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New signatures of the pseudogap phase of cuprate superconductors

Louis Taillefer

Université de Sherbrooke

Aspen Center for Physics, 9 March 2020

GORDON AND BETTY MOORE FOUNDATION

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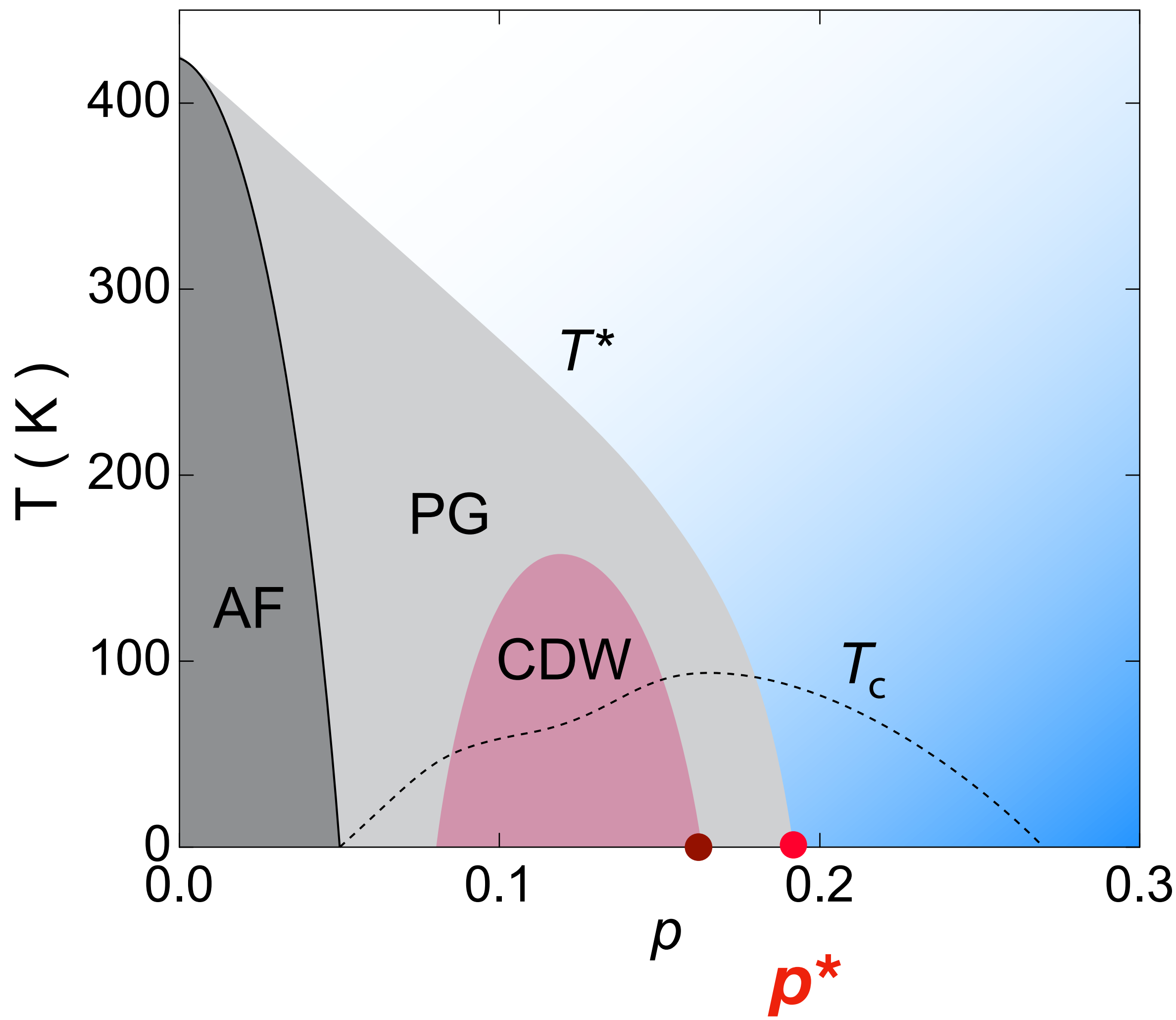
Taillefer Group

Université de Sherbrooke

Central puzzle : nature of pseudogap phase



Proust & Taillefer, Annual Reviews of CMP **10**, 409 (2019); arXiv:1807.05074

Main findings

1) Drop in carrier density — Badoux *et al*., Nature **531**, 210 (2016)

2) Fermi surface via ADMR — with Brad Ramshaw

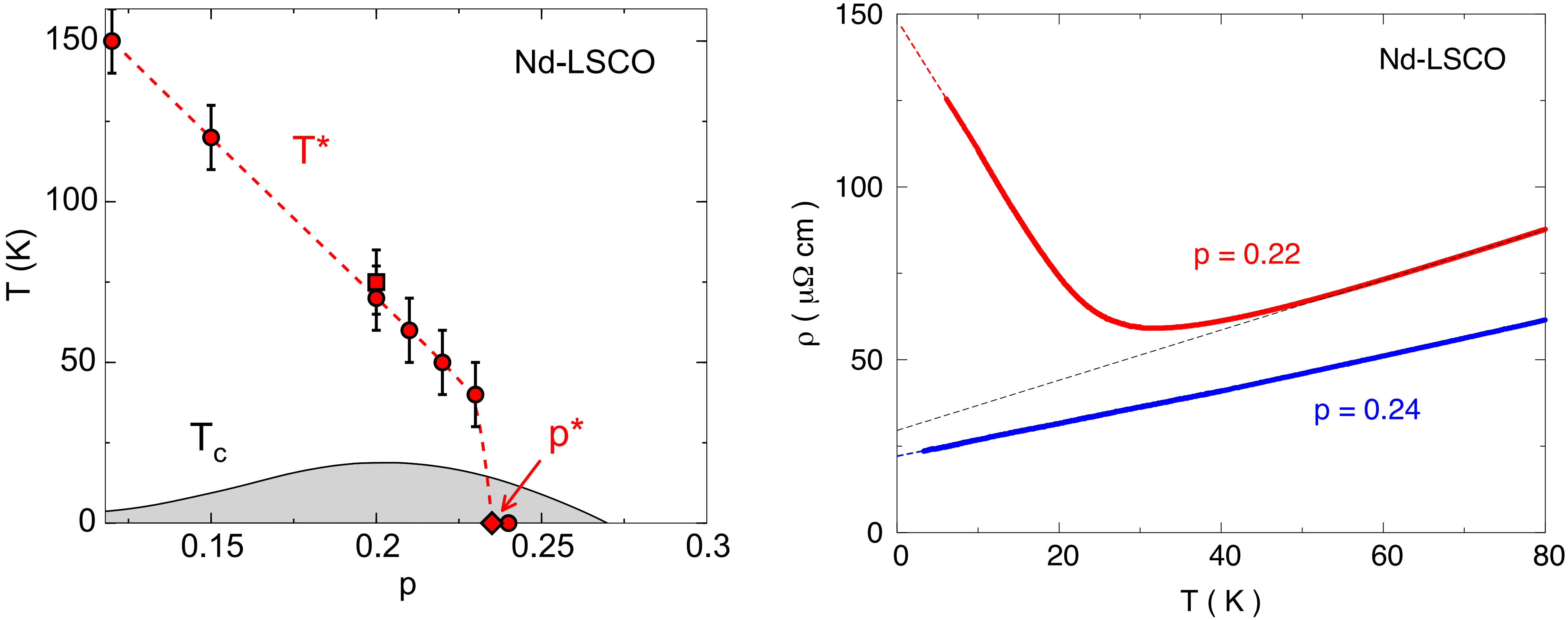
3) Planckian dissipation — Legros *et al*., Nature Physics **15**, 142 (2019)

4) Limit on QCP — Doiron-Leyraud *et al*., Nature Comm. **8**, 2044 (2017)

5) Giant thermal Hall signal — Grissonnanche *et al*., Nature **571**, 376 (2019)

Nd-LSCO

Linear-*T* resistivity & upturn

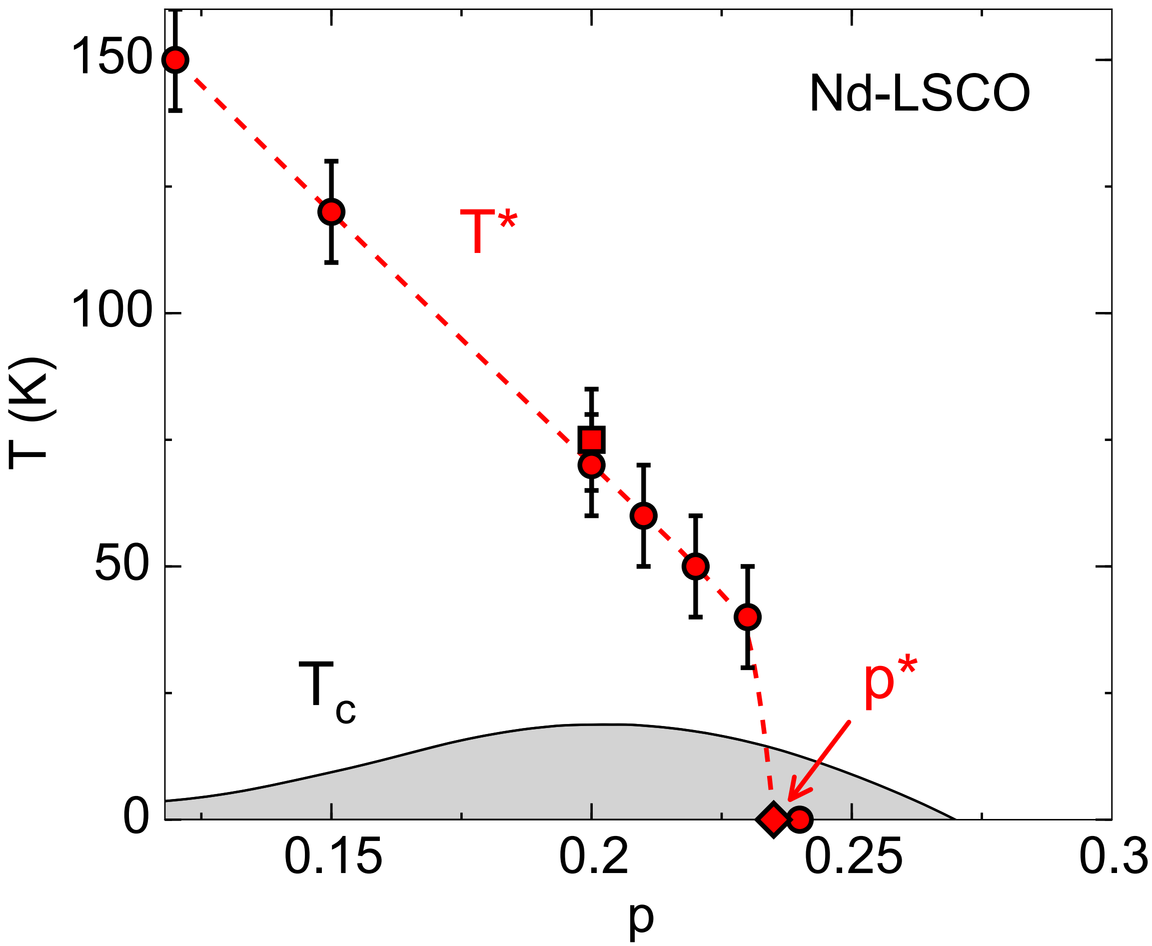


Collignon *et al.*, PRB **95**, 224517 (2017)

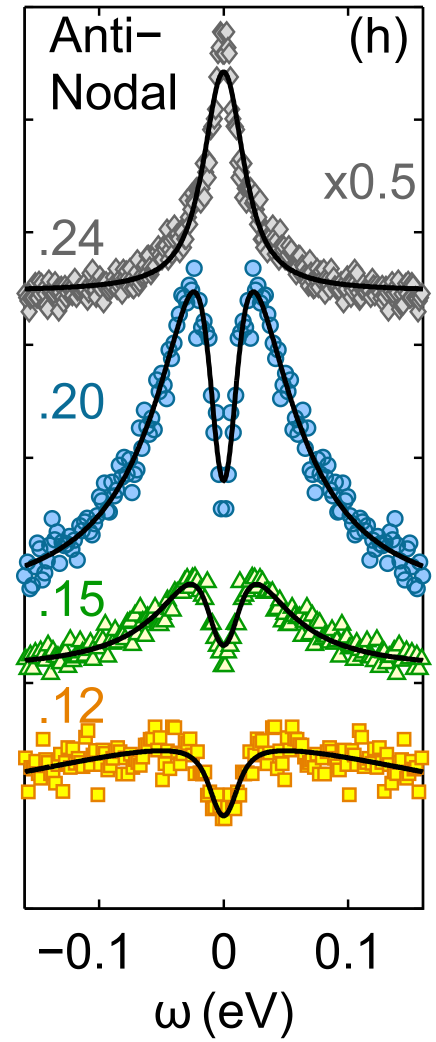
Daou *et al.*, Nature Physics **5**, 31 (2009)

Nd-LSCO

ARPES



ARPES



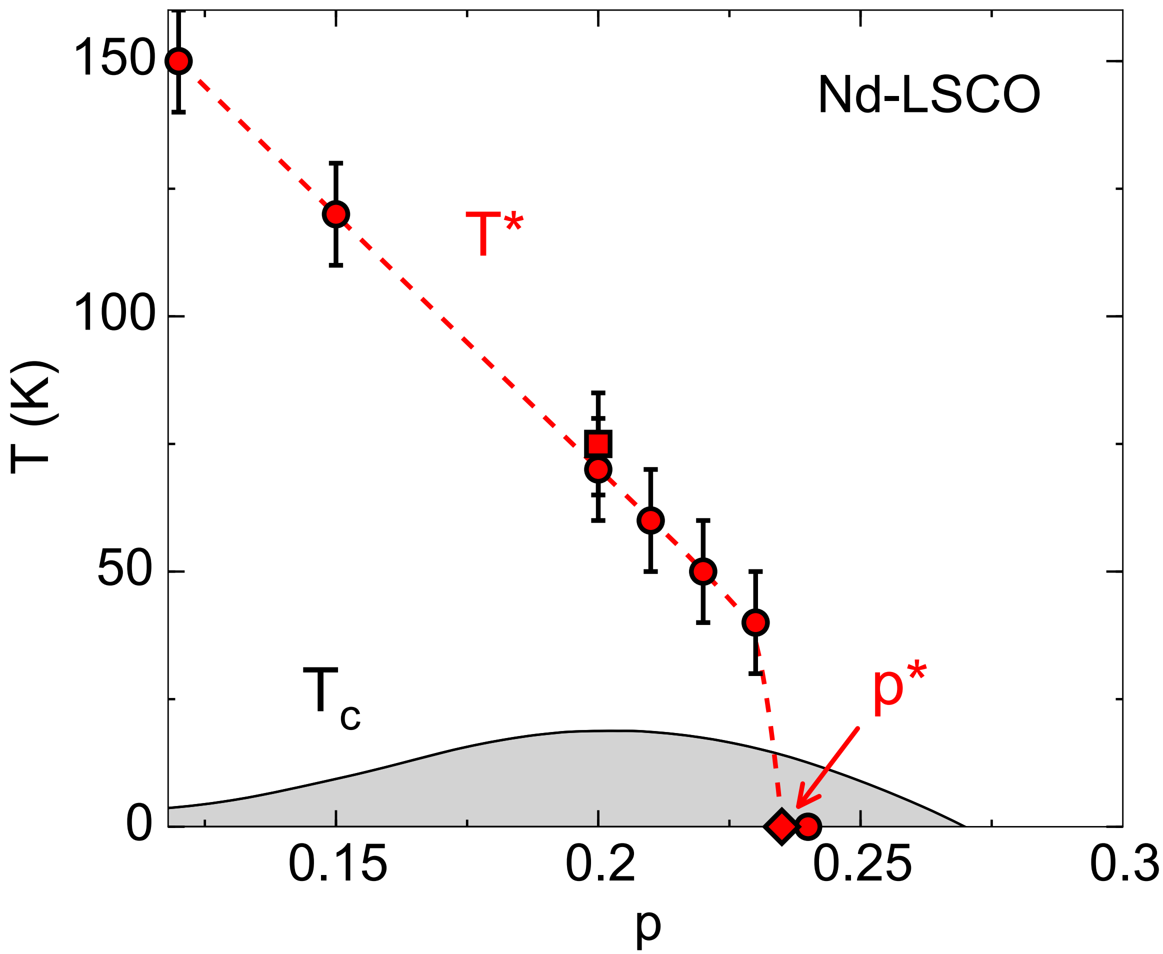
Collignon *et al.*, PRB **95**, 224517 (2017)

Daou *et al.*, Nature Physics **5**, 31 (2009)

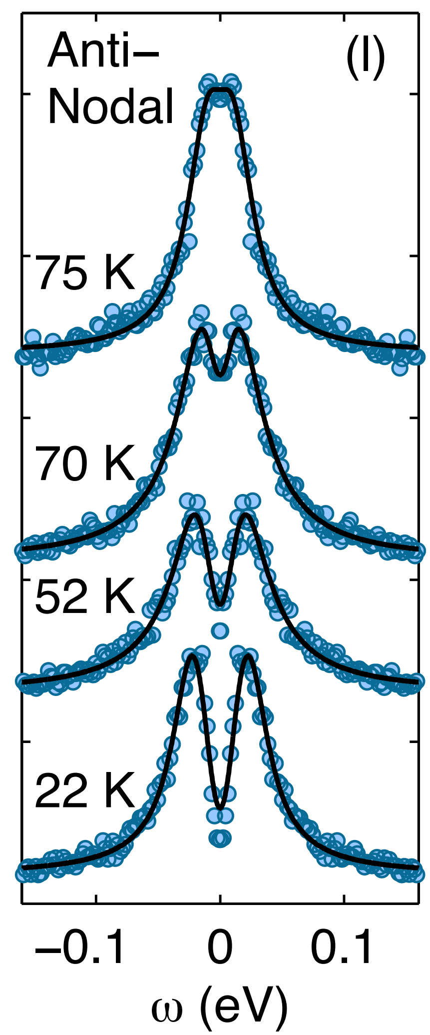
Matt *et al.*, PRB **92**, 134524 (2015)

Nd-LSCO

ARPES



ARPES

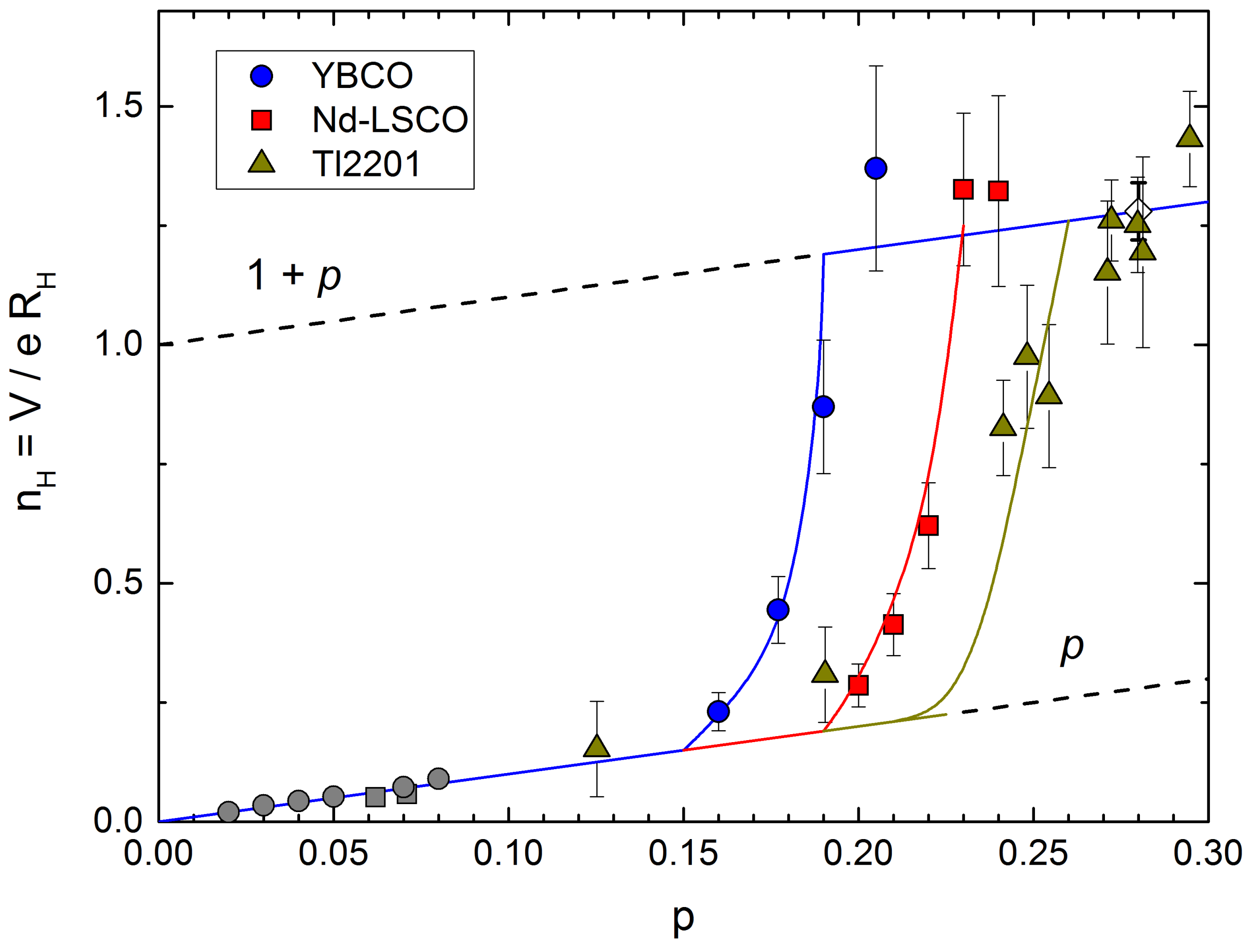


Collignon *et al.*, PRB **95**, 224517 (2017)

Daou *et al.*, Nature Physics **5**, 31 (2009)

Matt *et al.*, PRB **92**, 134524 (2015)

Hall number in cuprates



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

Putzke *et al.*, arXiv:1909.08102 (2019)

Collignon *et al.*, PRB **95**, 224517 (2017)

SIGNATURES OF THE PSEUDOGAP PHASE

1) Carrier density $\boldsymbol{n = 1 + p}$ —> $\boldsymbol{n = p}$ ***Generic***

Fermi surface transformation across the pseudogap critical point

CORNELL

Y. Fang
B. Ramshaw

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G. Grissonnanche
F. Laliberté
A. Legros
S. Verret
L. Taillefer

WARRICK

P. Goddard

NHMFL

D. Graf

TEXAS

J.-S. Zhou

ADMR

Nd-LSCO

Gaël Grissonnanche

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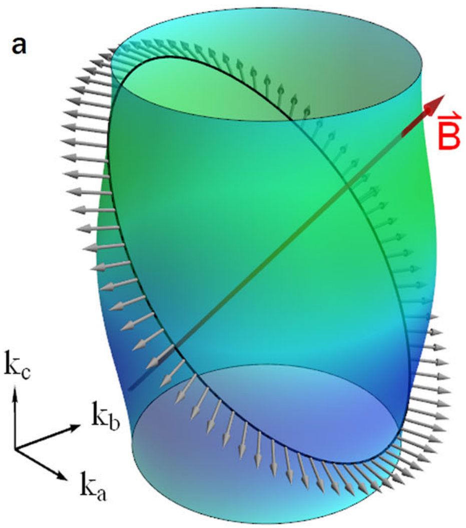
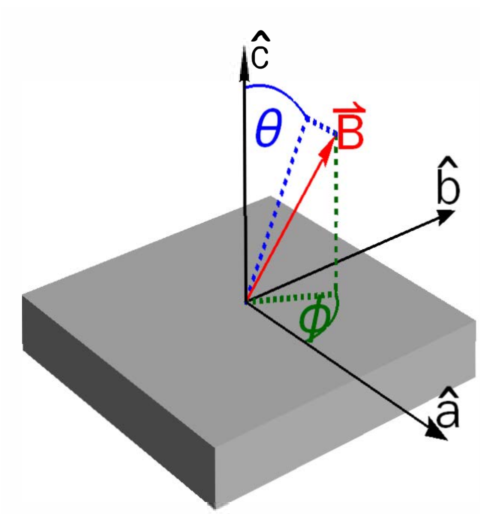
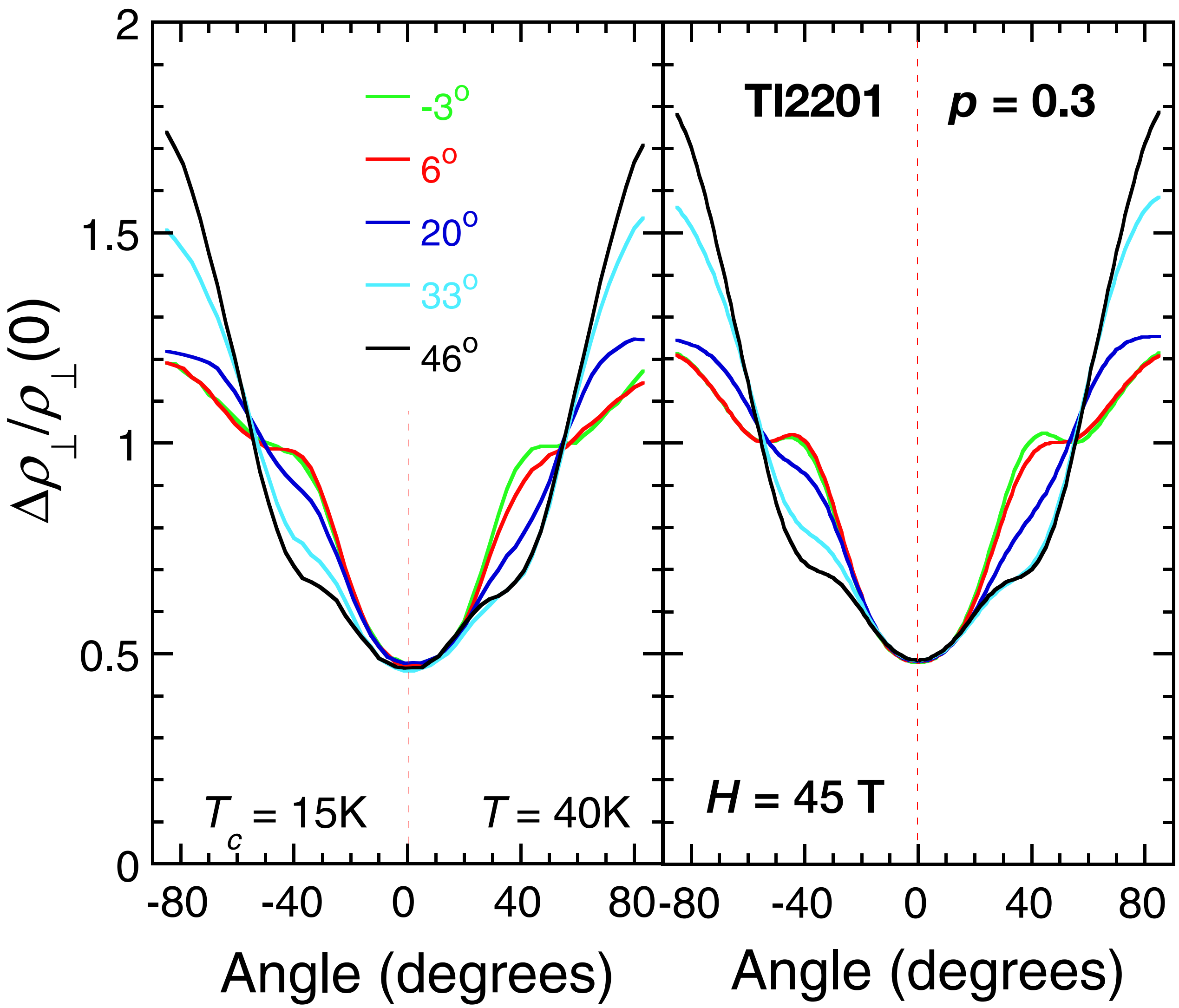
Angle-dependent magneto-resistance (ADMR)

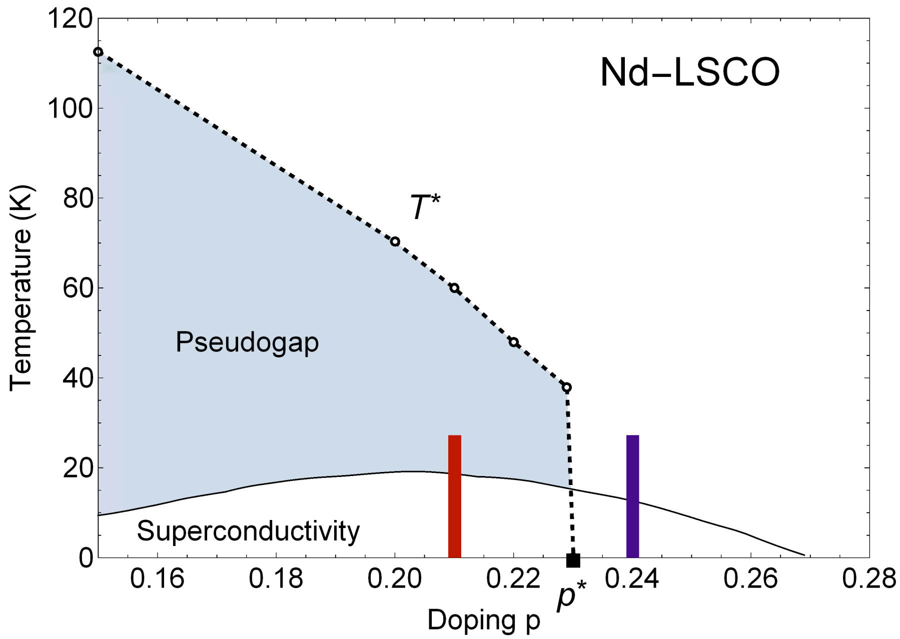
Hussey *et al.*, Nature **425**, 814 (2003)

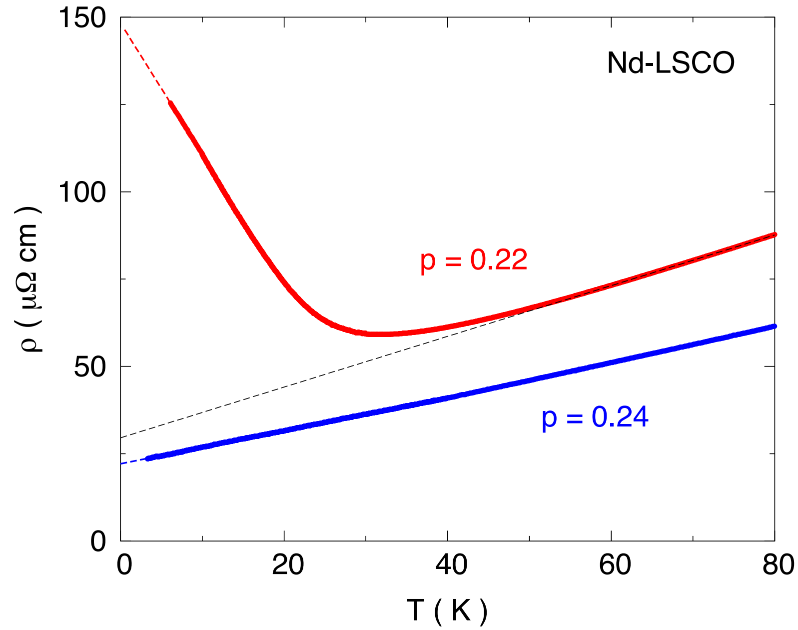






ADMR in Nd-LSCO





Our preprint will be posted soon !

UNIVERSITÉ DE SHERBROOKE

M. Lizaire

A. Legros

L. Taillefer

LNCMI

S. Benhabib

W. Tabis

B. Vignolle

C. Proust

LPS Orsay

H. Raffy

CEA Saclay

A. Forget

D. Colson

Anaëlle Legros

Legros *et al.*, Nature Physics **15**, 142 (2019)

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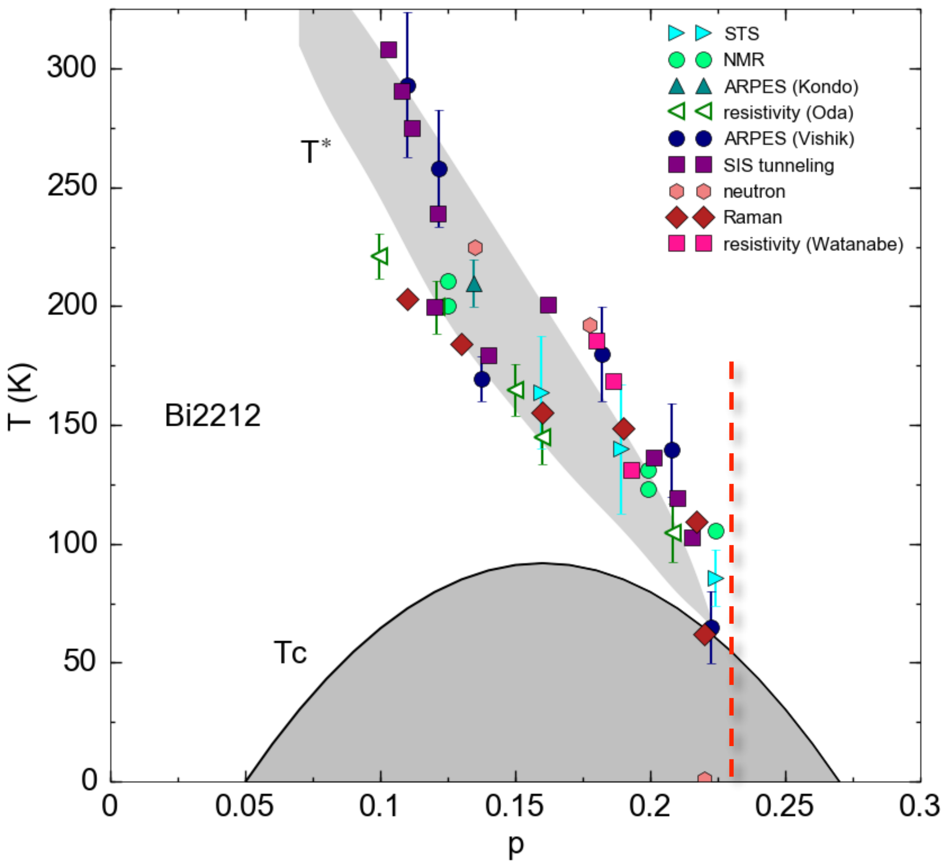
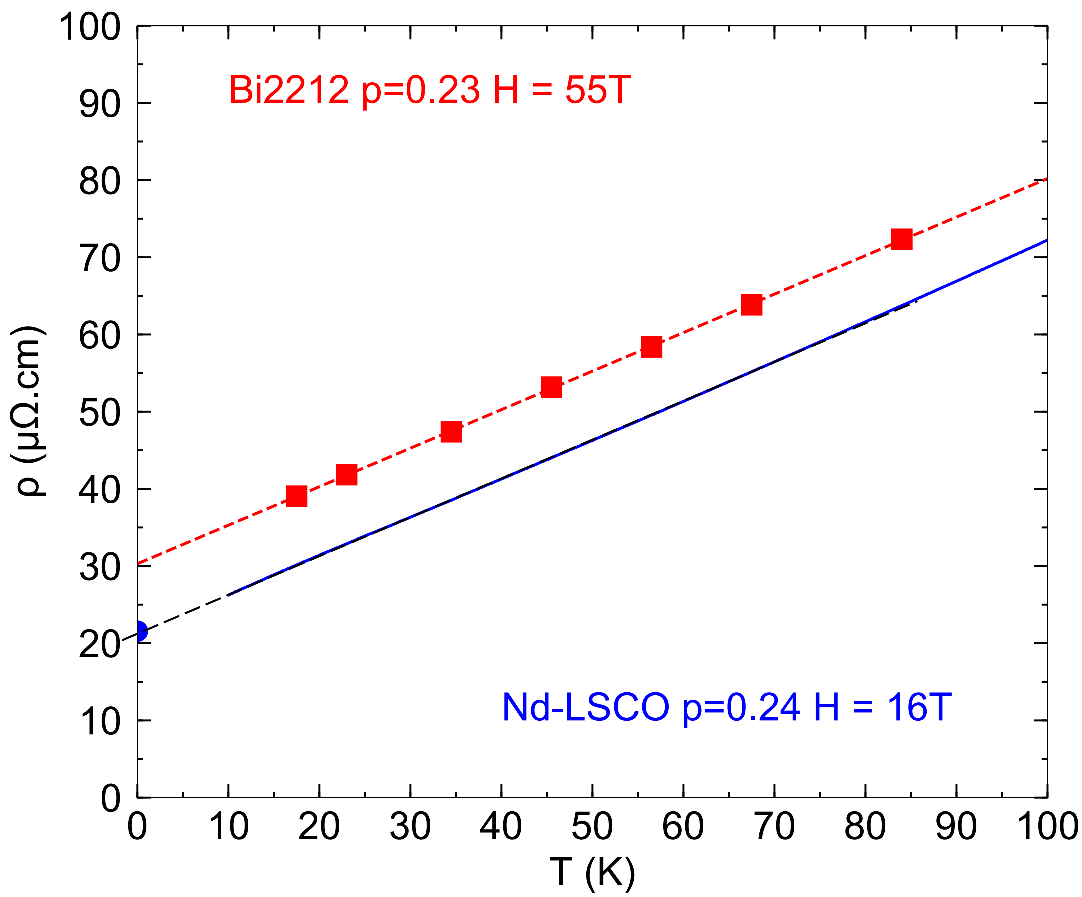
Bi2212

Phase diagram



Vishik *et al.*, PNAS **109**, 18332 (2012)

Resistivity



Legros *et al.*, Nature Physics **15**, 142 (2019)

Collignon *et al.*, PRB **95**, 224517 (2017)

Planckian dissipation

$$\rho(T) = \rho_0 + A_1 T, \qquad \rho = (m^* / n e^2)(1/\tau)$$

$$A_1 = (m^* / n e^2)(1/\tau)(1/T) = \alpha\,(m^*/n)(k_B / e^2 \hbar), \text{ with } \hbar/\tau \equiv \alpha\, k_B T.$$

Planckian limit : $\alpha \simeq 0.7 - 1.2$

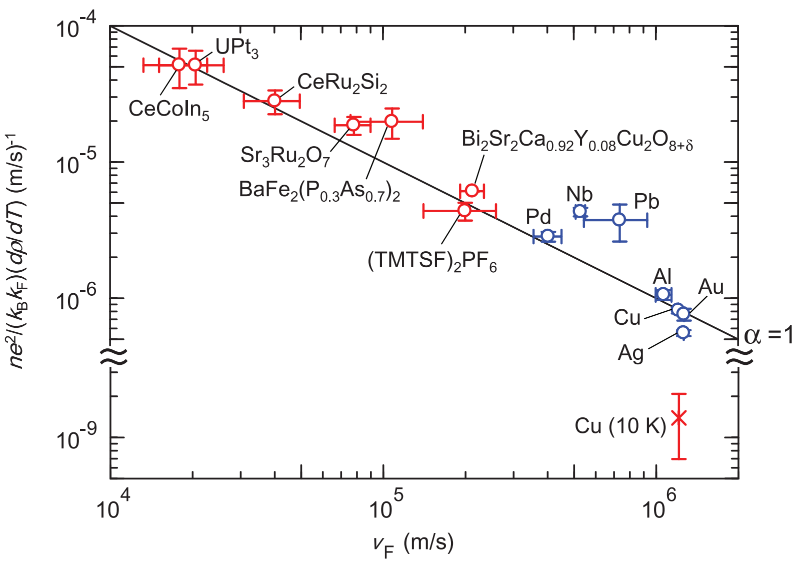


Table 1 | Slope of *T*-linear resistivity and Planckian limit in seven materials.

Material		n (10^{27} m^{-3})	m^* (m_0)	A_1/d (Ω / K)	$h/(2e^2 T_F)$ (Ω / K)	α
Bi2212	$p = 0.23$	6.8	8.4 ± 1.6	8.0 ± 0.9	7.4 ± 1.4	1.1 ± 0.3
Bi2201	$p \sim 0.4$	3.5	7 ± 1.5	8 ± 2	8 ± 2	1.0 ± 0.4
LSCO	$p = 0.26$	7.8	9.8 ± 1.7	8.2 ± 1.0	8.9 ± 1.8	0.9 ± 0.3
Nd-LSCO	$p = 0.24$	7.9	12 ± 4	7.4 ± 0.8	10.6 ± 3.7	0.7 ± 0.4
PCCO	$x = 0.17$	8.8	2.4 ± 0.1	1.7 ± 0.3	2.1 ± 0.1	0.8 ± 0.2
LCCO	$x = 0.15$	9.0	3.0 ± 0.3	3.0 ± 0.45	2.6 ± 0.3	1.2 ± 0.3
TMTSF	$P = 11$ kbar	1.4	1.15 ± 0.2	2.8 ± 0.3	2.8 ± 0.4	1.0 ± 0.3

Bruin *et al.*, Science **339**, 804 (2013)

Legros *et al.*, Nature Physics **15**, 142 (2019)

SIGNATURES OF THE PSEUDOGAP PHASE

1) Carrier density — ***$n = 1 + p$ —> $n = p$*** — ***Generic***

2) Resistivity — ***T - linear as T —> 0*** — ***Generic***

Planckian limit

SIGNATURES OF THE PSEUDOGAP PHASE

1) Carrier density — ***$n = 1 + p$ —> $n = p$*** — ***Generic***

2) Resistivity — **T - linear as T —> 0** — ***Generic***

Planckian limit

3) ADMR — **Fermi surface changes at p^***

$p = 0.24$ excellent agreement with large ARPES Fermi surface

$p = 0.21$ consistent with small nodal hole Fermi pockets

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T. Klein

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C. Marcenat

Michon *et al*., Nature **567**, 218 (2019)

Eu/Nd-LSCO

Specific heat

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Tokyo

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McMaster

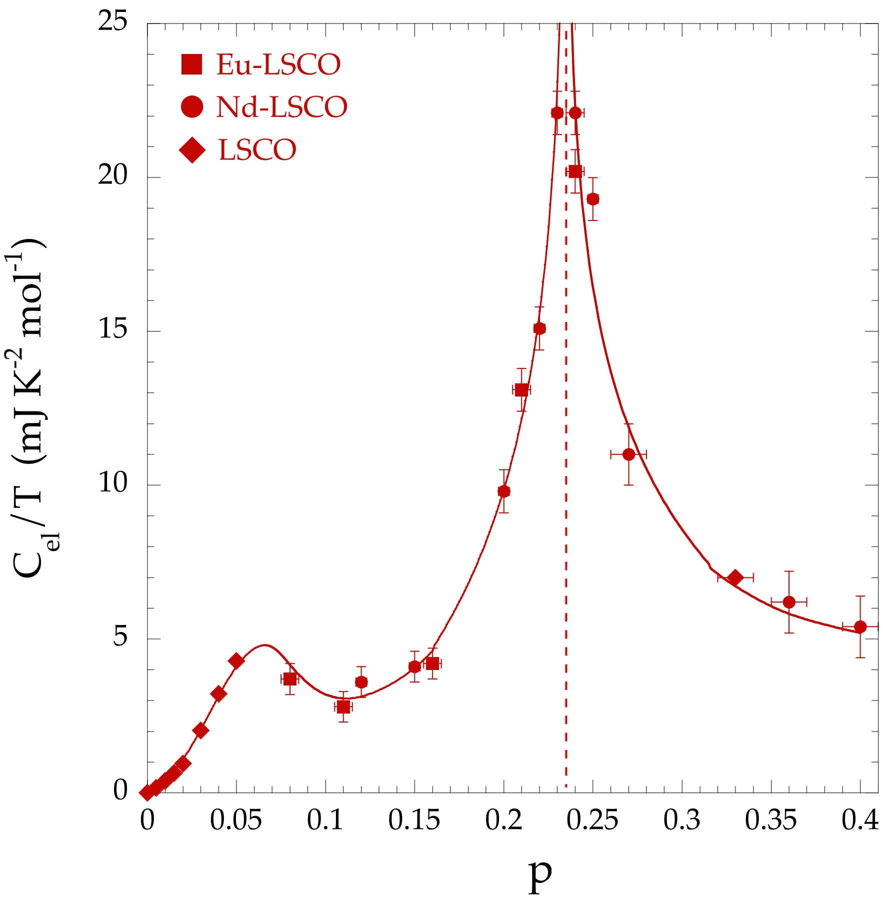
K. Ma

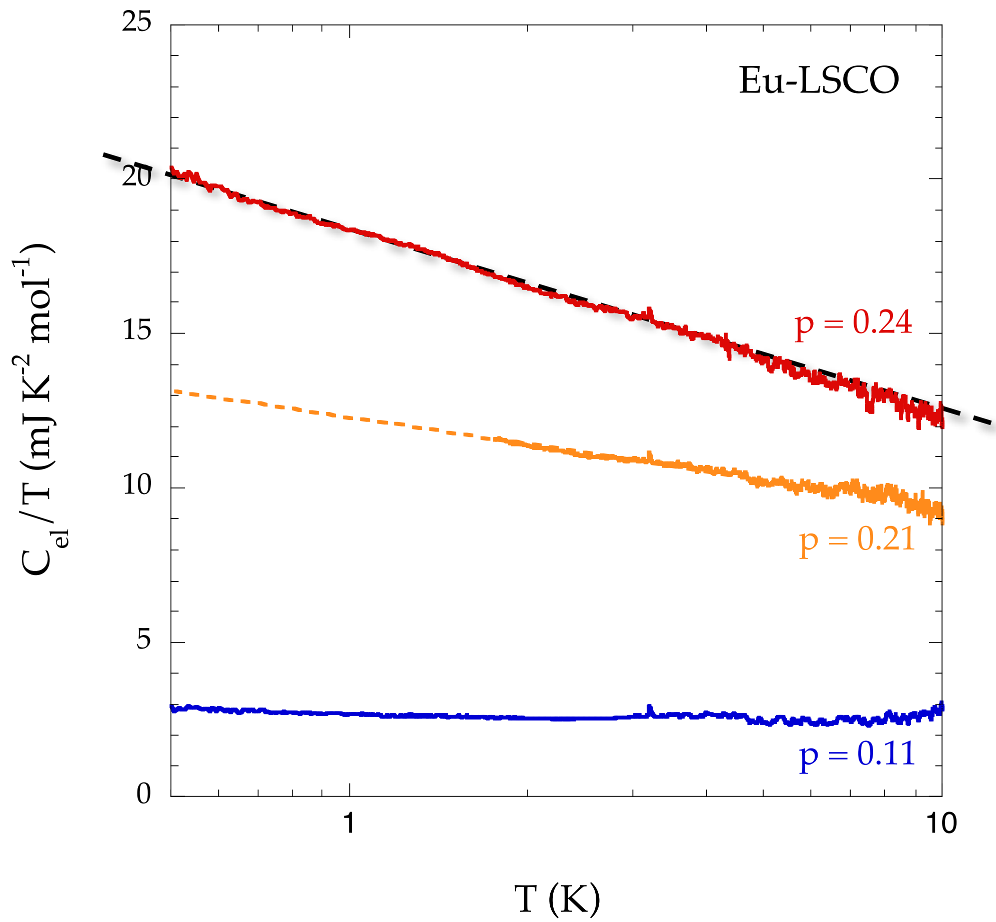
M. Dragomir

H. Dabowska

B. Gaulin

Two thermodynamic signatures of quantum criticality in cuprates





LSCO : Nakamae *et al.*, PRB **68**, 100502 (2003)
Komiya *et al.*, J. Phys. **150**, 052118 (2009)

$C / T \sim -\log(T)$

Michon *et al.*, Nature **567**, 218 (2019)

SIGNATURES OF THE PSEUDOGAP PHASE

1) Carrier density — ***$n = 1 + p$ —> $n = p$*** — ***Generic***

2) Resistivity — ***T* - linear as *T* —> 0** — ***Generic***

Planckian limit

3) ADMR — **Fermi surface changes at *p^****

4) Specific heat — ***C / T* peaks at *p^****

C / T* ~ log(1/*T*) , at *p^*

nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-017-02122-x OPEN

Pseudogap phase of cuprate superconductors confined by Fermi surface topology

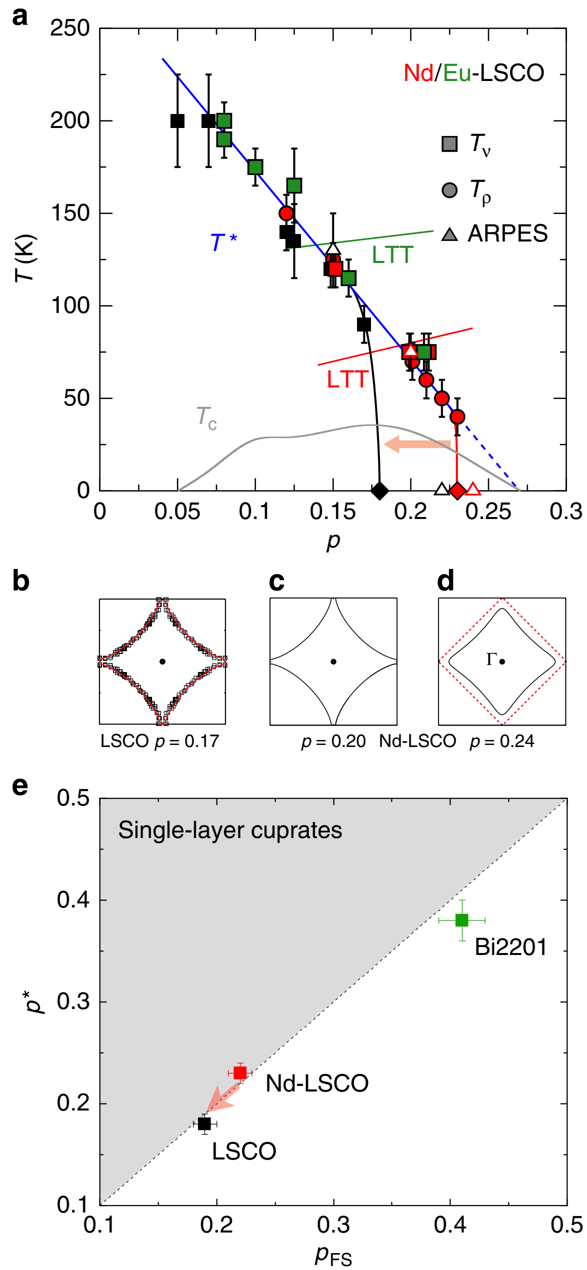
N. Doiron-Leyraud[1], O. Cyr-Choinière[1], S. Badoux[1], A. Ataei[1], C. Collignon[1], A. Gourgout[1], S. Dufour-Beauséjour[1], F.F. Tafti[1], F. Laliberté[1], M.-E. Boulanger[1], M. Matusiak[1,2], D. Graf[3], M. Kim[4,5], J.-S. Zhou[6], N. Momono[7], T. Kurosawa[8], H. Takagi[9] & Louis Taillefer[1,10]

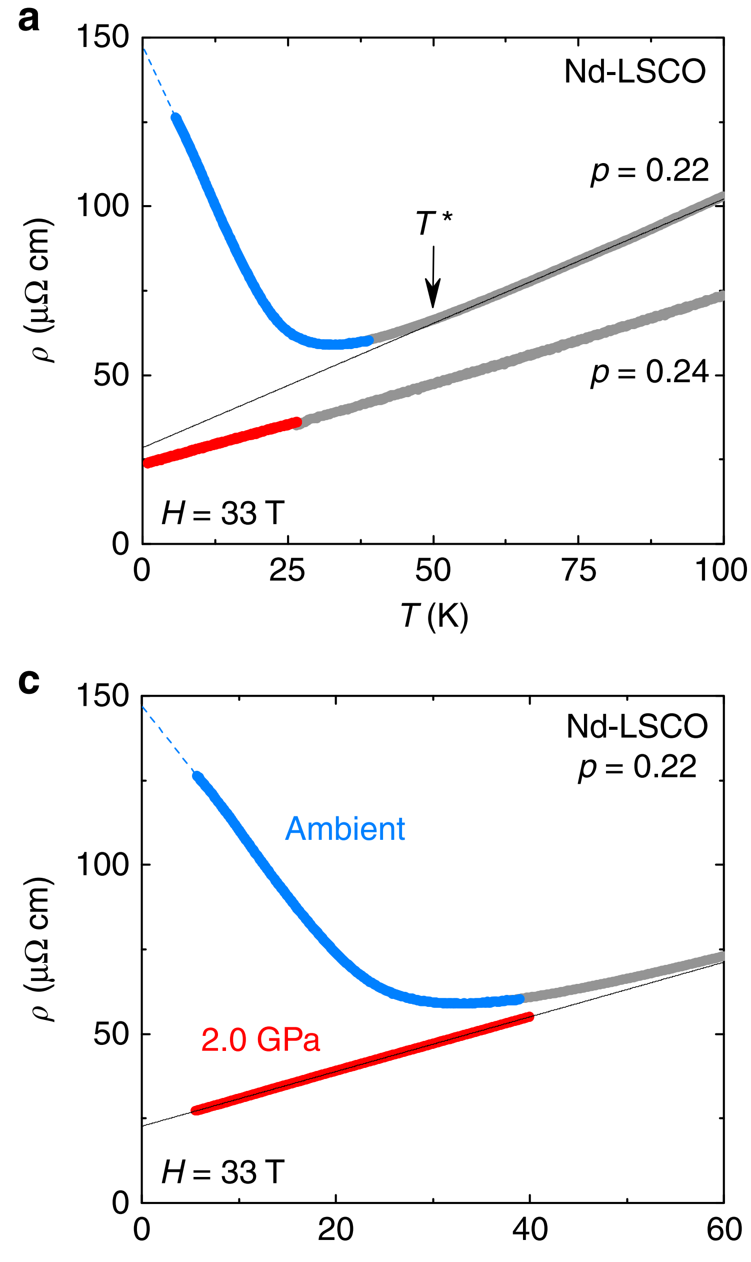
PHYSICAL REVIEW X **8,** 021048 (2018)

Pseudogap and Fermi-Surface Topology in the Two-Dimensional Hubbard Model

Wei Wu,[1,2] Mathias S. Scheurer,[3] Shubhayu Chatterjee,[3] Subir Sachdev,[3,4,5] Antoine Georges,[2,6,1,7] and Michel Ferrero[1,2]

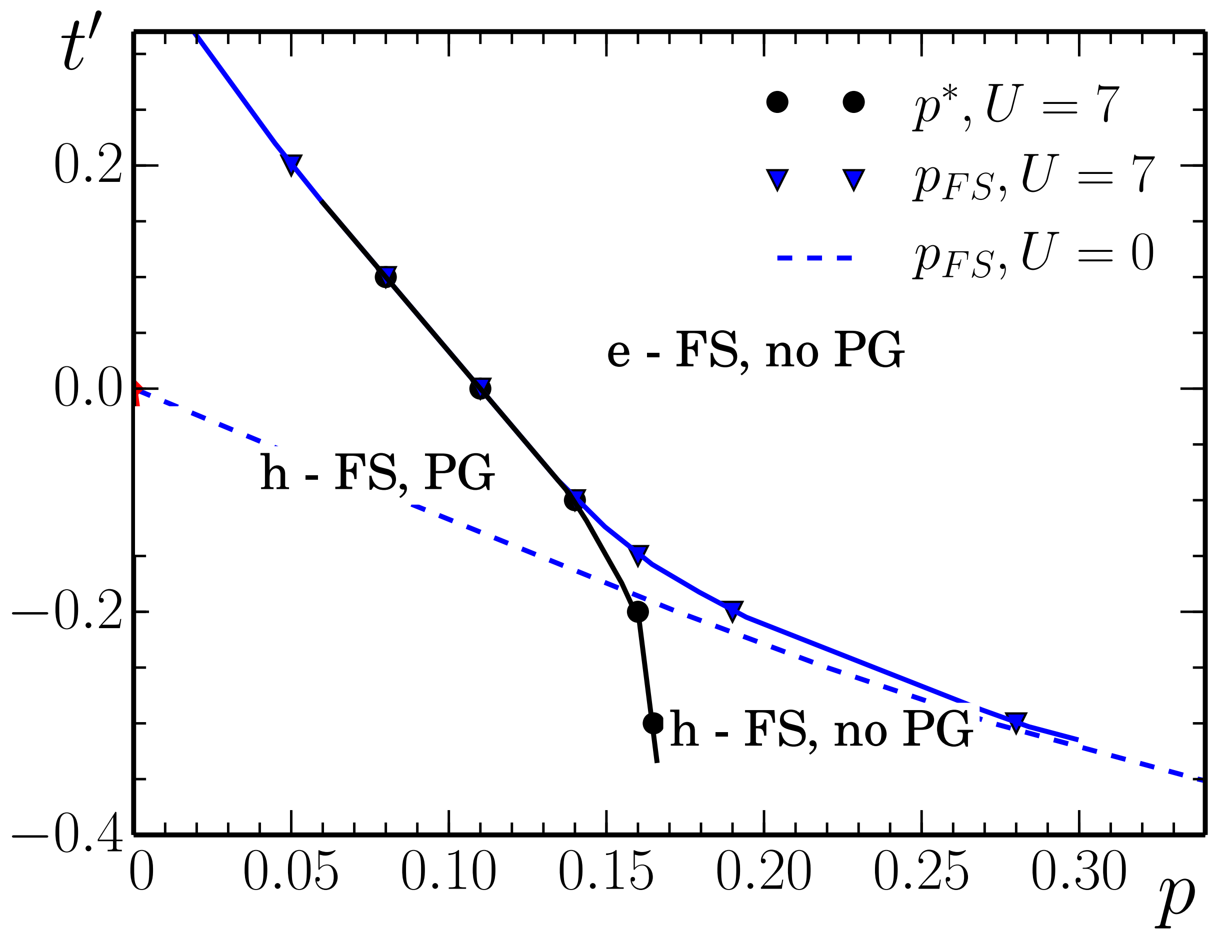
EXPERIMENT — Pseudogap phase confined by Fermi surface topology





Doiron-Leyraud *et al.*, Nature Comm. **8**, 2044 (2017)

THEORY — Pseudogap phase confined by Fermi surface topology



Wu *et al.*, PRX **8**, 021048 (2018)

SIGNATURES OF THE PSEUDOGAP PHASE

1) Carrier density	$n = 1 + p$ —> $n = p$	***Generic***
2) Resistivity	T **- linear as** T **—> 0**	***Generic***
	Planckian limit	
3) ADMR	**Fermi surface changes at** p^*	
4) Limit on QCP	p^* **< van Hove point**	***Generic***

Giant thermal Hall conductivity in the pseudogap phase of cuprates

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H. Takagi

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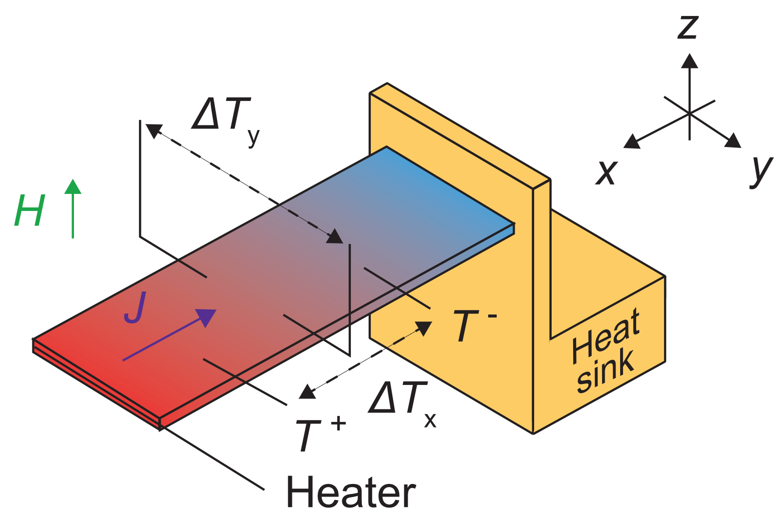
S. Ono

Grissonnanche *et al.*, Nature **571**, 376 (2019)

Measurement of the thermal Hall effect



Technical checks

Heat sink : Cu or LiF

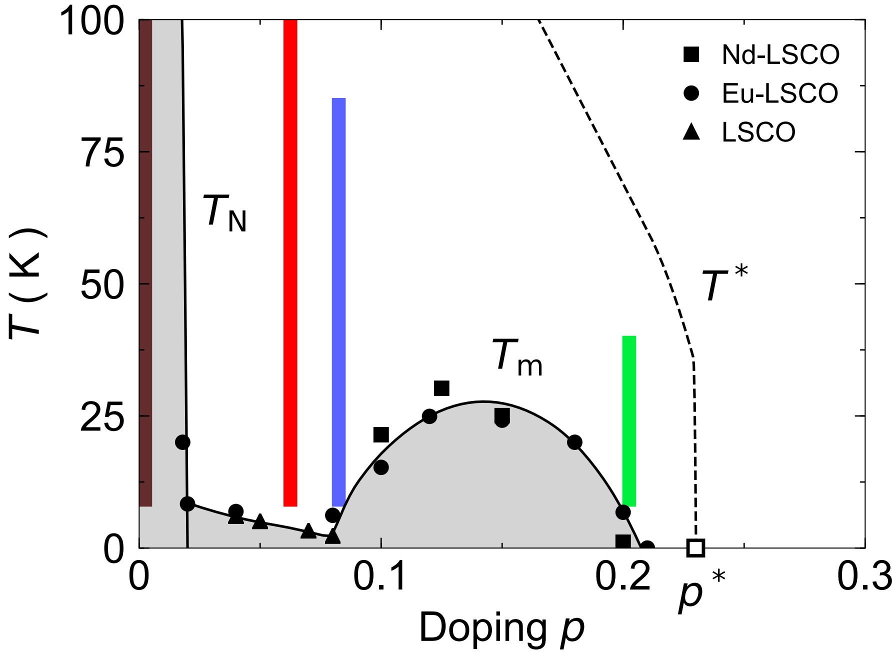
Thermometry : TC or sensors

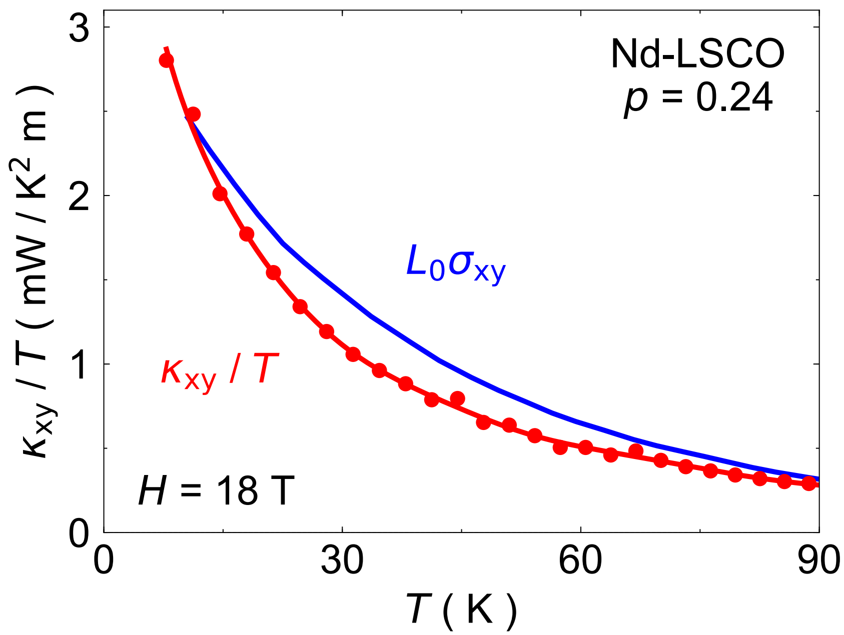
Sweeps : T or H

Reproducibility : consistent with other groups

$$\kappa_{xy} = -\kappa_{yy}\,(\Delta T_y / \Delta T_x)\,(L / w)$$

Giant thermal Hall conductivity in the pseudogap phase of cuprates





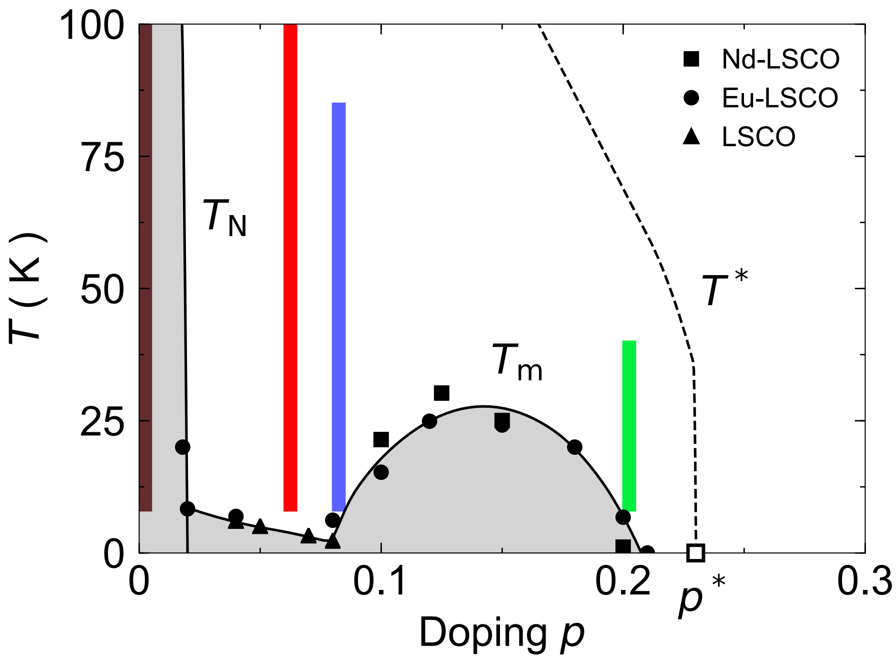
Wiedemann-Franz law

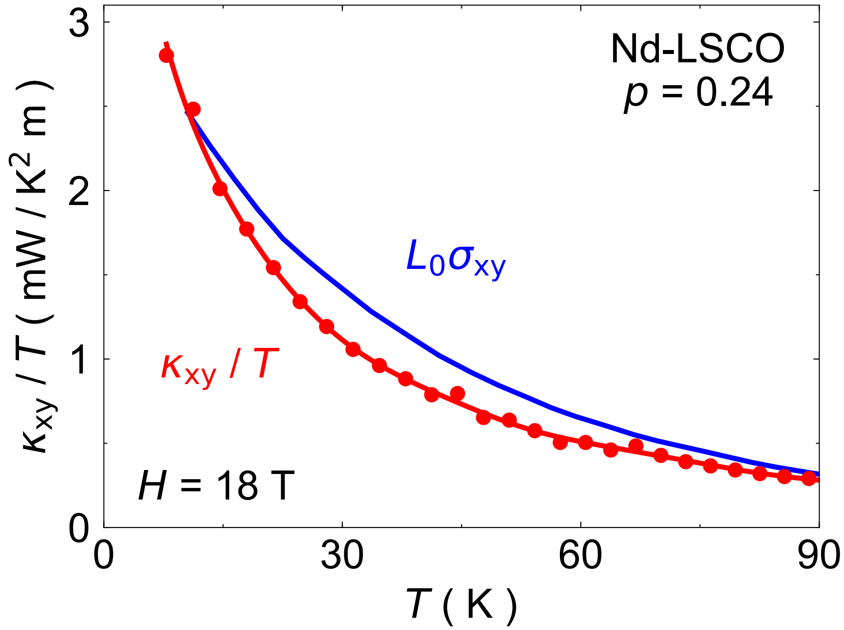
$$\kappa_{xy} / T = L_0 \sigma_{xy} \qquad (T \to 0)$$

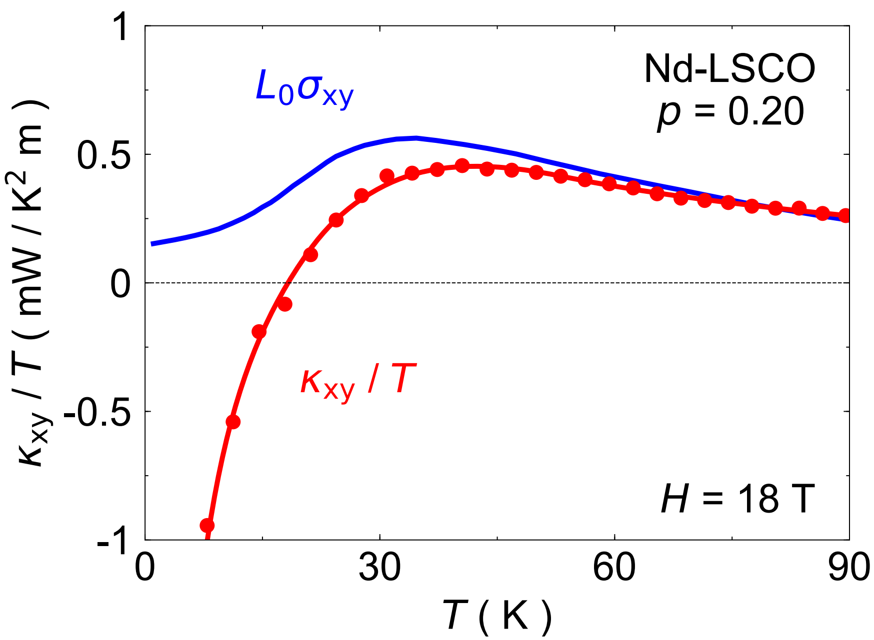
$$L_0 = (\pi^2/3)\ (k_B/e)^2$$

Grissonnanche *et al.*, Nature **571**, 376 (2019)

Giant thermal Hall conductivity in the pseudogap phase of cuprates

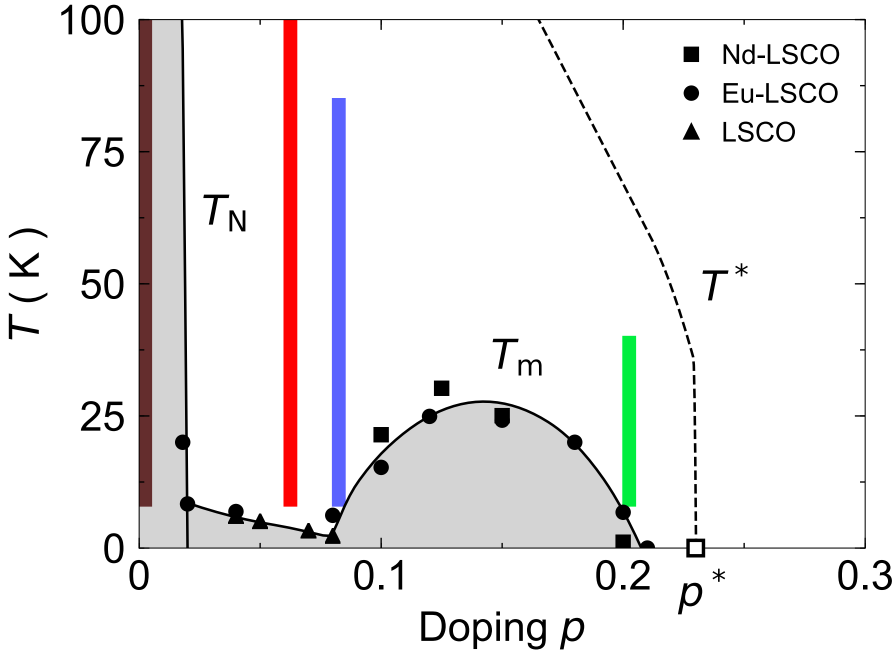


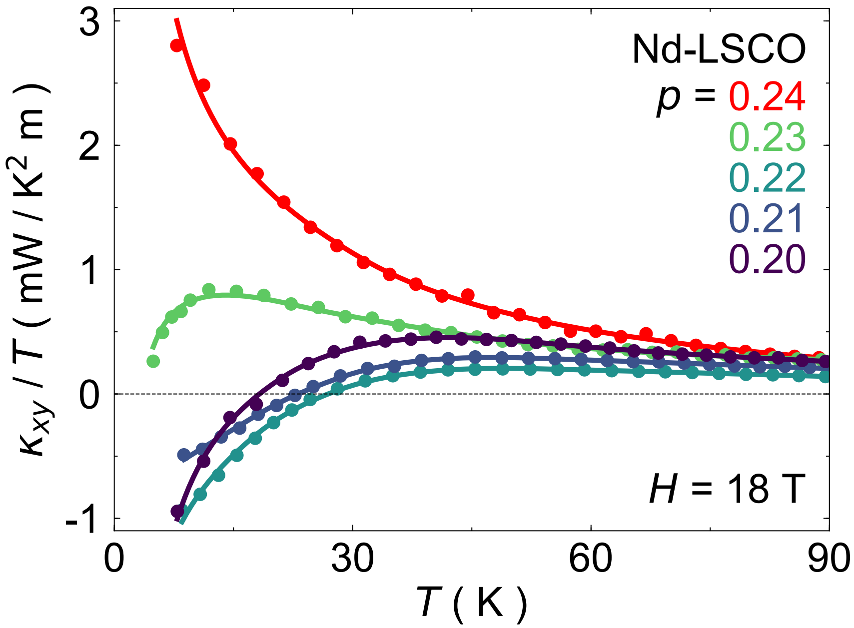


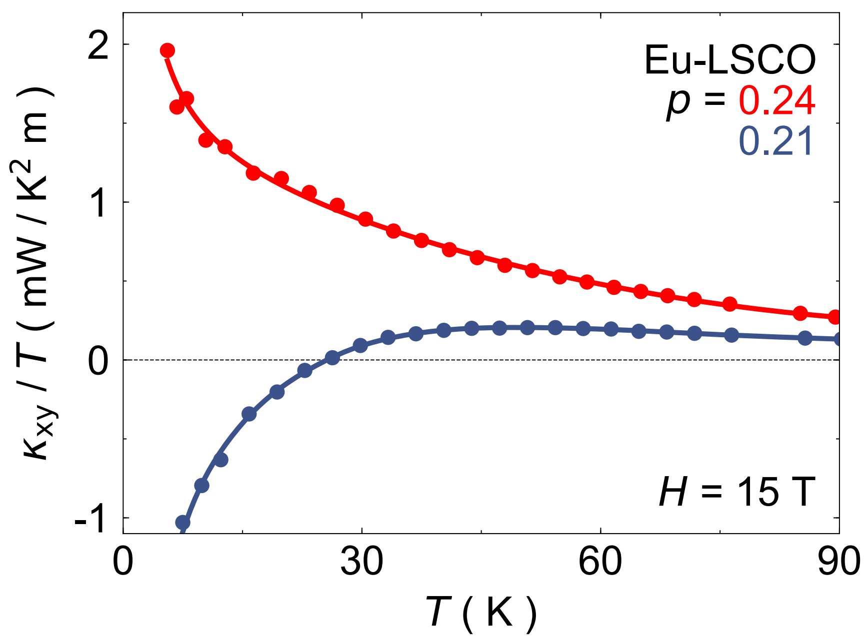


Grissonnanche *et al*., Nature **571**, 376 (2019)

Giant thermal Hall conductivity in the pseudogap phase of cuprates

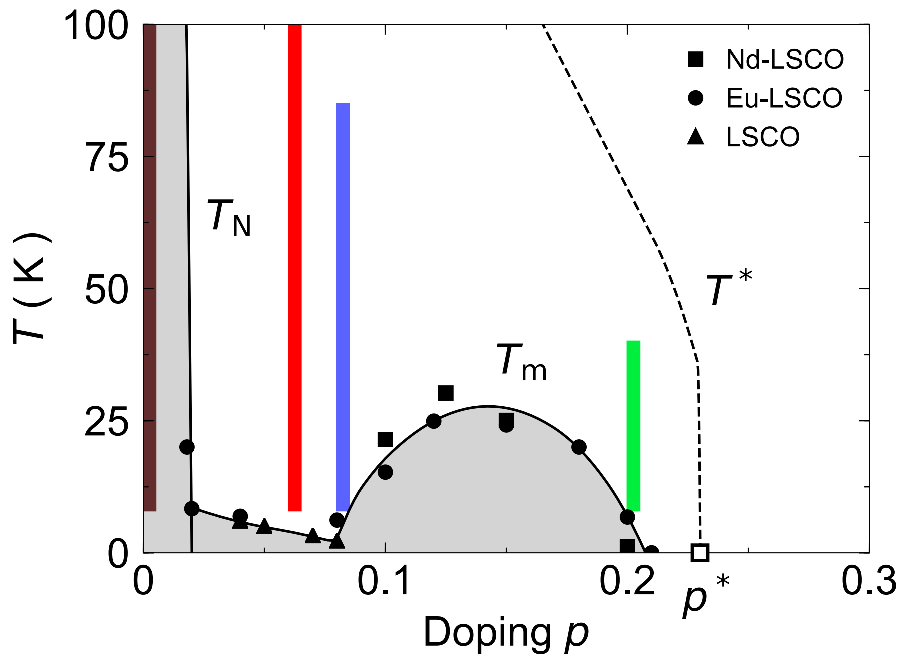


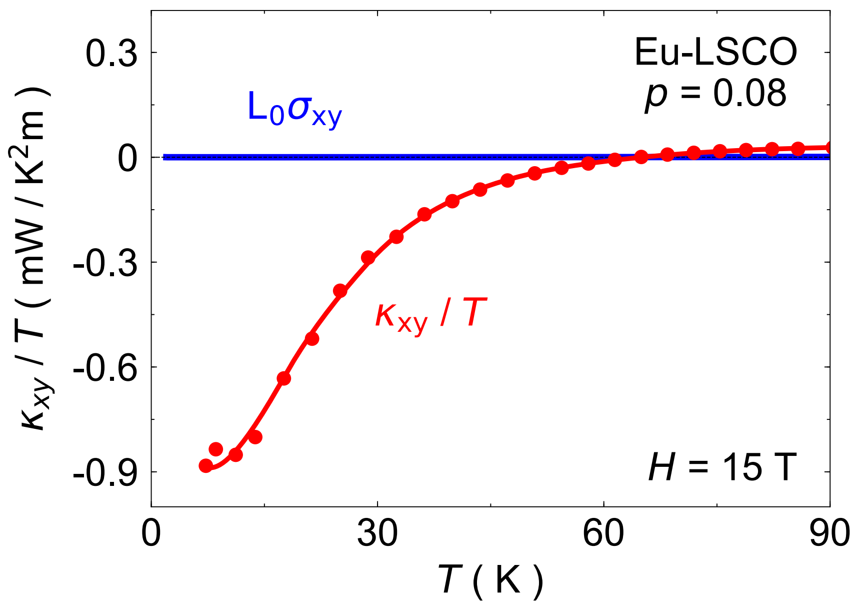




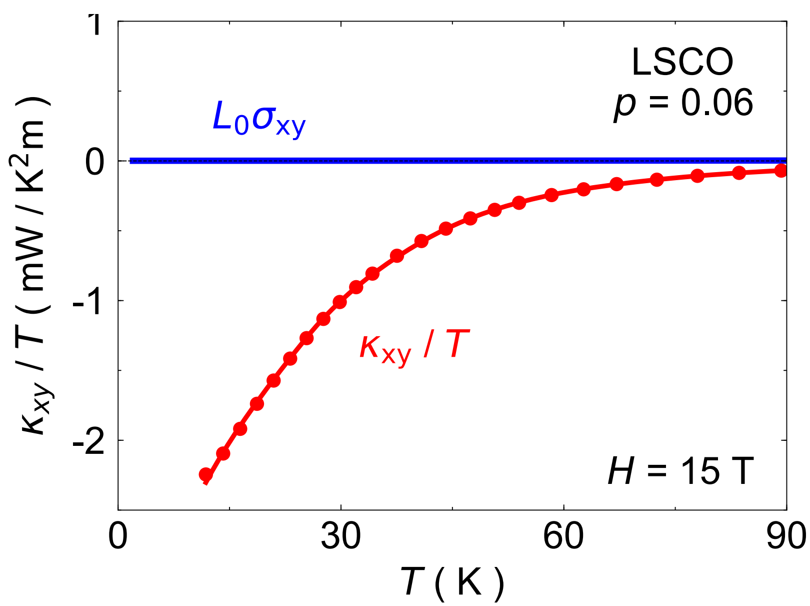
Grissonnanche *et al.*, Nature **571**, 376 (2019)

Giant thermal Hall conductivity in the pseudogap phase of cuprates



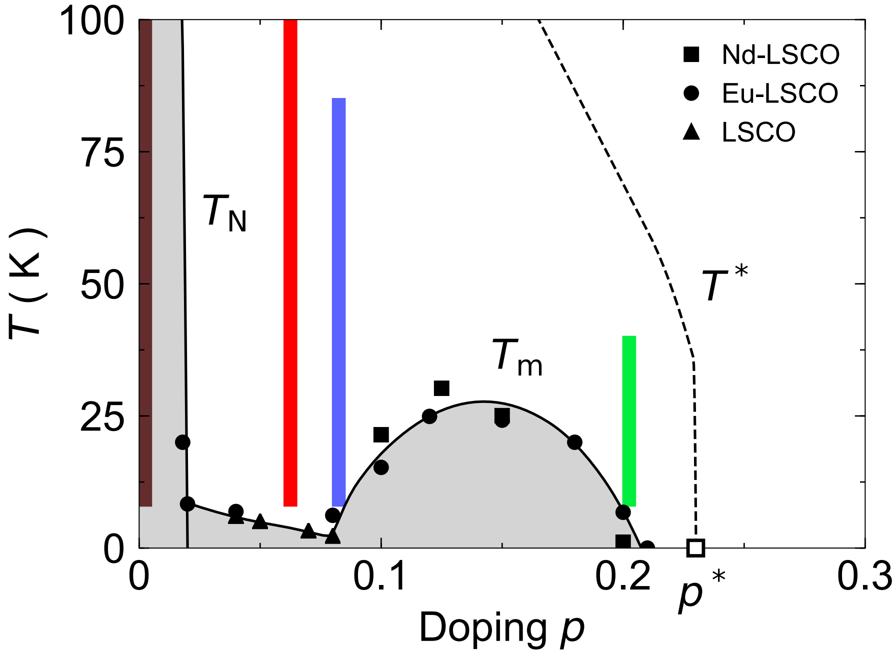


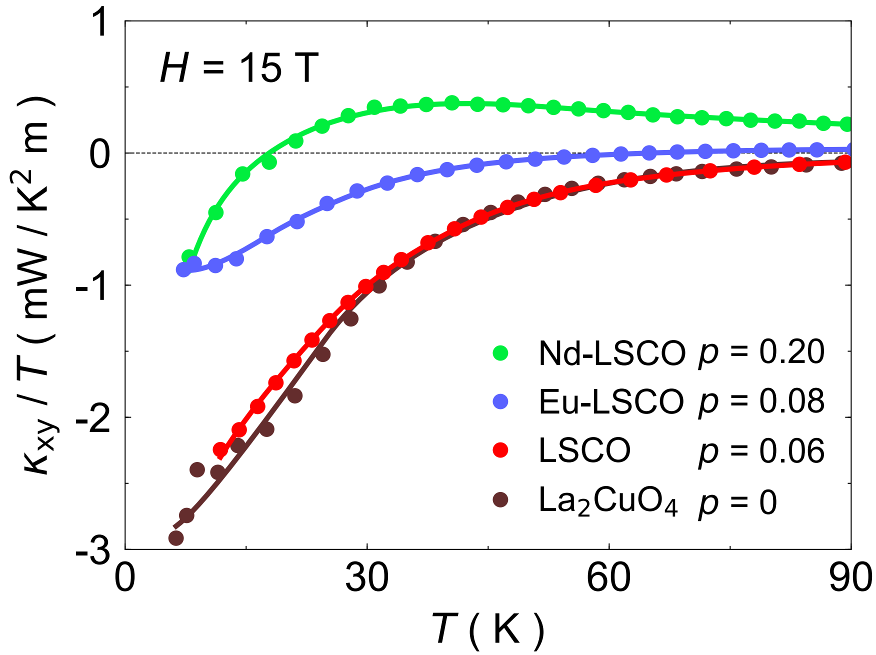
Electrons ? ***No*.**



Grissonnanche *et al*., Nature **571**, 376 (2019)

Giant thermal Hall conductivity in the pseudogap phase of cuprates





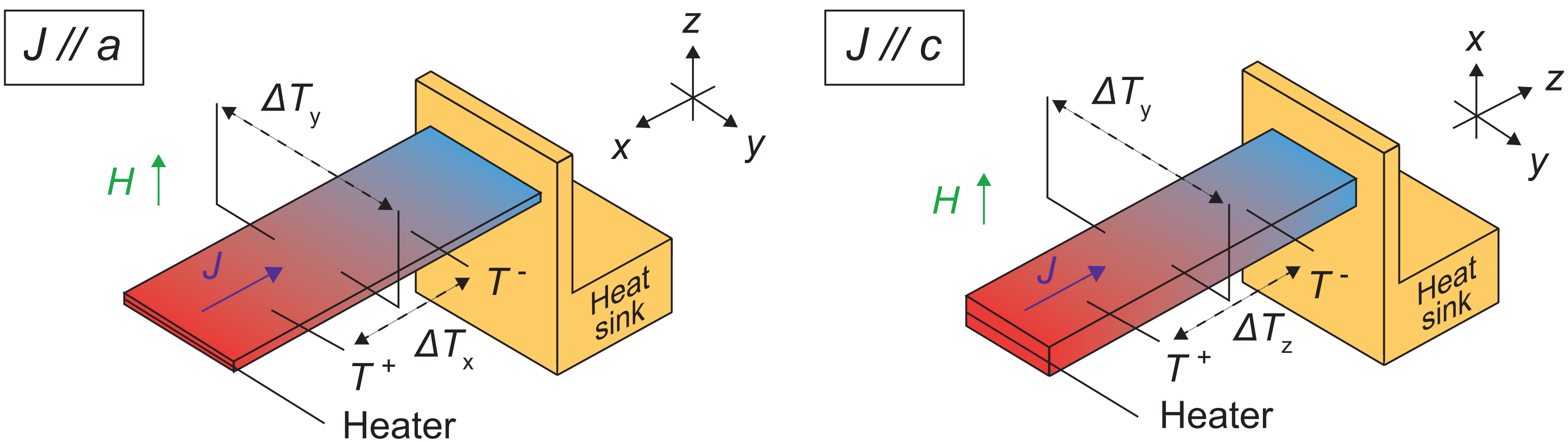
Electrons ? ***No*.**

Magnons ? ***No*.**

Phonons ? ***Maybe*.**

Grissonnanche *et al*., Nature **571**, 376 (2019)

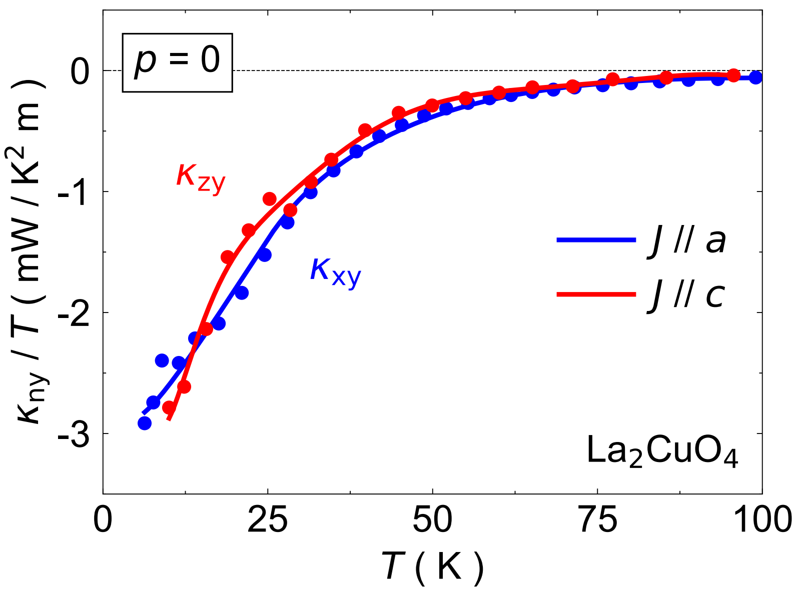
c-axis thermal Hall conductivity in cuprates



Simple approach to test for phonons :
apply heat current along the *c* axis

Grissonnanche *et al*., arXiv:2003.00111 (2020)

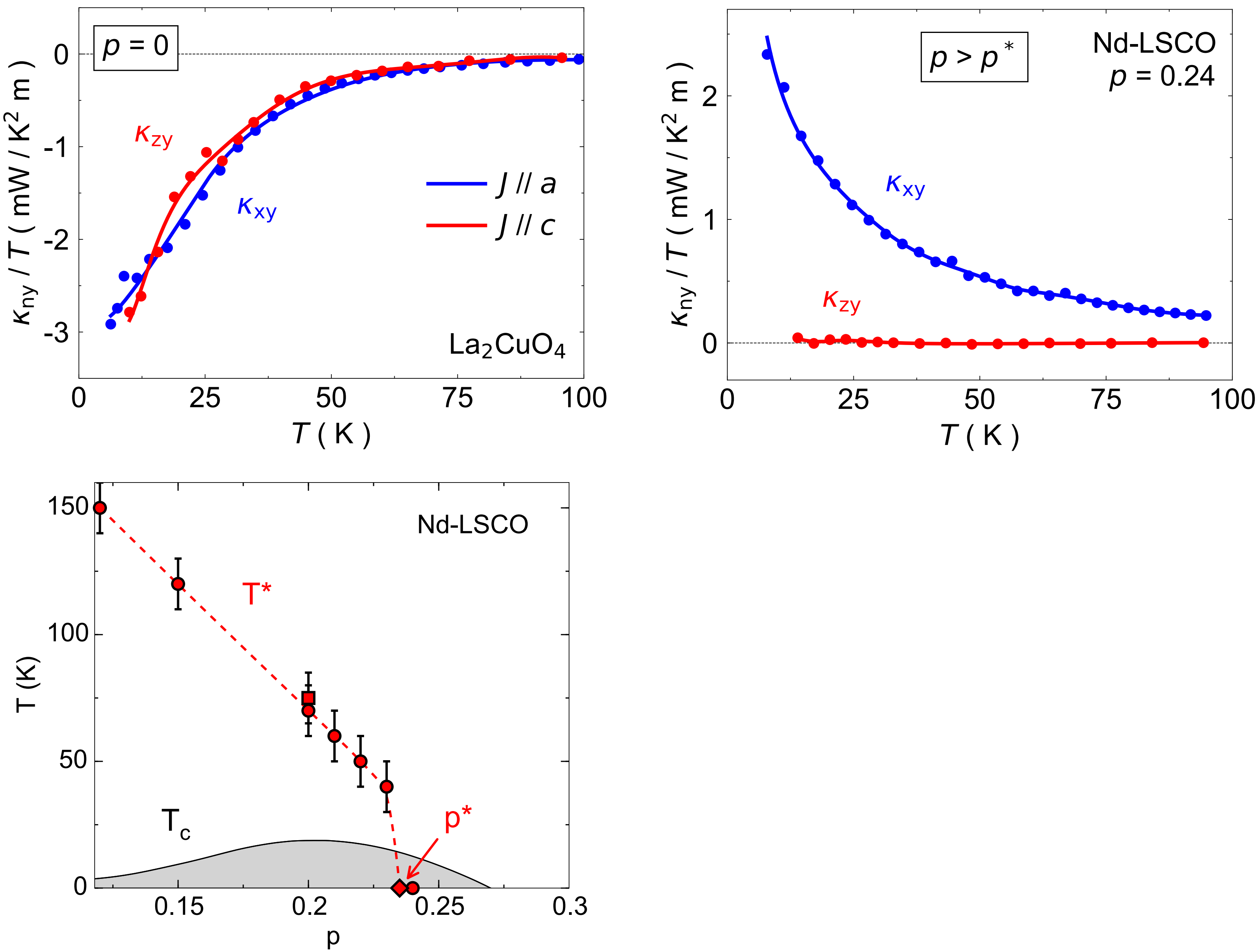
c-axis thermal Hall conductivity in cuprates



Phonons !!

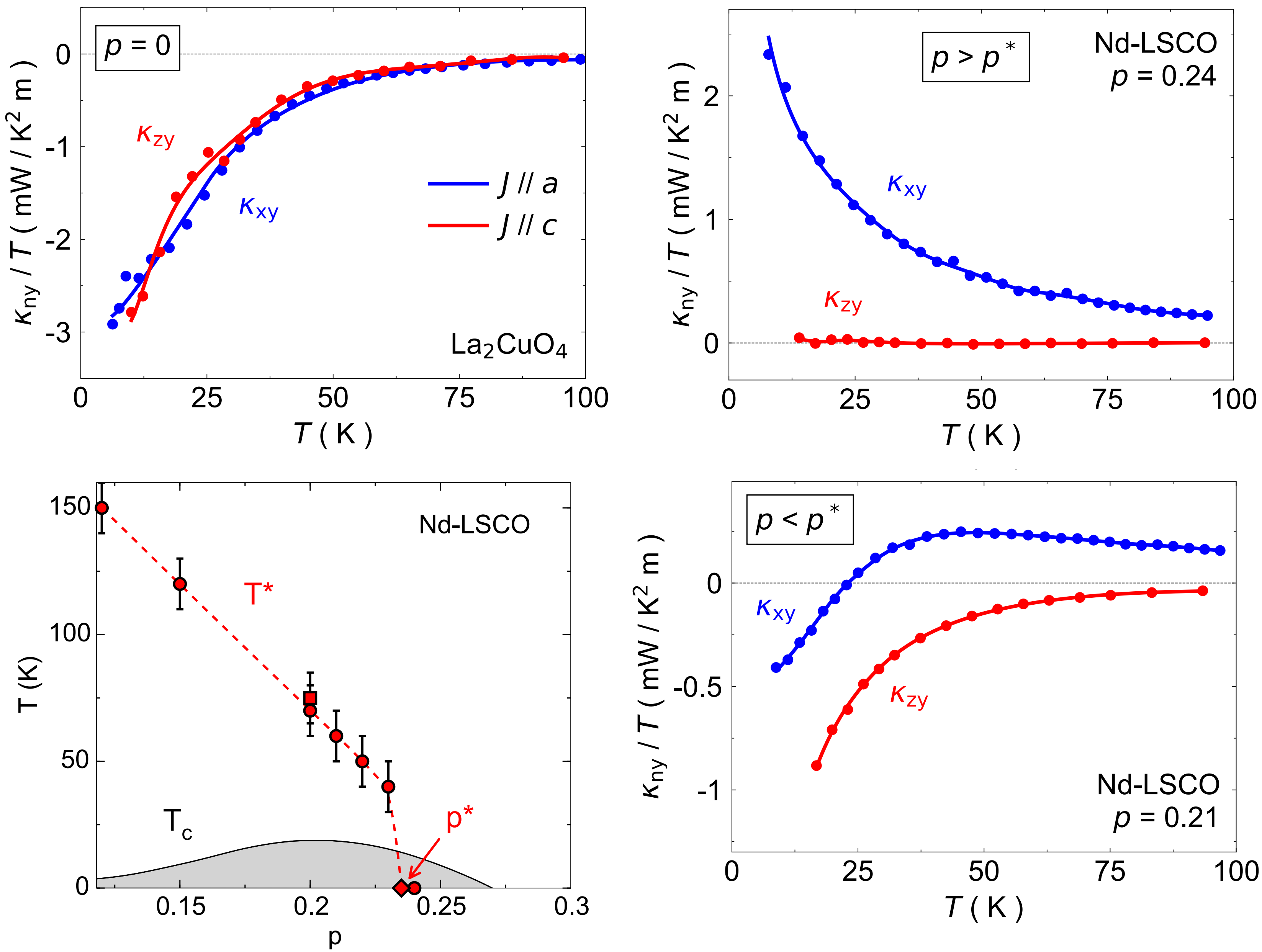
Grissonnanche *et al.*, arXiv:2003.00111 (2020)

c-axis thermal Hall conductivity in cuprates



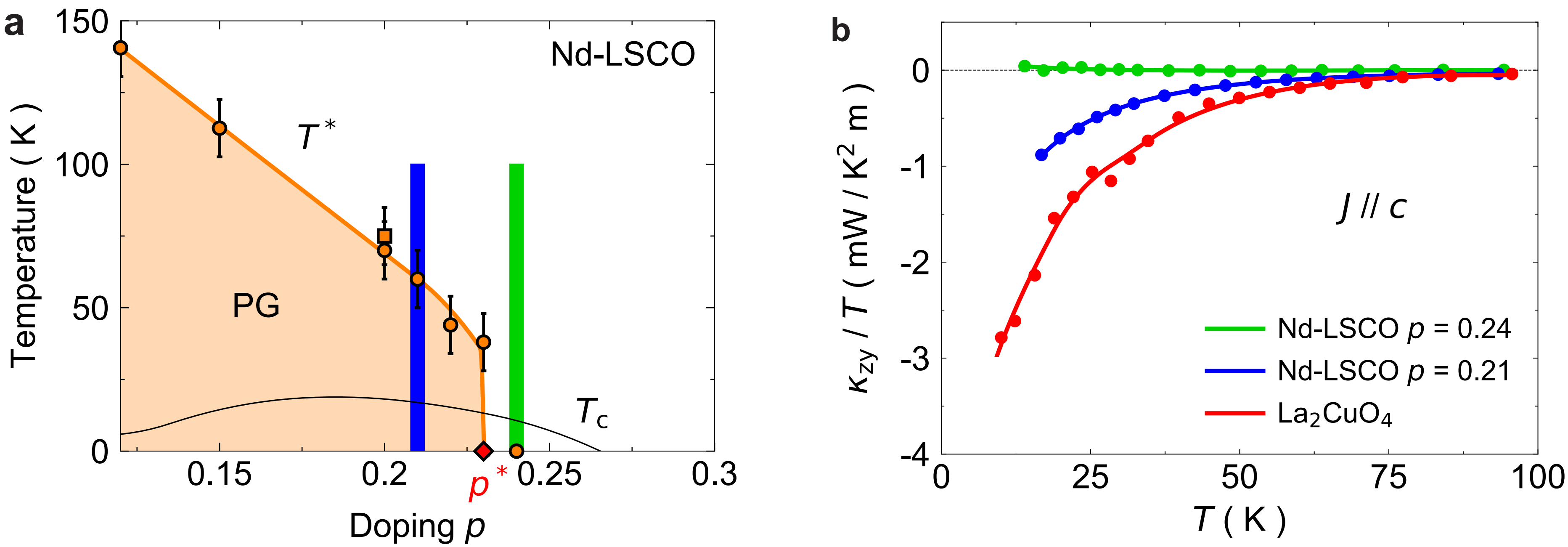
Grissonnanche *et al.*, arXiv:2003.00111 (2020)

c-axis thermal Hall conductivity in cuprates



Grissonnanche *et al.*, arXiv:2003.00111 (2020)

c-axis thermal Hall conductivity in cuprates



Phonons become CHIRAL in the pseudogap phase

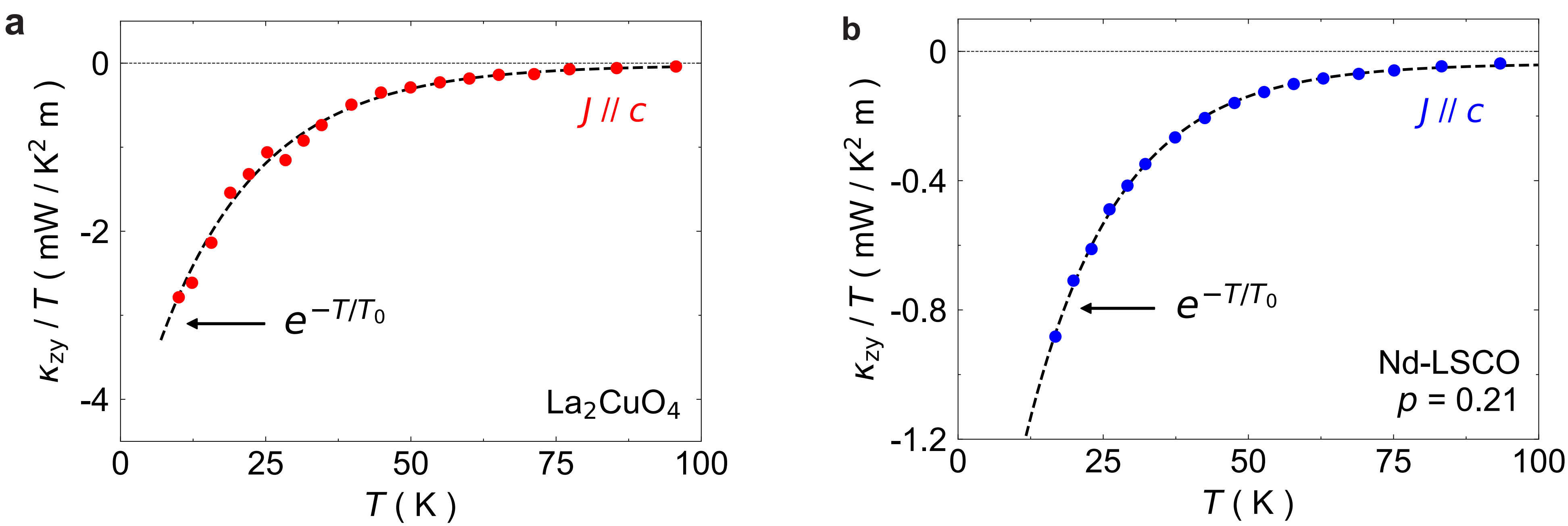
Grissonnanche *et al.*, arXiv:2003.00111 (2020)

c-axis thermal Hall conductivity in cuprates

Universal behavior of the anomalous thermal Hall conductivity

Yi-feng Yang,[1,2,3,*] Guang-Ming Zhang,[4,5,†] and Fu-Chun Zhang[6,‡]

arXiv:2001.08385



Phonons have *Berry curvature* ?

Grissonnanche *et al.*, arXiv:2003.00111 (2020)

SIGNATURES OF THE PSEUDOGAP PHASE

1) Carrier density	***n* = 1 + *p* —> *n* = *p***	***Generic***
2) Resistivity	***T* - linear as *T* —> 0** ***Planckian limit***	***Generic***
3) ADMR	**Fermi surface changes at *p****	
4) Limit on QCP	***p** < van Hove point**	
5) Thermal Hall	**phonons become chiral**	