High-field entropy transport in cuprates

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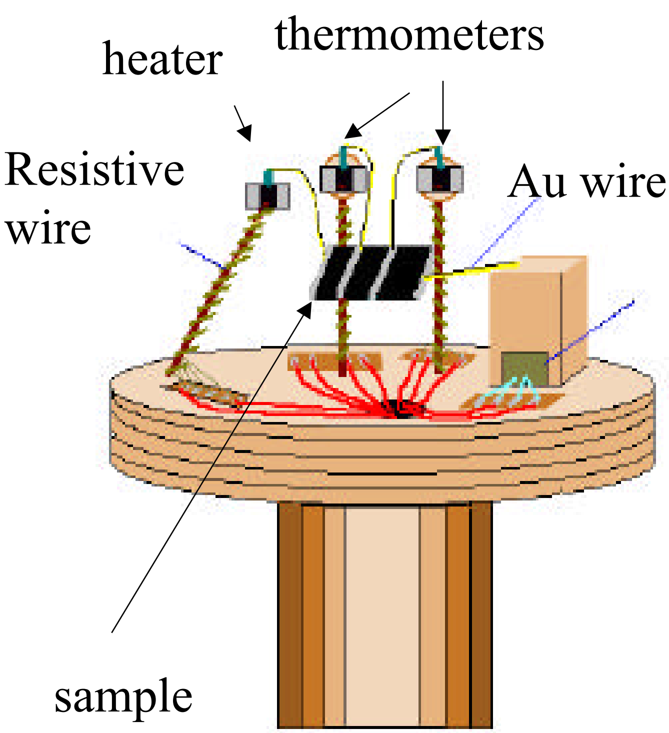
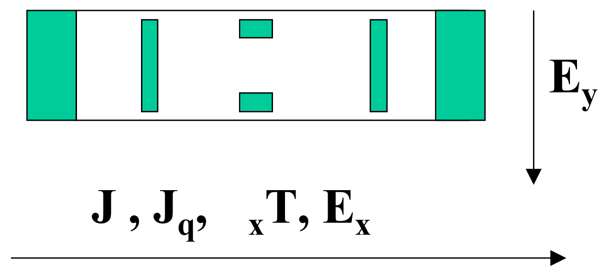
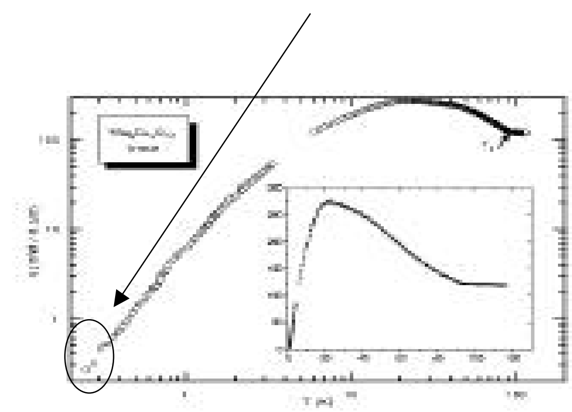
- Transport entropy of vortices

Measuring thermo-electric coefficients (ρ_{xx}, ρ_{xy}, $\mathbf{S_{xx}}$, $\mathbf{S_{xy}}$ **and** κ_{xx}) with a single set-up



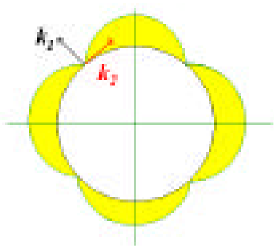


Residual quasi-particle thermal conductivity as a linear term in the ballistic regime ($\kappa_{ph} \propto T^3$)



A TALE OF TWO VELOCITIES!

(Durst , Lee '99)



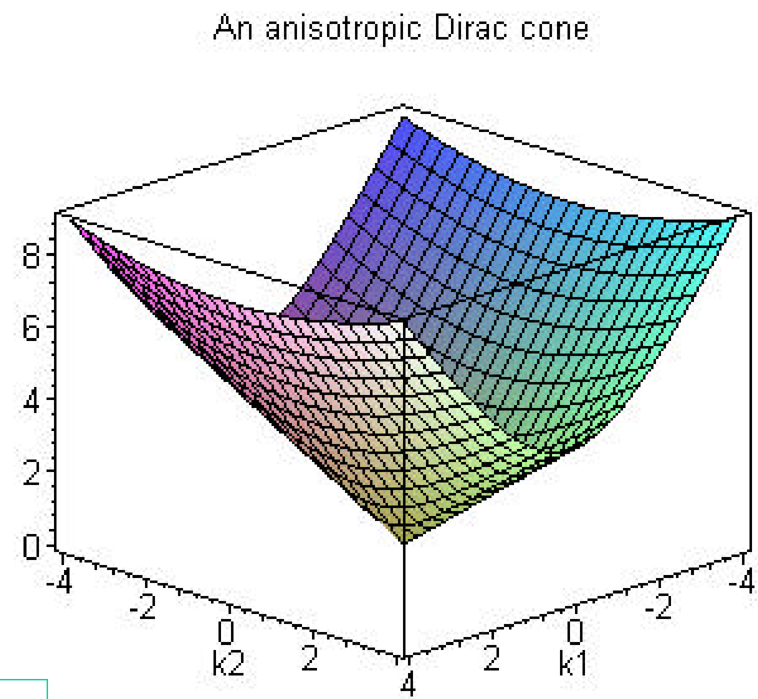
Excitation spectrum in

the vicinity of a node:

$$E(k) = (\varepsilon_k^2 + \Delta_k^2)^{1/2}$$
$$= (v_F^2 k_1^2 + v_2^2 k_2^2)^{1/2}$$

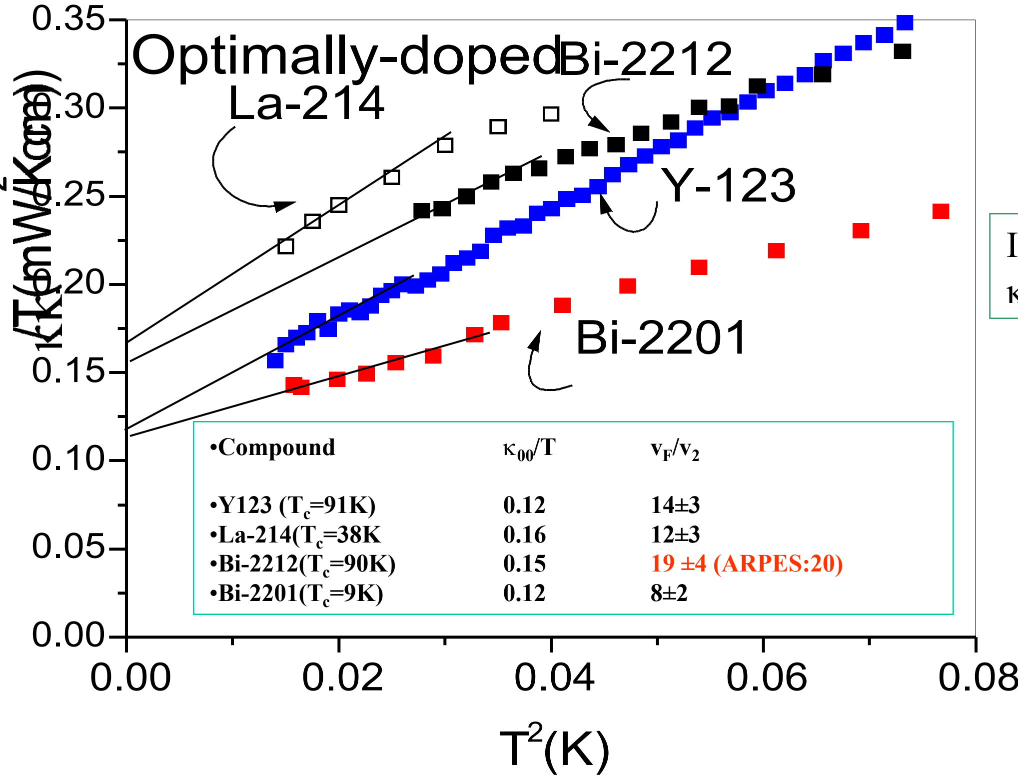
Fermi velocity : $v_F = d\varepsilon_k/dk_1$

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



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

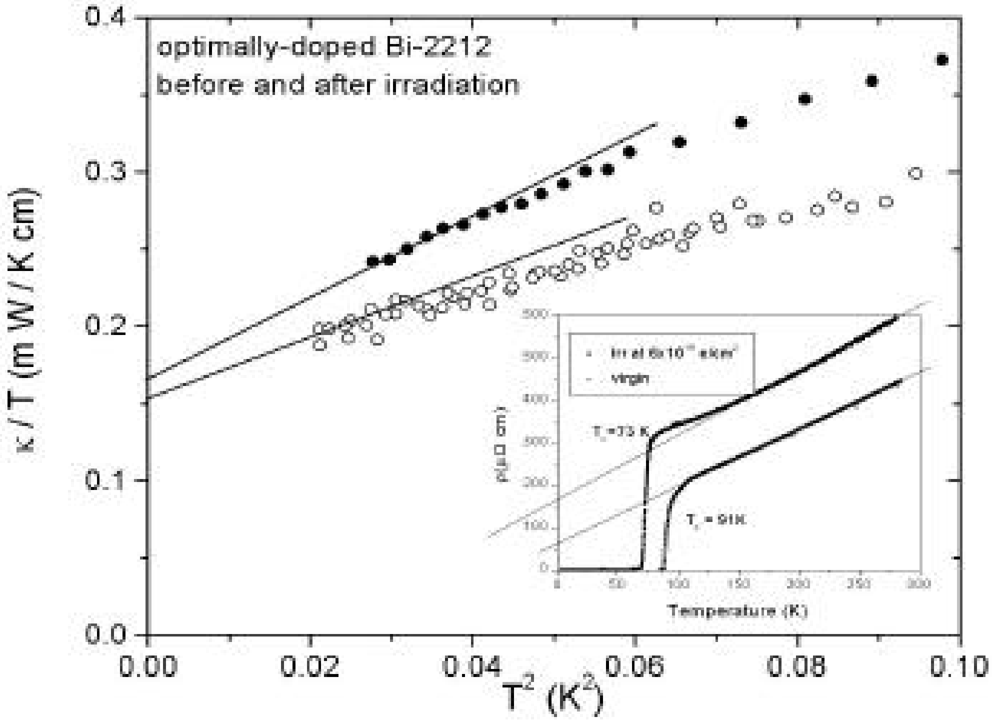
Residual quasi-particle conductivity in optimally-doped cuprates



•Compound	κ_{00}/T	v_F/v_2
•Y123 (T_c=91K)	0.12	14±3
•La-214(T_c=38K	0.16	12±3
•Bi-2212(T_c=90K)	0.15	19 ±4 (ARPES:20)
•Bi-2201(T_c=9K)	0.12	8±2

In the balistic regime
$\kappa = aT+bT^3$

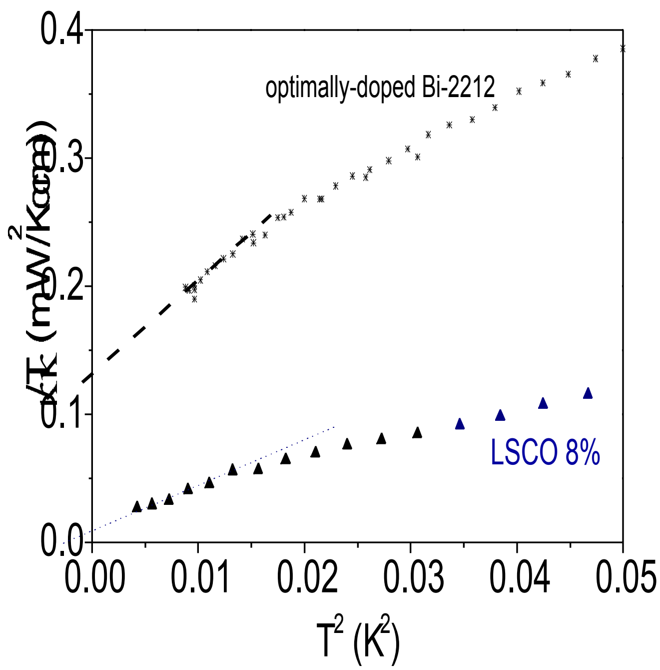
As theoretically predicted, the magnitude of the linear term is insensitive to the introduction of defects!

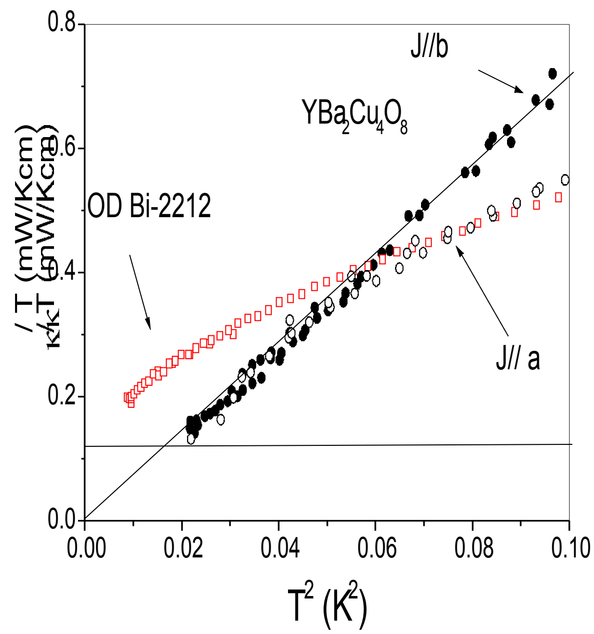


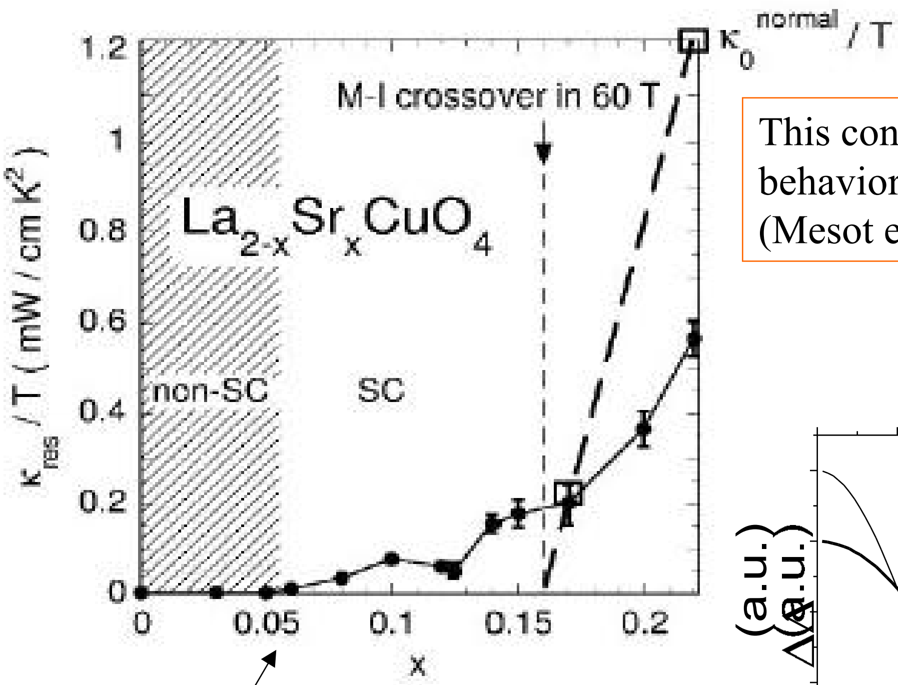
See Taillefer et al., PRL**79**, 489(1997) for Zn-doped YBCO

Sr_2RuO_4, another unconventional superconductor, displays a universal residual qp thermal conductivity (Suzuki et al. PRL**88**, 227004(2002))

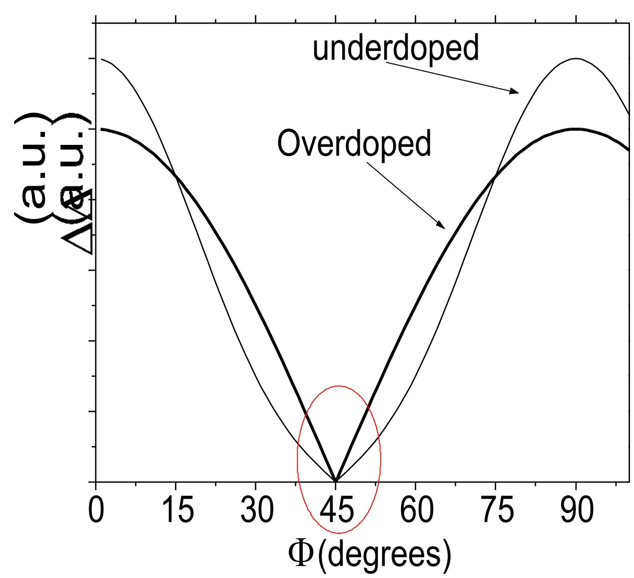
The residual quasi-particle conductivity is absent or dramatically reduced in underdoped cuprates!







This contradicts the expected v_F/v_2 behavior suggested by ARPES (Mesot et al. ‘01)



See also Takeya, Ando et al. (prl ’02) for a detailed study of doping dependence!

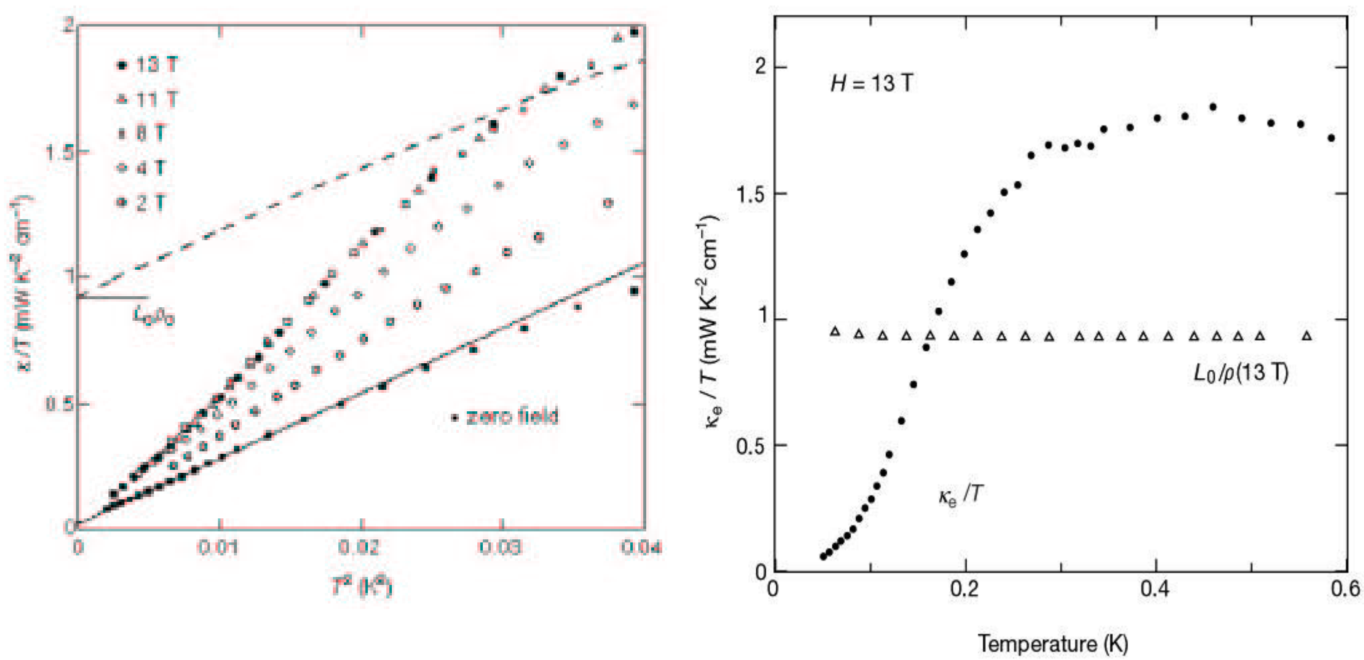
The Wiedemann-Franz law

- Relates the conduction of heat to conduction of charge in an electronic system:

$$\kappa\rho / T = L_0 = \pi^2/3 \; (k_B / e)^2$$

- A fundamental property of any Fermi liquid at T=0. Theoretically robust in presence of strong correlations.
- Experimentally checked in a variety of strongly-correlated electron systems (Heavy fermions, organic superconductors, Sr_2RuO_4…) .
- Would break down in case of electron fractionalization.

The violation of WF law in PCCO (Hill, Taillefer et al., Nature **414**, 711 (2001)



Two distinct violations: i) An excess of electronic heat conductivity above 0.3K ii) sudden vanishing below 0.3K

Recent theoretical scenarios for the violation of WF law in various contexts

- Mei-Rong Li & E. Orignac, cond-mat/0201291(2002) (disordered Luttinger liquid)
- Guo-Zhu Liu, Cond-mat/0203048 (2002) (chiral symmetry breaking)
- Wonkee Kim & J. P. Carbotte, Cond-mat/0202514(2002) (d-desnsity wave)
- Houghton, Lee Marston, PRB 65, 220503 (2002) (t-j model)

Additional degrees of freedom leads to L/L_0 exceeding 1.

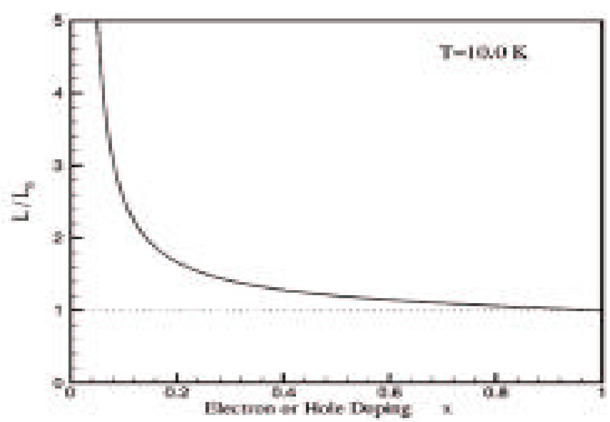
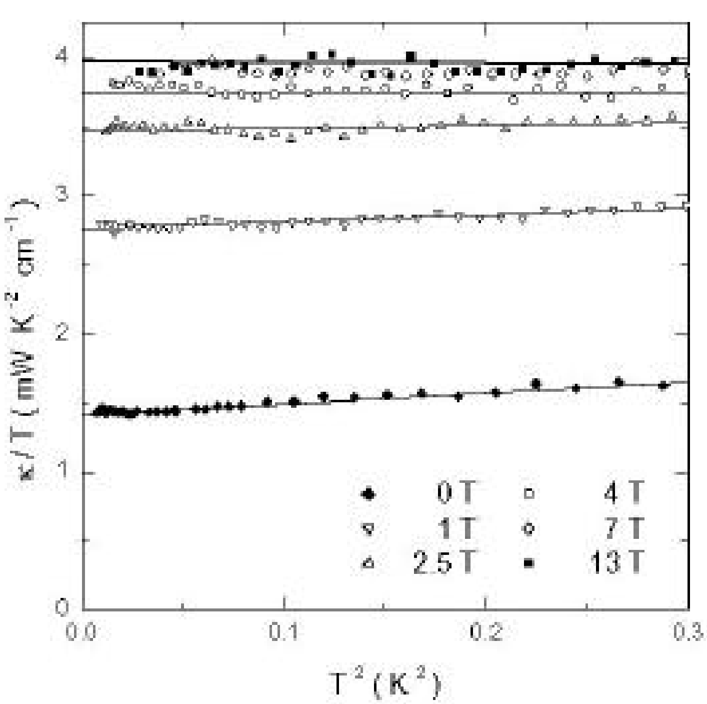
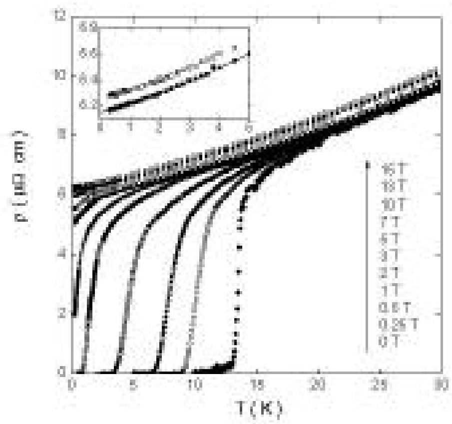


FIG. 1. The Lorenz ratio [Eqs. (12) and (13)] as a function of the doping for $t=0.44$ eV, $J=0.13$ eV. The ratio approaches unity in the dilute limit, $x \to 1$.

The validity of WF law in overdoped Tl-2201

(Proust, Boaknin, Hill, Taillefer, Mackenzie, cond-mat/ 0202101)



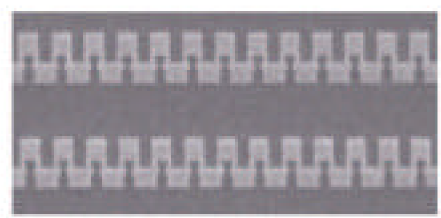


At H=13T, superconductivity is [apparently] destroyed and the magnitude of the linear term becomes identical with what is expected by the WF law !

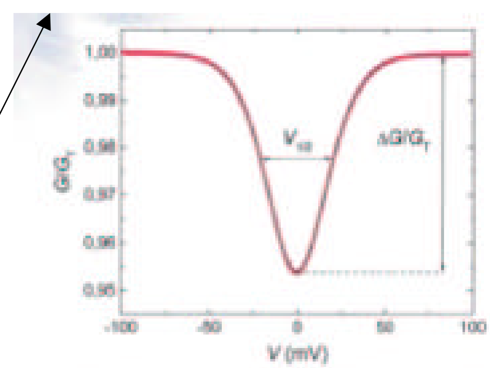
Measuring subkelvin thermal conductivity in a Bitter magnet (producing H >20T)

Non-exhaustive list of difficulties

- Reduced space
- Restricted time
- Vibrations due to water cooling
- **Low-temperature field-insensitive thermometers required** (no field-free zone available)



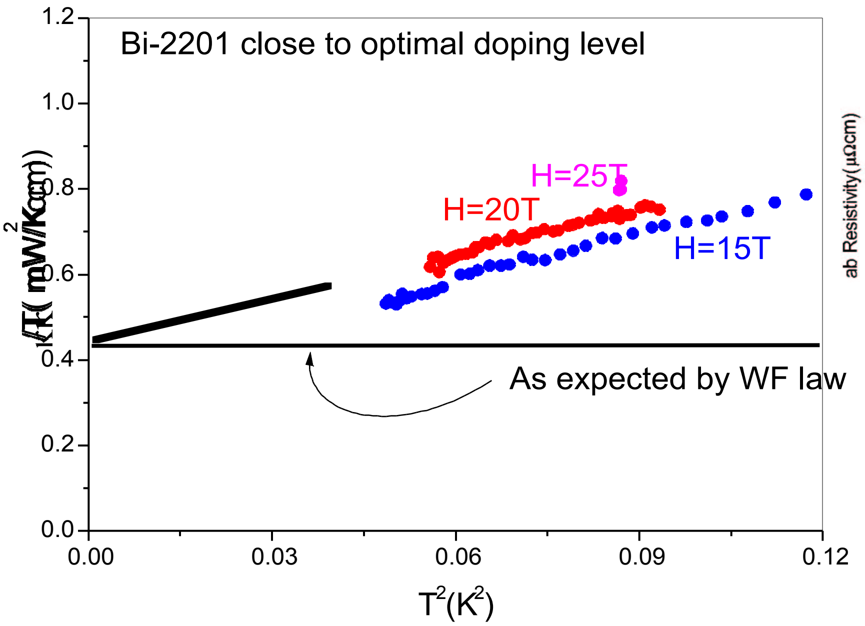
A SEM image of junction arrays of a Nanoway CBT Sensor 0.1.

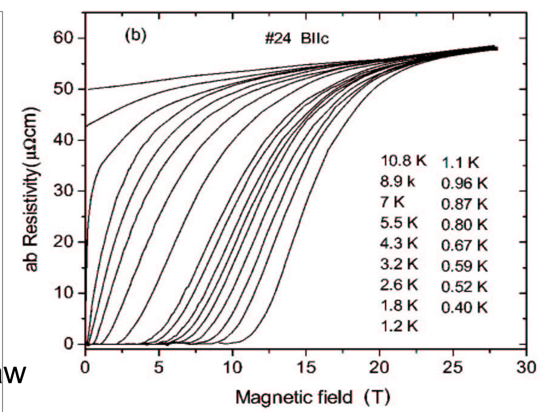


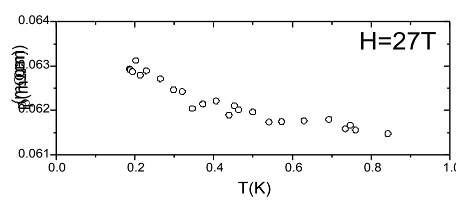
Normalised conductance, G/G_T, of a CBT sensor against bi voltage V. The theoretical curve of Eq. (1) is shown as a blac line.

Solution: Coulomb blockade thermometry using an array of single-electron tunnel junctions (Nanoway, Finaland)

Checking the WF law in optimally-doped Bi-2201

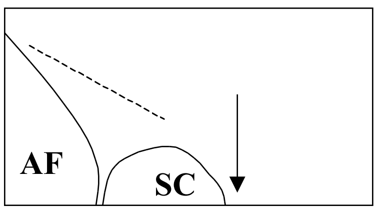


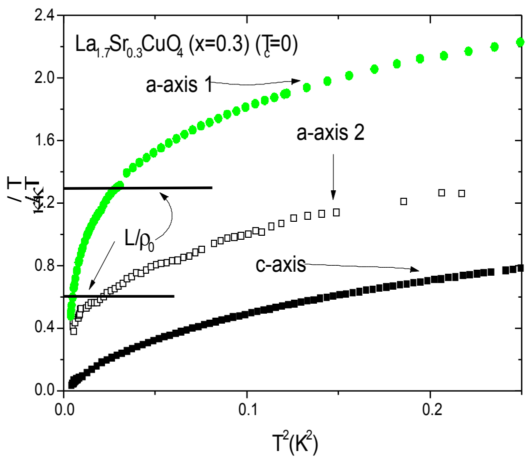


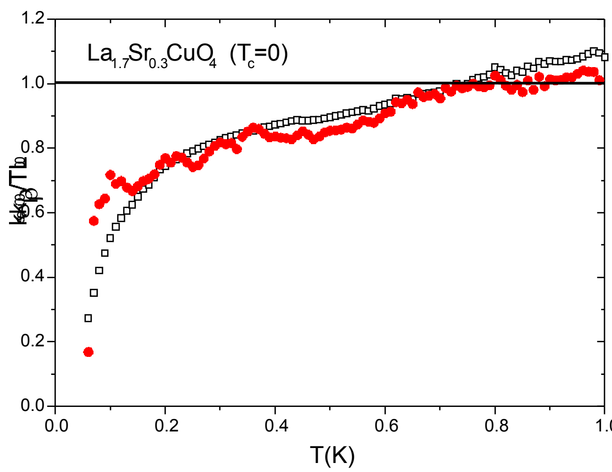


Even at optimal doping, the linear term at high fields is very close to the magnitude expected by the WF law!

The amazing case of non-superconducting heavily-overdoped LSCO



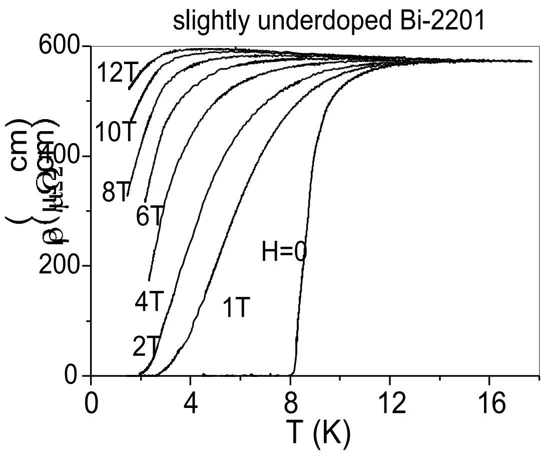




The collapse of linear term below 0.3K remains unexplained (reminiscent of PCCO!)

- Losing connection to electron thermal bath?
- A hidden, very small energy scale?

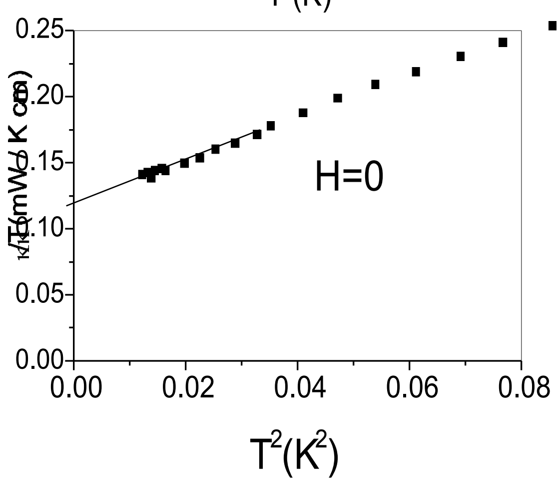
In underdoped cuprates the product of of κ_{00}/T and of ρ_0 exceeds L_0



$\kappa_{00}/T = 0.12$ mW/K^2 cm

& ρ_0 =600 $\mu\Omega$cm

$\rho_0\, \kappa_{00}/T \sim 3\, L_0$



For the WF law to be obeyed an unusual reduction of κ_{00}/T with magnetic field is expected!

A similar result reported for undedoped LSCO by Takeya, Ando et al., prl'02

Summary
of what has been observed regarding the WF law in cuprates

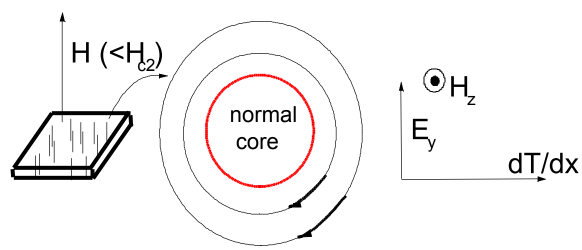
- Validity of WF law in the high-field « normal » state (overdoped Tl-2201 and optimally-doped Bi-2201)

- Unexpected downward deviation from the Wiedemann-Franz law, (heavily-overdoped LSCO, and electron-doped PCCO)

- A large linear term κ_{00}/T in the superconducting state compared to the residual resitivity of the normal state (underdoped Bi-2201 and La-214)

Nernst effect in the vortex state

A transverse voltage produced by a longitudinal thermal gradient : $S_{xy}= E_y/\Delta_x T$

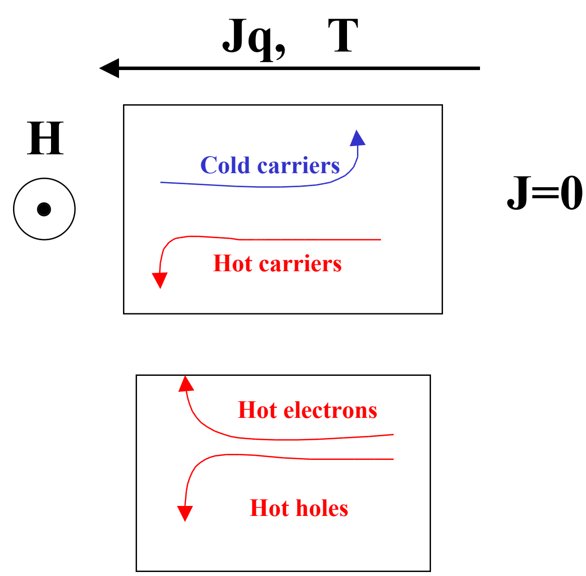


A vortex is:

- A quantum of magnetic flux
- An entropy reservoir S_ϕ
- A topological defect in a phase coherent environment

- Force on the vortex due to the thermal gradient: $F=S_\phi \quad T$
- The vortex moves: $F = \eta\, v$
- The movement leads to a transverse voltage: $E_y=vB_z$

Nernst coefficient in metals



Metal with a single type of charge carriers:
Absence of longitudinal charge current leads to the cancellation of Hall-like transverse voltage (Sodhemier '48), See also Wang et al., PRB '02

This is not true for a metal with several type of carriers!

$\mathbf{J}=\sigma\ \mathbf{E}+\alpha/T\quad T$

$\mathbf{J_q}=\alpha\,\mathbf{E}+\kappa\quad T$

In a Boltzmann picture: $\alpha\ \propto \partial\sigma/\partial\varepsilon\,\big|\,\varepsilon=\varepsilon_F$

(Thus, a possible finite Nernst signal due to an energy-dependent scattering rate)

Nernst effect in optimally-doped cuprates

(Ri, Heubner et al. 1994)

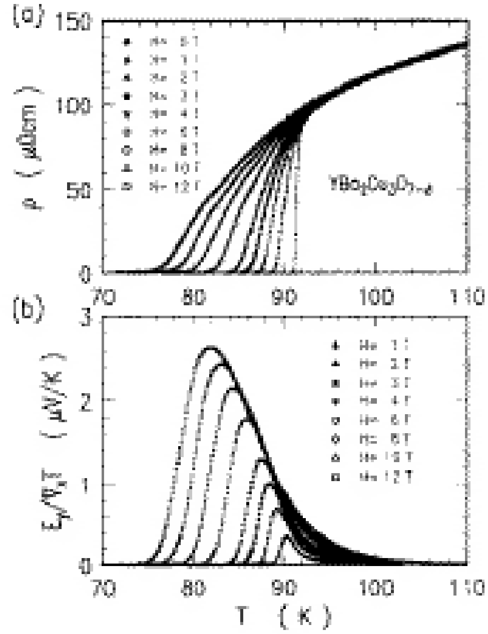
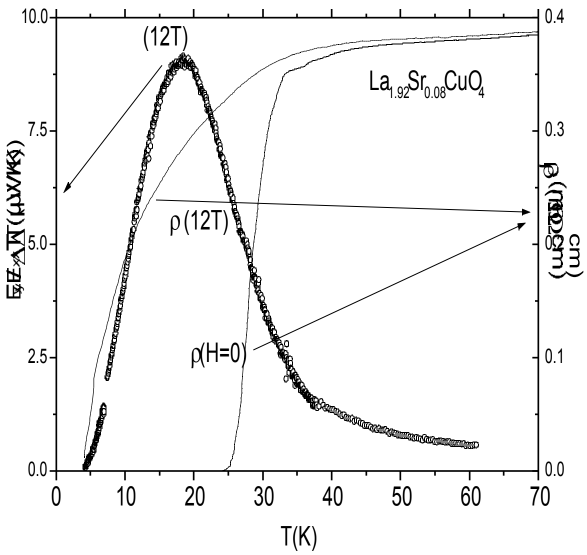
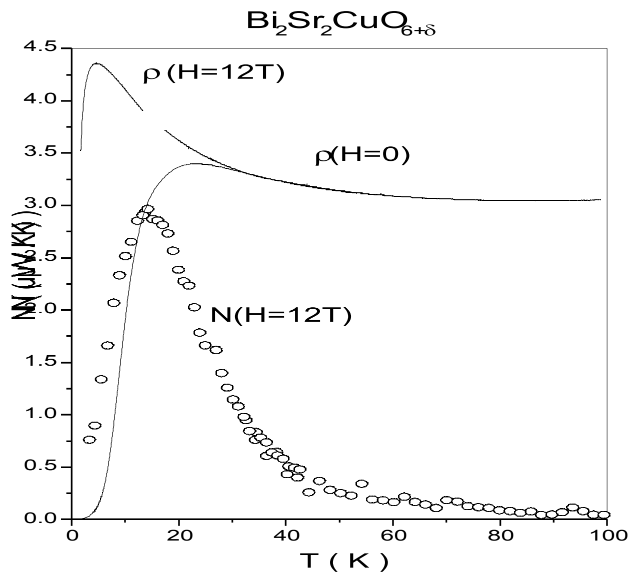


FIG. 3. Resistivity ρ (a) and normalized Nernst electric field $E_y/\nabla_x T$ (b) versus temperature for an epitaxial, c-axis-oriented $YBa_2Cu_3O_{7-\delta}$ film at different magnetic fields applied parallel to the c axis of the film.

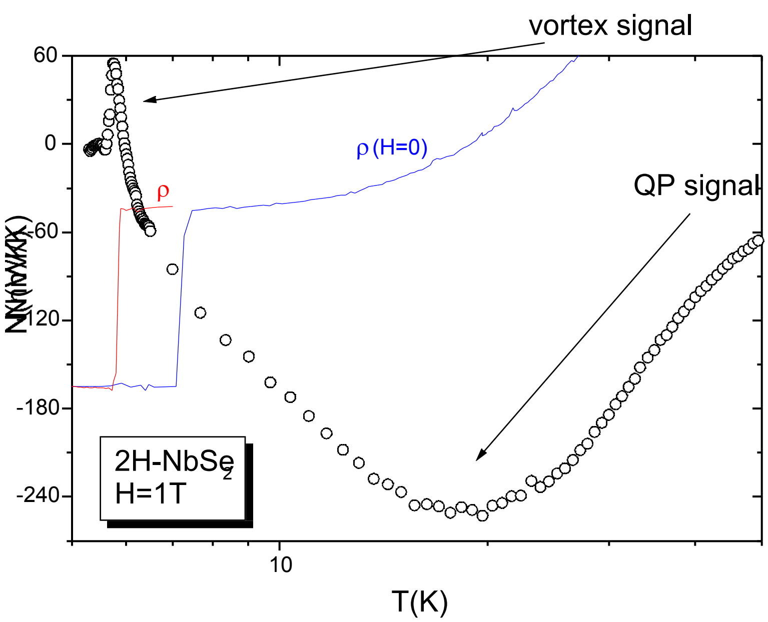
In underdoped cuprates Nernst coefficient remains finite for T>Tc

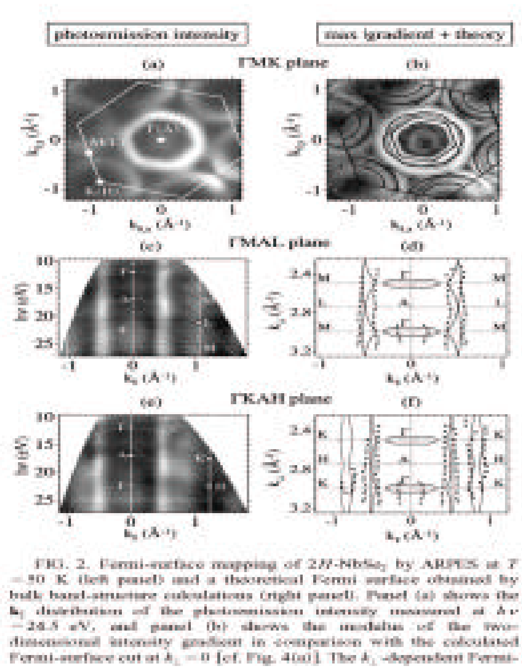




Vortex-like excitations in the Tc<T<T* window ? (First reported by Xu, Ong et al. Nature 406,486(2000))

A word of caution: the case of 2H-$NbSe_2$



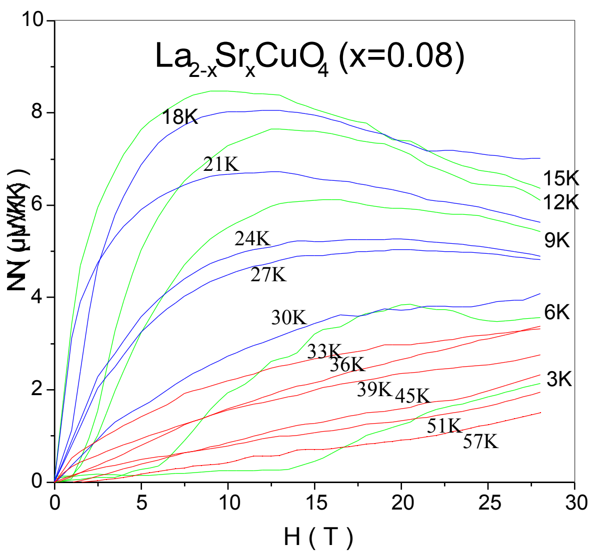


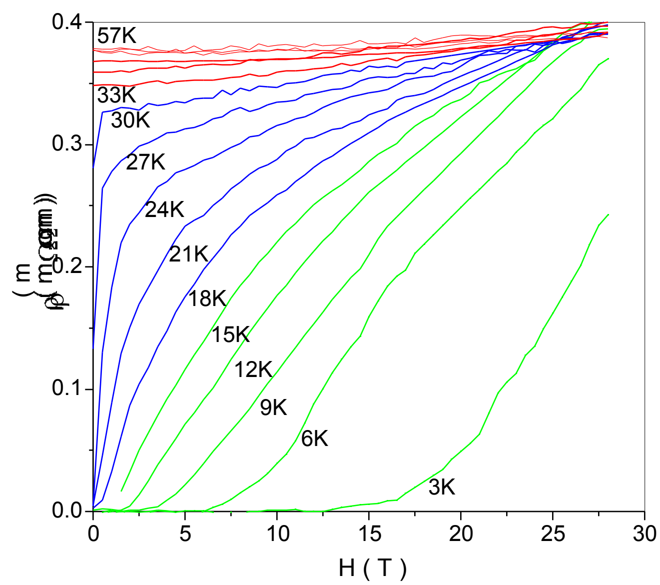
Complicated Fermi surface may lead to a sizeable qp Nernst signal of both signs!

Fermi surface

Rossnagel et al. PRB 64,235119 (2001)

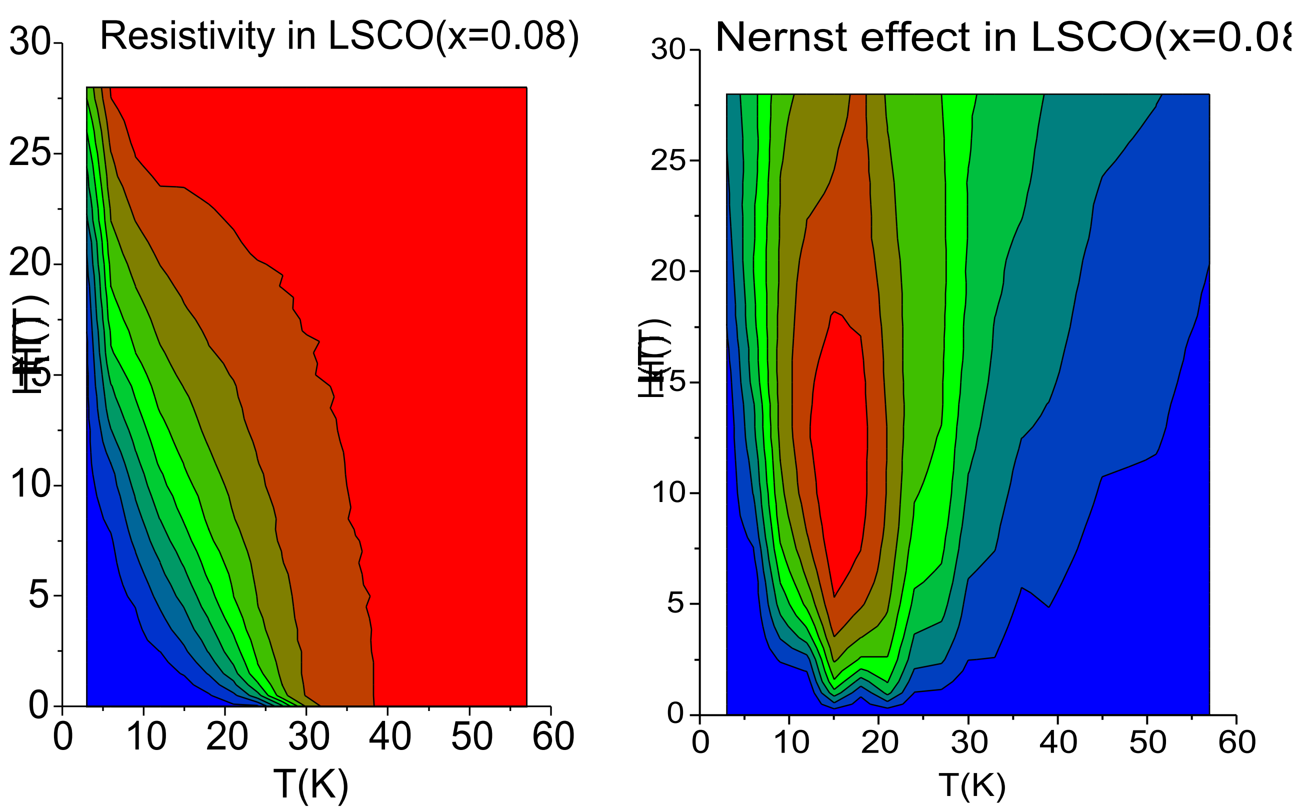
Field-dependence of the Nernst coefficient is highly non-linear!



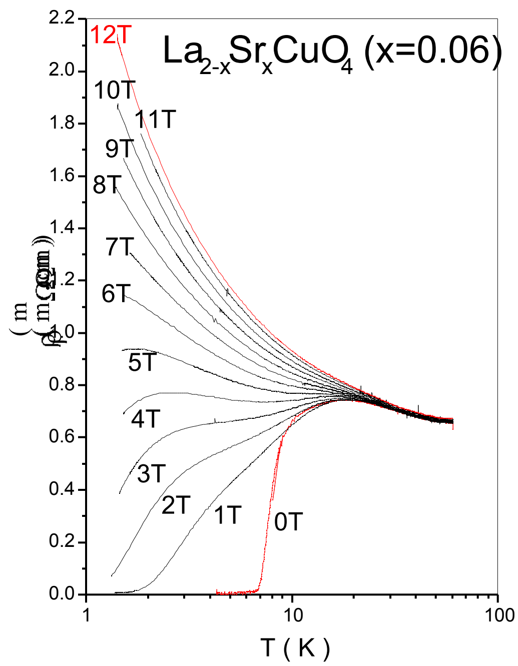


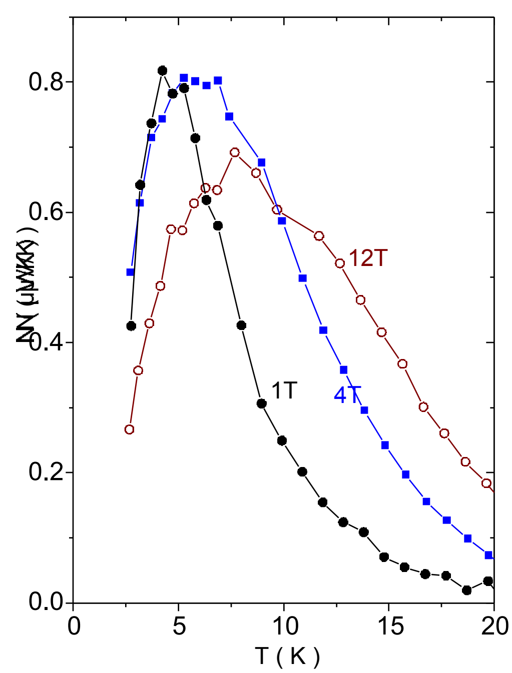
A finite Nernst signal persists at high fields even when resistivity displays localisation!

Two contrasting pictures of the destruction of superconductivity in a magnetic field!

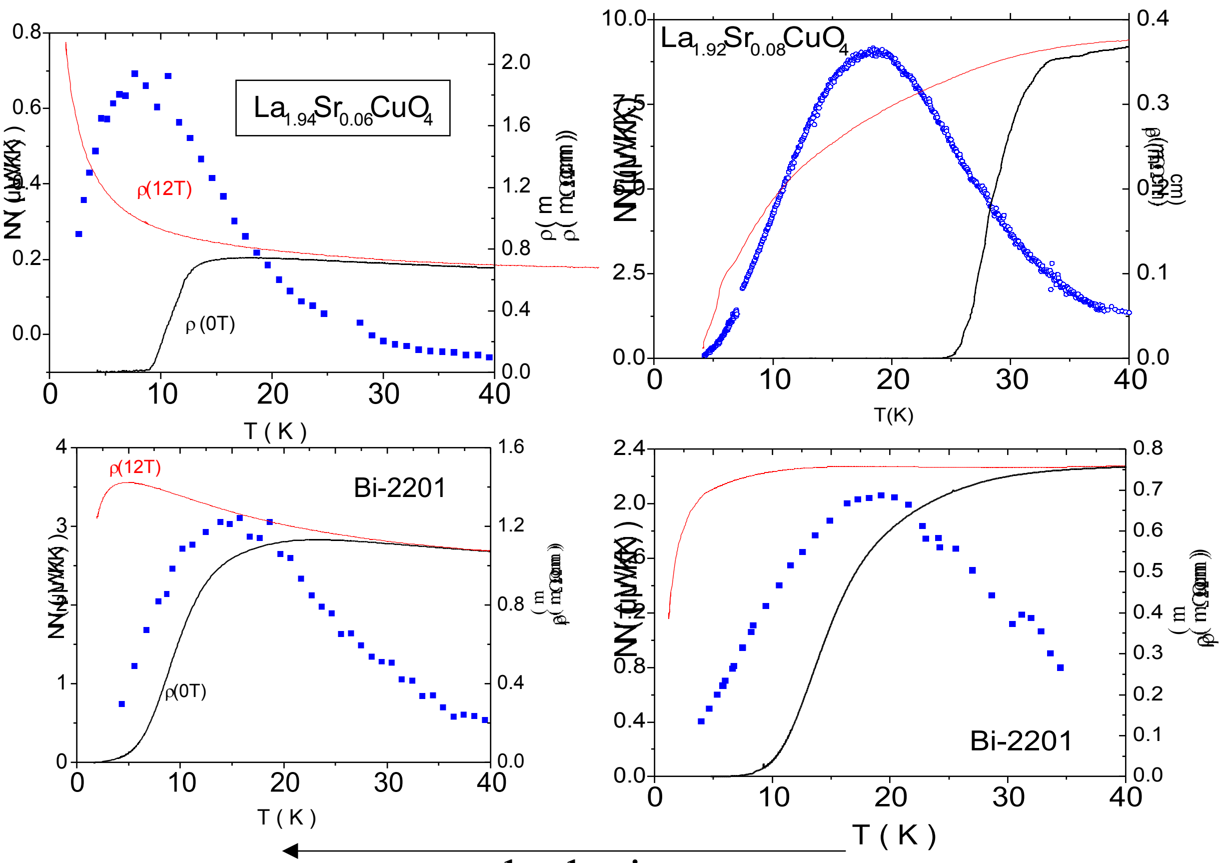


Field-induced superconductor-insulator transition and the Nernst effect

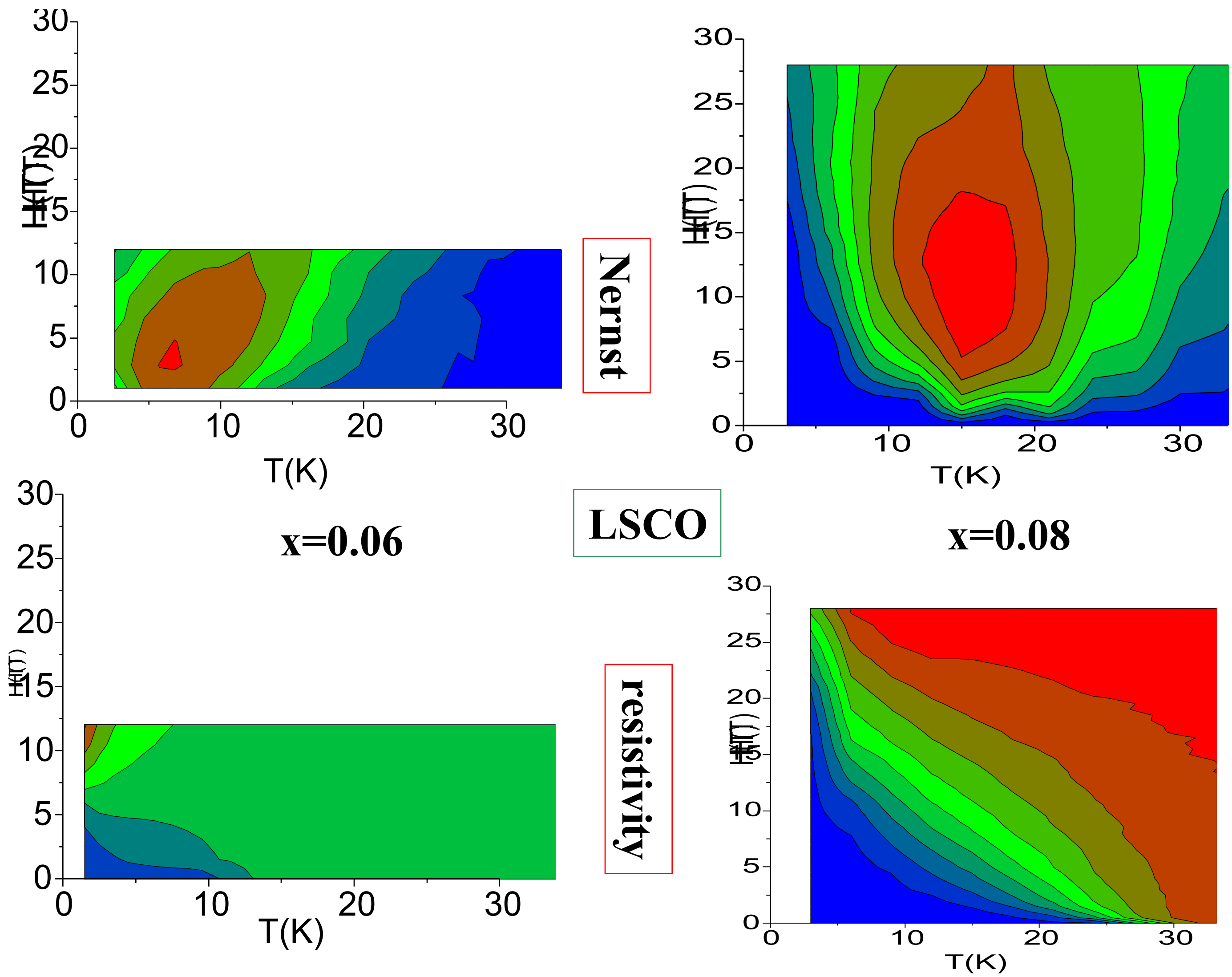


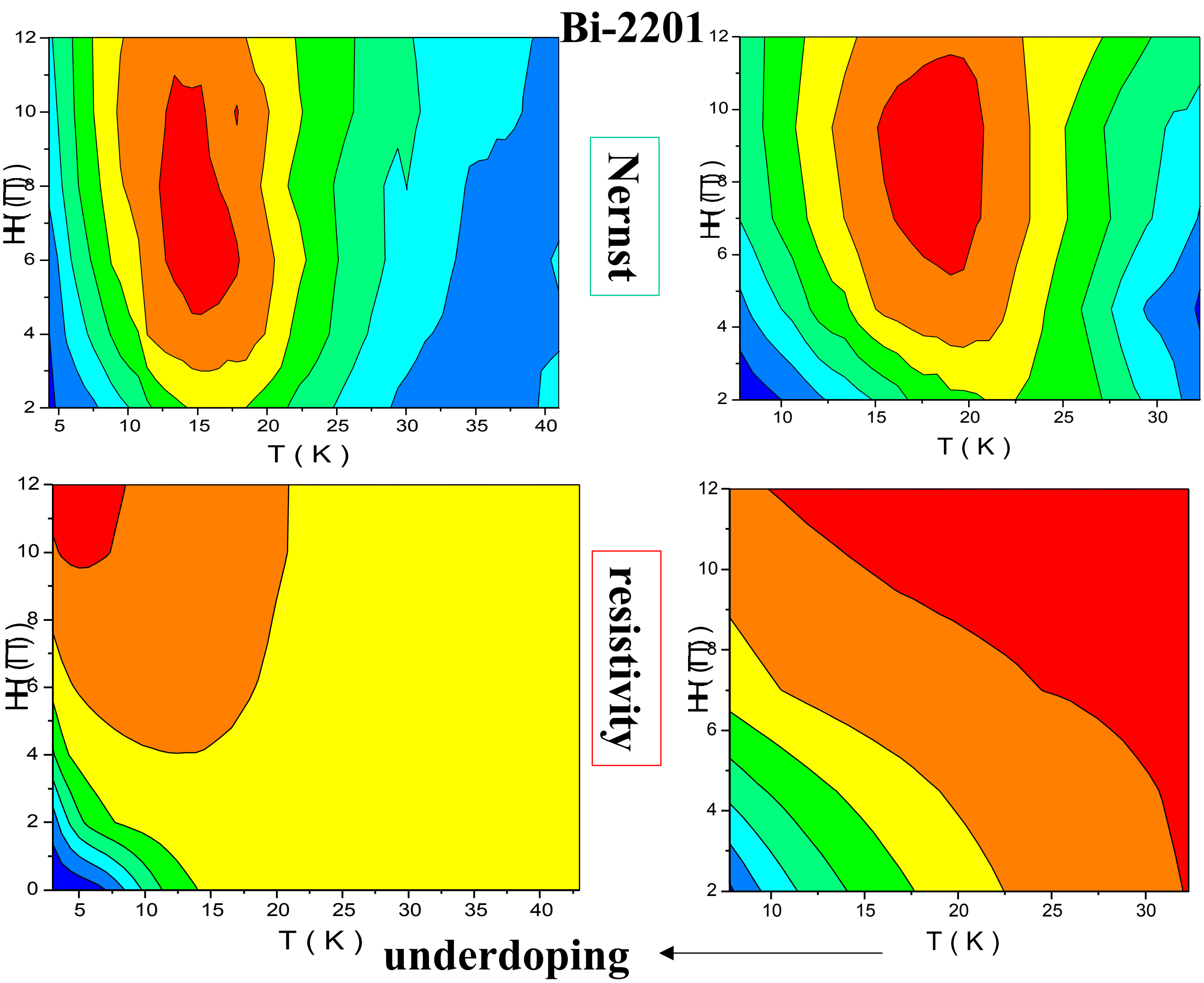


Evolution with increase in doping level at H=12T

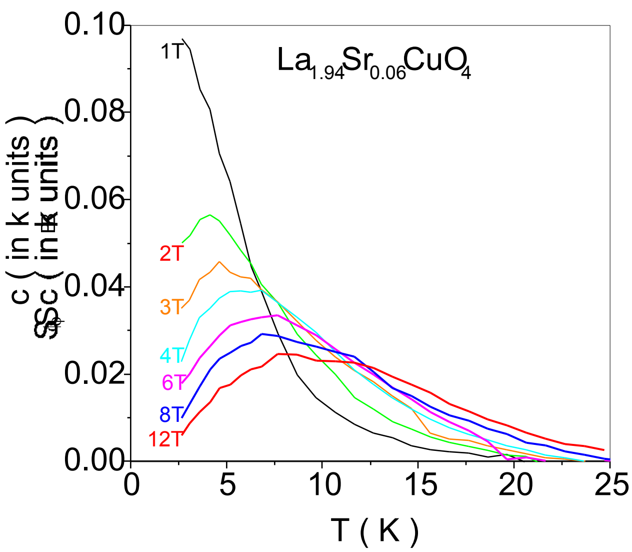


underdoping


Nernst
resistivity
LSCO
x=0.06
x=0.08
T(K)
T(K)
T(K)
T(K)


Bi-2201
Nernst
resistivity
underdoping
H (T)
T (K)

Transport entropy of vortices



For a thermal force :

$F_{th}=S_\phi \nabla T = \eta v$ & $E_y = vB$

$N = E_y / \nabla T = S_\phi B/ \eta$

For a Lorenz force:

$F_L = J\ \Phi_0 = \eta\ v$ & $E_x = vB$

$\rho = E_x/J = \Phi_0 B/ \eta$

Therefore: $S_\phi = N\Phi_0/ \rho$

is the excess of entropy associated with a single vortex **(Assuming that ρ is only due to flux flow!)**

In the extereme underdoped case, S_ϕ c is a fraction of k_B.
Two orders of magnitude smaller than in conventional superconductors!

$S_\phi = S_n - S_s = k_B(\ln\Omega_n - \Omega_s) = k_B\ln(\Omega_n/\Omega_s)$ (Ω_n/Ω_s) is not much larger than unity!

Recent scenarios proposed to for a Nernst signal in an extended region of the (H,T) phase diagram

•**Tesanavic, Vafek & Franz**, PRB 65, 180511 (2002), *Chiral symmetry breaking*

•**Weng & Muthukumur**, cond-mat/ 0202079, *Spontaneous vortices in RVB picture*

•**Ussishkin, Sondhi & Huse**, cond-mat/0204484, *Superconducting Gauusian fluctuations*

•**Kontani**, cond-mat/0204193, *AF fluctuations (No vortices)*

•**Ikeda**, cond-mat/0203221, *Quantum fluctuations due near the field-induced Superconductor-insulator Quantum Critical Point*

Address the question of discrepancy between ρ(H,T) and N(H,T)!

Fisher '90

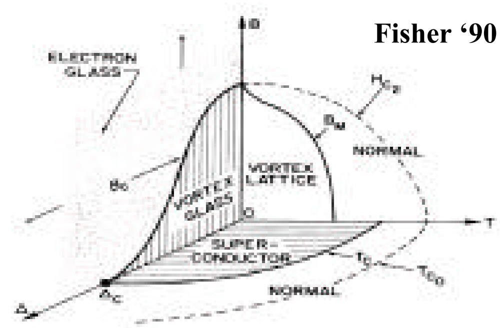


FIG. 1. Schematic phase diagram for disordered superconducting films. *Distinct* $T=0$ superconductor-insulator transitions occur at both critical disorder Δ_c *and* critical magnetic field B_c.

Summary

• In underdoped cuprates, a Nernst signal persists in an extended domain of the (H,T) plane

•Superconductivity seems to survive at high fields even in presence of a non-metallic resistivity

• The magnitude of extracted transport entropy in the underdoped regime is particularly small compared with conventional superconductors