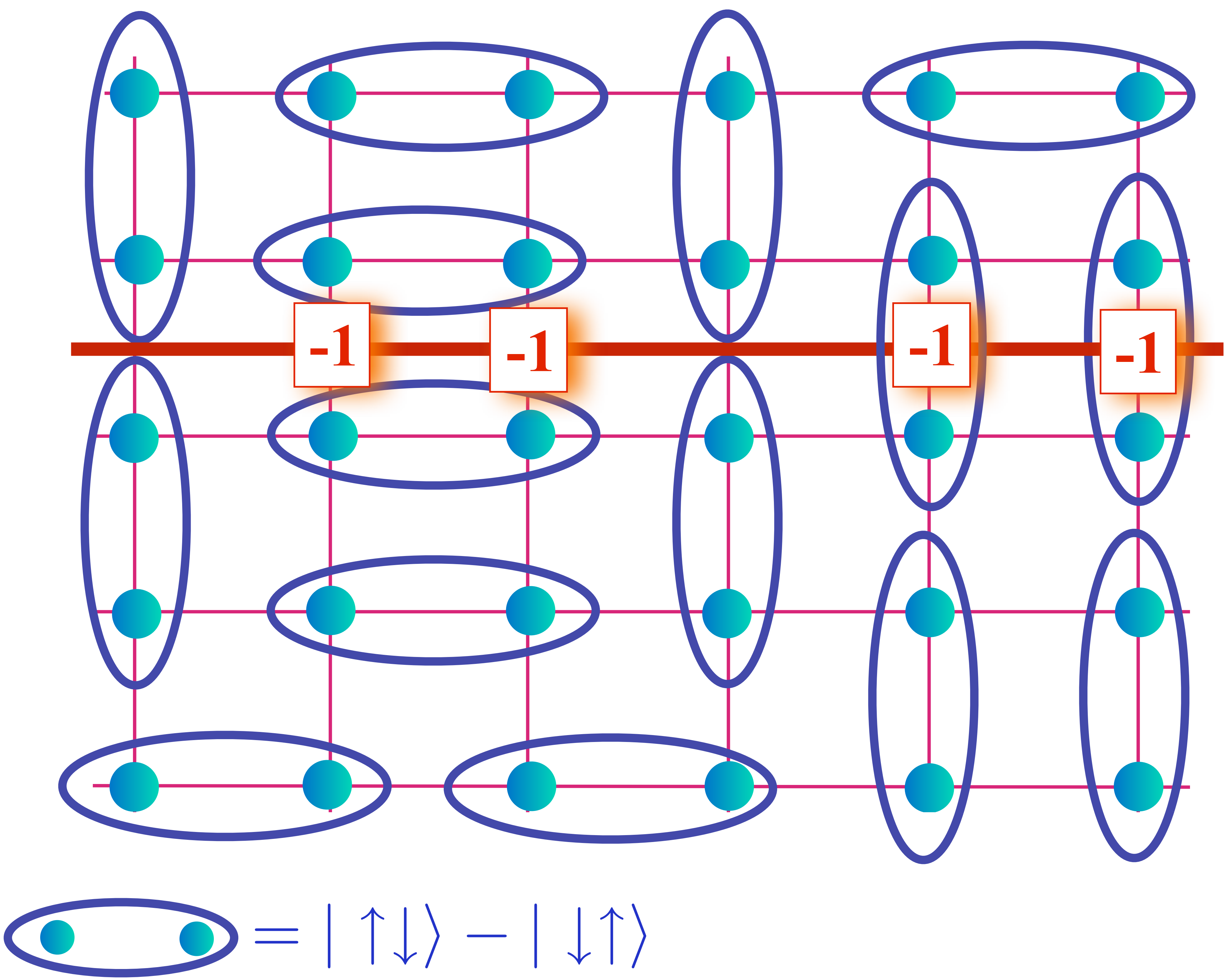

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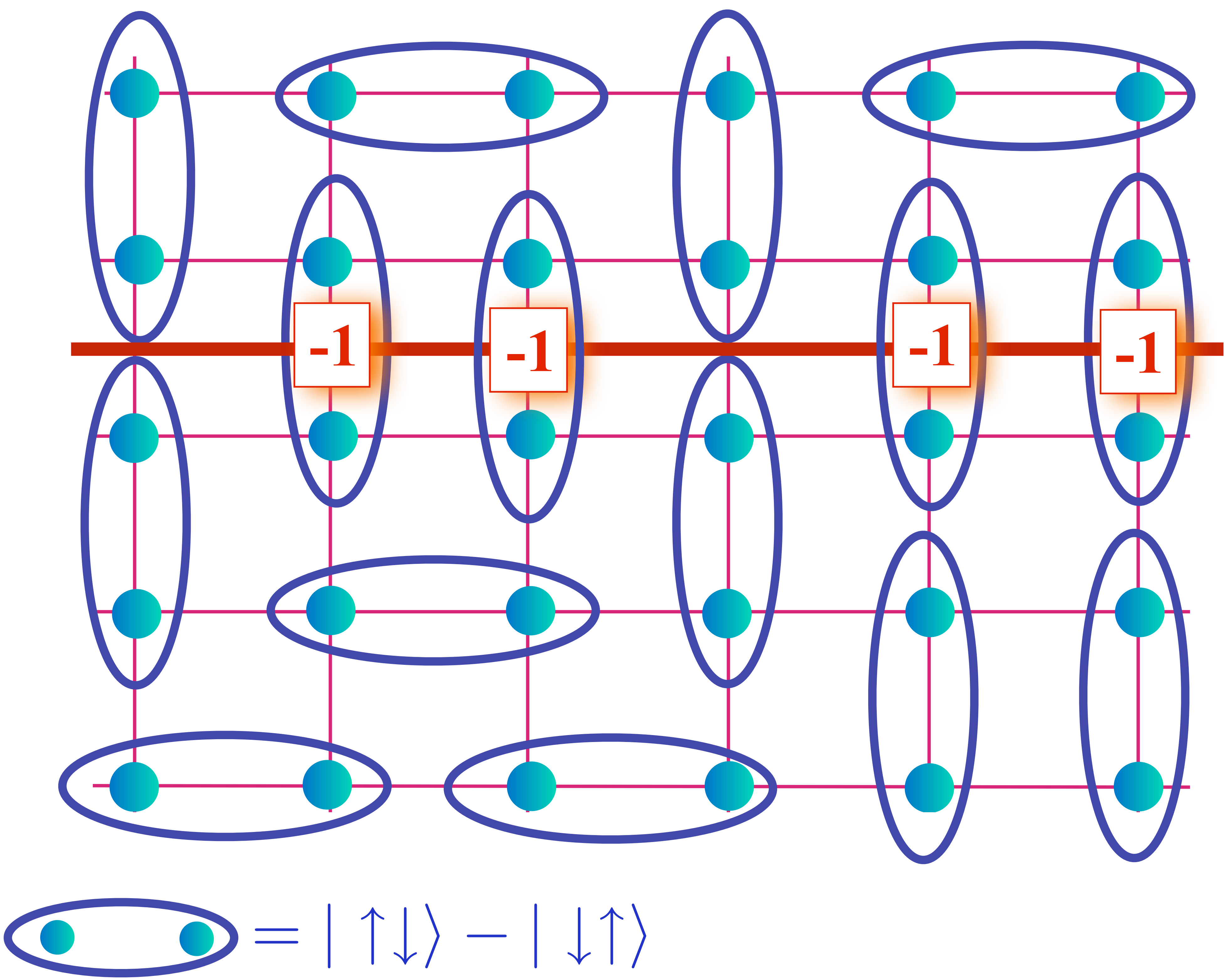

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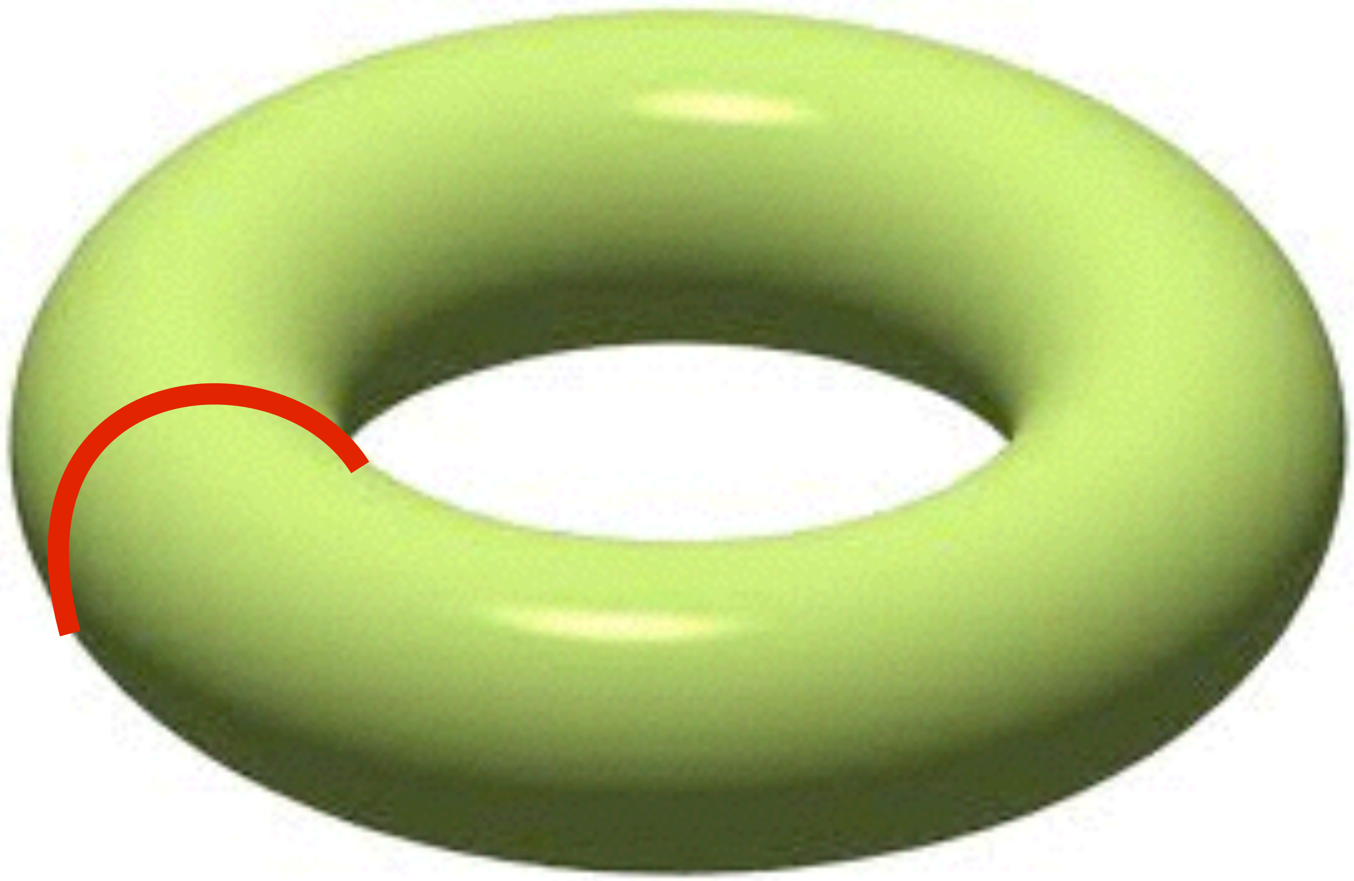
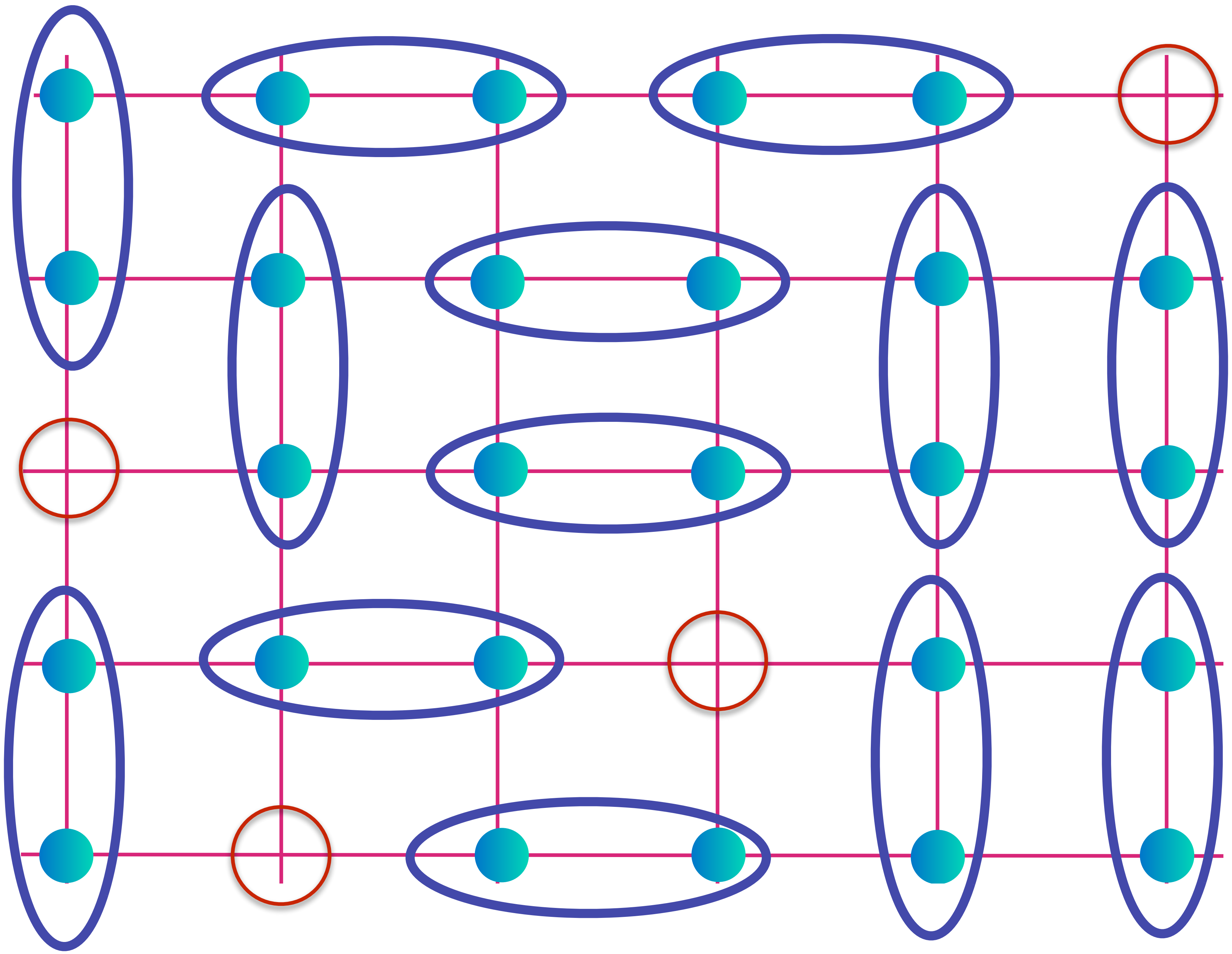
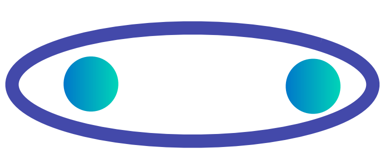
Place on a torus; to obtain "topological" states nearly degenerate with the ground state: change sign of every singlet bond across red line



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

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



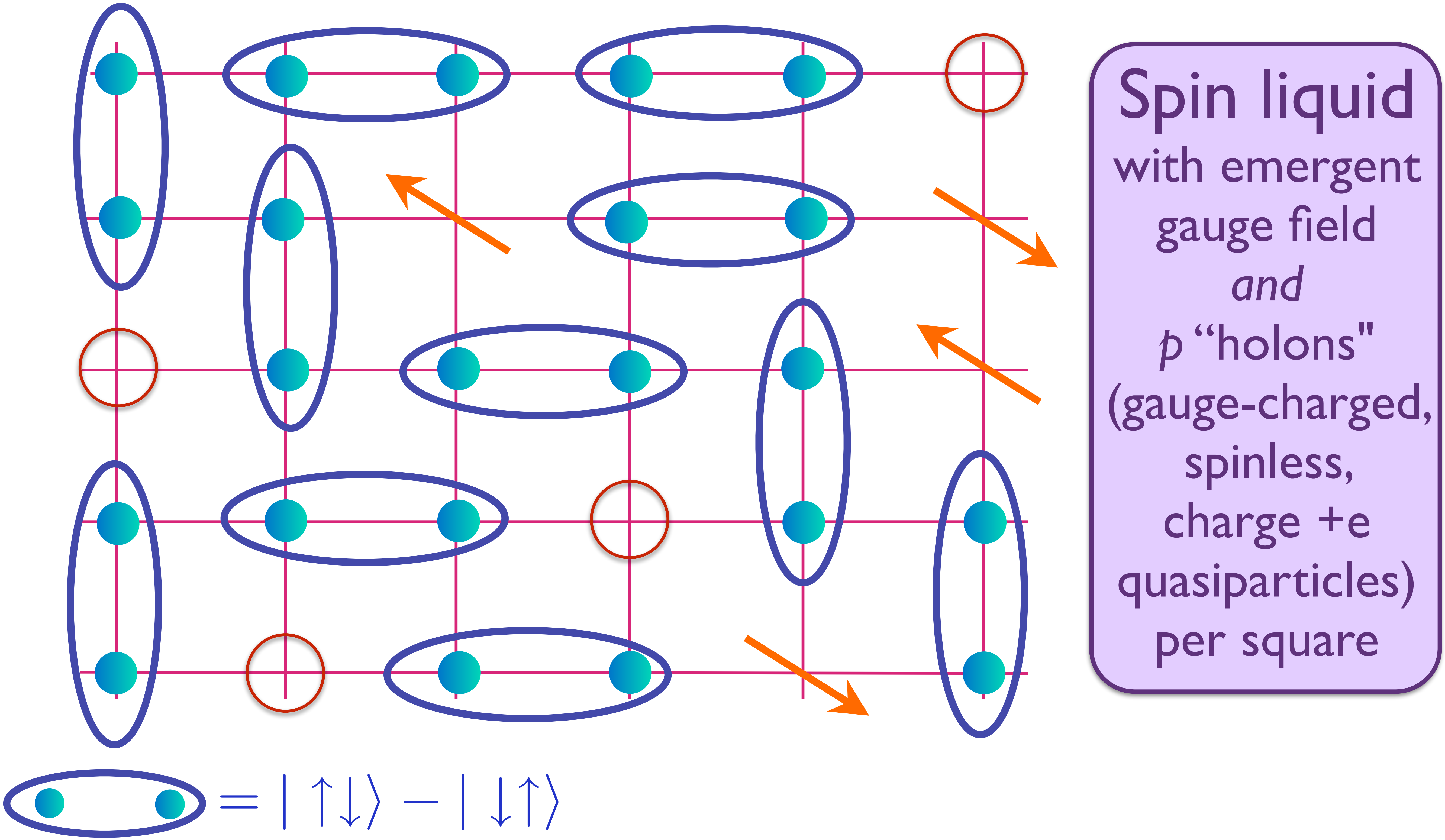
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

Spin liquid

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

Baskaran, Zou, Anderson, Fradkin, Kivelson…

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



Baskaran, Zou, Anderson, Fradkin, Kivelson…

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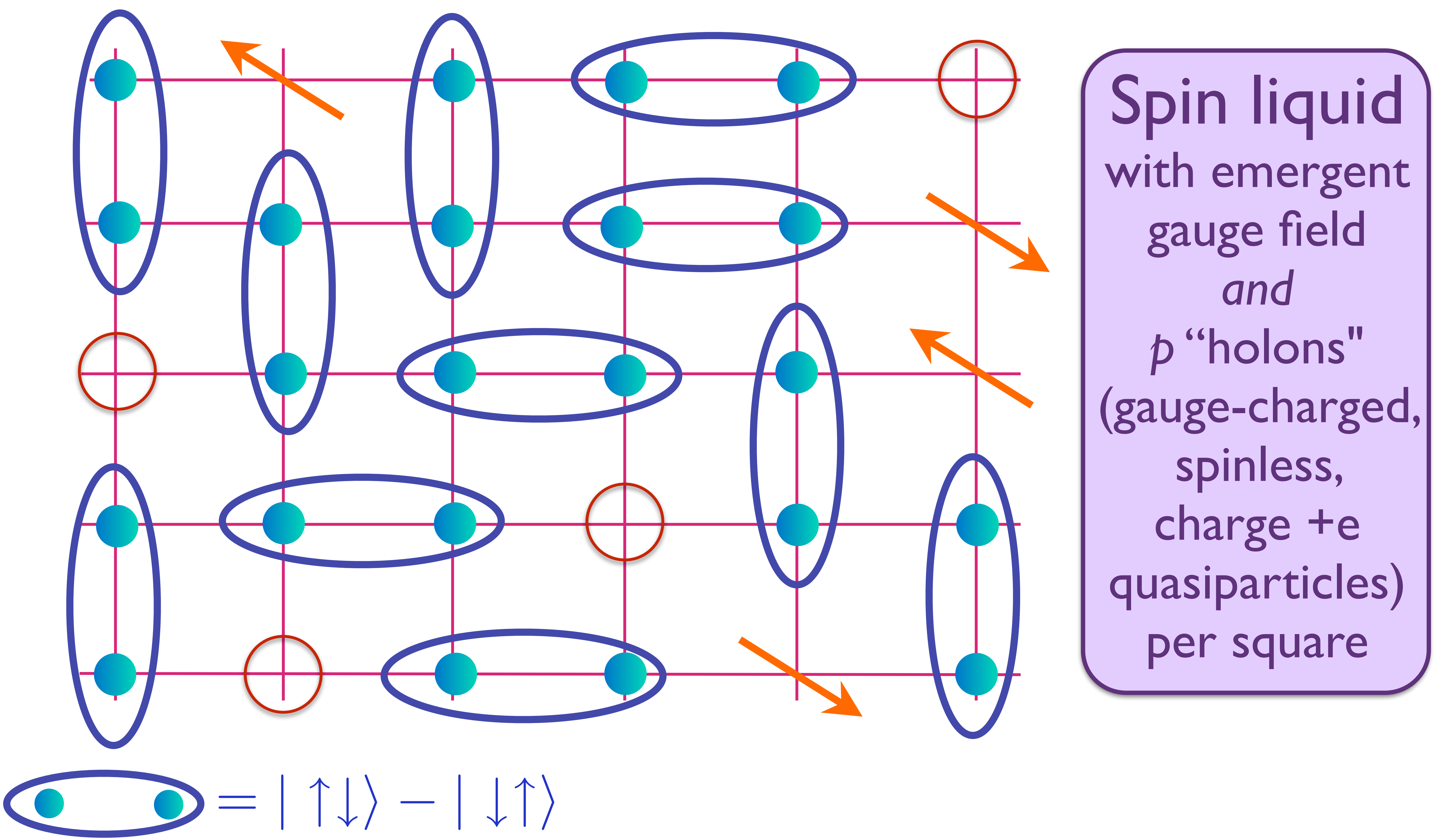
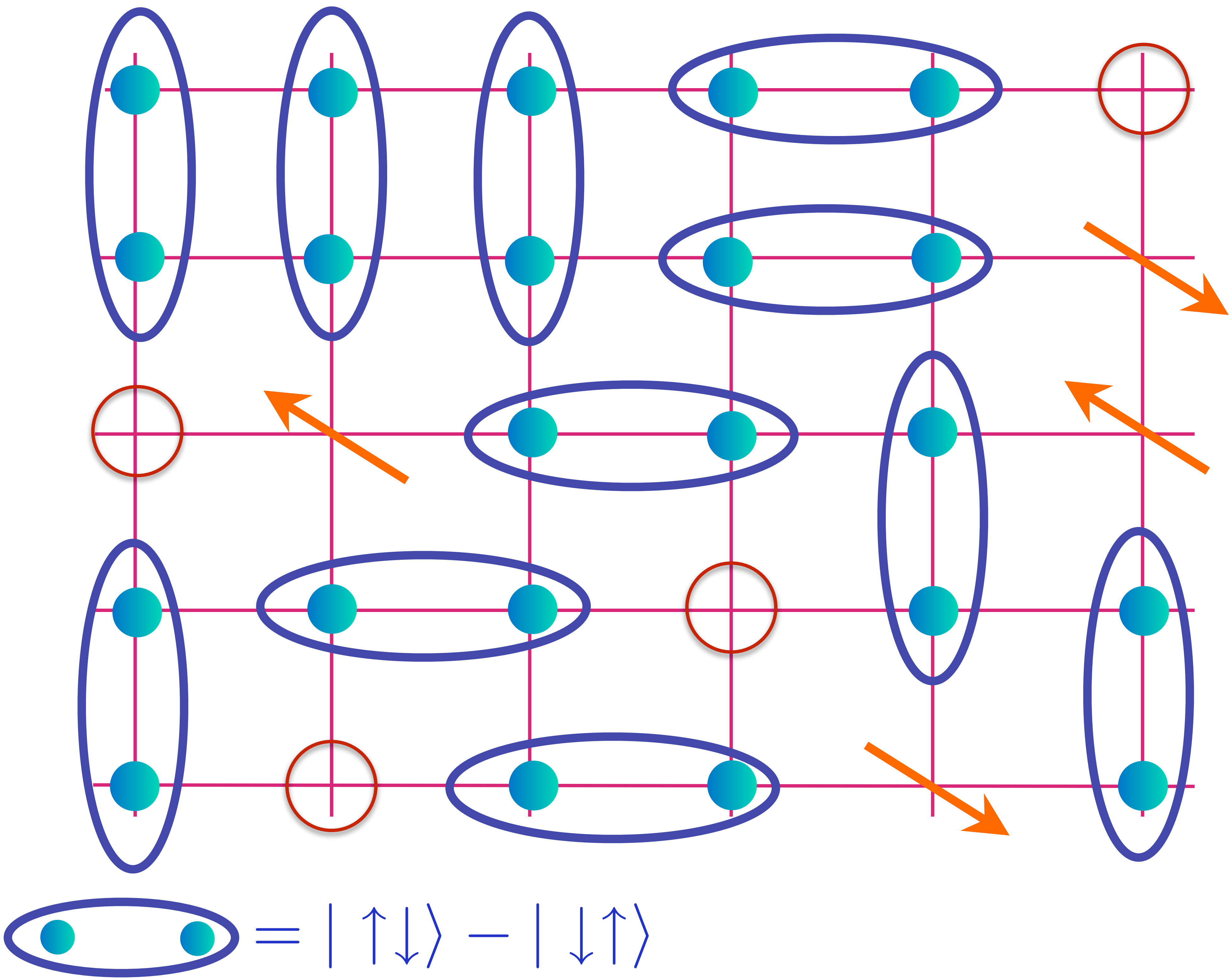


Baskaran, Zou, Anderson, Fradkin, Kivelson…

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



Spin liquid
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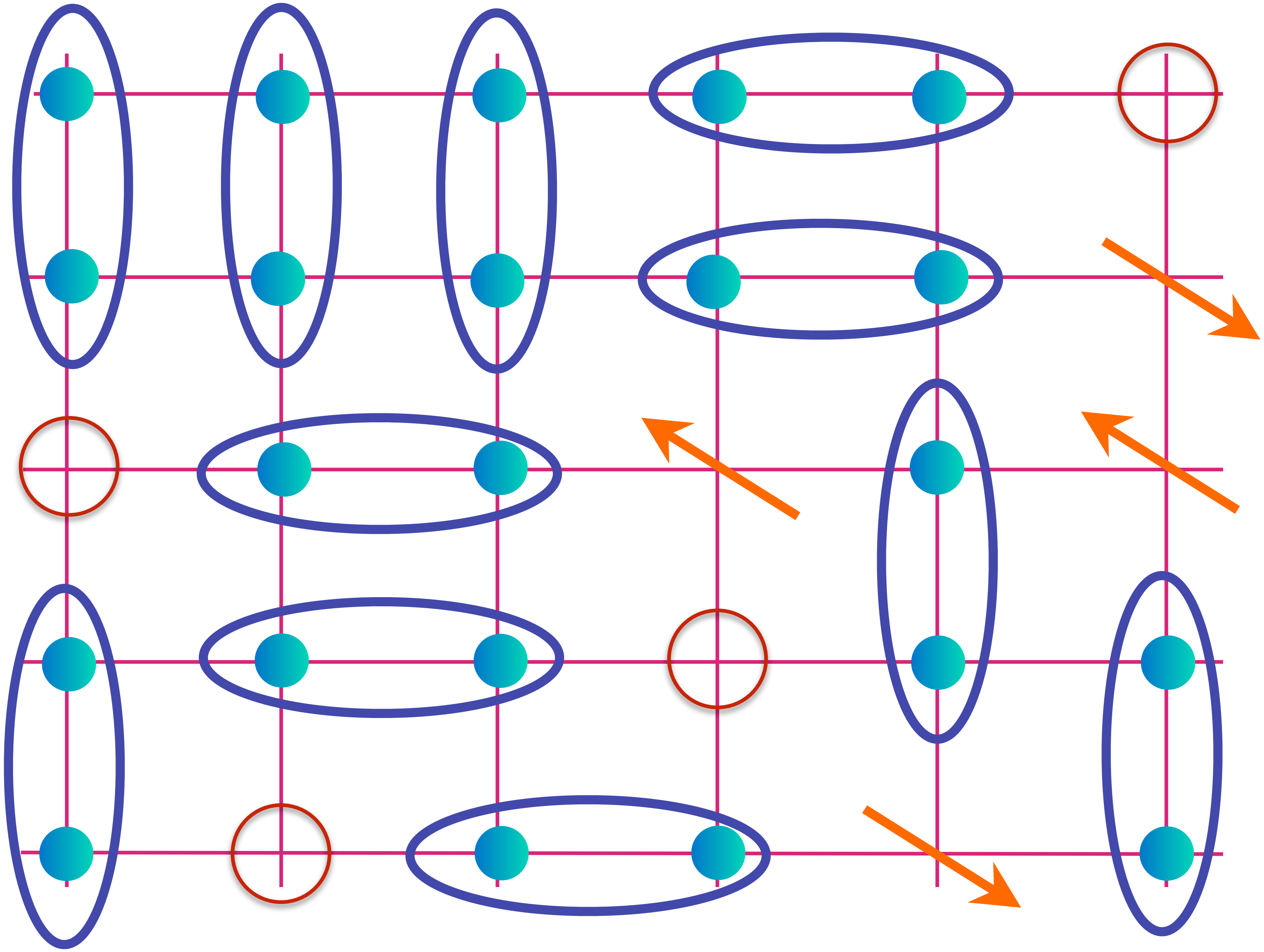
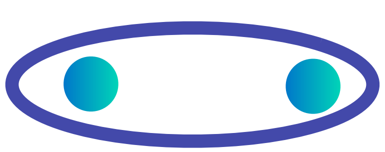
Baskaran, Zou, Anderson, Fradkin, Kivelson…

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

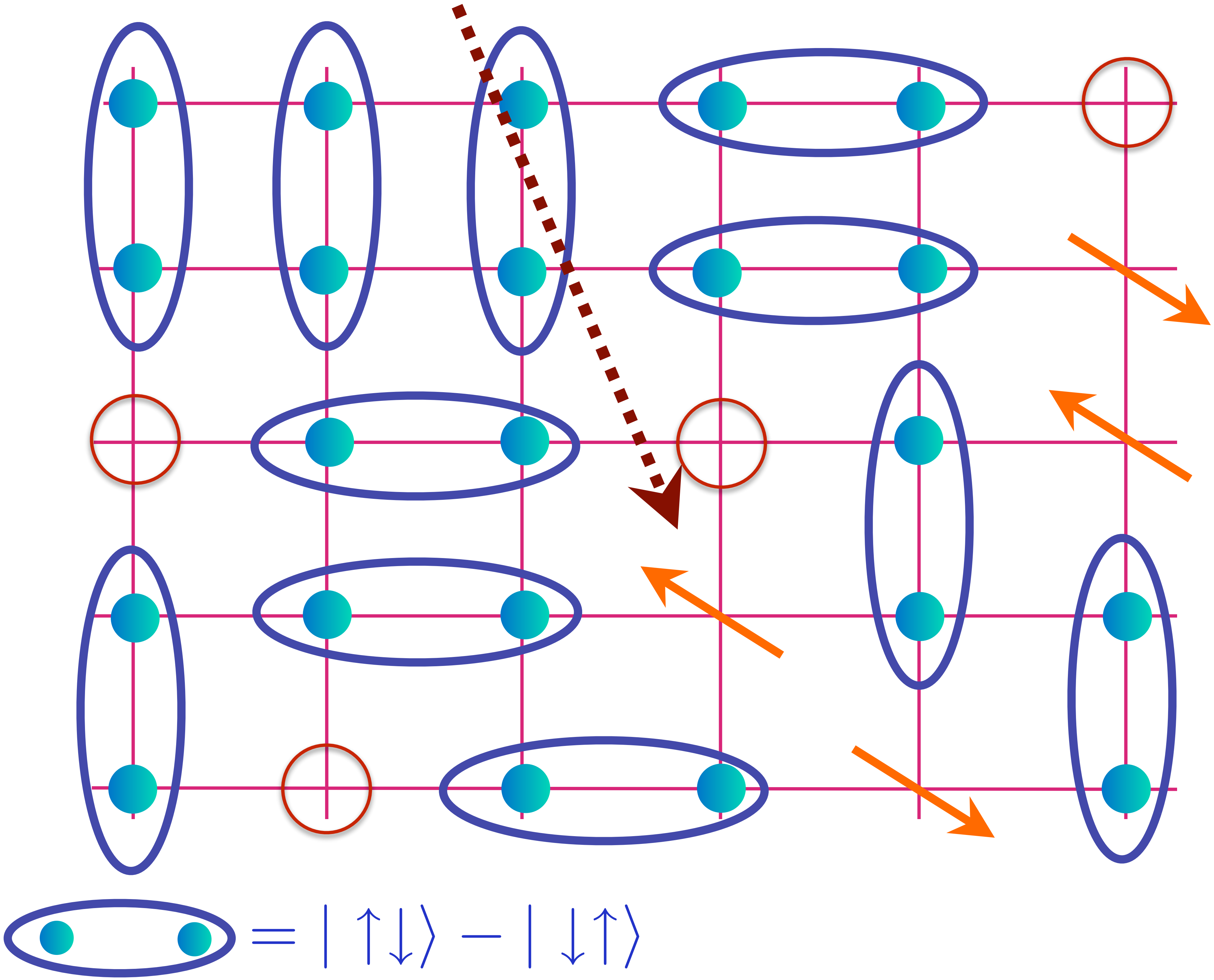


Spin liquid with emergent gauge field *and* p "holons" (gauge-charged, spinless, charge +e quasiparticles) per square

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

Baskaran, Zou, Anderson, Fradkin, Kivelson…

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



Spin liquid
with emergent gauge field
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R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, *Phys. Rev. B* **75**, 235122 (2007)

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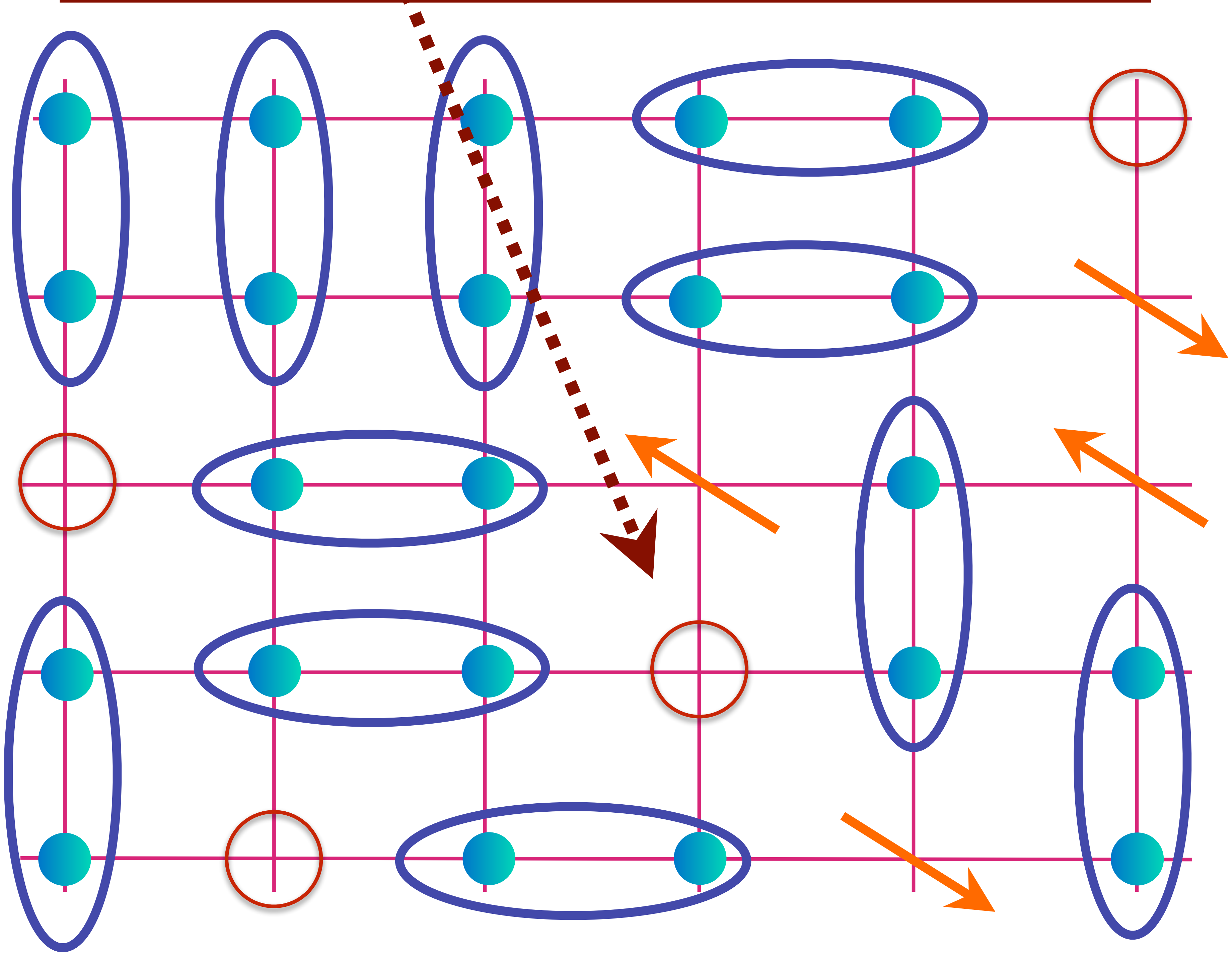

Spin liquid

with emergent gauge field

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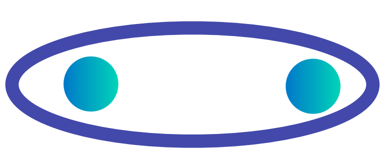
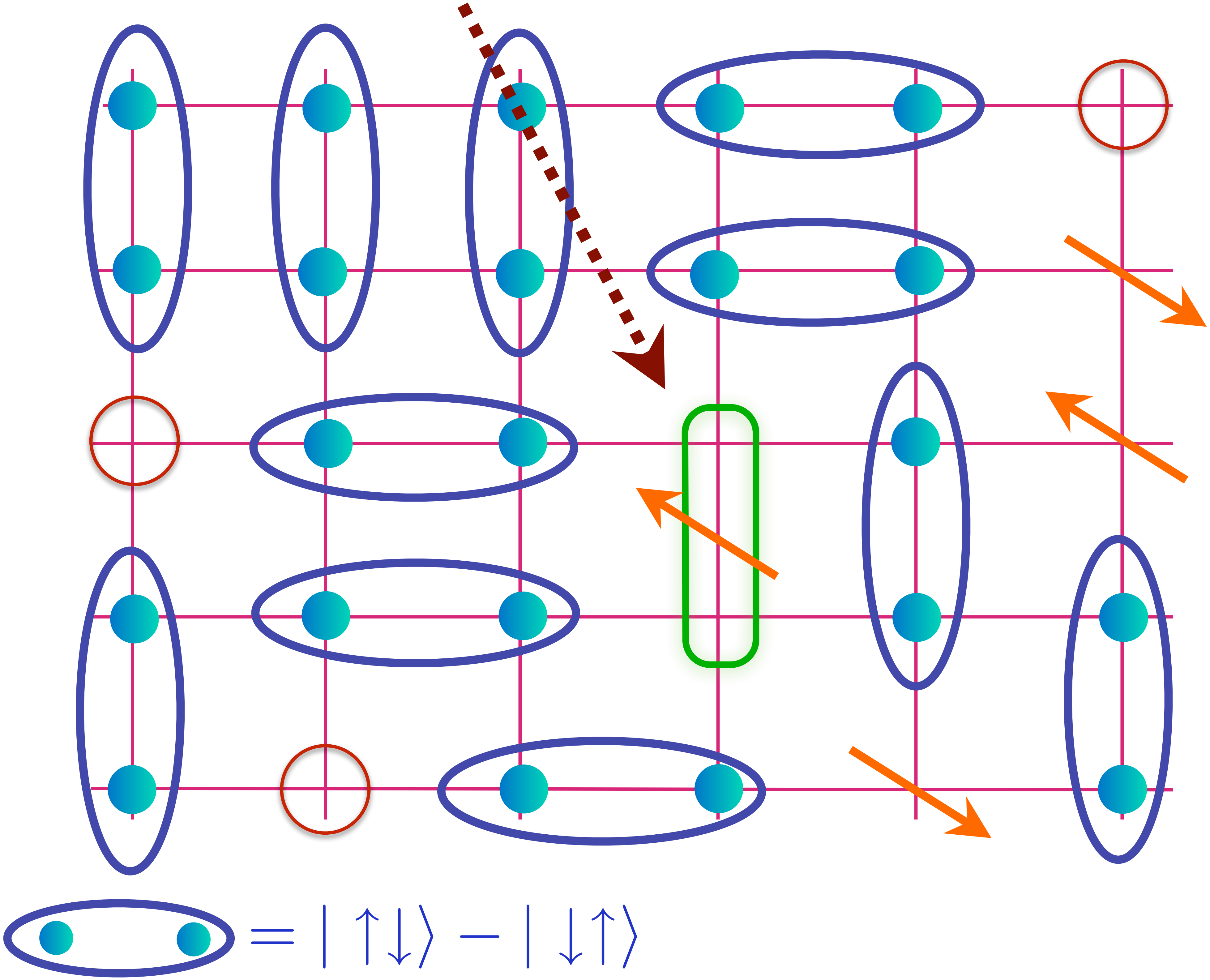
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

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

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



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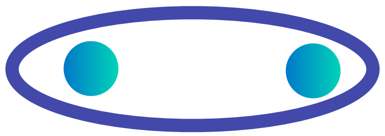
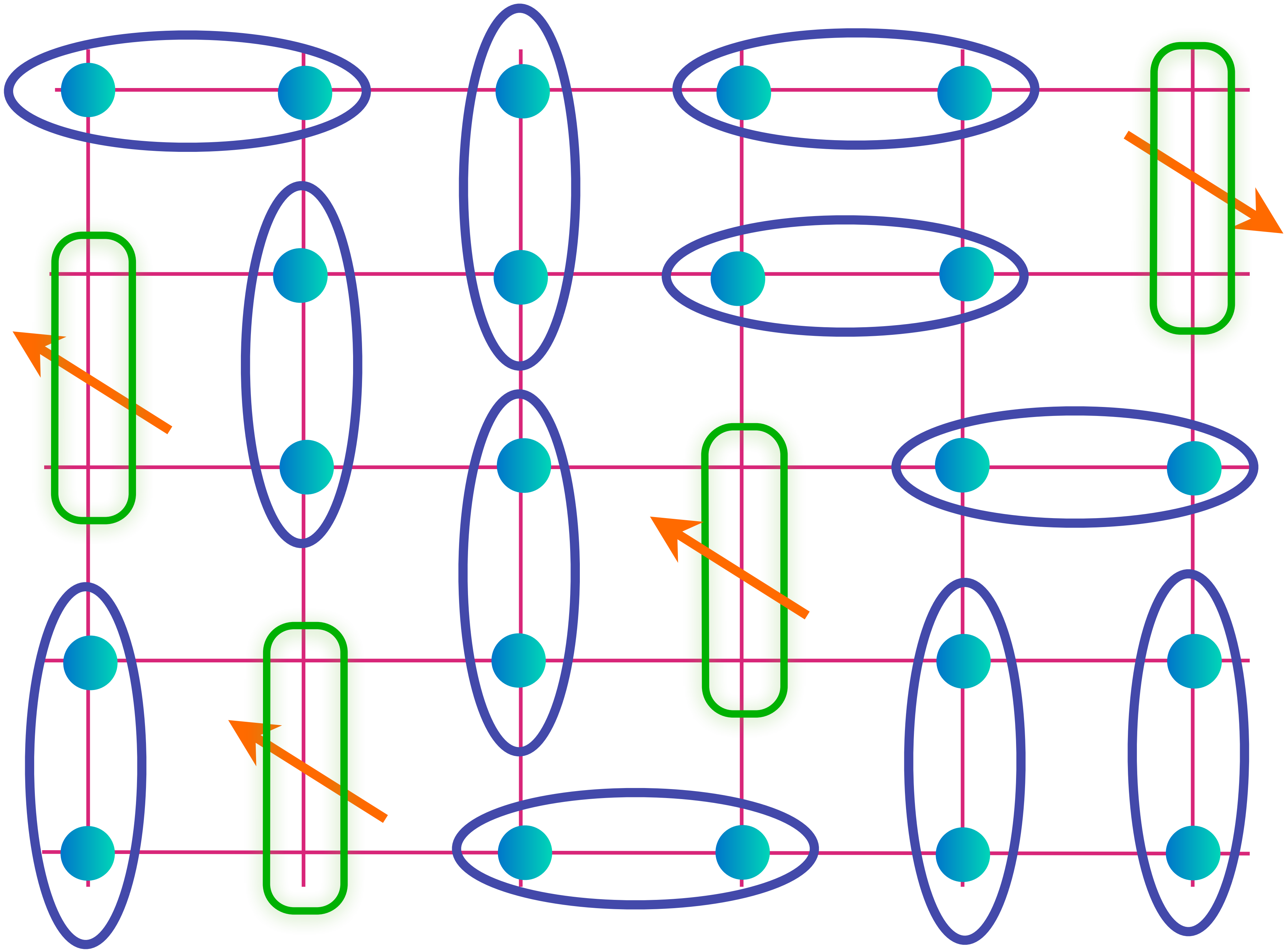
R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, *Phys. Rev. B* **75**, 235122 (2007)

Fractionalized Fermi liquid (FL*)

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



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

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.

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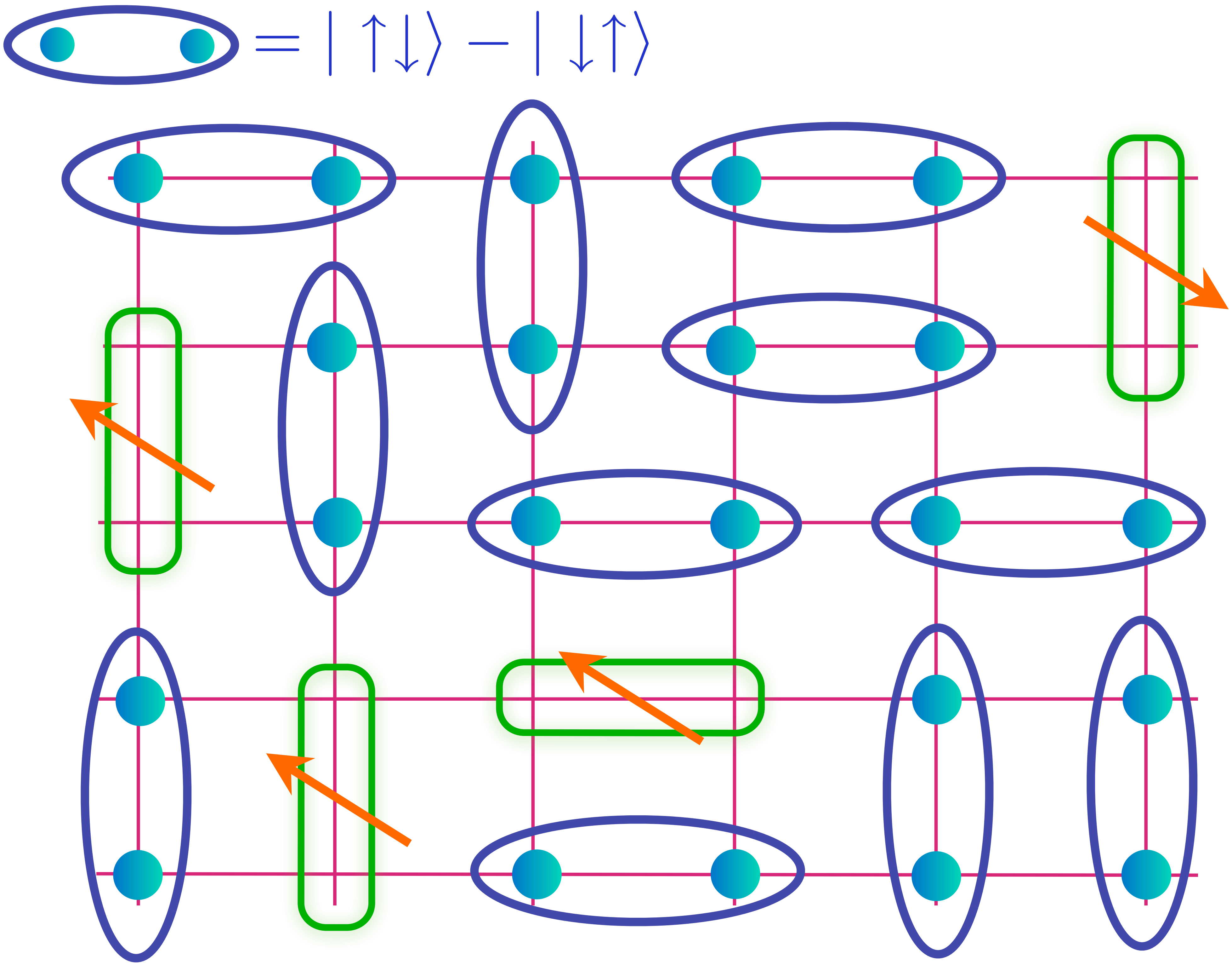

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T. Senthil, S. S., M. Vojta *Phys. Rev. Lett.* **90**, 216403 (2003)
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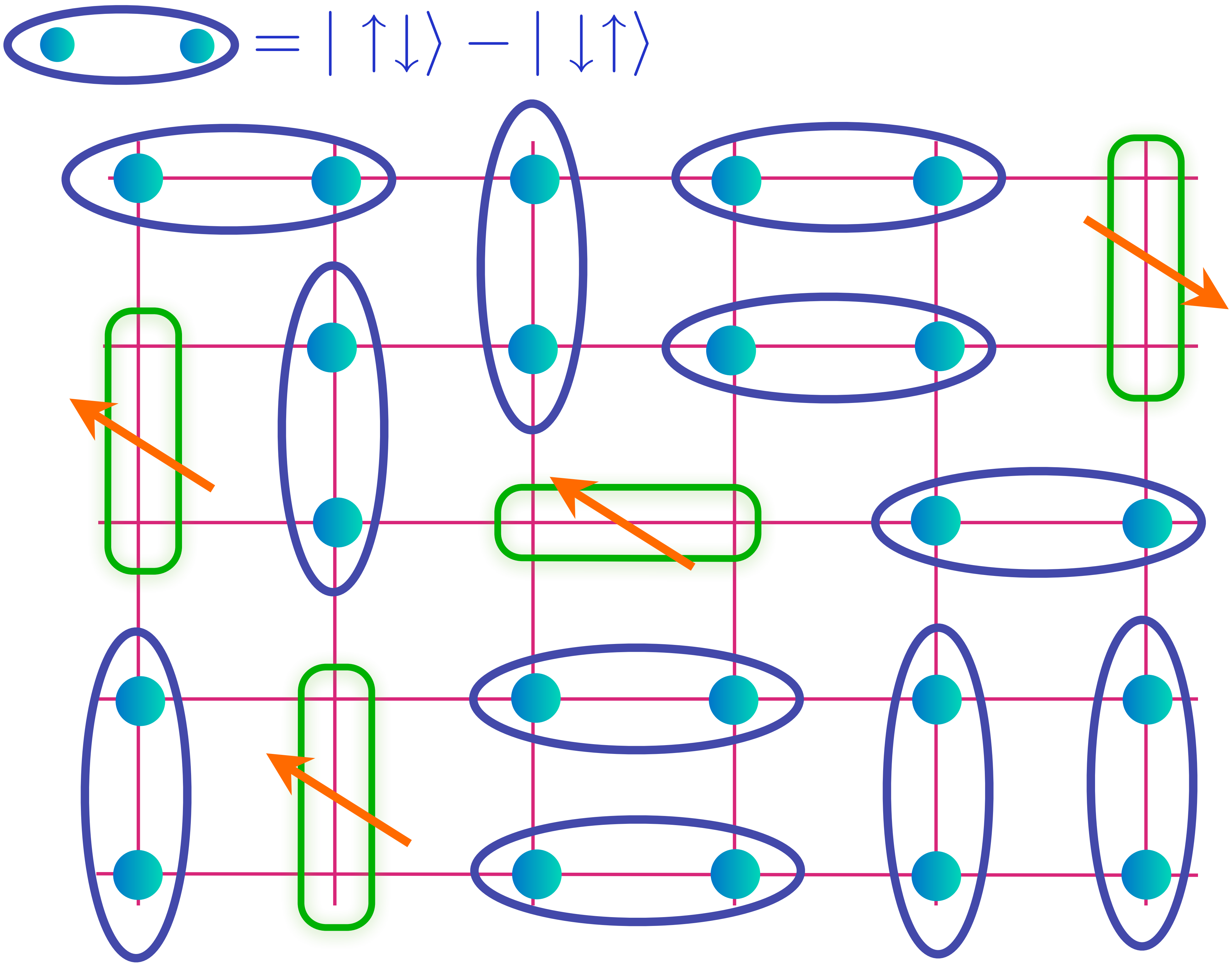

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T. Senthil, S. S., M. Vojta *Phys. Rev. Lett.* **90**, 216403 (2003)
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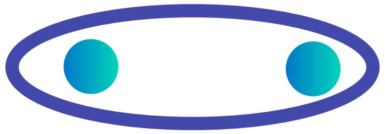
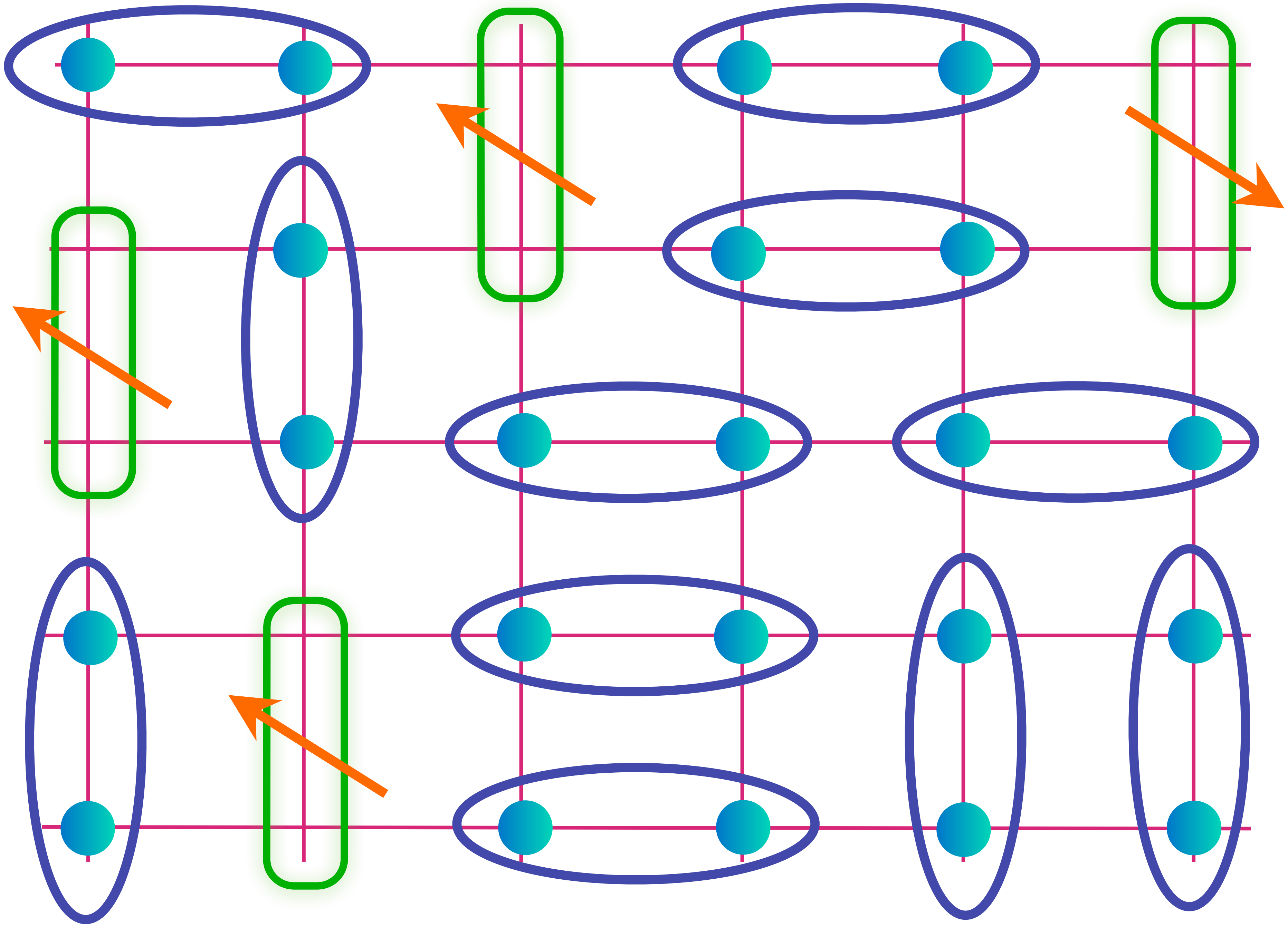
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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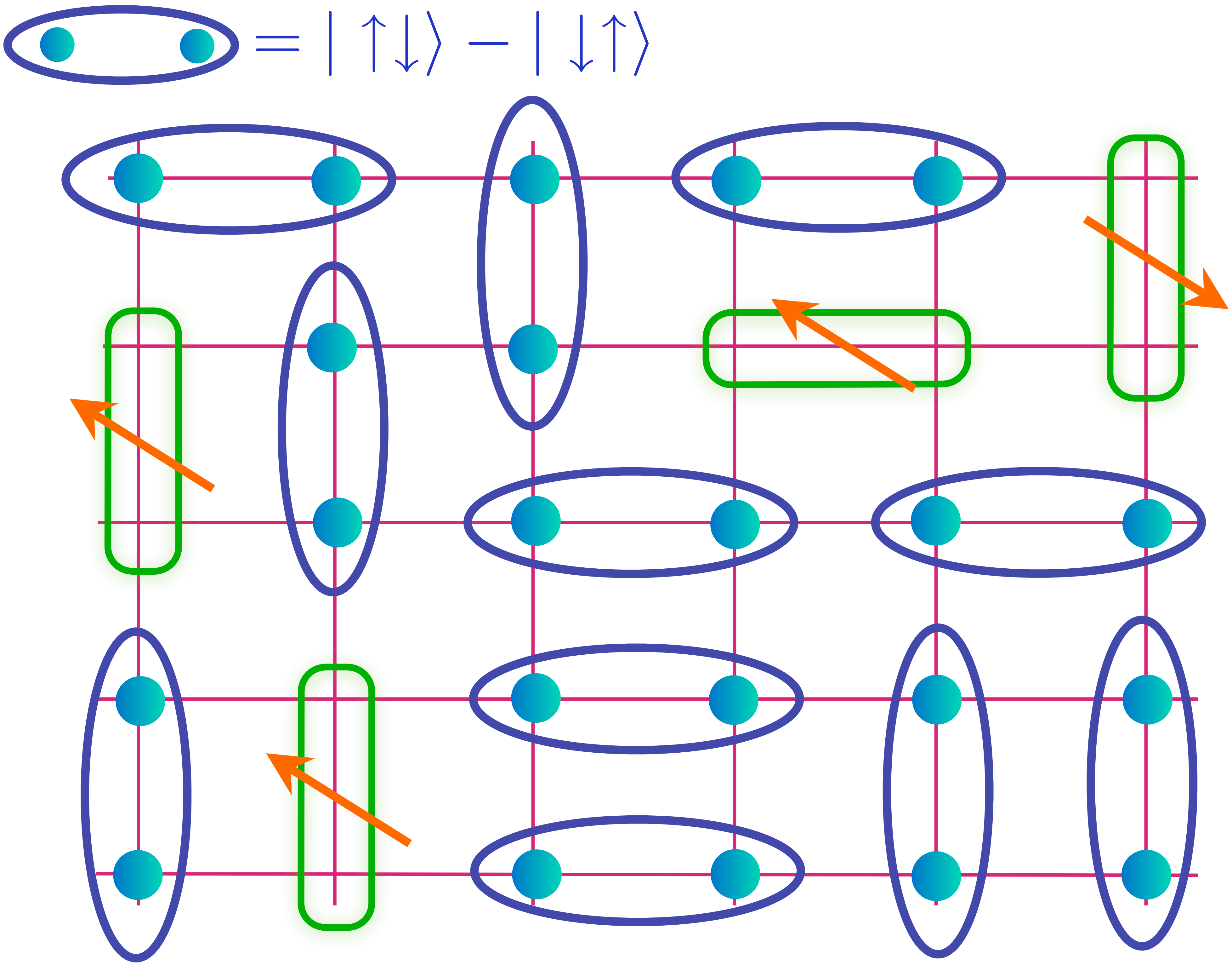

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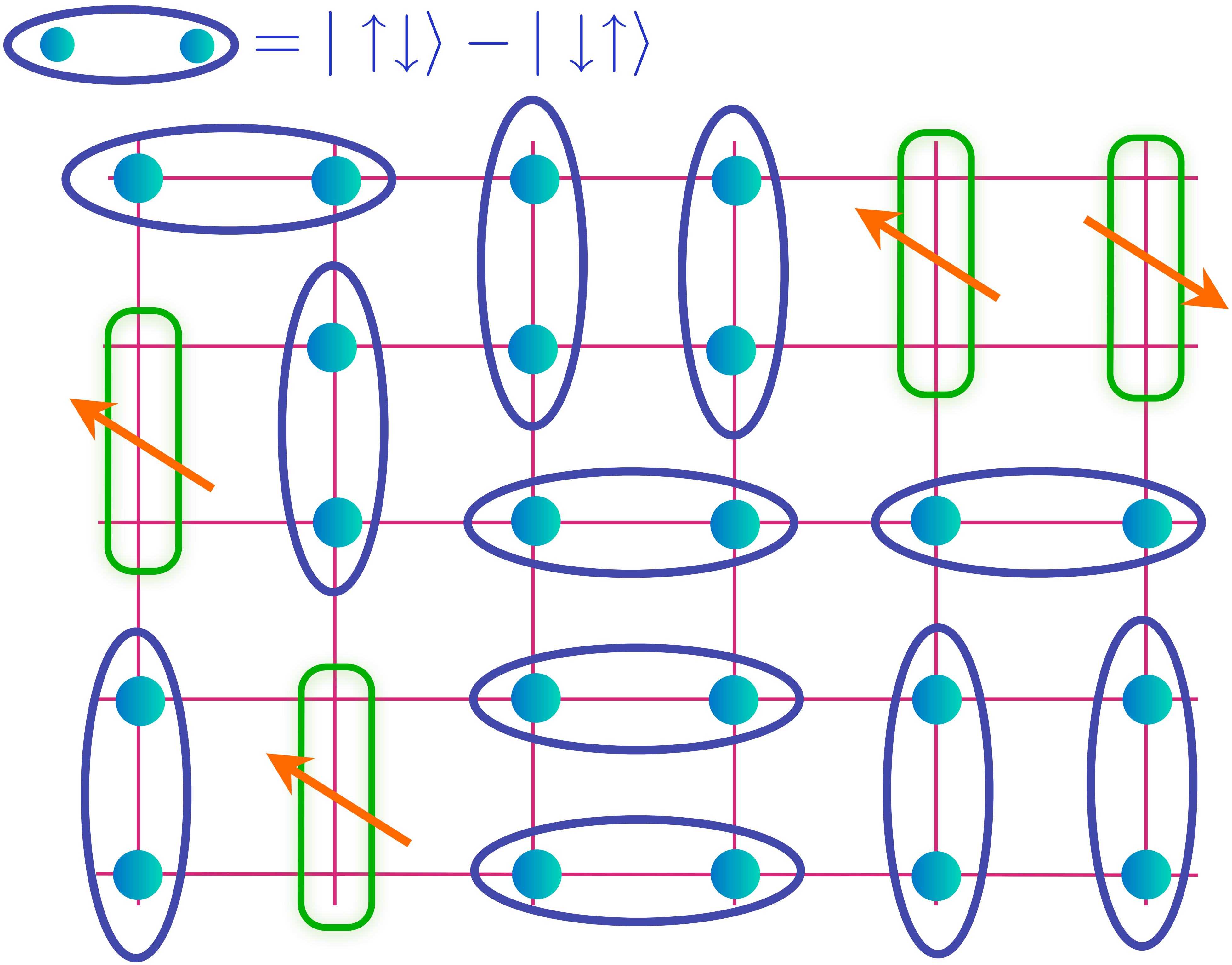

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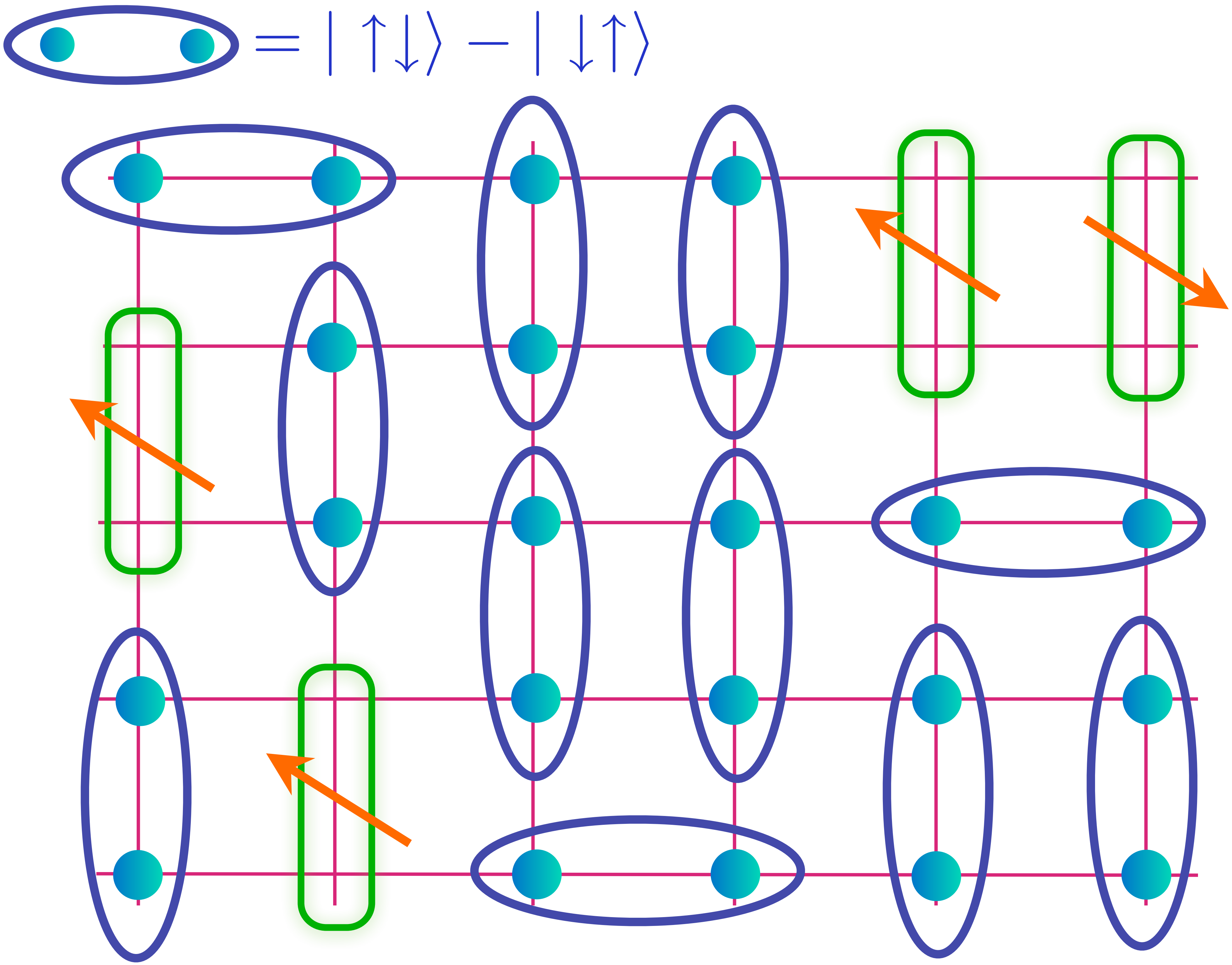

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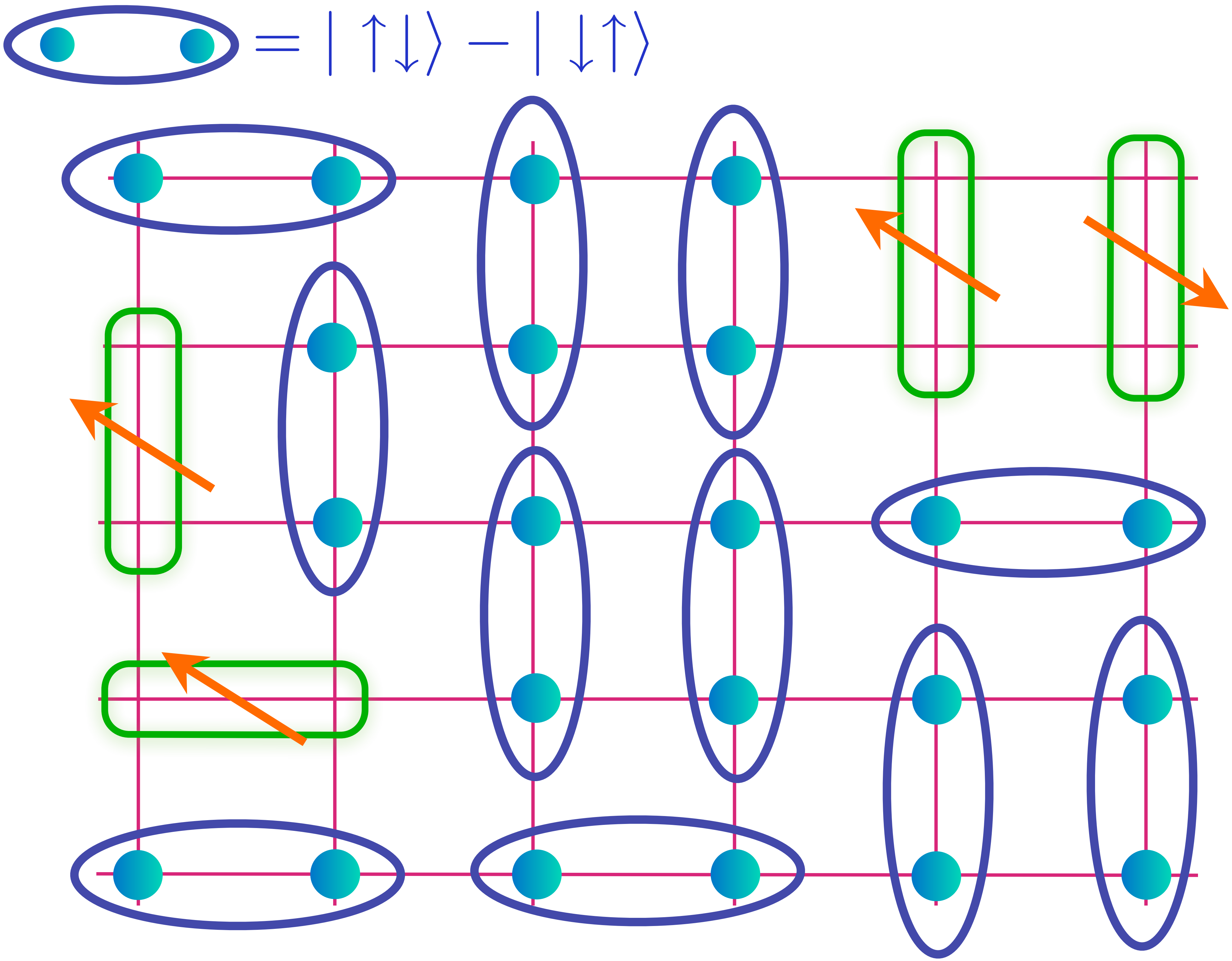

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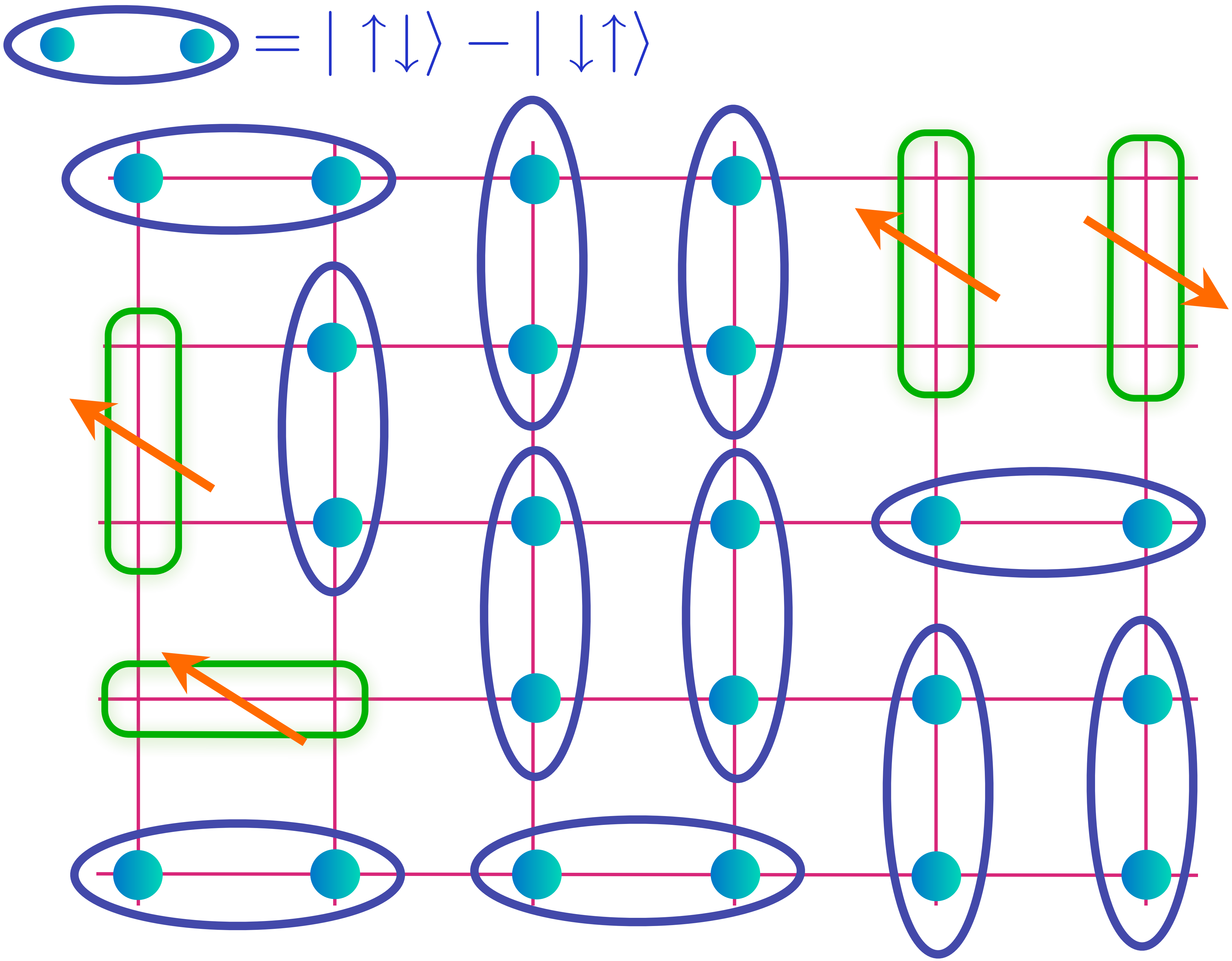
E. G. Moon and S. S. Phys. Rev. B **83**, 224508 (2011); M. Punk, A. Allais, and S. S., arXiv:1501.00978.

Fractionalized Fermi liquid (FL*)

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



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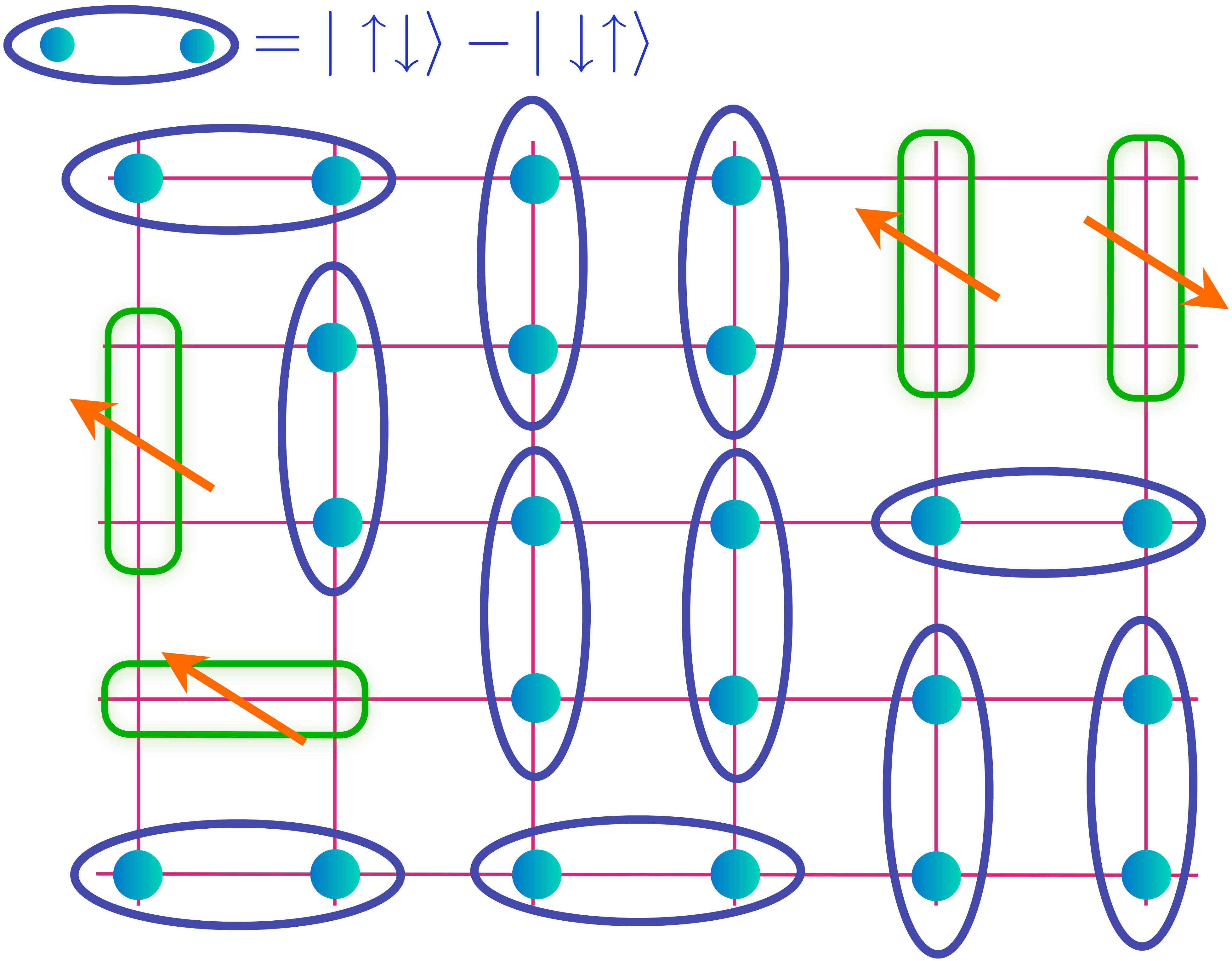
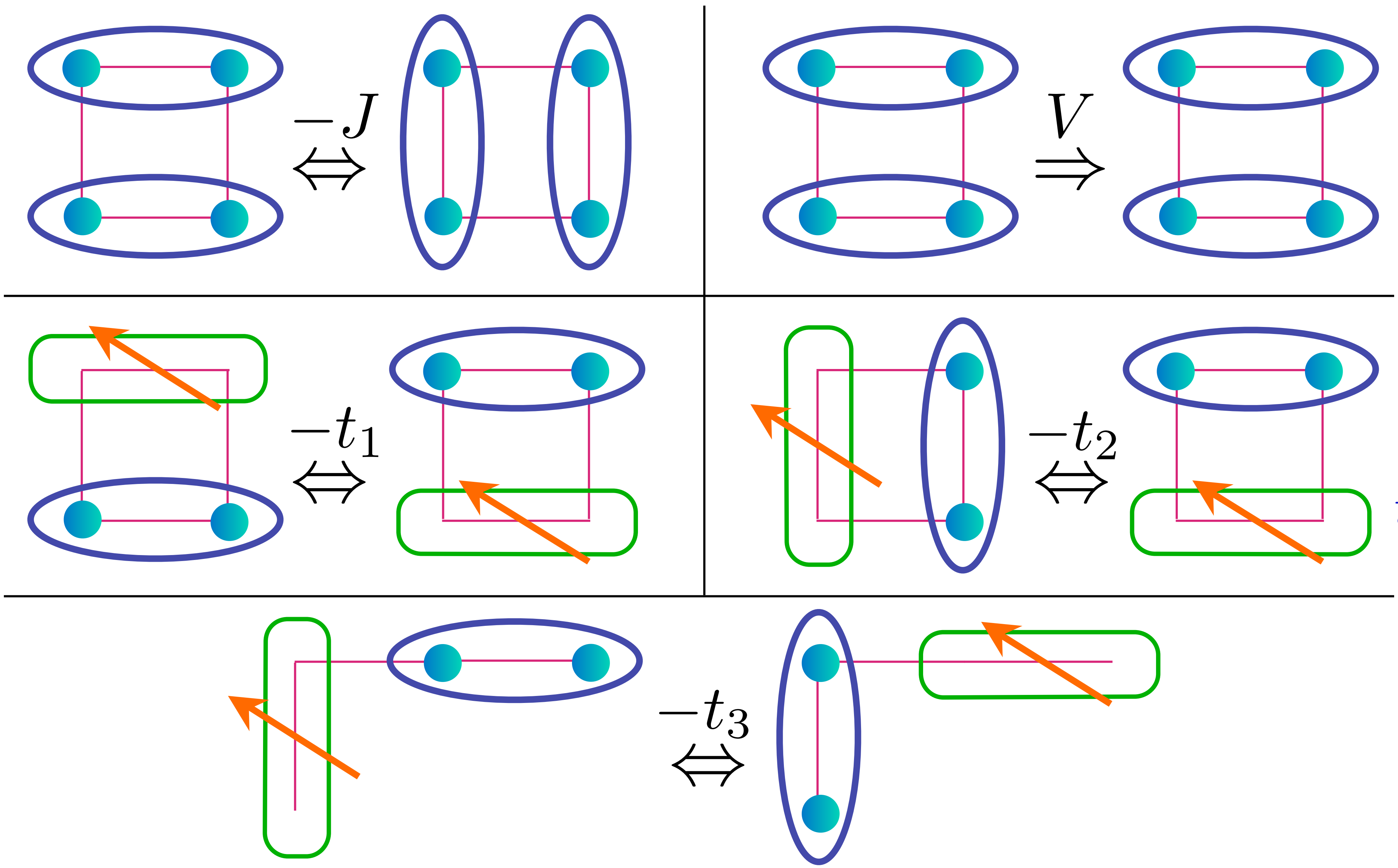


Realizes a metal with a Fermi surface of area p and "topological order"

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.

Quantum dimer model with bosonic and fermionic dimers



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

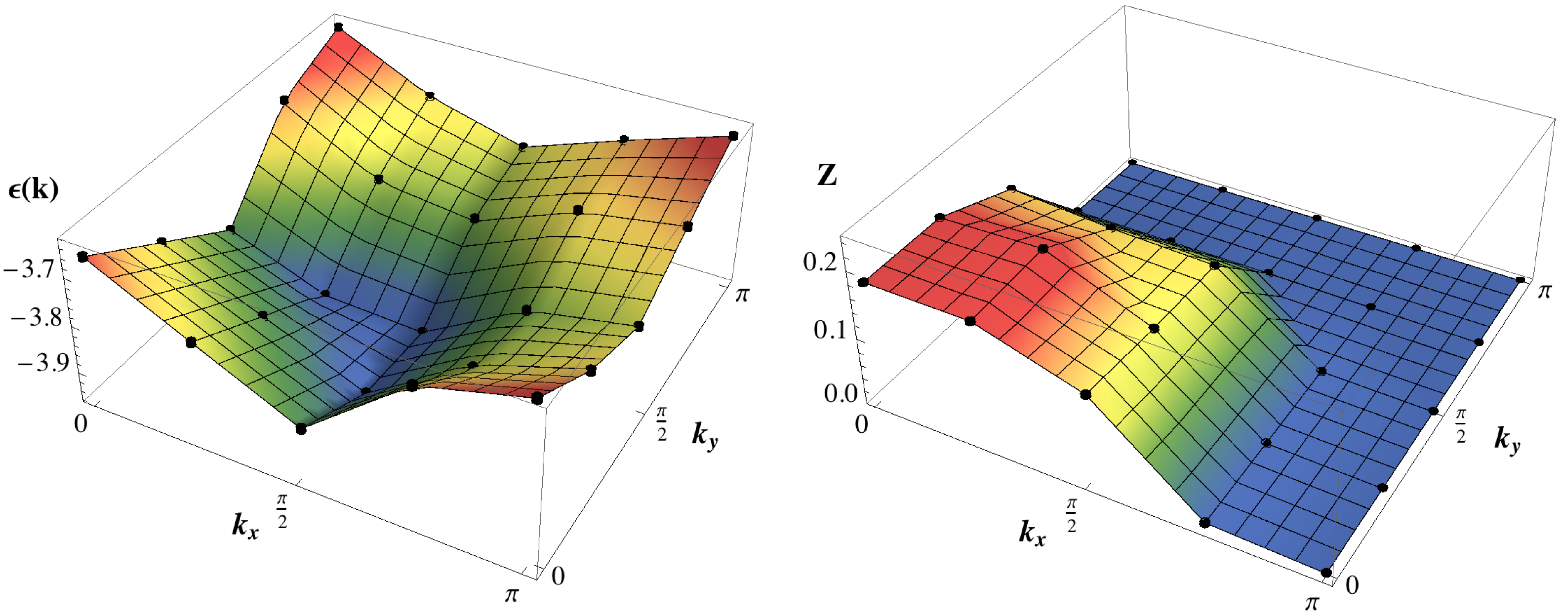
$t_1 = -(t + t')/2$

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

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

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

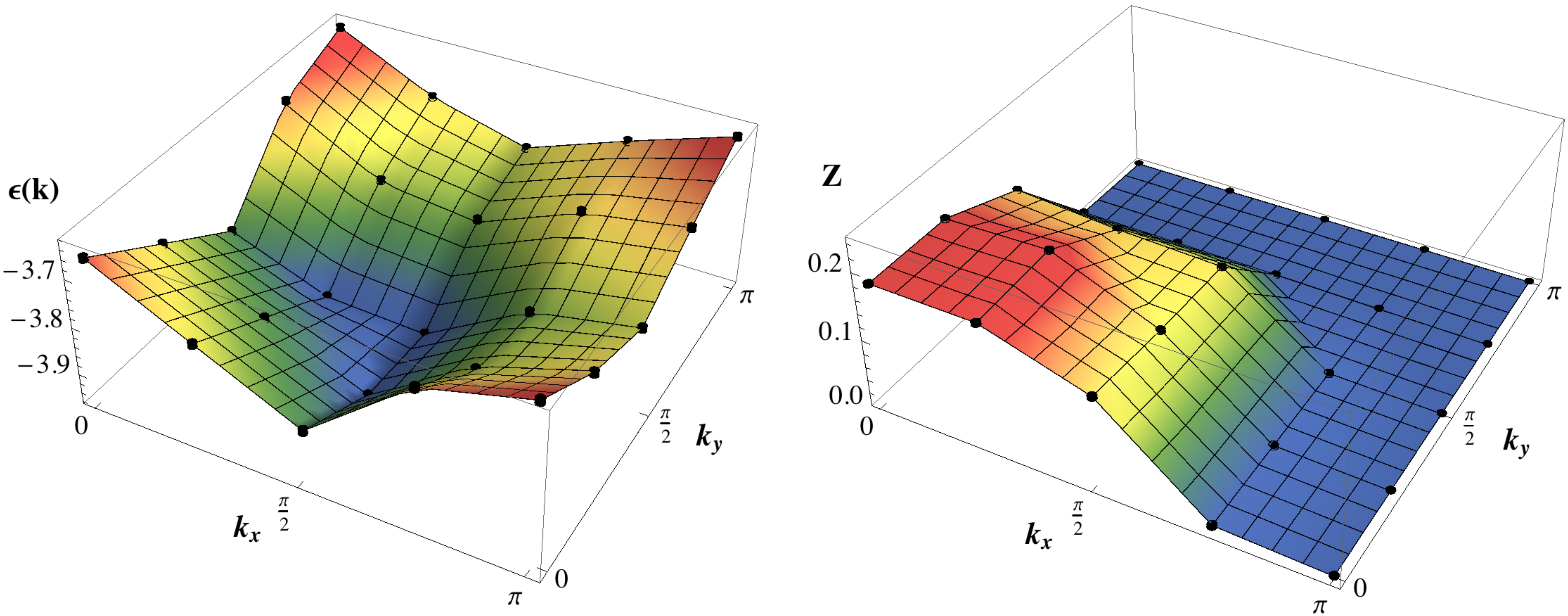
Quantum dimer model with bosonic and fermionic dimers



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

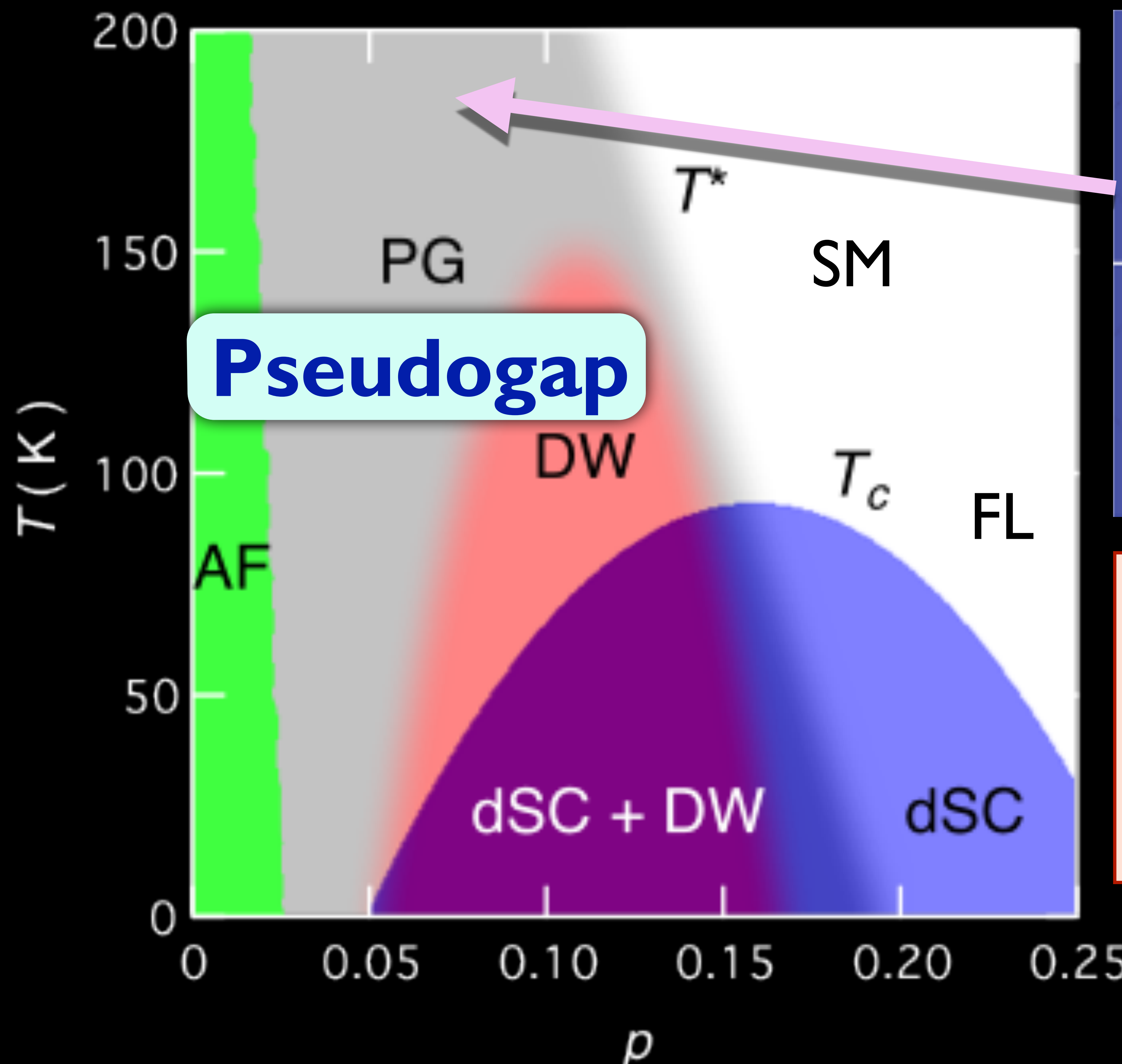
Quantum dimer model with bosonic and fermionic dimers

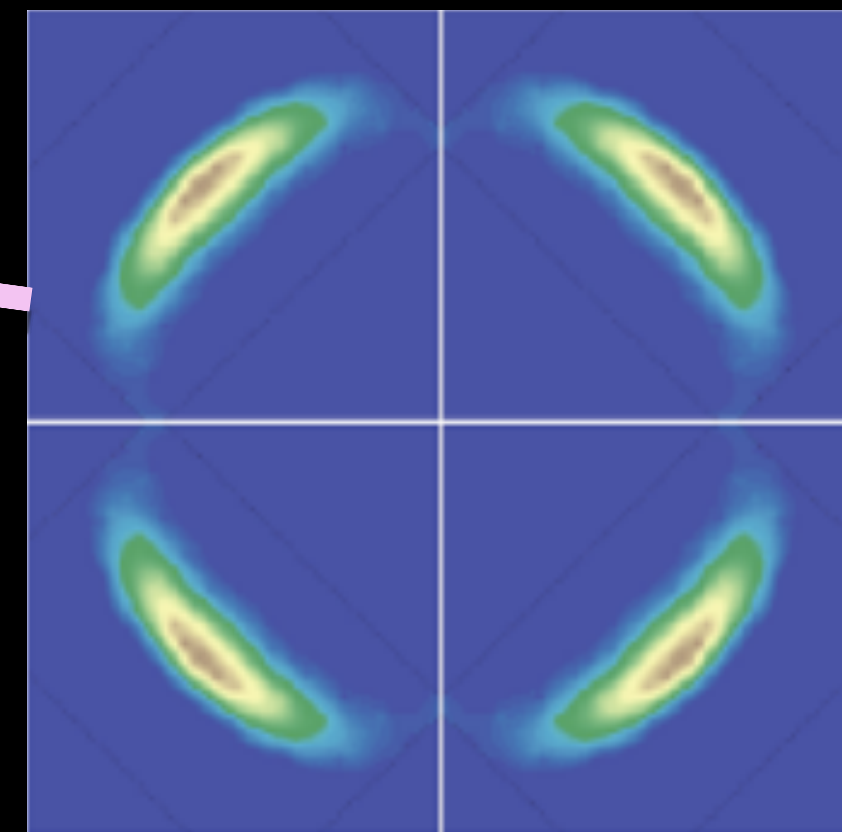


"Back side" of Fermi surface is suppressed for observables which add/remove electrons from the CuO_2 layer

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

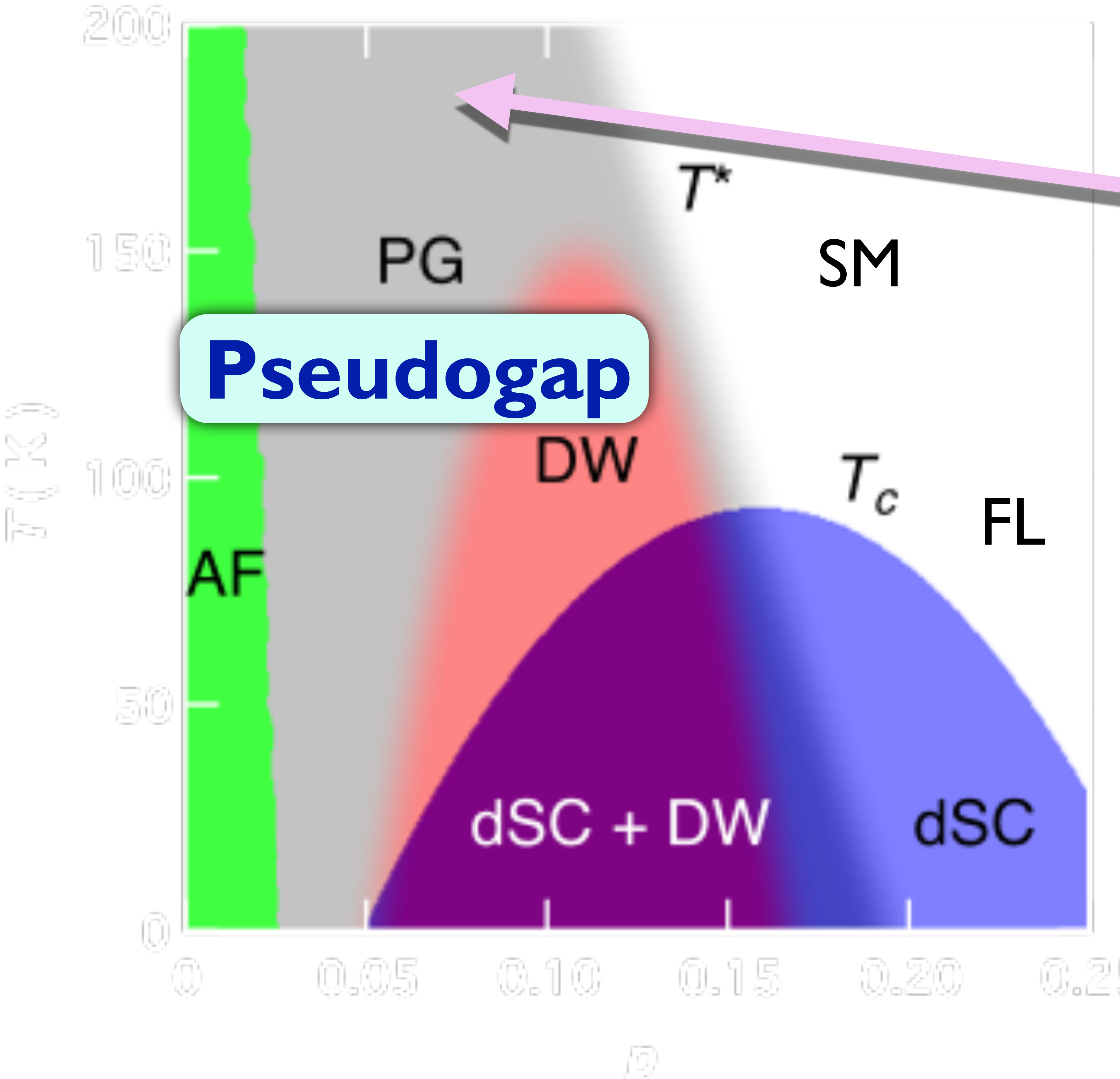
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)

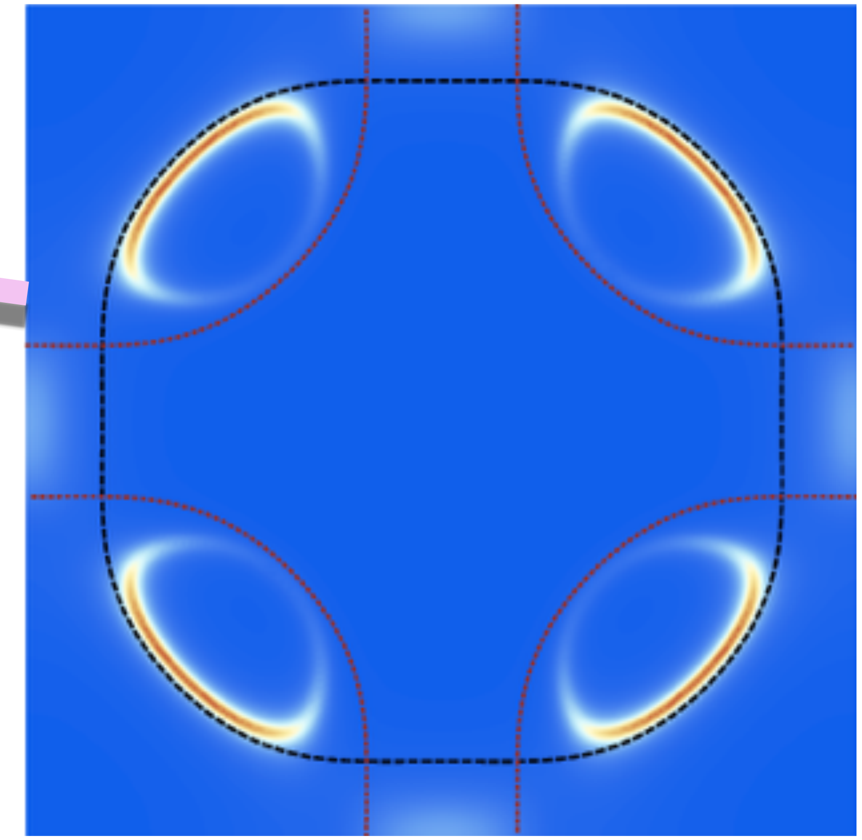




"Fermi arcs"
at
low p

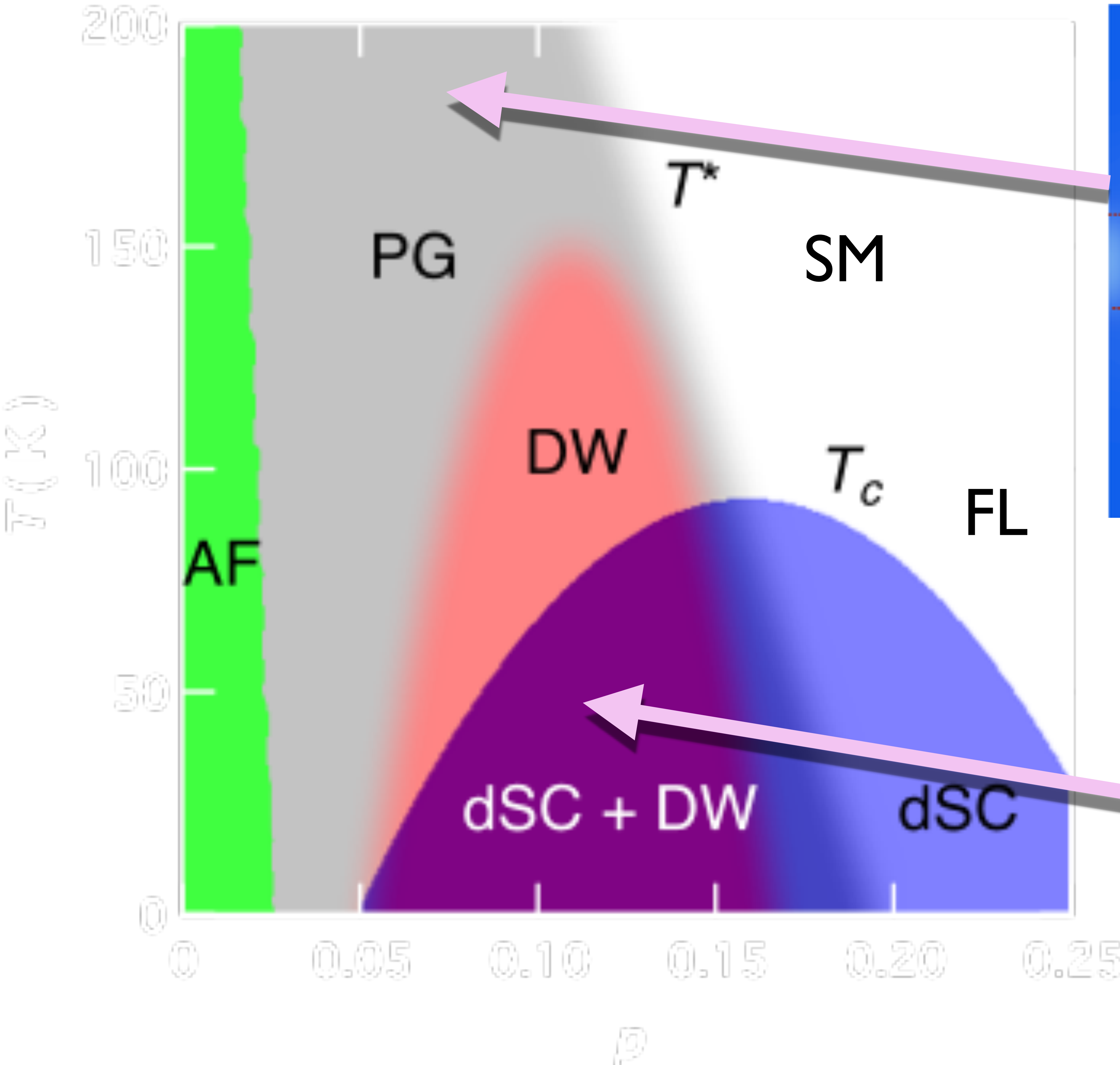
Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978

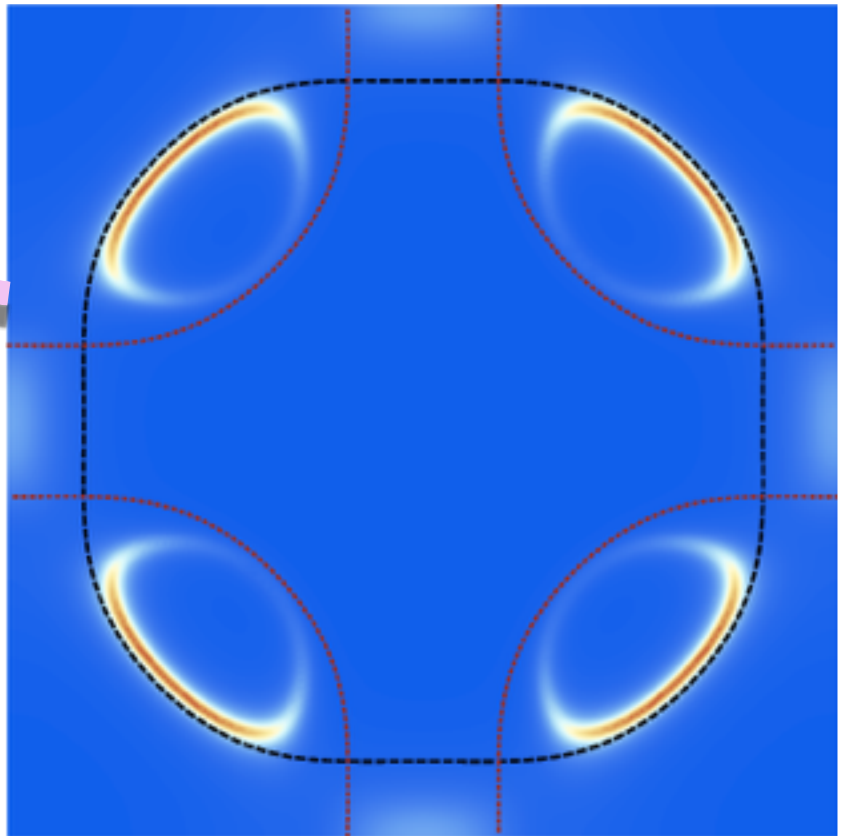


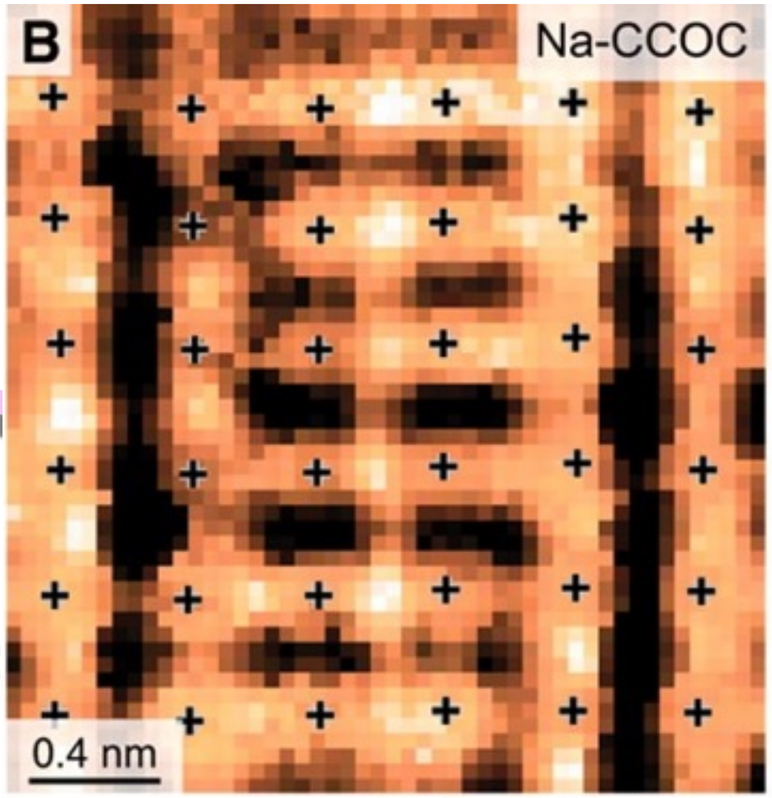


A new metal — a fractionalized Fermi liquid (FL*) — with electron-like quasiparticles on a Fermi surface of size p ?

Can the high T FL* help explain the "d-form factor density wave" observed at low T ?







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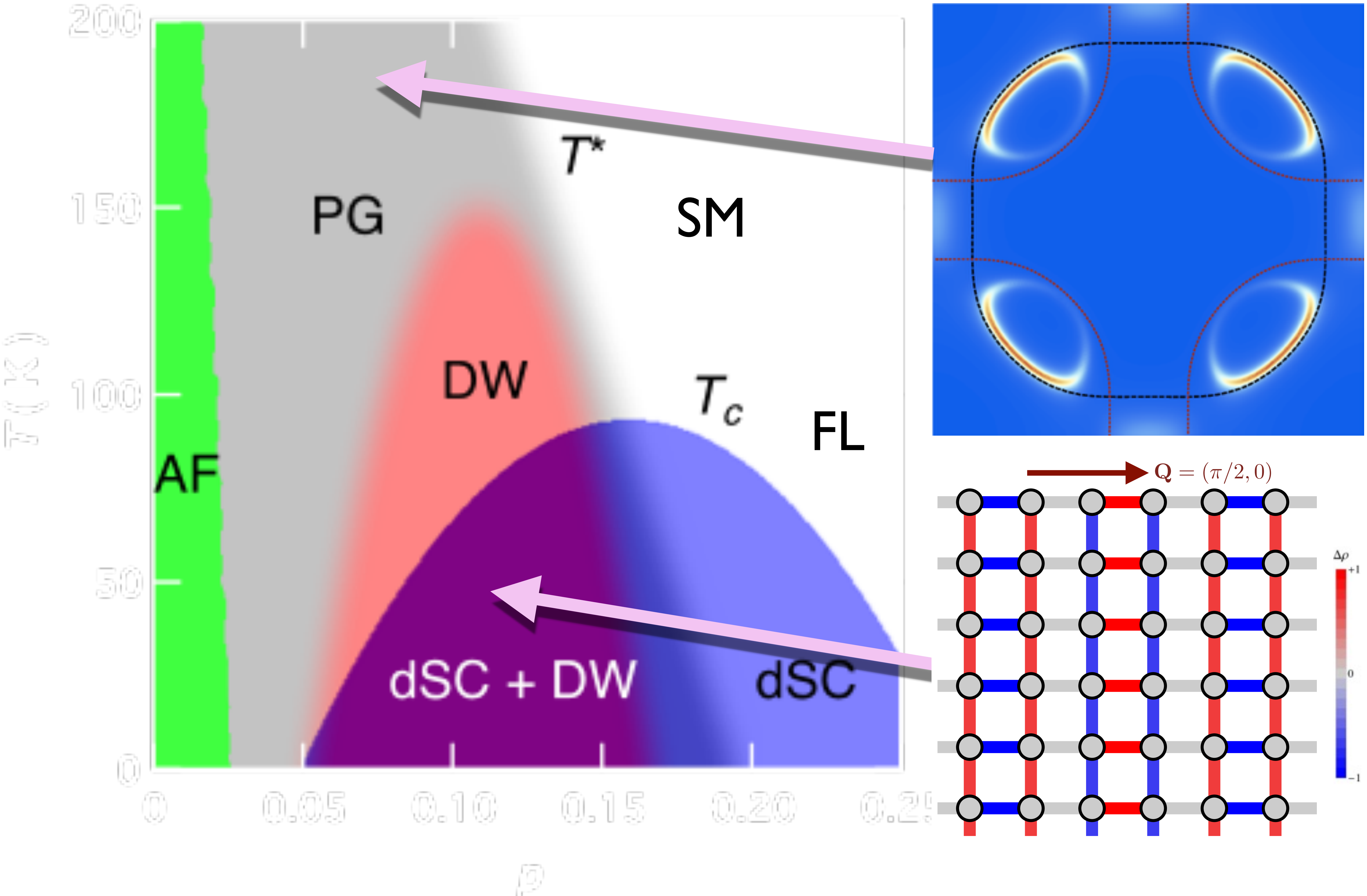
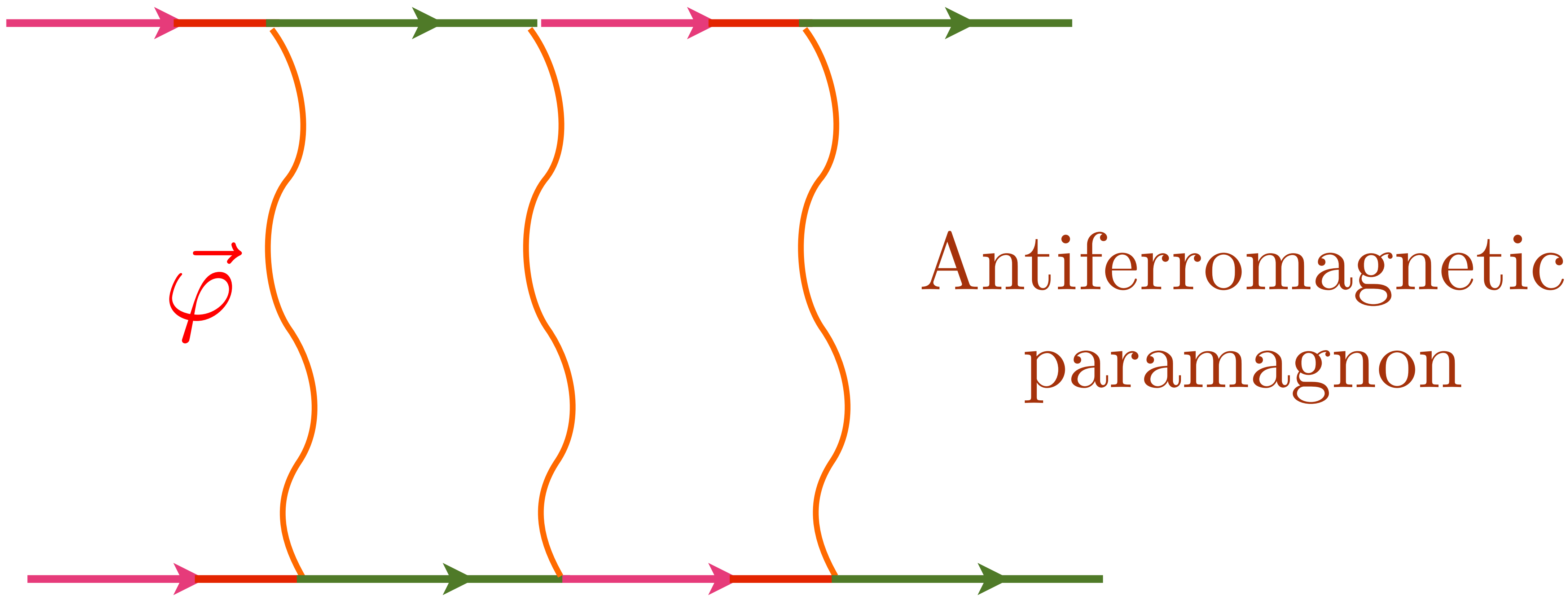


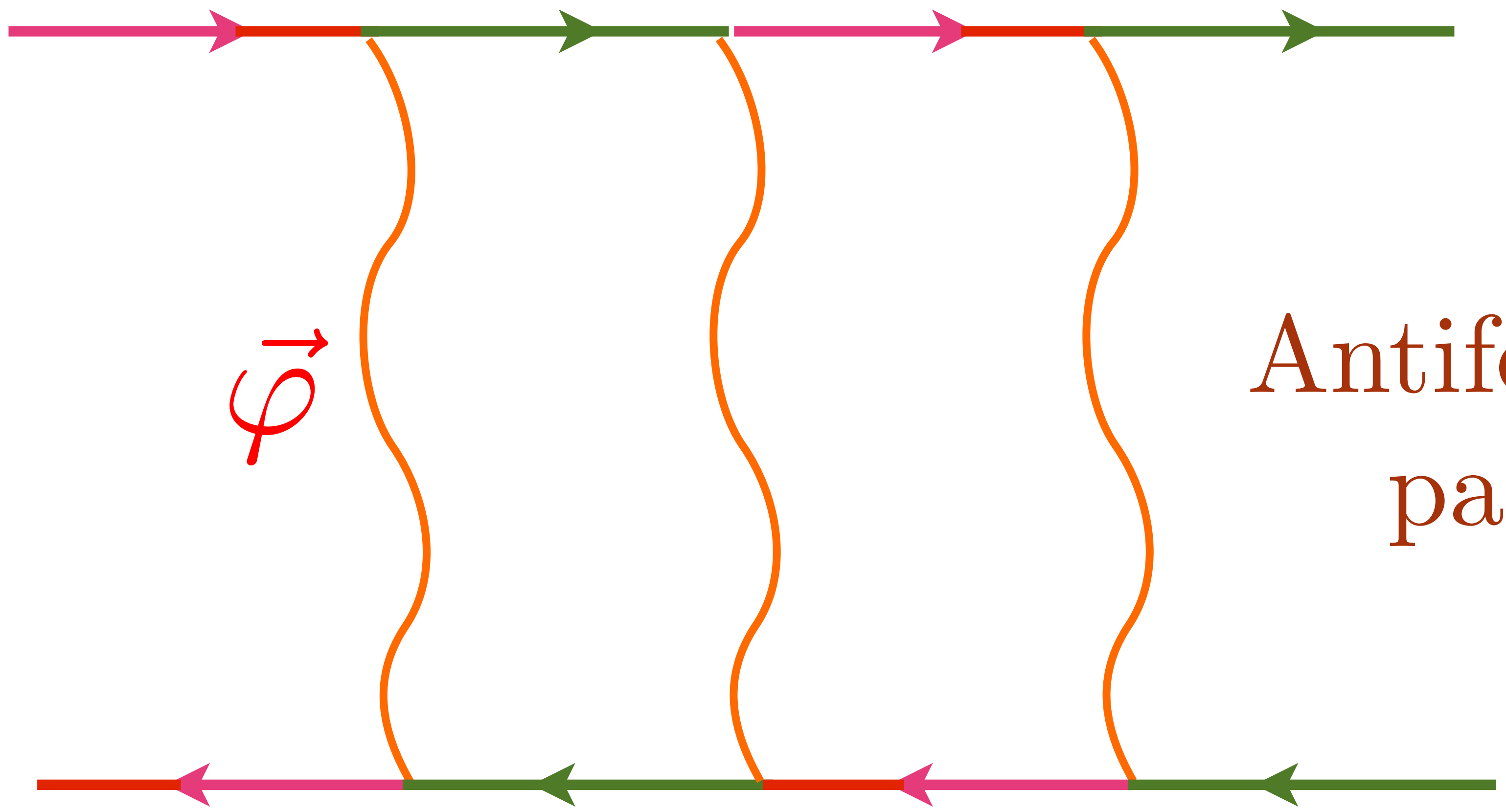
Pairing "glue" for d-wave superconductivity from antiferromagnetic fluctuations



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

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



Antiferromagnetic paramagnon

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)

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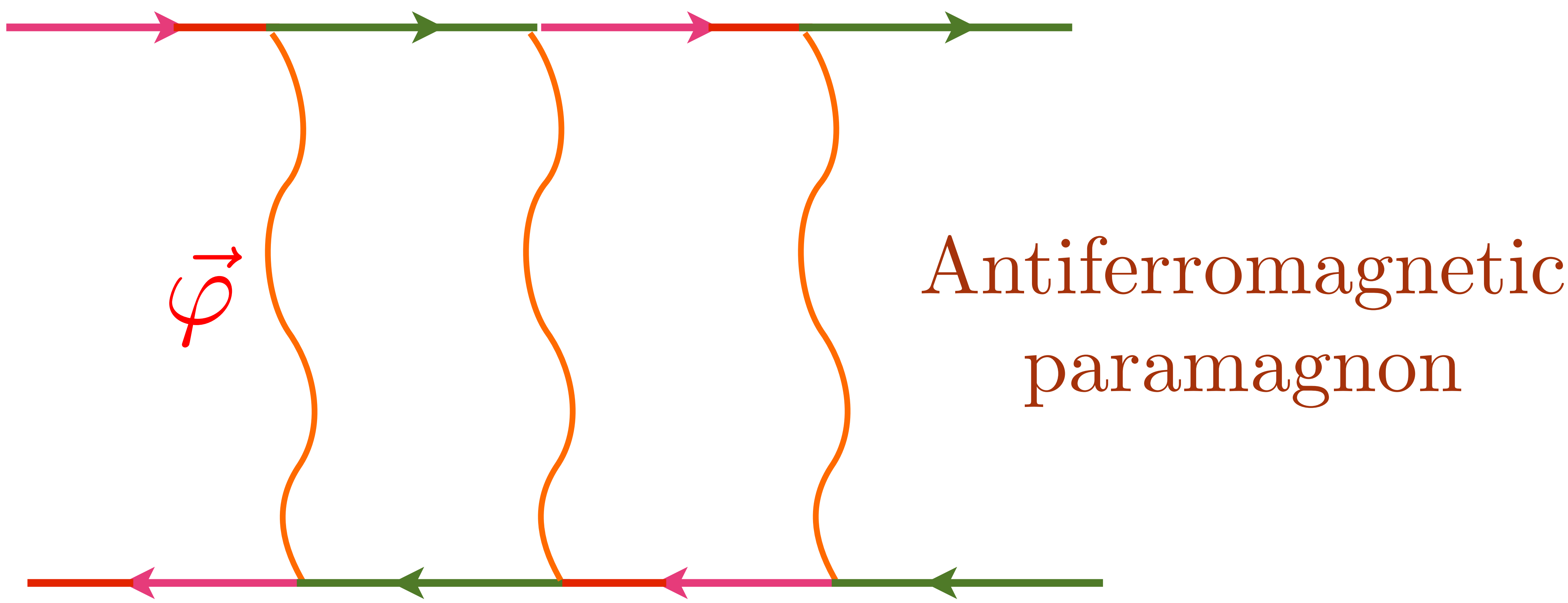
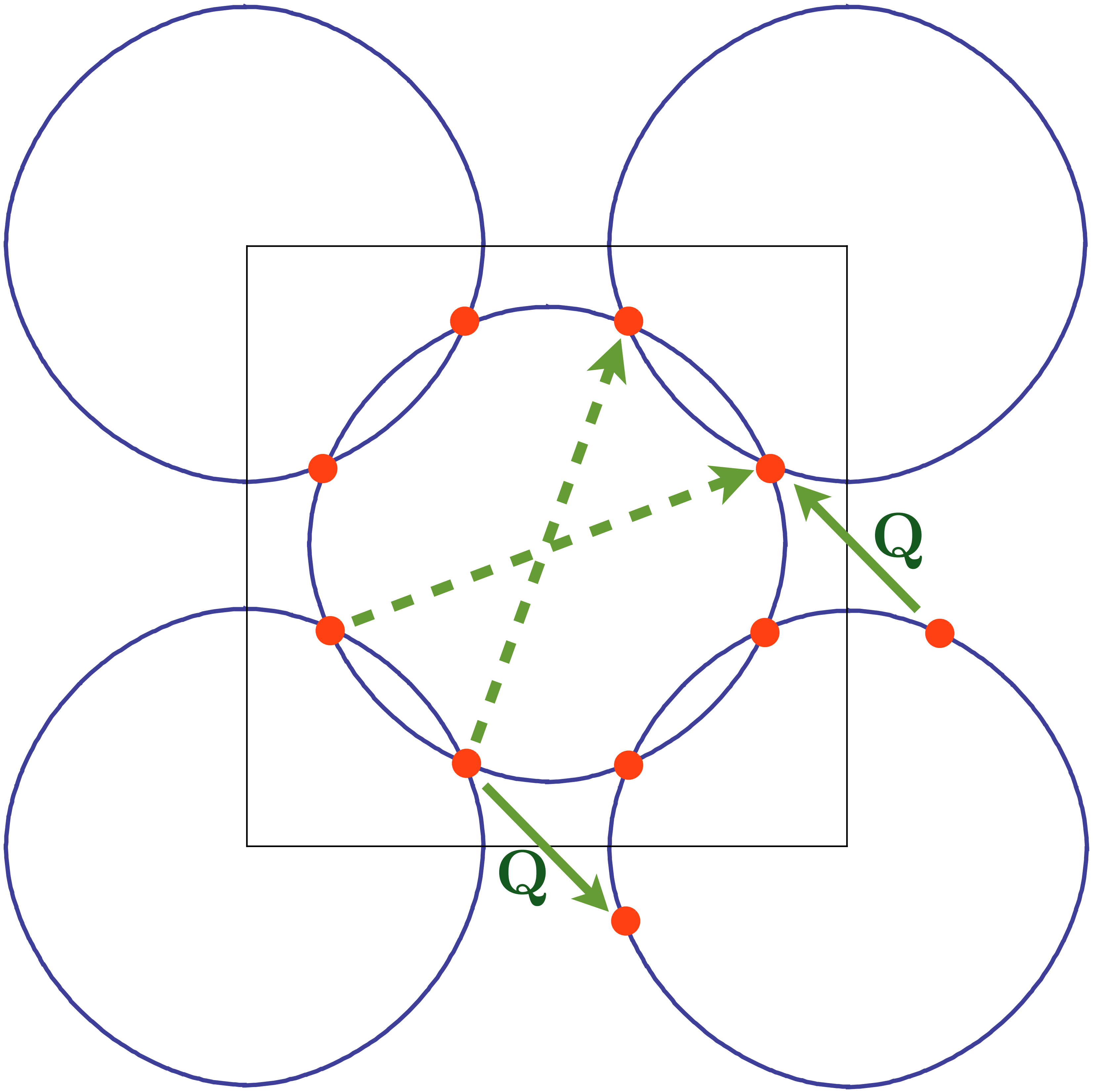


Leads to $\left\langle c^\dagger_{\mathbf{k}+\mathbf{Q}/2,\alpha} c_{\mathbf{k}-\mathbf{Q}/2,\alpha} \right\rangle =$

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

with $\mathcal{P}_d$ dominant.

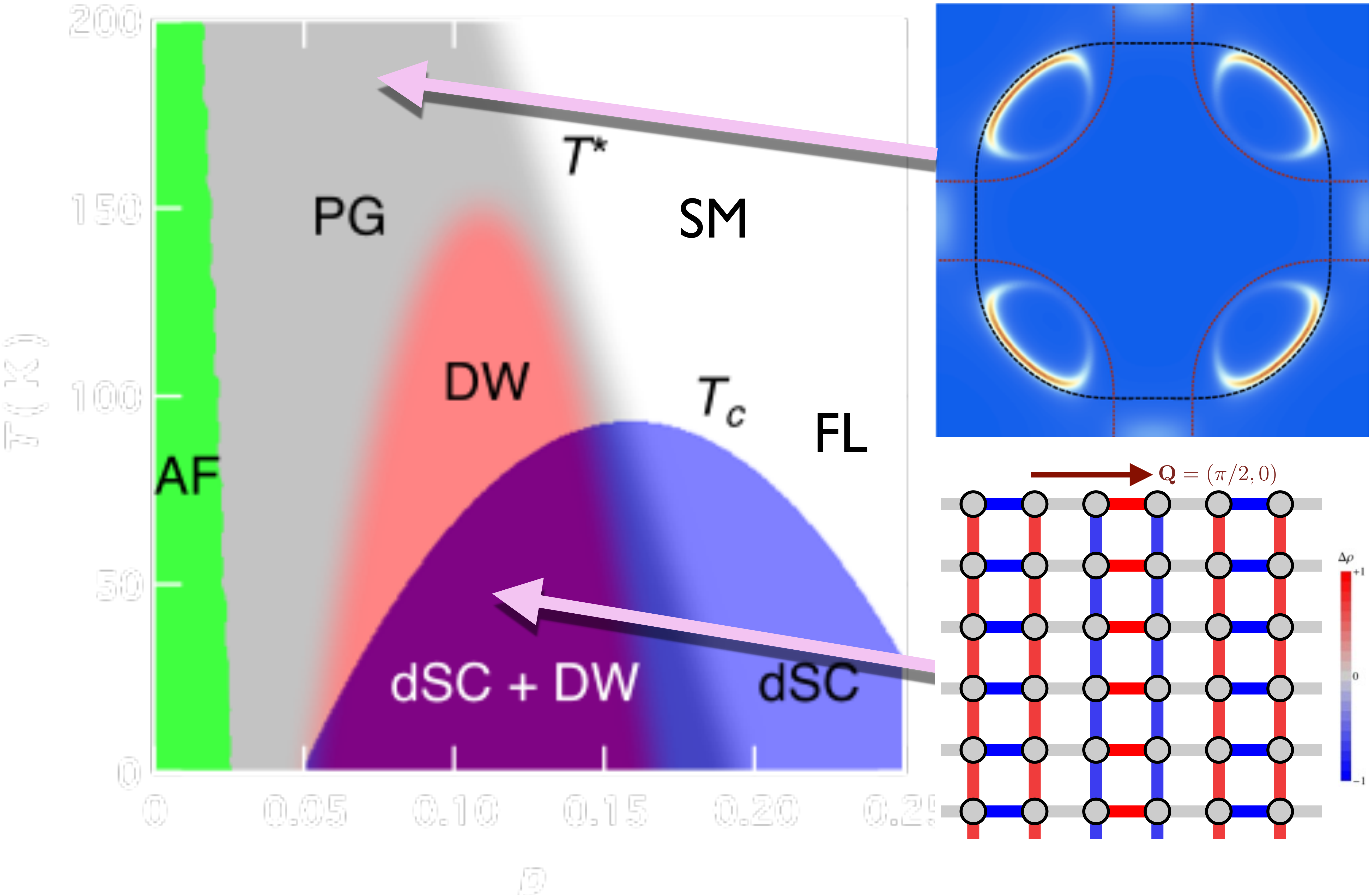
S. Sachdev and R. La Placa, Phys. Rev. Lett. **111**, 027202 (2013)



Density wave instability of large Fermi surface (FL) 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, PRB **85**, 075127 (2010); A. Thomson and S. Sachdev, PRB **91**, 115142 (2015)
W. A. Atkinson, A. P. Kampf, and S. Bulut, New Journal of Physics **17**, 013025 (2015)



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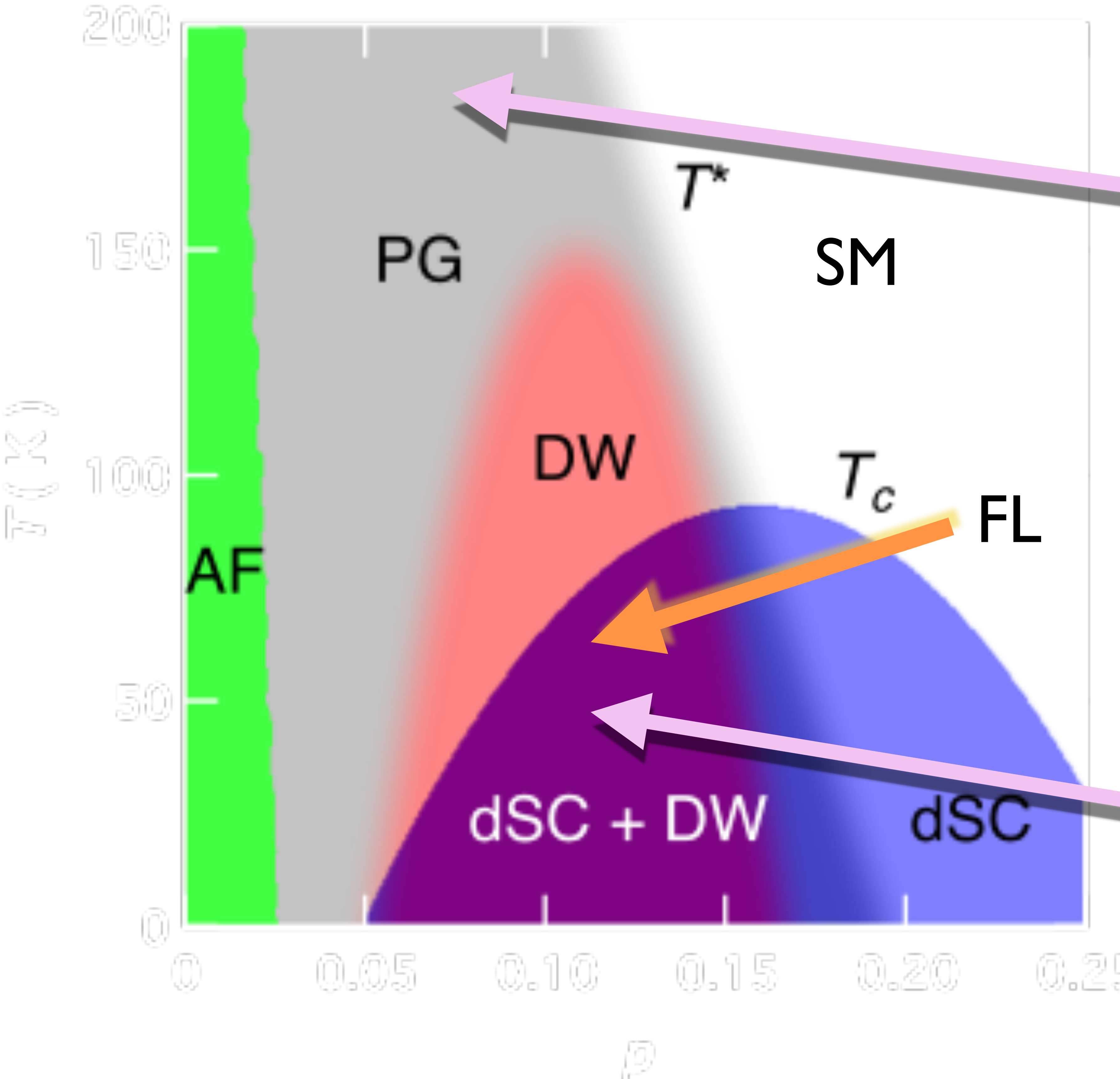
dSC + DW
dSC
Q = (π/2, 0)
Δρ
+1
0
−1



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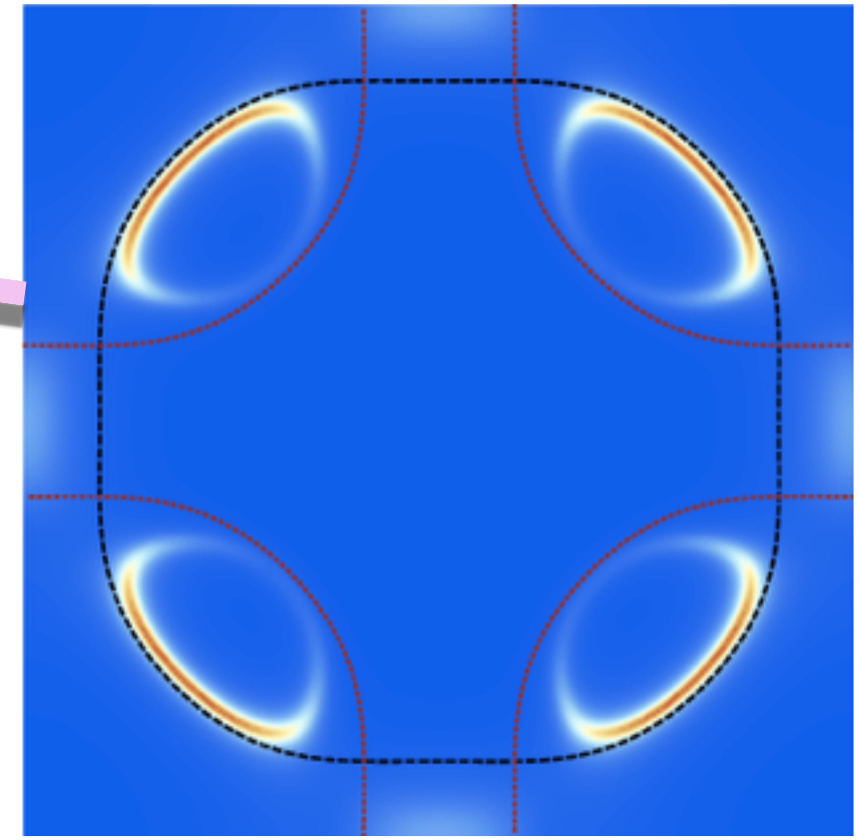
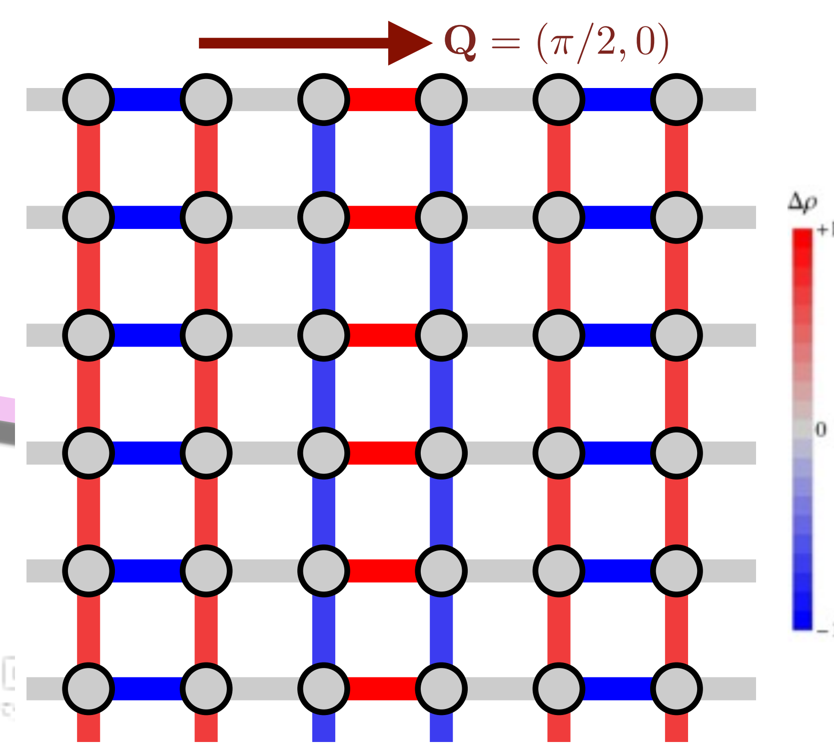
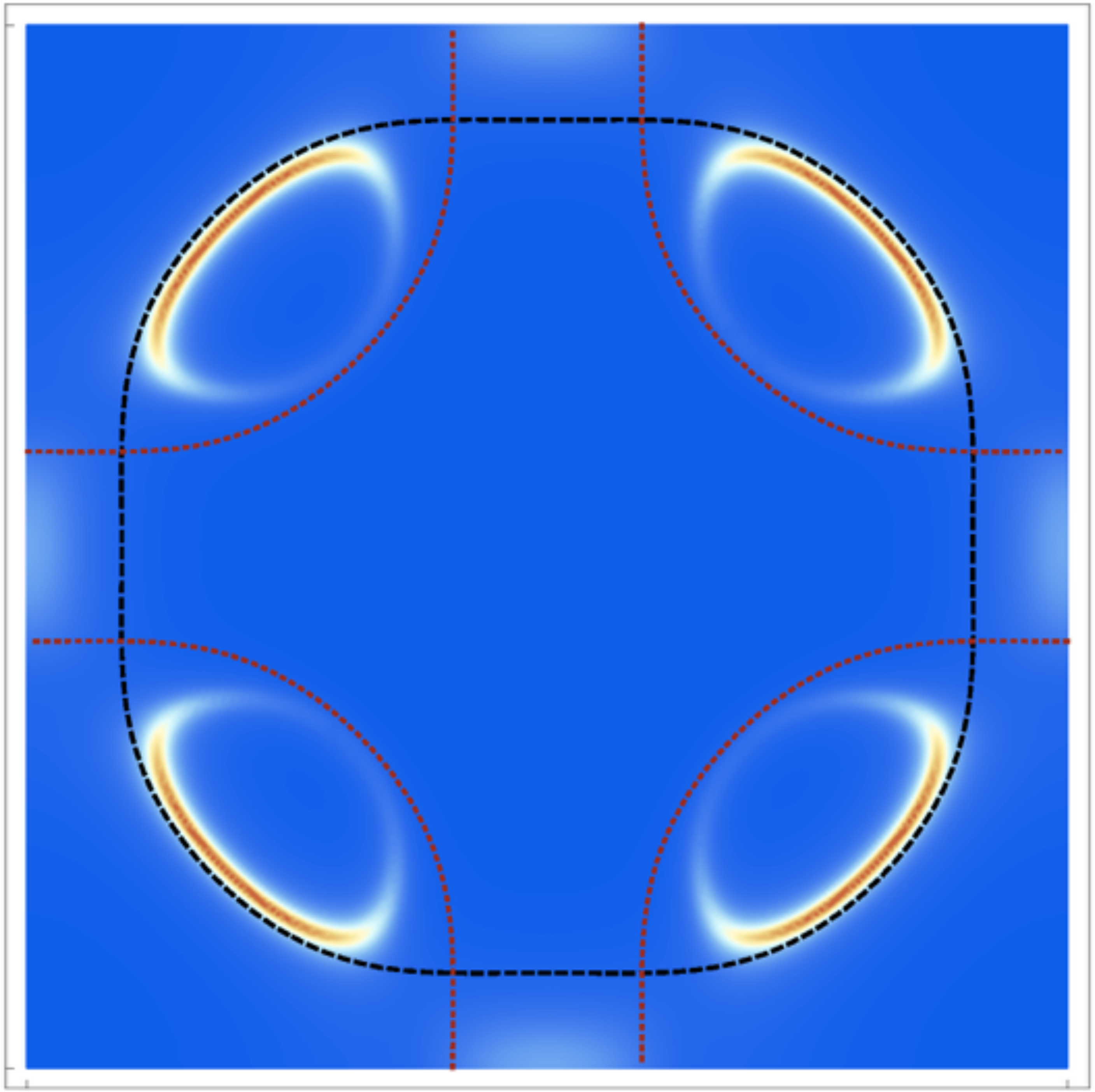
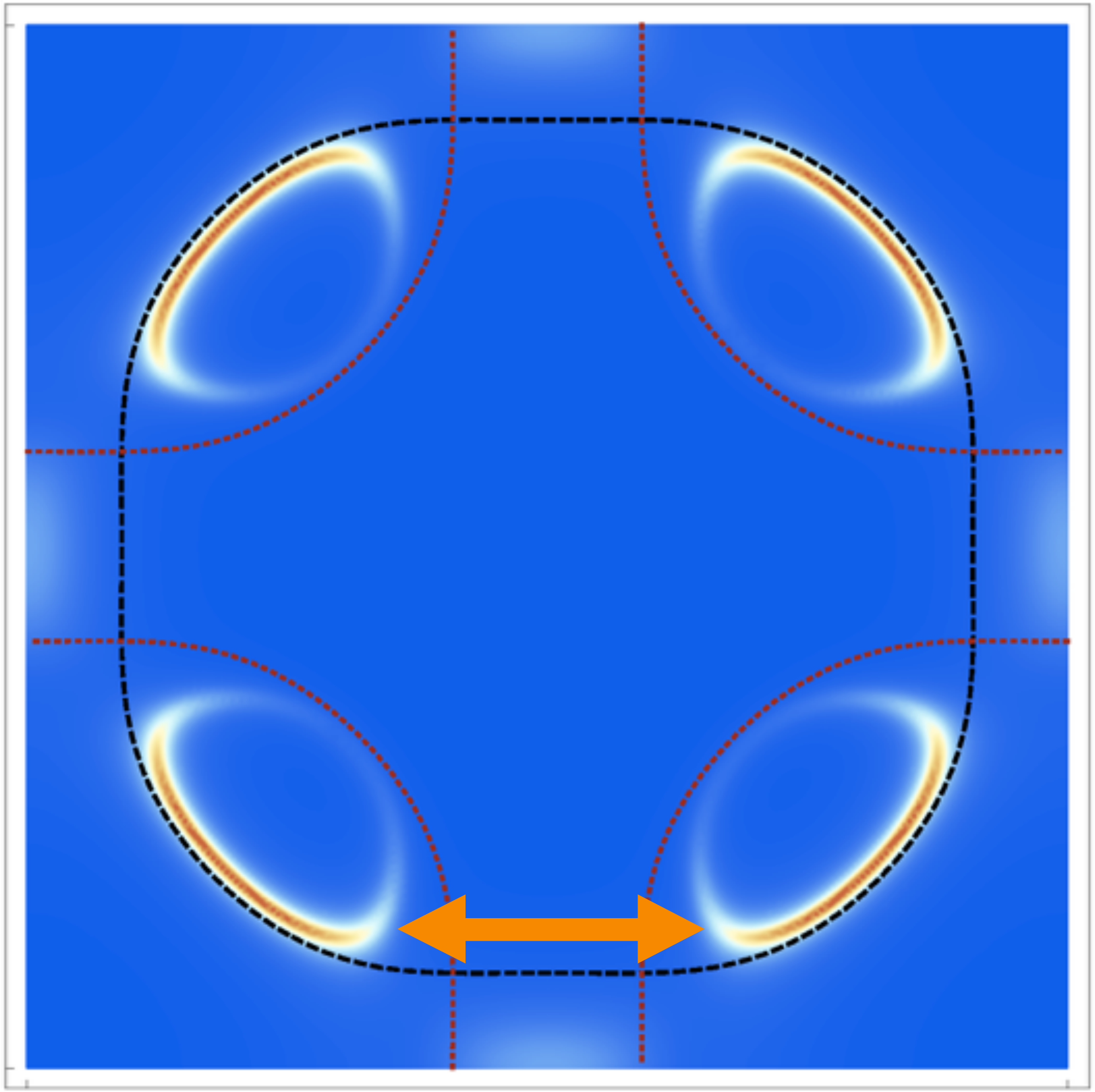



$\mathbf{Q} = (\pi/2, 0)$
$\Delta\rho$
+1
0
−1



Fermi surface of a fractionalized Fermi liquid (FL*)

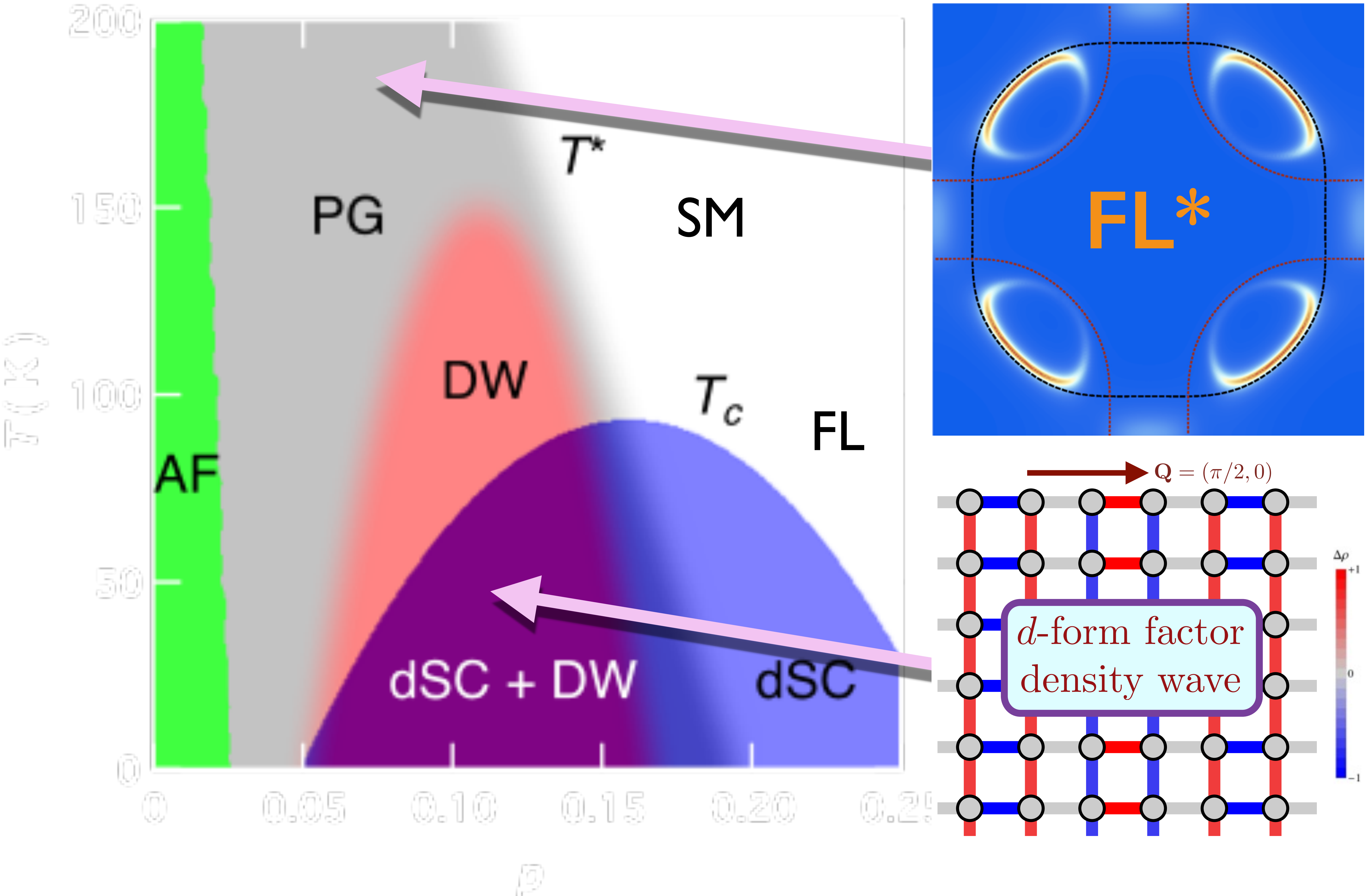
Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)



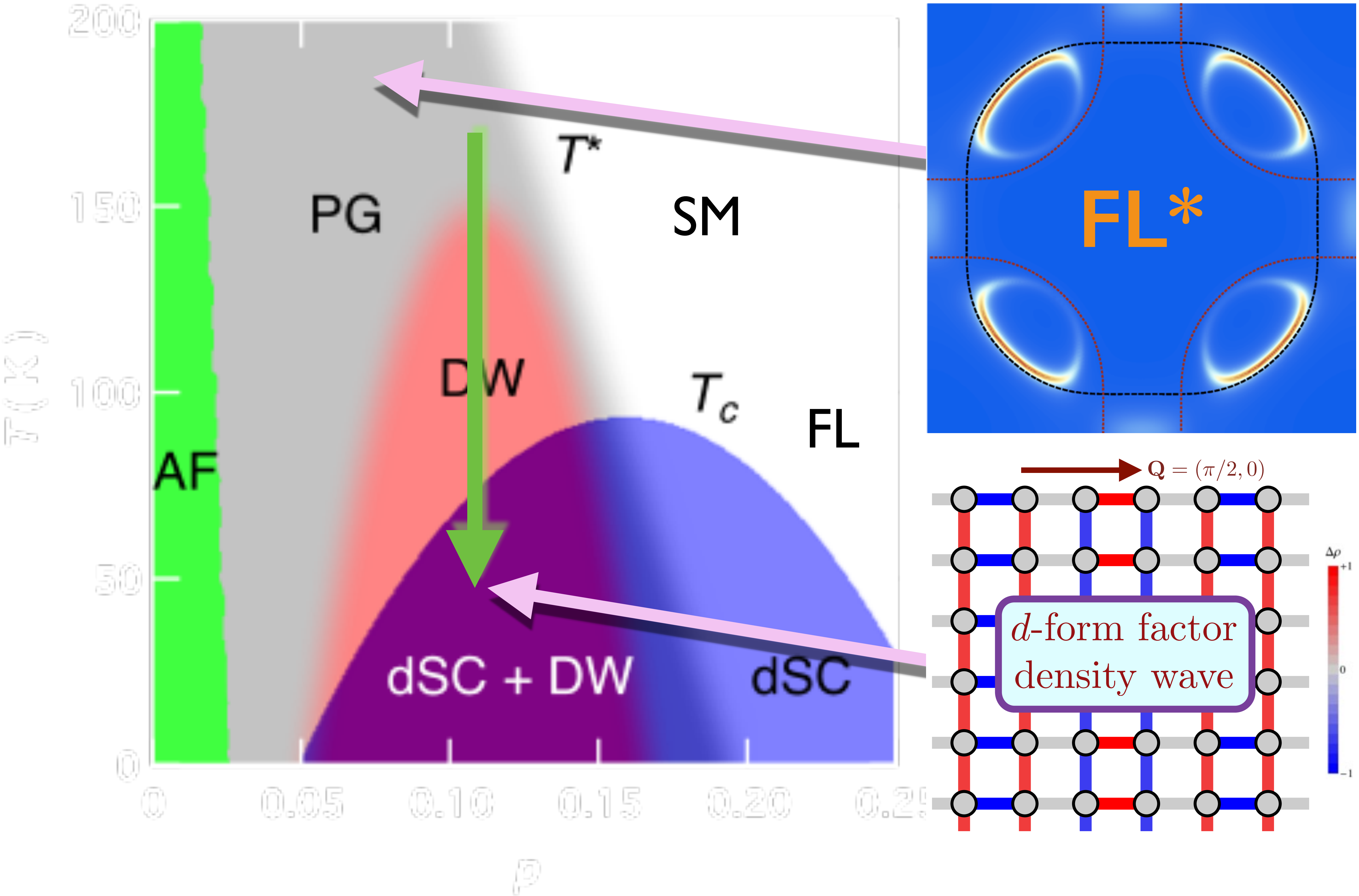
Density wave instability of FL* leads to the observed wavevector and form-factor

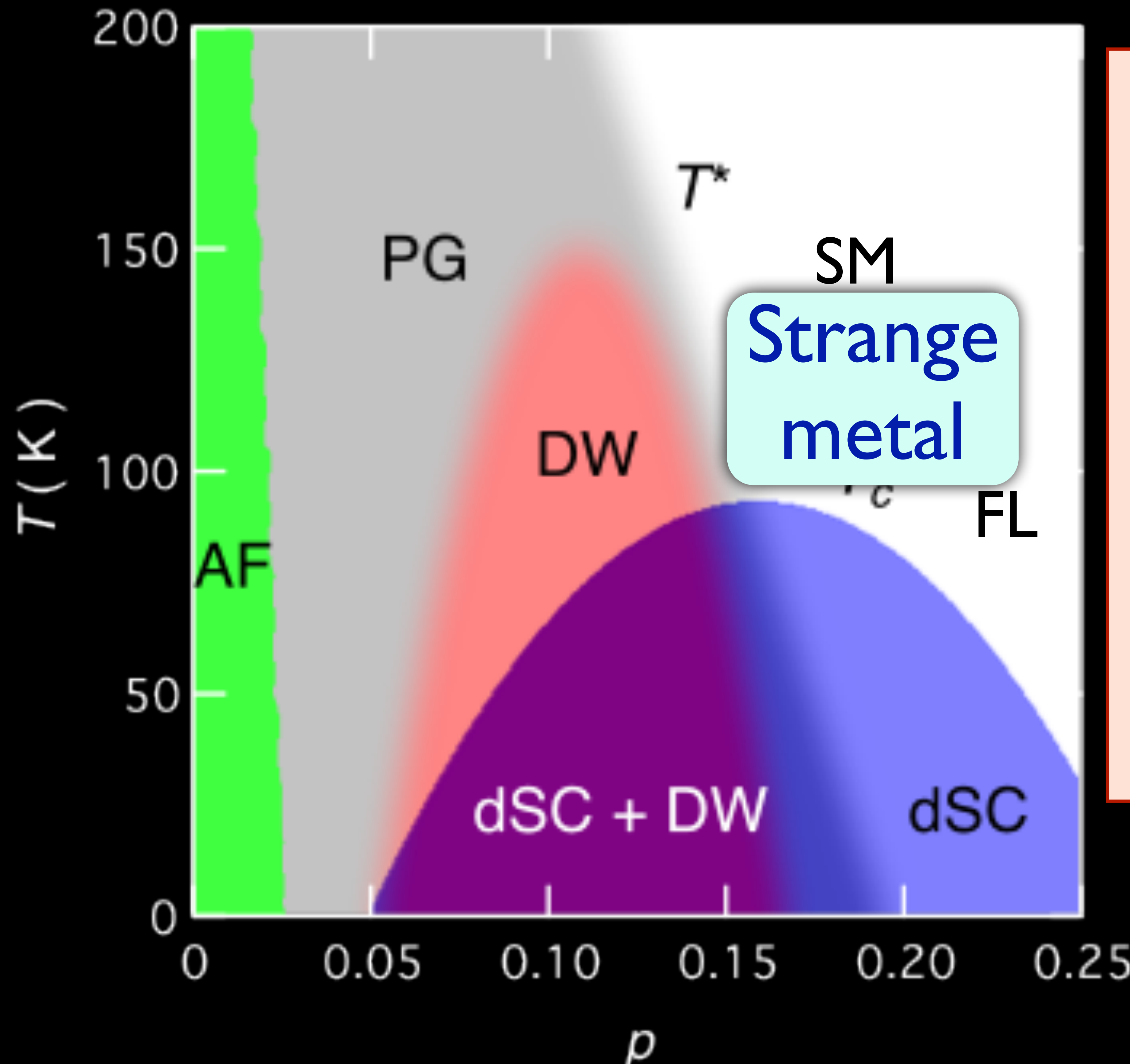
D. Chowdhury and S. Sachdev, Physical Review B **90**, 245136 (2014).

The high T FL* can help explain the "d-form factor density wave" observed at low T



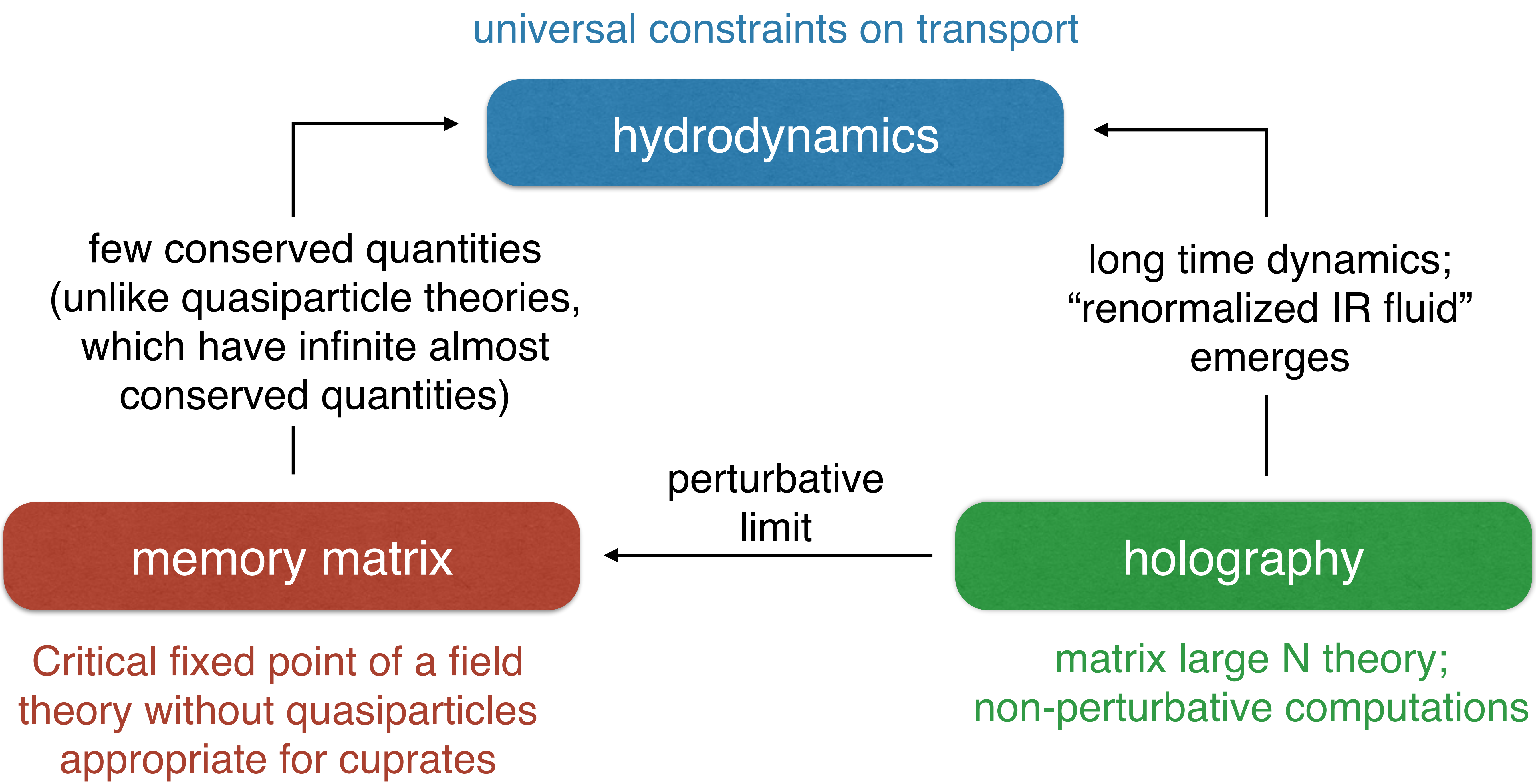
The high T FL* can help explain the "d-form factor density wave" observed at low T





Metal (gapless, compressible state) without quasi-particles

Theories of quantum matter without quasiparticles

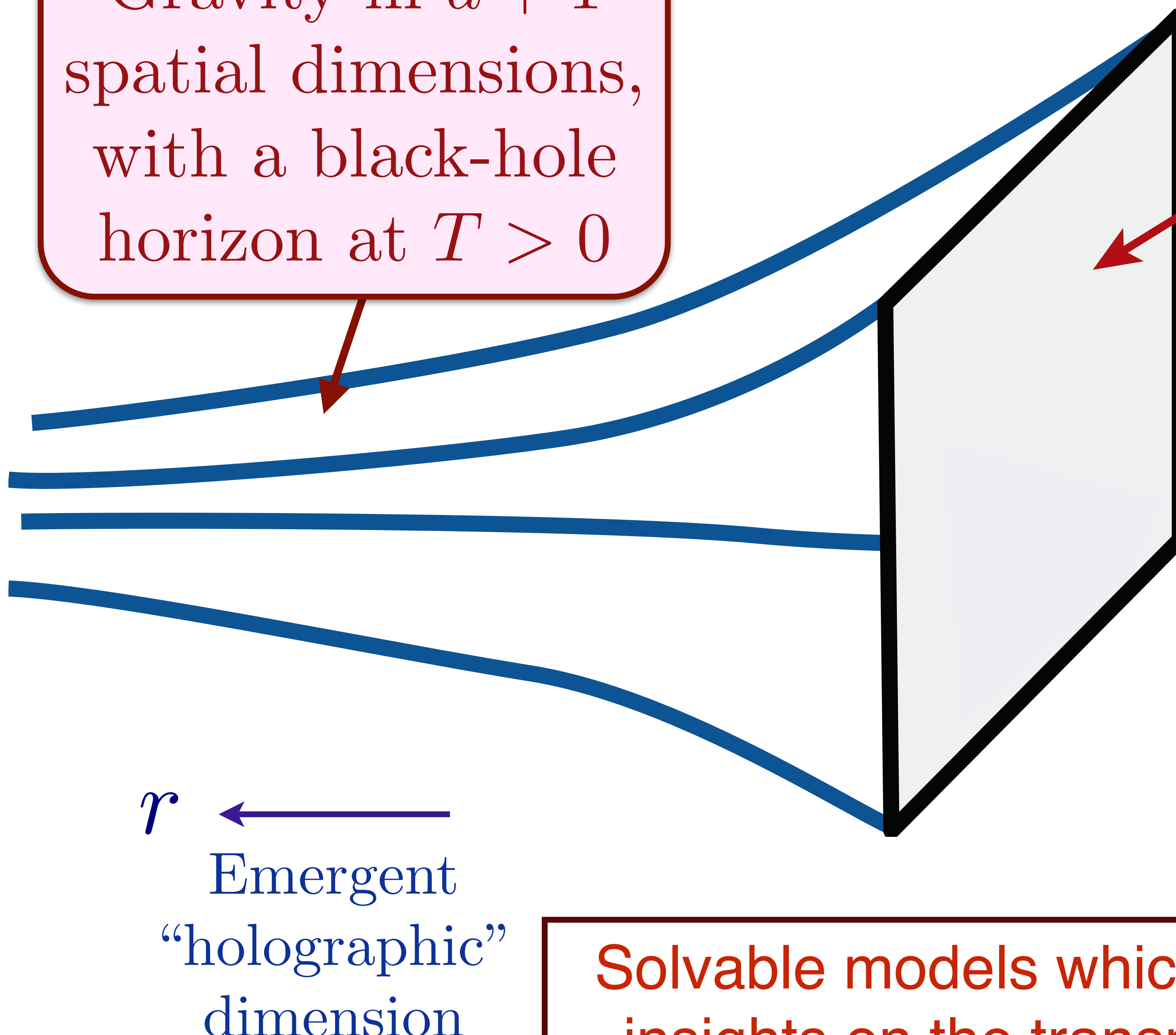


A. Lucas and S. Sachdev, arXiv:1502.04704

Holography of a conformal field theory: AdS/CFT

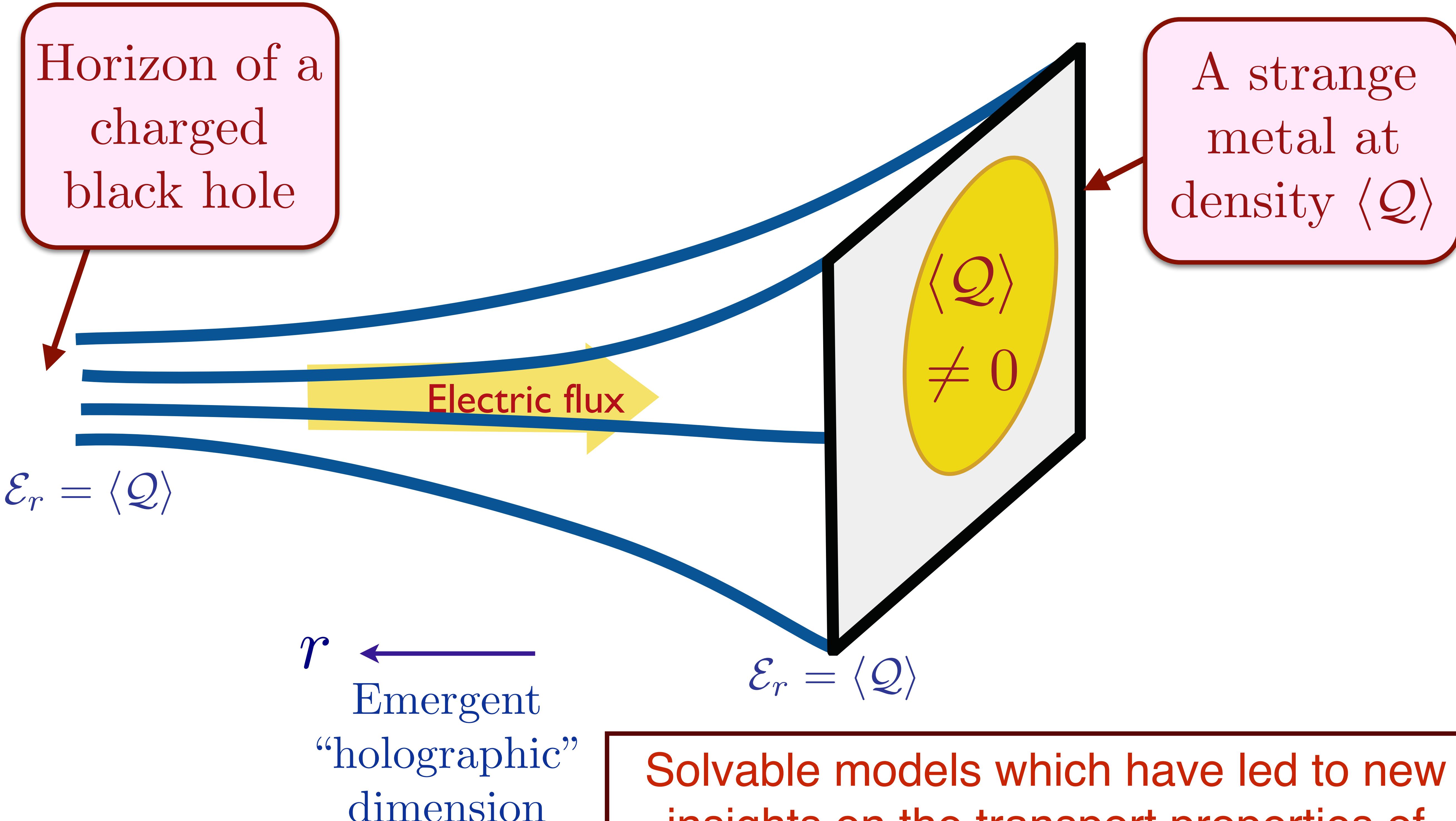
Gravity in $d+1$ spatial dimensions, with a black-hole horizon at $T > 0$

A CFT in d spatial dimensions: for $d \geq 2$, the simplest model without quasiparticles



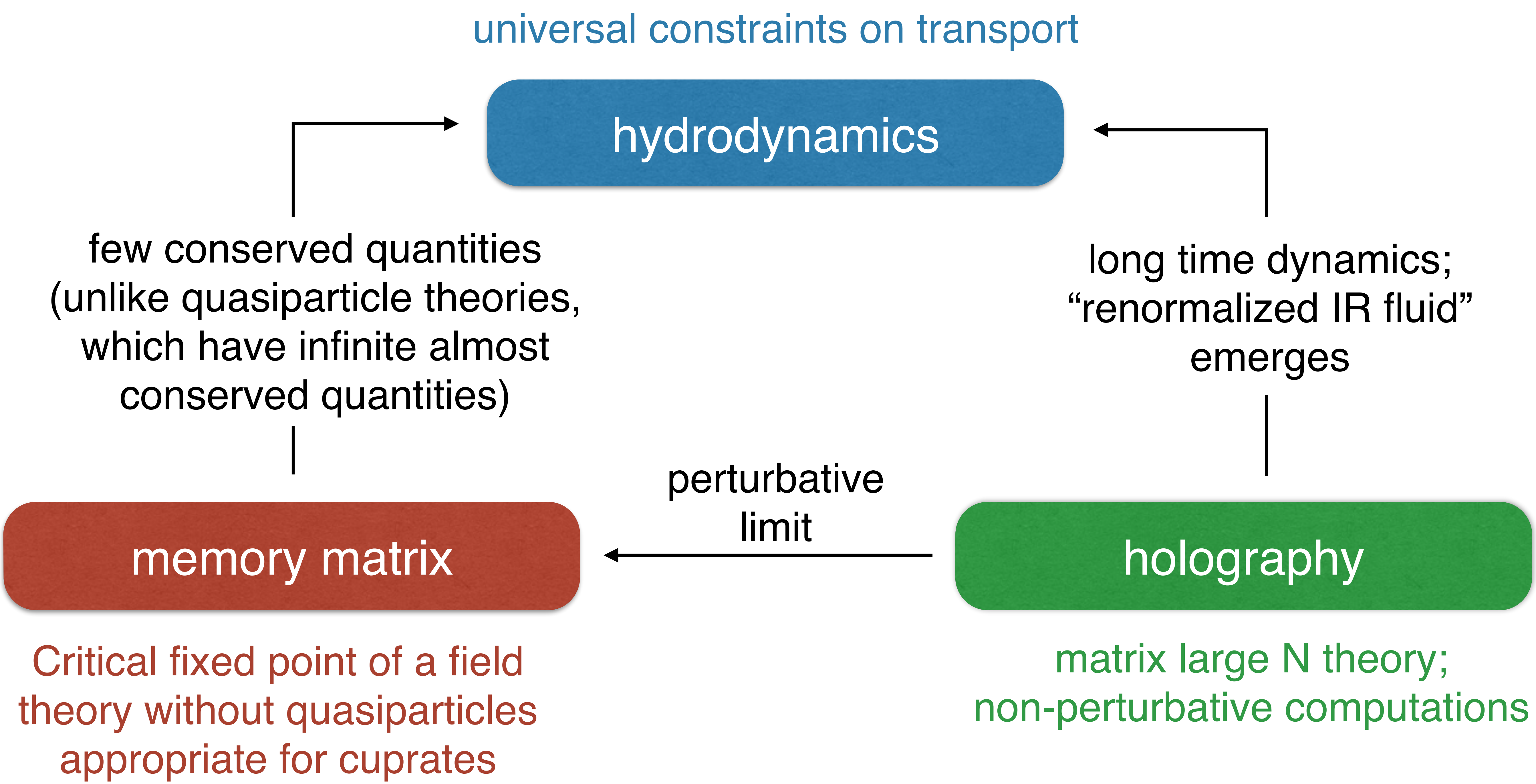
Solvable models which have led to new insights on the transport properties of *quantum matter without quasiparticles*

Holography of a strange metal: a charged black hole

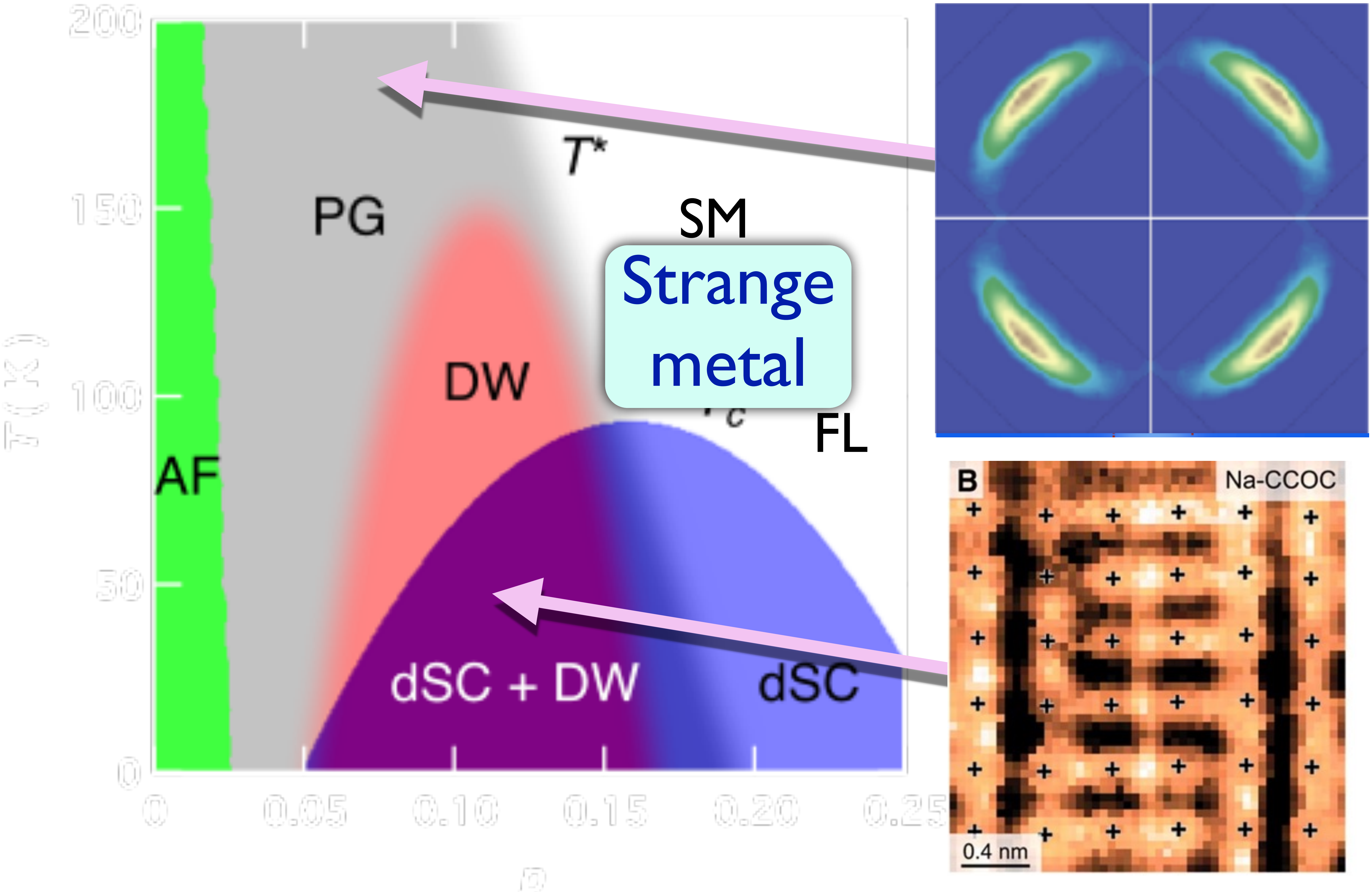


Solvable models which have led to new insights on the transport properties of <u>*quantum matter without quasiparticles*</u>

Theories of quantum matter without quasiparticles



A. Lucas and S. Sachdev, arXiv:1502.04704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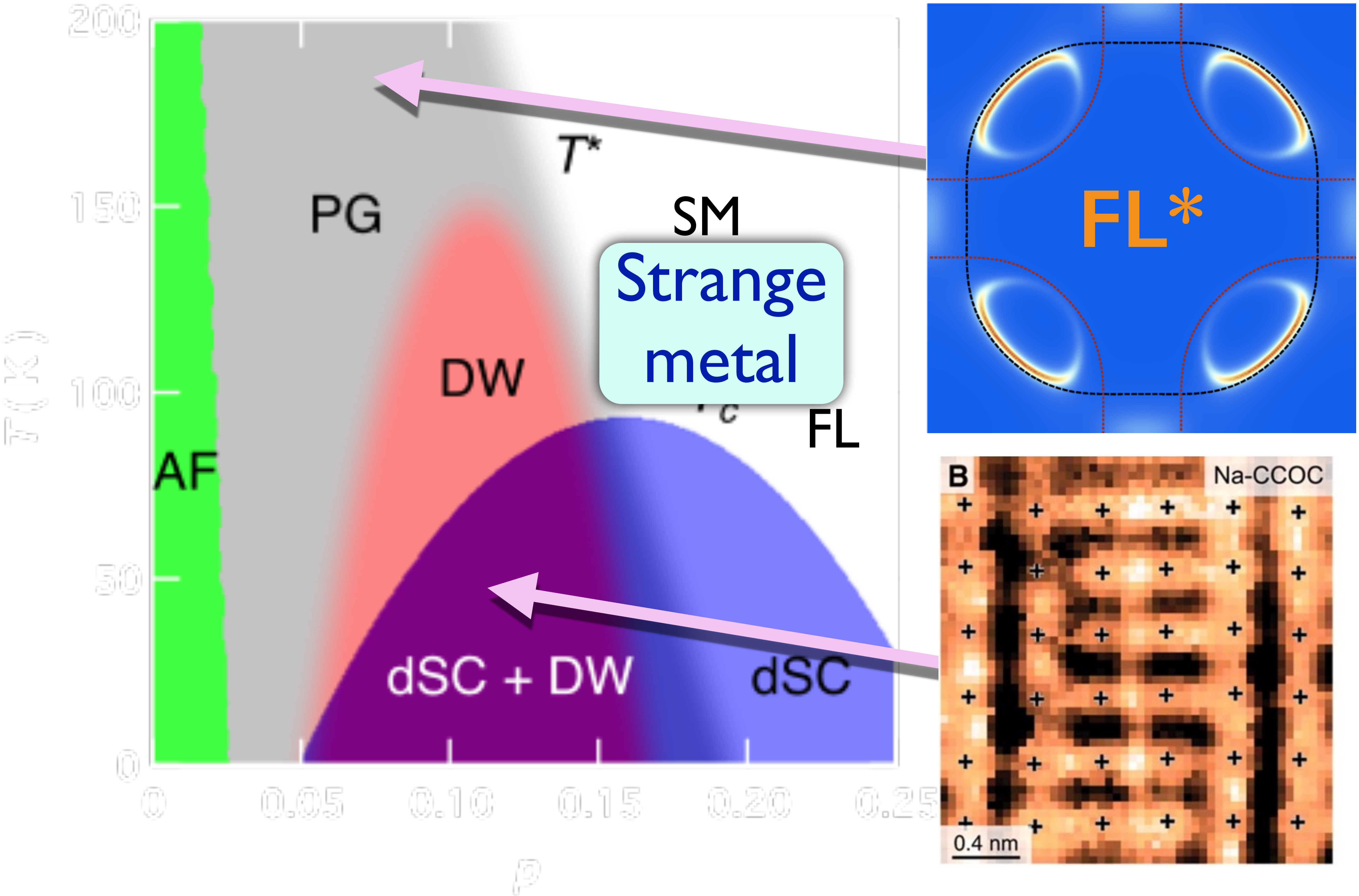
Na-CCOC
0.4 nm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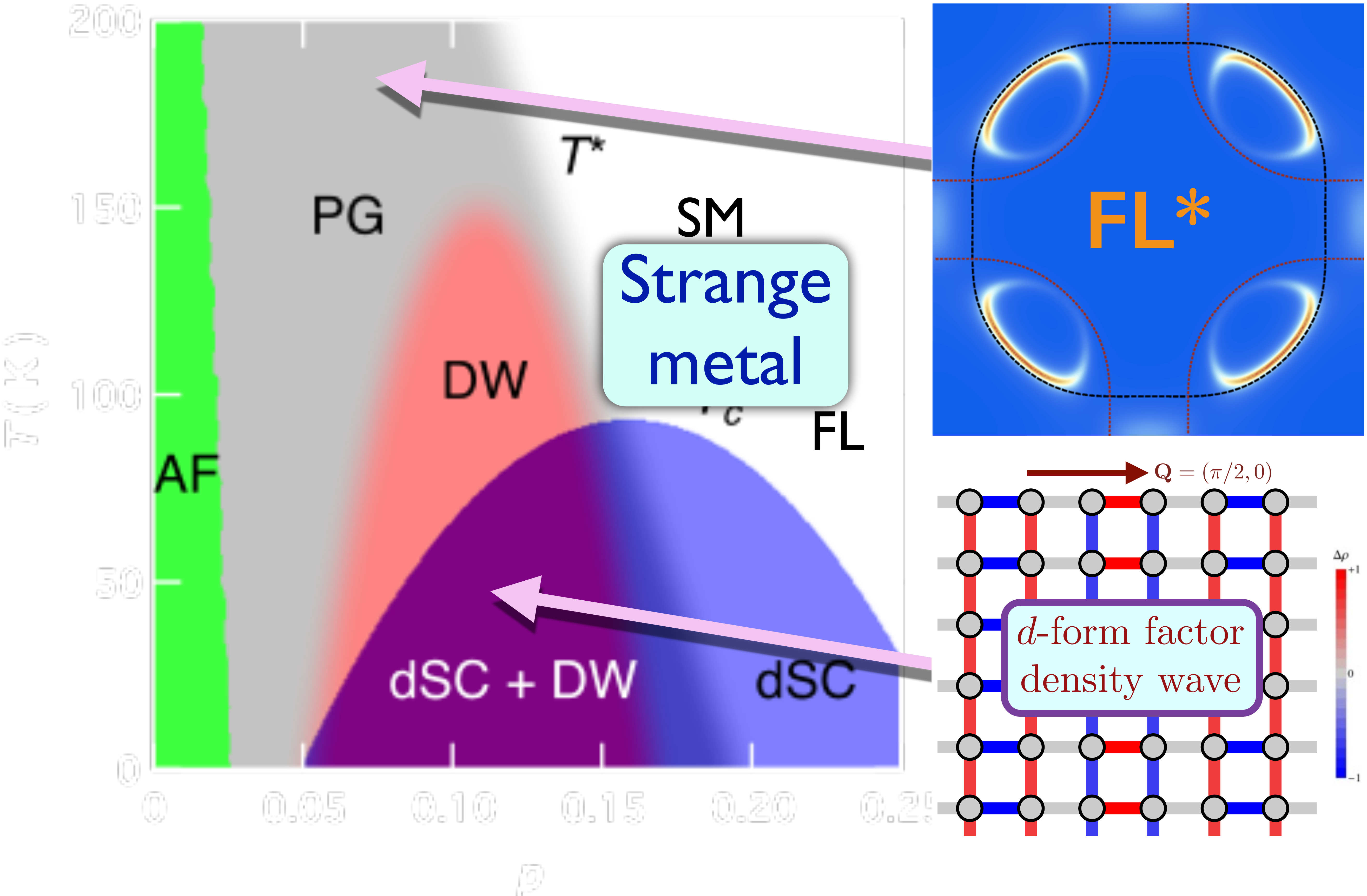

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Conclusions

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

2. Proposed the pseudogap metal is a fractionalized Fermi liquid (FL*): a Fermi liquid co-existing with topological order.

3. Many pseudogap properties can be understood in a simple model in which the "electron becomes a dimer".

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