Thermoelectricité comme sonde de l'orgnisation électronique dans les solides

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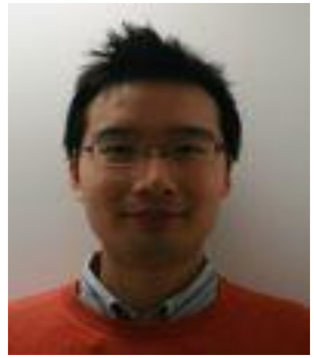

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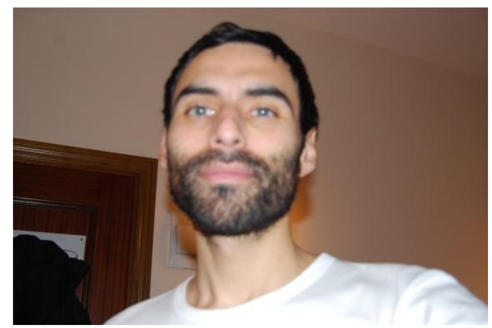

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Jacques Flouquet and his group, SPSMS-CEA, Grenoble

Outline

I. Introduction : electric vs. thermoelectric conductance

II. From Kondo effect to heavy-electron metals

III. The Nernst effect

IV. Quantum limit and dilute metals

- **J. M. Ziman, Electrons and phonons**
- **D. K. C. Macdonald, Thermoelectricity**

Flow of heat and charge

$$\vec{J}_e = \sigma \vec{E} - \alpha \vec{\nabla} T$$

$$\vec{J}_Q = \alpha T \vec{E} - \kappa' \vec{\nabla} T$$

Electric conductivity

Thermal conductivity

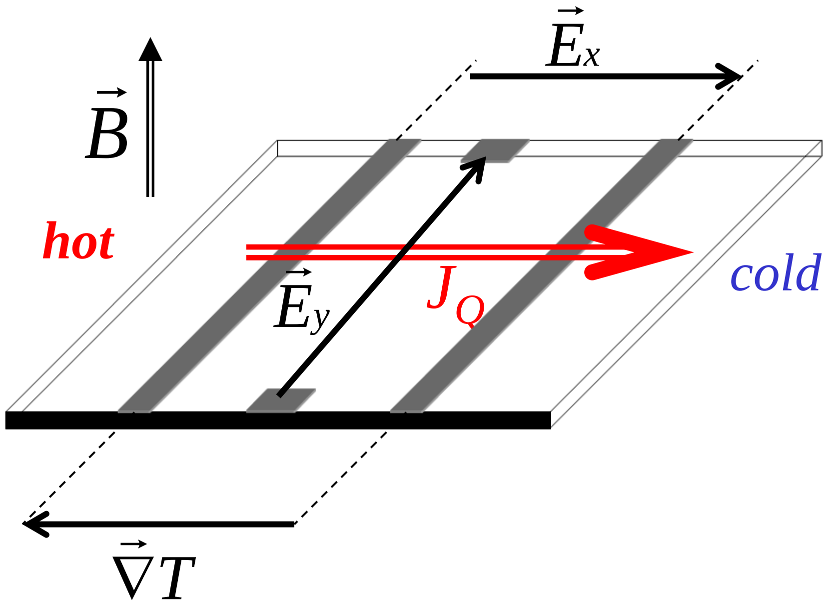
Thermo-electric conductivity

In general, σ, α and κ are tensors !
Off-diagonal components emerge in presence of magnetic field:
- Hall effect
- Nernst effect
- Righi-Leduc effect

Experimental access to thermoelectric coefficients

- Impose a thermal gradient!
- Impede charge flow (J_e=0)!

$$\sigma \vec{E} = \alpha \vec{\nabla} T$$



Seebeck $$S = \frac{\alpha}{\sigma} = \frac{E_x}{\nabla_x T}$$

Nernst $$N = S_{xy} = \frac{E_y}{\nabla_x T}$$

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

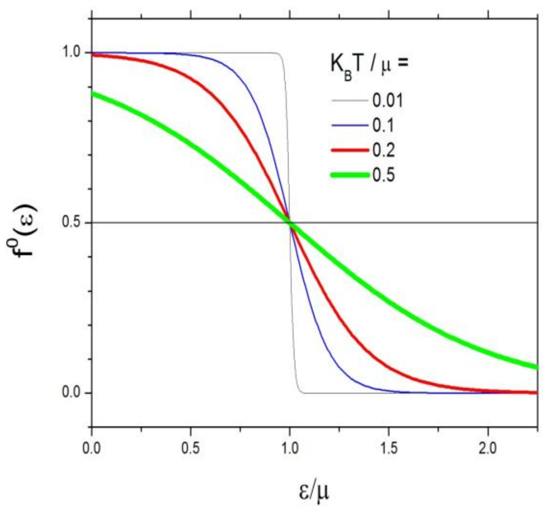
The linearized Boltzmann equation

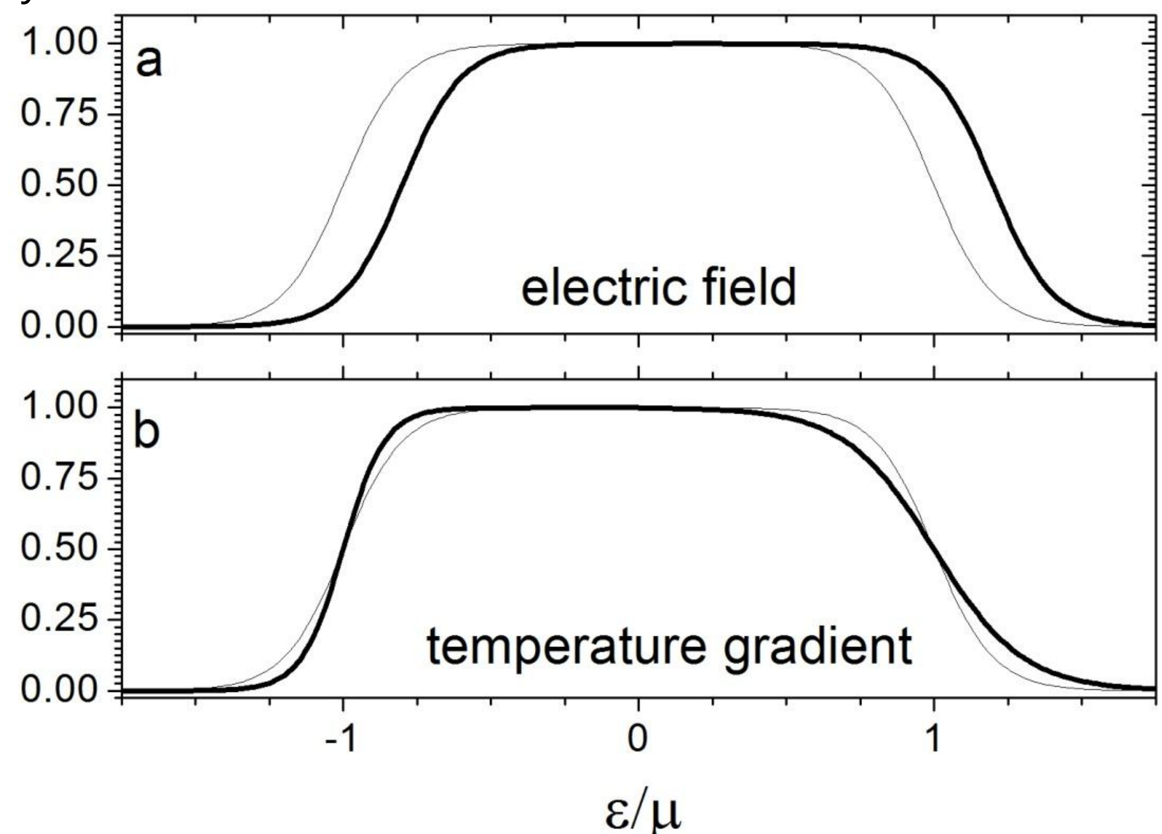
$$\frac{f_k(r) - f^0}{\tau} = \vec{v}_k \cdot \left(\frac{\partial f^0}{\partial T} \vec{\nabla} T + \frac{\partial f^0}{\partial \varepsilon_k} \vec{E} \right)$$

Scattering time

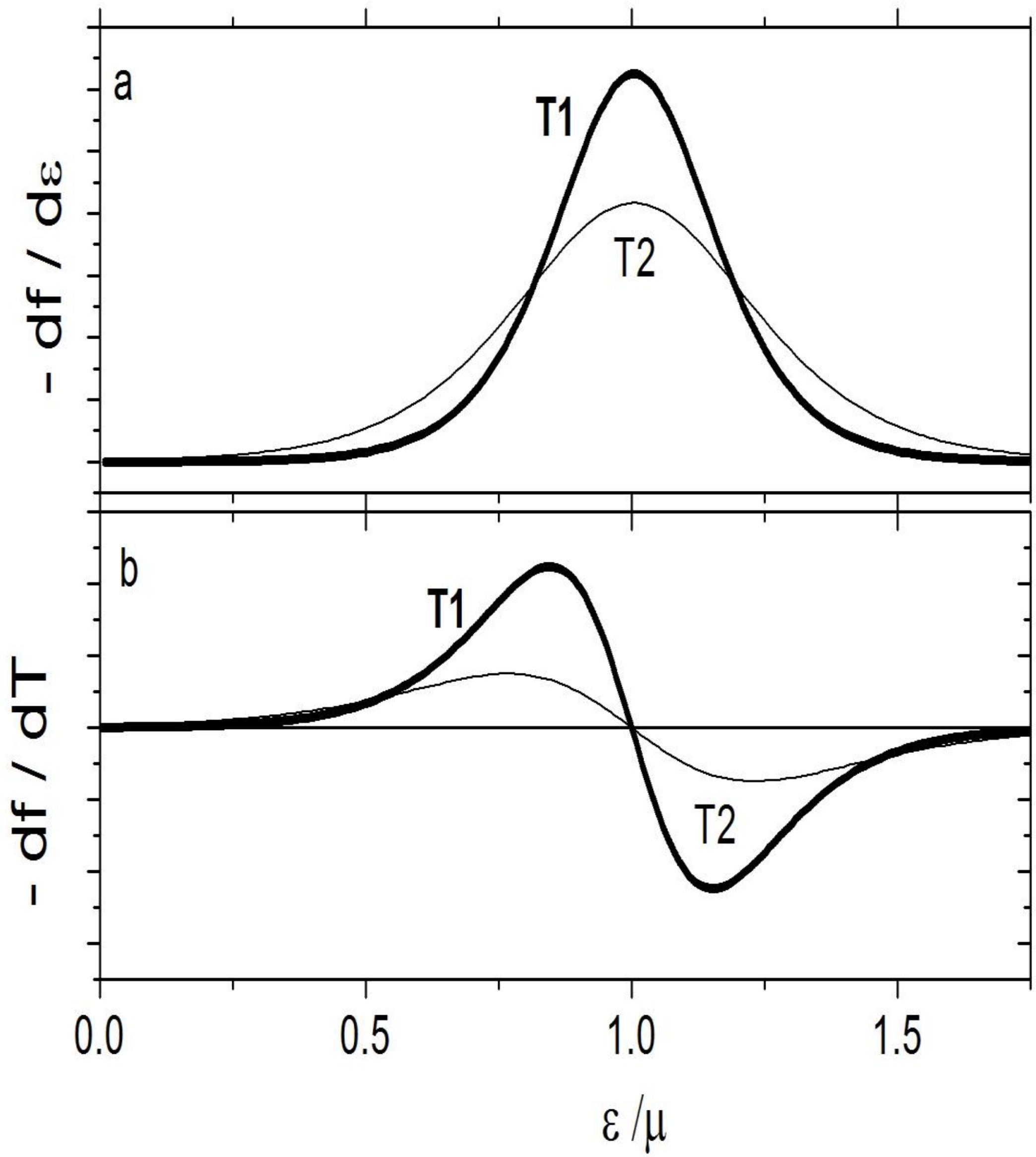
velocity

$$f^0 = \frac{1}{e^{(\varepsilon - \mu)/k_B T} + 1}$$





Electric and thermoelectric conductivity



$$\sigma = -e^2 \int \tau(k)(v_k)^2 \frac{\partial f^0}{\partial \epsilon_k} dk$$

Always positive

Dominant contributors: ε=μ

$$\alpha = e \int \tau(k)(v_k)^2 \frac{\partial f^0}{\partial T} dk$$

Can be positive or negative

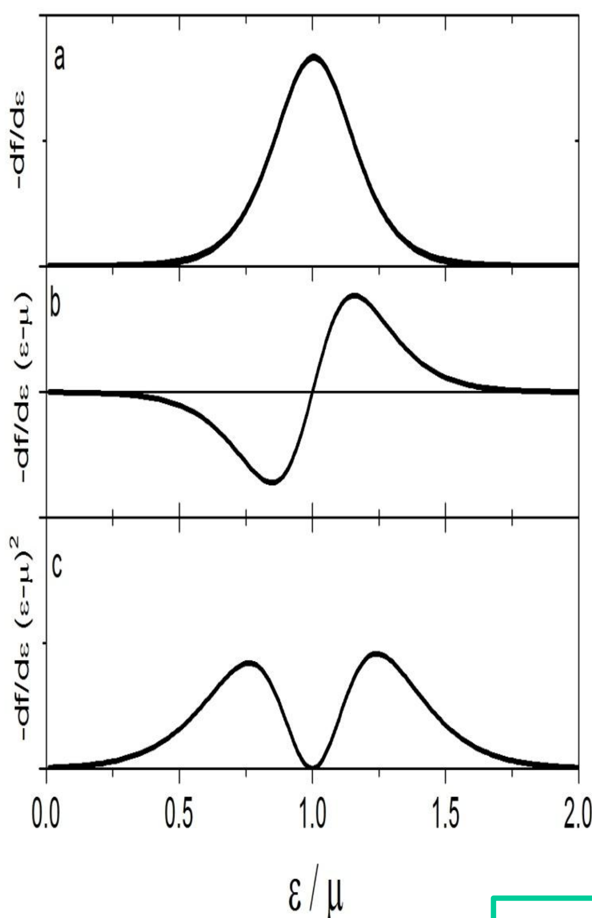
Dominant contributors:
ε<μ and ε>μ

Electrons which carry charge and those which carry heat!

electric

thermoelectric

thermal



Quanta of conductance

$$\sigma = 2\frac{e^2}{h}\int -\frac{\partial f}{\partial \epsilon}\,\Xi(\epsilon)d\epsilon$$

$$\alpha = 2\frac{ek_B}{h}\int -\frac{(\epsilon-\mu)}{k_B T}\frac{\partial f}{\partial \epsilon}\,\Xi(\epsilon)d\epsilon$$

$$\frac{\kappa}{T} = 2\frac{{k_B}^2}{h}\int [\frac{(\epsilon-\mu)}{k_B T}]^2\frac{\partial f}{\partial \epsilon}\,\Xi(\epsilon)d\epsilon$$

Transport distribution function

Transport distribution function

(Mahan & Sofo, 1996)

$$\Xi(\varepsilon) = \frac{h}{2} N(\varepsilon) v_k^2(\varepsilon)\tau(\varepsilon) = \frac{h}{2} N(\varepsilon) v_k(\varepsilon)\ell(\varepsilon)$$

It depends on both the electronic structure and scattering mechanism.
In the material.

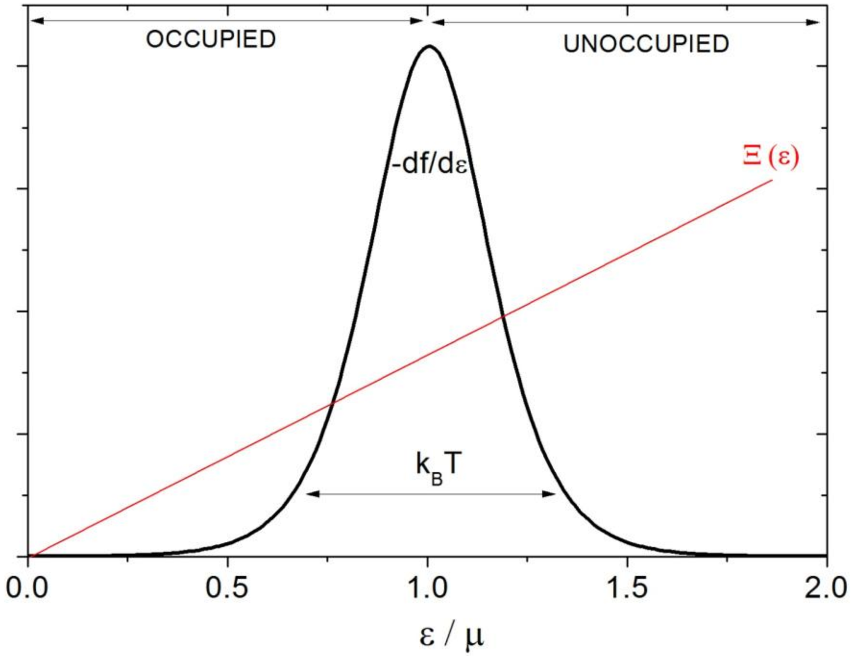
In a bulk solid, it replaces the transmission probability introduced by Landauer in the case of 1D systems!

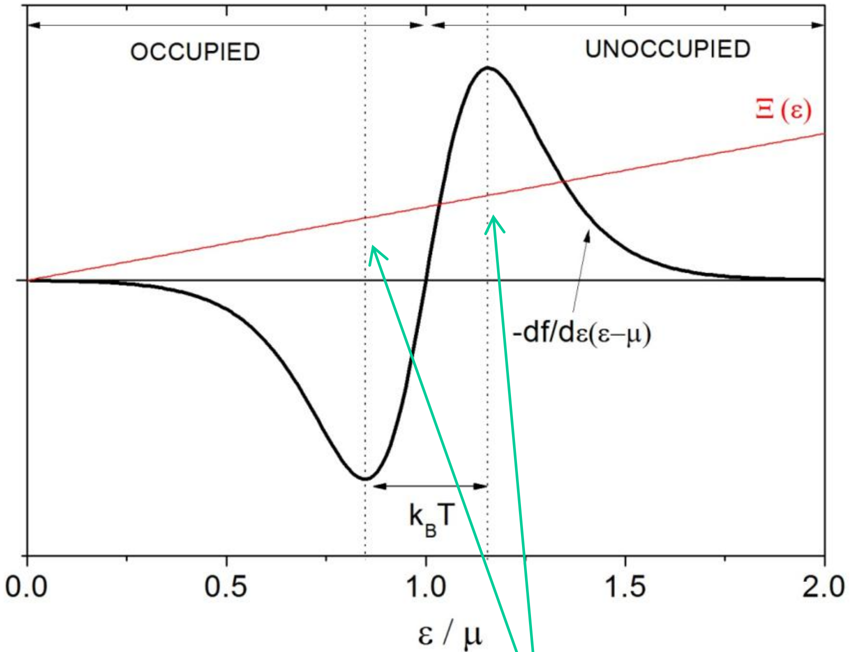
Electric and thermoelectric conductivity

Parabolic dispersion with constant mean–free–path

$$\sigma = \frac{2e^2}{h}\int(-\frac{\partial f}{\partial \varepsilon})\Xi(\varepsilon)d\varepsilon$$

$$\alpha = 2\frac{ek_B}{h}\int(-\frac{\partial f}{\partial \varepsilon})\frac{(\varepsilon-\mu)}{k_B T}\Xi(\varepsilon)d\varepsilon$$



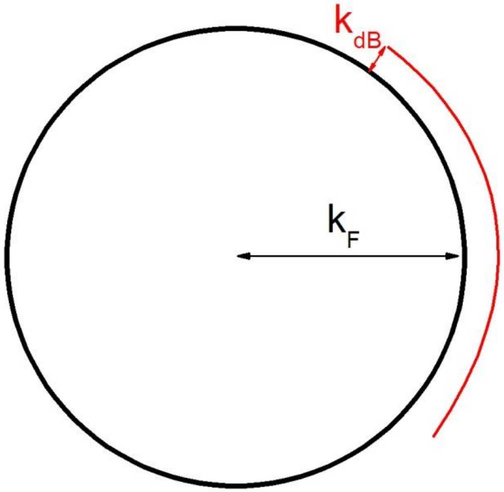


High–energy electrons are faster and denser

The free electron gas

$$\boxed{\sigma = \frac{e^2}{h} < {k_F}^2\, \ell >}$$

$$k_{dB}^2 = \frac{2m^* k_B T}{\hbar^2}$$



$$\boxed{\alpha = \frac{k_B e}{h} < {k_{dB}}^2\, \ell >}$$

de Broglie wavelength measures the thermal fuzziness of the Fermi surface!

$$S = \frac{\alpha}{\sigma} = \frac{k_B}{e} \frac{< k_{dB}^2 >}{< k_F^2 >} = \frac{\pi^2}{3} \frac{k_B}{e} \frac{T}{T_F}$$

The Seebeck coefficient becomes scattering-independent, if the mean-free-path is independent of energy.

In a degenerate Fermi liquid ($k_B T \ll \varepsilon_F$)

The Wiedemann–Franz law:

$$\frac{\kappa\alpha}{T} = \frac{\pi^2}{3}\frac{k_B^2}{e^2}$$

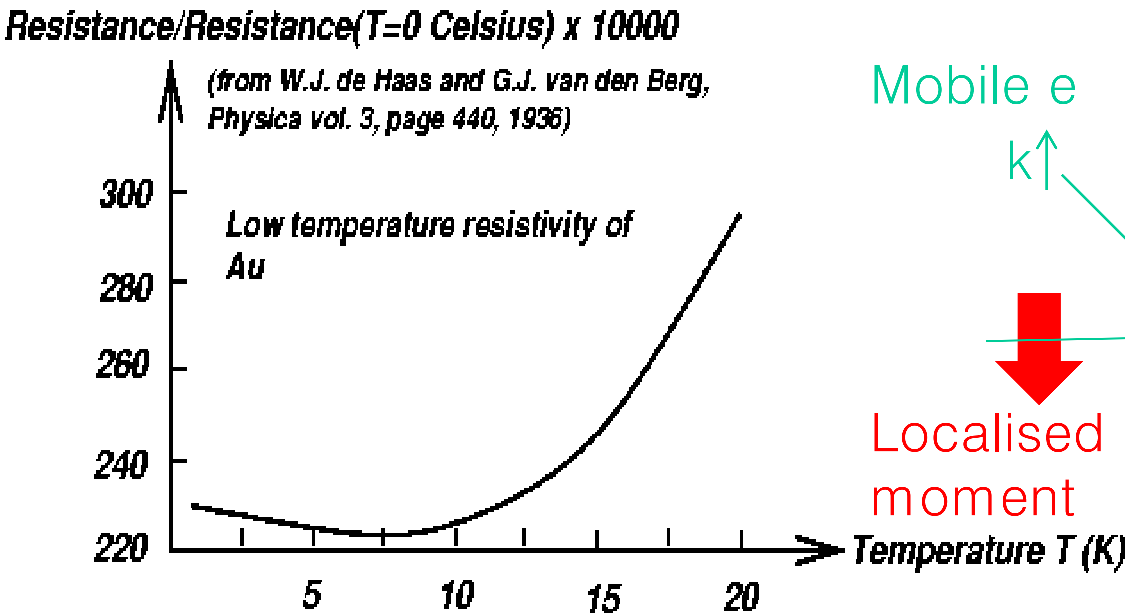
The Mott formula:

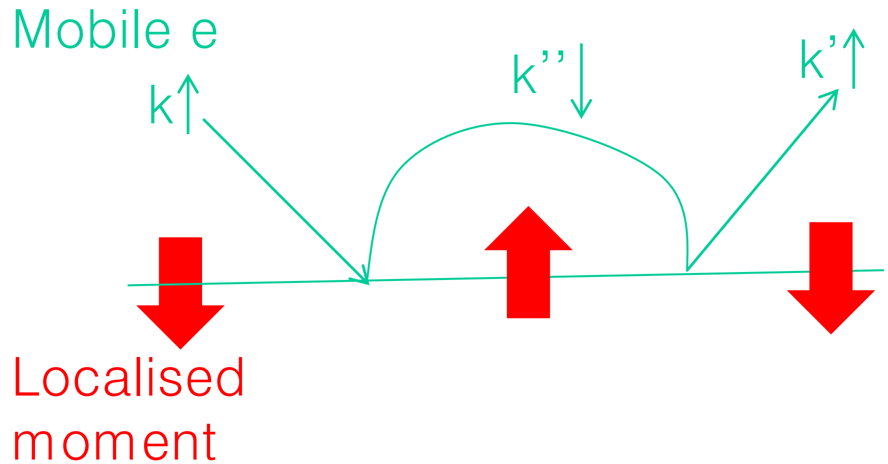
$$\alpha = \frac{\pi^2}{3}\frac{k_B^2}{e} T \left.\frac{\partial \sigma}{\partial \varepsilon}\right|_{\varepsilon=\mu}$$

$$S = \frac{\alpha}{\sigma} = \frac{\pi^2}{3}\frac{k_B^2}{e} T \left.\frac{\partial \ln \sigma}{\partial \varepsilon}\right|_{\varepsilon=\mu}$$

Thermoelectricity probes electronic states near ,but not exactly at, the chemical potential , !

The Kondo effect





1936: Mysterious upturn in resistivity of gold seen by de Haas
1950s: Role of MAGNETIC impurities pinned down
1960s: Giant Seebeck effect in thermopower in impure noble metals
1964: Kondo offers a solution (and defines a new problem)!

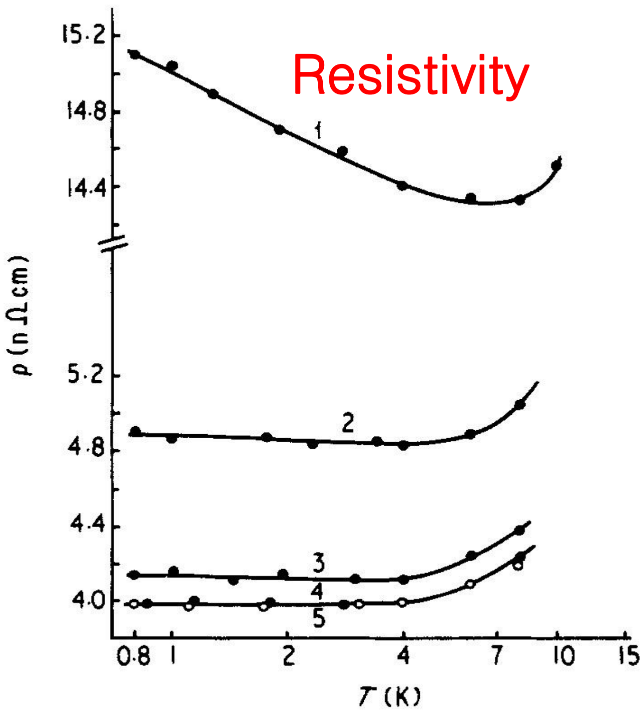
The isolated magnetic moment couples to the Fermi sea
Incoming electrons are spin-flipped and visit states of opposite spin!

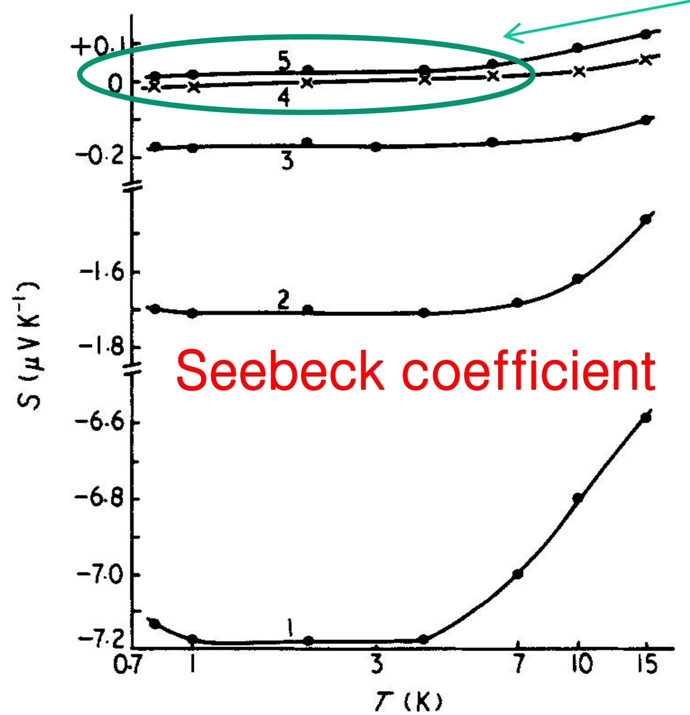
The Kondo effect

Table 1.

Specimen	Treatment time (h)	Fe concentration (ppm)	Resistivity (nΩ cm)	Thermopower (μV K^{-1})
1	0	13	14·4	−7·18
2	4·1	1	4·8	−1·71
3	8·2	0·1	4·1	−0·17
4	12·3	0·01	4·0	+0·01
5	16·4	0·001	4·0	+0·03

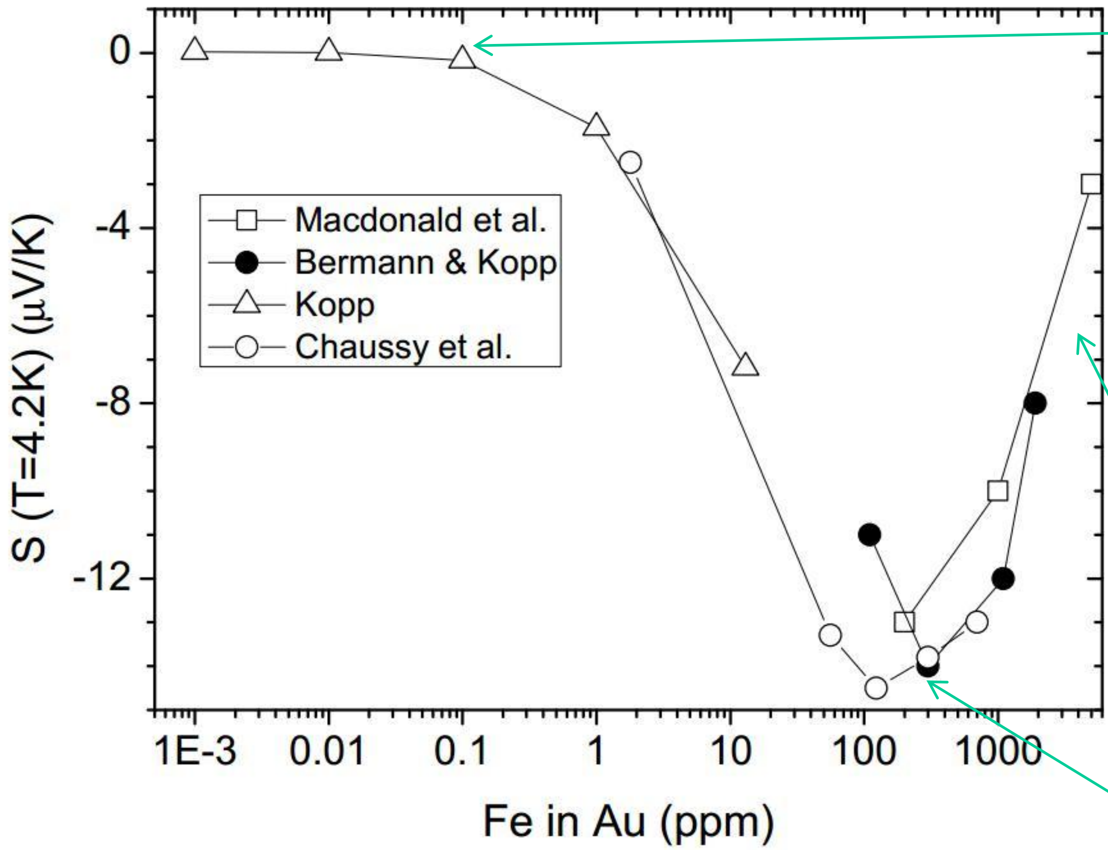
1ppb to 10ppb!





Iron impurities in gold, Kopp 1975

Magnitude of Seebeck peak in Au-Fe at 4.2 K



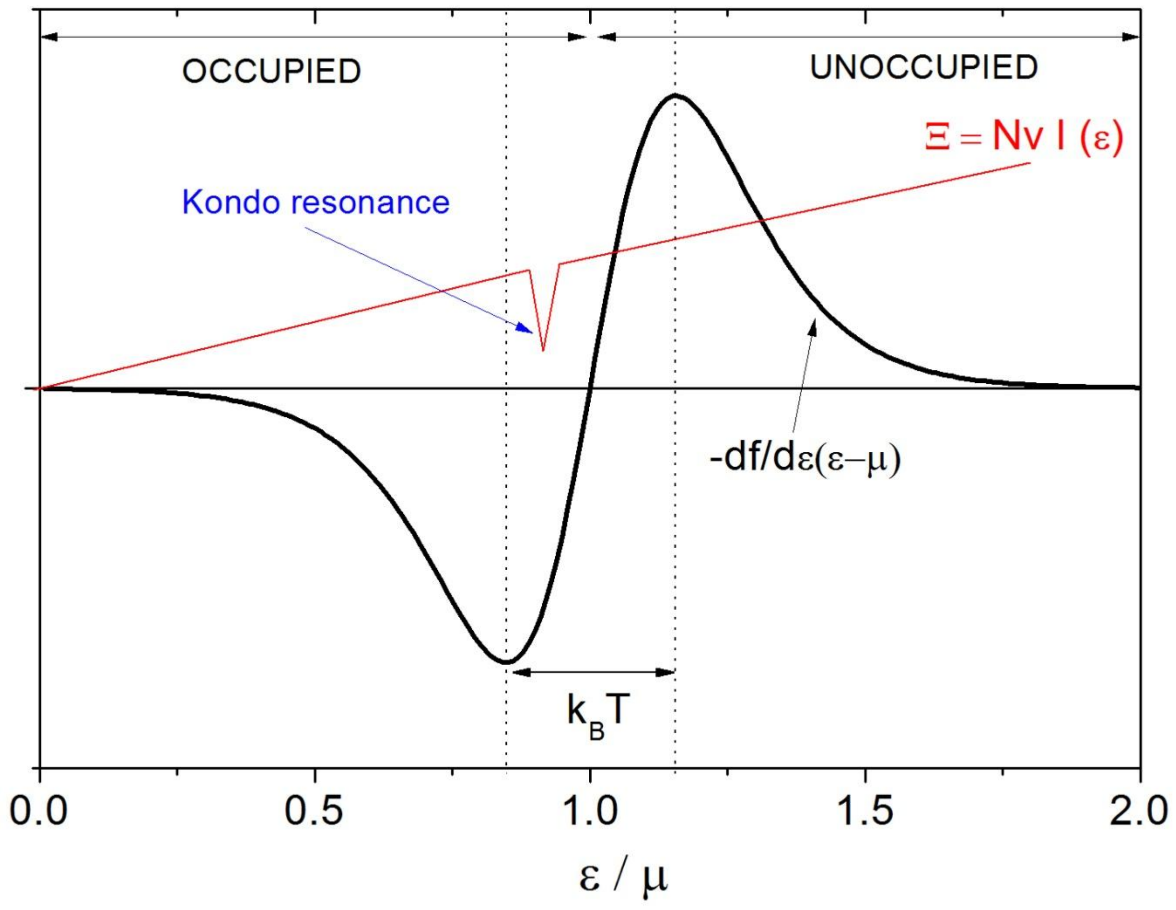
Still moves!

The system becomes a spin glass!

14μV/K peak at 100-300 ppm!

- The instrinsic diffusive Seebeck coefficient of gold is only 24nV/K @4.2K!
- AuFe (0.0.3 %): the most sensitive thermocouple at low T !

Why the effect is so drastic?



A resonance peak in one side of the dividing line!

Kondo lattices

•Intermetallics with atoms hosting f electrons ($CeAl_3$, $YbAl_3$, UPt_3 …)

•At high temperature, isolated magnetic moments in a Fermi sea

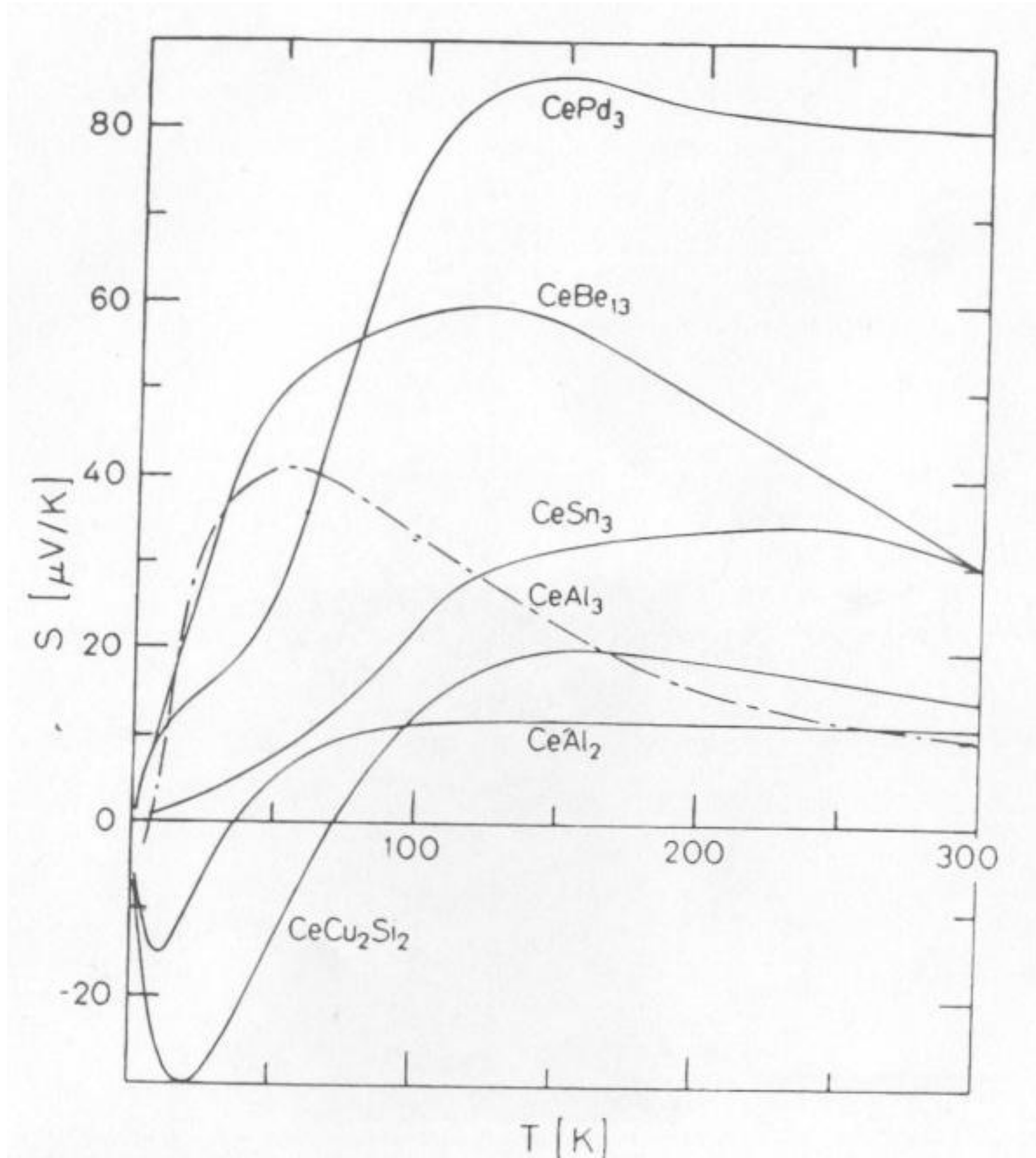
•At low temperature, no dichotomy between isolated spins and mobile charges. Both merge in to a sea of heavy electrons!

$$C_e = \frac{\pi^2}{3} k_B^2 T N(\varepsilon_F) = \frac{\pi^2}{3} k_B^2 T \frac{n}{T_F} \propto k_B T \frac{m^* n^{1/3}}{\hbar^2}$$

- An electronic specific heat several orders of magnitude larger than copper!

Large Seebeck coefficient in heavy–electron metals

Jaccard & Sierro 1982



Thermopower and specific heat

In a free electron gas :

$$S = -\frac{\pi^2}{3}\frac{k_B^2 T}{e}\frac{N(\epsilon_F)}{n}$$

$$C_{el} = \frac{\pi^2}{3}k_B^2 T N(\epsilon_F)$$

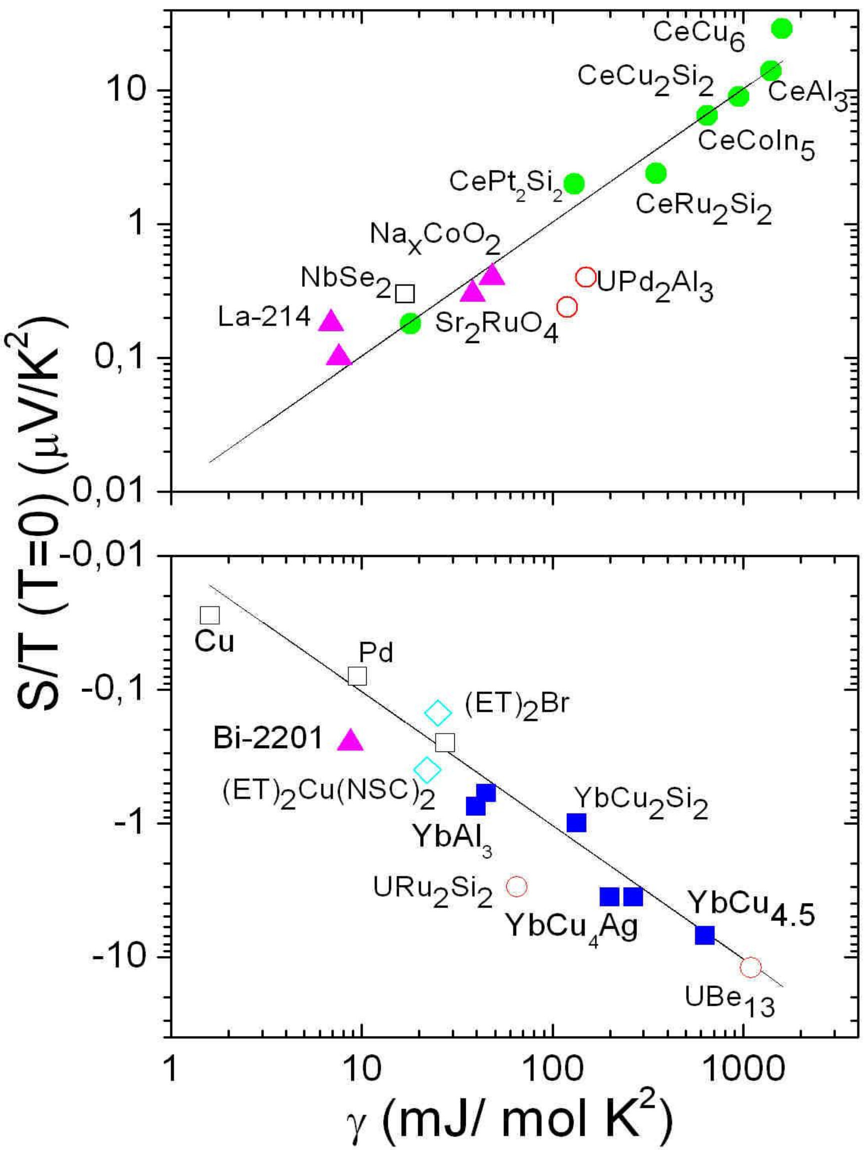
Thermopower is “specific heat per carrier”
[Macdonald 1962, Ziman, 1961, …]

The dimensionless ratio:

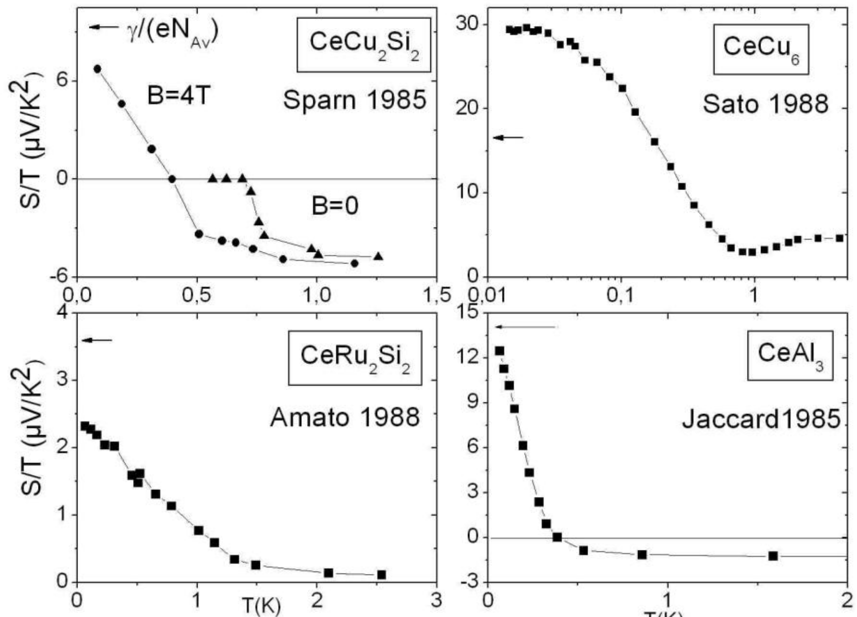
$$q = eN_{Av}\frac{S}{C}$$

is equal to –1 (+1) for free electrons (holes).

In many heavy-fermion metals q is close to unity!



Behnia, Jaccard & Flouquet,
JPCM 2004



See also Sakurai & Isikawa JSPJ 2005

Theory:
Miyake & Kohno JPSJ 2005
Zlatic et al., PRB 2007

Heavy Fermi liquids

- Enhanced specific heat

$$\gamma = \frac{\pi^2}{3} k_B^2 N(\varepsilon_F)$$

- Enhanced Pauli Susceptibility

$$\chi = \mu_B^2 N(\varepsilon_F)$$

- Enhanced inelastic resistivity

$$\rho = \rho_0 + AT^2$$

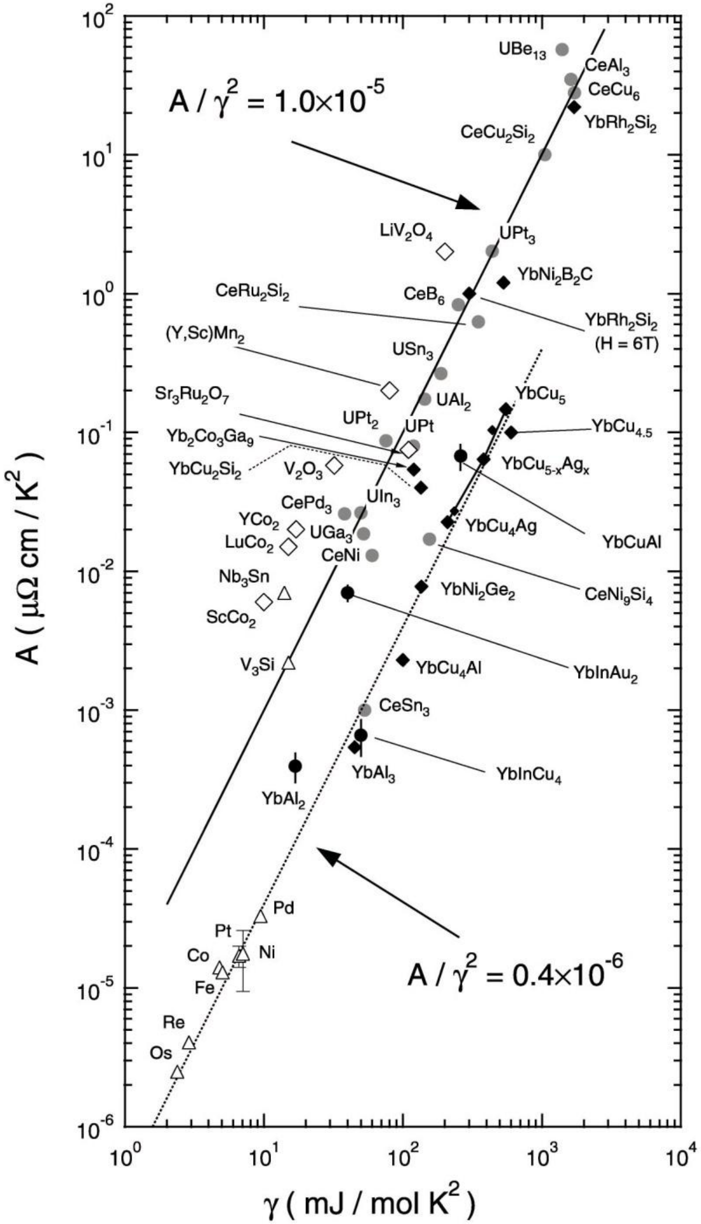
$$A \propto \frac{1}{\tau} \propto N(\varepsilon_F)^2$$

- Enhanced Seebeck coefficient

$$\frac{S}{T} = \frac{\pi^2}{3} k_B^2 \frac{N(\varepsilon_F)}{n}$$

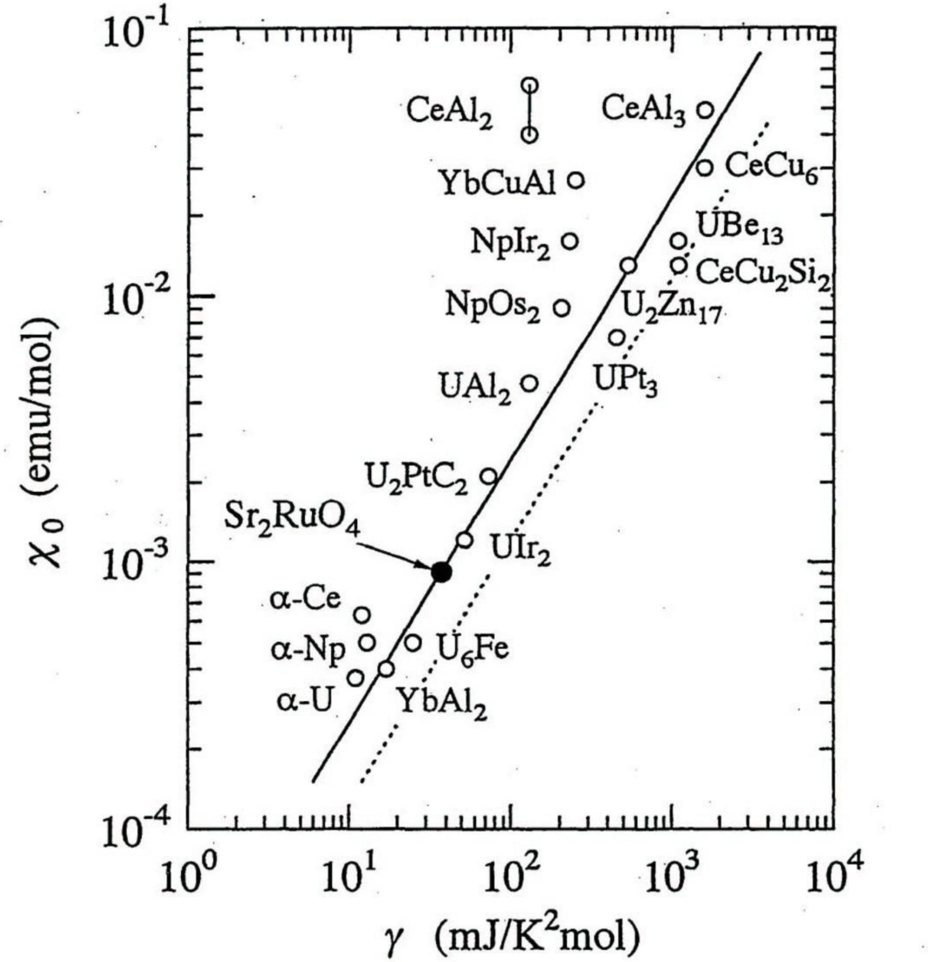
Fermi liquid ratios

The Kadowaki-Woods ratio



The Wilson ratio

$$R_W = \frac{\pi^2}{3}\frac{k^2{}_B}{\mu_B^2}\frac{\chi}{\gamma}$$



Current research on thermoelectricity of heavy electrons

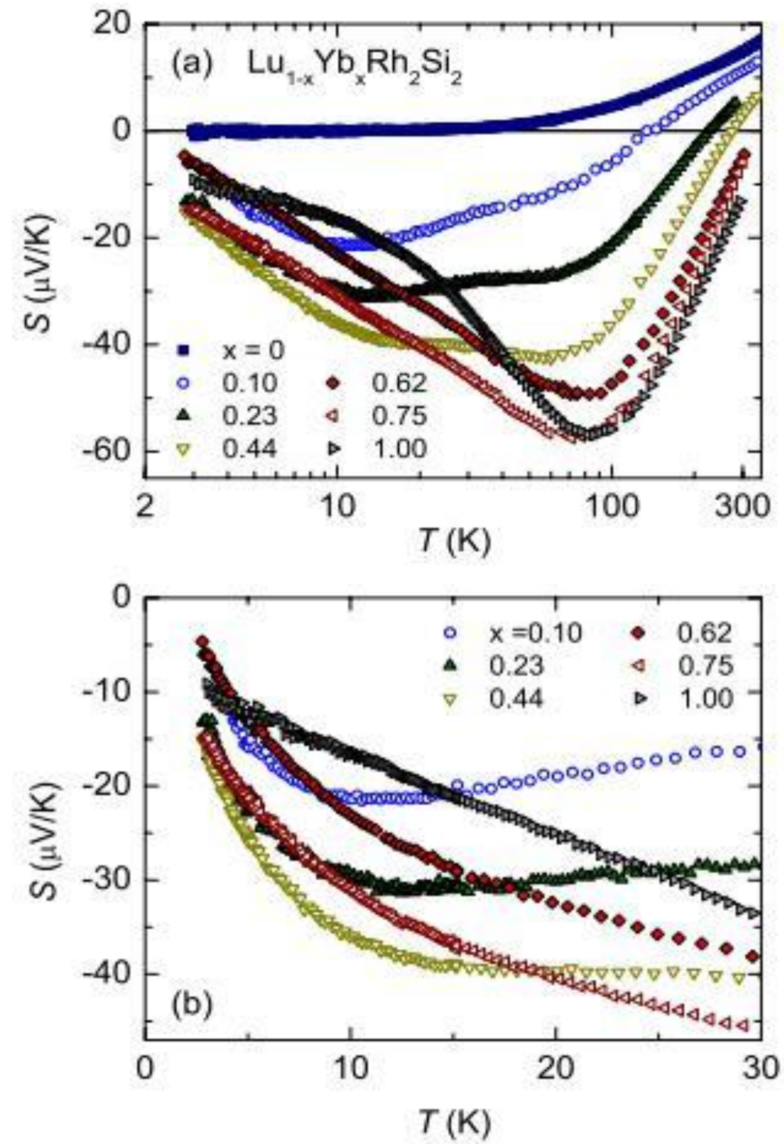
Main themes

- Quantum criticality
- Metamagnetic transitions
- Hidden electronic orders
- Fermi surface reconstruction
- Ferromagnetic superconductors

Principal actors

- Grenoble (Flouquet)
- Dresden (Steglich)
- Tokyo (Izawa)
- Ames (Canfield)
- Geneva (Jaccard)

Kohler et al., 2008 Dresden



Ferromagnetic superconductors

UGe_2

Saxena S.S. *et al.* Nature **406**, 587 (2000)

T_c = 52 K, T_{SC} =0.75 K

URhGe

Aoki D. *et al.* Nature **413**, 613 (2001)

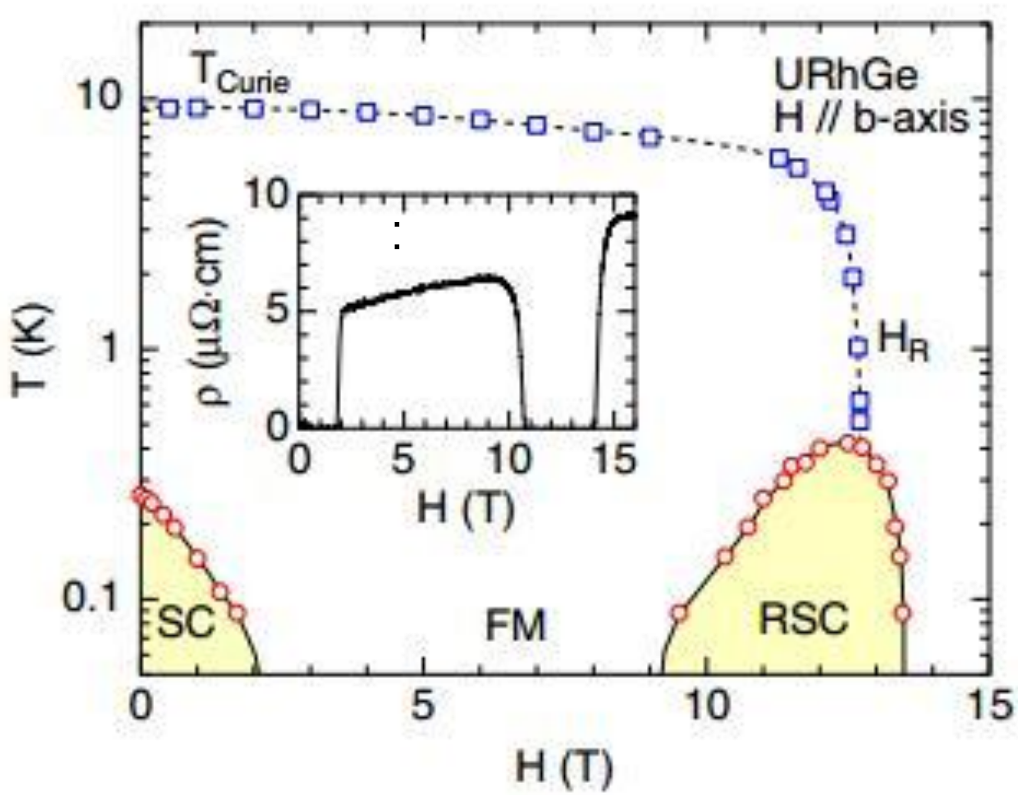
T_c = 9.5 K, T_{sc} = 0.25 K

UCoGe

Huy N.T. *et al.* PRL **99**, 067006 (2007)

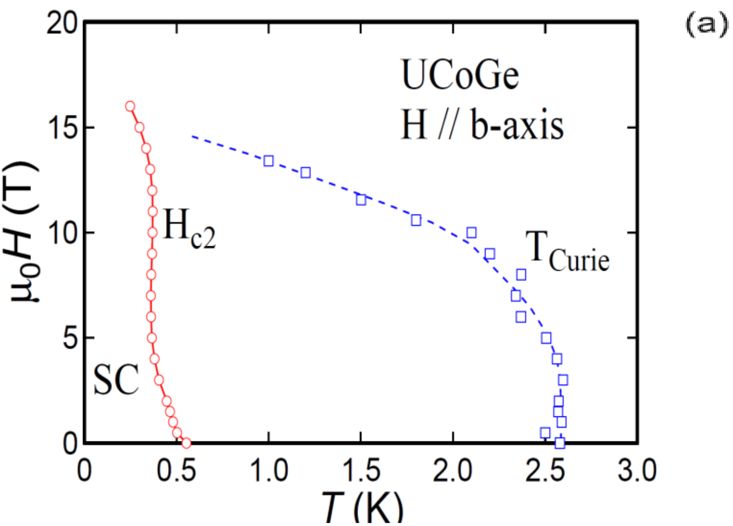
T_c = 2.5 K, T_{sc} = 0.6 K

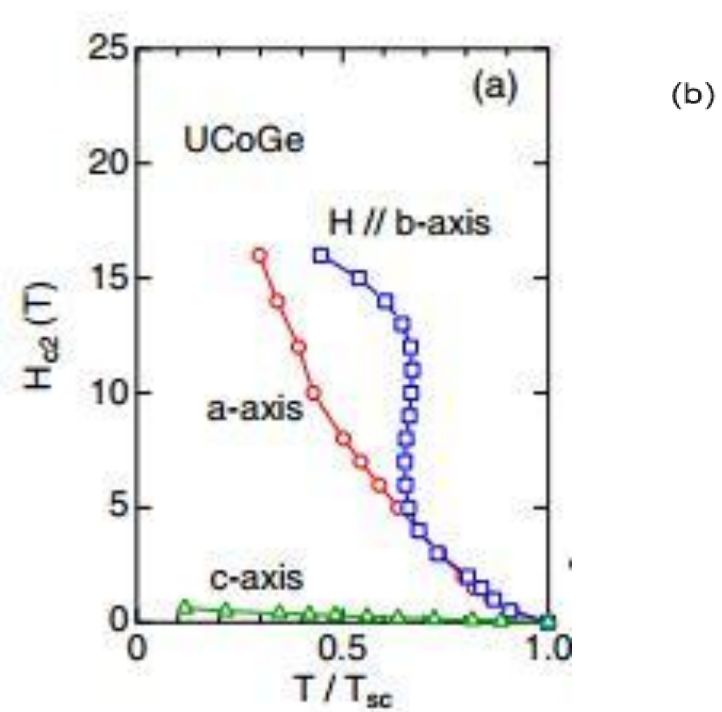
For a review, see:
D. Aoki & J. Flouquet, JPSJ 2012

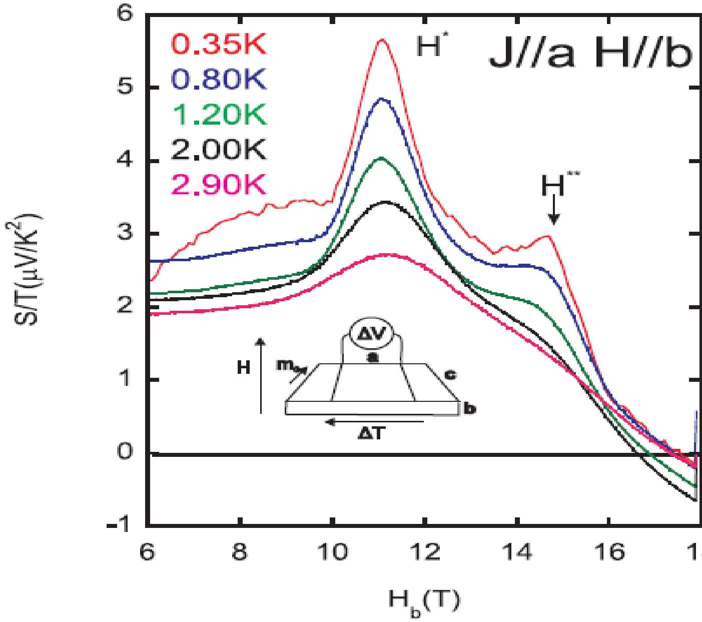


Reentrant superconductivity: Ferromagnetic fluctuations generate a SC dome!

S-shape $H_{c2}(T)$ in UCoGe

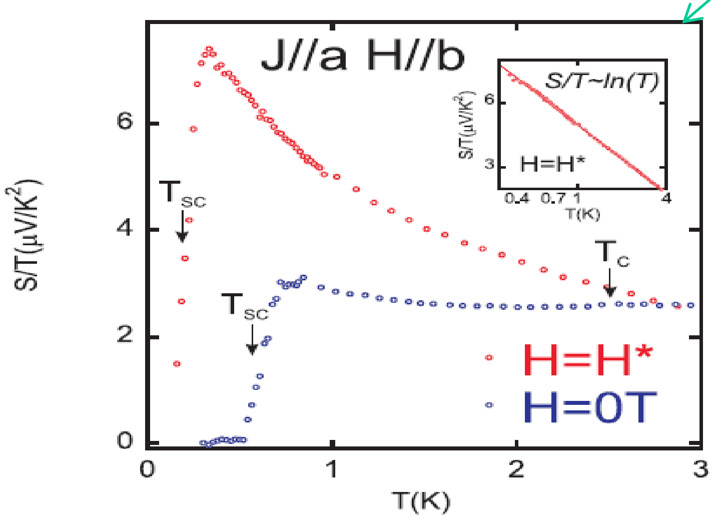






Both T_{sc} and S/T peak at H^*!

Logarithmic divergence of S/T at H^*!



Theory **for QCP** Paul, Kotliar,'03

Pourret et al., 2013

Thermoelectric Response Near a Quantum Critical Point of β-$YbAlB_4$ and $YbRh_2Si_2$: A Comparative Study

Y. Machida,[1] K. Tomokuni,[1] C. Ogura,[1] K. Izawa,[1] K. Kuga,[2] S. Nakatsuji,[2] G. Lapertot,[3] G. Knebel,[3] J.-P. Brison,[3] and J. Flouquet[3]

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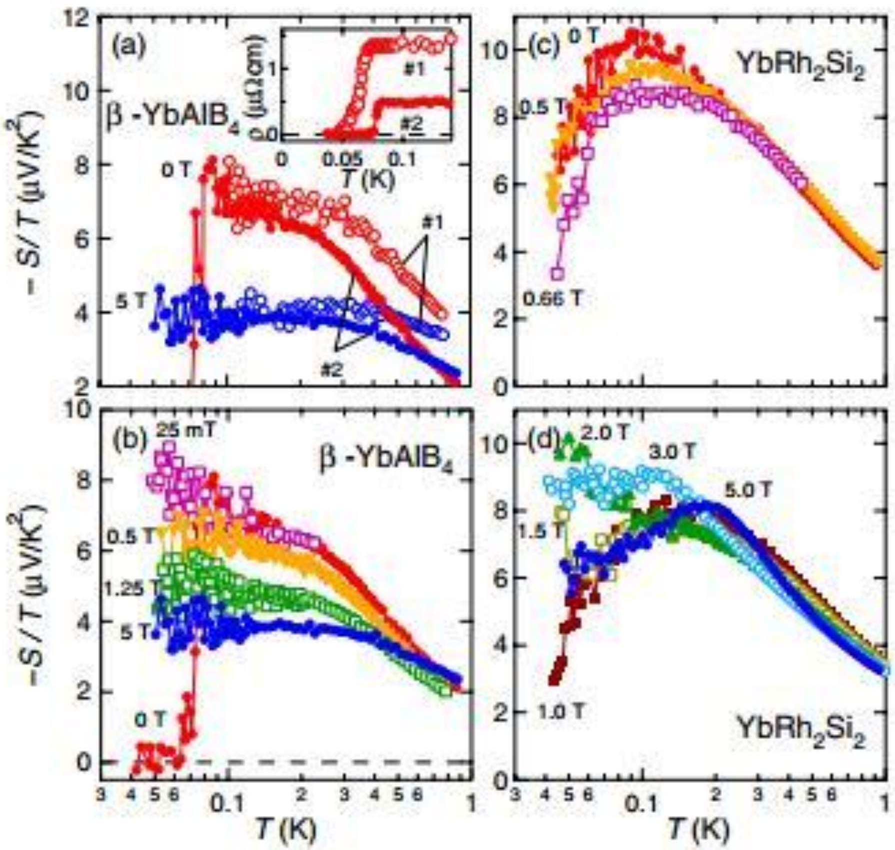
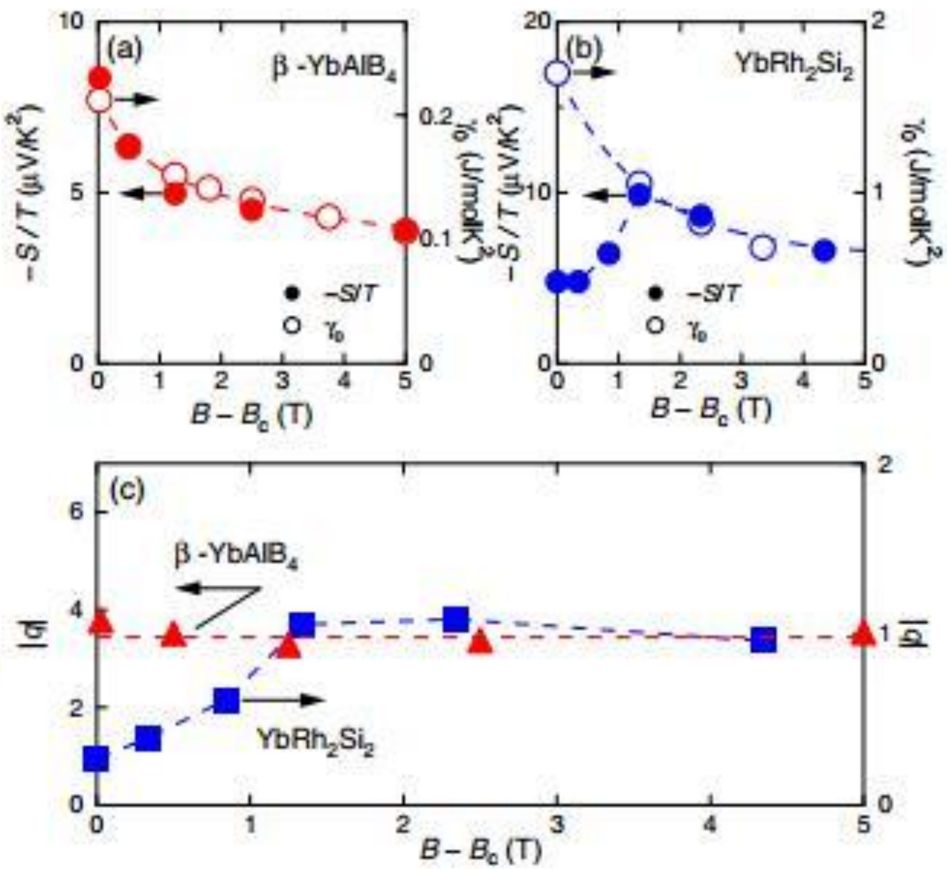




The effective Fermi temperature

- Resistivity

($\mu\Omega$cmK^{-2})

$$A = \frac{h}{e^2} a \frac{1}{T_F^2}$$

- Specfic heat

(JK^{-1} mol^{-1})

$$\gamma = \frac{\pi^2}{3} k_B n \frac{1}{T_F}$$

Material-dependent length scale

- Seebeck

(μVK^{-1})

$$\frac{S}{T} = \frac{\pi^2}{3} \frac{k_B}{e} \frac{1}{T_F}$$

Carrier density

All would diverge if T_F vanishes!

Seebeck coefficient is the only intensive coefficient (no geometric factor)!

The Nernst effect

$$\vec{J}_e = \sigma \vec{E} - \alpha \vec{\nabla} T$$

$$\vec{J}_Q = \alpha T \vec{E} - \kappa \vec{\nabla} T$$

α is now a tensor

$$0 = \sigma \vec{E} - \alpha \vec{\nabla} T \longrightarrow \begin{aligned} \sigma_{xx} E_x + \sigma_{xy} E_y &= \alpha_{xx} \nabla_x T + \alpha_{xy} \nabla_y T \\ -\sigma_{xy} E_x + \sigma_{yy} E_y &= -\alpha_{xy} \nabla_x T + \alpha_{yy} \nabla_y T \end{aligned}$$

$$\nabla_y T = 0 \longrightarrow [\sigma_{xy}{}^2 + \sigma_{xx}\sigma_{yy}] E_y = [\sigma_{xy}\alpha_{xx} - \sigma_{xx}\alpha_{xy}] \nabla_x T$$

$$N = \frac{-E_y}{\nabla_x T} = \frac{\alpha_{xy}\sigma_{xx} - \alpha_{xx}\sigma_{xy}}{\sigma_{xx}\sigma_{yy} + \sigma_{xy}^2}$$

Nernst effect and Hall mobility

$$N = \frac{\alpha_{xy}\sigma_{xx} - \alpha_{xx}\sigma_{xy}}{\sigma_{xx}^2 + \sigma_{xy}^2}$$

$$\Theta_H = \frac{\sigma_{xy}}{\sigma_{xx}} \longrightarrow \frac{\partial \Theta_H}{\partial \varepsilon} = \frac{\sigma_{xy}\frac{\partial \sigma_{xx}}{\partial \varepsilon} - \sigma_{xx}\frac{\partial \sigma_{xy}}{\partial \varepsilon}}{\sigma_{xx}^2 + \sigma_{xy}^2}$$

Extended Mott formula:

$$\alpha_{xx} = \frac{\pi^2}{3}\frac{k_B{}^2 T}{e}\frac{\partial \sigma_{xx}}{\partial \varepsilon} \qquad \alpha_{xy} = \frac{\pi^2}{3}\frac{k_B{}^2 T}{e}\frac{\partial \sigma_{xy}}{\partial \varepsilon}$$

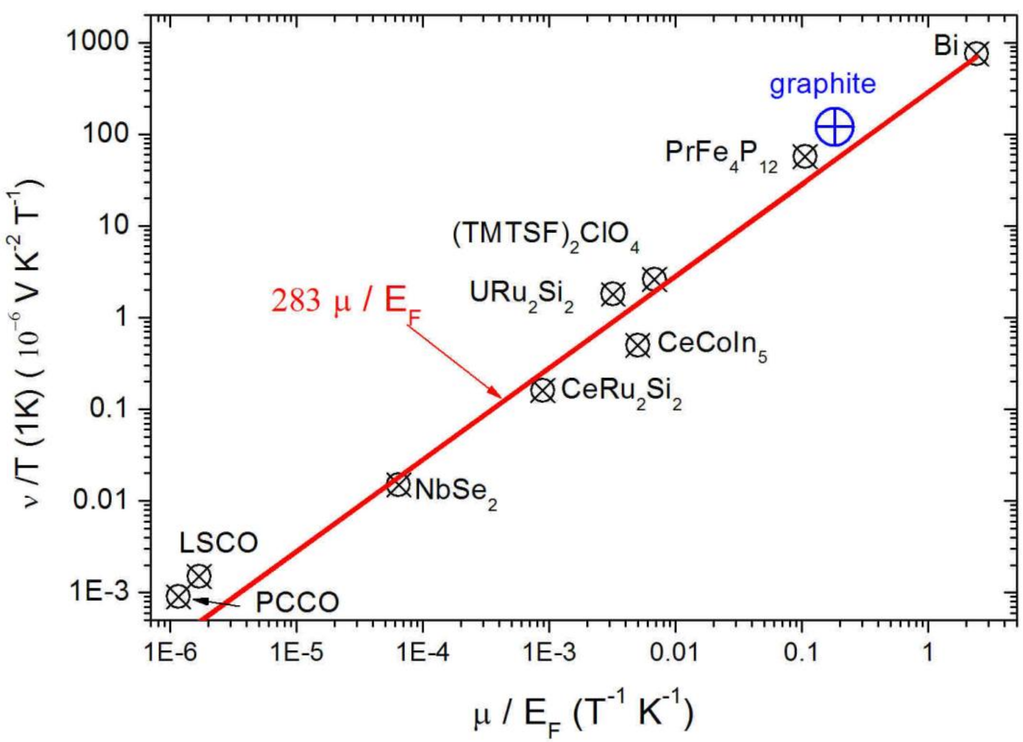
$$N = \frac{\pi^2}{3}\frac{k_B^2 T}{e}\frac{\partial \Theta_H}{\partial \epsilon}\Big|_{\varepsilon_F}$$

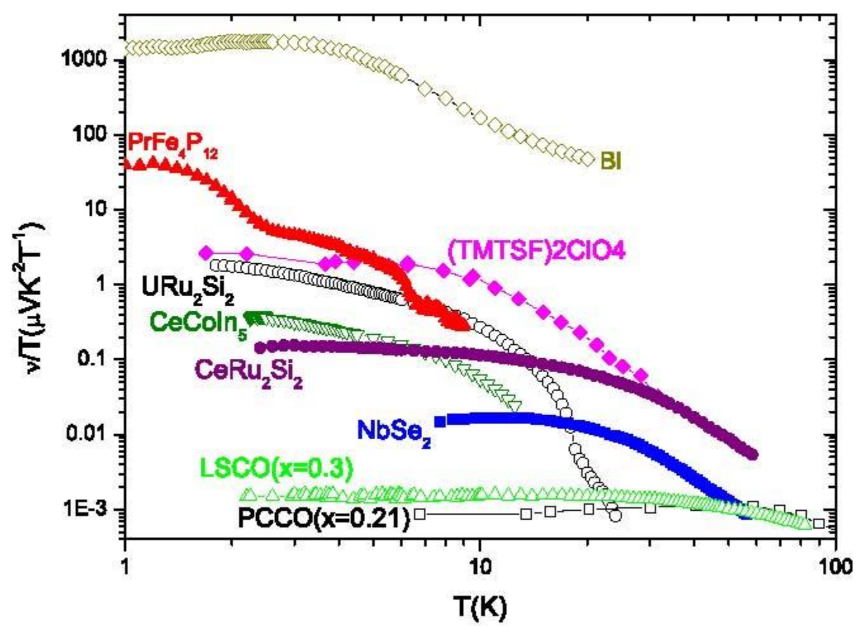
Nernst effect measures the change in the Hall mobility induced by shifting the Fermi level!

The Hall mobility

$$\Theta_H = \mu_H = \frac{e\tau}{m^*} = \frac{e}{\hbar}\frac{\ell}{k_F}$$

$$\Theta_H(\varepsilon) \propto \varepsilon^{\gamma} \qquad \frac{\nu}{T} = \frac{\pi^2}{3}\frac{k_B^2}{eB}\left.\frac{\partial \Theta_H}{\partial \varepsilon}\right|_{\varepsilon_F} \Rightarrow \frac{\nu}{T} \approx \frac{\pi^2}{3}\frac{k_B^2}{e}\left.\frac{\mu}{\varepsilon_F}\right|$$

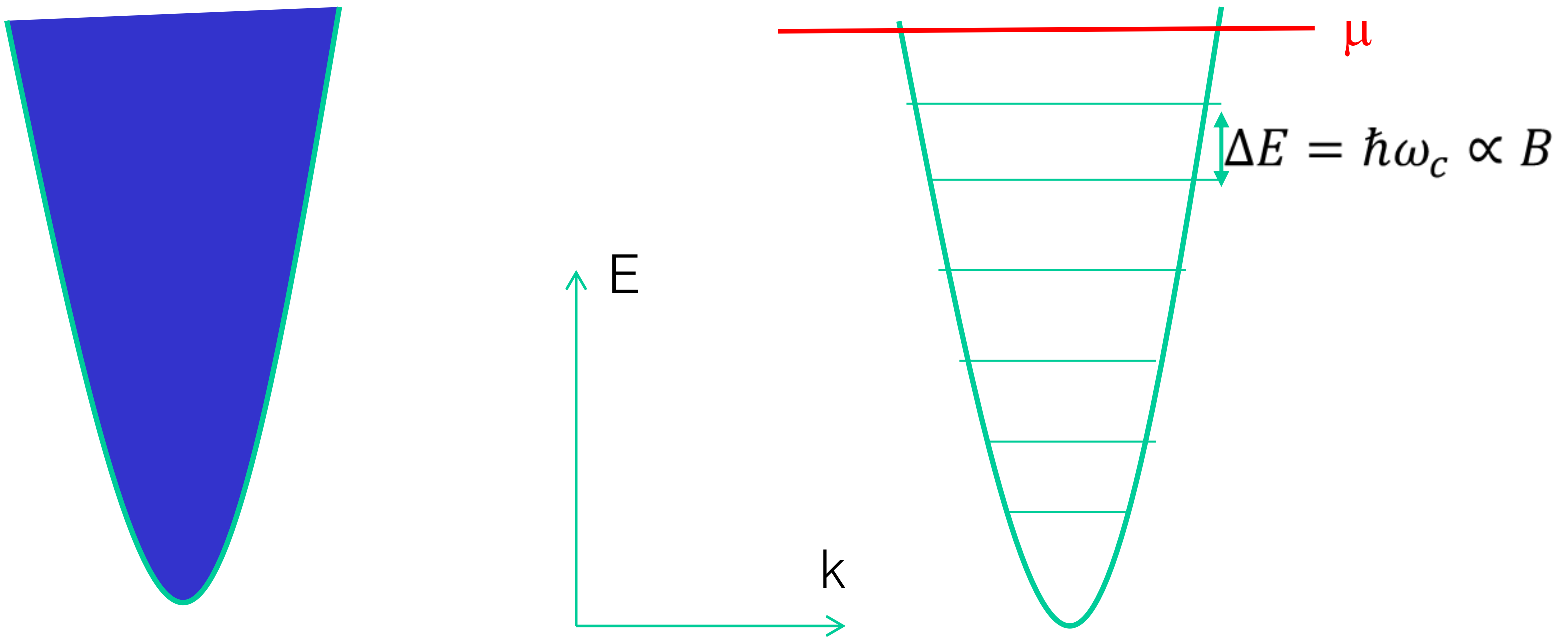




Quantum oscillations and the quantum limit

Landau quantization

$B = 0$ $\qquad\qquad$ $B \neq 0$



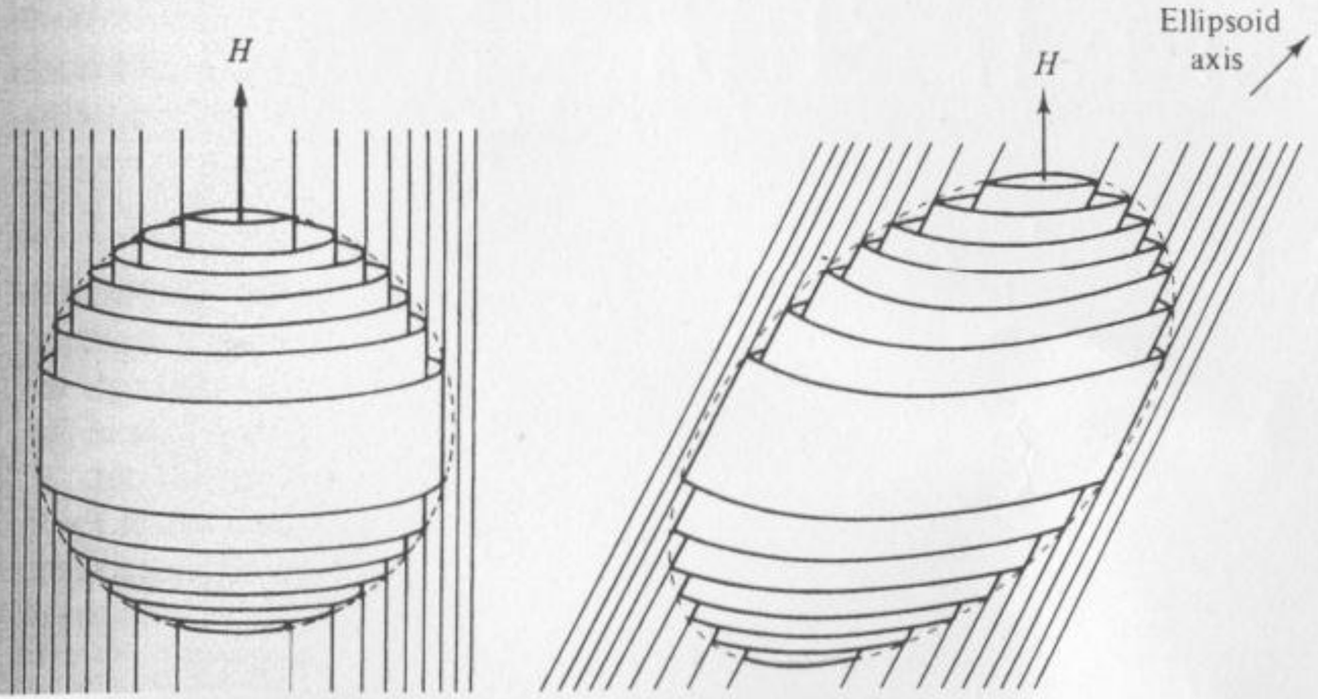
$$E = \frac{\hbar^2}{2m^*}(k_x^2 + k_y^2)$$

$$E_n = \hbar\omega_c(n + \frac{1}{2})$$

Electron energy spectrum is no more a continuum.

Fermi surface truncated by Landau tubes

Fig. 2.1. Schematic sketches of Landau tubes for (*a*) spherical surfaces of constant energy, (*b*) ellipsoidal surfaces of constant energy (direction of long axis shown by arrow). The FS is indicated by the broken curve and only the parts of the Landau tubes inside the FS are occupied at $T = 0$ (after Chambers 1956 and Gold 1968).



Shoenberg 1984

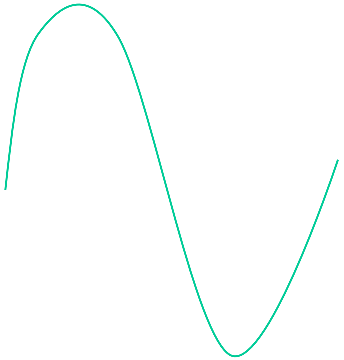
[redacted]

The magnetic field required to attain the quantum limit

When the magnetic length becomes shorter than the Fermi wave length!

$$\lambda_F \propto n^{-1/3}$$

$$l_B \propto B^{-1/2}$$



Particle (radius of curved trajectory)

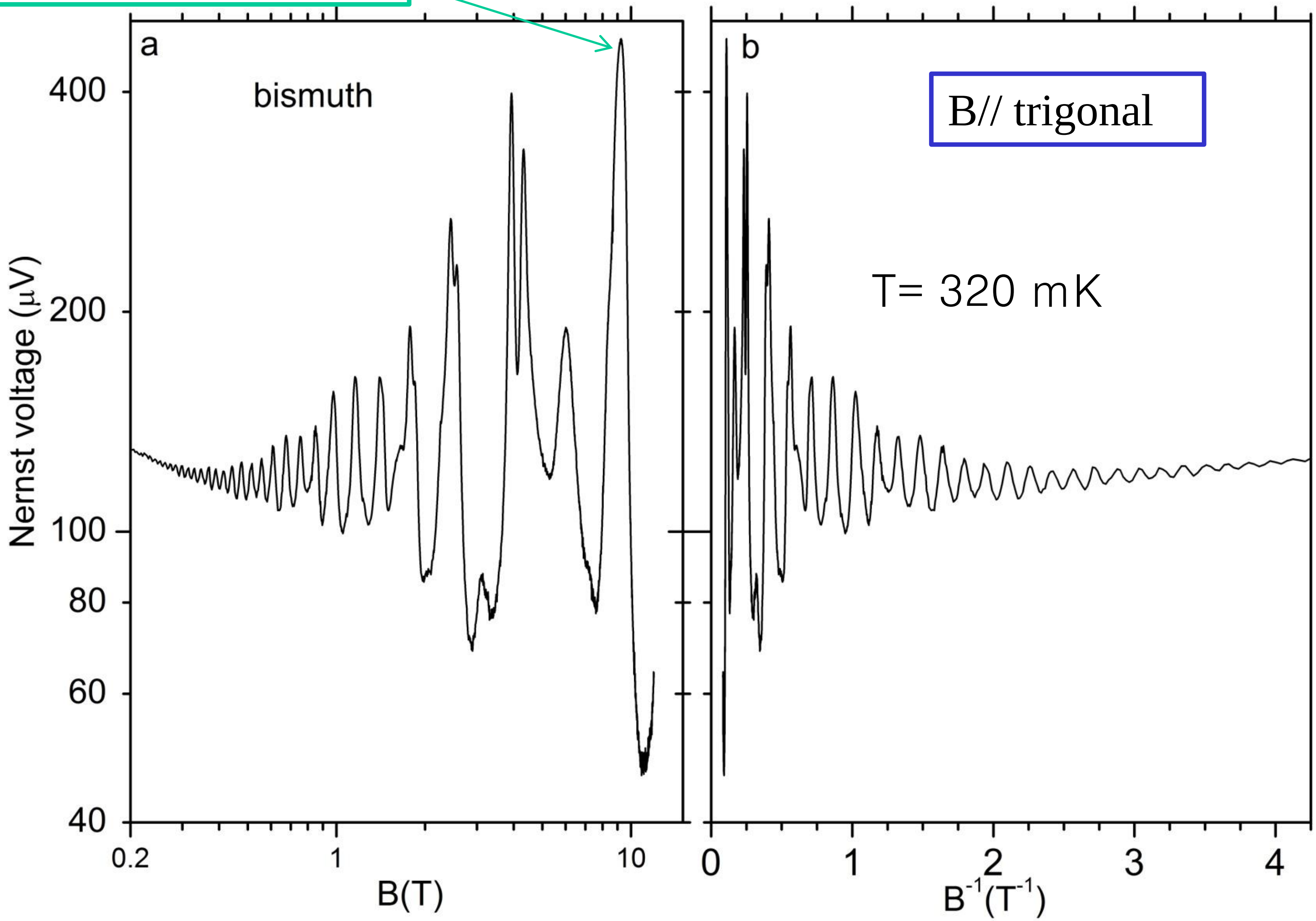
Wave (wave-length)

The lower the carrier density, the lower B_{QL}!

	Copper	bismuth
Carrier density (cm^{-3})	8.5 10^{22}	3 10^{17}
λ_F (nm)	0.5	47
B_{QL} (T)	30000	9

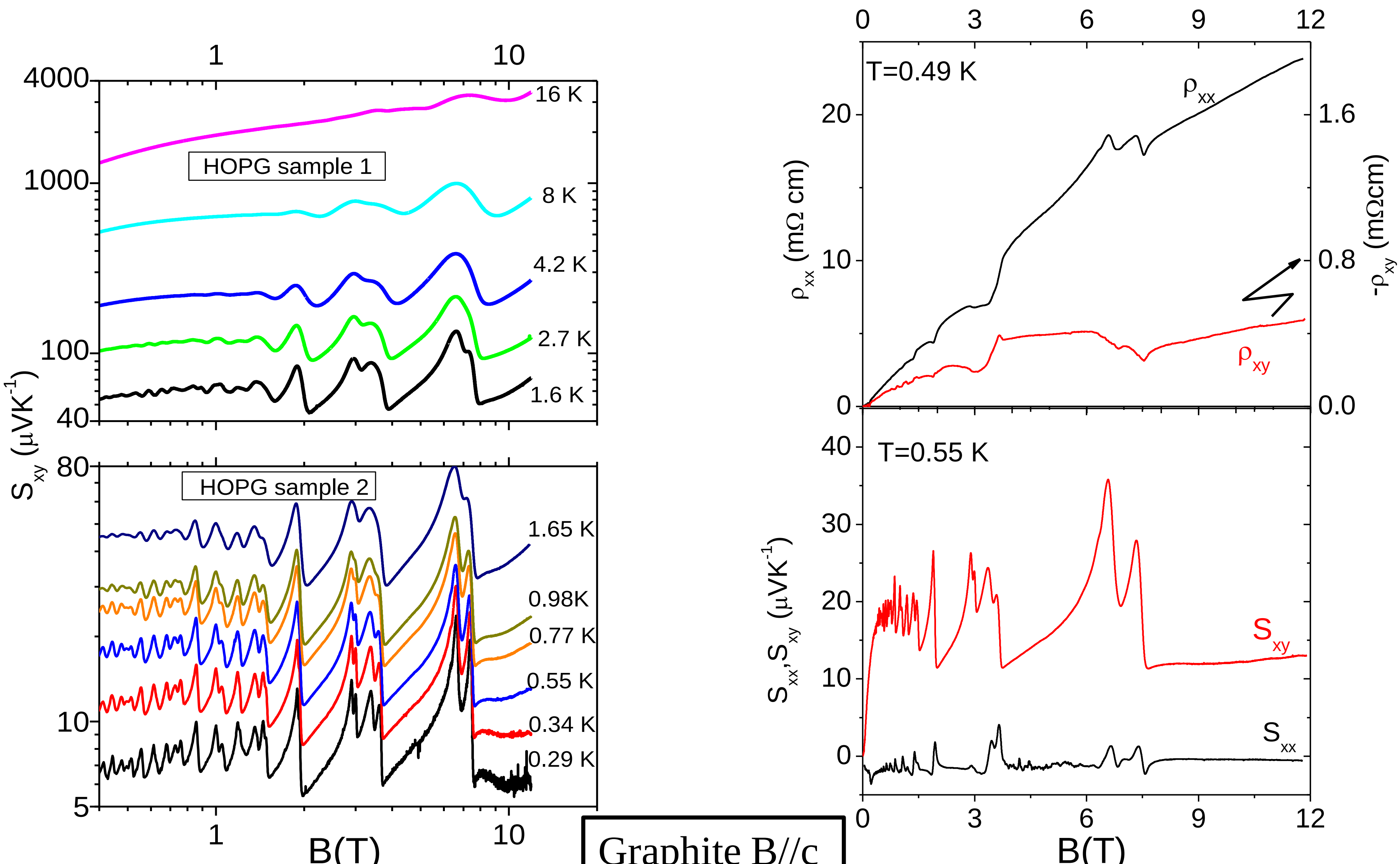
Giant quantum oscillations of the Nernst response

The last expected peak @ 9 T



Giant Nernst quantum oscillations in graphite

Zhu et al., Nature Physics 2009



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Nernst quantum oscillations in Graphene

Resistivity

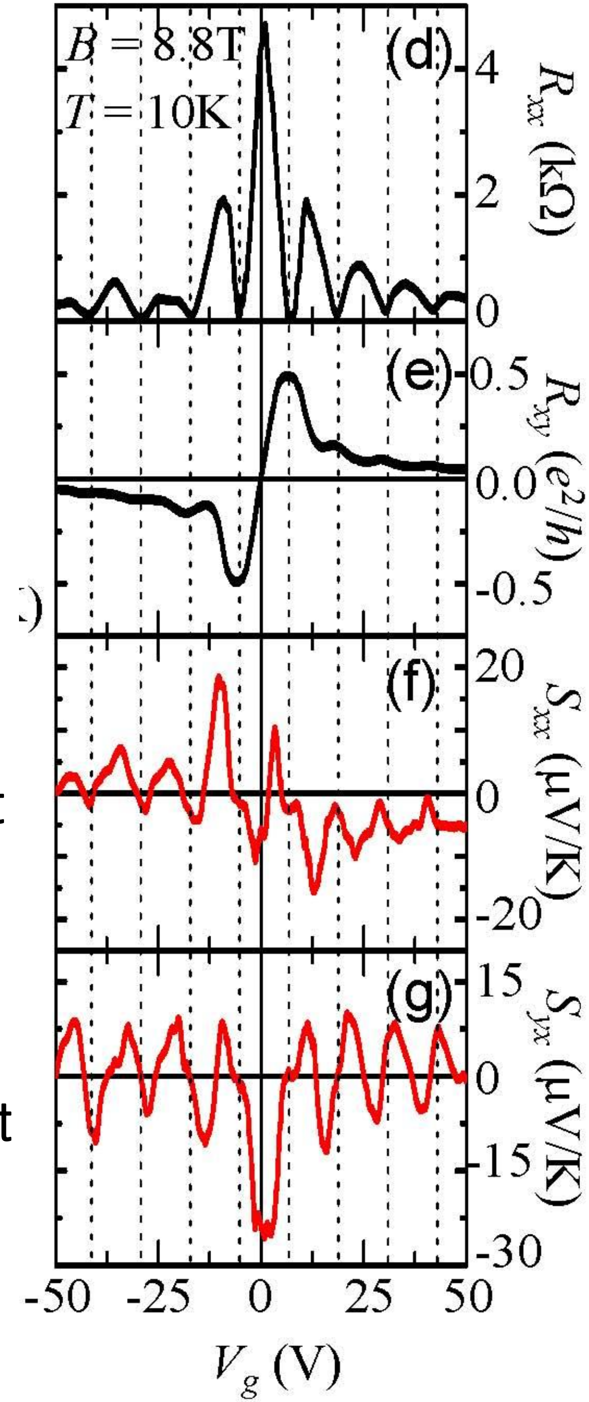
Hall effect

Zuev et al. (Philip Kim's group)
PRL 2009

Seebeck effect

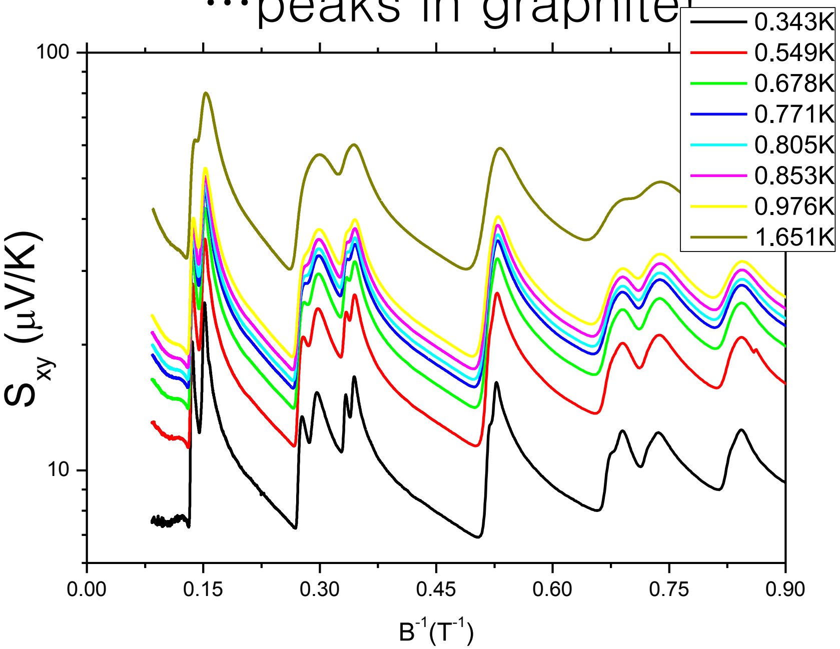
Magnetic field is kept constant
and the gate volage is scanned.

Nernst effect

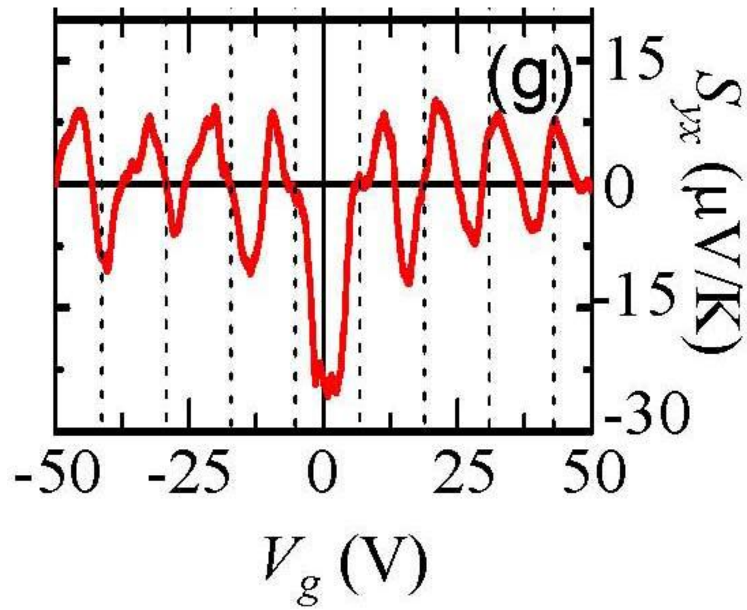


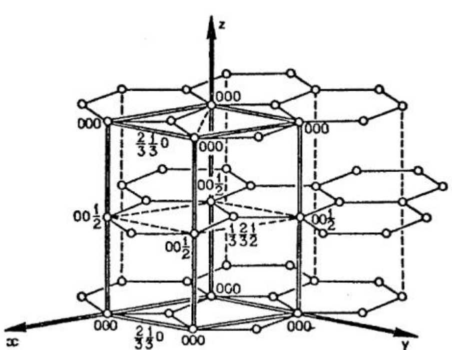
When a Landau level intersects the Fermi level, the Nernst response…

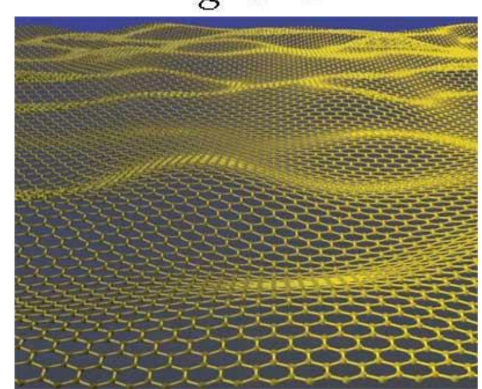
…peaks in graphite!



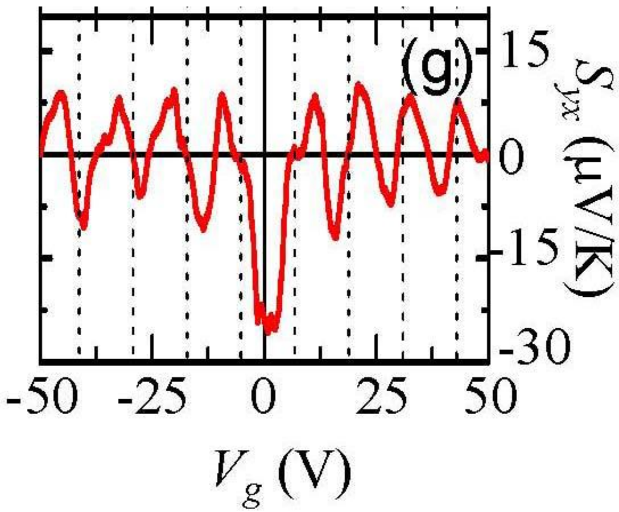
…vanishes in graphene!



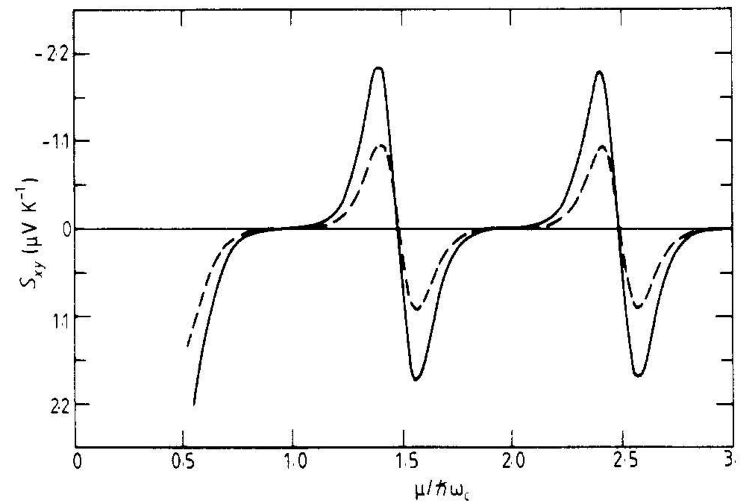




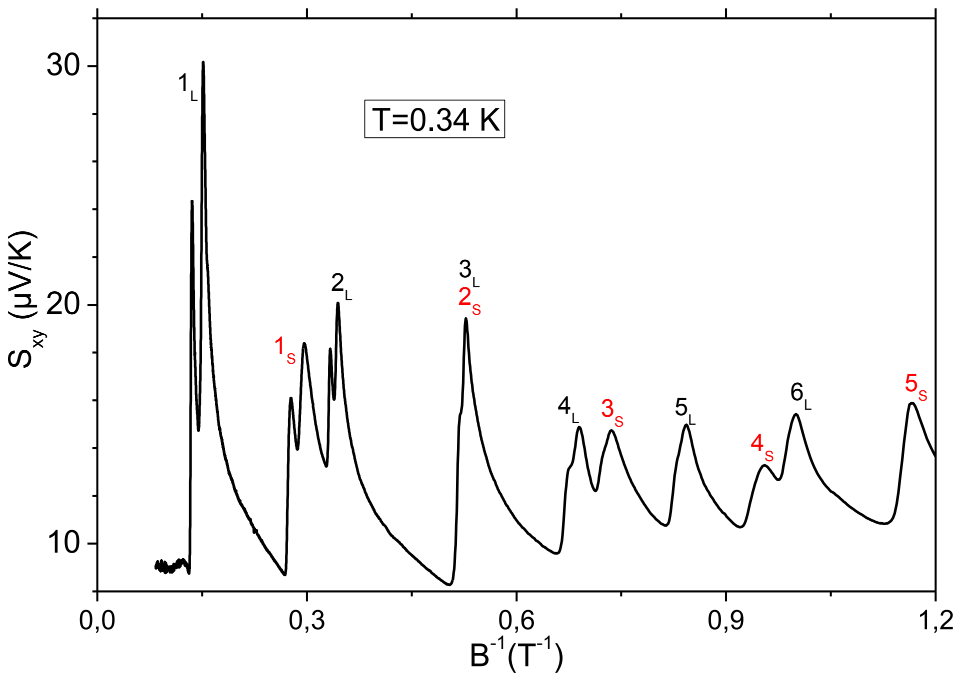
Experiment: graphene



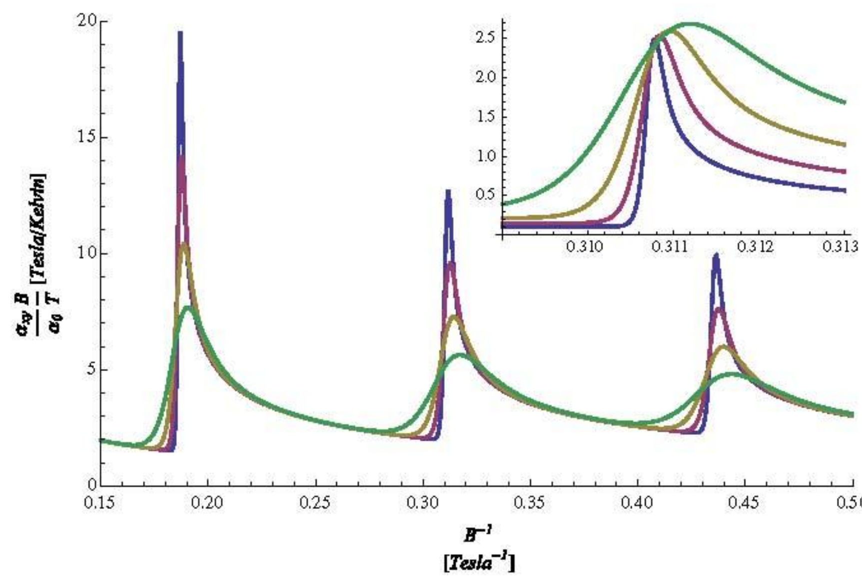
Theory :2D
(Girvin, Jonson PRB 1984)



Experiment:graphite



Theory :3D
(Bergman&Oganesyan PRL 2010)



Recent theory on Nernst quantum oscillations

PRL **104,** 066601 (2010) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2010

Theory of Dissipationless Nernst Effects

Doron L. Bergman[1] and Vadim Oganesyan[2]

[1]*Department of Physics, California Institute of Technology, Pasadena, California 91125, USA*
[2]*Department of Engineering Science and Physics, College of Staten Island, CUNY, Staten Island, New York 10314, USA*
(Received 14 October 2009; published 11 February 2010)

PHYSICAL REVIEW B **83**, 085103 (2011)

Oscillations of the Nernst coefficient in bismuth

Yu. V. Sharlai and G. P. Mikitik

B. Verkin Institute for Low Temperature Physics & Engineering, Ukrainian Academy of Sciences, Kharkov 61103, Ukraine
(Received 29 October 2010; published 9 February 2011)

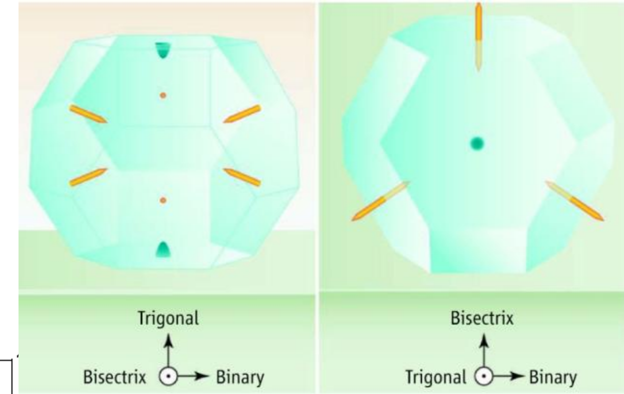
PRL **107,** 016601 (2011) PHYSICAL REVIEW LETTERS week ending 1 JULY 2011

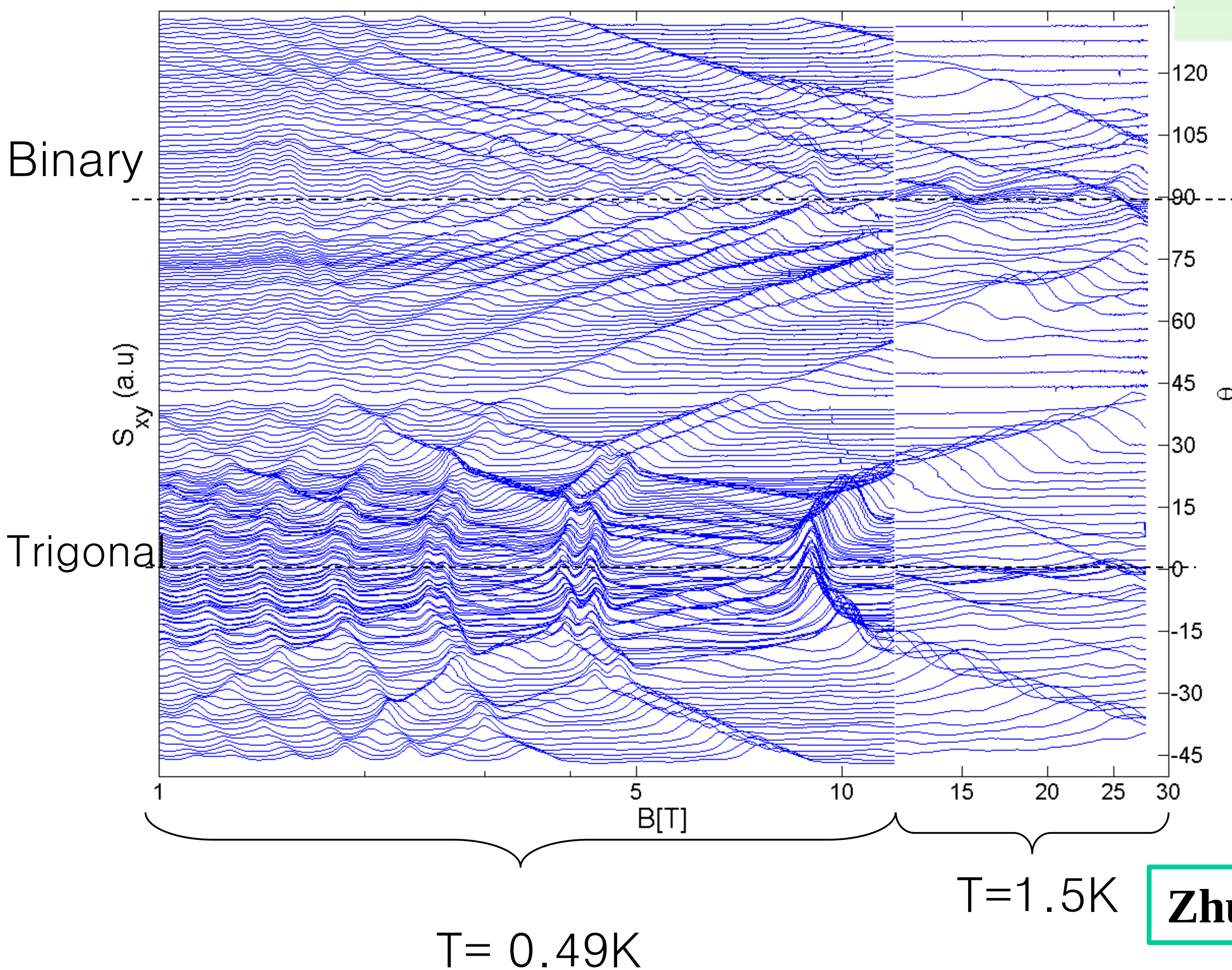
Giant Nernst-Ettingshausen Oscillations in Semiclassically Strong Magnetic Fields

Igor A. Luk'yanchuk,[1] Andrei A. Varlamov,[2] and Alexey V. Kavokin[3]

[1]*Laboratory of Condensed Matter Physics, University of Picardie Jules Verne, Amiens, 80039, France*
[2]*CNR-SPIN, Viale del Politecnico 1, I-00133 Rome, Italy*
[3]*Physics and Astronomy School, University of Southampton, Highfield, Southampton, SO171BJ, United Kingdom*
(Received 28 November 2010; published 29 June 2011)

Angle-resolved Nernst effect in bismuth

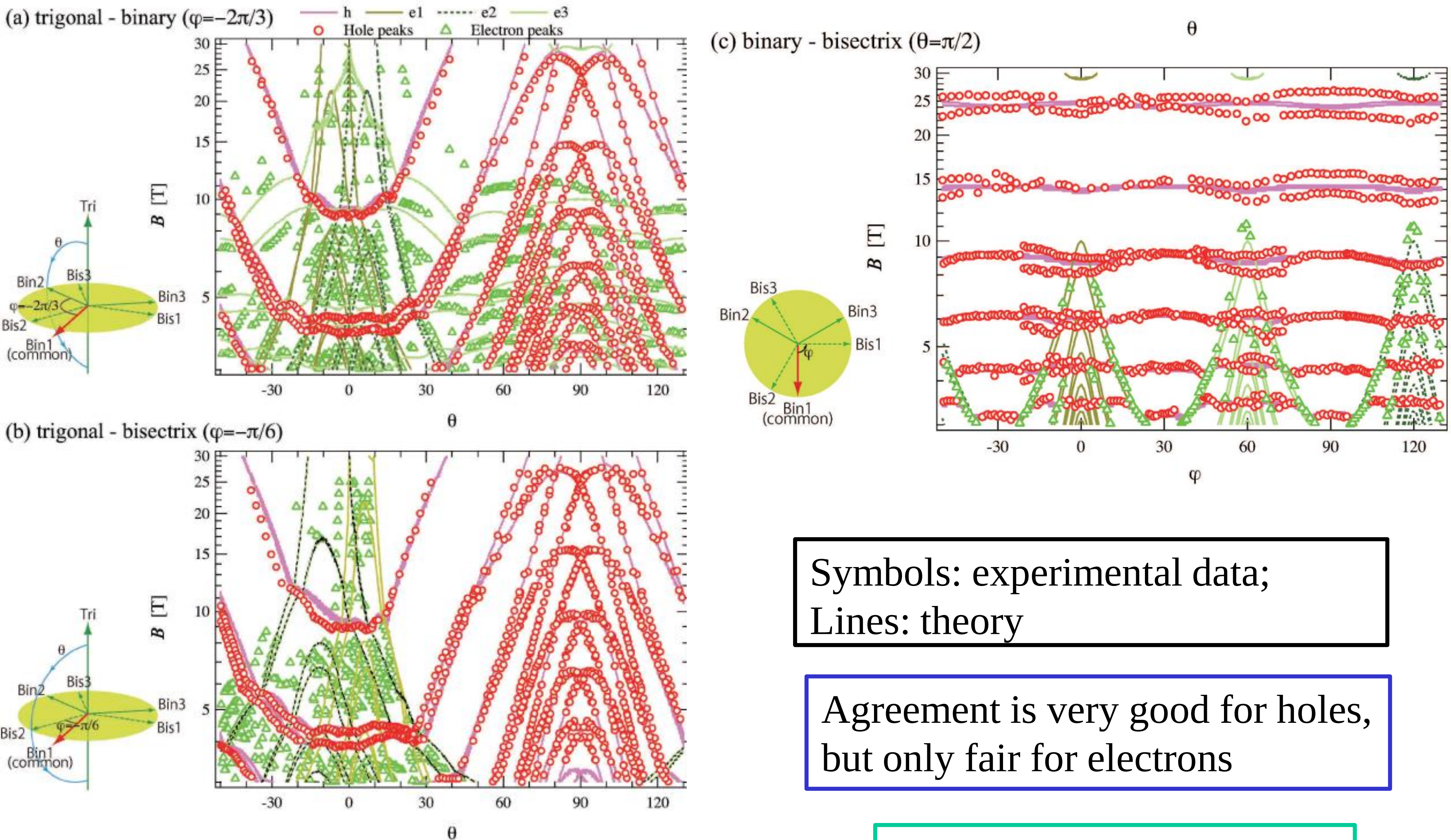




Nersnt peaks shift as the magnetic field tilts!

Zhu et al., PNAS (2012)

Angle-resolved Landau spectrum in bismuth (experiment and theory)

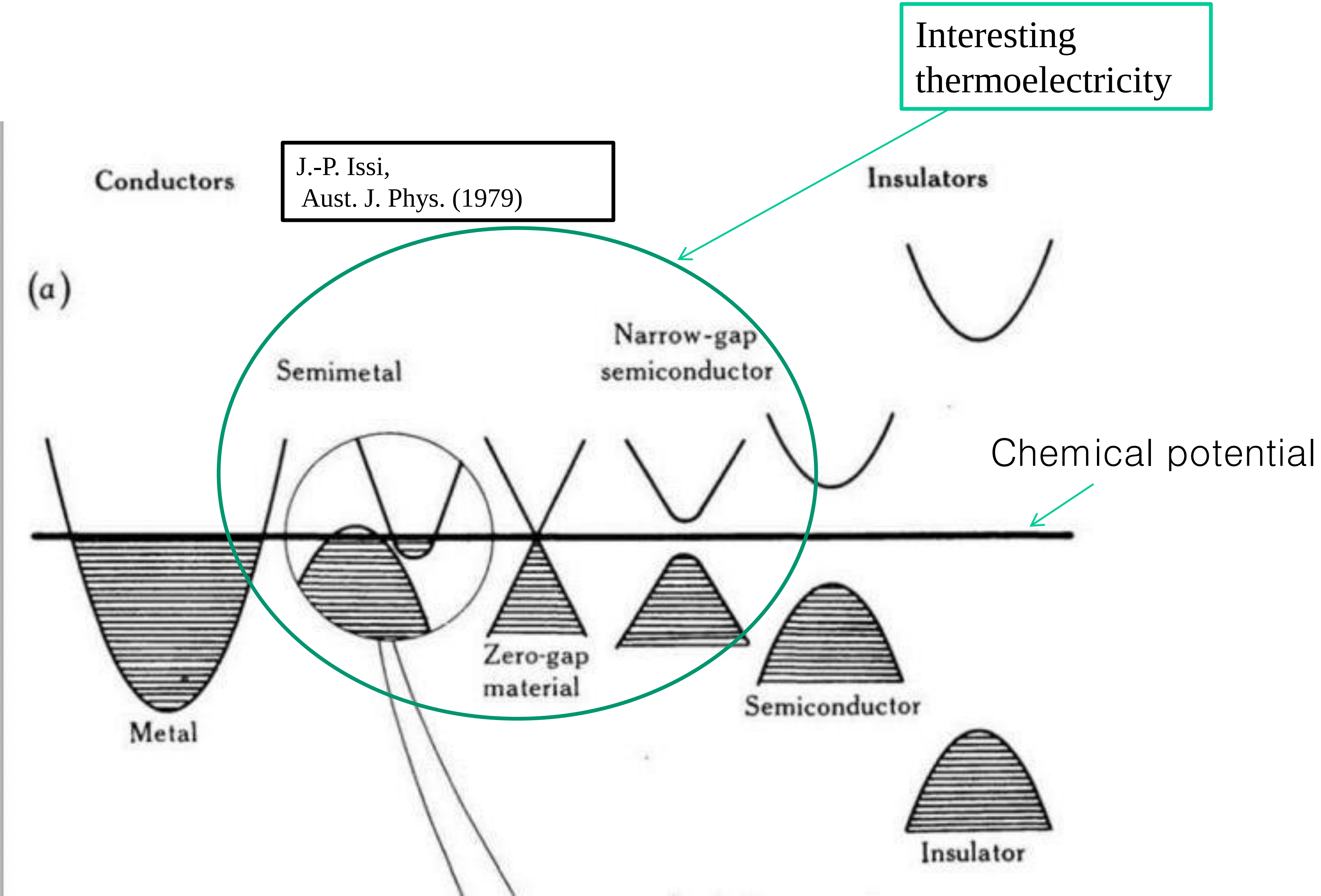


Symbols: experimental data;
Lines: theory

Agreement is very good for holes, but only fair for electrons

Zhu et al., PNAS (2012)

The band picture of metals and insulators!



How does an isulator become a metal?

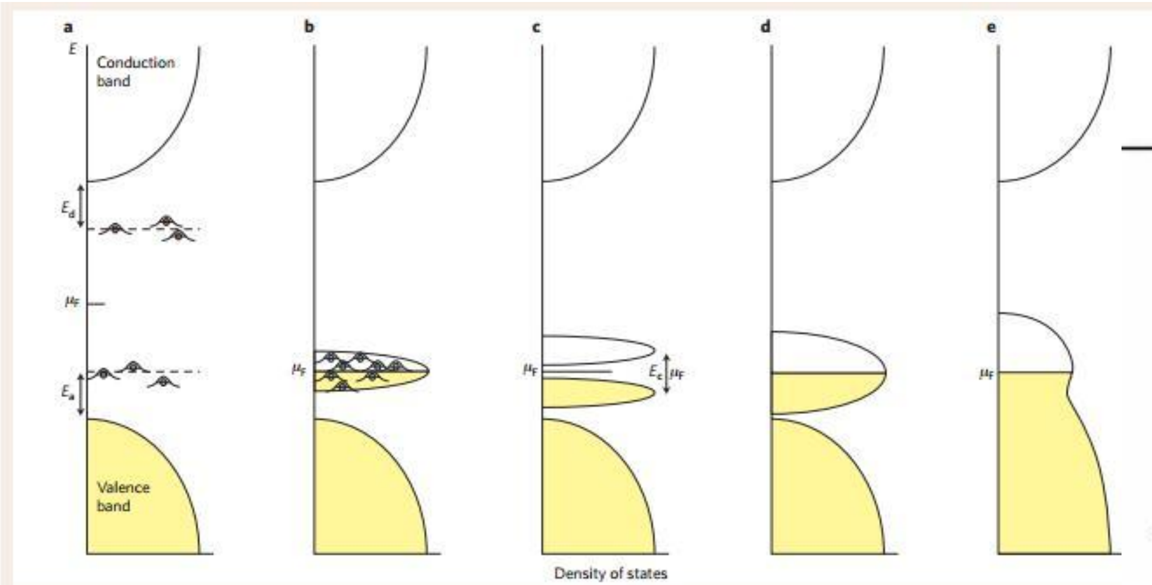
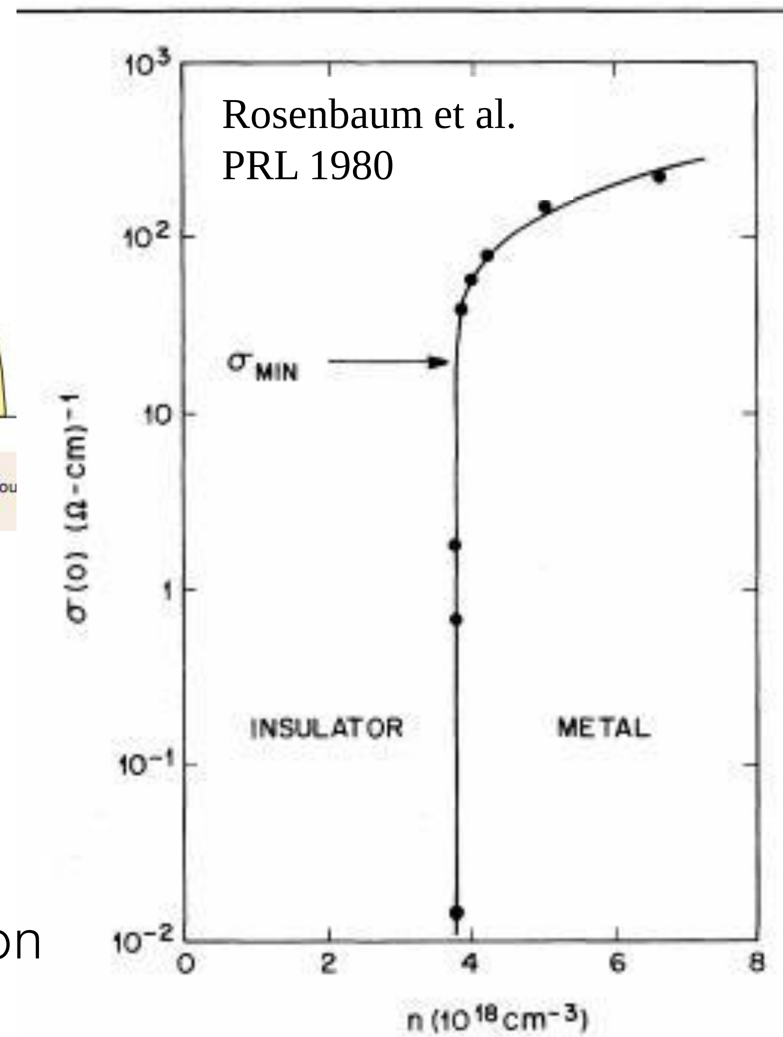


Figure B2 | Evolution of the electronic density of states and band structure with increasing p-type doping. Doping increases from **a** to **e**. Colou area represents filled states.

doping

X. Blase et al.,
Nature Materials (2009)



phosphorus-doped silicon

Fermiology of doped semi-conductors

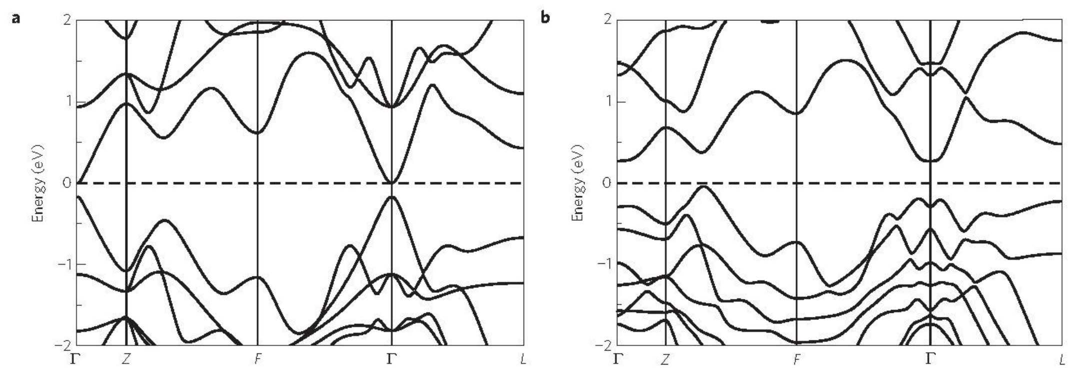
•**Self-doped Bi_2Se_3** believed to be a bulk topological insulator with non-trivial surface states.

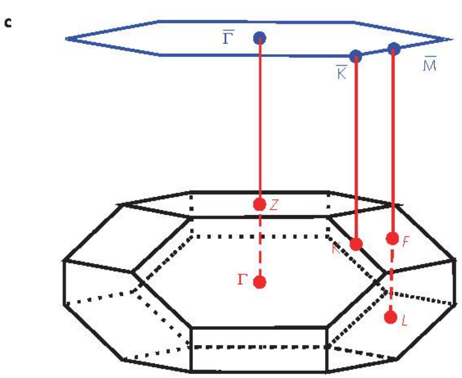
•**$SrTiO_{3-\delta}$** discovered in 1964 as the first case of a "semiconducting superconductor"

•Many others to be explored: PbTe, InSb, …)

ARTICLES
PUBLISHED ONLINE: 10 MAY 2009 | DOI: 10.1038/NPHYS1270
nature physics

Topological insulators in Bi_2Se_3, Bi_2Te_3 and Sb_2Te_3 with a single Dirac cone on the surface





d

Sb_2Se_3	$+-+-+-+-+-+---;+$	$(+)$
Sb_2Te_3	$+-+-++-+-+---+;-$	$(-)$
Bi_2Se_3	$+-+-+-+-+-+--+;-$	$(-)$
Bi_2Te_3	$+-+-+-++-+---+;-$	$(-)$

Figure 2 | Band structure, Brillouin zone and parity eigenvalues. a,**b**, Band structure for Bi_2Se_3 without (**a**) and with (**b**) SOC. The dashed line indicates the Fermi level. **c**, Brillouin zone for Bi_2Se_3 with space group $R\bar{3}m$. The four inequivalent time-reversal-invariant points are $\Gamma(0,0,0)$, $L(\pi,0,0)$, $F(\pi,\pi,0)$ and $Z(\pi,\pi,\pi)$. The blue hexagon shows the 2D Brillouin zone of the projected (1, 1, 1) surface, in which the high-symmetry **k** points $\bar{\Gamma}$, $\bar{K}$ and $\bar{M}$ are labelled. **d**, The parity of the band at the Γ point for the four materials Sb_2Te_3, Sb_2Se_3, Bi_2Se_3 and Bi_2Te_3. Here, we show the parities of fourteen occupied bands, including five s bands and nine p bands, and the lowest unoccupied band. The product of the parities for the fourteen occupied bands is given in brackets on the right of each row.

Toplogical? Sure!
Insulator? Hum…

Which side of the metal-insulator transition?

Critical density for metal-insulator transition

The Mott criterion:
Metallicity emerges when two length scales become comparable

$$a_H n^{1/3} \cong 0.26$$

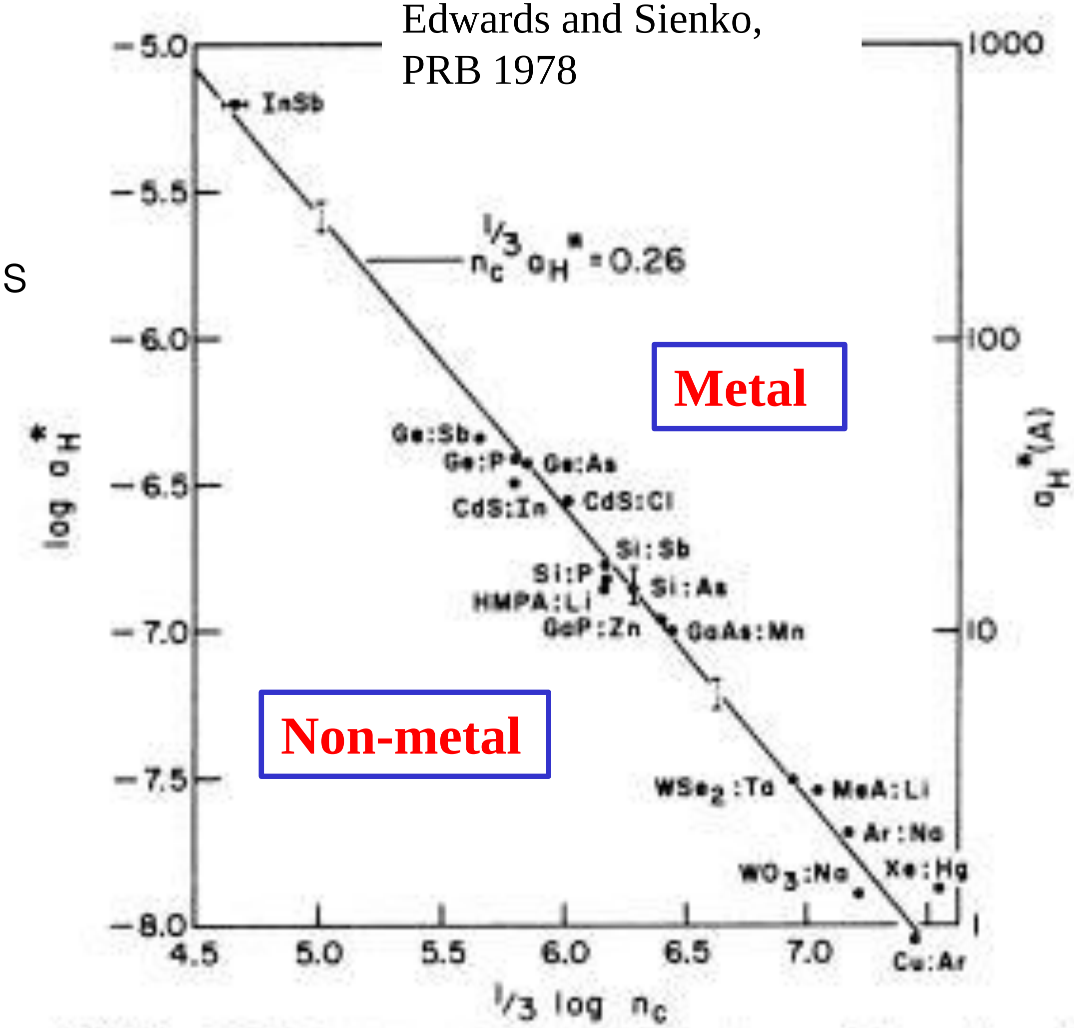
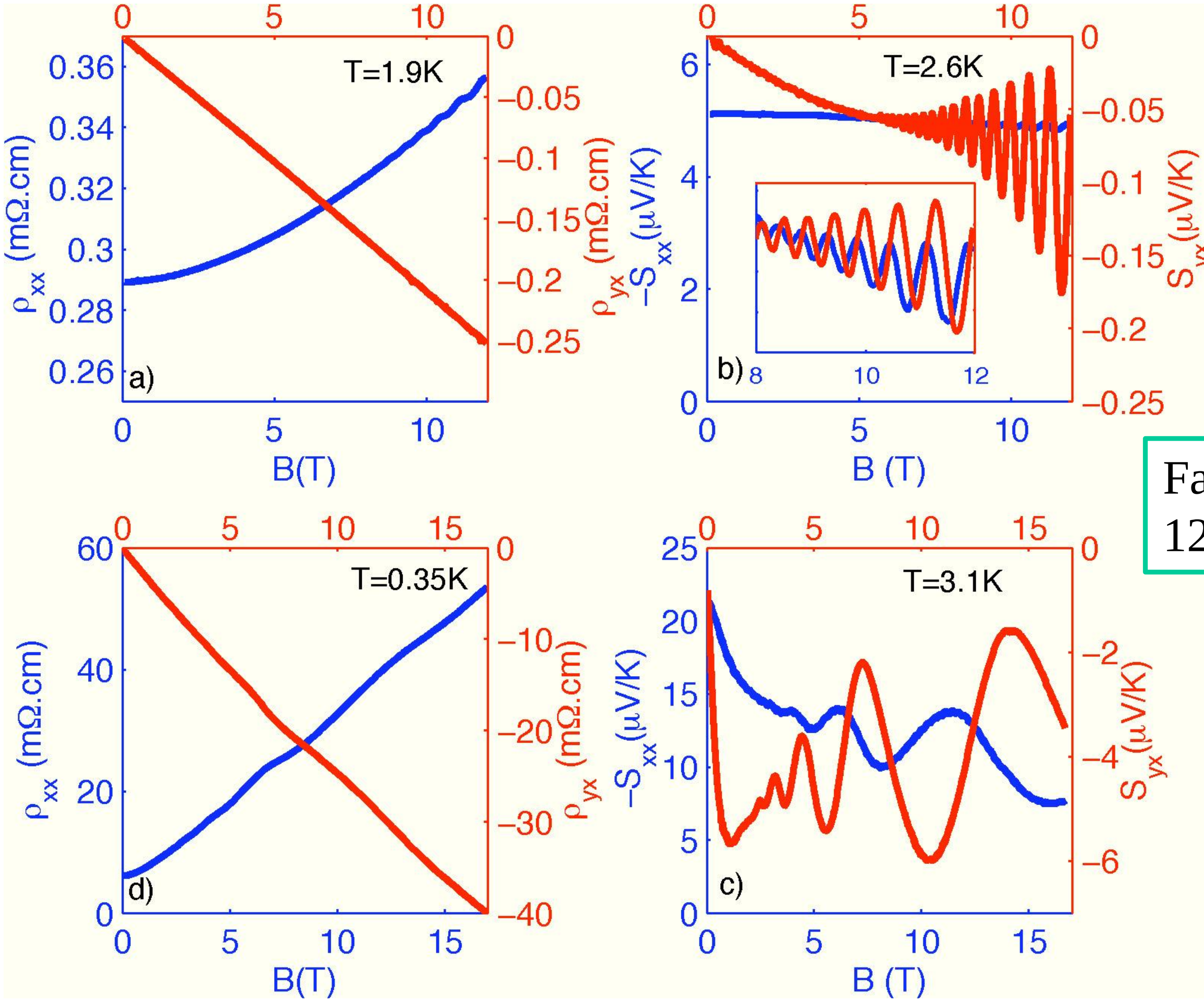


FIG. 1. Metal–nonmetal transition in condensed media. A plot of $\log a_H^*$ vs $\frac{1}{3}\log n_c$ (symbols defined in the text).

The effective Bohr radius: $a_H = \dfrac{\varepsilon_r \hbar^2}{m^* e^2}$

The interdopant distance: $n^{1/3}$

Quantum oscillations of the Nernst effect in Bi_2Se_3



n = 10^{19} cm^{-3}

Fauqué et al., arXiv: 1209.1312

n = 10^{17} cm^{-3}

A sharp bulk Fermi surface down to 10^{17} cm^{-3}

Two routes towards Fermi temperature

Thermopower

$$\frac{S}{T} = \frac{\pi^2}{3}\frac{K_B}{e}\frac{1}{T_F}$$

@10^{19} cm^{-3}

S/T= −0.45 μVK

F=170 T

m$*$=0.2m$_e$

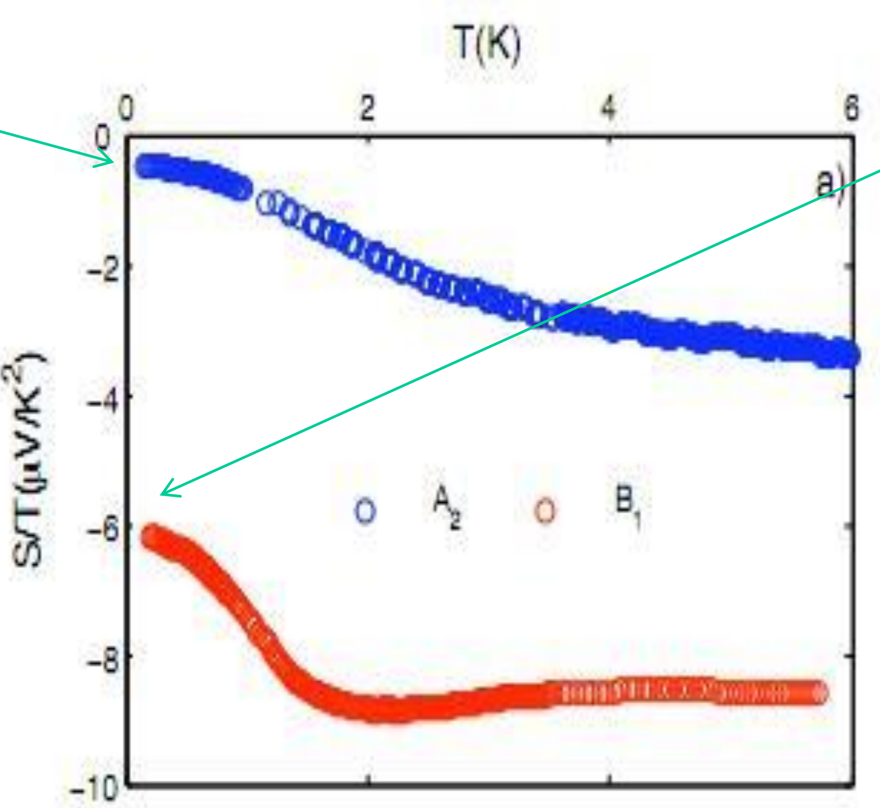
T$_F$=900 K

Quantum oscillations:

$$k_B T_F = \frac{\hbar^2 k_F^2}{2m^*}$$

@10^{17} cm^{-3}

Fauqué et al., PRB (2013)



S/T= −6.1 μVK^{-2}

F=15 T

m$*$ =0.18m$_e$

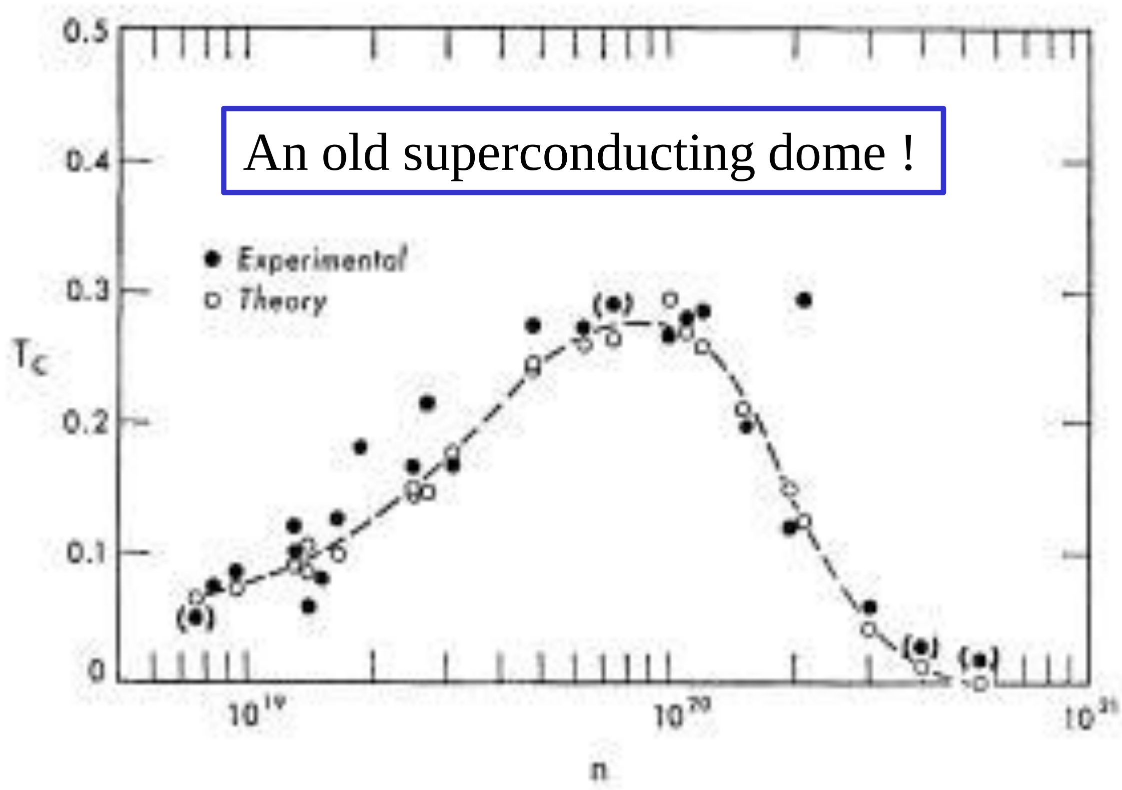
T$_F$=87 K

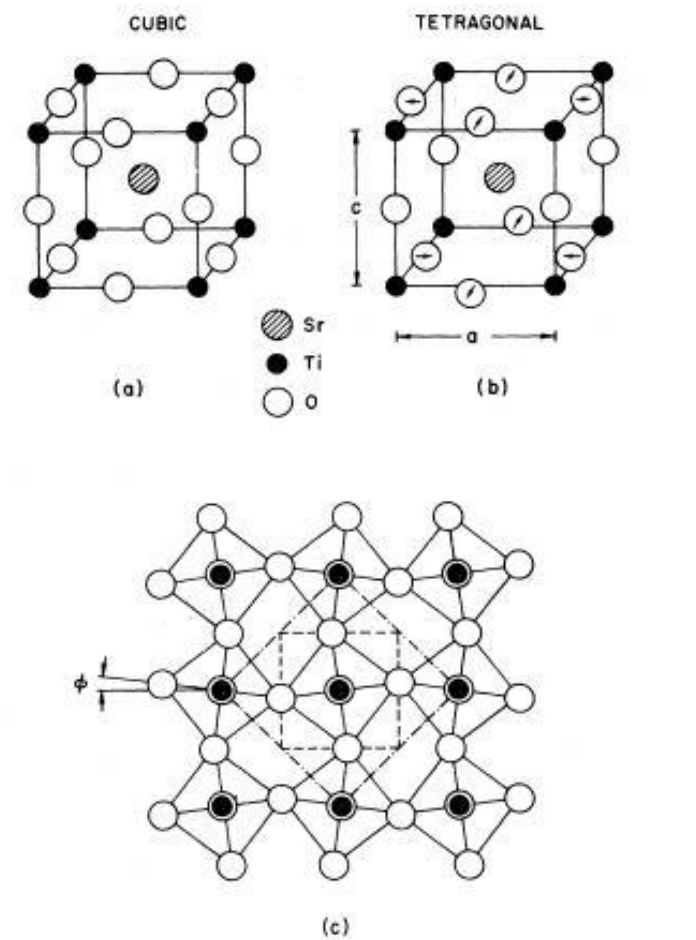
n- doped $SrTiO_3$

PHYSICAL REVIEW VOLUME 163, NUMBER 2 10 NOVEMBER 1967

Superconducting Transition Temperatures of Semiconducting $SrTiO_3$

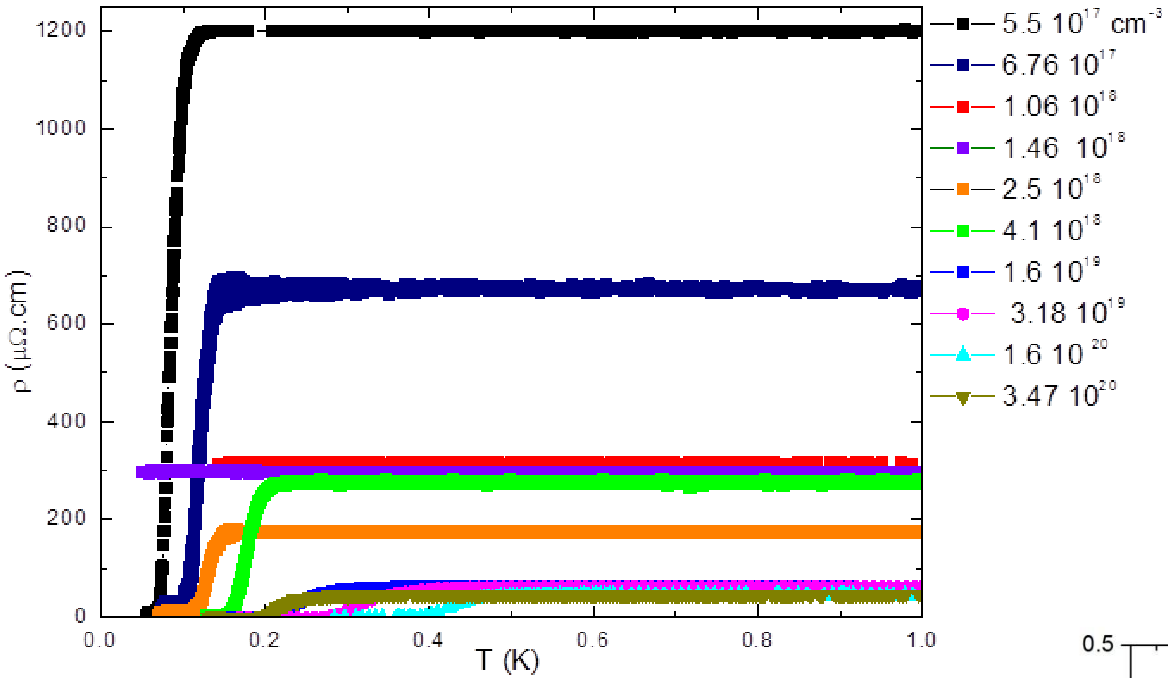
C. S. Koonce* and Marvin L. Cohen†
Department of Physics, University of California, Berkeley, California
and
J. F. Schooley,‡ W. R. Hosler,§ and E. R. Pfeiffer
National Bureau of Standards, Washington, D. C.
(Received 5 July 1967)





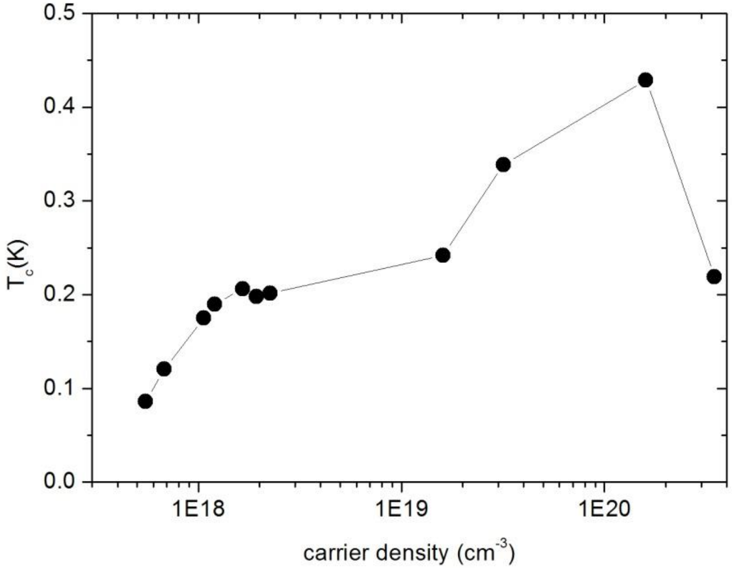
Superconductivity in bulk n-doped $SrTiO_3$

Lin et al., PRX 2013

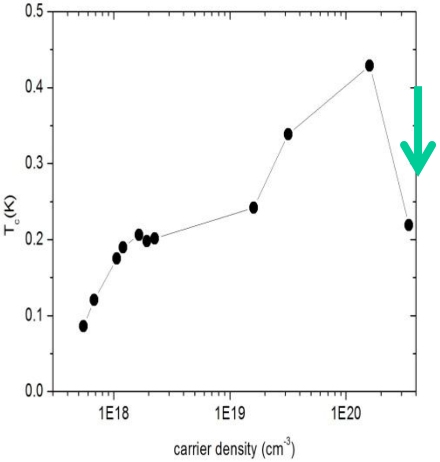


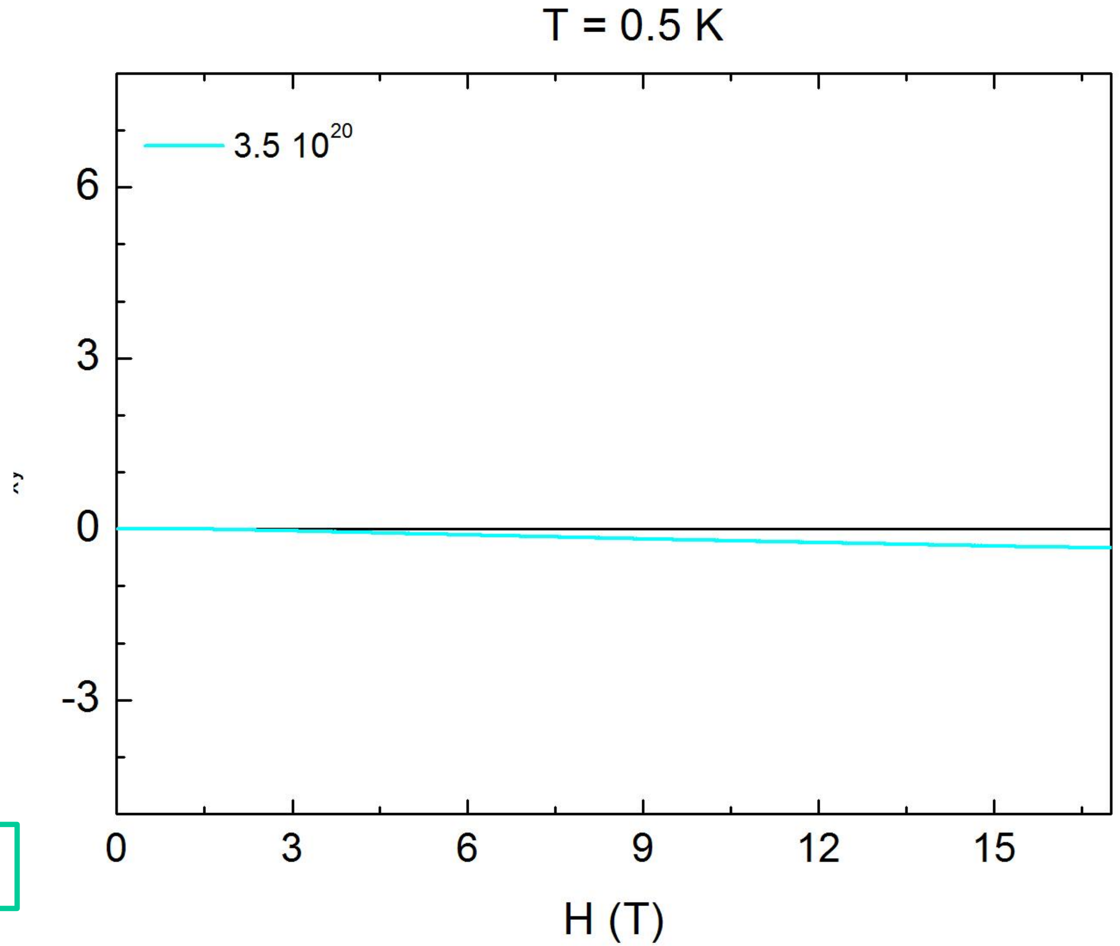
•**n-doping:**
removing oxygen or
replacing Ti with Nb

•**Carrier density window:**
between $5 10^{17}$ to $3\ 10^{20}$ cm^{-3}



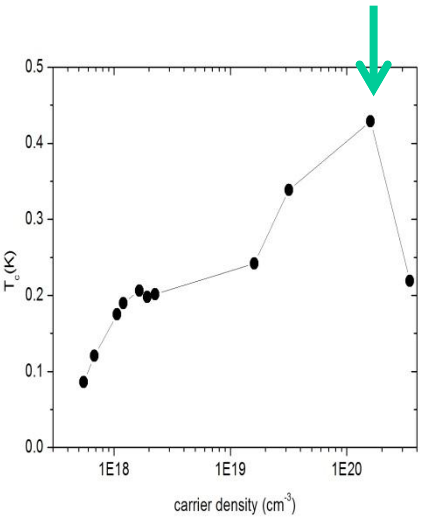
Emergence of Nernst oscillations with underdoping

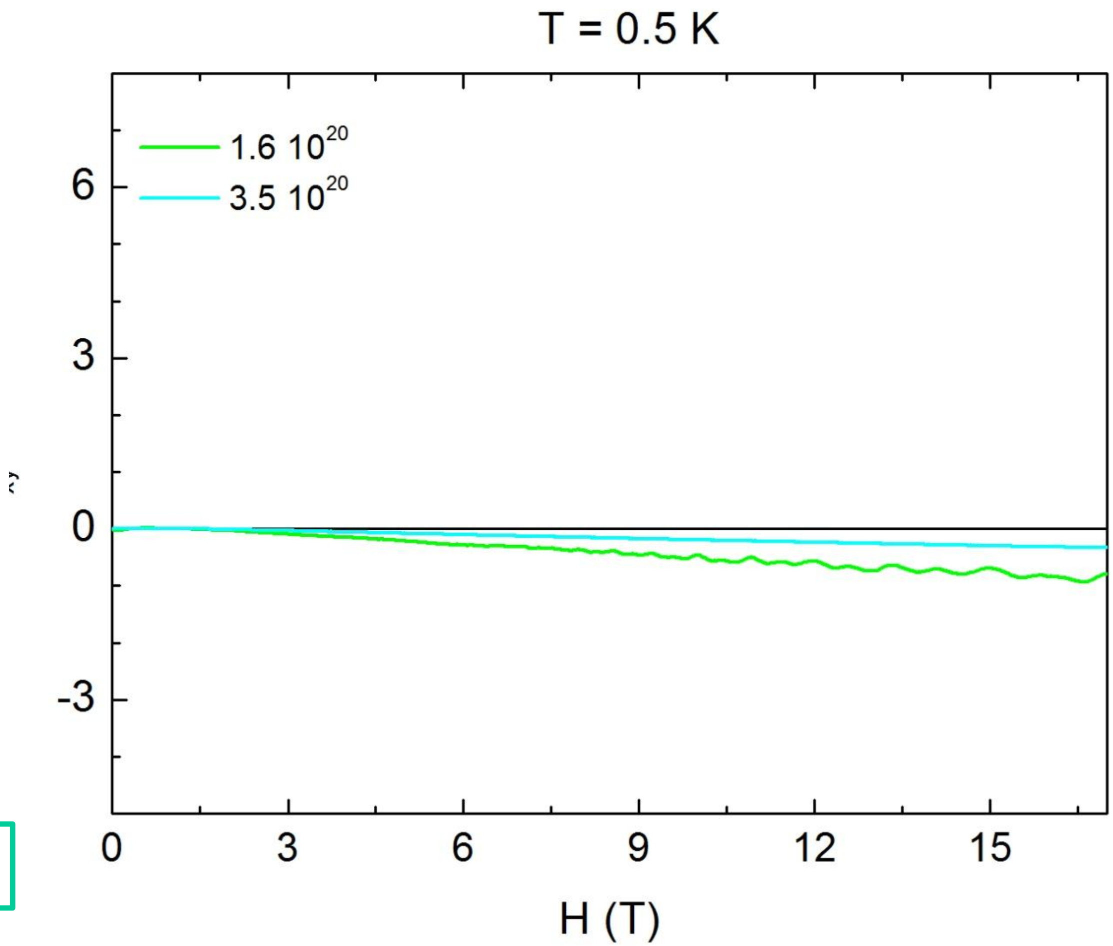




Lin et al., PRX 2013

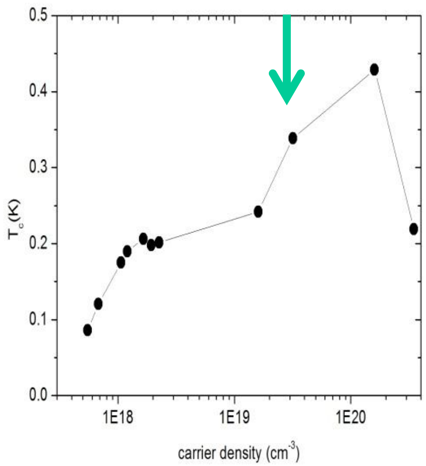
Emergence of Nernst oscillations with underdoping

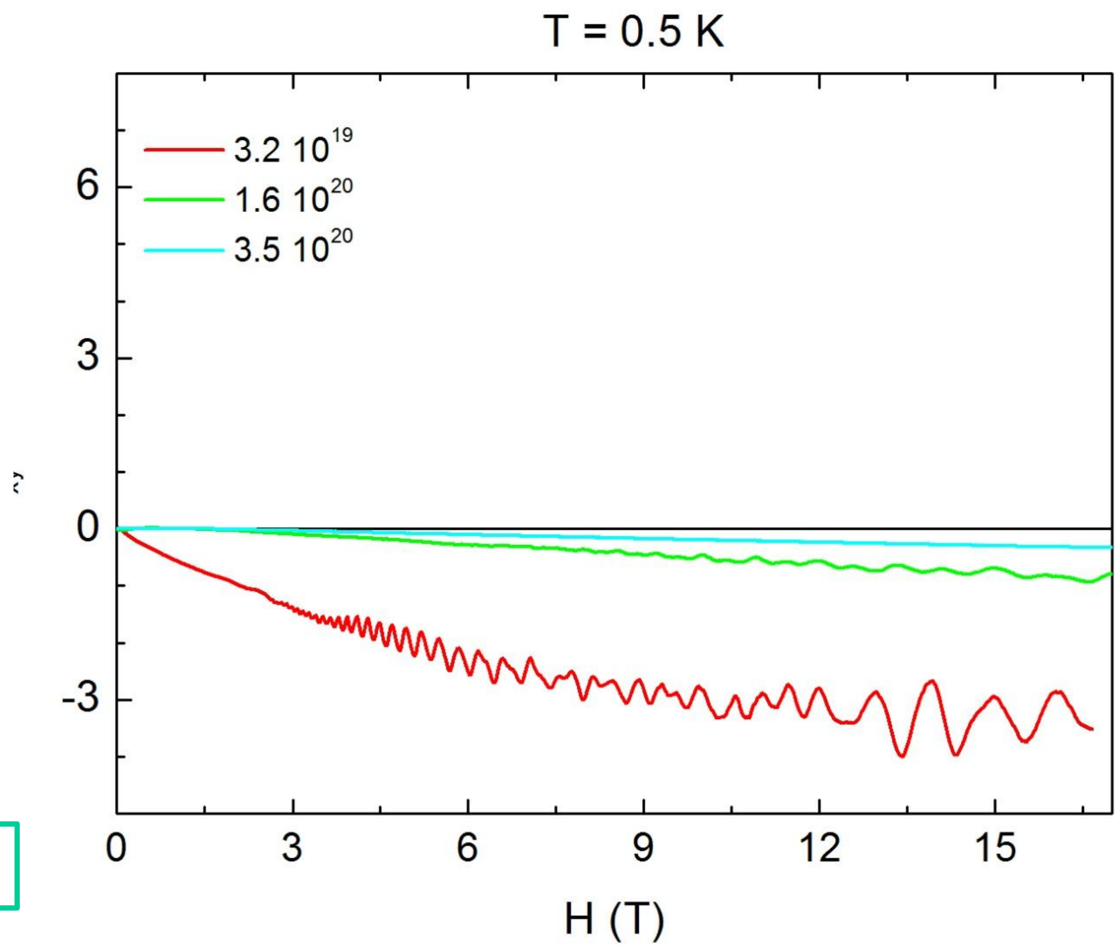




Lin et al., PRX 2013

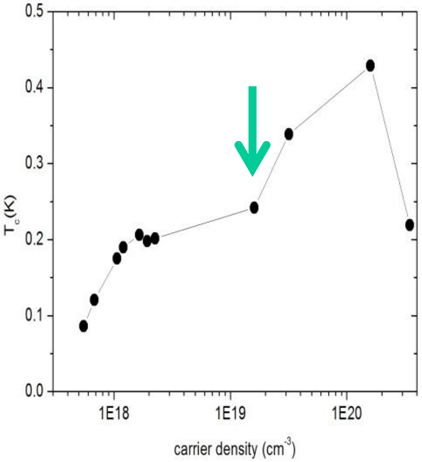
Emergence of Nernst oscillations with underdoping



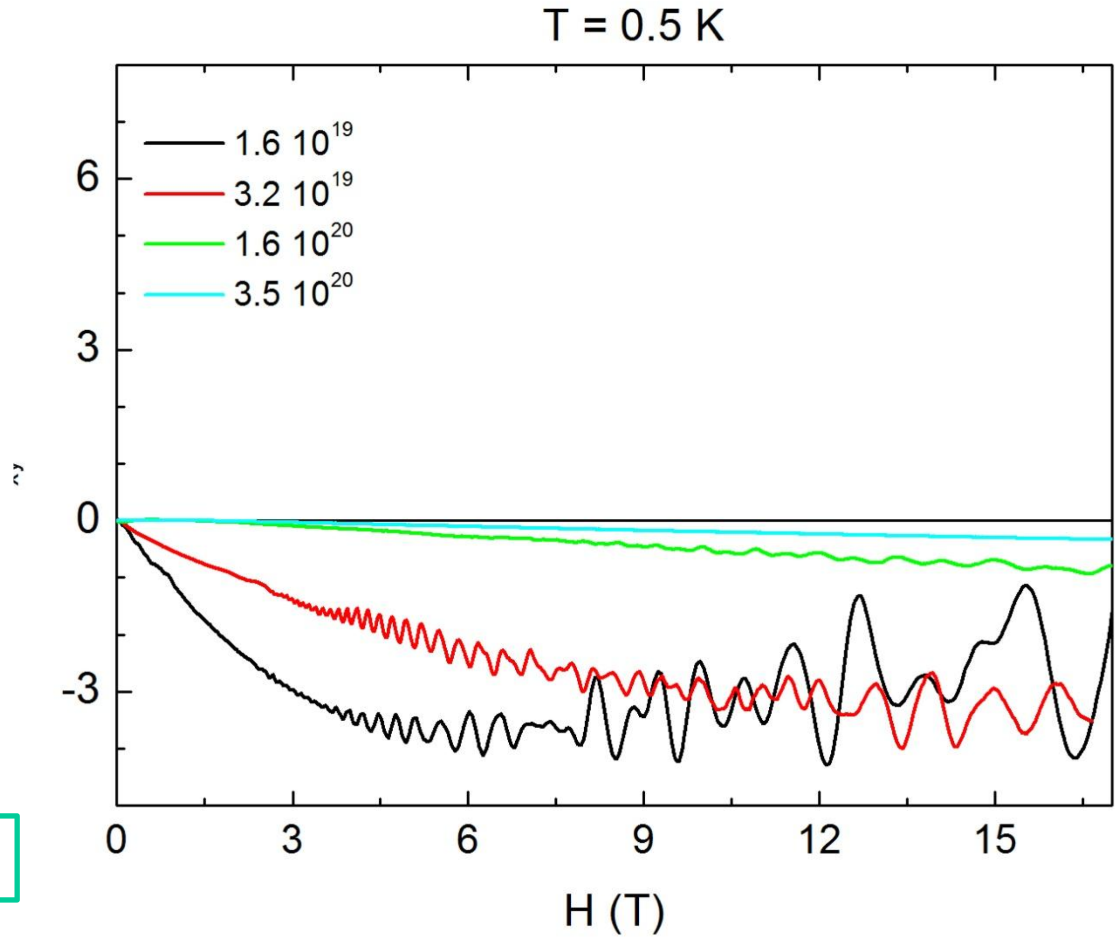


Lin et al., PRX 2013

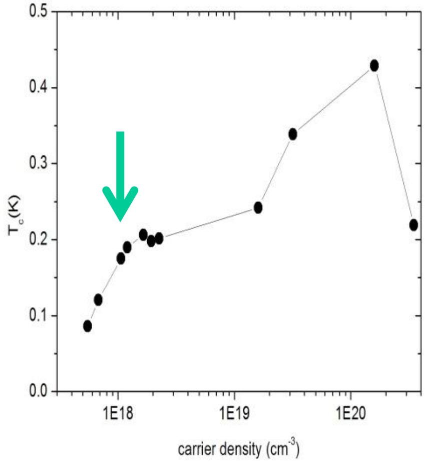
Emergence of Nernst oscillations with underdoping



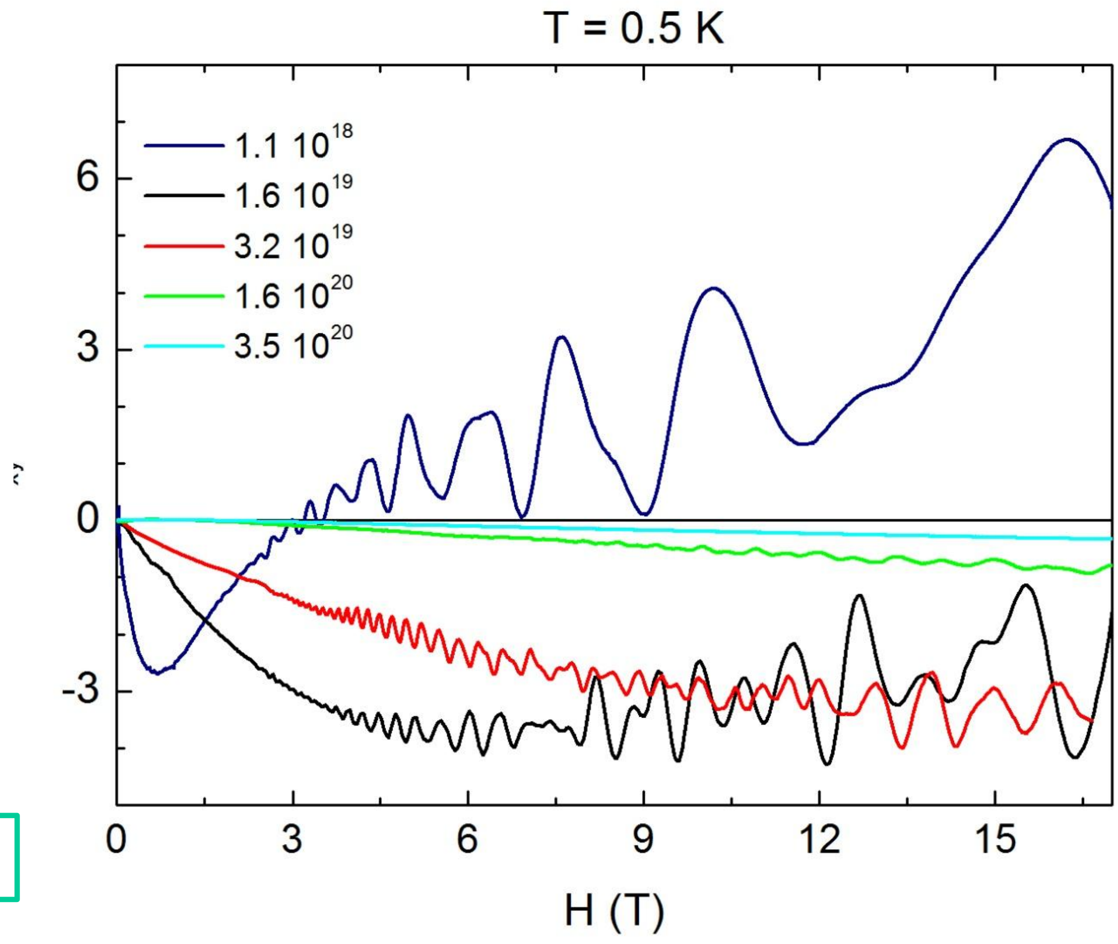
Lin et al., PRX 2013



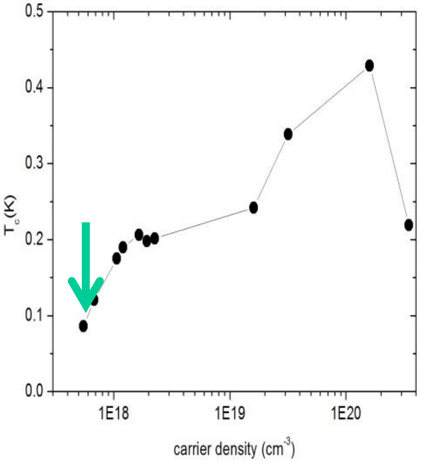
Emergence of Nernst oscillations with underdoping

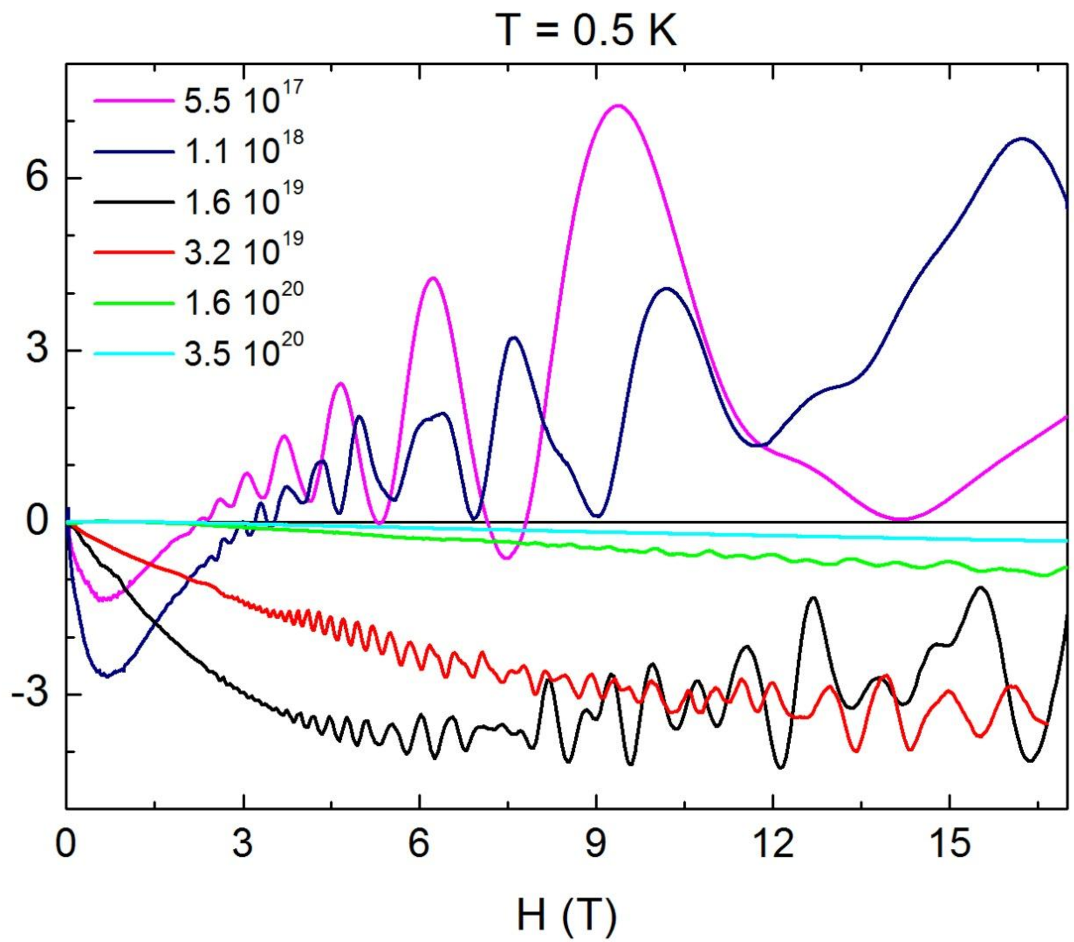


Lin et al., PRX 2013



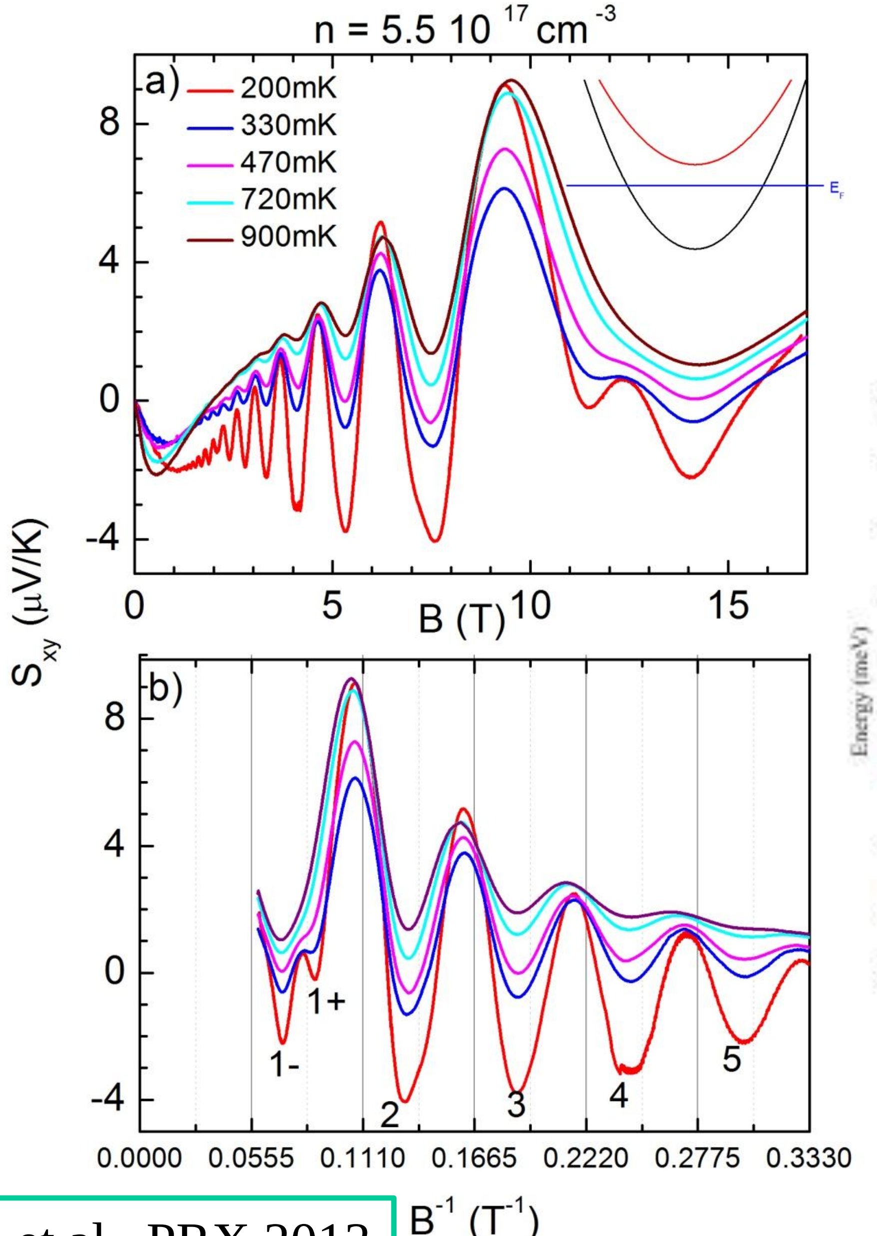
Emergence of Nernst oscillations with underdoping





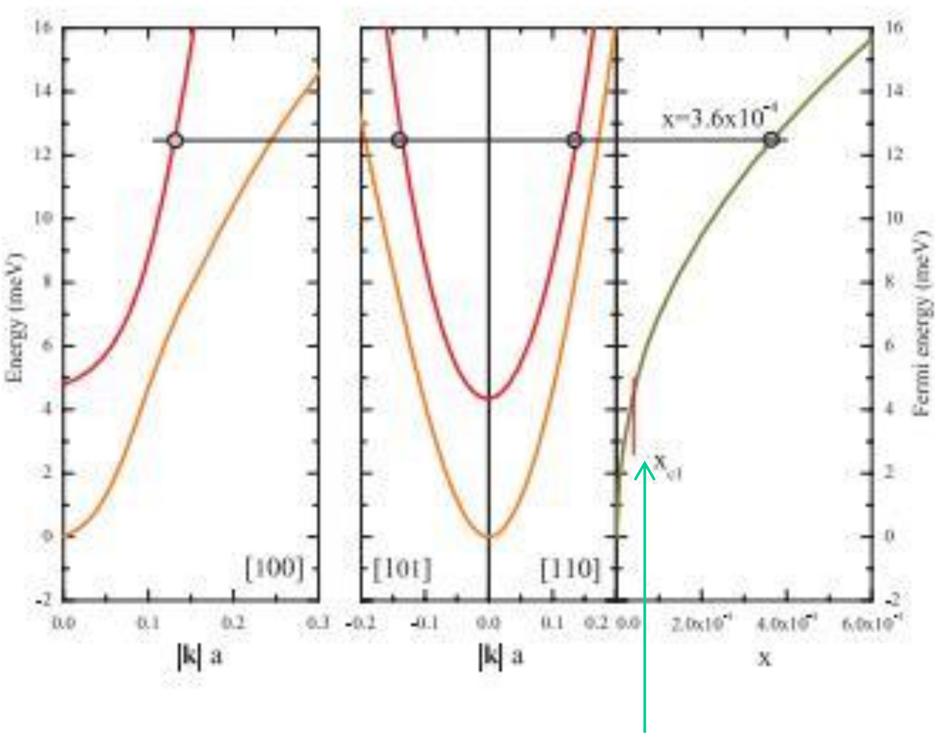
Lin et al., PRX 2013

The lowest concentration has a single frequency



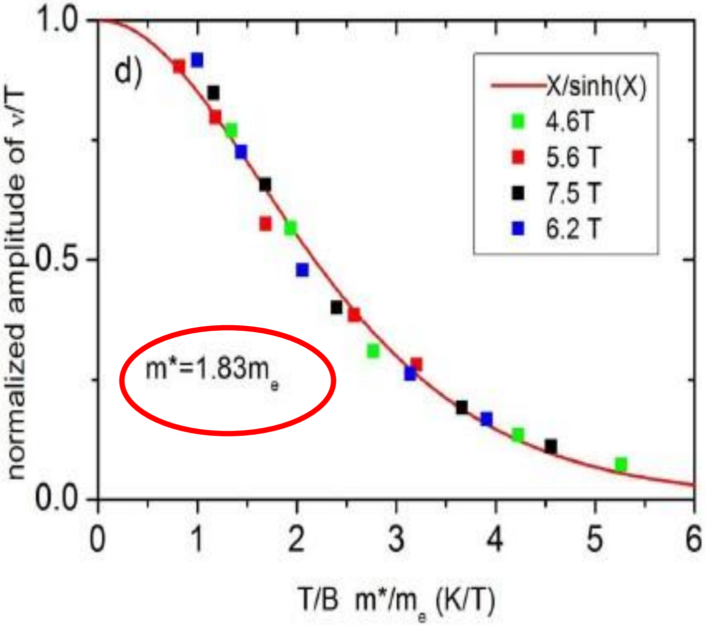
Lin et al., PRX 2013

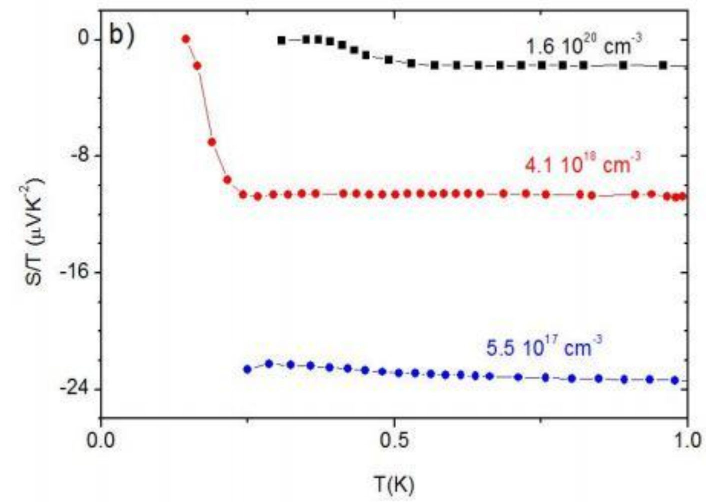
Band calculations:
van der Marel, van Mechelen and Mazin PRB (2011)

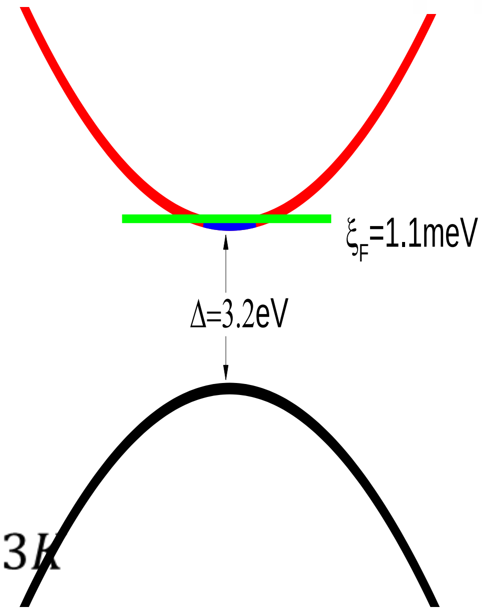


6.8 10^{17} cm^{-3}

Two ways to estimate the Fermi energy







$S/T = (\pi^2/3)(k_B/e)\ 1/T_F$

$m^* = 1.83 m_e$

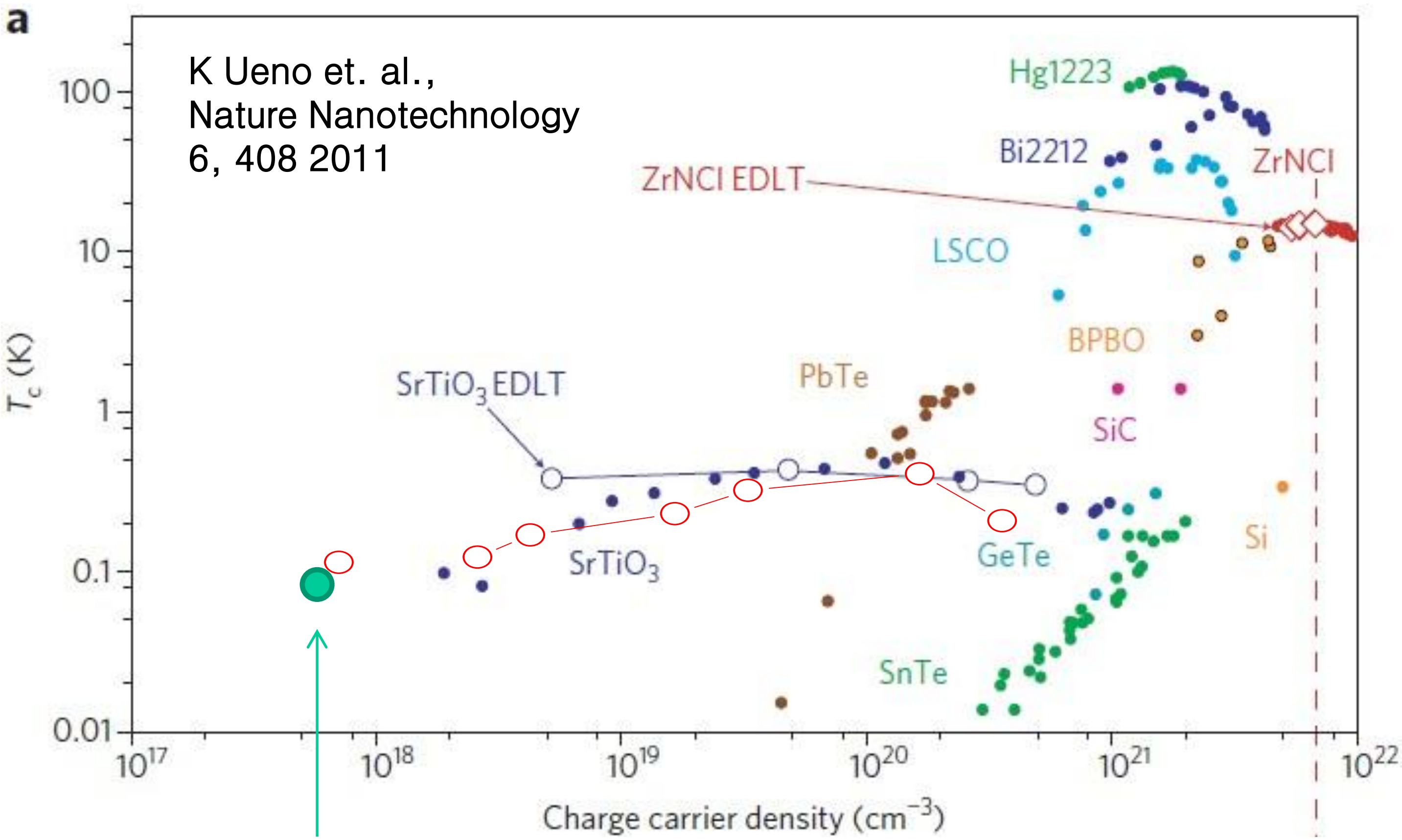
$k_F = 2.35\ 10^6\ cm^{-1}$

$$\varepsilon_F = \frac{(\hbar k_F)^2}{2m^*} = 1.15\ meV,\ T_F = 13K$$

$T_F = 12.9$ k

Lin et al., PRX 2013

Dilute superconductors



$\mathbf{5.5\ 10^{17}}\ \boldsymbol{cm^{-3}}$

$SrTiO_{3-\delta}$ [With $\delta \approx 10^{-5}$] is the most dilute superconductor!

SUMMARY

•Thermoelectricity is poorly understood and barely explored in many solids! Often, it opens another window to electronic properties.

•At the boundary between metals and insulators, a large entropy is shared by few carriers with a remarkable thermoelectric response .

•In dilute metals, when few landau tubes survive, the exit of each of them generates a large Nernst oscillation.

•Many interesting thermoelectric materials are on the metalic side of metal–insulator transition and have a Fermi surface.

Neville Mott on metals and non–metals

Dear Peter
I've thought a lot about "What is a metal" & I think one can only answer the question at T = 0.
There a metal conducts, & a non-metal doesn't.
Yours
Nevill

Dear Peter, I've thought a lot about 'What is a metal?' and I think one can only answer the question at $T = 0$ [the absolute zero of temperature]. There a metal conducts, and a non-metal doesn't.

(Edwards 1998)

Edwards, Phil. Trans. R. Soc. A **368**, 941–965 (2010)

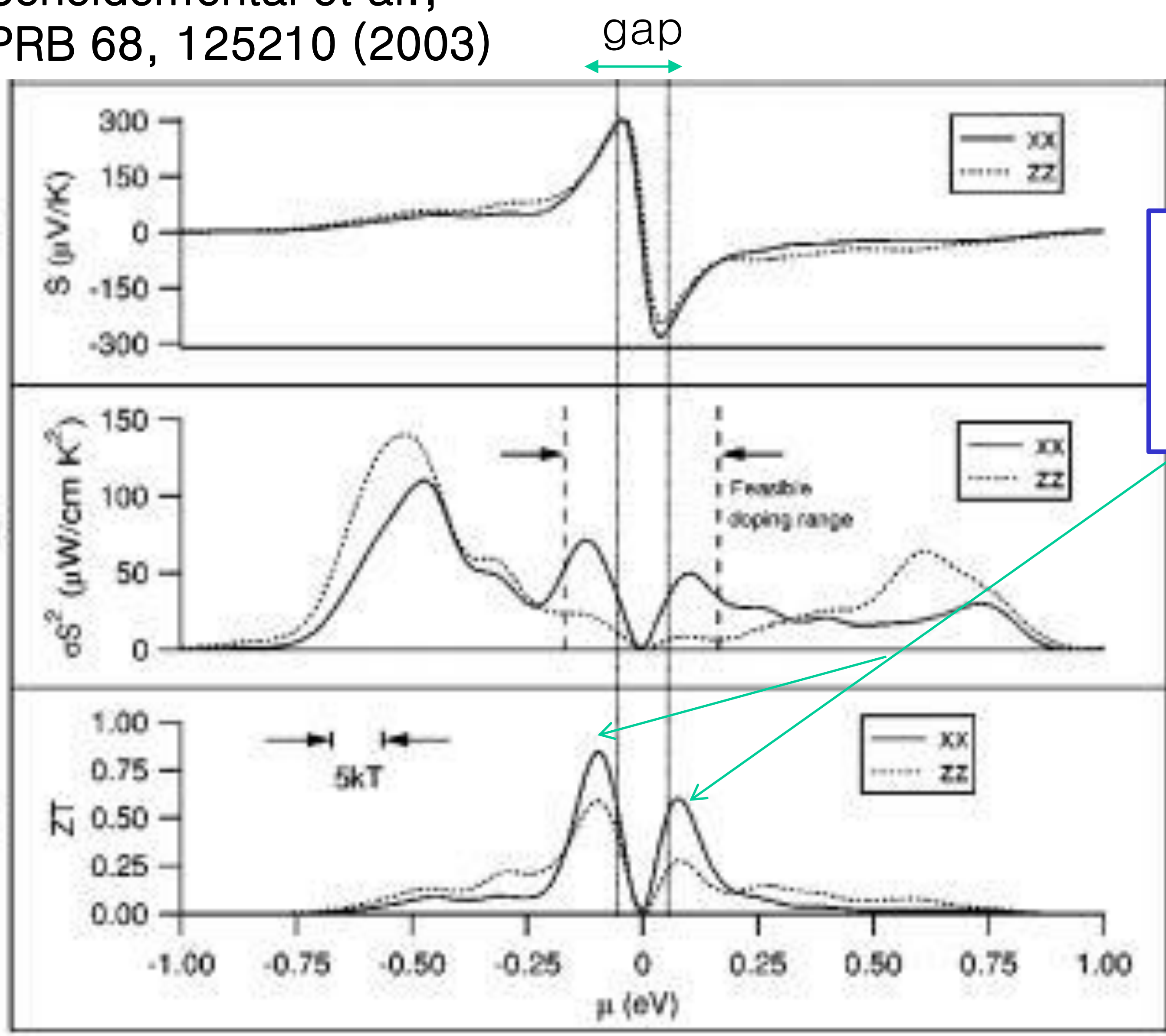
"Everyone knows what a metal is and can describe many of its characteristics. It is safe to say, however, that few people would define a metal as a 'solid with a Fermi surface'. This may nevertheless be the most meaningful definition of a metal…and provides a precise explanation of the main physical properties …"

A. R. Mackintosh

Scientific American 1963

First-principle calculations for Bi_2Te_3

Scheidemental et al.,
PRB 68, 125210 (2003)



ZT peaks on the metallic side of the metal-insulator transition!