Transport of entropy in cuprates

Kamran Behnia

**Laboratoire de Physique
et d'Etude des Matériaux**

Ecole Supérieure de Physique et de Chimie Industrielles

Transport of entropy in cuprates

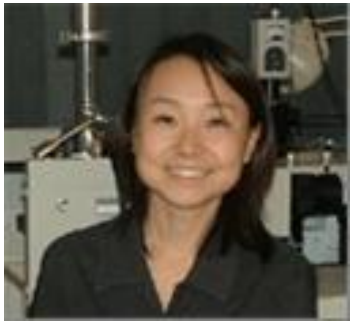
Orsay 1995–2000; Paris 2000–2007

Hervé Aubin

[1994–1997;2004–2007]

Cigdem Capan

[1999–2002]



Saco Nakamae

[2000–2002]

[2001–2004]

Alexandre Pourret

[2004–2007]

Cyril Proust

Toulouse 2002 présent

Contents

I. Thermal conductivity

- Heat transport in conventional and unconventional superconductors

- Sub-kelvin thermal conductivity as a probe of gap structure

II. Nernst effect

Sources of Nernst signal

- superconducting vortices

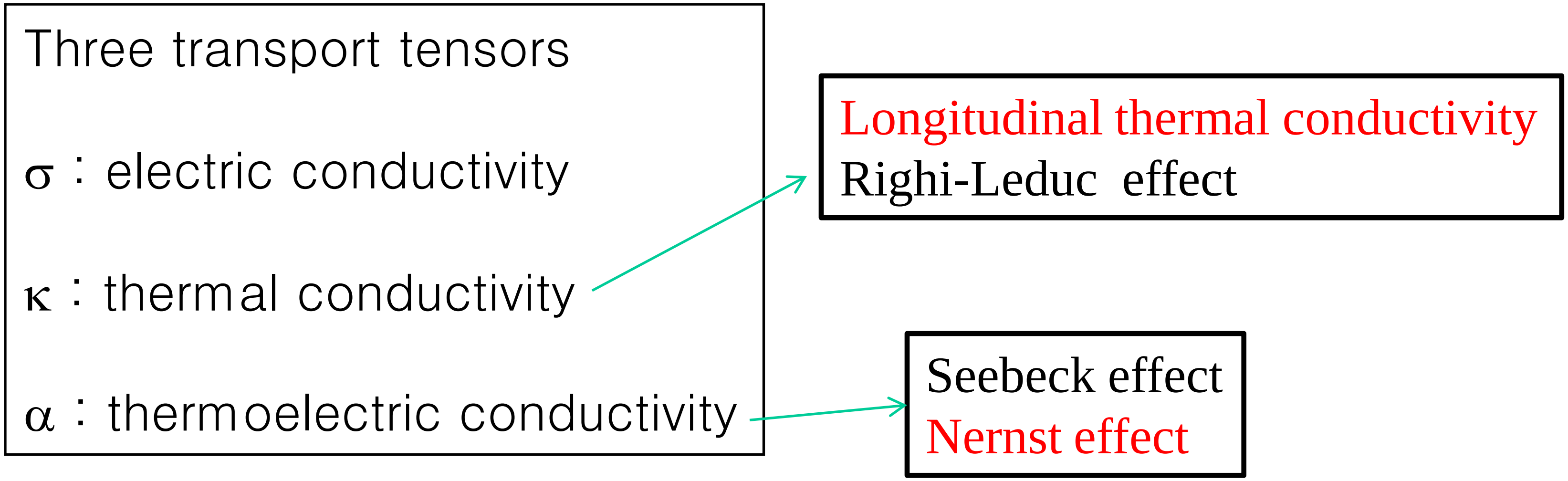
- short-lived Cooper pairs

- Normal quasi-particles

Heat and charge current in a solid

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

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



Three transport tensors

σ : electric conductivity

κ : thermal conductivity

α : thermoelectric conductivity

Longitudinal thermal conductivity
Righi-Leduc effect

Seebeck effect
Nernst effect

Only components in red will be treated in this talk!

Kinetic theory of gases

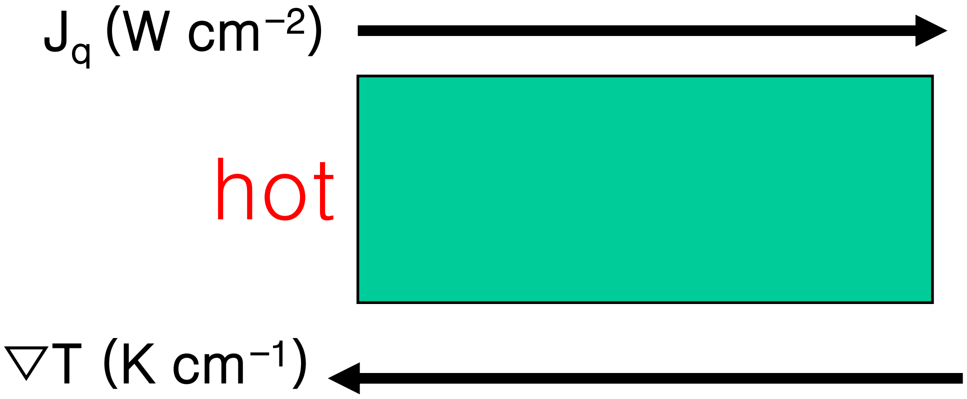
$$\kappa = 1/3\ C\ v\ l$$

Thermal conductivity

Heat capacity

velocity

mean-free-path



J_q (W cm^{-2})

hot

cold

∇T (K cm^{-1})

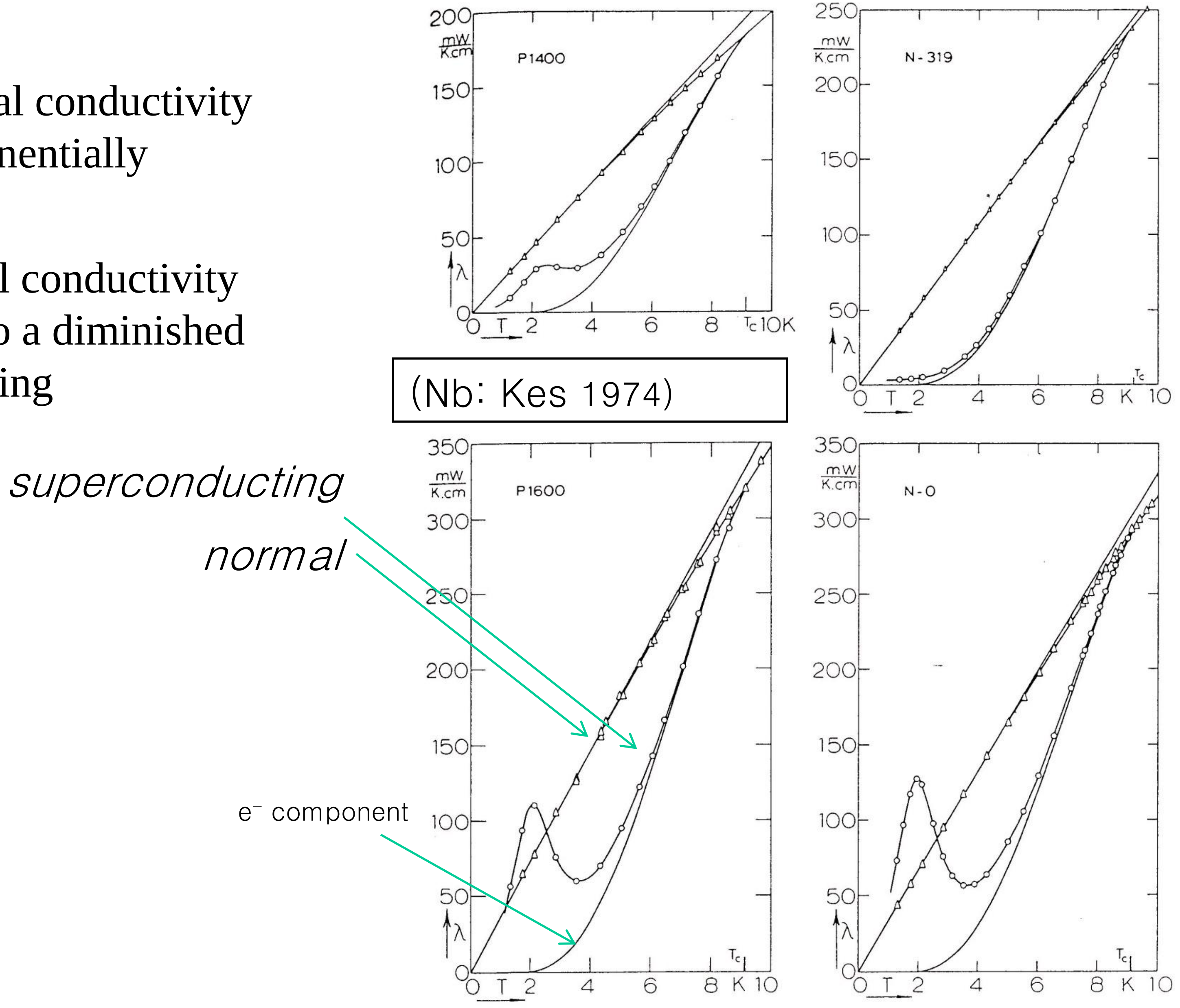
$\kappa = J_q / (-\nabla T)$
[WK^{-1}cm^{-1}]

Thermal conductivity of superconductors

- Above T_c both mobile electrons and phonons carry heat.
- Below T_c, mobile electrons condensate in a macroscopic quantum state: electronic heat carriers vanish!
- A superconductor can be assimilated to a thermal insulator!

Conventional superconductors

- Electron thermal conductivity decreases exponentially
- Phonon thermal conductivity increases due to a diminished electron scattering



(Nb: Kes 1974)

superconducting

normal

e⁻ component

Unconventional superconductors

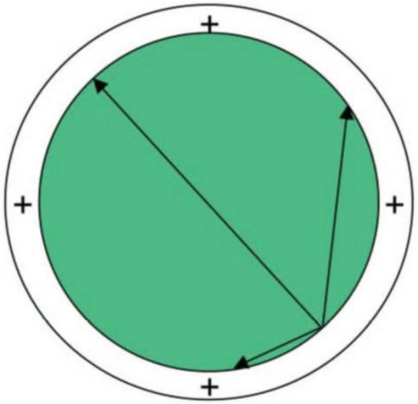
- The order parameter of the is less symmetric than the Fermi surface.
- The gap function may vanish along particular orientations (nodes).
- Nodal quasi–particles can carry heat!

Effect of an unconventional superconducting transition on thermal transport

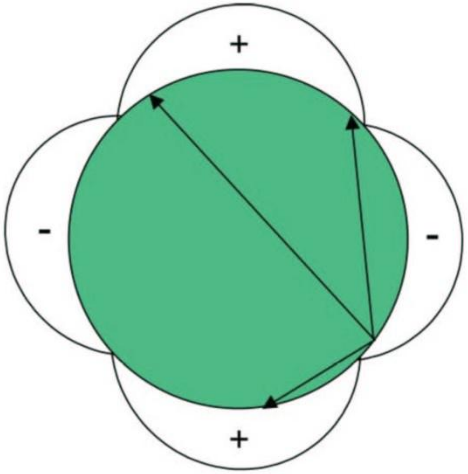
- The electronic thermal transport does NOT decrease exponentially

- It can even increase below T_c, due to an increase in the electronic mean-free-path

Scattering events are restricted in an unconventional superconductor



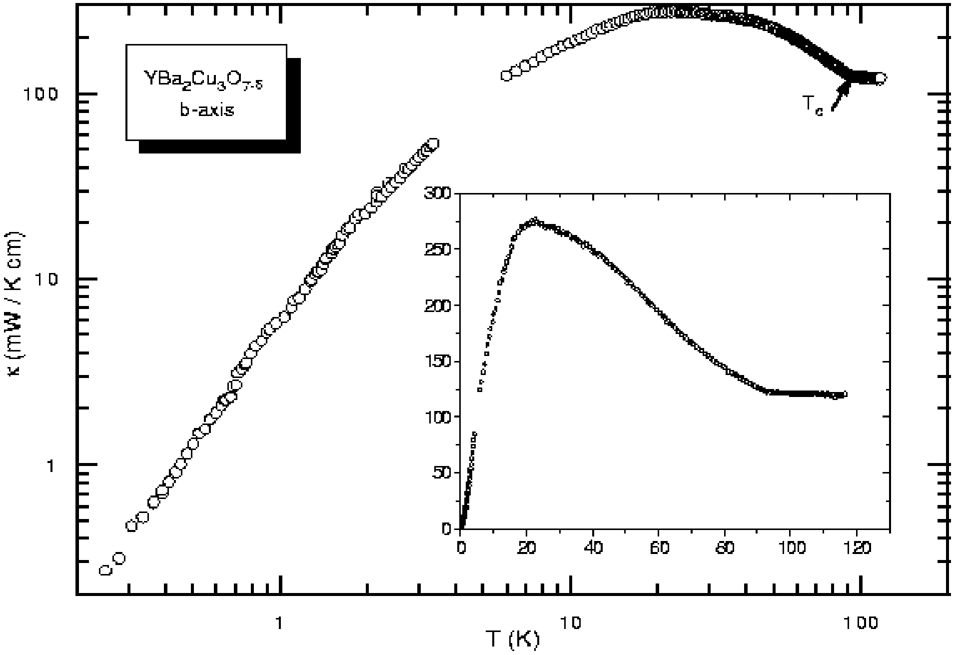
s–wave



d–wave

Heat conduction in high-T_c superconductors

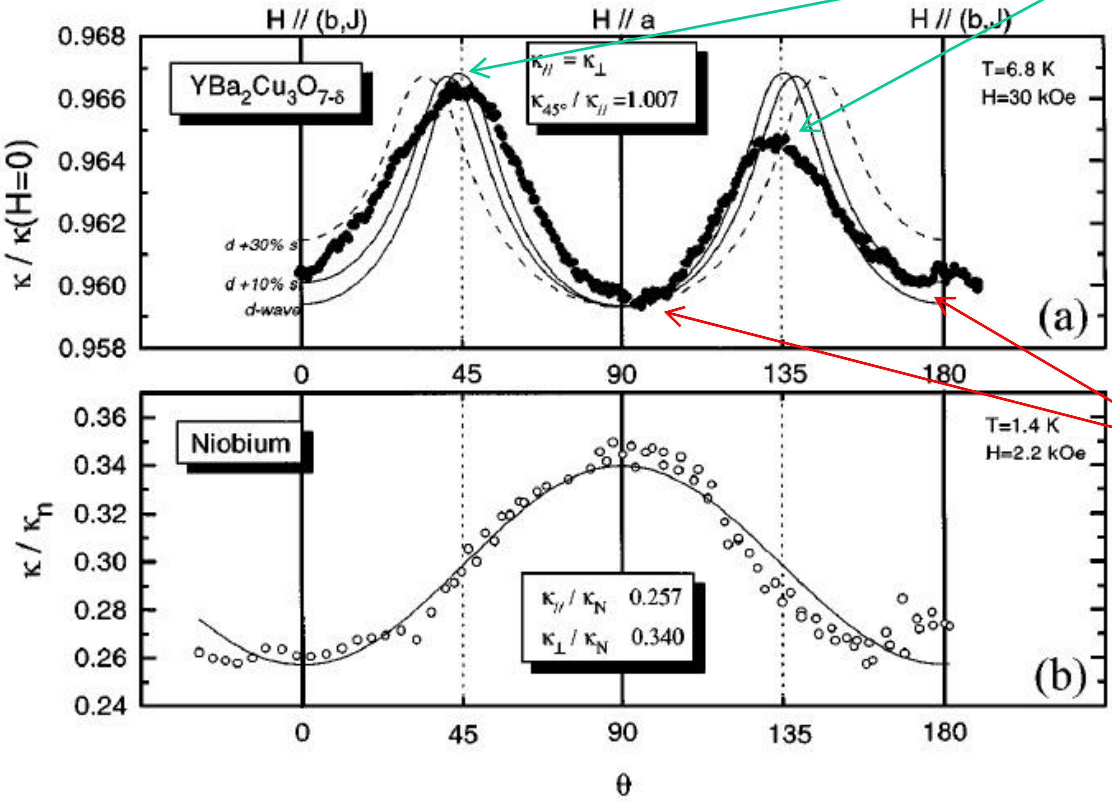
Aubin *at al.* , 1997



The increase in thermal conductivity below T_c is due to electrons!

Heat conduction in high-T_c superconductors

Aubin *at al.* , 1997



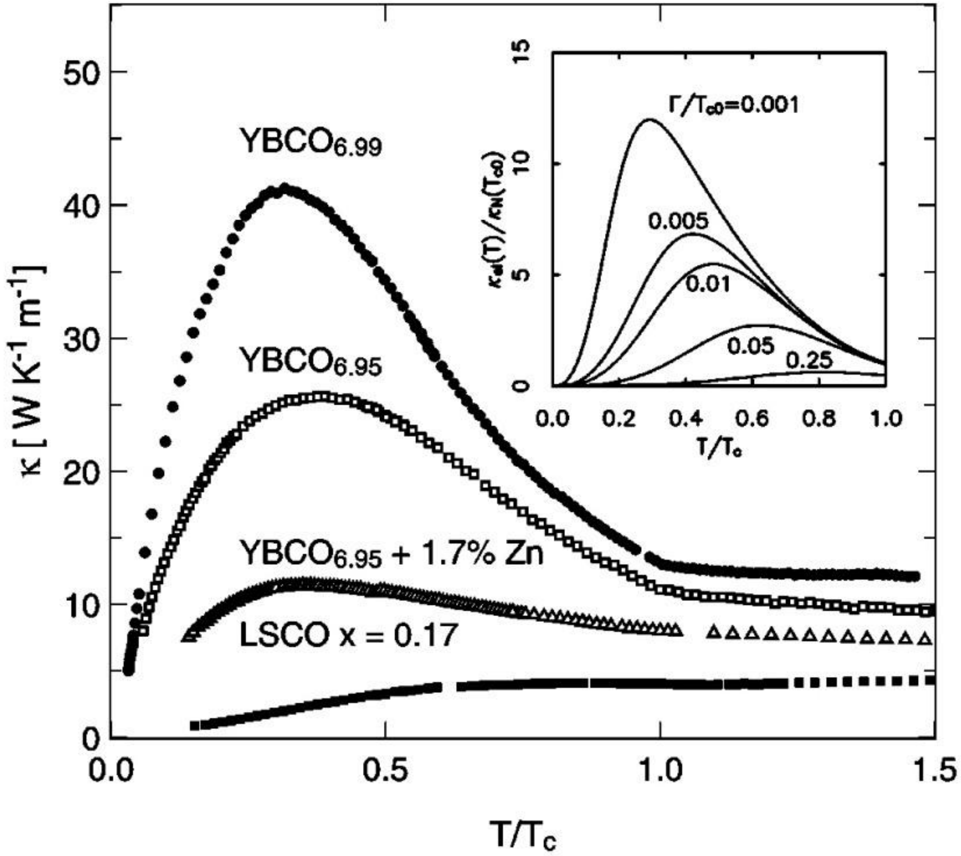
Nodal qps travel parallel to vortices

Nodal qps travel perpendicular to vortices

Angular-dependent thermal conductivity reveals angular position of gap minima!

Heat conduction in high-Tc superconductors

Sutherland at al., 2003



Cleaner systems show larger enhancement below T_c

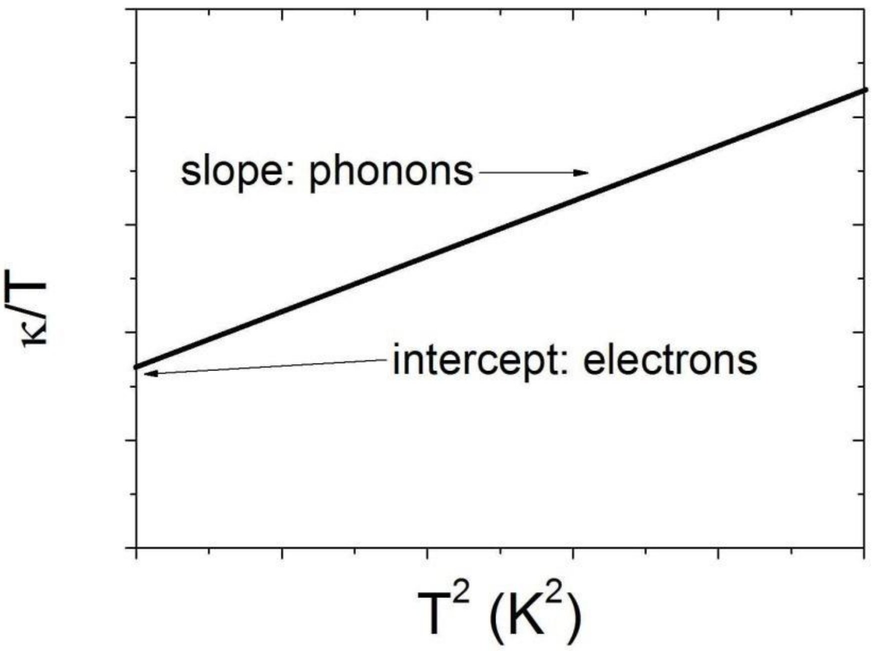
In the zero temperature limit

Mean-free-path of both electrons and phonons attains its maximum value, then

$\kappa_{ph} \propto T^3$ (phonons are bosons)

$\kappa_e \propto T$ (electrons are fermions)

In principle, one can separate the two contributions!



Example

Taillefer *et al.*, PRL '97

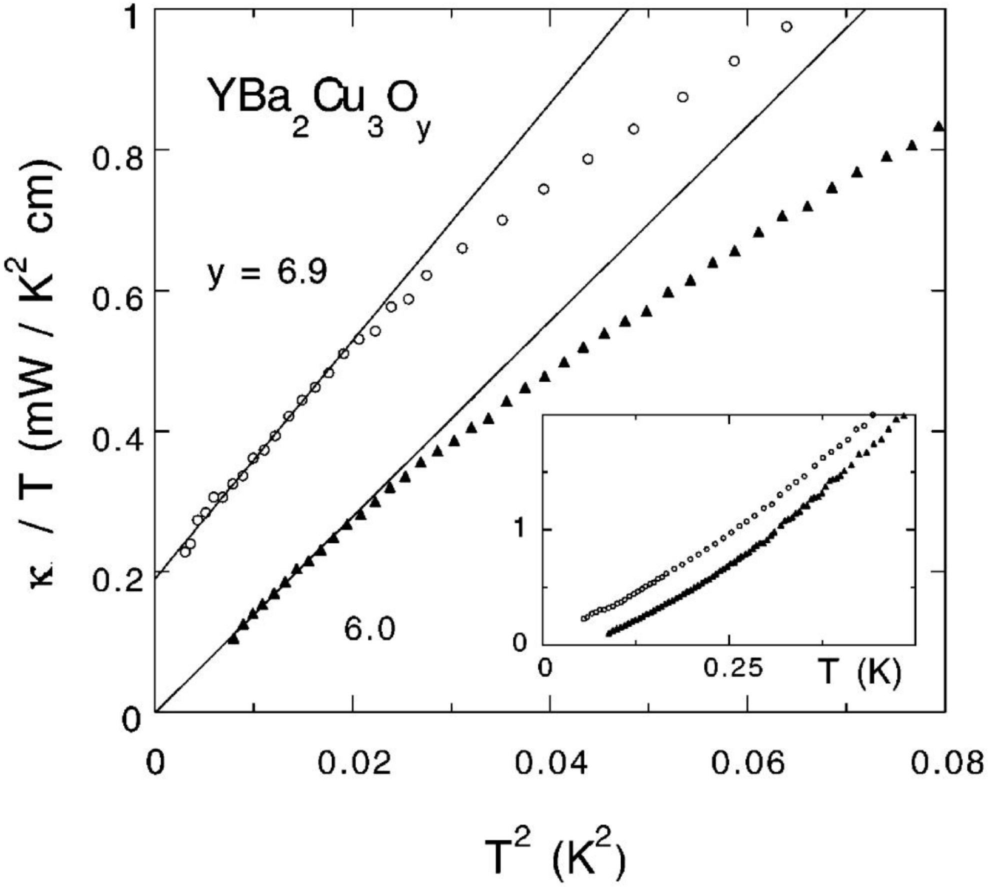
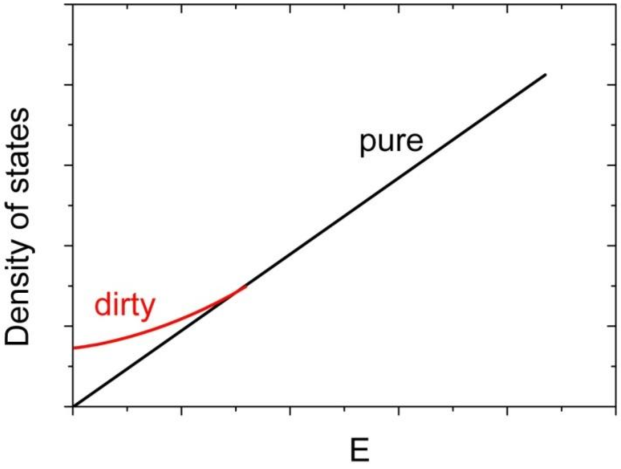


FIG. 1. *a*-axis thermal conductivity of the two $YBa_2Cu_3O_y$ crystals, one superconducting ($y = 6.9$; circles) and one insulating ($y = 6.0$; triangles). Main panel: κ/T vs T^2; lines are fits to $a + bT^2$ for $T < 0.15$ K. Inset: κ/T vs T.

A residual normal fluid at zero temperature!



Universal thermal conductivity

- In a d-wave superconductor κ_0 is expected to be independent of impurity concentration

Impurities:

Decrease the mean-free-path

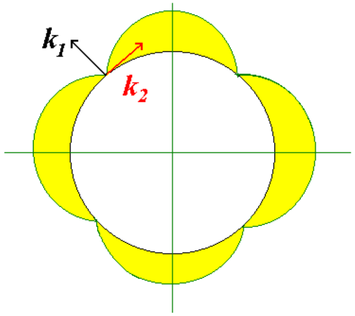
Enhance the specific heat

These two cancel out!

$$\kappa = 1/3\ C\ v\ l$$

A TALE OF TWO VELOCITIES!

(Durst , Lee ’99)



Excitation spectrum in

the vicinity of a node:

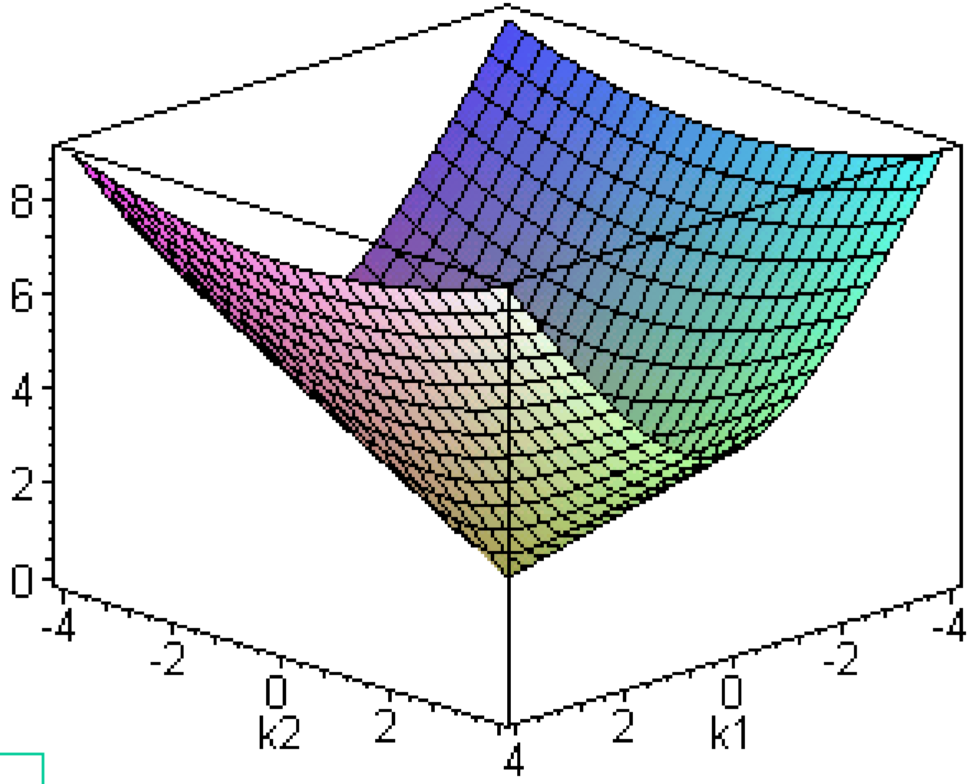
$$E(k) = (\varepsilon_k^2 + \Delta_k^2)^{1/2}$$

$$= (v_F^2 k_1^2 + v_2^2 k_2^2)^{1/2}$$

Fermi velocity : $v_F = d\varepsilon_k/dk_1$

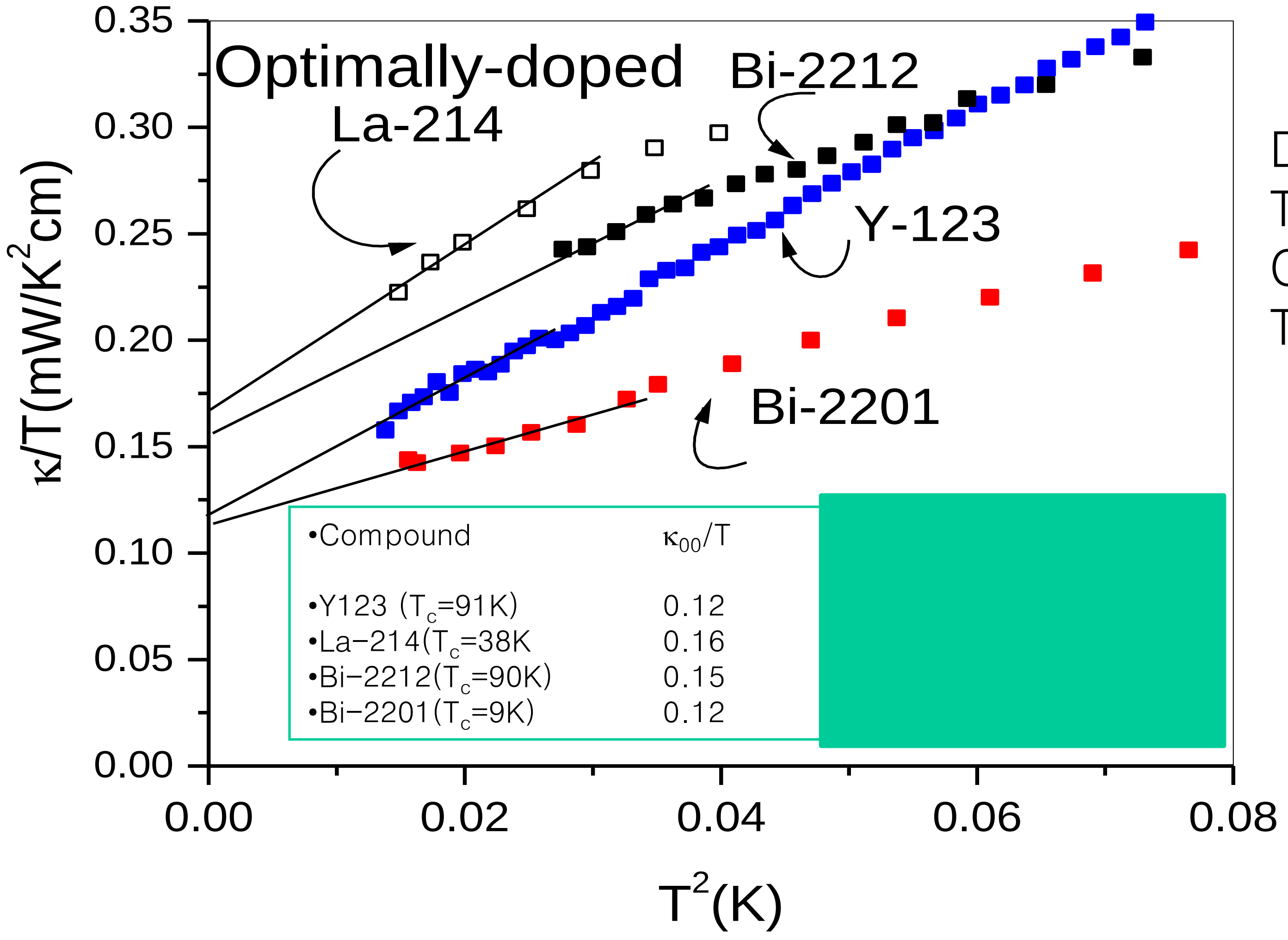
Gap velocity: $v_2 = d\Delta_k/dk_2$

An anisotropic Dirac cone



$\kappa_{00}/T = (nk_B^2/3\hbar)\ (v_F / v_2)$

Residual quasi-particle conductivity in optimally-doped cuprates



•Compound	κ_{00}/T
•Y123 (T_c=91K)	0.12
•La−214(T_c=38K	0.16
•Bi−2212(T_c=90K)	0.15
•Bi−2201(T_c=9K)	0.12

Data from
Toronto group
Orsay group
Tokyo group

Experimental observation of universal thermal conductivity

(Taillefer et al., 1997)

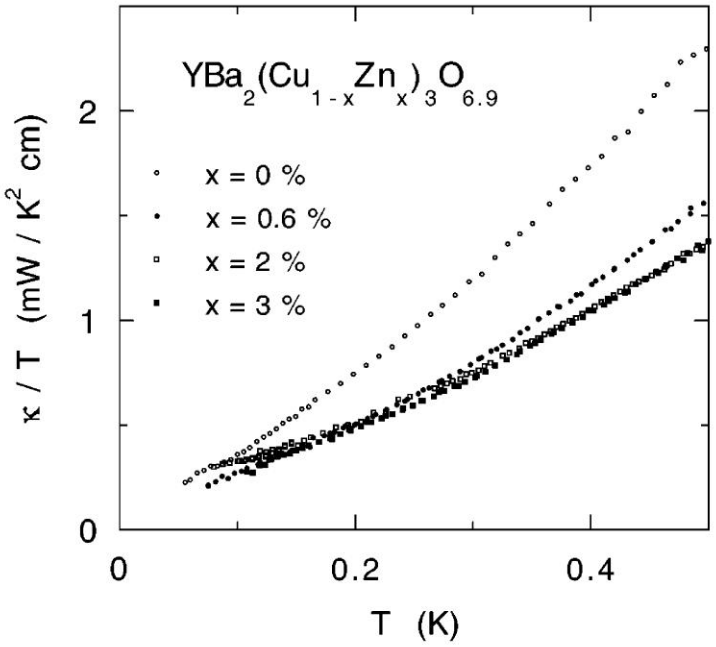


FIG. 2. *a*-axis thermal conductivity of the four Zn-doped crystals, plotted as κ/T vs T.

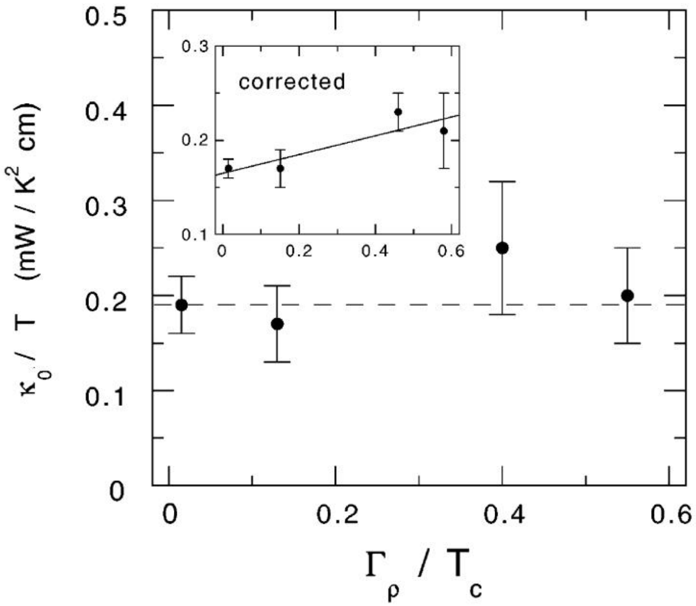
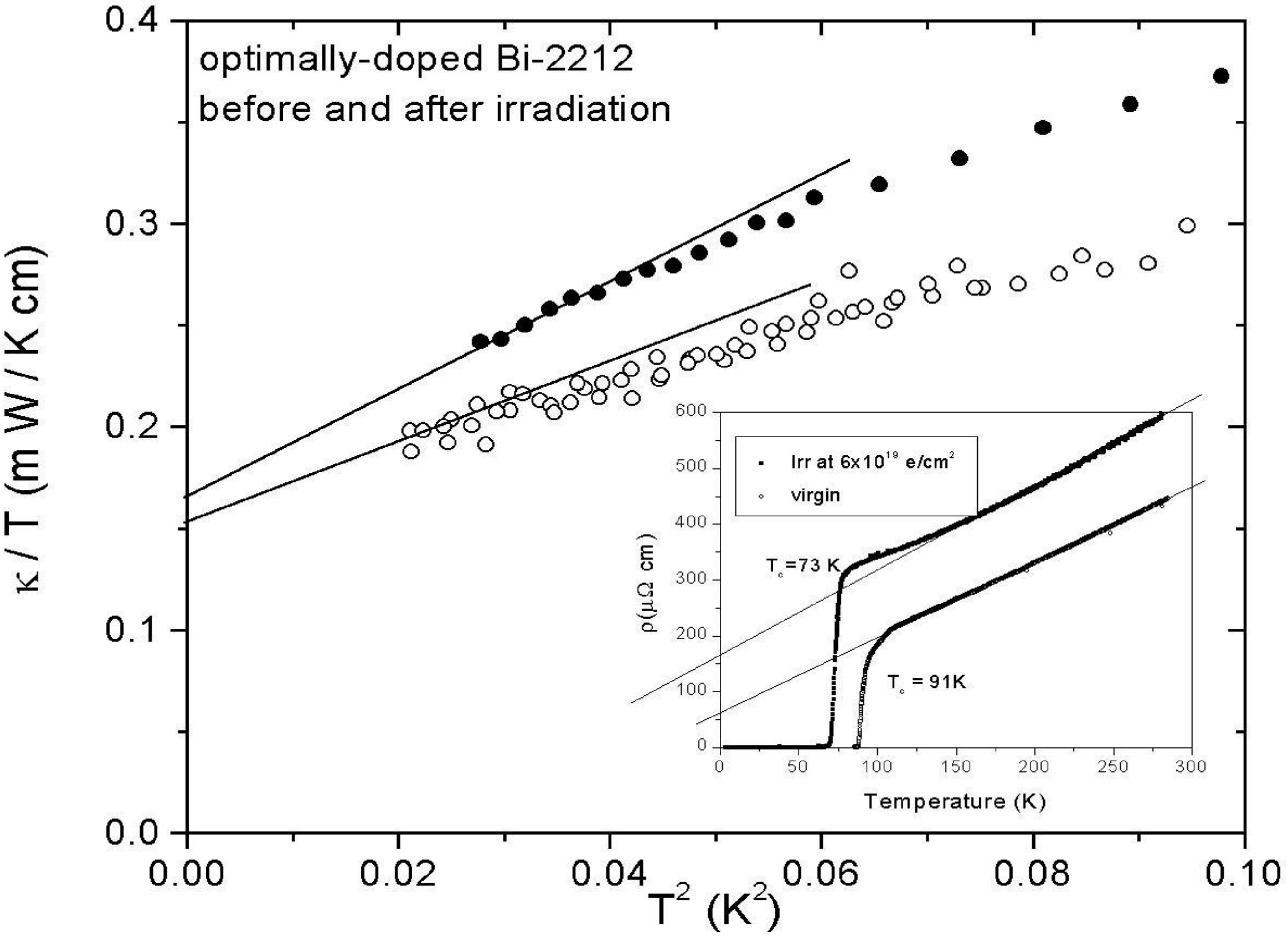


FIG. 3. Residual linear term vs scattering rate for the four crystals of $YBa_2(Cu_{1-x}Zn_x)_3O_{6.9}$; the dashed line indicates a constant at 0.19 mW K^{-2} cm^{-1}. Inset: same, but with corrected values (see text); the solid line is a least-squares fit.

A 30-fold decrease in mean-free-path in Zn-doped YBCO leaves κ_0 unchanged

The magnitude of the linear term is barely affected by the introduction of defects!

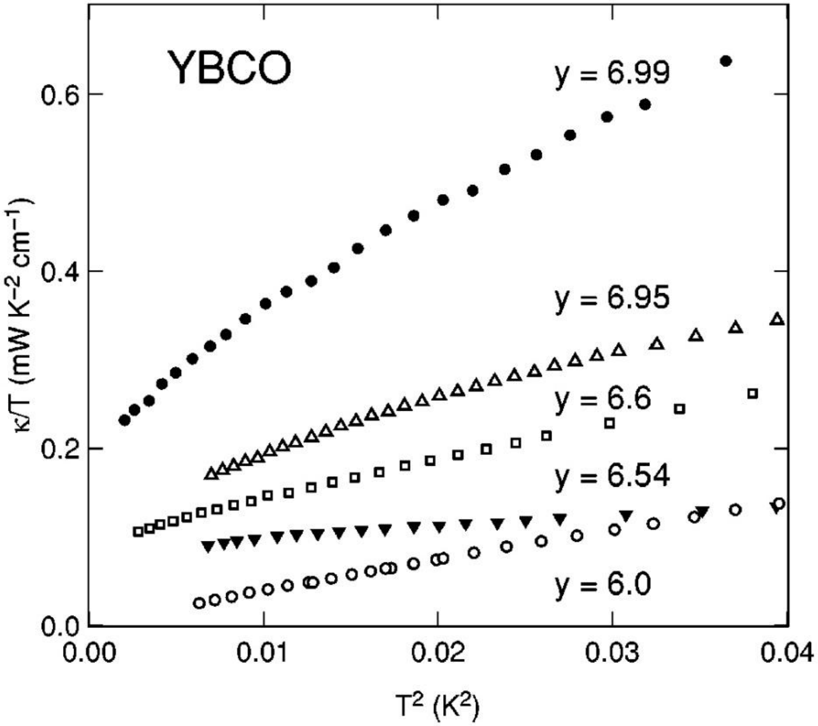


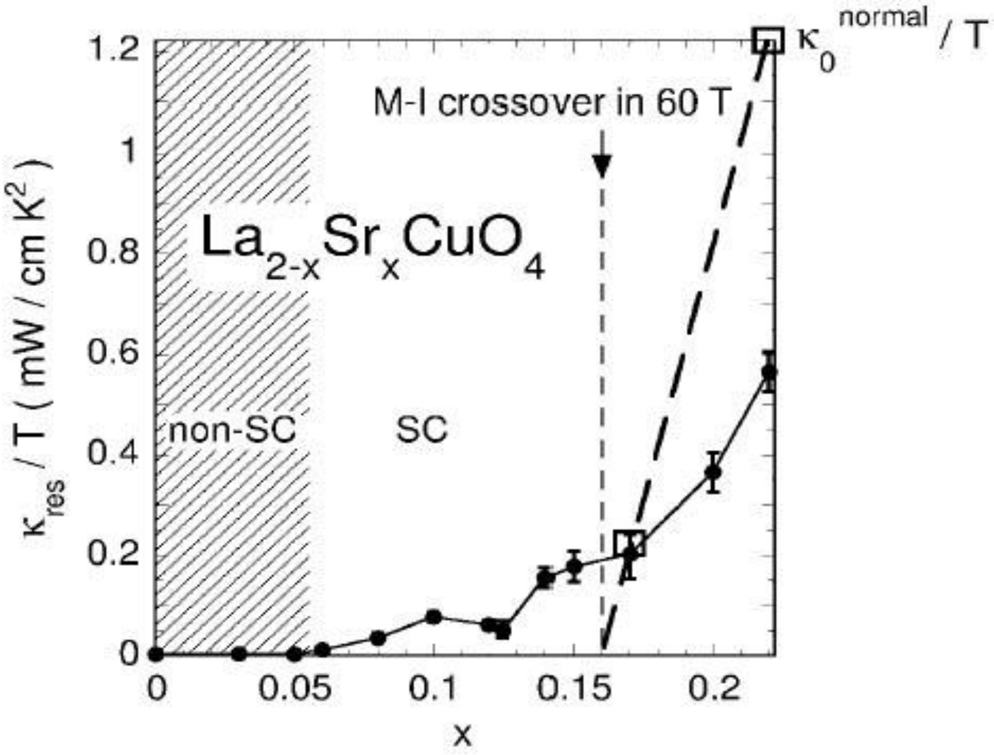
Nakamae et al., 2001

Evolution of the residual thermal conductivity with doping

Sutherland et al., 2003

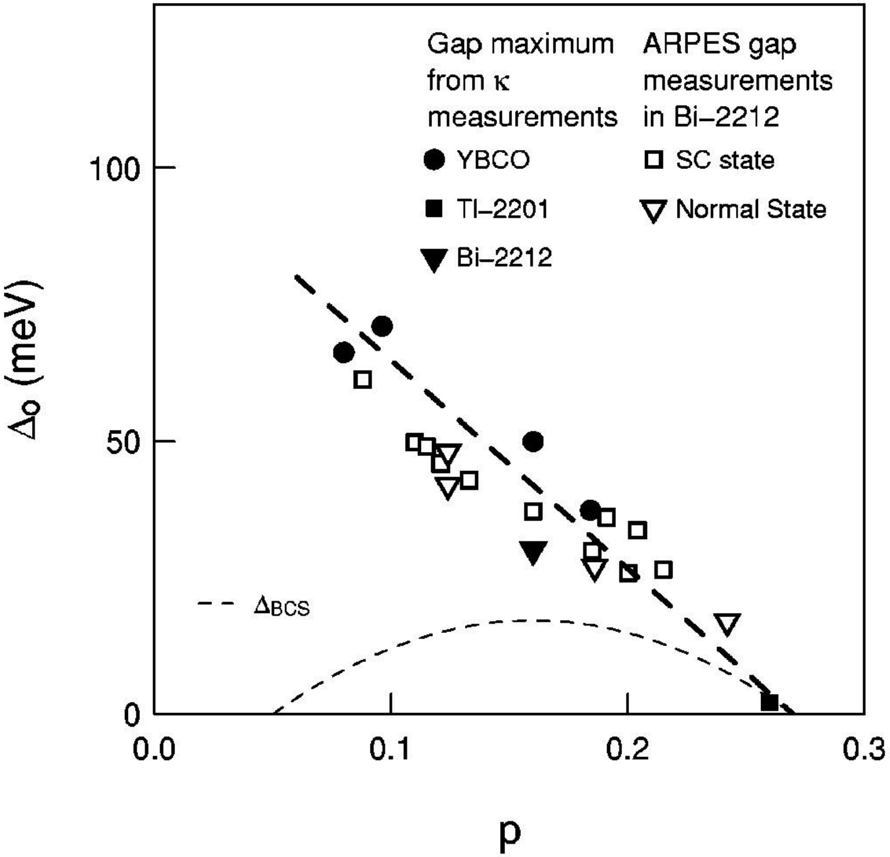
Takeya et al., 2002



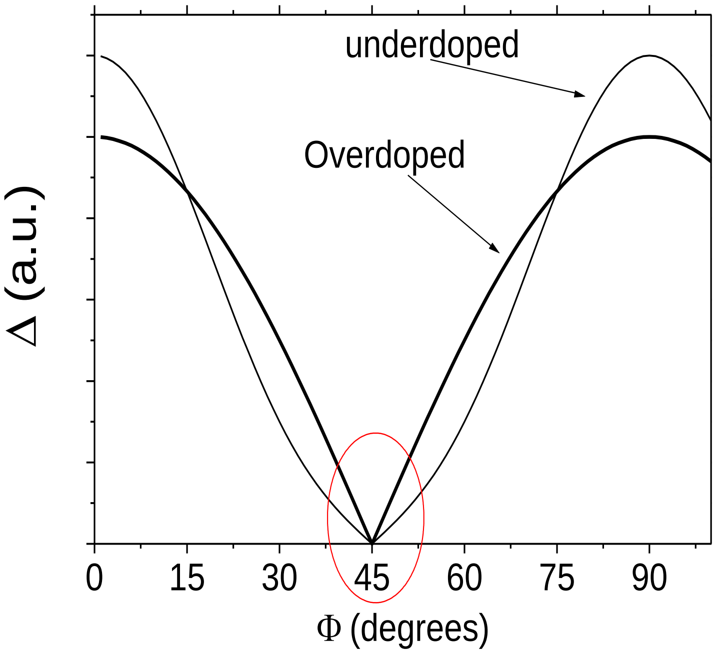


Suggesting an enhancement of v_F/v_2 with increasing doping!

Assuming that κ/T is inversely proportional to the superconducting



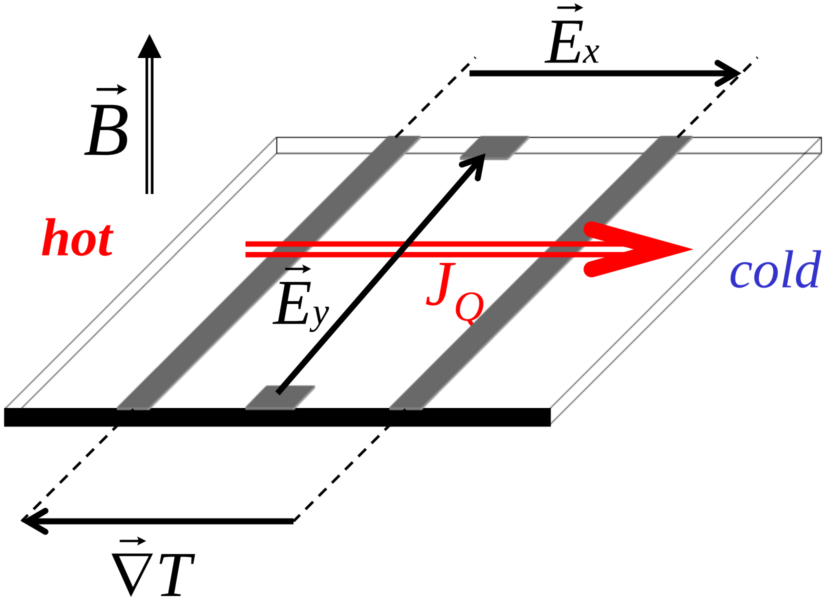
The interpretation is ambigous on the underdoped side!



But the nodal structure evolves with doping!

Nernst effect

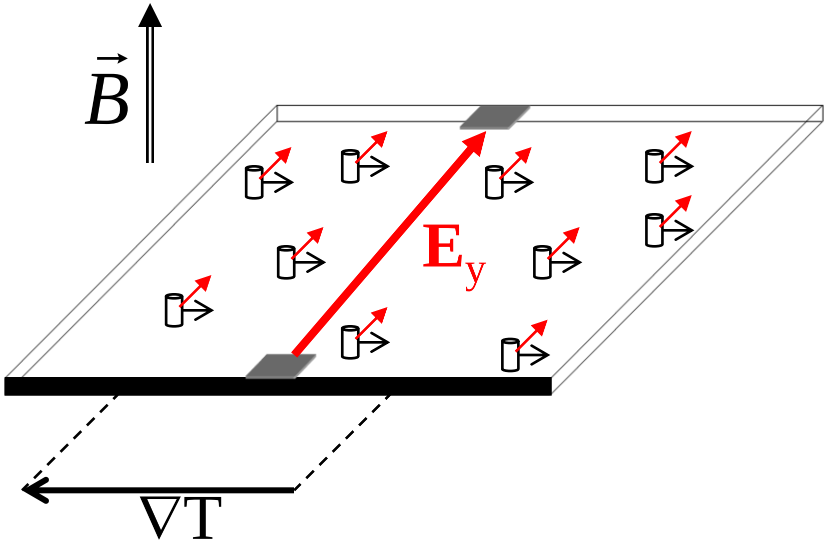
- In presence of a thermal gradient, electrons produce an electric field.
- Seebeck and Nernst effect refer to the longitudinal and the transverse components of this field.



$$N[= S_{xy} = e_y = e_N] = \frac{-E_y}{\nabla_x T}$$

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

Nernst effect in the vortex state



A superconducting vortex is:

- A quantum of magnetic flux
- An entropy reservoir
- A topological defect

- Thermal force on the vortex : $F=-S_\phi \nabla T$ (S_ϕ : vortex entropy)
- The vortex moves
- The movement leads to a transverse voltage: $E_y=v_x B_z$

Nernst effect in optimally-doped YBCO

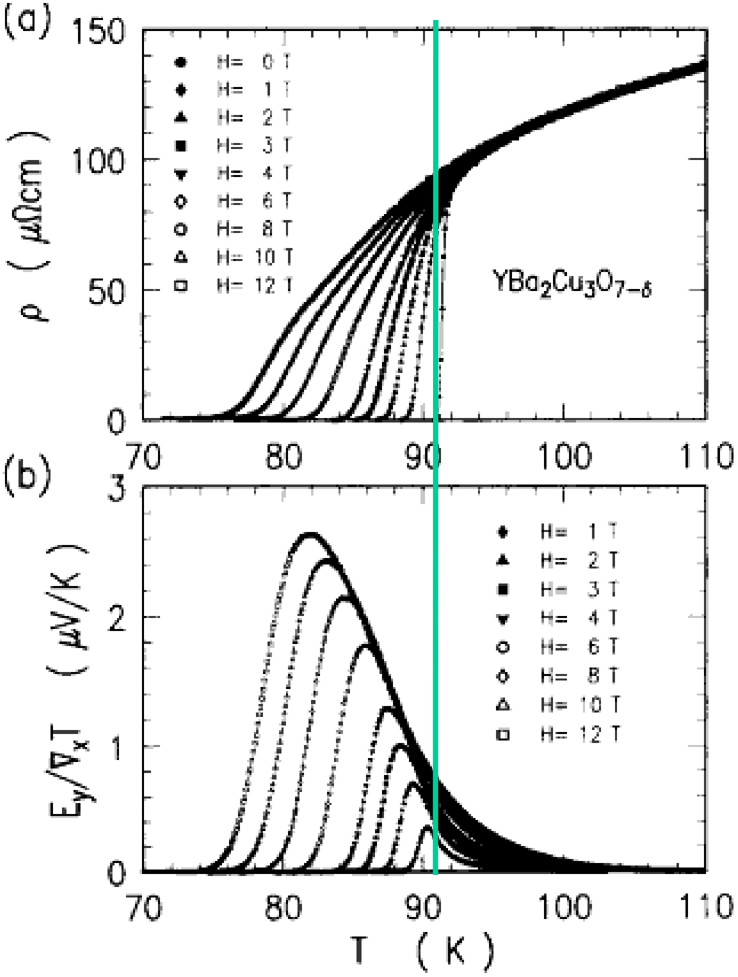


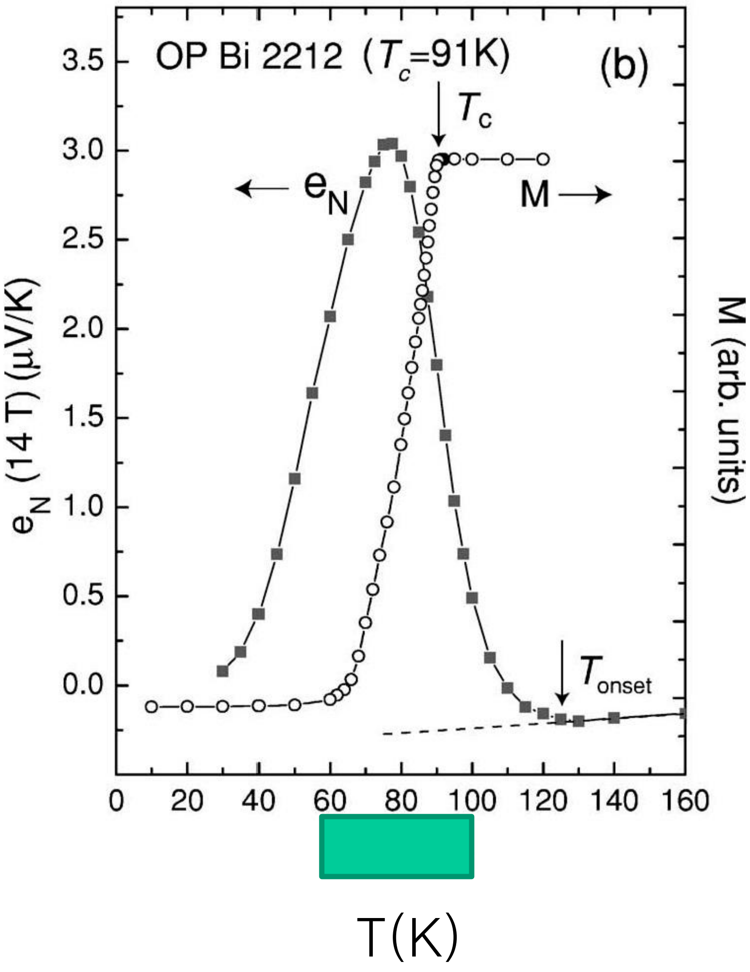
FIG. 3. Resistivity ρ (a) and normalized Nernst electric field $E_y/\nabla_x T$ (b) versus temperature for an epitaxial, *c*-axis-oriented $YBa_2Cu_3O_{7-\delta}$ film at different magnetic fields applied parallel to the *c* axis of the film.

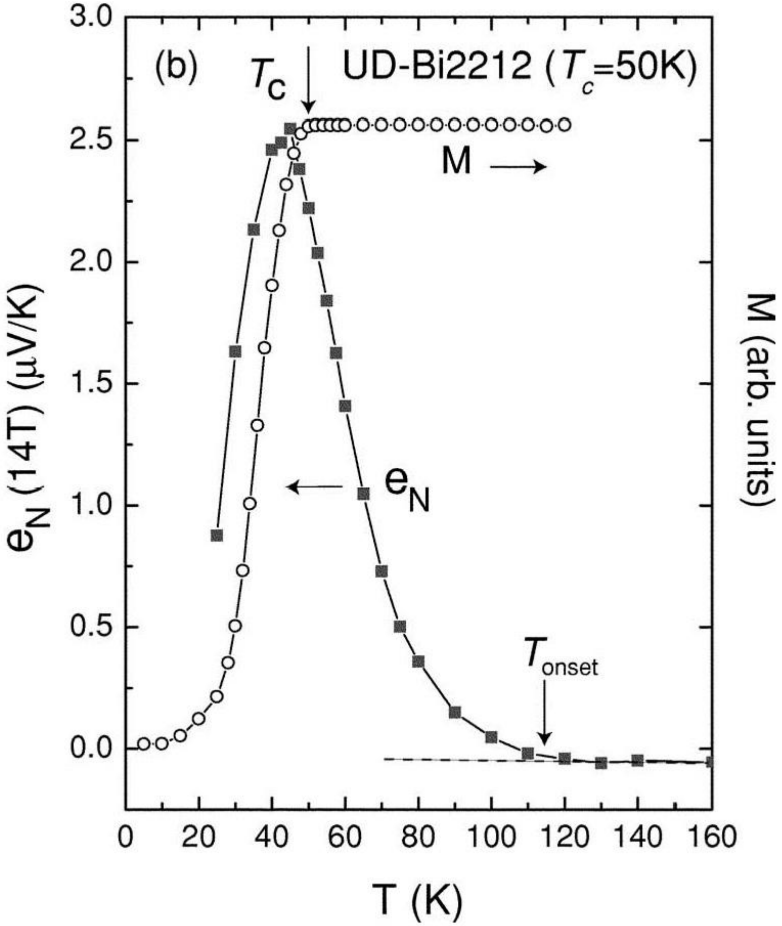
The Nernst coefficient is finite only in the vortex liquid state!

(Ri, et al. 1994)

A positive Nernst signal survives above T_c

Wang, Li and Ong, 2006

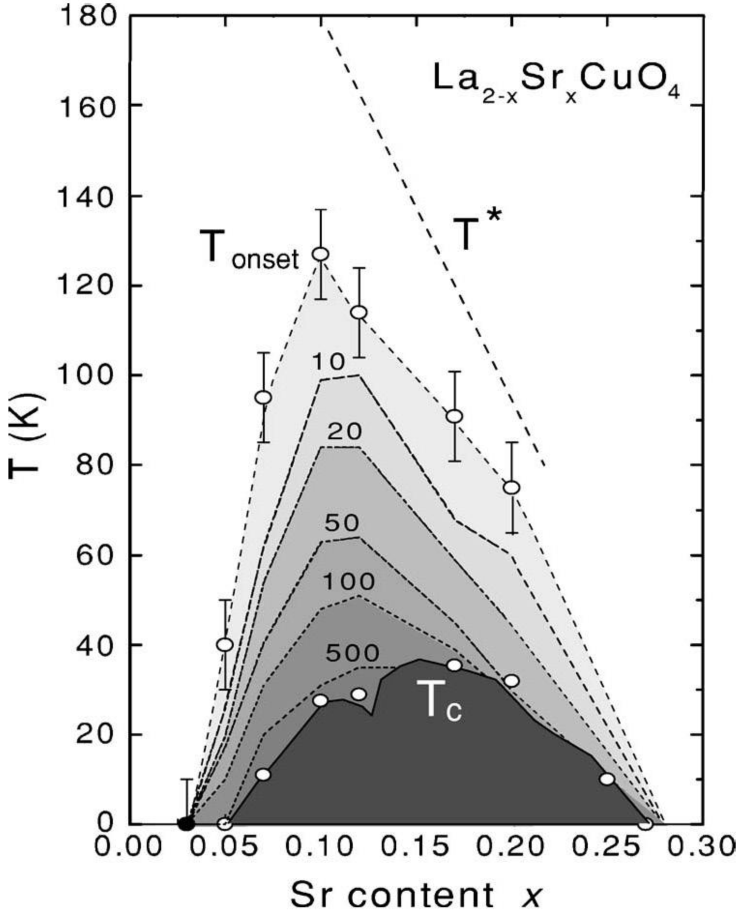


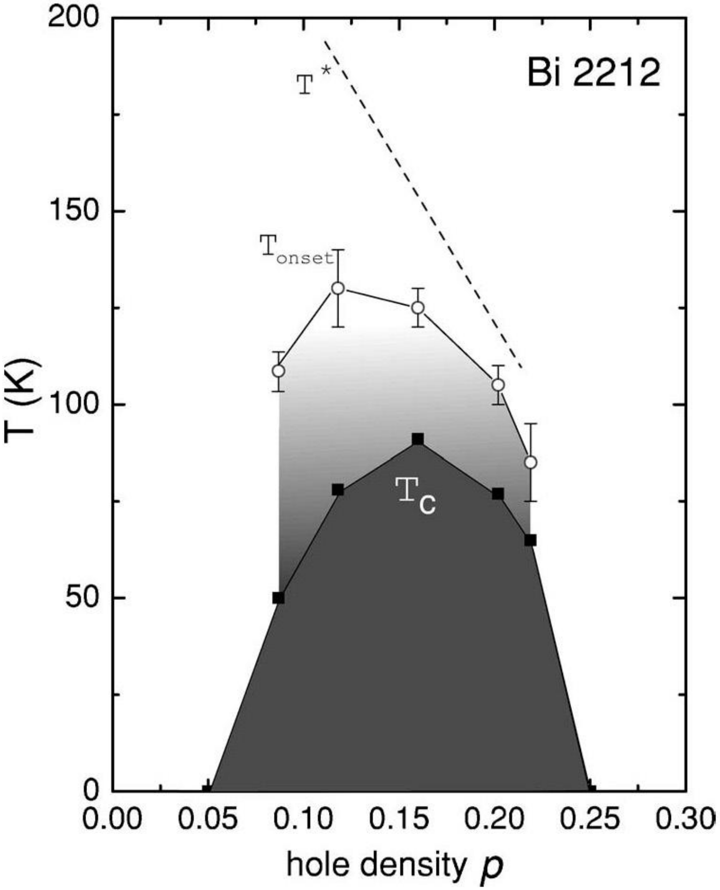


The fluctuating tail is longer in the underdoped regime

Vortex-like excitations in the normal state of the underdoped cuprates?

Wang, Li and Ong, 2006





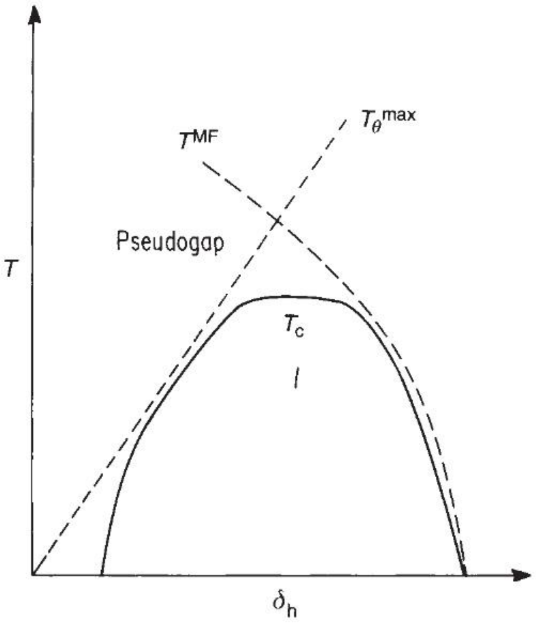
A finite Nernst signal in a wide temperature range above T_c

Preformed Cooper pairs in the pseudogap state?

Importance of phase fluctuations in superconductors with small superfluid density

V. J. Emery* & S. A. Kivelson†

* Department of Physics, Brookhaven National Laboratory, Upton,
New York 11973, USA
† Department of Physics, University of California at Los Angeles,
Los Angeles, California 90095, USA



Nature 1995

Two distinct temperature scales for superconductivity:

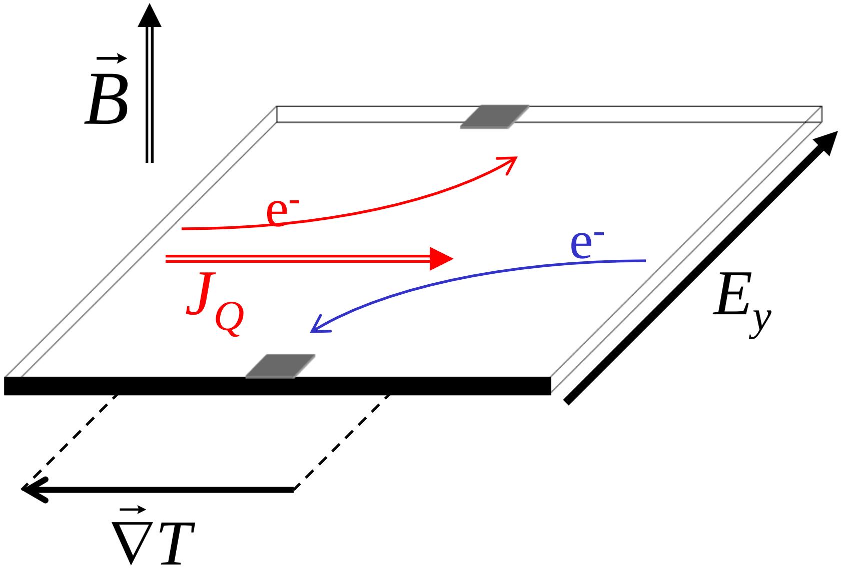
T^* as the onset of phase fluctuating Cooper pairs ?
T_c as the onset of Phase coherence?

The Nernst response of normal electrons

Nernst effect in a single–band metal

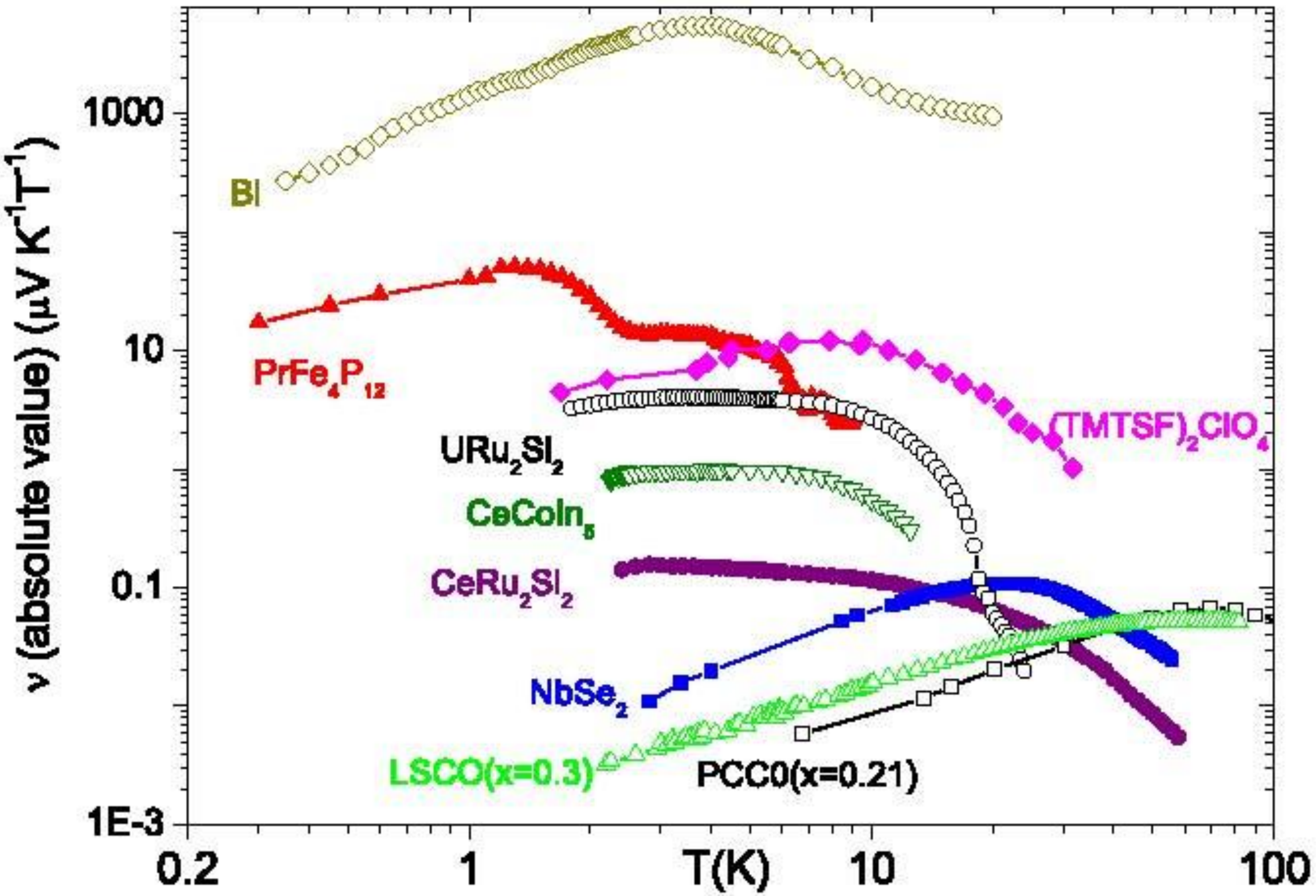
Absence of charge current leads to a counterflow of hot and cold electrons:

$$\boxed{J_Q \neq 0\ ;\ J_e = 0\ ;\ E_y = 0}$$



In an ideally simple metal, the Nernst effect vanishes!
(« Sondheimer cancellation », 1948)

In real metals Nernst coefficient can be large!



Close-up on Sondheimer cancellation

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

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

$J_e=0$

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

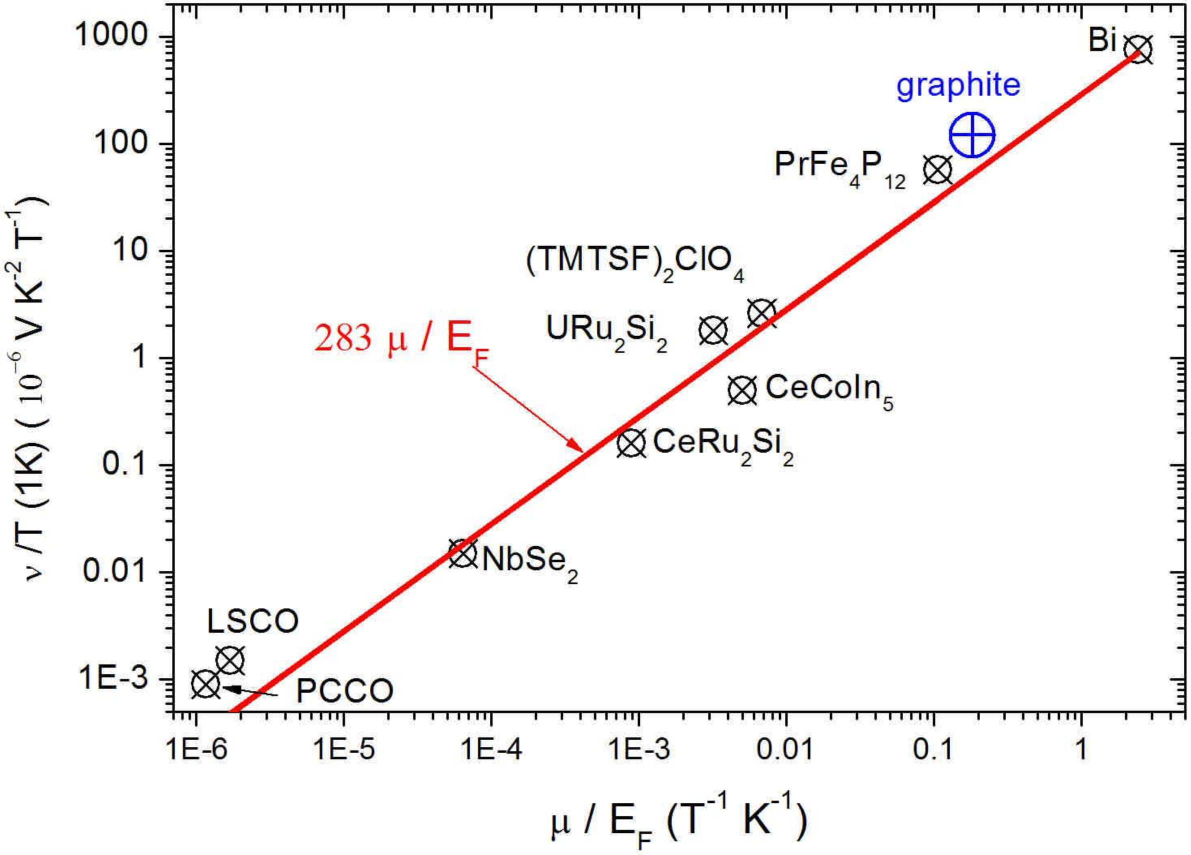
Boltzmann picture: $\overline{\alpha} = \frac{\pi^2}{3}\frac{k_B^2 T}{e}\frac{\partial \overline{\sigma}}{\partial \epsilon}\Big|_{\varepsilon_F} \longrightarrow N = \frac{\pi^2}{3}\frac{k_B^2 T}{e}\frac{\partial \Theta_H}{\partial \epsilon}\Big|_{\varepsilon_F}$

If the Hall angle, Θ_H, does not depend on the position of the Fermi level, then the Nernst signal vanishes!

Recipe for a large diffusive Nernst response:

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

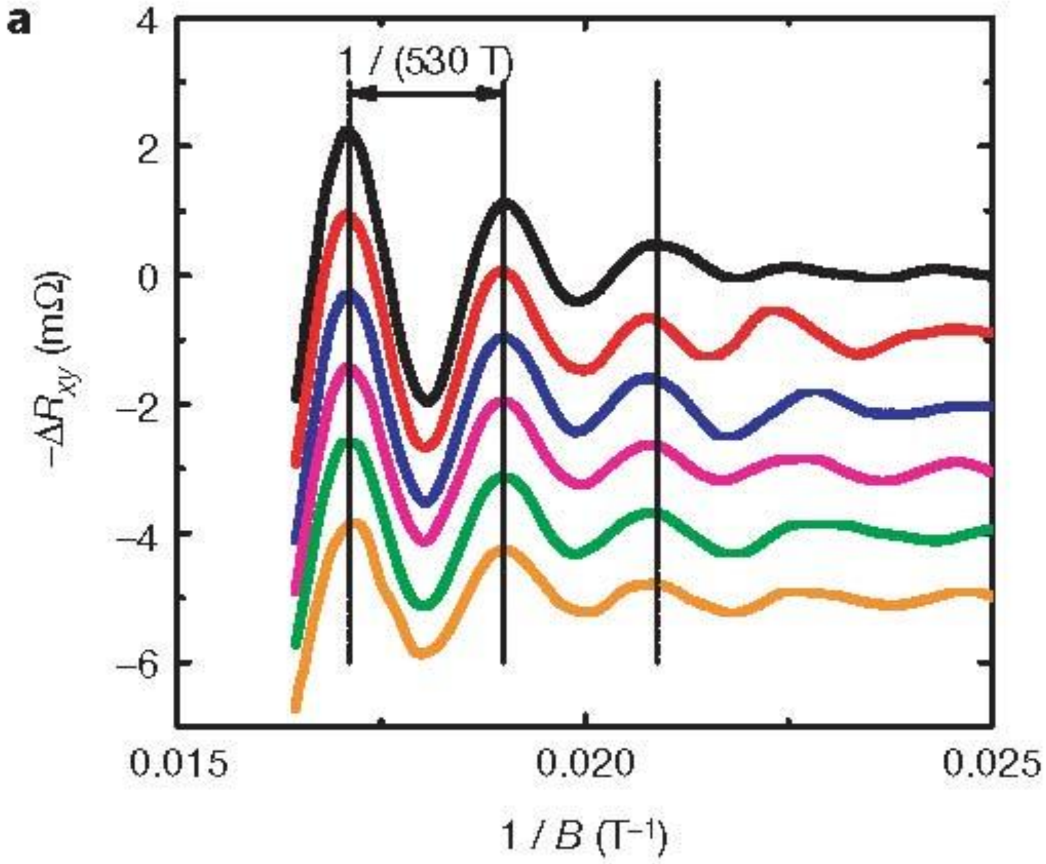
$$\nu \sim (\pi^2/3)\, k^2_B T/e\ \mu\ /\ E_F$$



- High mobility
- Small Fermi energy
- Ambipolarity

Quantum oscillations and the Fermi surface in an underdoped high-T_c superconductor

Nicolas Doiron-Leyraud[1], Cyril Proust[2], David LeBoeuf[1], Julien Levallois[2], Jean-Baptiste Bonnemaison[1], Ruixing Liang[3,4], D. A. Bonn[3,4], W. N. Hardy[3,4] & Louis Taillefer[1,4]



A small Fermi surface
Highly mobile electrons

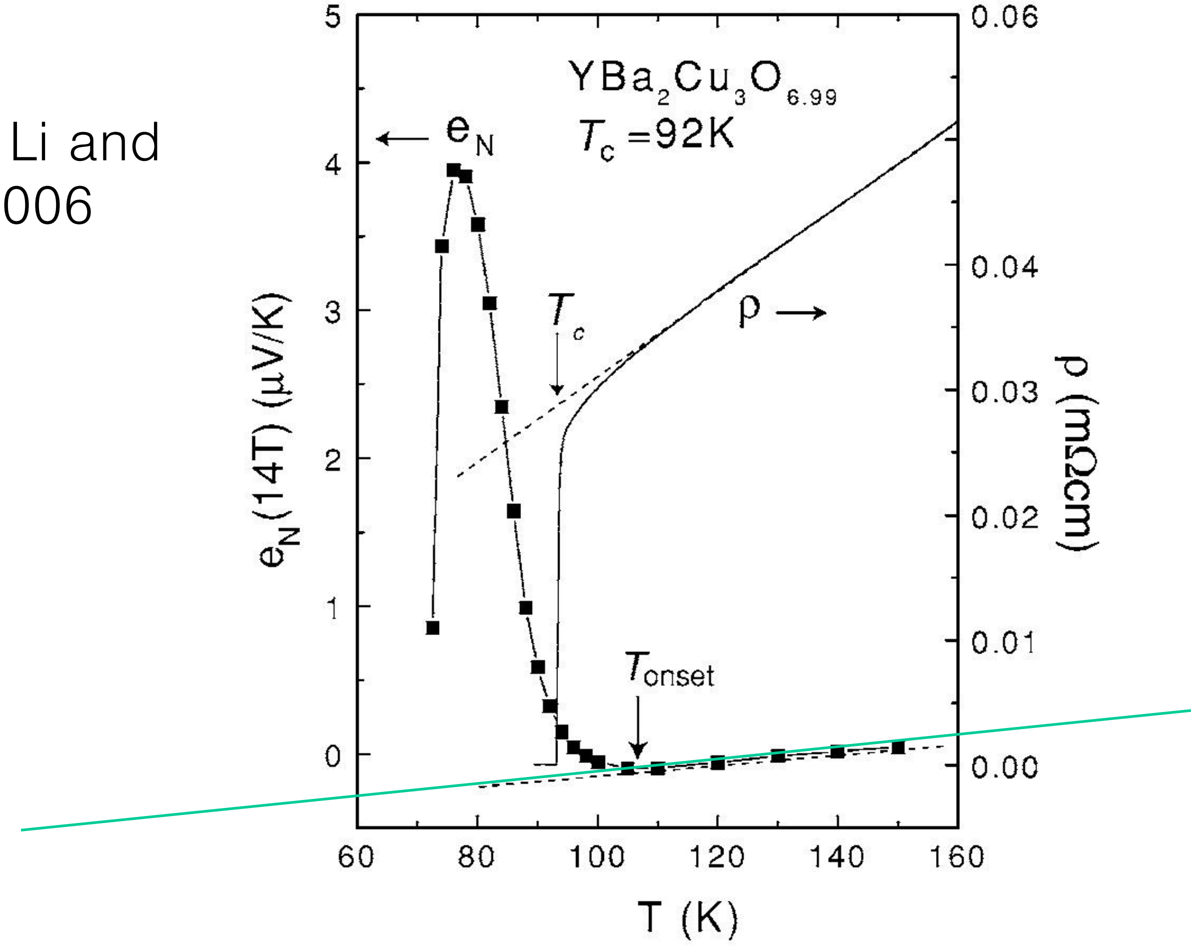
Only seen in YBCO

Electron pockets in the Fermi surface of hole-doped high-T_c superconductors

David LeBoeuf[1], Nicolas Doiron-Leyraud[1], Julien Levallois[2], R. Daou[1], J.-B. Bonnemaison[1], N. E. Hussey[3], L. Balicas[4], B. J. Ramshaw[5], Ruixing Liang[5,6], D. A. Bonn[5,6], W. N. Hardy[5,6], S. Adachi[7], Cyril Proust[2] & Louis Taillefer[1,6]

The Nernst coefficient in YBCO

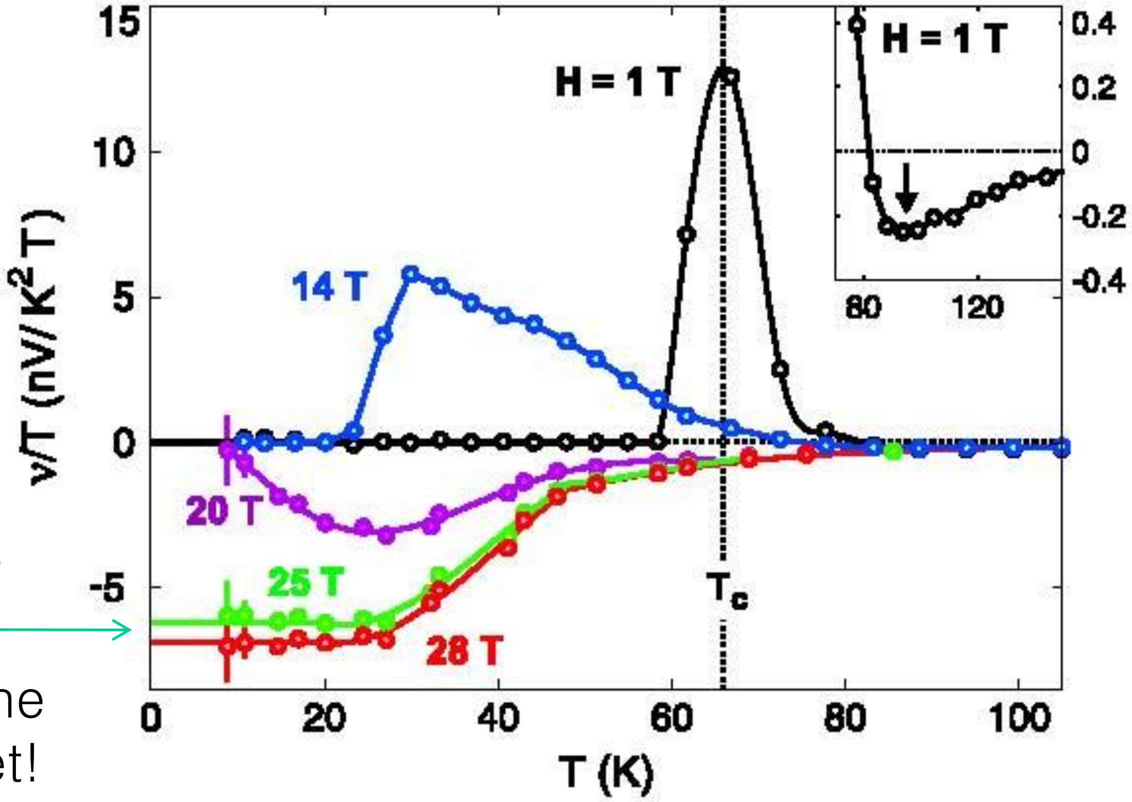
Wang, Li and Ong, 2006



The background signal is negative!

The small electron pocket is the source of a negative Nernst signal in YBCO!

Chang et al., 2010



Within a factor of 2 of what is expected for the electron pocket!

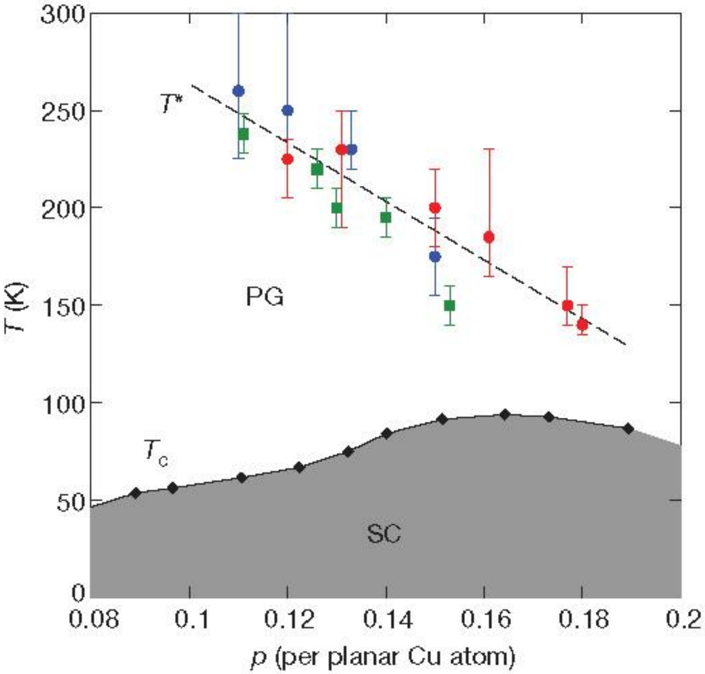
YBCO y =6.67 T_c=66 K

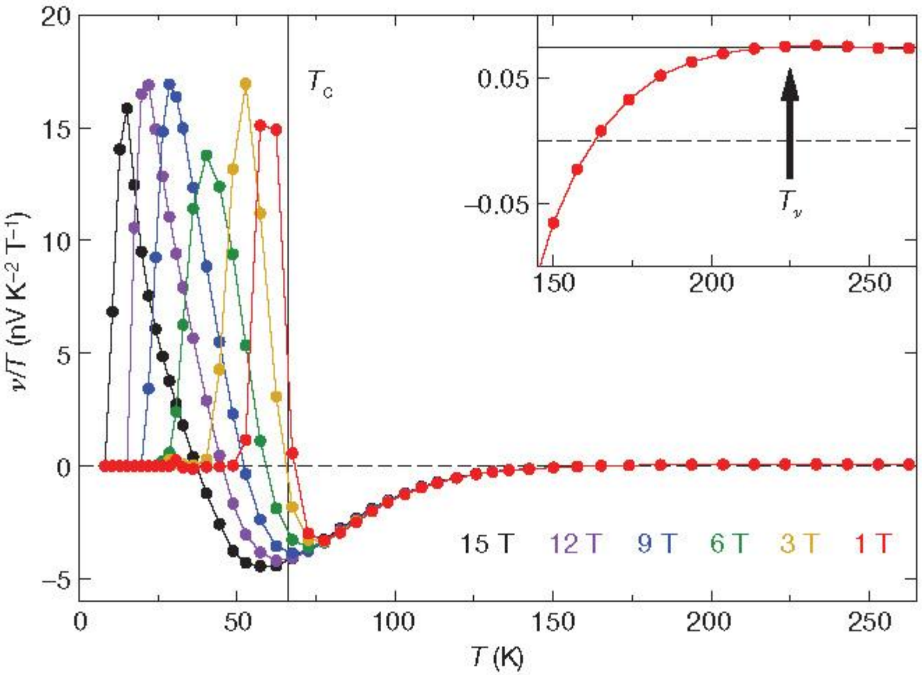
Broken rotational symmetry in the pseudogap phase of a high-T_c superconductor

Nature 2010

R. Daou[1]†, J. Chang[1], David LeBoeuf[1], Olivier Cyr-Choinière[1], Francis Laliberté[1], Nicolas Doiron-Leyraud[1],
B. J. Ramshaw[2], Ruixing Liang[2,3], D. A. Bonn[2,3], W. N. Hardy[2,3] & Louis Taillefer[1,3]

YBCO y =6.67 T_c=66 K



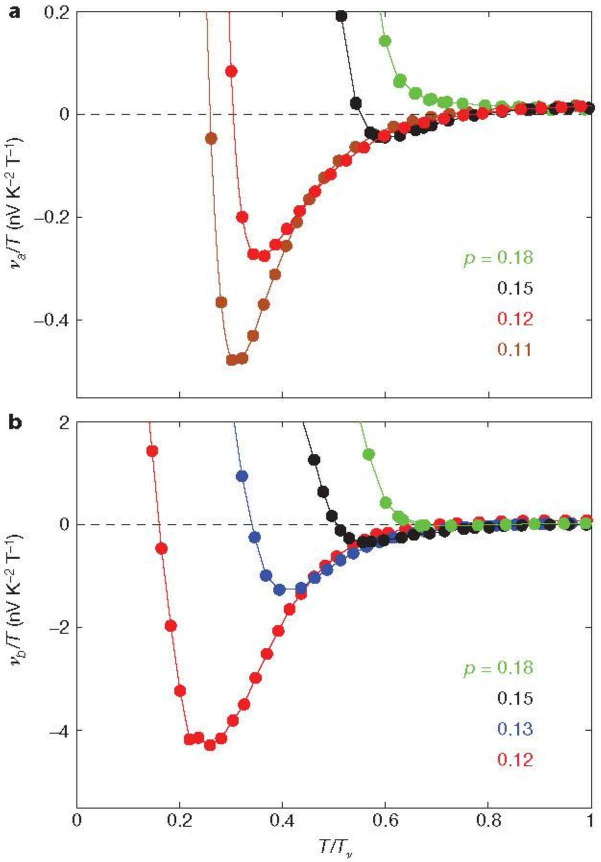


The negative Nernst signal in YBCO emerges below T^* !!!???

Broken rotational symmetry in the pseudogap phase of a high-T_c superconductor

Nature 2010

R. Daou[1]†, J. Chang[1], David LeBoeuf[1], Olivier Cyr-Choinière[1], Francis Laliberté[1], Nicolas Doiron-Leyraud[1], B. J. Ramshaw[2], Ruixing Liang[2,3], D. A. Bonn[2,3], W. N. Hardy[2,3] & Louis Taillefer[1,3]



The Nernst response is extremely anisotropic in the pseudogap state!

Nernst effect due to Gaussian fluctuations of the amplitude of the superconducting order parameter (Usshishkin, Sondhi & Huse, 2002)

In 2D:

$$\alpha_{xy}^{SC} = \frac{1}{6\pi}\frac{k_B e}{\hbar}\frac{\xi^2}{\ell_B^2}$$

$$\ell_B = \sqrt{\frac{\hbar}{eB}}$$

Magnetic length

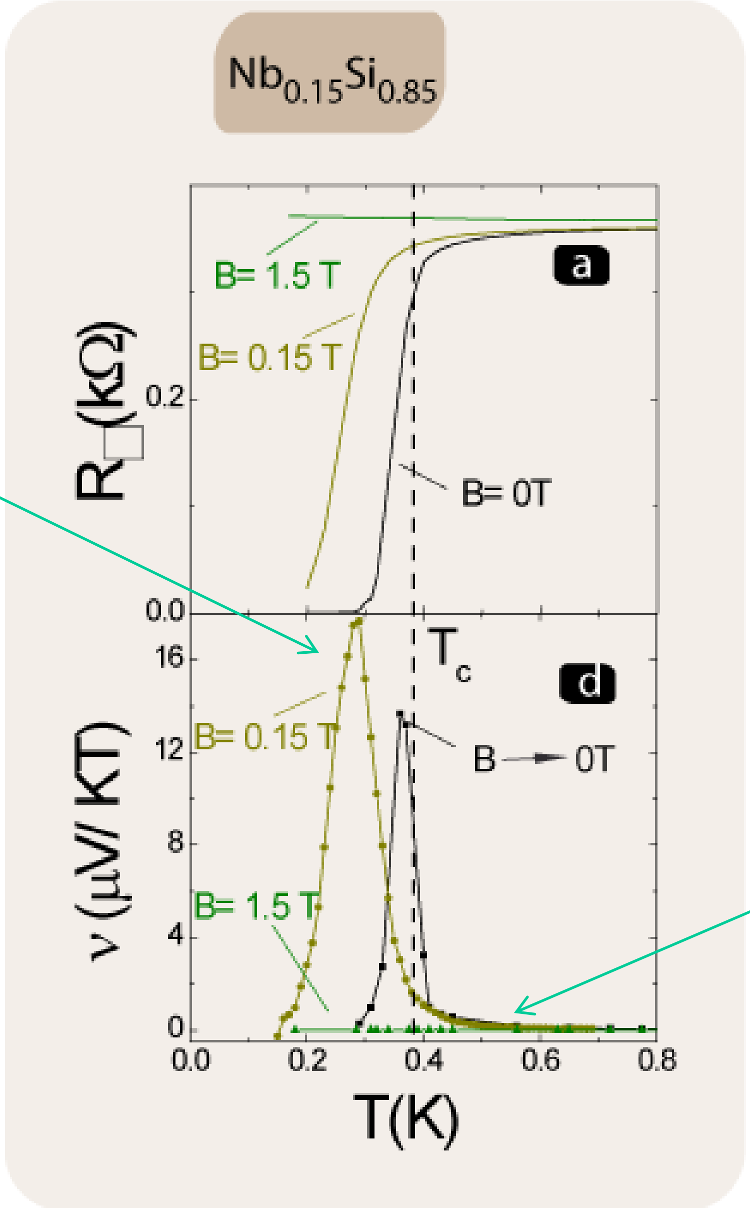
Quantum of thermo-electric conductance (21 nA/K)

In two dimensions, the coherence length is the unique parameter!

Nernst effect in a conventional superconductor

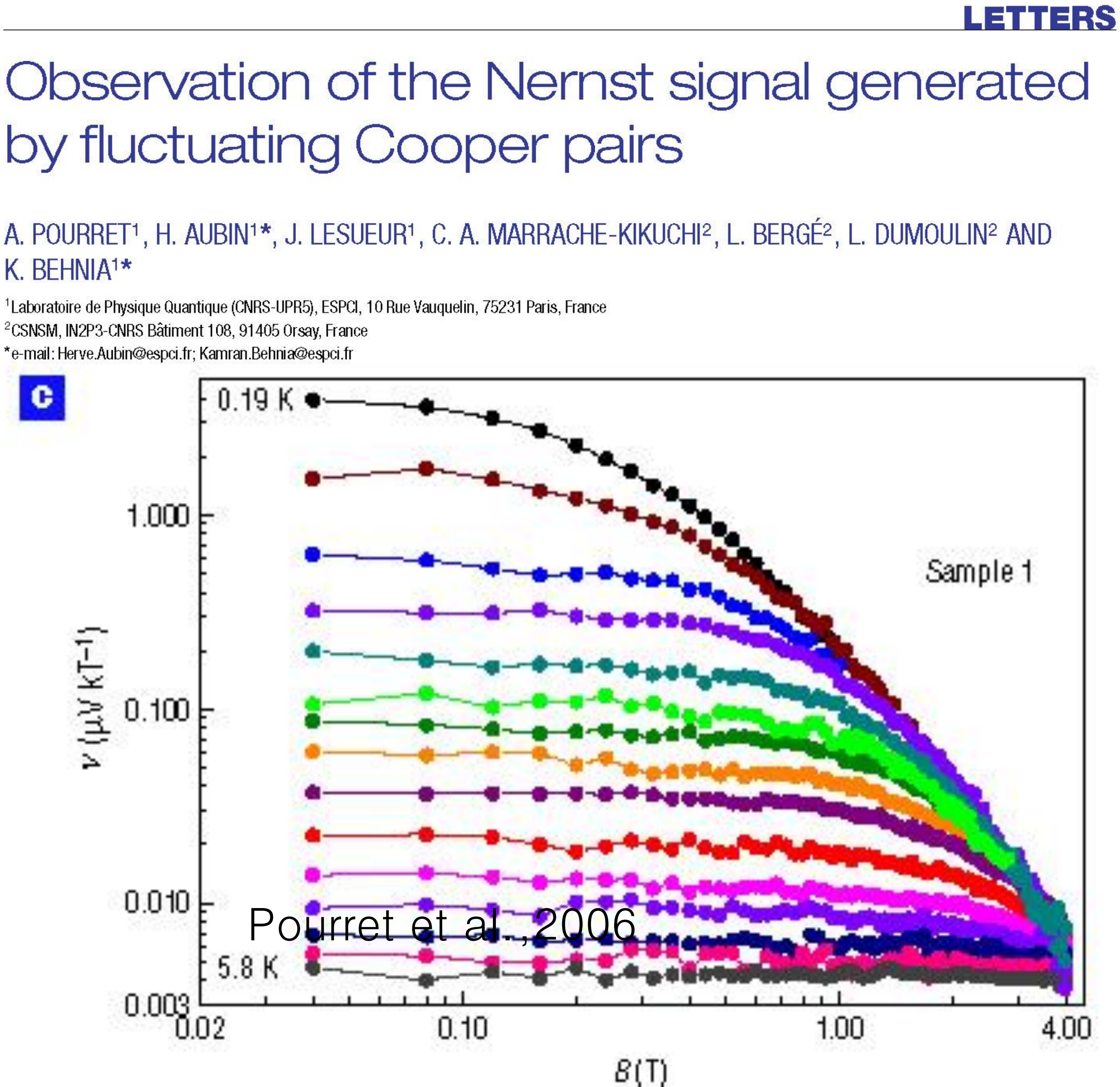
- A large vortex signal below T_c

Pourret et al.,2006



•A long tail above T_c

Surviving deep in to the normal state!



LETTERS

Observation of the Nernst signal generated by fluctuating Cooper pairs

A. POURRET[1], H. AUBIN[1]*, J. LESUEUR[1], C. A. MARRACHE-KIKUCHI[2], L. BERGÉ[2], L. DUMOULIN[2] AND K. BEHNIA[1]*

[1] Laboratoire de Physique Quantique (CNRS-UPR5), ESPCI, 10 Rue Vauquelin, 75231 Paris, France

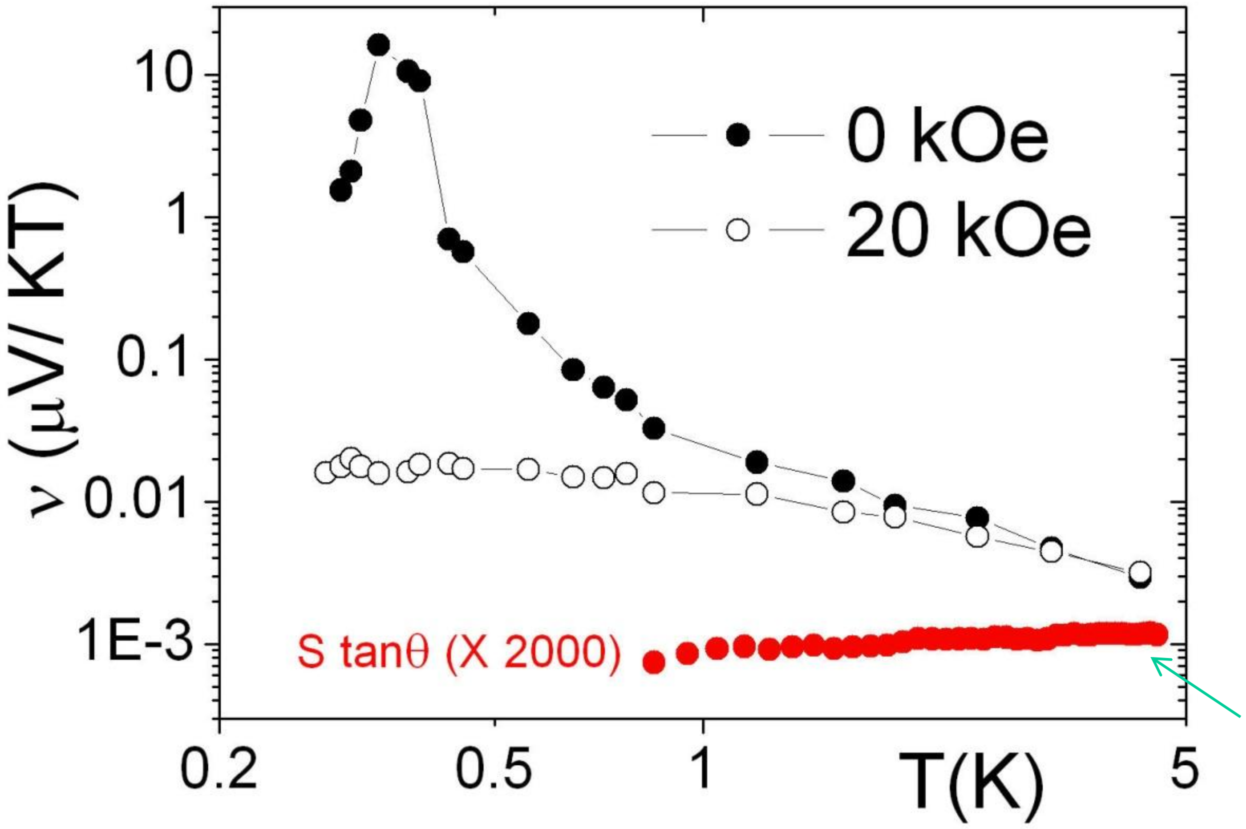
[2] CSNSM, IN2P3-CNRS Bâtiment 108, 91405 Orsay, France

*e-mail: Herve.Aubin@espci.fr; Kamran.Behnia@espci.fr

Pourret et al., 2006

The Nernst signal of the normal electrons is negligible!

Pourret et al. 2006

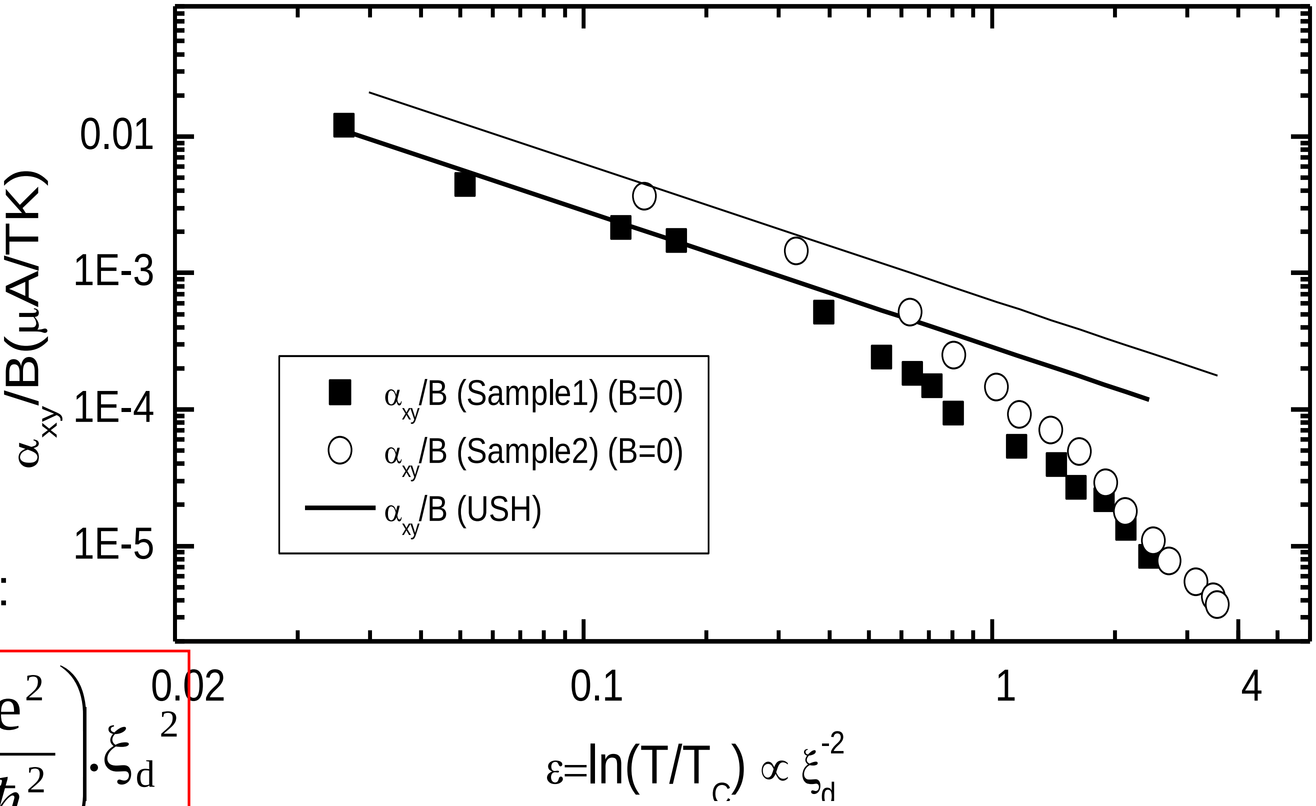


Even at 6K :
The normal state contribution is three orders of magnitude smaller than ν/T !

Comparison with theory

Experiment:

$$\frac{\alpha_{xy}}{B} = \frac{\nu}{R_{square}}$$



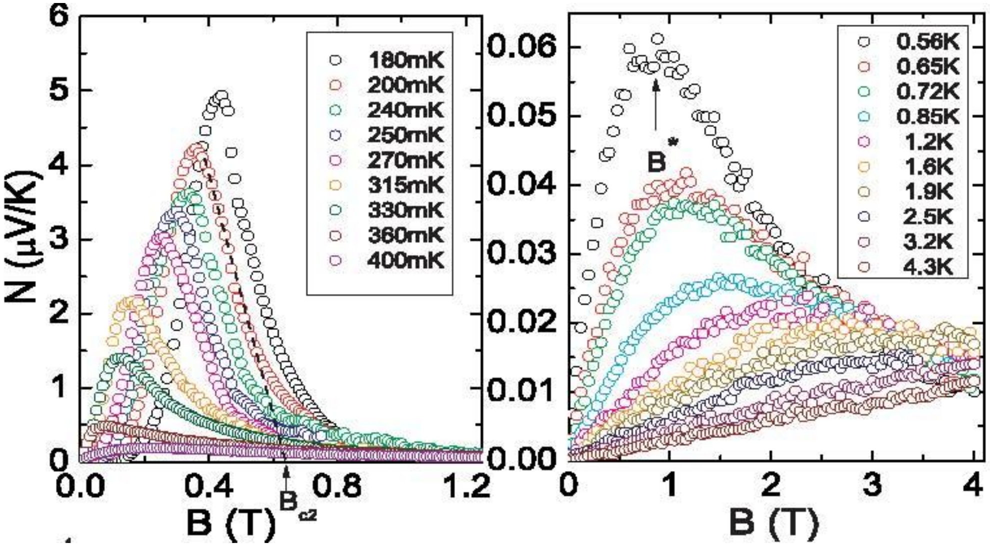
Theory:

$$\left.\frac{\alpha_{xy}}{B}\right|_{USH} = \left(\frac{k_B e^2}{6\pi\hbar^2}\right)\cdot\xi_d^2$$

Satisfactory agreement close to T_c

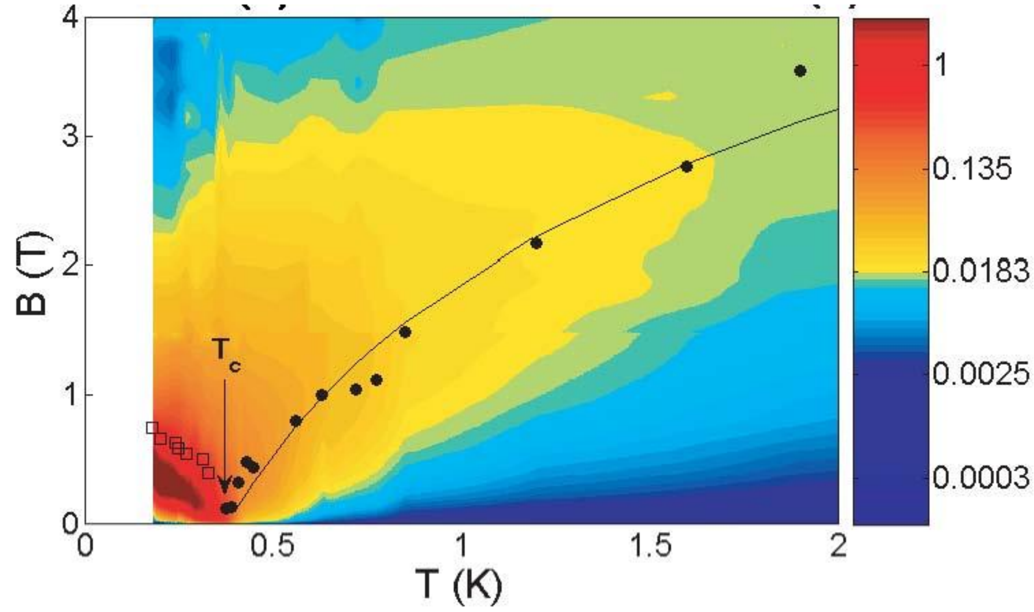
The ghost critical field

Below T_c Above T_c



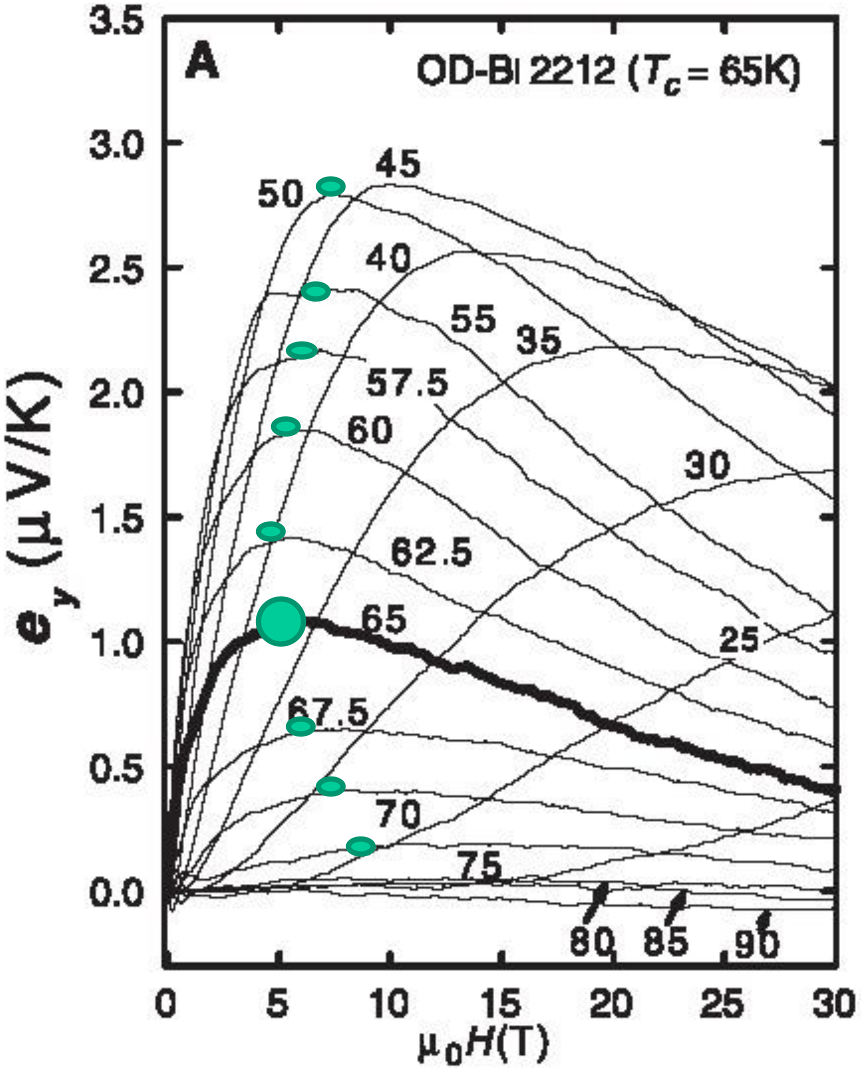
$Nb_{0.15}Si_{0.85}$

Pourret et al. 2006



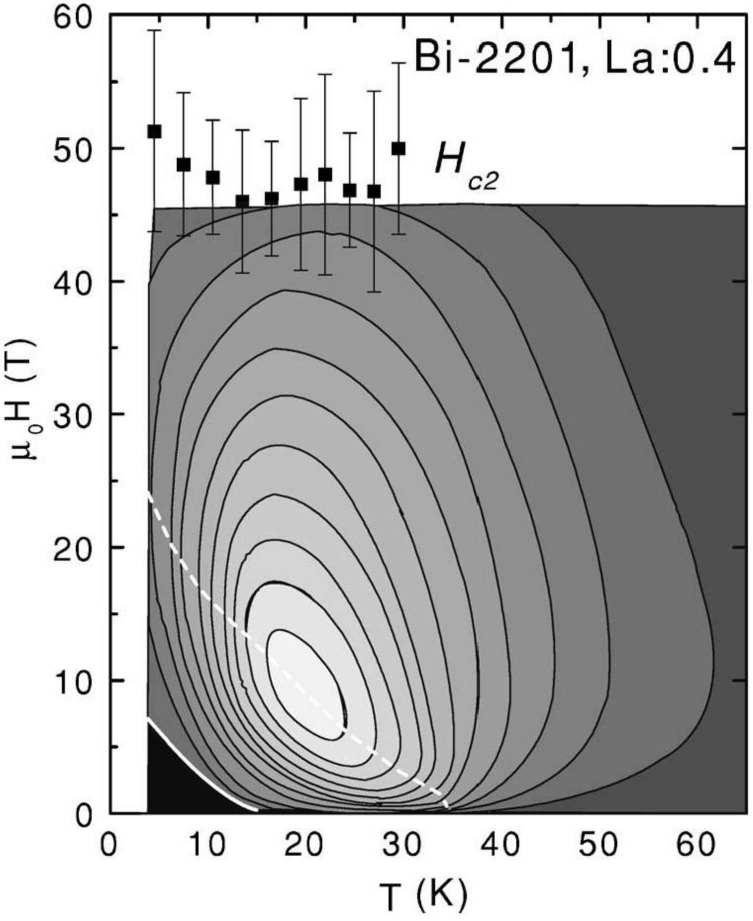
Back to cuprates: upper critical field and the ghost critical field

Wang et al., 2006



The critical field vanishes at T_c

Wang et al., 2006



The upper critical field?

A brief summary

The Nernst signal in cuprates can come from:

- Normal quasi-particles:

The negative Nernst signal in YBCO is generated by Fermi surface reconstruction

- Gaussian fluctuations:

Source of a positive Nernst signal above T_c in any superconductor

Is there still room for phase fluctuations?

Questions

Is there any additional temperature scale associated with superconductivity?

Probably, no!

- Why the sign of the Nernst signal in YBCO differ from other cuprates?

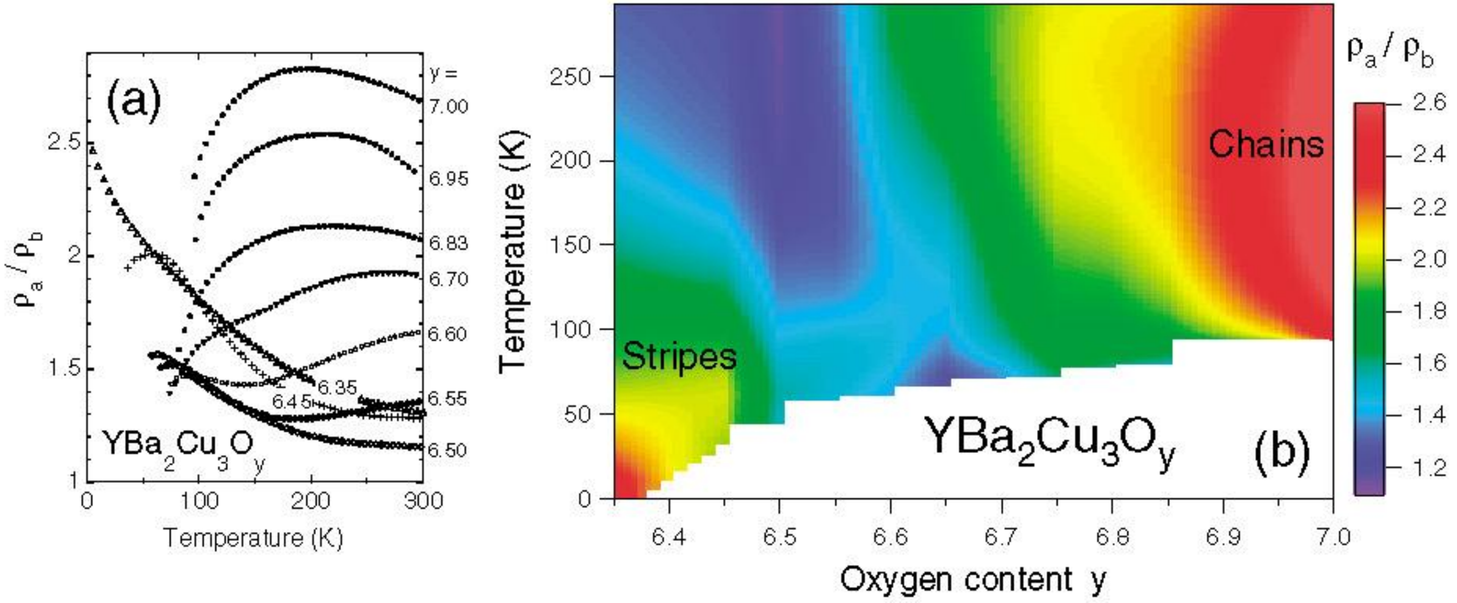
Chains? Stripe commensurability?

Stripes?

Electrical Resistivity Anisotropy from Self-Organized One Dimensionality in High-Temperature Superconductors

Yoichi Ando, Kouji Segawa, Seiki Komiya, and A. N. Lavrov
Central Research Institute of Electric Power Industry, Komae, Tokyo 201-8511, Japan

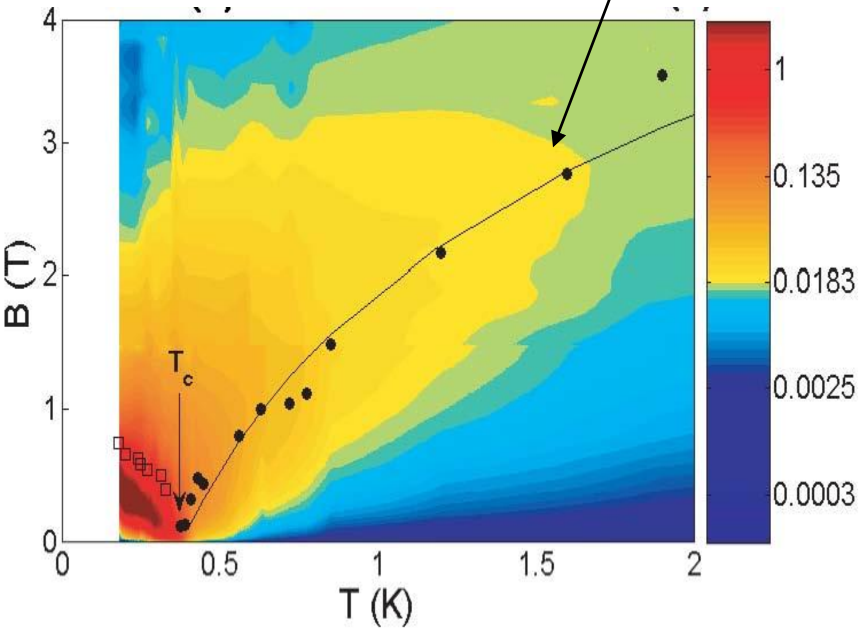
(Received 31 July 2001; published 19 March 2002)



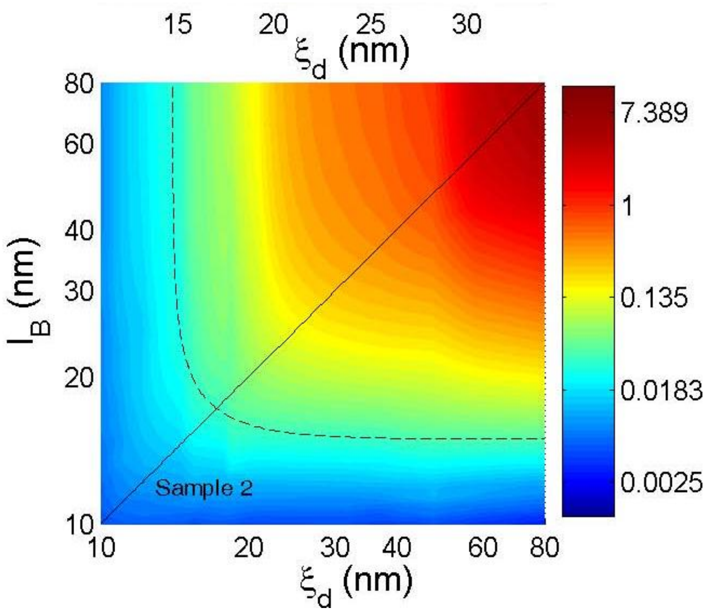
Le champ critique fantôme

$H_c = \phi_0 / 2\pi\xi^2$

N



→



On peut traduire T et B en longueurs correspondantes!
Même pour T >>Tc la supraconductivité est la source du signal Nernst !