The two unusual metals in the cuprates

EPIQS Investigator Symposium
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Subir Sachdev

Talk online: sachdev.physics.harvard.edu

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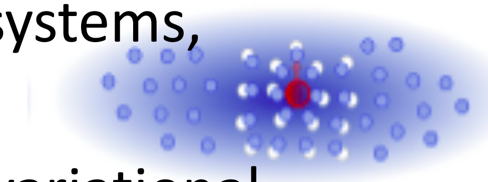
EPIQS Postdoctoral Fellows

Fabian Grusdt

Richard Davison

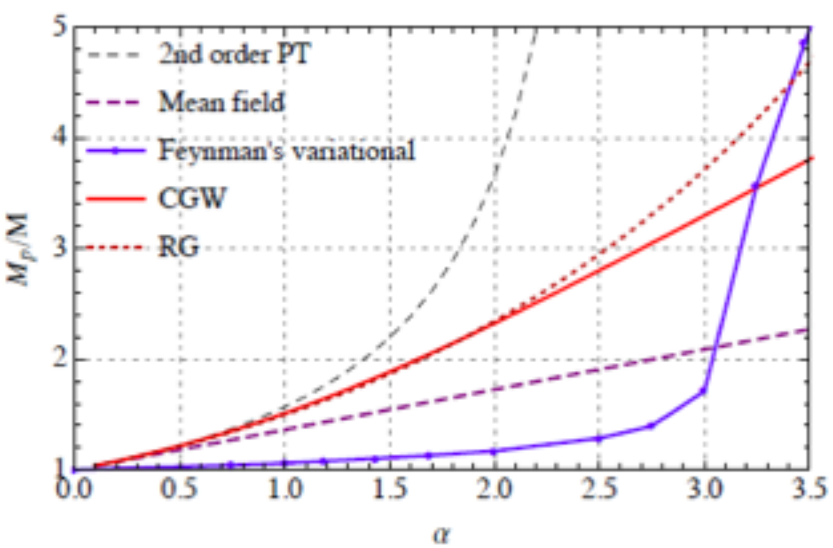
Polarons in BEC

Related to Frolich polarons in solid state systems, electrons in magnetic systems

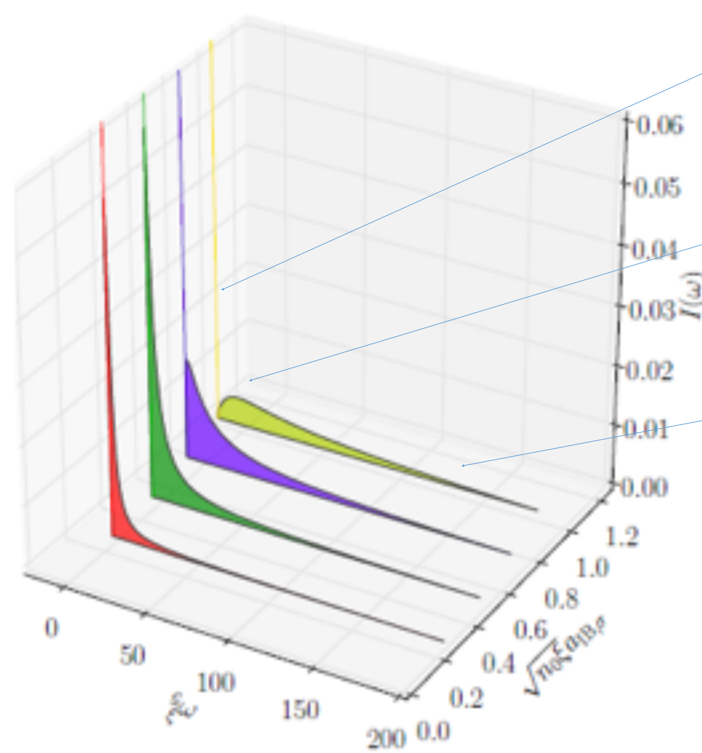


Used non-perturbative approaches (RG, variational wavefunctions) to study equilibrium and non-equilibrium properties of Bose polarons

Effective mass



RF spectroscopy



Quasiparticle peak

Universal (dimension dependent) low frequency spectrum: signature of many-body orthogonality catastrophe

Universal (dimension dependent) high frequency tail: related to two particle physics

Fabian Grusdt, et al.,
Phys. Rev. A 89:053617 (2014)
Phys. Rev. A 90:063610 (2014)
Scientific Reports 5:12124 (2015)

Richard Davison

Oxford, Leiden, Harvard

What are the effective theories of charge and heat transport in systems without quasiparticles?

- A clean system has multiple different conduction mechanisms.

RD, Goutéraux, Hartnoll 1507.07137

- Each has a characteristic timescale and imprints on the frequency-dependent conductivities in a specific way.

RD, Goutéraux 1505.05092

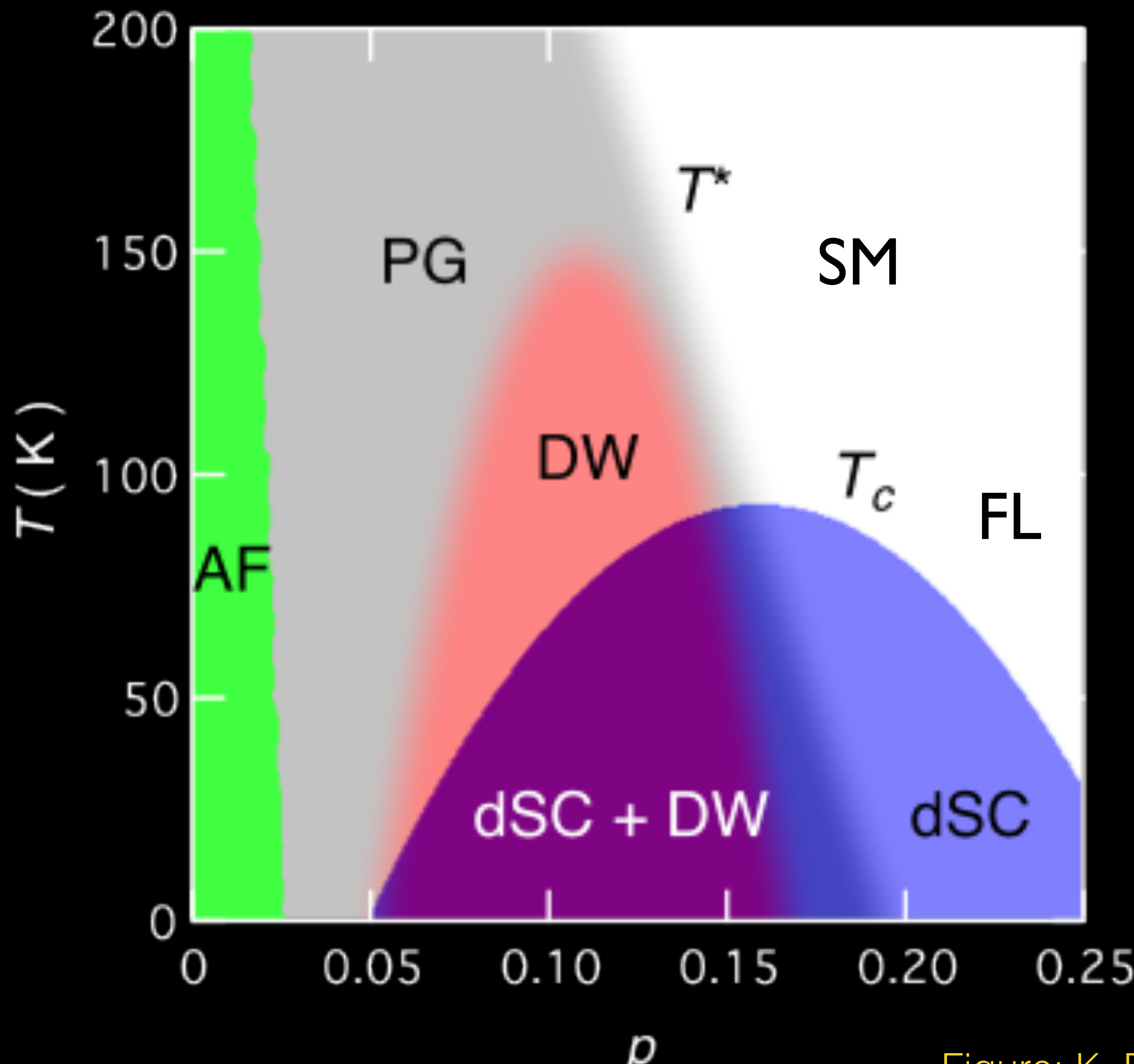
- Can calculate the T-dependence of the conductivities under various assumptions.

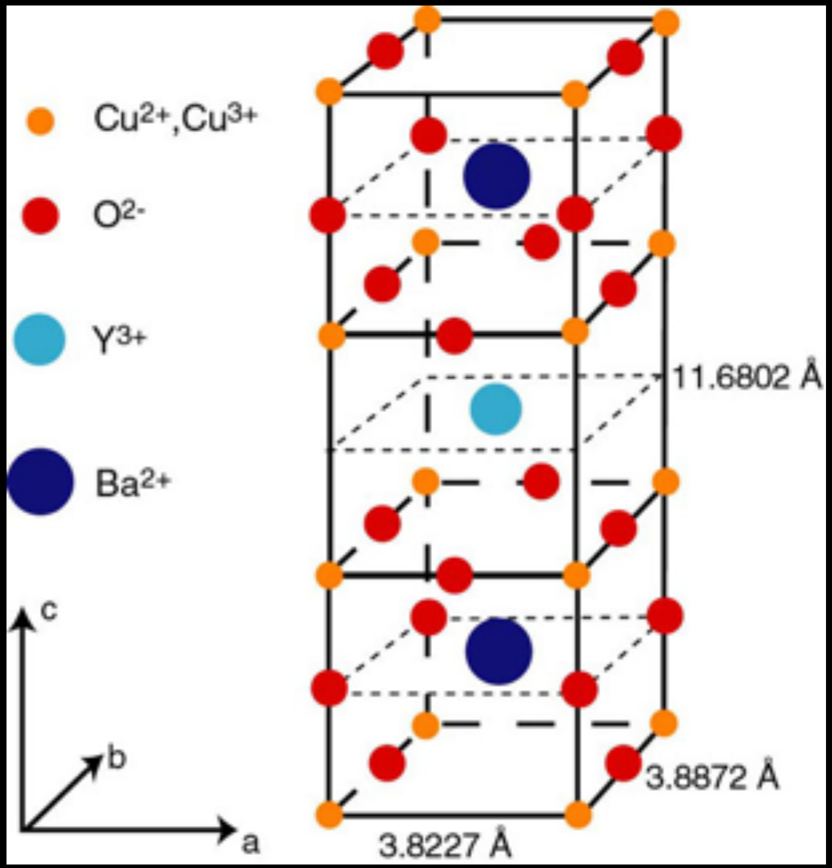
RD, Schalm, Zaanen 1311.2451

RD, Goutéraux, Hartnoll 1507.07137

- As the system becomes dirtier, there is a qualitative change in the conduction mechanisms and what timescales control them.

RD, Goutéraux 1411.1062

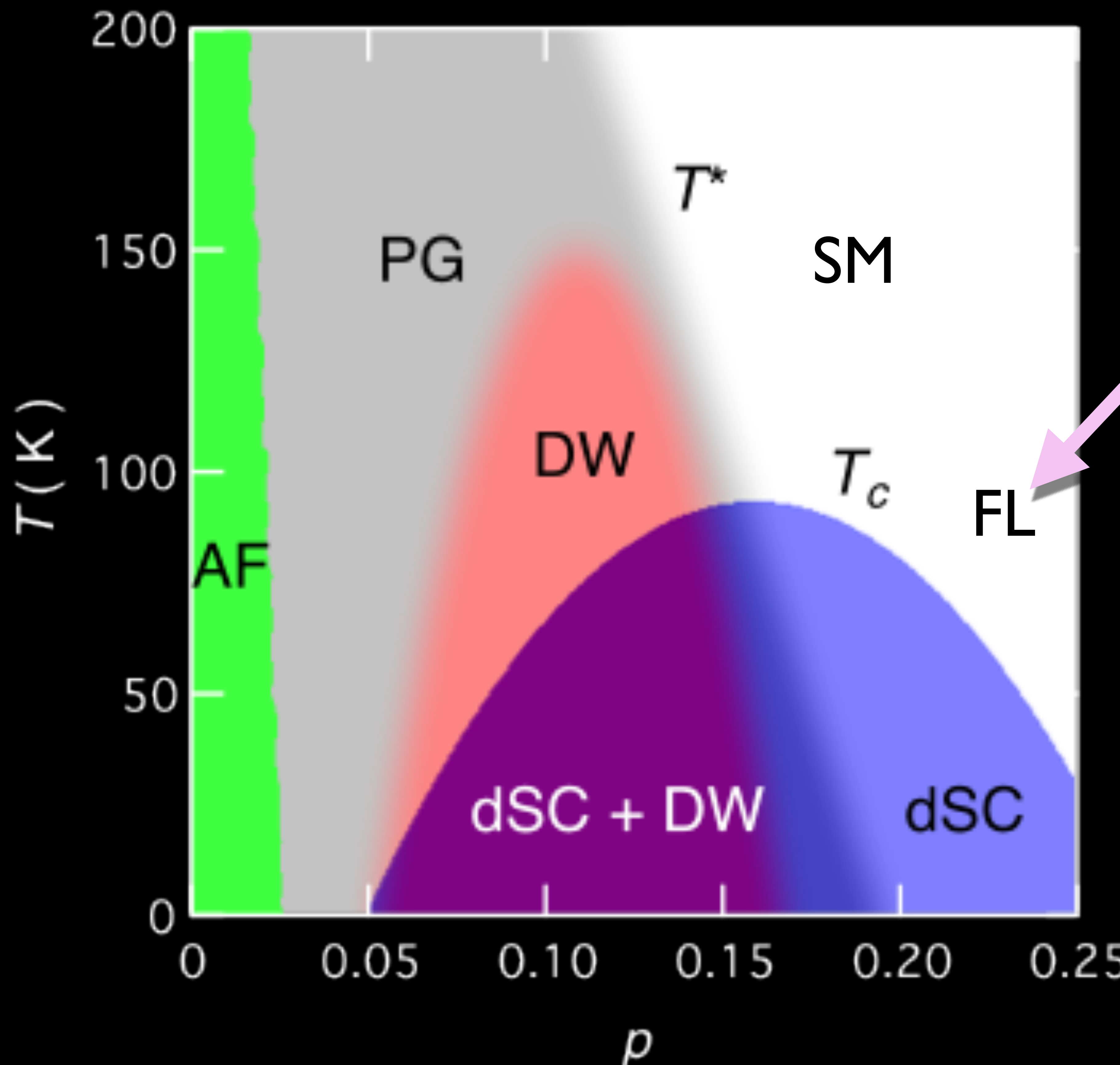


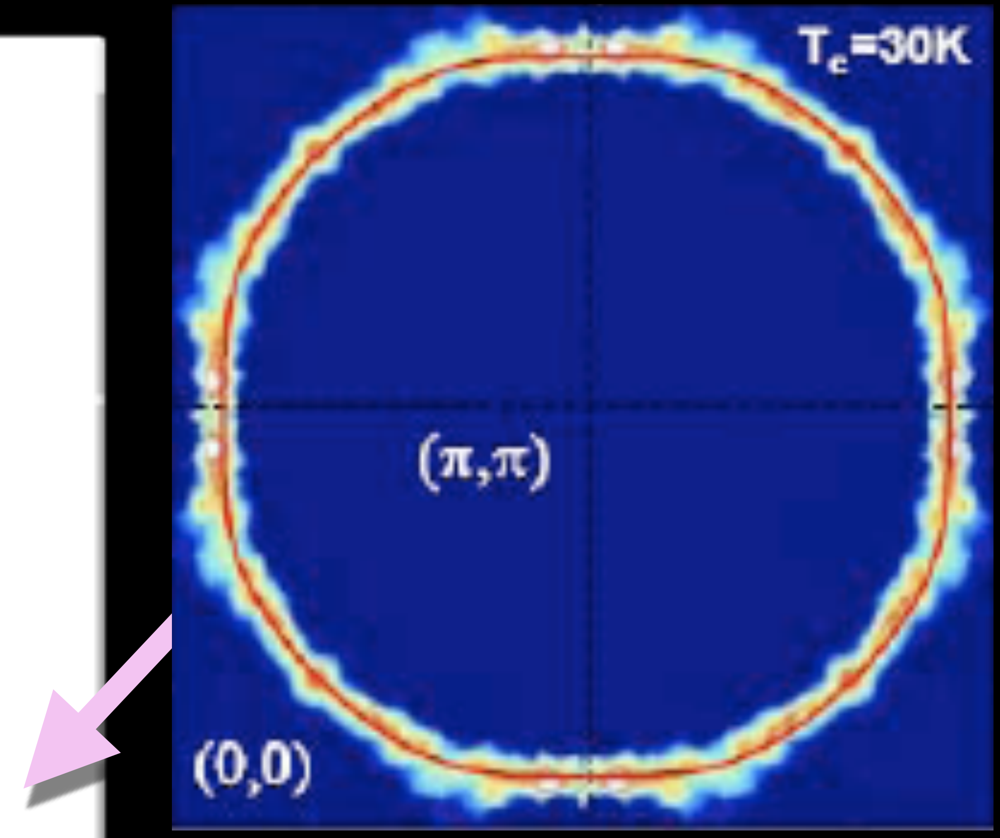


$YBa_2Cu_3O_{6+x}$

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)

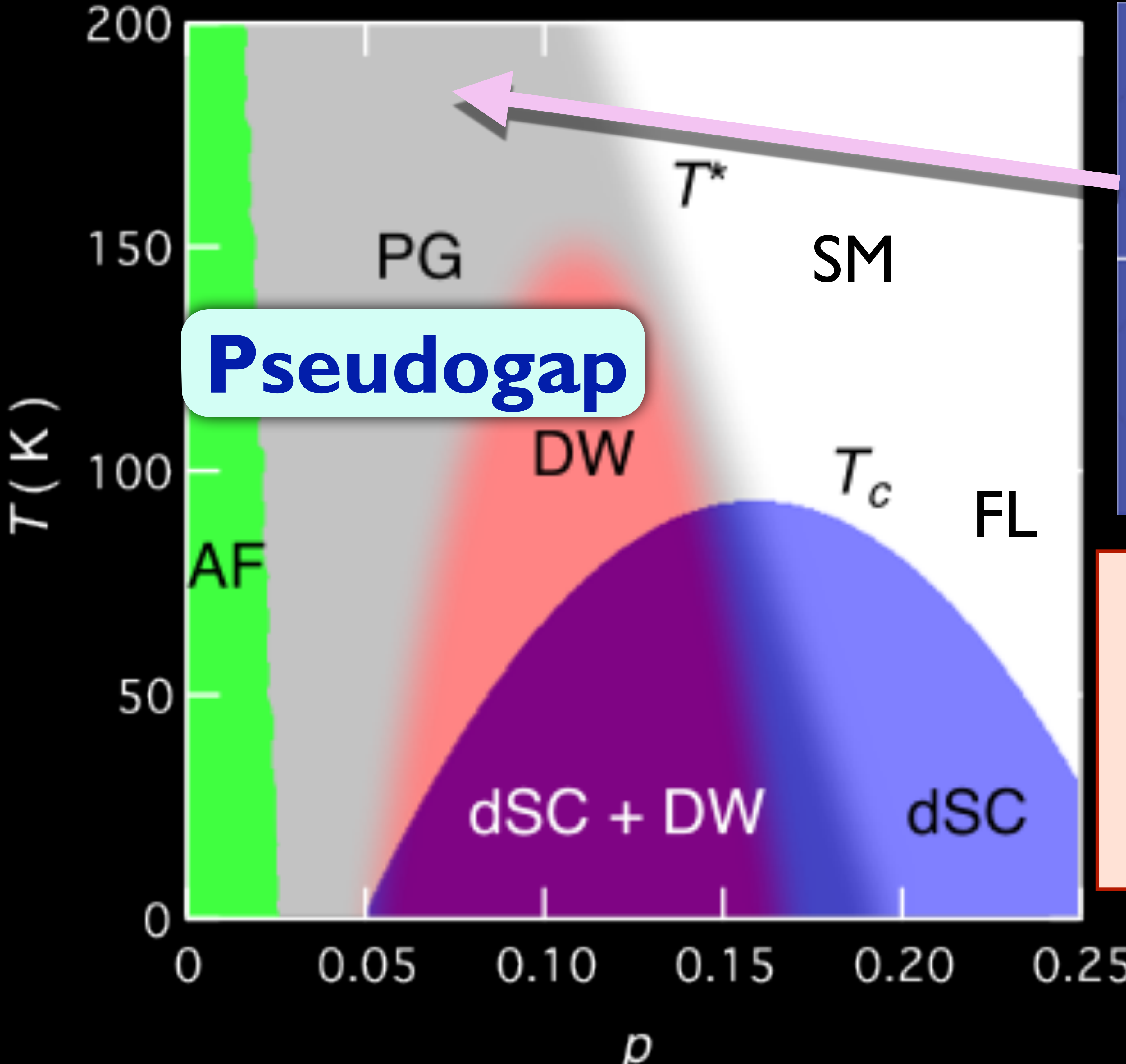


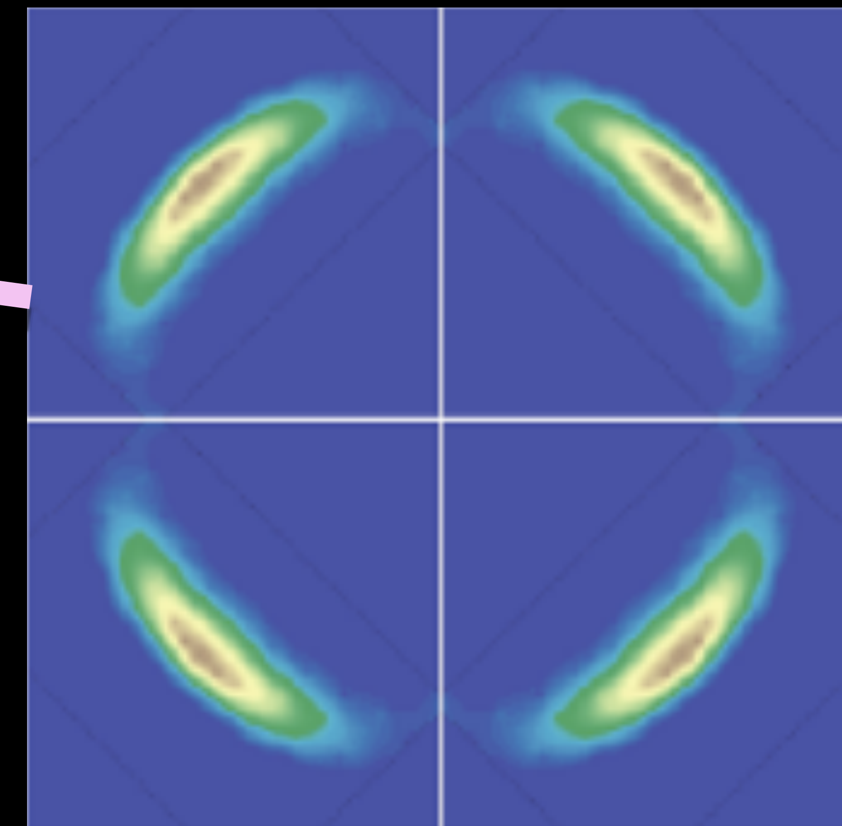


Conventional metal

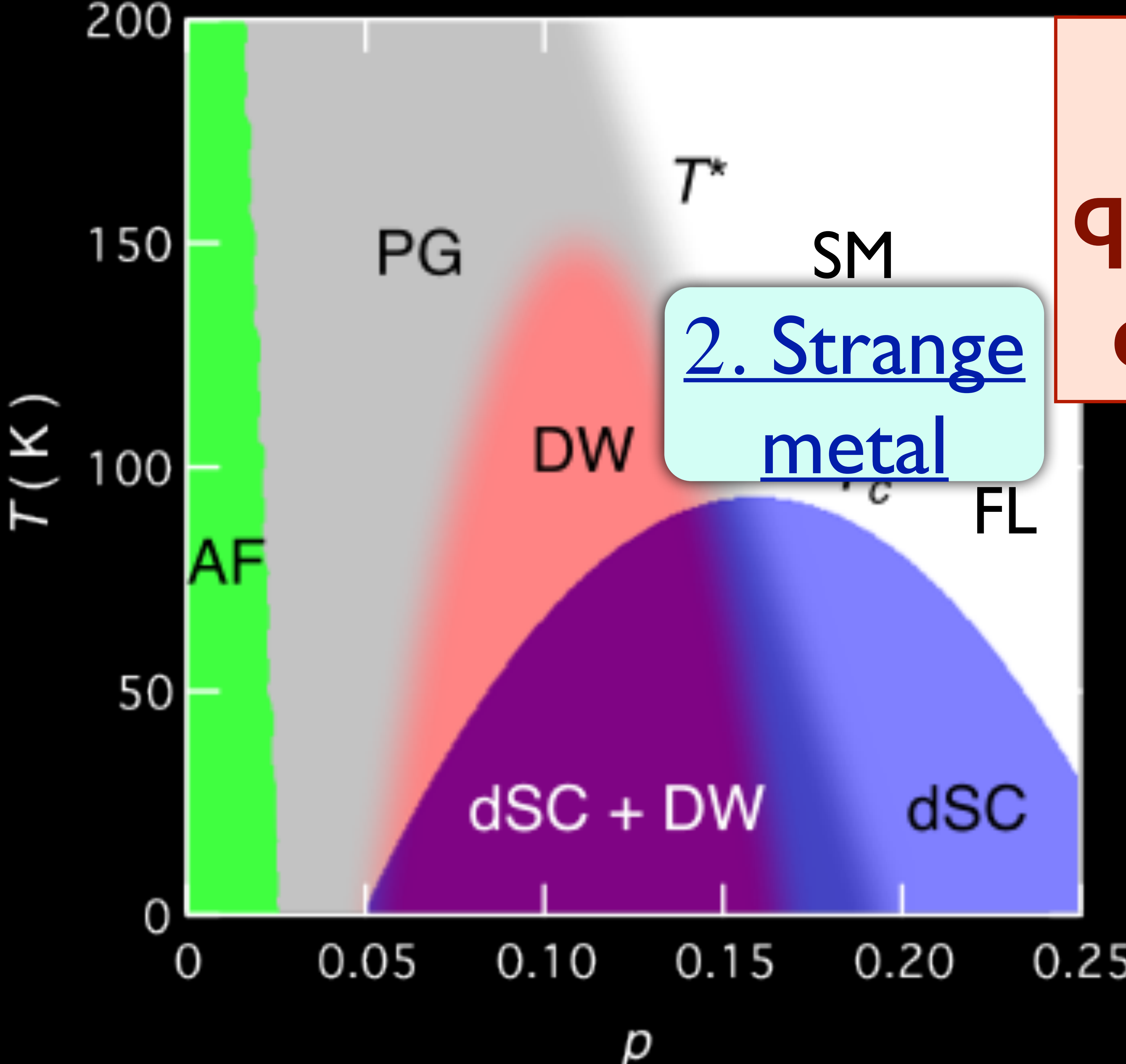
Area enclosed by Fermi surface =1+p

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)





1. Pseudogap metal at low p



2. Strange metal

No quasiparticle excitations

Outline

1. Quasiparticle transport in ordinary metals

   Bloch vs. Peierls

2. Transport without quasiparticles in strange metals

   Application to (less) strange metal in graphene

3. The pseudogap metal

   Fermi liquid co-existing with topological order

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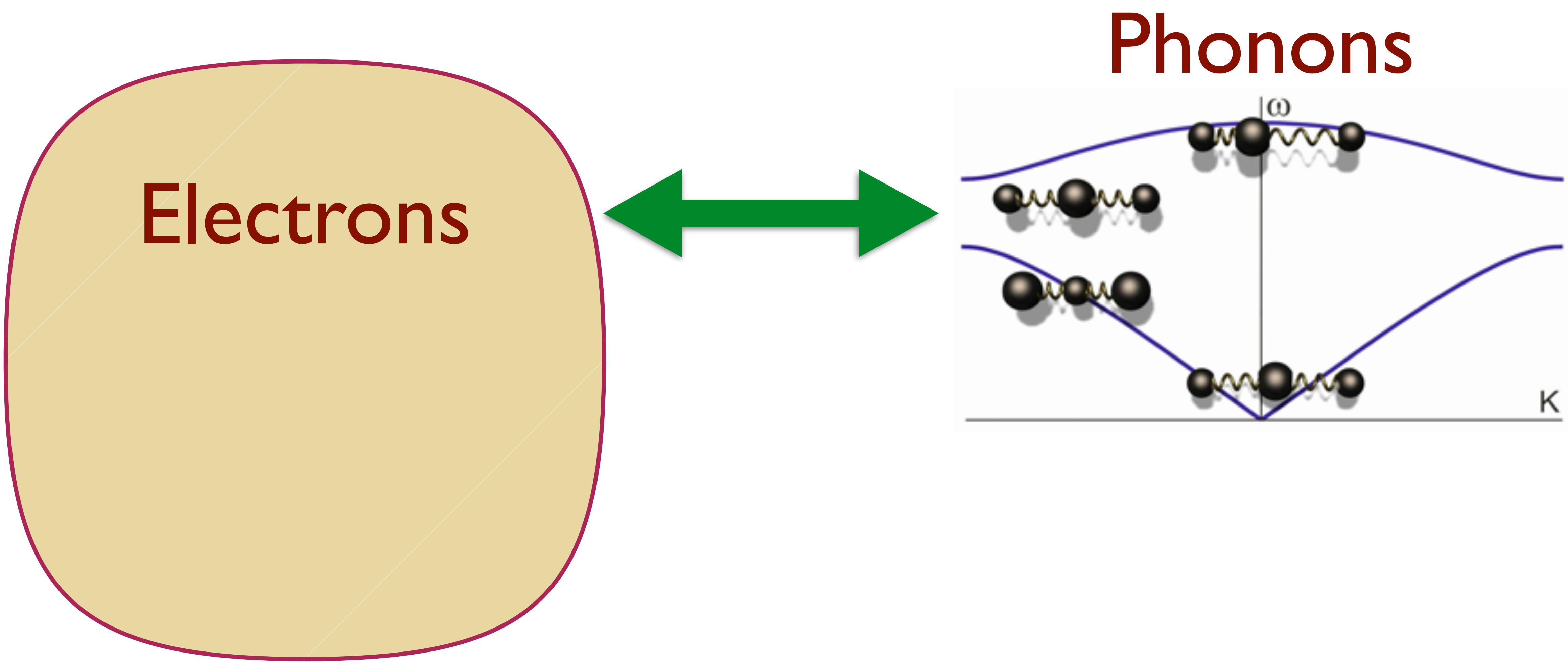
Quasiparticle transport in metals:

- Compute the scattering rate of charged quasiparticles off phonons: this leads to Bloch's law (1930) : a resistivity $\rho(T) \sim T^5$.



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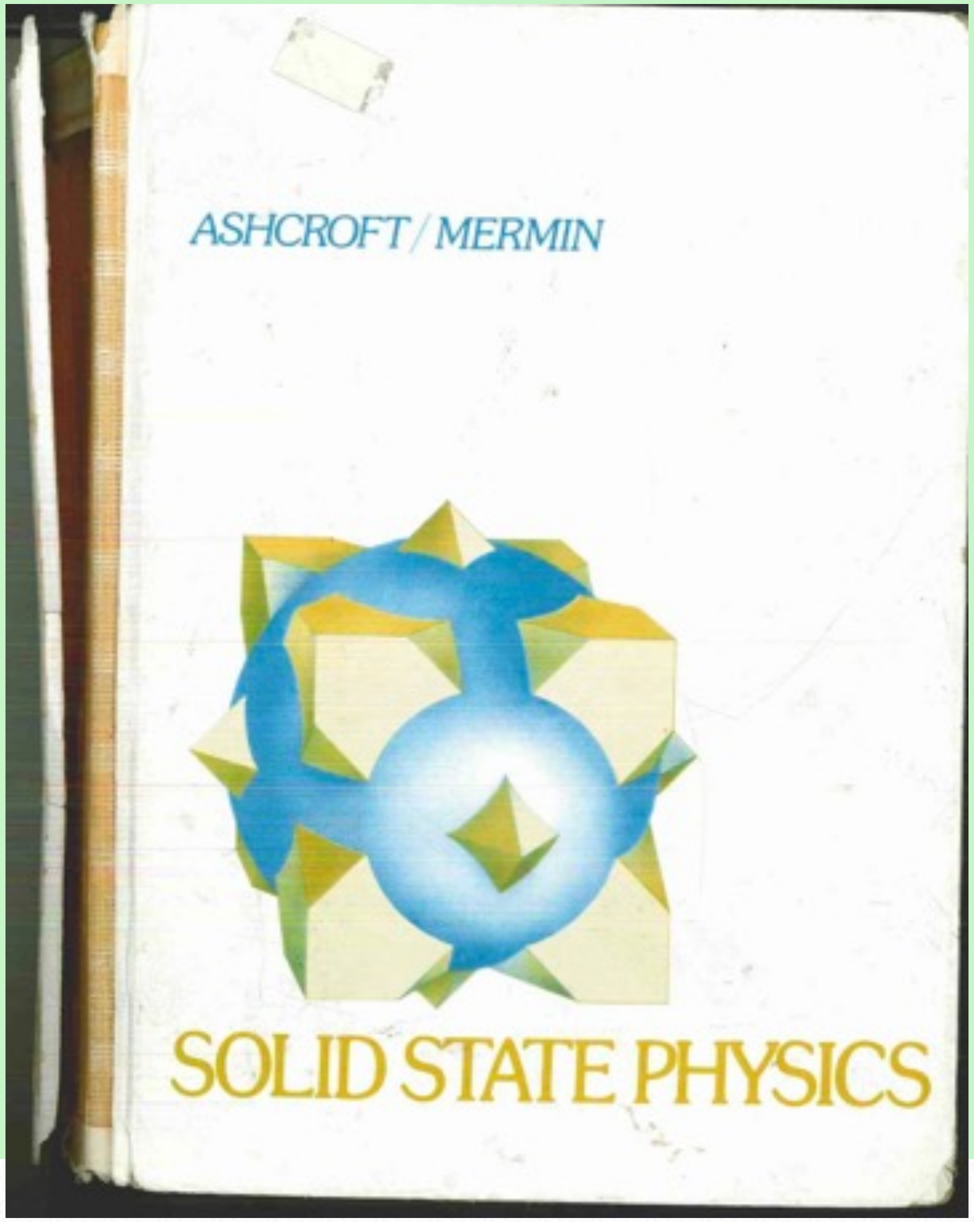


However, this ignores "phonon drag"

PHONON DRAG

Peierls[28] pointed out a way in which the low temperature resistivity might decline more rapidly than T^5. This behavior has yet to be observed,

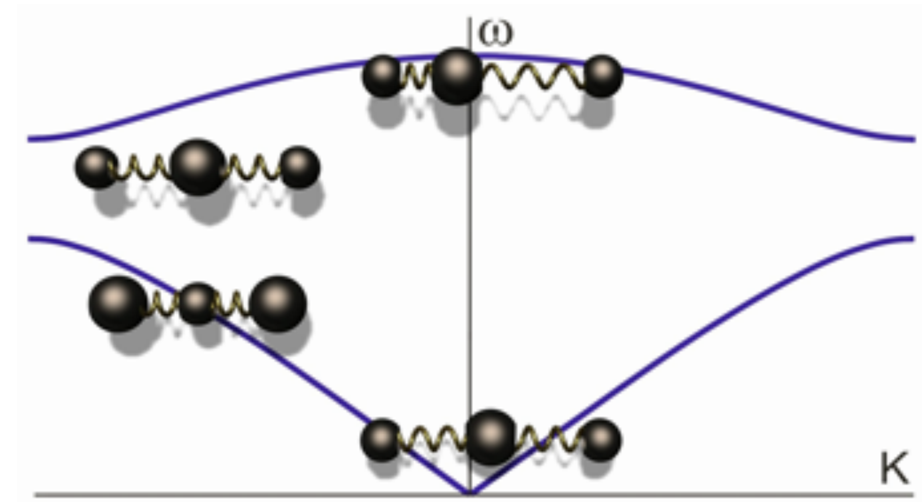
[28] R. E. Peierls, *Ann. Phys.* (5) **12**, 154 (1932).

Rates of Momentum Flow

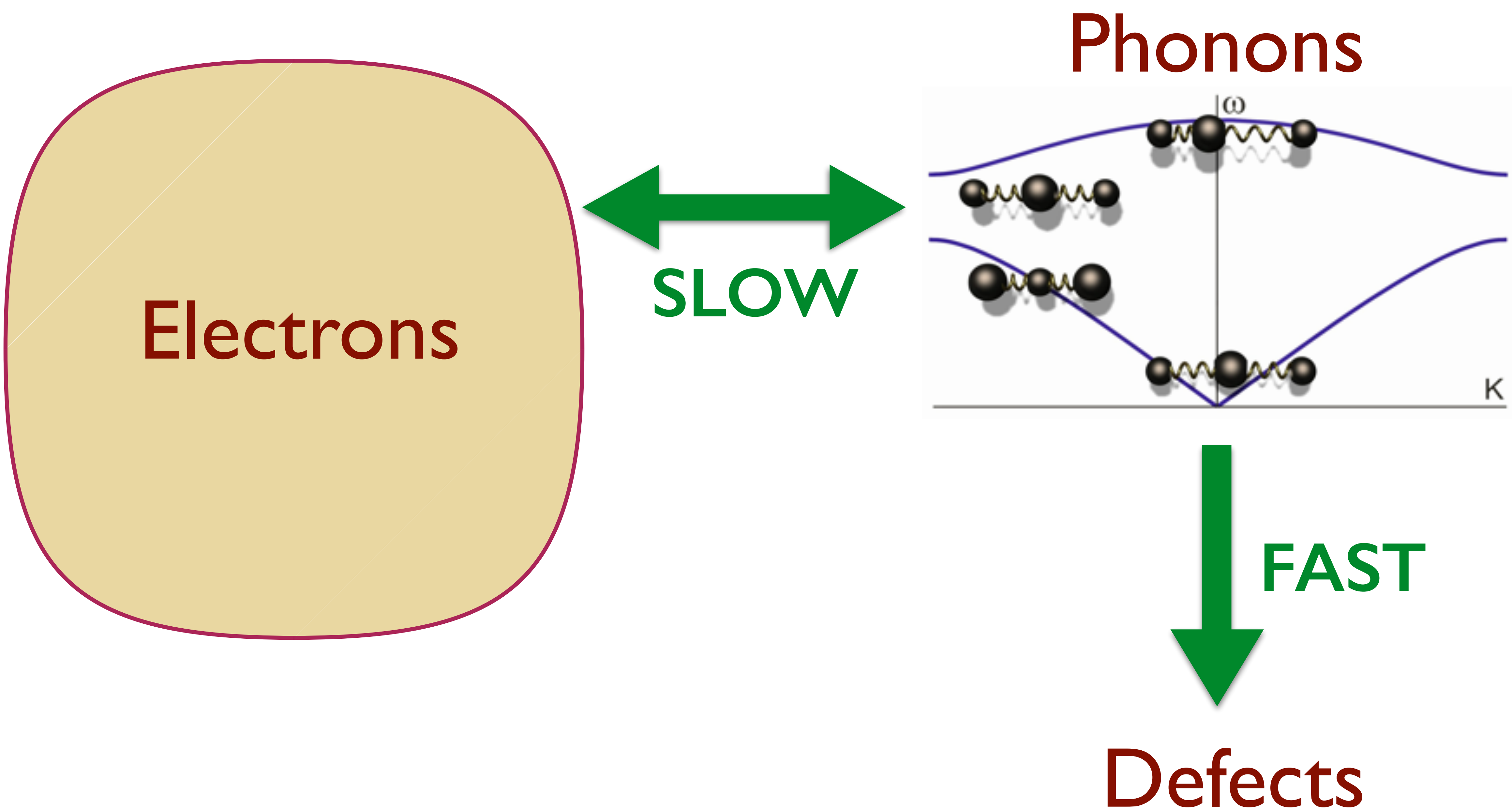
Phonons

Electrons

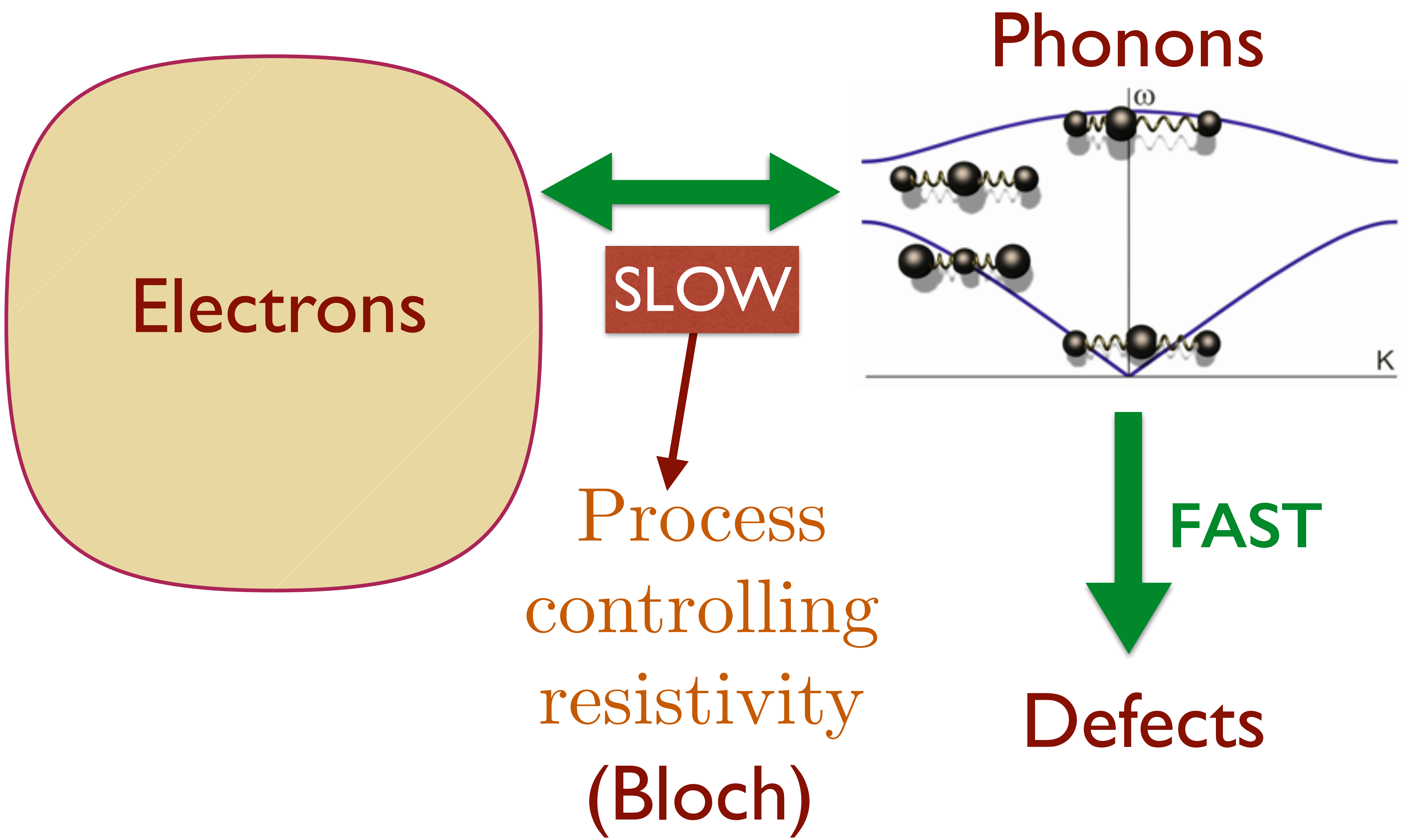
SLOW



Rates of Momentum Flow



Rates of Momentum Flow



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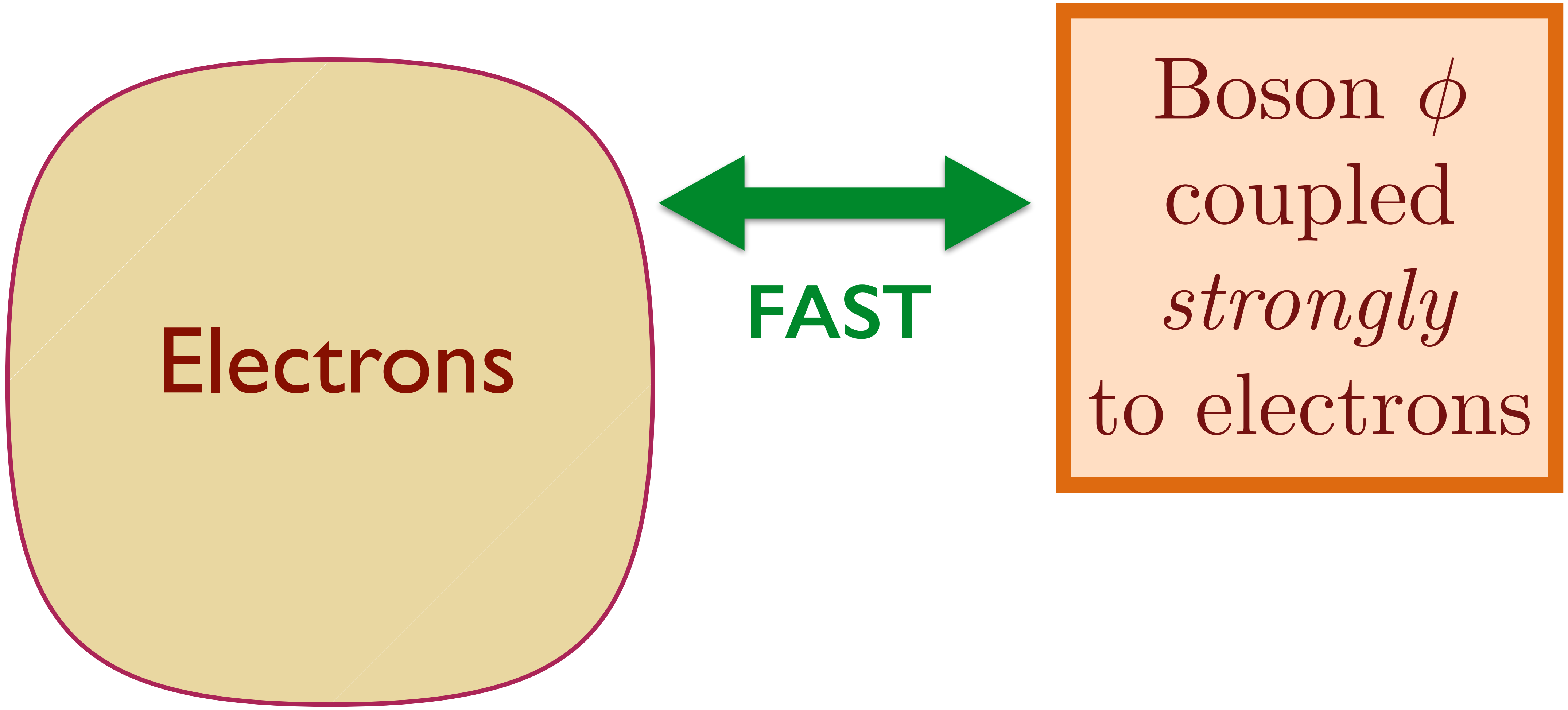
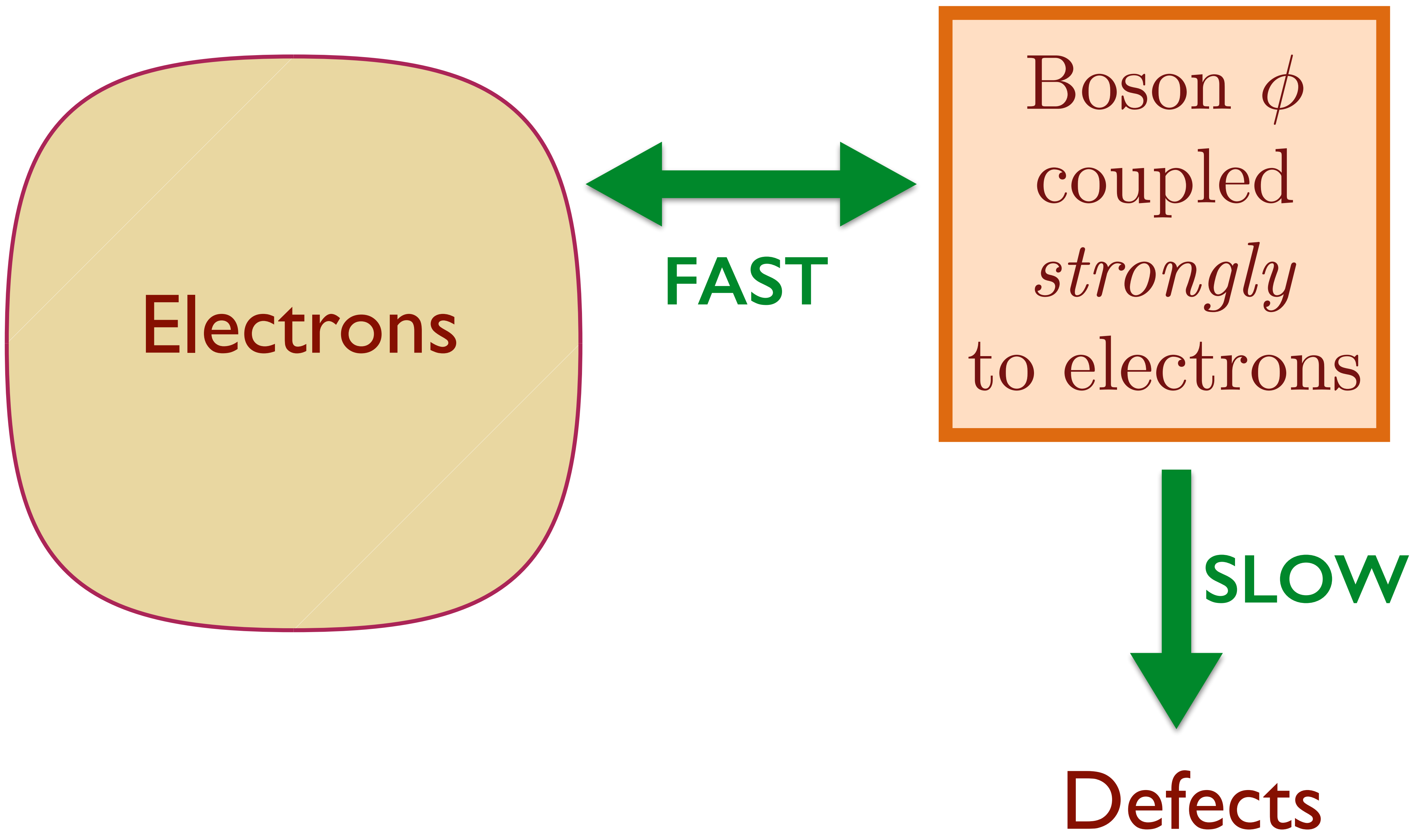
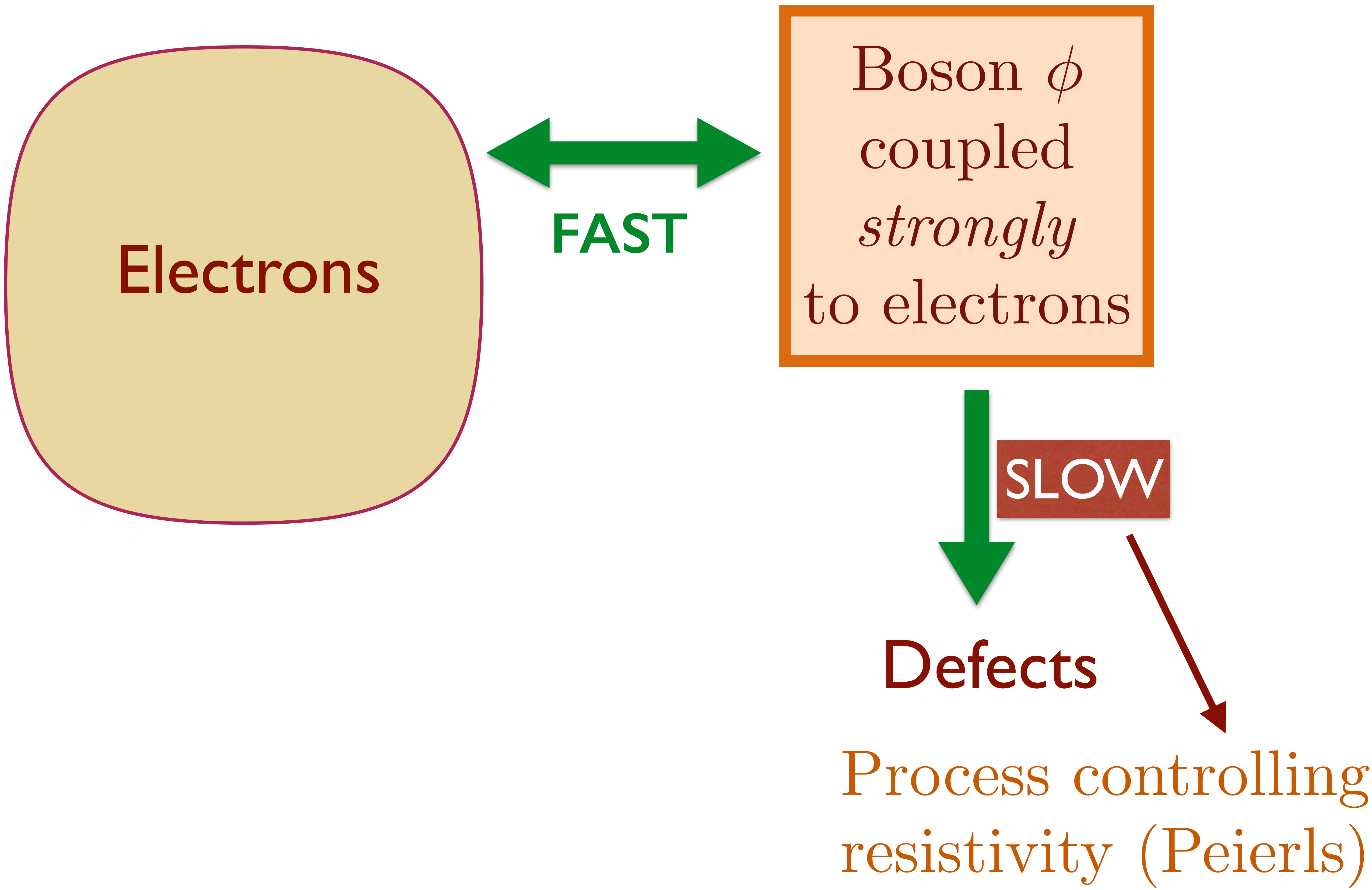


Rates of Momentum Flow



Rates of Momentum Flow



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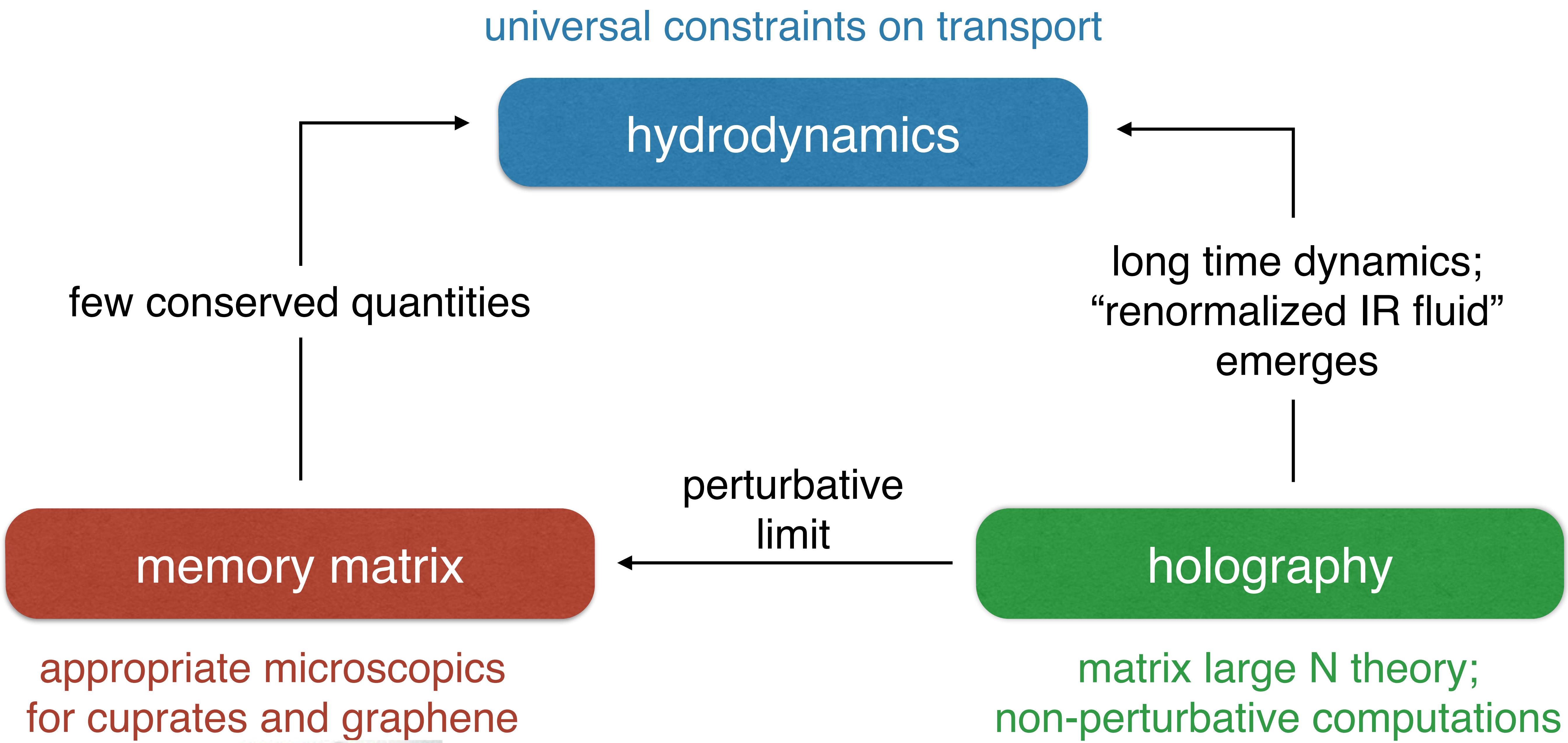

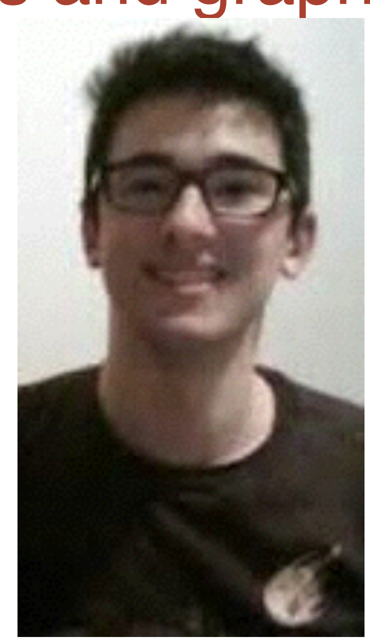

Andrew
Lucas

Richard
Davison

A. Lucas and S. Sachdev, Physical Review B **91**, 195122 (2015)

Thermoelectric transport coefficients

Transport has two components: a "momentum drag" term, and a "quantum critical" term.

$$\sigma = \frac{\mathcal{Q}^2}{\mathcal{M}} \pi \delta(\omega) + \sigma_Q(\omega)$$

$$\alpha = \frac{\mathcal{S}\mathcal{Q}}{\mathcal{M}} \pi \delta(\omega) + \alpha_Q(\omega)$$

$$\bar{\kappa} = \frac{T\mathcal{S}^2}{\mathcal{M}} \pi \delta(\omega) + \bar{\kappa}_Q(\omega)$$

with entropy density $\mathcal{S}$, $\mathcal{Q} \equiv \chi_{J_x, P_x}$, and $\mathcal{M} \equiv \chi_{P_x, P_x}$.

Obtained in hydrodynamics, holography, and by memory functions

S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)

A. Lucas and S. Sachdev, PRB **91**, 195122 (2015)

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In theories which are relativistic at high energies (including graphene), $T\alpha_Q(\omega) = -\mu\sigma_Q(\omega)$, $T\bar{\kappa}_Q(\omega) = \mu^2 \sigma_Q(\omega)$, $\mathcal{M} = T\mathcal{S} + \mu\mathcal{Q} = \mathcal{H}$ the enthalpy density, and $\mathcal{Q} = n$ the electron density

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$$\bar{\kappa} = \frac{T\mathcal{S}^2}{\mathcal{M}} \frac{1}{(-i\omega + 1/\tau)} + \bar{\kappa}_Q(\omega)$$

Momentum relaxation by an external source h coupling to the operator $\mathcal{O}$

$$H = H_0 - \int d^d x \, h(x) \, \mathcal{O}(x).$$

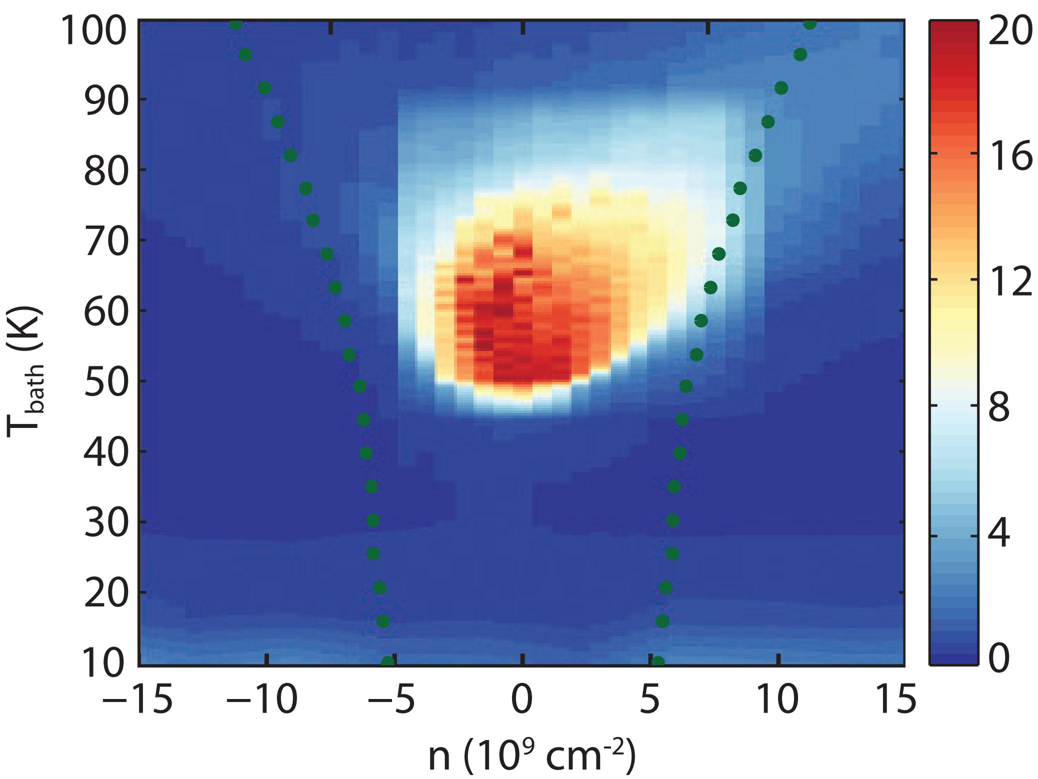
$$\frac{\mathcal{M}}{\tau} = \lim_{\omega \to 0} \int d^d q \, |h(q)|^2 q_x^2 \frac{\mathrm{Im}\left(G^{\mathrm{R}}_{\mathcal{O}\mathcal{O}}(q,\omega)\right)_{H_0}}{\omega} + \text{higher orders in } h$$

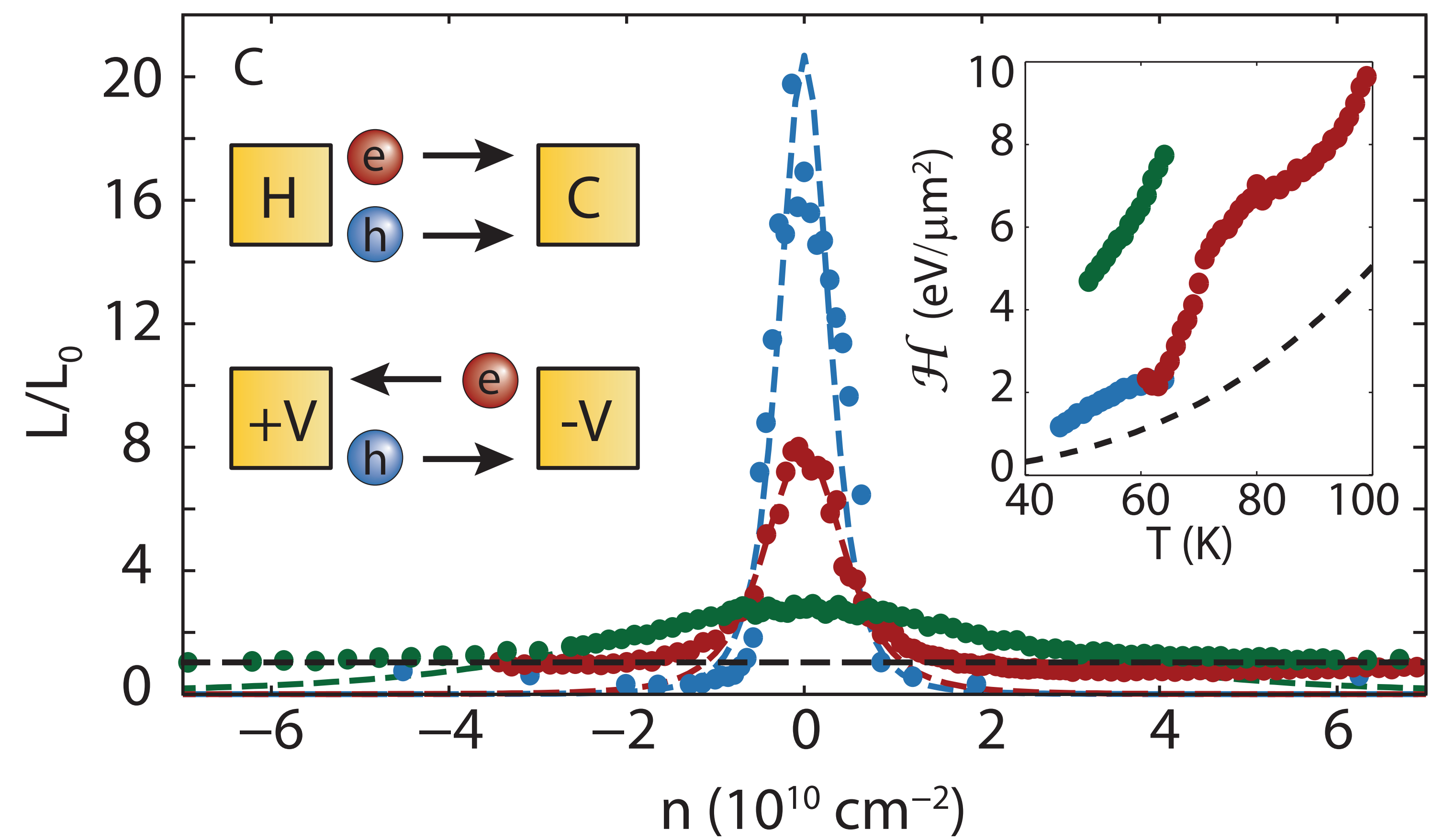
S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)
A. Lucas and S. Sachdev, PRB **91**, 195122 (2015)

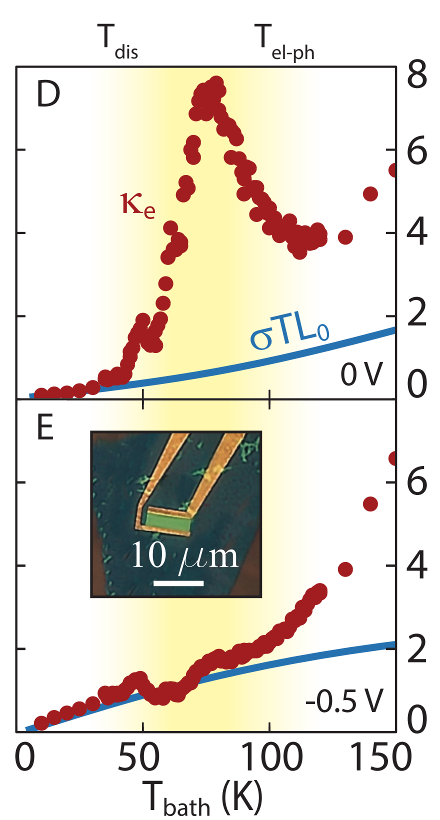
(submitted)

Observation of the Dirac fluid and the breakdown of the Wiedemann-Franz law in graphene

Jesse Crossno,[1,2] Jing K. Shi,[1] Ke Wang,[1] Xiaomeng Liu,[1] Achim Harzheim,[1] Andrew Lucas,[1] Subir Sachdev,[1,3] Philip Kim,[1,2,*] Takashi Taniguchi,[4] Kenji Watanabe,[4] Thomas A. Ohki,[5] and Kin Chung Fong[5,†]



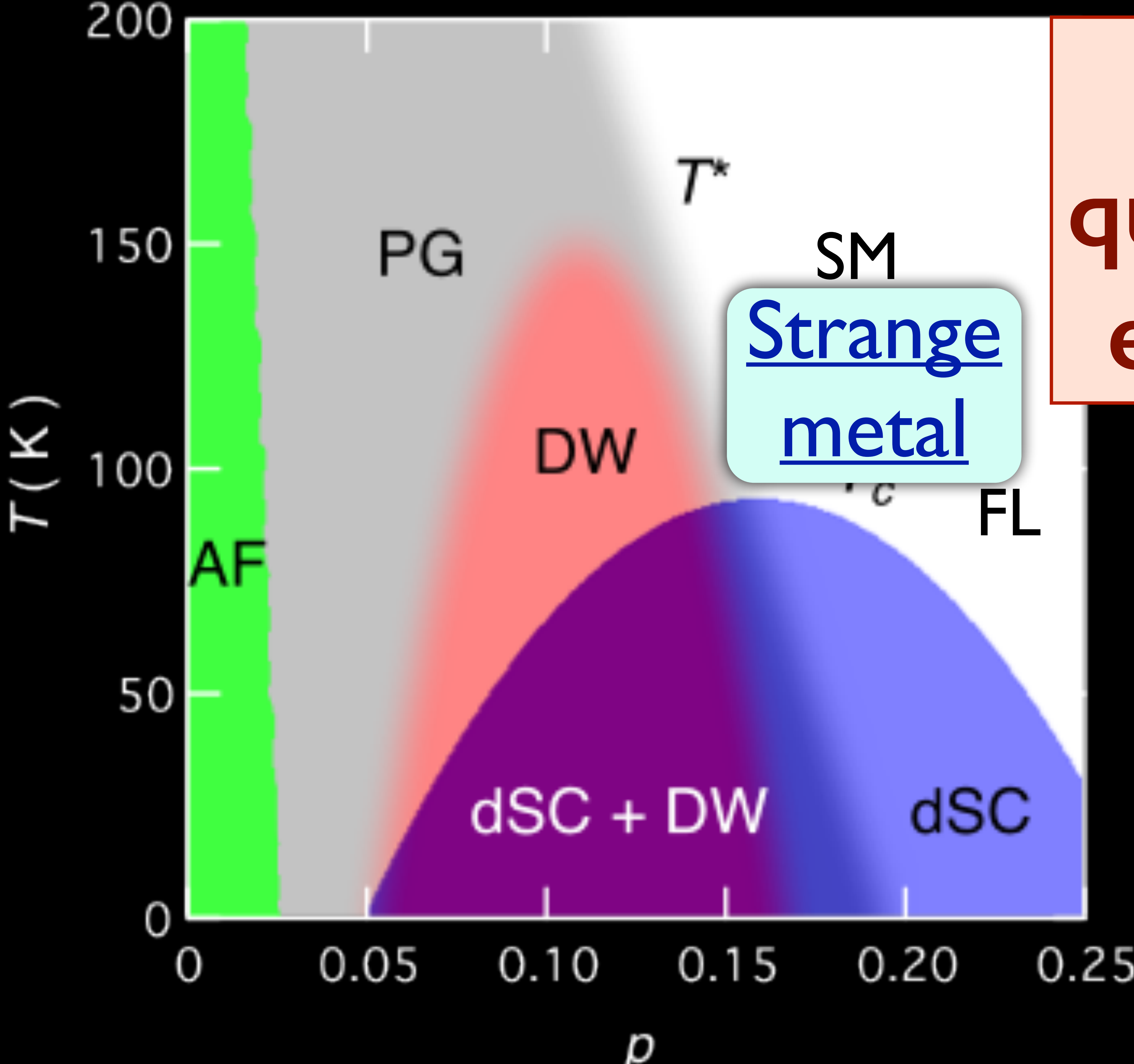




Thermal conductivity $\kappa = \bar{\kappa} - T\alpha^2/\sigma$

Lorentz ratio $L = \kappa/(T\sigma)$

$$= \frac{\mathcal{H}\tau}{T^2\sigma_Q} \frac{1}{\left(1 + n^2\tau/(\mathcal{H}\sigma_Q)\right)^2}$$



No quasiparticle excitations

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$$\sigma_{xy} = \frac{2(\tau^{-1} - i\omega)\mathcal{M}\sigma_Q + \mathcal{Q}^2 + B^2\sigma_Q^2}{\mathcal{Q}^2 B^2 + ((\tau^{-1} - i\omega)\mathcal{M} + B^2\sigma_Q)^2}B\mathcal{Q}.$$

Electrical and thermal magnetotransport with no additional parameters
(assuming σ_Q is field-independent)

S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)
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Electrical and thermal magnetotransport with no additional parameters
(assuming σ_Q is field-independent)

Blake and Donos: With $\sigma_Q \sim 1/T$ and $\tau \sim 1/T^2$, we obtain $\sigma_{xx} \sim 1/T$ and $\tan(\theta_H) = \sigma_{xy}/\sigma_{xx} \sim 1/T^2$, in agreement with data on cuprates (Ong, PRL 1991); such data cannot be explained in a quasiparticle model.

M. Blake and A. Donos, PRL **114**, 021601 (2015)

S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007)
A. Lucas and S. Sachdev, PRB **91**, 195122 (2015)

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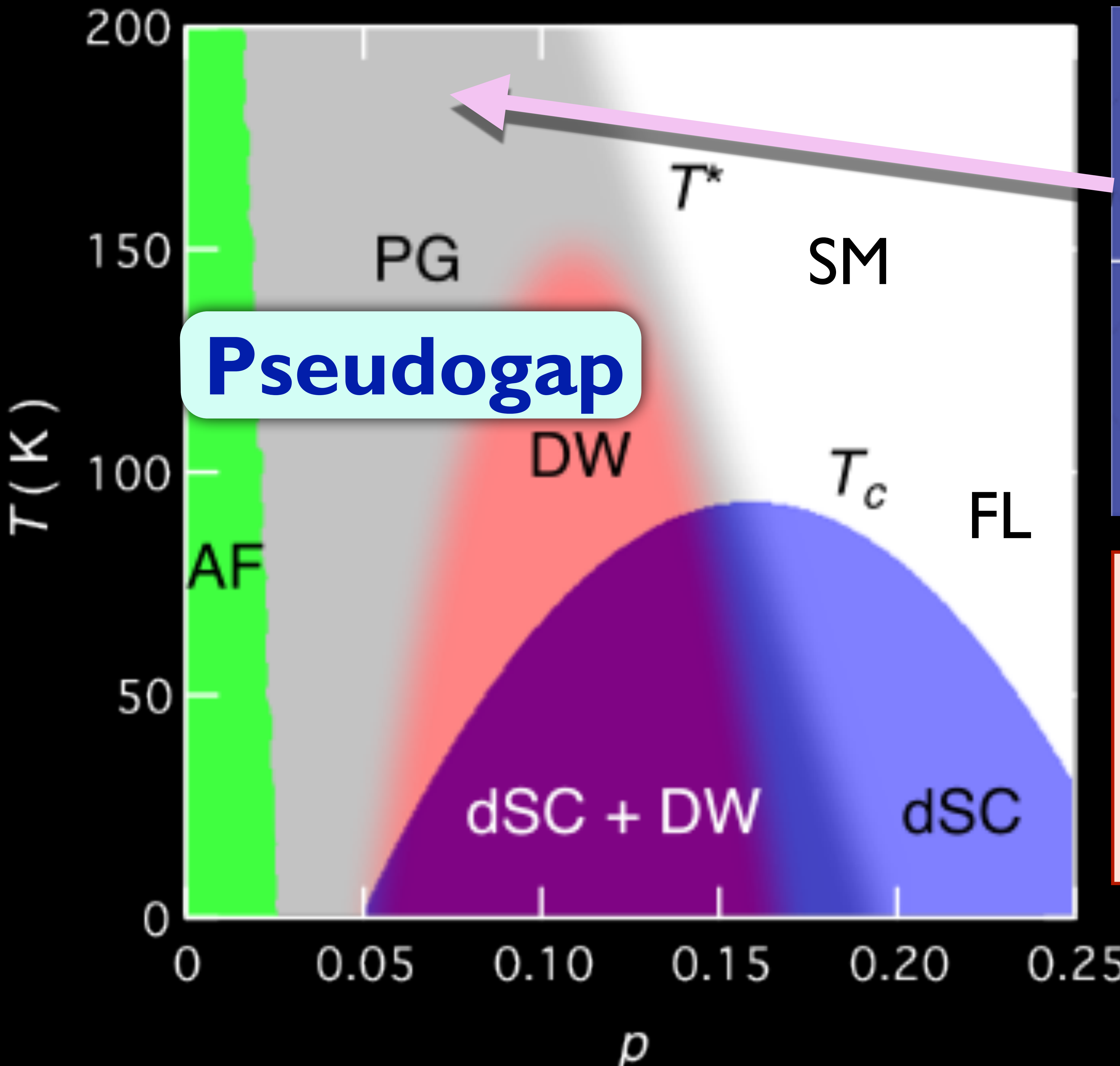
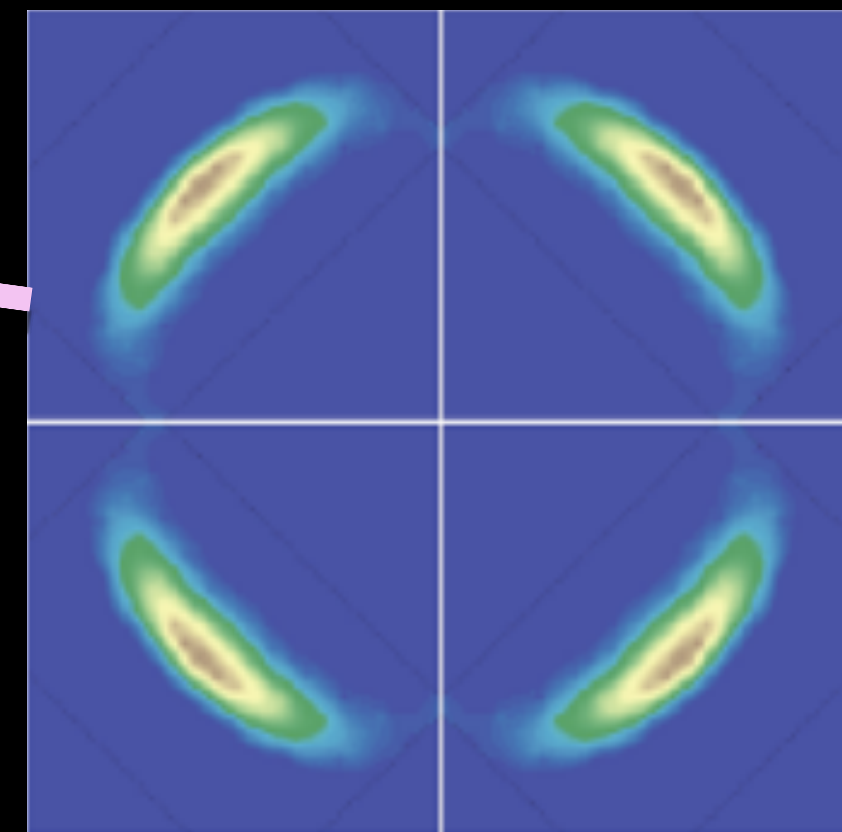




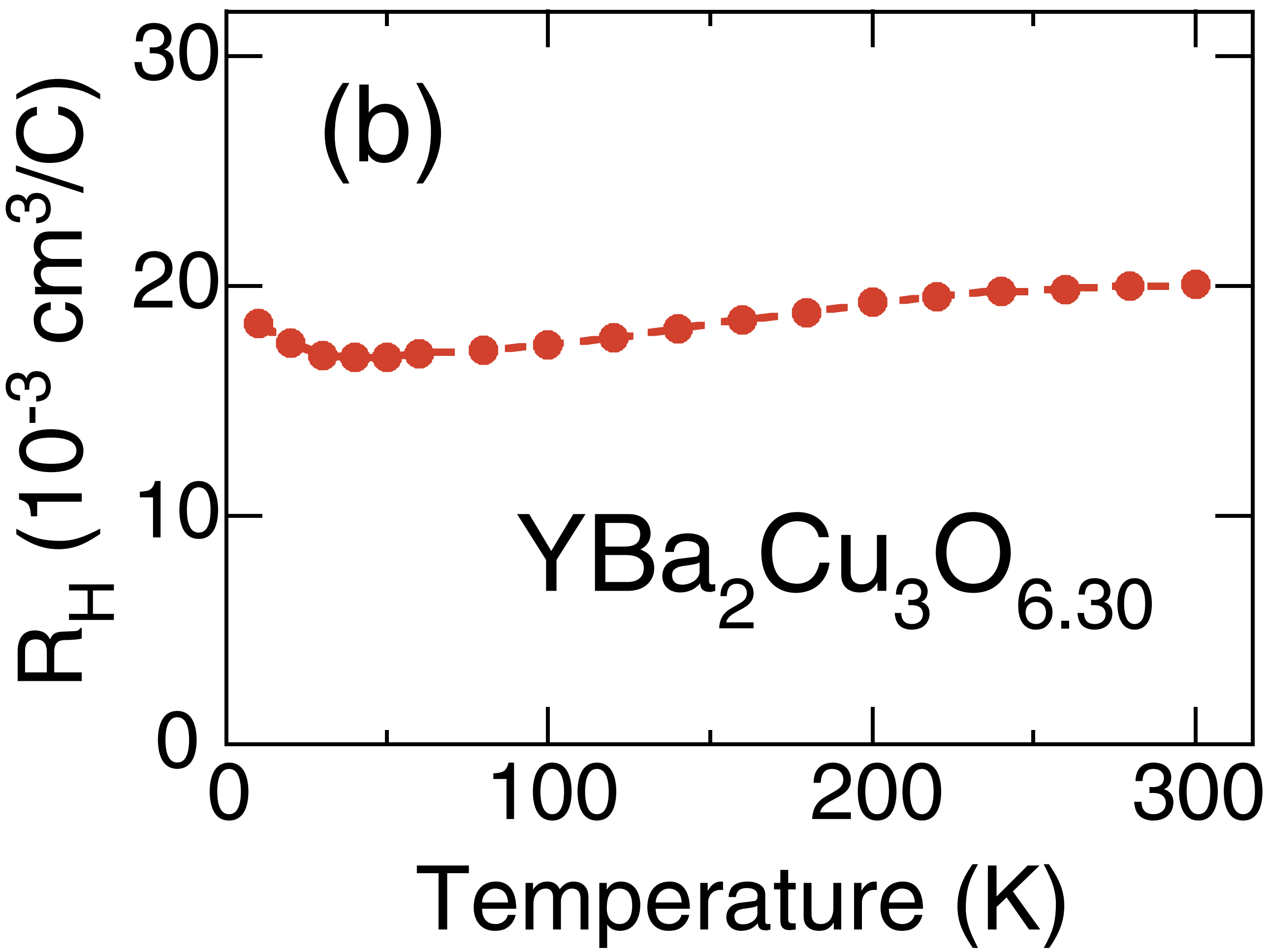
Pseudogap metal at low p

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)

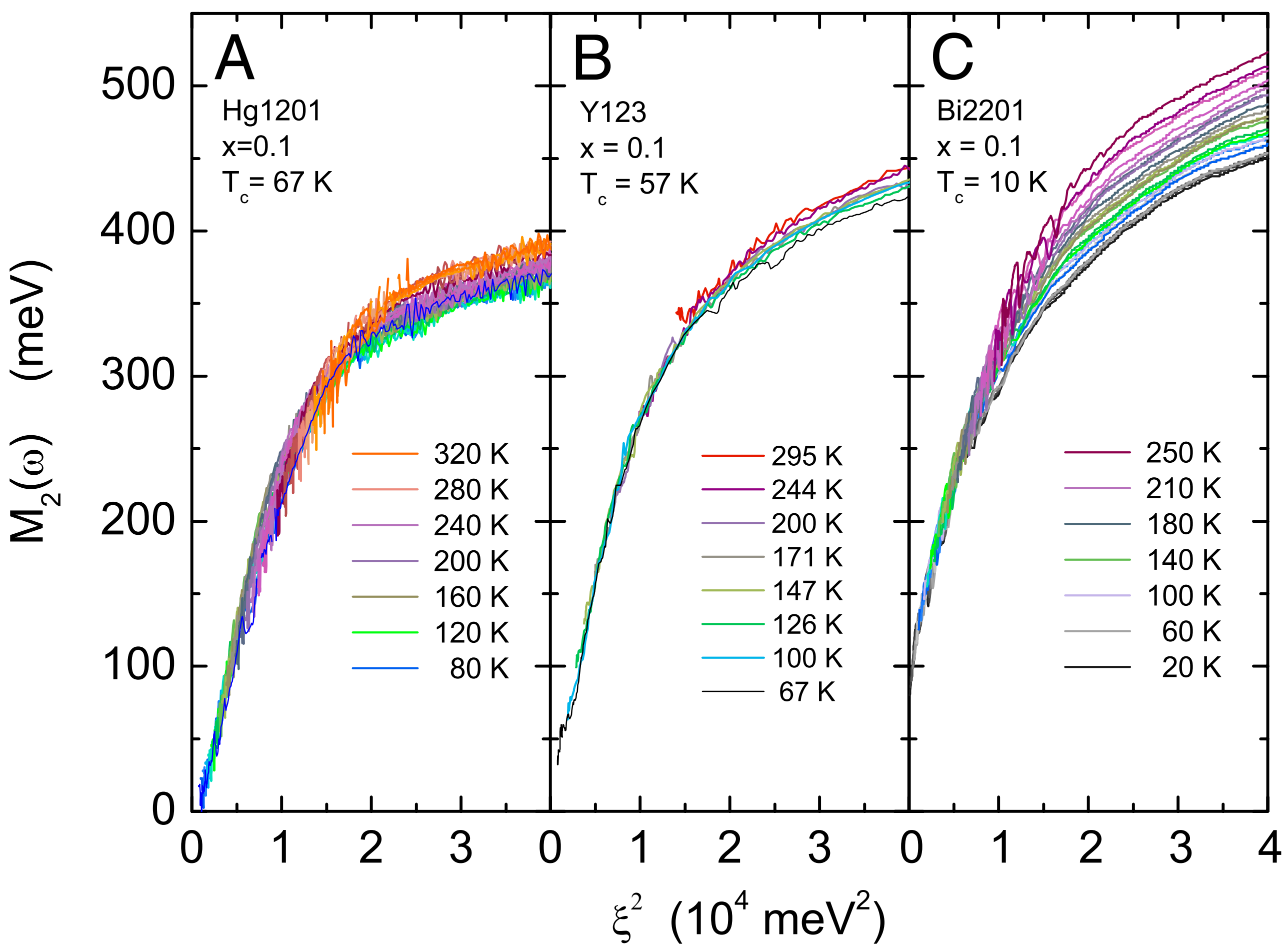


Fig. 6. Collapse of the frequency and temperature dependence of the relaxation rate of underdoped cuprate materials. Normal state $M_2(\omega, T)$ as a function of $\xi^2 \equiv (\hbar\omega)^2 + (p\pi k_B T)^2$

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

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

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.

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

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

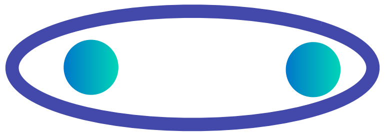
Can we have a metal with no broken translational symmetry, and with long-lived electron-like quasiparticles on a Fermi surface of size p ?

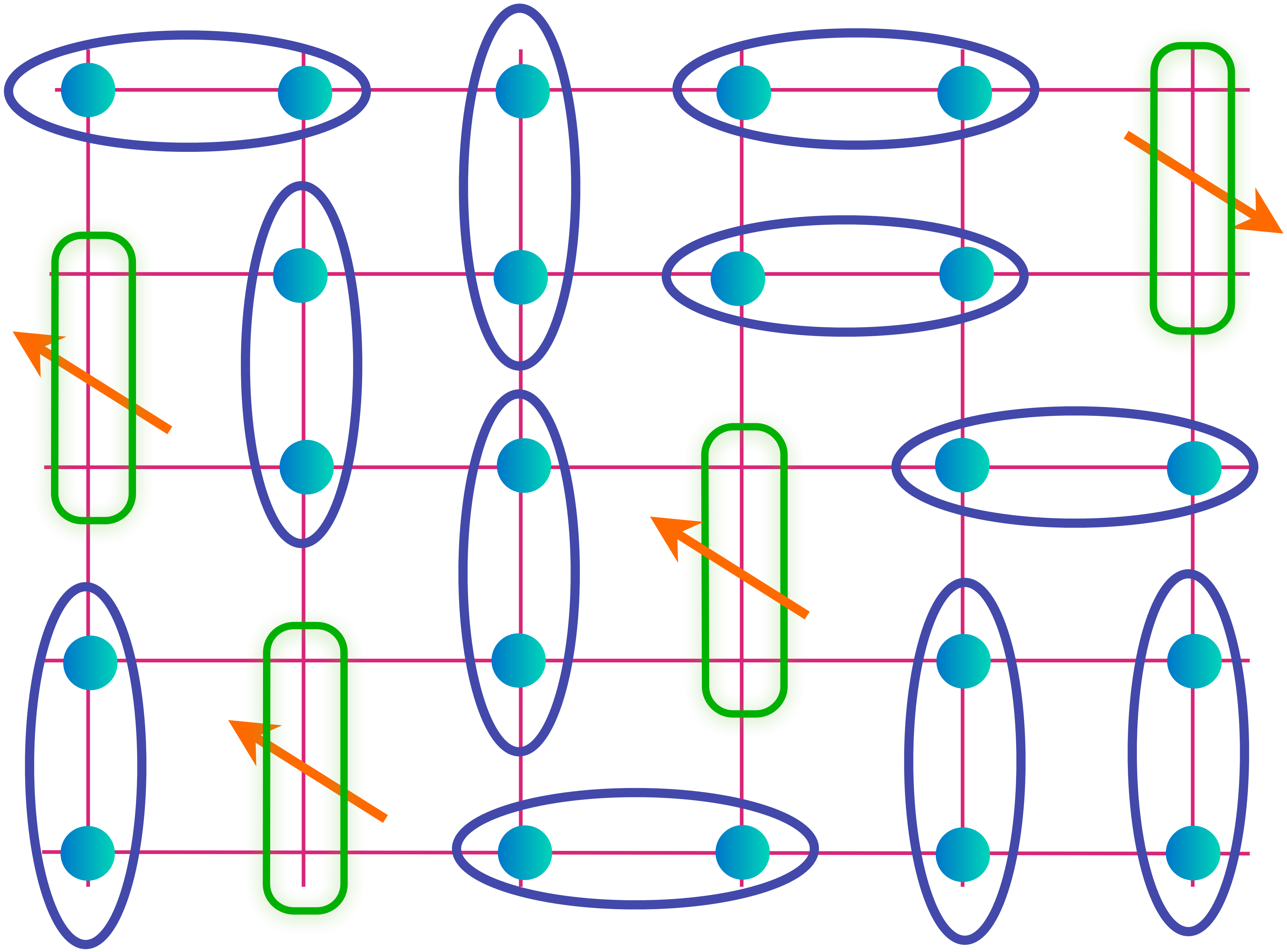
Can we have a metal with no broken translational symmetry, and with long-lived electron-like quasiparticles on a Fermi surface of size p ?

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

Fractionalized Fermi liquid (FL*)

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



Realizes a metal with a Fermi surface of area p co-existing with "topological order"

M. Punk, A. Allais, and S. S., arXiv:1501.00978, PNAS to appear

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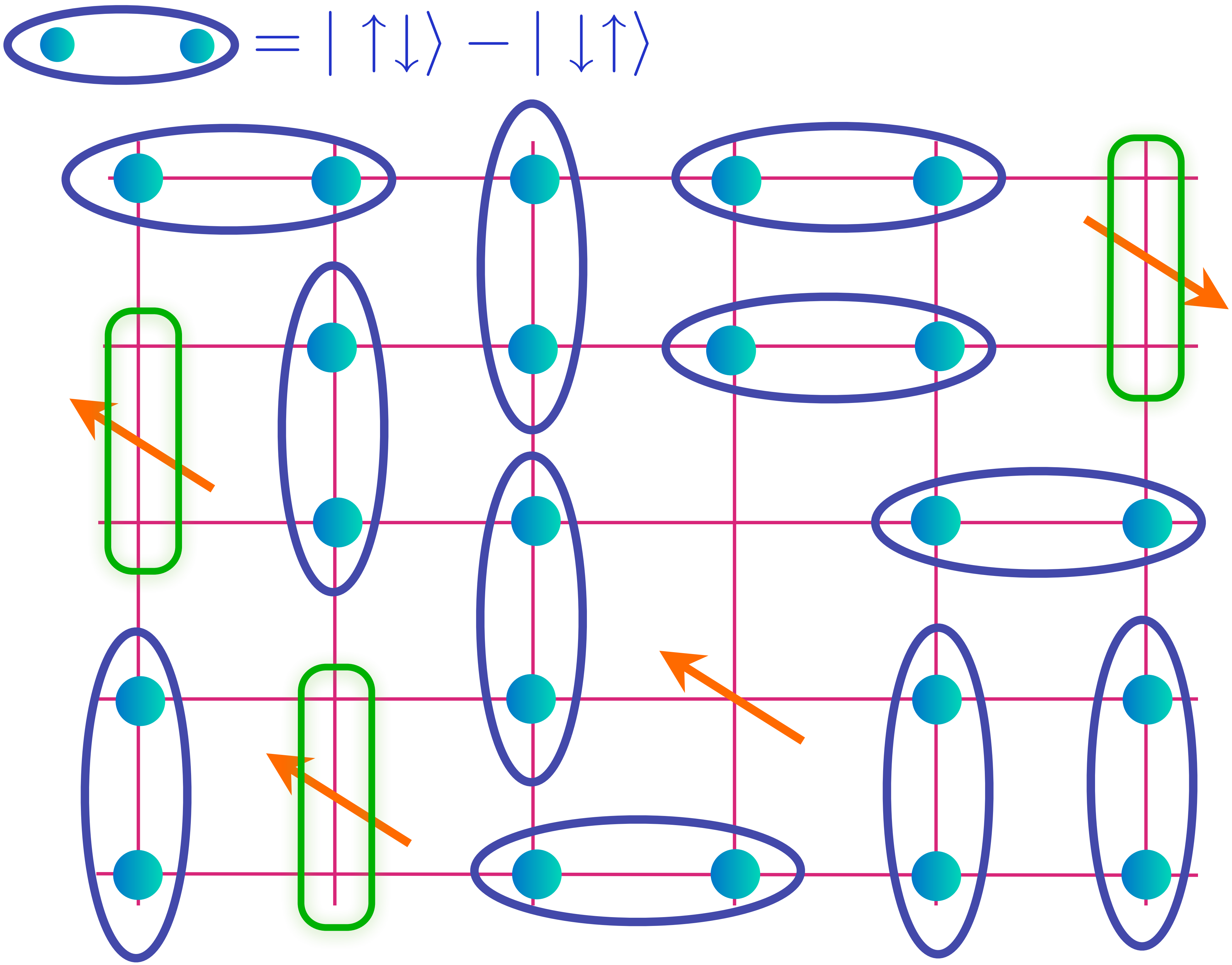

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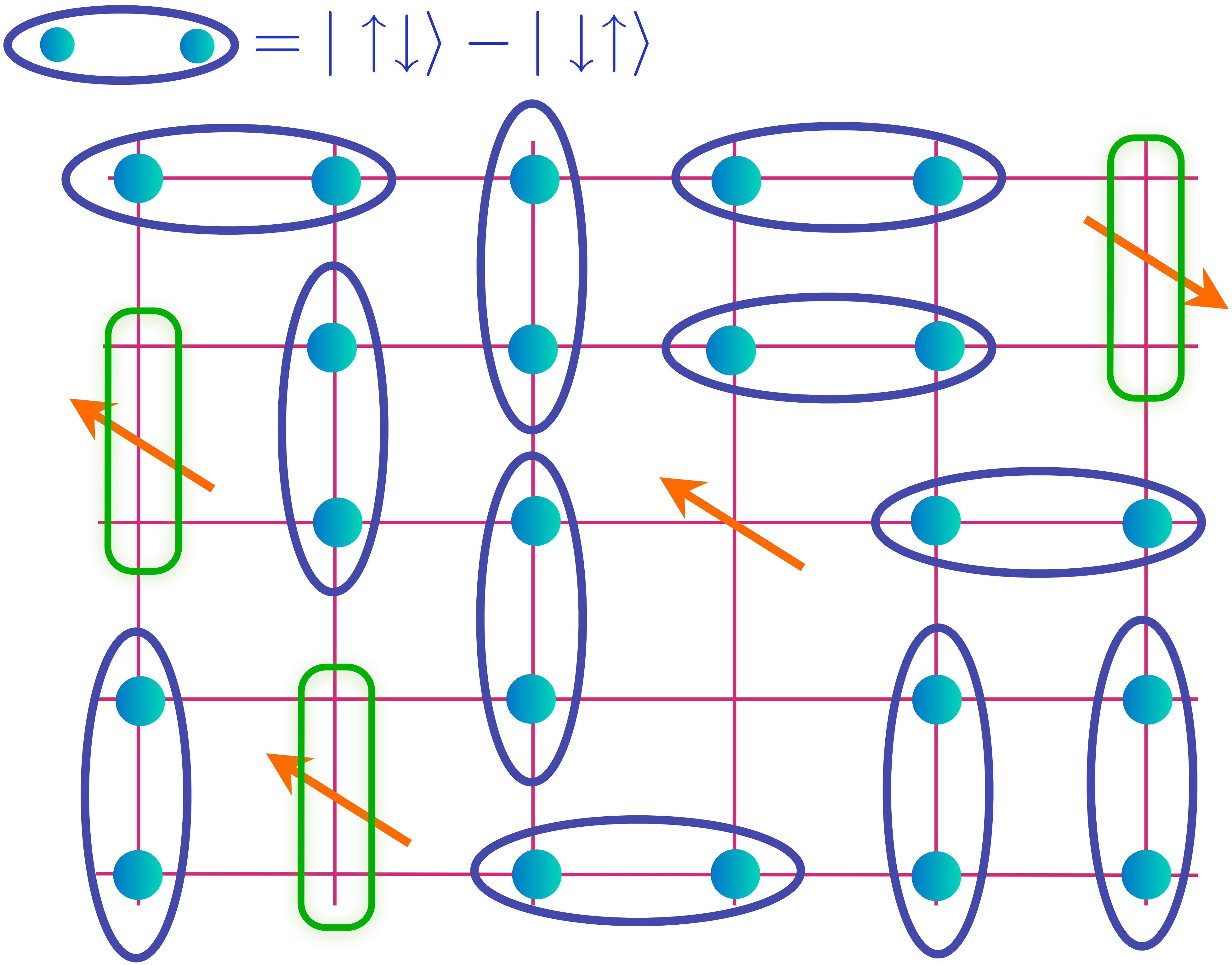

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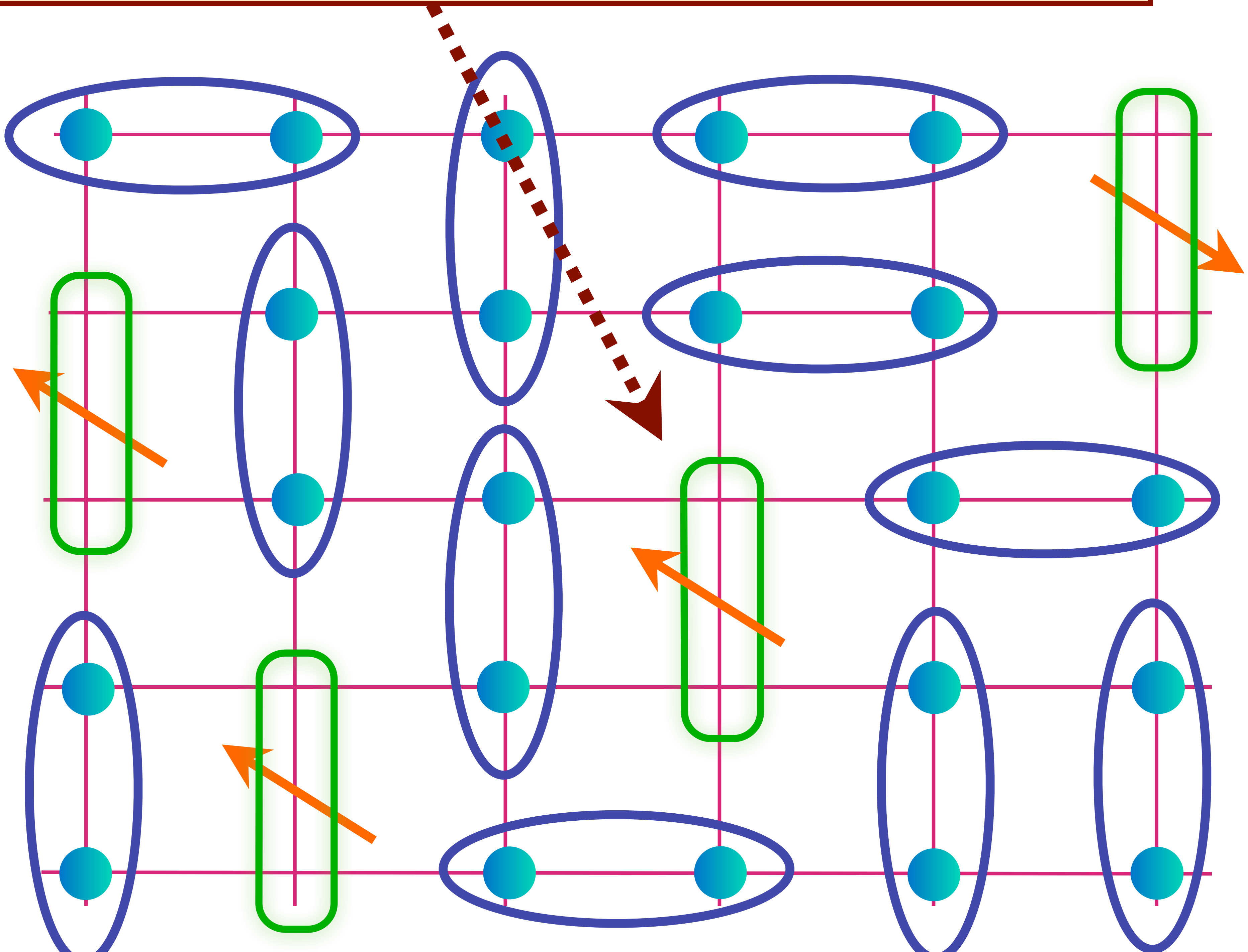
A fermionic "dimer" describing a "bonding" orbital between two sites

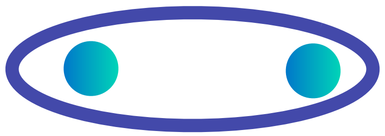


Realizes a metal with a Fermi surface of area p co-existing with "topological order"

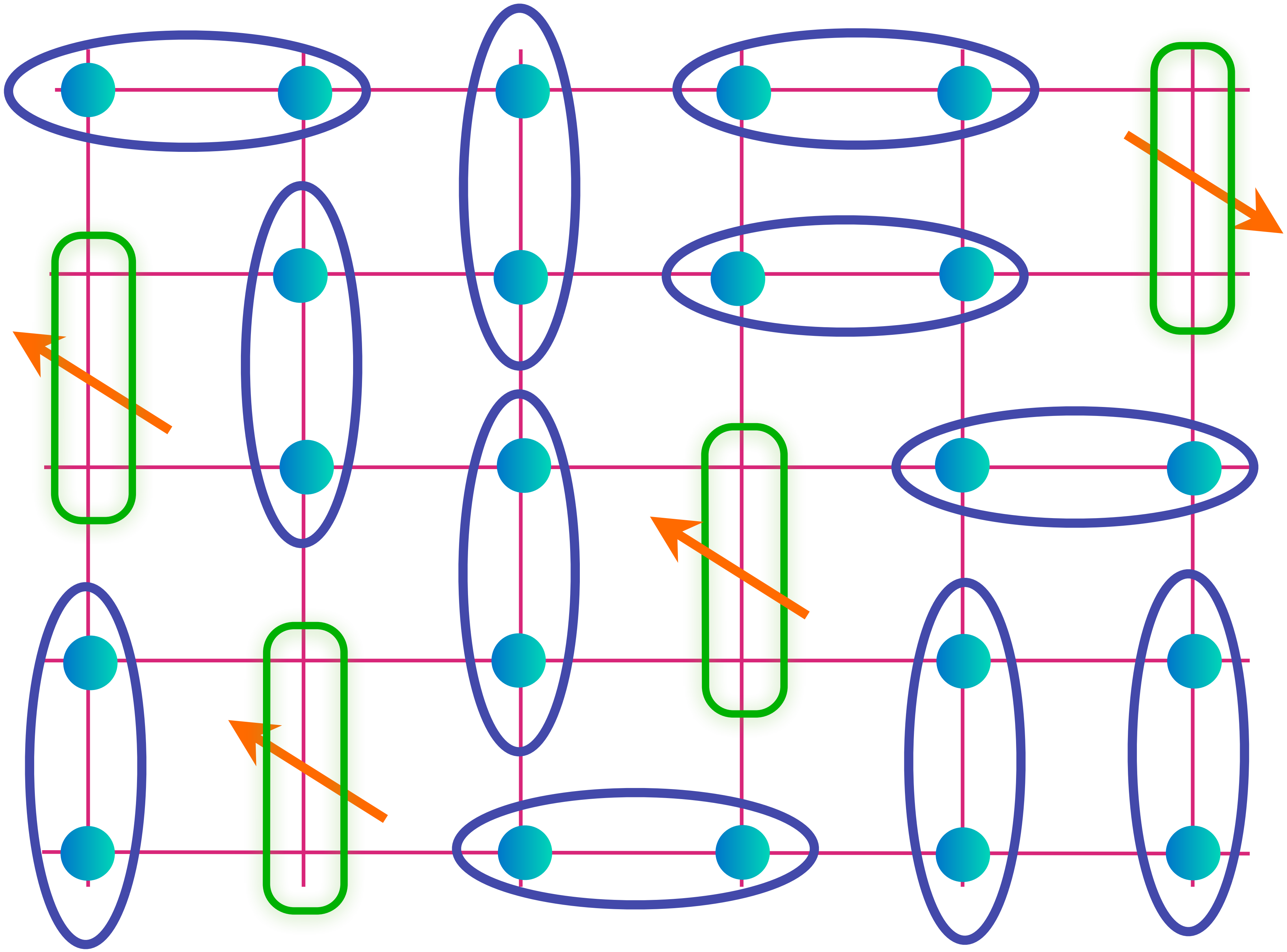
Density of fermionic dimers = p;
density of holes relative to filled band = $1 + p$

M. Punk, A. Allais, and S. S., arXiv:1501.00978, PNAS to appear

Fractionalized Fermi liquid (FL*)



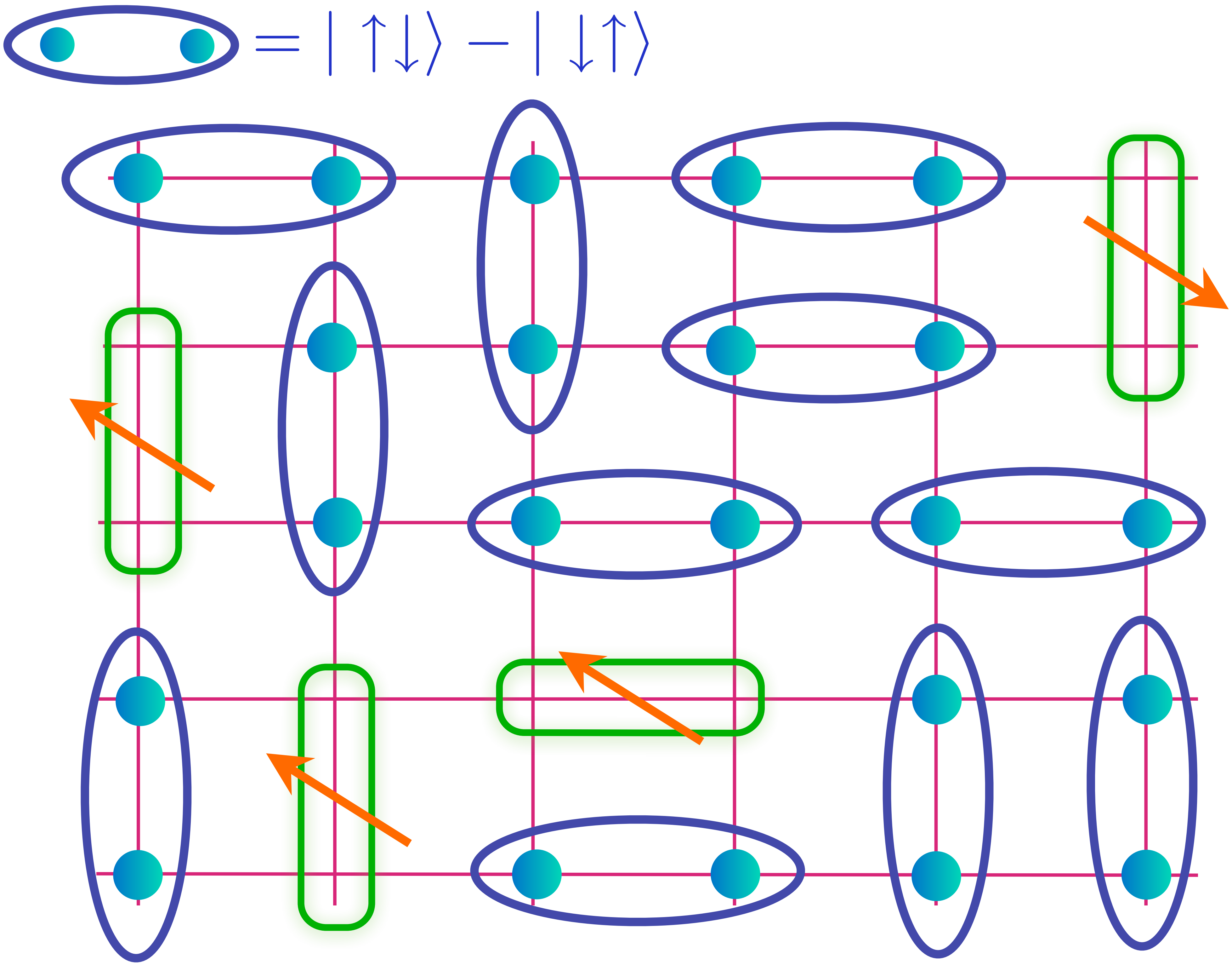
$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



Realizes a metal with a Fermi surface of area p co-existing with "topological order"

M. Punk, A. Allais, and S. S., arXiv:1501.00978, PNAS to appear

Fractionalized Fermi liquid (FL*)



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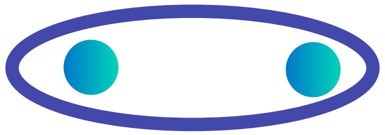
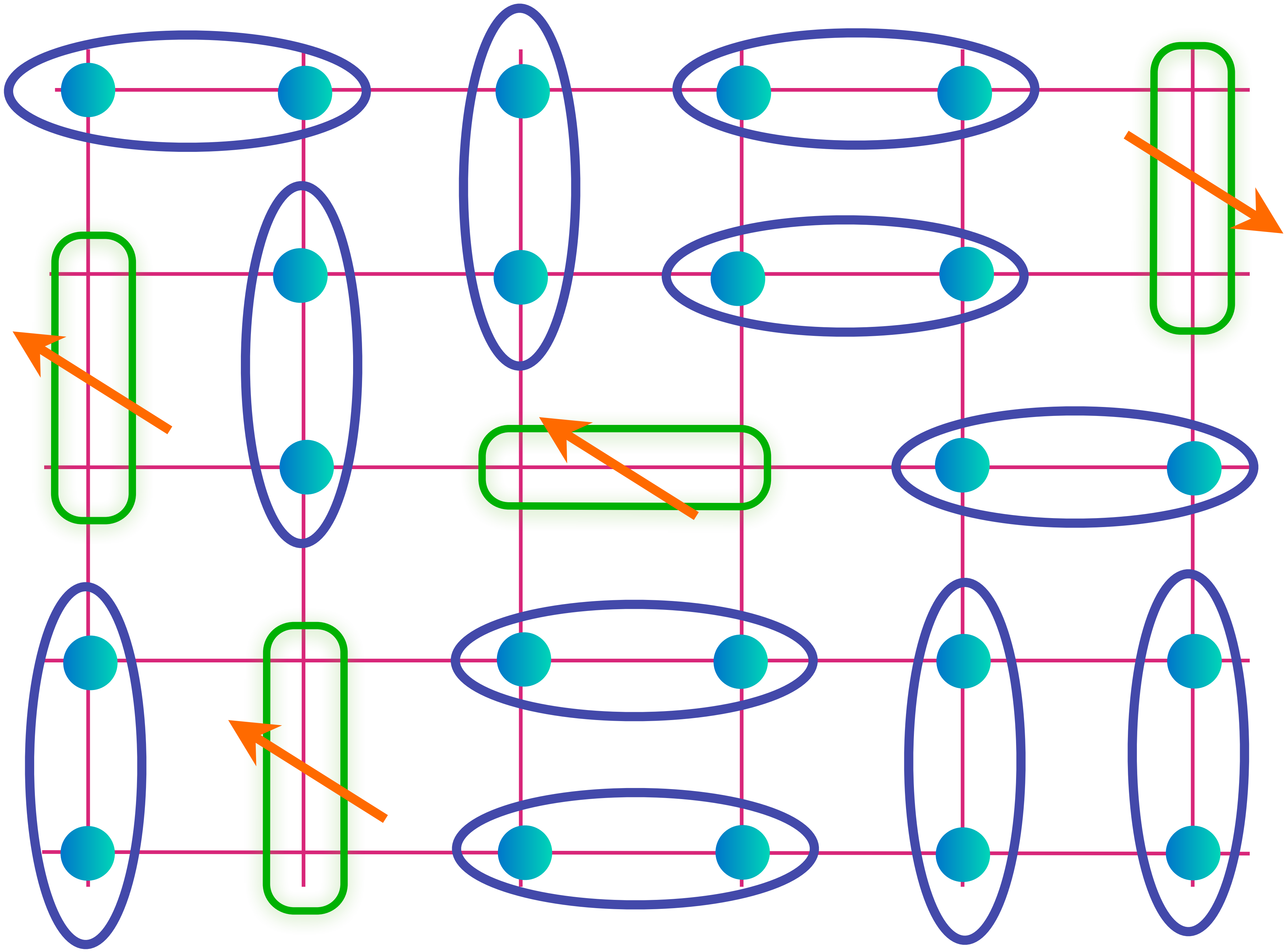
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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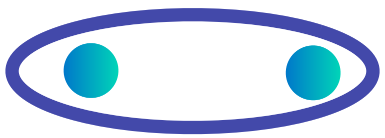
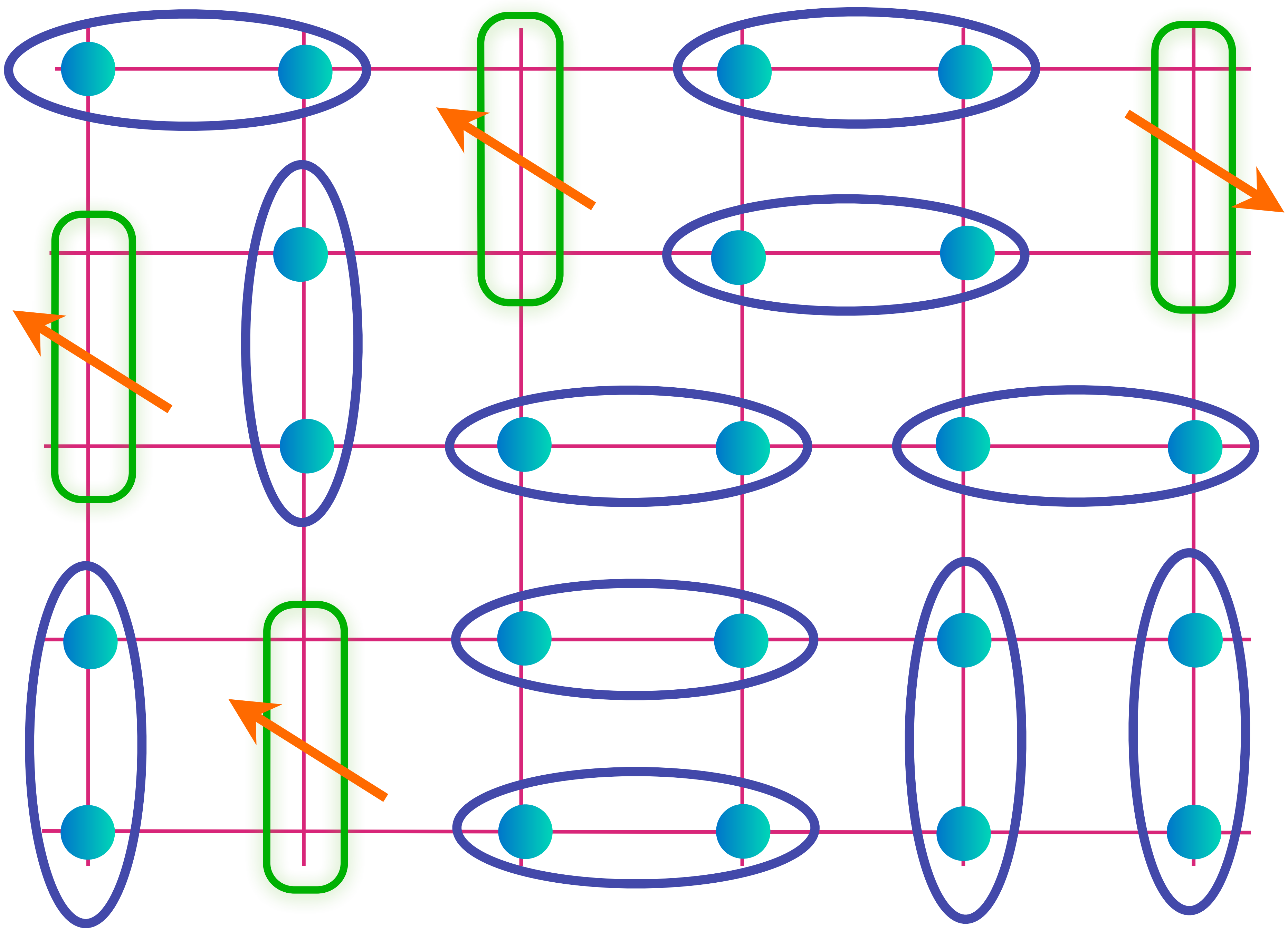


$= | \uparrow\downarrow\rangle - | \downarrow\uparrow\rangle$



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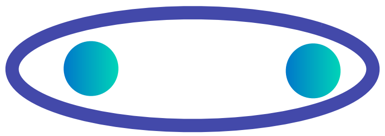
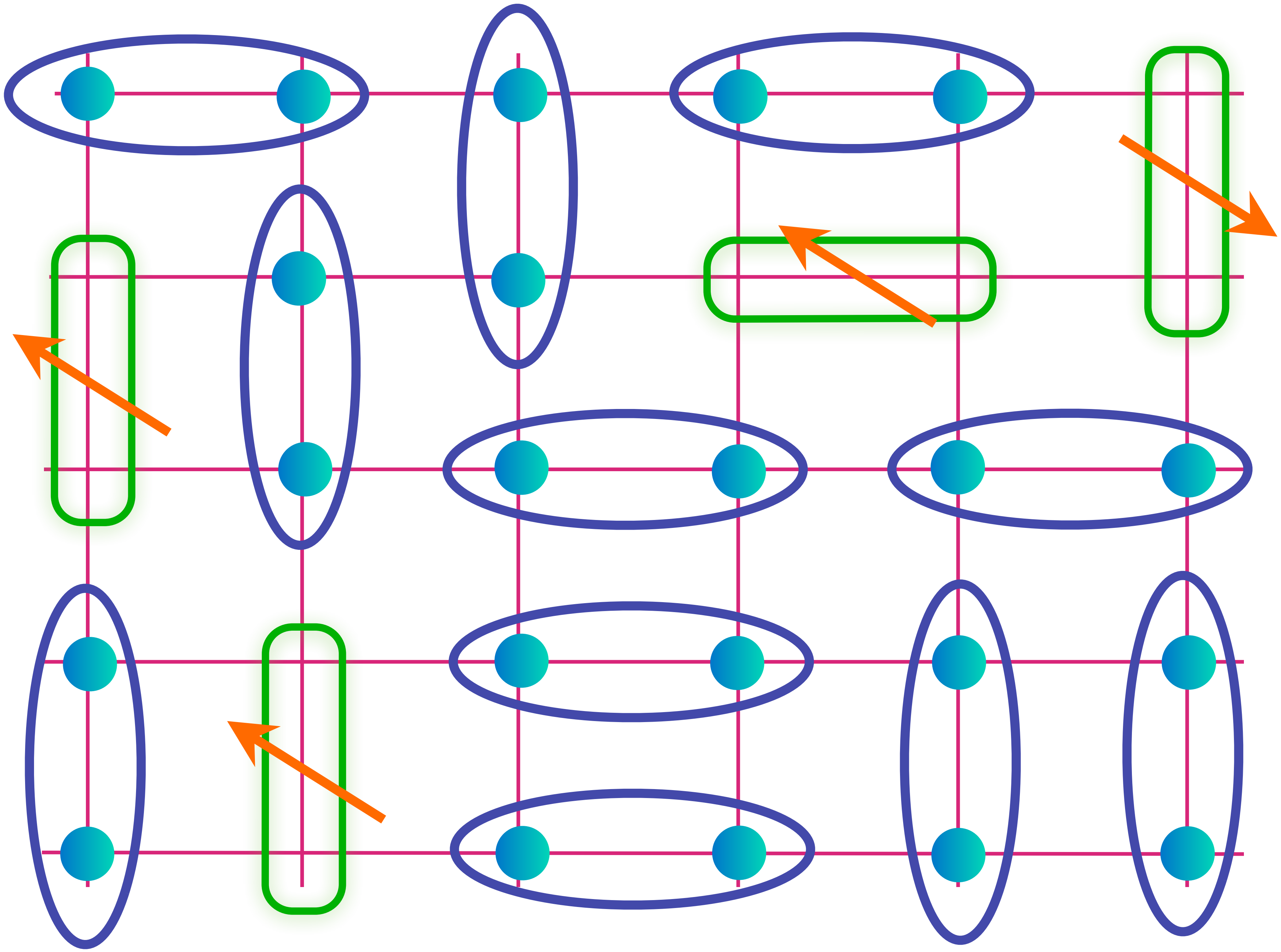
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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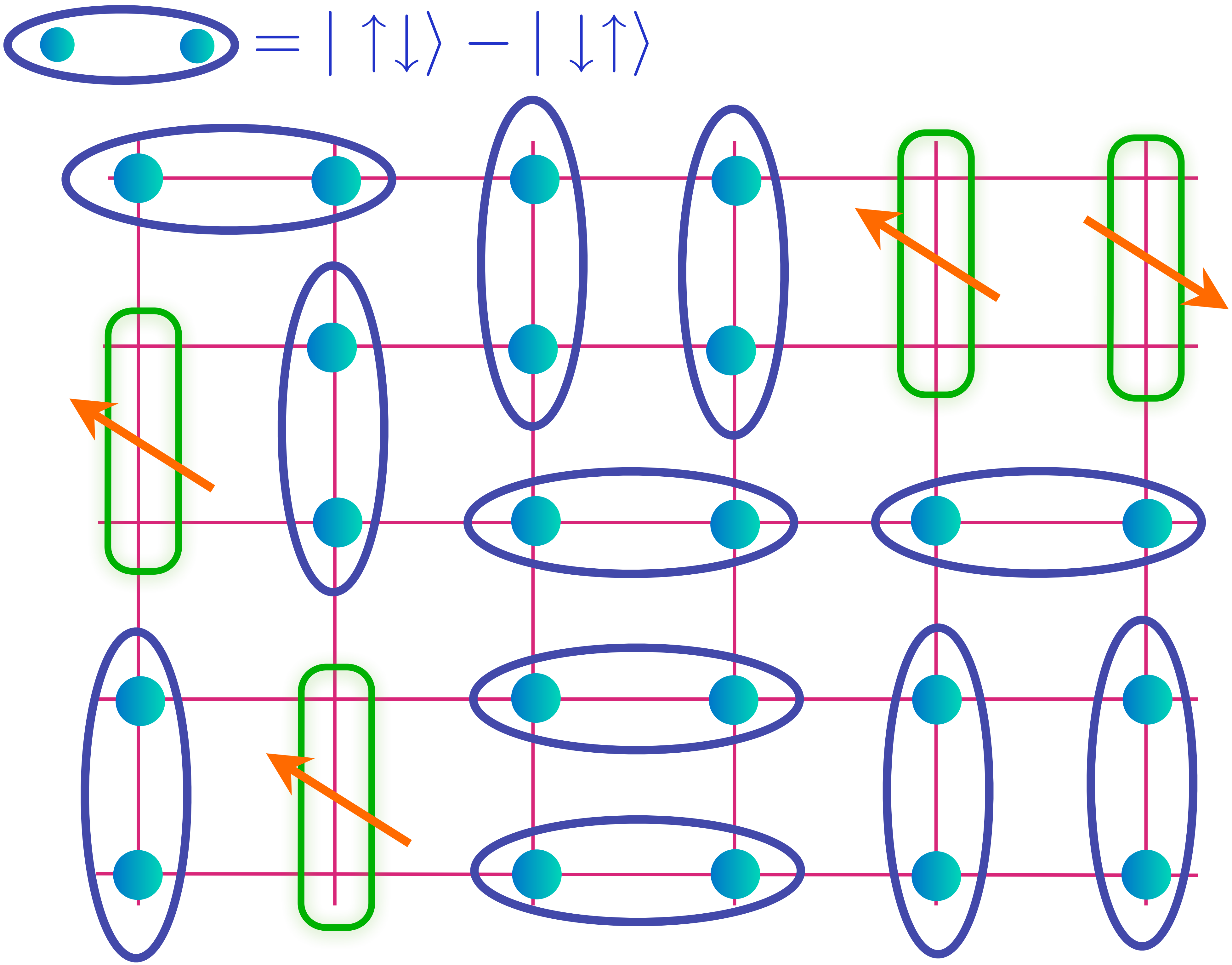

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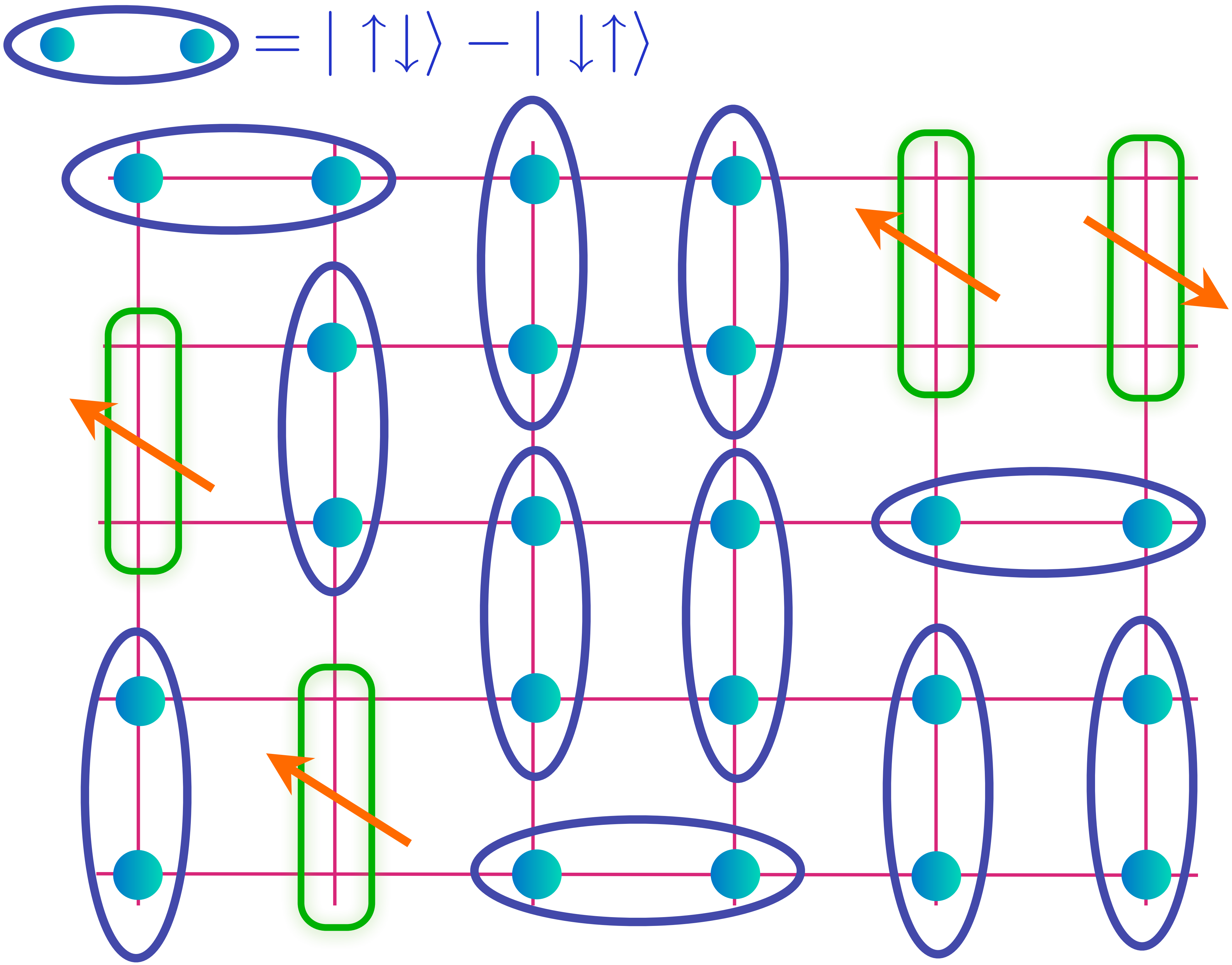

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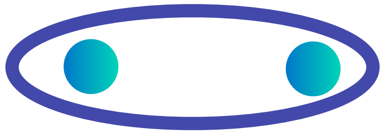
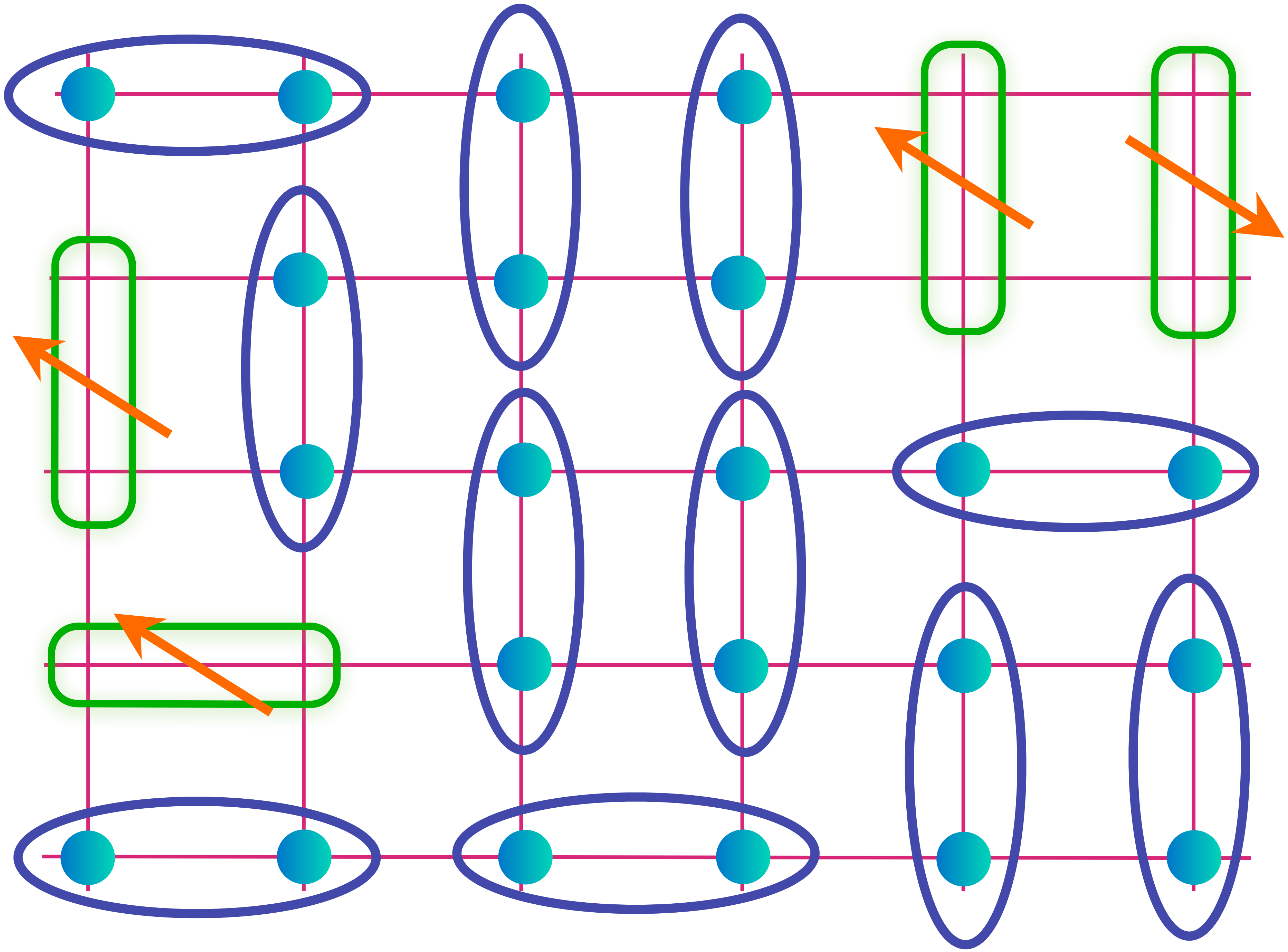
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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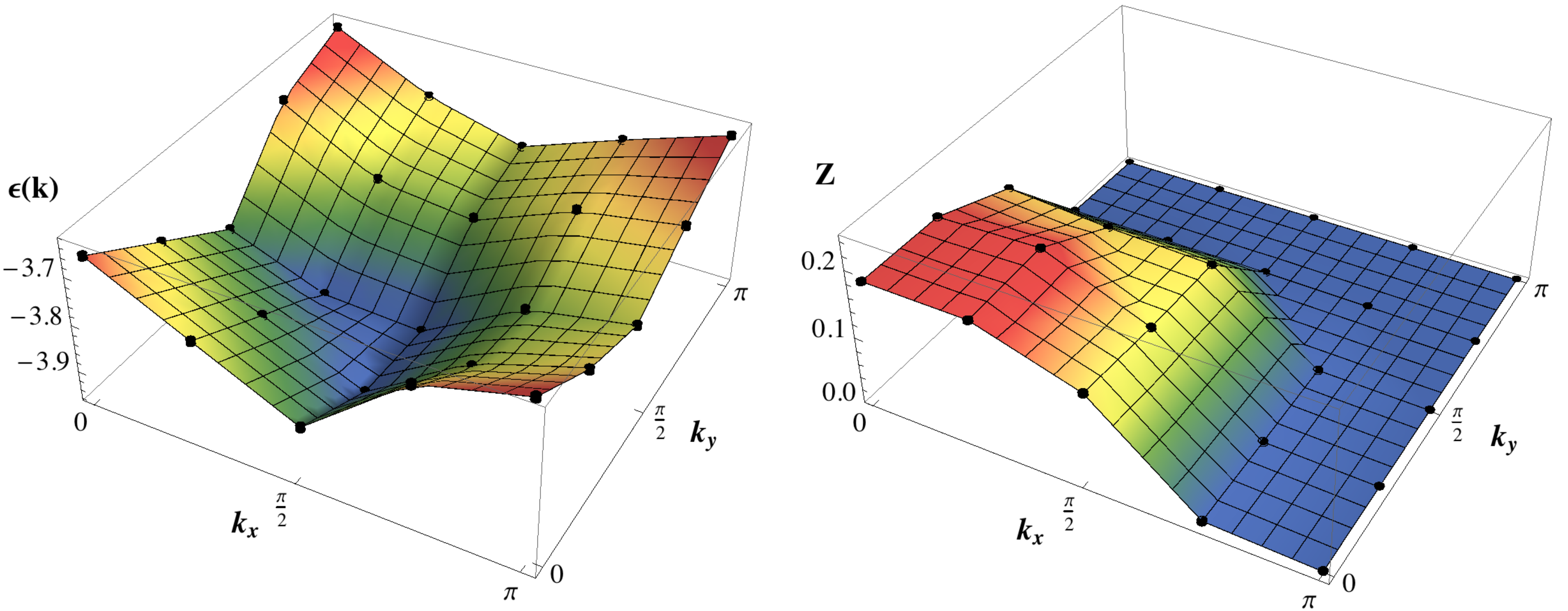
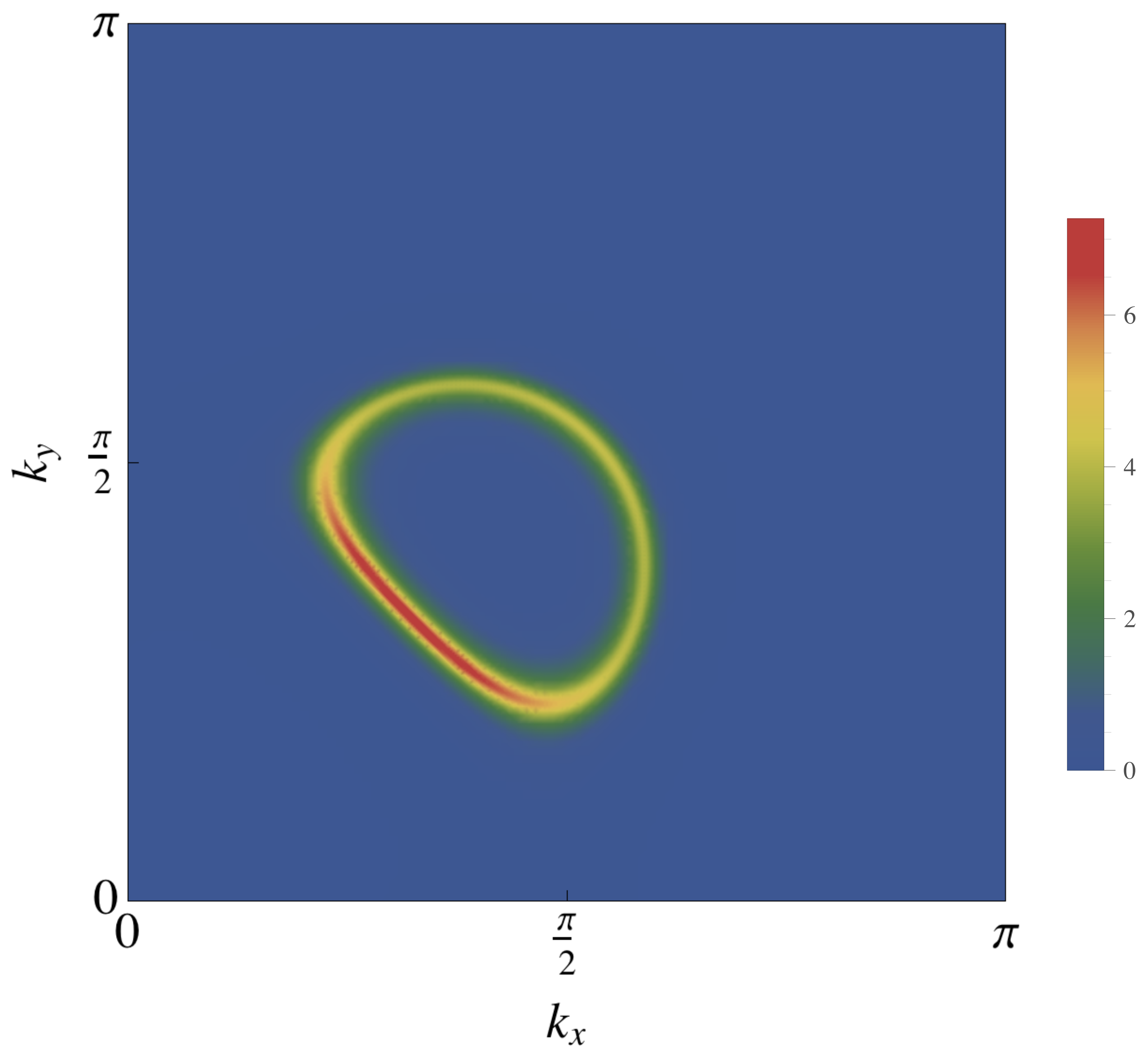
Quantum dimer model with bosonic and fermionic dimers

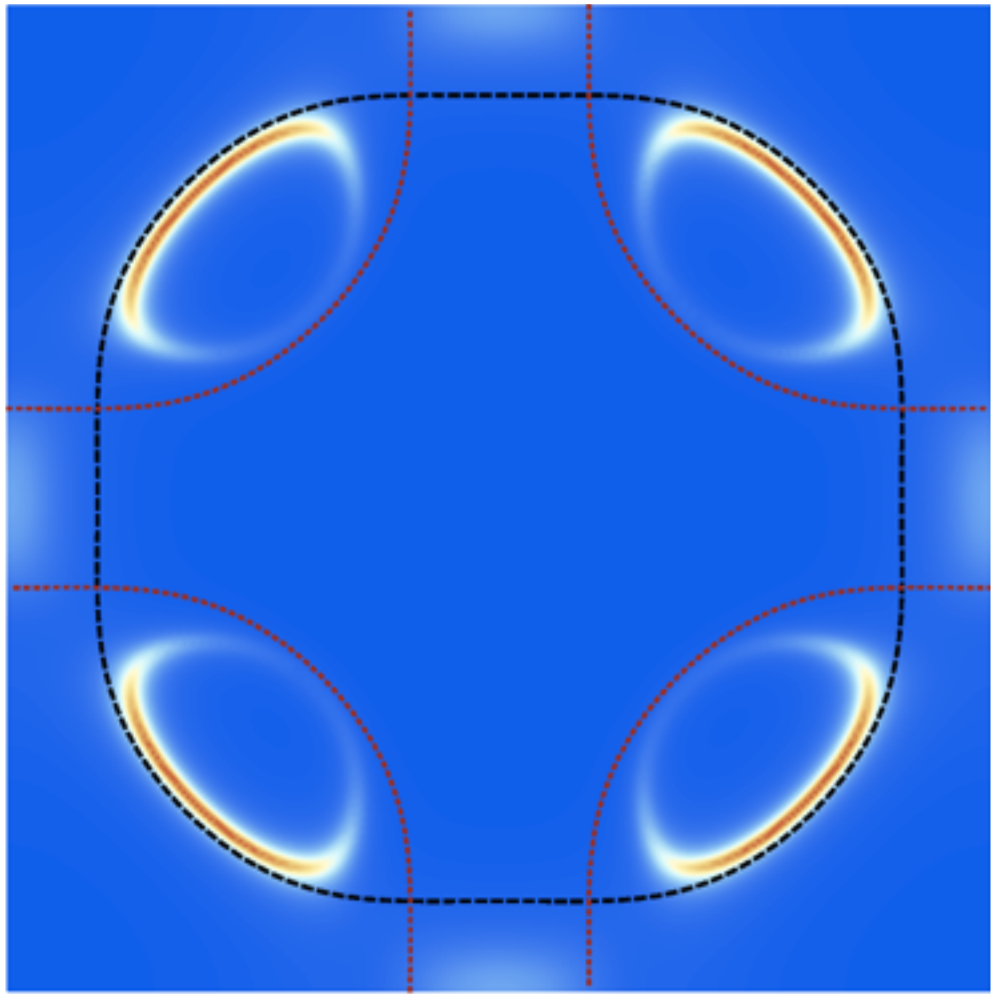


Dispersion and quasiparticle residue of a single fermionic dimer for $J = V = 1$, and hopping parameters obtained from the t-J model for the cuprates, $t_1 = -1.05$, $t_2 = 1.95$ and $t_3 = -0.6$, on a 8×8 lattice.

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



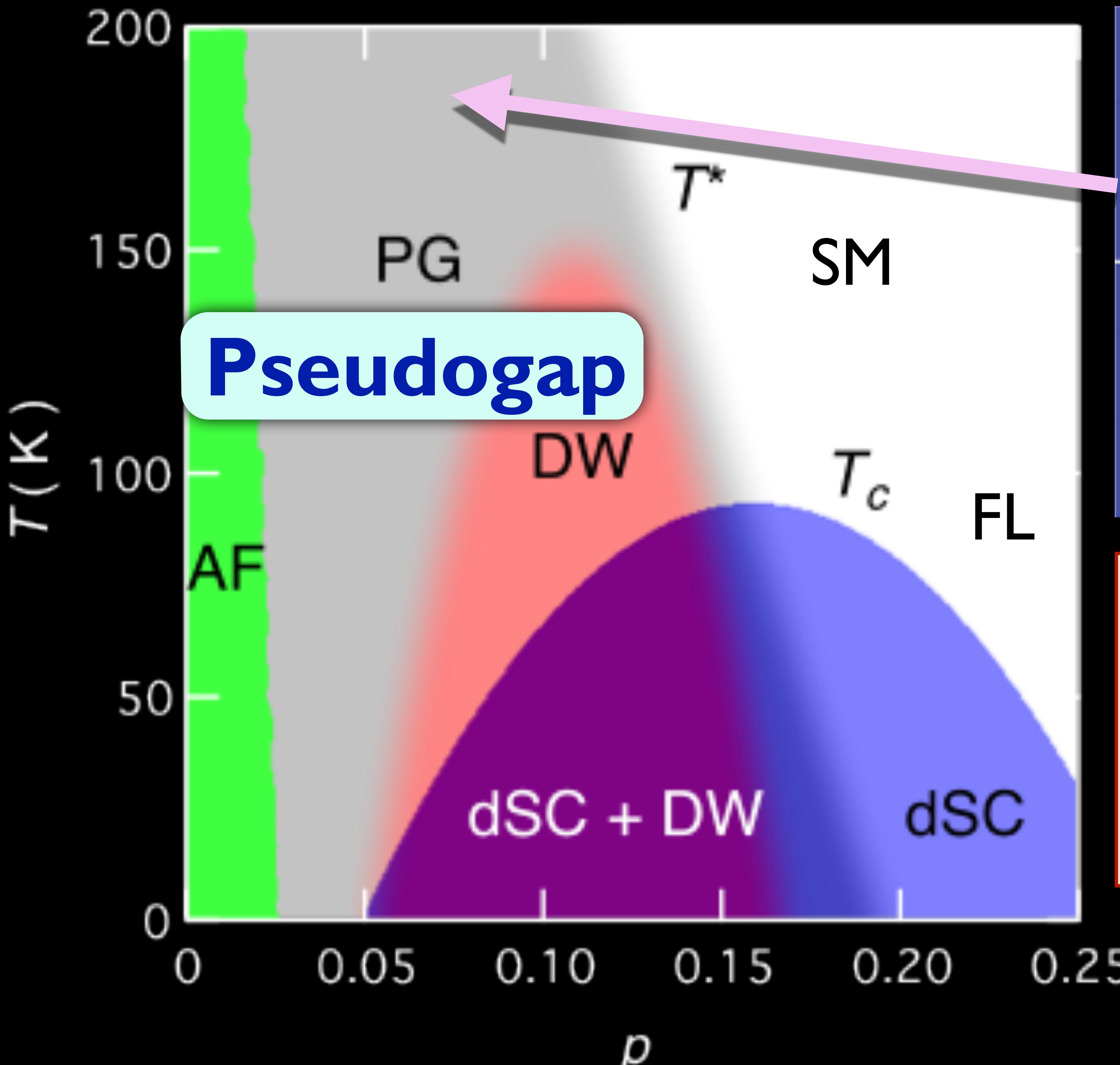
M. Punk, A. Allais, and S. S., arXiv:1501.00978, PNAS to appear

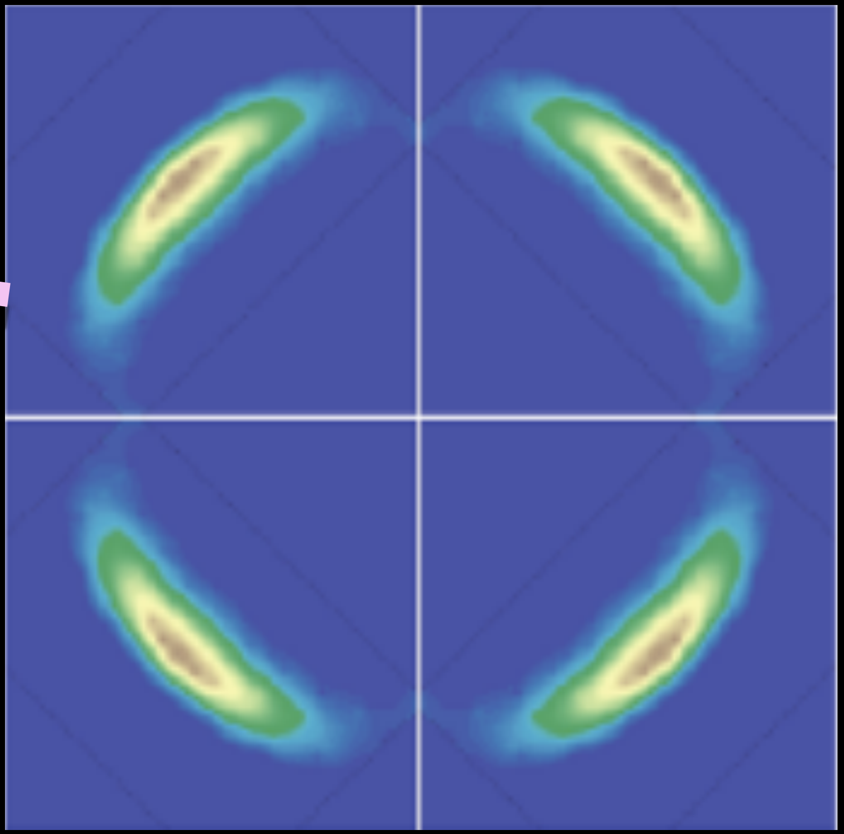


Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)

"Back side" of Fermi surface is suppressed for observables which change electron number in the square lattice

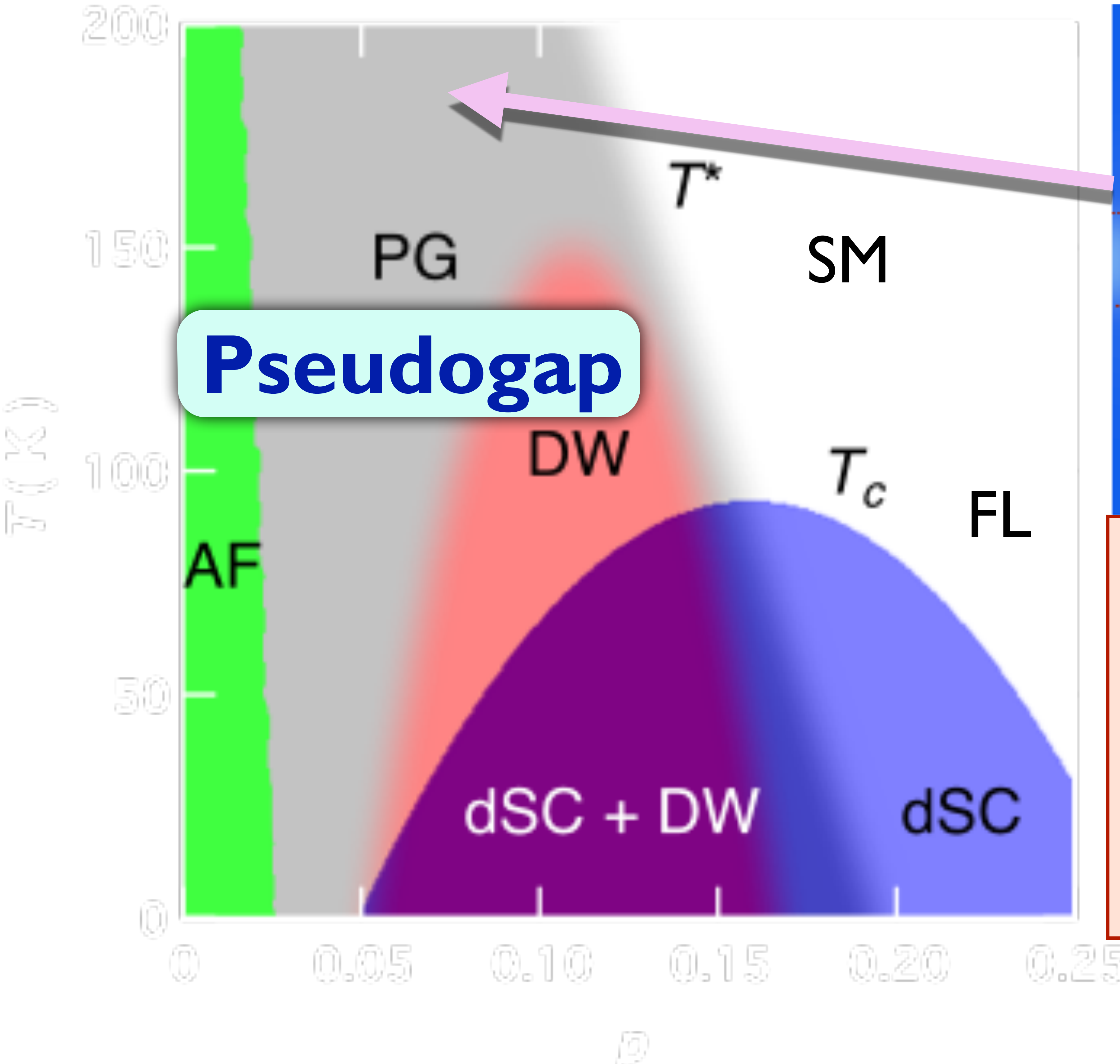
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)

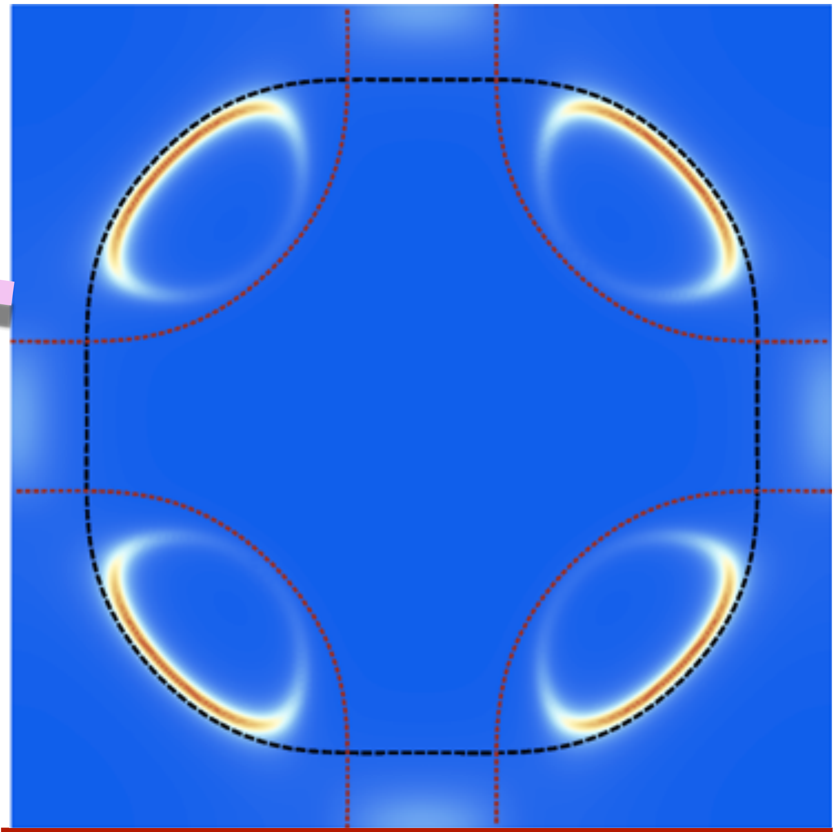




Pseudogap metal at low p

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

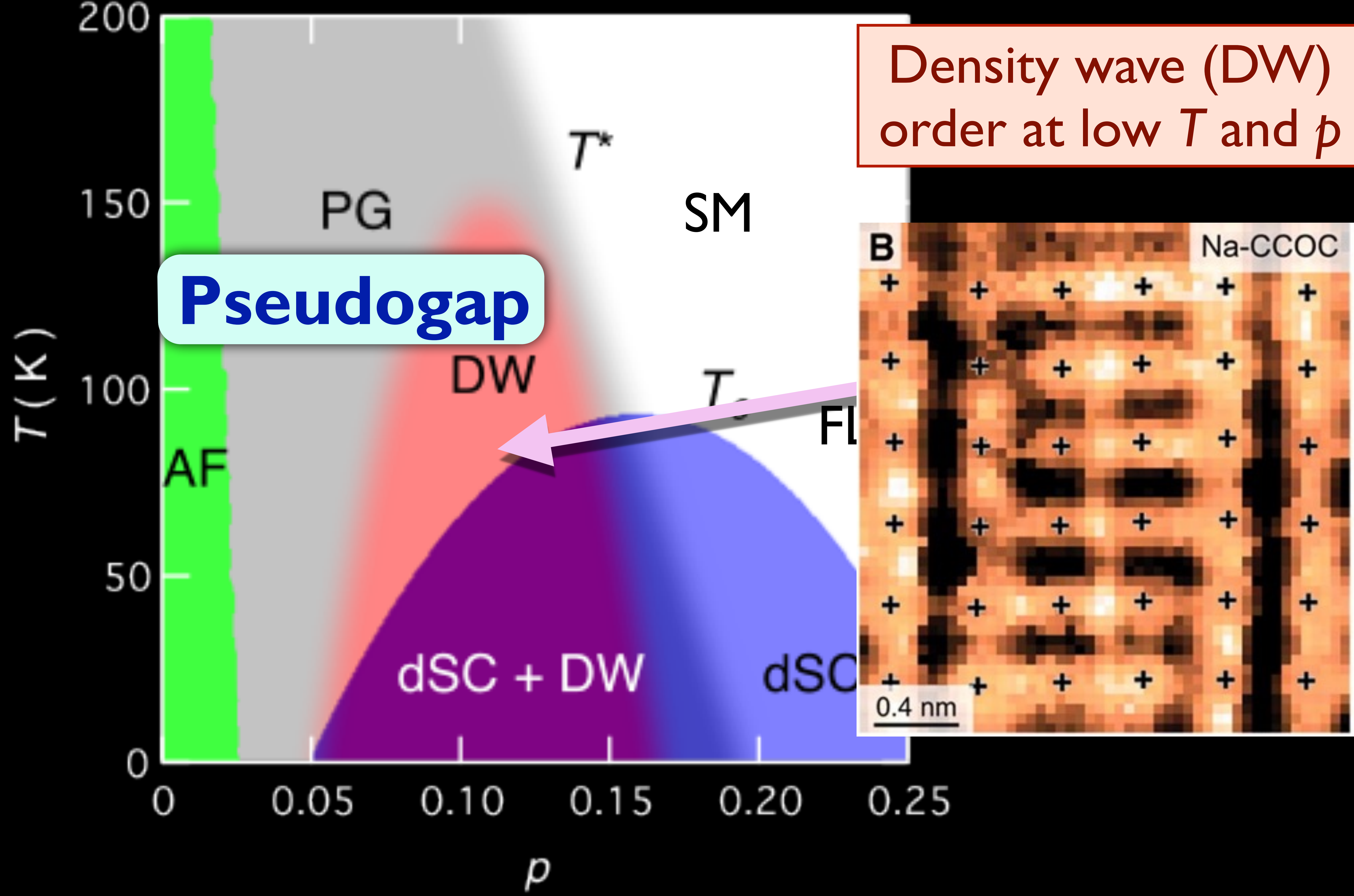




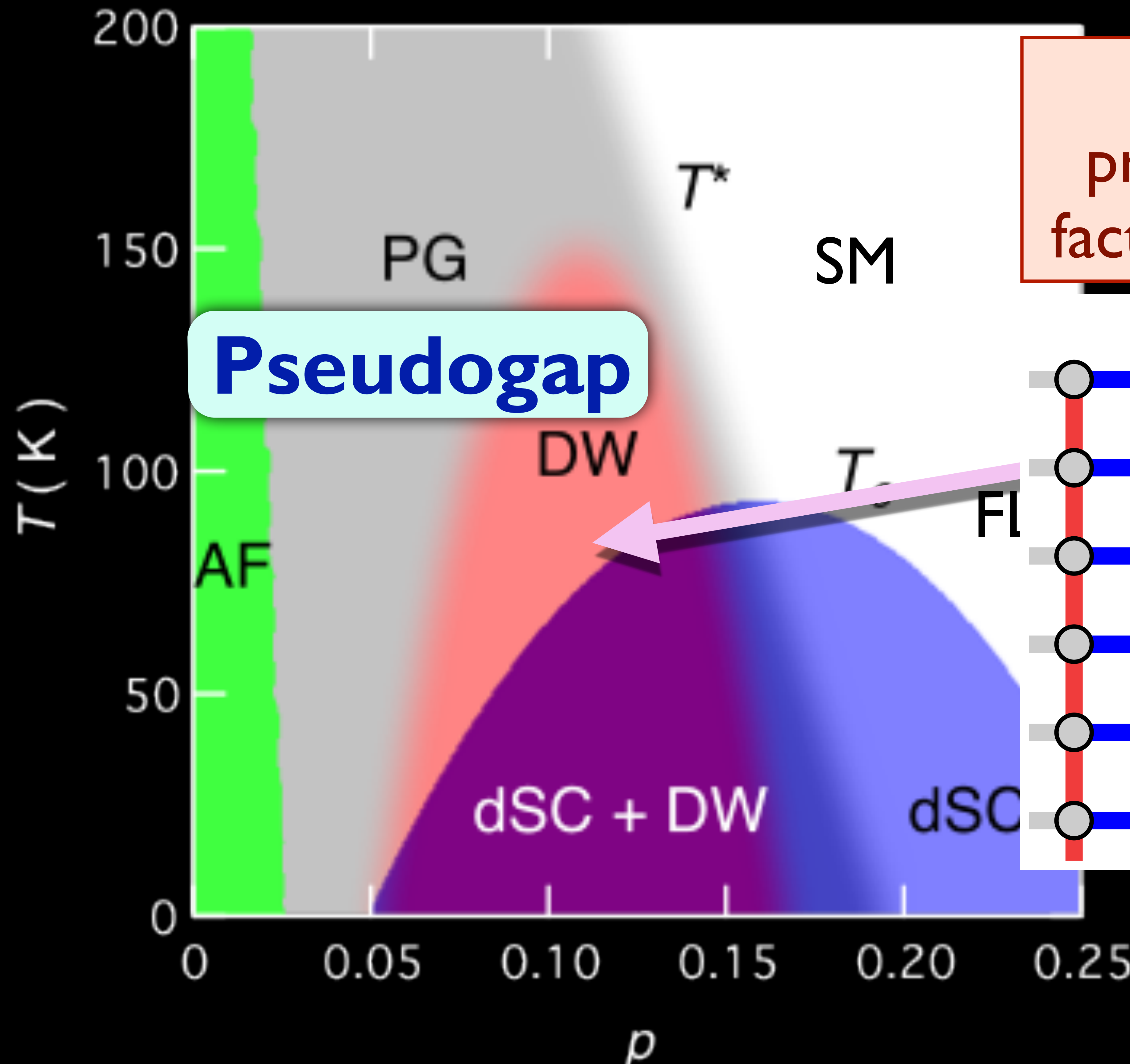
A fractionalized Fermi liquid (FL*) — with electron-like quasiparticles on a Fermi surface of size p coexisting with **topological order**

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

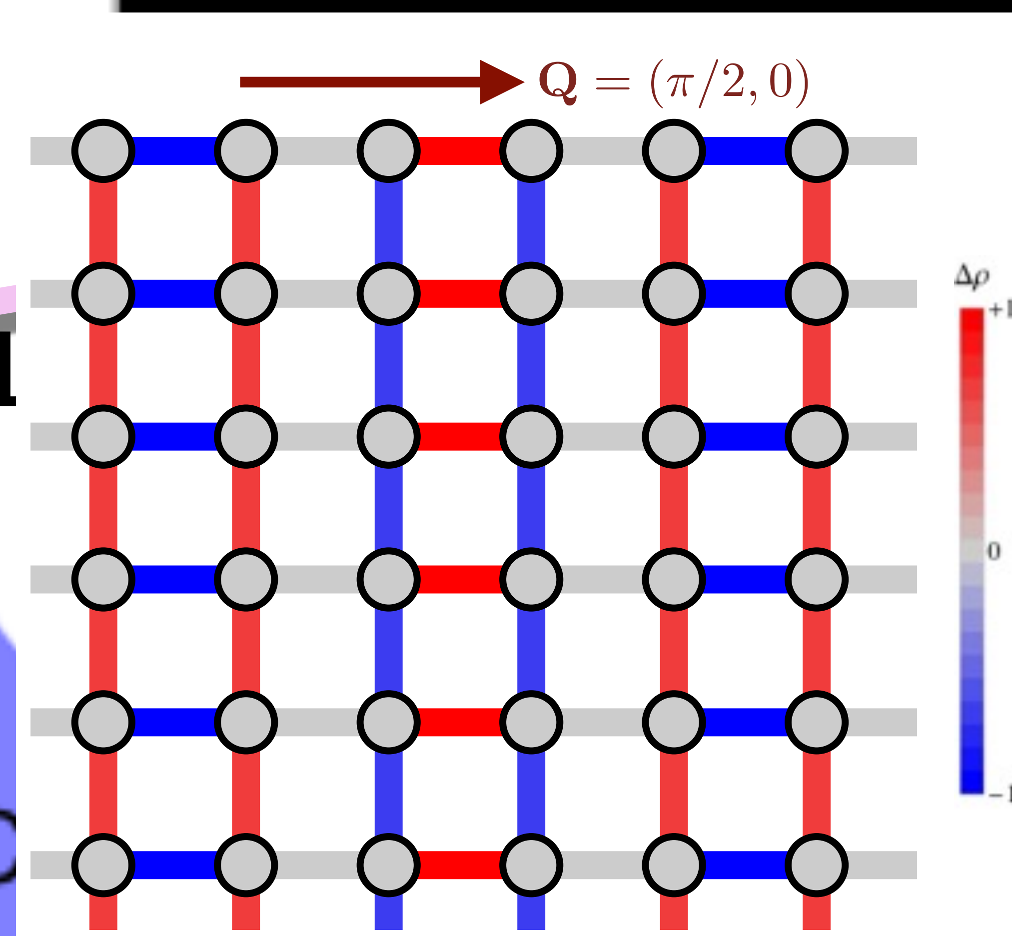
Density wave (DW) order at low *T* and *p*

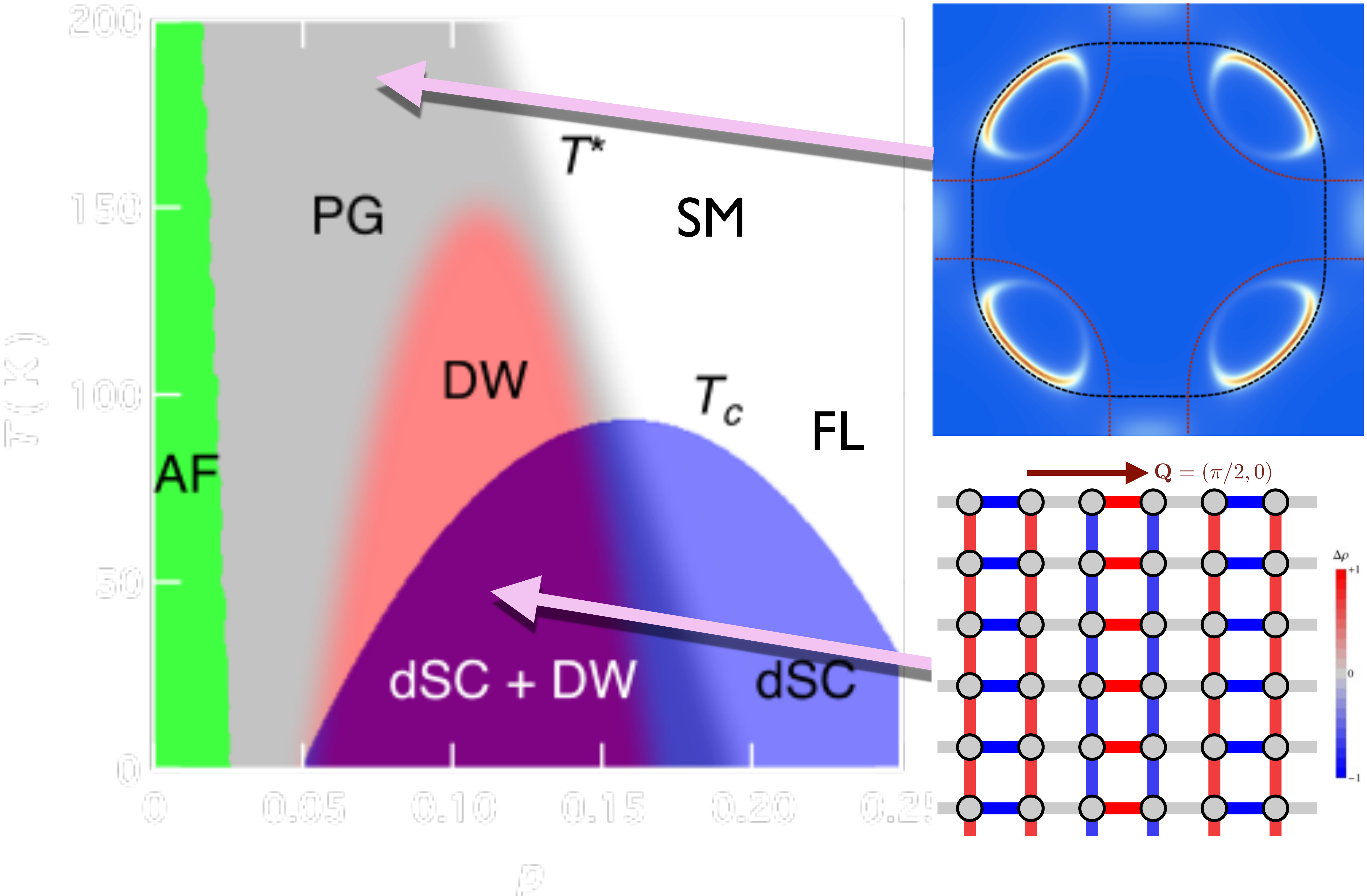


M. A. Metlitski and S. Sachdev, PRB **82**, 075128 (2010). S. Sachdev R. La Placa, PRL **111**, 027202 (2013).
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS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

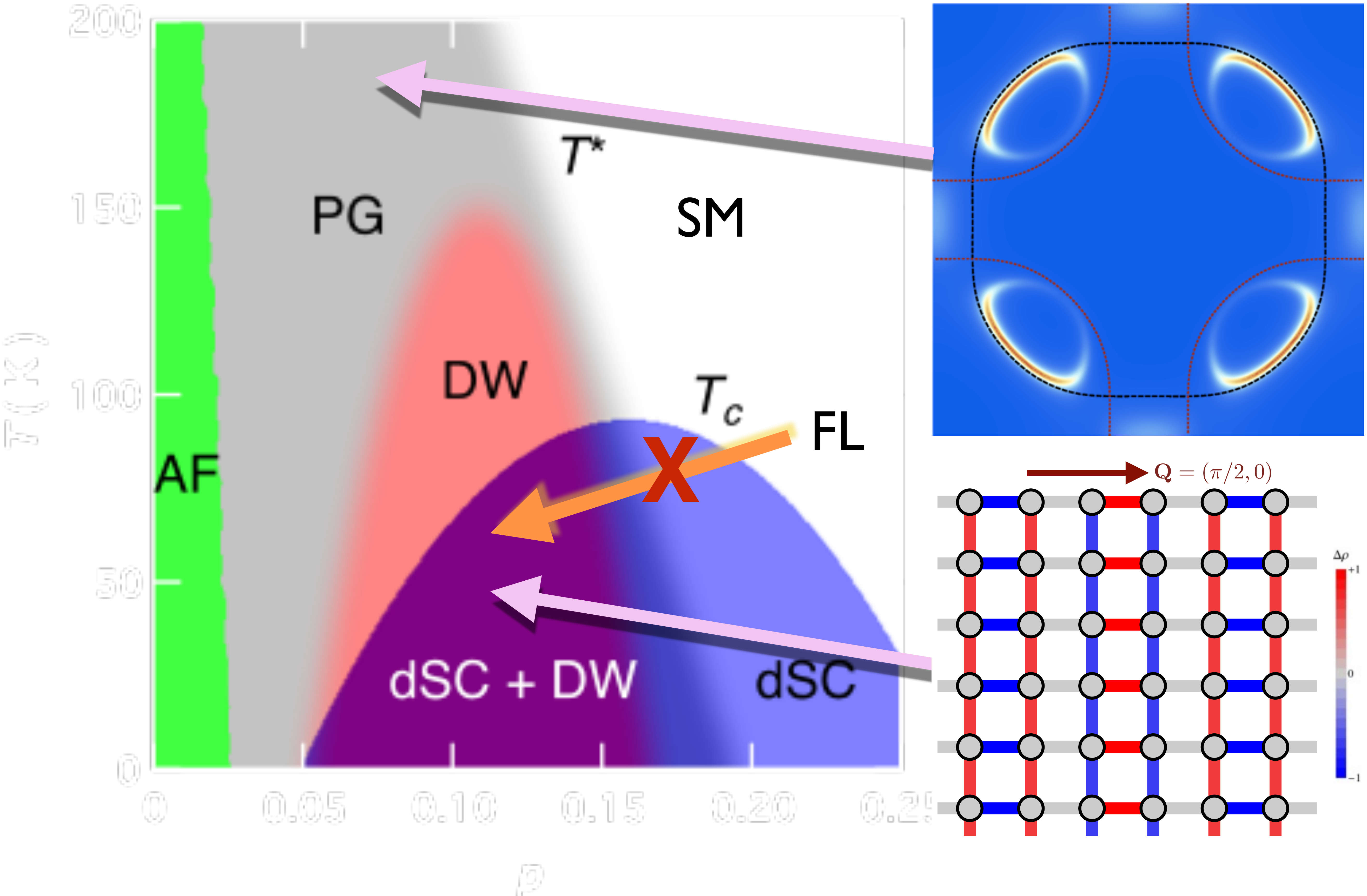


Identified as a predicted "*d*-form factor density wave"



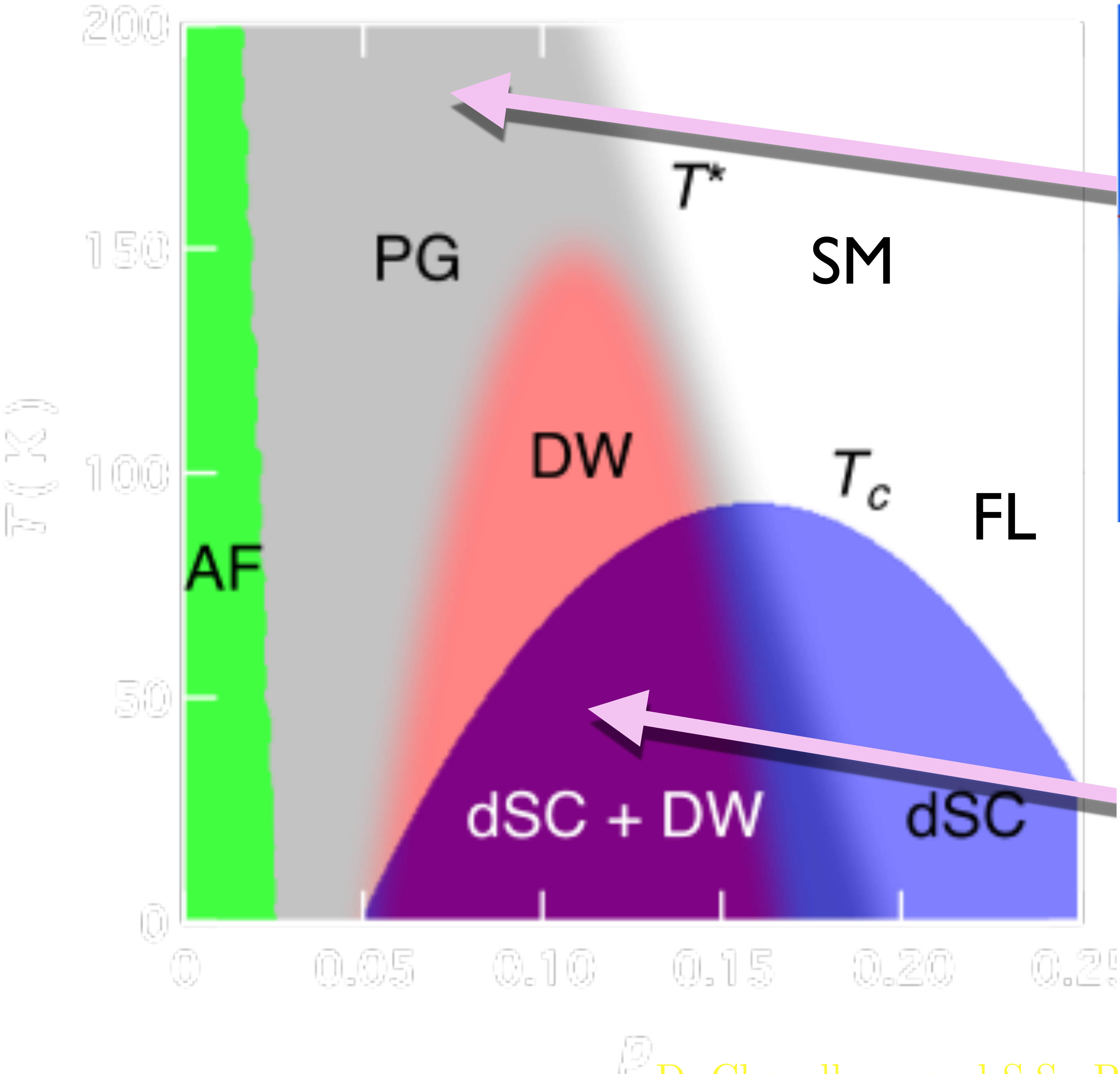


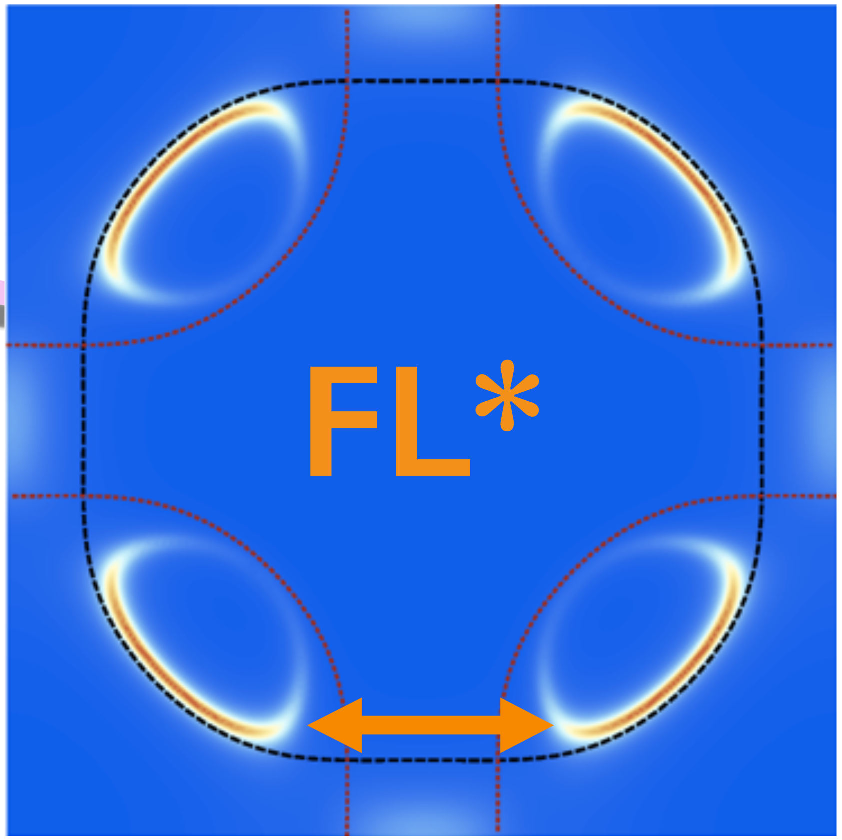
PG
SM
DW
AF
FL
dSC + DW
dSC
T^*
T_c
T (K)
p
$\mathbf{Q} = (\pi/2, 0)$
$\Delta\rho$

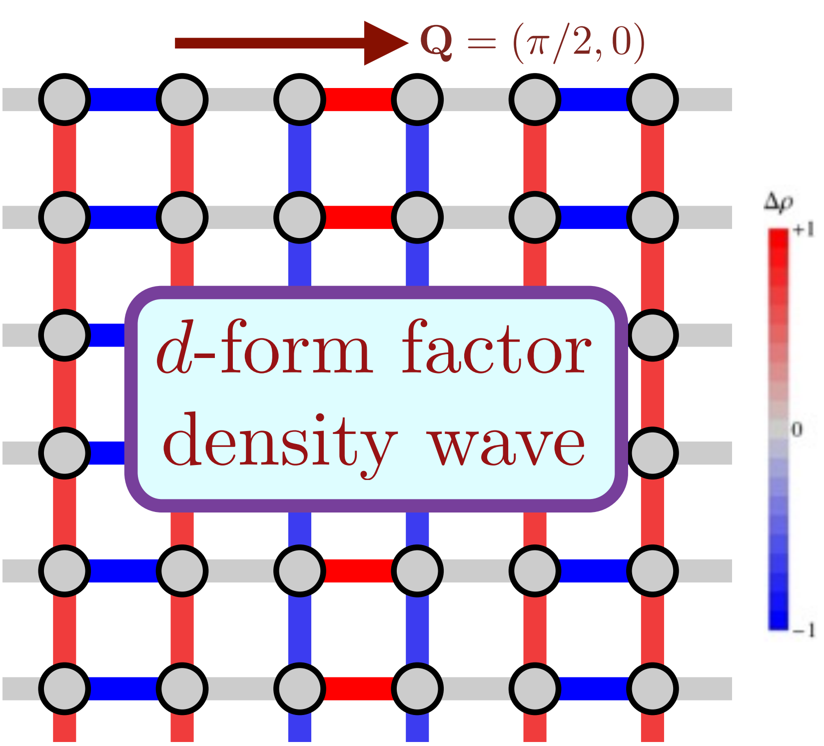


200
150
100
50
0
T (K)
0
0.05
0.10
0.15
0.20
p
AF
PG
T^*
SM
DW
T_c
FL
X
dSC + DW
dSC
$\mathbf{Q} = (\pi/2, 0)$
Δρ
+1
0
−1

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







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

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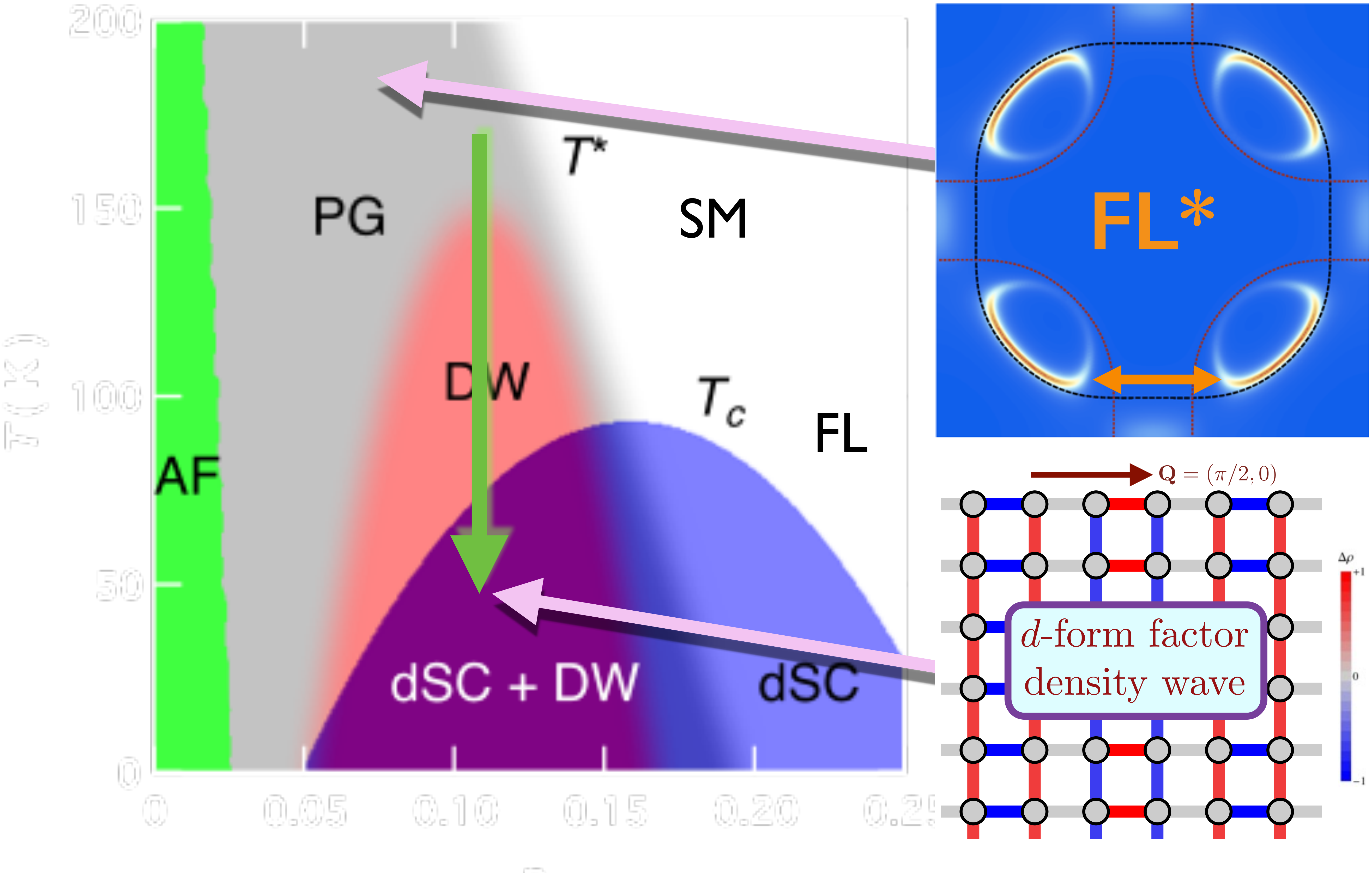

D. Chowdhury and S.S., Phys. Rev. B **90**, 245136 (2014)