Thermoelectrical response beyond the quantum limit of 3D electron gas systems

Benoît Fauqué['4K']

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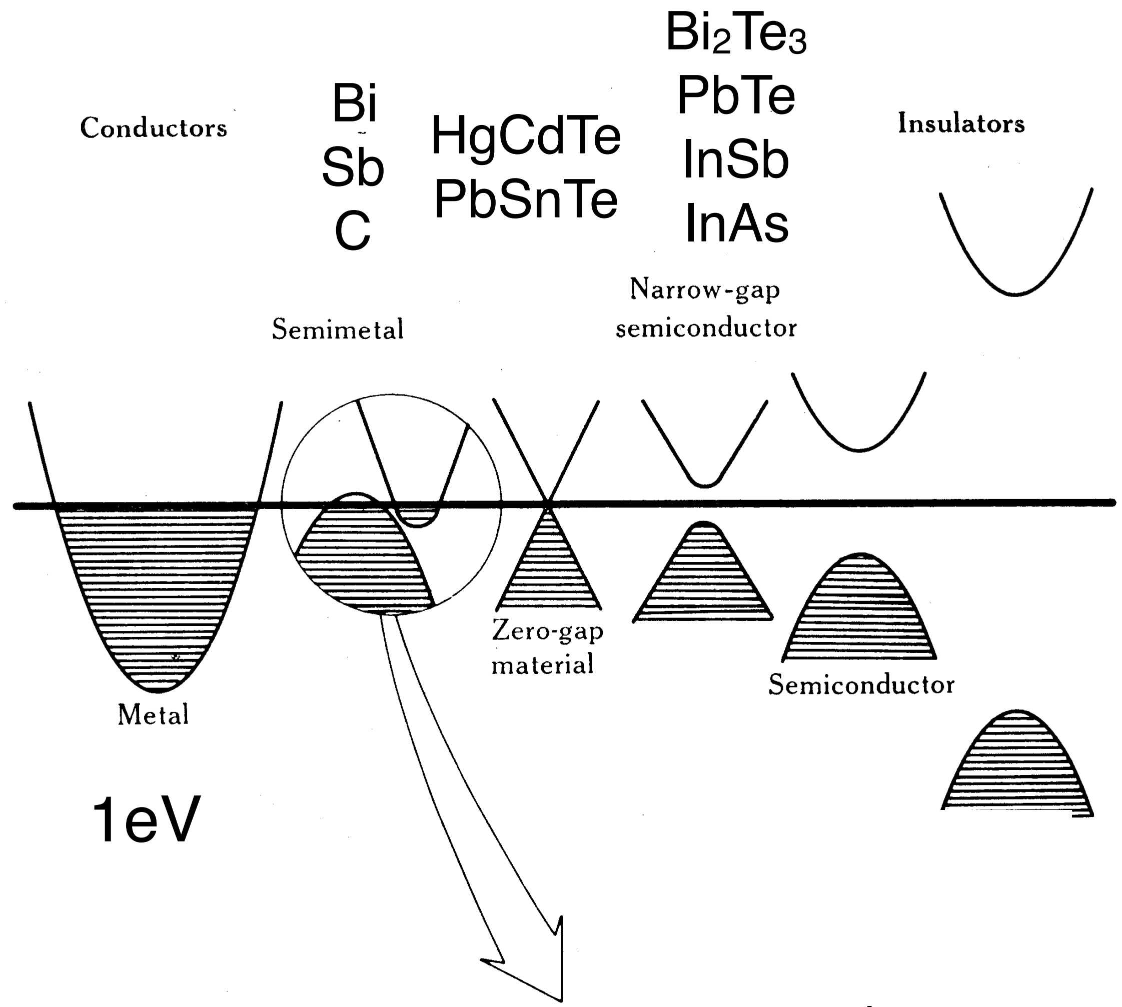
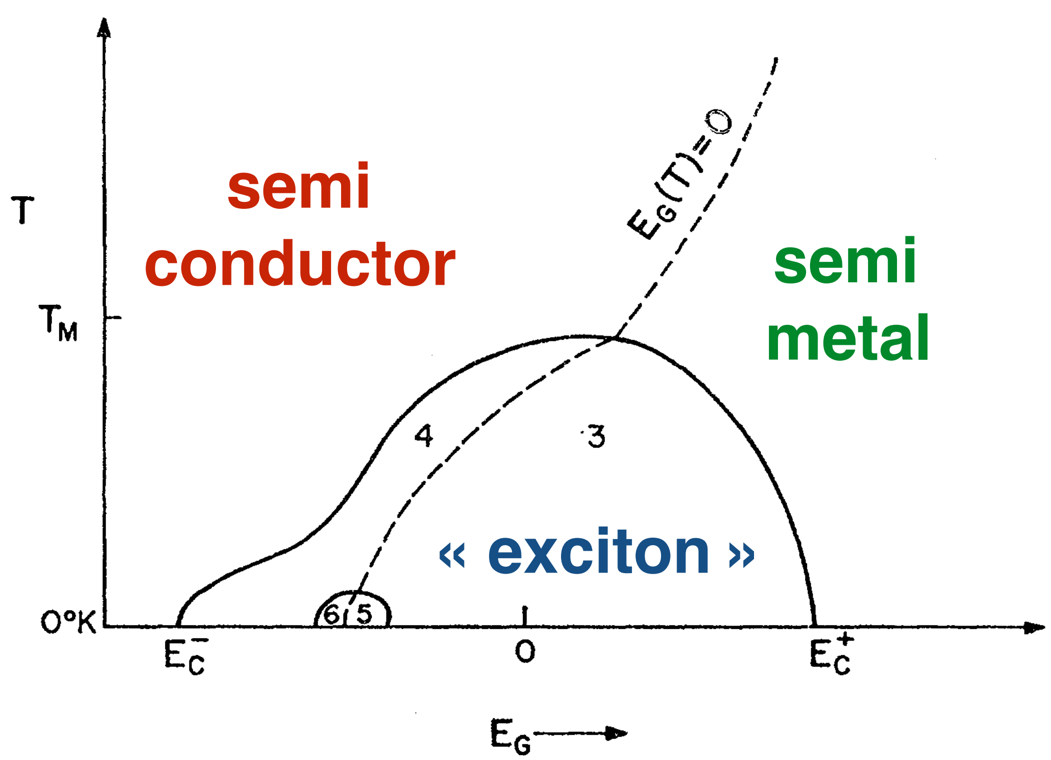
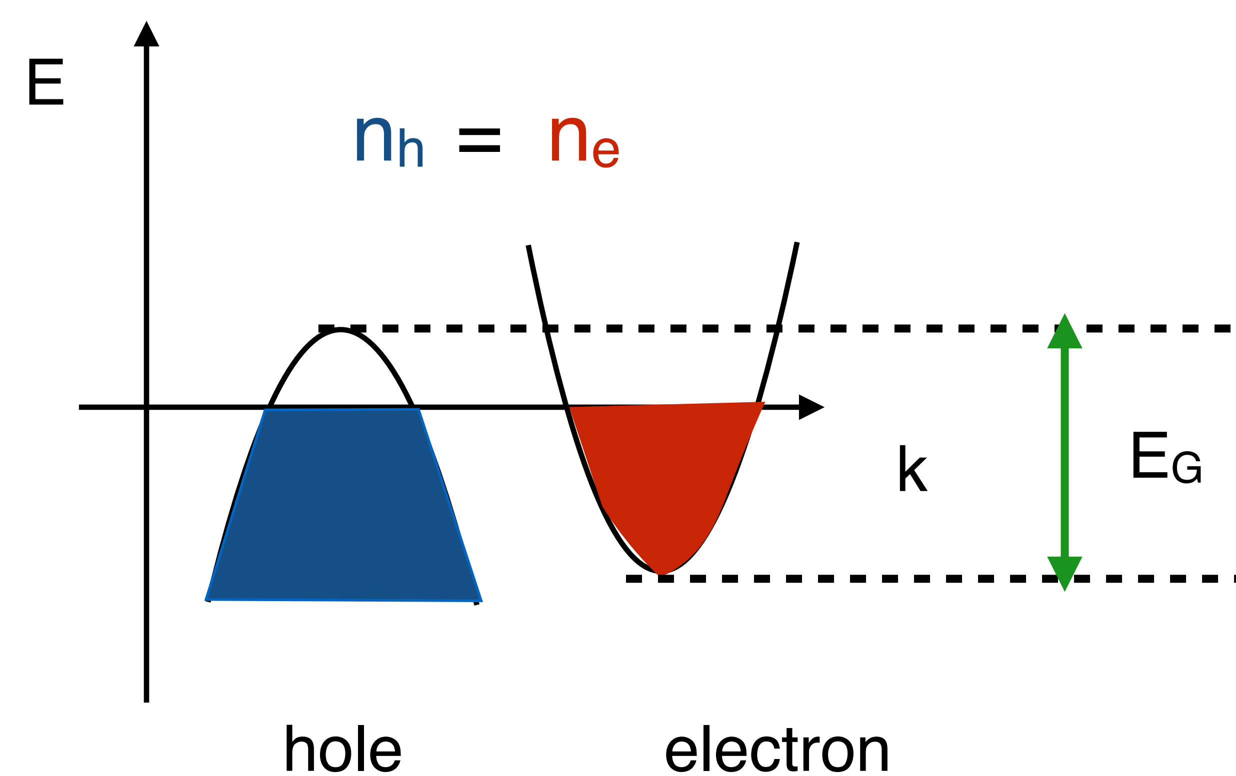
Introduction : dilute metals



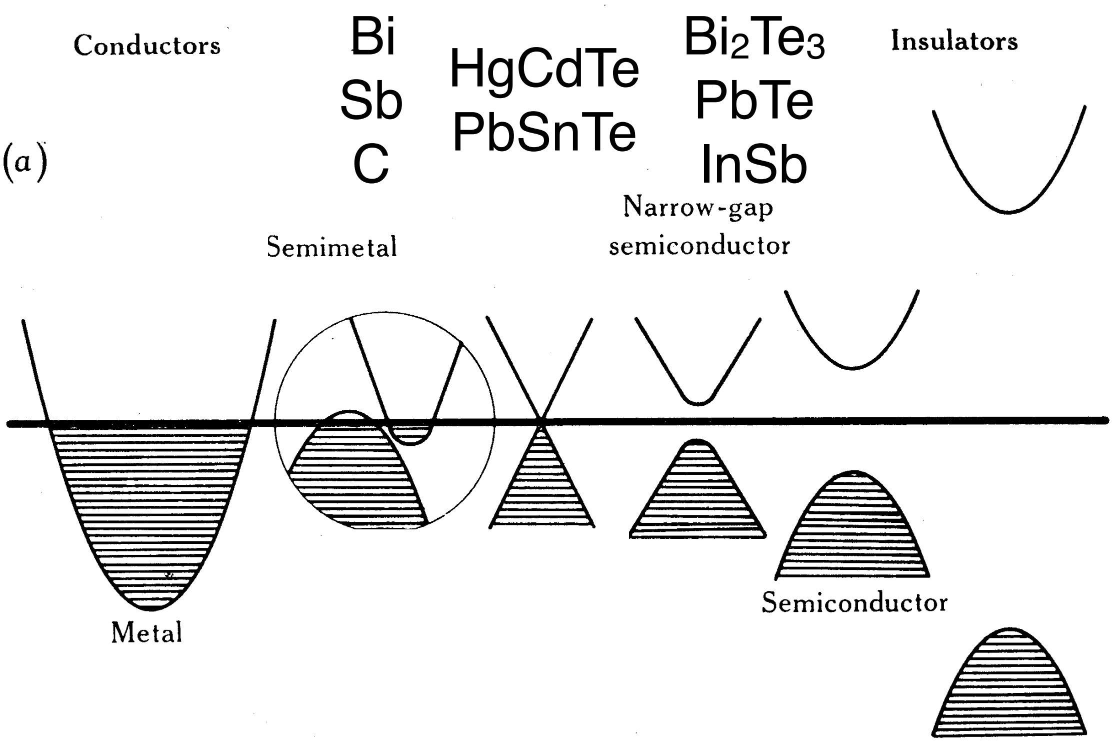


Dilute metals:
low carrier conductors
($n=1e18cm^{-3}$ => small $E_F \simeq 10meV$)
+
well defined Fermi Surface resolved by QO

Enhancement of the effect of the interaction:
$E_F \sim E_C$
N.F Mott, Phil. Mag **6**, 287, (1961)
BCS like instability when n->0 :
electrons-holes form bound pairs -
« an excitonic insulator »



Introduction : dilute metals

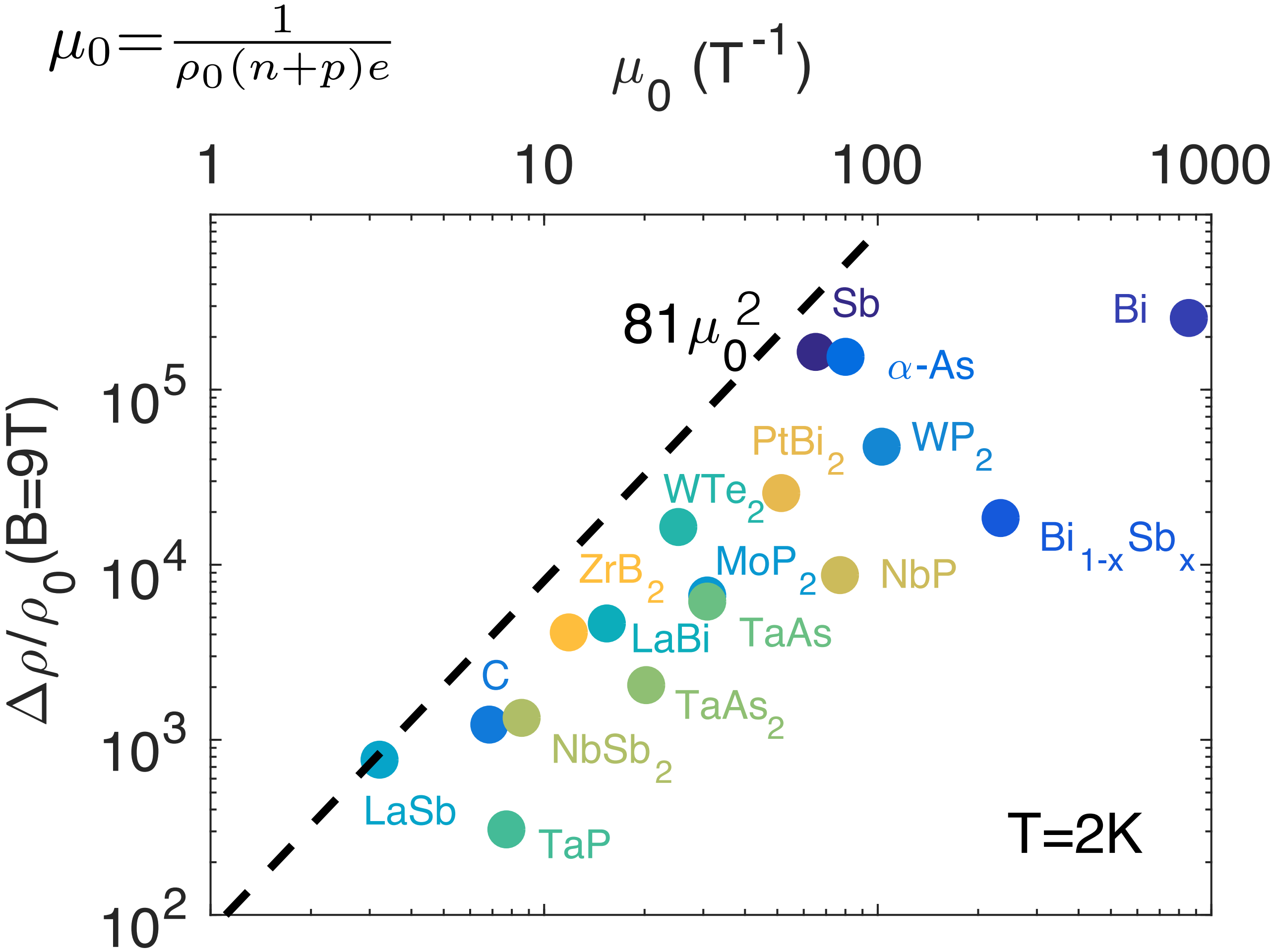


Dilute metals:
low carrier conductors
($n=1e18cm^{-3}$ => small E_F)
+
well defined Fermi Surface resolved by QO

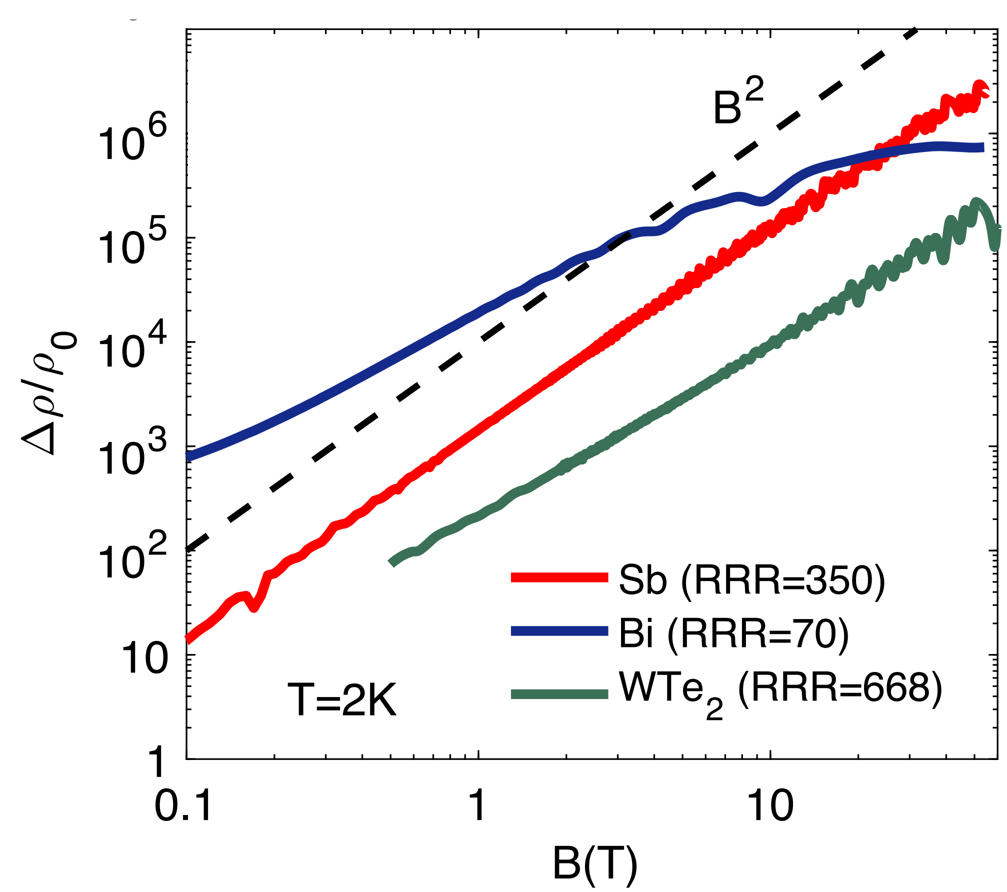
Dirac like dispersion in 3D :
3D « Dirac » dispersion Na_3Bi, Cd_3As_2
Type-II Weyl semi-metals WTe_2, WP_2 ...

$$\mu_0 = \frac{1}{\rho_0 (n+p) e}$$

Perfect semi-metal : $\Delta\rho/\rho_0 = \mu_0 B^2$



B. Fauqué and al., PRM (2018)



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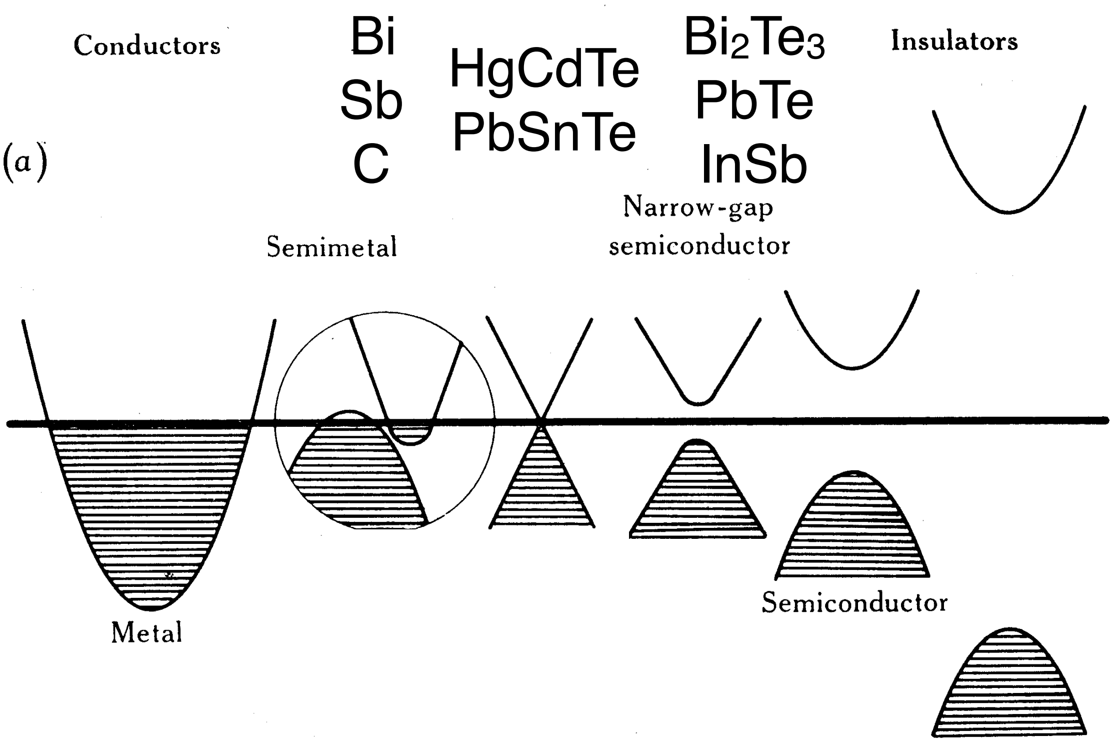

Dilute metals:
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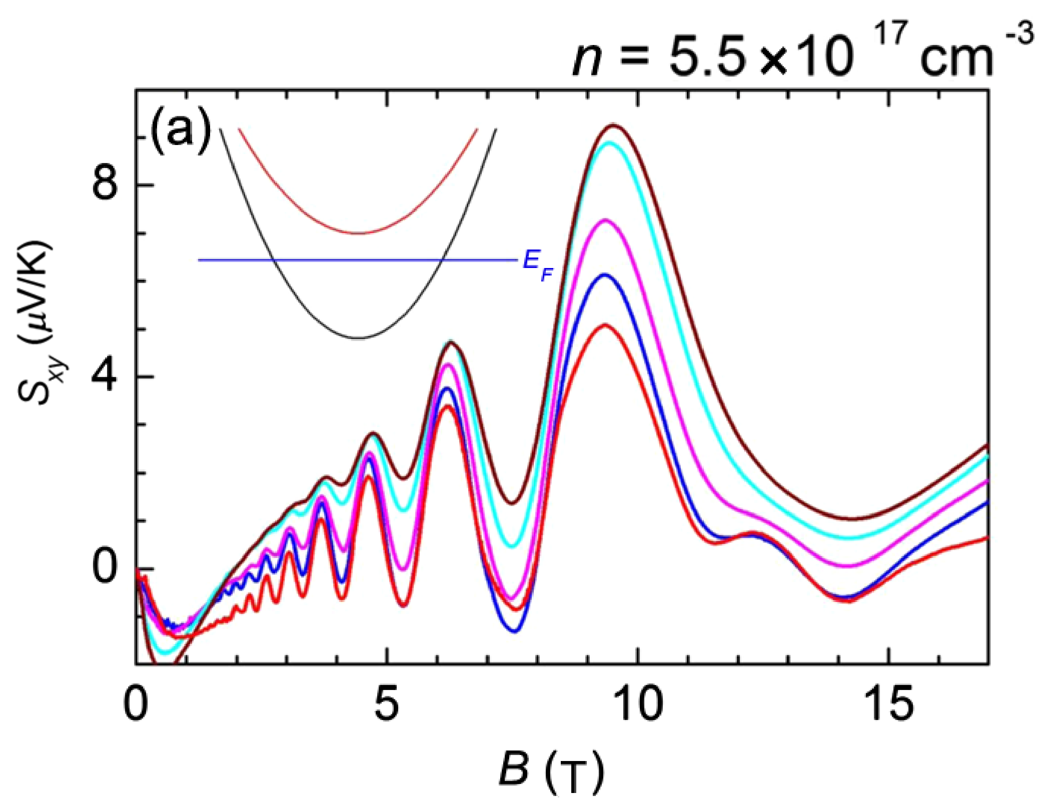
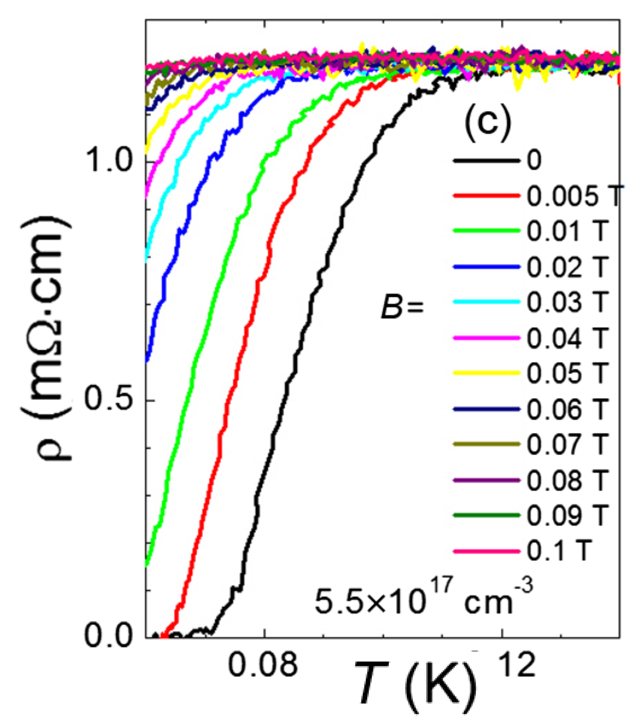
(n=1e18cm^{-3} => small E_F)
+
well defined Fermi Surface resolved by QO

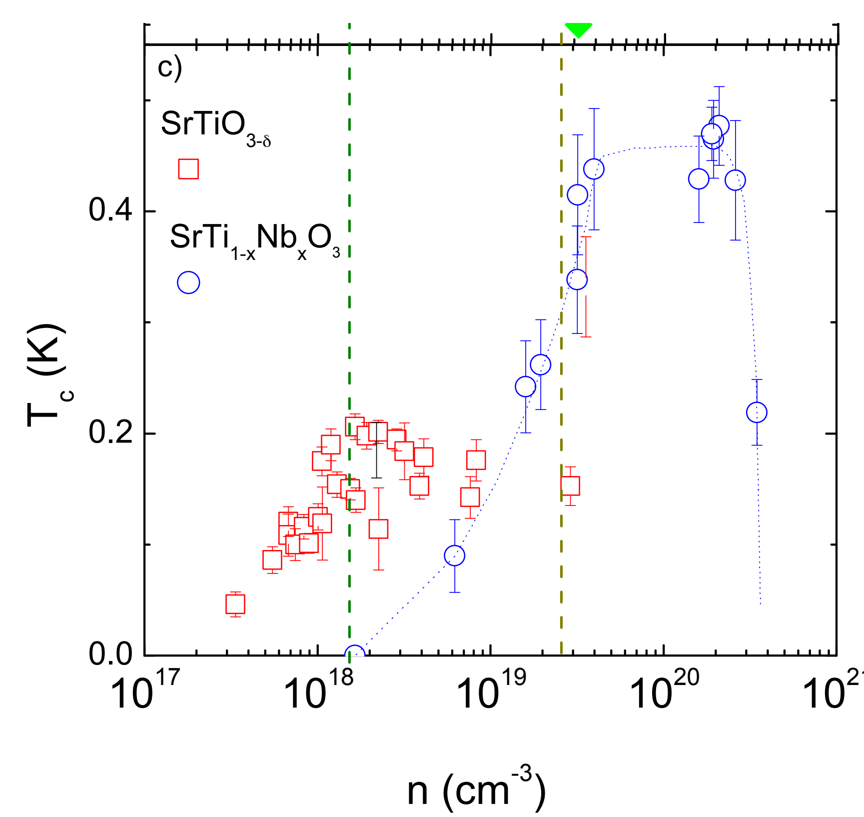
Superconductivity :
anti-adiabatic limit $E_F < k_B \Theta_D$
$SrTiO_{3-x}$: X. Lin and al., PRX, **3**, 021002 (2013)
C. Collignon and al., arXiv1804.07067
Bi : Science (2017)



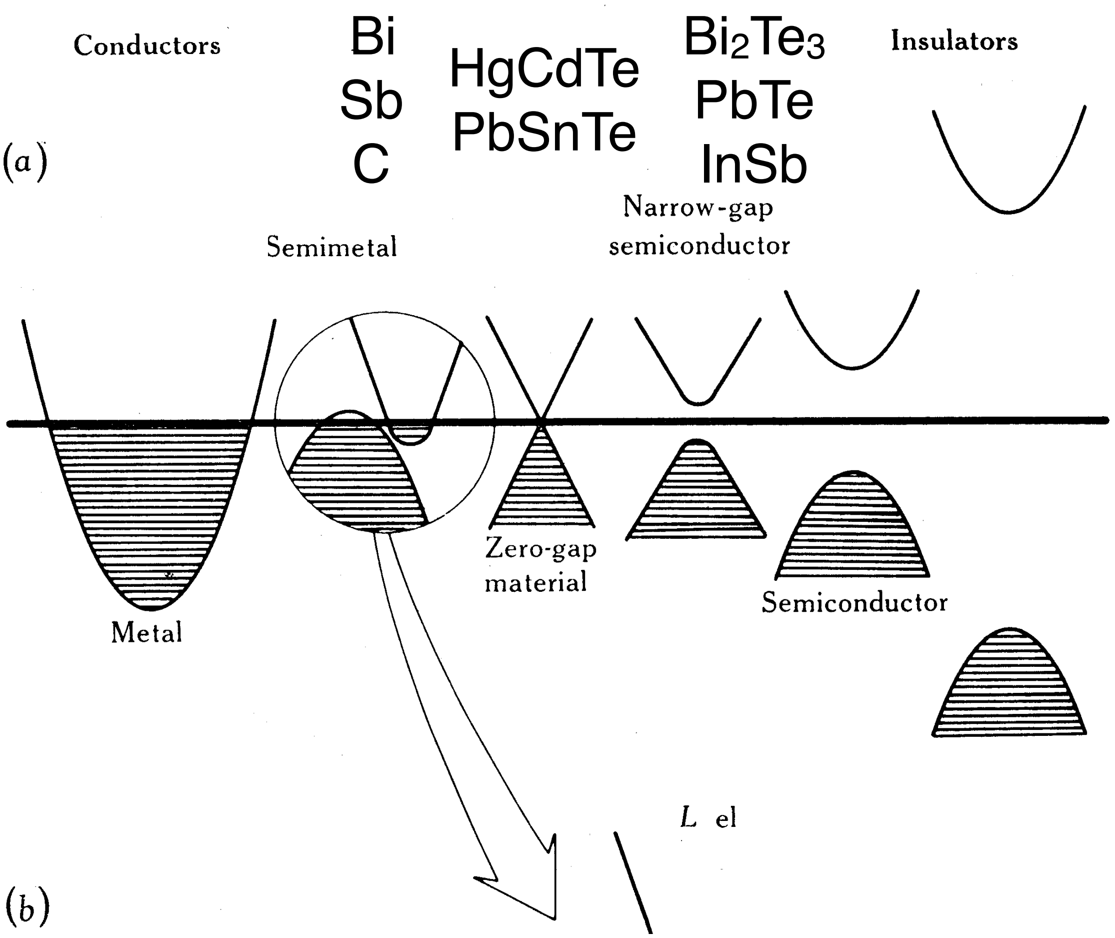
T_F=13K<<Θ_D

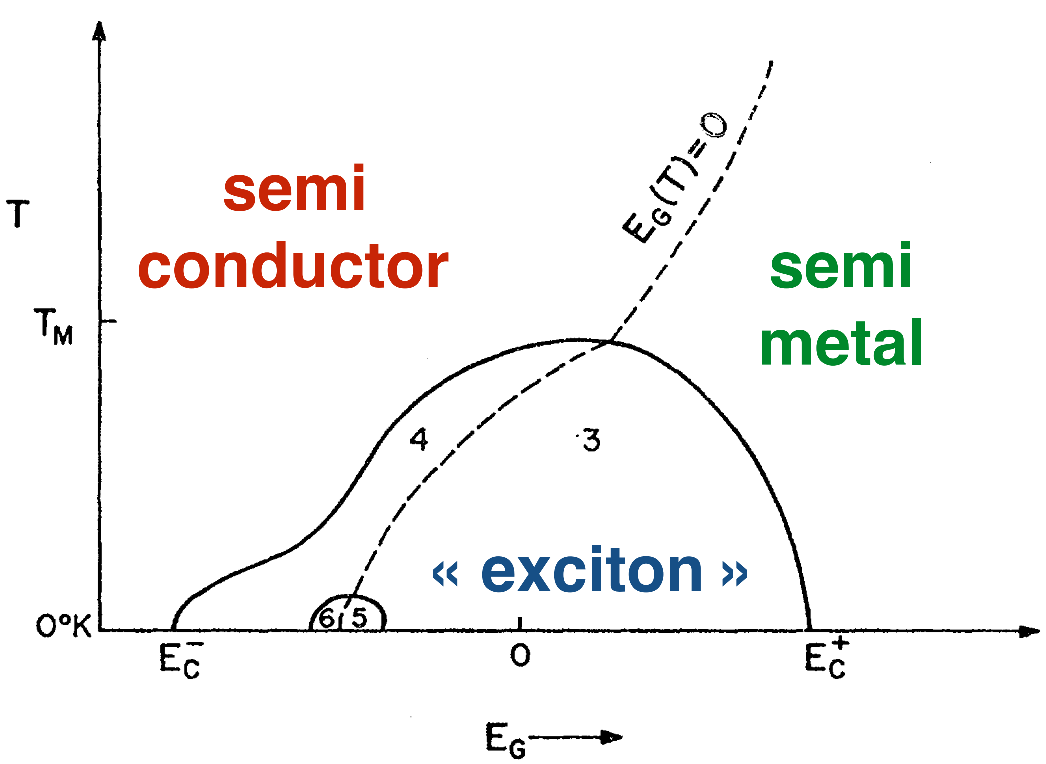


T_C=80mK



Motivations





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n->0: electrons-holes form bound pairs -
« an excitonic insulator »

Dirac like dispersion in 3D :
3D « Dirac » dispersion Na_3Bi, Cd_3As_2, WTe_2…

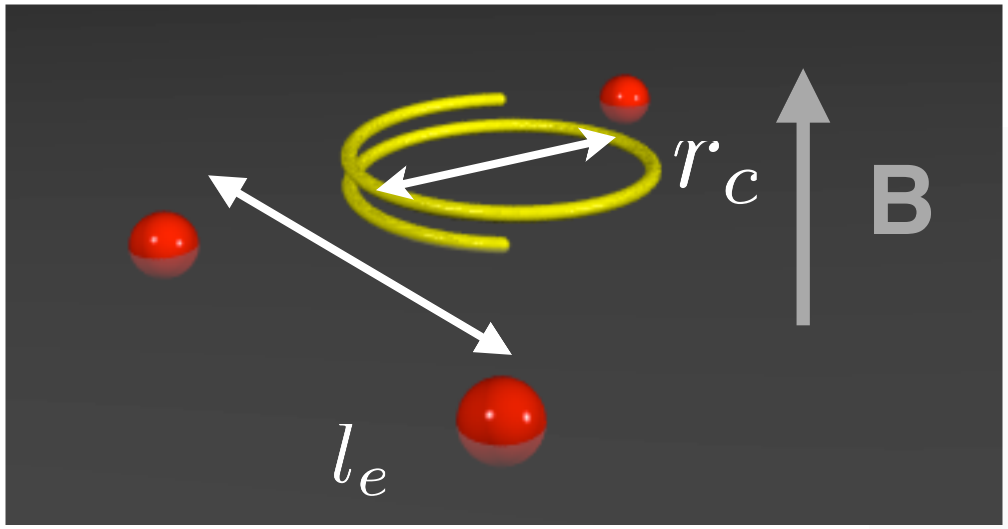
Thermoelectricity : High thermoelectric properties

Superconductivity : anti-adiabatic limit $E_F < k_B\Theta_D$

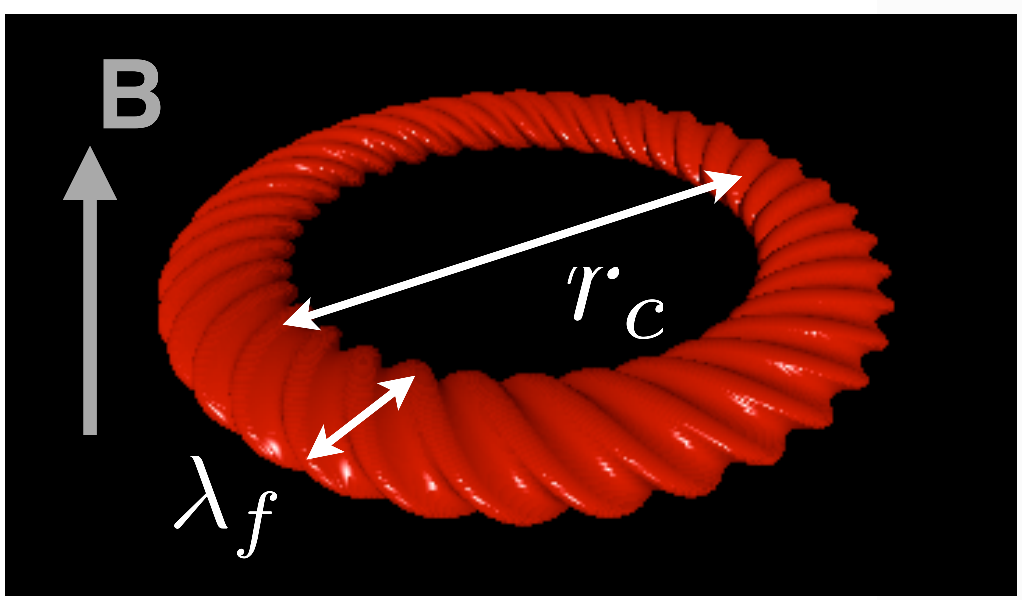
Quantum limit : $E_F \sim \hbar\omega_c$

Motivation - Quantum limit

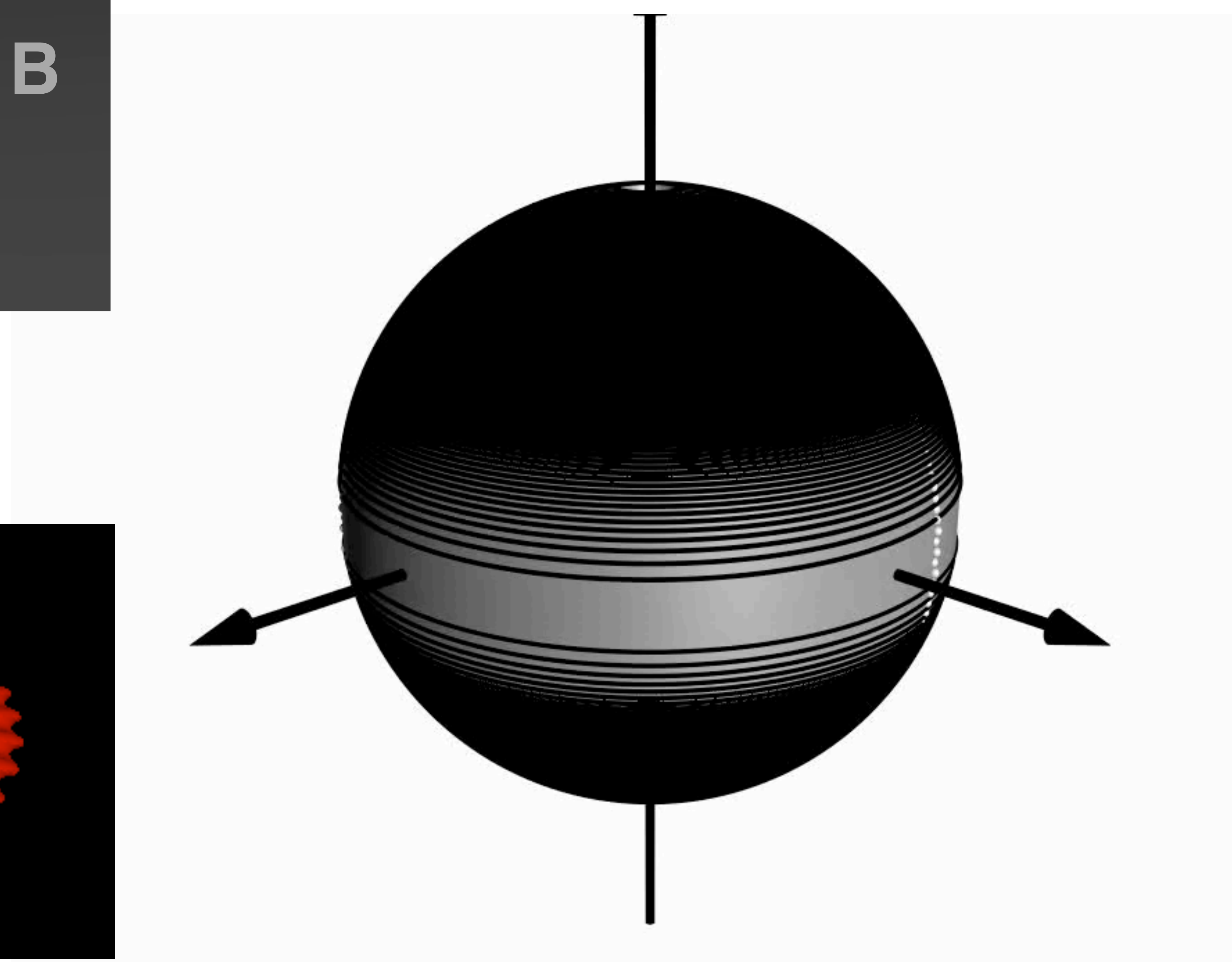
B



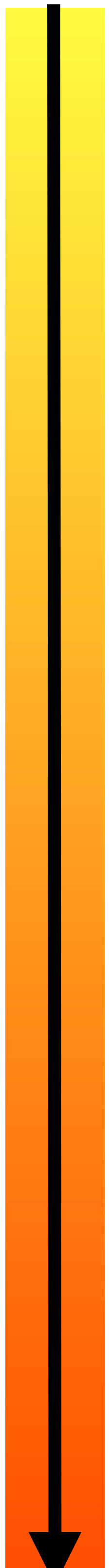
Semi-Classical limit

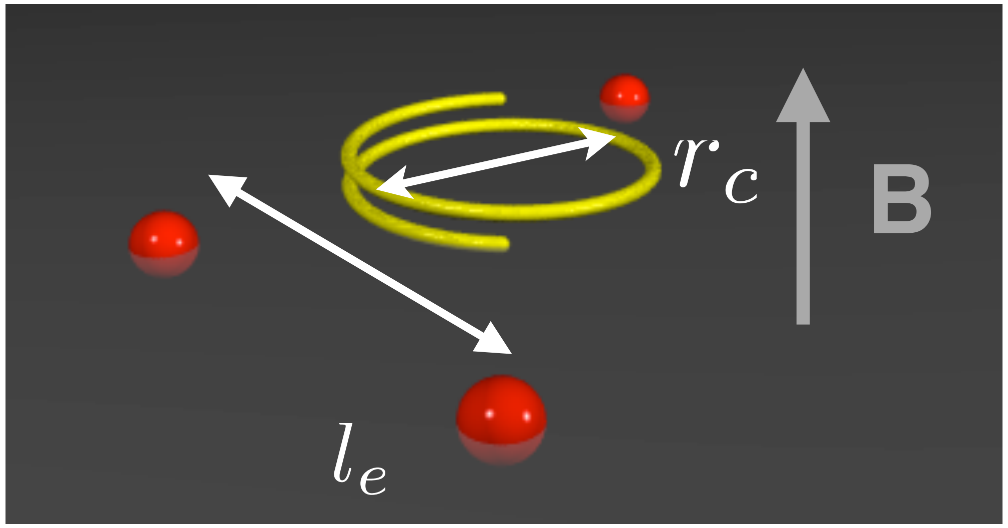


Quantum limit

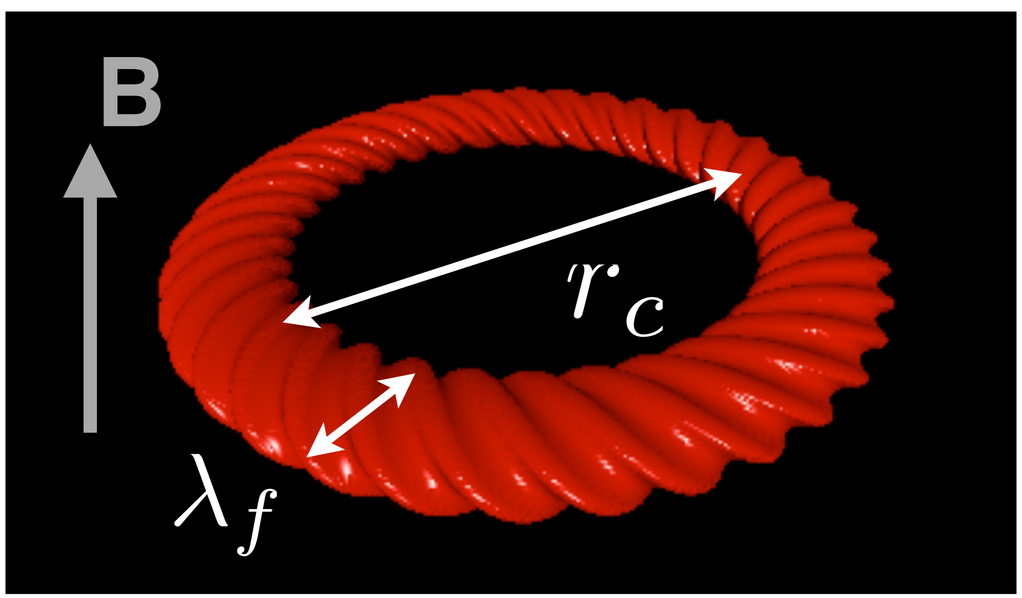


Motivation - Quantum Limit (QL)



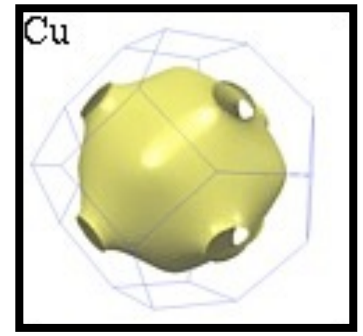
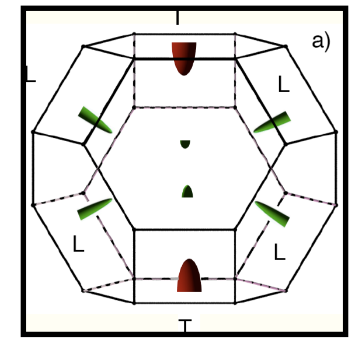
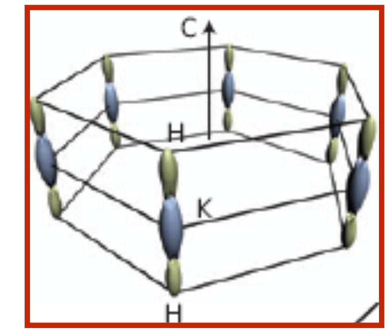


Semi-Classical limit



Quantum limit

B

	Copper	Bismuth	Graphite
			
n	8.5 10^{22} cm^{-3}	3 10^{17} cm^{-3}	3 10^{18} cm^{-3}
QL	~5000T	~9T	~7.5T

but also in doped SC : InSb, PbTe, SrTiO3 and Weyl system i.e TaP

What is the electronic ground state of a 3D metal pushed in the quantum limit ?

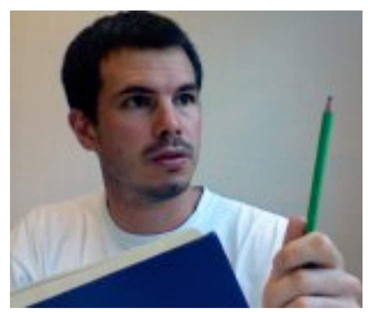
Acknowledgements

A. Jaoui

W. Rischau

K.Behnia

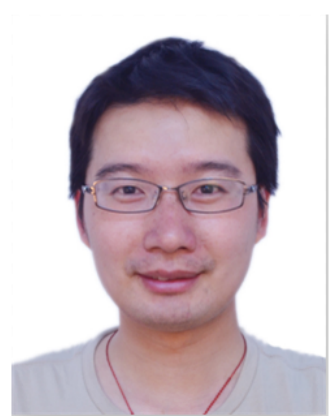
LNCMI- G/T



D. Le Boeuf (US)

G.Seyfarth

C.Proust



Z. Zhu

Wuhan

Thermoelectrical response beyond the quantum limit of 3D electron gas systems

Introduction

Nernst effect as a probe of quantum oscillations in semi-metals

Transport and thermodynamic measurements in the quantum limit of graphite

Narrow gap semi-conductors in the quantum limit: the case of InAs

Conclusion

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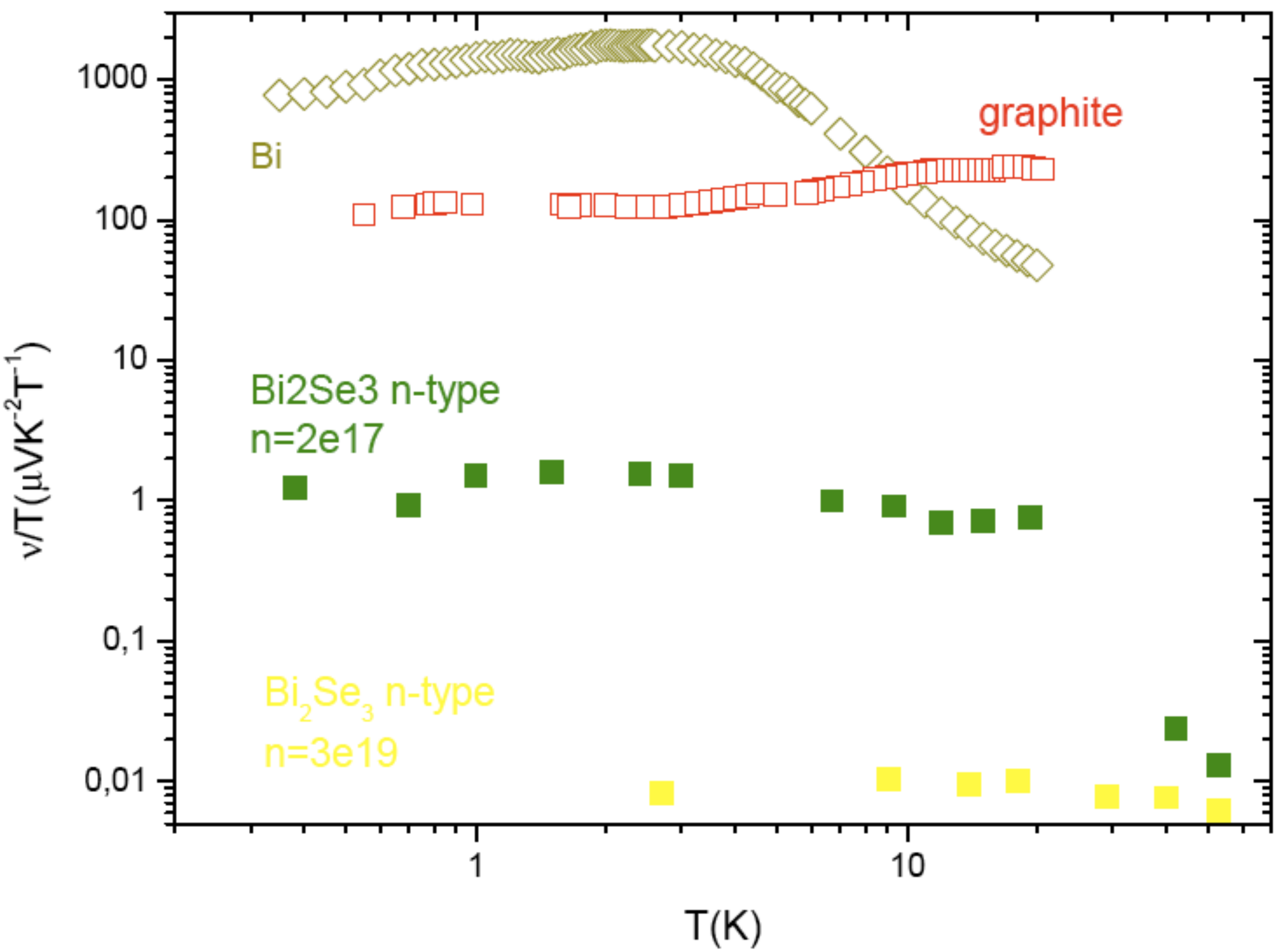
Nernst effect : low field regime

$$\nu = \frac{-E_y}{\nabla_x T B_z} \qquad \nu = N/B = -\frac{\pi^2}{3}\frac{k_B^2 T}{m^*}\frac{\partial \tau}{\partial \epsilon}|_{\epsilon=\epsilon_F}$$

	$\mu(T^{-1})$	E_f (K^{-1})	$286\ \mu/T_f$ $(\mu V\ K^{-2}$
Bi	500	130	914
C	30	220	40
Bi_2Se_3	0.45	90	1.4
Bi_2Se_3	0.05	1200	0.04

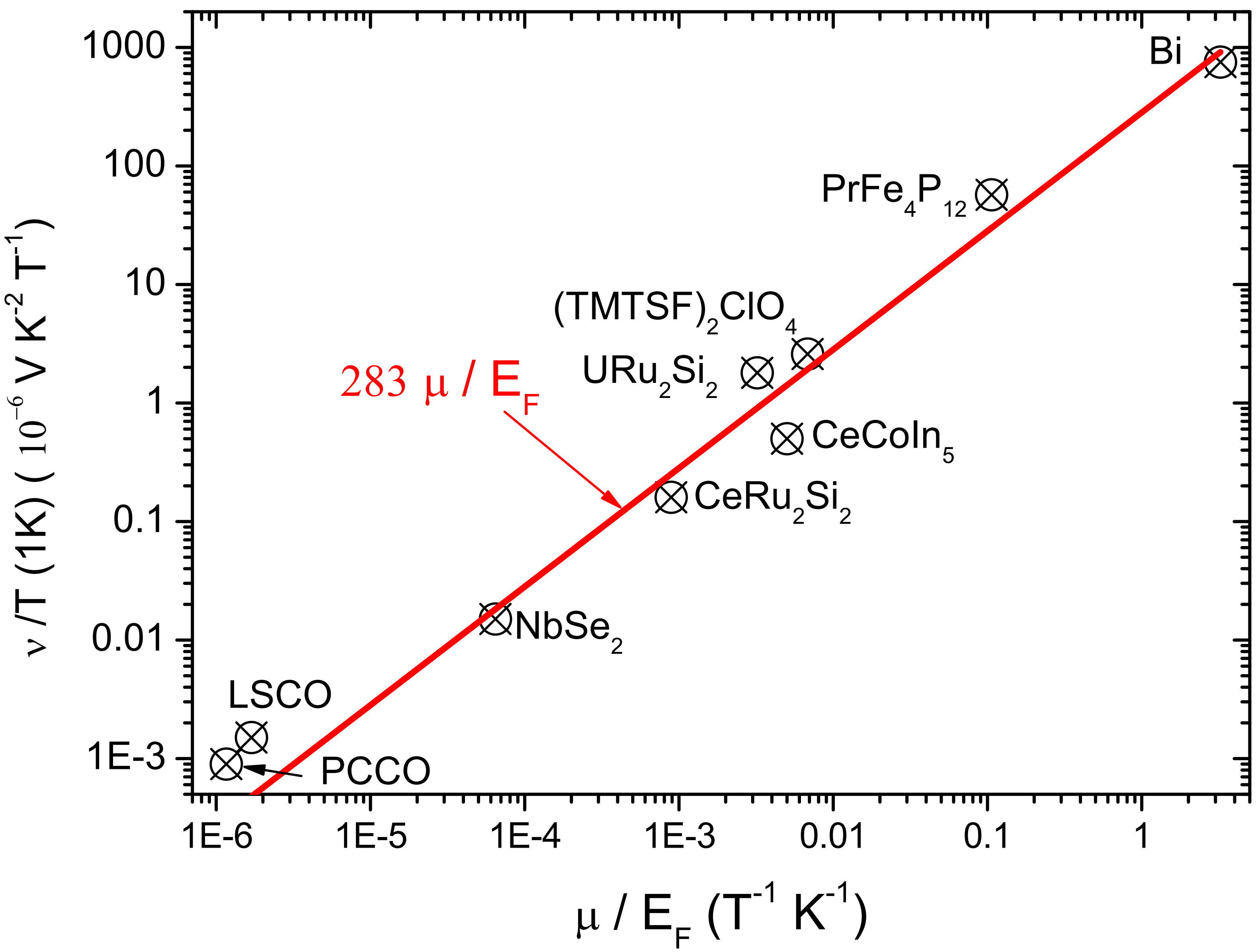


$$\frac{\nu}{T} = -\frac{\pi^2}{3}\frac{k_B^2}{m^*}\frac{\partial \tau}{\partial \epsilon}|_{\epsilon=\epsilon_f} \approx 283\frac{\mu}{\epsilon_f}[\mu V K^{-1} T^{-1}]$$

K. Behnia, J. Phys.: Condens. Matter
21, 113101 (2009)

Nernst effect : low field regime

$$\nu = \frac{-E_y}{\nabla_x T B_z}$$



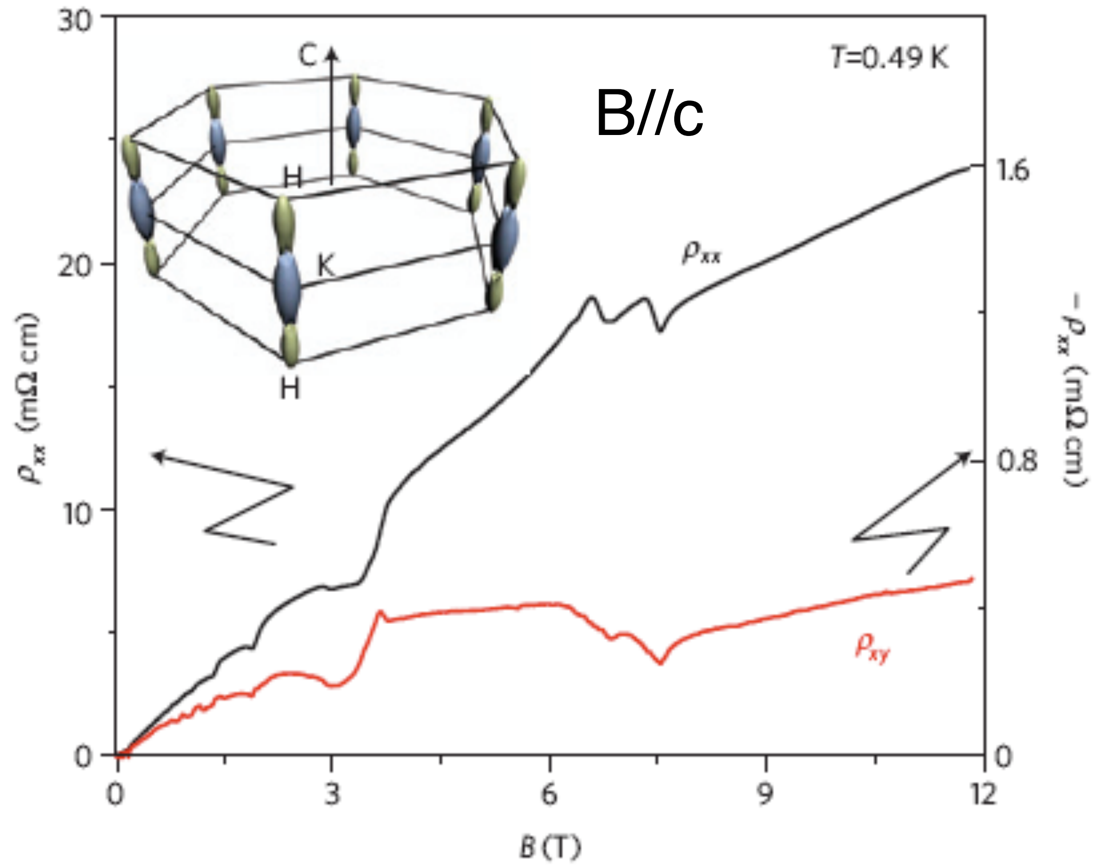
	μ(T^{-1})	E_f (K^{-1})	286 μ/T_f (μV K^{-2}
Bi	500	130	914
C	30	220	40
Bi_2Se_3	0.45	90	1.4
Bi_2Se_3	0.05	1200	0.04

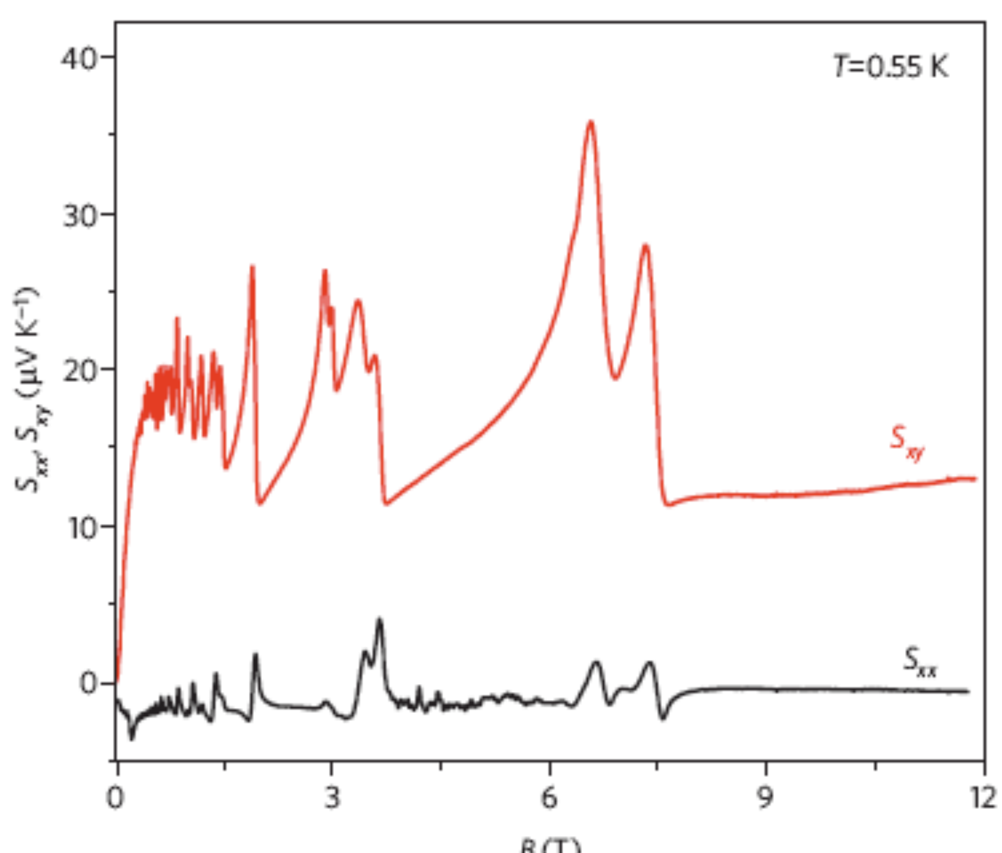
In the case of bismuth
the combination of
(i) high mobility
(iii) low Fermi energy
give a large Nernst effect

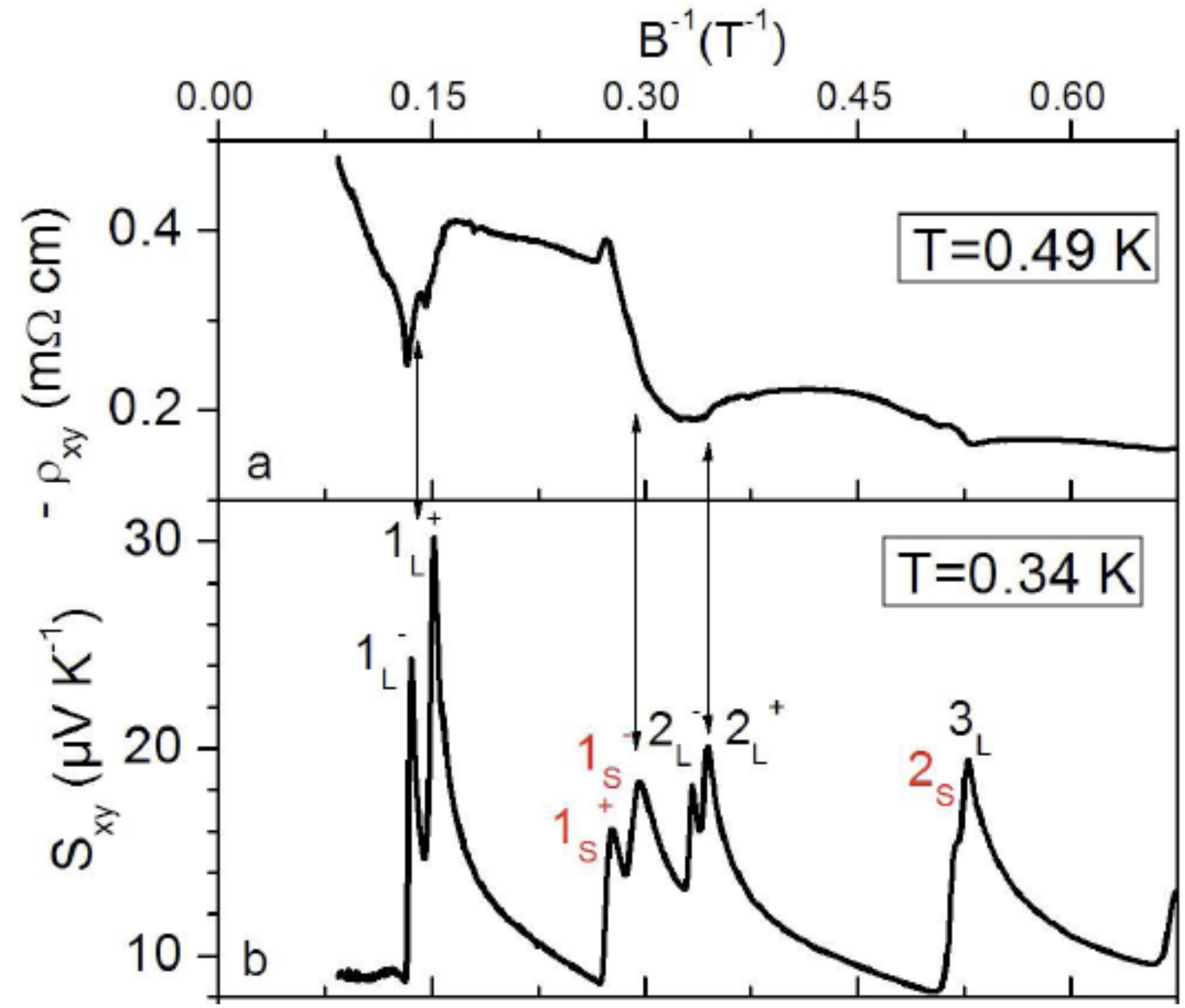
K. Behnia, J. Phys.: Condens. Matter
21, 113101 (2009)

Graphite : Nernst effect up to 12T

(HOPG) Z.Zhu et al., Nature Physics **4**,166602 (2009)

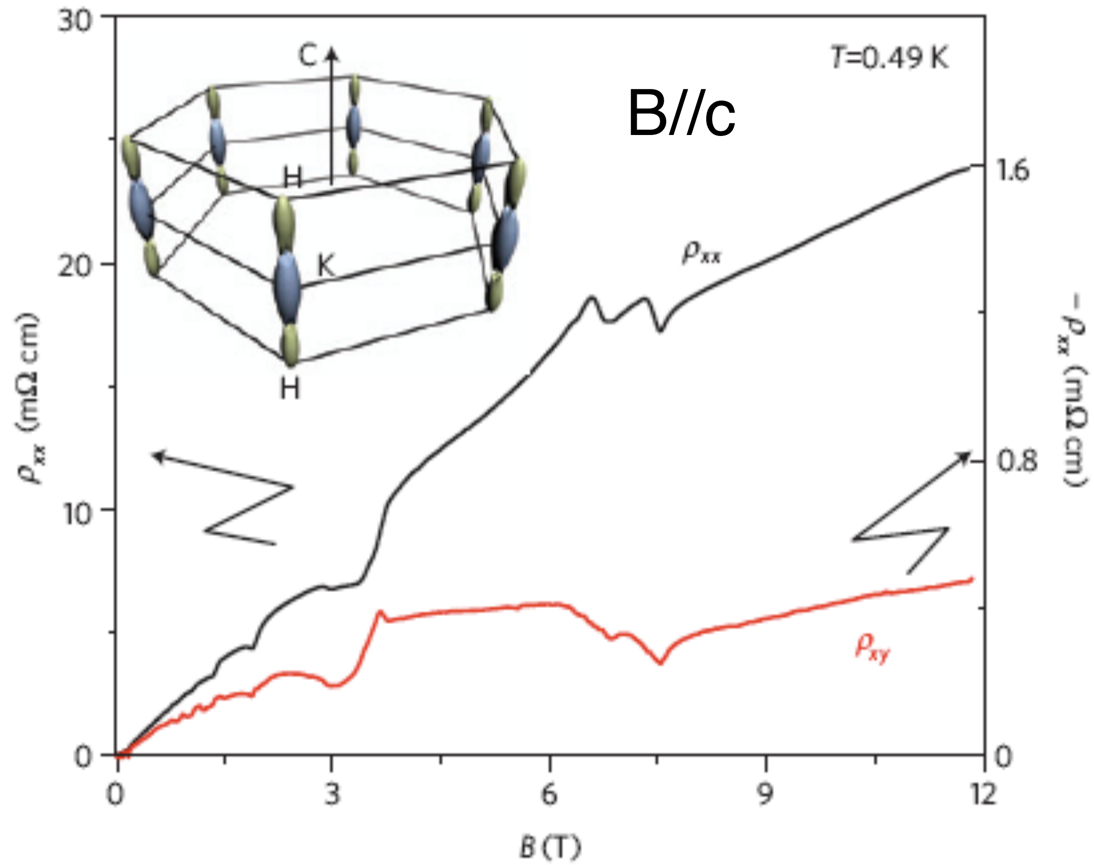


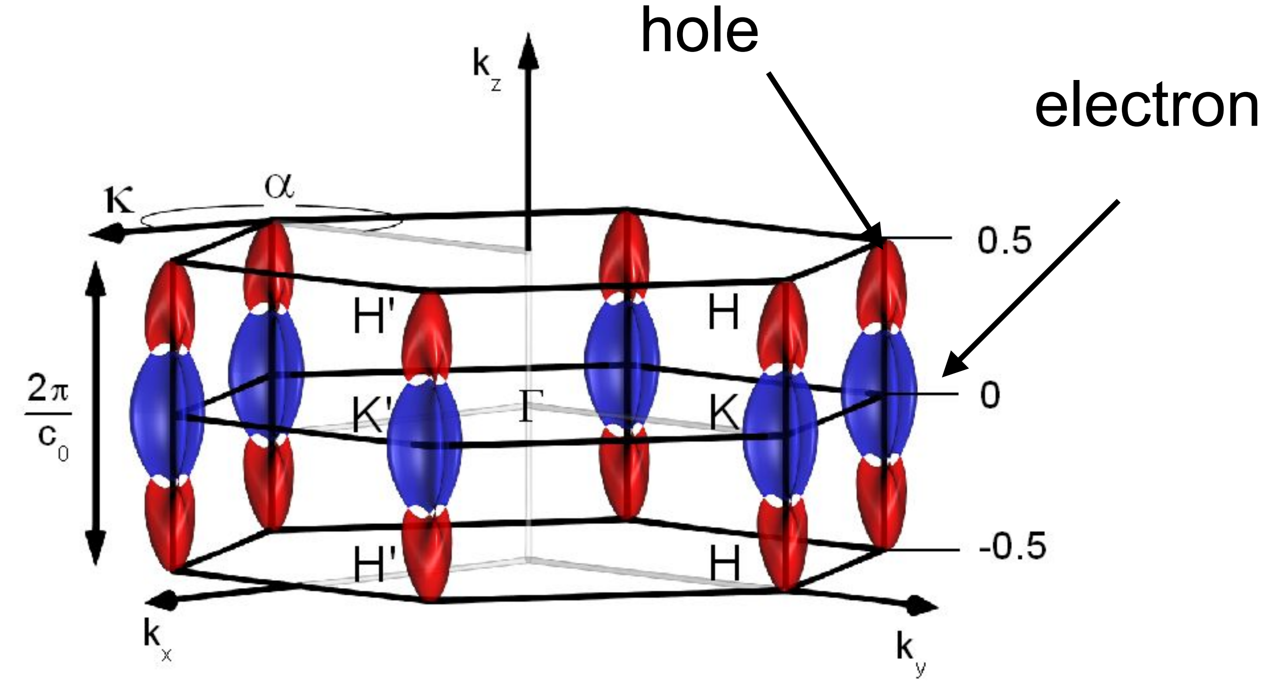




Fermi surface of Graphite

(HOPG) Z.Zhu et al., Nature Physics **4**,166602 (2009)

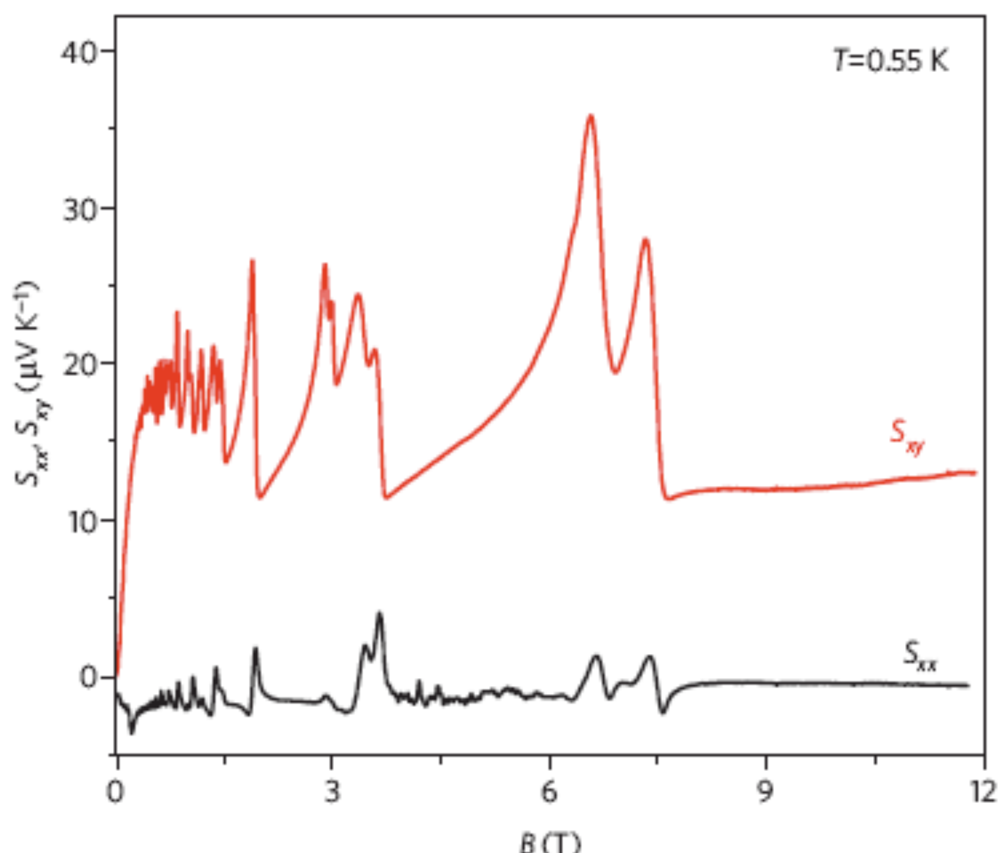


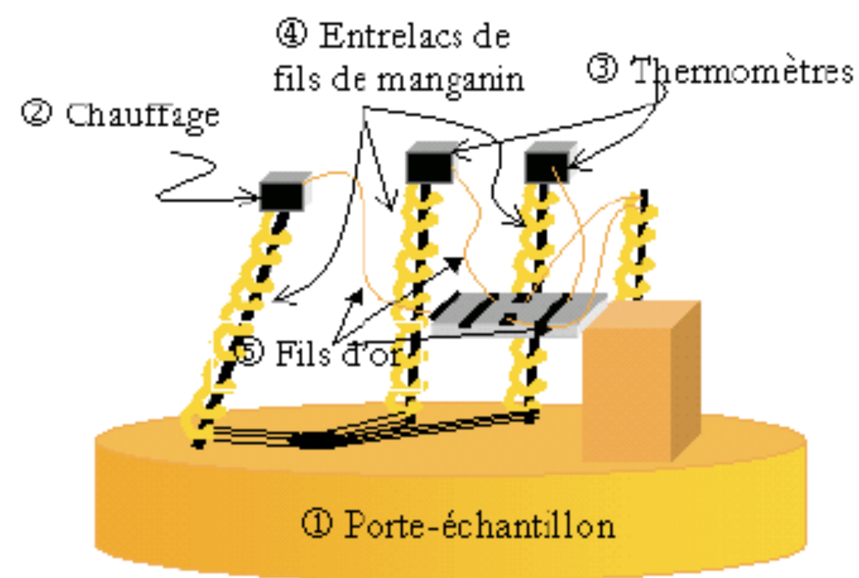


S.B. Hubbard and al., PRB (2011)

hole : Schrödinger type

electron : Schrödinger or Dirac type ?





$$S_{xx} = \frac{-E_x}{\nabla_x T}$$

$$S_{xy} = \frac{-E_y}{\nabla_x T}$$

Graphite : Nernst effect up to 12T

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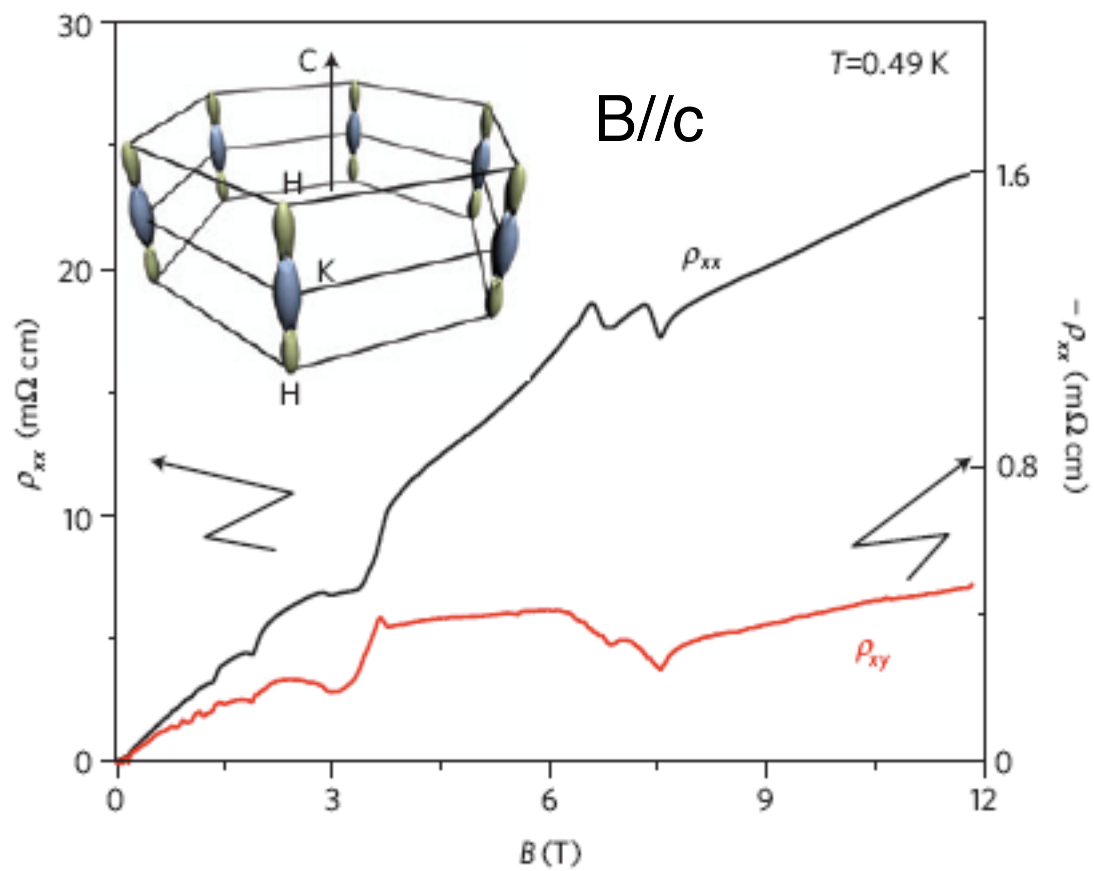
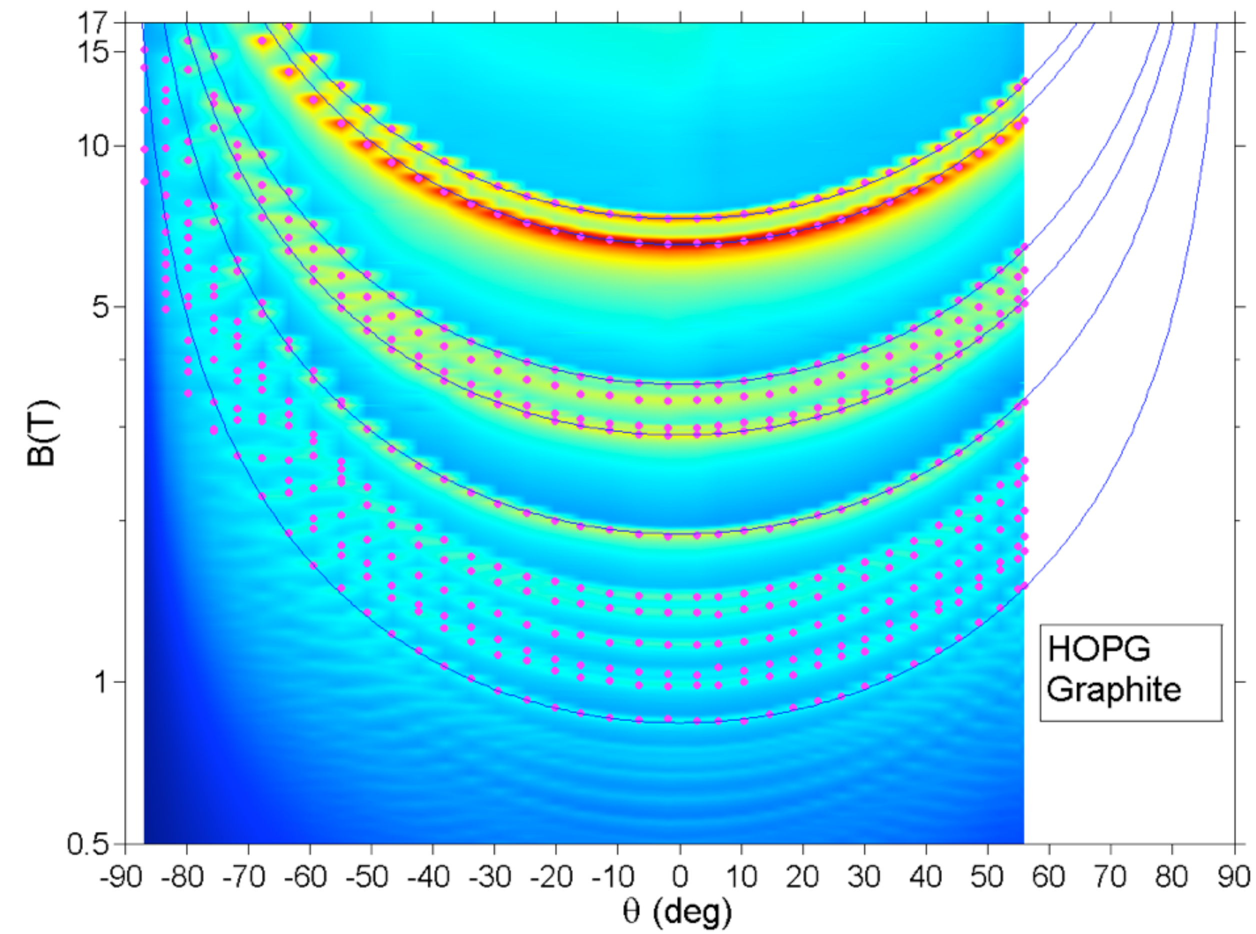
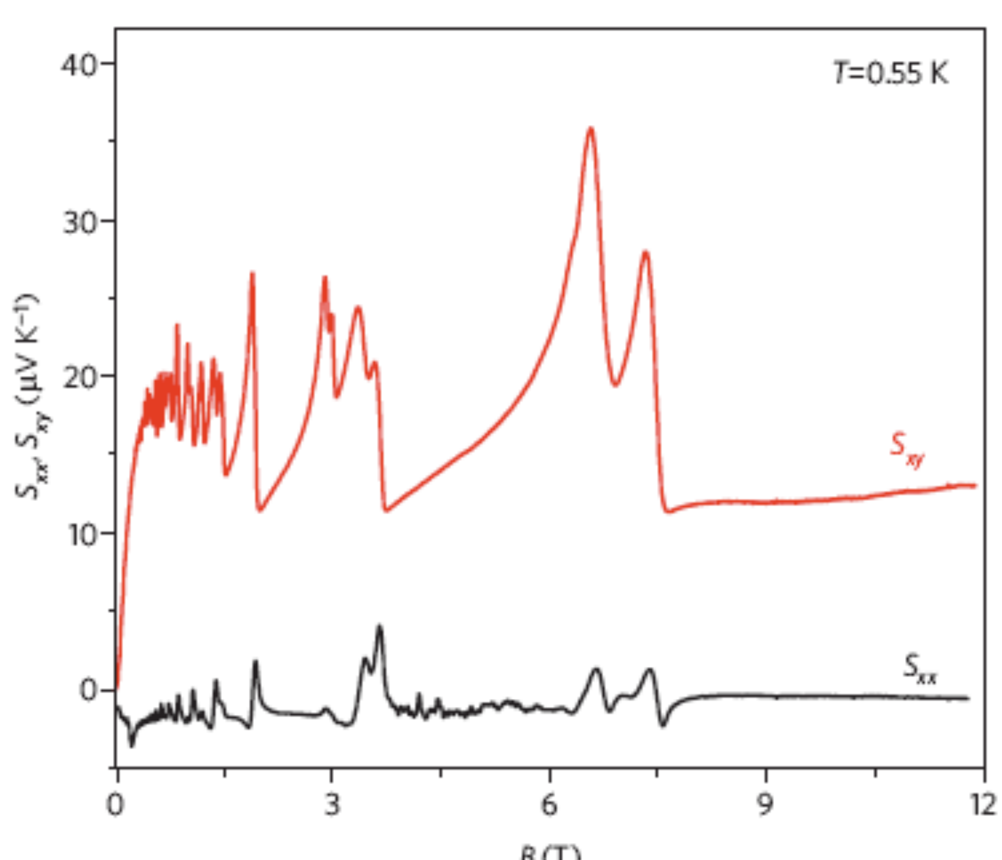




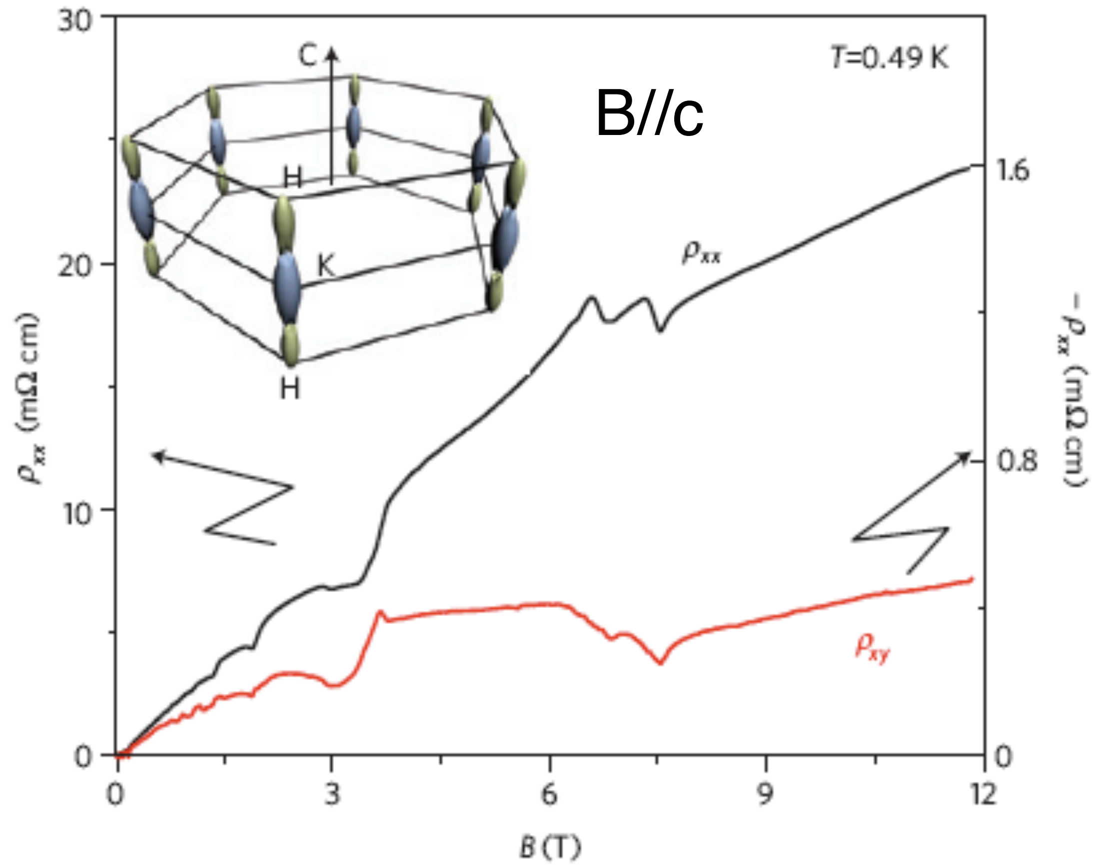


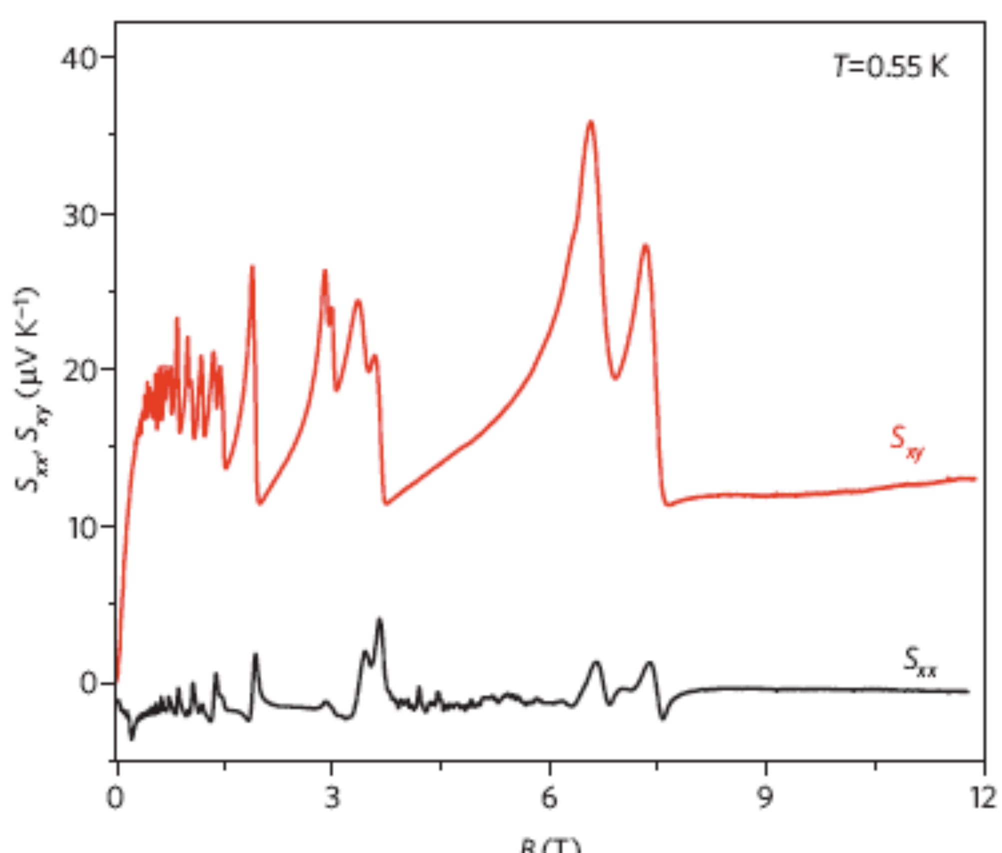
Nernst effect as a probe of the quantum limit in graphite

Graphite vs graphene

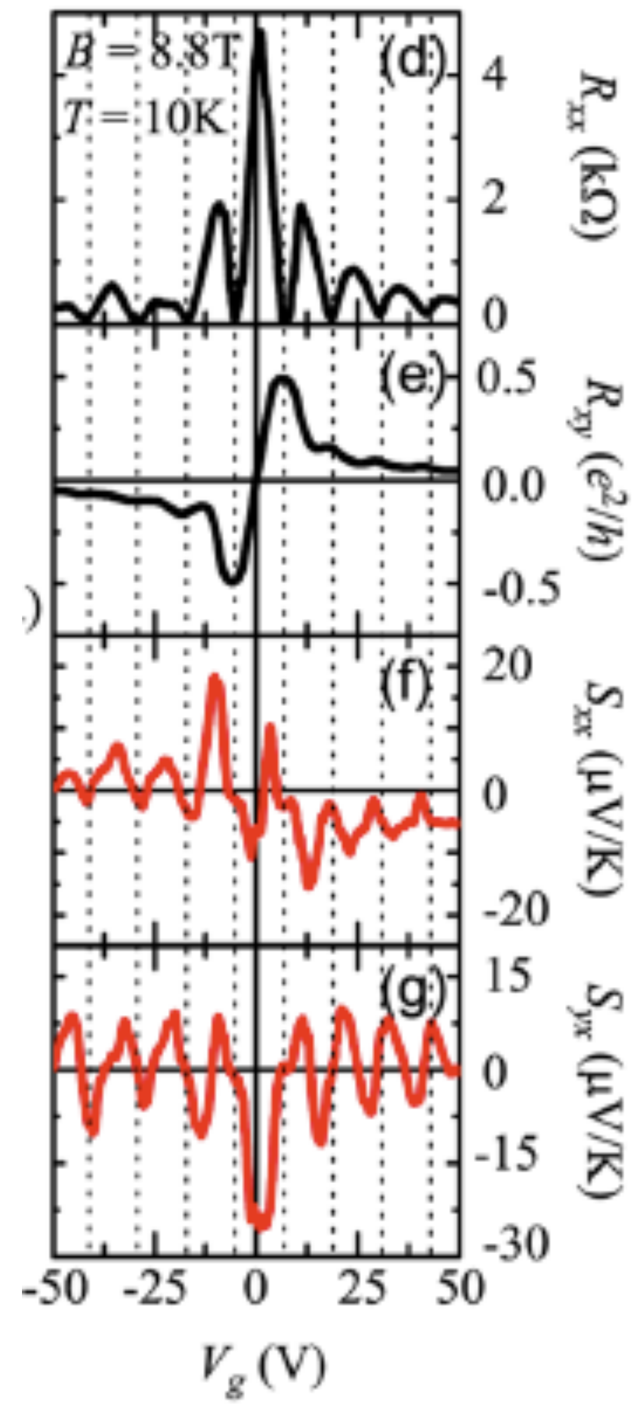
(HOPG) Z.Zhu et al., Nature Physics **4**,166602 (2009)

Y.M Zuev et al, PRL,102, 096807 (2009)





2D : Graphene



Theory

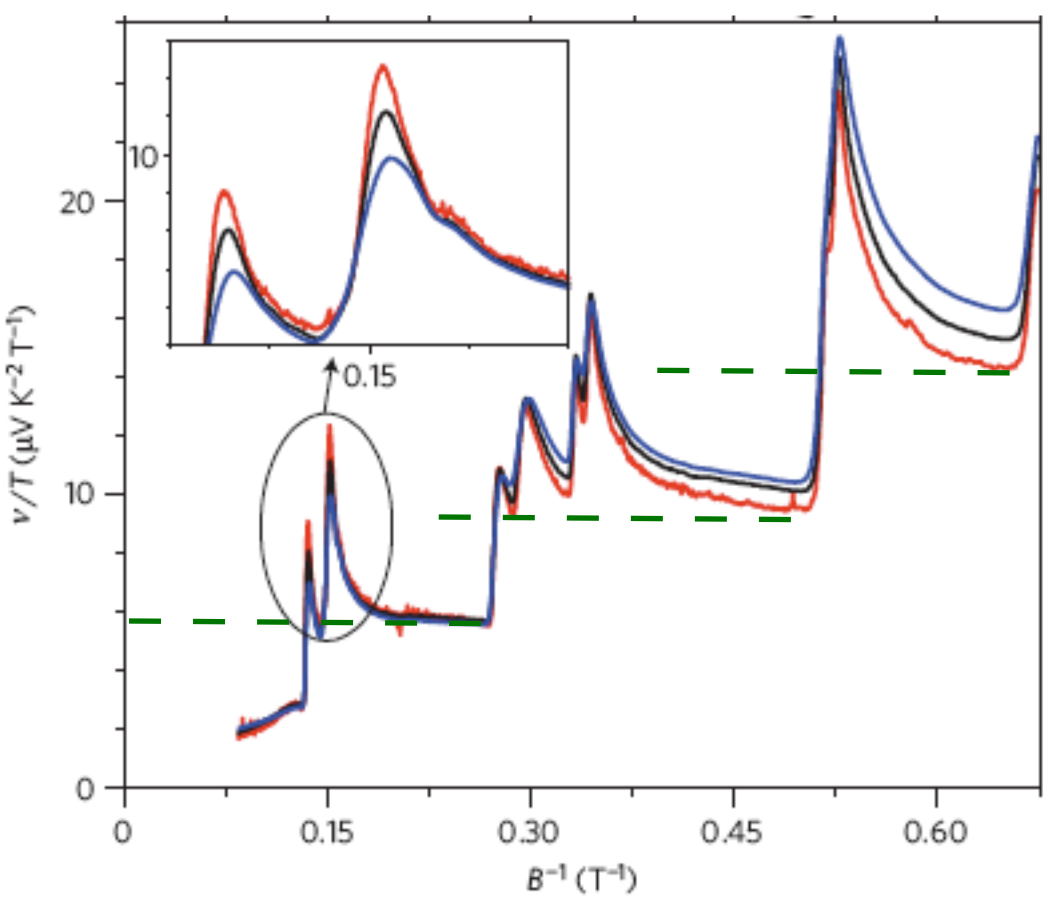
D. Bergman et al, PRL,**104**, 066601 (2010)

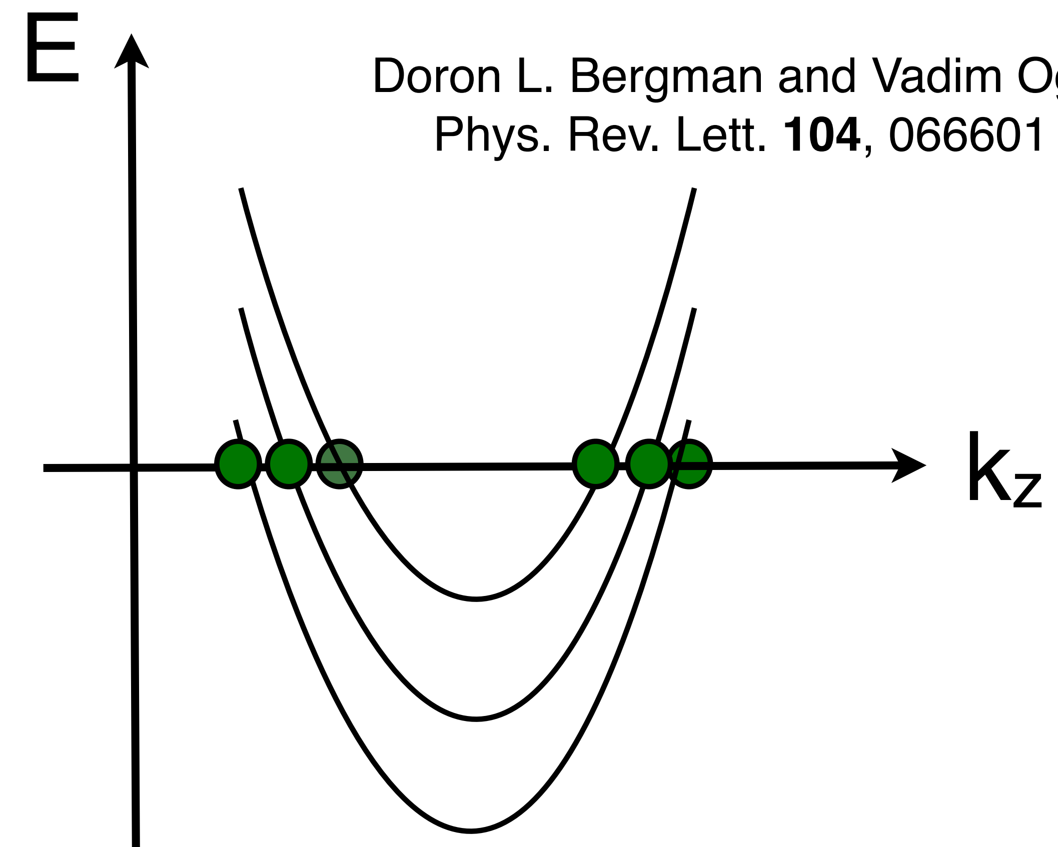
I. Luk'yanchuk et al, PRL,**107**, 016601 (2011)

Origin of the giant Nernst quantum oscillations

Between the peaks, the Nernst effect is “step like”
In this regime, the electronic spectrum is:

$$\alpha_{xy} = -\frac{ek_B}{h}\frac{\pi^2}{3}\sum_{n=0}^{n_{\max}}\frac{k_B T}{2\pi\hbar v_{Fn}},$$





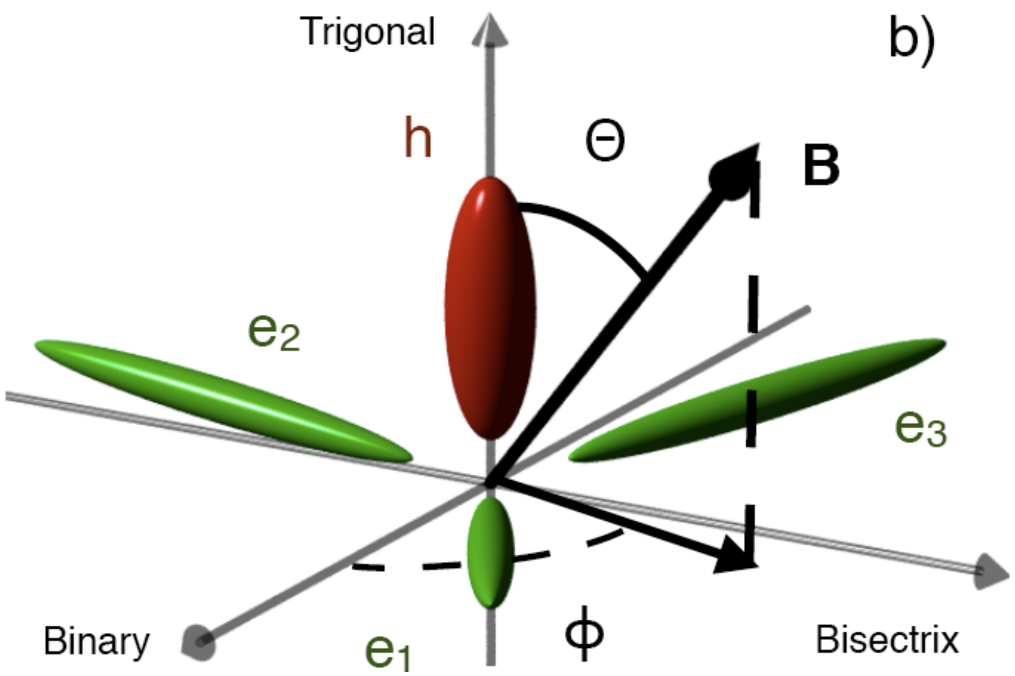
Doron L. Bergman and Vadim Oganesyan
Phys. Rev. Lett. **104**, 066601 (2010)

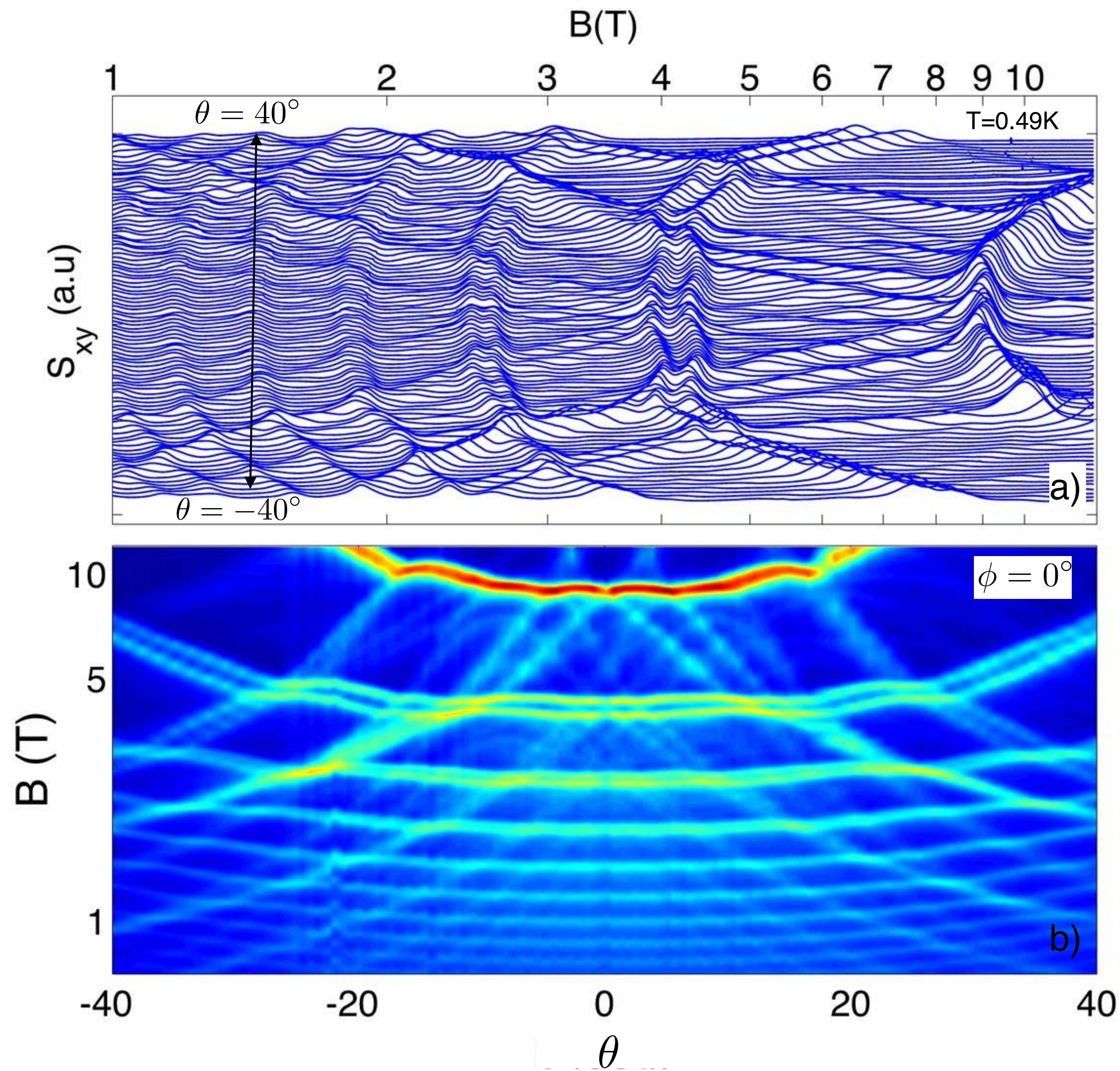
$$E_{n,s} = (n+\frac{1}{2})\hbar\omega_c + \frac{1}{2}\frac{k_z^2}{m} \pm \frac{1}{2}g\mu_B B^2$$

The Nernst effect is dominated by the green spots of each of the (full) Landau levels. As long as the chemical potential is far from the bottom of the Landau levels, the Nernst effect is nearly constant.

Landau level spectrum of Bi

Z.Zhu and al., PRB 84,115137 (2011)





Hole : parabolic dispersion
Spin Mass anisotropic

Electrons (3 valleys):
Dirac dispersion

Charge neutrality :
$n_{e1} + n_{e2} + n_{e3} = n_h \neq n(0T)$

Landau level spectrum of Bi

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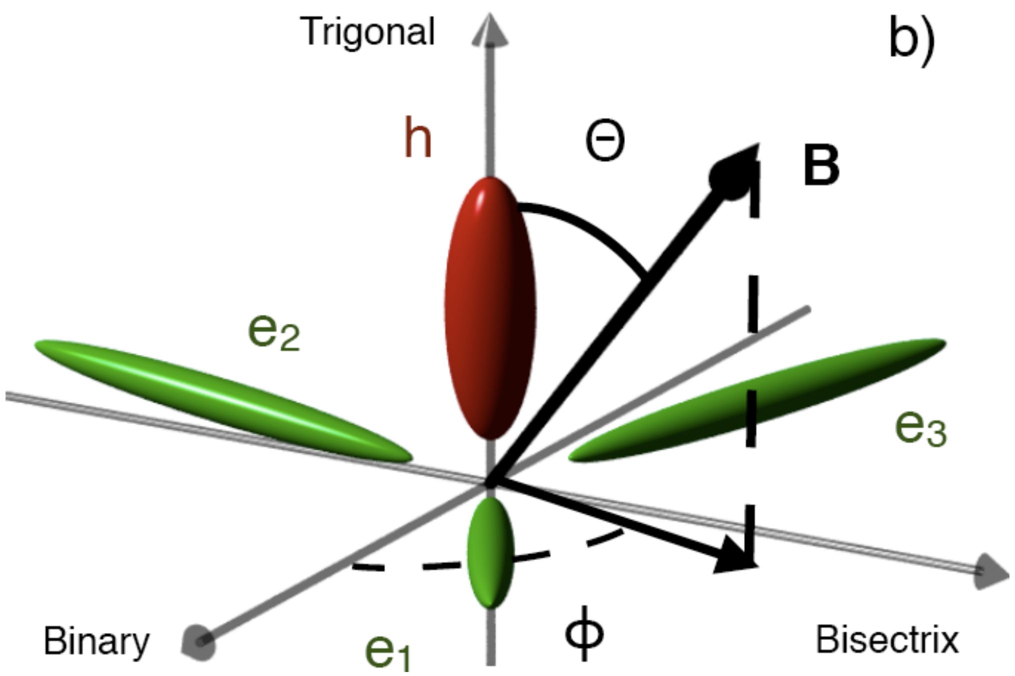

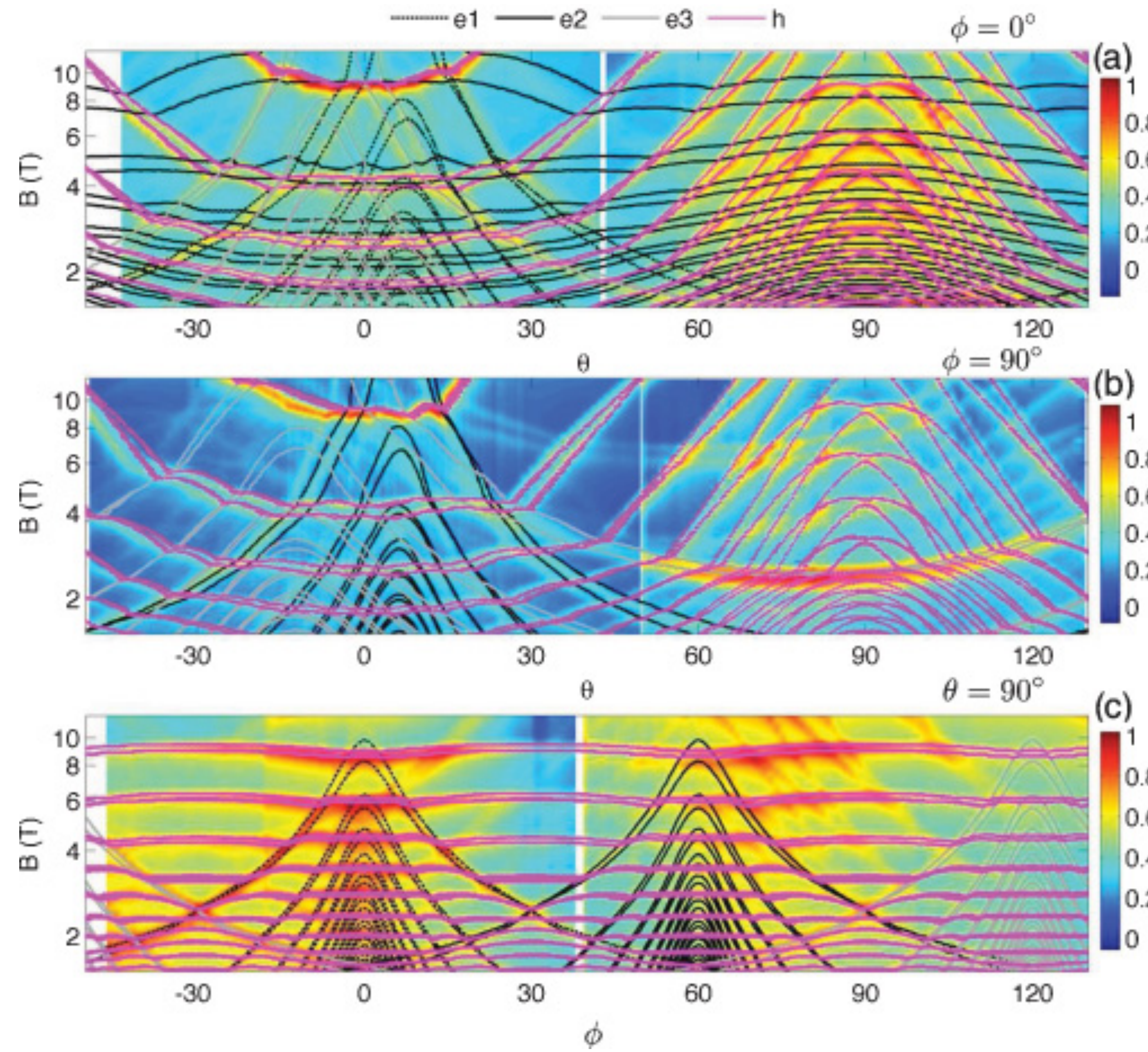

Hole : parabolic dispersion
Spin Mass anisotropic

Electrons (3 valleys):
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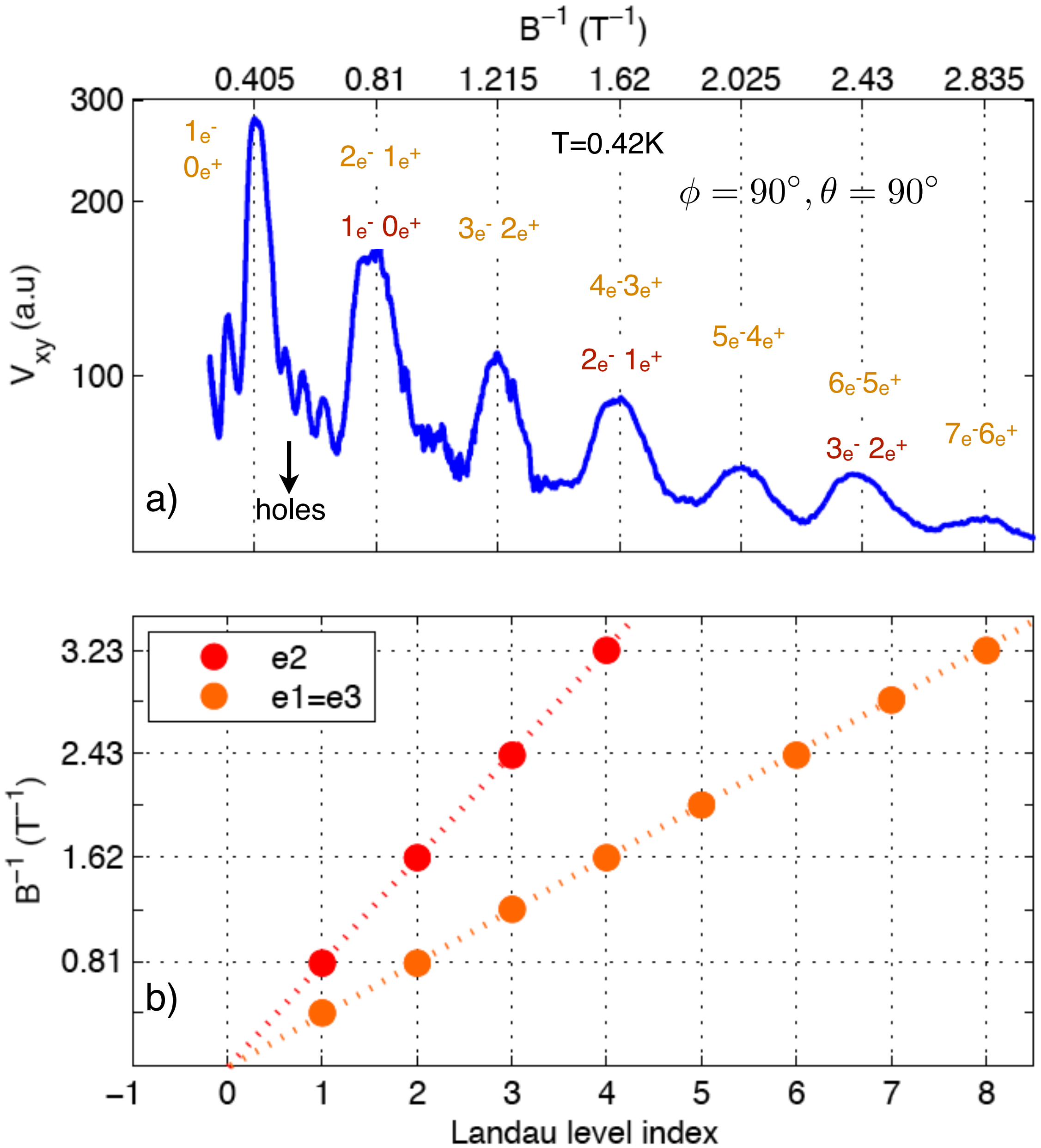
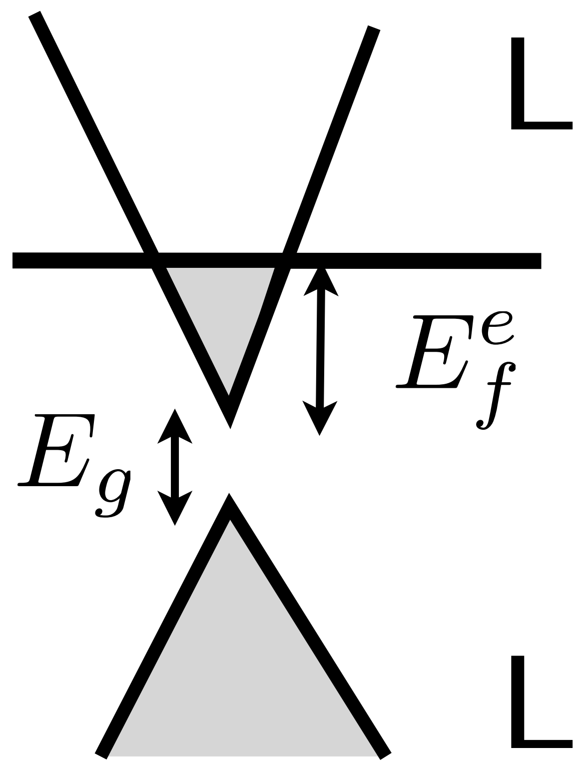
Dirac electrons in Bismuth : L-point

Z.Zhu and al., PRB 84,115137 (2011)





At the L-point:
two bands with a small ga
+ SO interaction

Dirac like dispersion !

$$\mathcal{S}_{\rm F} = \frac{2\pi}{\ell_{\rm B}^2}(n+\gamma),$$

Schrödinger electrons : (γ=1/2)

$$E_{N,k_z} = (N + \frac{1}{2})\hbar\omega_c + \frac{\hbar^2 k_z^2}{2m},$$

Dirac electrons : (γ=0)

$$E_{N,k_z} = \sqrt{(m_{\rm D} v^2)^2 + \left(\frac{\sqrt{2N}\hbar v}{\ell_{\rm B}}\right)^2 + (\hbar v k_z)^2},$$

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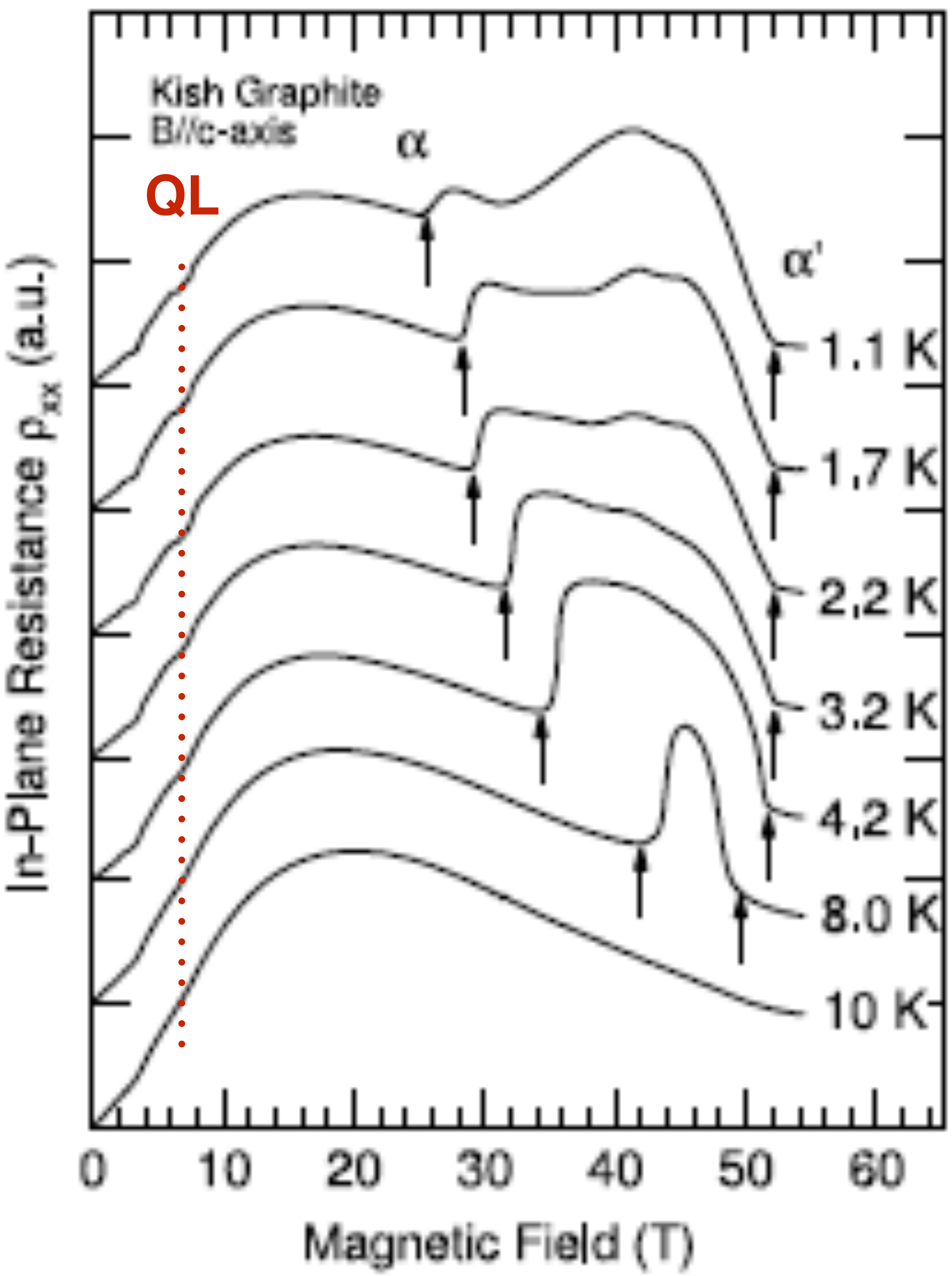
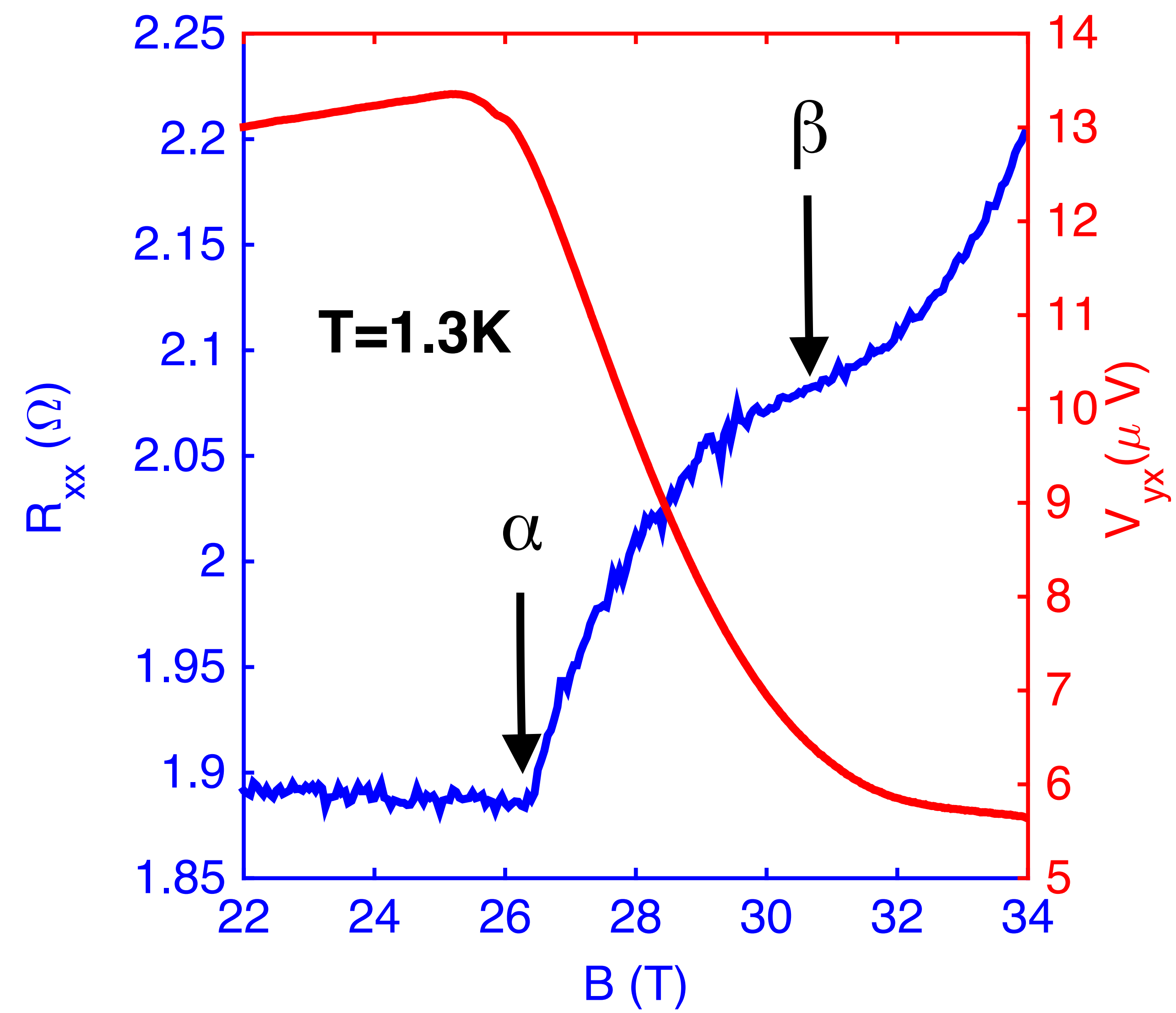
Graphite in the quantum limit regime

H. Yaguchi et al, PRL **81**,5193 (1998)



B.Fauqué et K.B,
Basic Physics of Functionalized Graphite,
Springer (2016)



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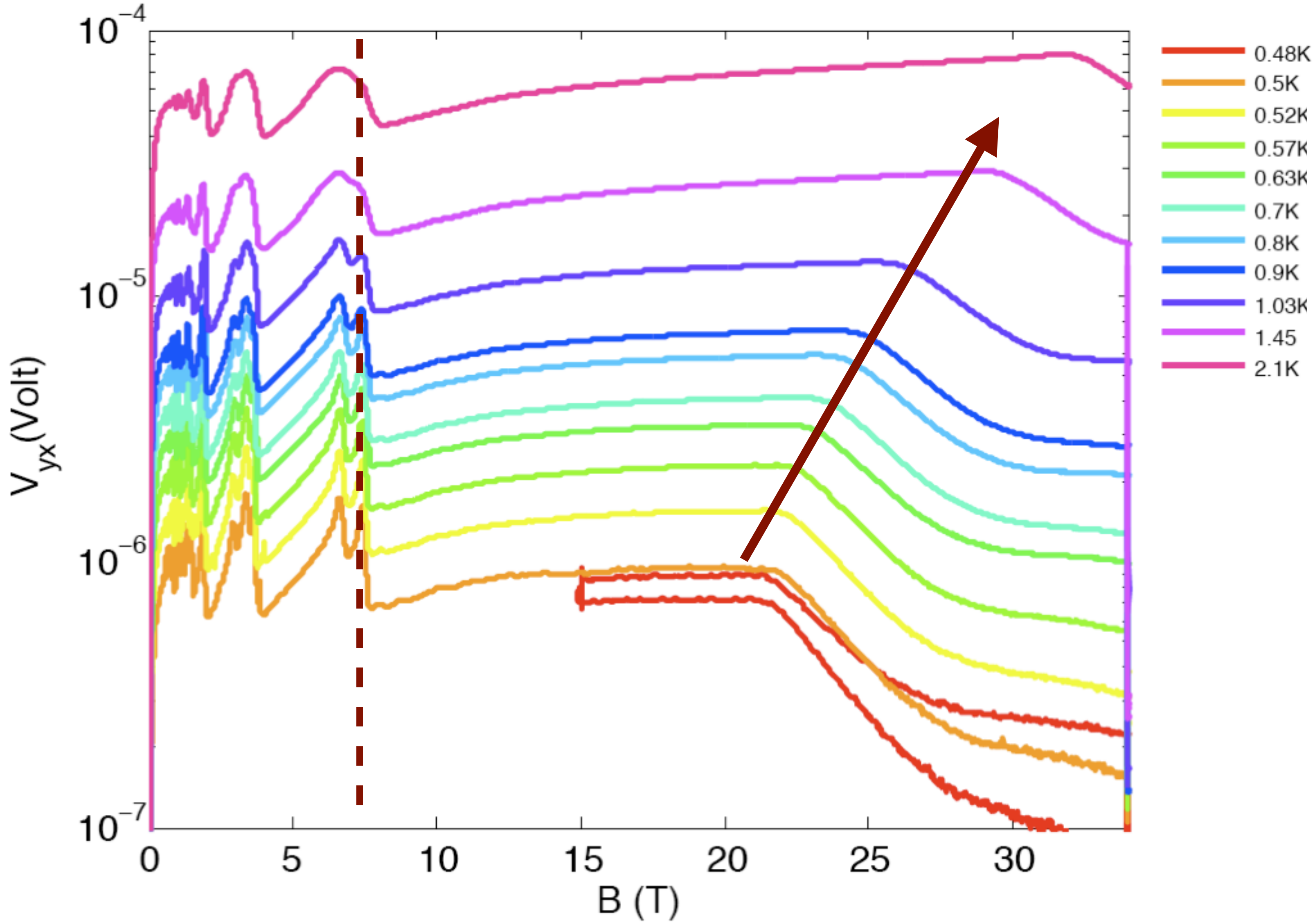
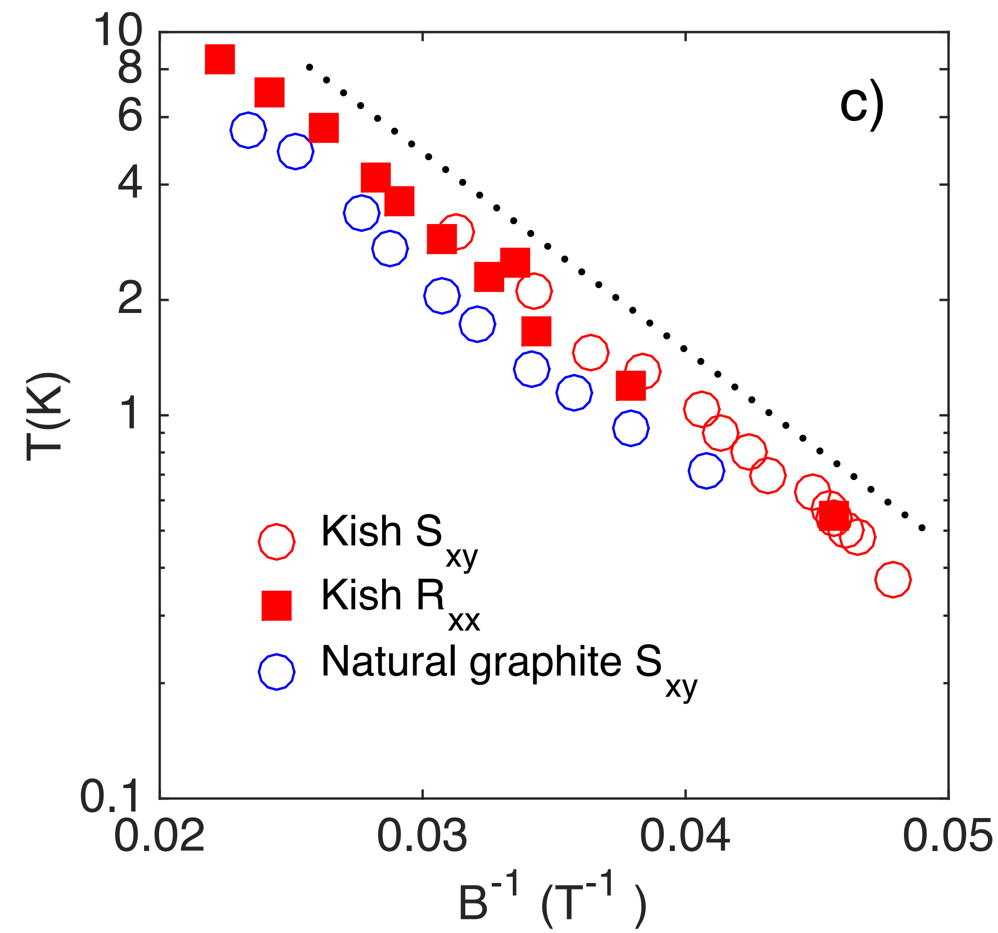
B. Fauqué et al, PRL, **106**, 246405 (2011)





BCS-type formula for mean-field-type pairing

$$T_c = T^* \exp(-\frac{B^*}{B})$$

$$k_B T_c(B) = 1.14 E_F \exp\left(-\frac{1}{N(E_F)V}\right)$$

T*=80K~T_F

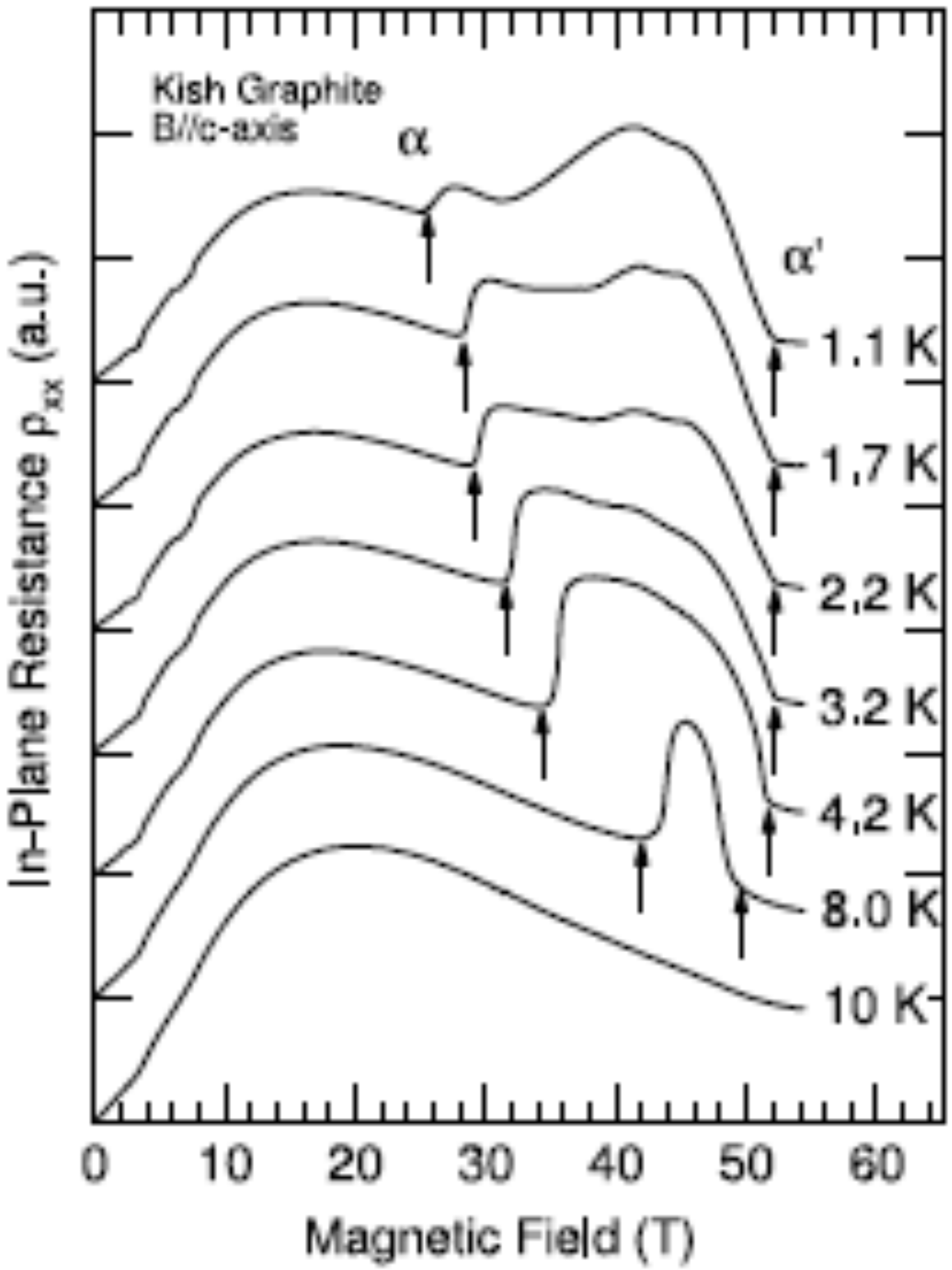
N(E_F) scales with B the Landau level degeneracy

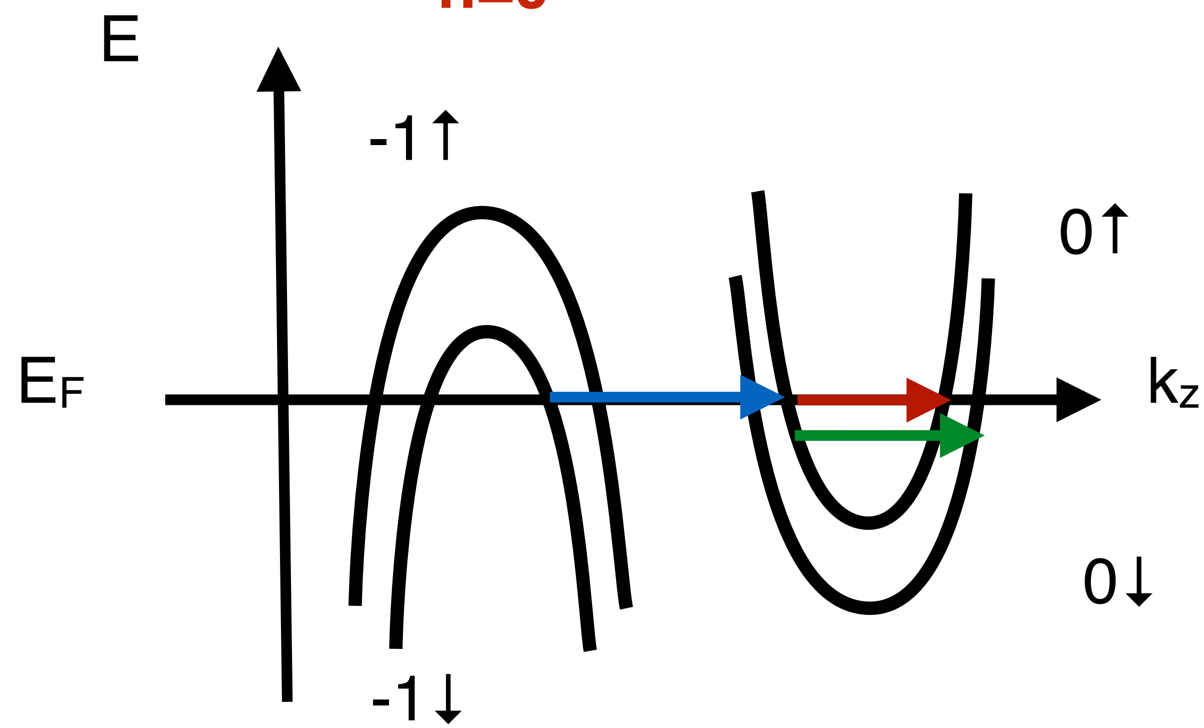
Graphite in the quantum limit regime

$$E_{n,s} = (\cancel{n} + \frac{1}{2})\hbar\omega_c + \frac{1}{2}\frac{k_z^2}{m} \pm \frac{1}{2}g\mu_B B^2$$

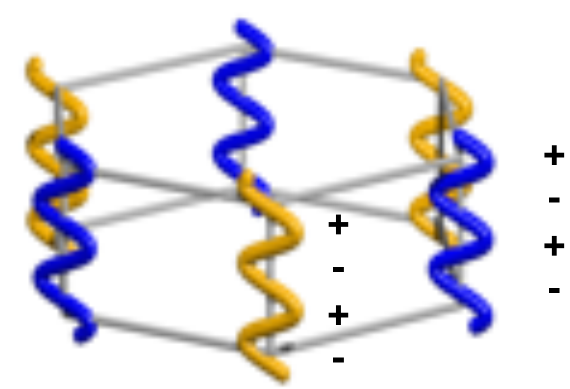
n=0

H. Yaguchi et al, PRL **81**,5193 (1998)





1981 Yoshioka-Fukuyama : **CDW** in the (0,↑)
CDWs are out of phase in each valley to minimize the Coulomb interaction



« Valley Density Wave »
Z. Tezanovic et al.,
Phys. Rev. B **36**,488(1987)

1994 : Takahashi-Takada : transverse **SDW** forms in the (n=0,↓↑)

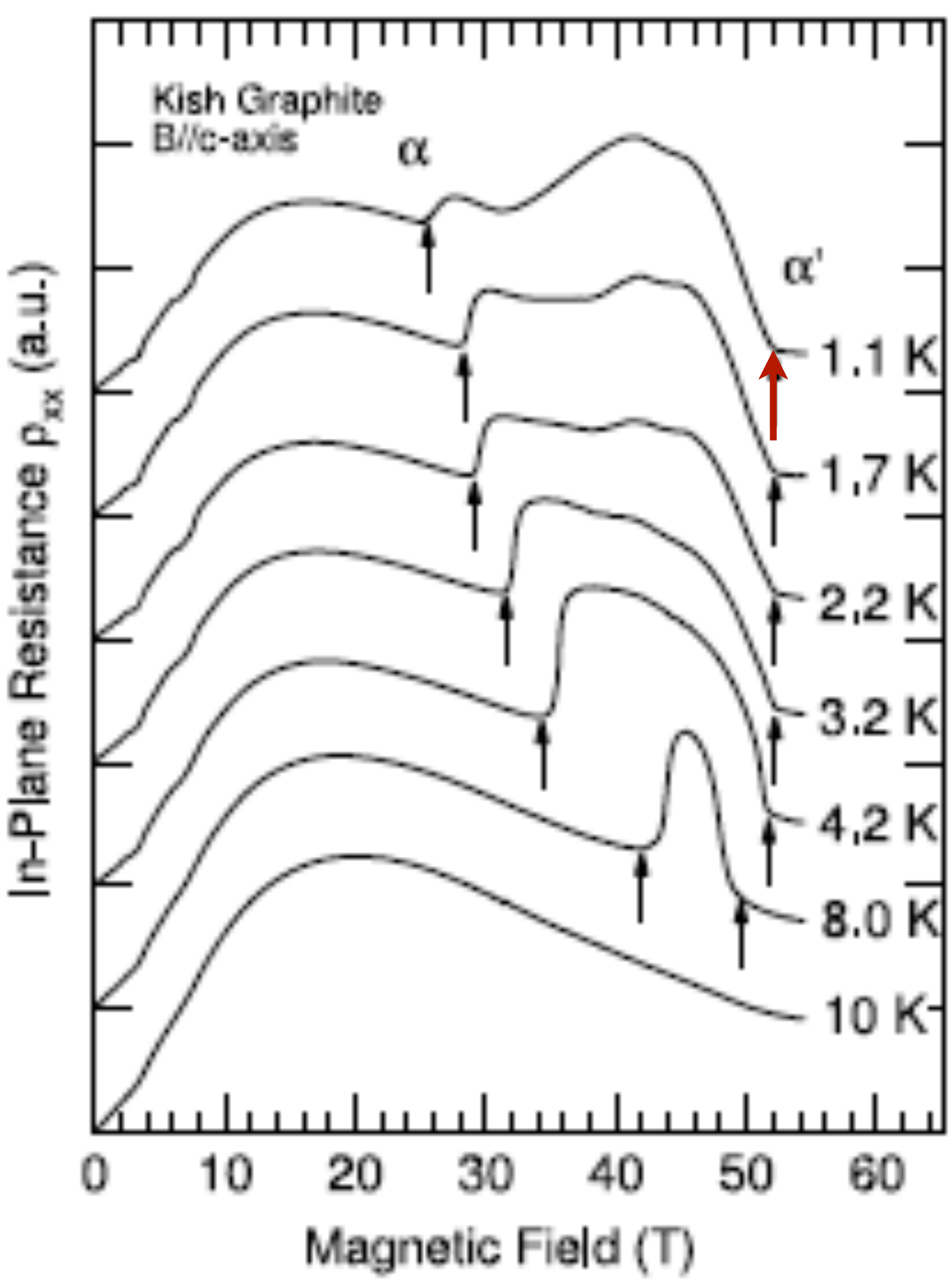
2015 : K. Akiba et al., arXiv:1503.04414
excitonic scenario
J. Phys. Soc. Jpn. 84, 054709-1-6 (2015)

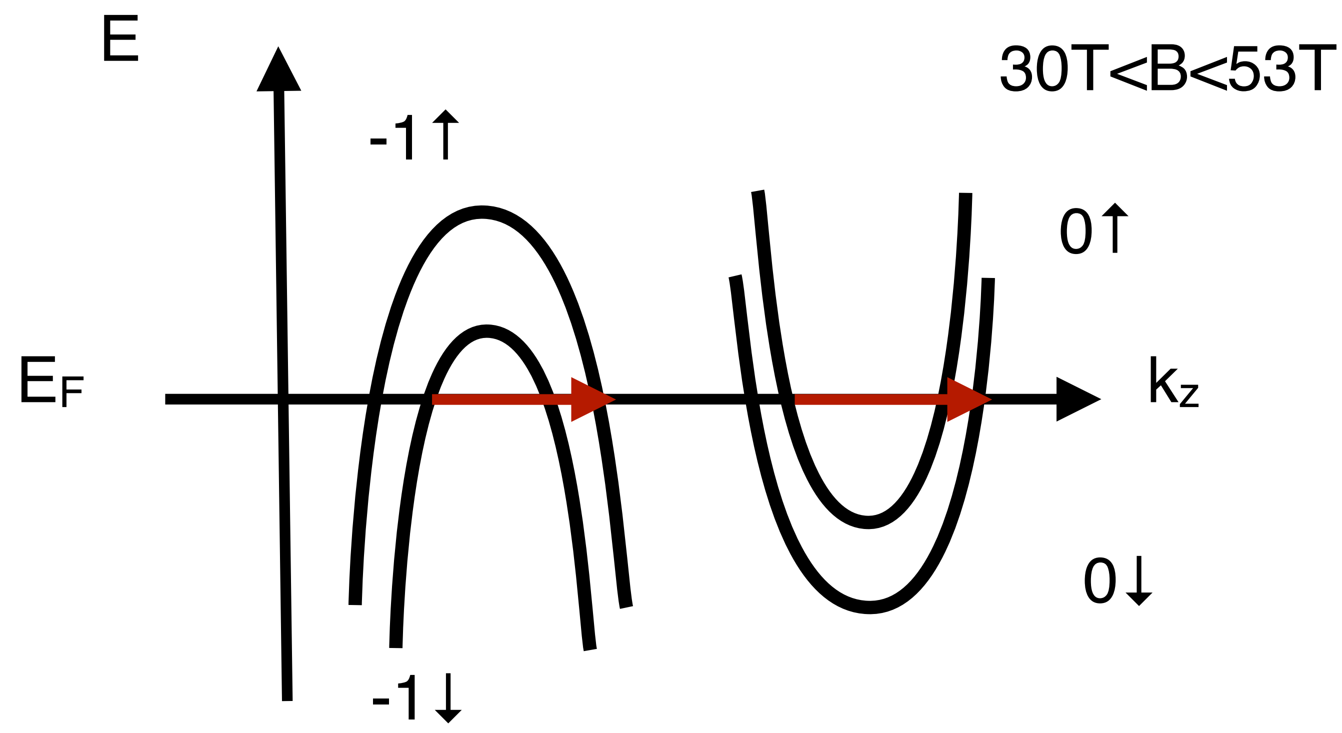
Graphite in the quantum limit regime

$$E_{n,s} = (\cancel{n} + \frac{1}{2})\hbar\omega_c + \frac{1}{2}\frac{k_z^2}{m} \pm \frac{1}{2} g\mu_B B^2$$

n=0

H. Yaguchi et al, PRL **81**,5193 (1998)





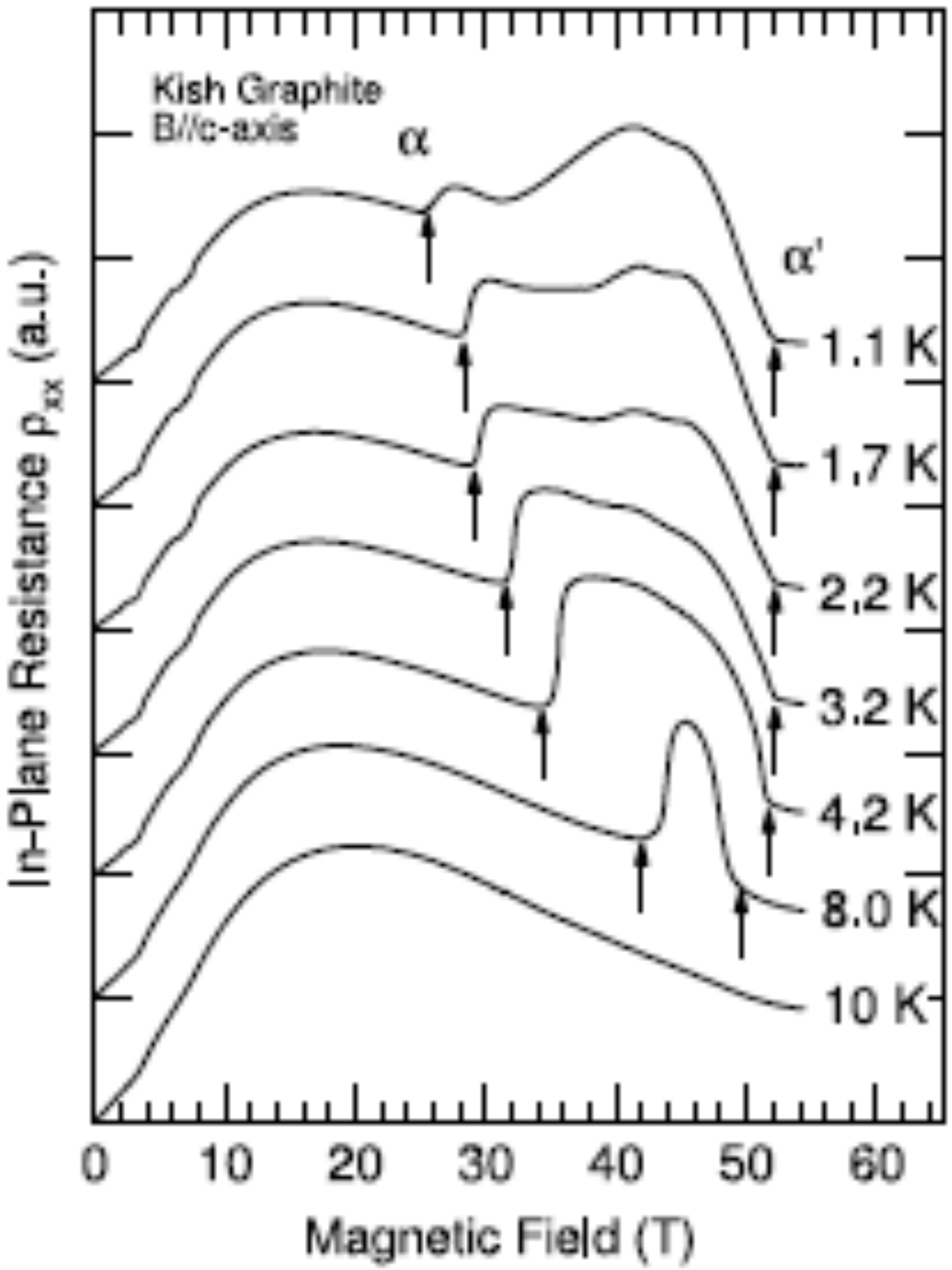
Nesting vector for both pockets
along the c axis (Yoshioka-Fukuyama scenario)

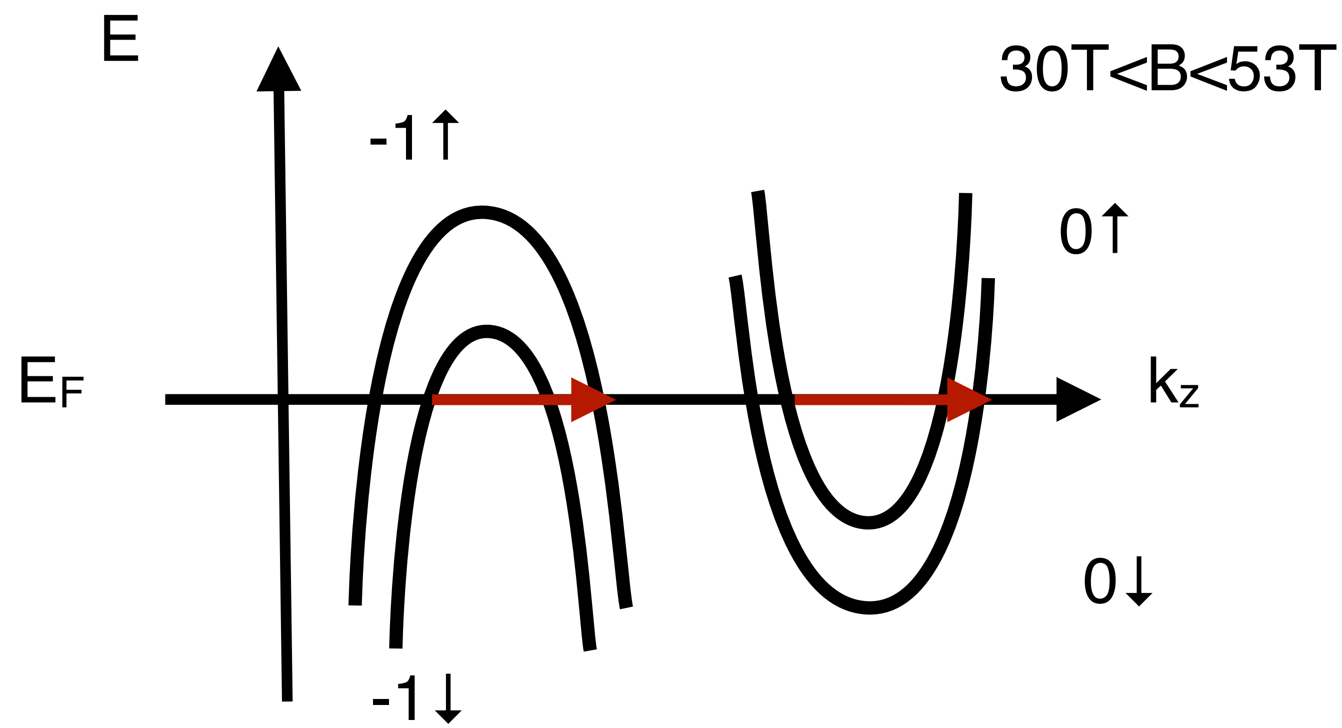
Graphite in the quantum limit regime

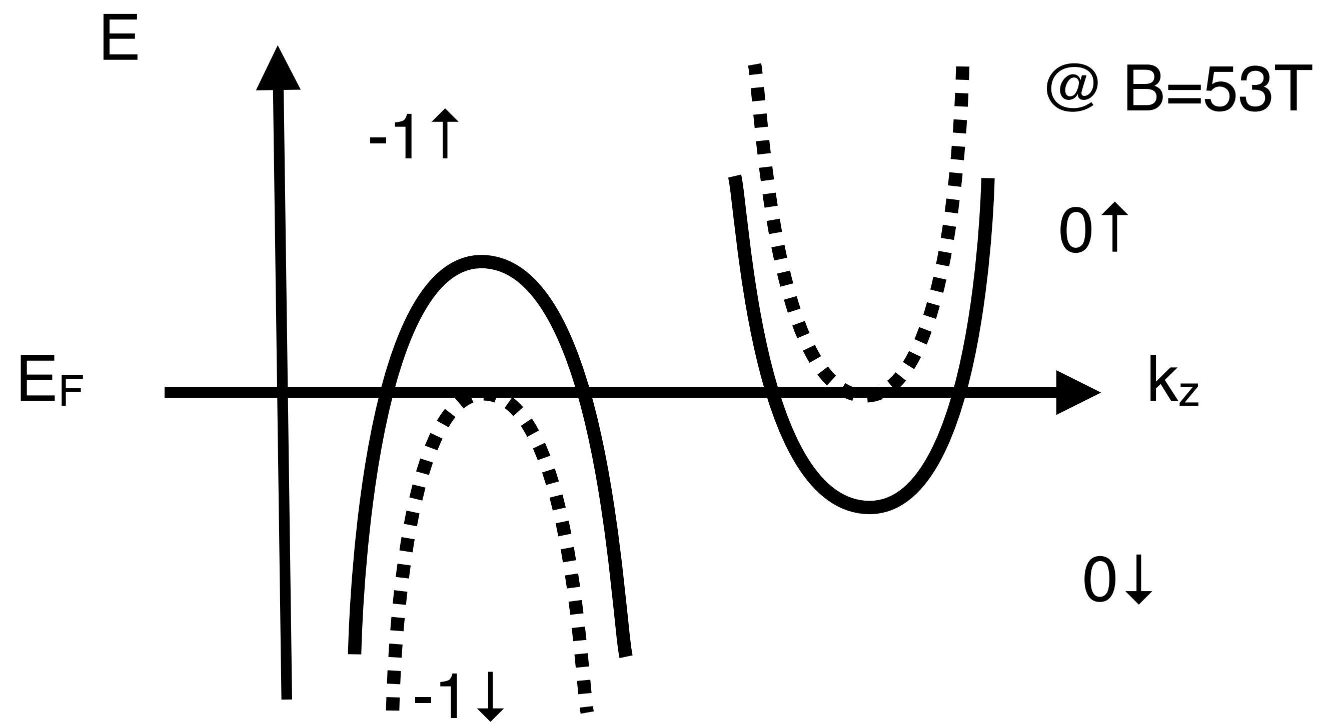
$$E_{n,s} = (\cancel{n} + \frac{1}{2})\hbar\omega_c + \frac{1}{2}\frac{k_z^2}{m} \pm \frac{1}{2}g\mu_B B^2$$

n=0

H. Yaguchi et al, PRL **81**,5193 (1998)



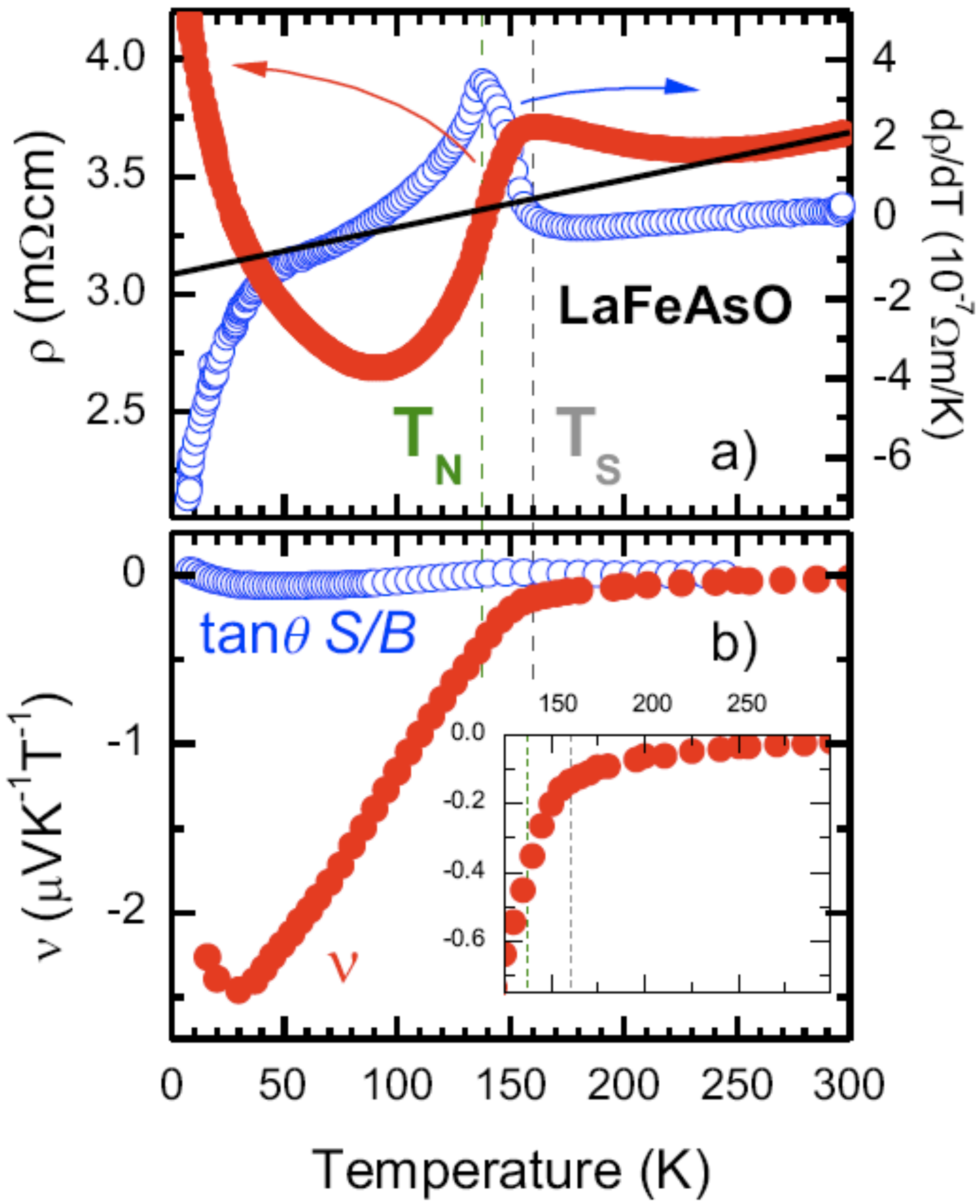


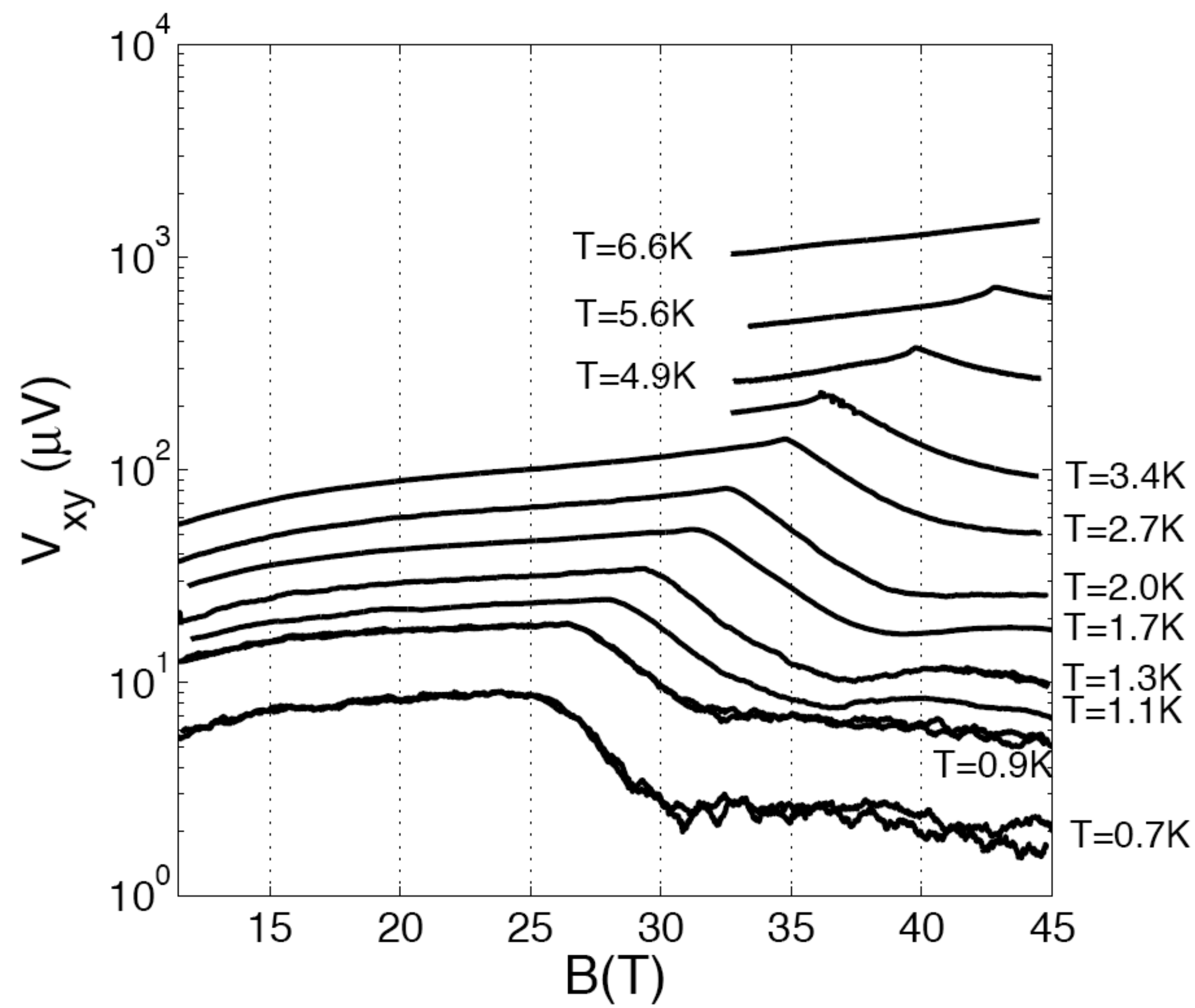


The re-entrance transition is associated with the crossing of the Landau levels (0,↑) of electrons and (-1,↓) of holes .

Graphite: origin of the field induced electronic instability ?

C. Hess, arxiv/1202.2959





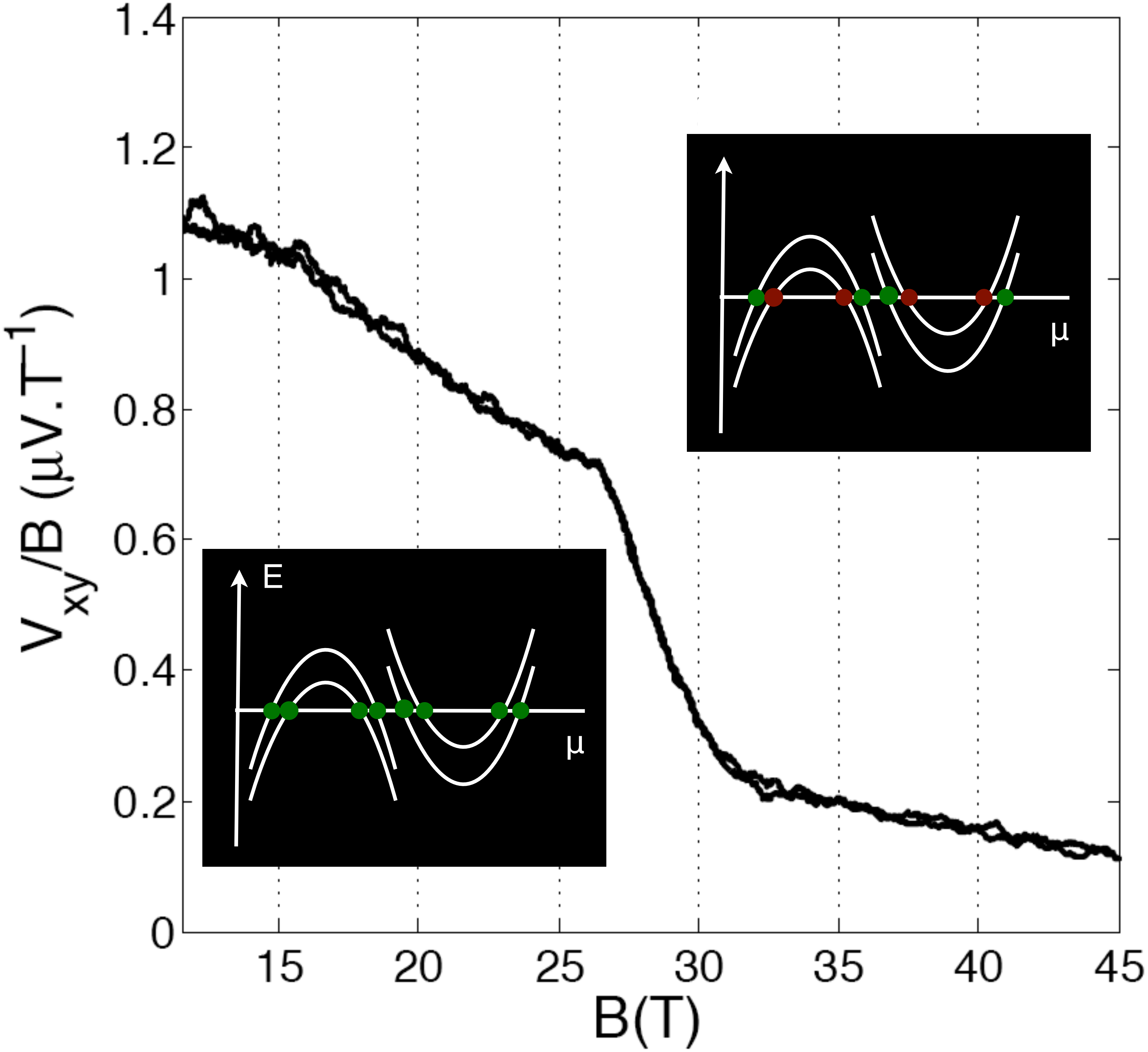
see also the case :

URu_2Si_2 : R. Bel et al., PRB **70**, 220501(R) (2004)

$PrFe_4P_{12}$: A.Pourret, PRL **96,** 176402 (2006)

Can a DW decrease the Nernst response in the QL regime?

Graphite: origin of the field induced electronic instability ?



$$E_{n,s} = (n + \frac{1}{2})\hbar\omega_c + \frac{1}{2}\frac{k_z^2}{m} \pm \frac{1}{2}g\mu_B B^2$$

When the chemical potential is far from the bottom of one of the Landau level, the Nernst effect is dominated by the green spots of each of the (full) Landau levels.

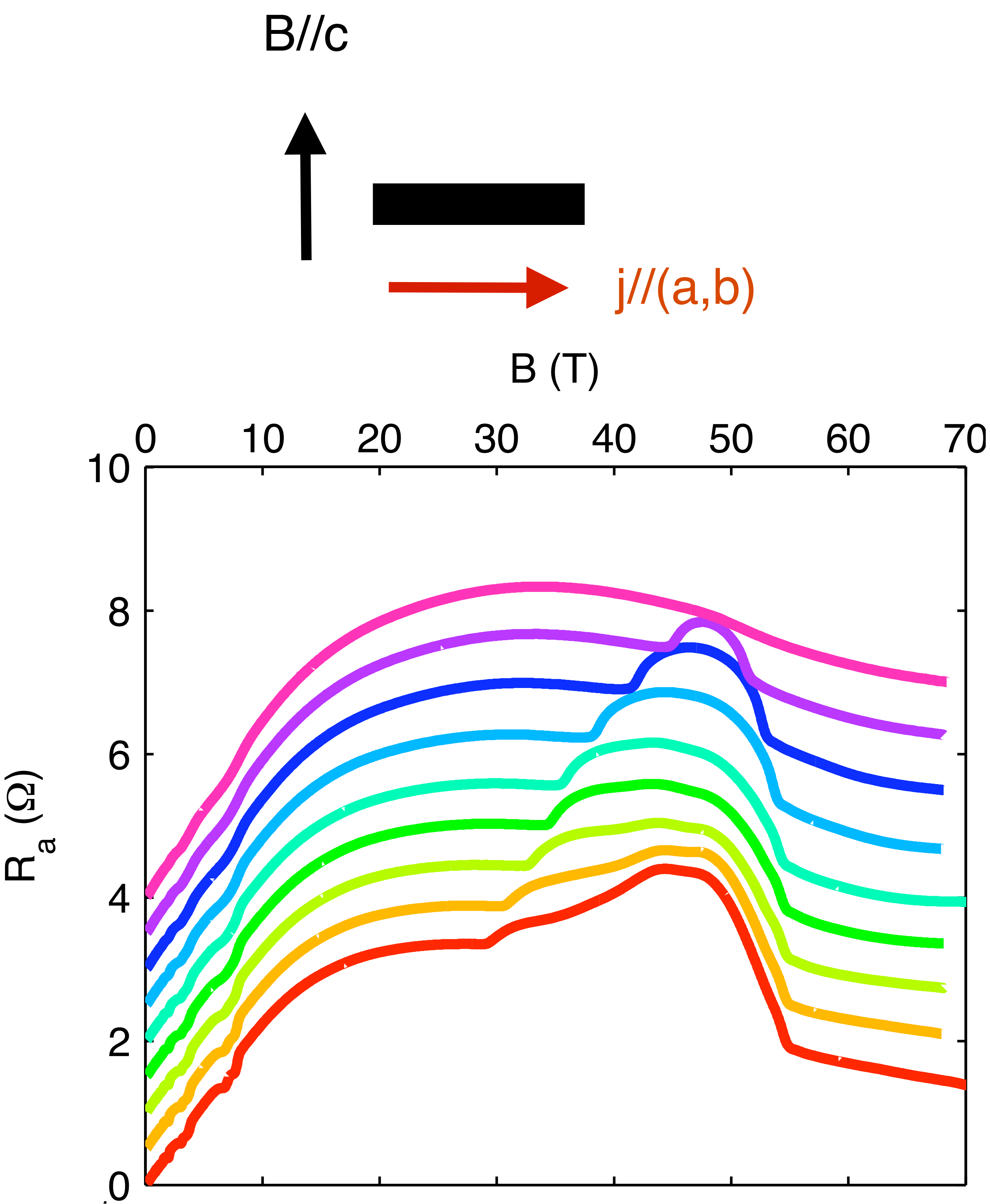
In a presence of DW, we lost the contribution in the Nernst response of the Landau levels where the gap is opening

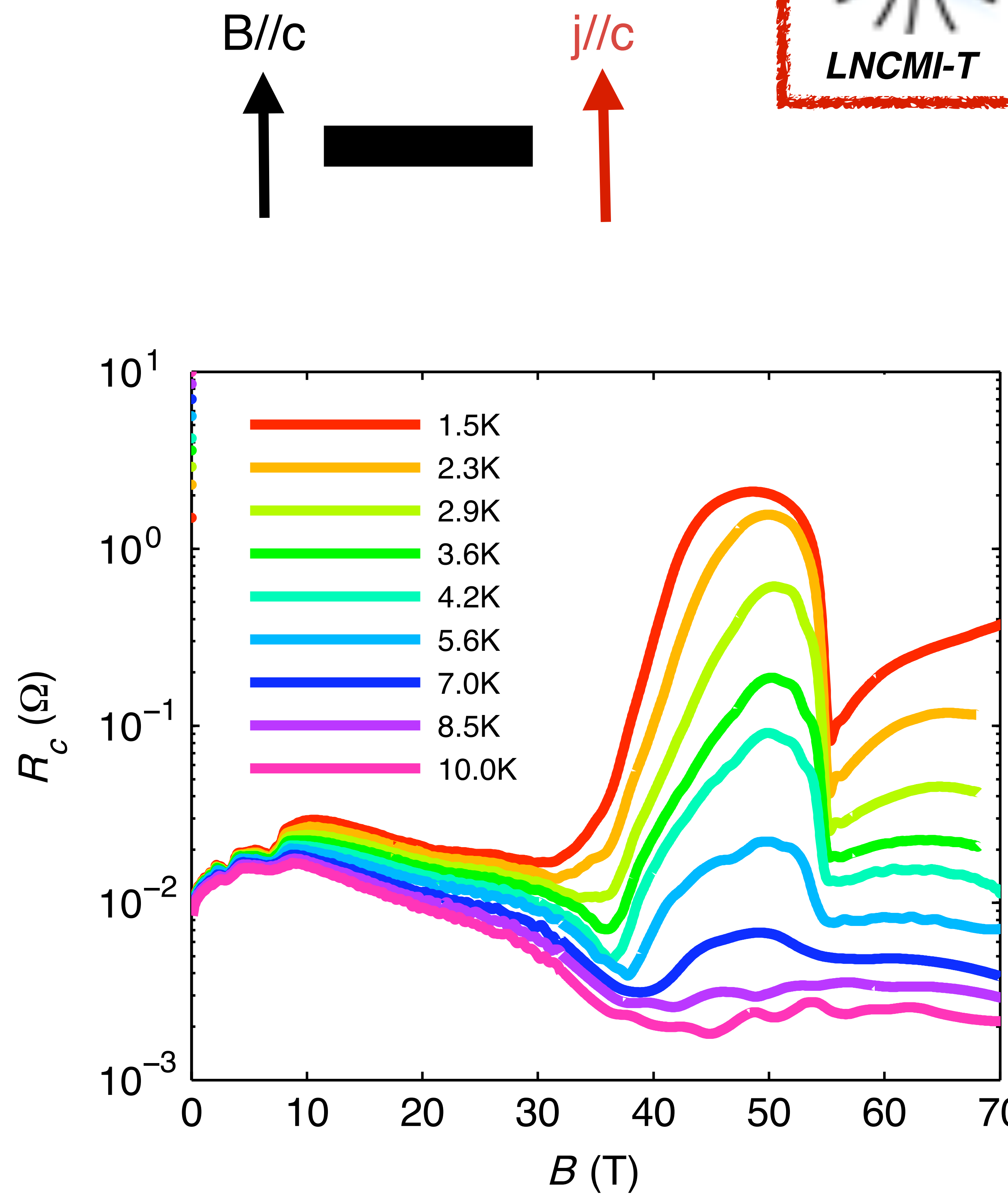
The DW scenario in the QL regime can explain the decrease of the Nernst coefficient

Electrical transport : R_{xx} vs R_{zz}

Kish Graphite

LNCMI-T

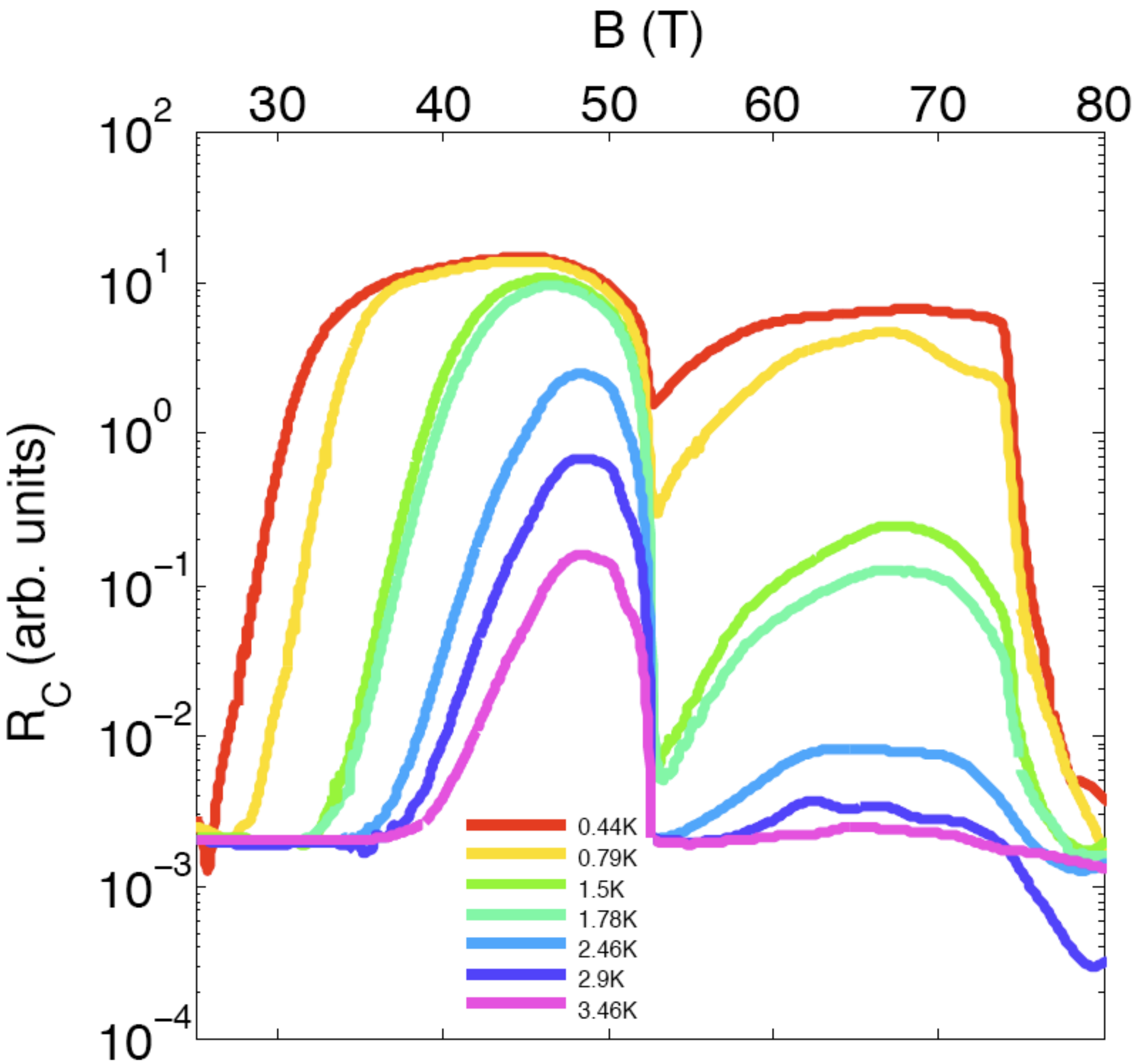


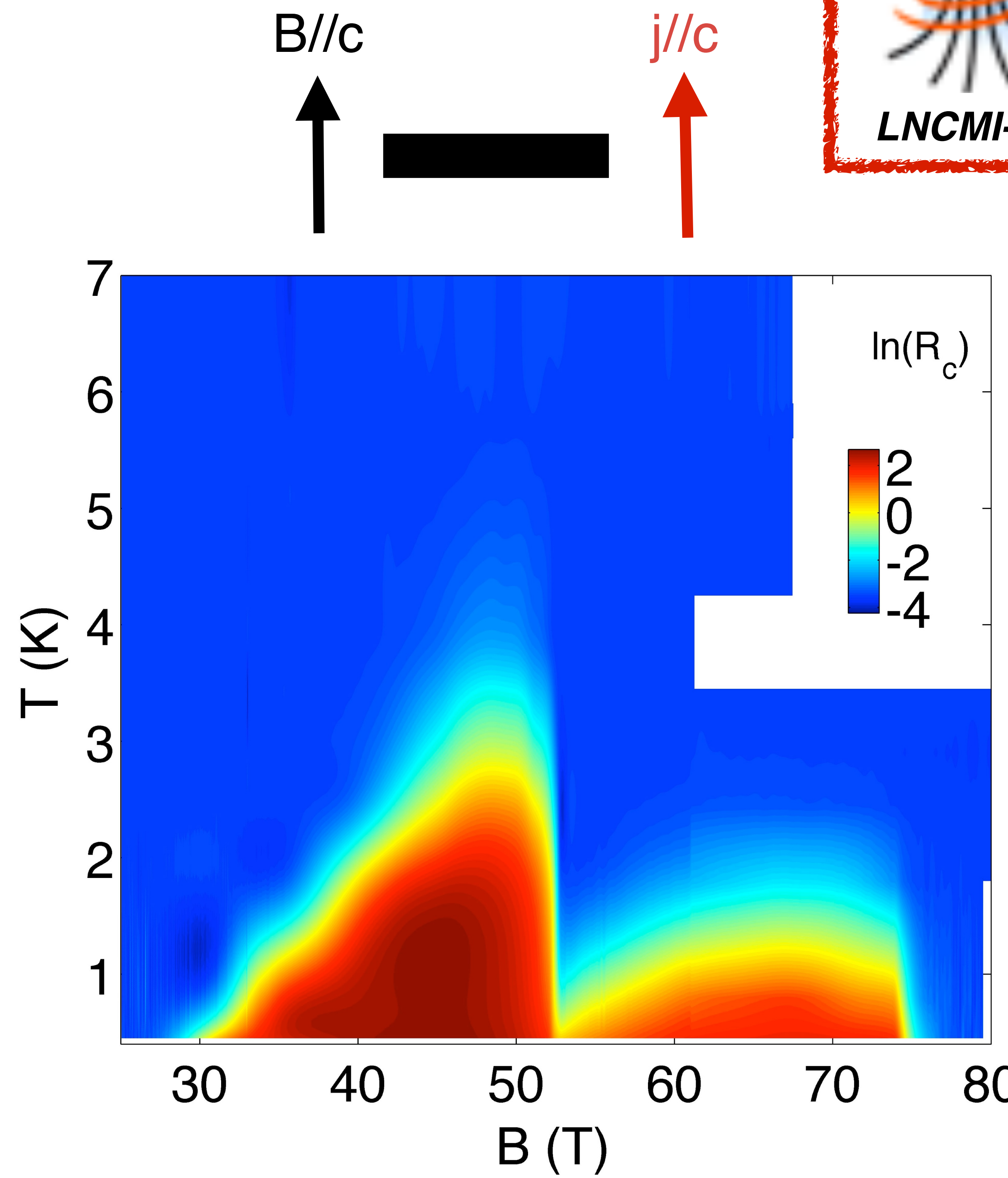


B. Fauqué et al, PRL **110**,266601 (2013)

Electrical transport : R_{zz}

Kish Graphite





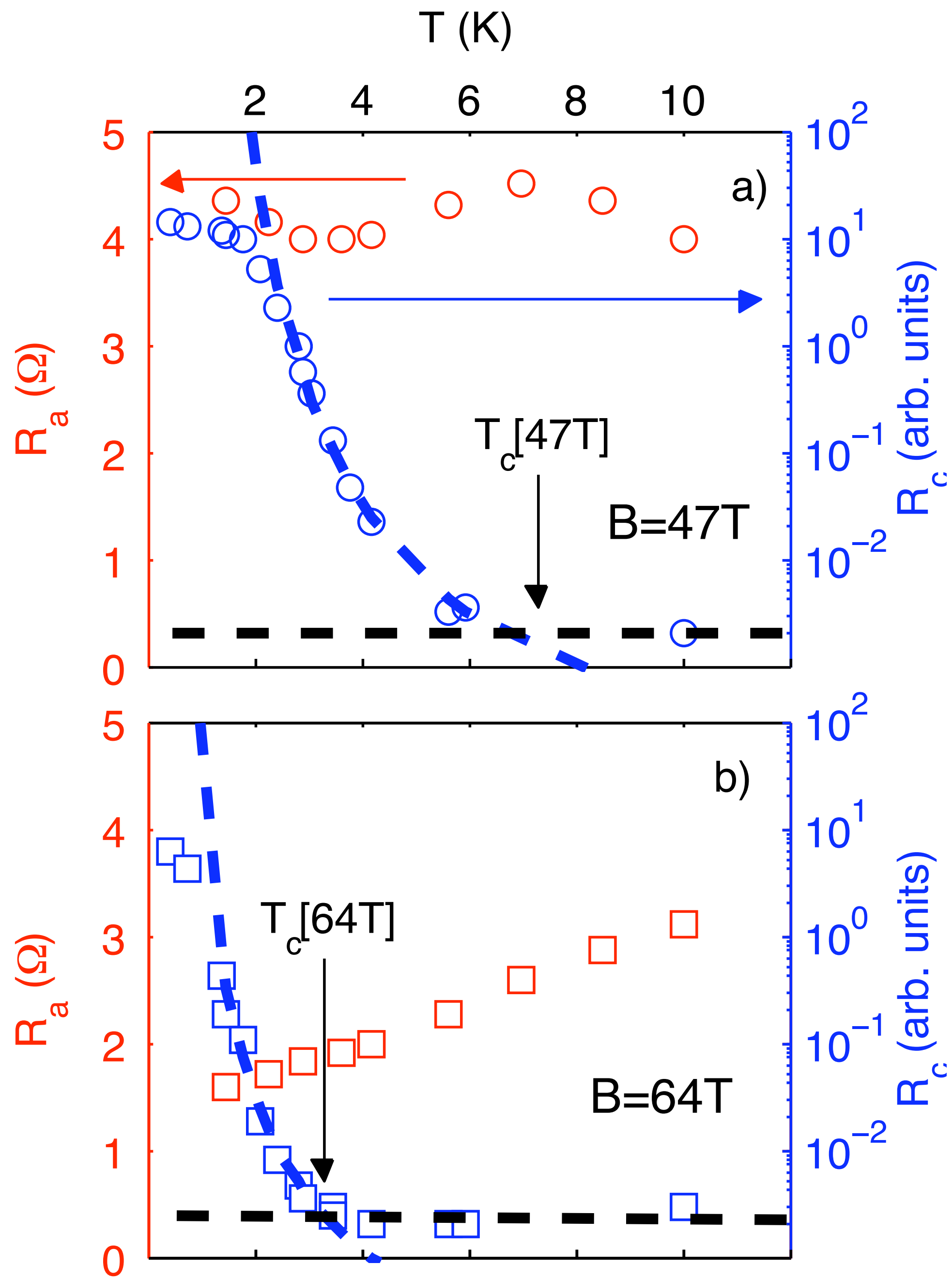
There is still a life above 53T !

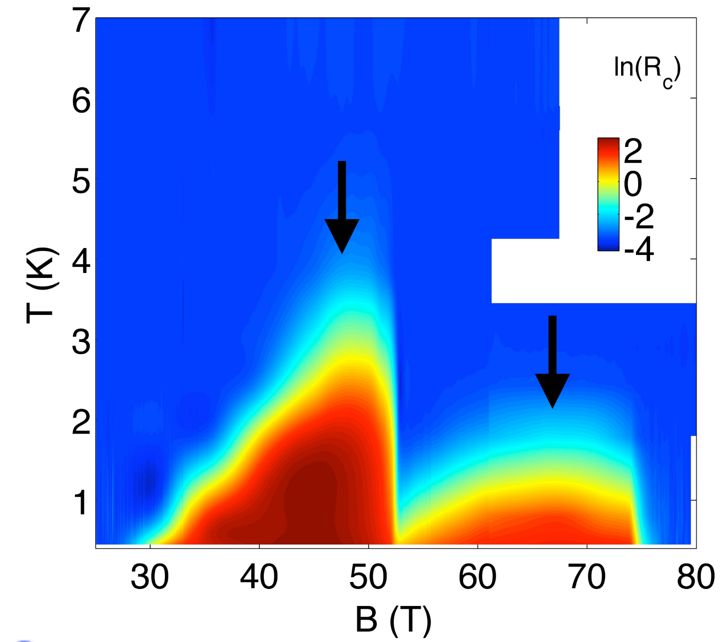
A second transition induced by a magnetic field in Graphite

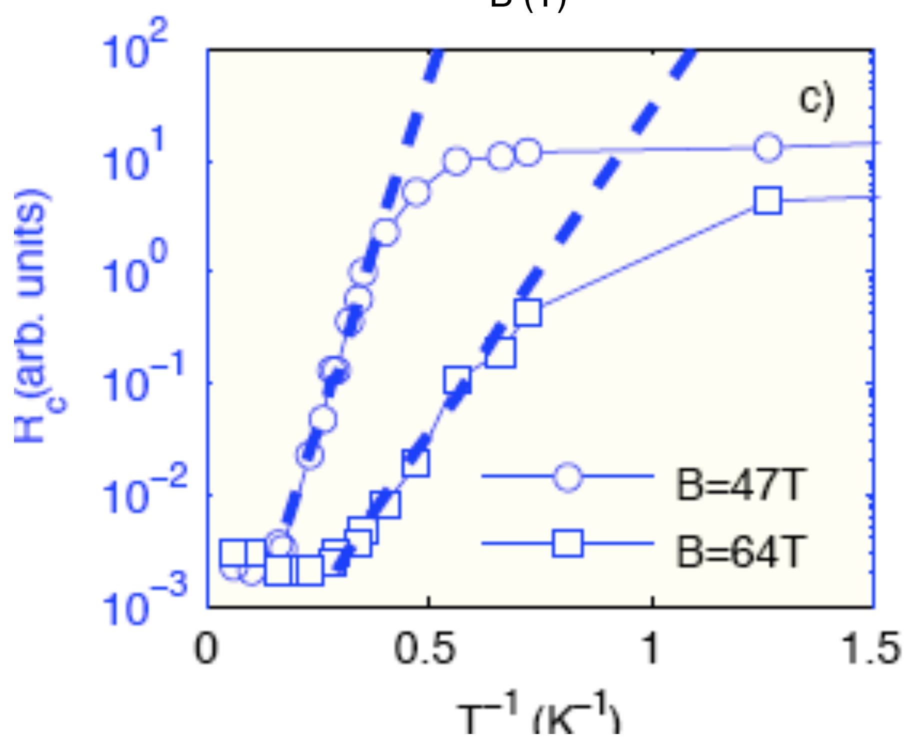
B. Fauqué et al, PRL **110**,266601 (2013)

Electrical transport : R_{xx} vs R_{zz}

$$R_c \propto \exp(\frac{2\Delta}{k_B T})$$





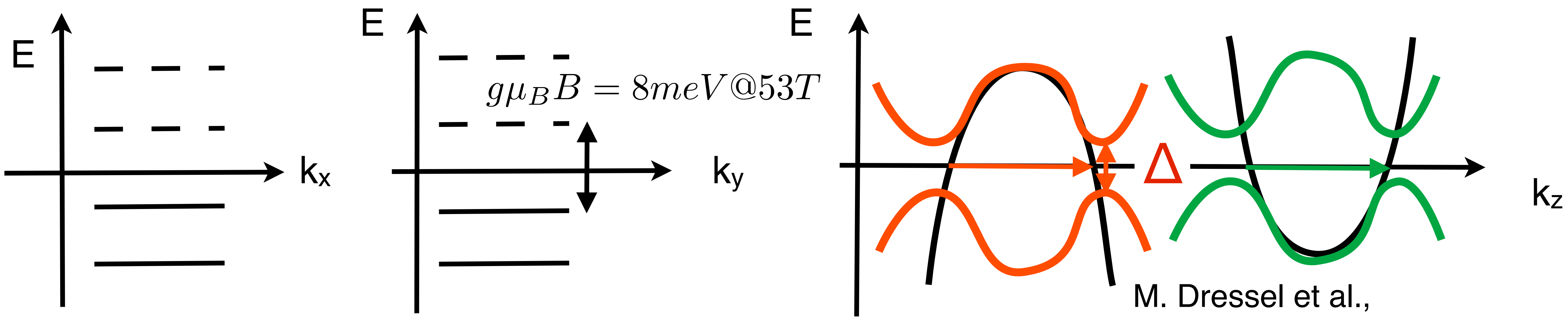


c-axis : all the Landau levels are gapped

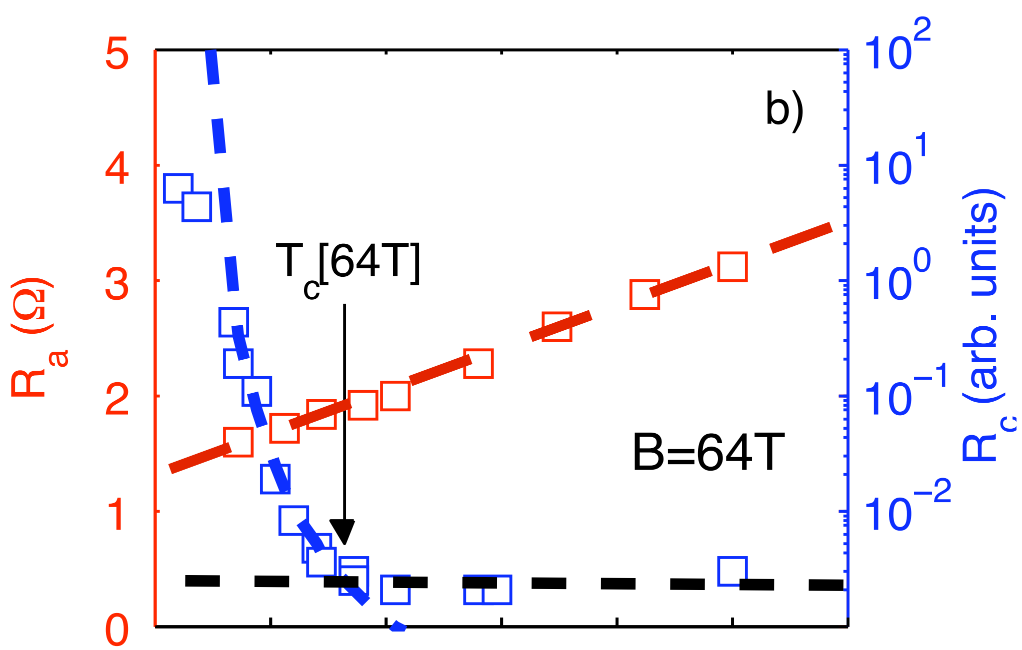
$$2\Delta[47T] = 2.4meV \qquad 2\Delta[64T] = 1.1meV$$

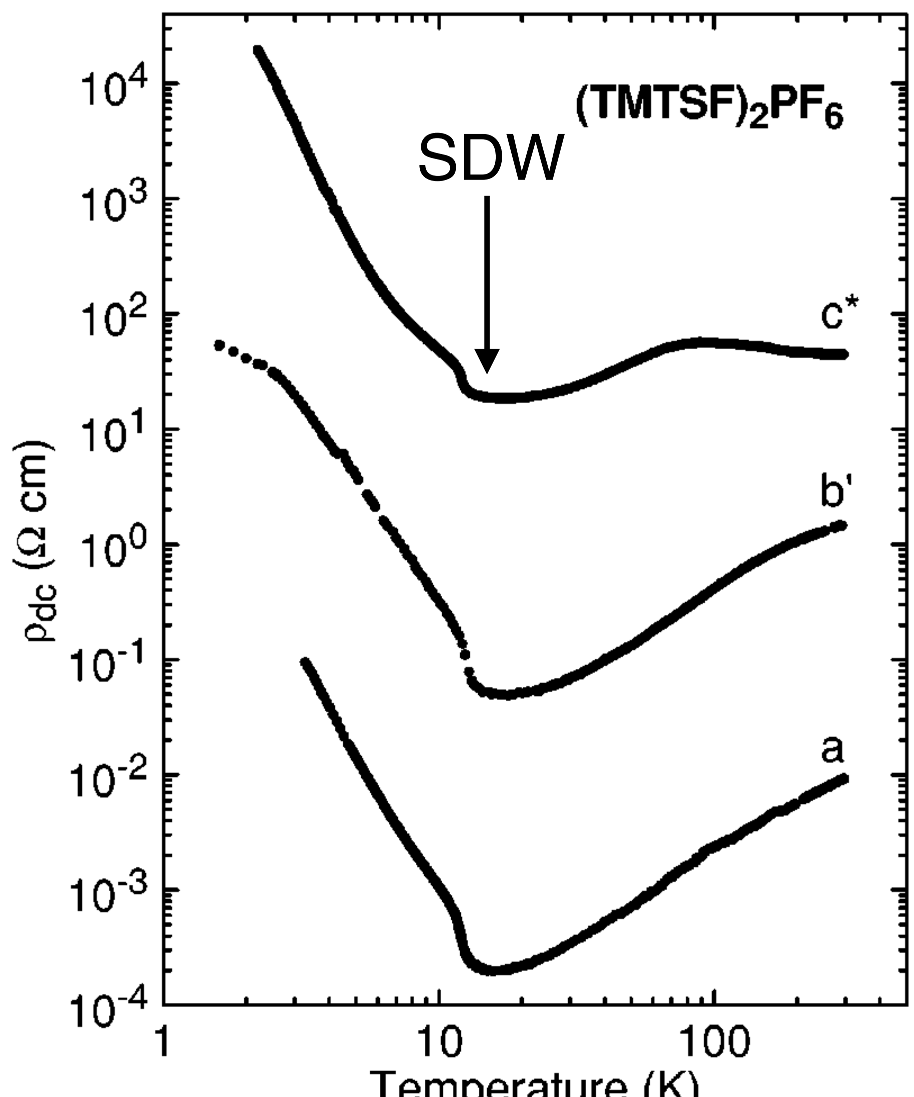
Electrical transport : R_{xx} vs R_{zz}

Kish Graphite



M. Dressel et al.,
Phys. Rev. B **71**, 075104 (2005)

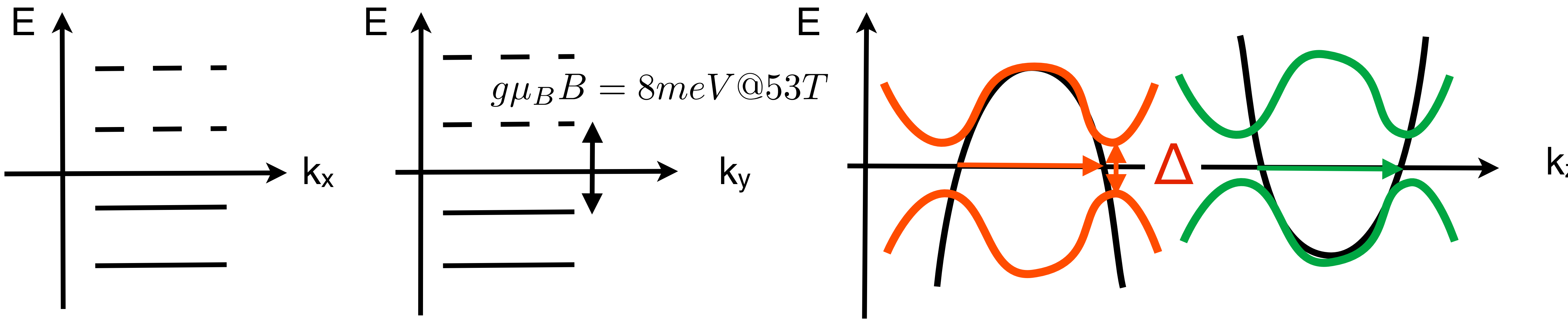


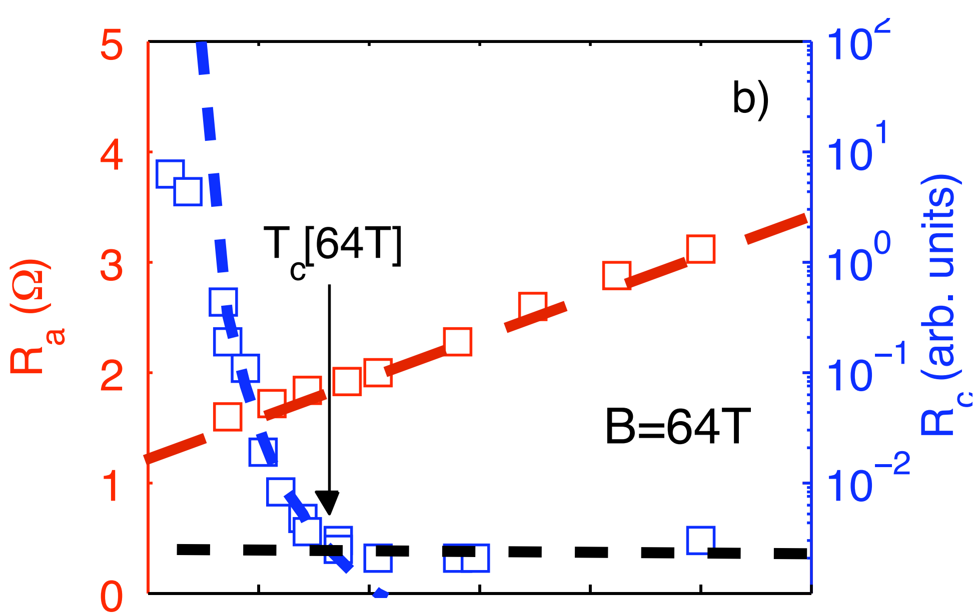


Although the electronic spectrum in the two field induced states is gapped, the in-plane resistance is metallic !!

Electrical transport : R_{xx} vs R_{zz}

Kish Graphite





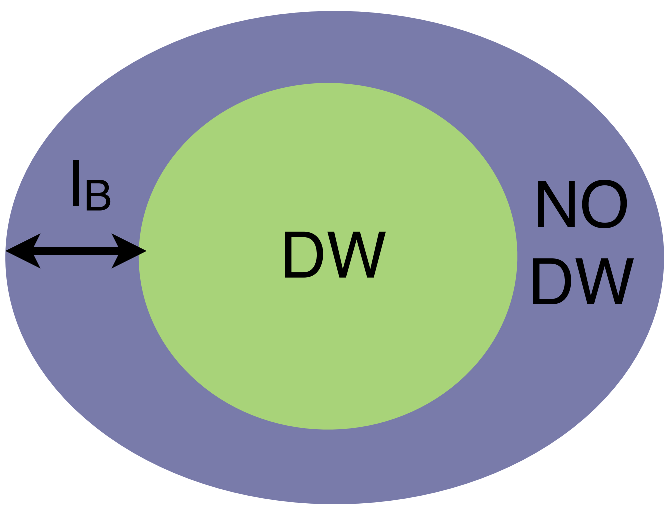
$$\sigma_{xx} = n * \sigma^0_{xx}$$

$$\sigma^0_{xx} \approx \frac{e^2}{h}$$

n=150000 layers

$R_{xx} \simeq 0.2\Omega$

$$l_B = \sqrt{\frac{\hbar}{eB}} \approx 35\mathring{A}$$



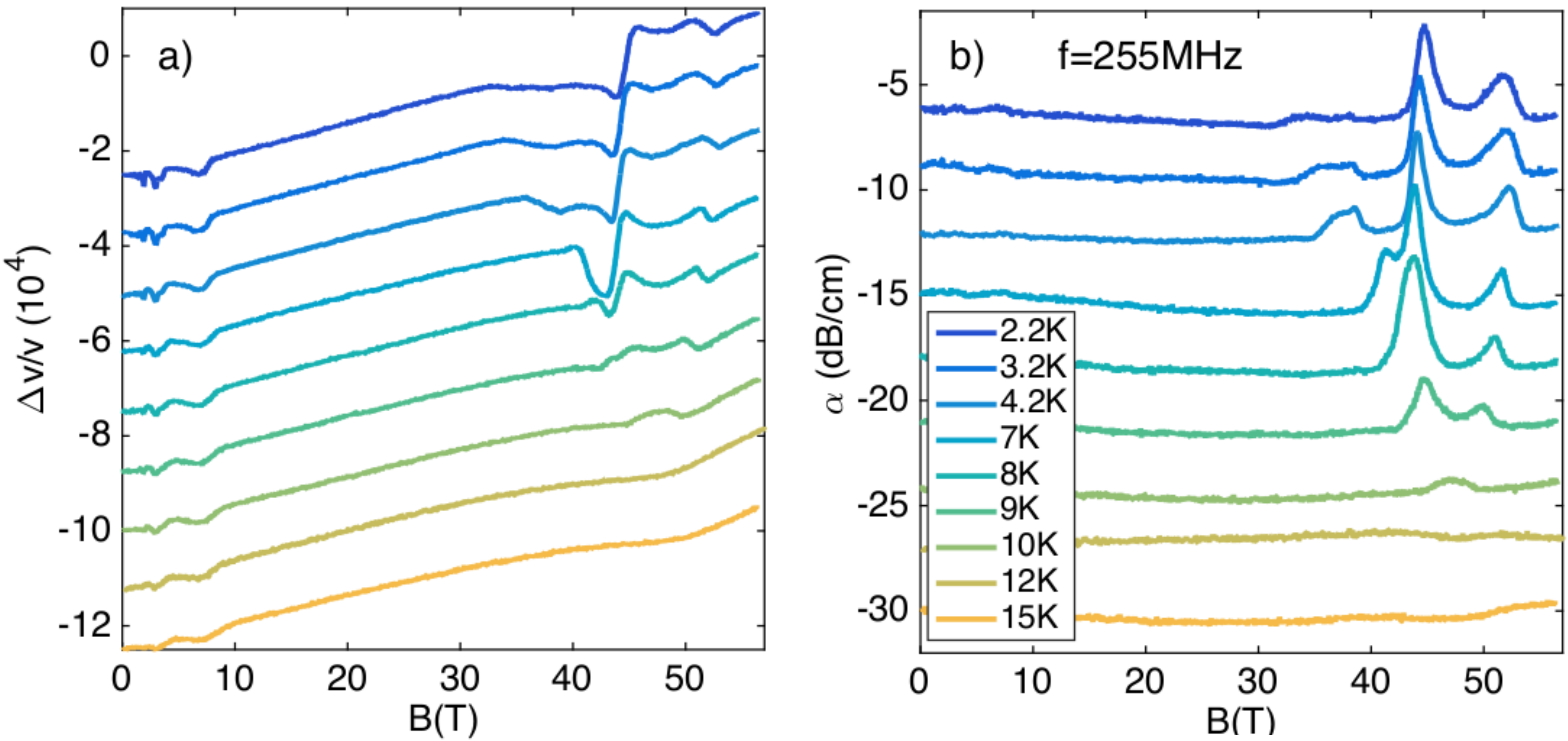
B. Fauqué et al, PRL **110**,266601 (2013)

weak 3D topological phase

Ultrasound measurements

D. Le Boeuf and al., Nat Com (2017)

Longitudinal mode : **B//q//c** f=255Mhz

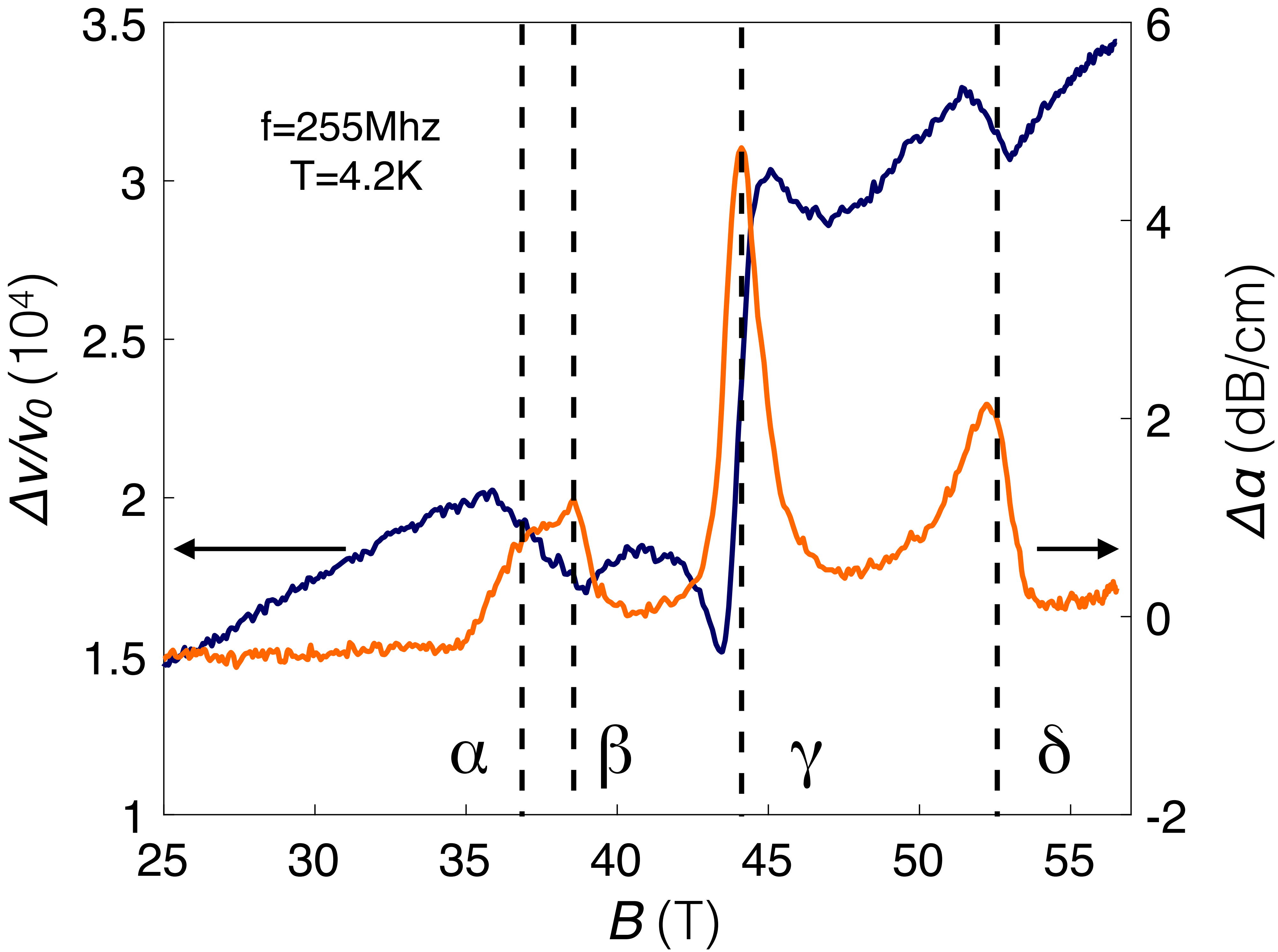


$v=(c_{33}/\rho)^{1/2}$

$\Delta v/v=(v(B)-v(0))/v(0)=1/2\Delta c_{33}/c_{33}(0)$

Ultrasound measurements

D. Le Boeuf and al., Nat Com (2017)



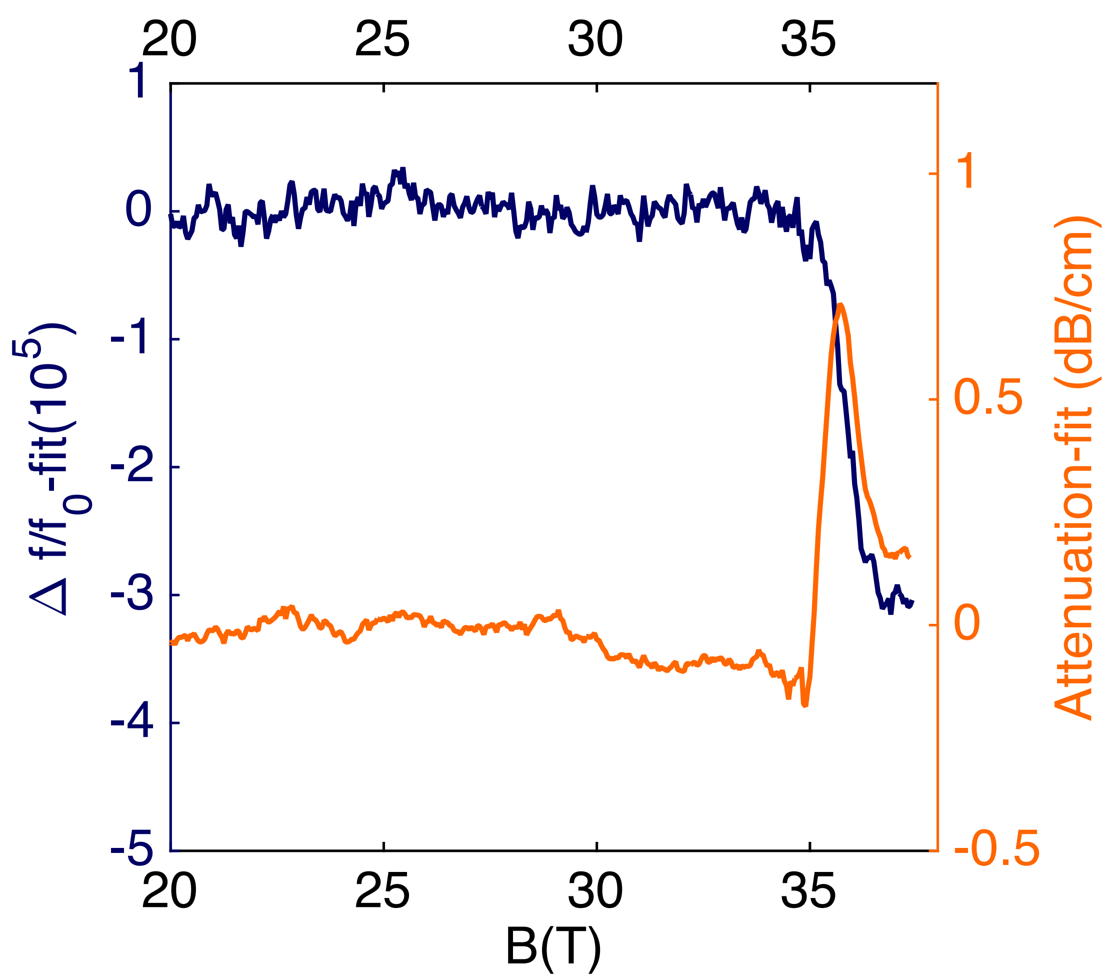
A succession of thermodynamic electronic phase transitions with a large lattice response !

α-transition : A second order phase transition

D. Le Boeuf and al., Nat Com (2017)

Erhenfest relationships

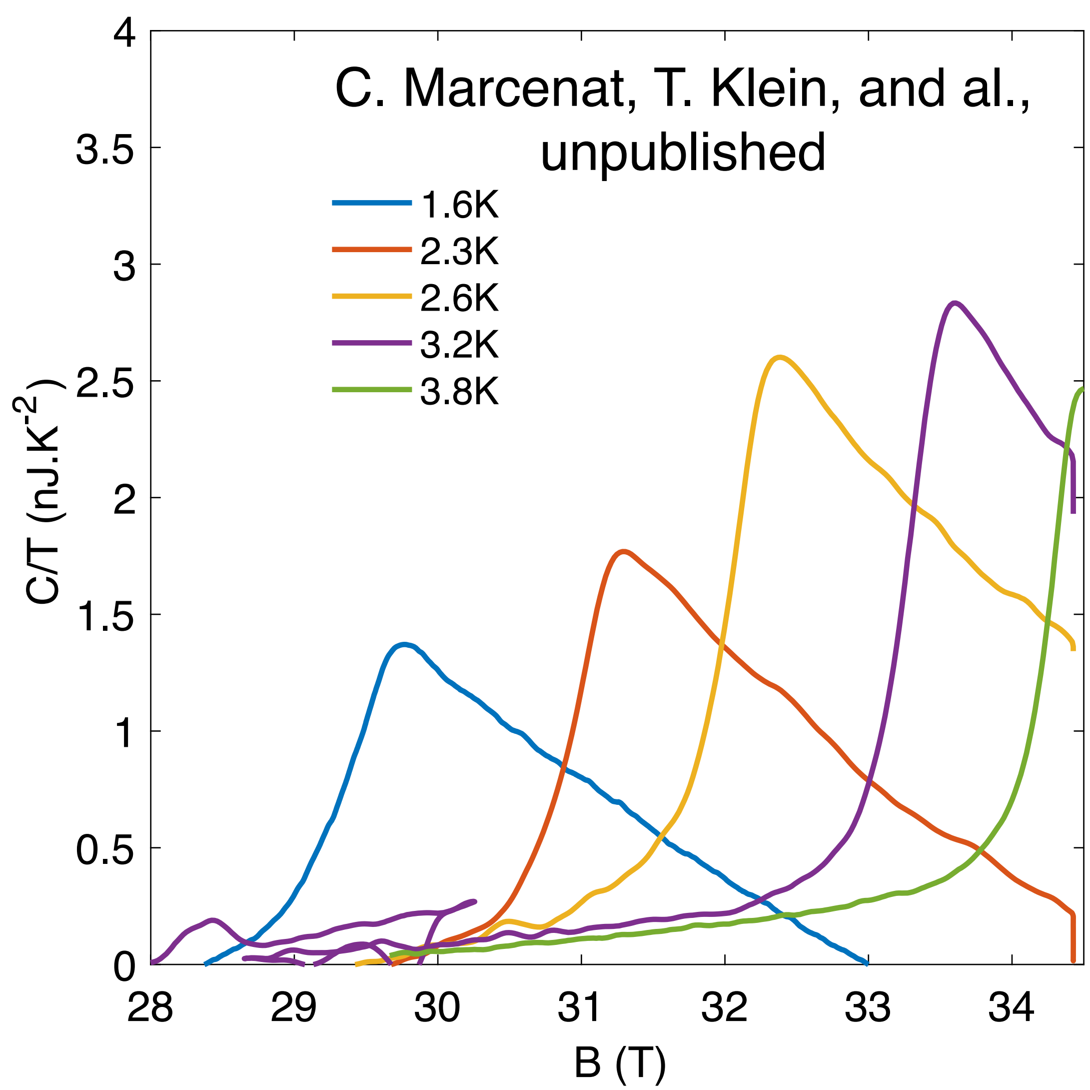
$$\Delta c_{ii}(T_c) = -\frac{\Delta C_p(T_c)}{V_{\mathrm{mol}}T_c}\left(\frac{\mathrm{d}T_c}{d\varepsilon_i}\right)^2$$



Negative jump of v
=> >0 jump in the specific heat

We do find a jump
in the specific heat !

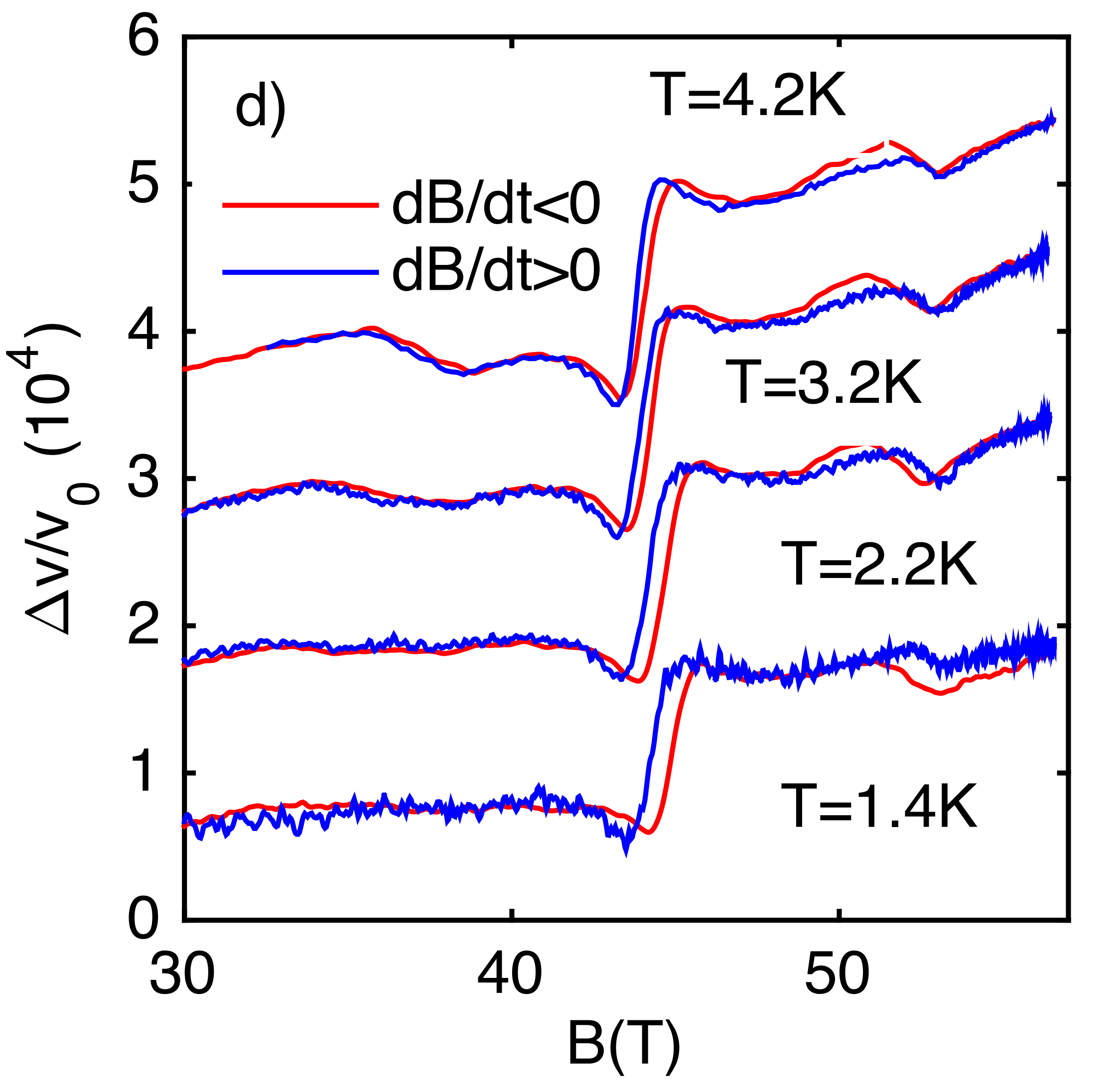
LNCMI- G/T



γ-transition : first order transition from ICDW to CCDM

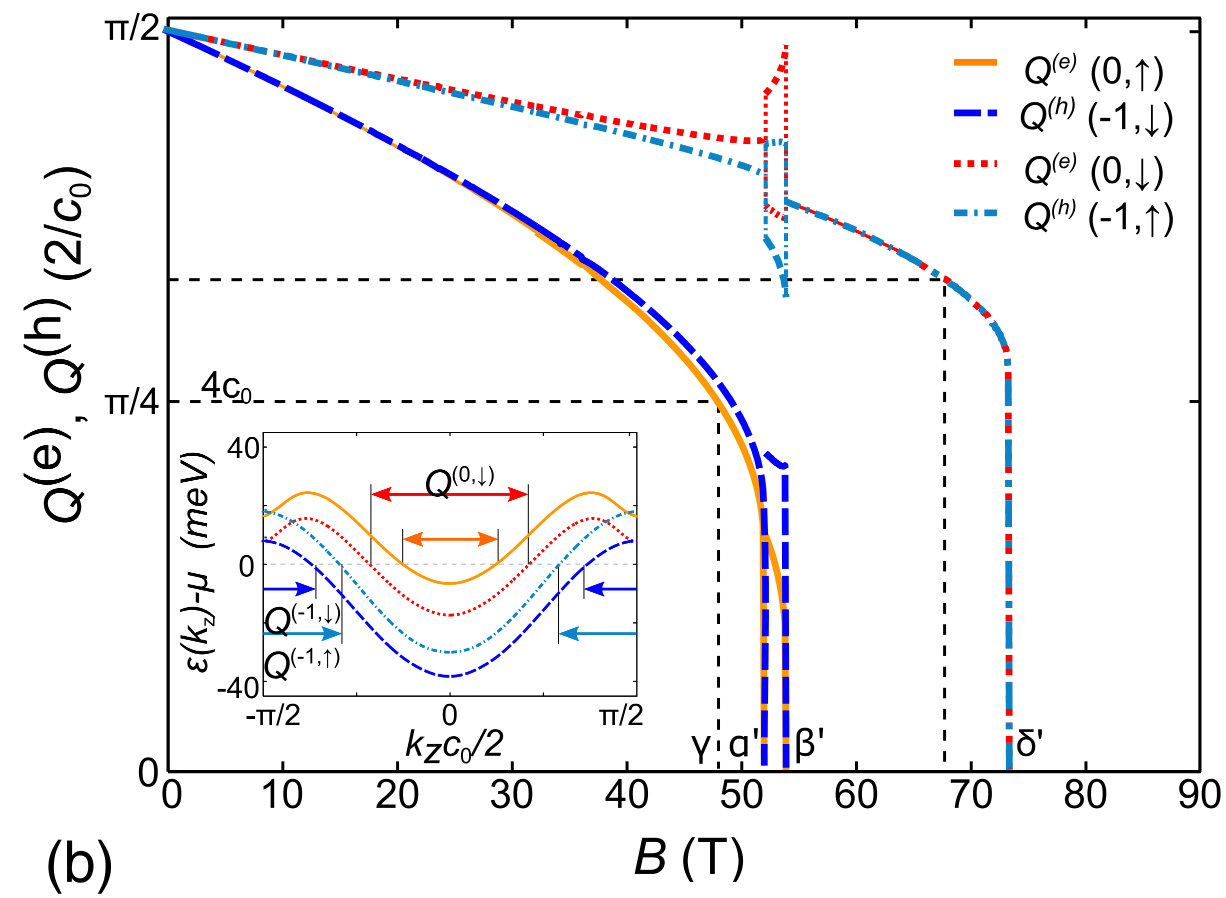
D. Le Boeuf and al., Nat Com (2017)

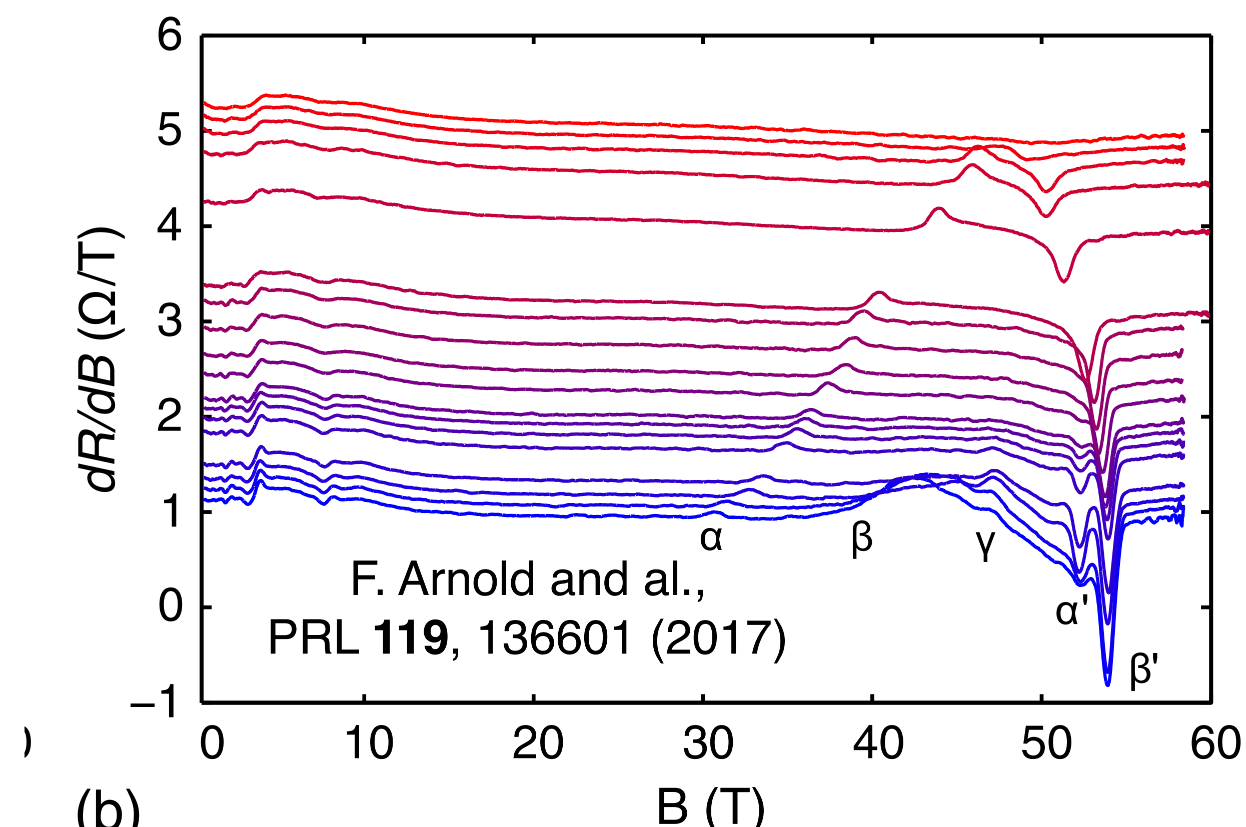
Hysteretic behaviour
observed at γ-transition



γ-transition :
Lockin transition of the α-transition ?

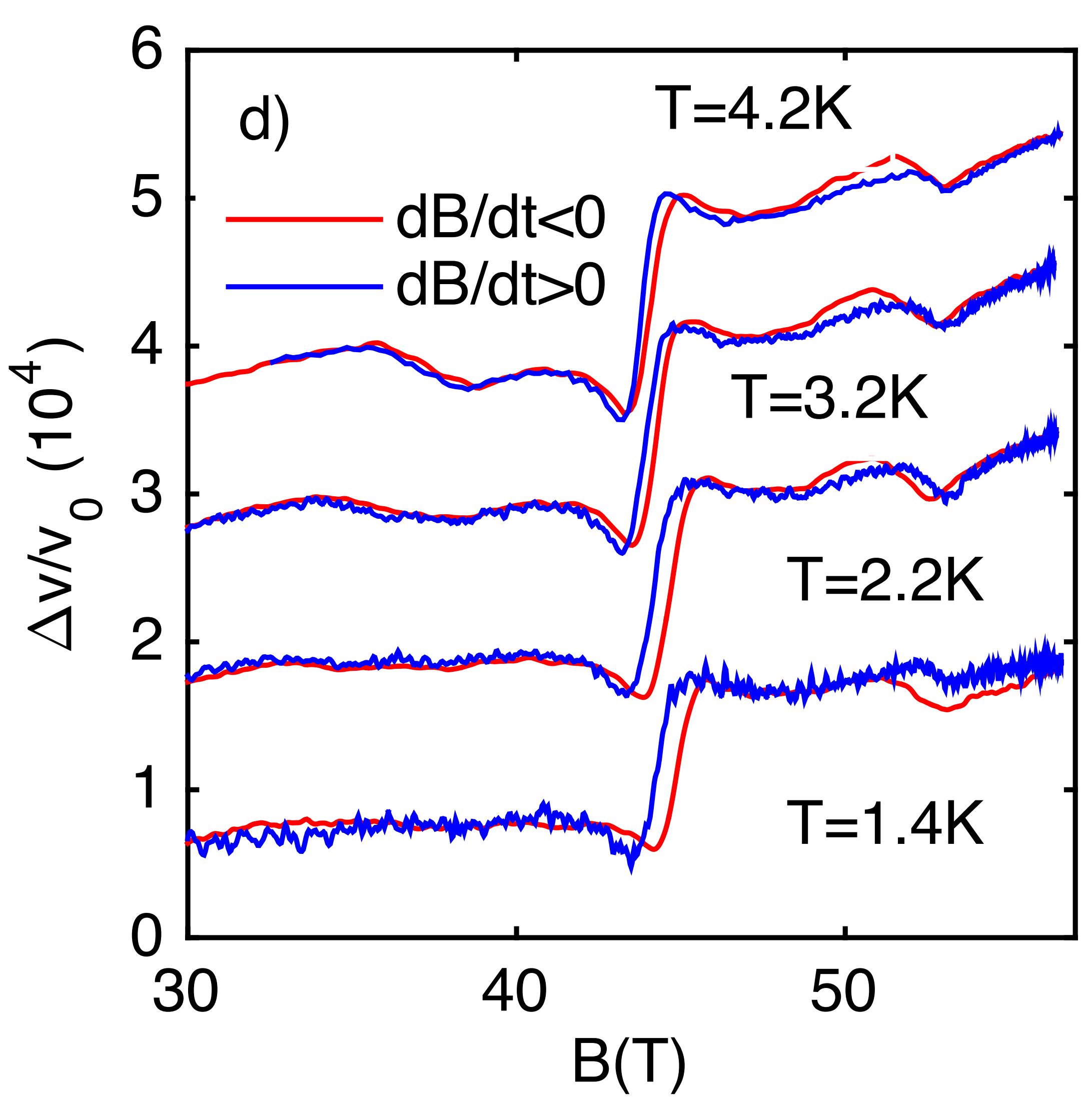
Nesting vector for two CDW phases

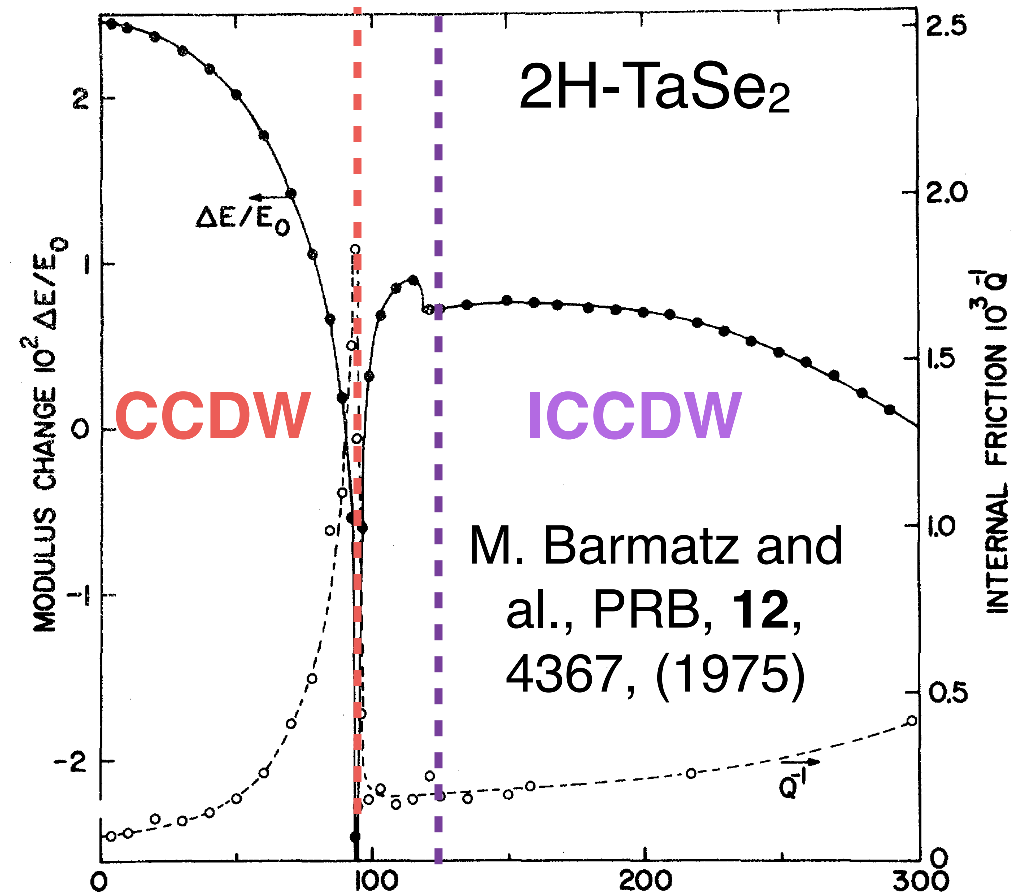


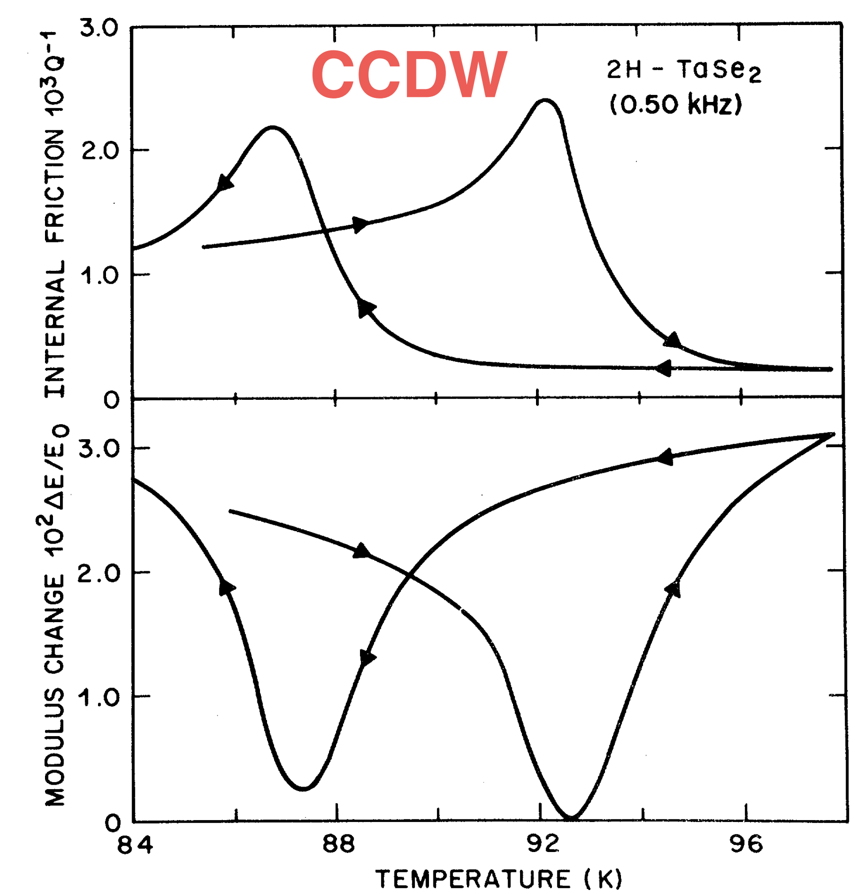


γ-transition : first order transition from ICDW to CCDM

Hysteretic behaviour observed at γ-transition



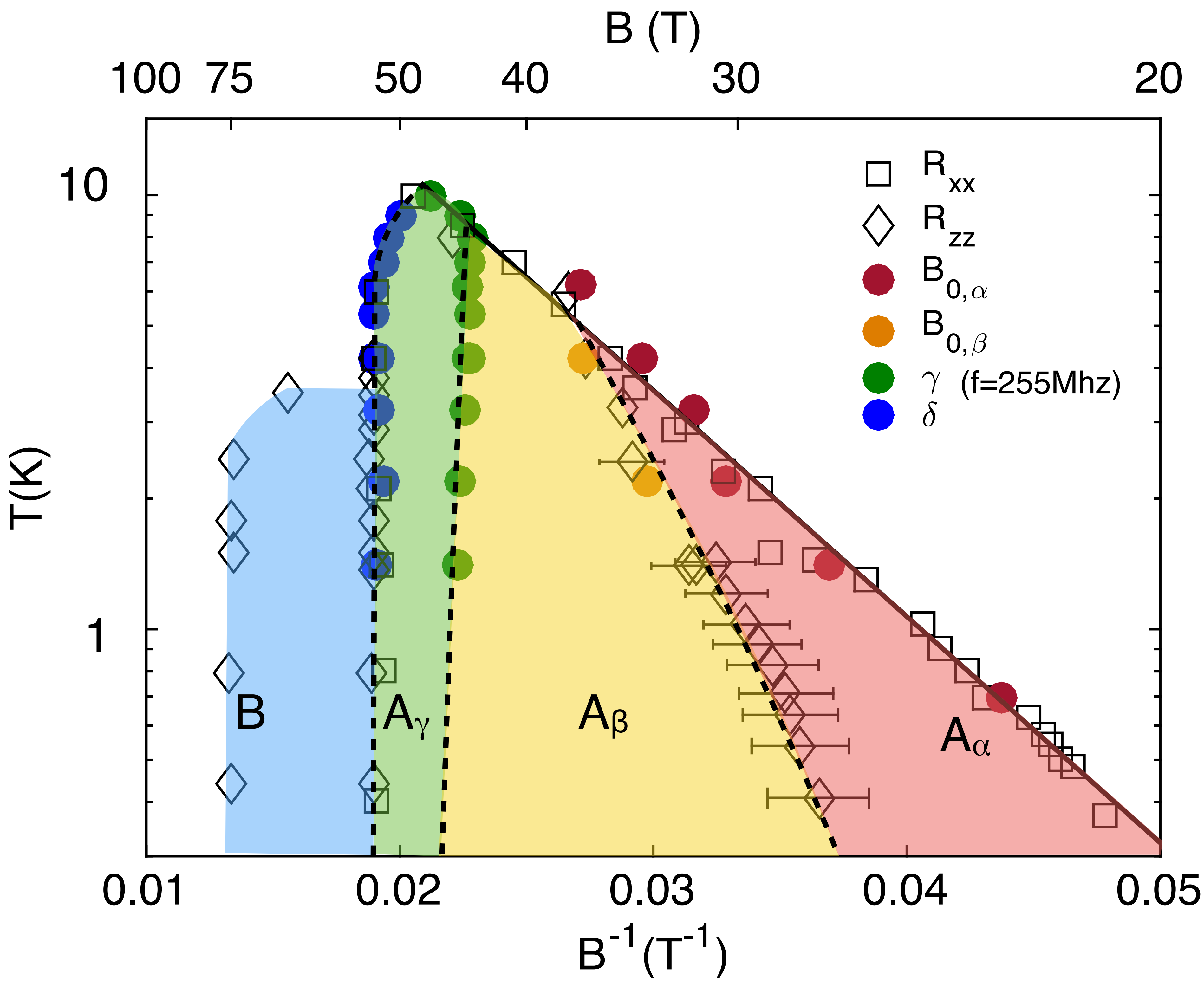




γ-transition :
from IC to C CDW phase ?

Ultrasound measurements :

D. Le Boeuf and al., Nat Com (2017)

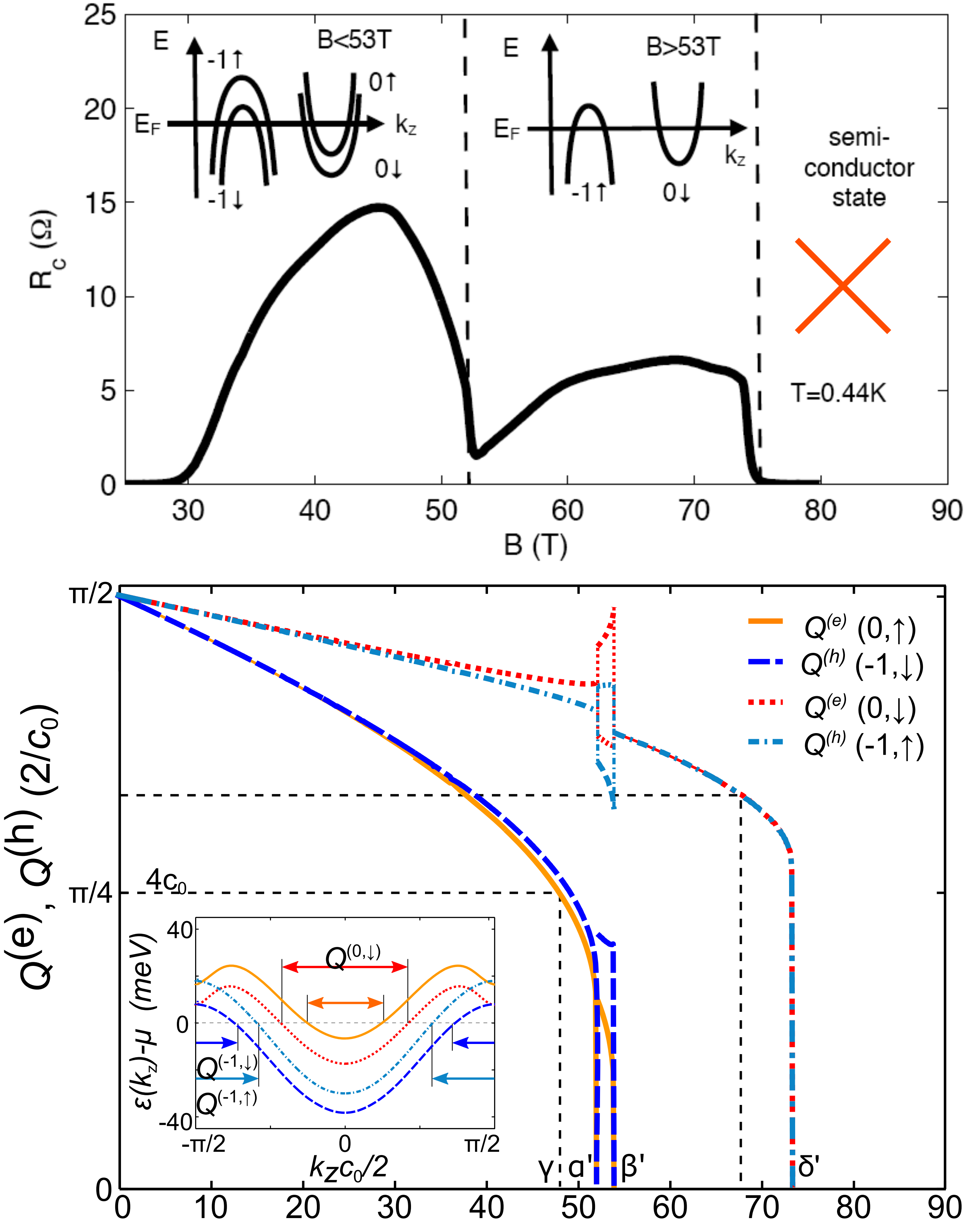


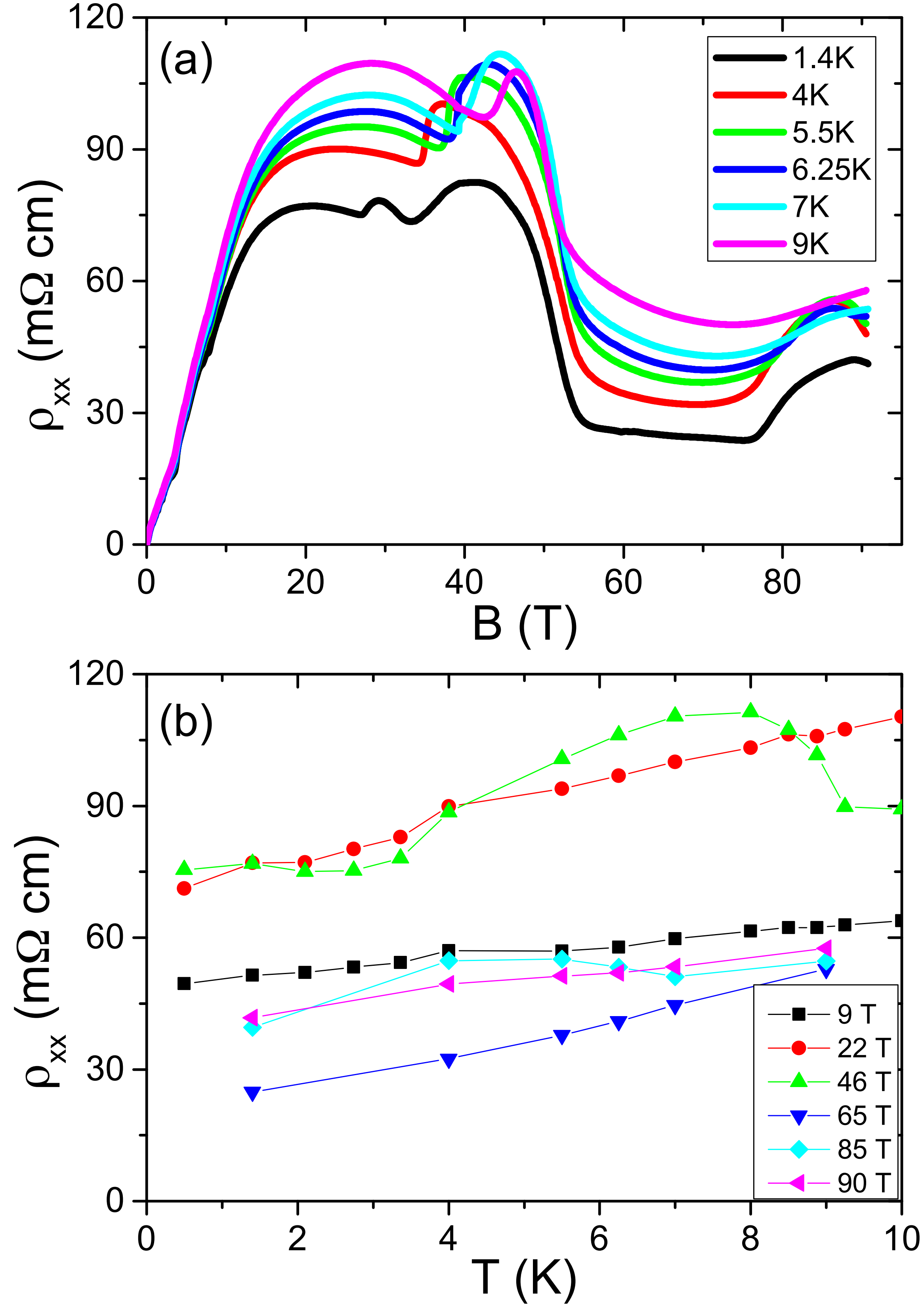
The onset of the field induced state (α-transition)
is a second order thermodynamic phase transition

Nature of the 75T re-entrance ?

Theory : SM-SC transition @ 75T

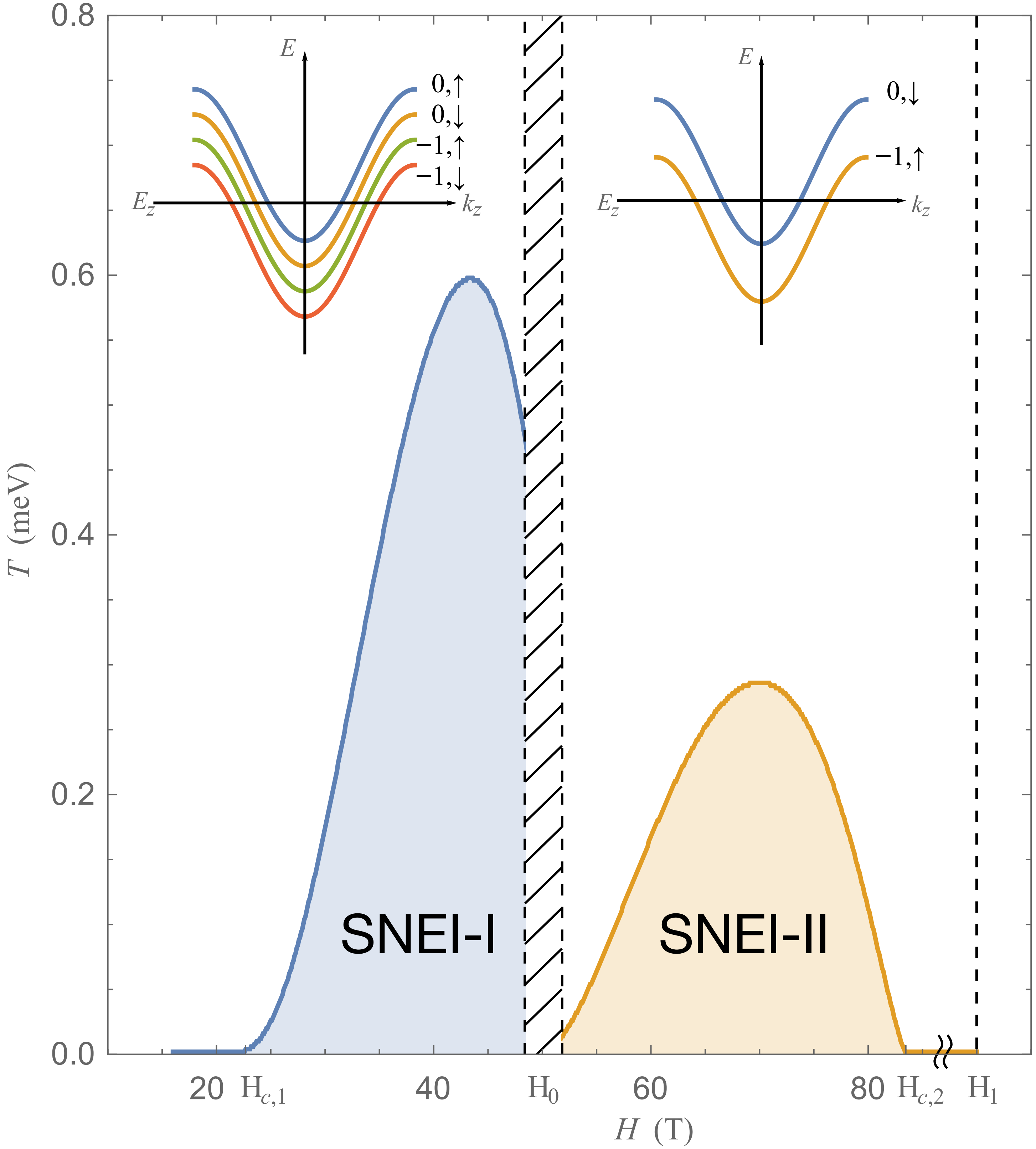
Experiment : B>75T a new (?) metallic phase





Z. Zhu and al.,PRX (accepted)

Nature of the 75T re-entrance in the EI insulator



arXiv:1802.10253v5

Umklapp process :

(i) lock the *total* displacement field

(ii) lock the « spin superconducting » phase

In this picture the 75T re-entrance corresponds to a divergence of the quantum fluctuation of the phase induced by the electronic correlation

No LL depopulation at 75T !

$$\omega_g \propto (H_{c,2} - H)^{z/\nu_2} = (H_{c,2} - H)^{1/\nu_2},$$

$$\nu_2 = \frac{1}{2} \sum_{a=2,3} \left(K_a + K_a^{-1}\right) - 2.$$

Rem : a CDW can be superposed to the EI!

Thermoelectrical response beyond the quantum limit of 3D electron gas systems

Introduction

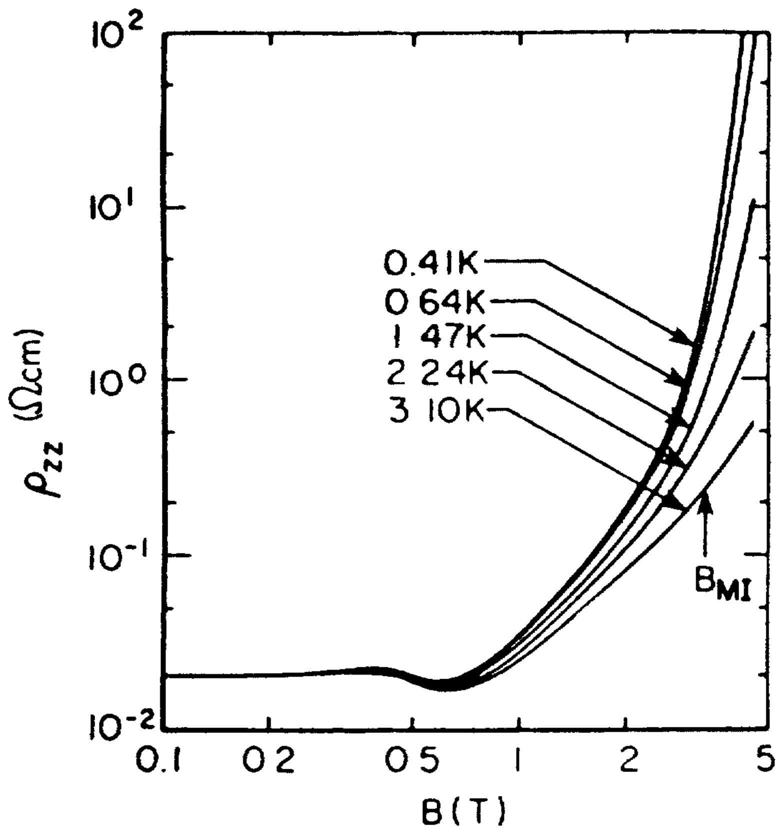
Nernst effect as a probe of quantum oscillations in semi-metals : the case of bismuth and graphite

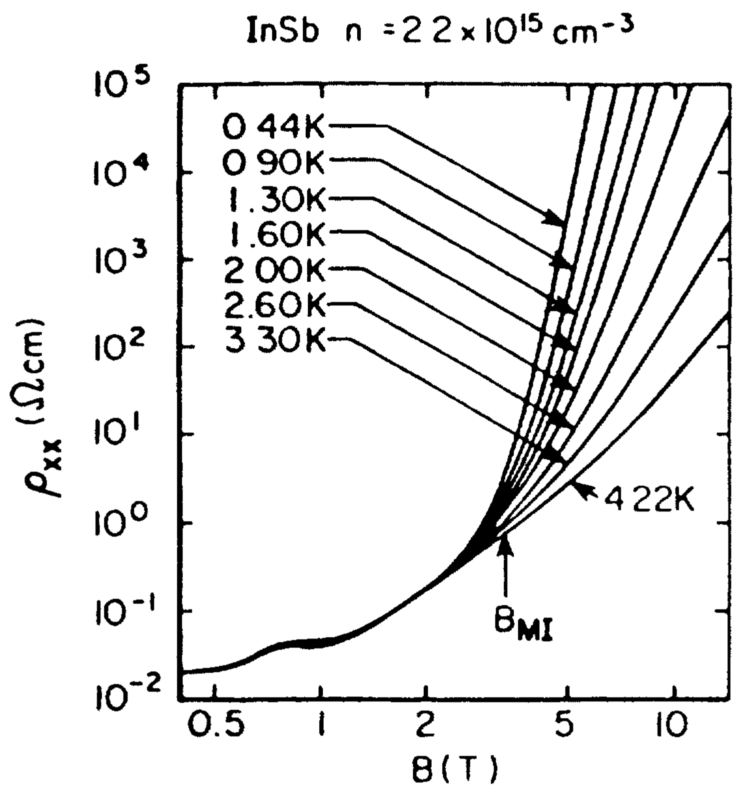
Transport and thermodynamic measurements in the quantum limit of graphite

Narrow gap semi-conductors in the quantum limit: the case of InAs

Conclusion

Narrow gap semi-conductors in the quantum limit : *magnetic freeze-out*

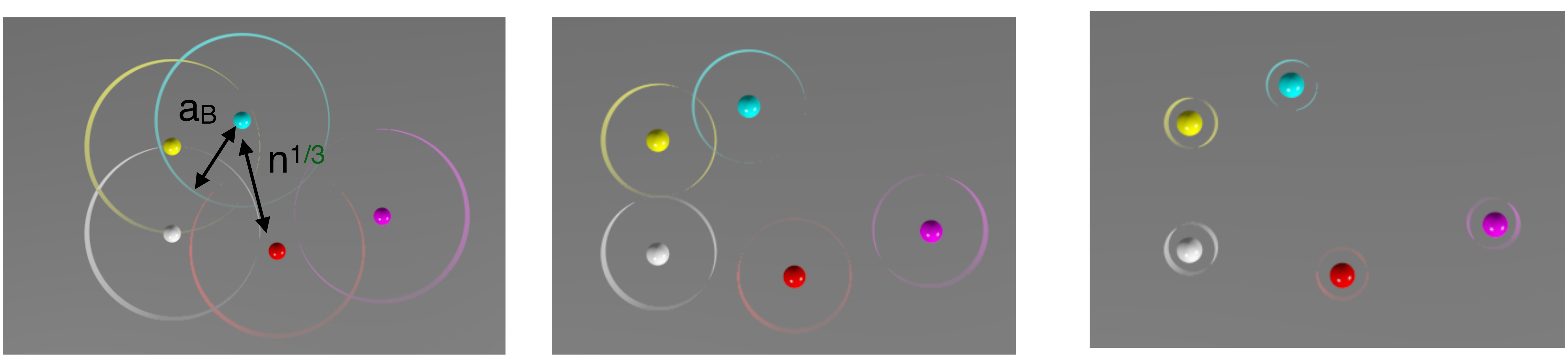




Mott-Anderson transition assisted by the magnetic field

$$a_B^* n_c^{\frac{1}{3}} \approx 0.25$$

$$a_B^* = (a_{\perp,B}^2 * a_{//,B})$$



$a_B^* n^{\frac{1}{3}} >> 1$

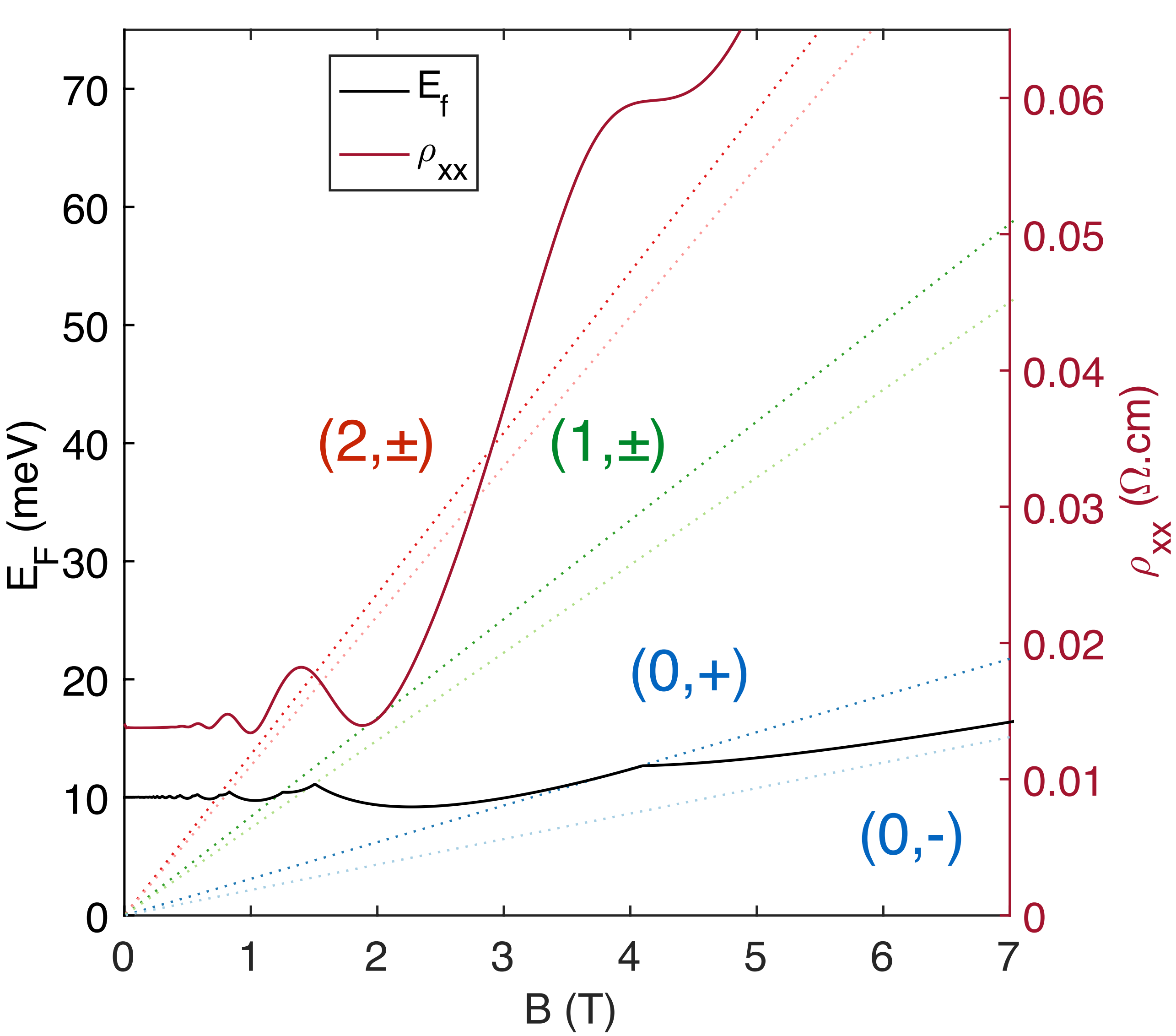
$a_B^* n^{\frac{1}{3}} << 1$

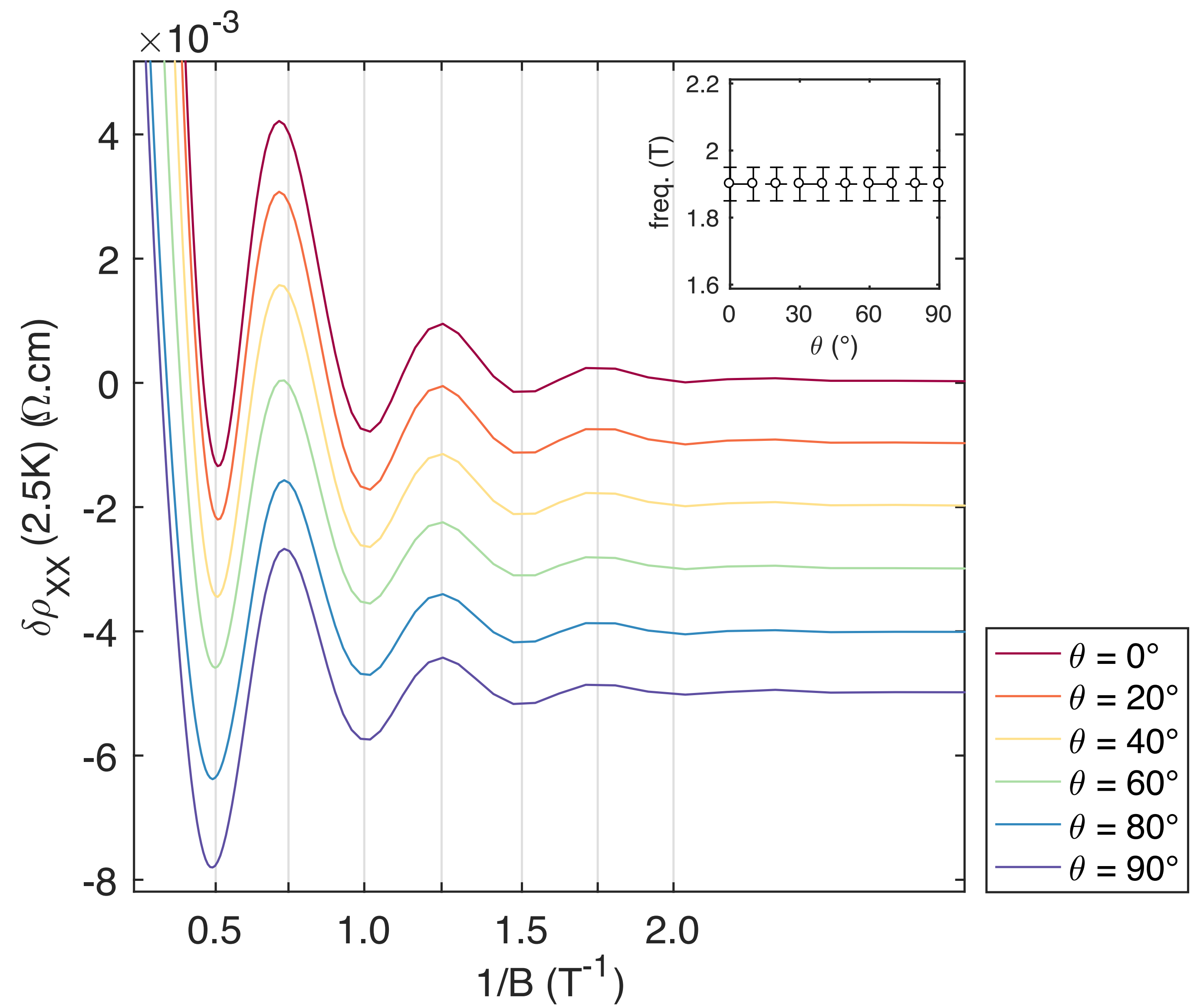
B

The case of InAs : Fermi surface

A. Jaoui and al., unpublished

n=2e16cm^{-3}

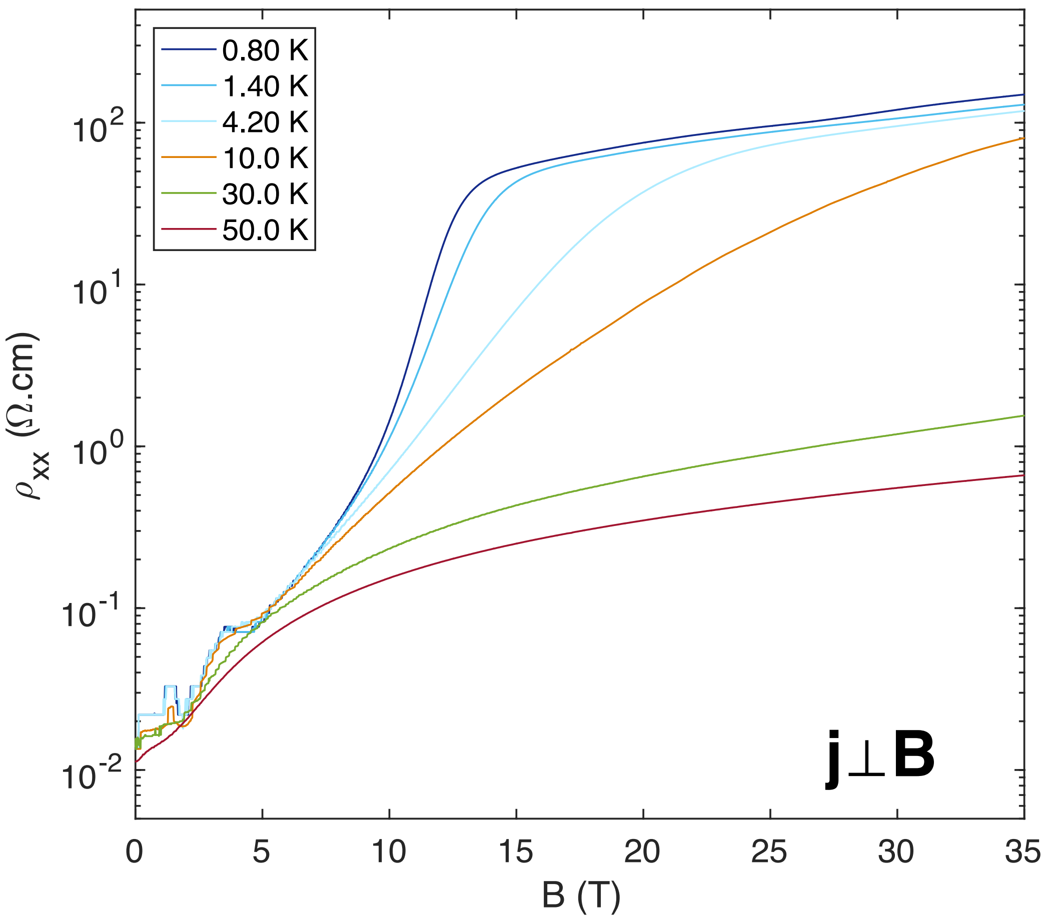


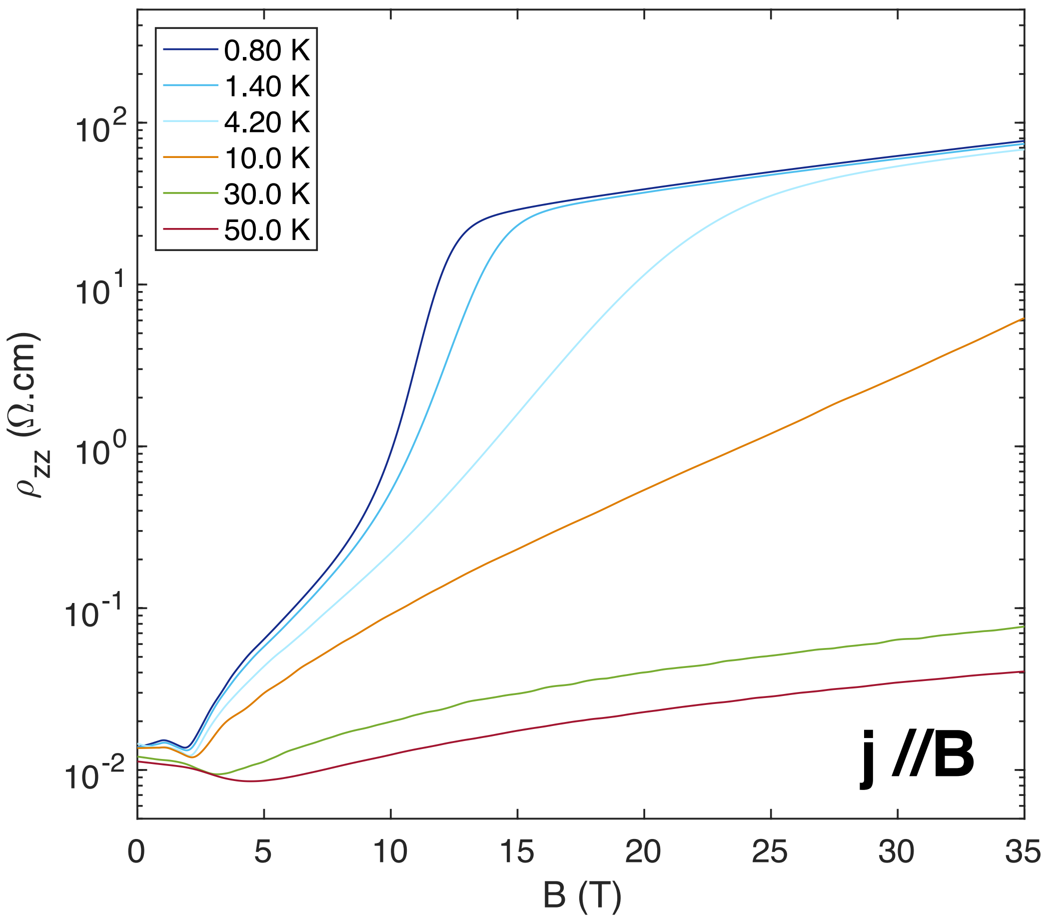


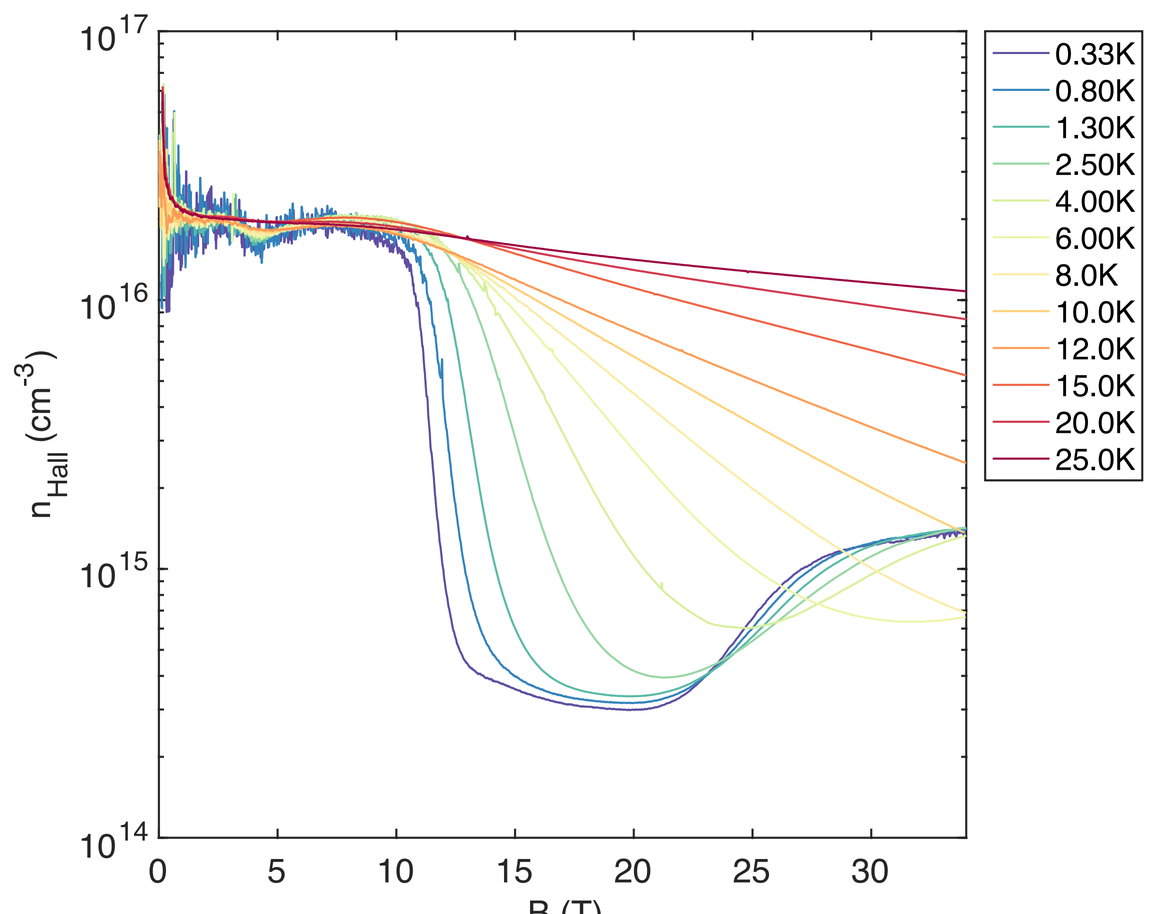
A spherical Fermi surface where all the electrons are confined in the lowest (0,-) Landau level at B=4.5T

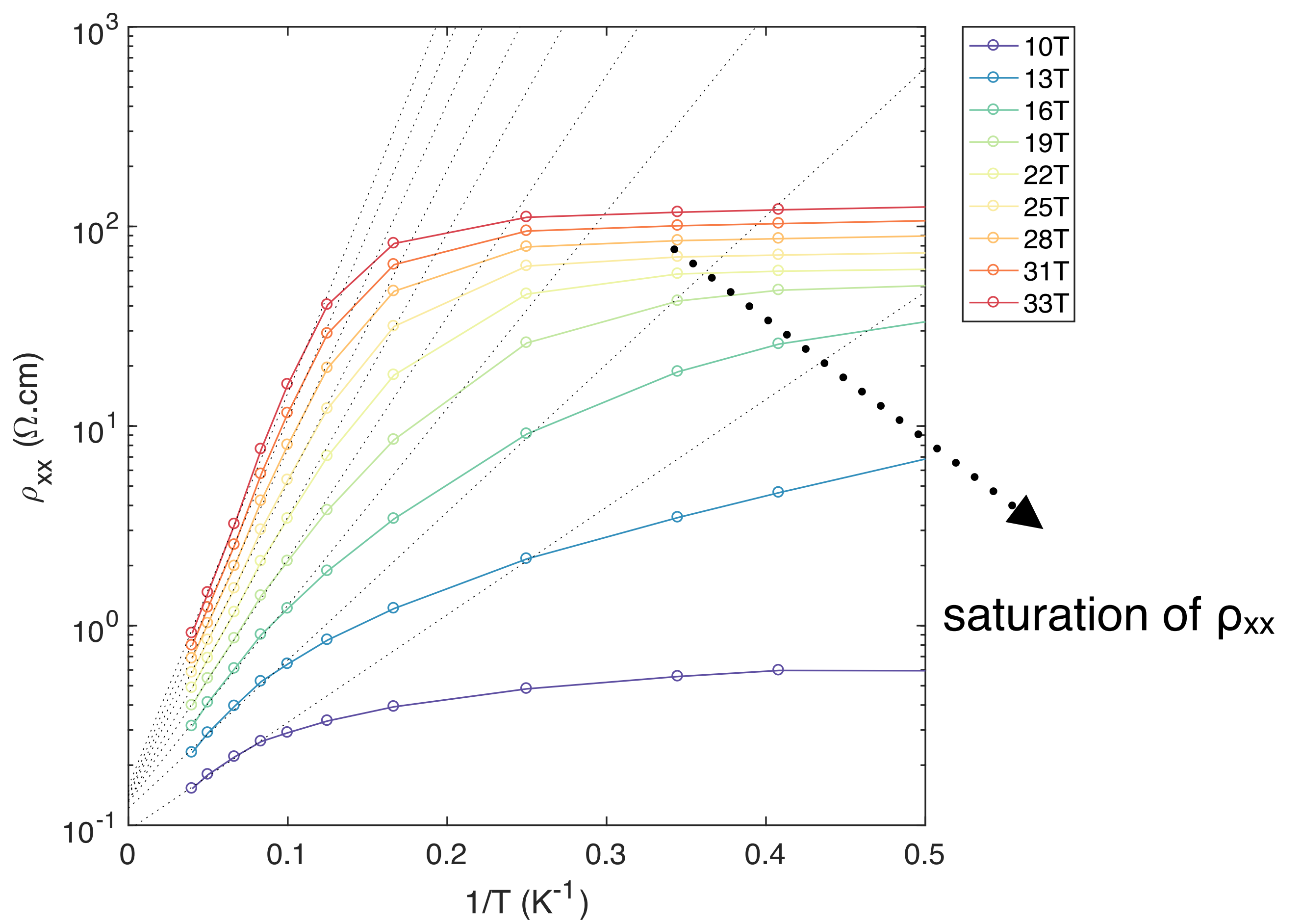
The case of InAs : electrical transport

A. Jaoui and al., unpublished



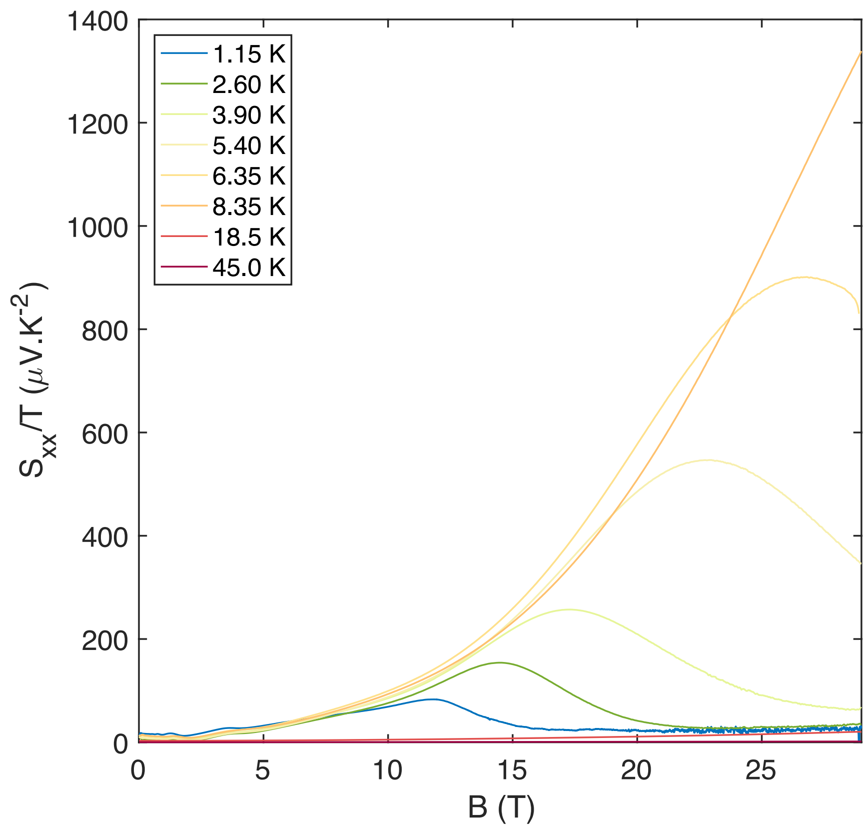


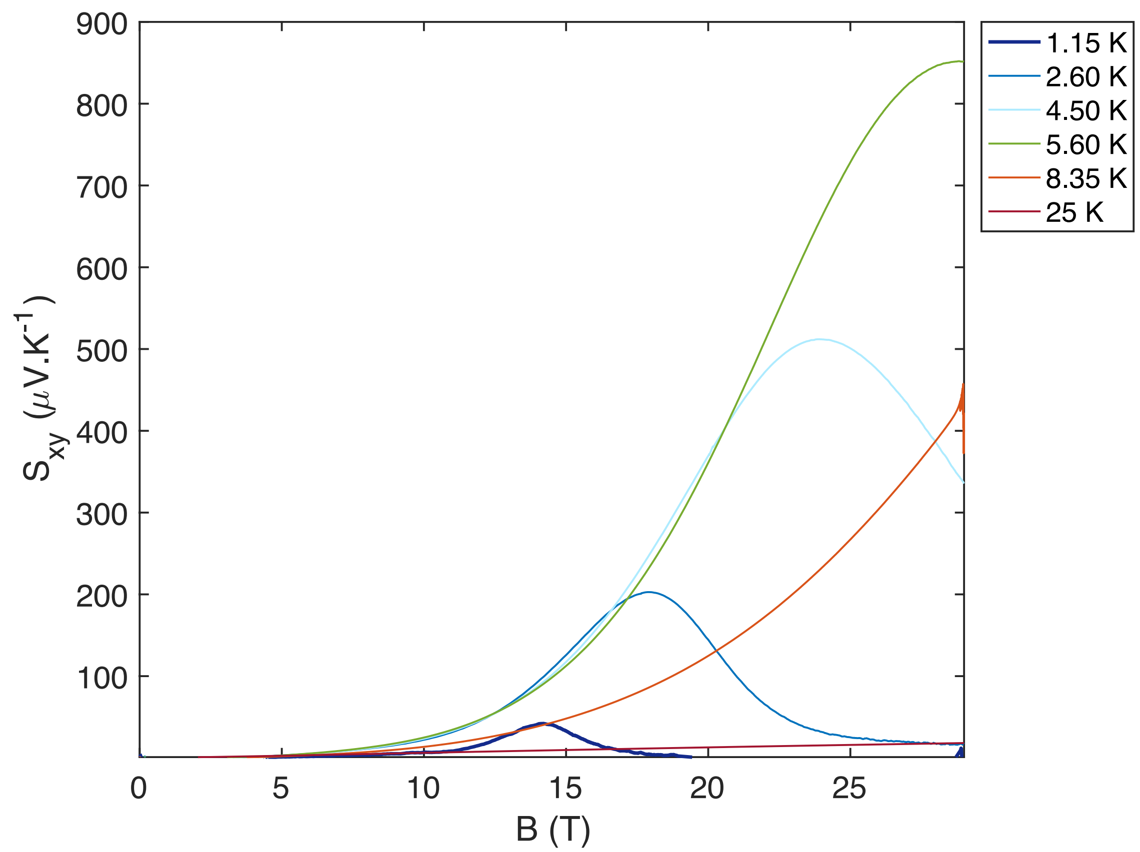


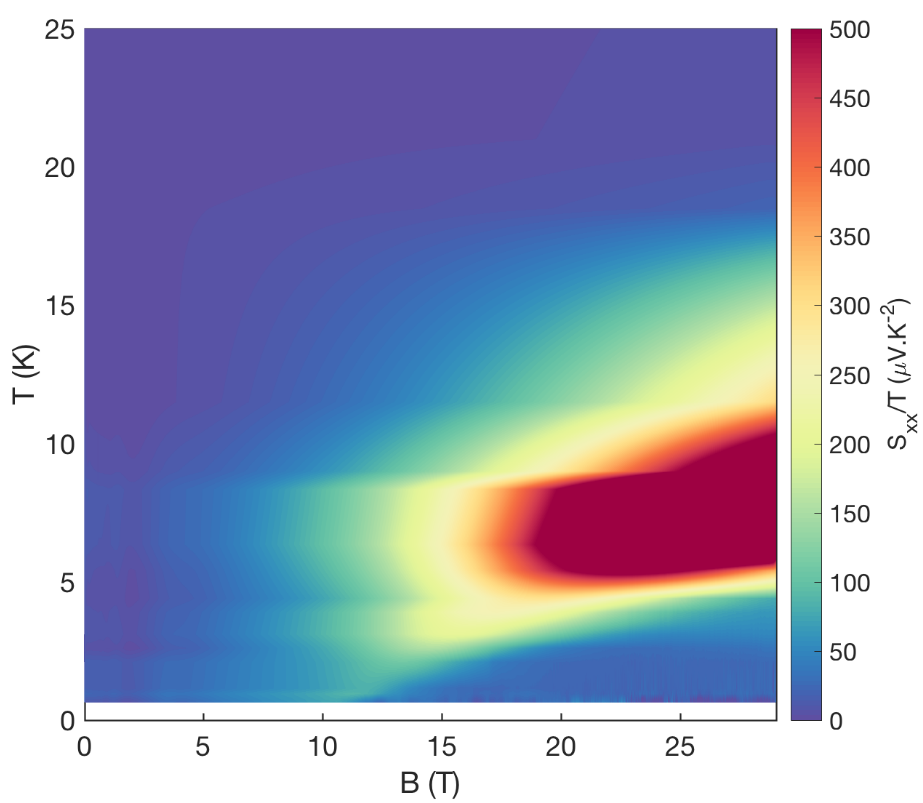


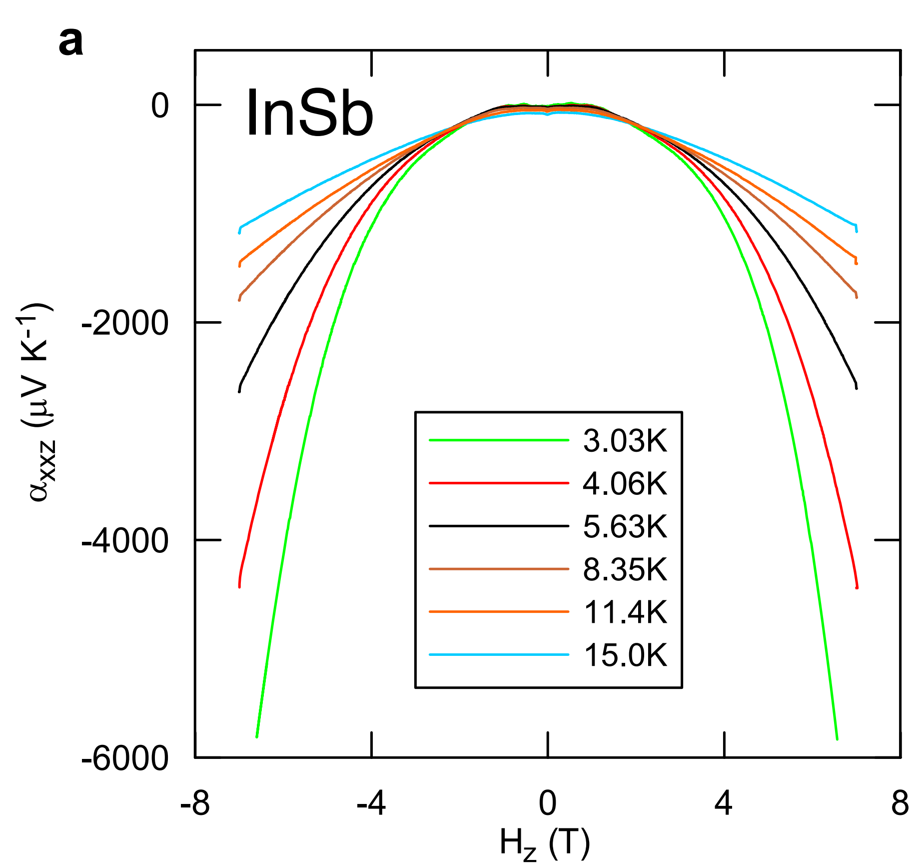
The case of InAs : Thermopower and Nernst effect

A vanishising thermopower and Nernst effect in the field induced state of InAs !









Nature(2012)

The case of InAs : a second channel of conduction ?

In presence of two channels of conductance

we have :

$$\sigma_T = \sigma_1 + \sigma_2$$

$$S_T = (\sigma_1 S_1 + \sigma_2 S_2)/\sigma_T$$

If (1), the bulk, goes to insulator :

$$\sigma_1 \propto \exp(-\frac{\Delta}{k_B T}) \text{ -> 0} \qquad \sigma_T \approx \sigma_2$$

$$S_1 \propto \frac{\Delta}{k_B T} \text{ -> } \infty \qquad S_T \approx S_2$$

Charge Accumulation at InAs Surfaces ?

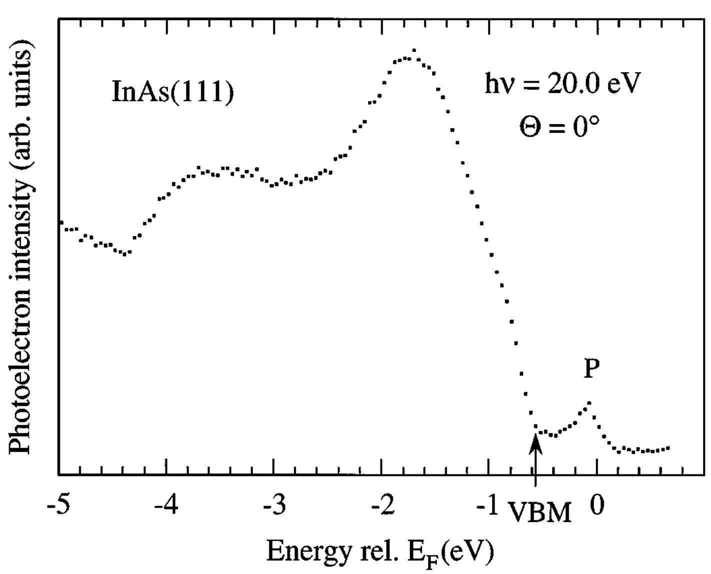
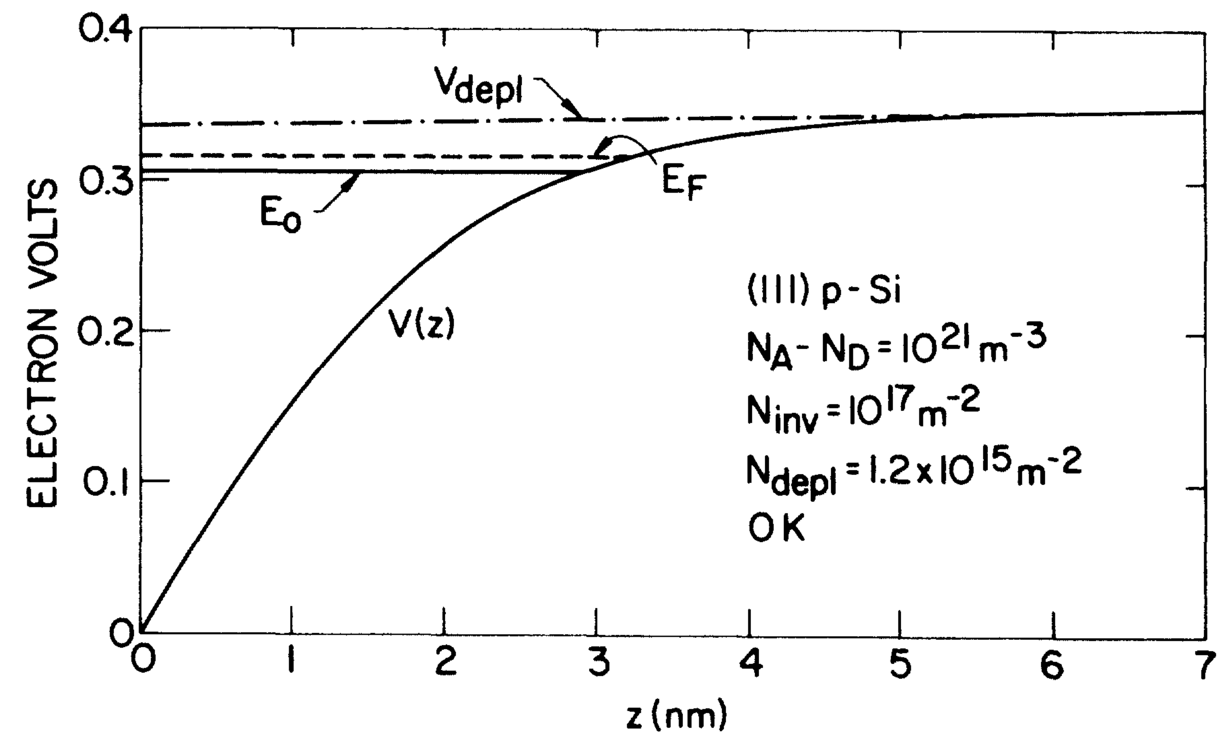


FIG. 1. Photoelectron spectrum from an IBA-prepared InAs(111)-(2 × 2) surface showing the presence of a narrow peak "P" just below E_F. The E_F energy was determined by photoemission from a Mo foil.



L. Olsson and al., PRL 76,3626 (1996)

F. Stern, PRB 5,4891 (1972)

Conclusions

The effect of the magnetic field deep in the QL is generally to turn your metal into an insulating state. However the nature of the insulating state strongly depend of the system under consideration !

For graphite we have a succession thermodynamic transitions with activation gap in charge conductivity along the c-axis which coexists with in-plane metallicity.

In the case of narrow semi-conductor we have an activation gap for all direction of the current injection. Like graphite we have an extra channel of conduction may be due to a charge accumulation layers on the surface.

Theory of the Three Dimensional Quantum Hall Effect in Graphite

B. Andrei Bernevig[1], Taylor L. Hughes[2], Srinivas Raghu[2] and Daniel P. Arovas[2,3]
[1] *Princeton Center for Theoretical Physics, Princeton University, Princeton, NJ 08544*
[2] *Department of Physics, Stanford University, Stanford, CA 94305 and*
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(Dated: February 22, 2012)

We predict the existence of a three dimensional quantum Hall effect plateau in a graphite crystal subject to a magnetic field. The plateau has a Hall conductivity quantized at $\frac{4e^2}{h}\frac{1}{c_0}$ with c_0 the c-axis lattice constant. We analyze the three-dimensional Hofstadter problem of a realistic tight-binding Hamiltonian for graphite, find the gaps in the spectrum, and estimate the critical value of the magnetic field above which the Hall plateau appears. When the Fermi level is in the bulk Landau gap, Hall transport occurs through the appearance of chiral surface states. We estimate the magnetic field necessary for the appearance of the three dimensional quantum Hall Effect to be 15.4 T for electron carriers and 7.0 T for hole carriers.

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The field actually induces a many body gap !! Phys. Rev. Lett. **99**, 146804 (2007)