Topological order in quantum matter

Indian Institute of Science Education and Research, Pune

Subir Sachdev
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Talk online: sachdev.physics.harvard.edu

PHYSICS

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HARVARD

1. Classical XY model in 2 and 3 dimensions

2. Topological order in the classical XY model in 3 dimensions

3. Topological order in the quantum XY model in 2+1 dimensions

4. Topological order in the Hubbard model

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\begin{aligned}
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H &= -J \sum_{\langle ij \rangle} \cos(\theta_i - \theta_j)
\end{aligned}
$$

Describes non-zero *T* phase transitions of superfluids, magnets with `easy-plane' spins,

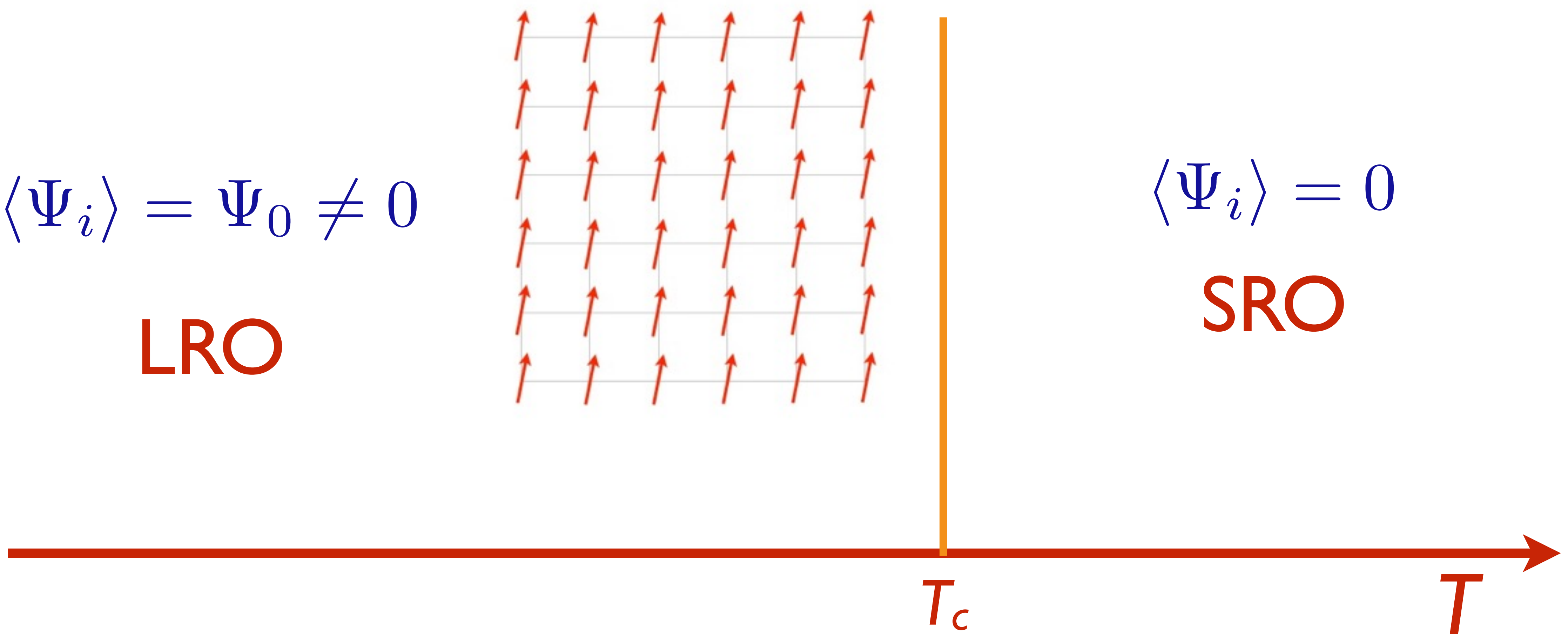
.....

In spatial dimension $d = 3$, in the low T phase, the symmetry $\theta_i \to \theta_i + c$ is "spontaneously broken". There is (off-diagonal) long-range order (LRO) characterized by ($\Psi_i \equiv e^{i\theta_i}$)

$$\lim_{|r_i - r_j| \to \infty} \langle \Psi_i \Psi_j^* \rangle = |\Psi_0|^2 \neq 0\,.$$

We break the symmetry by choosing an overall phase so that

$$\langle \Psi_i \rangle = \Psi_0 \neq 0$$



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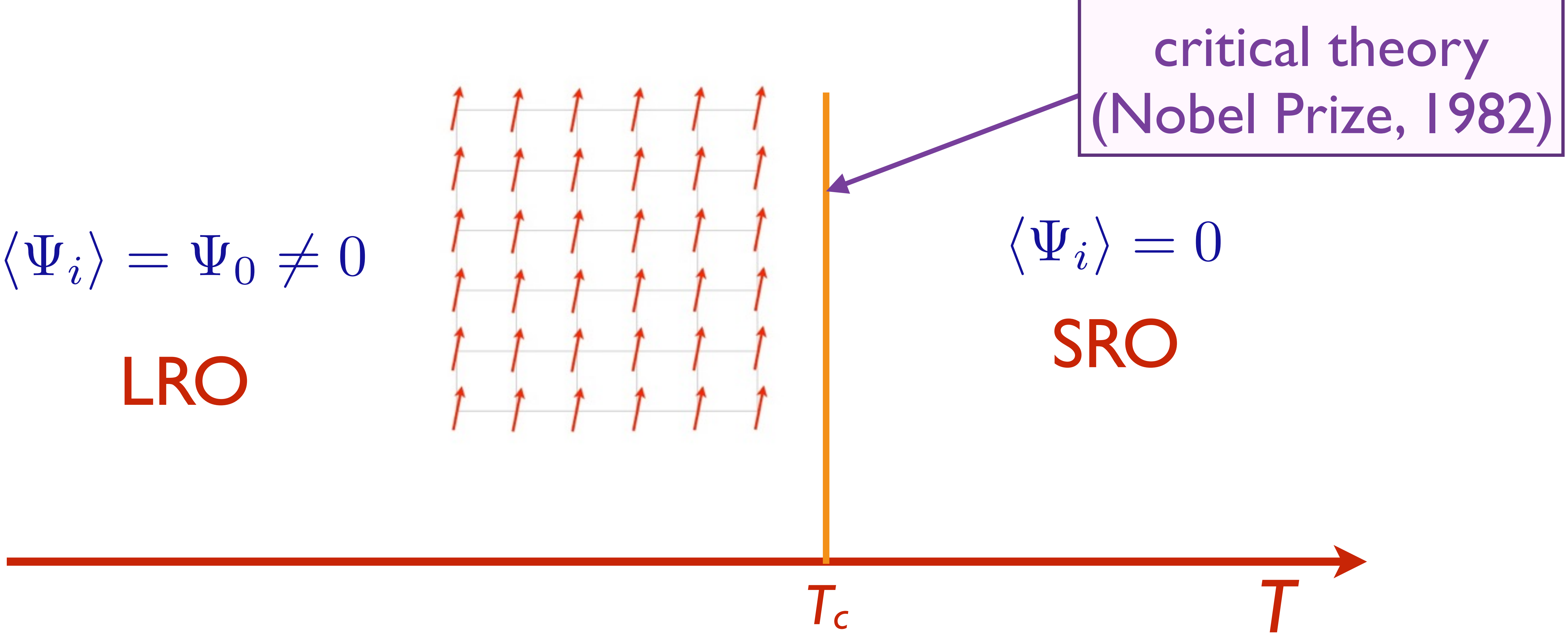


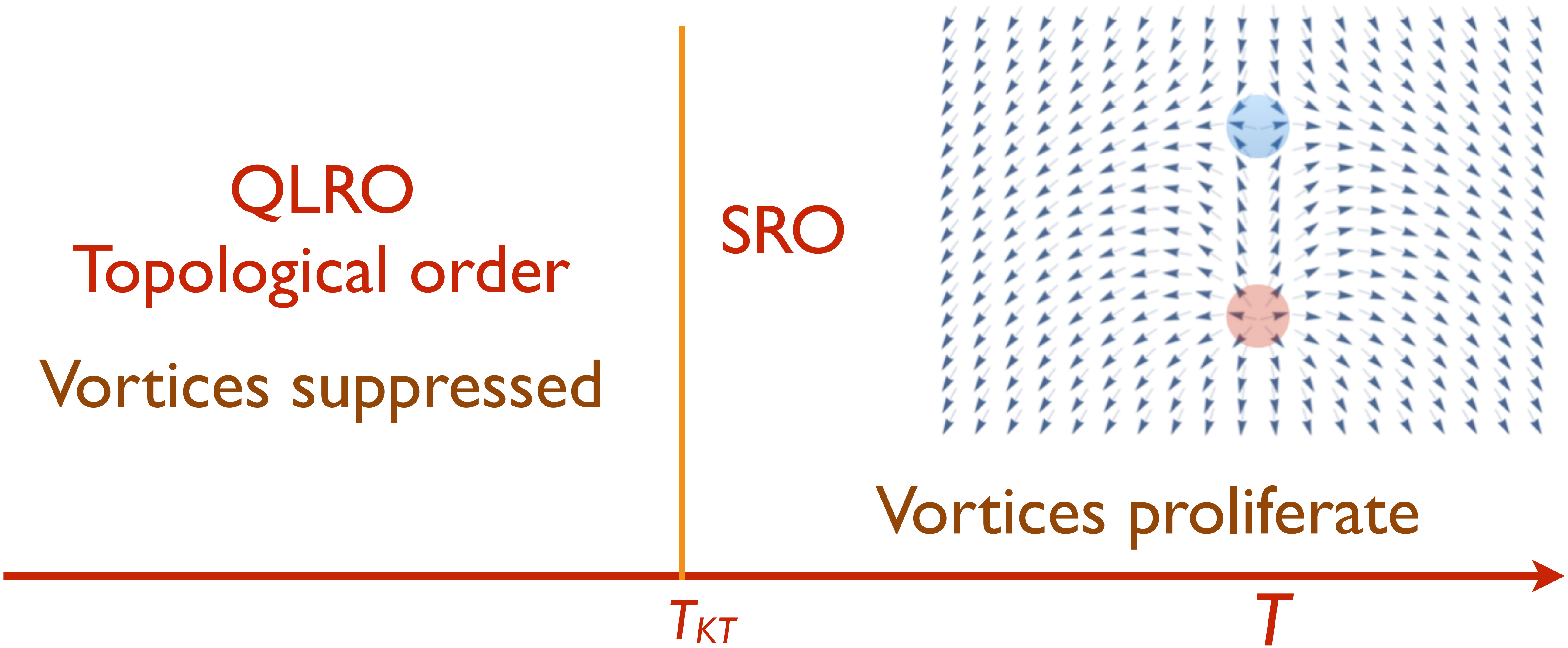
In spatial dimension $d = 2$, the symmetry $\theta_i \to \theta_i + c$ is preserved at all non-zero T. There is no LRO, and

$$\langle \Psi_i \rangle = 0 \text{ for all } T > 0.$$

Nevertheless, there is a phase transition at $T = T_{KT}$, where the nature of the correlations changes

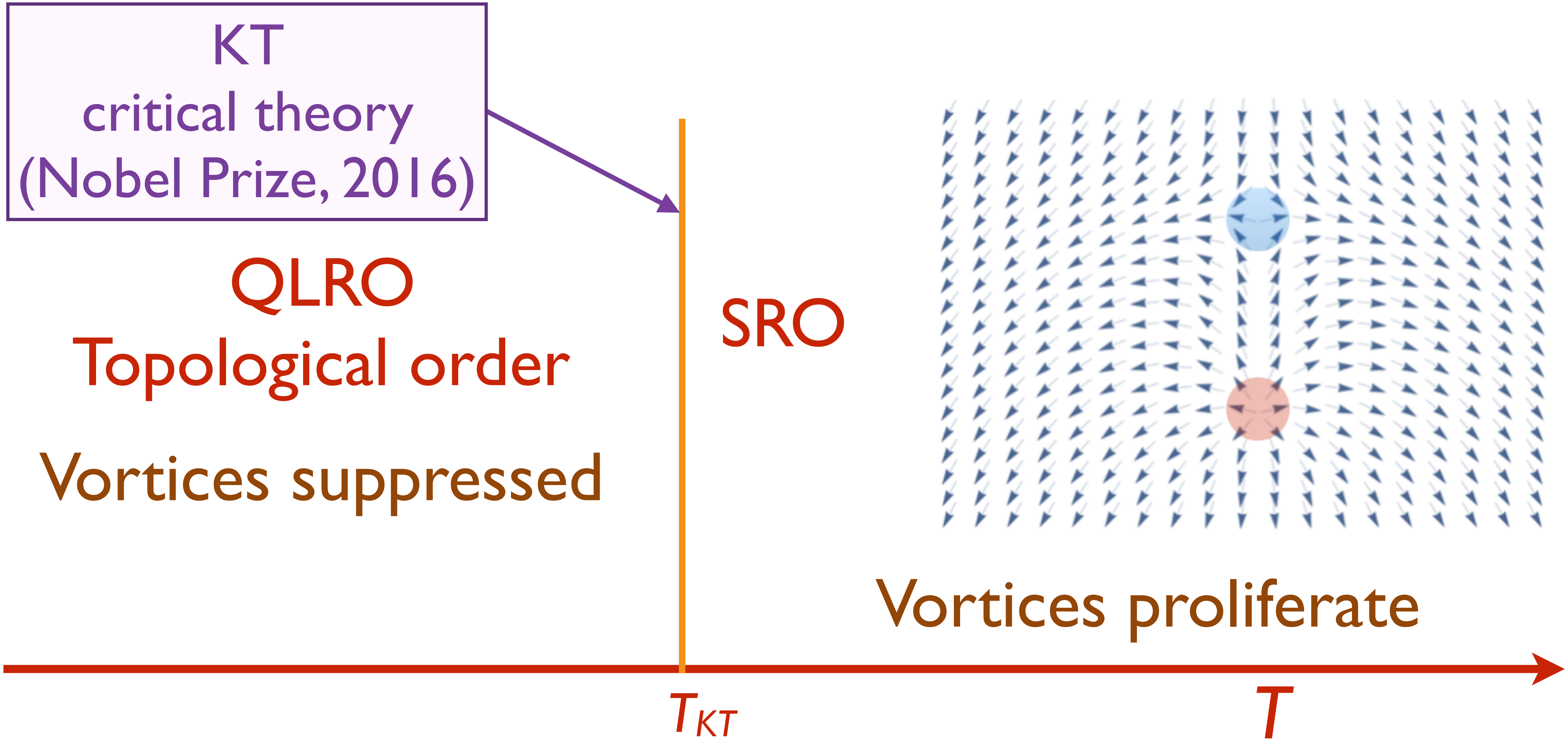
$$\lim_{|r_i - r_j| \to \infty} \left\langle \Psi_i \Psi_j^* \right\rangle \sim \begin{cases} |r_i - r_j|^{-\alpha}, & \text{for } T < T_{KT}, \text{ (QLRO)} \\ \exp(-|r_i - r_j|/\xi), & \text{for } T > T_{KT}, \text{ (SRO)} \end{cases}$$

Kosterlitz-Thouless theory in d=2



The low T phase also has **topological order** associated with the suppression of vortices.

Kosterlitz-Thouless theory in *d*=2



The low T phase also has **topological order** associated with the suppression of vortices.

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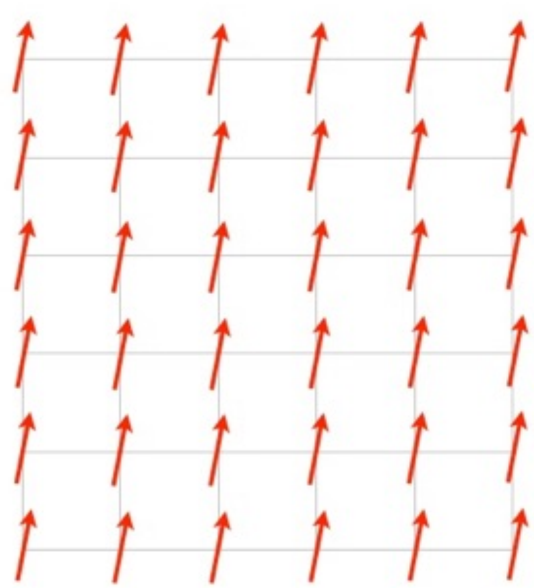
Can we modify the XY model Hamiltonian to obtain a phase with "topological order" in d=3 ?

$\langle \Psi_i \rangle = 0$

SRO

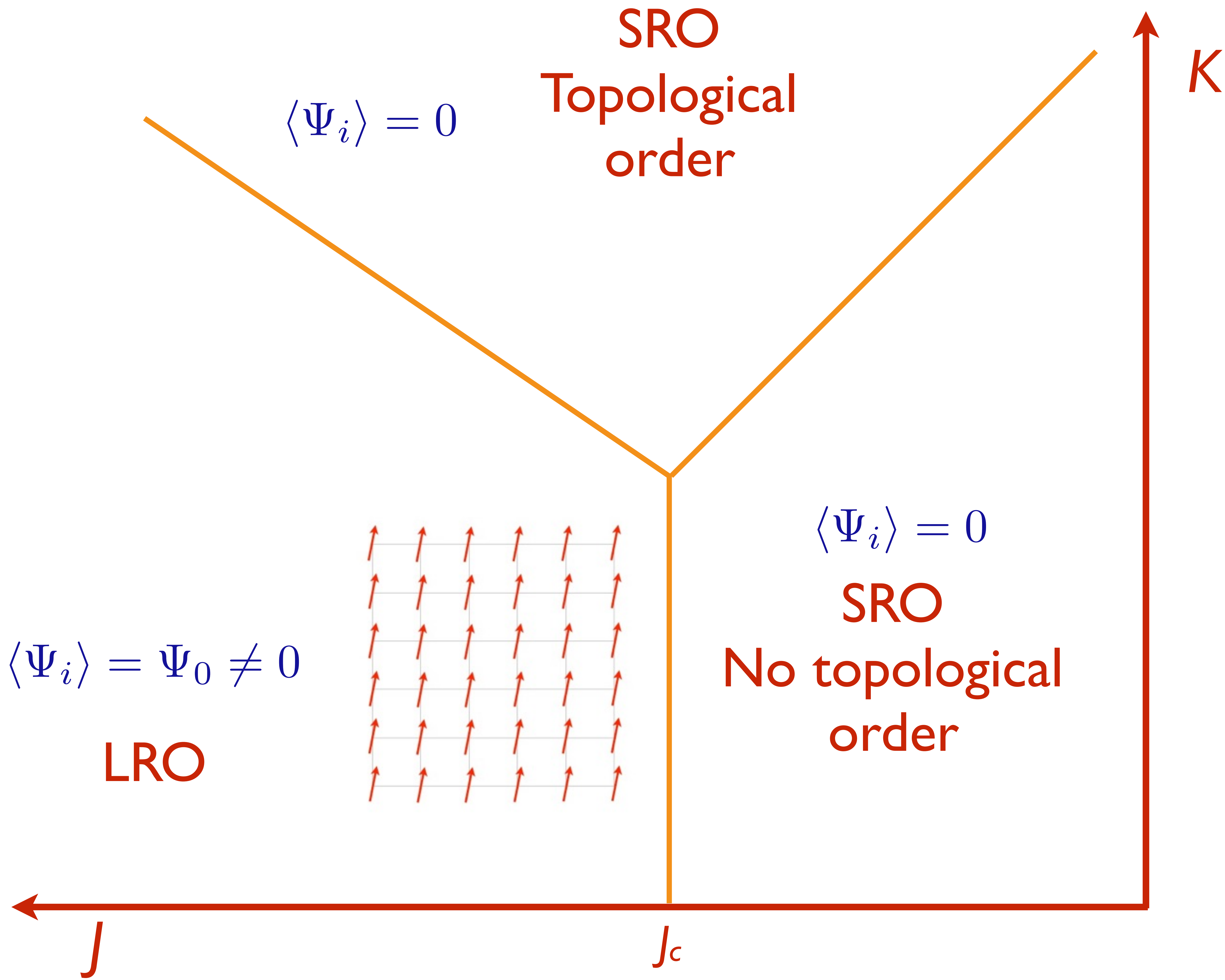
$\langle \Psi_i \rangle = \Psi_0 \neq 0$

LRO



J

J_c


SRO
Topological
order
$\langle \Psi_i \rangle = 0$
K
$\langle \Psi_i \rangle = 0$
SRO
No topological
order
$\langle \Psi_i \rangle = \Psi_0 \neq 0$
LRO
J
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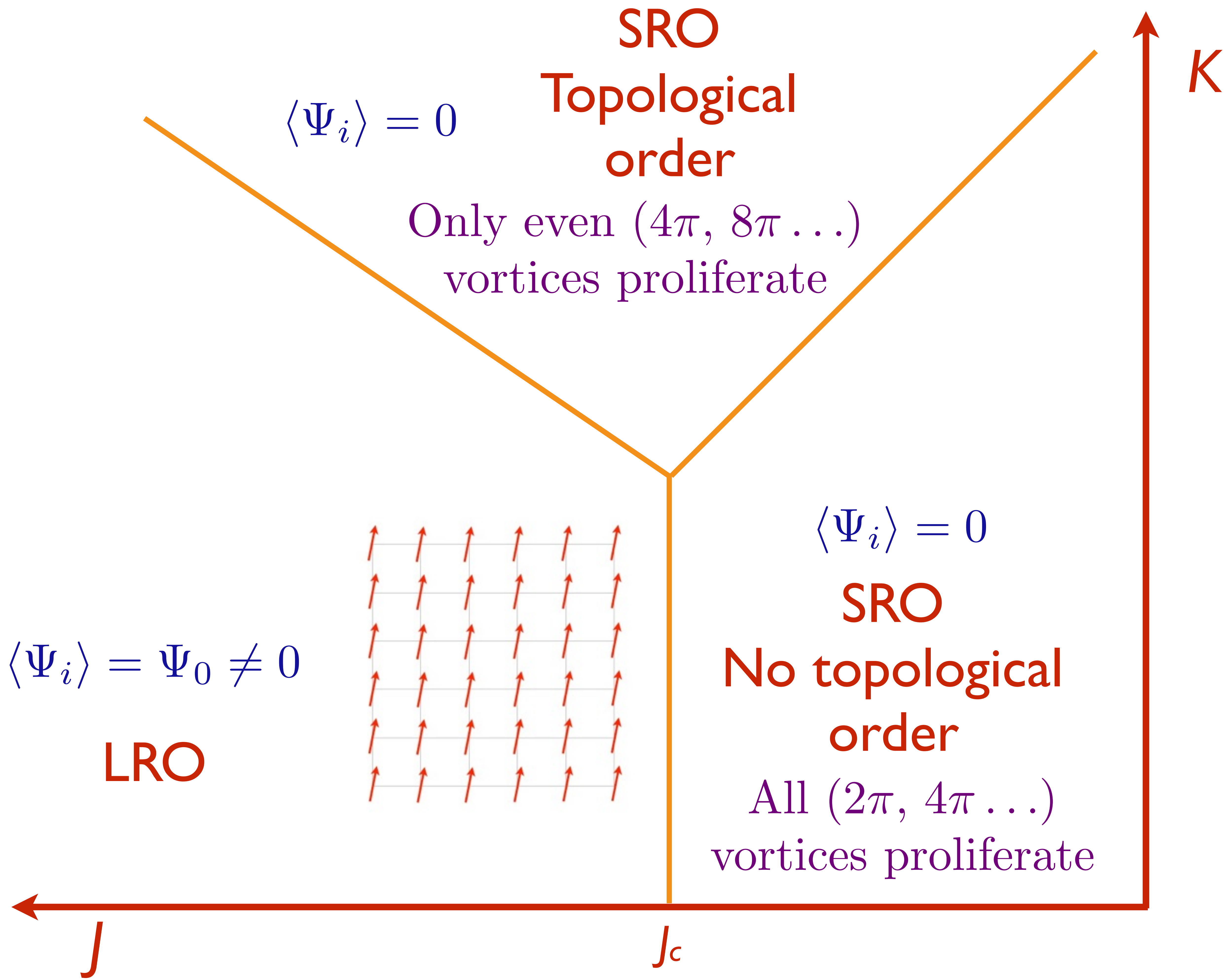

SRO
Topological
order
$\langle \Psi_i \rangle = 0$
Only even $(4\pi,\ 8\pi \ldots)$
vortices proliferate
K
$\langle \Psi_i \rangle = 0$
SRO
No topological
order
All $(2\pi,\ 4\pi \ldots)$
vortices proliferate
$\langle \Psi_i \rangle = \Psi_0 \neq 0$
LRO
J
J_c

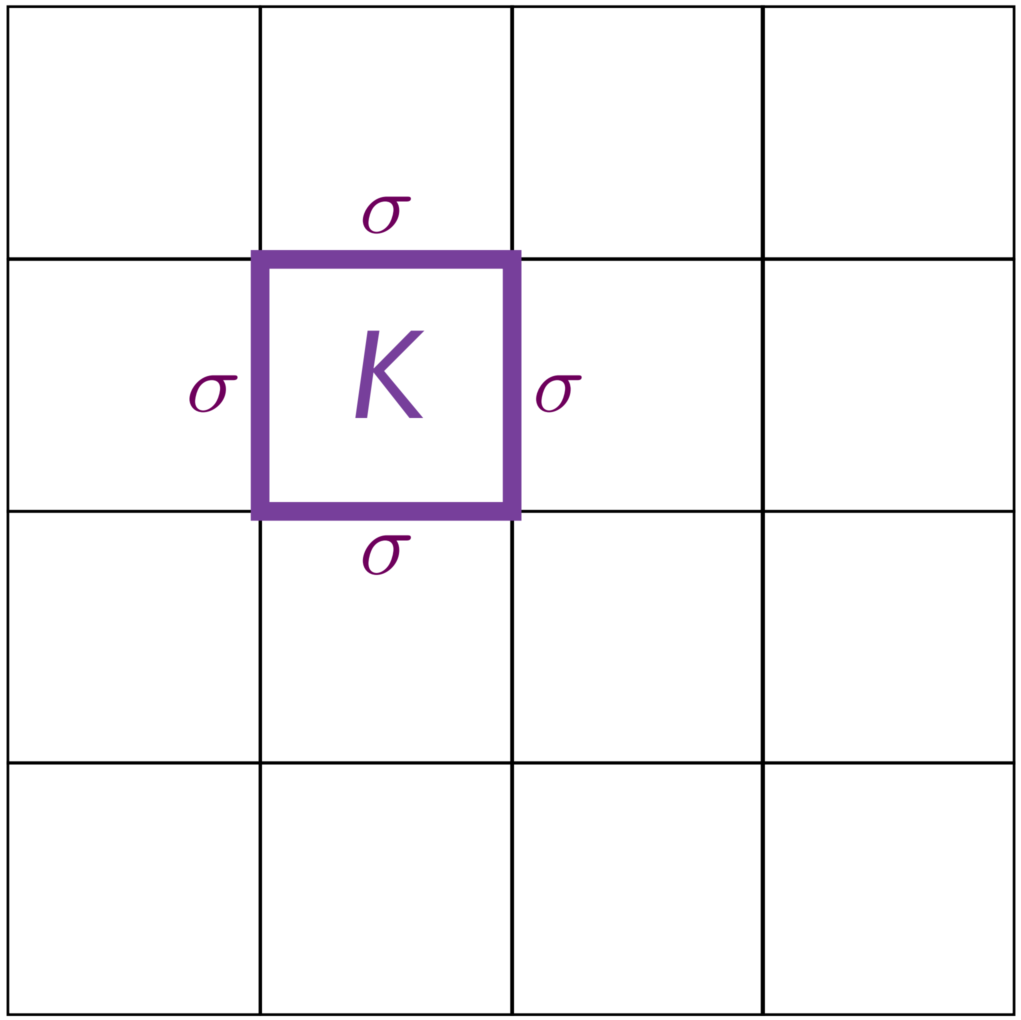
$$\widetilde{\mathcal{Z}}_{XY} = \prod_i \int_0^{2\pi} \frac{d\theta_i}{2\pi} \exp\left(-\widetilde{H}/T\right)$$

$$\widetilde{H} = -J \sum_{\langle ij \rangle} \cos(\theta_i - \theta_j) + \ldots\ldots$$

Add terms which suppress single but not double vortices…..

$$\widetilde{\mathcal{Z}}_{XY} = \sum_{\{\sigma_{ij}\}=\pm 1} \prod_i \int_0^{2\pi} \frac{d\theta_i}{2\pi} \exp\left(-\widetilde{H}/T\right)$$

$$\widetilde{H} = -J \sum_{\langle ij \rangle} \sigma_{ij} \cos\left[(\theta_i - \theta_j)/2\right] - K \sum_{\square} \prod_{(ij)\in\square} \sigma_{ij}$$



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- With $K = 0$, we can explicitly sum over σ_{ij}, and the theory reduces to the ordinary XY model.

$$
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\end{aligned}
$$

- The theory has a $\mathbb{Z}_2$ gauge invariance: we can change

$$
\begin{aligned}
\theta_i &\to \theta_i + \pi(1-\eta_i) \\
\sigma_{ij} &\to \eta_i \sigma_{ij} \eta_j \,,
\end{aligned}
$$

  with $\eta_i = \pm 1$, and the energy remains unchanged.

- The XY order parameter $\Psi_i = e^{i\theta_i}$ is gauge invariant, as are all physical observables. So this is an XY model with a modified Hamiltonian, and no additional degrees of freedom have been introduced.

$$\widetilde{\mathcal{Z}}_{XY} = \sum_{\{\sigma_{ij}\}=\pm 1} \prod_i \int_0^{2\pi} \frac{d\theta_i}{2\pi} \exp\left(-\widetilde{H}/T\right)$$

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- A single (odd) 2π vortex in θ_i has $\prod_{(ij)\in\square} \cos\left[(\theta_i - \theta_j)/2\right] < 0$.
- So for $J > 0$, such a vortex will prefer $\prod_{(ij)\in\square} \sigma_{ij} = -1$, *i.e.* a 2π vortex has $\mathbb{Z}_2$ flux $= -1$ in its core.
- So a large $K > 0$ will suppress (odd) 2π vortices.
- There is no analogous suppression of (even) 4π vortices.

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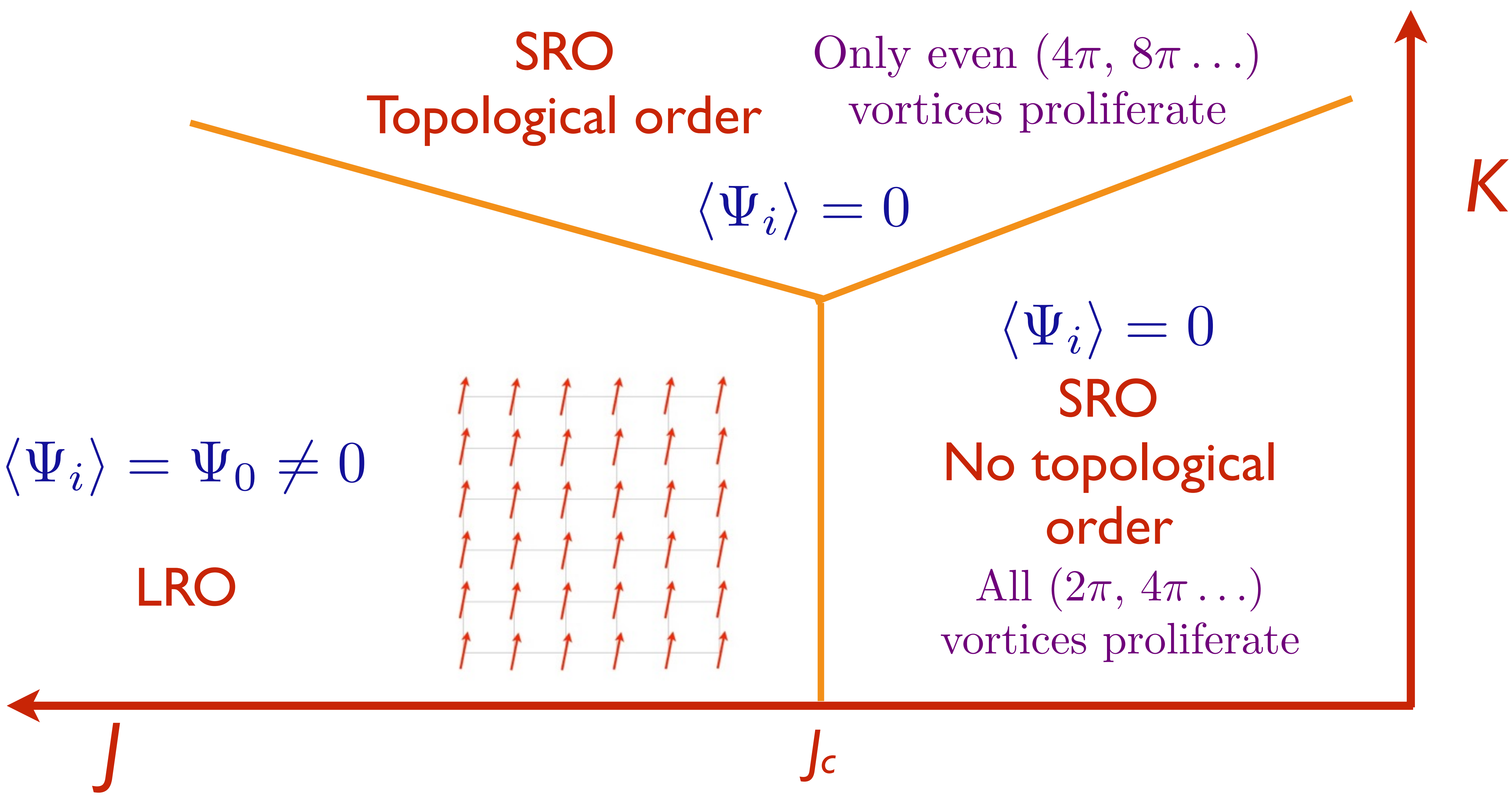

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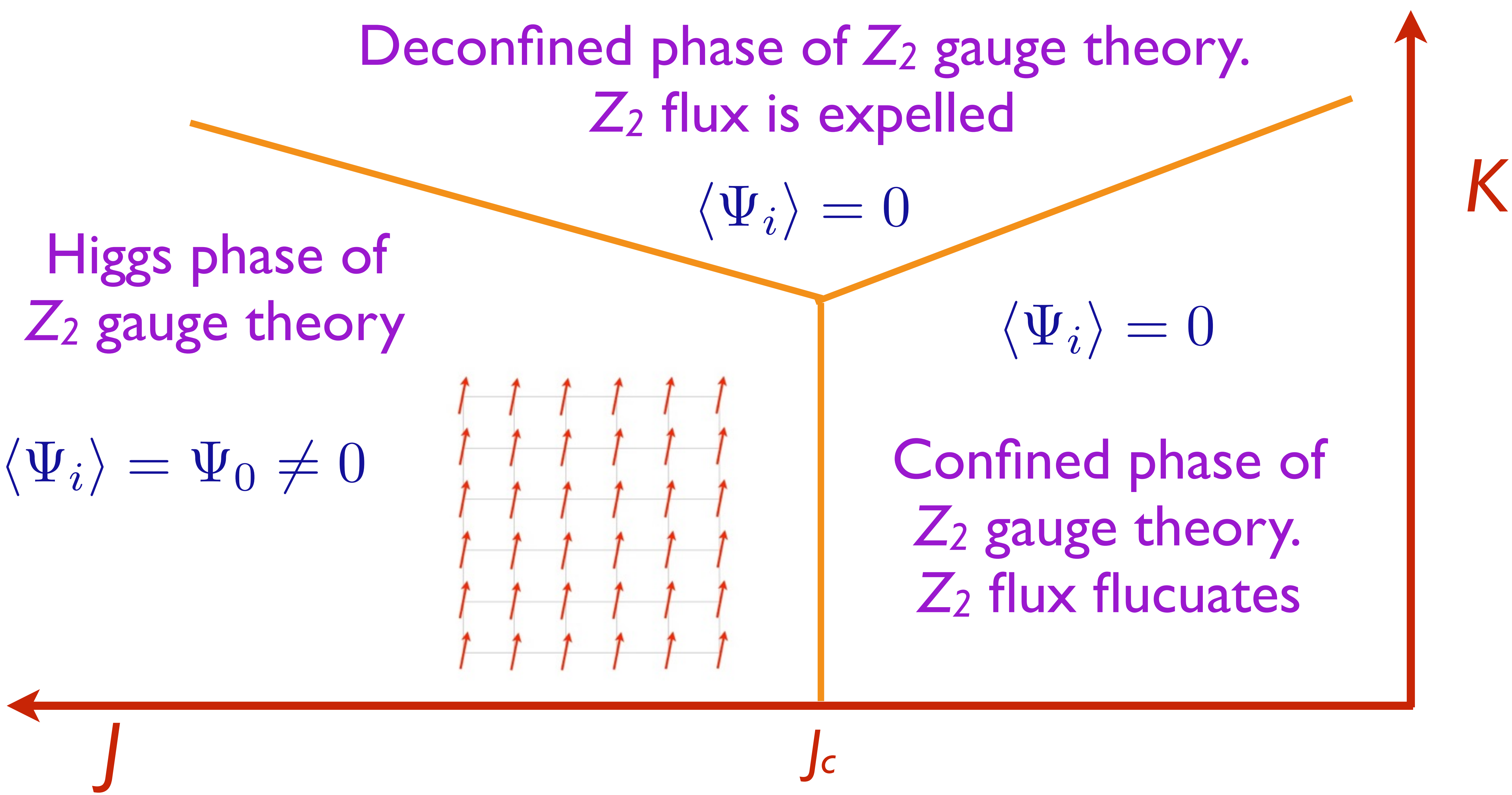

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A quantum Hamiltonian in 2+1 dimensions

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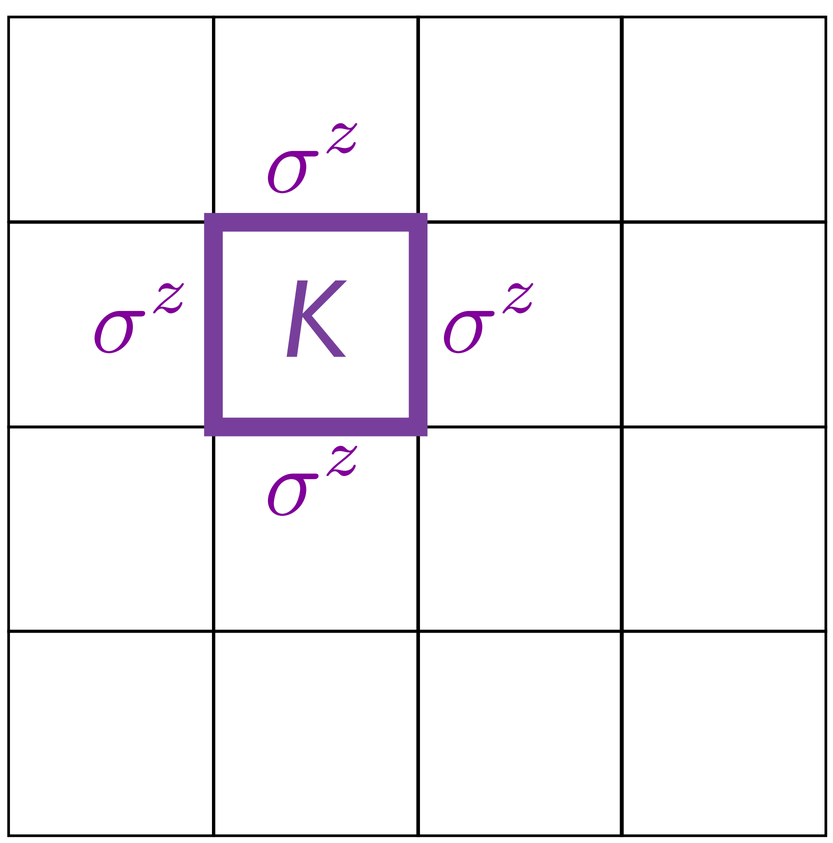
\begin{aligned}
\widetilde{H} \;=\; & -J \sum_{\langle ij \rangle} \sigma^z_{ij} \cos\left[(\theta_i - \theta_j)/2\right] - K \sum_{\square} \prod_{(ij)\in\square} \sigma^z_{ij} \\
& -U \sum_i \frac{\partial^2}{\partial \theta_i^2} - g \sum_{\langle ij \rangle} \sigma^x_{ij}
\end{aligned}
$$



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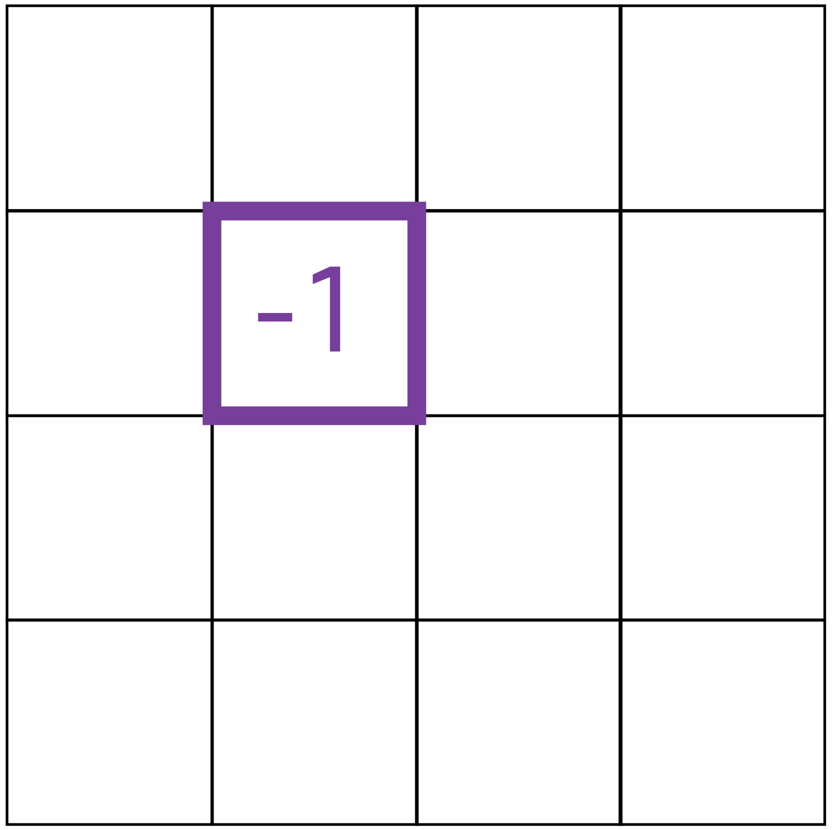
&\quad - U \sum_i \frac{\partial^2}{\partial \theta_i^2} - g \sum_{\langle ij \rangle} \sigma^x_{ij}
\end{aligned}
$$

- In the topological phase, the suppressed Z_2 fluxes of -1 become well-defined gapped quasiparticle excitations ('visons') above the ground state.



A quantum Hamiltonian in 2+1 dimensions

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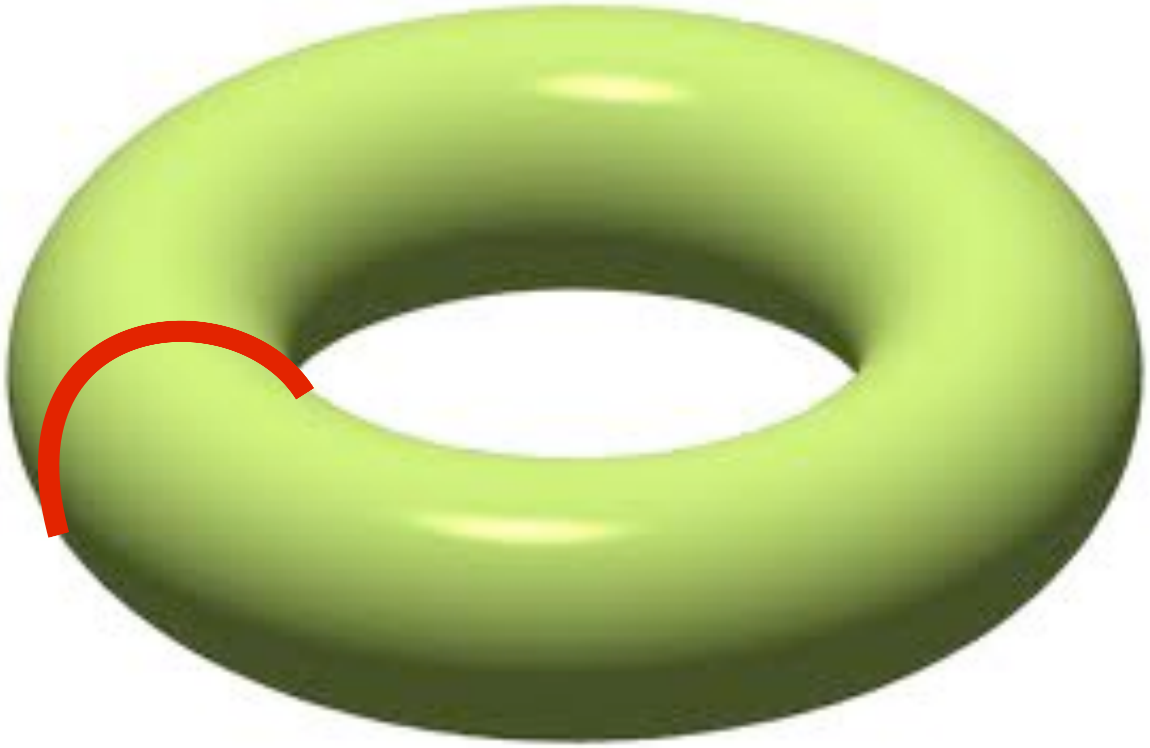
$$- U \sum_i \frac{\partial^2}{\partial \theta_i^2} - g \sum_{\langle ij \rangle} \sigma^x_{ij}$$

- In the topological phase, on a torus, inserting the Z_2 flux of -1 into one of the cycles of the torus leads to an orthogonal state whose energy cost vanishes exponentially in the size of the torus: there are 4 degenerate ground states on a large torus.



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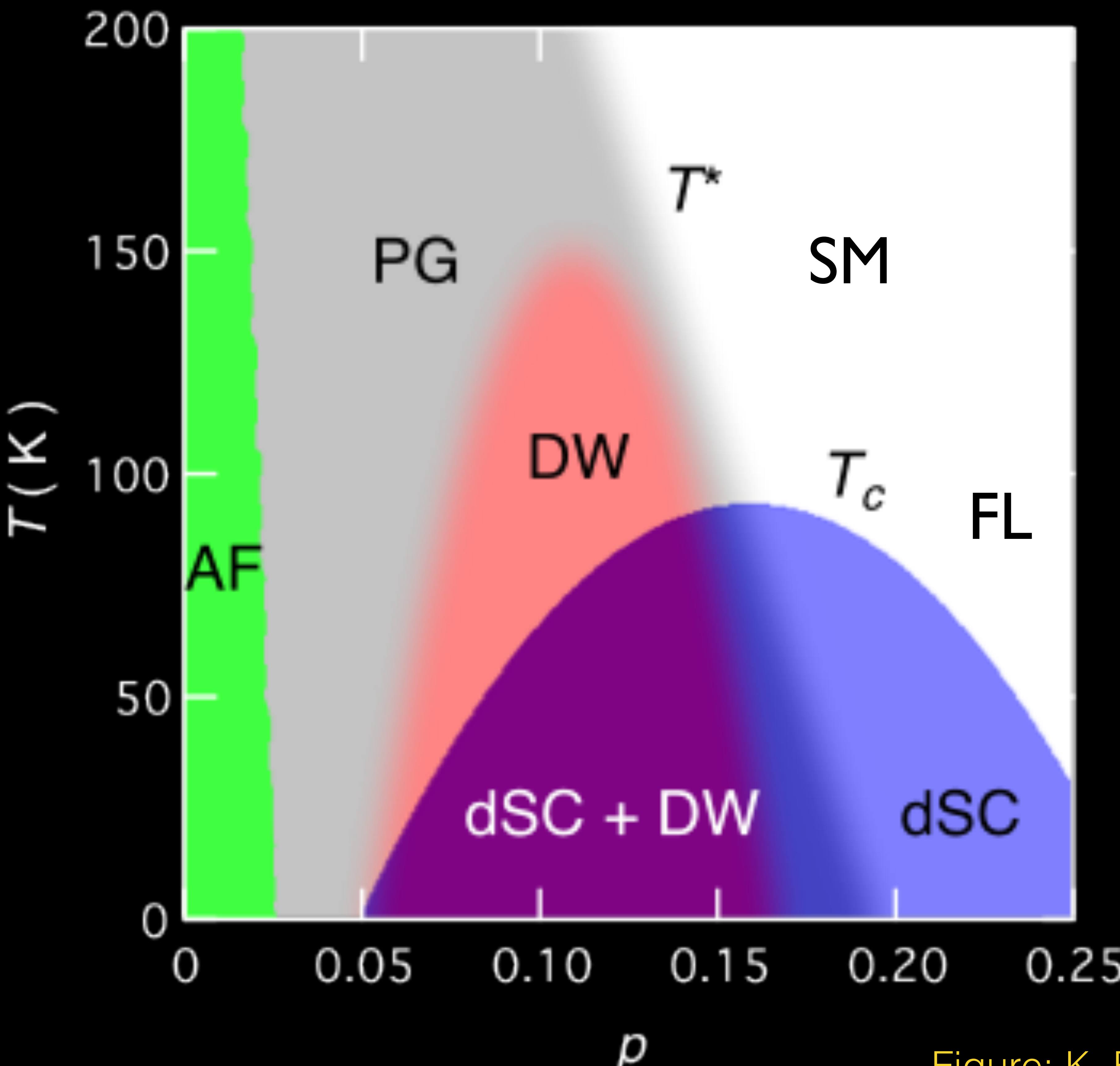
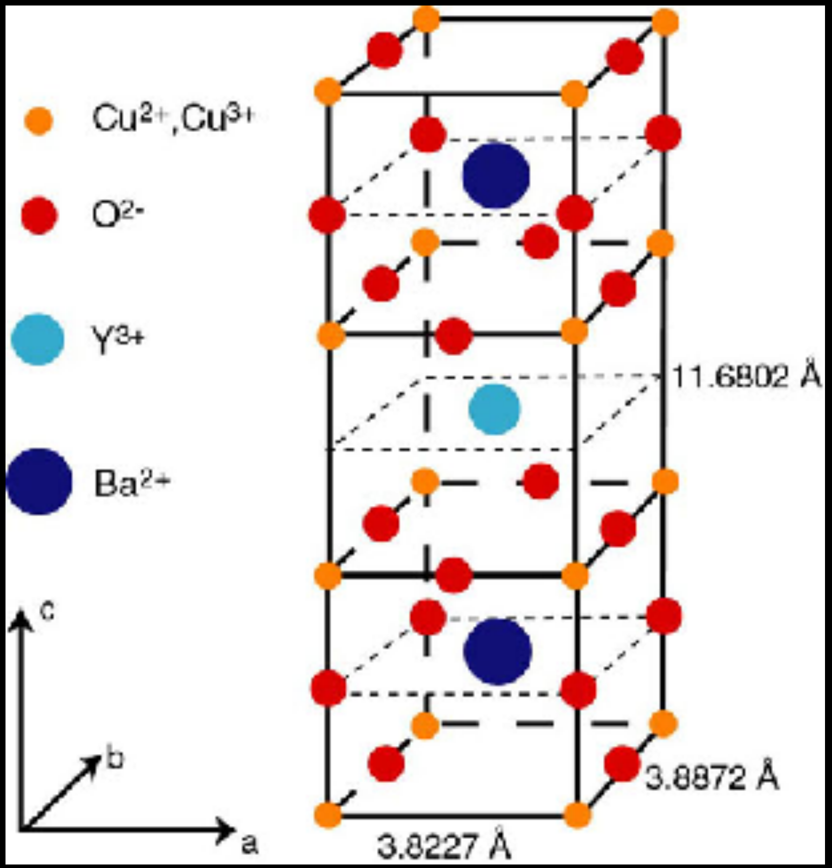
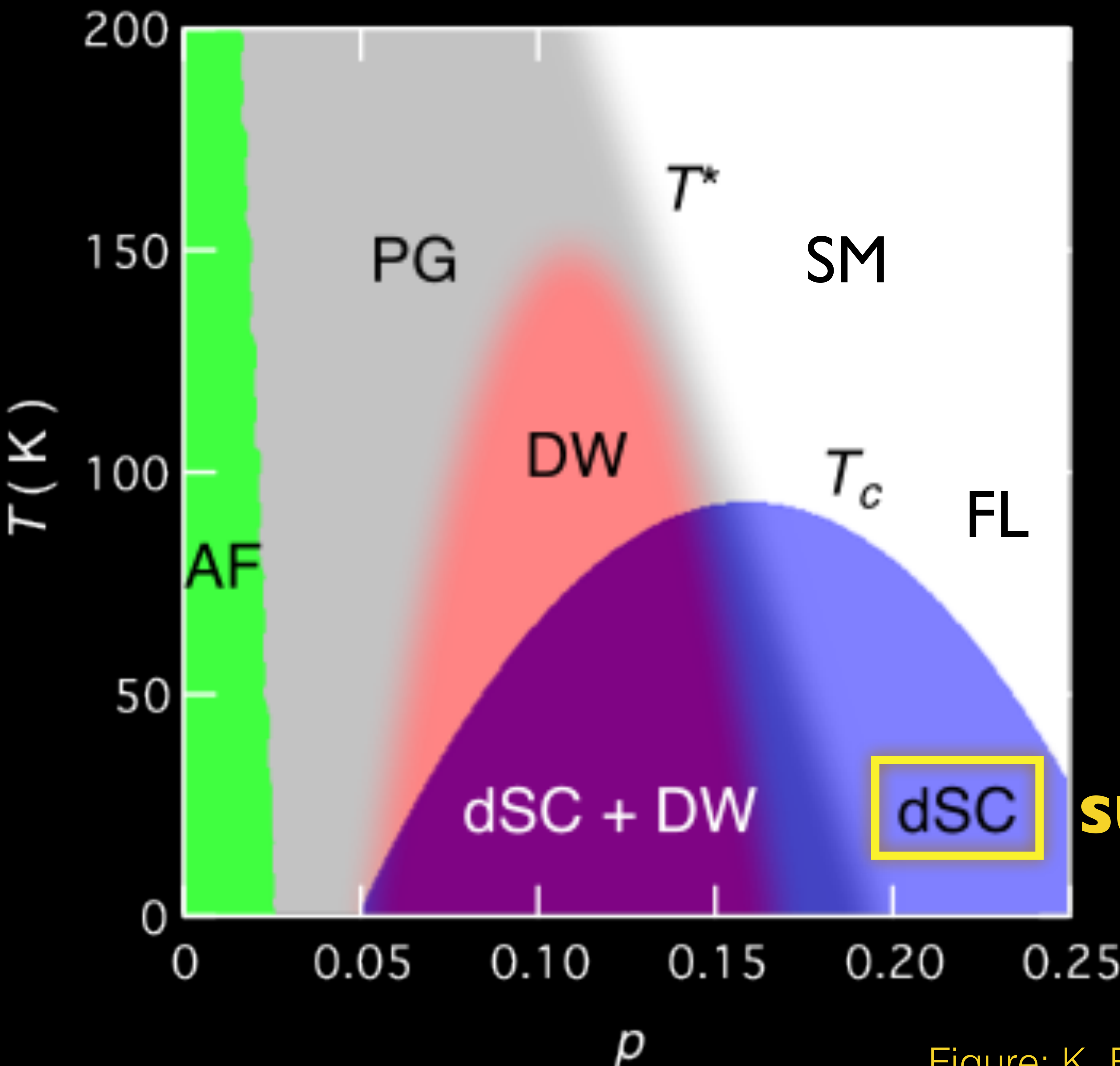
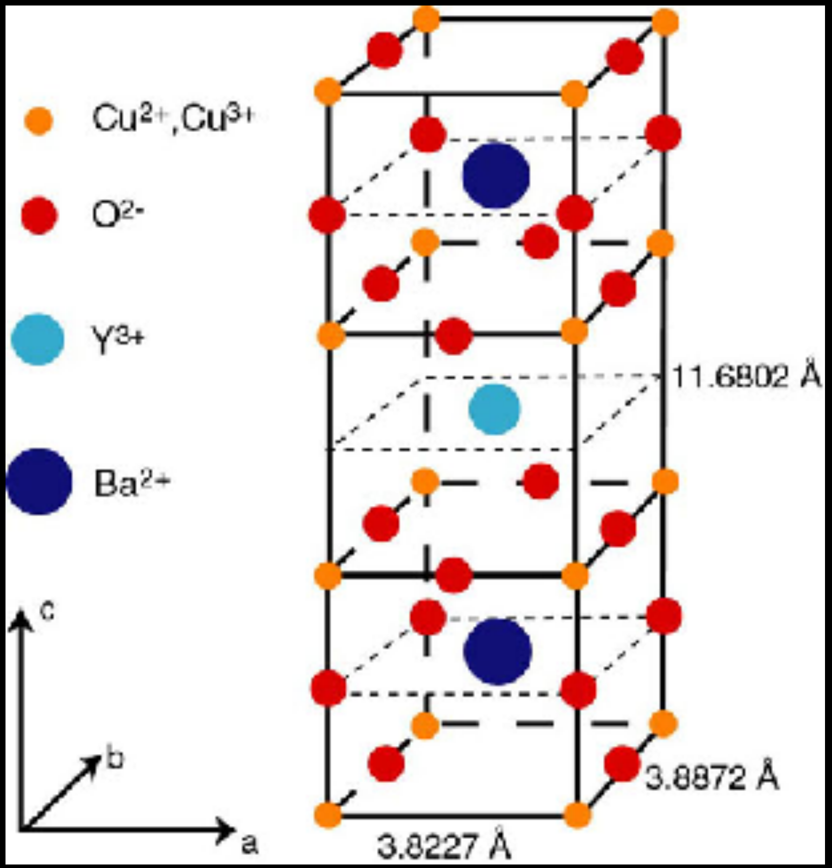




$YBa_2Cu_3O_{6+x}$

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





$YBa_2Cu_3O_{6+x}$

d-wave superconductor

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

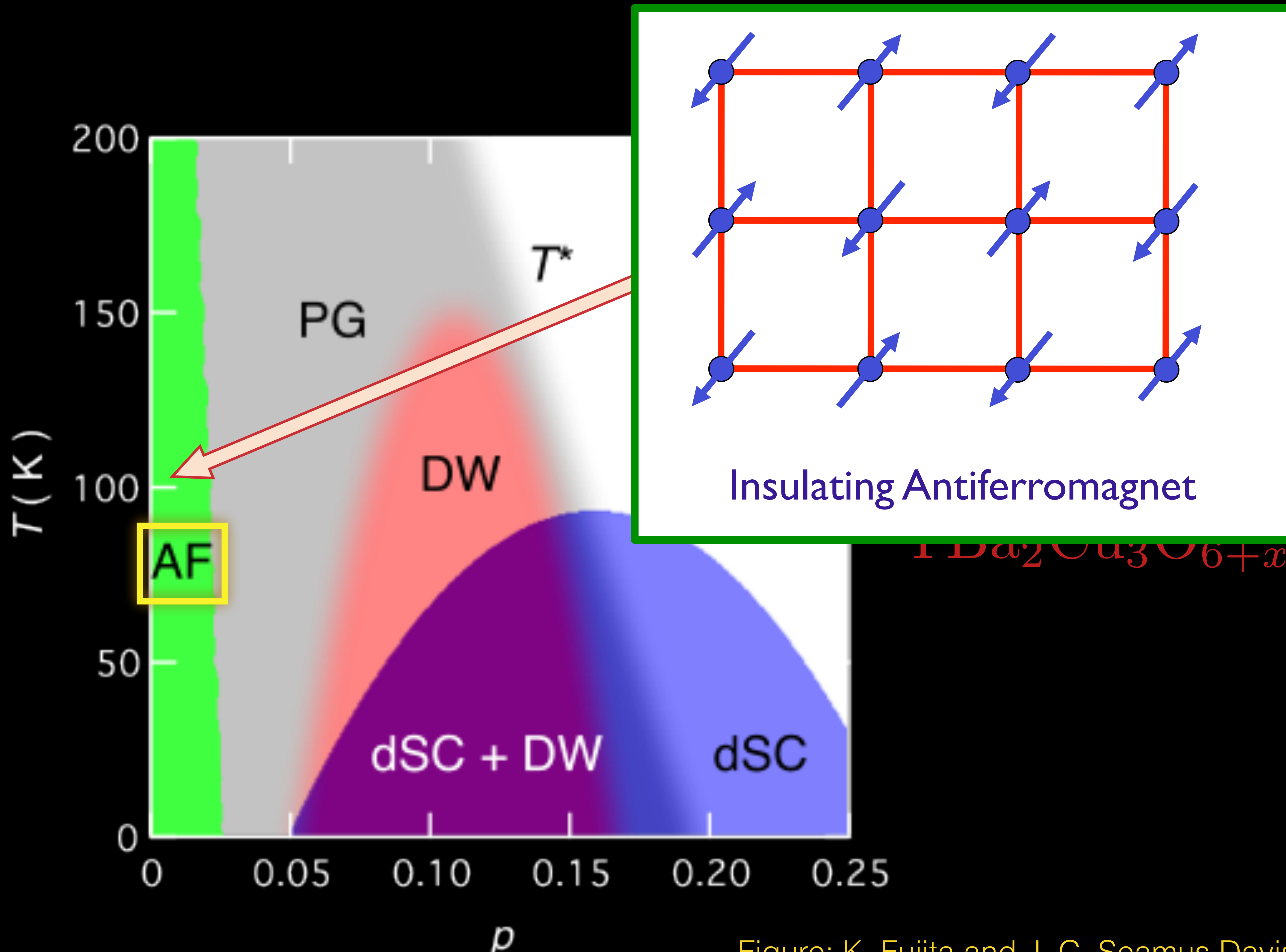
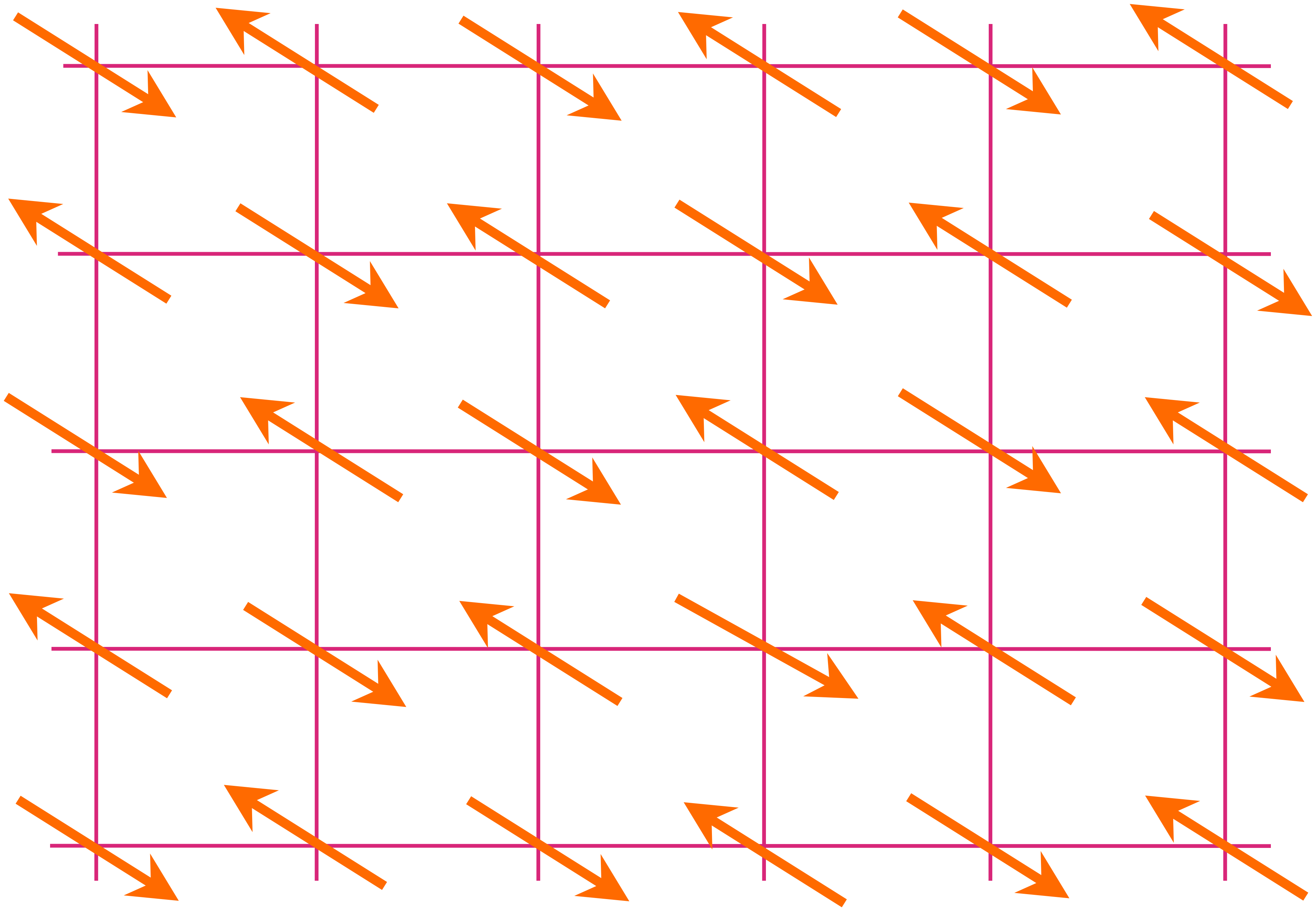
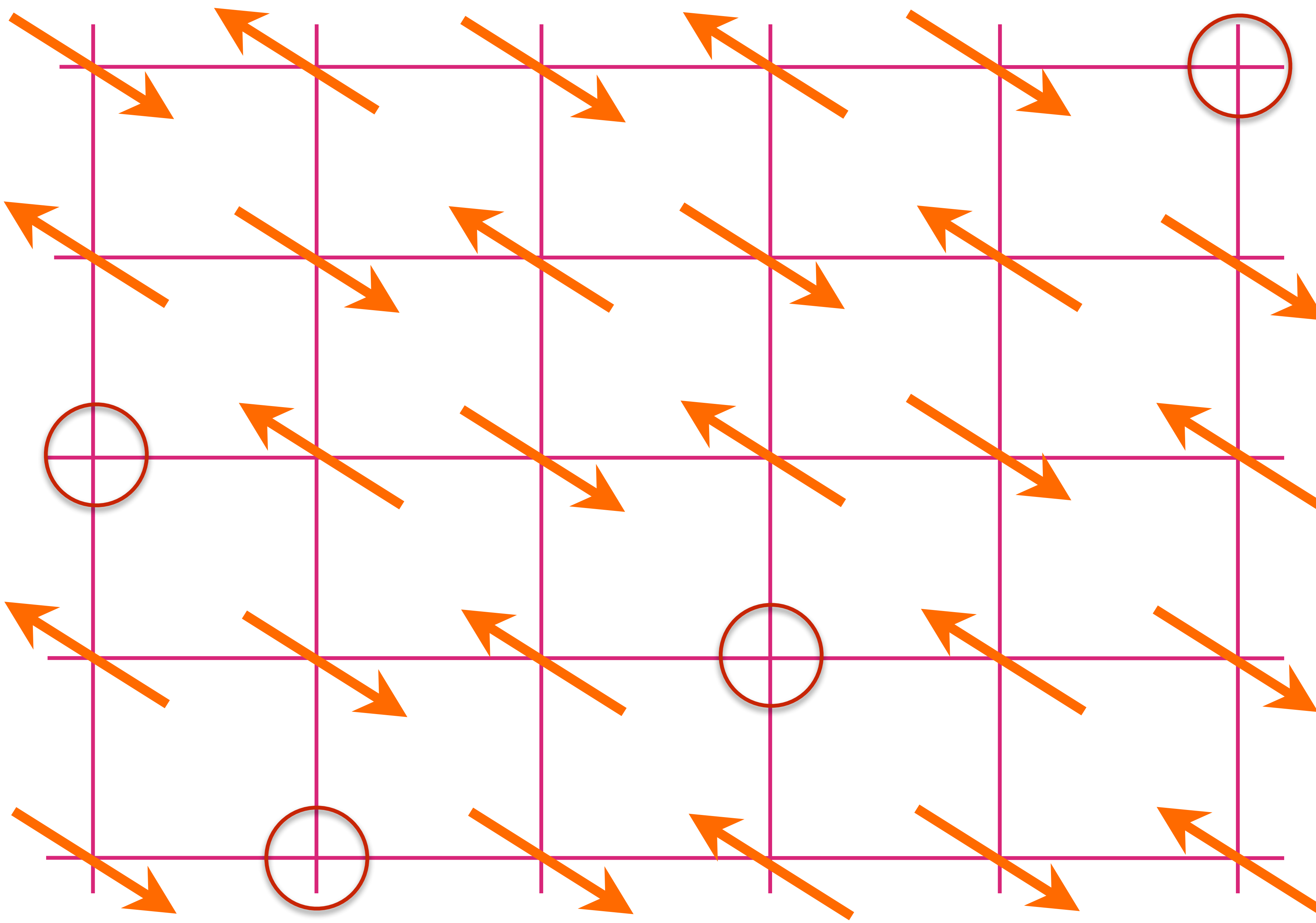


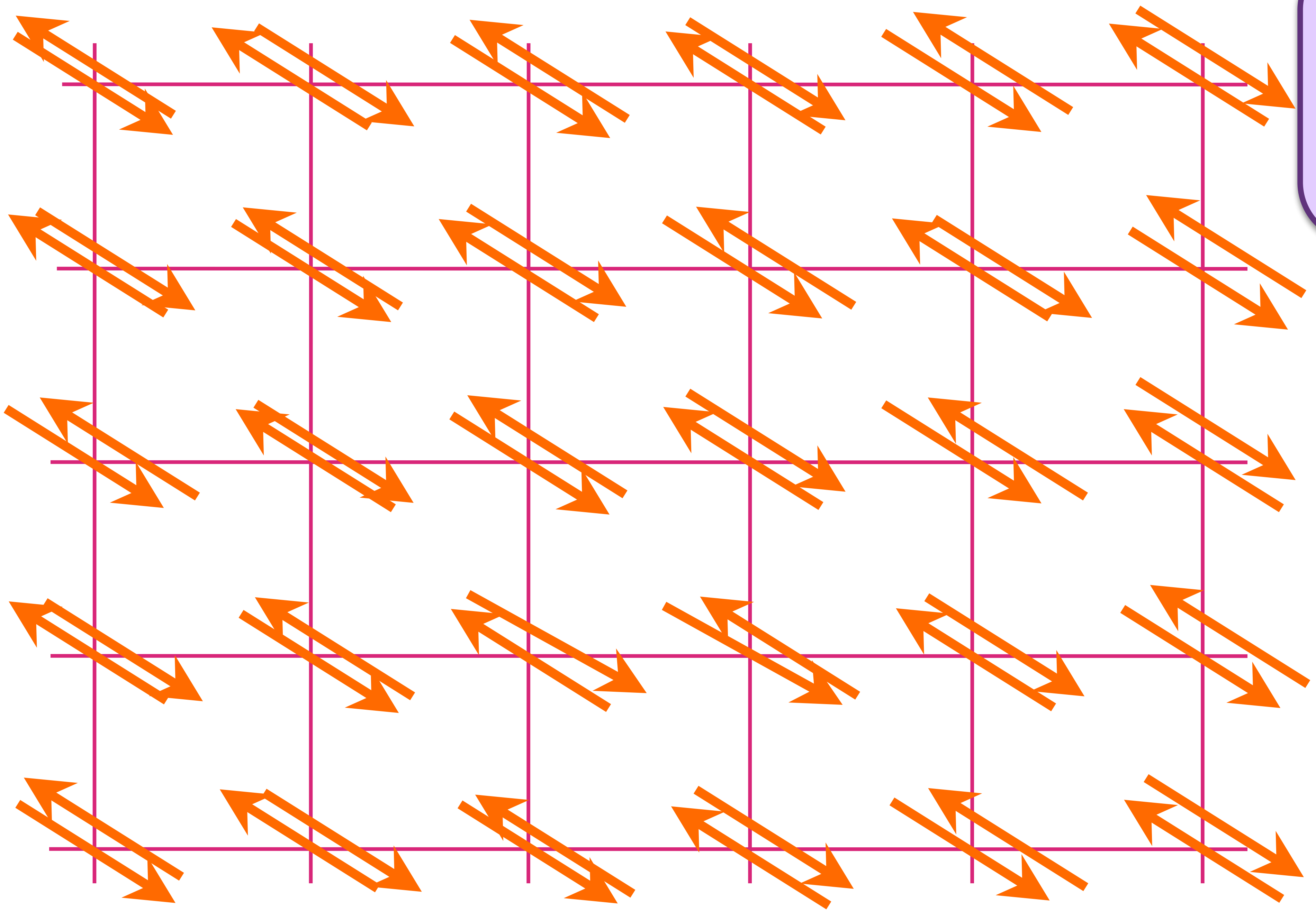
Figure: K. Fujita and J. C. Seamus Davis



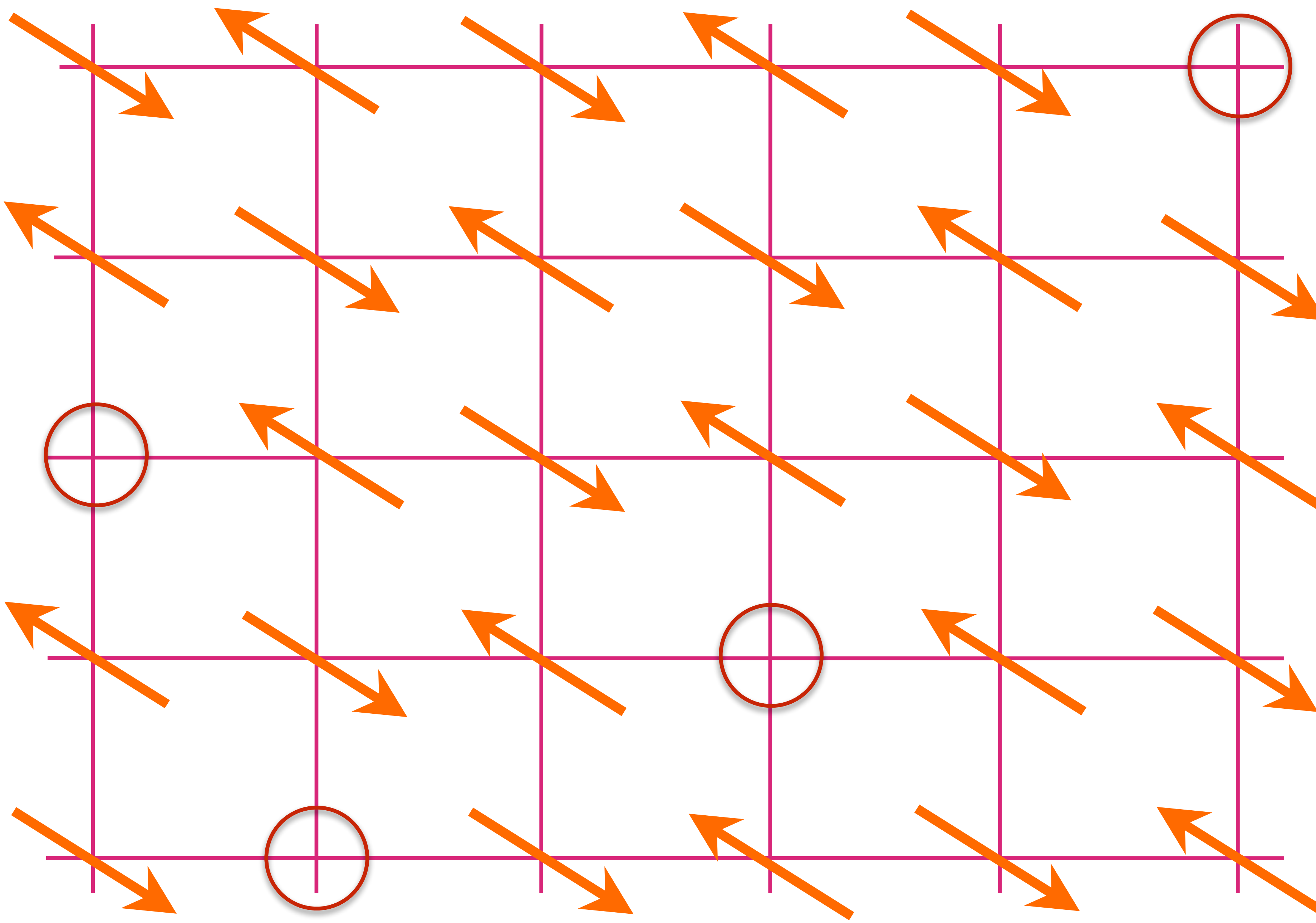
"Undoped" insulating anti-ferromagnet



Anti-
ferromagnet
with p mobile
holes
per square

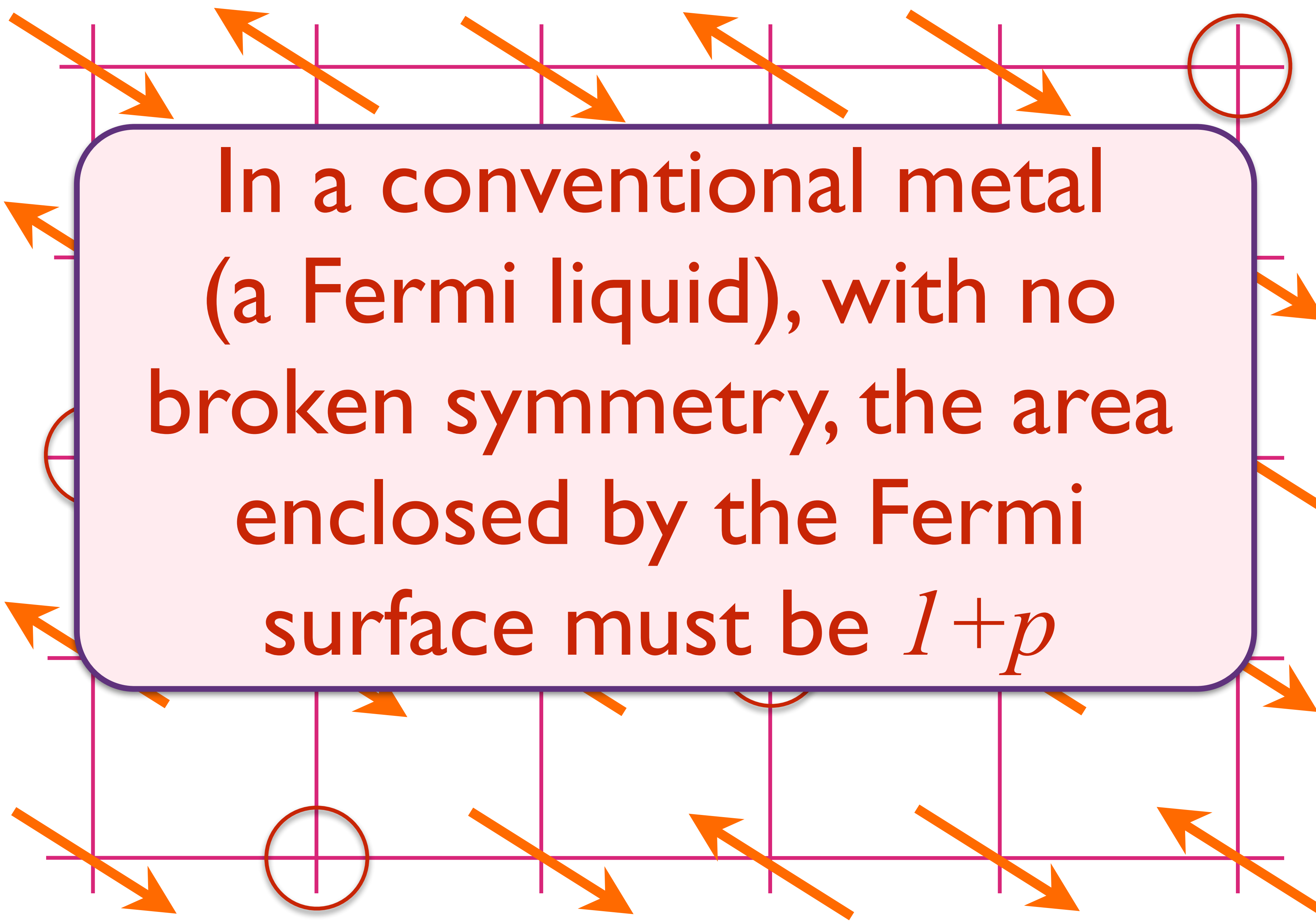


Filled Band



Anti-ferromagnet with p mobile holes per square

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

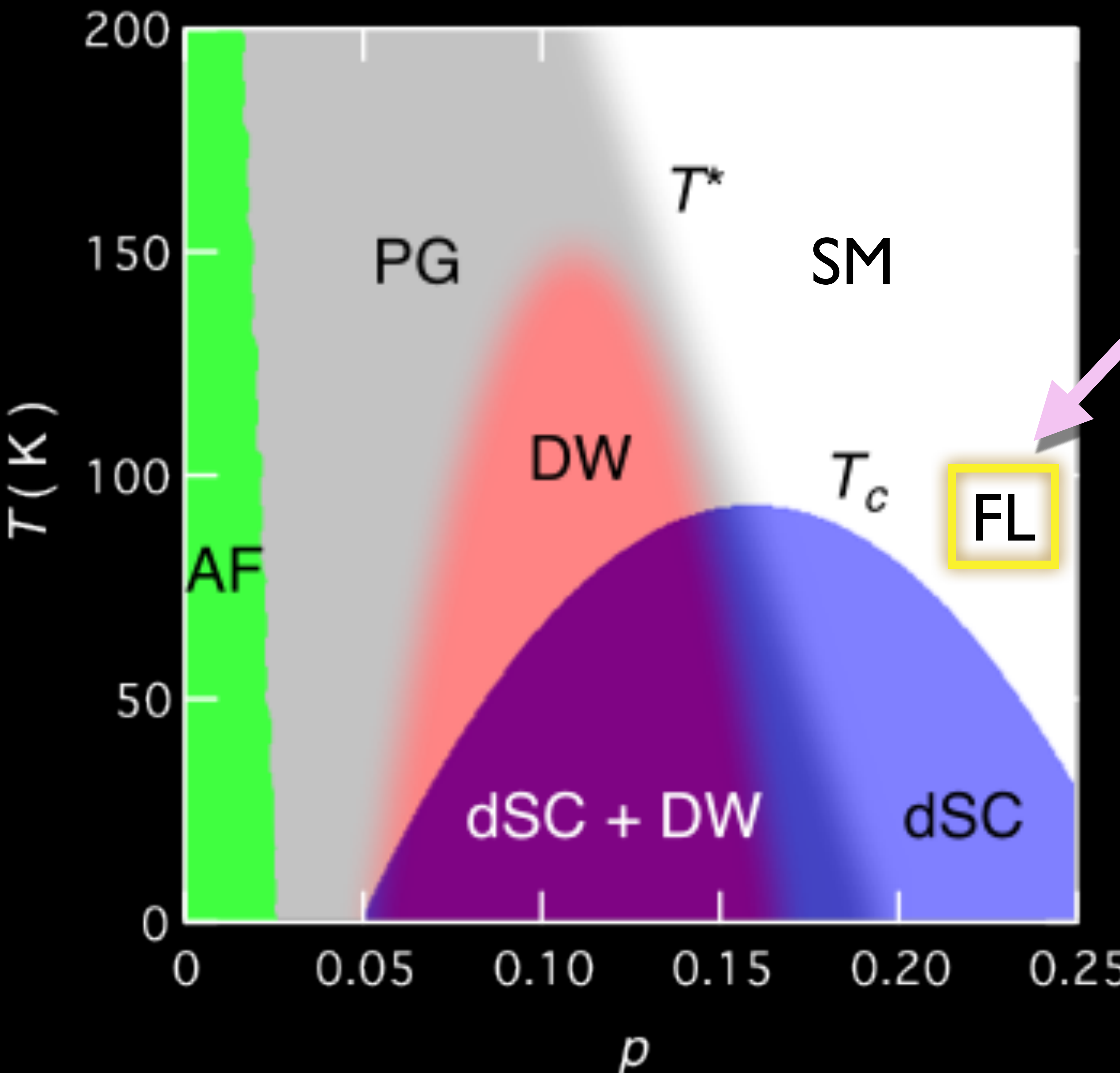


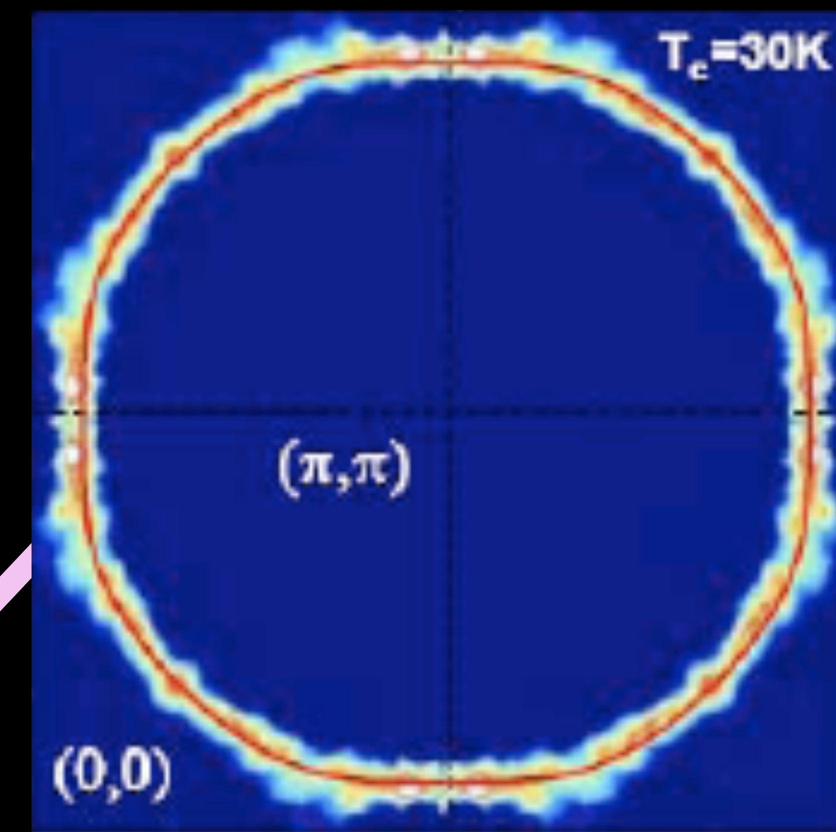
In a conventional metal (a Fermi liquid), with no broken symmetry, the area enclosed by the Fermi surface must be $1+p$

Anti-ferromagnet with p mobile holes per square

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

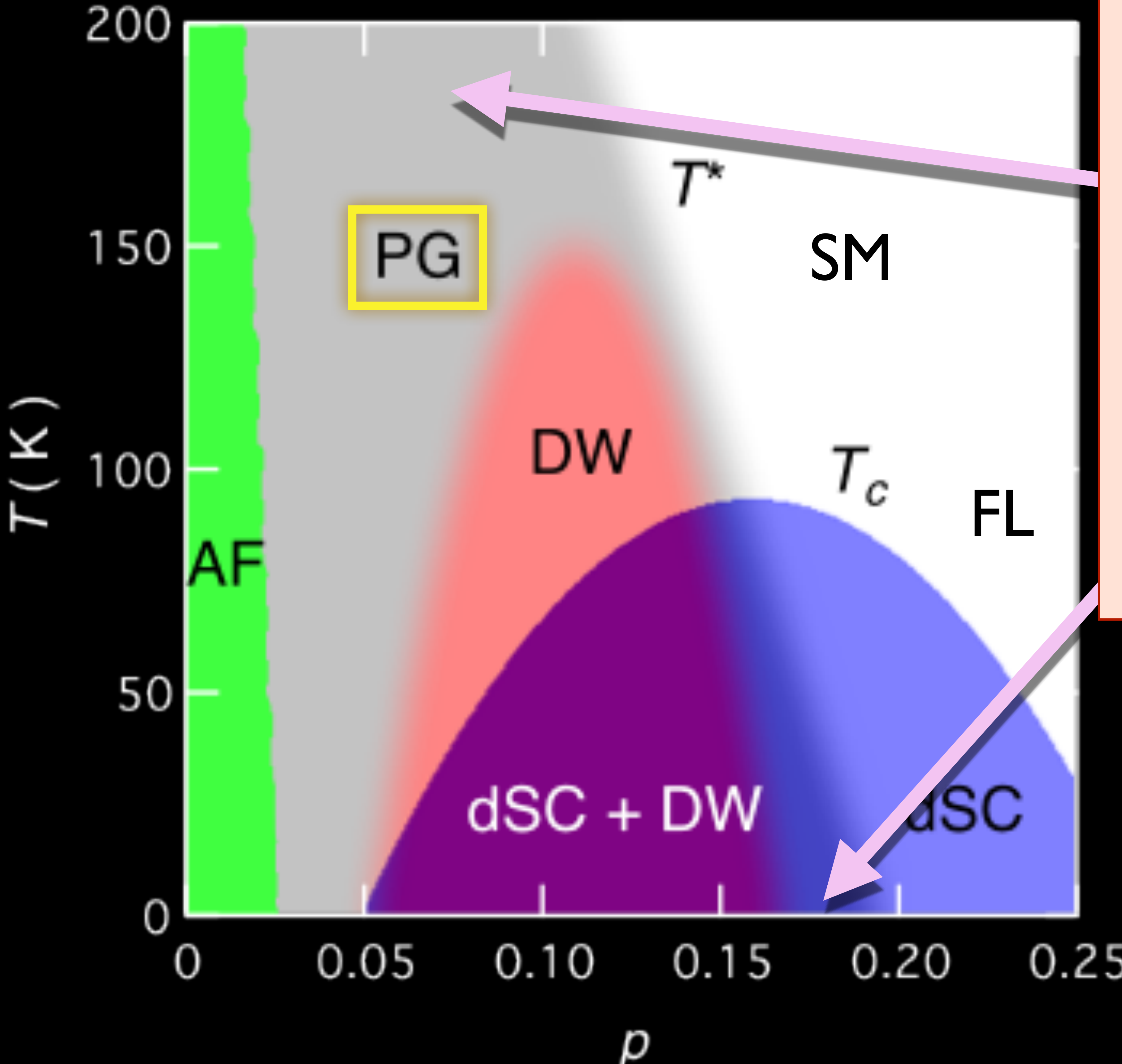
M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)





A conventional metal:
the Fermi liquid with Fermi surface of size *1+p*

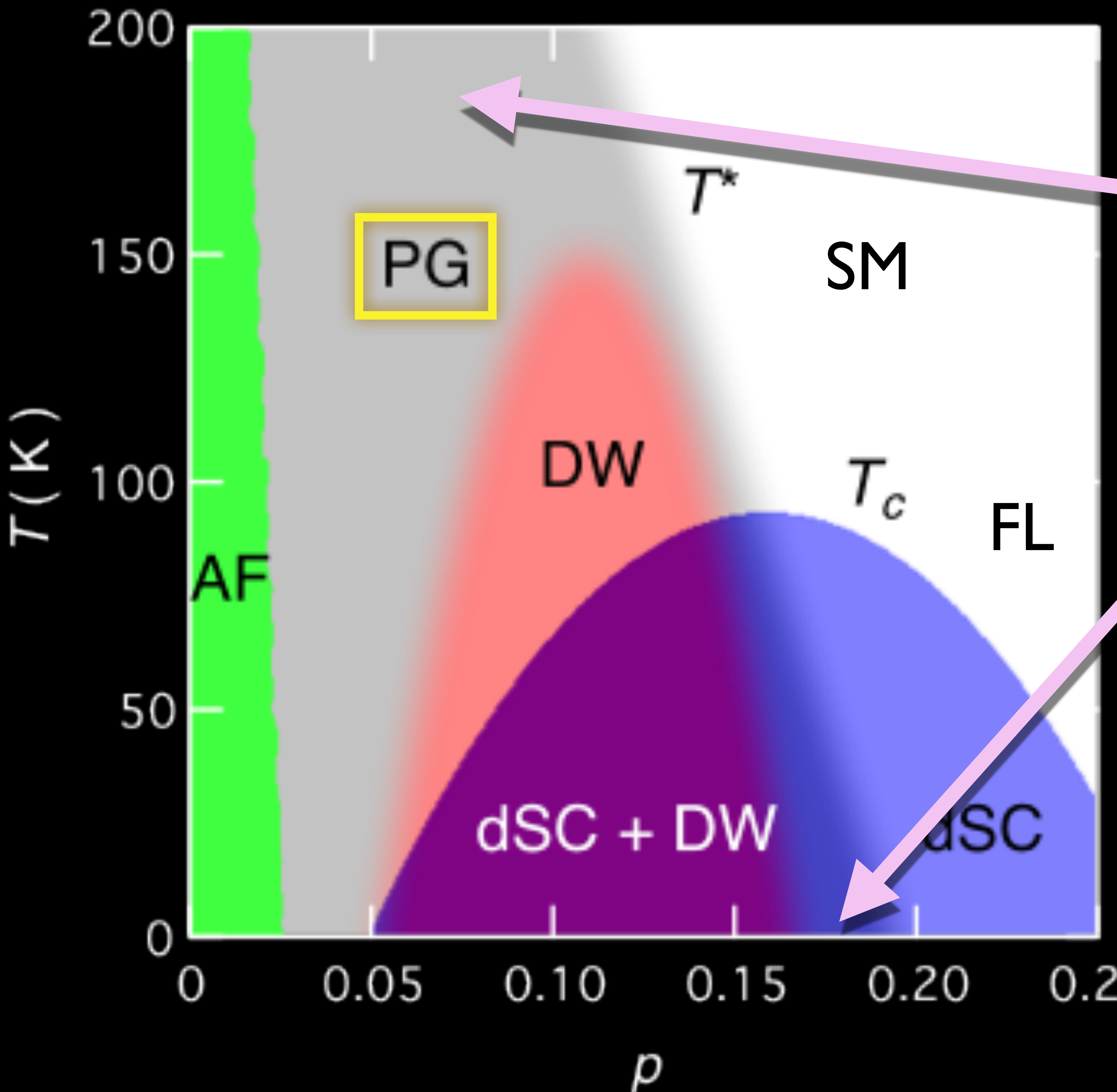
S. Badoux, W. Tabis, F. Laliberté, G. Grissonnanche, B. Vignolle, D. Vignolles, J. Béard, D.A. Bonn, W.N. Hardy, R. Liang, N. Doiron-Leyraud, L. Taillefer, and C. Proust, Nature **531**, 210 (2016).



Pseudogap metal at low *p*

Many indications that this metal behaves like a Fermi liquid, but with Fermi surface size p and *not* $1+p$.

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



Pseudogap metal at low p

Many indications that this metal behaves like a Fermi liquid, but with Fermi surface size p and *not* $1+p$.

If present at $T=0$, a metal with a size p Fermi surface (and translational symmetry preserved) *must* have *topological order*

The Hubbard Model

$$H = -\sum_{i<j} t_{ij} c_{i\alpha}^\dagger c_{j\alpha} + U \sum_i \left(n_{i\uparrow} - \frac{1}{2} \right) \left(n_{i\downarrow} - \frac{1}{2} \right) - \mu \sum_i c_{i\alpha}^\dagger c_{i\alpha}$$

$t_{ij} \rightarrow$ "hopping". $U \rightarrow$ local repulsion, $\mu \rightarrow$ chemical potential

Spin index $\alpha = \uparrow, \downarrow$

$$n_{i\alpha} = c_{i\alpha}^\dagger c_{i\alpha}$$

$$c_{i\alpha}^\dagger c_{j\beta} + c_{j\beta} c_{i\alpha}^\dagger = \delta_{ij}\delta_{\alpha\beta}$$
$$c_{i\alpha} c_{j\beta} + c_{j\beta} c_{i\alpha} = 0$$

Will study on the square lattice

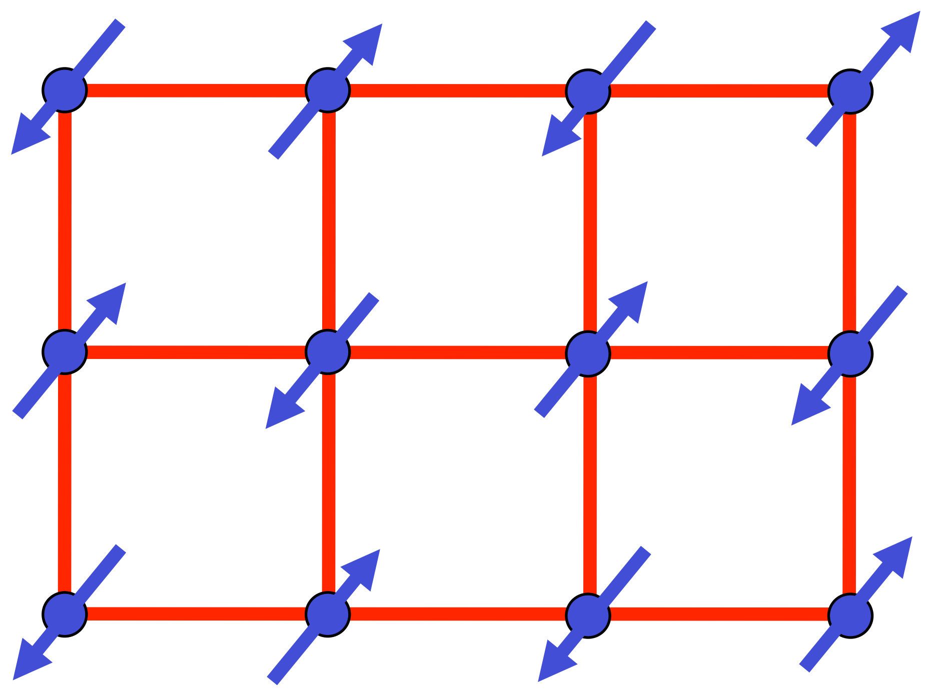
Fermi surface+antiferromagnetism

Electron spin

$$\left\langle \vec{S}_i \right\rangle = \eta_i \, \vec{\Phi}_i$$

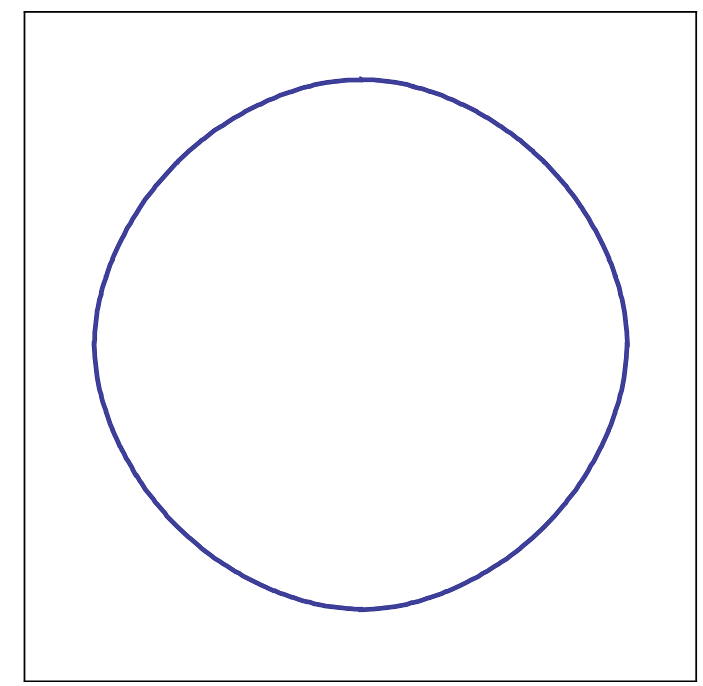
where $\eta_i = \pm 1$

p=0



$\langle \vec{\Phi} \rangle \neq 0$

Insulator with
AF order



$\langle \vec{\Phi} \rangle = 0$

Metal with "large"
Fermi surface
of size 1

U/t

We can (exactly) transform the Hubbard model to the "spin-fermion" model: **electrons** $c_{i\alpha}$ on the square lattice with dispersion

$$\mathcal{H}_c = -\sum_{i,\rho} t_\rho \left(c_{i,\alpha}^\dagger c_{i+\boldsymbol{v}_\rho,\alpha} + c_{i+\boldsymbol{v}_\rho,\alpha}^\dagger c_{i,\alpha} \right) - \mu \sum_i c_{i,\alpha}^\dagger c_{i,\alpha} + \mathcal{H}_{\text{int}}$$

are coupled to an **antiferromagnetic order parameter** $\Phi^\ell(i)$**,** $\ell = x, y, z$

$$\mathcal{H}_{\text{int}} = -\lambda \sum_i \eta_i \Phi^\ell(i) c_{i,\alpha}^\dagger \sigma_{\alpha\beta}^\ell c_{i,\beta} + V_\Phi$$

where $\eta_i = \pm 1$ on the two sublattices. (For suitable V_Φ, integrating out the Φ yields back the Hubbard model).

We can (exactly) transform the Hubbard model to the "spin-fermion" model: **electrons** $c_{i\alpha}$ on the square lattice with dispersion

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are coupled to an **antiferromagnetic order parameter** $\Phi^\ell(i)$**,** $\ell = x, y, z$

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where $\eta_i = \pm 1$ on the two sublattices. (For suitable V_Φ, integrating out the Φ yields back the Hubbard model).

When $\Phi^\ell(i) =$ (non-zero constant) independent of i, we have long-range AF order, which gaps out the fermions into an insulating state.

For fluctuating antiferromagnetism, we transform to a rotating reference frame using the SU(2) rotation R_i

$$\left(\begin{array}{c} c_{i\uparrow} \\ c_{i\downarrow} \end{array} \right) = R_i \left(\begin{array}{c} \psi_{i,+} \\ \psi_{i,-} \end{array} \right),$$

in terms of fermionic "chargons" ψ_s and a **Higgs field** $H^a(i)$

$$\sigma^\ell \Phi^\ell(i) = R_i \, \sigma^a H^a(i) \, R_i^\dagger$$

The Higgs field is the AFM order in the rotating reference frame.

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$$\sigma^\ell \Phi^\ell(i) = R_i \, \sigma^a H^a(i) \, R_i^\dagger$$

The Higgs field is the AFM order in the rotating reference frame. Note that this representation is ambiguous up to a SU(2) gauge transformation, V_i

$$\left(\begin{array}{c} \psi_{i,+} \\ \psi_{i,-} \end{array} \right) \rightarrow V_i \left(\begin{array}{c} \psi_{i,+} \\ \psi_{i,-} \end{array} \right)$$

$$R_i \rightarrow R_i V_i^\dagger$$

$$\sigma^a H^a(i) \rightarrow V_i \, \sigma^b H^b(i) \, V_i^\dagger .$$

Fluctuating antiferromagnetism

The simplest effective Hamiltonian for the fermionic chargons is the same as that for the electrons, with the AFM order replaced by the Higgs field.

$$\mathcal{H}_\psi = -\sum_{i,\rho} t_\rho \left(\psi_{i,s}^\dagger \psi_{i+\boldsymbol{v}_\rho,s} + \psi_{i+\boldsymbol{v}_\rho,s}^\dagger \psi_{i,s} \right) - \mu \sum_i \psi_{i,s}^\dagger \psi_{i,s} + \mathcal{H}_{\rm int}$$

$$\mathcal{H}_{\rm int} = -\lambda \sum_i \eta_i H^a(i) \psi_{i,s}^\dagger \sigma_{ss'}^a \psi_{i,s'} + V_H$$

Fluctuating antiferromagnetism

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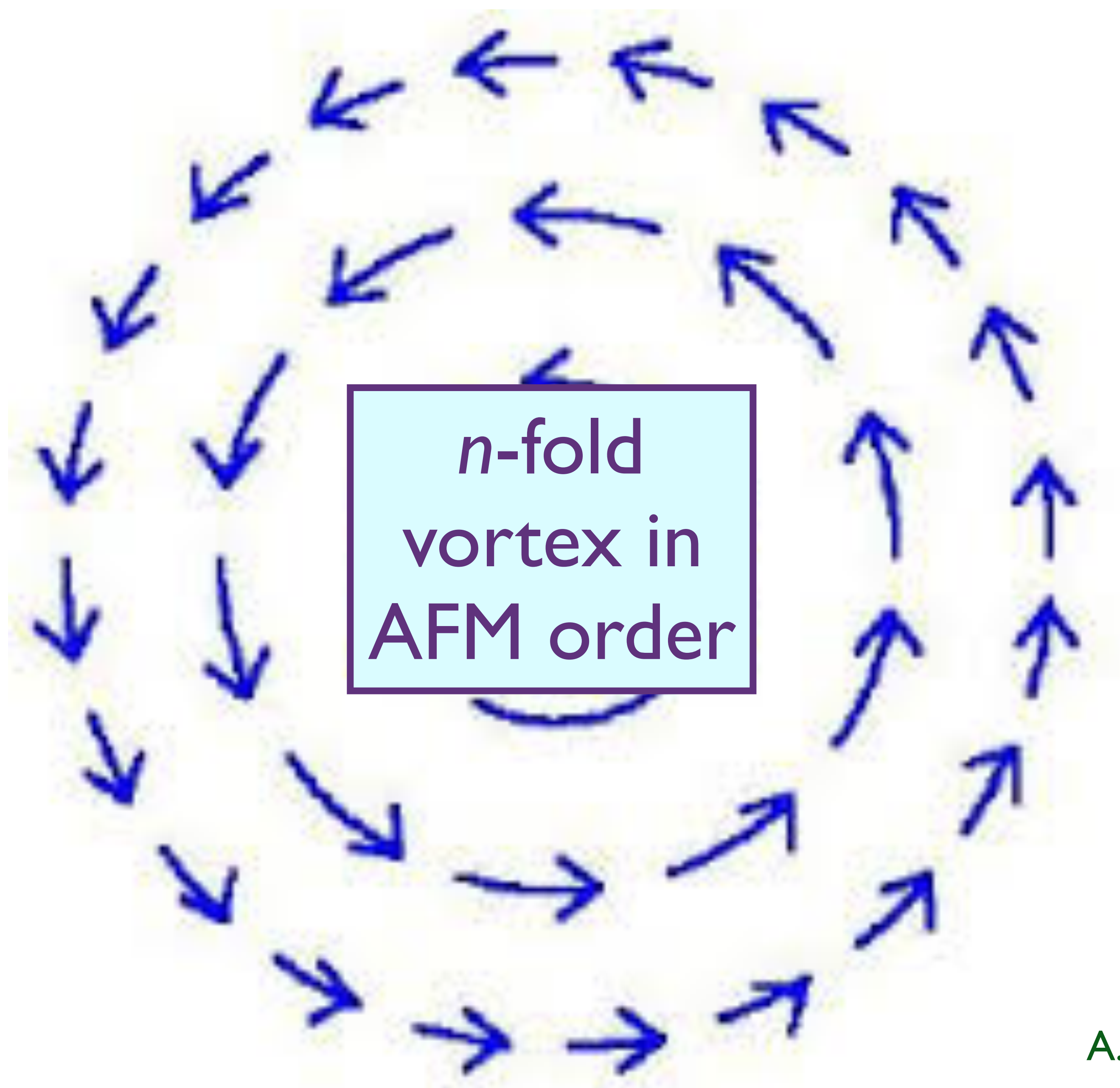
IF we can transform to a rotating reference frame in which $H^a(i) =$ a constant independent of i and time, **THEN** the ψ fermions in the presence of fluctuating AFM will inherit the insulating nature of the electrons in the presence of static AFM.

Fluctuating antiferromagnetism

We cannot always find a single-valued SU(2) rotation R_i to make the Higgs field $H^a(i)$ a constant !



A.V. Chubukov, T. Senthil and S. Sachdev, PRL **72**, 2089 (1994);
S. Sachdev, E. Berg, S. Chatterjee, and Y. Schattner, PRB **94**, 115147 (2016)

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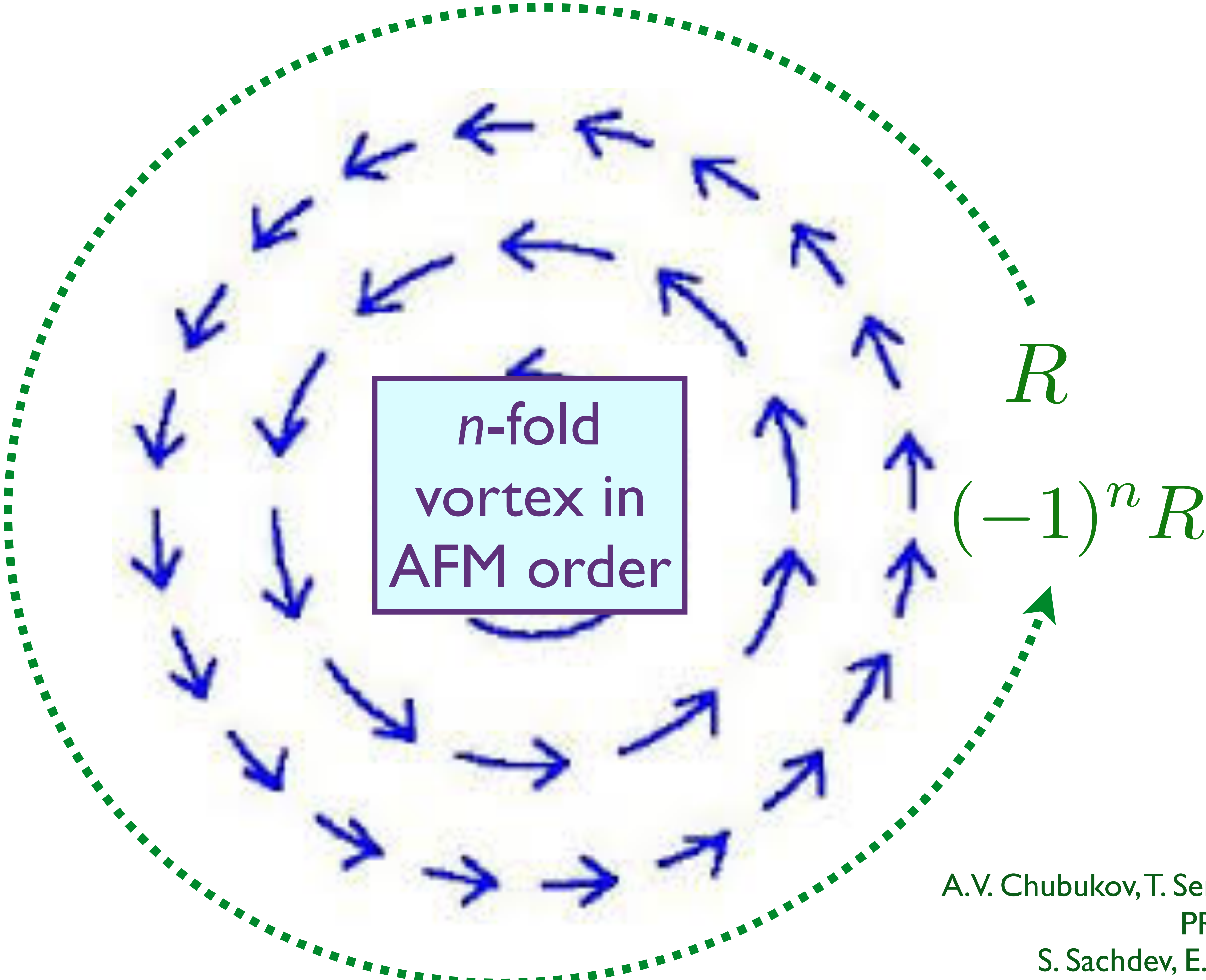

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Topological order

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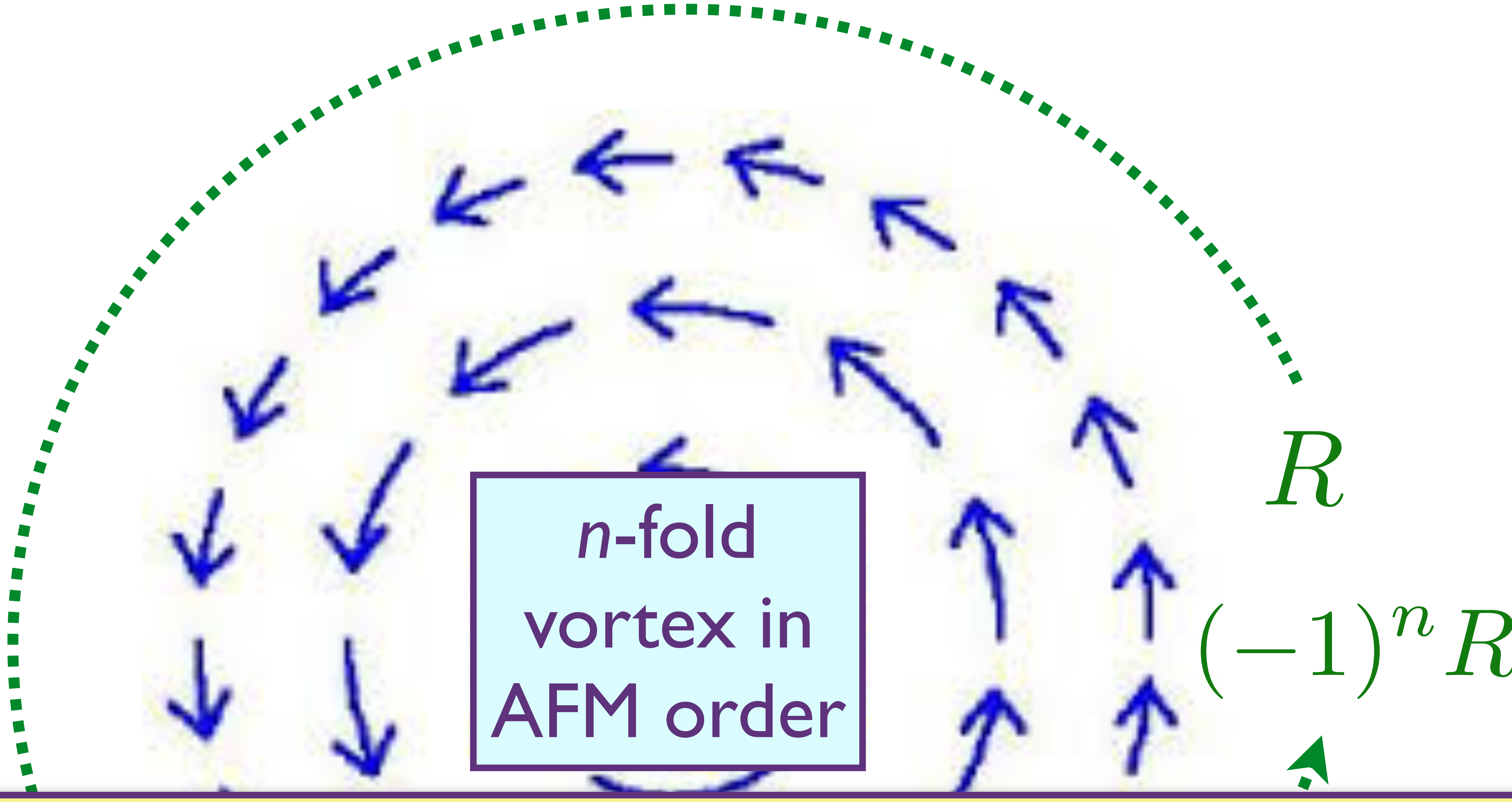


Vortices with n odd must be suppressed: such a metal with "fluctuating antiferromagnetism" has BULK $\mathbb{Z}_2$ TOPOLOGICAL ORDER and fermions which inherit the insulating behavior of the antiferromagnetic metal.

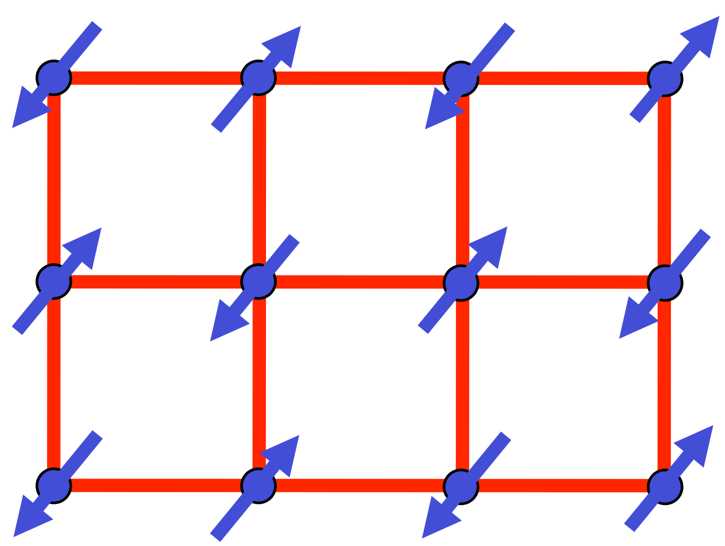
Fermi surface+antiferromagnetism

Electron spin

$$\left\langle \vec{S}_i \right\rangle = \eta_i \, \vec{\Phi}_i$$

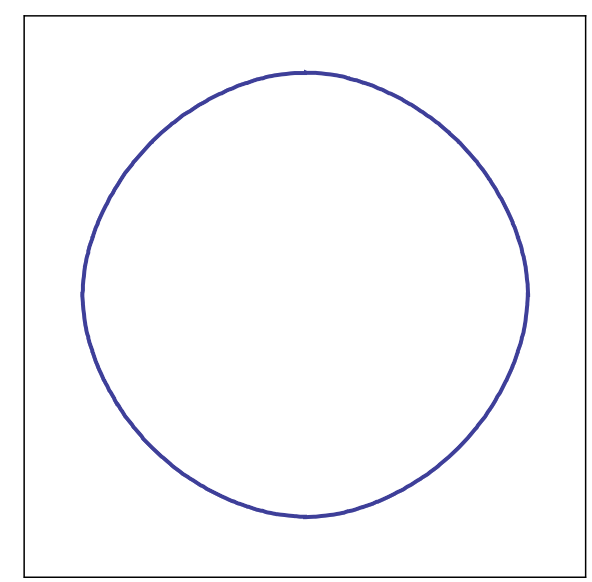
where $\eta_i = \pm 1$

p=0



$\langle \vec{\Phi} \rangle \neq 0$

Insulator with
AF order

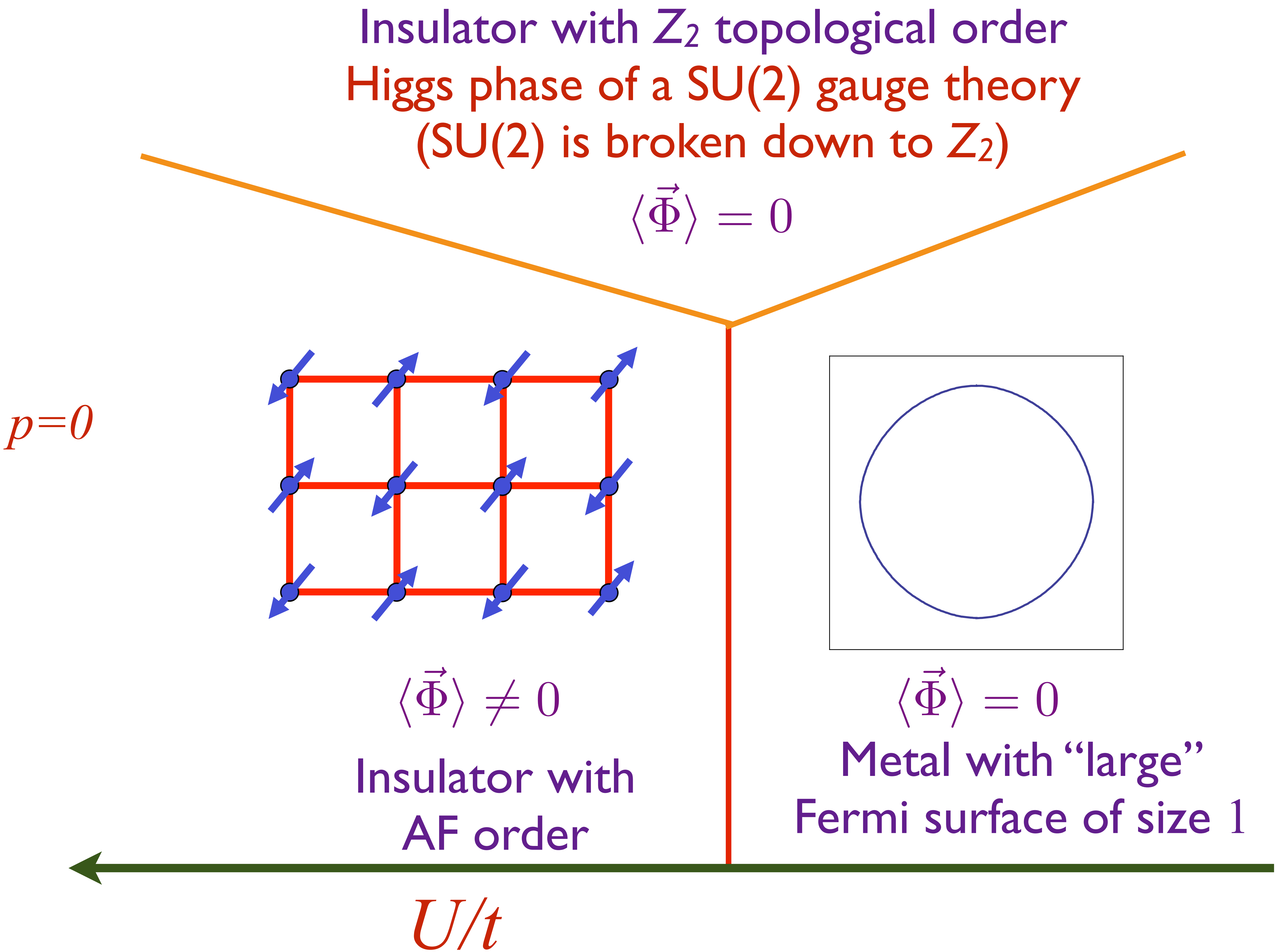


$\langle \vec{\Phi} \rangle = 0$

Metal with "large"
Fermi surface of size 1

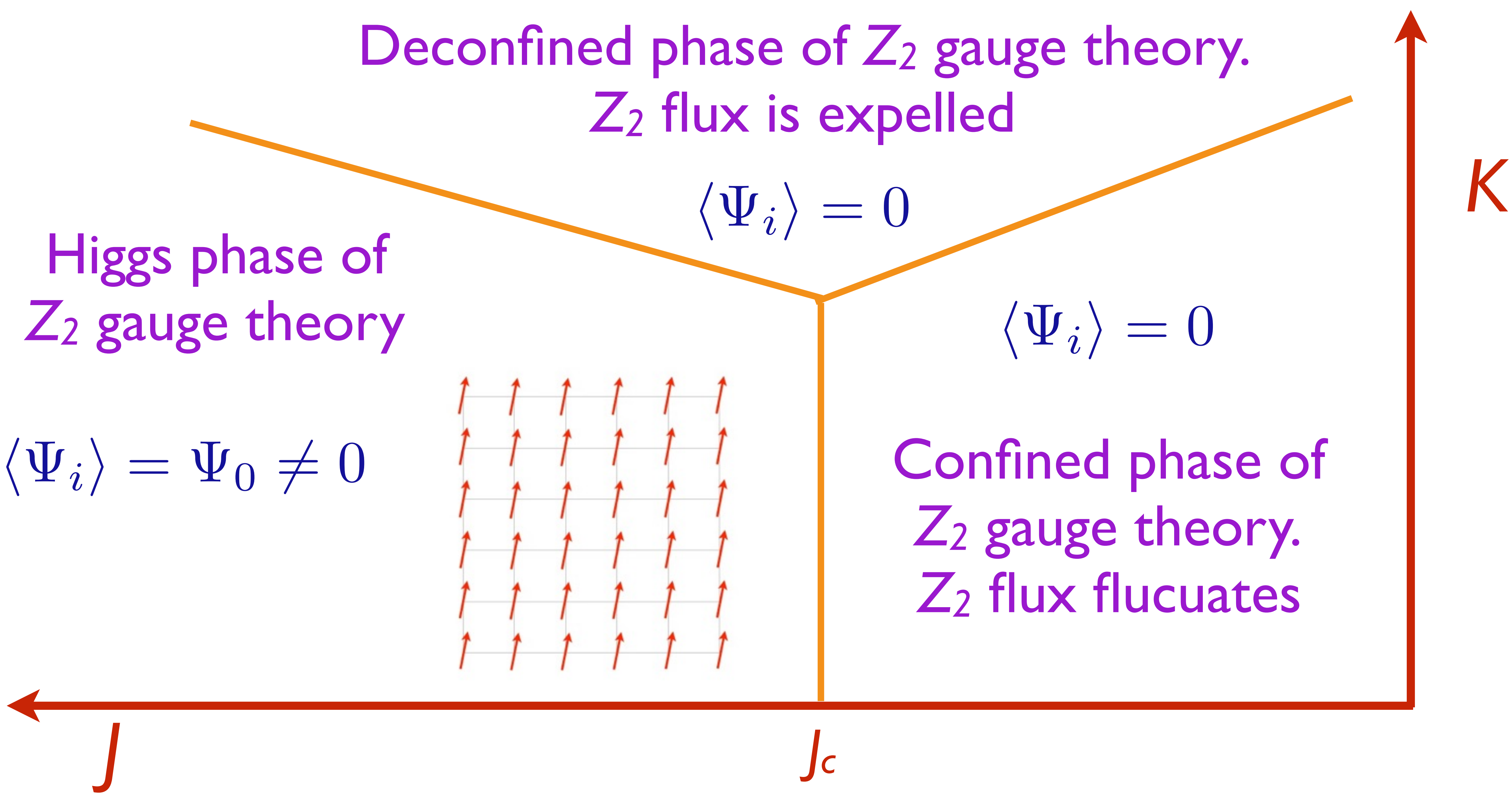
U/t

Fermi surface+antiferromagnetism+topological order

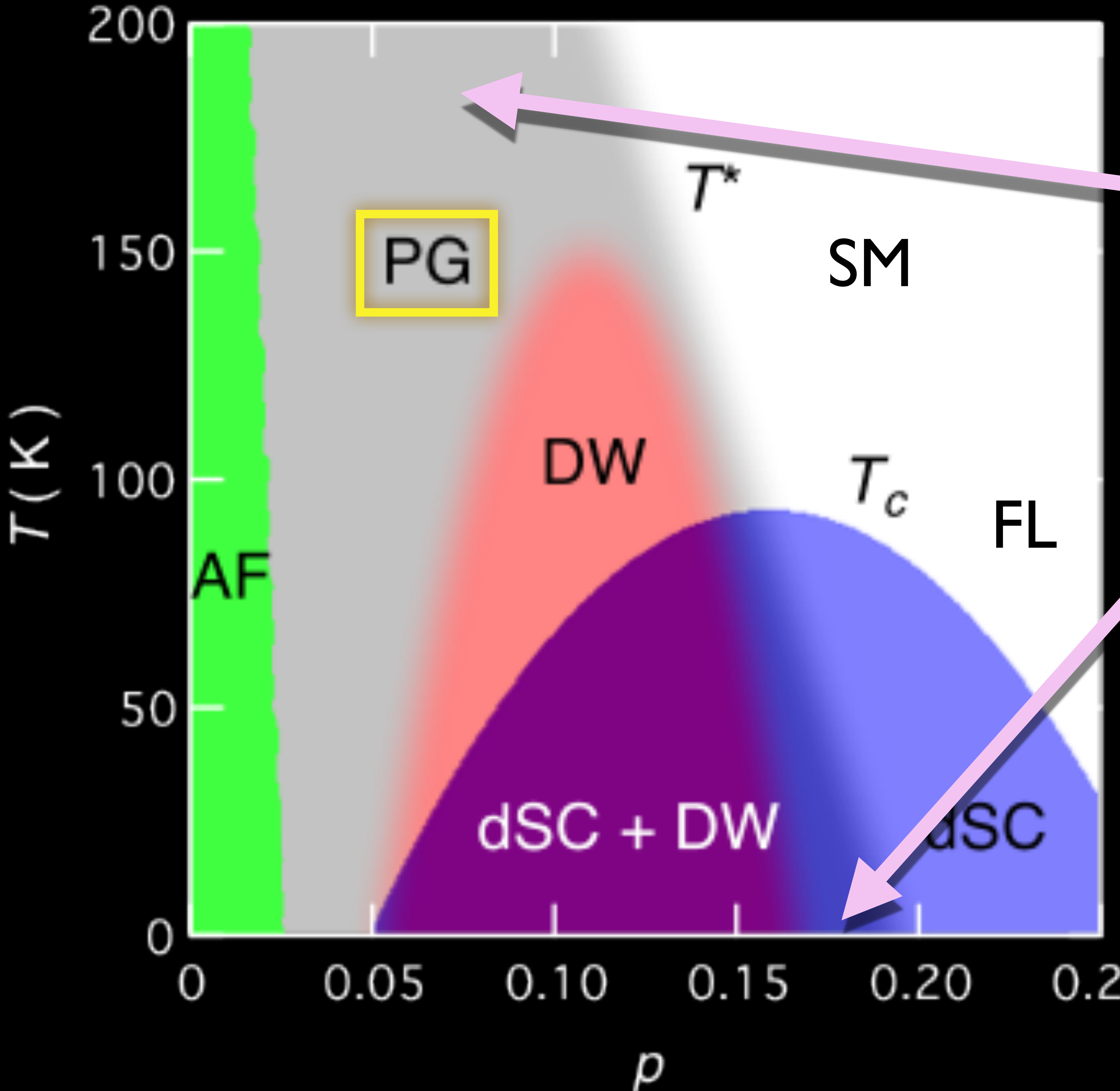


$$\widetilde{\mathcal{Z}}_{XY} = \sum_{\{\sigma_{ij}\}=\pm 1} \prod_i \int_0^{2\pi} \frac{d\theta_i}{2\pi} \exp\left(-\widetilde{H}/T\right)$$

$$\widetilde{H} = -J\sum_{\langle ij \rangle} \sigma_{ij} \cos\left[(\theta_i - \theta_j)/2\right] - K \sum_{\square} \prod_{(ij)\in\square} \sigma_{ij}$$



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



Pseudogap metal at low p

Many indications that this metal behaves like a Fermi liquid, but with Fermi surface size p and *not* $1+p$.

If present at $T=0$, a metal with a size p Fermi surface (and translational symmetry preserved) *must* have *topological order*

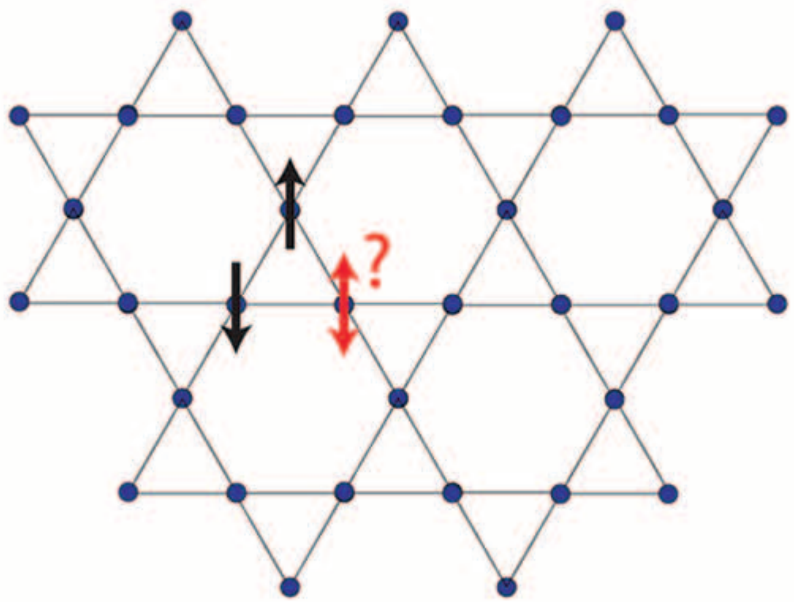
Topological order in the pseudogap metal

Mathias S. Scheurer,[1] Shubhayu Chatterjee,[1] Wei Wu,[2,3] Michel Ferrero,[2,3] Antoine Georges,[2,4,3,5] and Subir Sachdev[1,6,7]

We compute the electronic Green's function of the topologically ordered Higgs phase of a SU(2) gauge theory of fluctuating antiferromagnetism on the square lattice. The results are compared with cluster extensions of dynamical mean field theory, and quantum Monte Carlo calculations, on the pseudogap phase of the strongly interacting hole-doped Hubbard model. Good agreement is found in the momentum, frequency, hopping, and doping dependencies of the spectral function and electronic self-energy. We show that lines of (approximate) zeros of the zero-frequency electronic Green's function are signs of the underlying topological order of the gauge theory, and describe how these lines of zeros appear in our theory of the Hubbard model. We also derive a modified, non-perturbative version of the Luttinger theorem that holds in the Higgs phase.

to appear…..

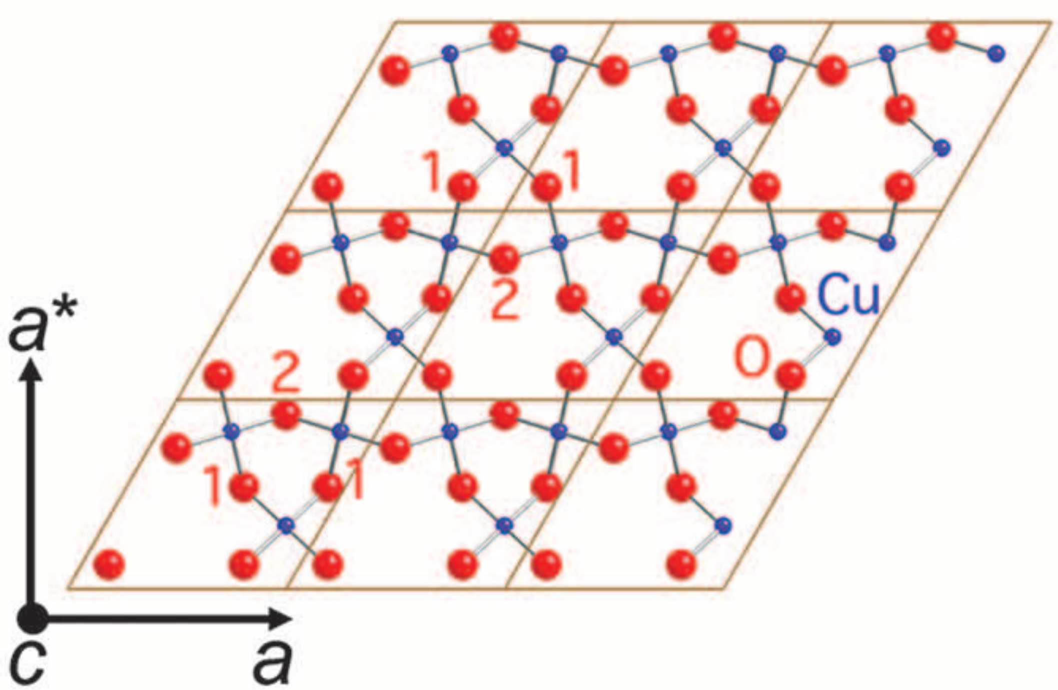
Kagome lattice antiferromagnet

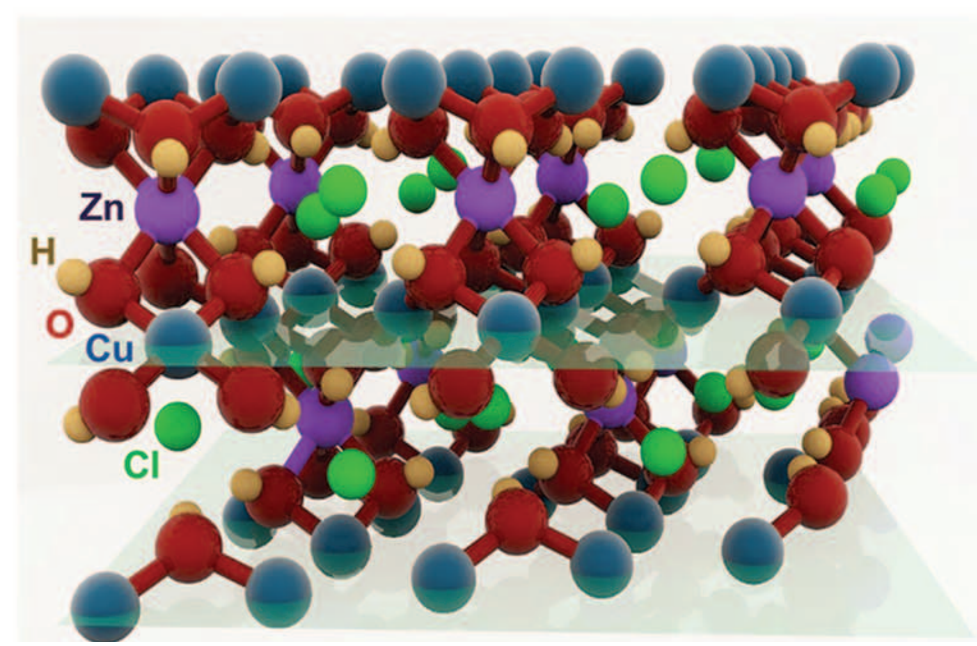


Candidate for an insulator with $\mathbb{Z}_2$ topological order which has charge neutral, spin $S = 1/2$, "spinon" excitations.

S. Sachdev, Physical Review B **45**, 12377 (1992)

See talk tomorrow by H. Changlani





Herbertsmithite: $\mathrm{ZnCu_3\ (OH)_6\ Cl_2}$

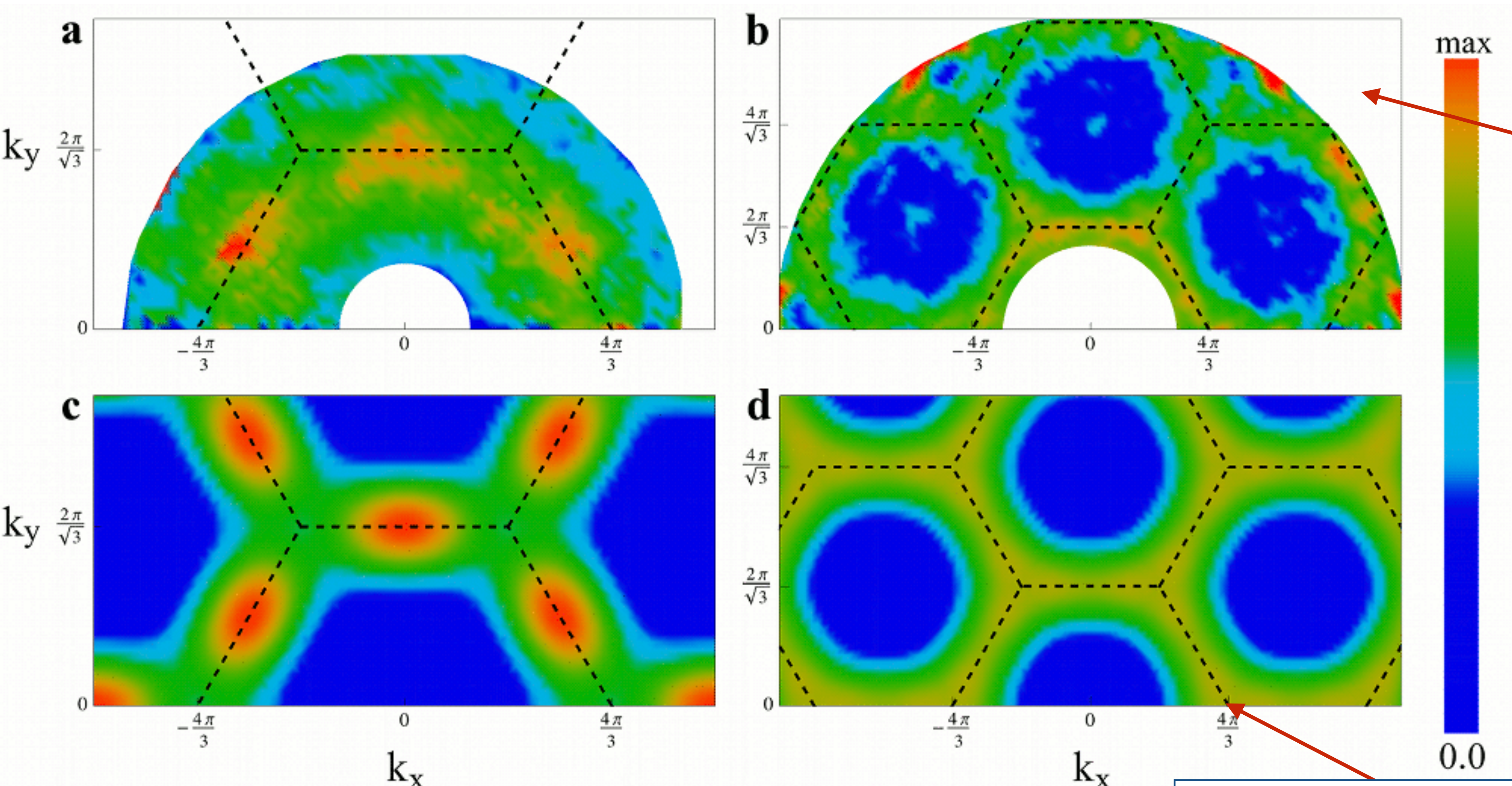
Evidence for a gapped spin-liquid ground state in a kagome Heisenberg antiferromagnet

Mingxuan Fu,[1] Takashi Imai,[1,2*] Tian-Heng Han,[3,4] Young S. Lee[5,6]

The kagome Heisenberg antiferromagnet is a leading candidate in the search for a spin system with a quantum spin-liquid ground state. The nature of its ground state remains a matter of active debate. We conducted oxygen-17 single-crystal nuclear magnetic resonance (NMR) measurements of the spin-1/2 kagome lattice in herbertsmithite [$ZnCu_3(OH)_6Cl_2$], which is known to exhibit a spinon continuum in the spin excitation spectrum. We demonstrated that the intrinsic local spin susceptibility χ_{kagome}, deduced from the oxygen-17 NMR frequency shift, asymptotes to zero below temperatures of 0.03*J*, where *J* ~ 200 kelvin is the copper-copper superexchange interaction. Combined with the magnetic field dependence of χ_{kagome} that we observed at low temperatures, these results imply that the kagome Heisenberg antiferromagnet has a spin-liquid ground state with a finite gap.

Gap to topological $S = 1/2$ spinon excitations: $\approx J/20$.

Science 350, 655 (2015)



Neutron scattering observations

T Han, Young Lee, et al, Nature **492**, 406 (2012)

Theory by Punk, Chowdhury, Sachdev Nature Physics, 2013

Gapped Spin-1/2 Spinon Excitations in a New Kagome Quantum Spin Liquid Compound $Cu_3Zn(OH)_6FBr$*

Zili Feng (冯子力)[1], Zheng Li (李政)[1,2], Xin Meng (孟鑫)[1], Wei Yi (衣玮)[1], Yuan Wei (魏源)[1], Jun Zhang (张骏)[3], Yan-Cheng Wang (王艳成)[1], Wei Jiang (蒋伟)[4], Zheng Liu (刘峥)[5], Shiyan Li (李世燕)[3,6]

Chinese Physics Letters, Volume 34, Number 7

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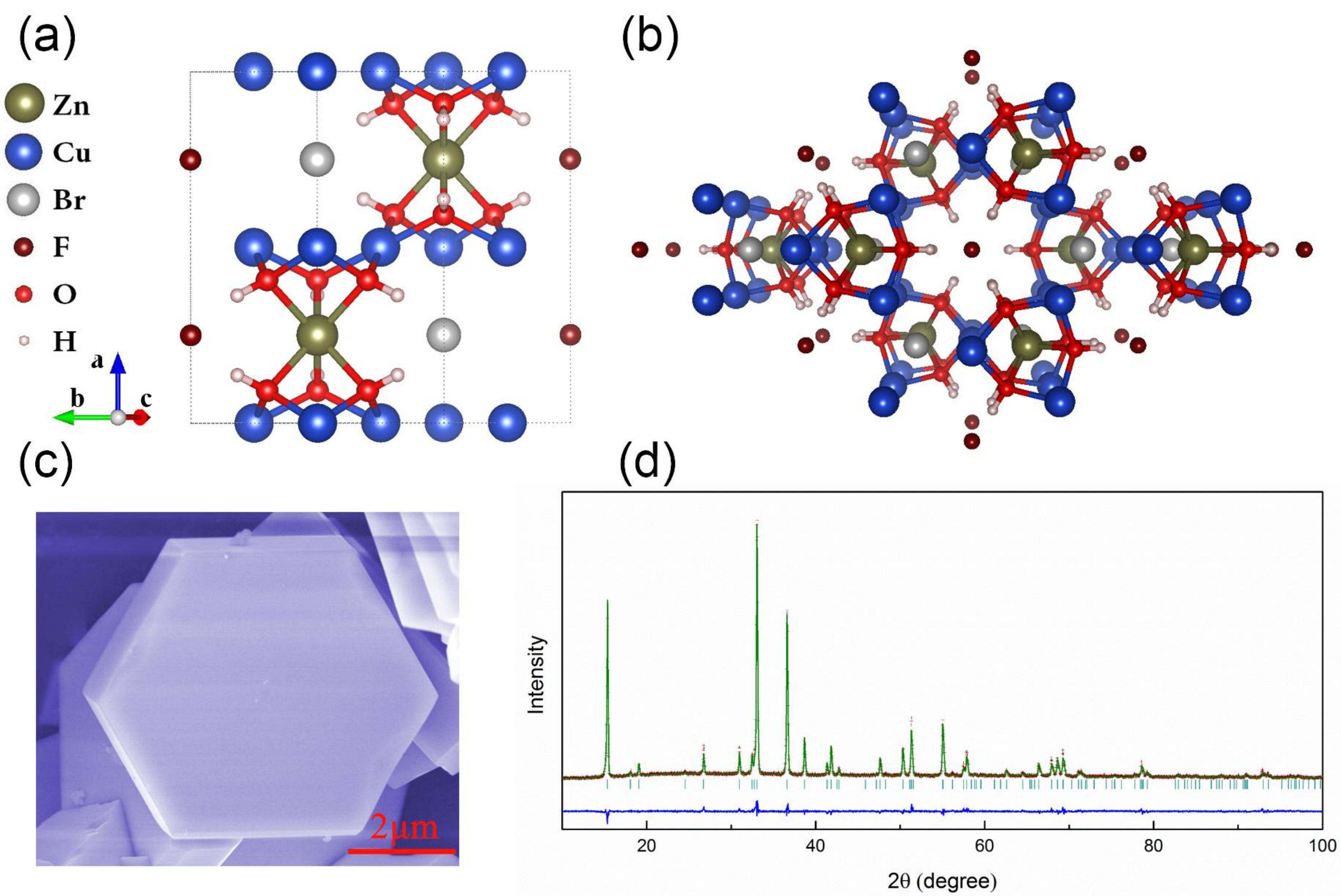

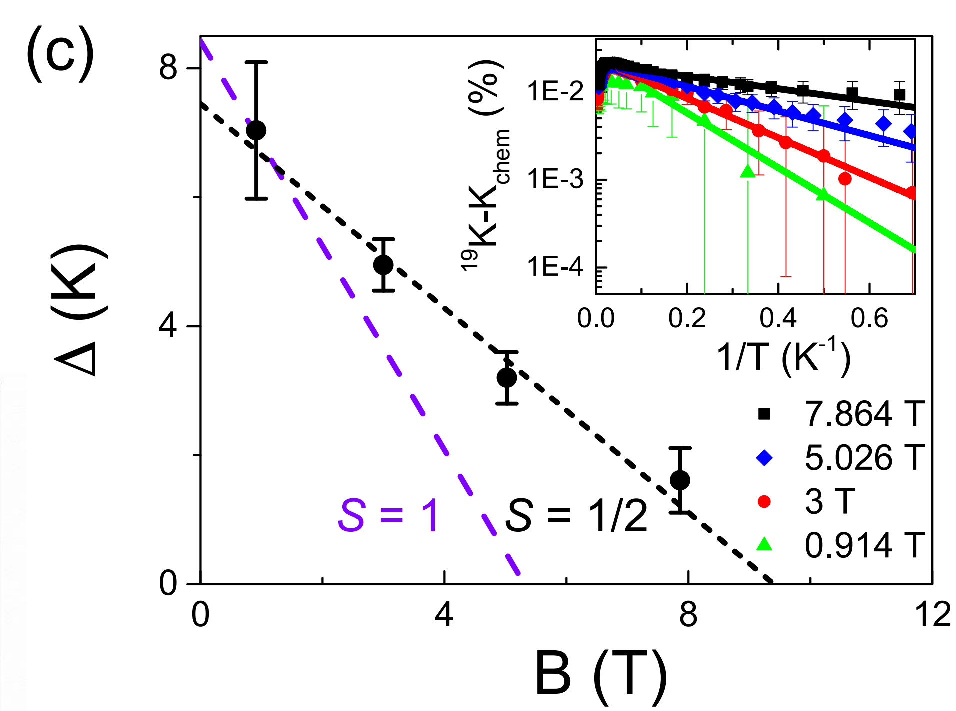

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- Direct evidence for topological order in kagome antiferromagnets