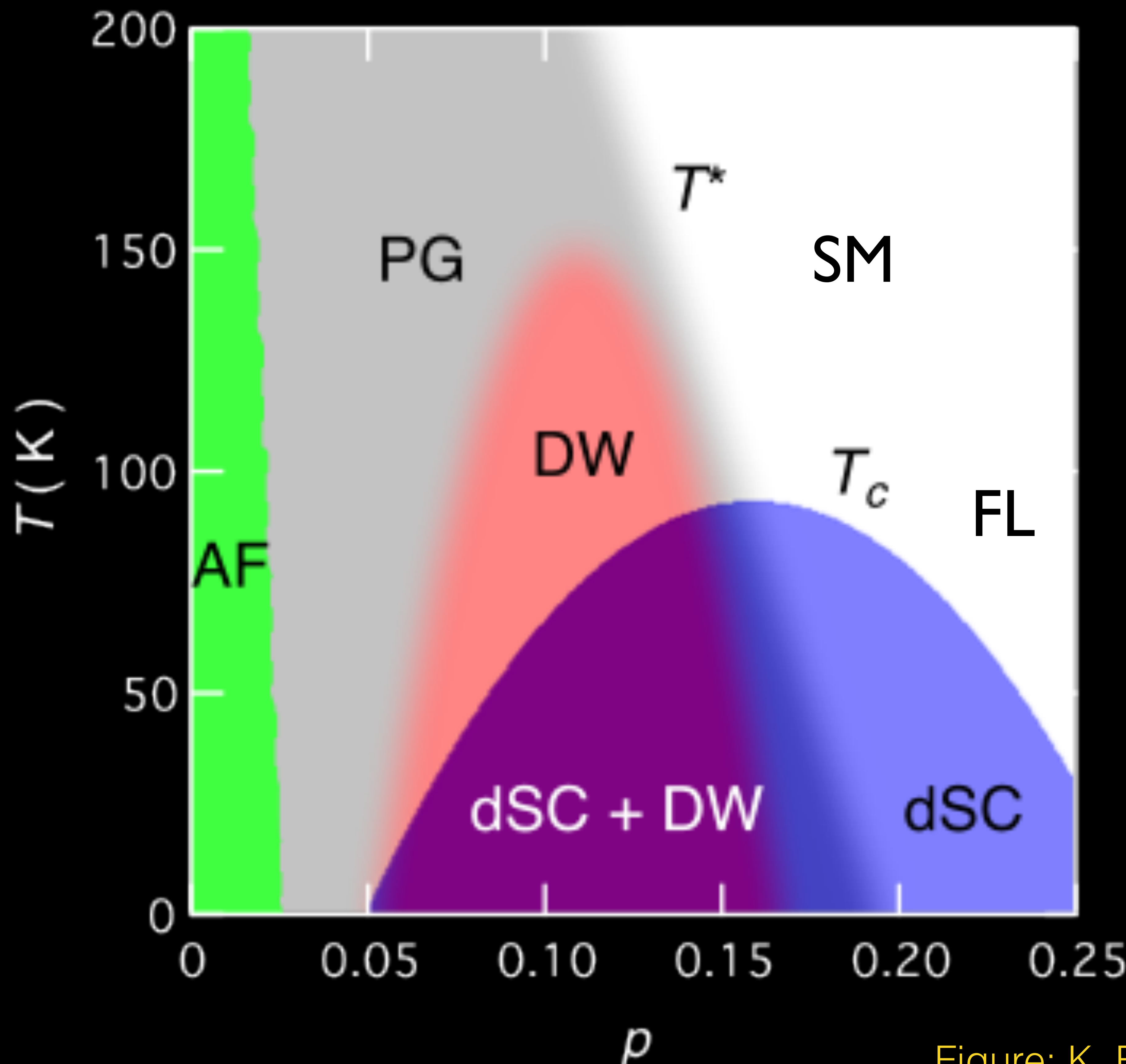
Topology, quantum entanglement, and criticality in the high temperature superconductors

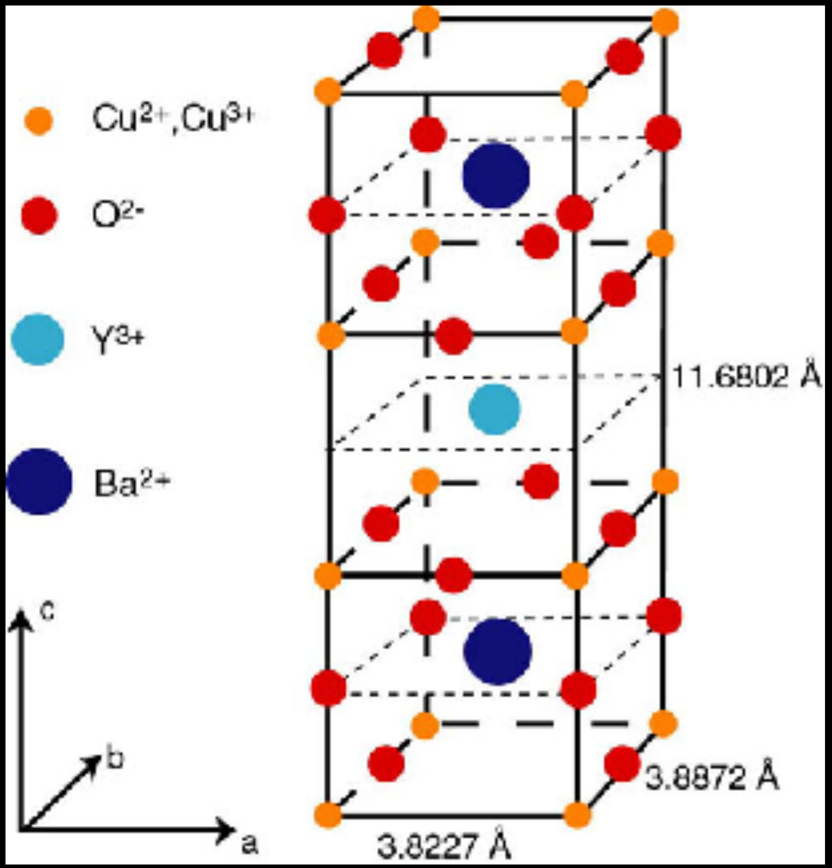
Exploring quantum phenomena and quantum matter
in ultrahigh magnetic fields,
National Science Foundation, Alexandria VA

Subir Sachdev
September 21, 2017

Talk online: sachdev.physics.harvard.edu

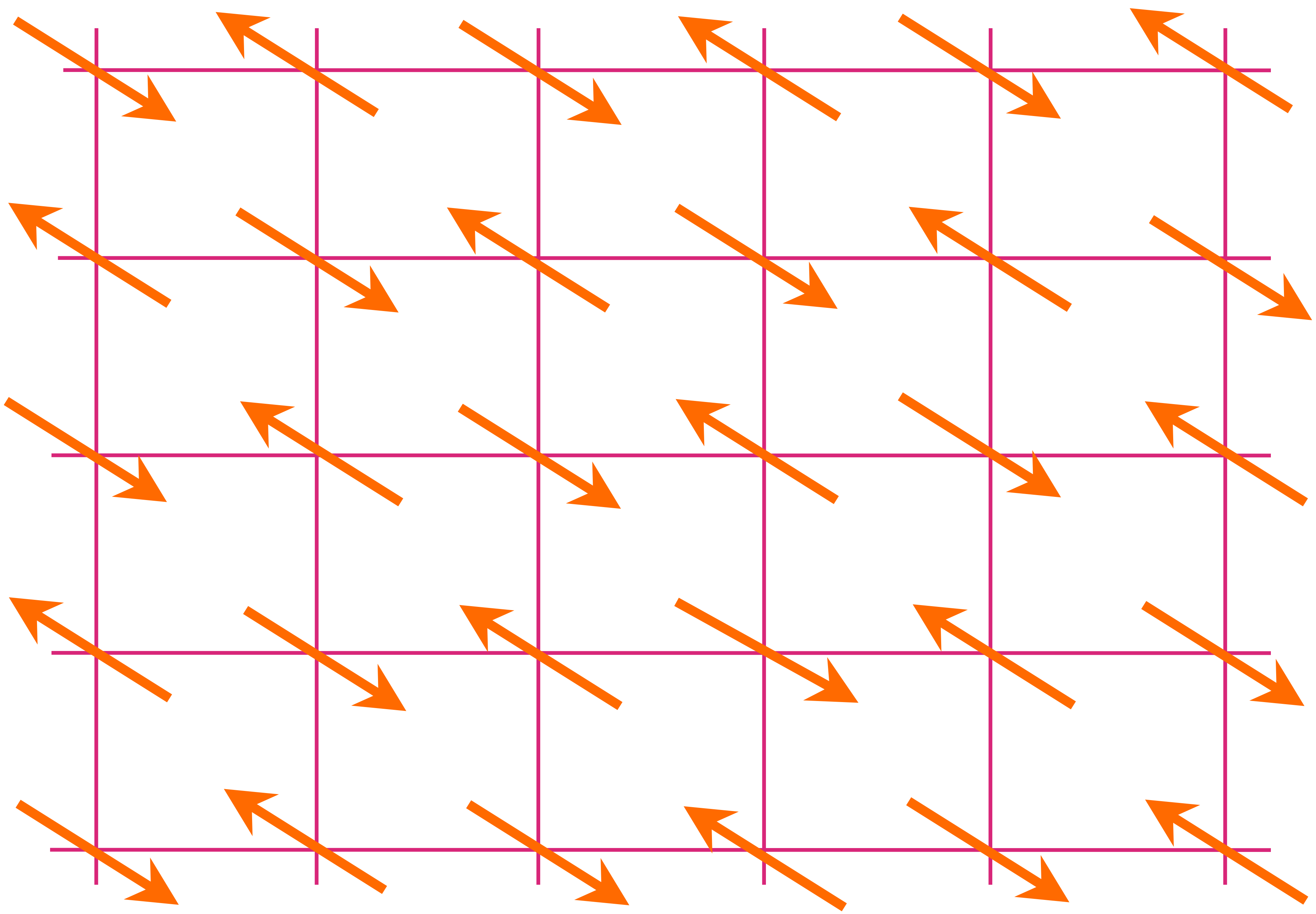
PHYSICS
HARVARD



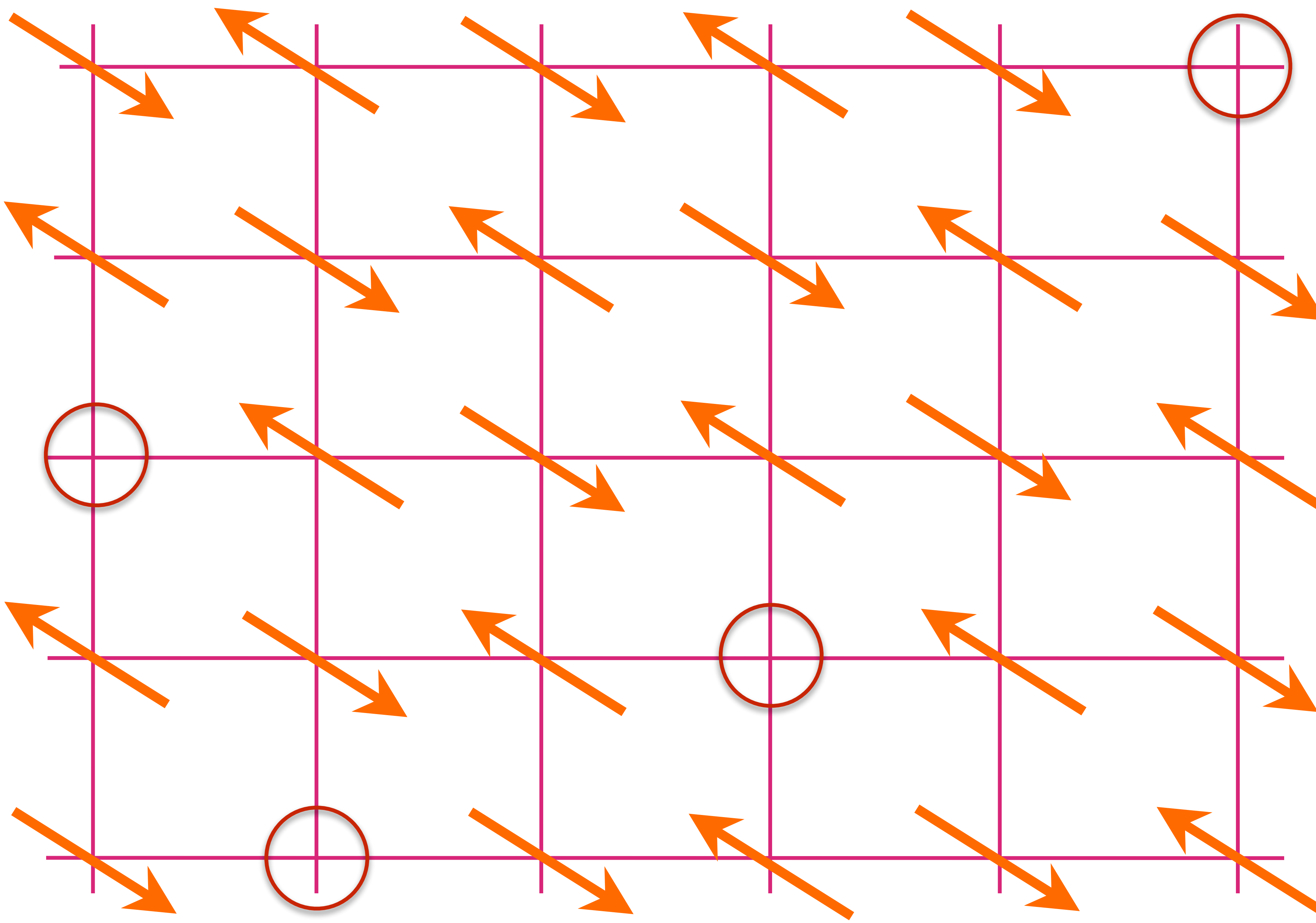


$YBa_2Cu_3O_{6+x}$

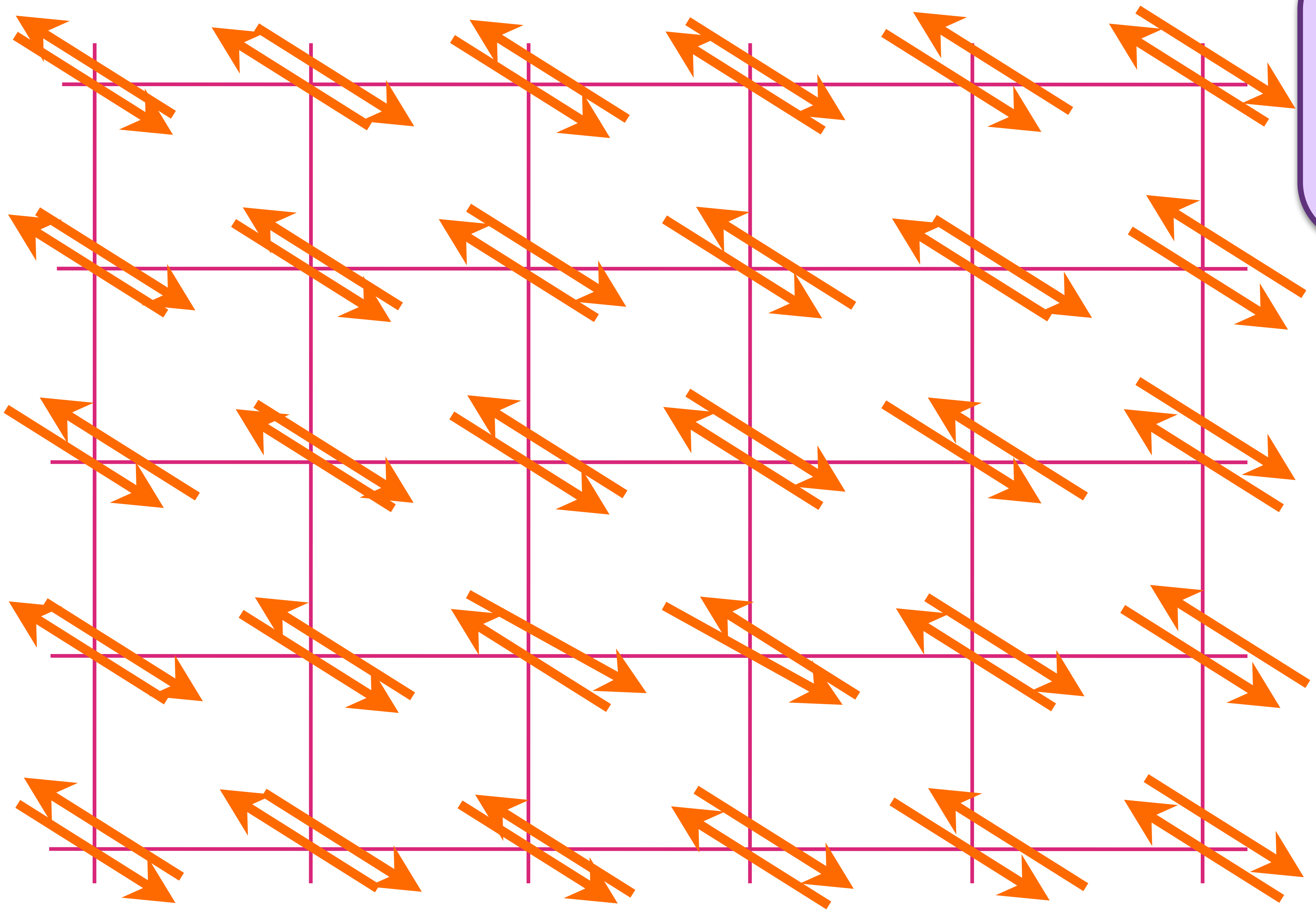
Figure: K. Fujita and J. C. Seamus Davis



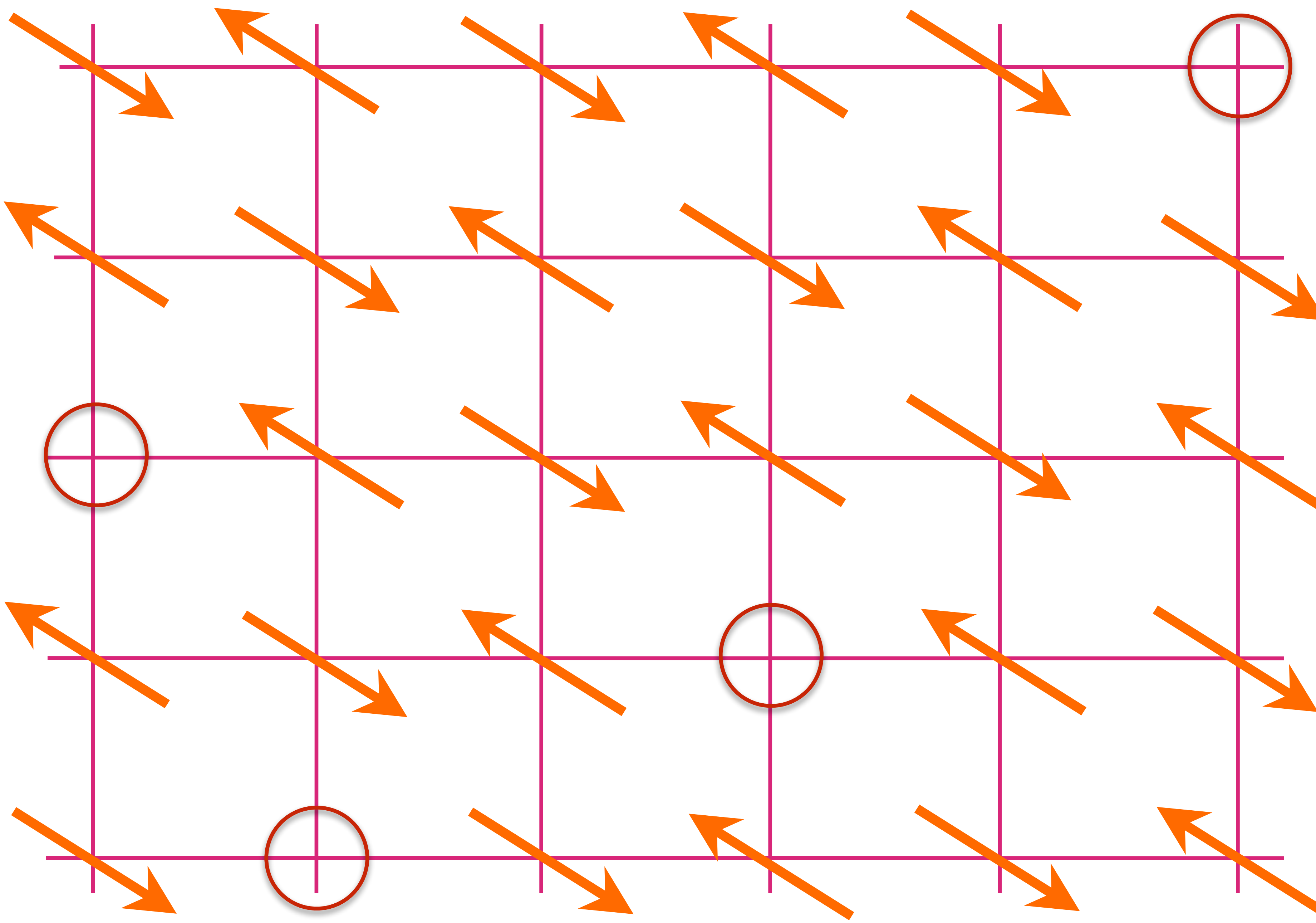
"Undoped" insulating anti-ferromagnet



Anti-
ferromagnet
with p mobile
holes
per square

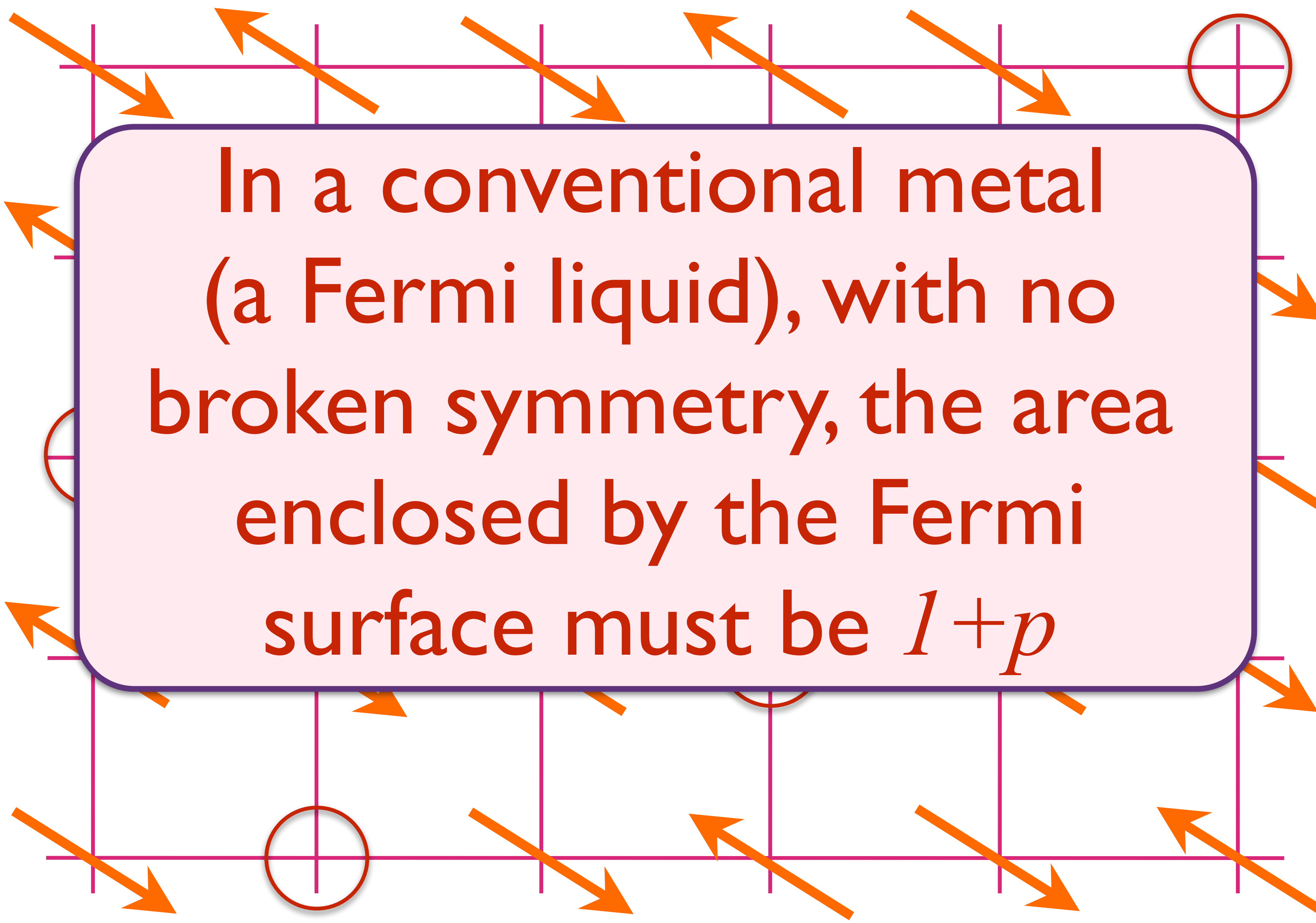


Filled Band



Anti-ferromagnet with p mobile holes per square

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

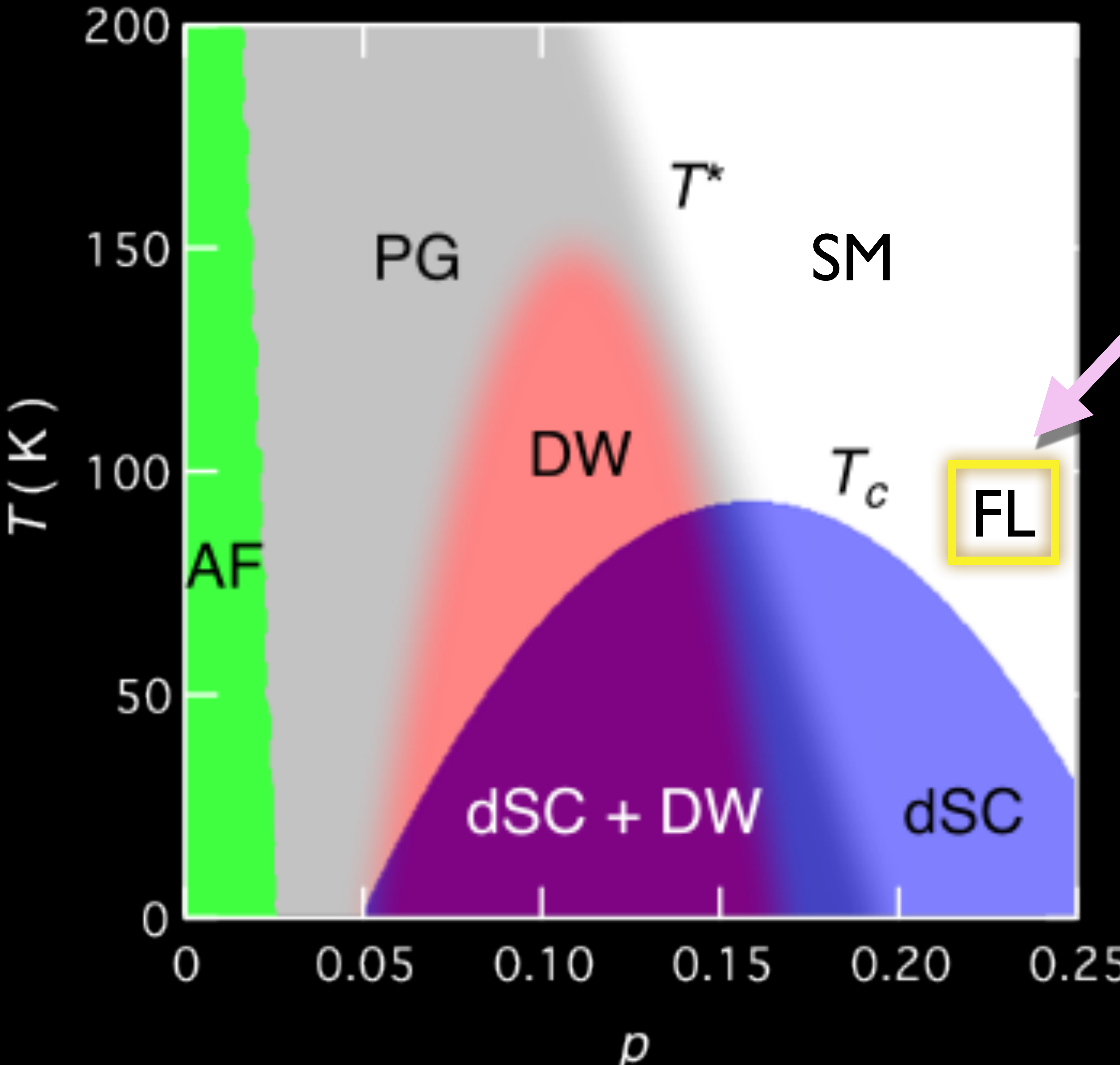


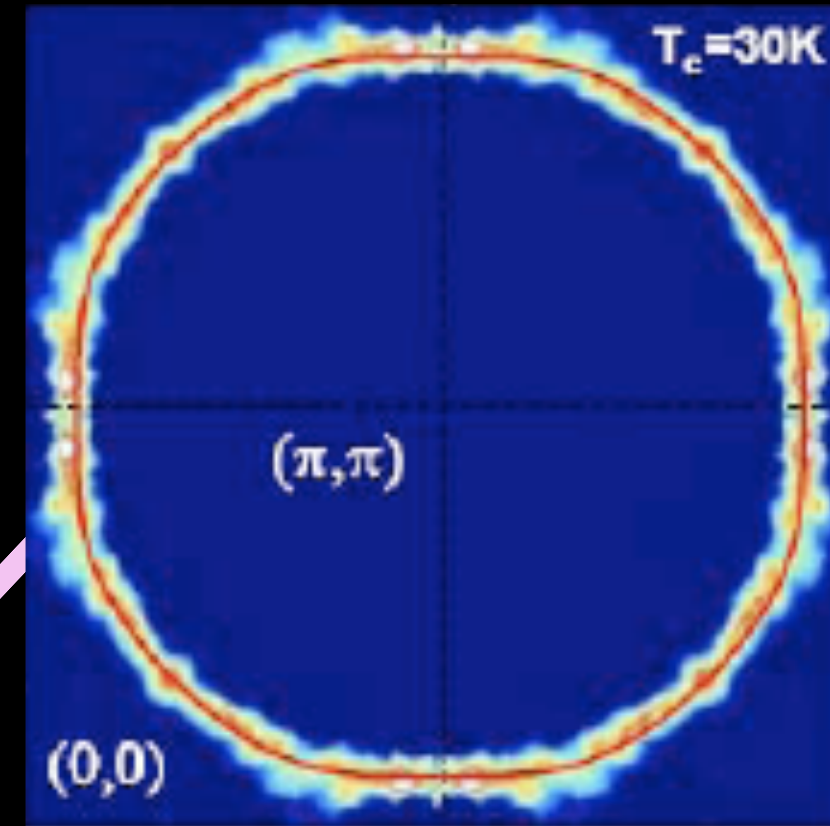
In a conventional metal (a Fermi liquid), with no broken symmetry, the area enclosed by the Fermi surface must be $1+p$

Anti-ferromagnet with p mobile holes per square

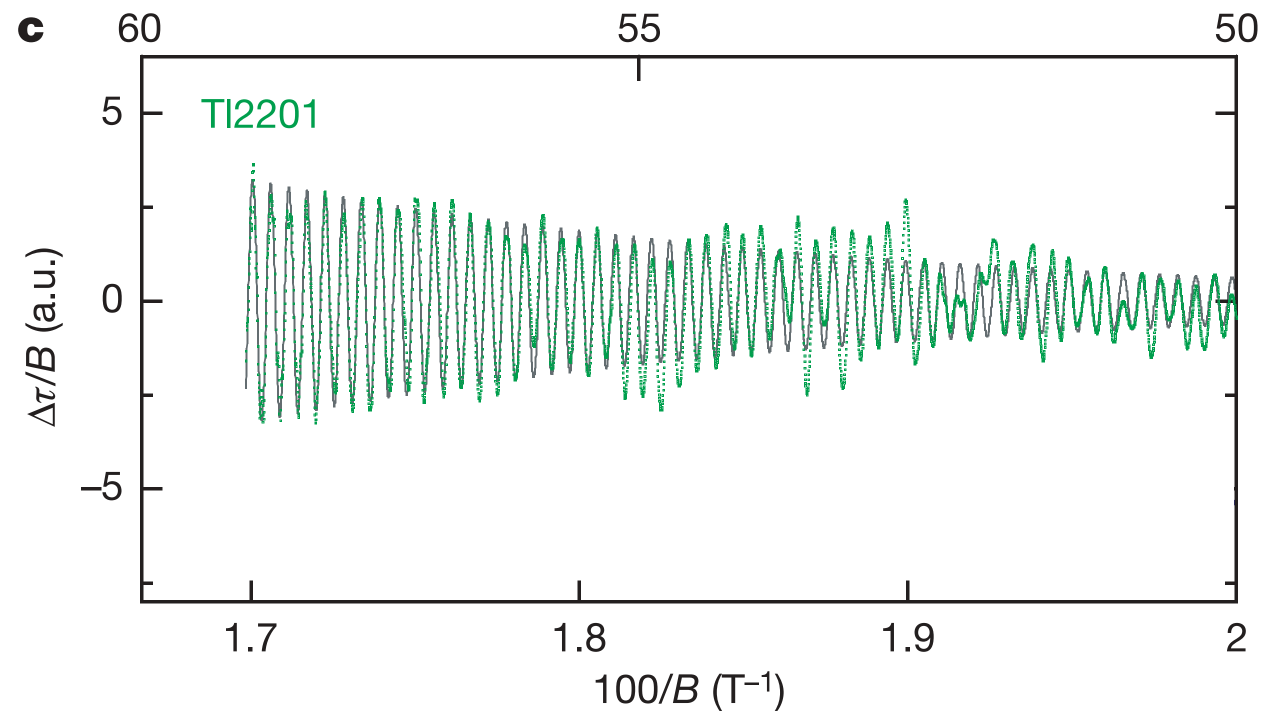
But relative to the band insulator, there are $1+p$ holes per square

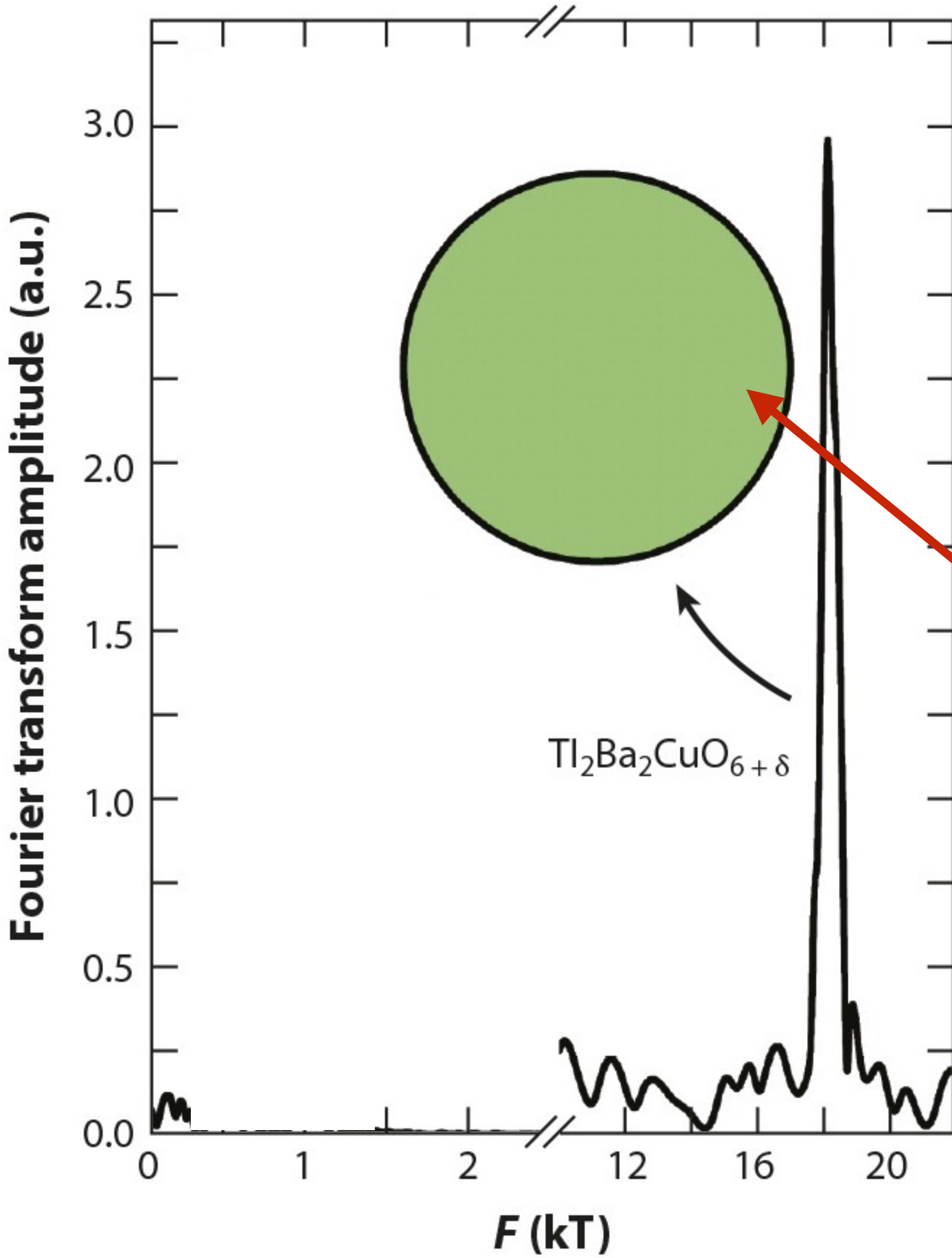
M. Platé, J. D. F. Mottershead, I. S. Elfimov, D. C. Peets, Ruixing Liang, D. A. Bonn, W. N. Hardy, S. Chiuzbaian, M. Falub, M. Shi, L. Patthey, and A. Damascelli, Phys. Rev. Lett. **95**, 077001 (2005)





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

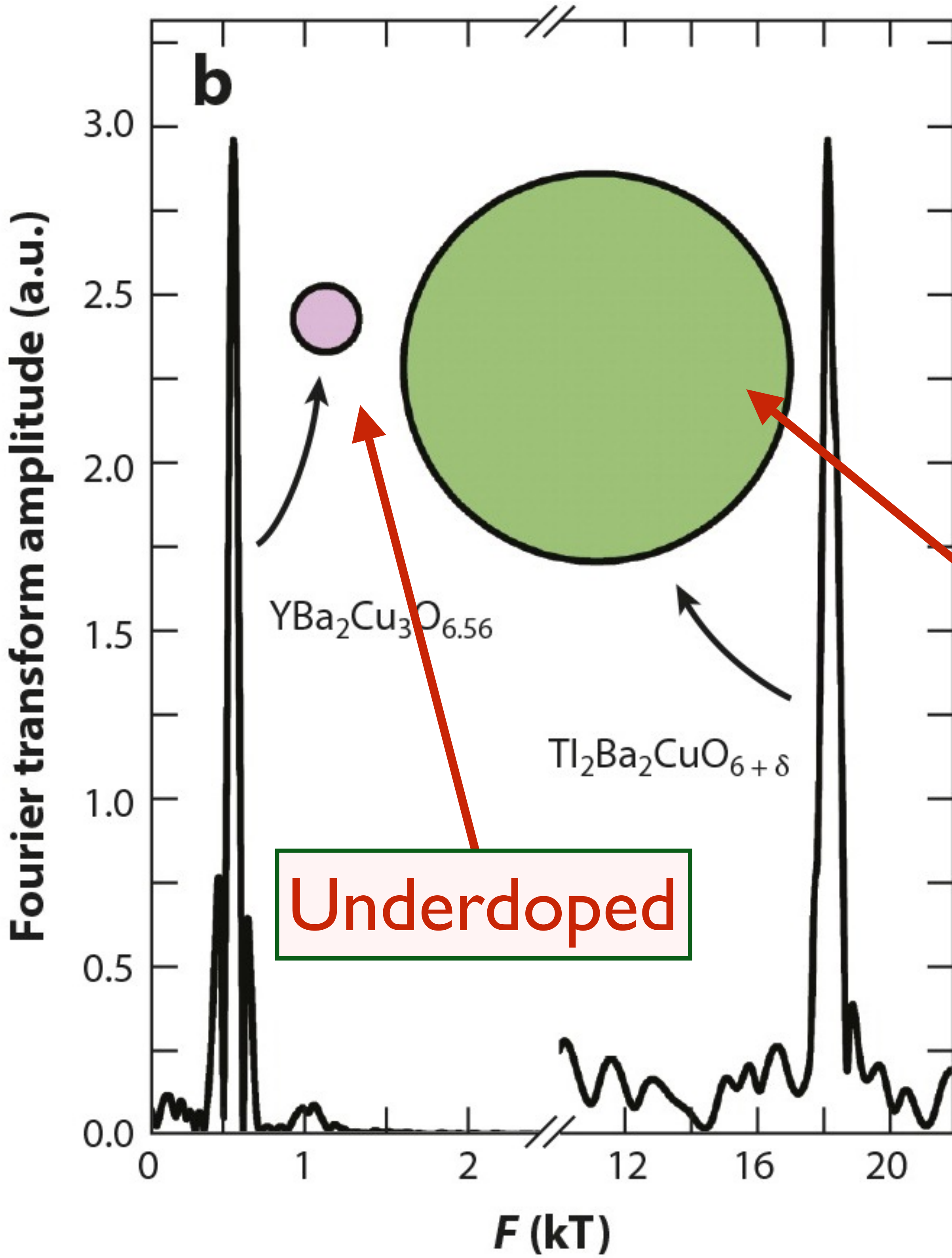


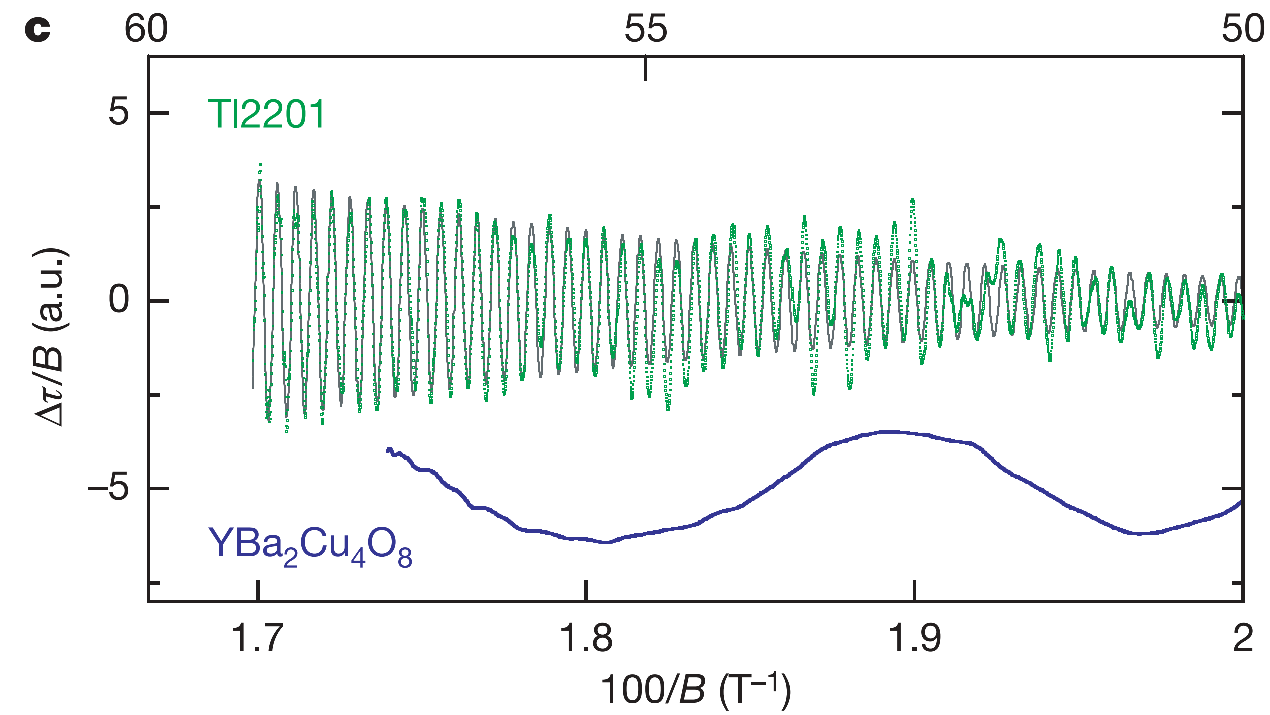


Overdoped

Vignolle B, Carrington A, Cooper RA, French MMJ, Mackenzie AP, Jaudet C, Vignolles D, Proust C and Hussey NE. 2008. *Nature* 455:952-955

S. Sebastian and C. Proust, Annual Reviews of Condensed Matter Physics, 6 (2015) 411-30





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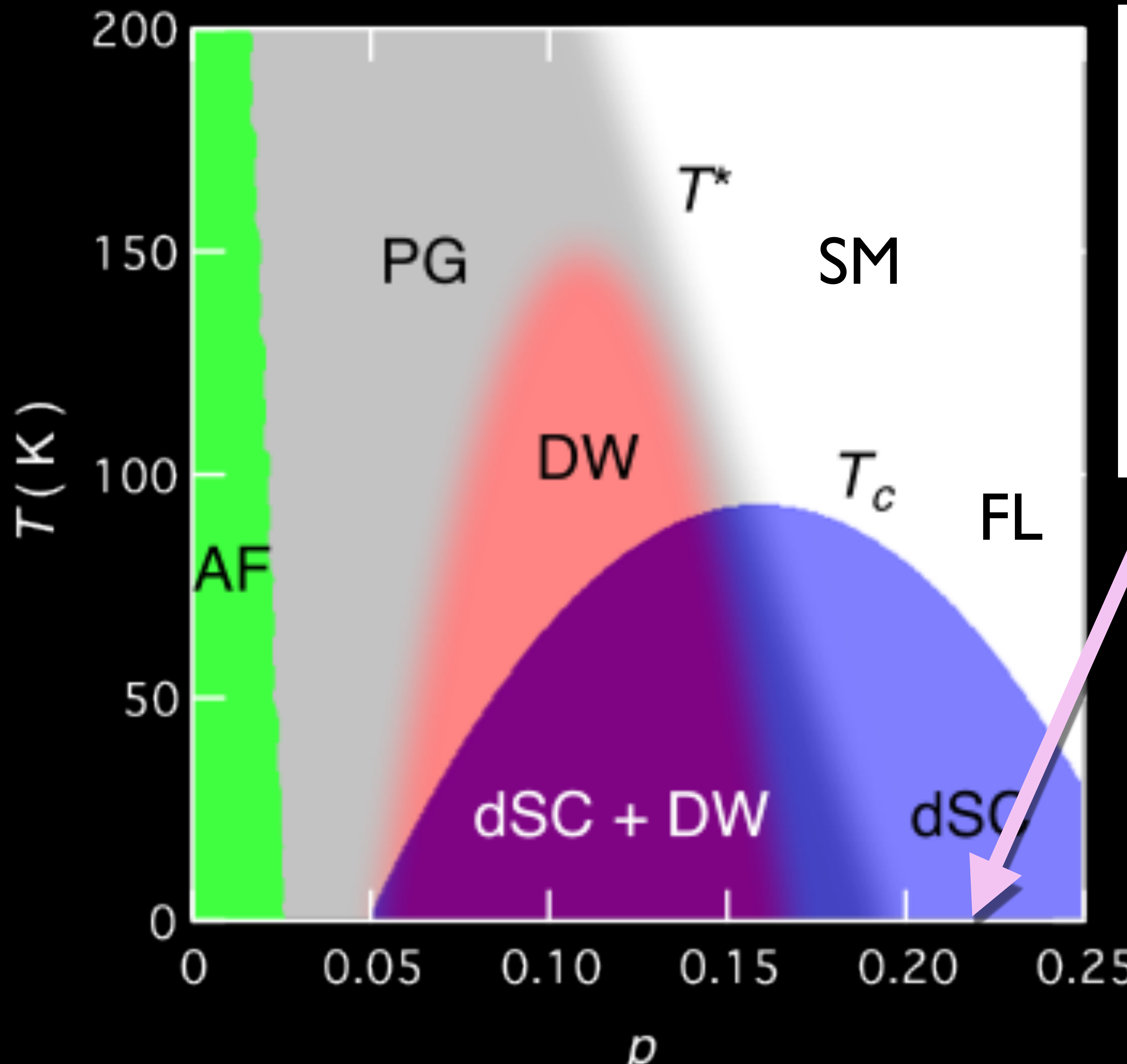
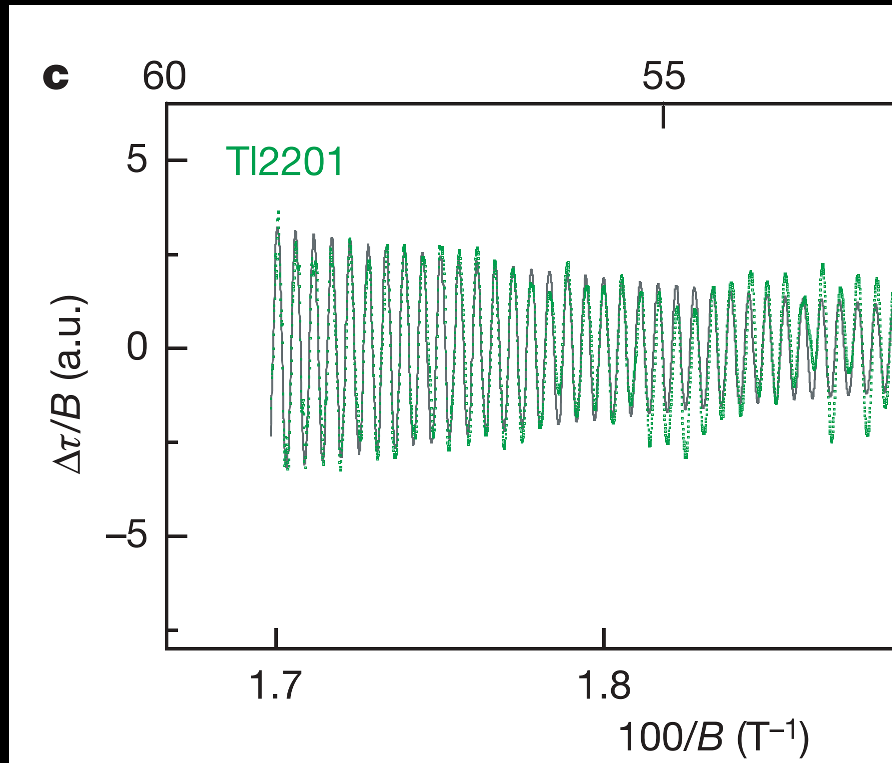
Doiron-Leyraud N, Proust C, LeBoeuf D, Levallois J, Bonnemaison JB, Liang R, Bonn DA, Hardy WN, Taillefer L. 2007. *Nature* 447:565-568

S. Sebastian and C. Proust, Annual Reviews of Condensed Matter Physics, 6 (2015) 411-30

B. Vignolle, A. Carrington, R.A. Cooper, M.M.J. French, A.P. Mackenzie, C. Jaudet, D. Vignolles, C. Proust and N.E. Hussey, Nature **455**, 952 (2008)





A conventional metal:
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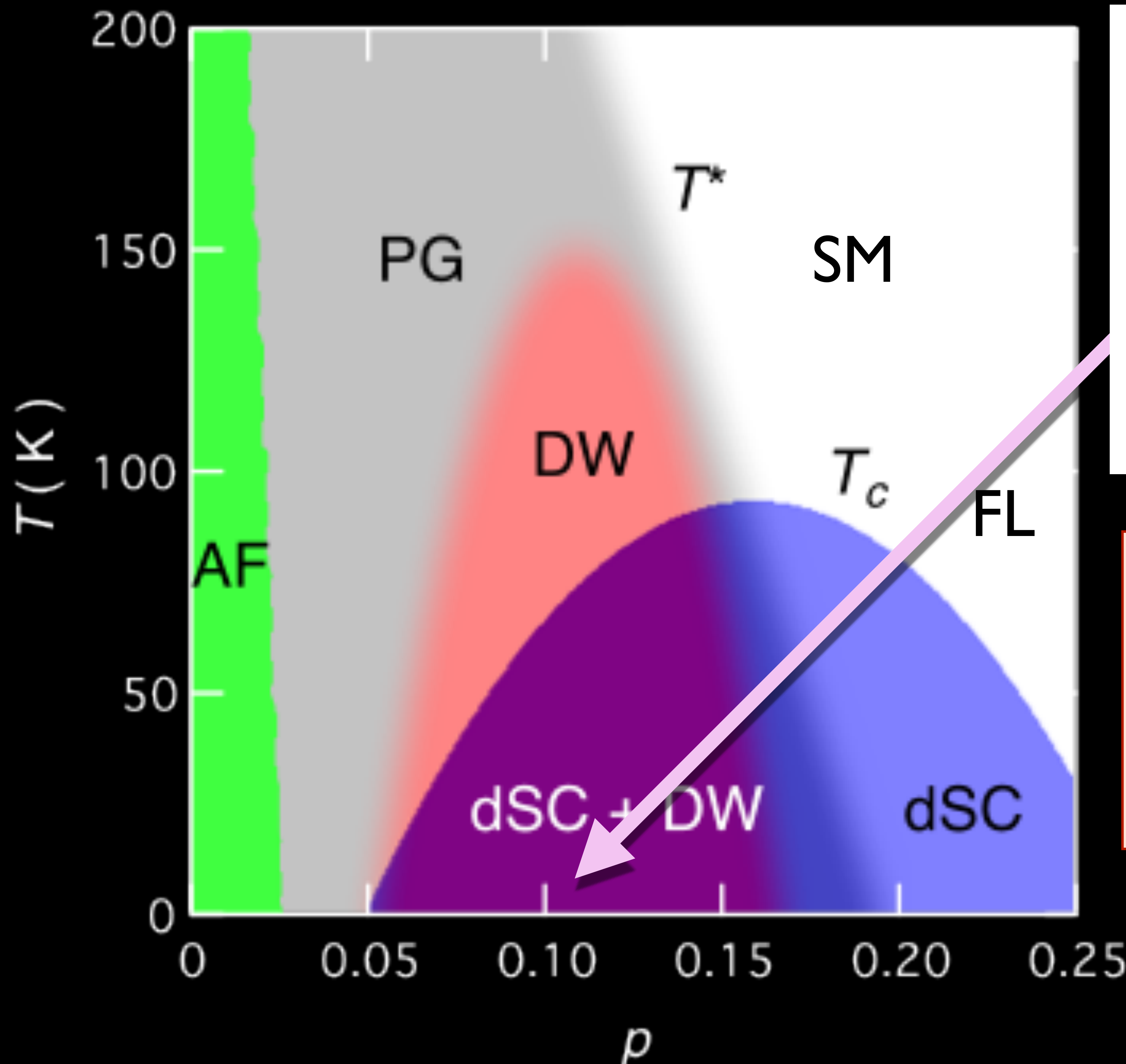
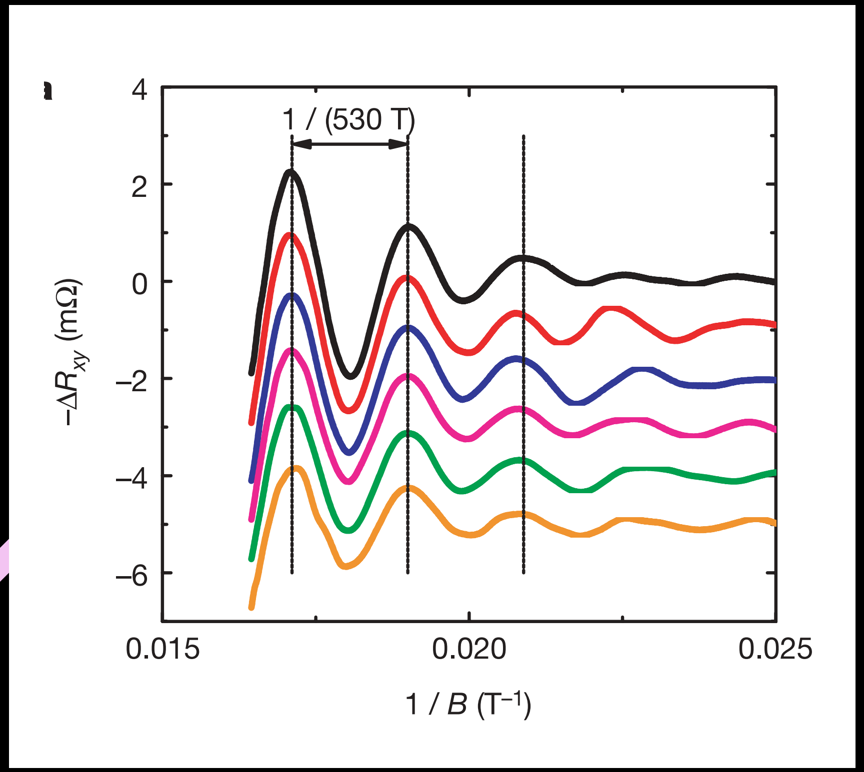
1+p

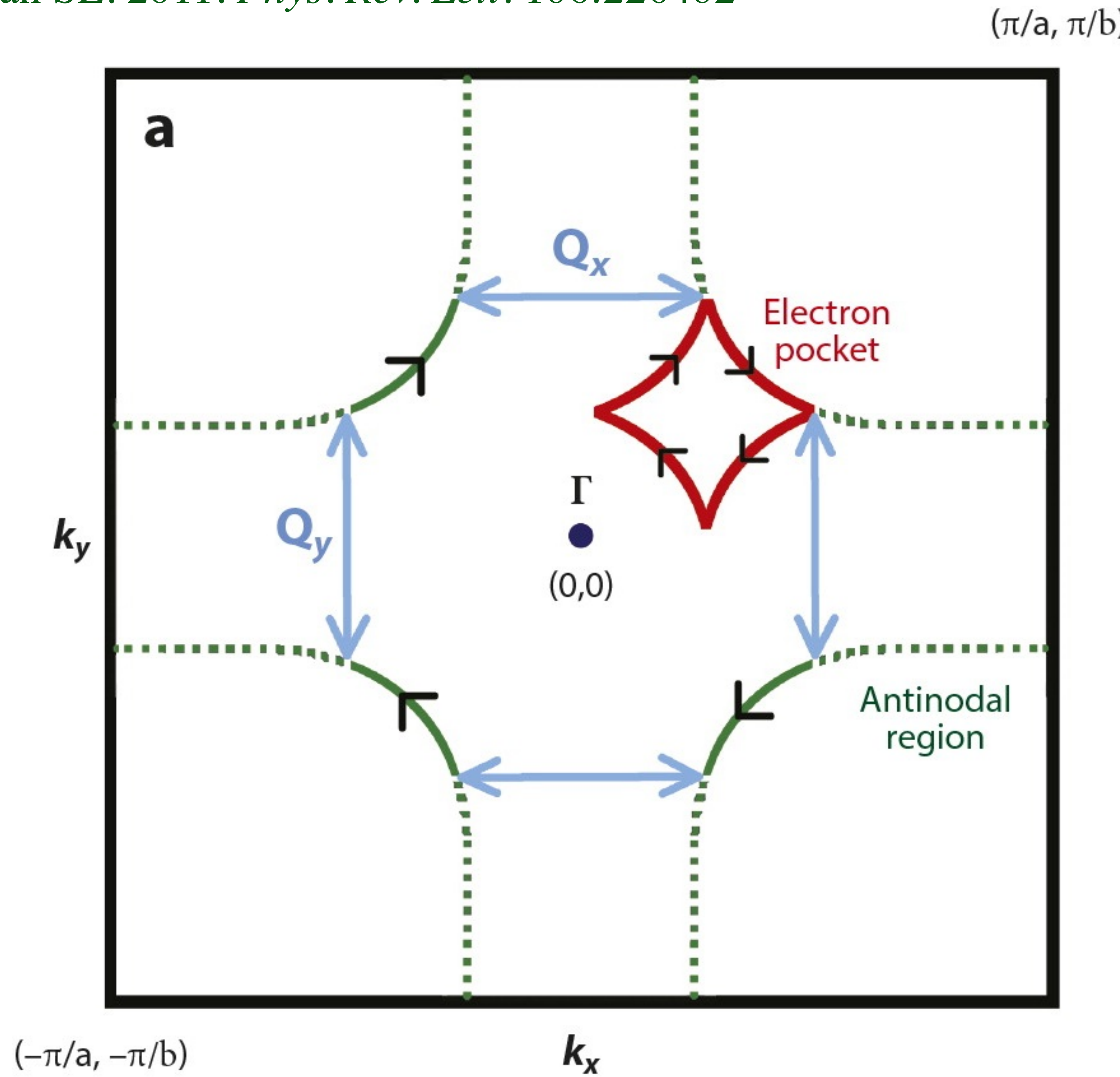
N. Doiron-Leyraud, C. Proust, D. LeBoeuf, J. Levallois, J.B. Bonnemaison, R. Liang, D.A. Bonn, W.N. Hardy, L. Taillefer, Nature **447**, 565 (2007)





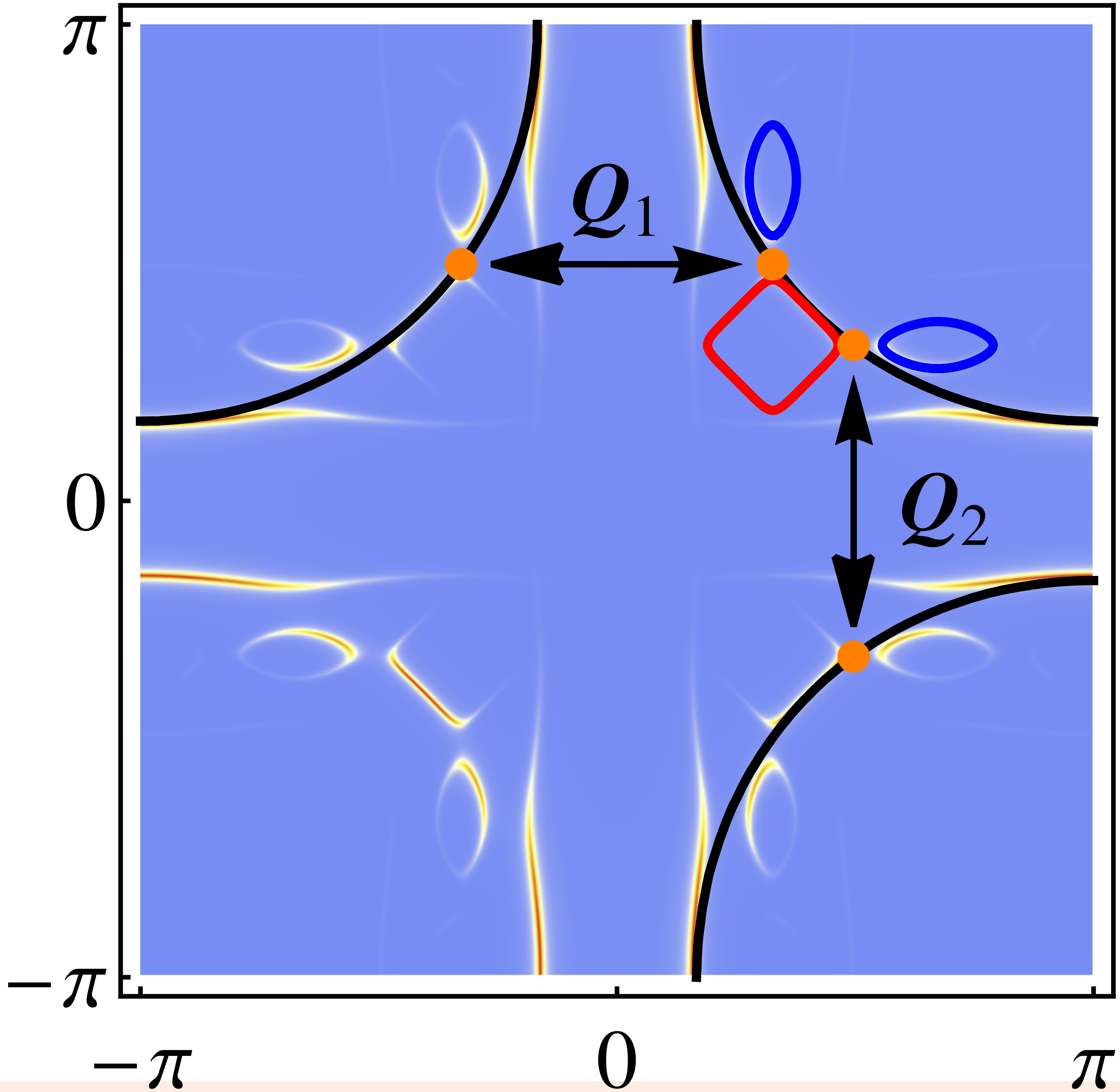
Quantum oscillations of a Fermi surface of size close to p

Harrison N, Sebastian SE. 2011. *Phys. Rev. Lett.* 106:226402



Great deal of evidence that underdoped quantum oscillations are due to an electron pocket which is created by field-induced long-range charge density wave order

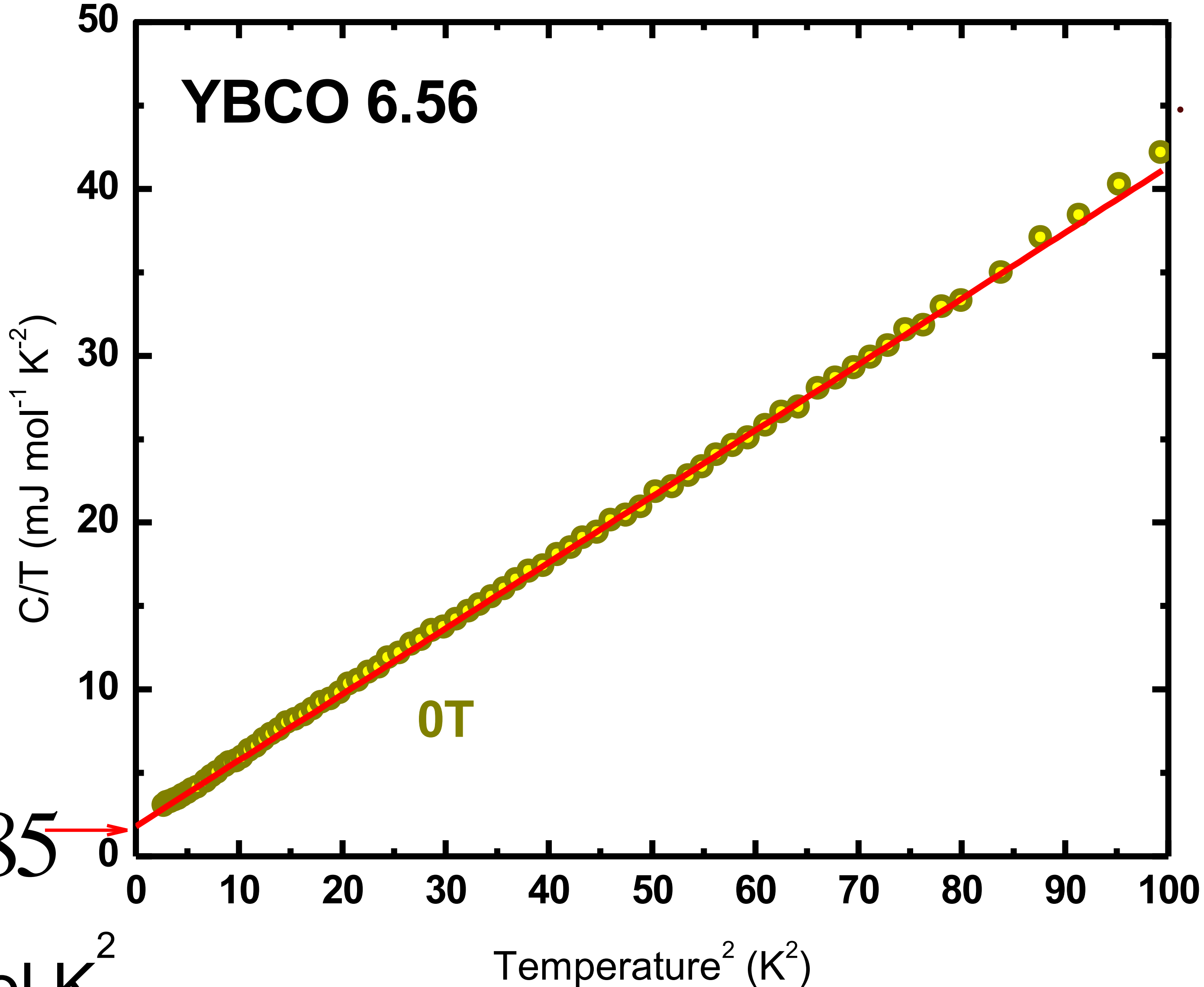
Allais A, Chowdhury D, Sachdev S. 2014. *Nature Commun*. 5:5771



Reconstructing the large Fermi surface by CDW order inevitably leads to many more Fermi surfaces, apart from the electron pocket

Specific heat measurements in field-induced normal state of under doped YBCO

Zero field "gamma"

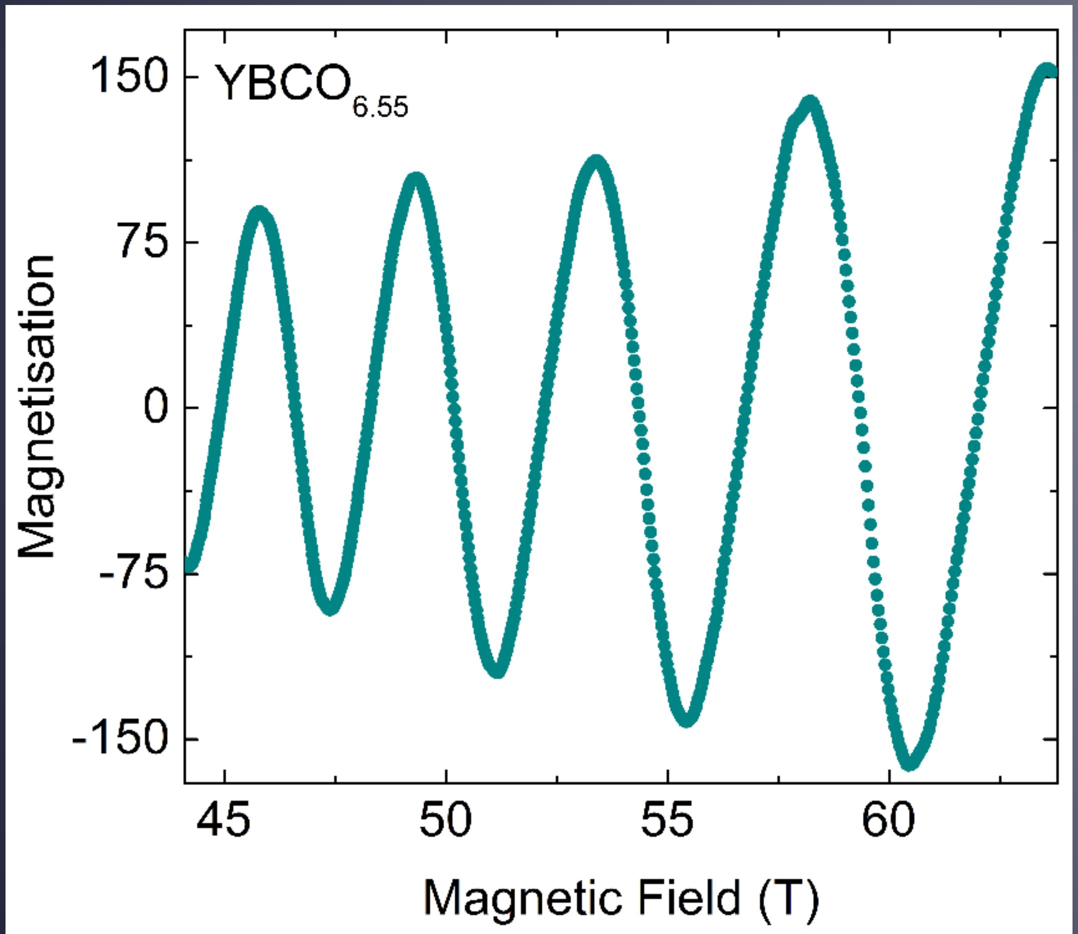


γ=1.85 mJ/mol K^2

. Riggs SC, Vafek O, Kemper JB, Betts JB, Migliori A, Balakirev FF, Hardy WN, Liang R, Bonn DA, Boebinger GS. 2011. *Nature Phys.* 7:332-335

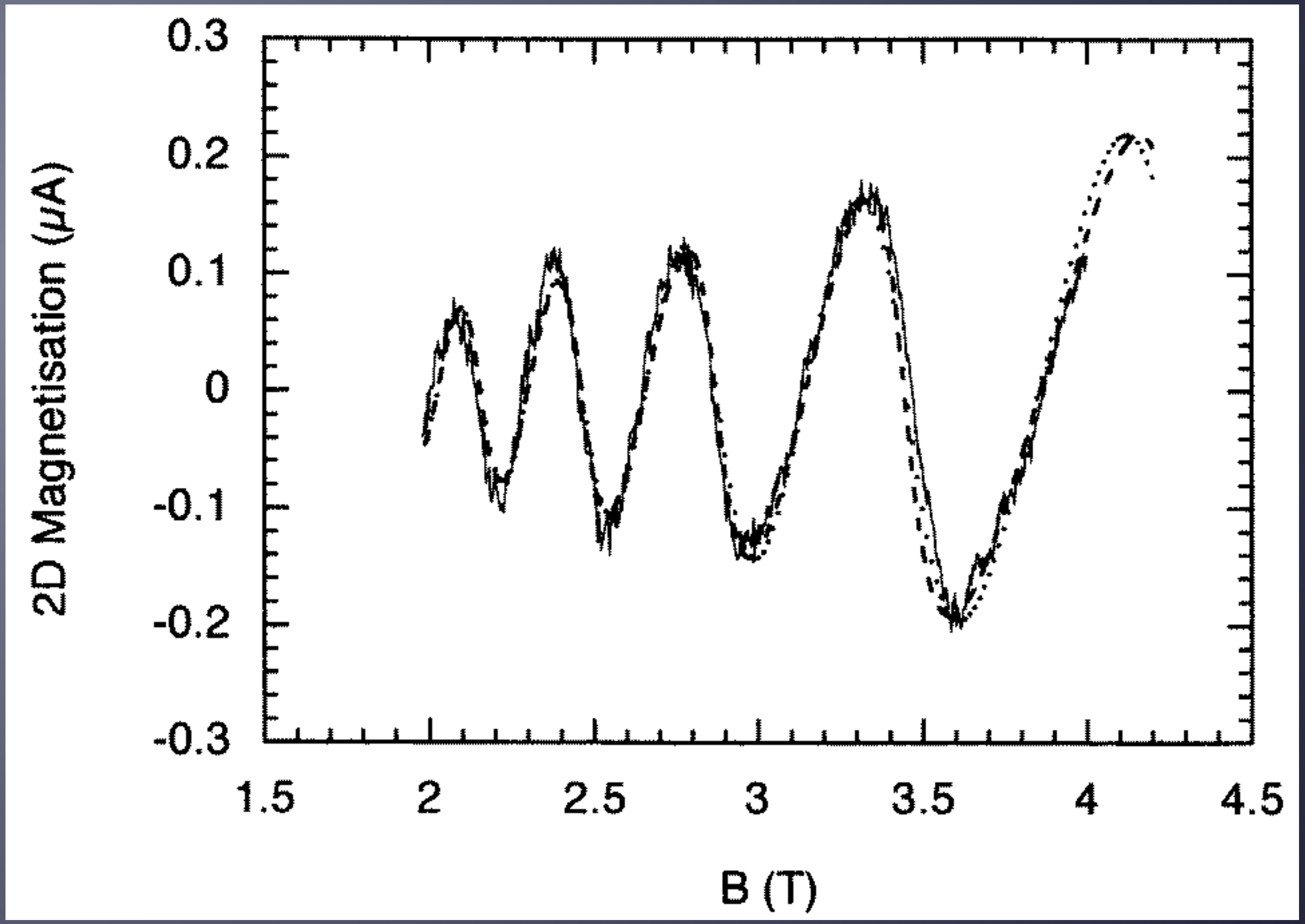
Value is only consistent with a single electron pocket

Sawtooth waveform characteristic of an ideal 2D Fermi gas



Y. –T. Hsu, M. Hartstein, J. Porras, T. Loew *et al.* (unpublished)

2D electrons in GaAs/AlGaAs heterostructures



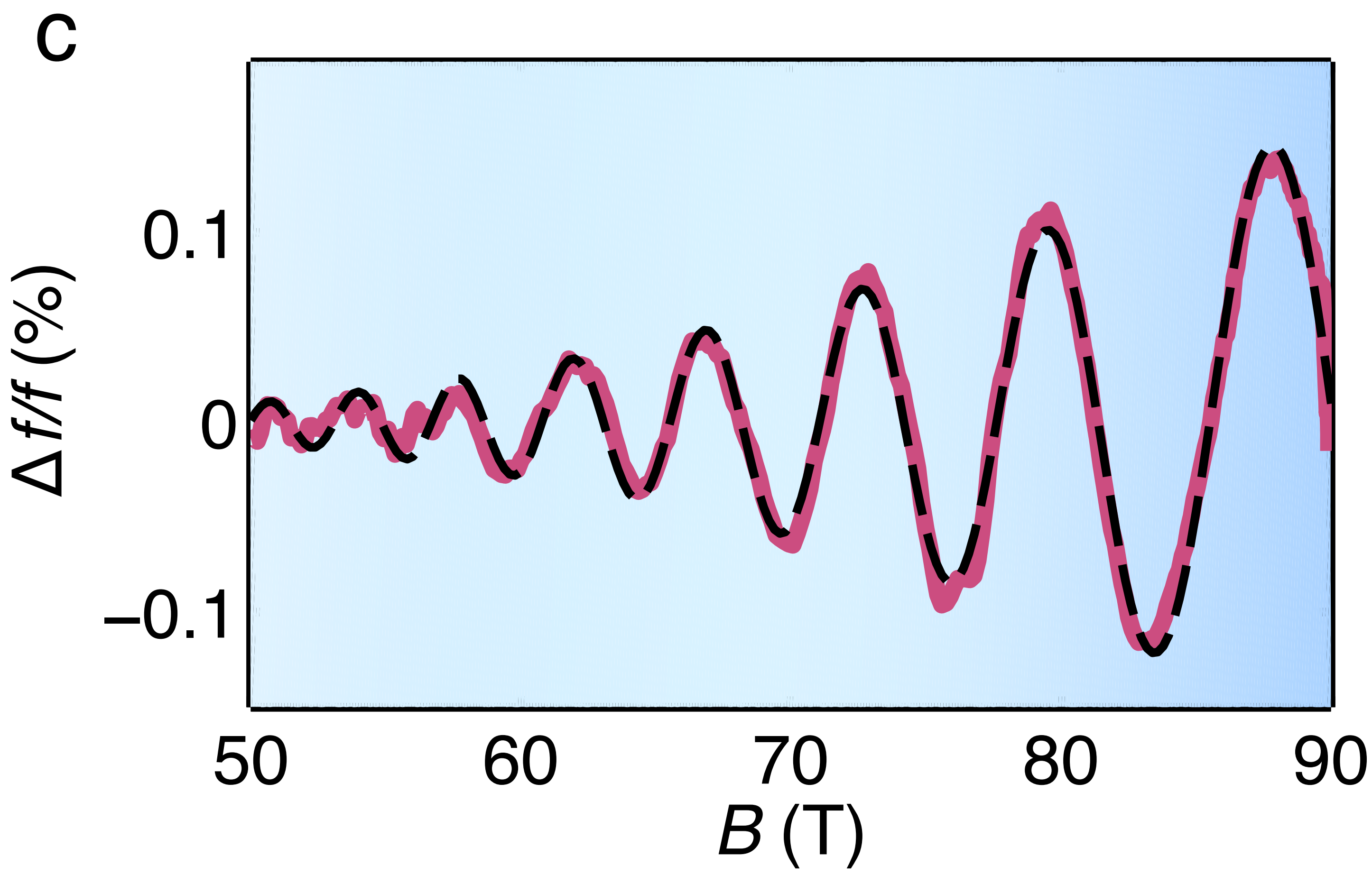
A. Potts et al. J. Phys.: Condens. Matter **8,** 5189–5207 (1996)

Consistent with a single electron pocket

Single reconstructed Fermi surface pocket in an underdoped single layer cuprate superconductor

M. K. Chan,[1,2,*] N. Harrison,[1,*] R. D. McDonald,[1] B. J. Ramshaw,[1] K. A. Modic,[1] N. Barišić,[3,2] and M. Greven[2]

Nature Communications 7, 12244 (2016)



And shape of quantum oscillations also support only a single electron pocket

- The parent “pseudogap metal”, without CDW order, cannot have a large Fermi surface, and should be gapped in the anti-nodal region

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- Such a Fermi surface violates the Luttinger theorem of Fermi-liquid theory

- However, such a Fermi surface can appear in a metal with bulk topological order, which has long-range, many-body quantum entanglement

T. Senthil, M. Vojta and S. Sachdev, PRB **69**, 035111 (2004)
A. Paramekanti and A. Vishwanath, PRB **70**, 245118 (2004).

A simple model:

Fluctuating antiferromagnetism leads to small Fermi surfaces and bulk topological order with long-range quantum entanglement

Begin with 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.

When $\Phi^\ell(i)$ =constant independent of i, we have long-range AFM, and a gap in the fermion spectrum at the anti-nodes.

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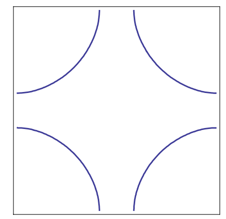

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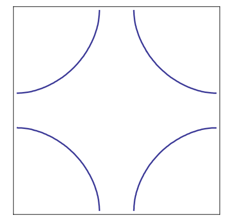

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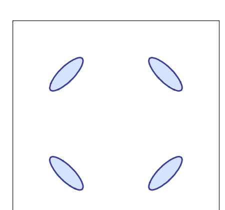

For fluctuating antiferromagnetism, we transform to a rotating reference frame using the SU(2) rotation R_i

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

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.

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.

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

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

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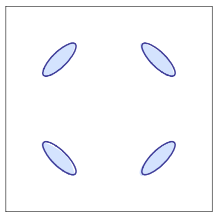
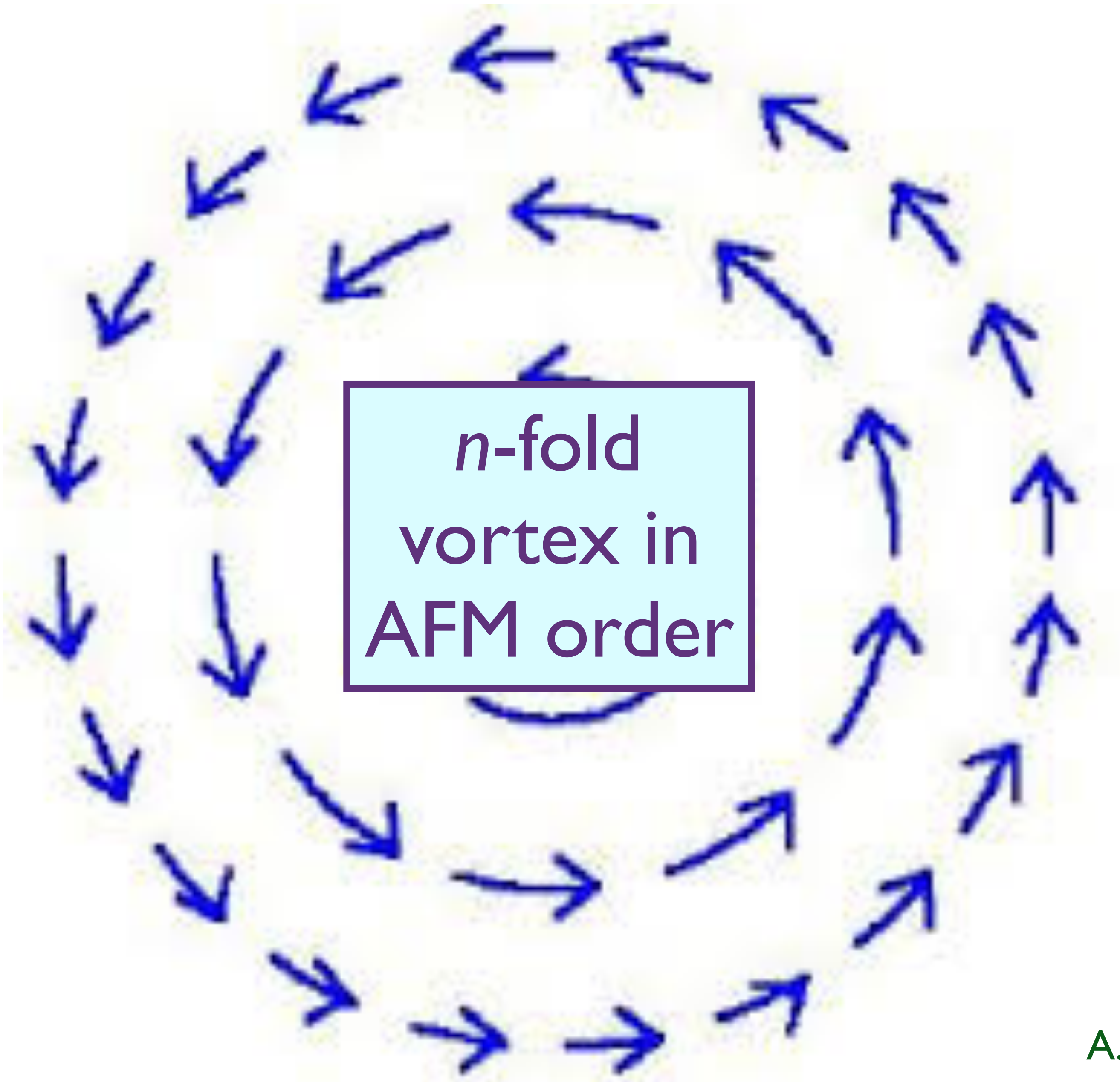
$$\mathcal{H}_{\rm int} = -\lambda \sum_i \eta_i H^a(i) \psi_{i,s}^\dagger \sigma_{ss'}^a \psi_{i,s'} + V_H$$

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 anti-nodal gap 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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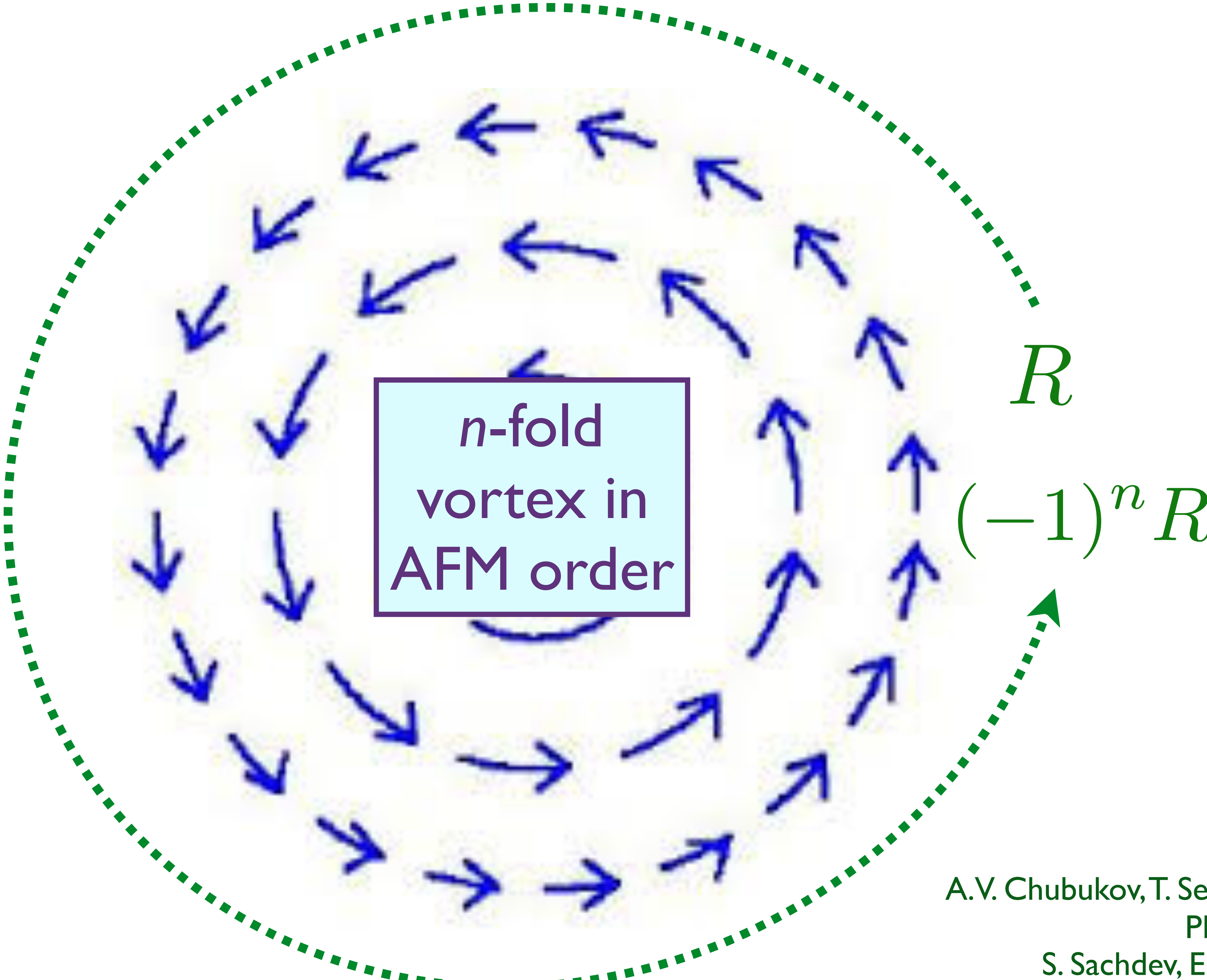

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Topological order

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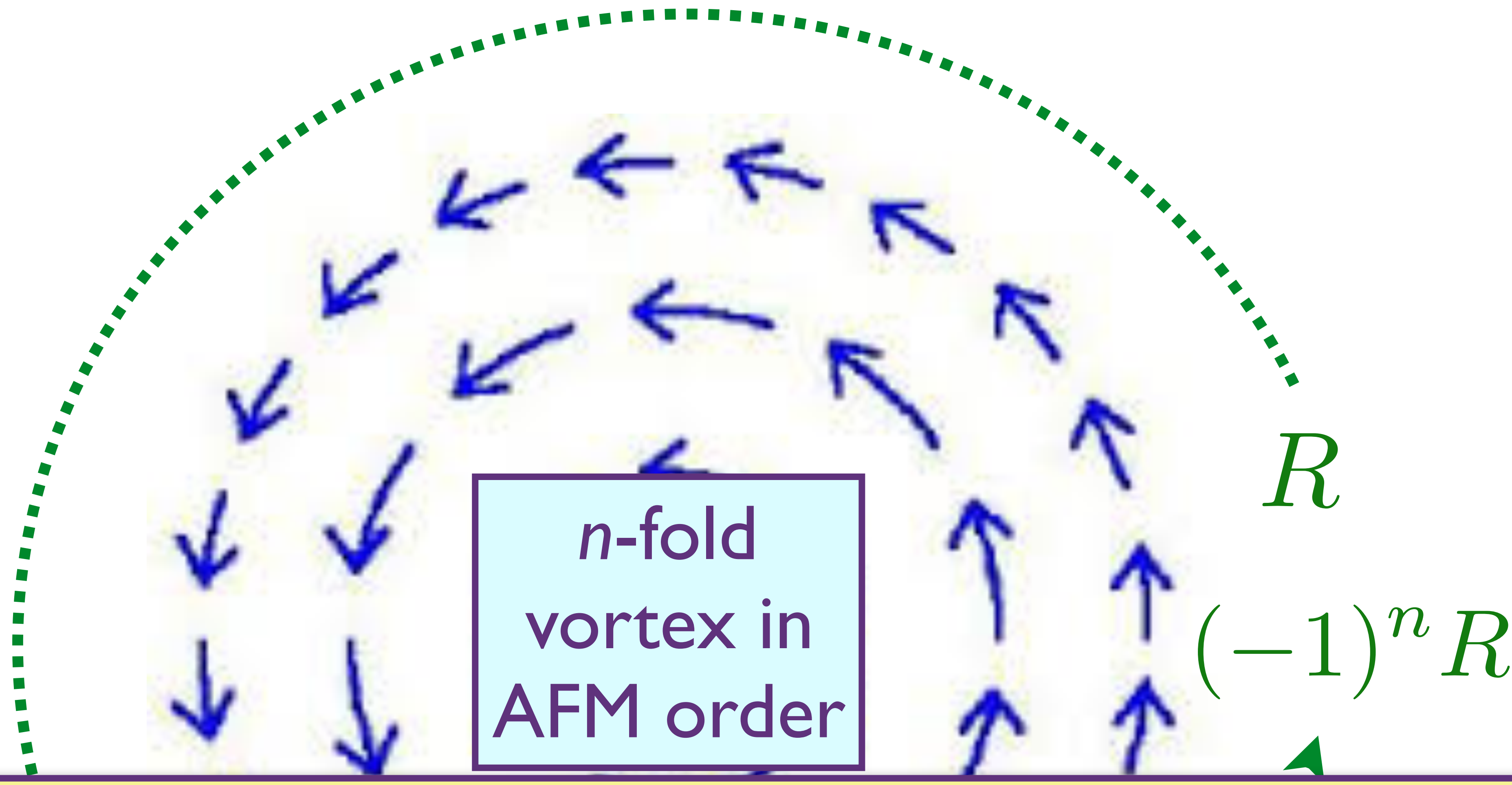
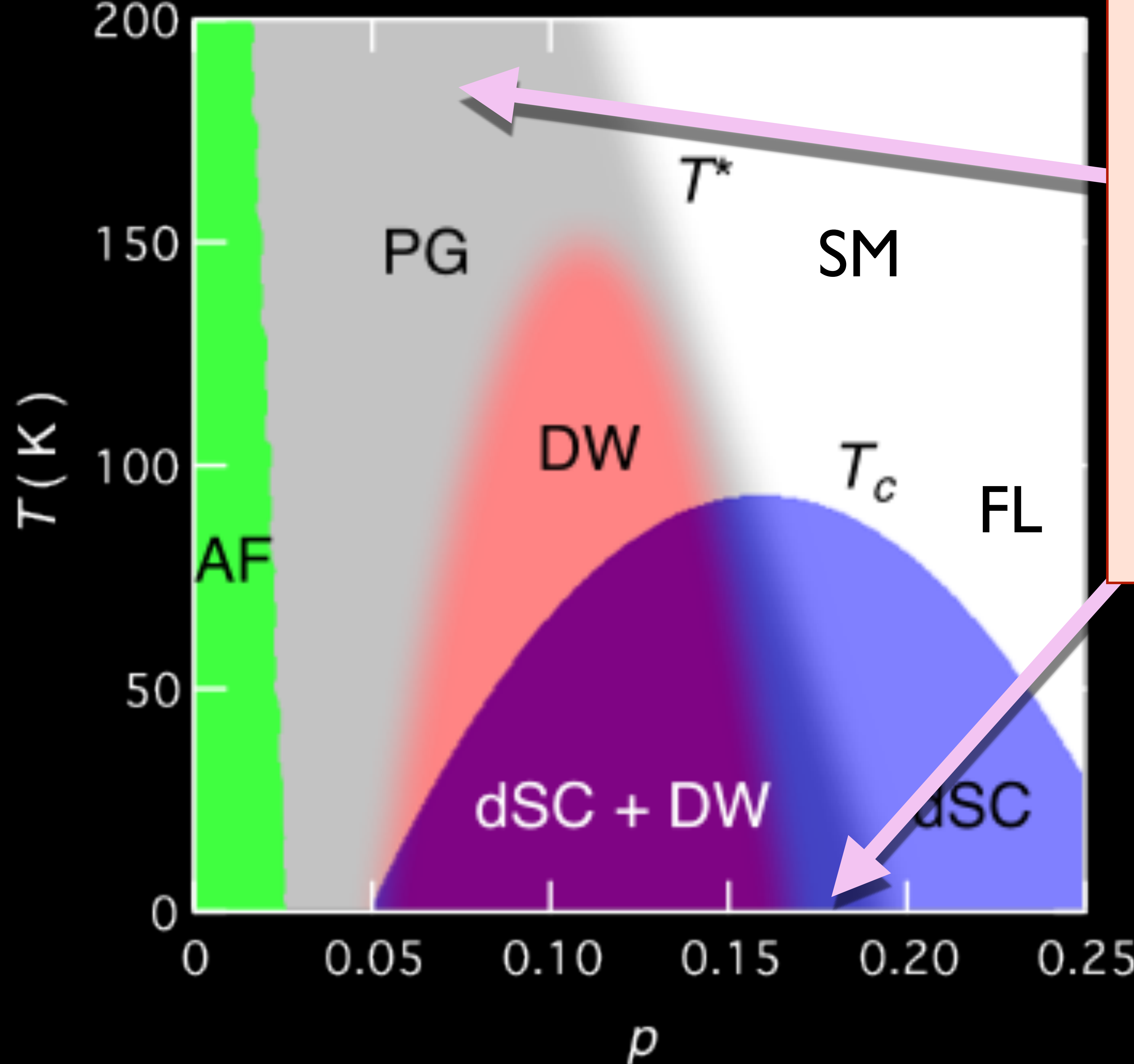
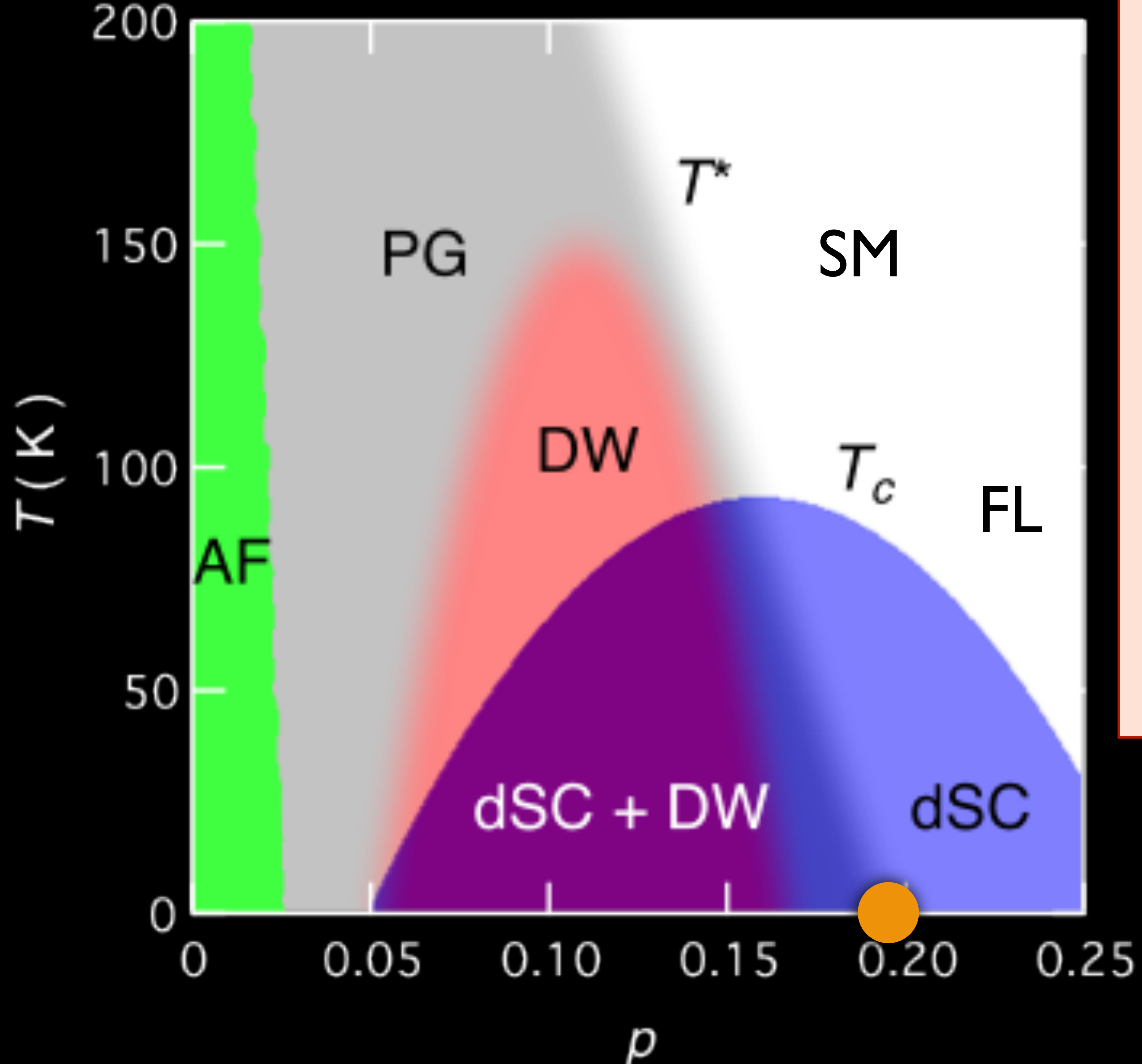


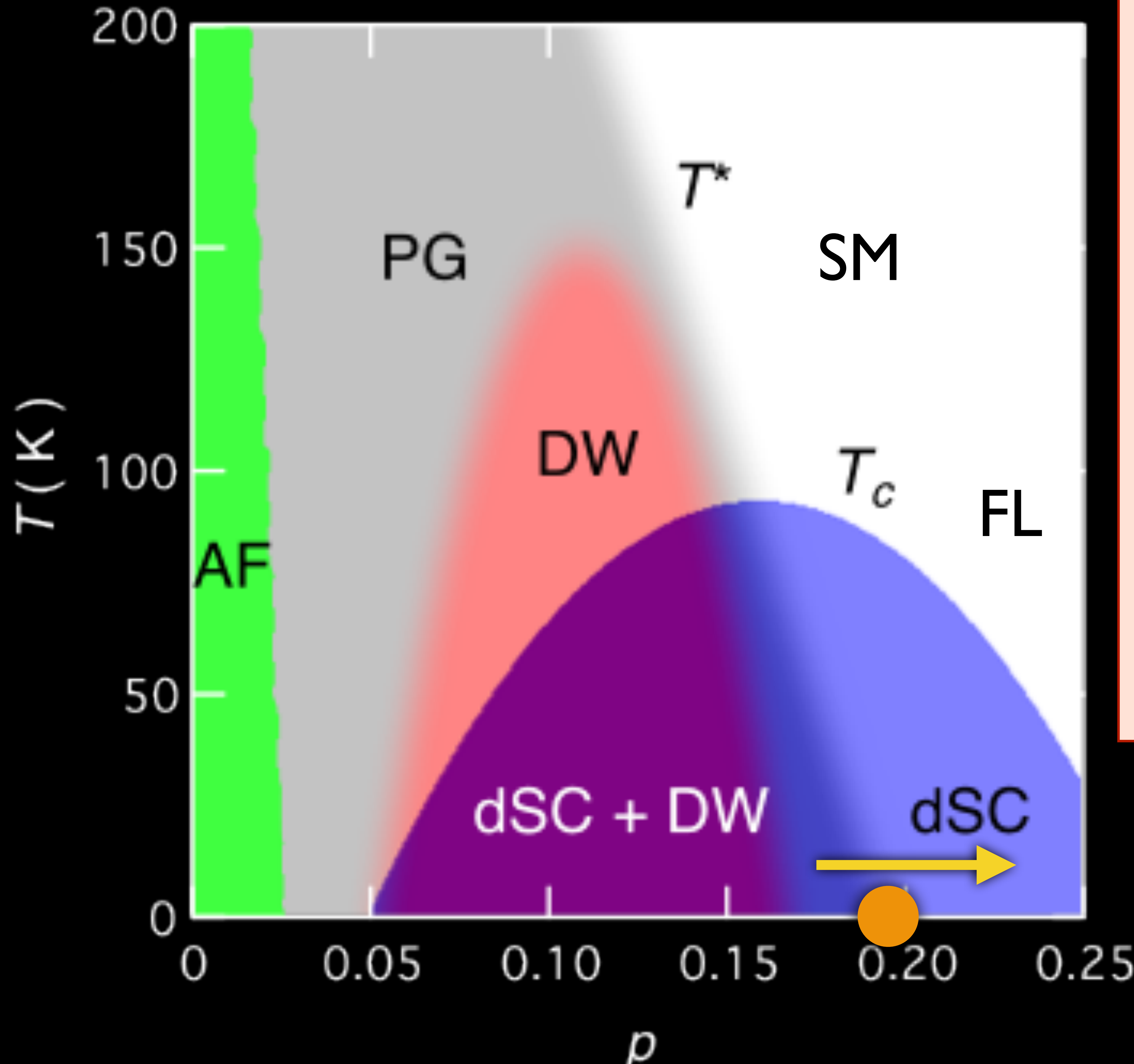
Vortices with n odd must be suppressed: such a metal with "fluctuating antiferromagnetism" has BULK $\mathbb{Z}_2$ TOPOLOGICAL ORDER and fermions which inherit the "pocket" Fermi surfaces of the antiferromagnetic metal *i.e.* a pseudogap. Odd vortices in antiferromagnetism are stable bulk quasiparticles ('visons') which could be observed in STM.



Pseudogap metal with bulk topological order?

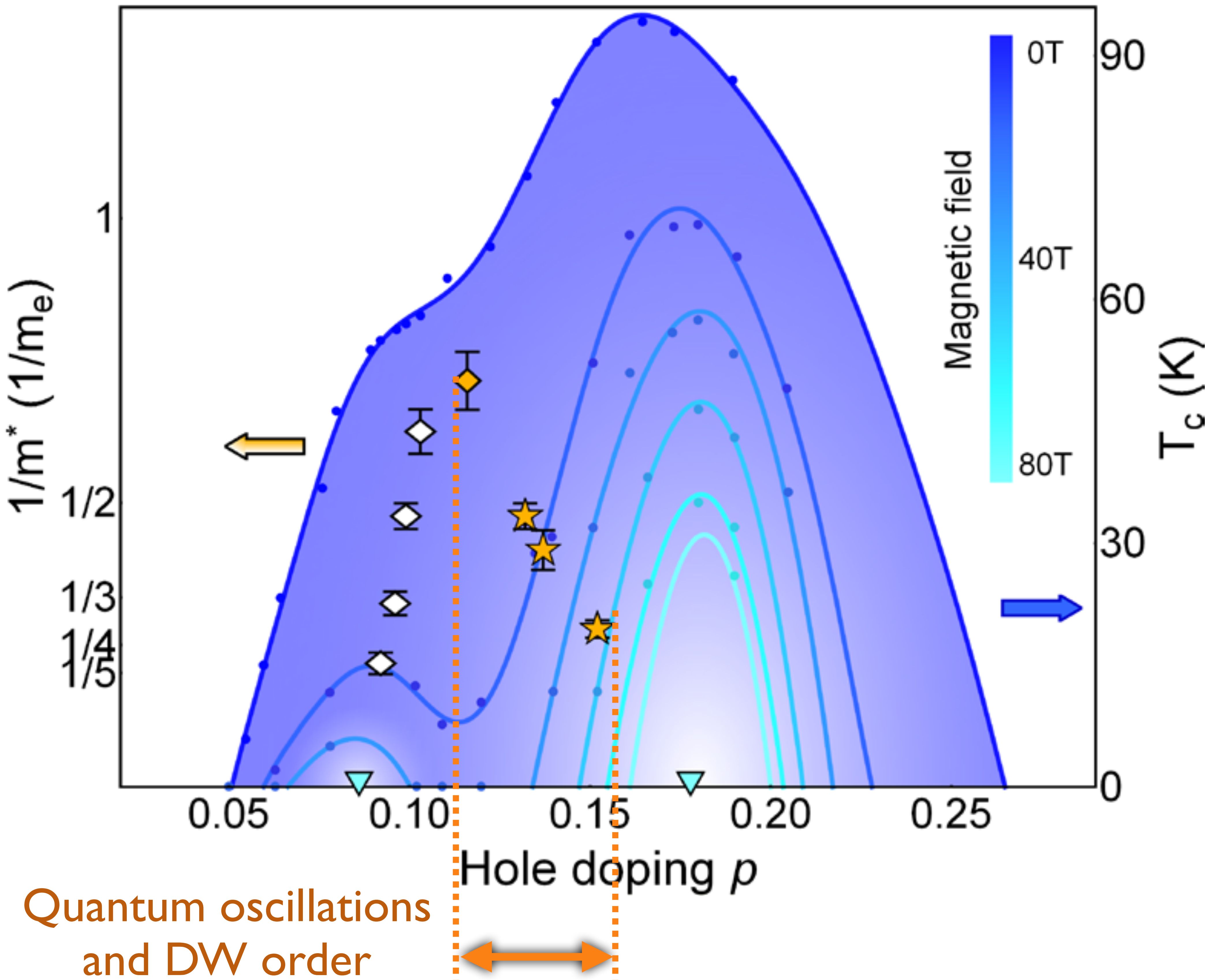


Gauge theory for a topological Higgs-to-confinement phase transition



Gauge theory for a topological Higgs-to-confinement phase transition

Phase diagram in a high magnetic field



B. J. Ramshaw, S. E. Sebastian, R. D. McDonald, James Day, B. S. Tan, Z. Zhu, J. B. Betts, Ruixing Liang, D. A. Bonn, W. N. Hardy, N. Harrison, Science **348**, 6232 (2105).

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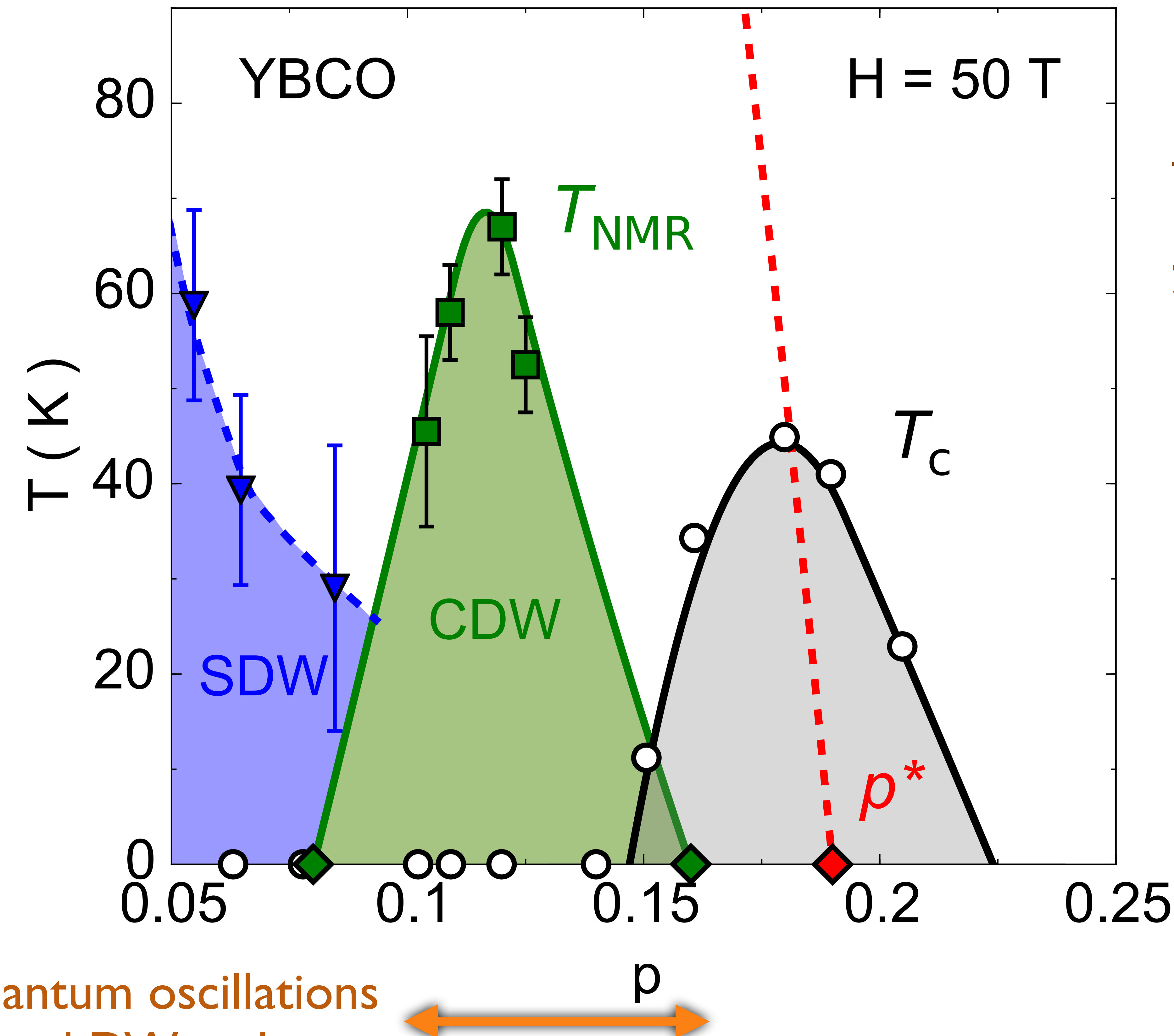
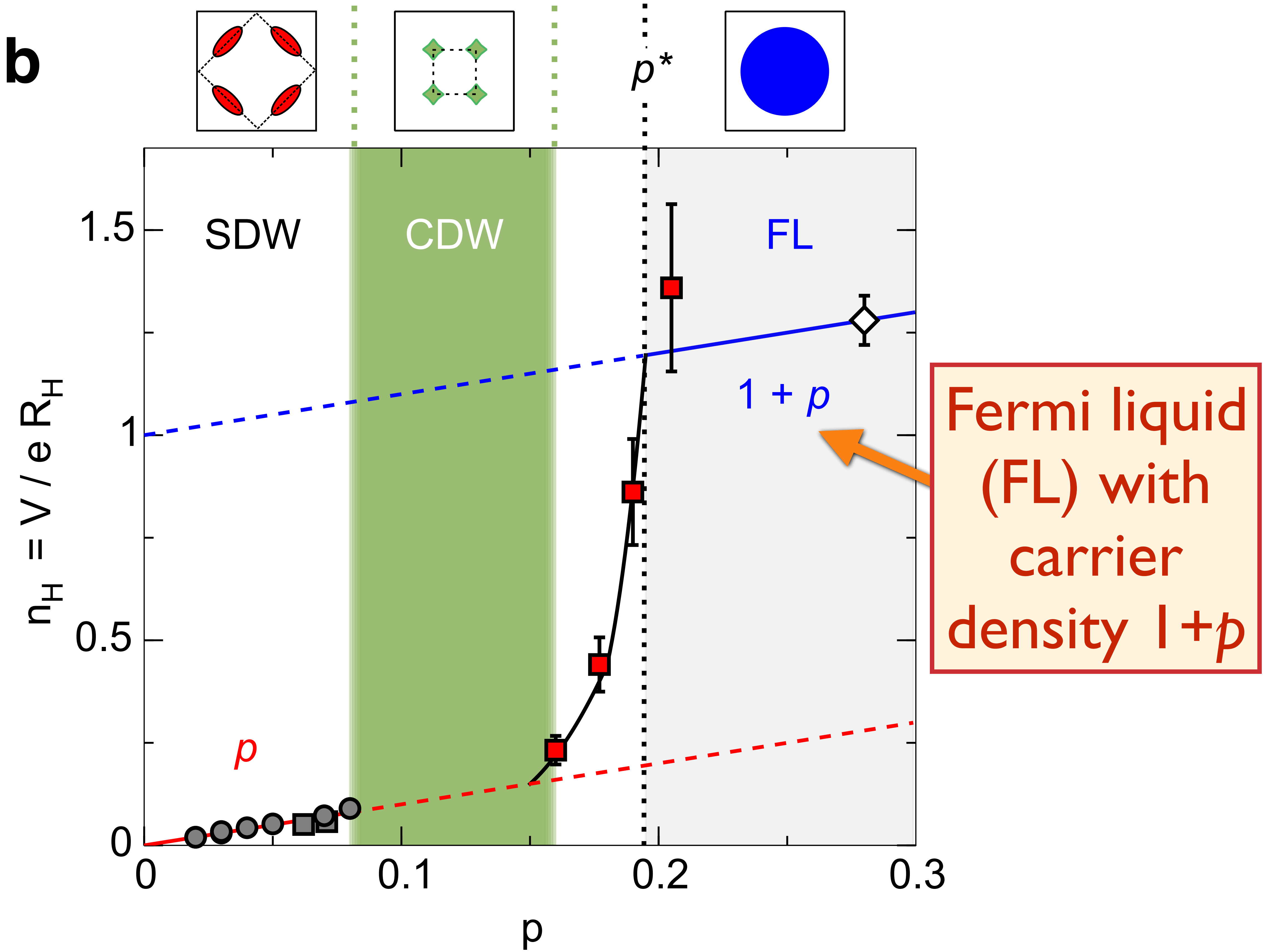


Badoux, Proust, Taillefer et al., Nature **531**, 210 (2016)

Quantum oscillations and DW order

Hall effect measurements in YBCO



Badoux, Proust, Taillefer et al., Nature **531**, 210 (2016)

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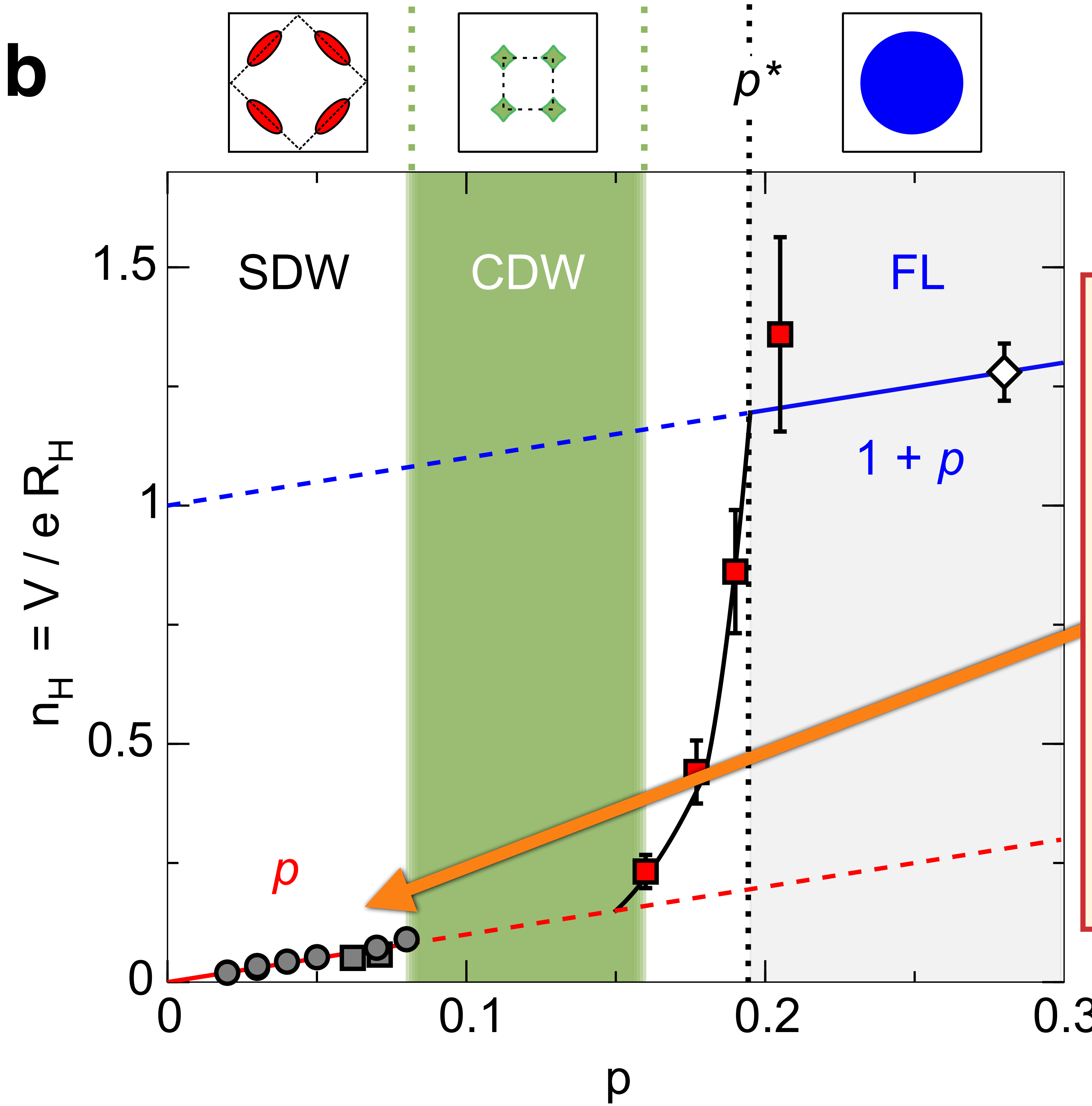
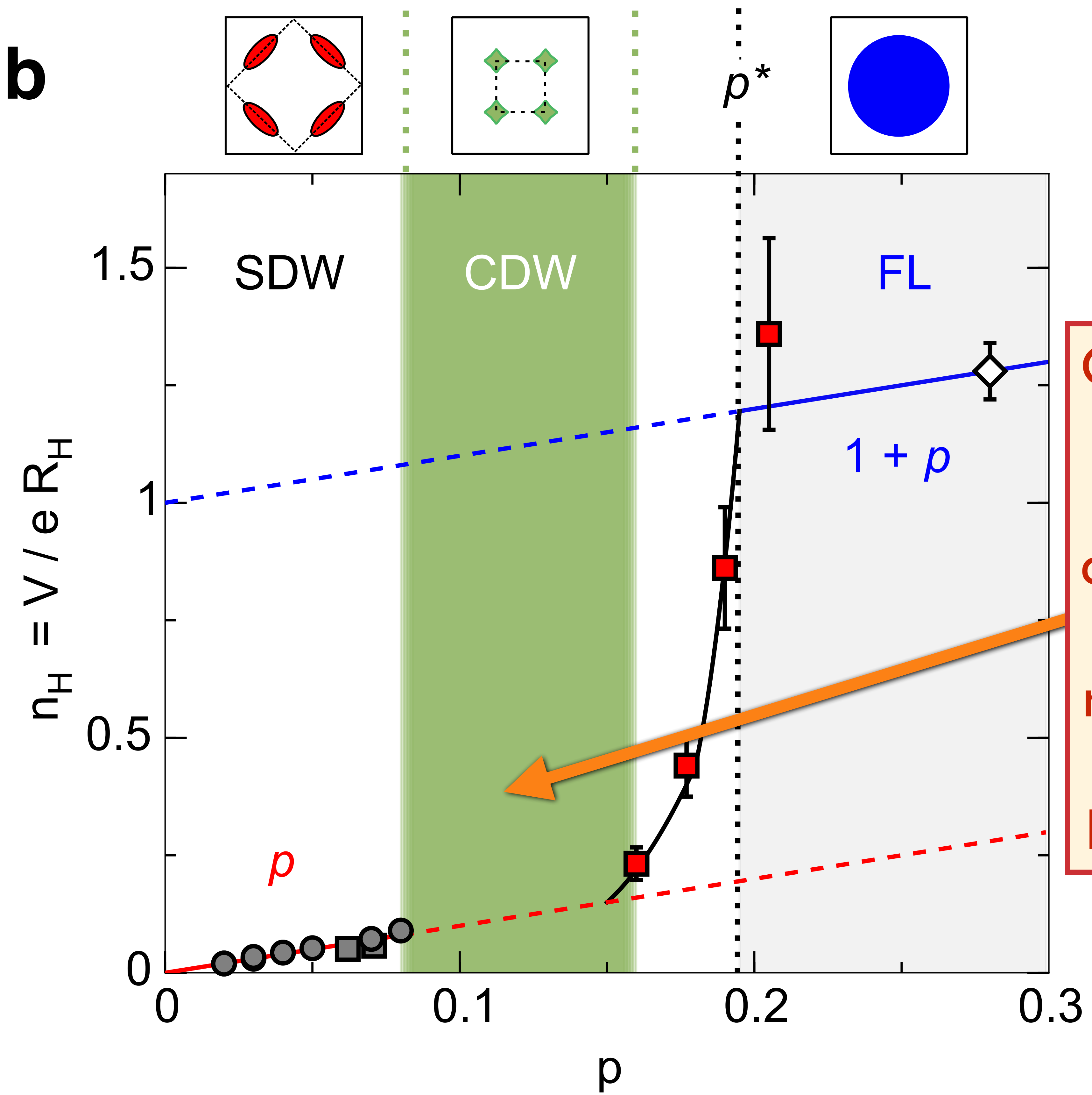


Spin density wave (SDW) breaks translational invariance, and the Fermi liquid then has carrier density *p*

Badoux, Proust, Taillefer et al., Nature **531**, 210 (2016)

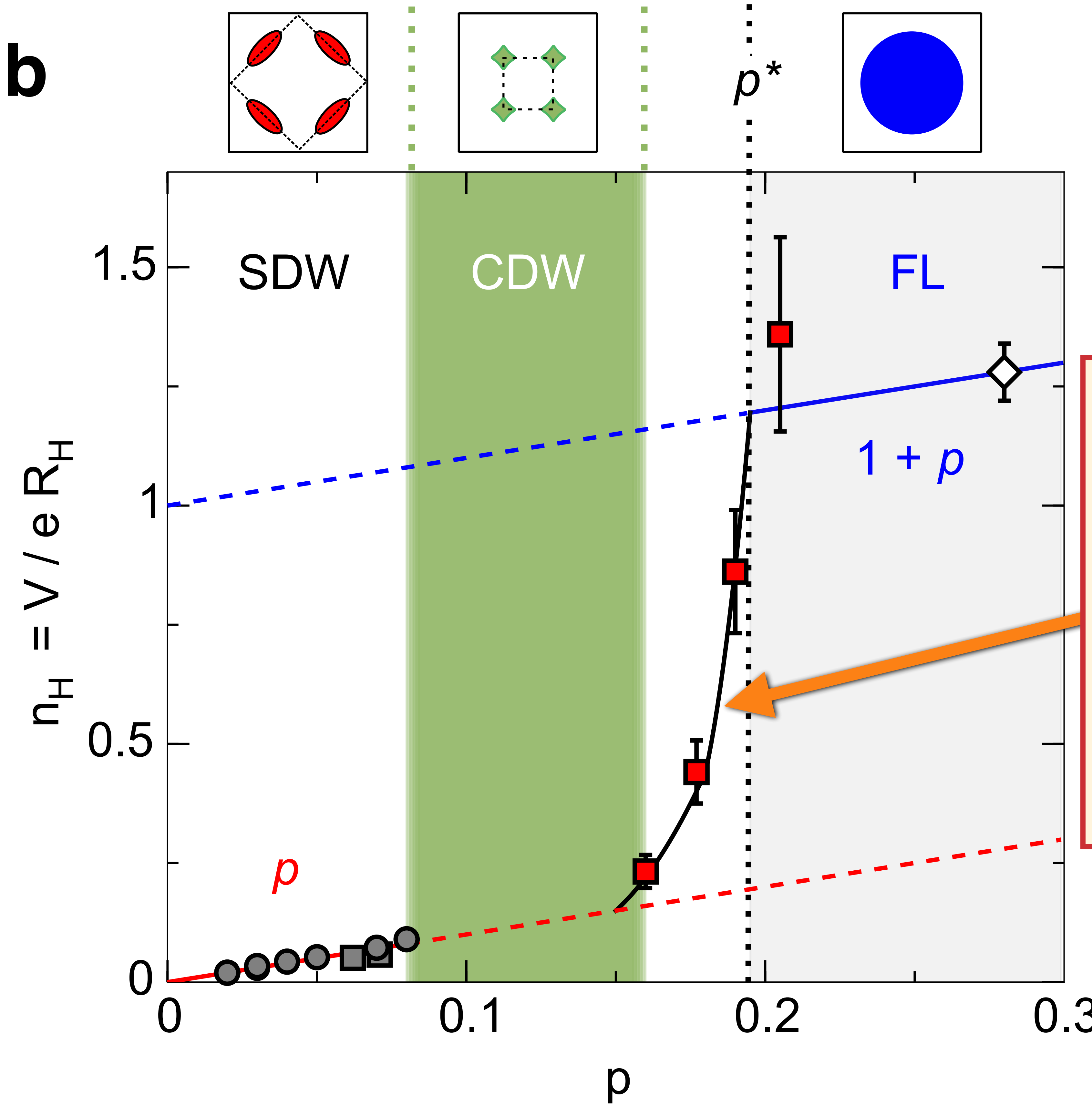
Hall effect measurements in YBCO



Charge density wave (CDW) leads to complex Fermi surface reconstruction and negative Hall resistance

Badoux, Proust, Taillefer et al., Nature **531**, 210 (2016)

Hall effect measurements in YBCO



Rapid increase in carrier density due to a quantum phase transition at *p=0.19 ?*

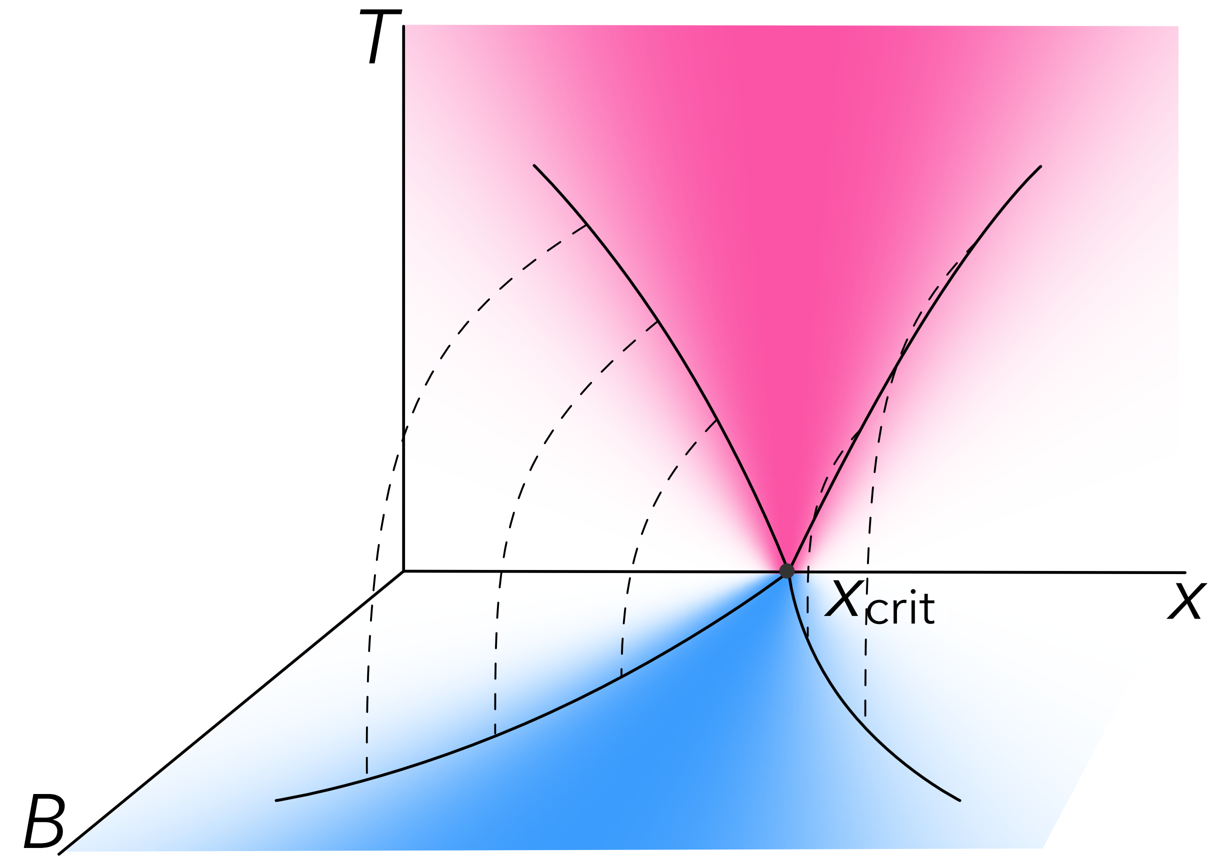
Badoux, Proust, Taillefer et al., Nature **531**, 210 (2016)

Scale-invariant magnetoresistance in a cuprate superconductor

P. Giraldo-Gallo,[1] J. A. Galvis,[1] Z. Stegen,[1] K. A. Modic,[2] F. F Balakirev,[3] J. B. Betts,[3] X. Lian,[1] C. Moir,[1] S. C. Riggs,[1] J. Wu,[4] A. T. Bollinger,[4] X. He,[4,5] I. Božović,[4,5] B. J. Ramshaw,[6,3] R. D. McDonald,[3] G. S. Boebinger,[1,7] and A. Shekhter[1,*]

Here we report a high-field magnetoresistance study of thin films of $La_{2-x}Sr_xCuO_4$ cuprates in close vicinity to critical doping, $0.161 \leq x \leq 0.190$. We find that the metallic state exposed by suppressing superconductivity is characterized by a magnetoresistance that is linear in magnetic field up to the highest measured fields of 80T. The slope of the linear-in-field resistivity is temperature-independent at very high fields. It mirrors the magnitude and doping evolution of the linear-in-temperature resistivity that has been ascribed to Planckian dissipation near a quantum critical point.

arXiv:1705.05806



- High field studies of cuprates have been crucial to unraveling their phase diagram
- Plethora of evidence for an exotic metal underlying the underdoped regime
- A metal with bulk topological order (*i*.e. long-range quantum entanglement) can explain existing experiments

- Novel quantum criticality likely associated with a deconfined-confined transition in a gauge theory
- Higher field studies, with more experimental probes (STM…), promise to answer many open questions, and could lead to direct detection of topological order.
- An understanding of these issues is crucial to understanding the origin of the high critical temperature for superconductivity