Exploring quantum matter in the high temperature superconductors

Perimeter Institute, Waterloo
June 23, 2015

Subir Sachdev

PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

Talk online: sachdev.physics.harvard.edu

PHYSICS
VE RI TAS
HARVARD

Flavors of Quantum Matter

Flavors of Quantum Matter

A. Ordinary quantum matter

Independent electrons, or pairs of electrons

Flavors of Quantum Matter

A. Ordinary quantum matter

Independent electrons, or pairs of electrons

B. Topological quantum matter

Long-range quantum entanglement leads to sensitivity to spatial topology

Flavors of Quantum Matter

A. Ordinary quantum matter

Independent electrons, or pairs of electrons

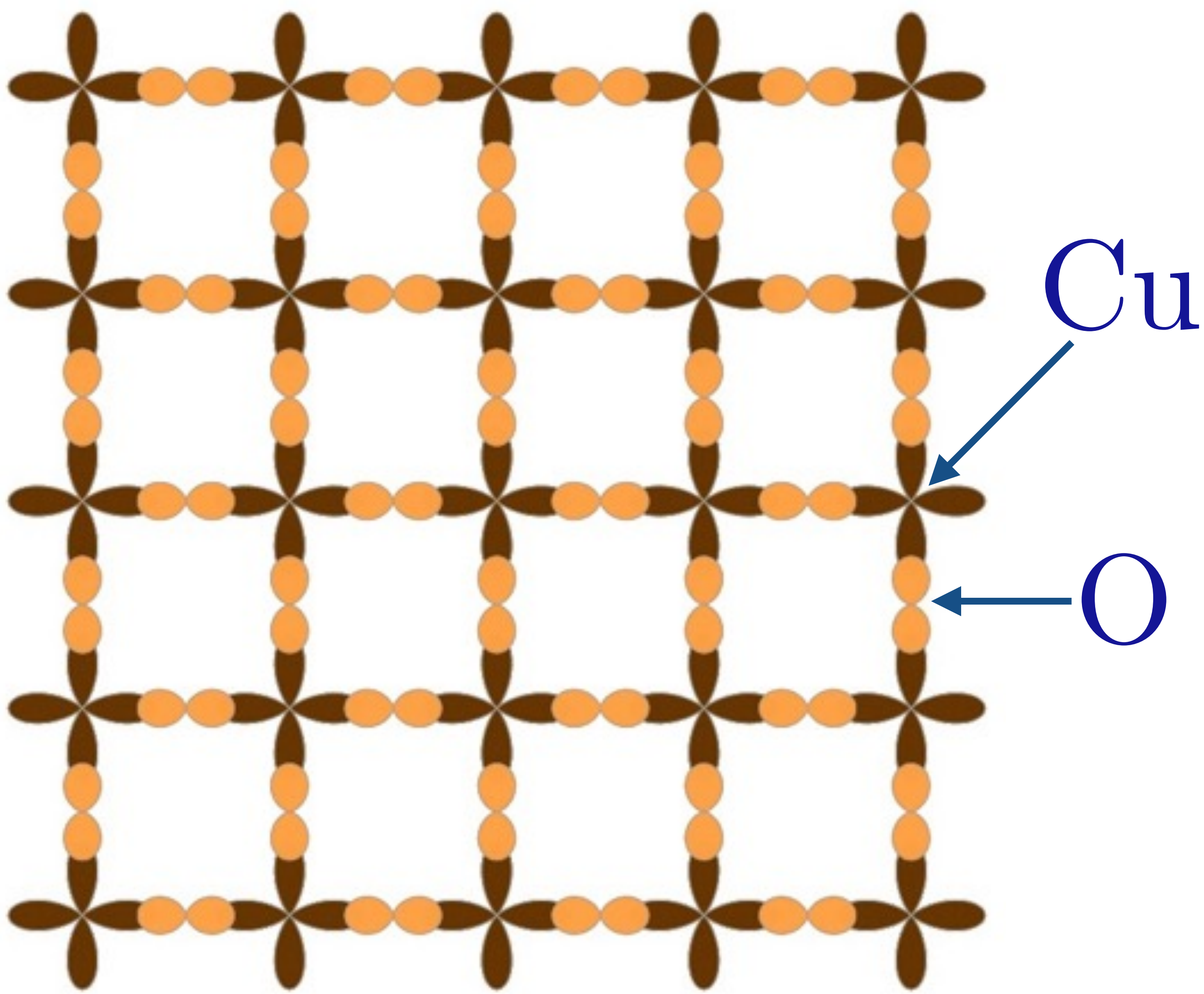
B. Topological quantum matter

Long-range quantum entanglement leads to sensitivity to spatial topology

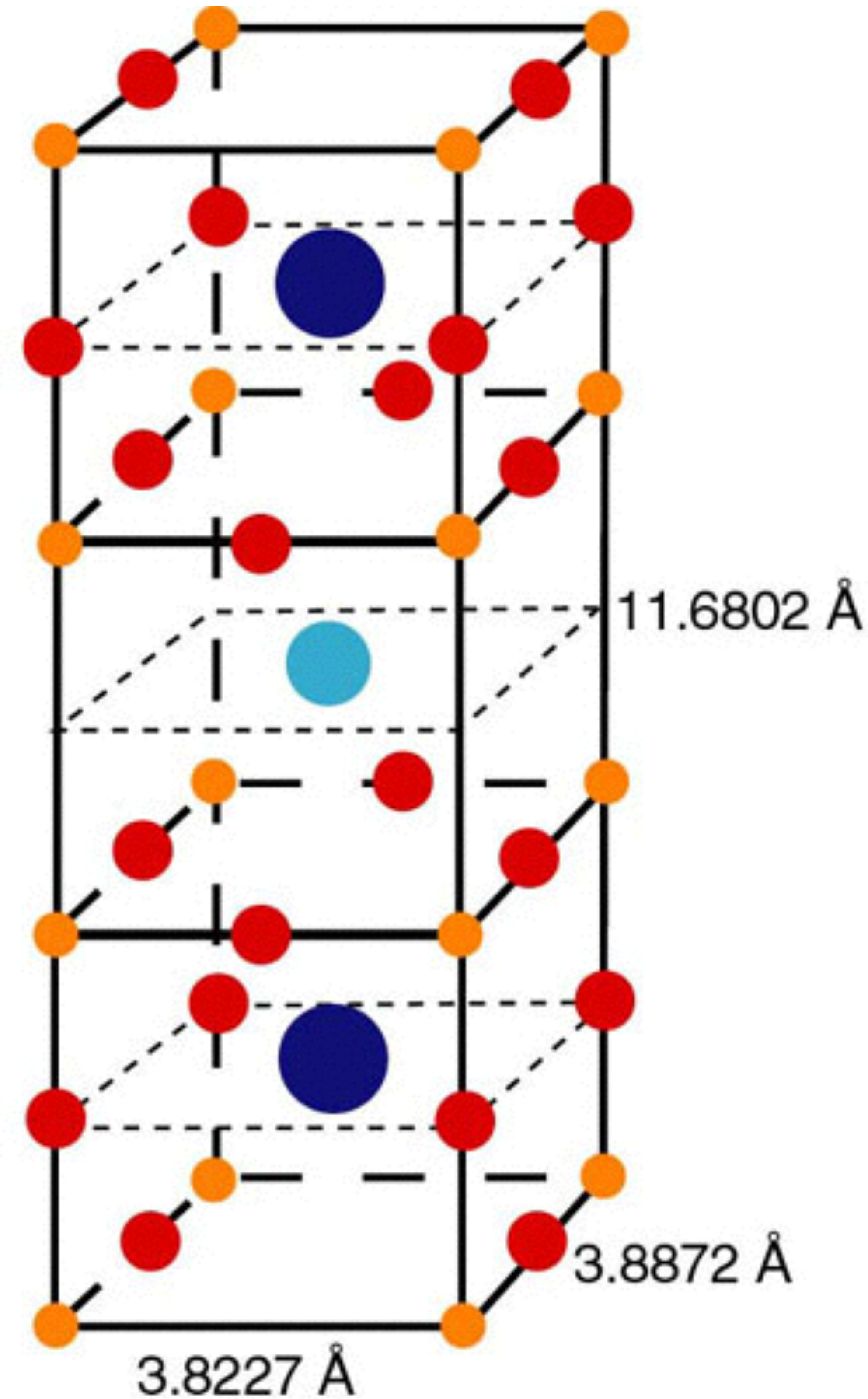
C. Quantum matter without quasiparticles

Strange metals: infinite-range model maps to extremal charged black holes and yields Bekenstein-Hawking entropy

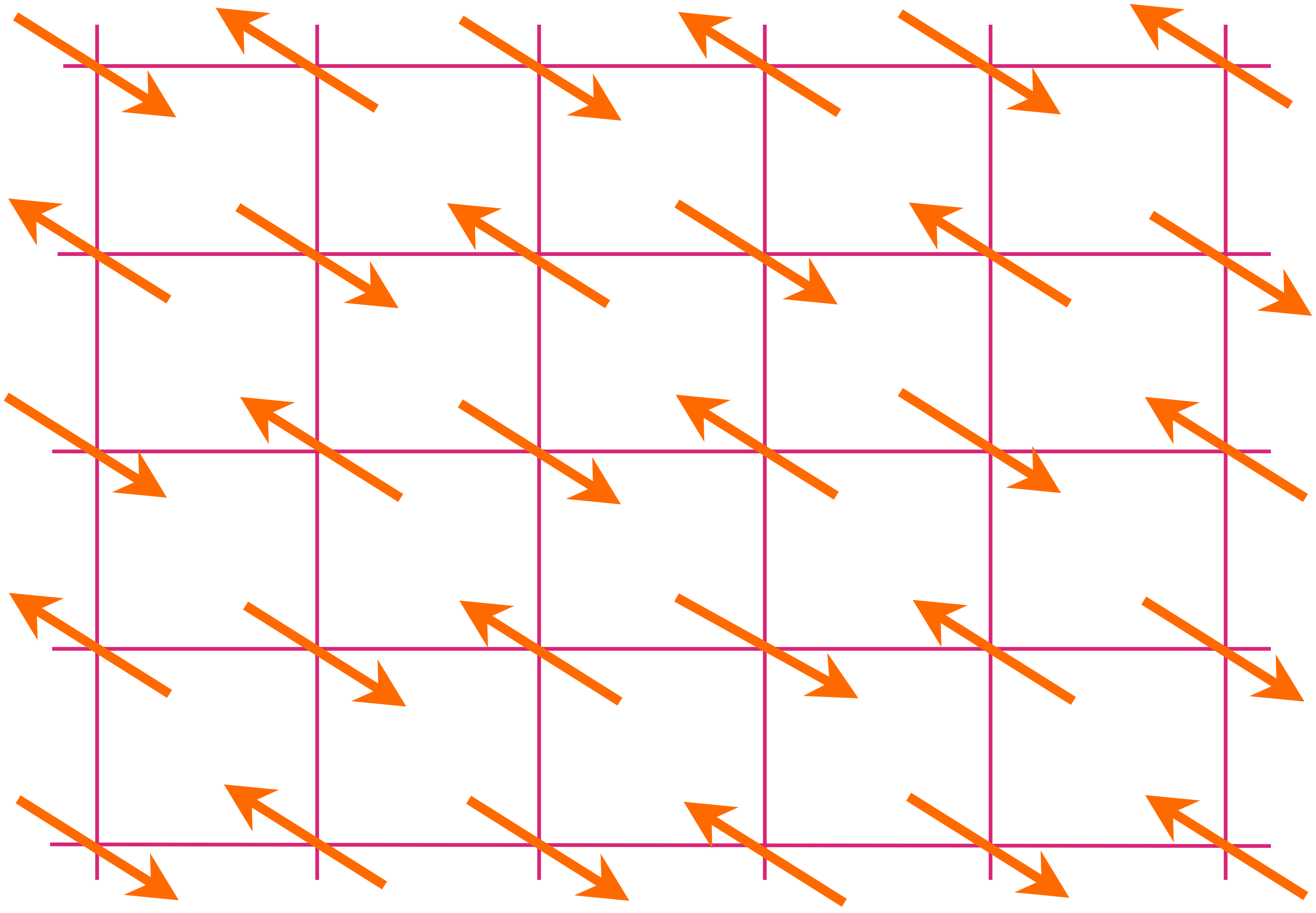
High temperature superconductors



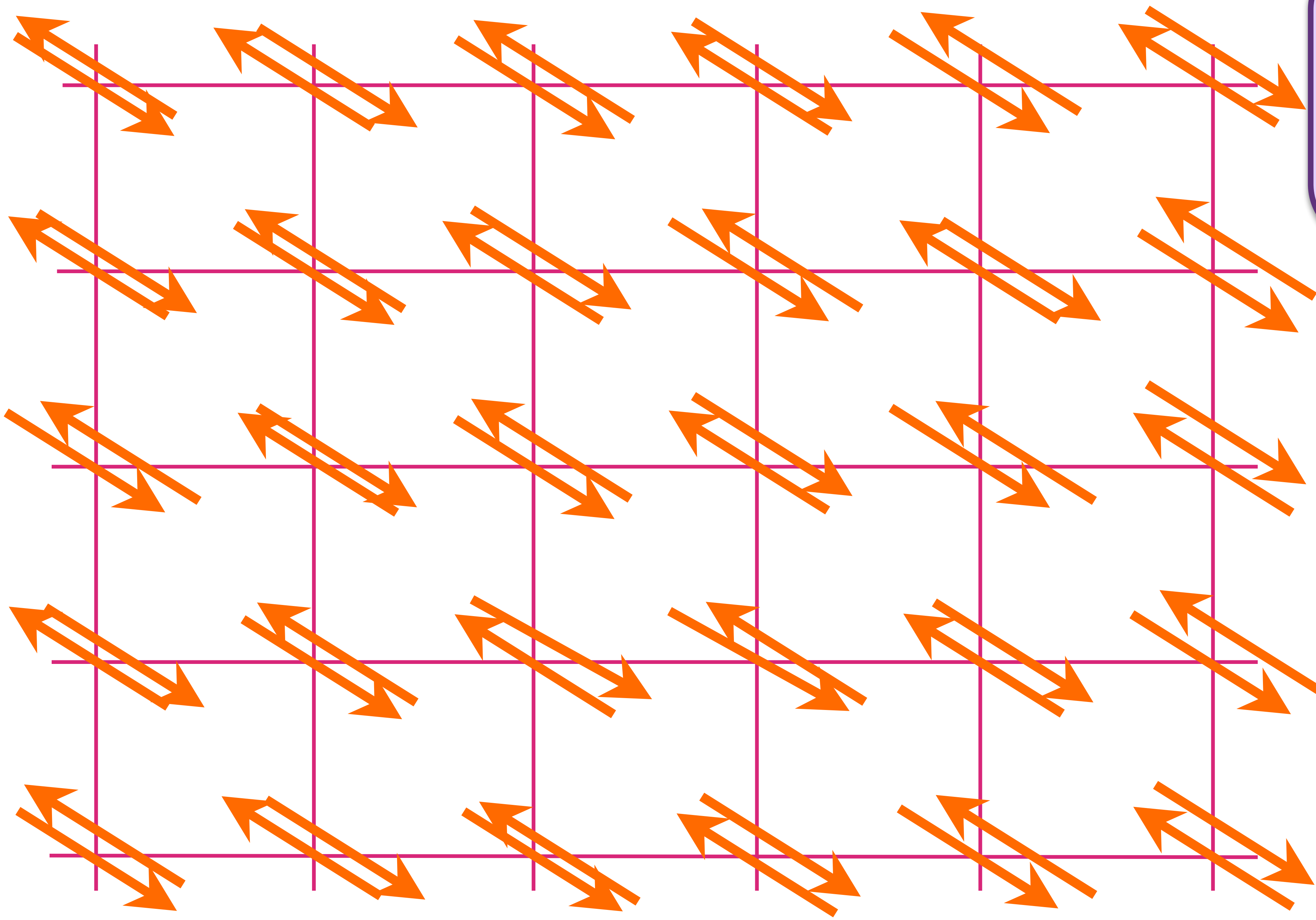
CuO_2 plane



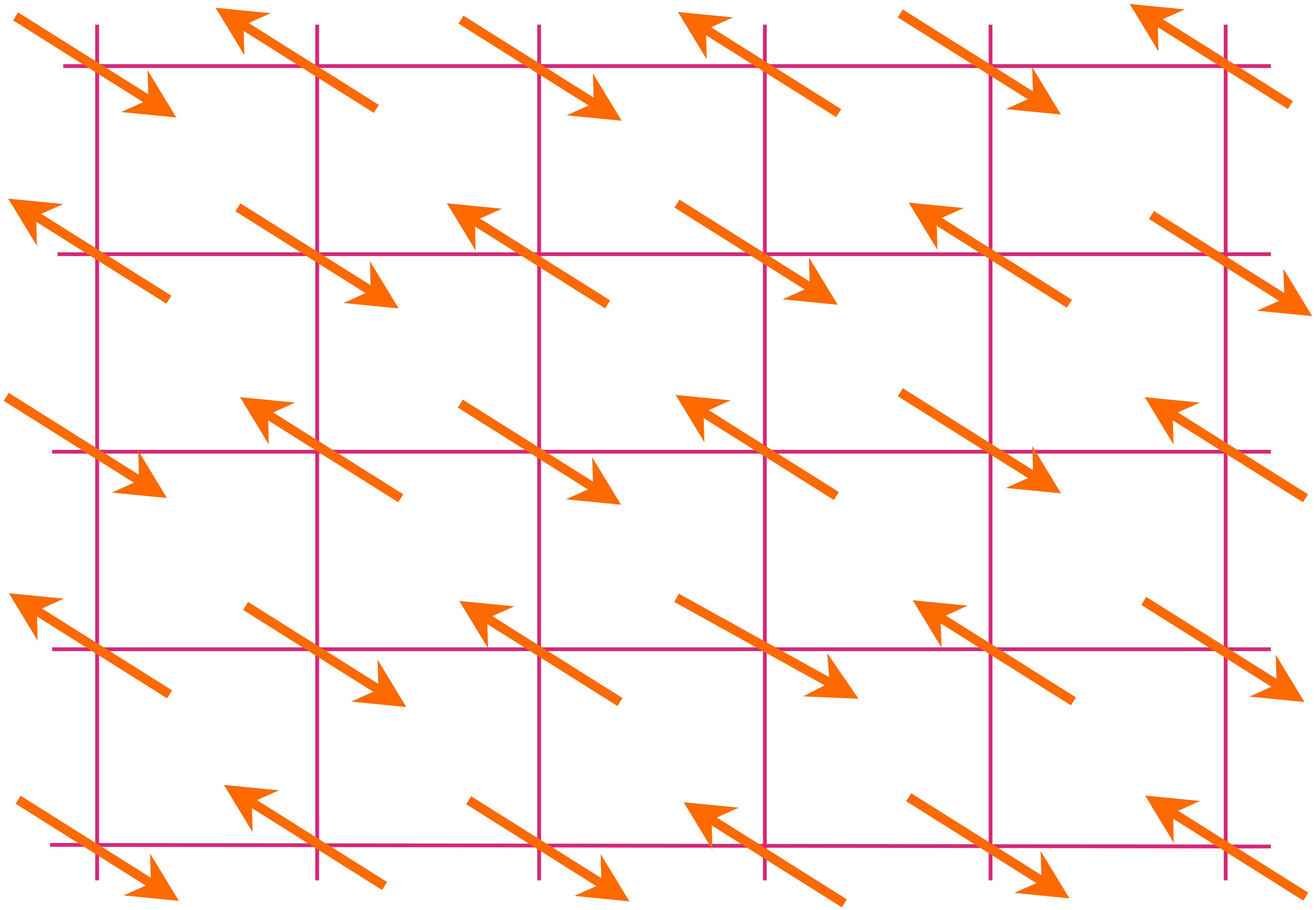
$YBa_2Cu_3O_{6+x}$



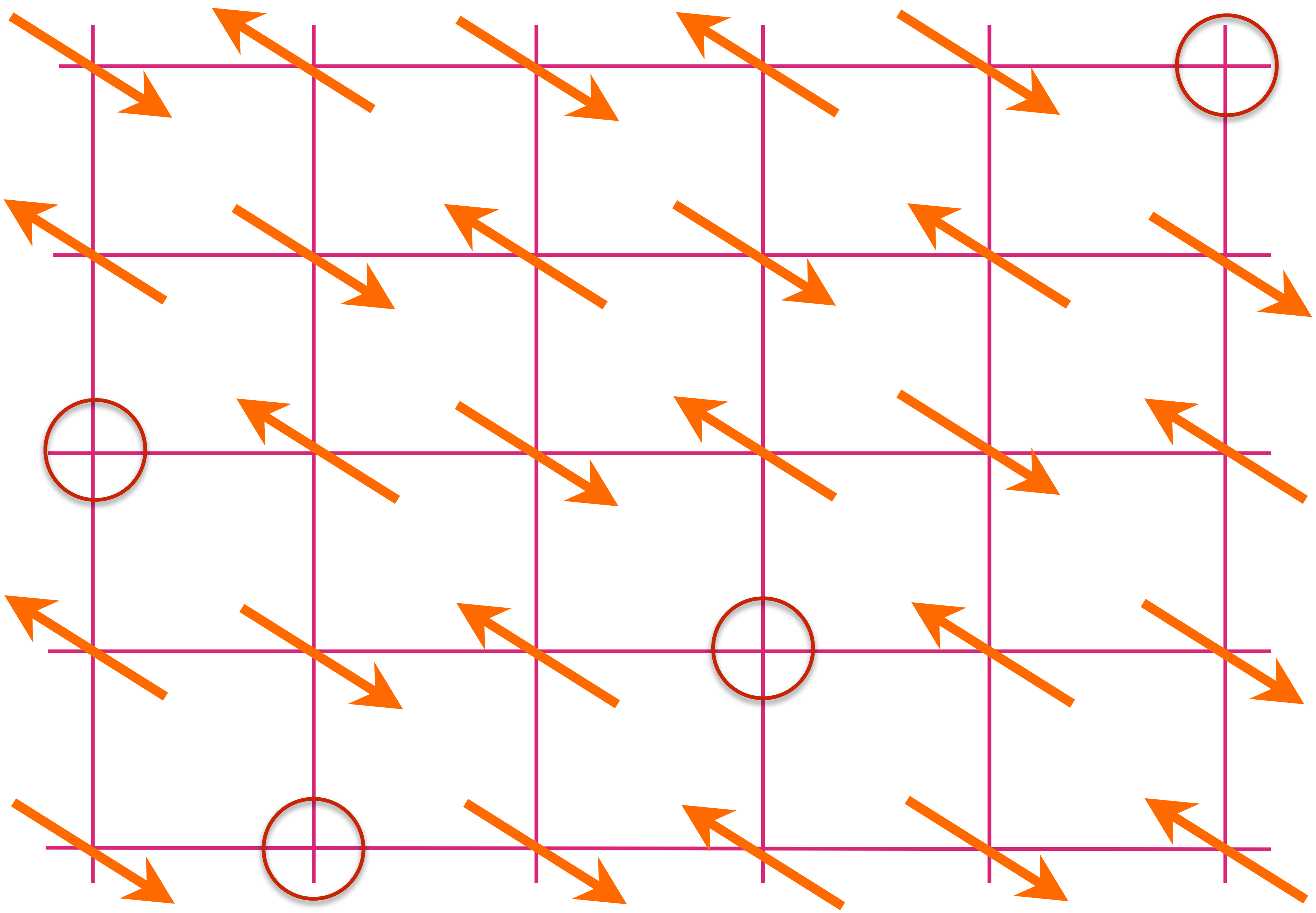
“Undoped” Anti-ferromagnet



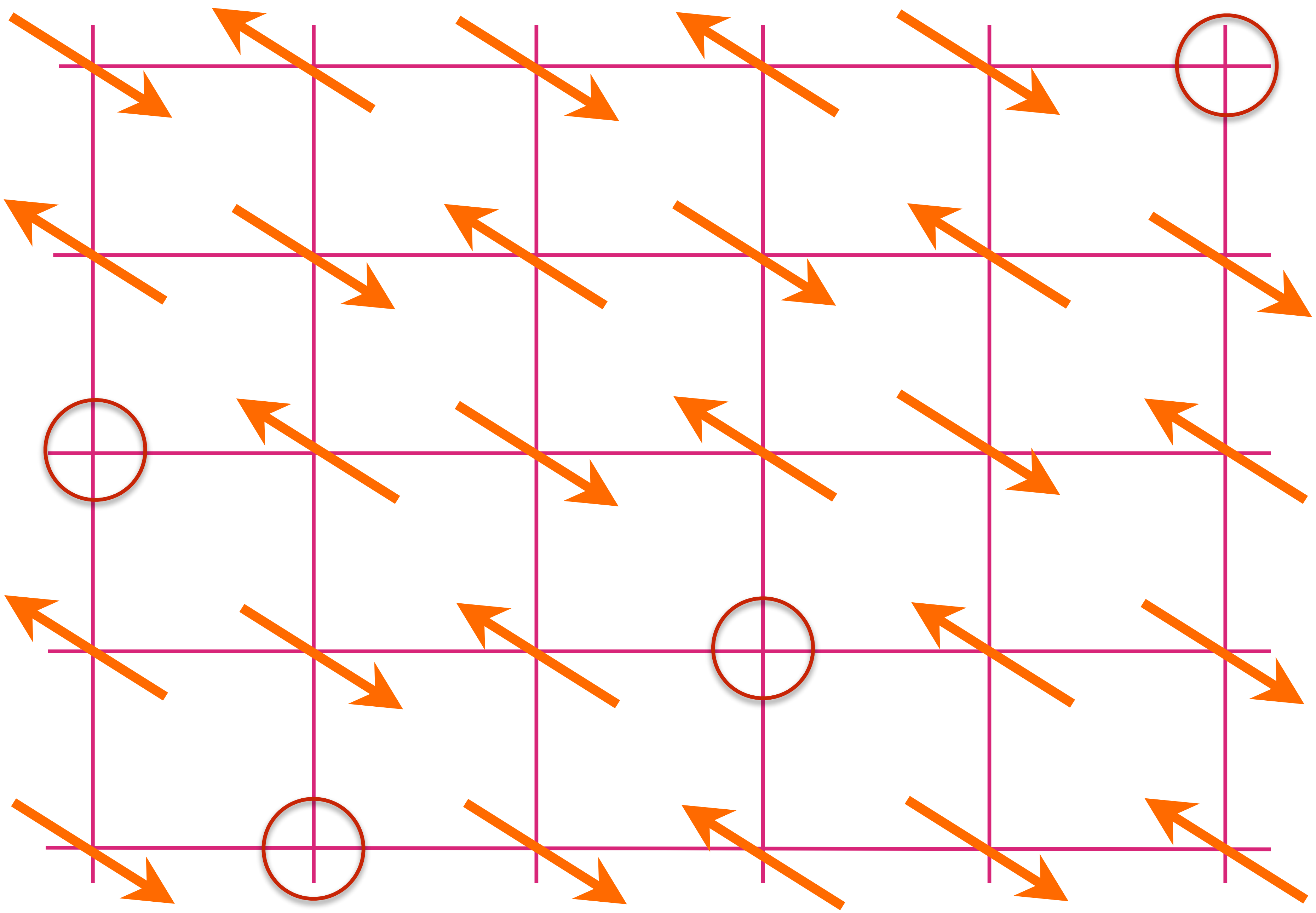
Filled Band



“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

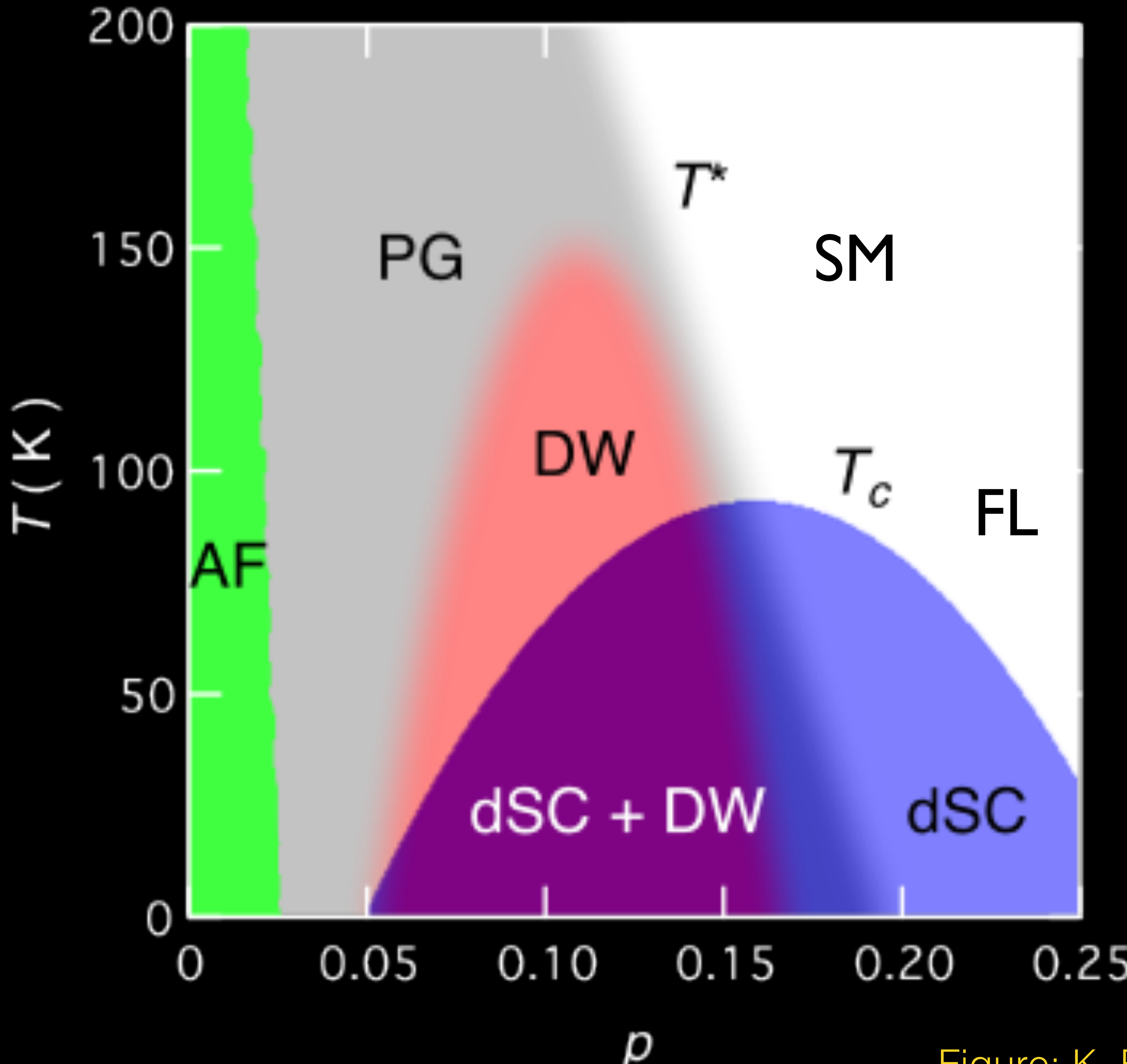


Figure: K. Fujita and J. C. Seamus Davis

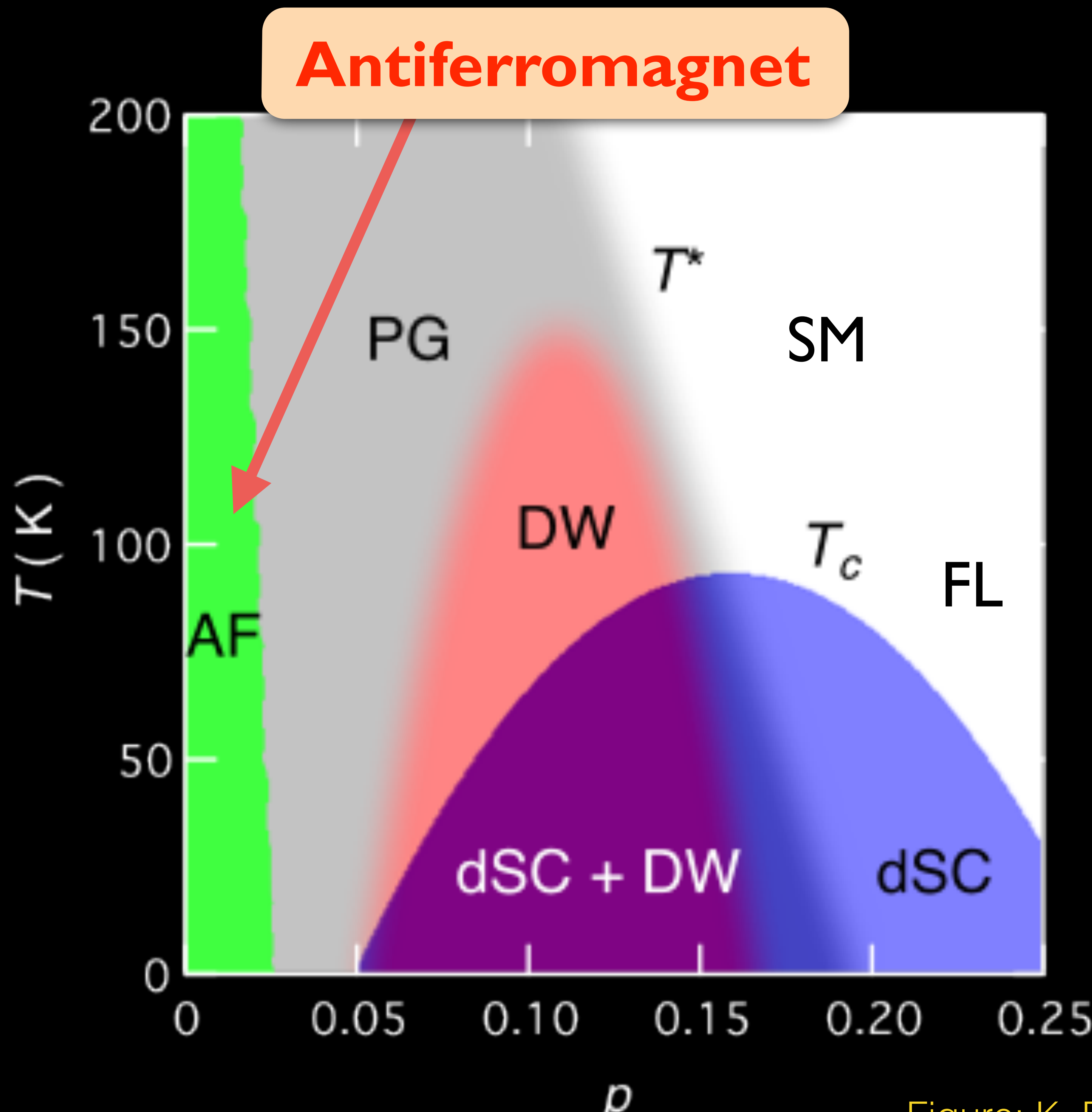
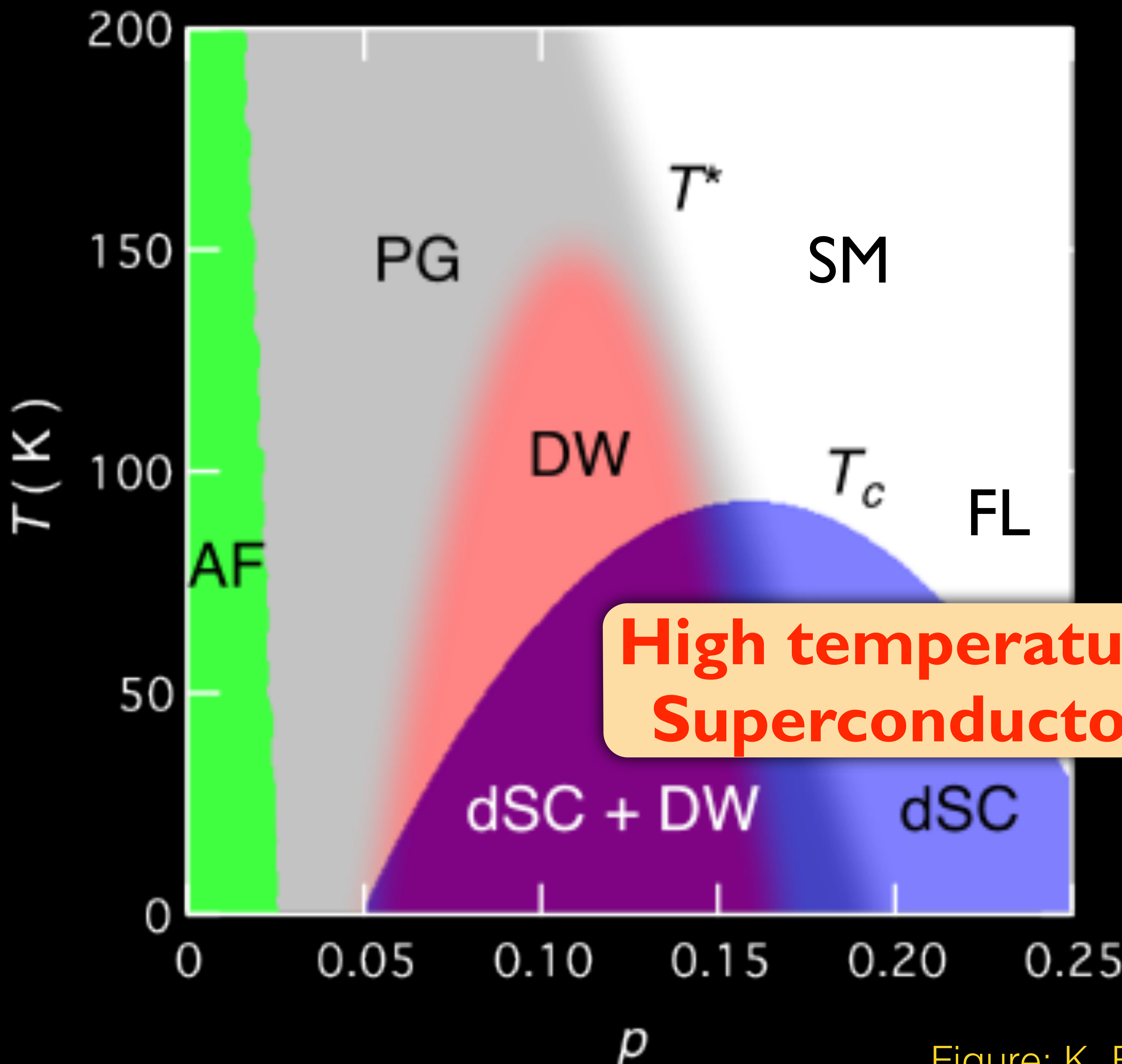


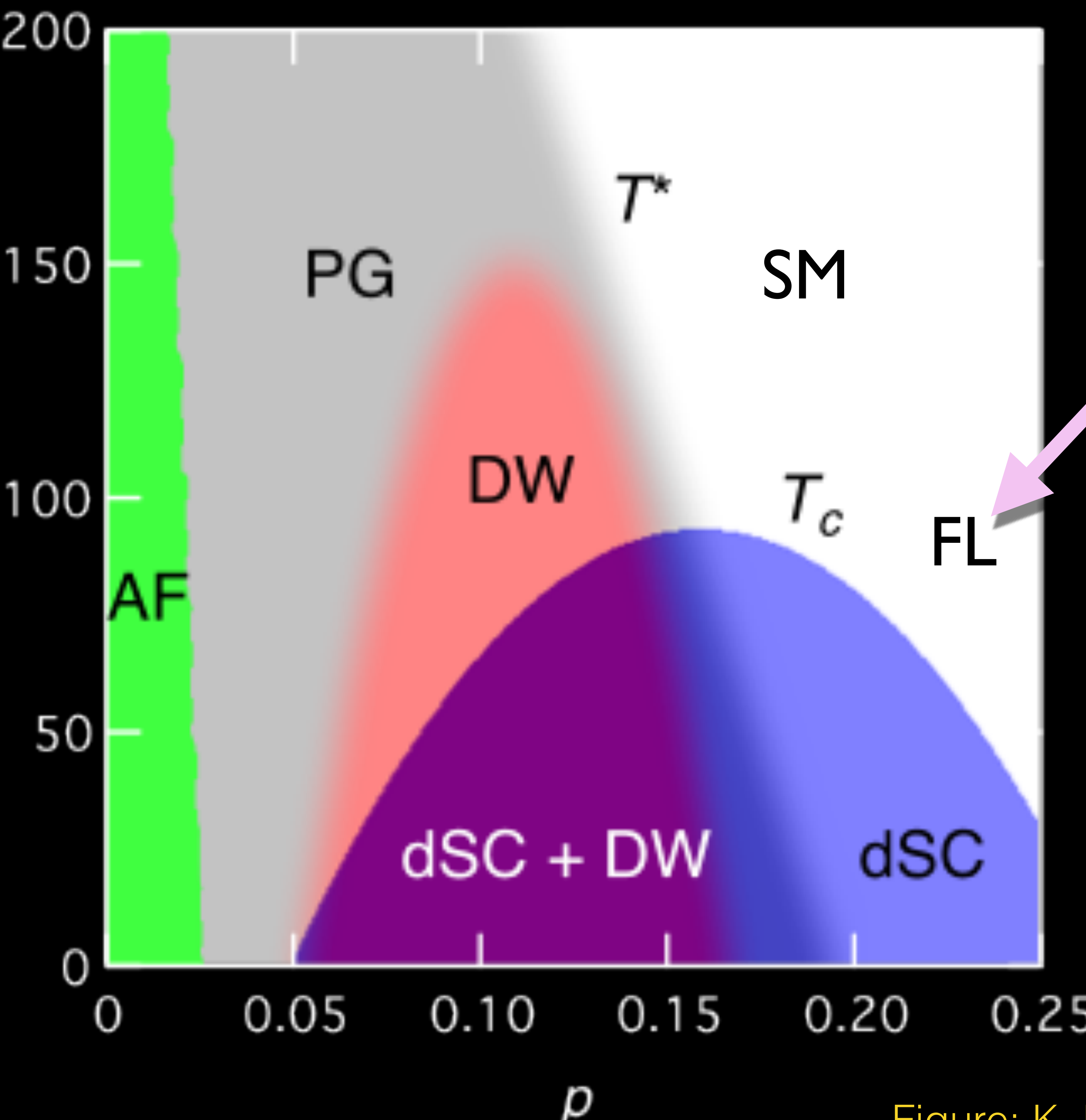
Figure: K. Fujita and J. C. Seamus Davis

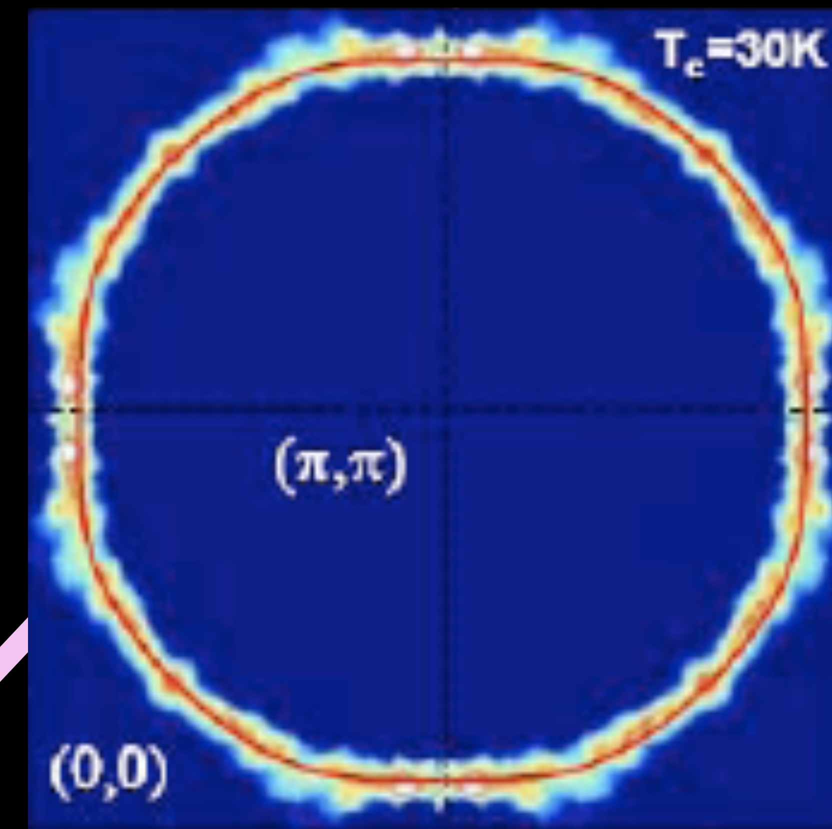


High temperature Superconductor

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)



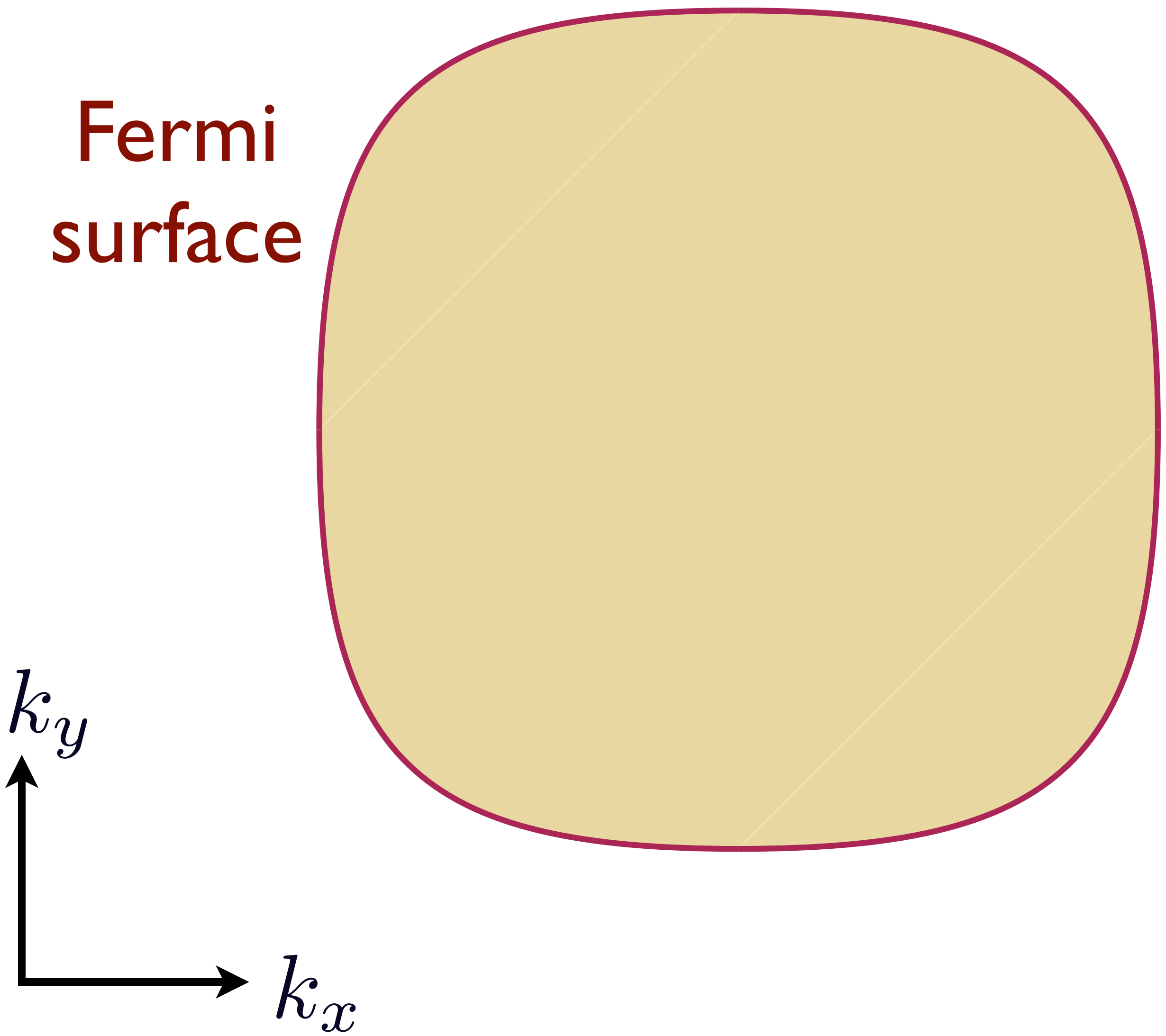


Conventional metal

Area enclosed by Fermi surface $=1+p$

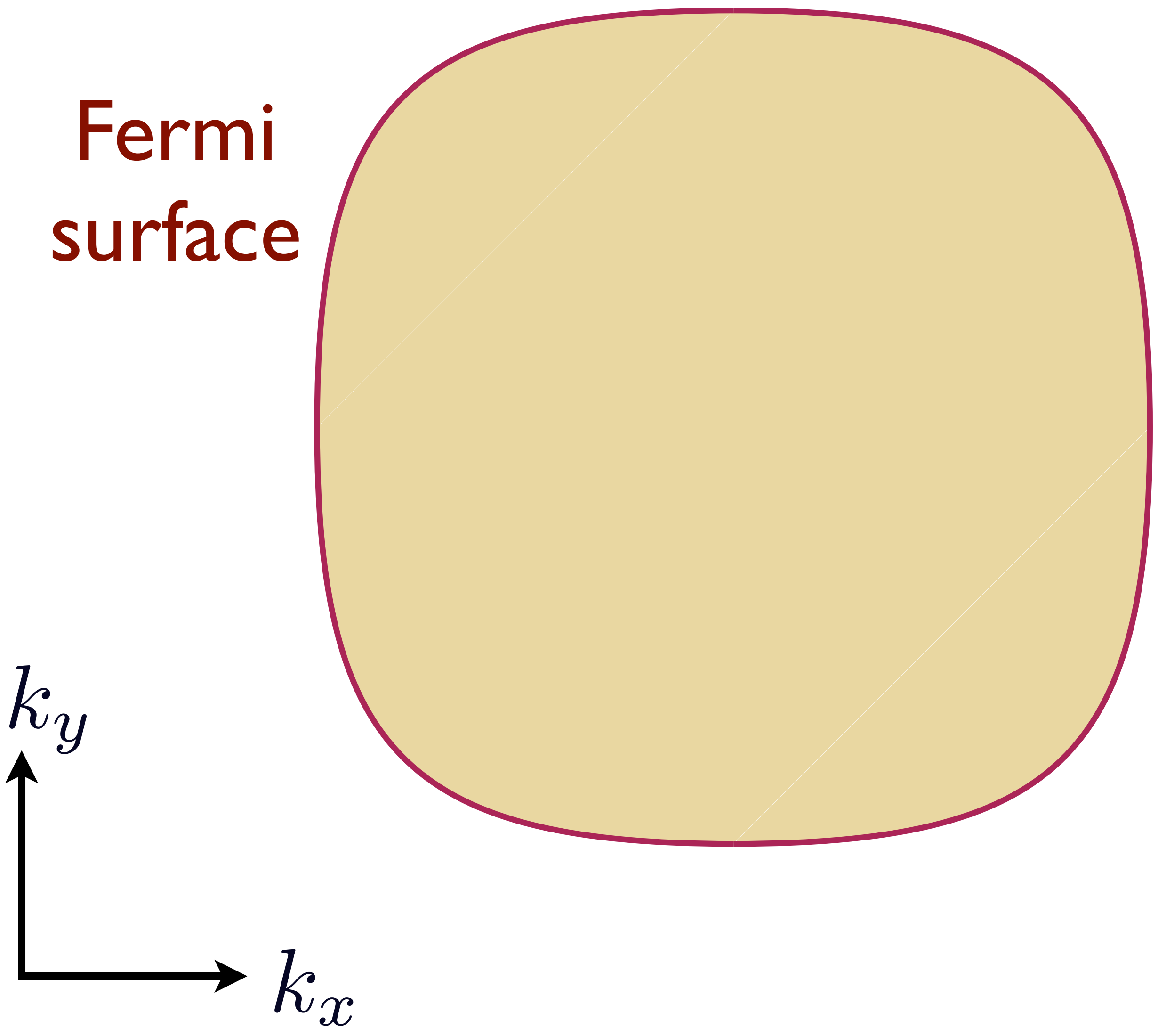
Figure: K. Fujita and J. C. Seamus Davis

Ordinary quantum matter: the Fermi liquid (FL)



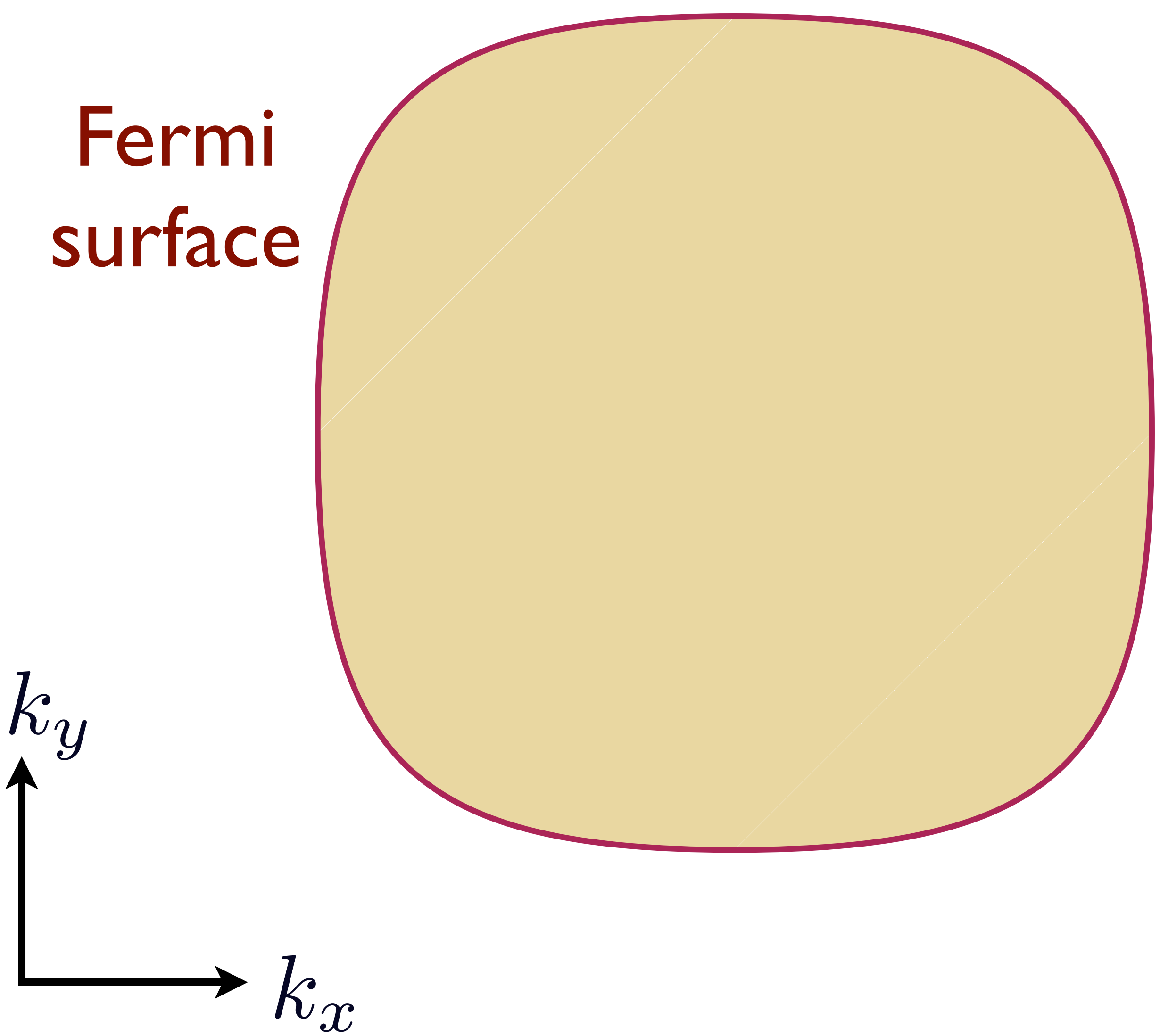
- Fermi surface separates empty and occupied states in momentum space.

Ordinary quantum matter: the Fermi liquid (FL)



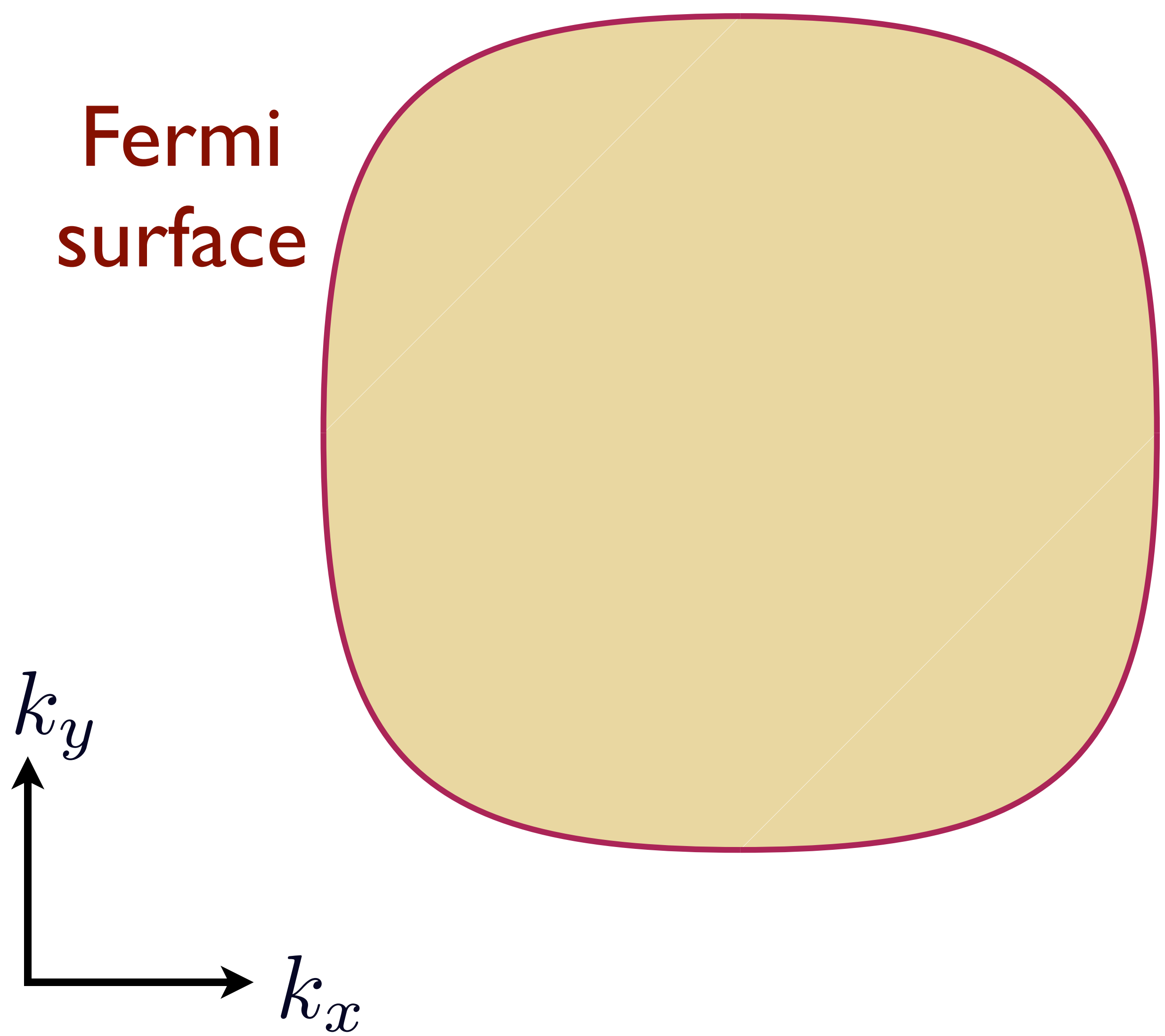
- Fermi surface separates empty and occupied states in momentum space.
- Area enclosed by Fermi surface = total density of electrons (mod 2) = $1+p$.

Ordinary quantum matter: the Fermi liquid (FL)



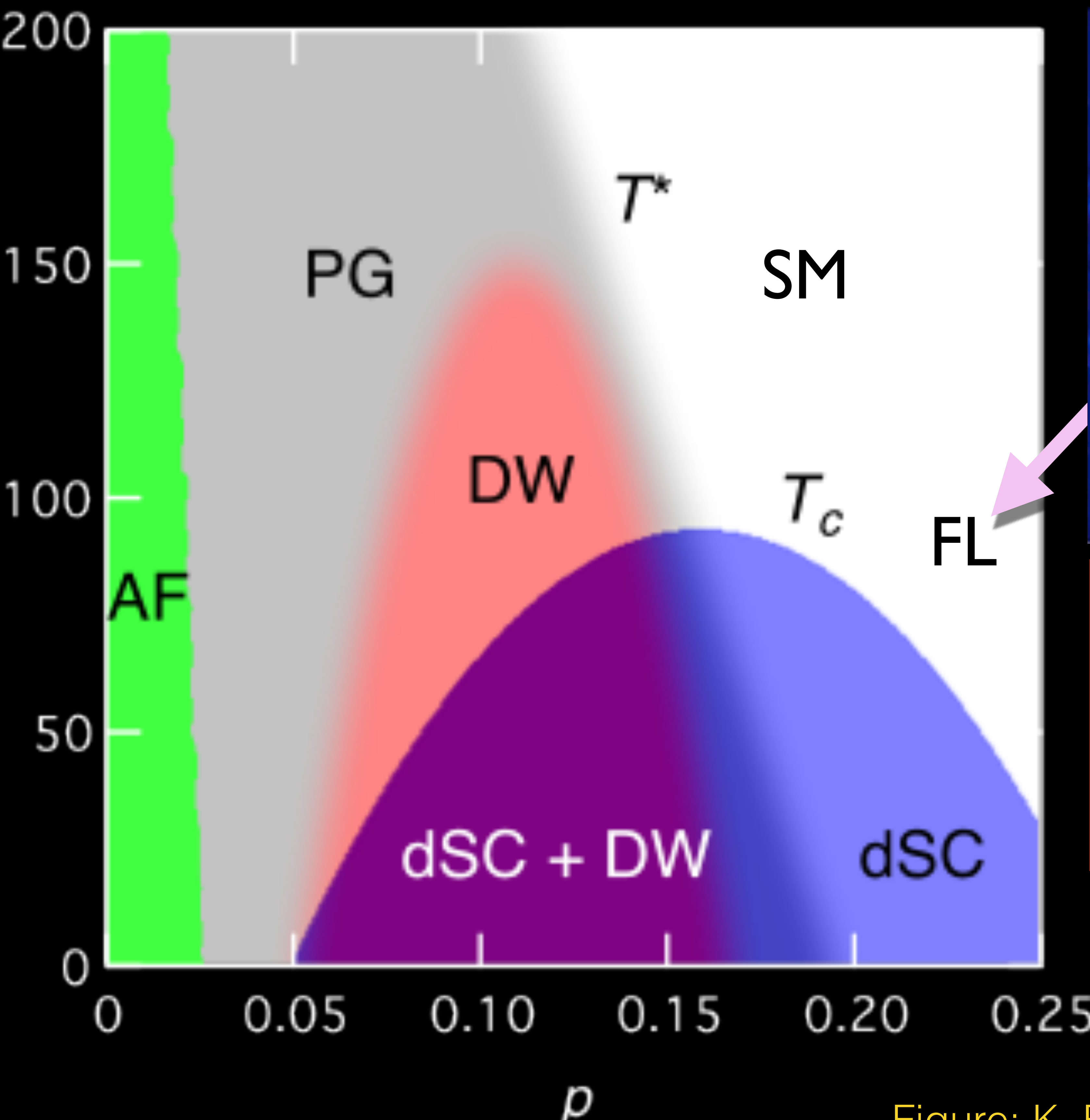
- Fermi surface separates empty and occupied states in momentum space.
- Area enclosed by Fermi surface = total density of electrons (mod 2) = $1+p$.
- Density of electrons can be continuously varied at zero temperature.

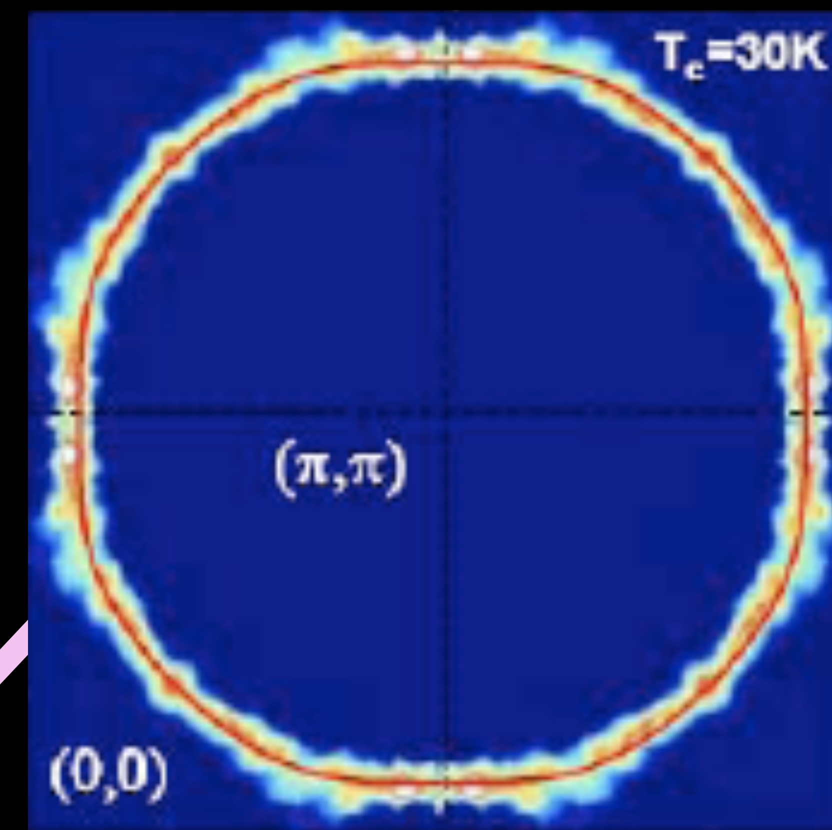
Ordinary quantum matter: the Fermi liquid (FL)



- Fermi surface separates empty and occupied states in momentum space.
- Area enclosed by Fermi surface = total density of electrons (mod 2) = $1+p$.
- Density of electrons can be continuously varied at zero temperature.
- Long-lived electron-like quasiparticle excitations near the Fermi surface: lifetime of quasiparticles $\sim 1/T^2$.

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)



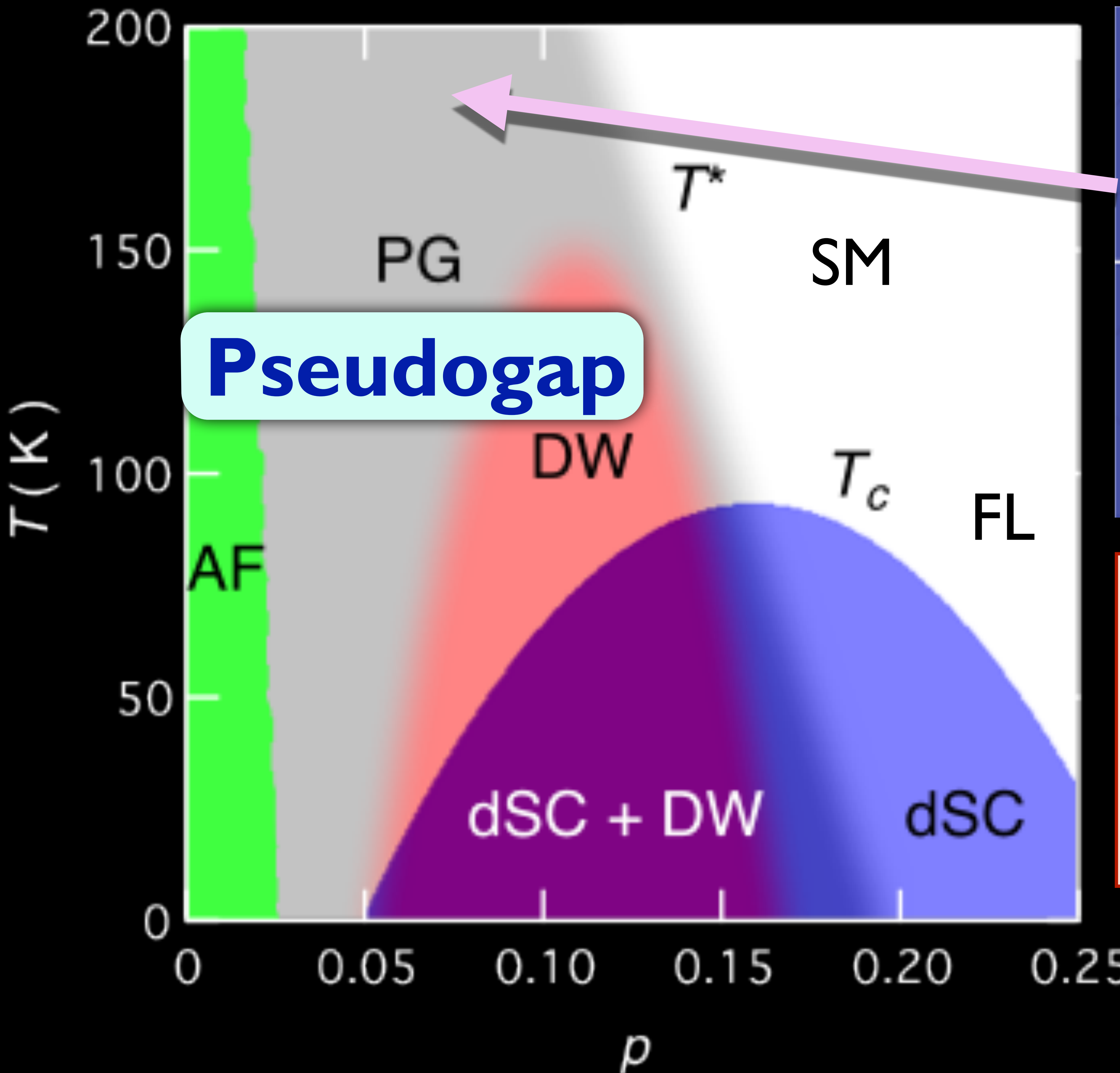


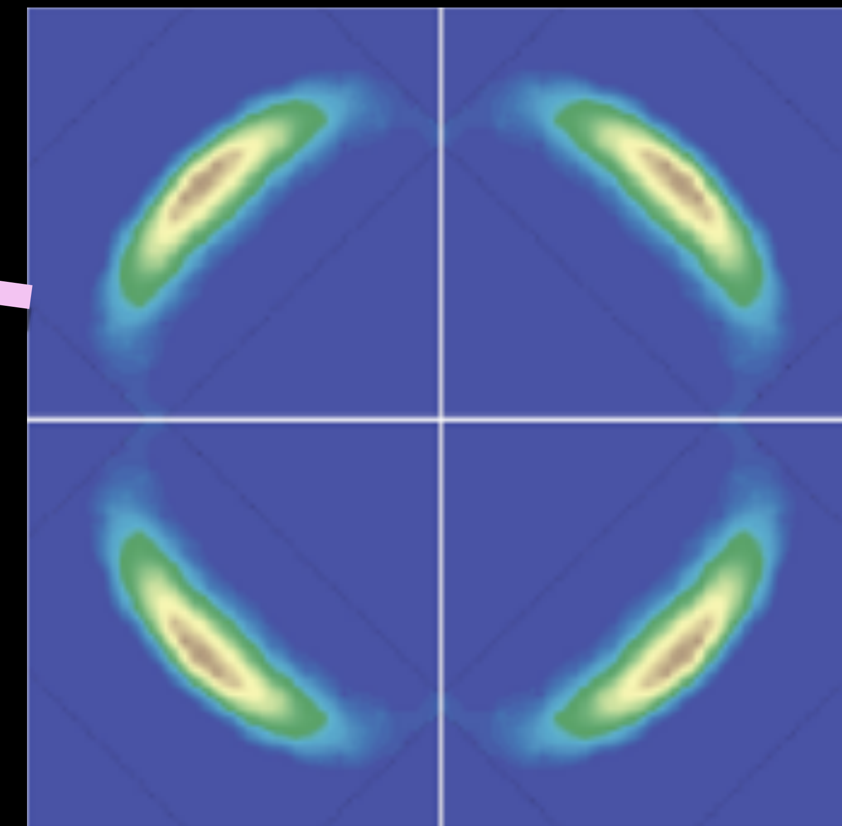
Conventional metal

Area enclosed by Fermi surface =1+p

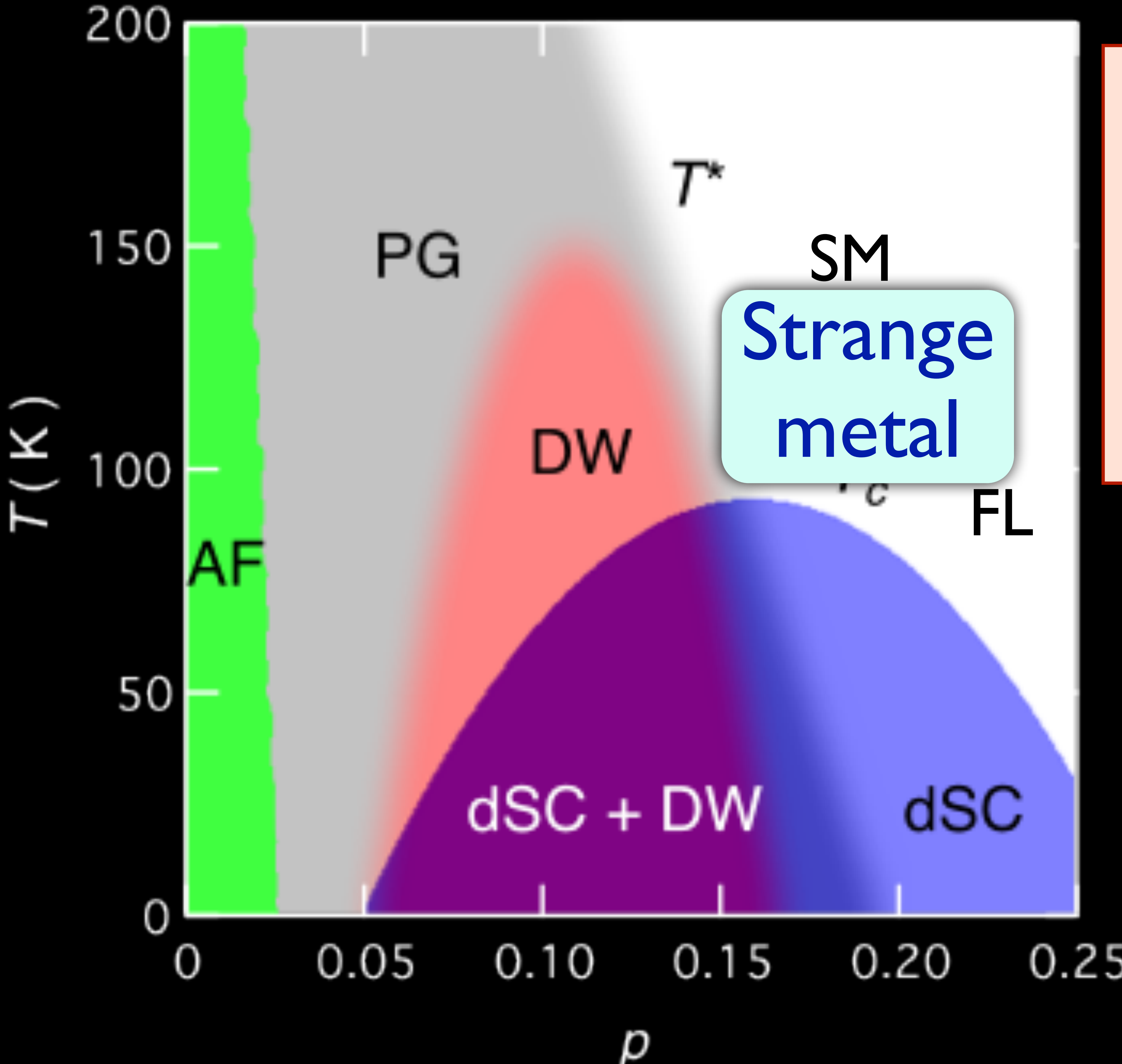
Figure: K. Fujita and J. C. Seamus Davis

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



Metal without quasi-particles

Outline

1. The pseudogap metal

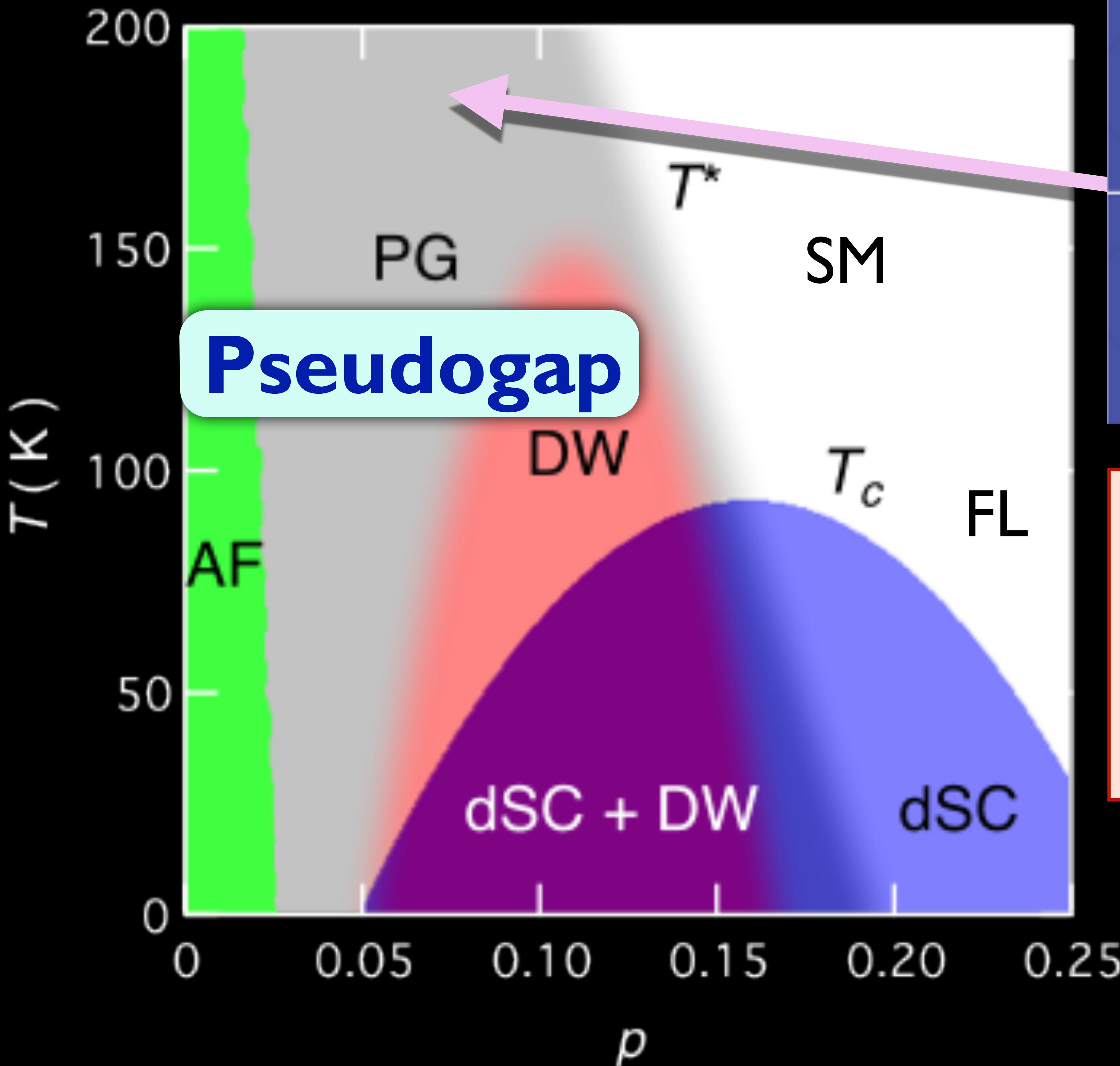
   Fermi liquid co-existening with topological order

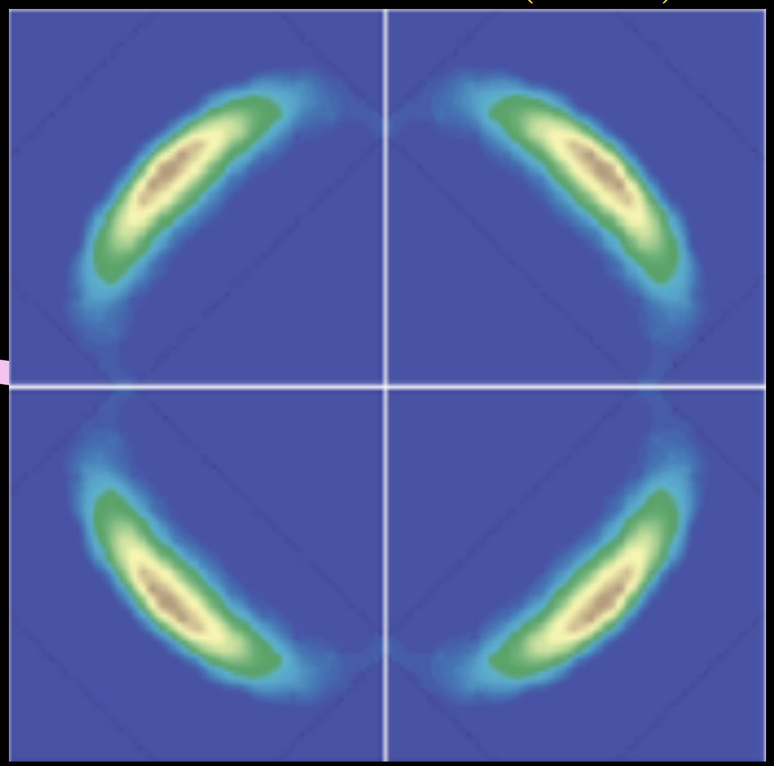
2. The strange metal

   Metal without quasiparticles

   Infinite-range model: dual to extremal charged black holes and yields Bekenstein-Hawking entropy

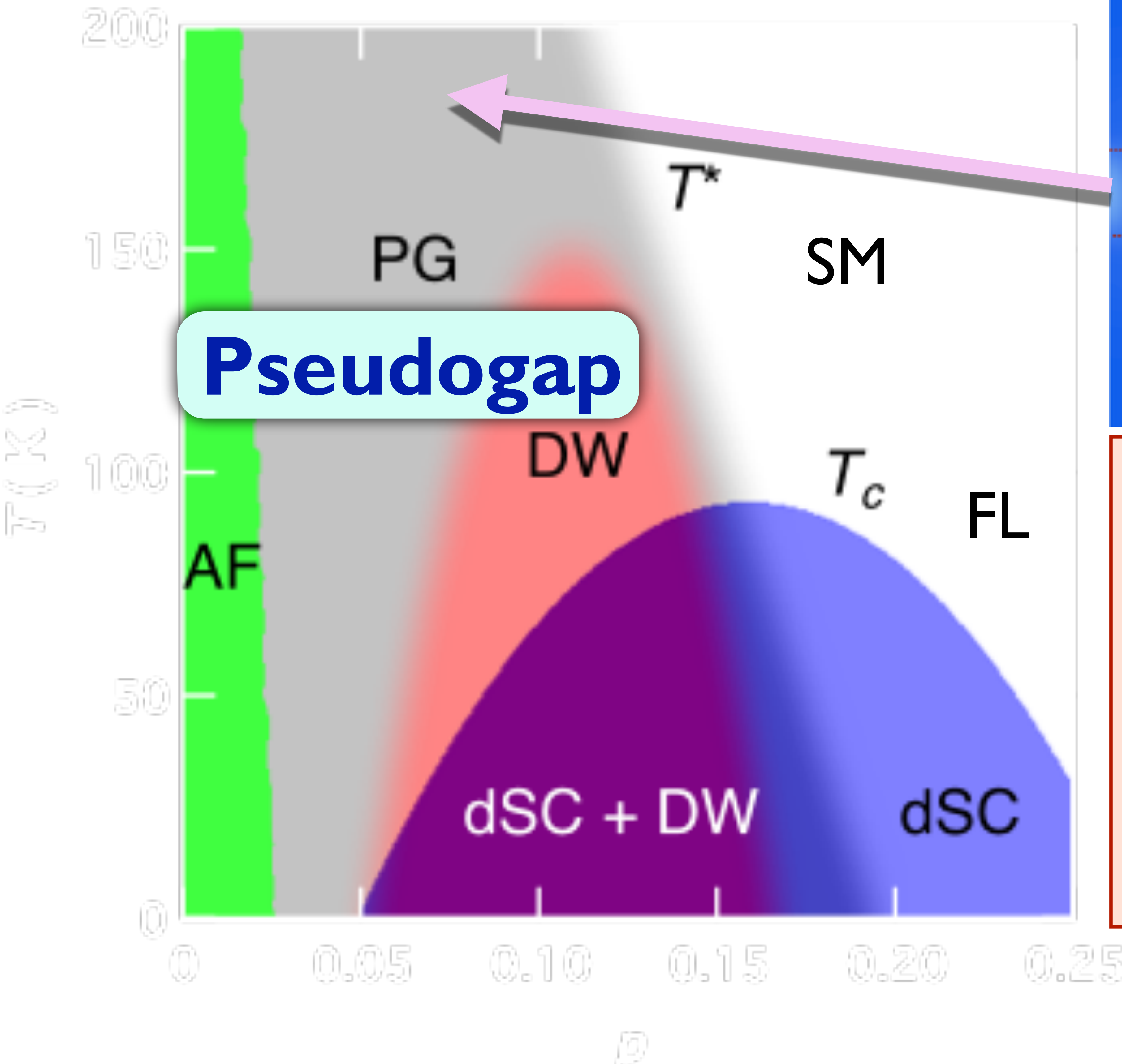
Kyle M. Shen, F. Ronning, D. H. Lu, F. Baumberger, N. J. C. Ingle, W. S. Lee, W. Meevasana, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, Z.-X. Shen, Science **307**, 901 (2005)

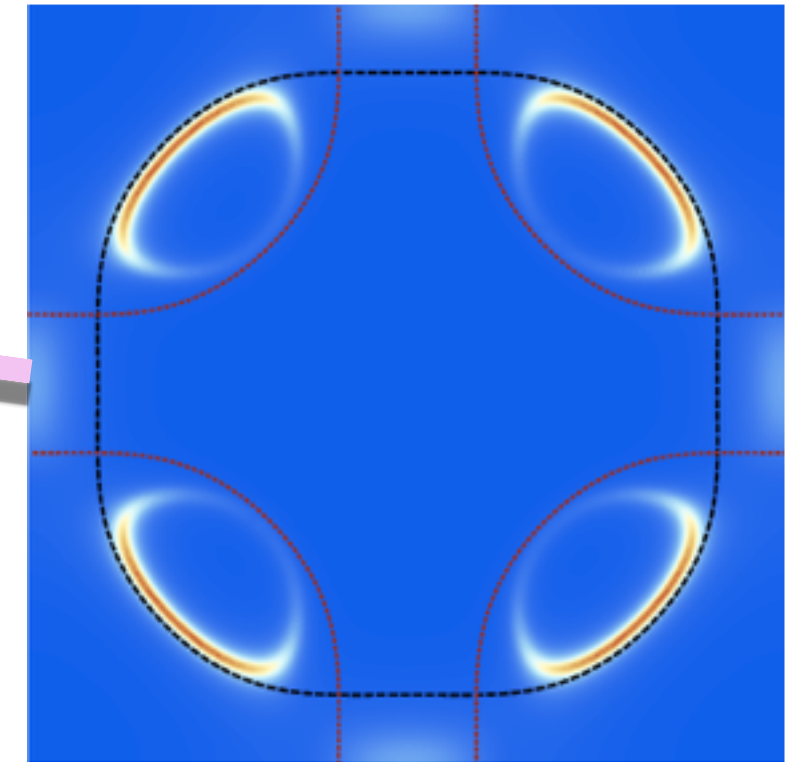




“Fermi arcs”
at
low p

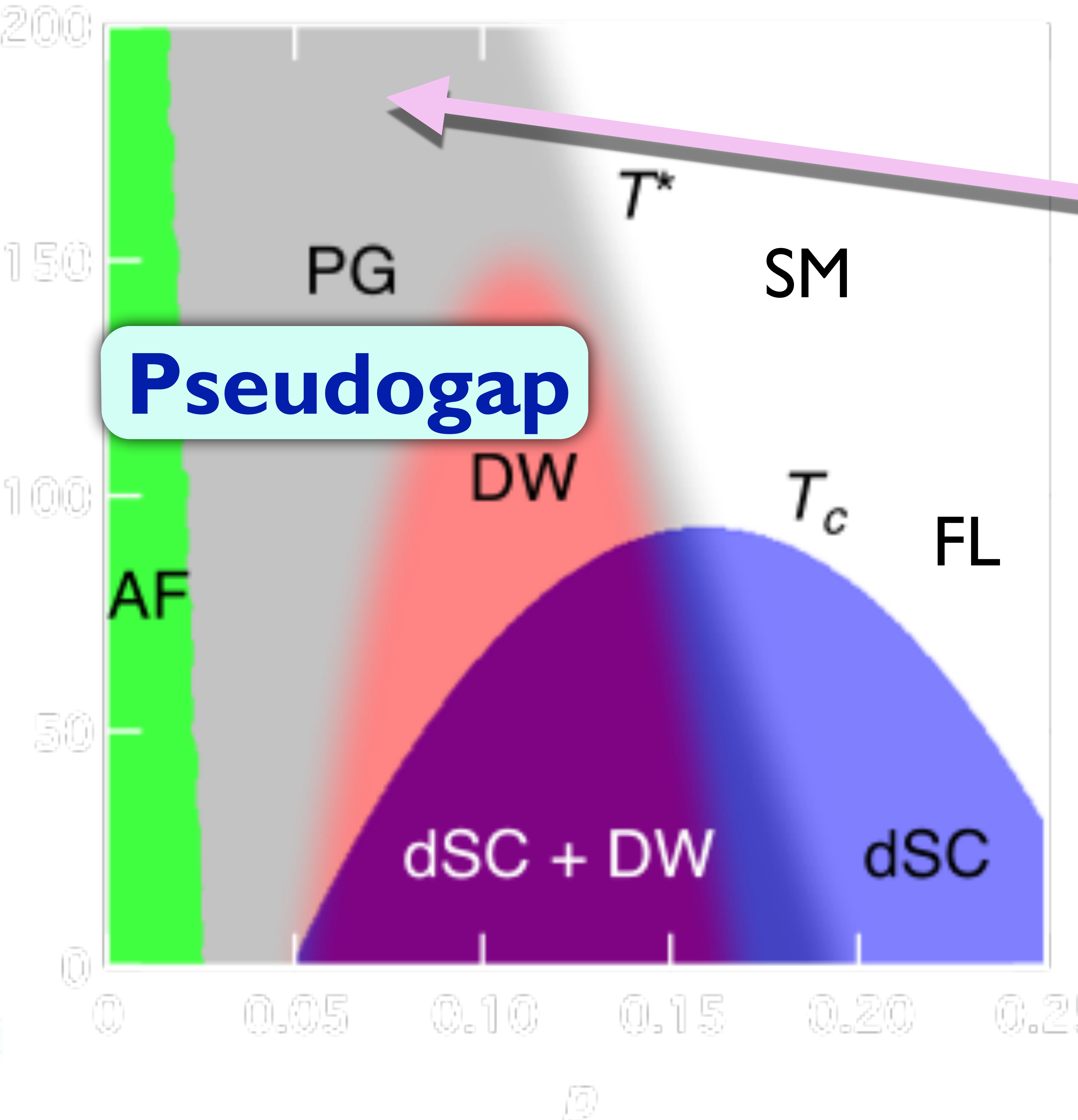
Y. Qi and S. Sachdev, Phys. Rev. B **81**, 115129 (2010)
M. Punk, A. Allais, and S. Sachdev, arXiv:1501.00978

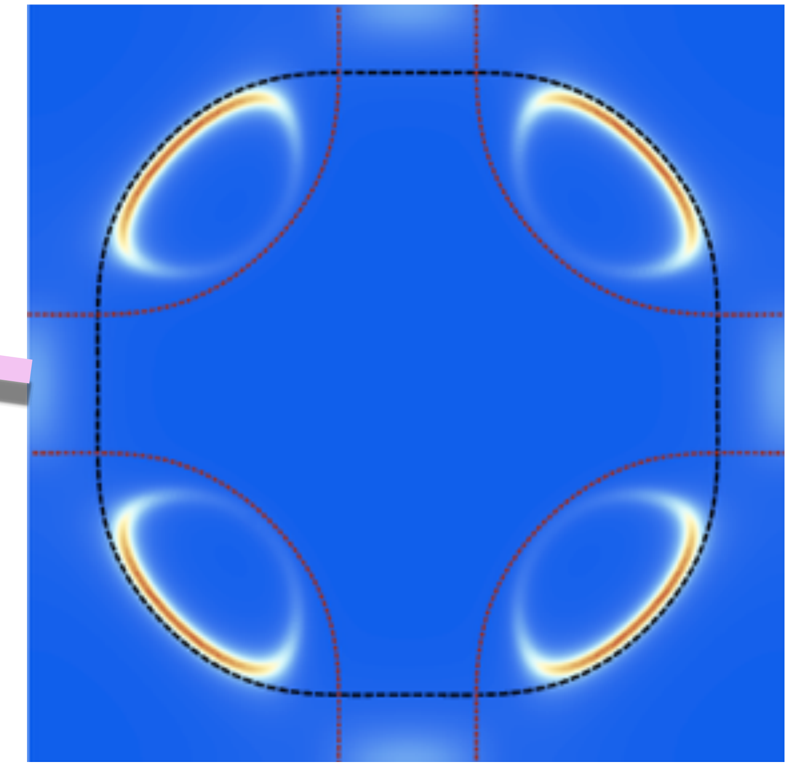




A new metal — a fractionalized Fermi liquid (FL*) — with electron-like quasiparticles on a Fermi surface of size p

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





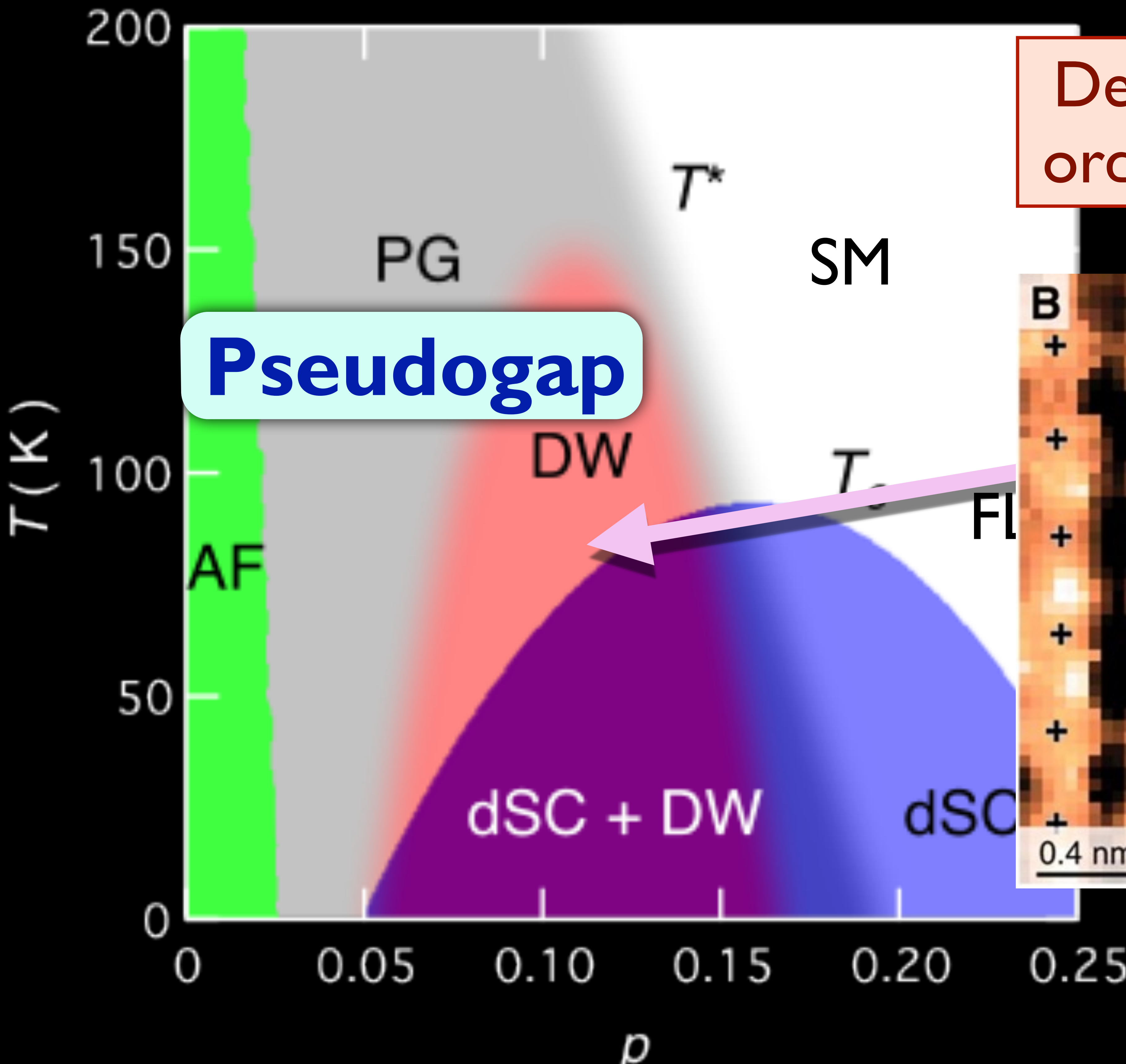
A new metal — a fractionalized Fermi liquid (FL*) — with electron-like quasiparticles on a Fermi surface of size p coexisting with **<u>topological order</u>**

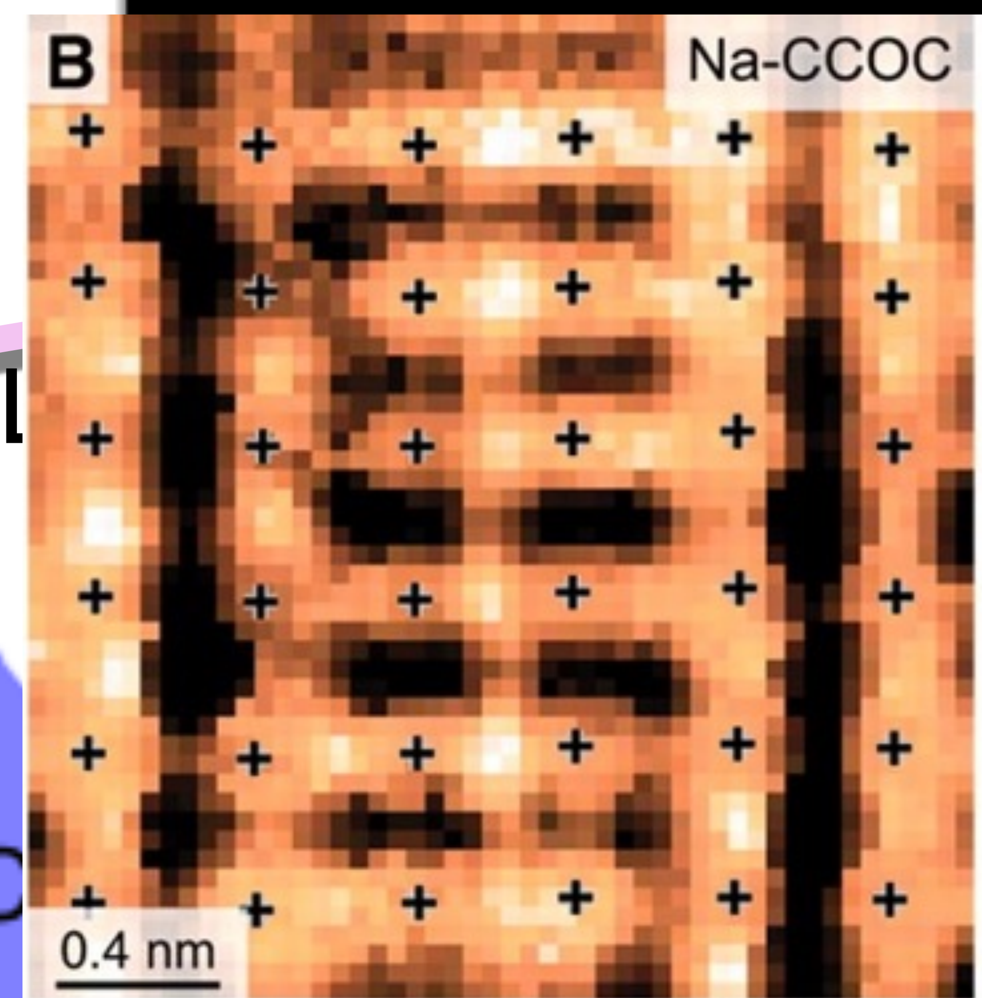
Evidence for Fermi surface of long-lived quasiparticles of density p

- Hall effect (Ando PRL 2004)
- Optical conductivity (van der Marel PNAS 2013)
- Magnetoresistance (Greven PRL 2014)
- Scanning Tunneling Microscopy (Seamus Davis, PNAS 2014): *d*-form factor density wave

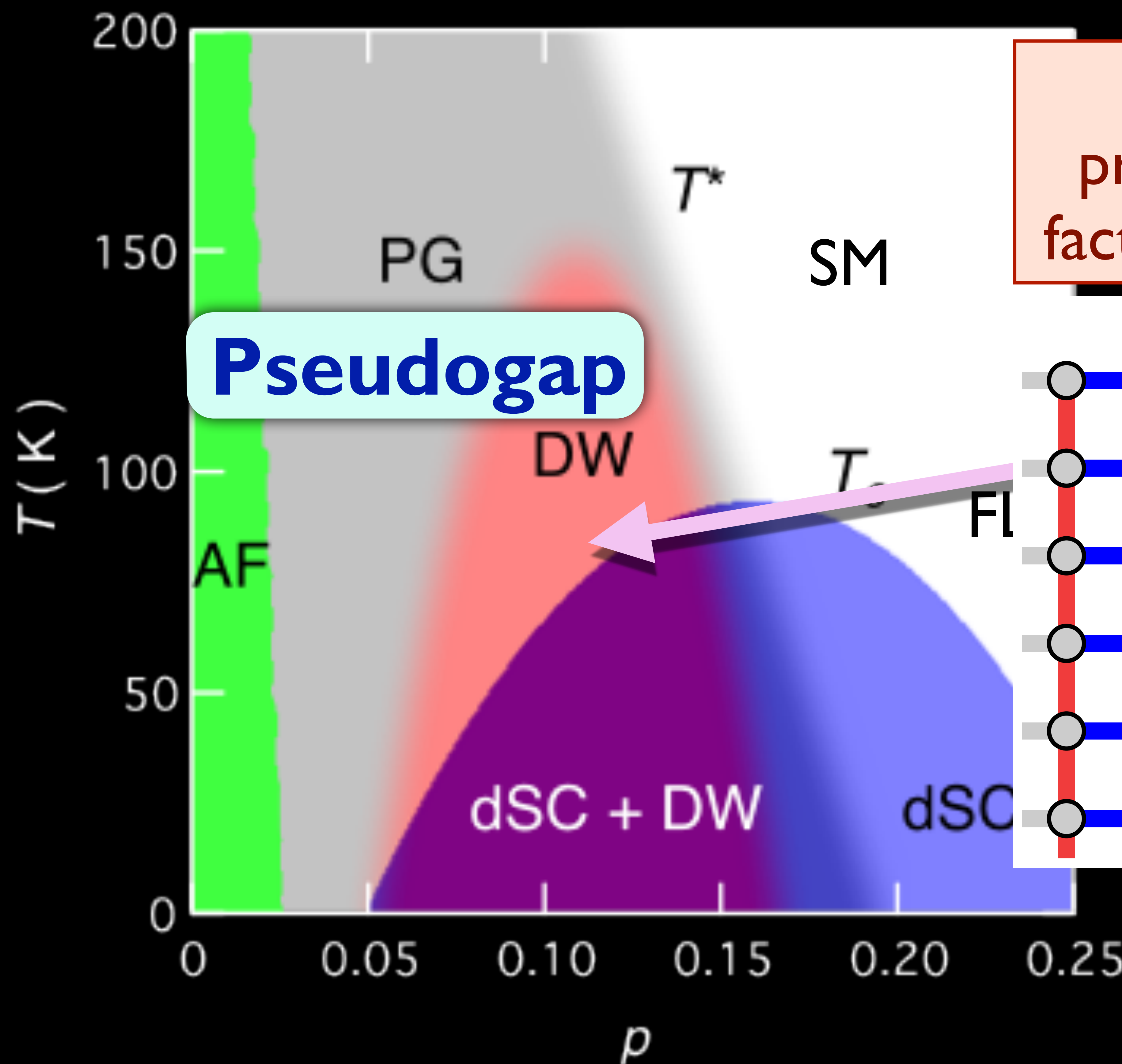
Y. Kohsaka *et al.*, Science **315**, 1380 (2007)

Density wave (DW) order at low T and p

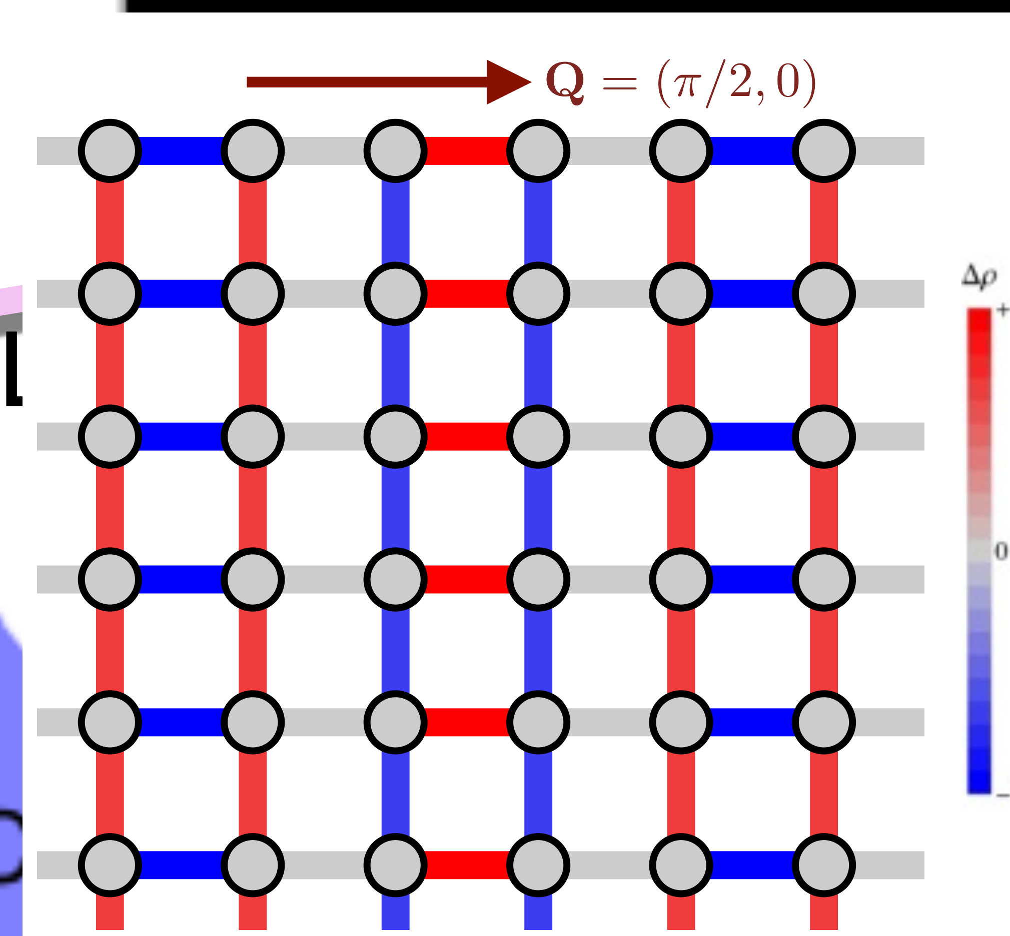


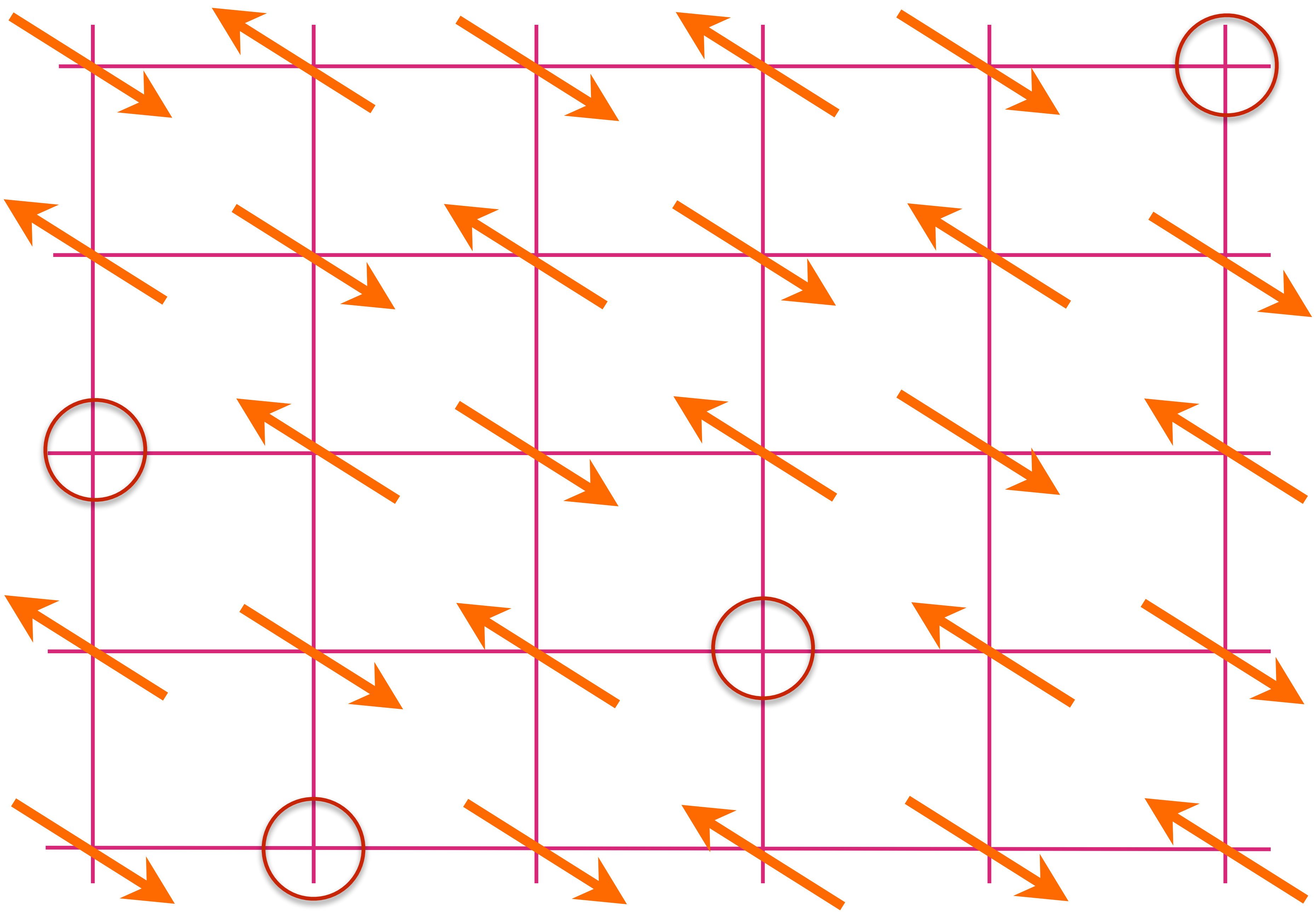


M. A. Metlitski and S. Sachdev, PRB **82**, 075128 (2010). S. Sachdev R. La Placa, PRL **111**, 027202 (2013).
K. Fujita, M. H Hamidian, S. D. Edkins, Chung Koo Kim, Y. Kohsaka, M. Azuma, M. Takano, H. Takagi, H. Eisaki, S. Uchida, A. Allais, M. J. Lawler, E.-A. Kim, S. Sachdev, and J. C. Davis, PNAS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



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

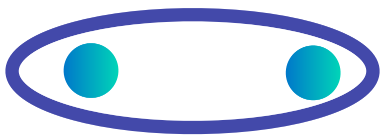




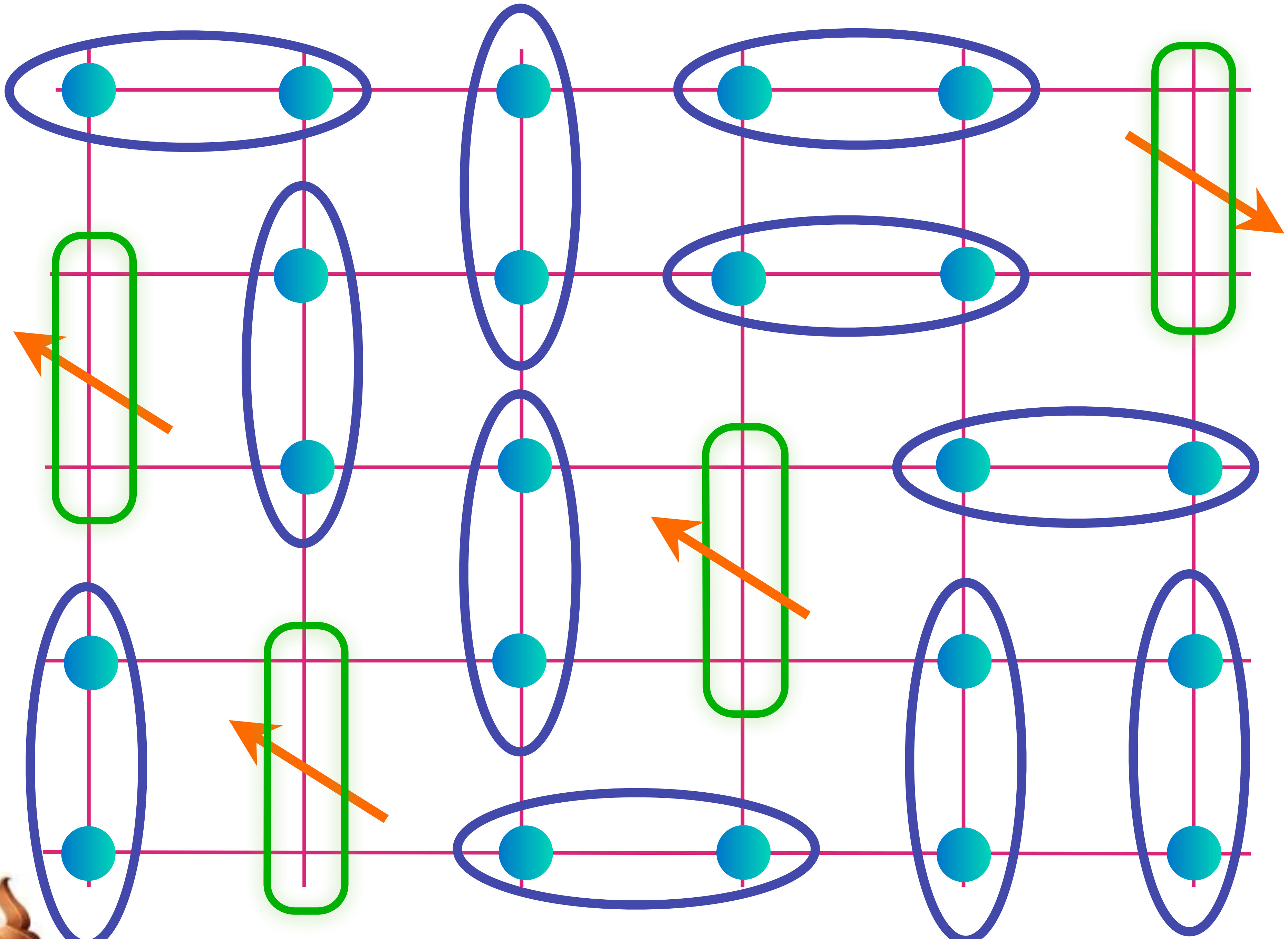
Anti-
ferromagnet
with p holes
per square

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

Fractionalized Fermi liquid (FL*)



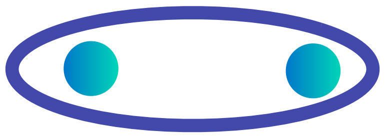
$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

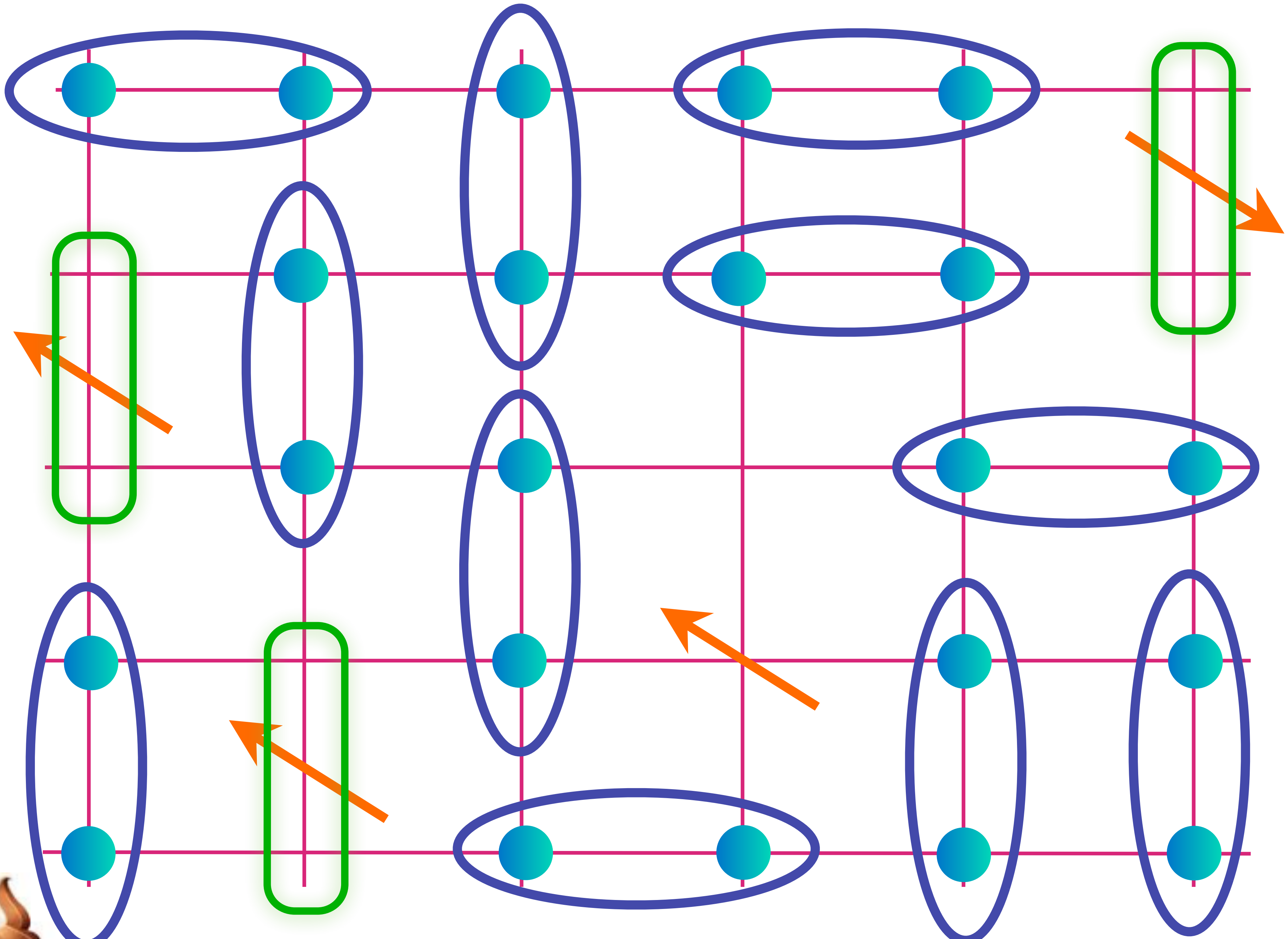


Realizes a metal with a Fermi surface of area p co-existing with "topological order"

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

Fractionalized Fermi liquid (FL*)

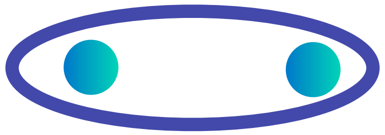
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



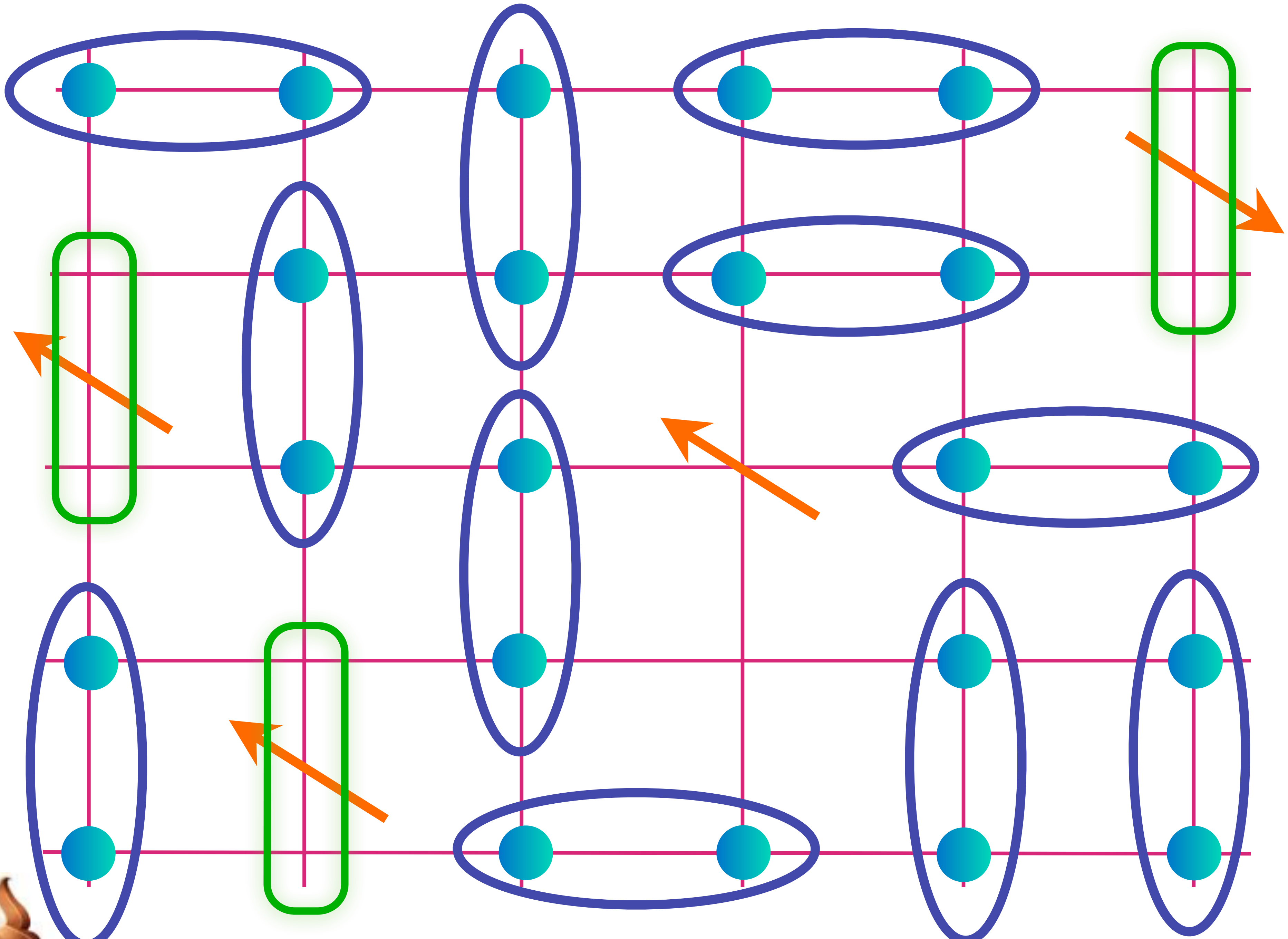
Realizes a metal with a Fermi surface of area p co-existing with "topological order"

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

Fractionalized Fermi liquid (FL*)



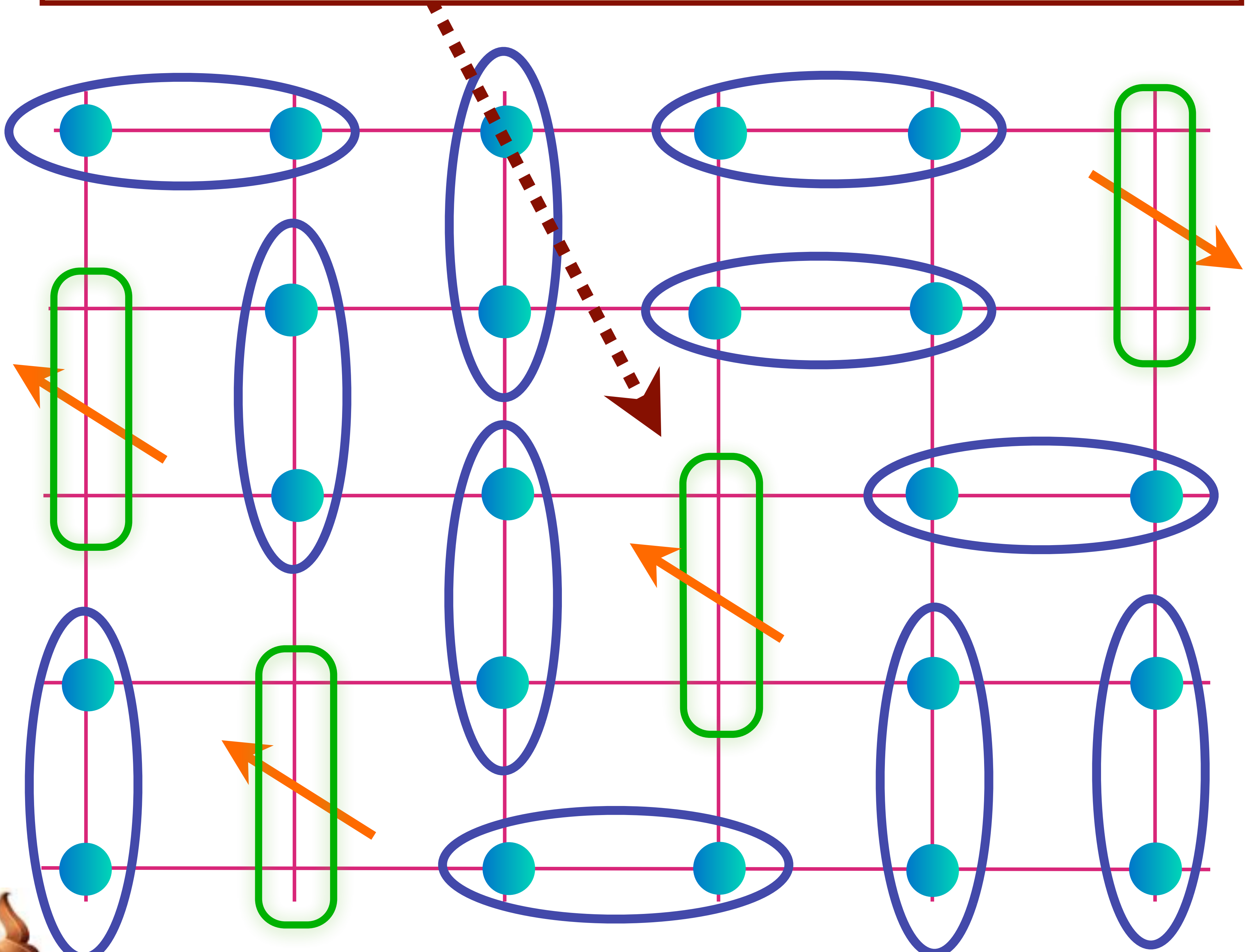
$= | \uparrow\downarrow\rangle - | \downarrow\uparrow\rangle$



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.

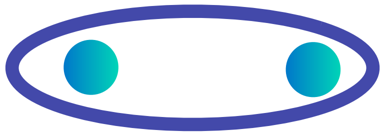
A fermionic “dimer” describing a “bonding” orbital between two sites

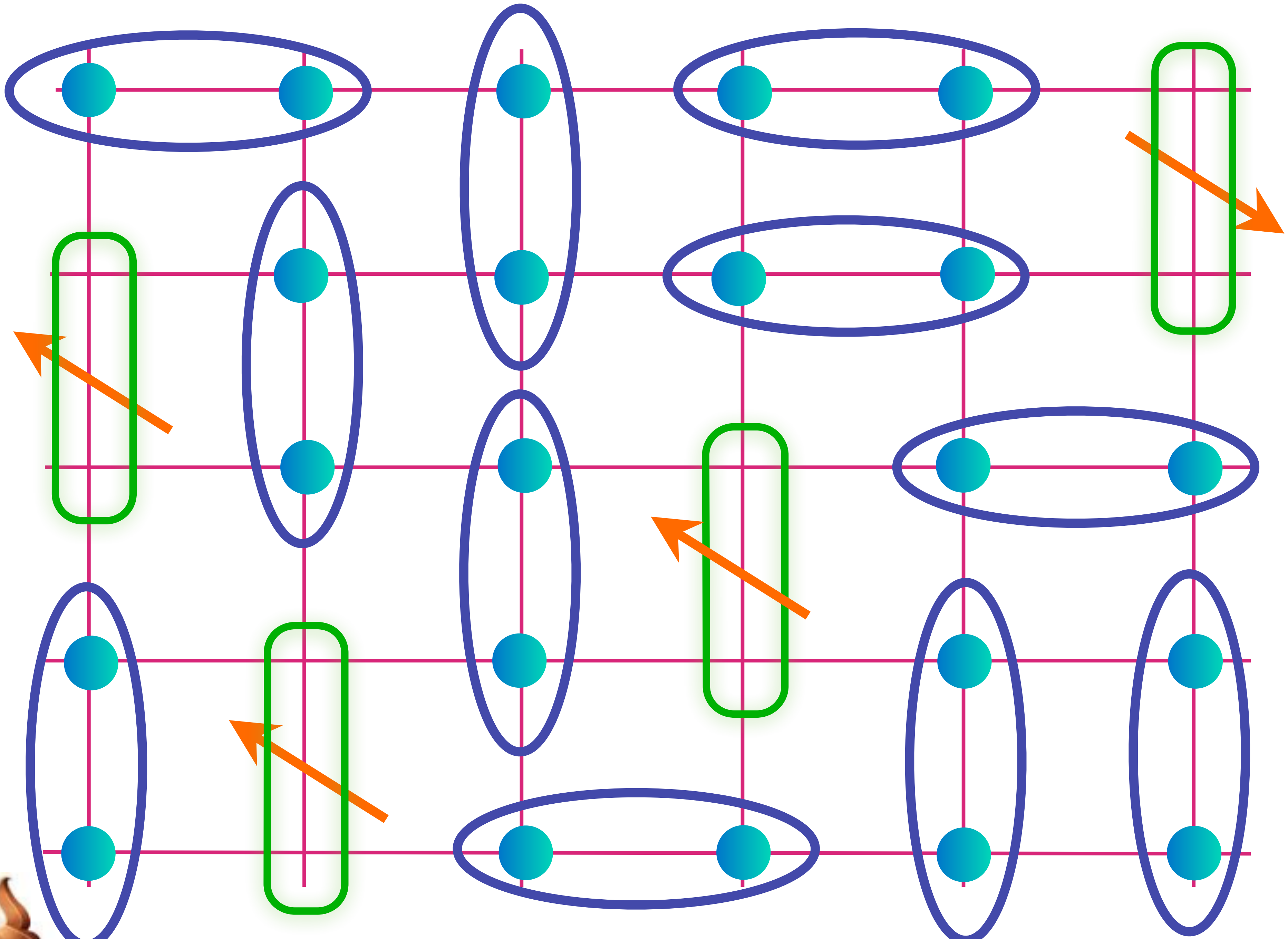


Realizes a metal with a Fermi surface of area p co-existing with “topological order”

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

Fractionalized Fermi liquid (FL*)

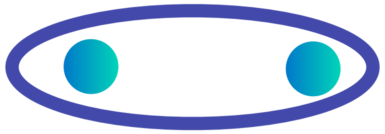
 $= | \uparrow\downarrow \rangle - | \downarrow\uparrow \rangle$

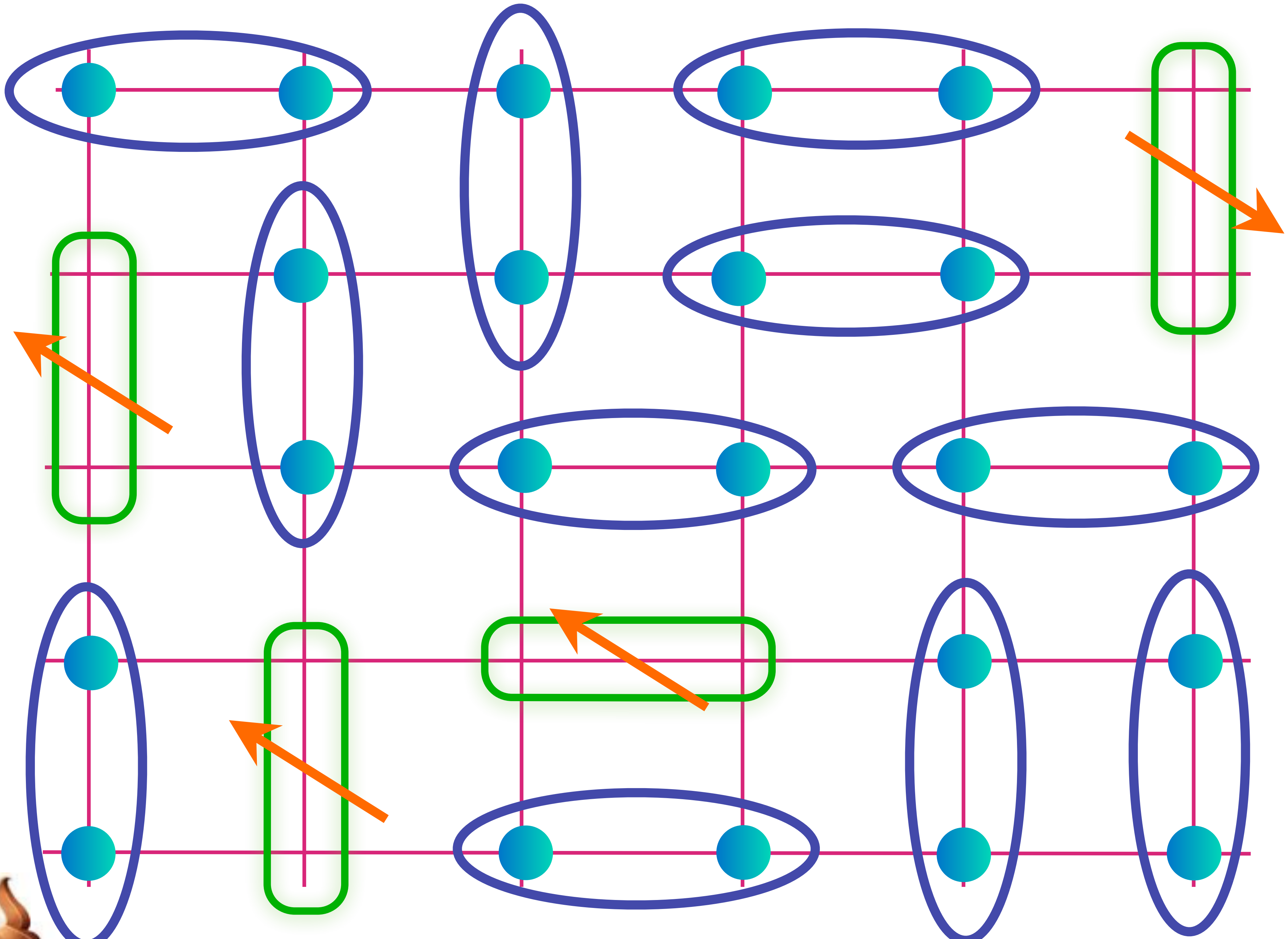


Realizes a metal with a Fermi surface of area p co-existing with "topological order"

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

Fractionalized Fermi liquid (FL*)

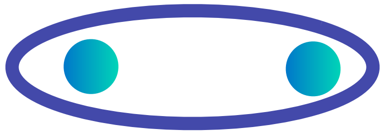
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

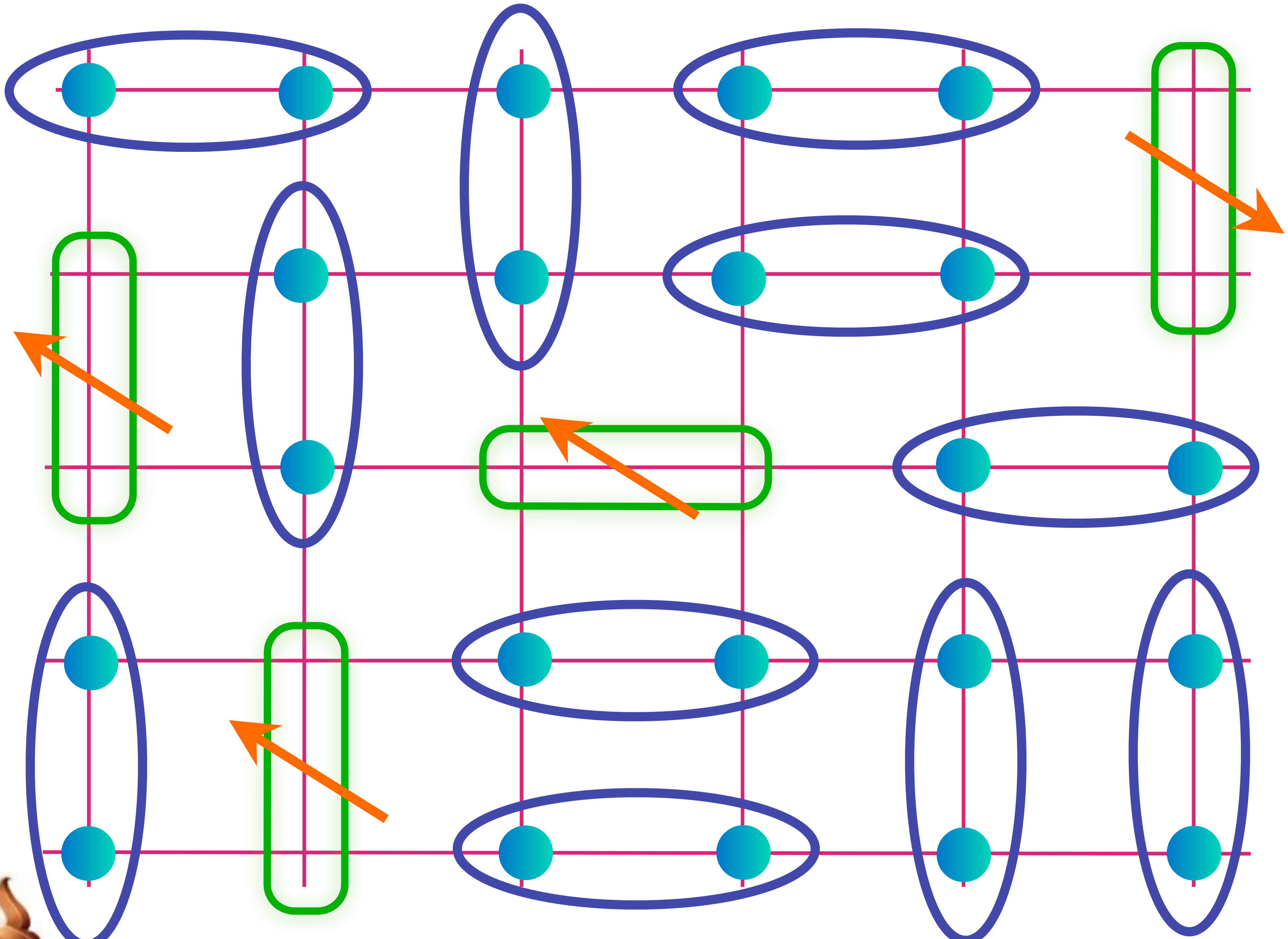


Realizes a metal with a Fermi surface of area p co-existing with "topological order"

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

Fractionalized Fermi liquid (FL*)

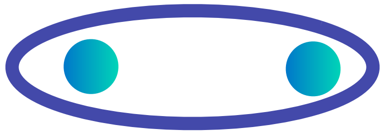
 $= | \uparrow\downarrow\rangle - | \downarrow\uparrow\rangle$

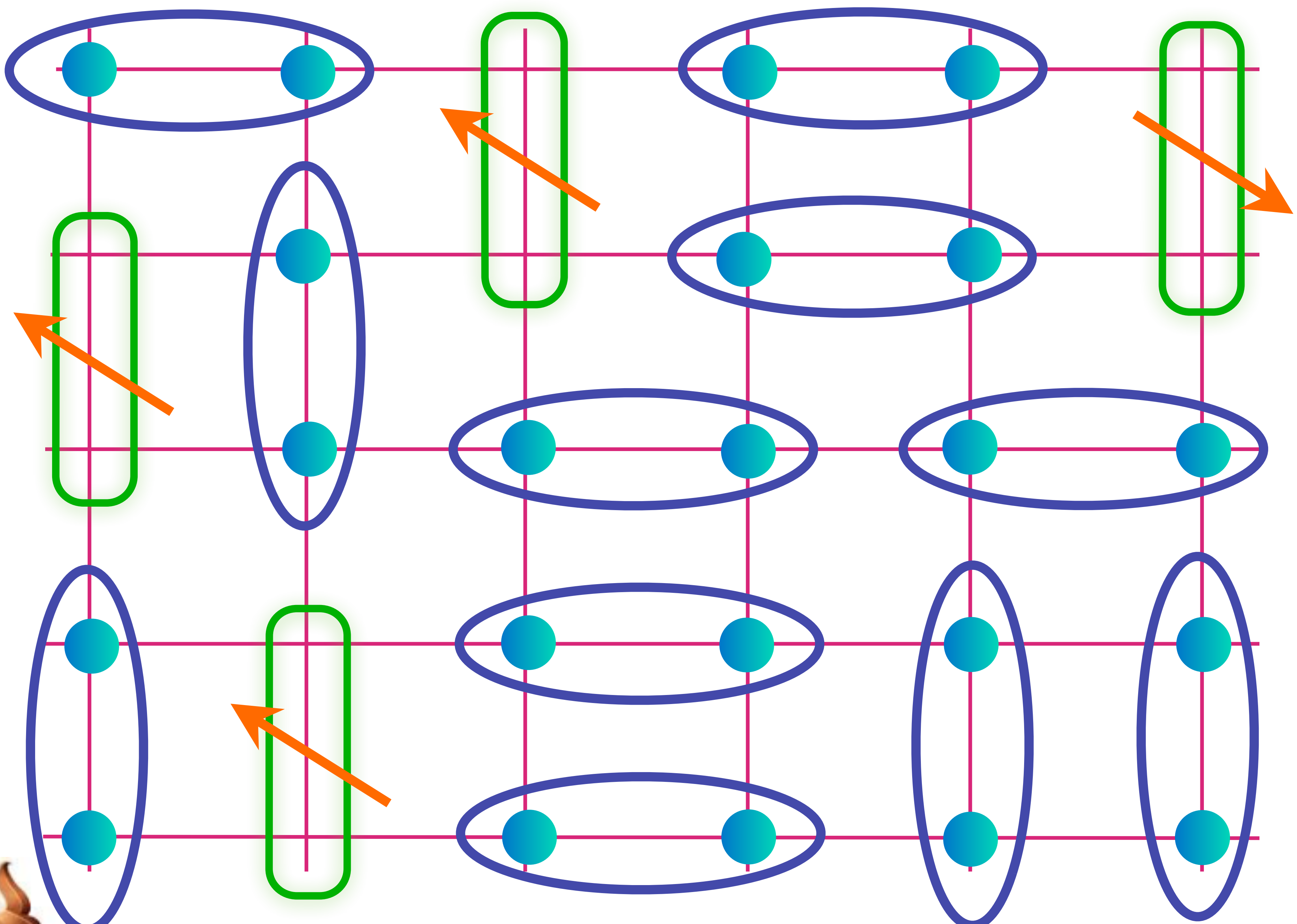


Realizes a metal with a Fermi surface of area p co-existing with "topological order"

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

Fractionalized Fermi liquid (FL*)

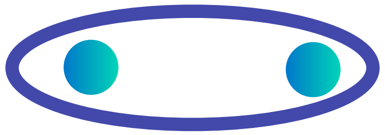
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

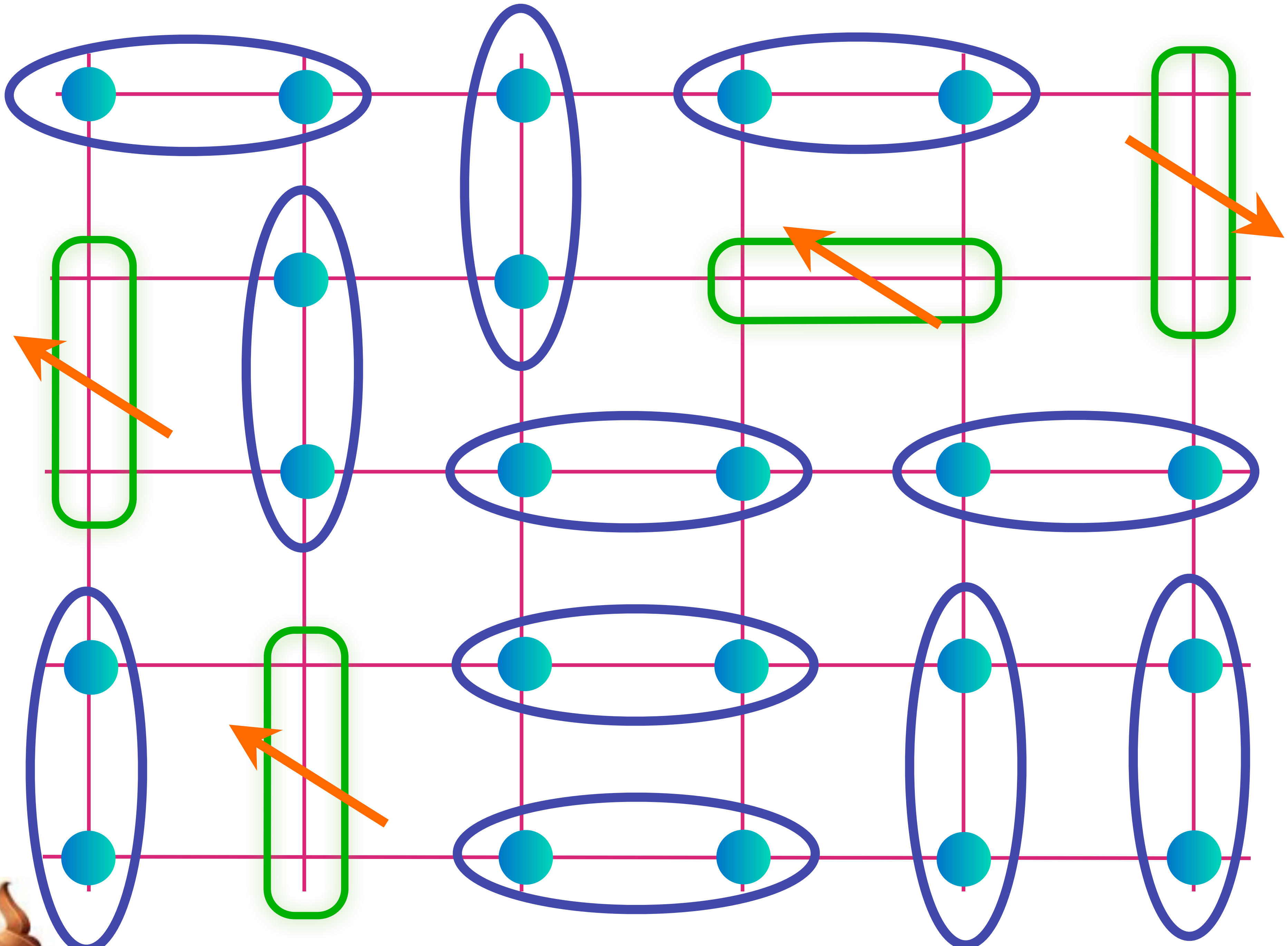


Realizes a metal with a Fermi surface of area p co-existing with "topological order"

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

Fractionalized Fermi liquid (FL*)

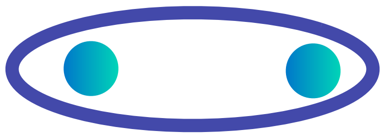

$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

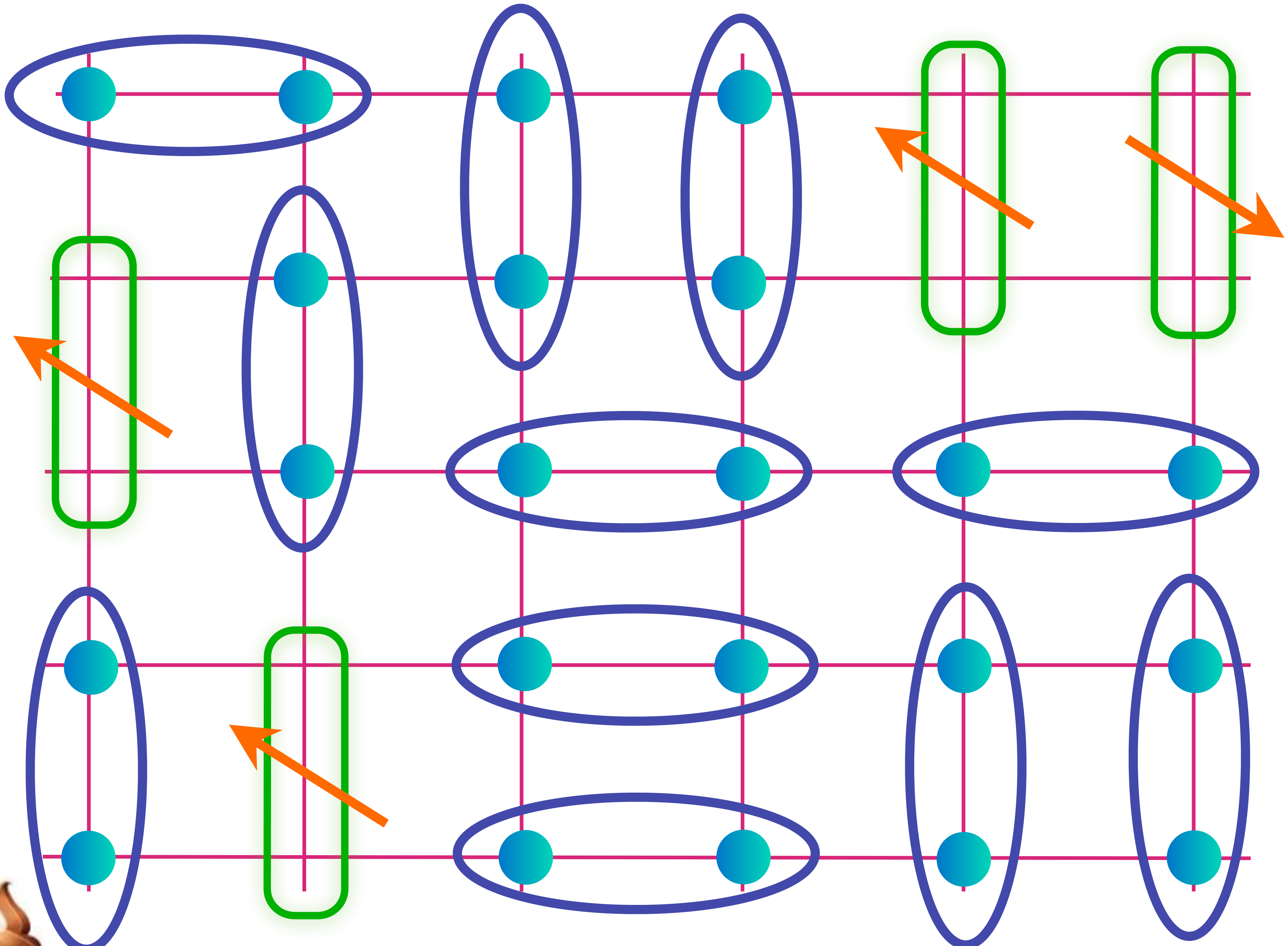


Realizes a metal with a Fermi surface of area p co-existing with "topological order"

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

Fractionalized Fermi liquid (FL*)

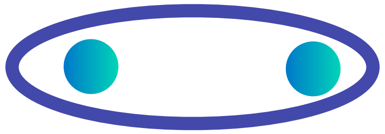
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$

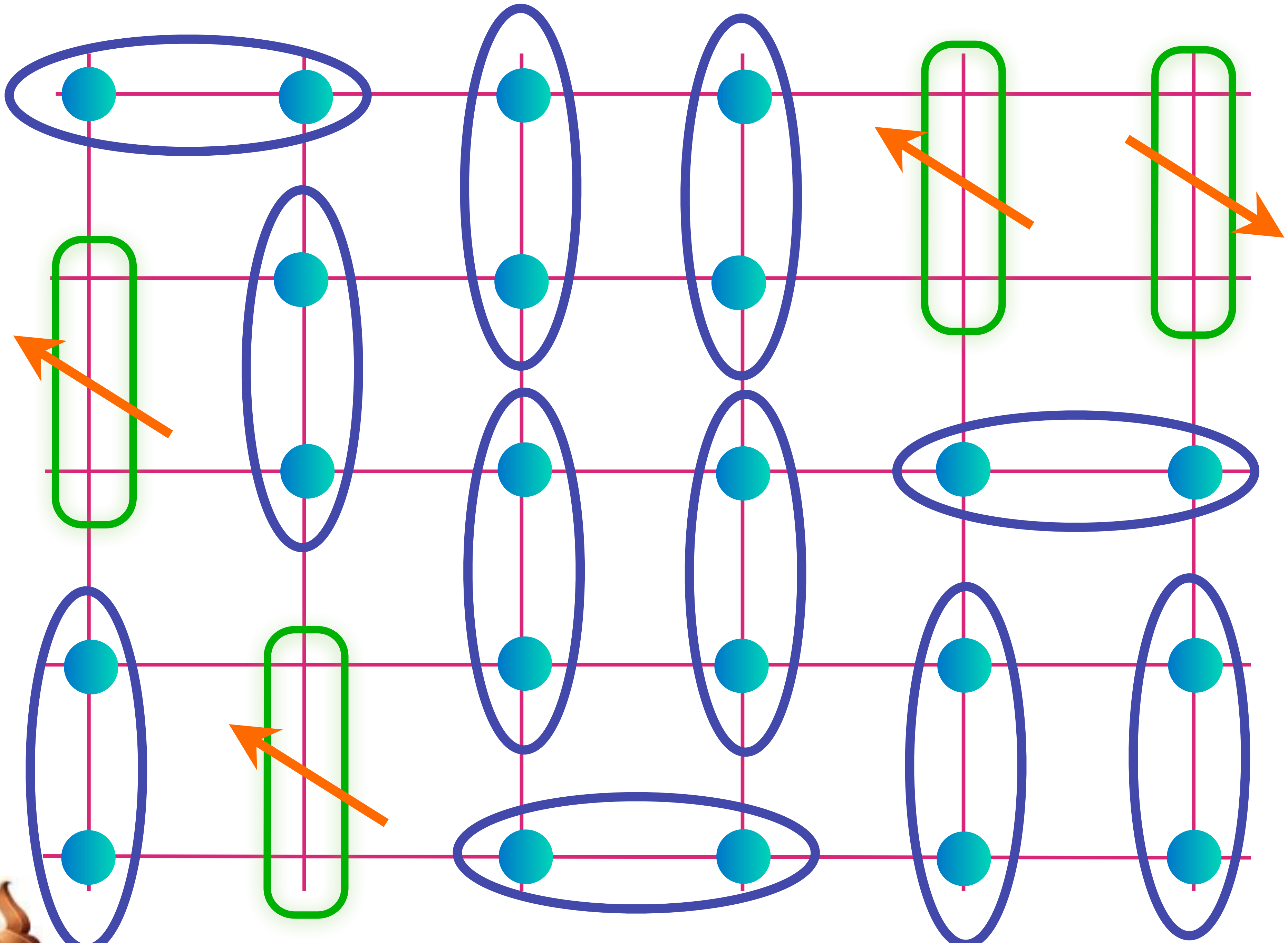


Realizes a metal with a Fermi surface of area p co-existing with “topological order”

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

Fractionalized Fermi liquid (FL*)

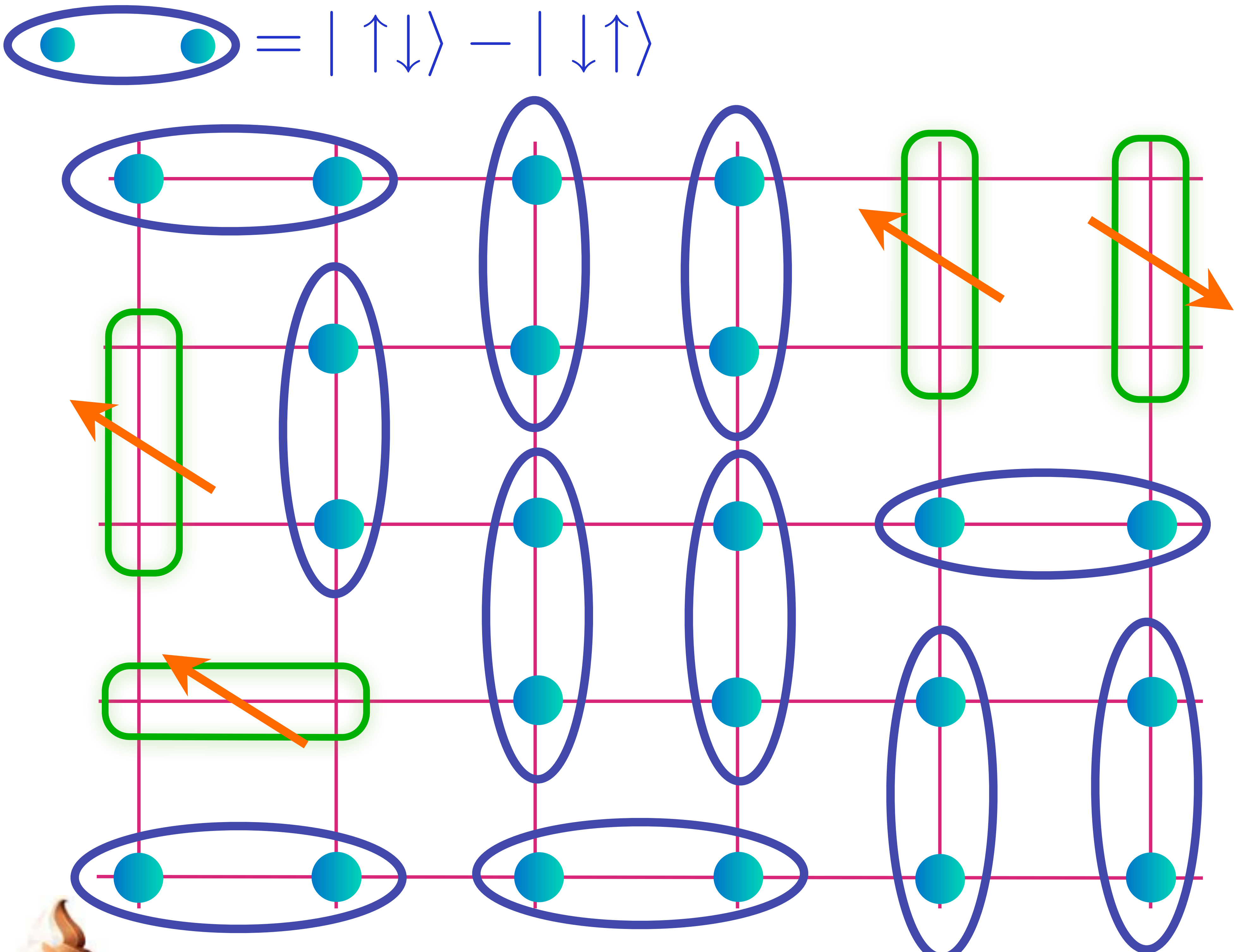
 $= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



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.

Fractionalized Fermi liquid (FL*)



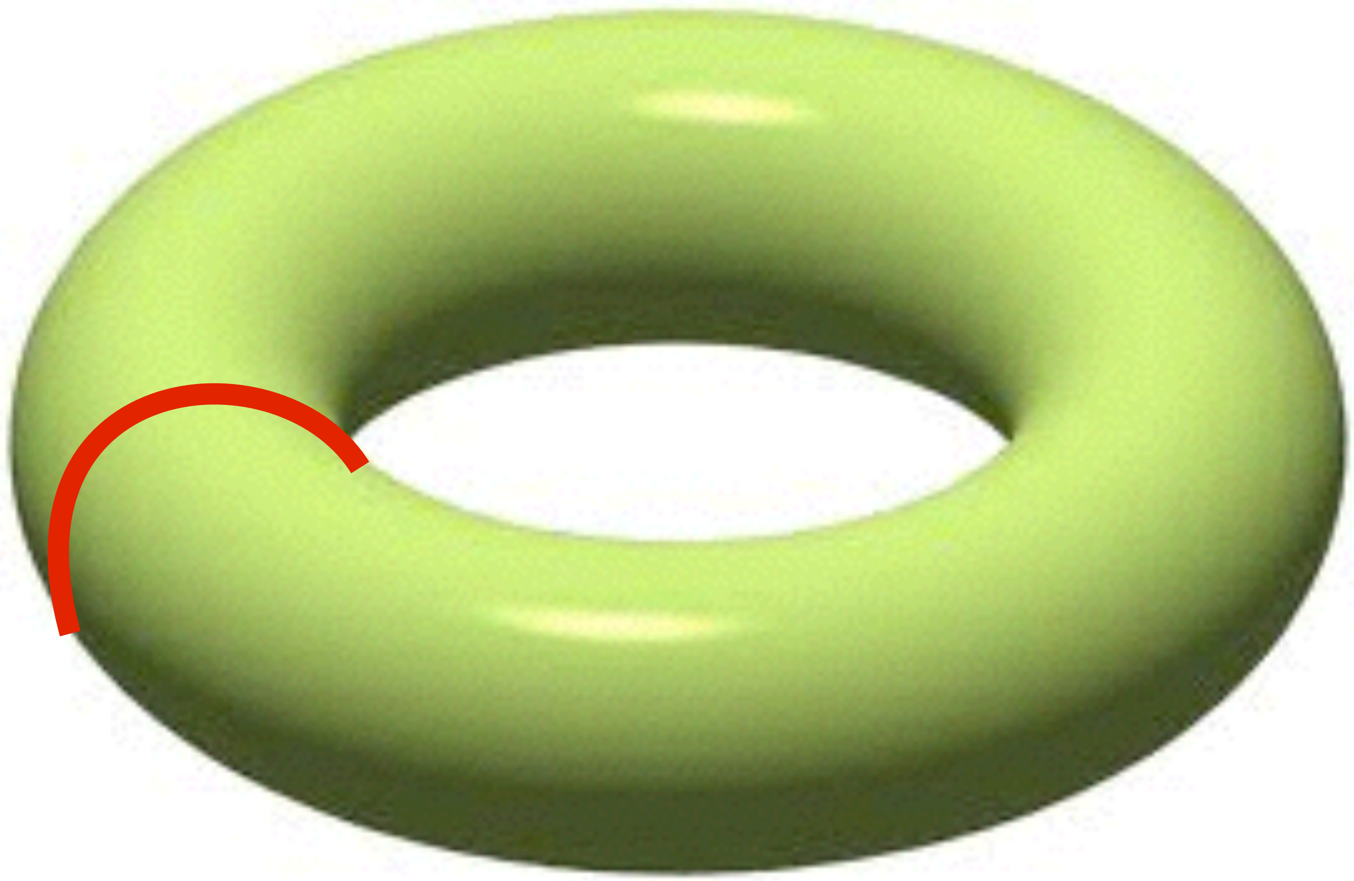
Realizes a metal with a Fermi surface of area p co-existing with "topological order"

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

Topological order

Place pseudogap metal on a torus;

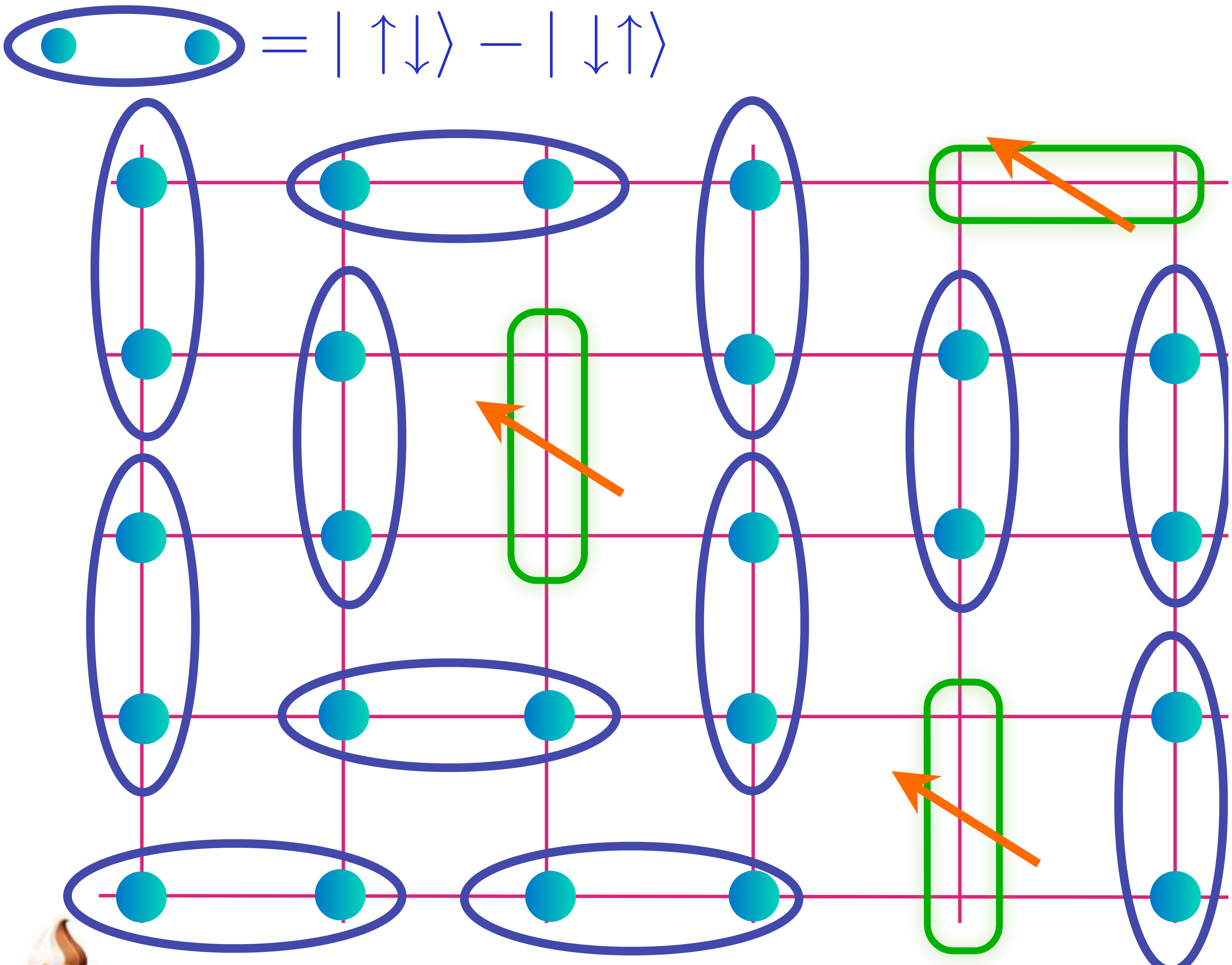
Topological order



Place pseudogap metal on a torus;

obtain "topological" states nearly degenerate with the ground state: change sign of every dimer across red line

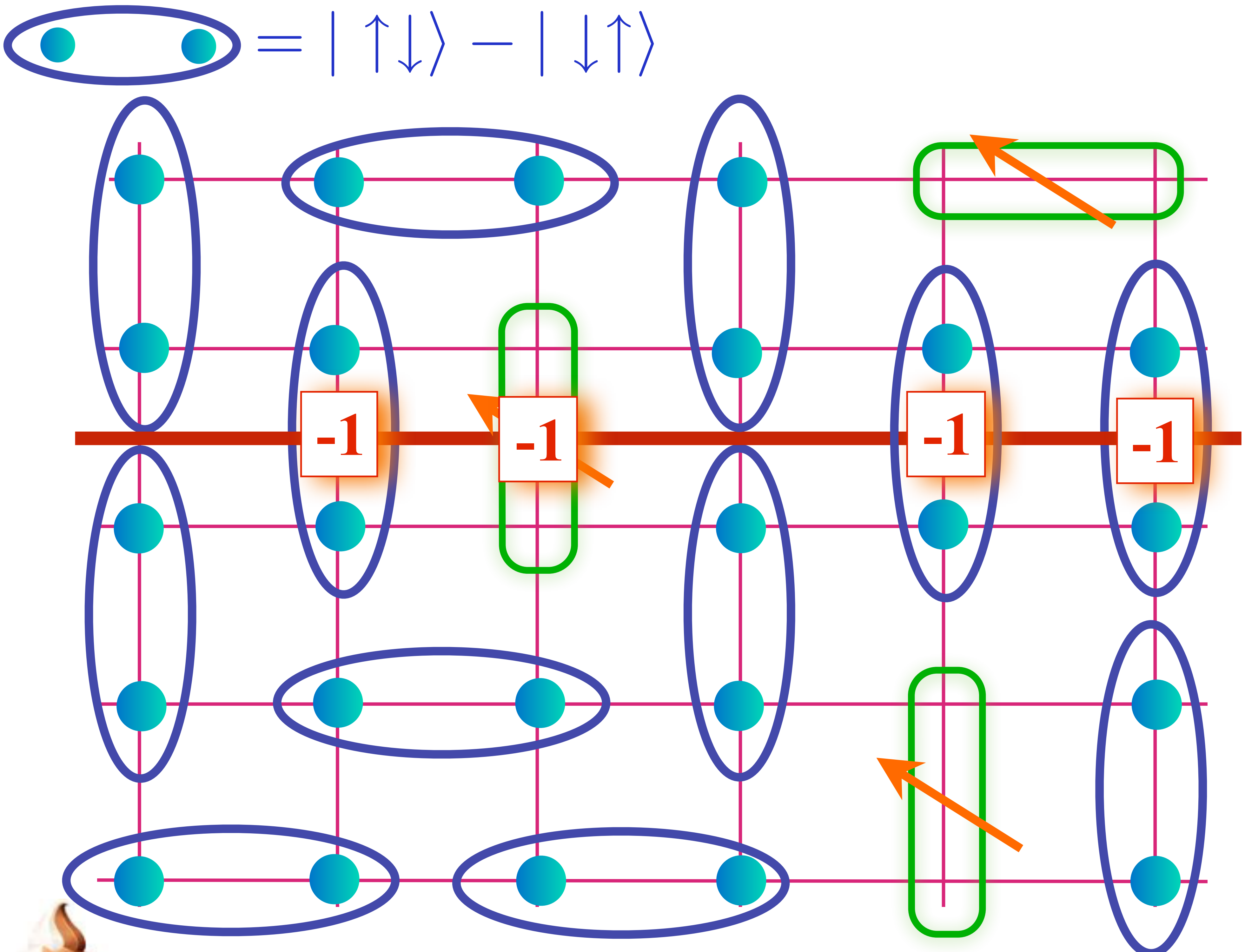
Topological order



Place pseudogap metal on a torus;

obtain "topological" states nearly degenerate with the ground state: change sign of every dimer across red line

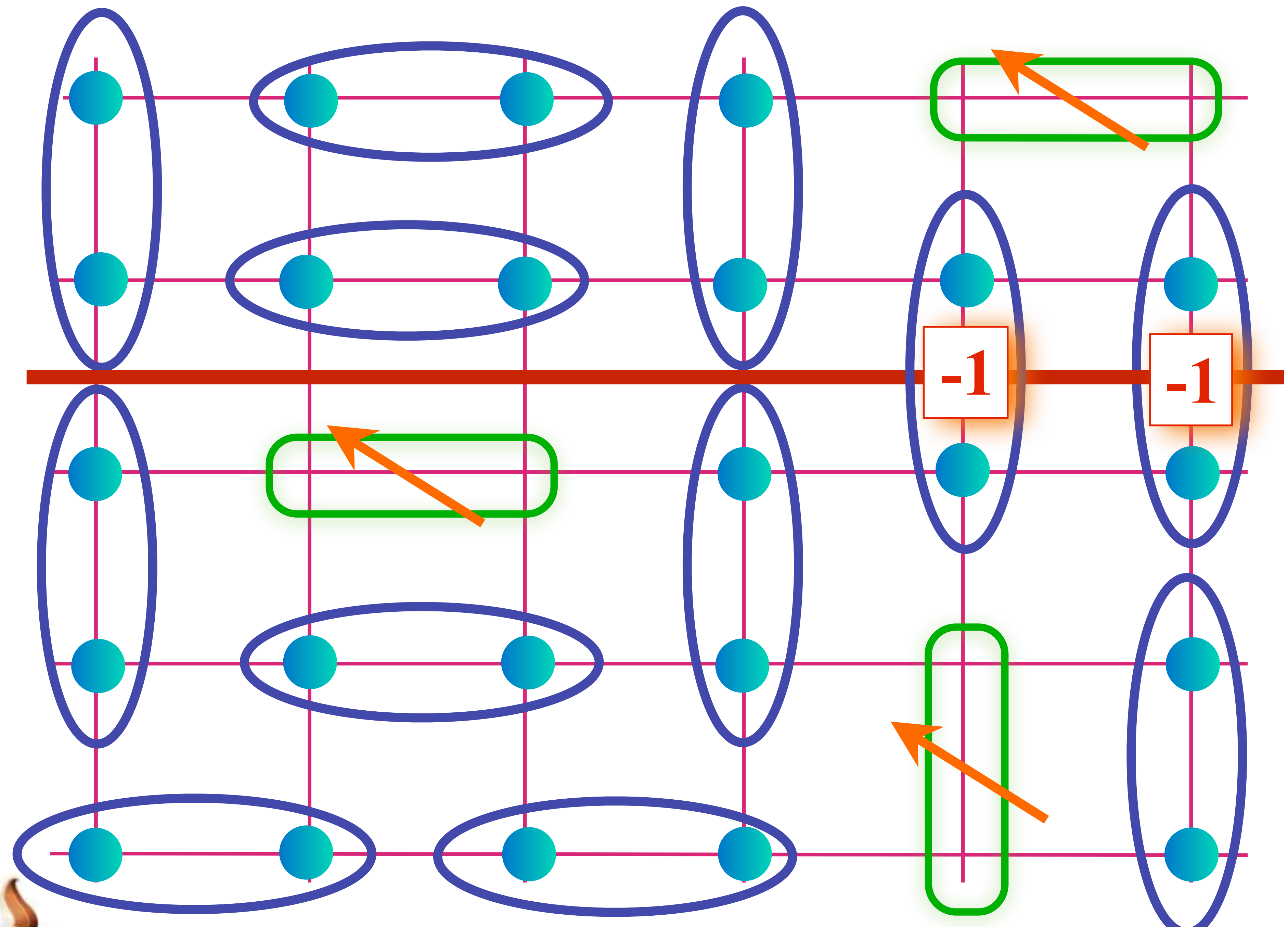
Topological order



Place pseudogap metal on a torus; obtain "topological" states nearly degenerate with the ground state: change sign of every dimer across red line

Topological order

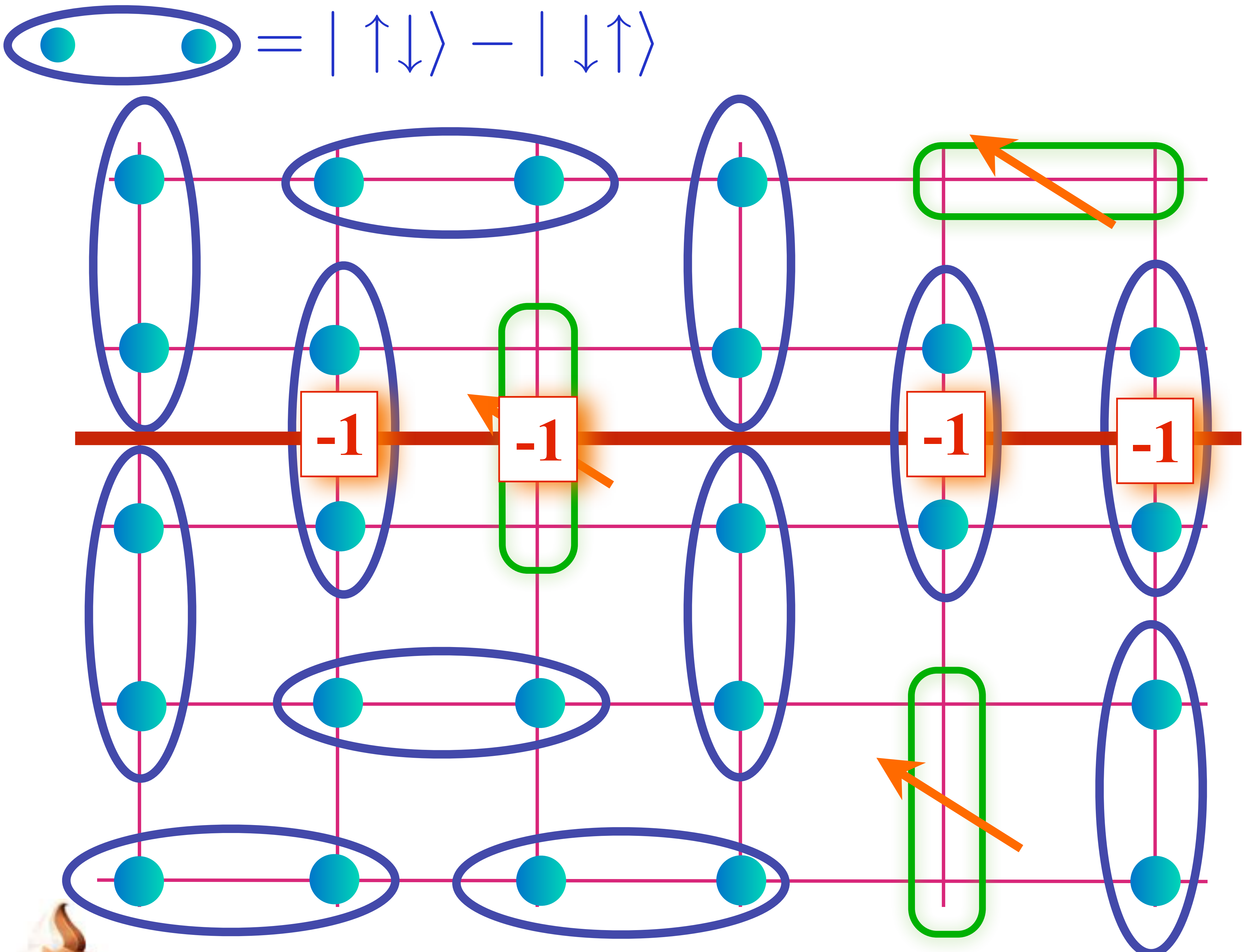
$= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$



Place pseudogap metal on a torus;

obtain "topological" states nearly degenerate with the ground state: change sign of every dimer across red line

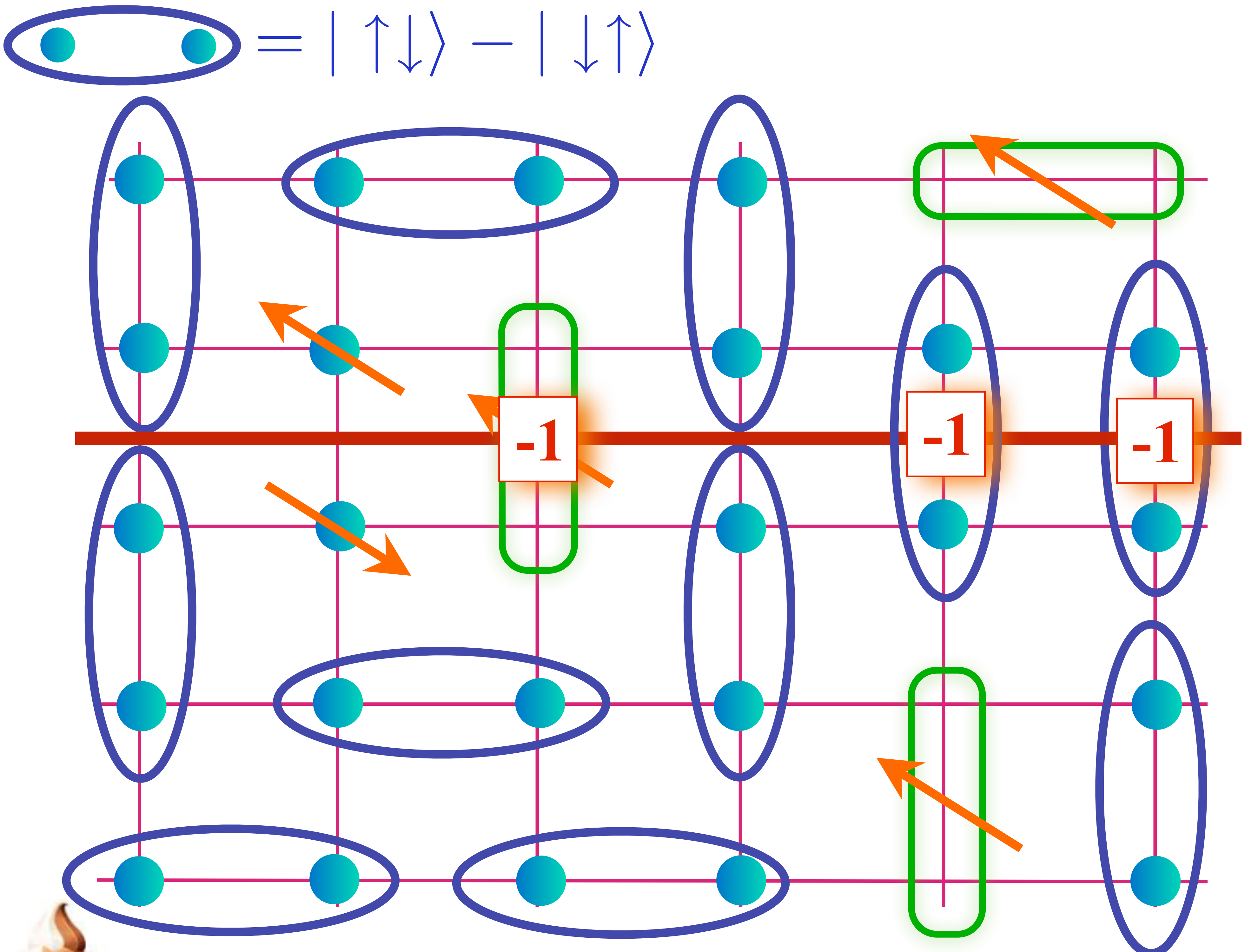
Topological order



Place pseudogap metal on a torus;

obtain "topological" states nearly degenerate with the ground state: change sign of every dimer across red line

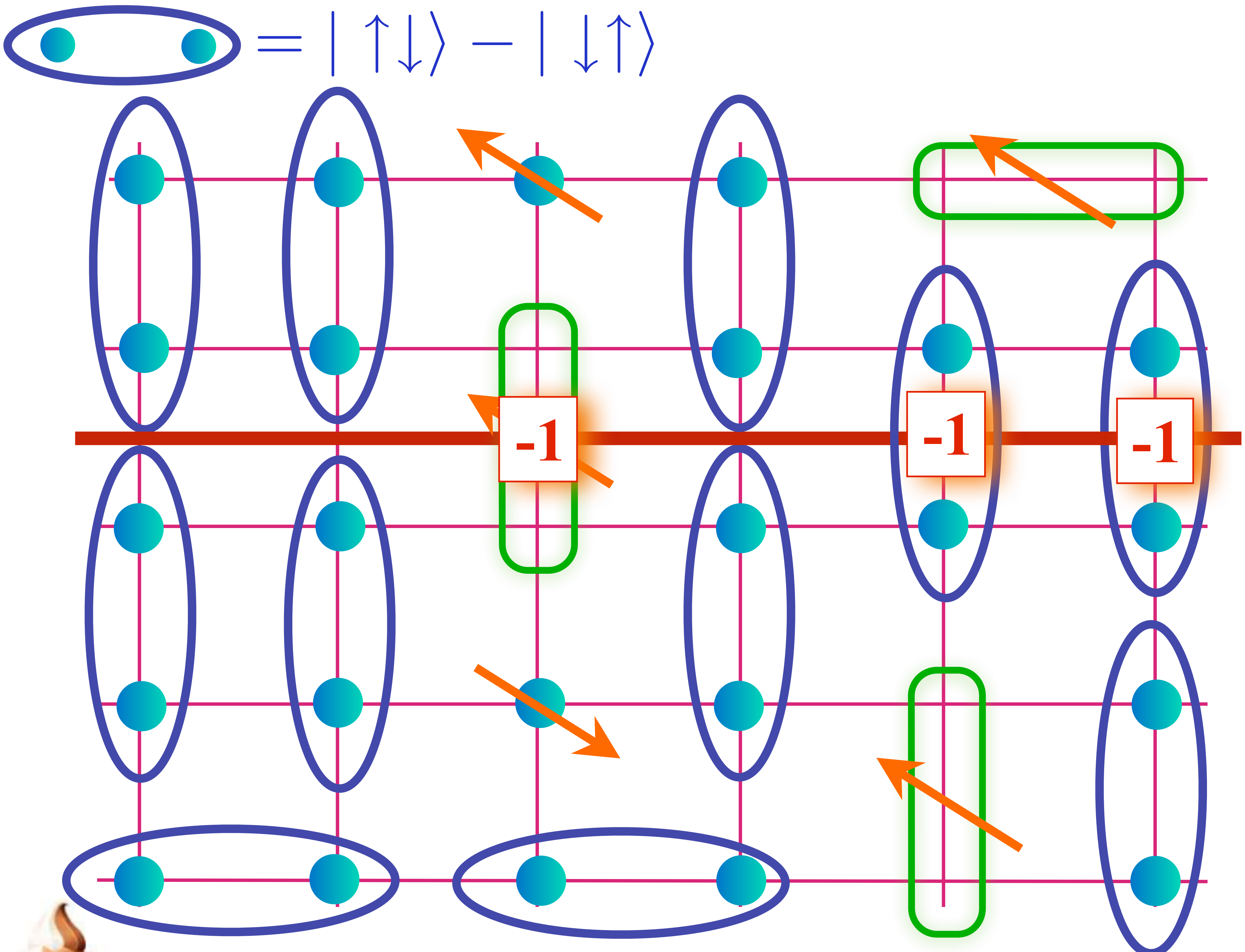
Topological order



Place pseudogap metal on a torus;

to change overall sign, a pair of "spinons" have to be moved globally around a circumference of the torus

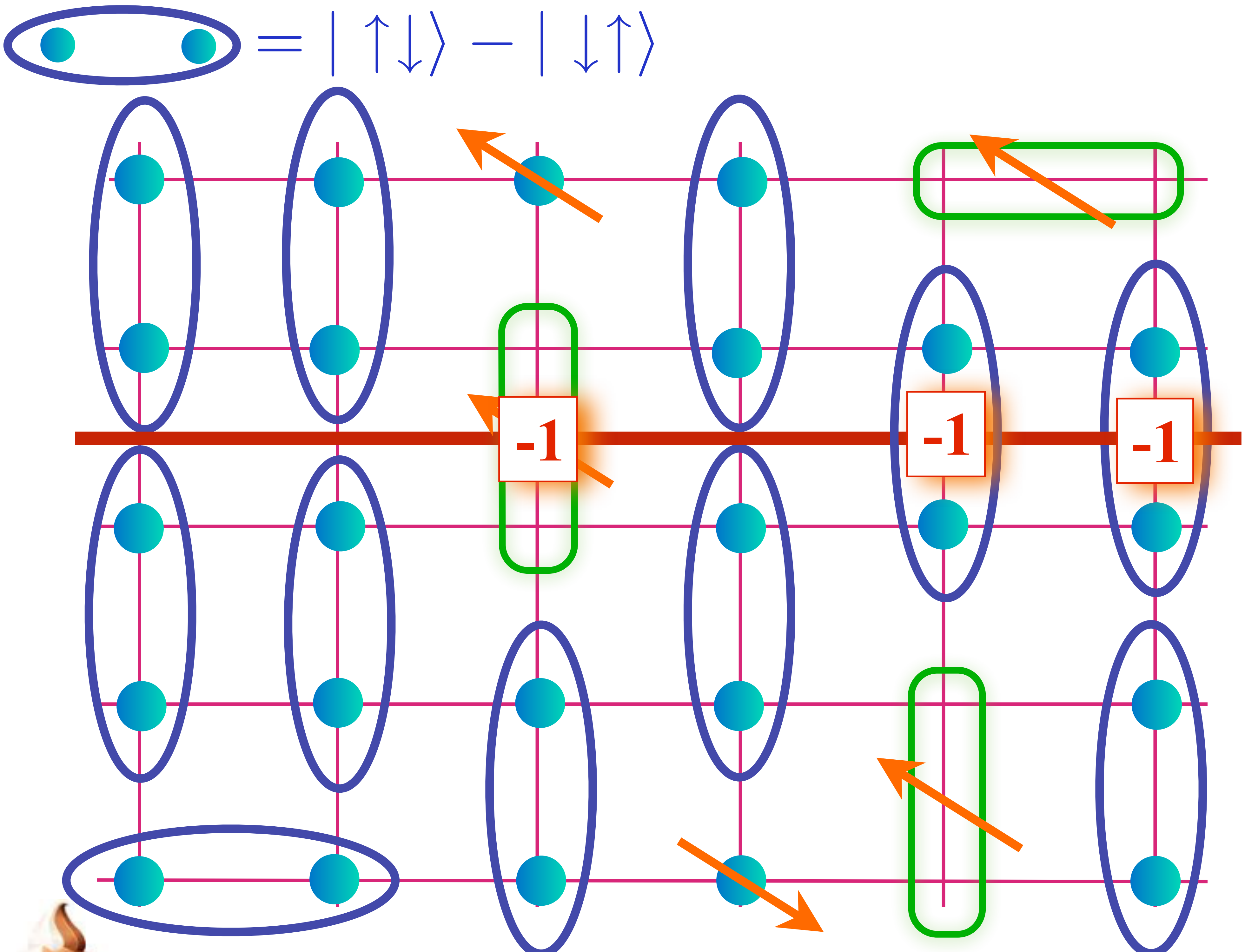
Topological order



Place pseudogap metal on a torus;

to change overall sign, a pair of "spinons" have to be moved globally around a circumference of the torus

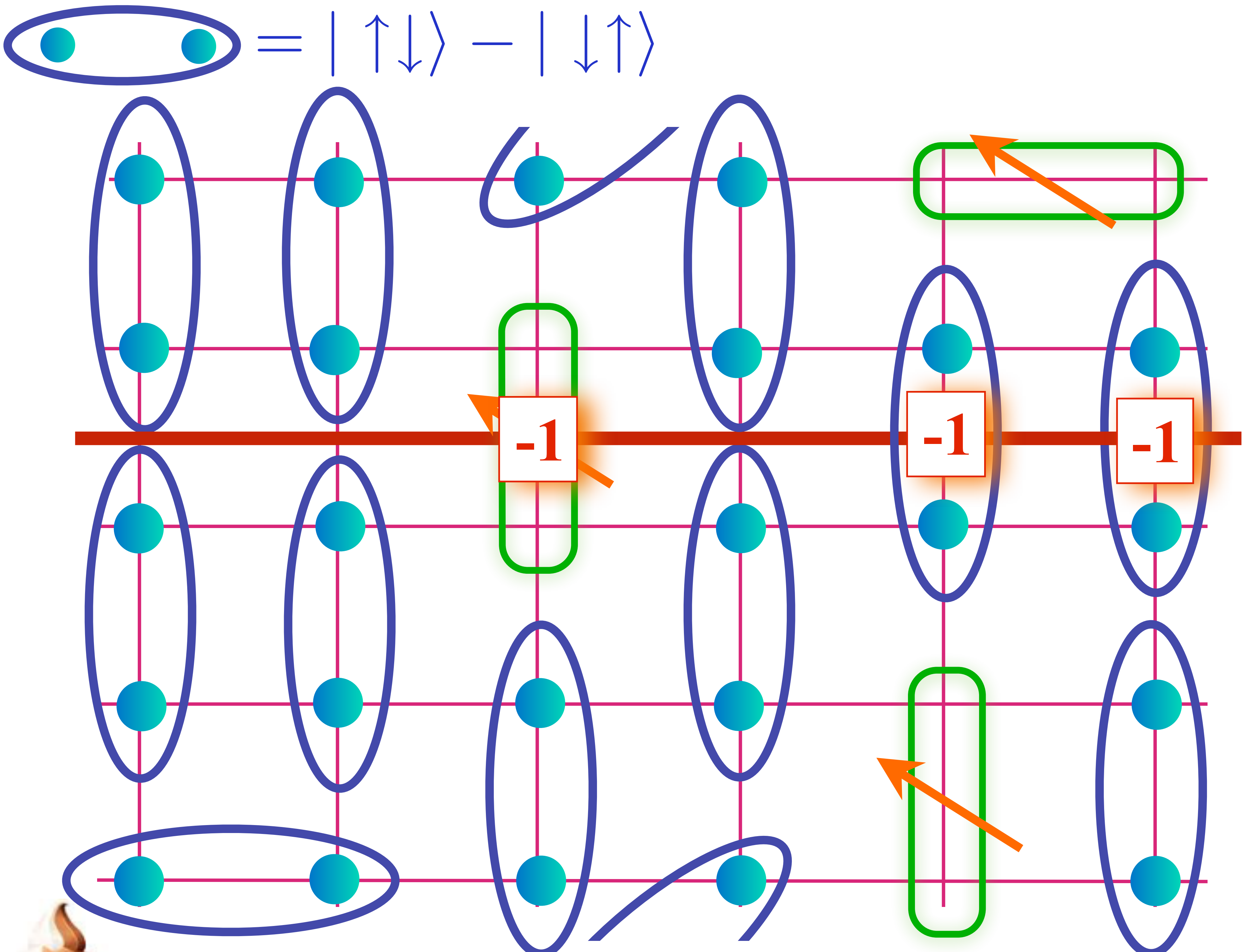
Topological order



Place pseudogap metal on a torus;

to change overall sign, a pair of "spinons" have to be moved globally around a circumference of the torus

Topological order



Place pseudogap metal on a torus;

to change overall sign, a pair of "spinons" have to be moved globally around a circumference of the torus

Outline

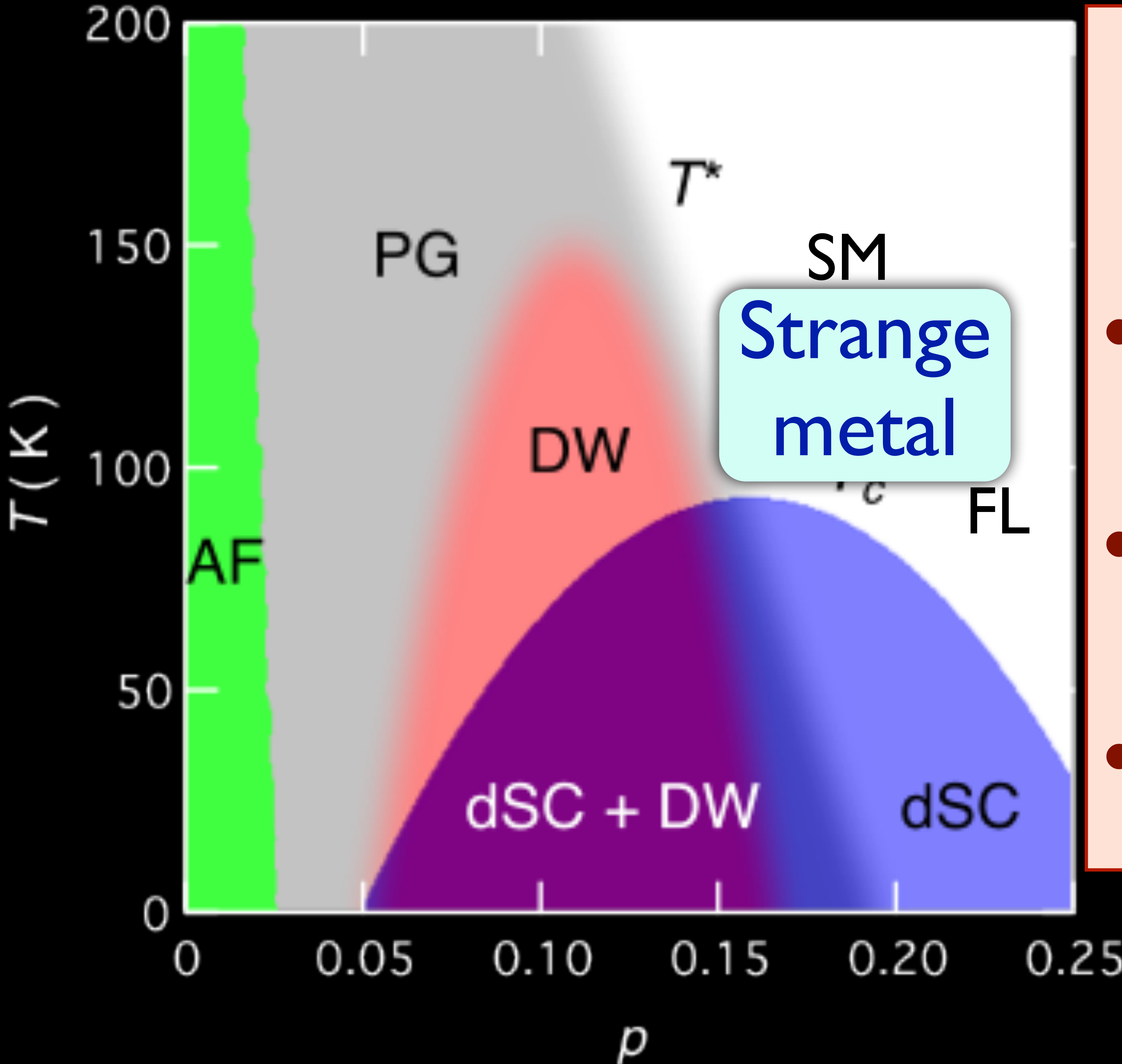
1. The pseudogap metal

Fermi liquid co-existening with topological order

2. The strange metal

Metal without quasiparticles

Infinite-range model: dual to extremal charged black holes and yields Bekenstein-Hawking entropy



Many experimental indications of a quantum state which has:

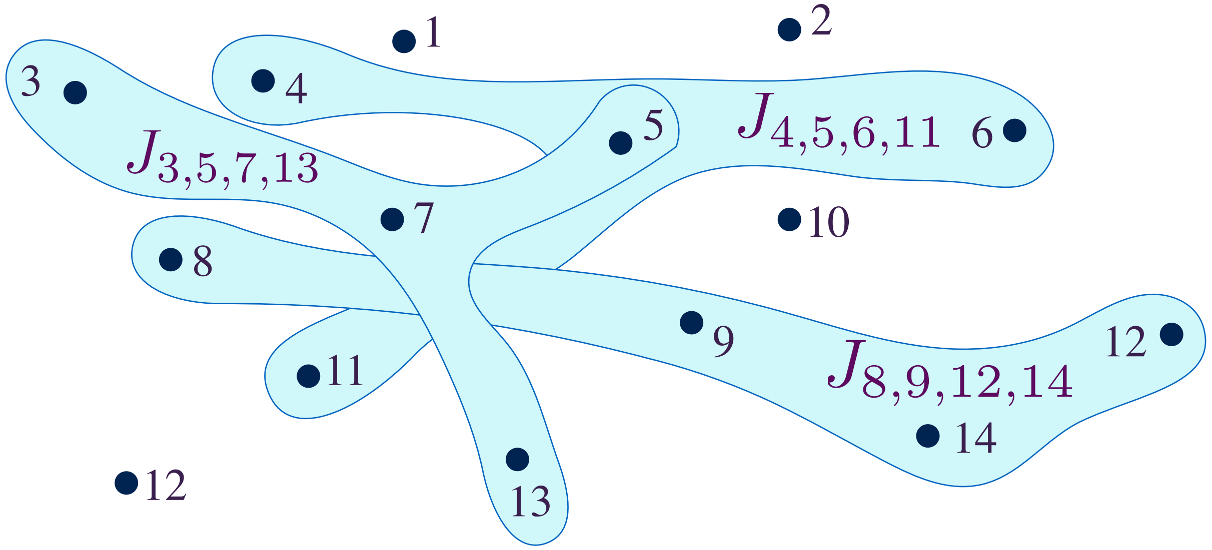
- a continuously variable density at zero temperature,
- bulk excitations of arbitrarily low energy,
- and no long-lived quasiparticles.

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$

$$c_i c_j + c_j c_i = 0$$

$$c_i c_j^\dagger + c_j^\dagger c_i = \delta_{ij}$$

$J_{ij;k\ell}$ independent random numbers



$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

An infinite-range model of a strange metal

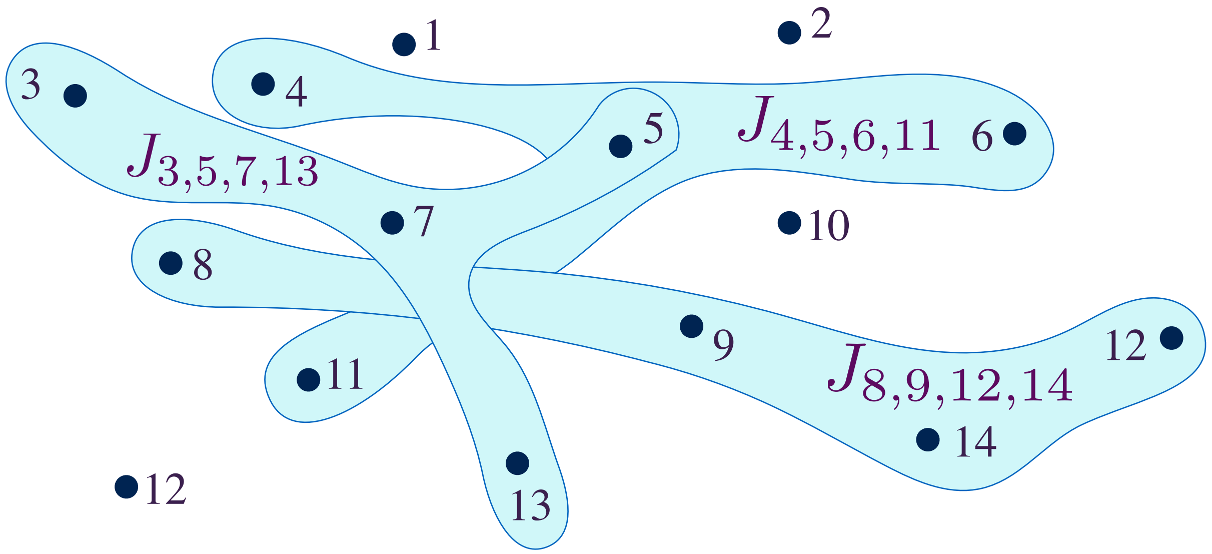
S. Sachdev and J. Ye, Phys. Rev. Lett. **70**, 3339 (1993)
A. Kitaev, unpublished
S. Sachdev, arXiv:1506.05111

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$

$$c_i c_j + c_j c_i = 0$$

$$c_i c_j^\dagger + c_j^\dagger c_i = \delta_{ij}$$

$J_{ij;k\ell}$ independent random numbers



$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

Local fermion density of states

$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \ \omega > 0 \\ e^{-2\pi\mathcal{E}} \, |\omega|^{-1/2} & , \ \omega < 0. \end{cases}$$

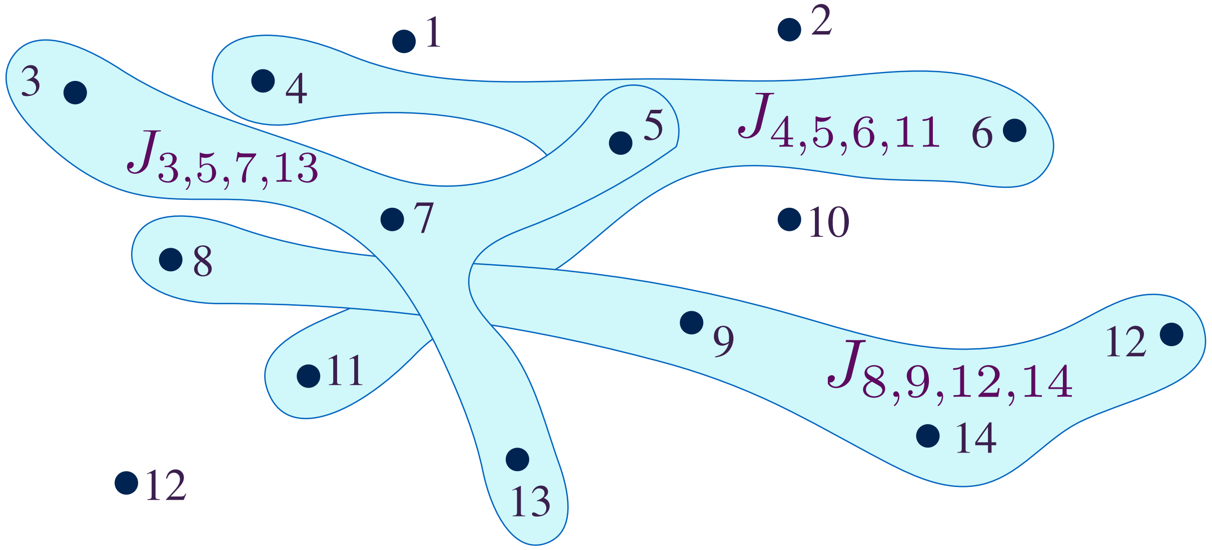
S. Sachdev and J. Ye, Phys. Rev. Lett. **70**, 3339 (1993)

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$

$$c_i c_j + c_j c_i = 0$$

$$c_i c_j^\dagger + c_j^\dagger c_i = \delta_{ij}$$

$J_{ij;k\ell}$ independent random numbers



$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

Local fermion density of states

$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \omega > 0 \\ e^{-2\pi\mathcal{E}}\, |\omega|^{-1/2}, & \omega < 0. \end{cases}$$

Known 'equation of state' determines $\mathcal{E}$ as a function of $\mathcal{Q}$

$$\mathcal{Q} = \frac{1}{4}(3 - \tanh(2\pi\mathcal{E})) - \frac{1}{\pi} \tan^{-1}\left(e^{2\pi\mathcal{E}}\right)$$

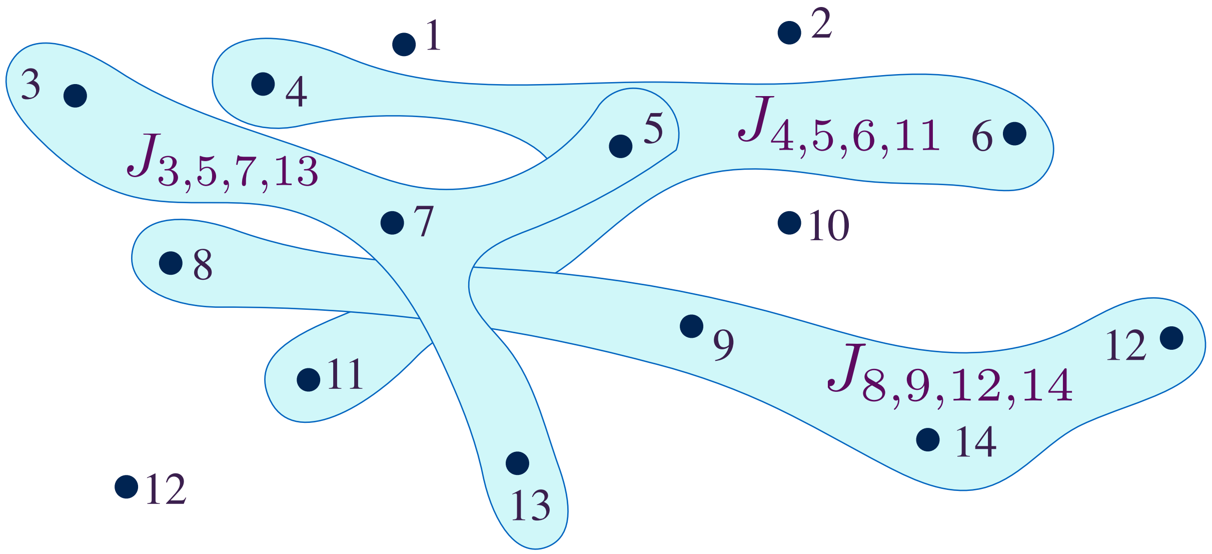
A. Georges, O. Parcollet, and S. Sachdev
Phys. Rev. B **63**, 134406 (2001)

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$

$$c_i c_j + c_j c_i = 0$$

$$c_i c_j^\dagger + c_j^\dagger c_i = \delta_{ij}$$

$J_{ij;k\ell}$ independent random numbers



$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

Local fermion density of states

$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \ \omega > 0 \\ e^{-2\pi\mathcal{E}}\, |\omega|^{-1/2} & , \ \omega < 0. \end{cases}$$

Known 'equation of state' determines $\mathcal{E}$ as a function of $\mathcal{Q}$

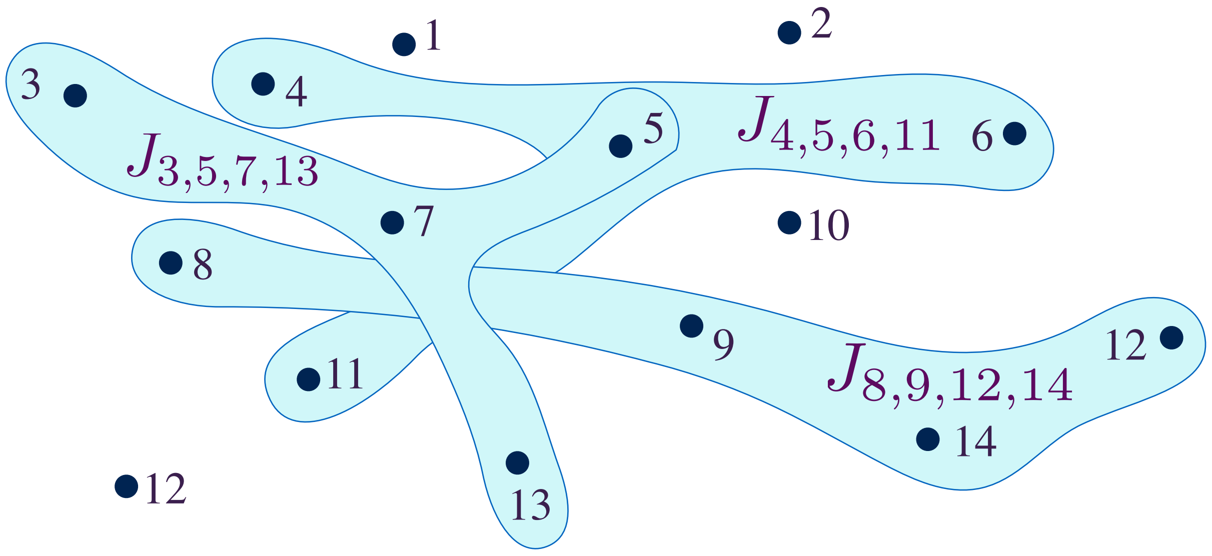
Microscopic zero temperature entropy density, $\mathcal{S}$, obeys

$$\frac{\partial \mathcal{S}}{\partial \mathcal{Q}} = 2\pi\mathcal{E}$$

O. Parcollet, A. Georges, G. Kotliar, and A. Sengupta
Phys. Rev. B **58**, 3794 (1998)

A. Georges, O. Parcollet, and S. Sachdev
Phys. Rev. B **63**, 134406 (2001)

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$



$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

Local fermion density of states

$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \omega > 0 \\ e^{-2\pi\mathcal{E}}\, |\omega|^{-1/2} & , \omega < 0. \end{cases}$$

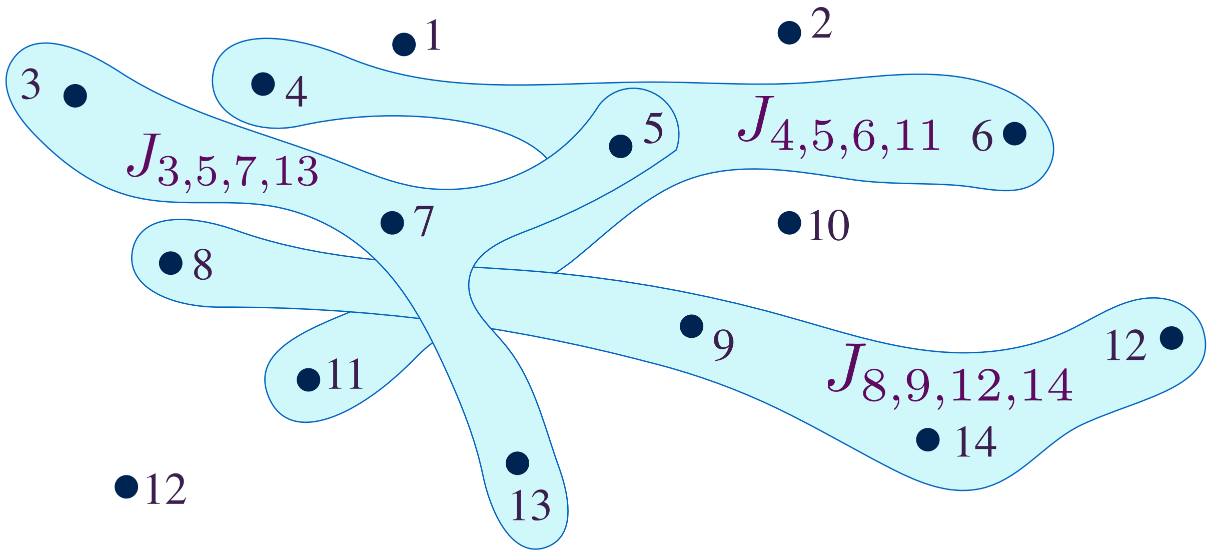
Known 'equation of state' determines $\mathcal{E}$ as a function of $\mathcal{Q}$

Microscopic zero temperature entropy density, $\mathcal{S}$, obeys

$$\frac{\partial \mathcal{S}}{\partial \mathcal{Q}} = 2\pi\mathcal{E}$$

Einstein-Maxwell theory
+ cosmological constant

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$



$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

Local fermion density of states

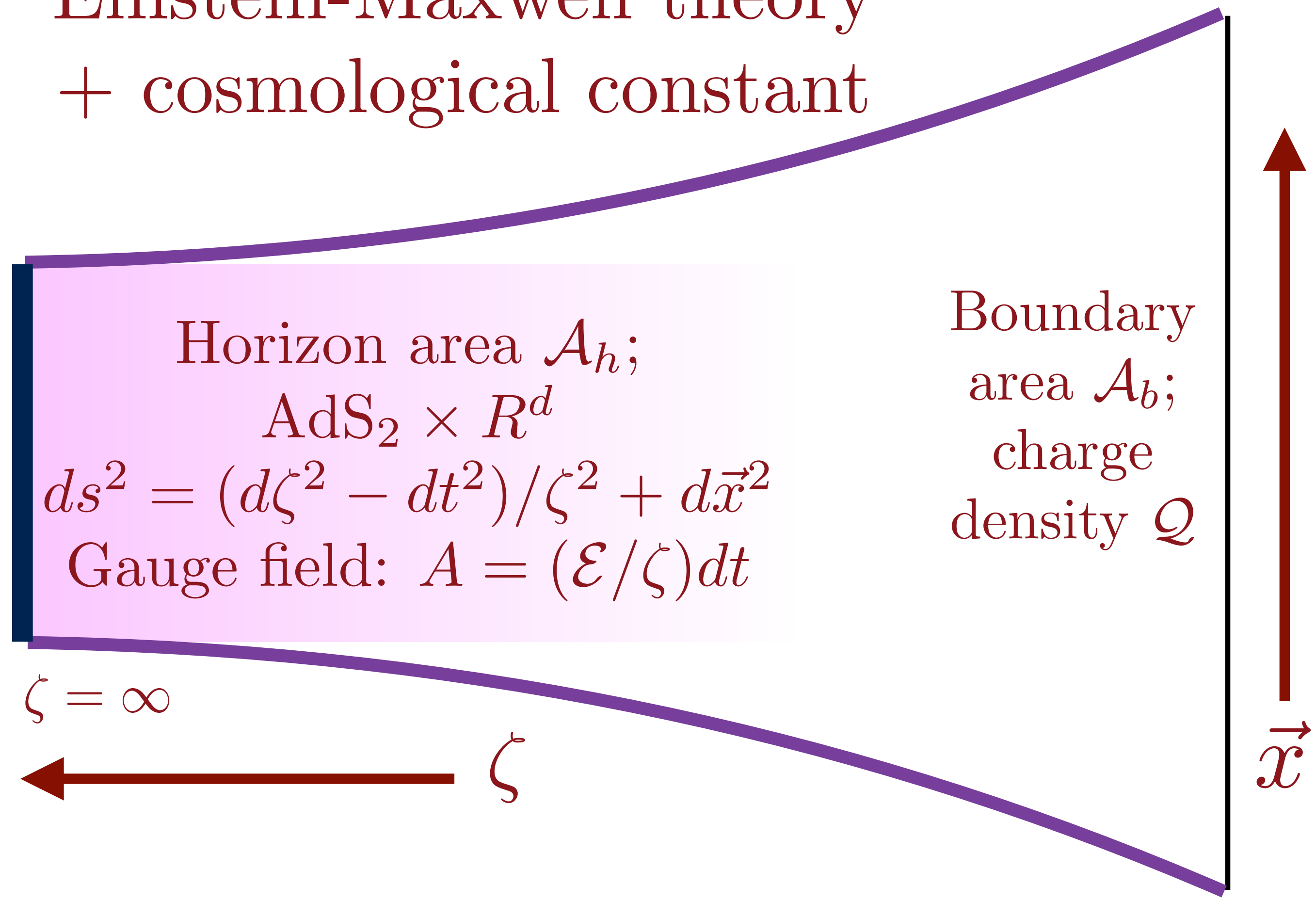
$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \ \omega > 0 \\ e^{-2\pi\mathcal{E}}\, |\omega|^{-1/2}, & \omega < 0. \end{cases}$$

Known 'equation of state' determines $\mathcal{E}$ as a function of $\mathcal{Q}$

Microscopic zero temperature entropy density, $\mathcal{S}$, obeys

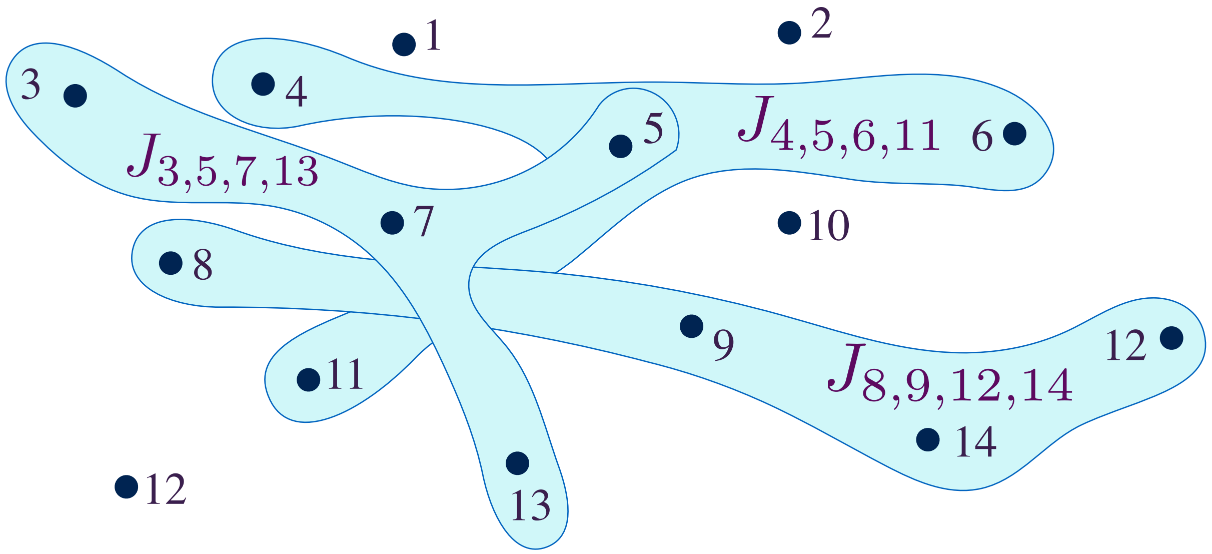
$$\frac{\partial \mathcal{S}}{\partial \mathcal{Q}} = 2\pi\mathcal{E}$$

Einstein-Maxwell theory + cosmological constant



A. Chamblin, R. Emparan, C.V. Johnson, and R.C. Myers
Phys. Rev. D **60**, 064018 (1999)

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$



$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

Local fermion density of states

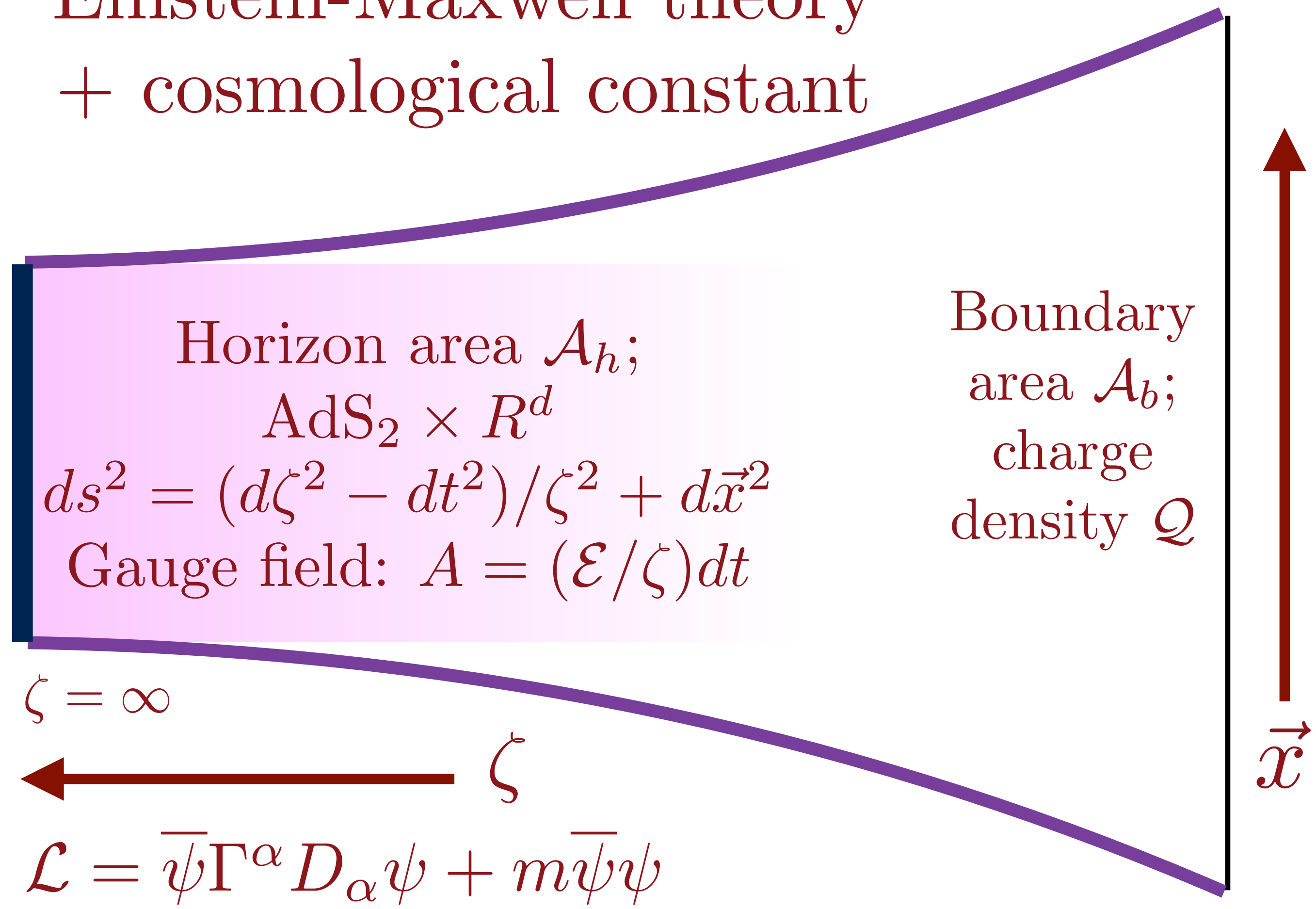
$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \omega > 0 \\ e^{-2\pi\mathcal{E}}\, |\omega|^{-1/2} & , \omega < 0. \end{cases}$$

Known 'equation of state' determines $\mathcal{E}$ as a function of $\mathcal{Q}$

Microscopic zero temperature entropy density, $\mathcal{S}$, obeys

$$\frac{\partial \mathcal{S}}{\partial \mathcal{Q}} = 2\pi\mathcal{E}$$

Einstein-Maxwell theory
+ cosmological constant



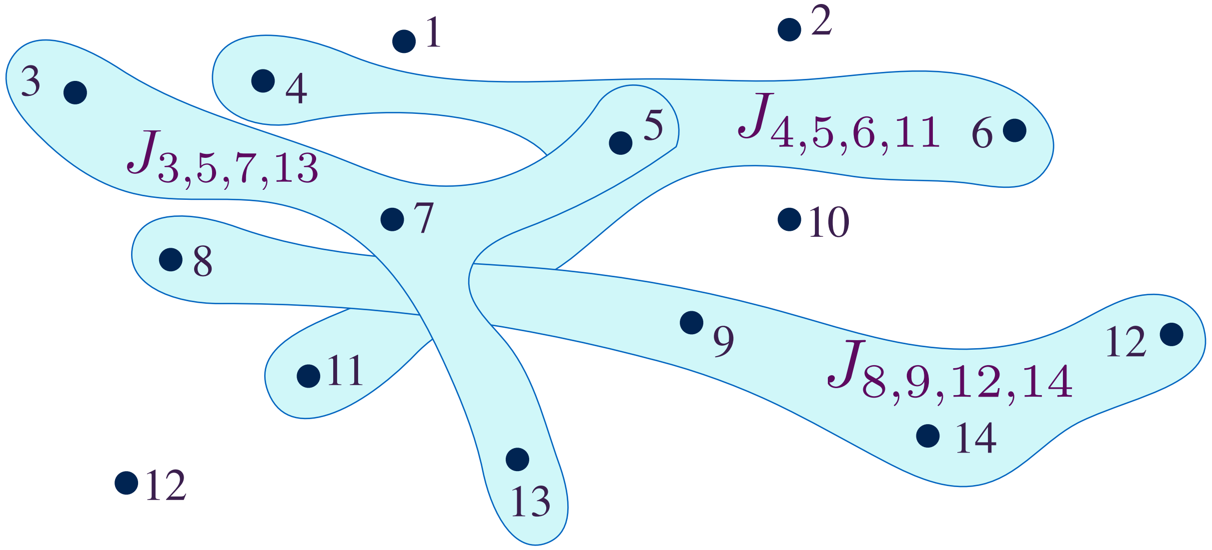
$$\mathcal{L} = \overline{\psi}\Gamma^\alpha D_\alpha \psi + m\overline{\psi}\psi$$

Local fermion density of states

$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \omega > 0 \\ e^{-2\pi\mathcal{E}}\, |\omega|^{-1/2} & , \omega < 0. \end{cases}$$

T. Faulkner, Hong Liu, J. McGreevy, and D. Vegh
Phys. Rev. D **83**, 125002 (2011)

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$



$$\mathcal{Q} = \frac{1}{N}\sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

Local fermion density of states

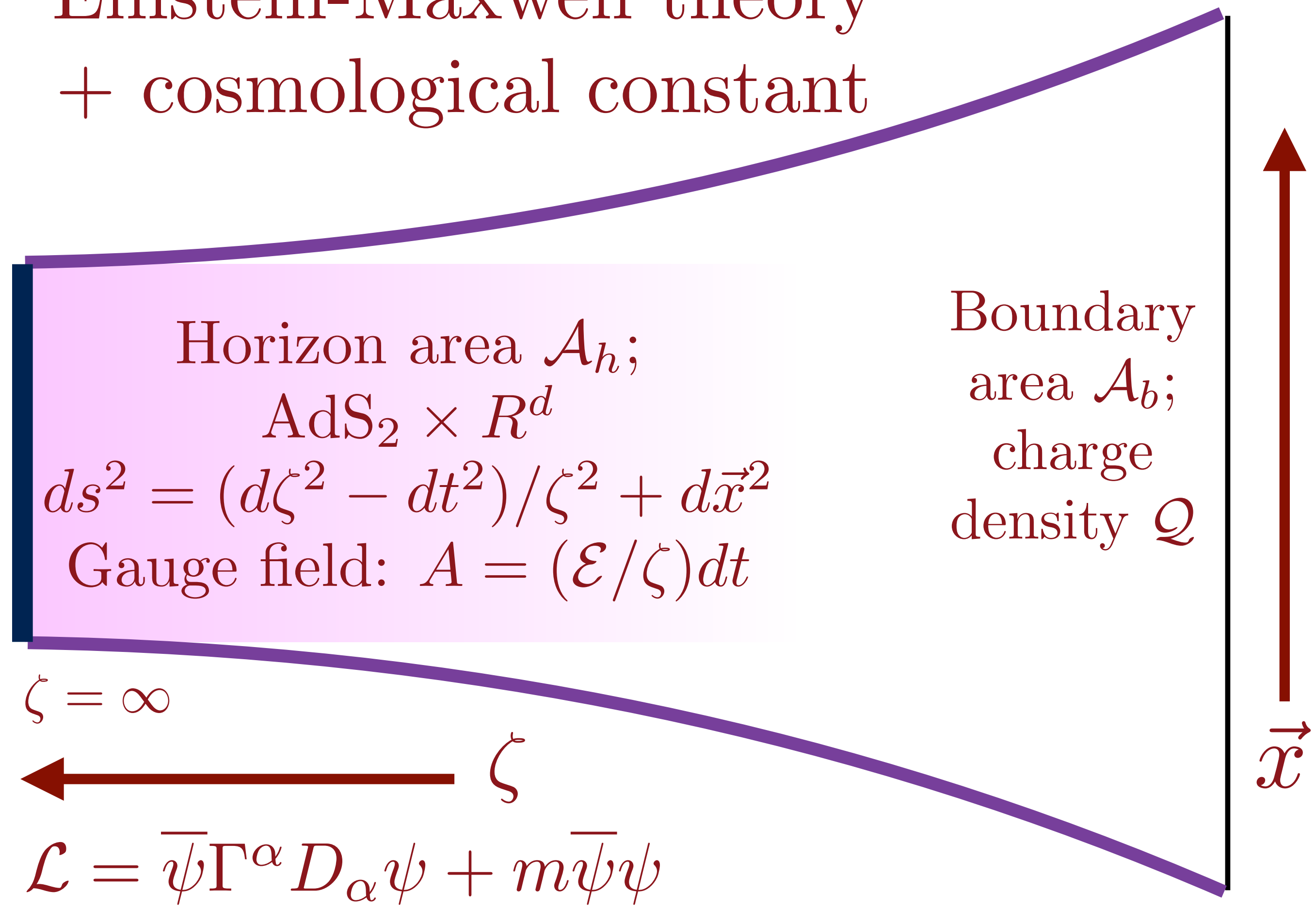
$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \ \omega > 0 \\ e^{-2\pi\mathcal{E}}\, |\omega|^{-1/2}, & \omega < 0. \end{cases}$$

Known 'equation of state' determines $\mathcal{E}$ as a function of $\mathcal{Q}$

Microscopic zero temperature entropy density, $\mathcal{S}$, obeys

$$\frac{\partial \mathcal{S}}{\partial \mathcal{Q}} = 2\pi\mathcal{E}$$

Einstein-Maxwell theory + cosmological constant



$$\mathcal{L} = \overline{\psi}\Gamma^\alpha D_\alpha \psi + m\overline{\psi}\psi$$

Local fermion density of states

$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \ \omega > 0 \\ e^{-2\pi\mathcal{E}}\, |\omega|^{-1/2}, & \omega < 0. \end{cases}$$

'Equation of state' relating $\mathcal{E}$ and $\mathcal{Q}$ depends upon the geometry of spacetime far from the AdS_2

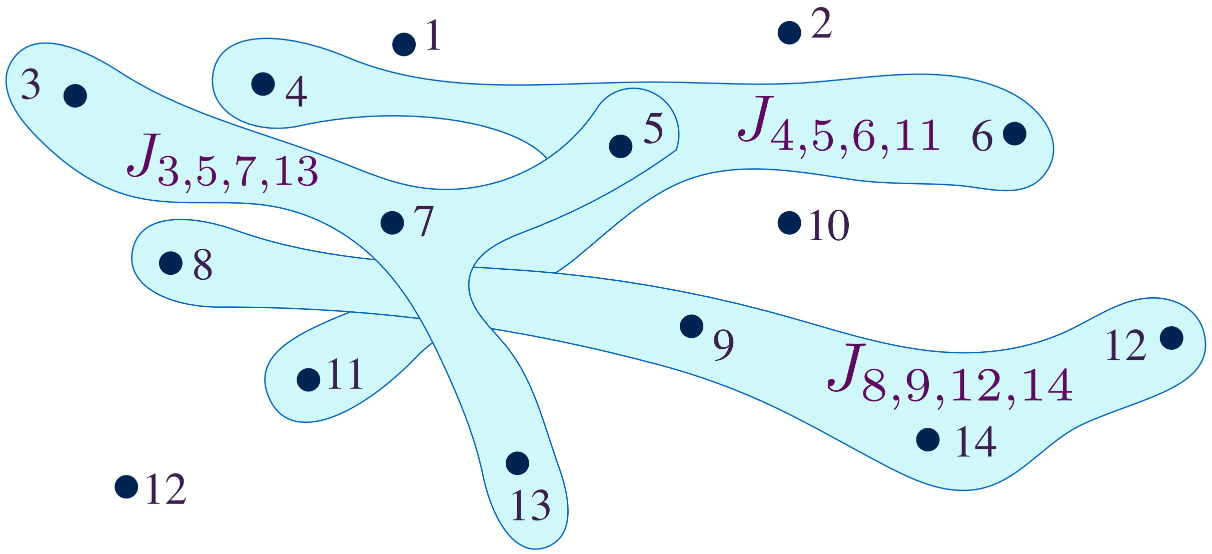
Eliminate r_0 between

$$\mathcal{Q} = \frac{r_0^{d-1}\sqrt{2d\left[(d-1)R^2 + (d+1)r_0^2\right]}}{\kappa^2 g_F}$$

$$\mathcal{E} = \frac{g_F r_0 \sqrt{2d\left[(d-1)R^2 + (d+1)r_0^2\right]}}{2\left[(d-1)^2R^2 + d(d+1)r_0^2\right]}$$

S. Sachdev, arXiv:1506.05111

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$



$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

Local fermion density of states

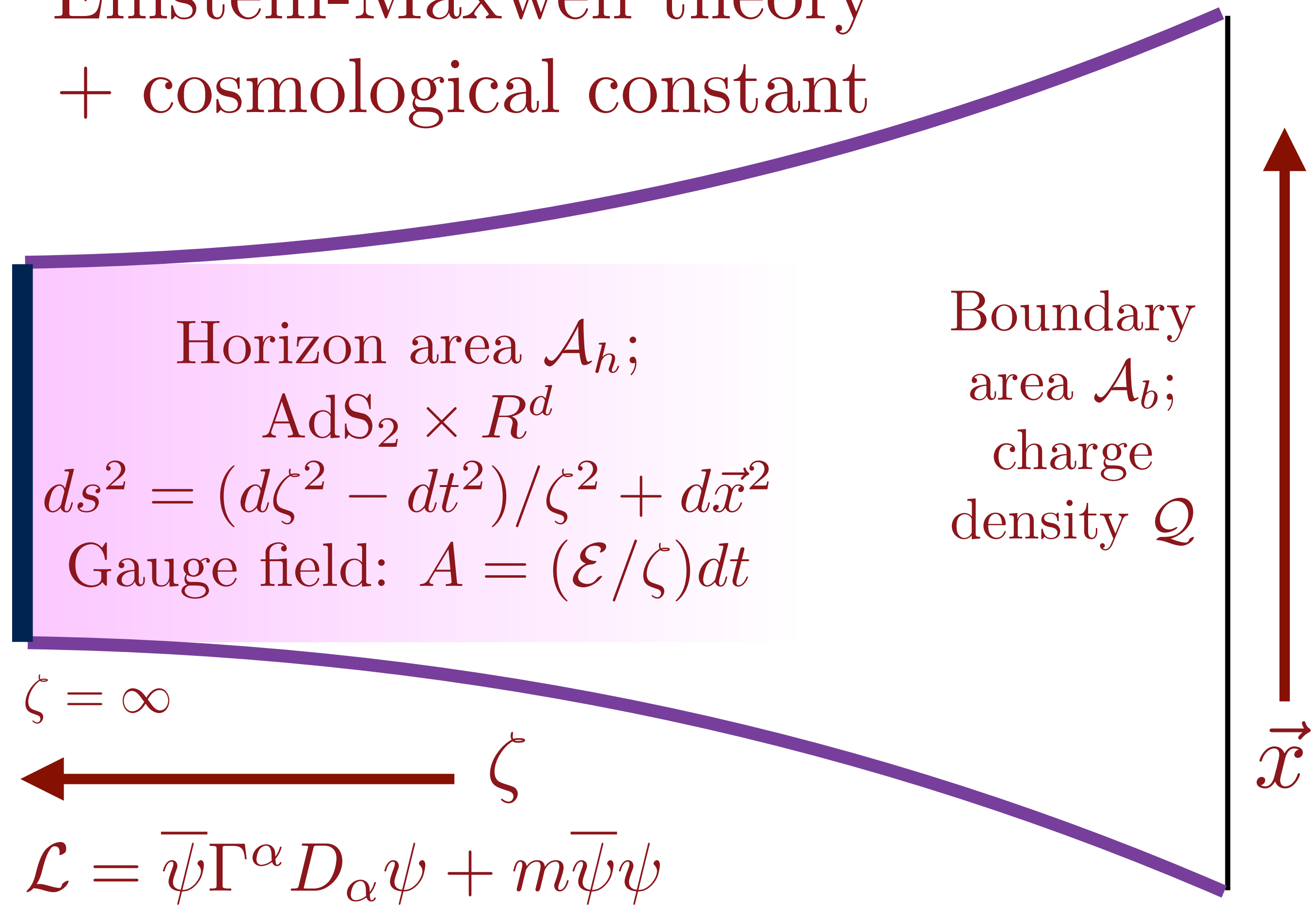
$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \ \omega > 0 \\ e^{-2\pi\mathcal{E}}\, |\omega|^{-1/2}, & \omega < 0. \end{cases}$$

Known 'equation of state' determines $\mathcal{E}$ as a function of $\mathcal{Q}$

Microscopic zero temperature entropy density, $\mathcal{S}$, obeys

$$\frac{\partial \mathcal{S}}{\partial \mathcal{Q}} = 2\pi\mathcal{E}$$

Einstein-Maxwell theory
+ cosmological constant



$$\mathcal{L} = \overline{\psi}\Gamma^\alpha D_\alpha \psi + m\overline{\psi}\psi$$

Local fermion density of states

$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \ \omega > 0 \\ e^{-2\pi\mathcal{E}}\, |\omega|^{-1/2}, & \omega < 0. \end{cases}$$

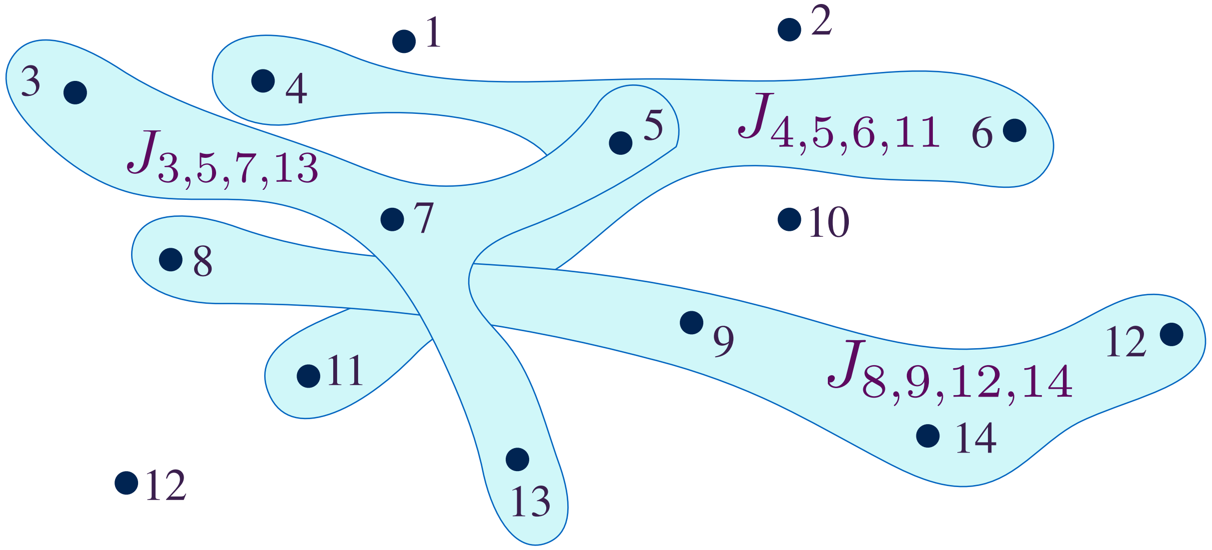
'Equation of state' relating $\mathcal{E}$ and $\mathcal{Q}$ depends upon the geometry of spacetime far from the AdS_2

Black hole thermodynamics (classical GR) yields

$$\frac{1}{\mathcal{A}_b} \frac{\partial \mathcal{A}_h}{\partial \mathcal{Q}} = 8\pi G_N \mathcal{E}$$

A. Sen, arXiv:hep-th/0506177; S. Sachdev, arXiv:1506.0511

$$H = \frac{1}{(2N)^{3/2}} \sum_{i,j,k,\ell=1}^{N} J_{ij;k\ell}\, c_i^\dagger c_j^\dagger c_k c_\ell$$



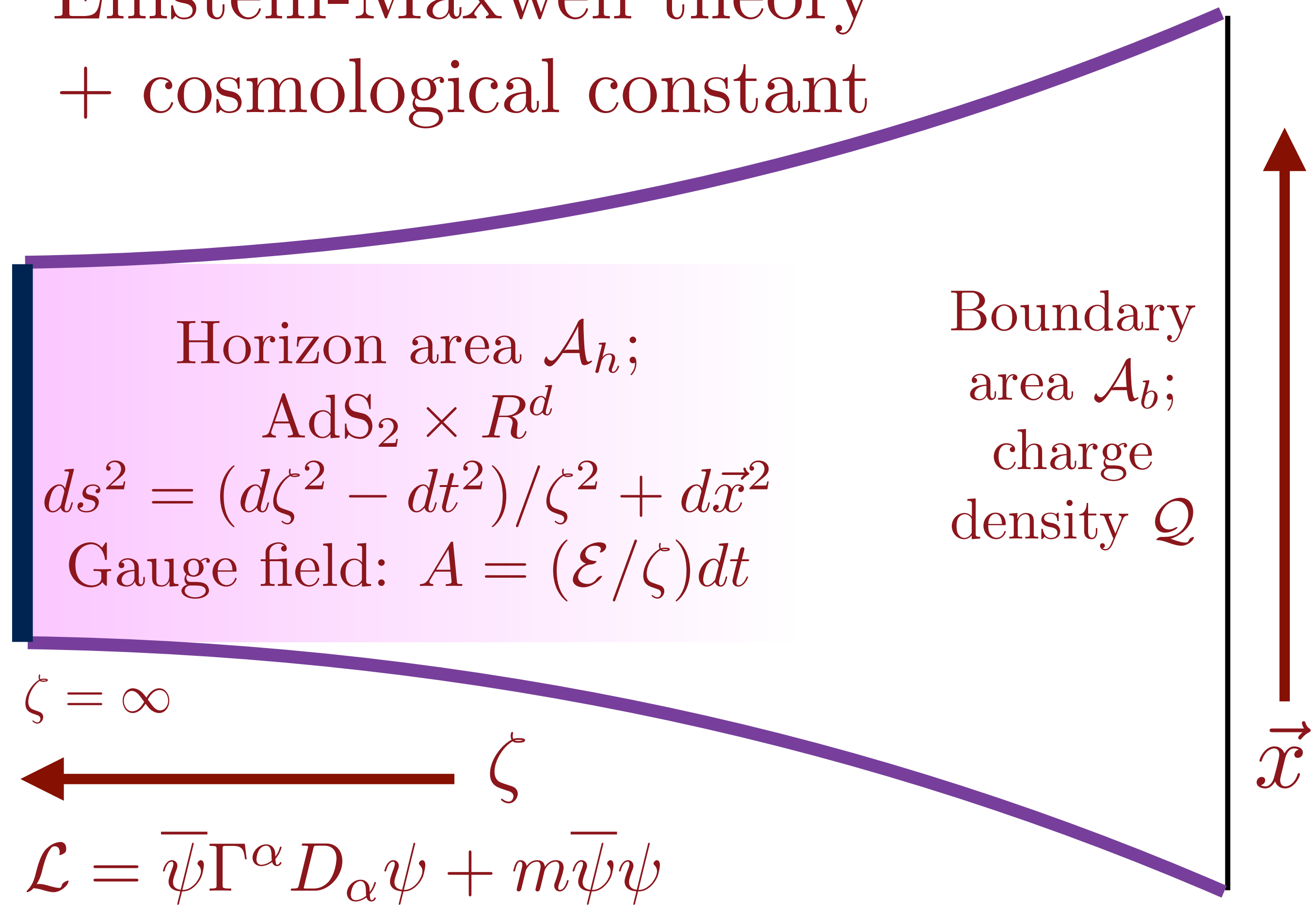
$$\mathcal{Q} = \frac{1}{N} \sum_i \left\langle c_i^\dagger c_i \right\rangle .$$

Local fermion density of states

$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \omega > 0 \\ e^{-2\pi\mathcal{E}} \, |\omega|^{-1/2}, & \omega < 0. \end{cases}$$

Known 'equation of state' determines $\mathcal{E}$ as a function of $\mathcal{Q}$

Einstein-Maxwell theory
+ cosmological constant



$$\mathcal{L} = \overline{\psi}\Gamma^\alpha D_\alpha \psi + m\overline{\psi}\psi$$

Local fermion density of states

$$\rho(\omega) \sim \begin{cases} \omega^{-1/2} & , \omega > 0 \\ e^{-2\pi\mathcal{E}} \, |\omega|^{-1/2}, & \omega < 0. \end{cases}$$

'Equation of state' relating $\mathcal{E}$ and $\mathcal{Q}$ depends upon the geometry of spacetime far from the AdS_2

Microscopic zero temperatu
entropy density, $\mathcal{S}$, obeys

$$\frac{\partial \mathcal{S}}{\partial \mathcal{Q}} = 2\pi\mathcal{E}$$

Combination:

$$\mathcal{S} = \frac{\mathcal{A}_h}{4 G_N \mathcal{A}_b}$$

lack hole thermodynamics
(classical GR) yields

$$\frac{1}{\mathcal{A}_b} \frac{\partial \mathcal{A}_h}{\partial \mathcal{Q}} = 8\pi G_N \mathcal{E}$$

S. Sachdev, arXiv:1506.05111

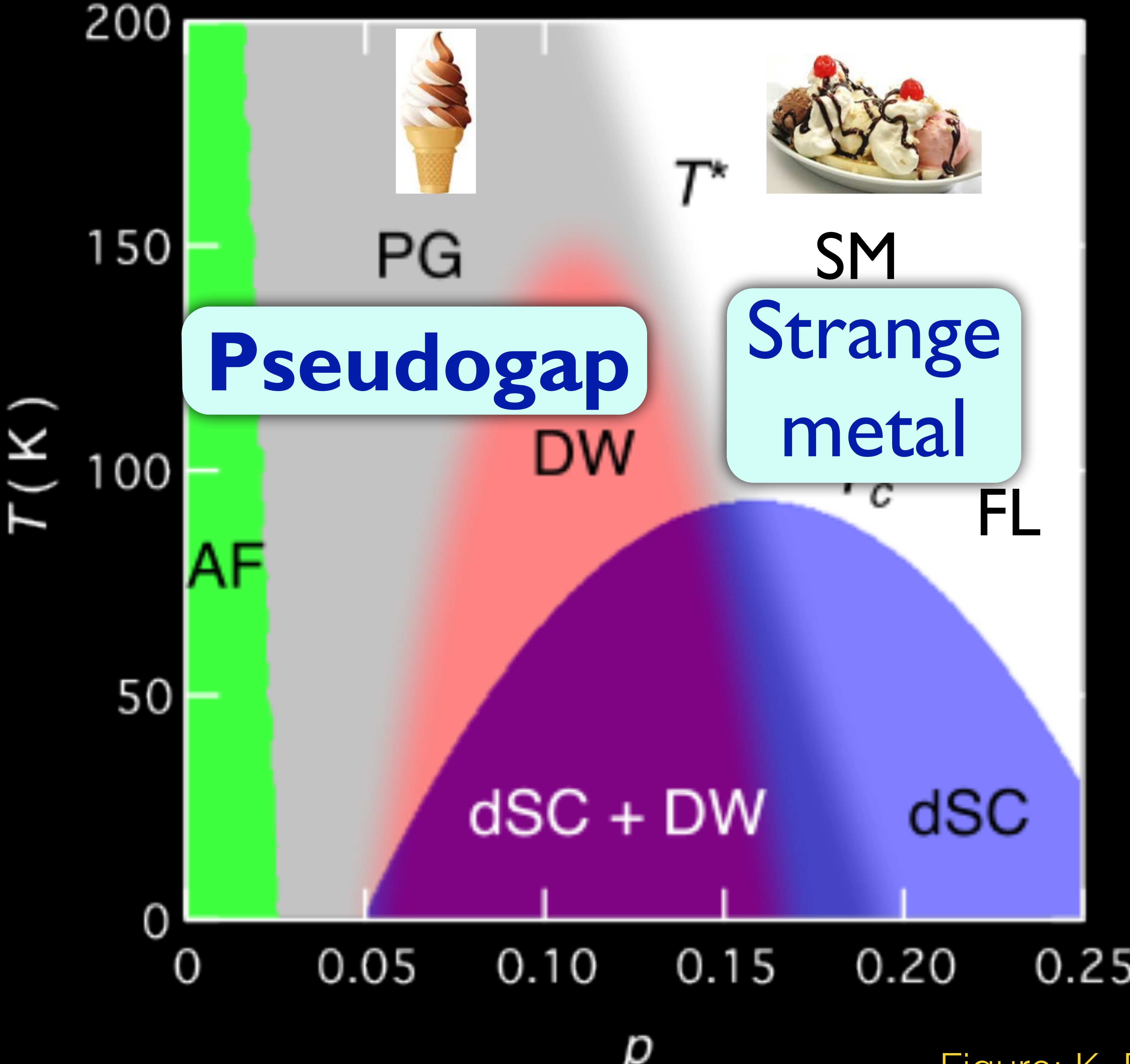


Figure: K. Fujita and J. C. Seamus Davis

1. The pseudogap metal

Fermi liquid co-existening with topological order

2. The strange metal

Metal without quasiparticles

Infinite-range model: dual to extremal charged black holes and yields Bekenstein-Hawking entropy