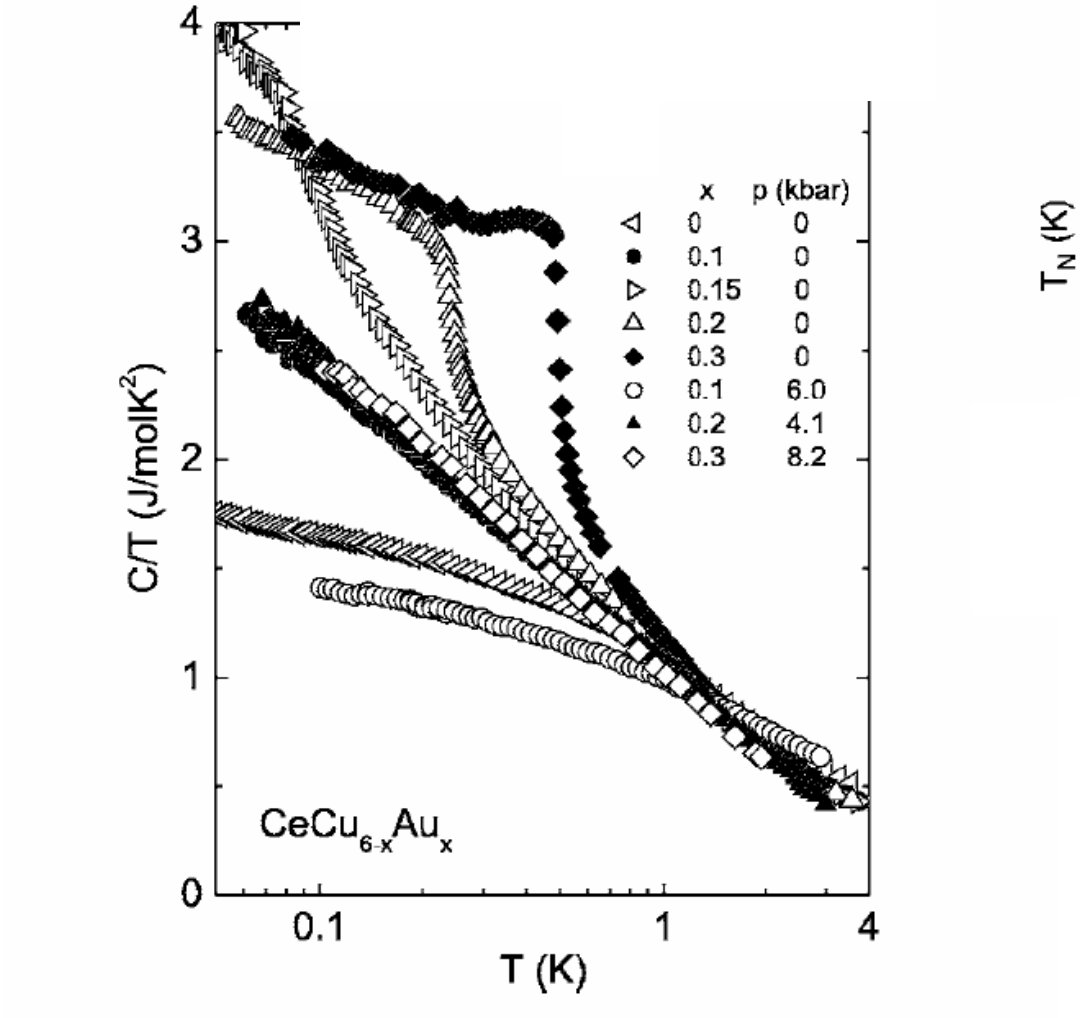
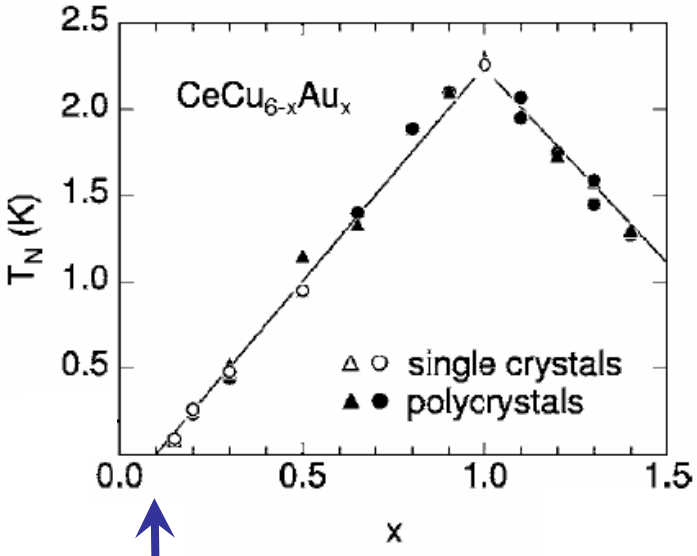
Quantum Criticality



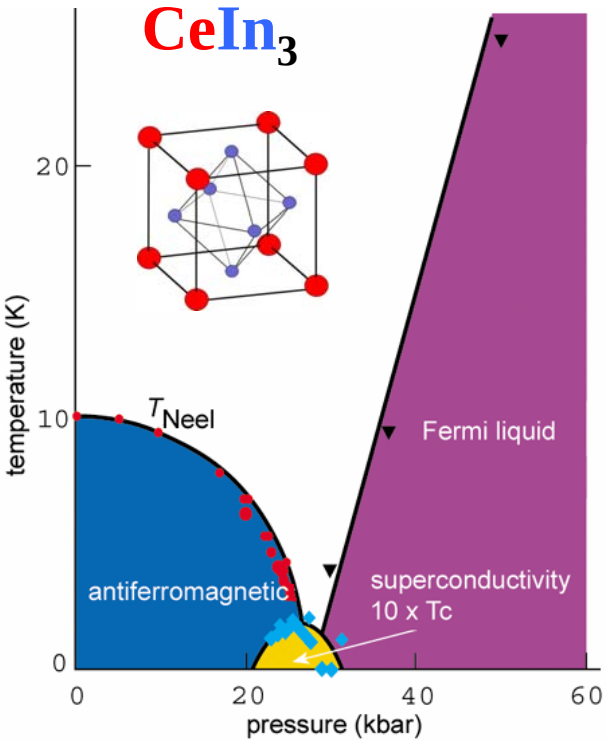


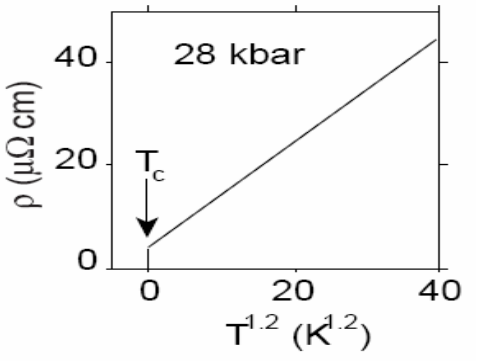
QCP

H.v. Löhneysen et al., PRL 1994

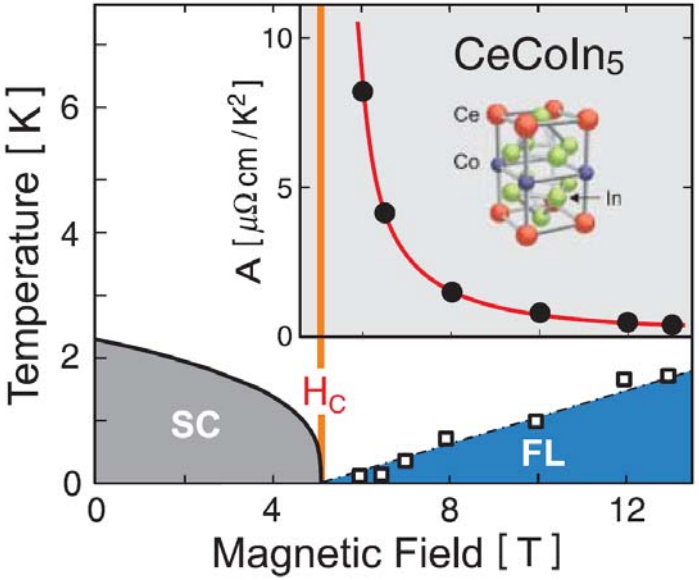
Quantum Criticality & Superconductivity

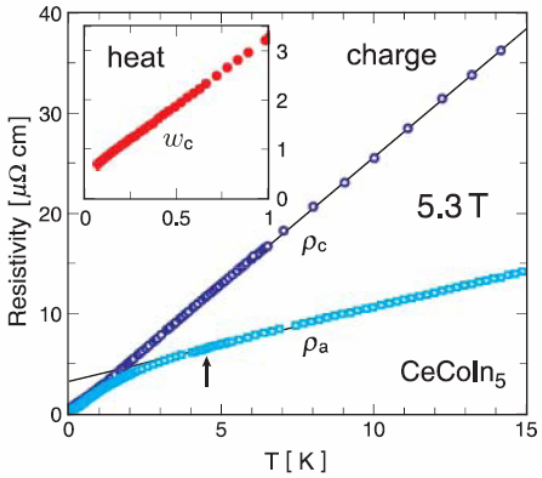
Mathur et al., Nature 1998





Paglione et al., PRL 2003

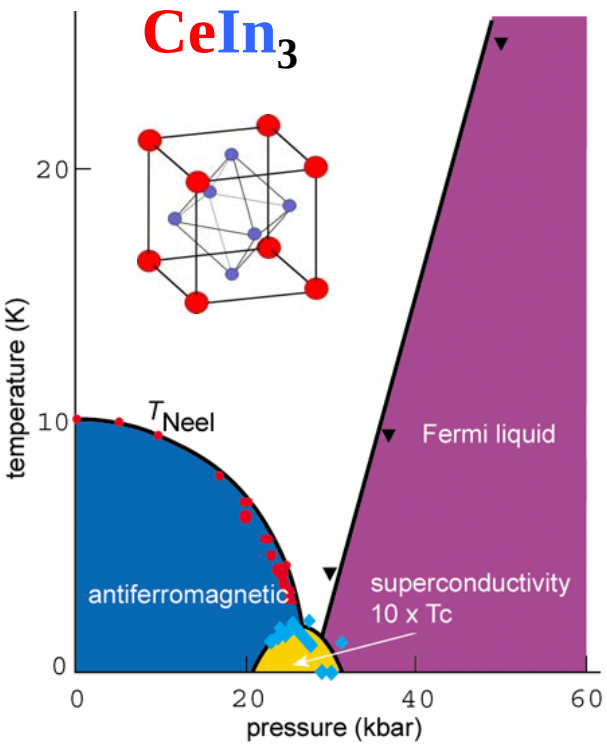


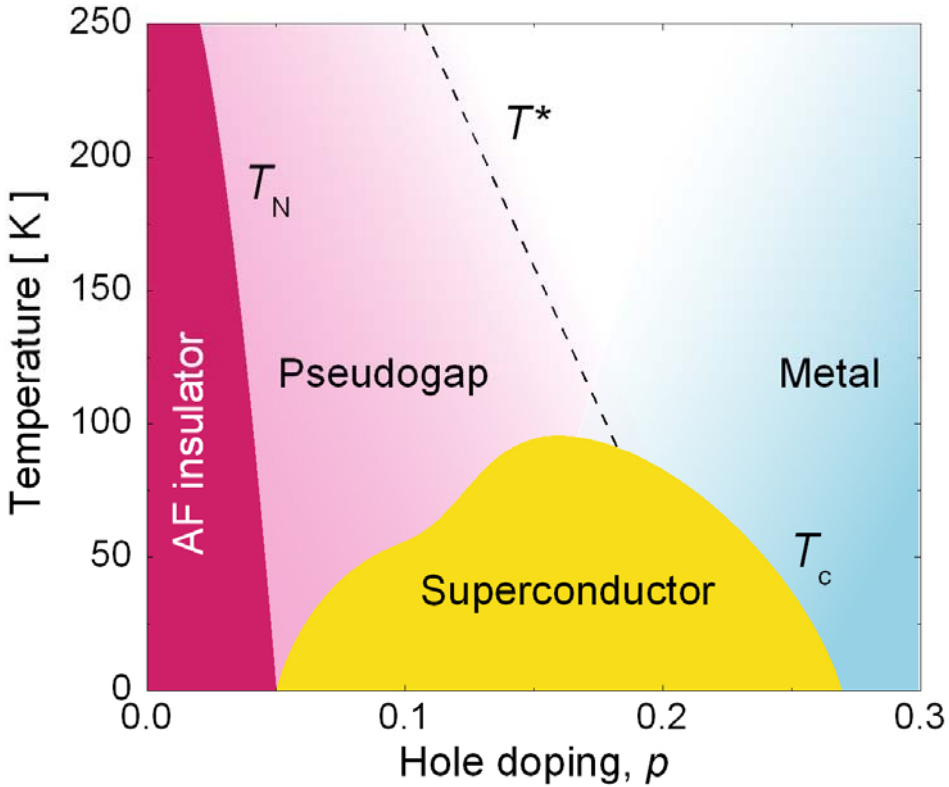


Tanatar et al., Science 2007

Phase diagram of hole-doped cuprates

N. Mathur et al., Nature 1998

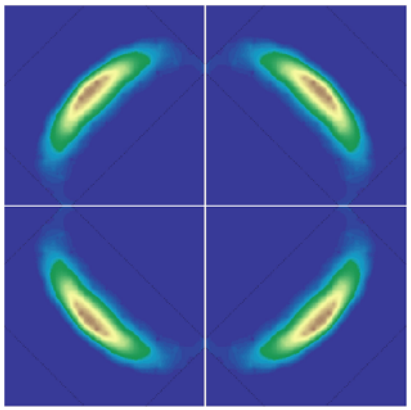




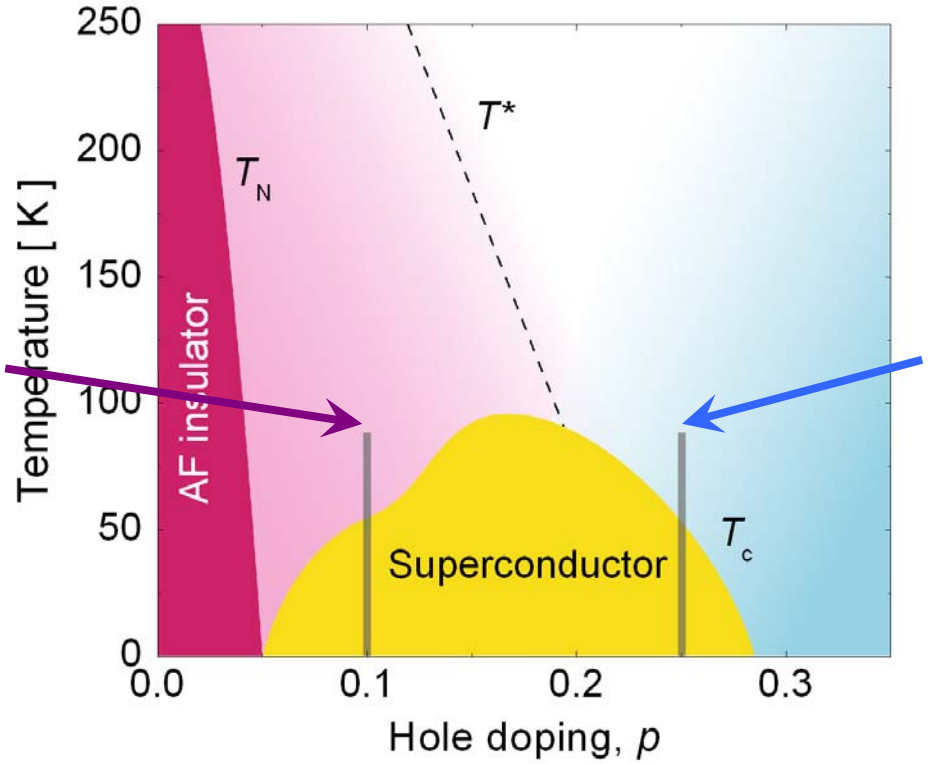
What causes superconductivity ?

What is the pseudogap phase ?

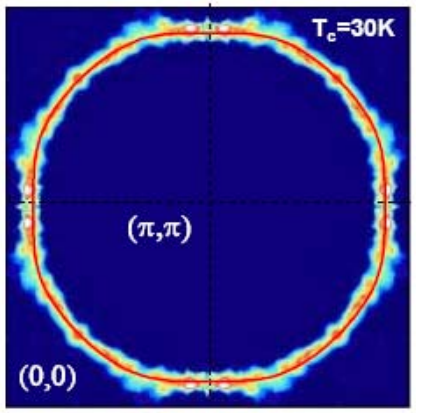
Fermi surface of hole-doped cuprates ?



K.M. Shen et al., Science 2005



$n = 1 + p$



M. Platé et al., PRL 2005

??

$R_H = + V / e (1+p)$

A. Tyler et al., PRB 1996

What is the Fermi surface in the pseudogap phase ?

The Fermi surface of high-T_c superconductors - I

NHMFL, Tallahassee

Nicolas Doiron-Leyraud
David LeBoeuf
Ramzy Daou
J.-B. Bonnemaison

Cyril Proust
Julien Levallois

Luis Balicas

N.E. Hussey – Bristol

Canadian Institute for Advanced Research

Brad Ramshaw
Ruixing Liang
Doug Bonn
Walter Hardy

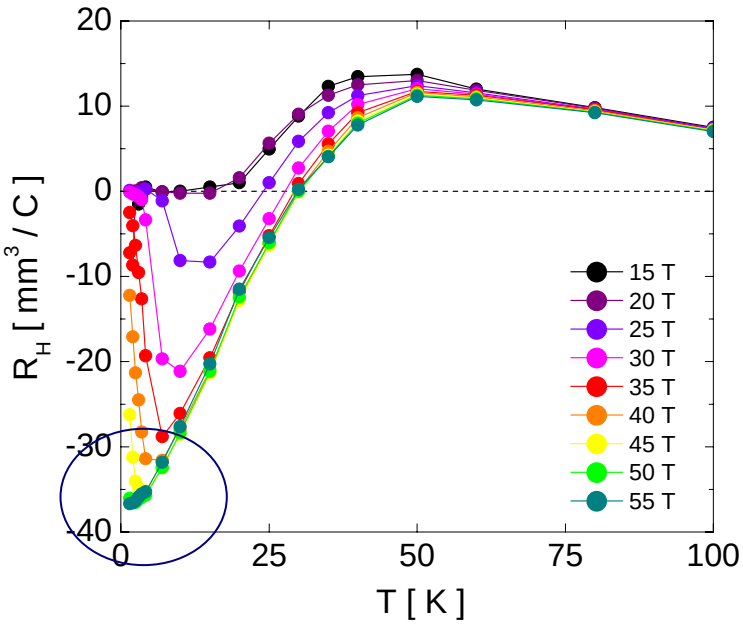
S. Adachi – Tokyo

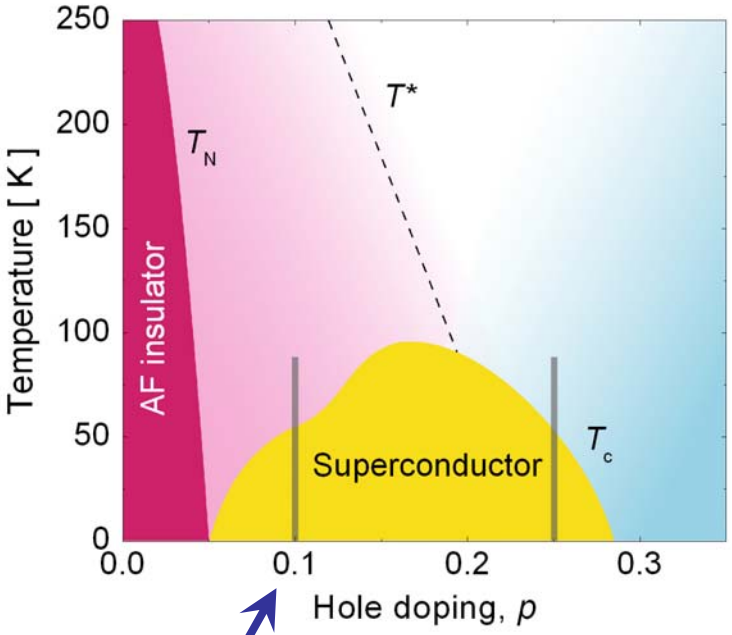
*N. Doiron-Leyraud et al., Nature **447**, 565 (2007)*

*D. LeBoeuf et al., Nature **450**, 533 (2007)*

Hall coefficient in YBCO

p = 0.10



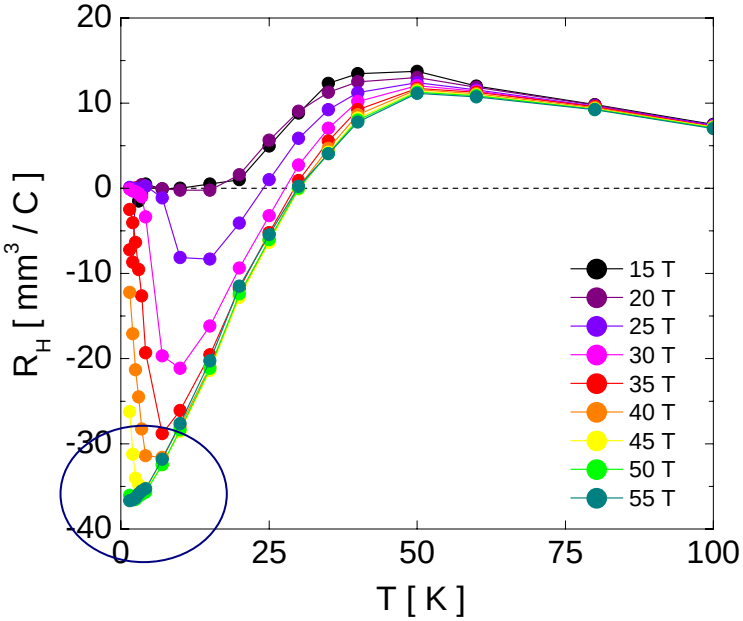


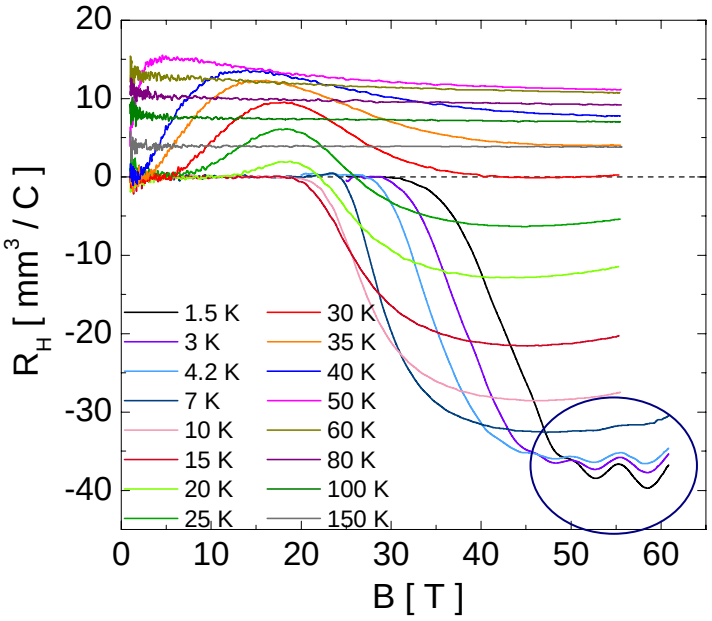
$R_H < 0$

D. LeBoeuf et al., Nature 2007

Hall coefficient in YBCO

p = 0.10





R_H < 0 ***Quantum oscillations***

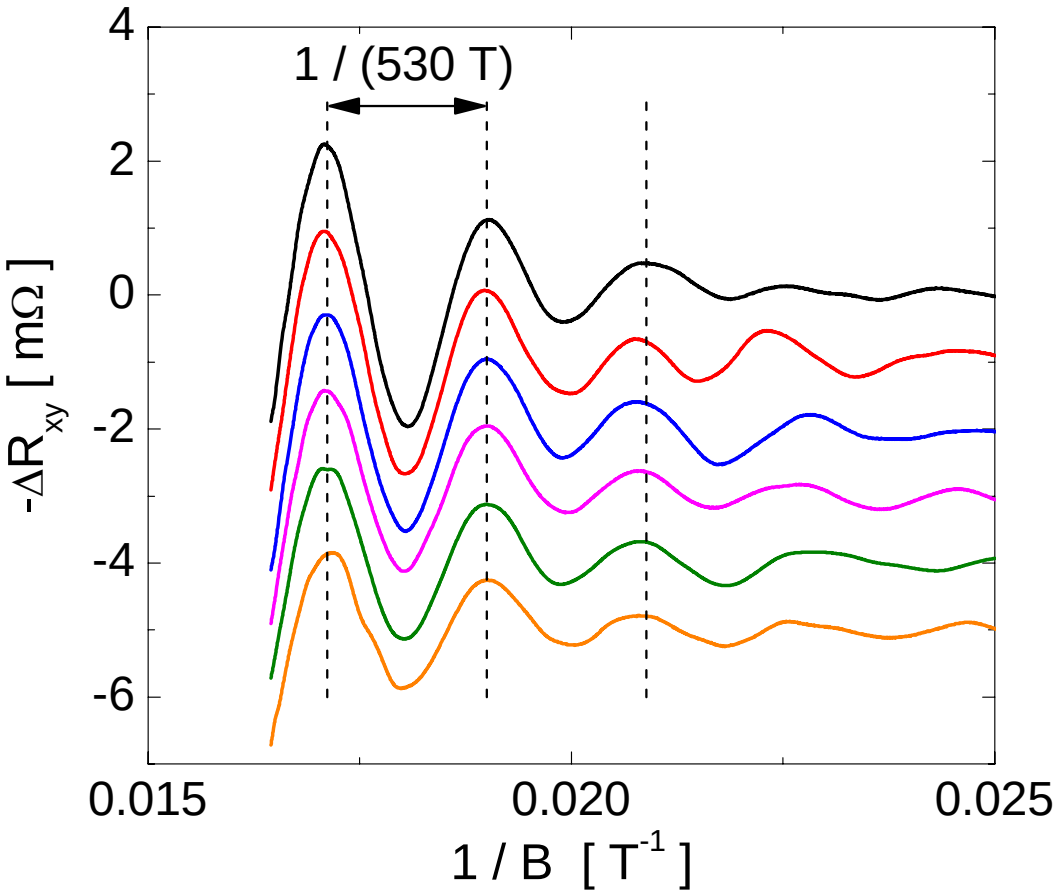
Fermi surface includes a small *electron* pocket !

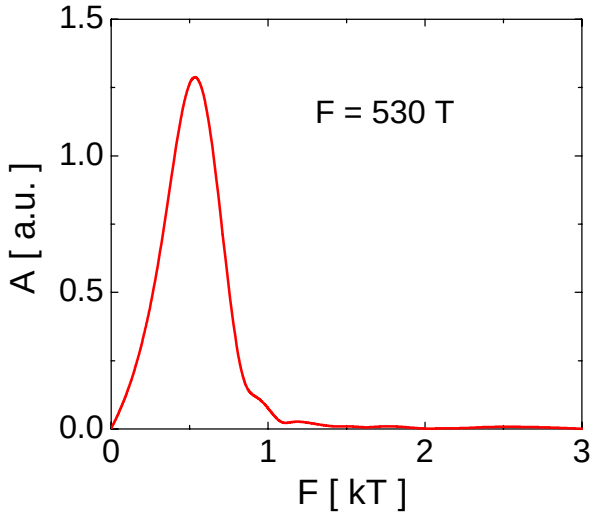
D. LeBoeuf et al., Nature 2007

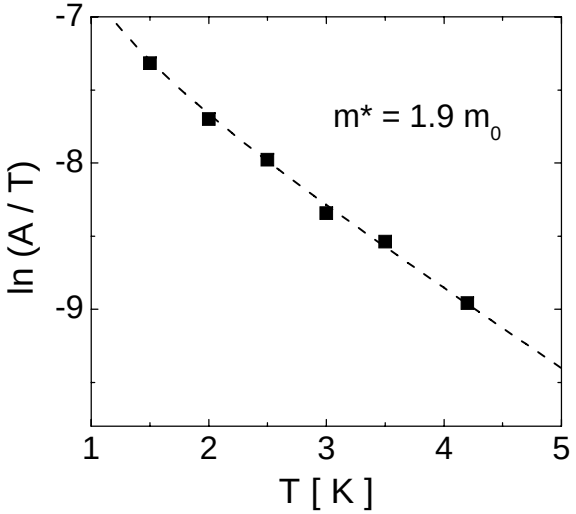
N. Doiron-Leyraud et al., Nature 2007

Quantum oscillations in YBCO

p = 0.10







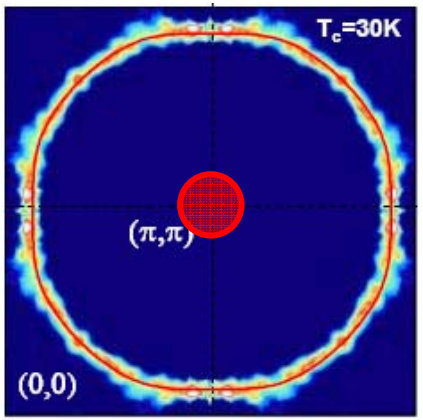
N. Doiron-Leyraud et al., Nature 2007

Quantum oscillations in YBCO

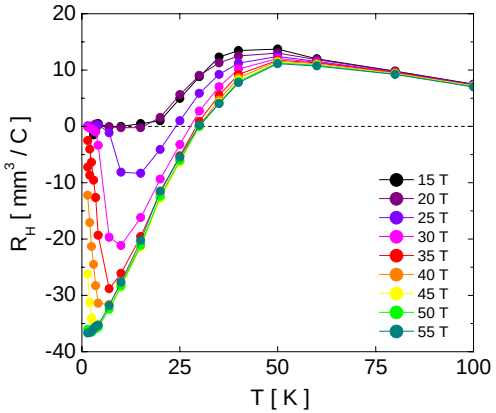
	Method	*F (T)*	*Mass (m_0)*
Y123 – II	*SdH*	*530 ± 20*	*1.9 ± 0.1*
Y123 – II	*dHvA*	*540 ± 4*	*1.76 ± 0.07*
Y124	*SdH*	*660 ± 30*	*2.7 ± 0.3*
Y124	*TDO*	*660 ± 15*	*3.0 ± 0.3*

Small FS a generic feature of underdoped cuprates

A_k ~ 3 % of FS area of Tl-2201 (p = 0.25)

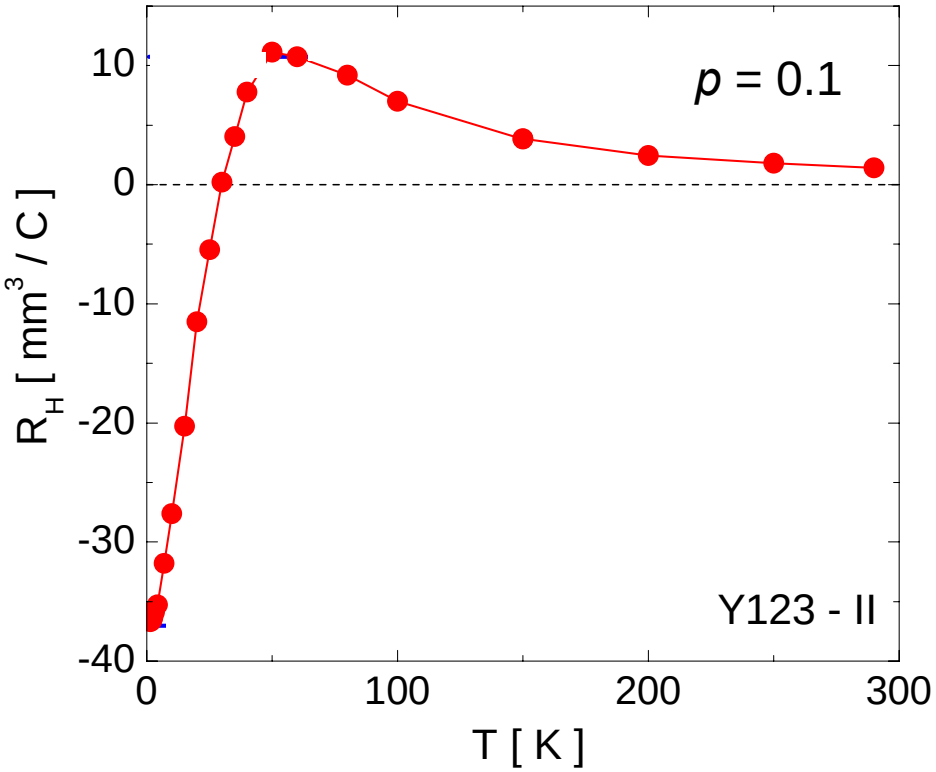


Sign of R_H



$R_H < 0$

$at\ T = 0$



Electron pocket in FS

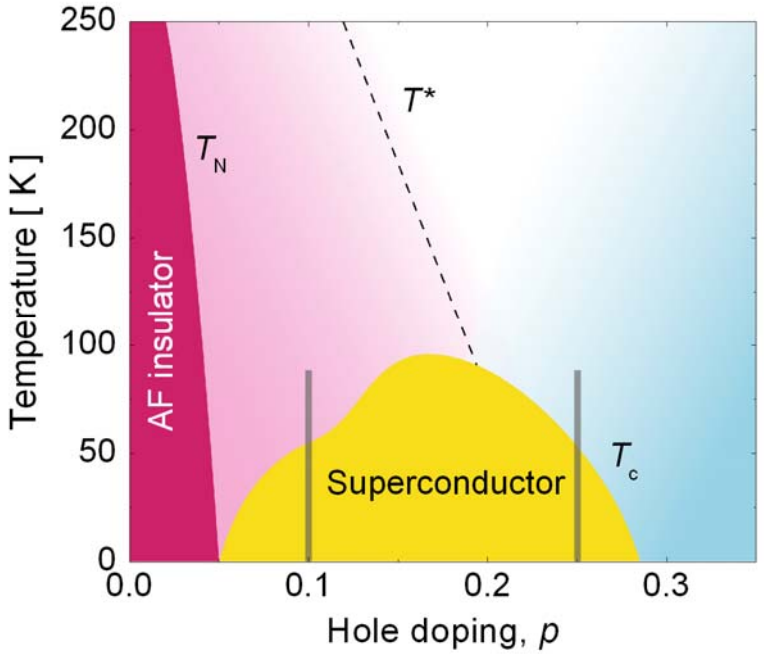
D. LeBoeuf et al., Nature 2007

Summary – Part I

Fermi surface transformation :

p = 0.25 *Large HOLE surface*

p = 0.10 *Small ELECTRON surface*



Mechanism ?

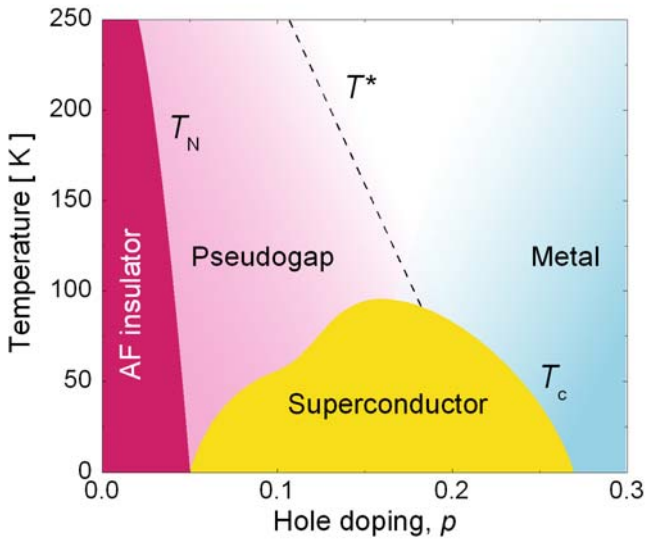
Fermi surface reconstruction

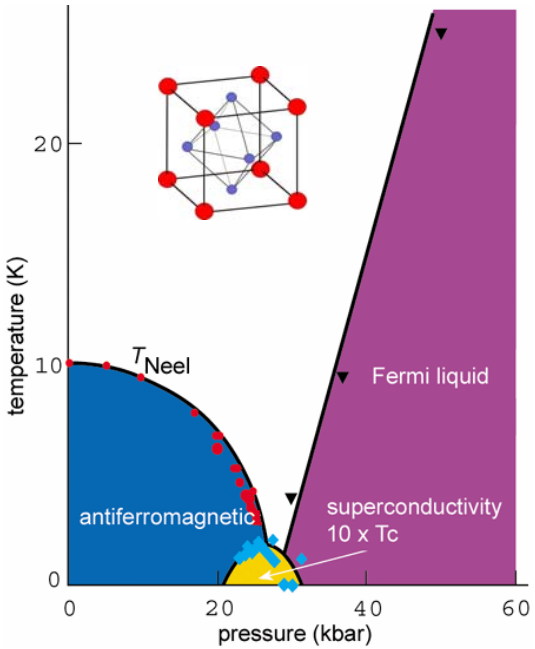
Electron pocket → broken symmetry

Pseudogap phase : onset of "hidden" order, with broken translational symmetry

Example : Antiferromagnetic order

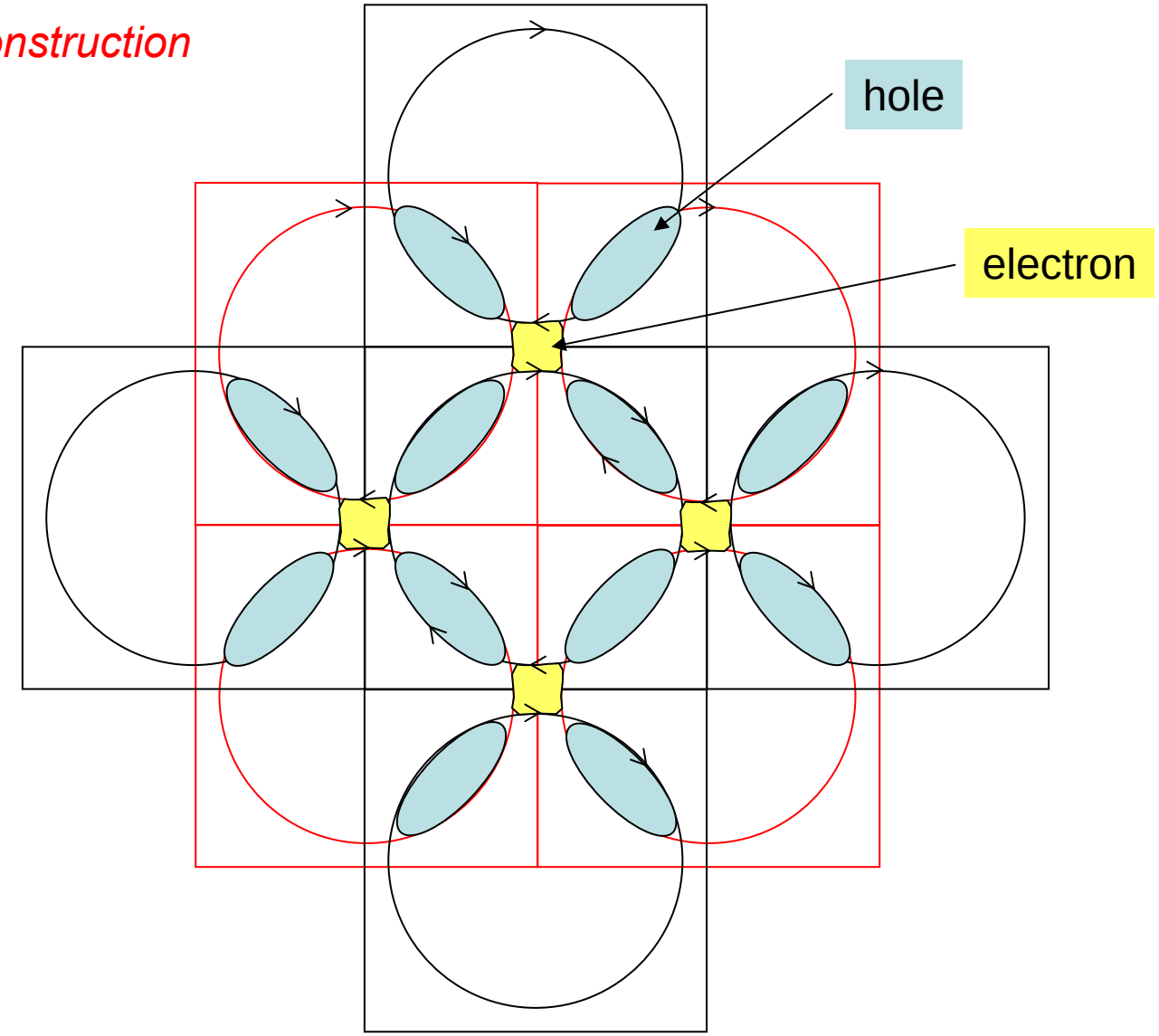
$CeIn_3$





Fermi surface reconstruction

(π, π) reconstruction

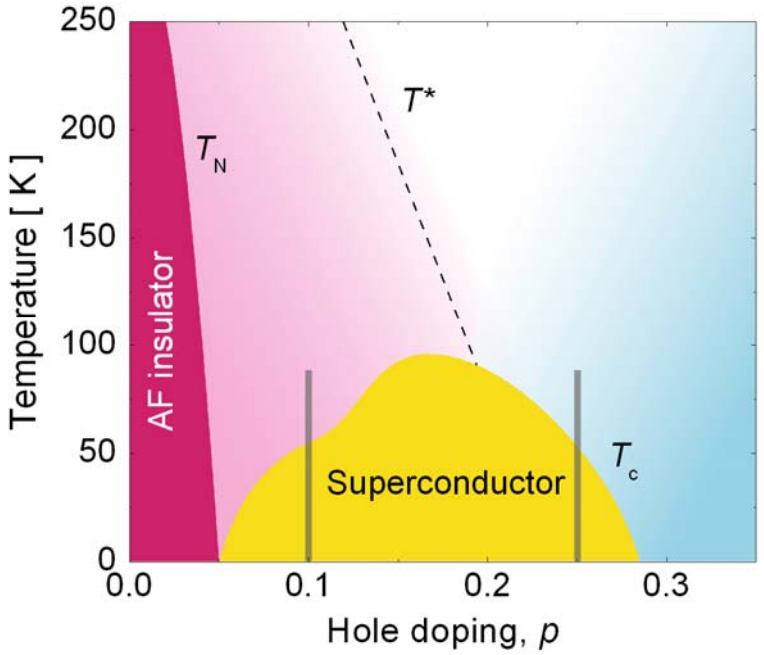


Summary – Part I

The Fermi surface of underdoped cuprates contains an *electron* pocket

FS reconstruction by some order

Pseudogap phase = ordered phase

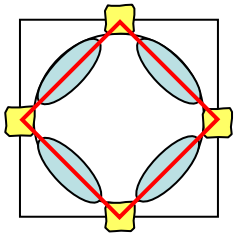


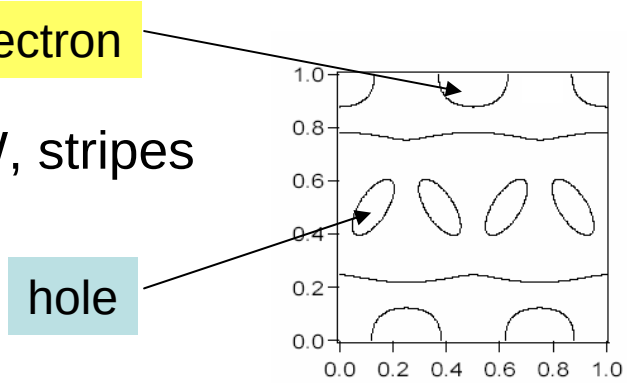
Nature of the order ?

Where is the QCP ?

Types of order

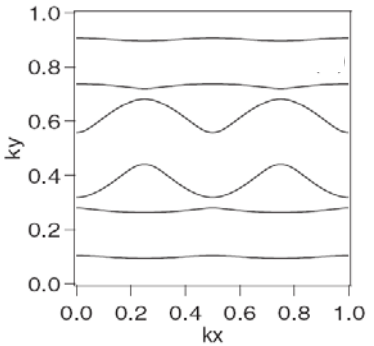
SPIN Antiferromagnetism, SDW, stripes



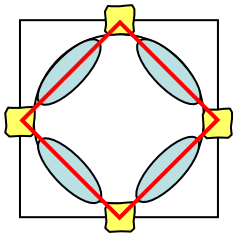


Millis and Norman, PRB 2007

CHARGE CDW, stripes



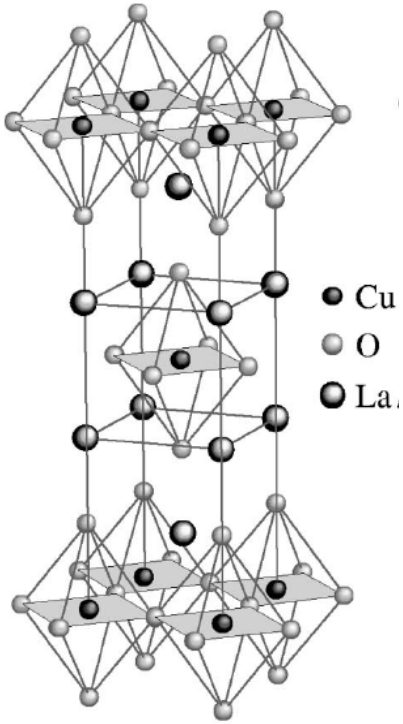
CURRENTS DDW, …



Chakravarty et al., PRB 2001

Part II : Cuprate with "stripe order"

$La_{2-y-x}Nd_ySr_xCuO_4$



Chosen for two reasons :

- *Long-range spin / charge order*

  Tranquada et al., Nature 1995

- *Superconductivity can be suppressed by a DC magnetic field*

NB : *Eu-LSCO is very similar*

The Fermi surface of high-T_c superconductors - II

UNIVERSITÉ DE SHERBROOKE

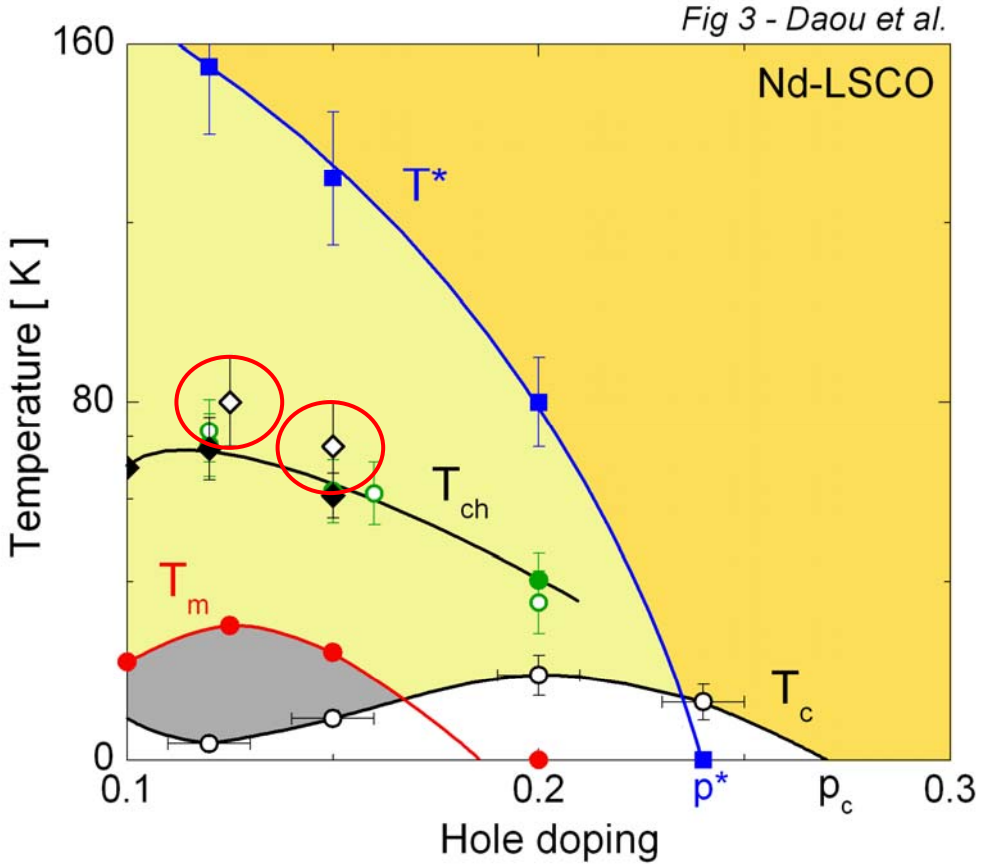
Nicolas Doiron-Leyraud
David LeBoeuf
Ramzy Daou
Olivier Cyr-Choinière
Francis Laliberté

Austin, Texas

Jianshi Zhou
J.-Q. Yan
J.B. Goodenough

R. Daou et al., arXiv:0806.2881

Fermi surface transformation in Nd-LSCO

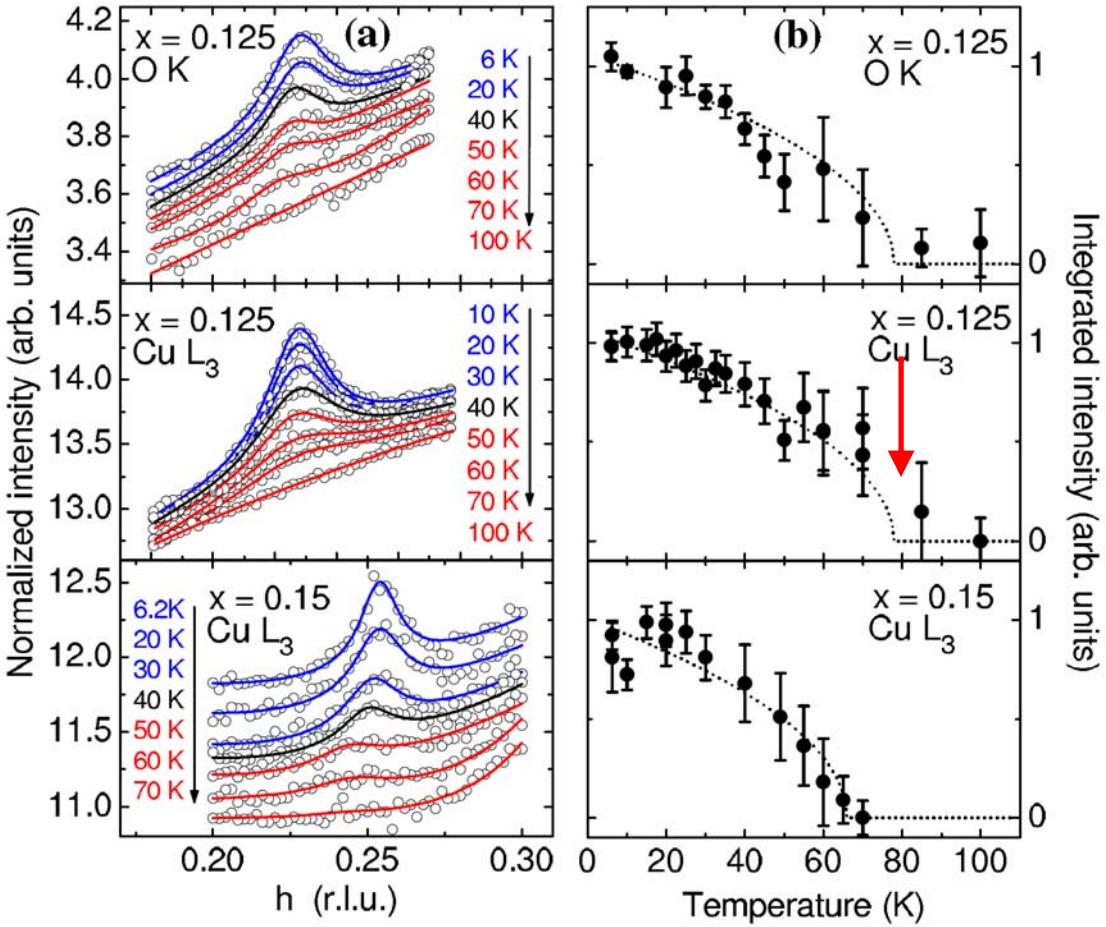


R. Daou *et al*. (2008)

Charge order in Eu-LSCO

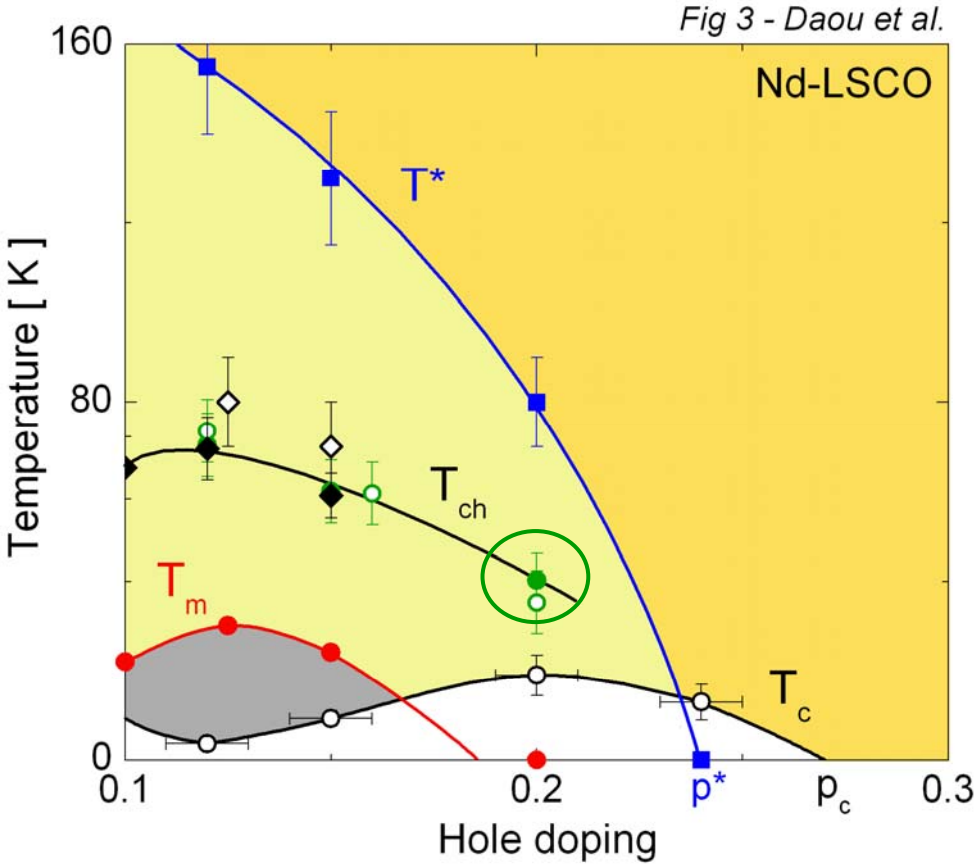
Charge order in $La_{1.8-x}Eu_{0.2}Sr_xCuO_4$ studied by resonant soft X-ray diffraction

J. Fink,[1,2] E. Schierle,[3] E. Weschke,[3] J. Geck,[4] D. Hawthorn,[4] H. Wadati,[4]
H.-H. Hu,[5] H. A. Dürr,[1] N. Wizent,[2] B. Büchner,[2] G.A. Sawatzky,[4]



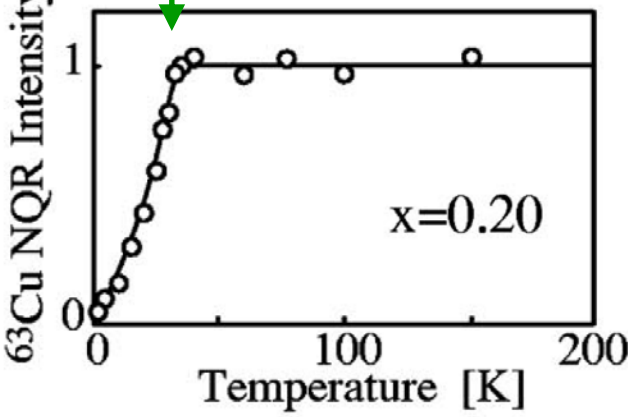
T_{RSXS} = 80 K

Fermi surface transformation in Nd-LSCO



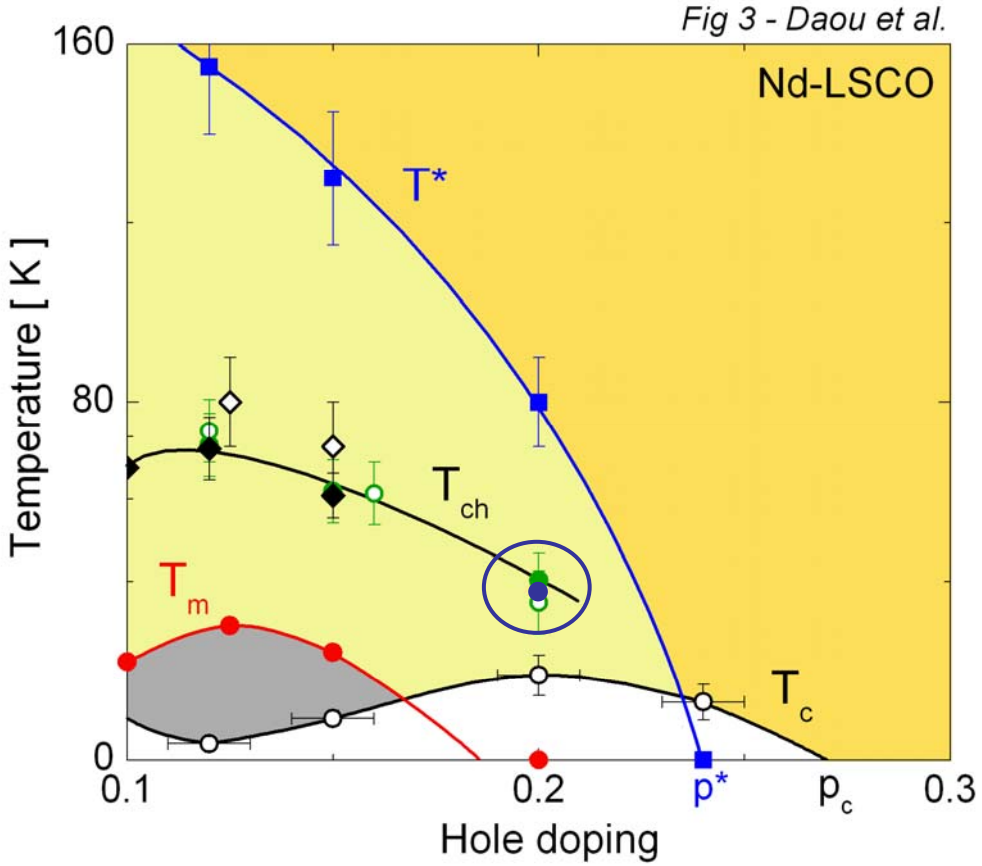
R. Daou *et al*. (2008)

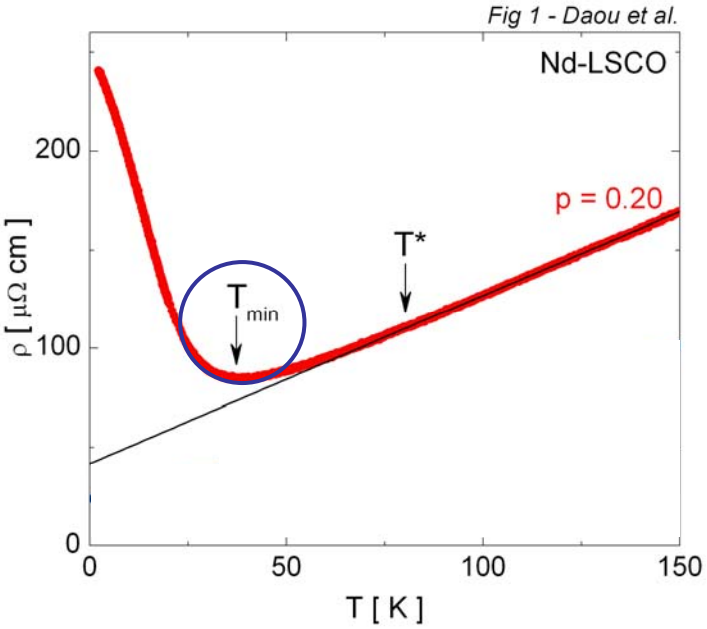
T_{NQR} = 40 K



A.W. Hunt *et al*., PRB (2001)

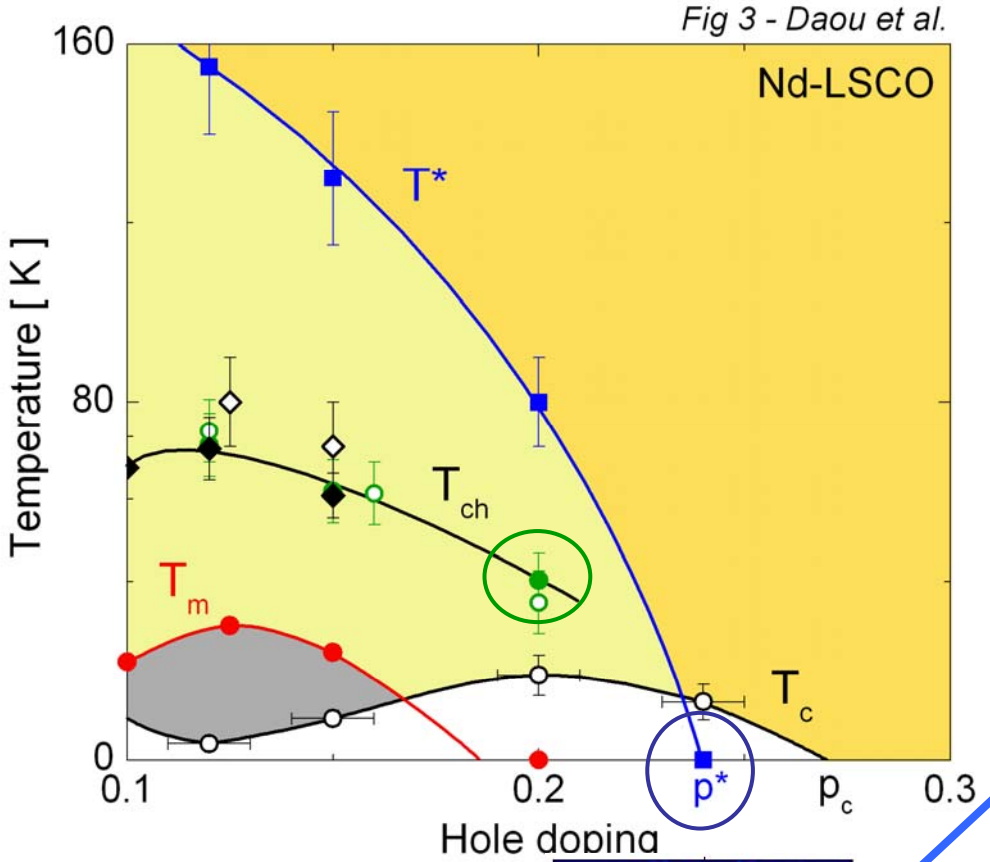
Fermi surface transformation in Nd-LSCO

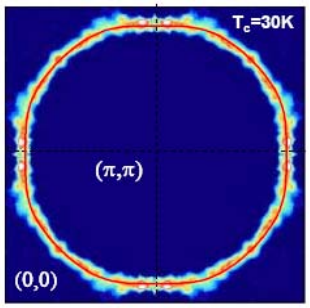




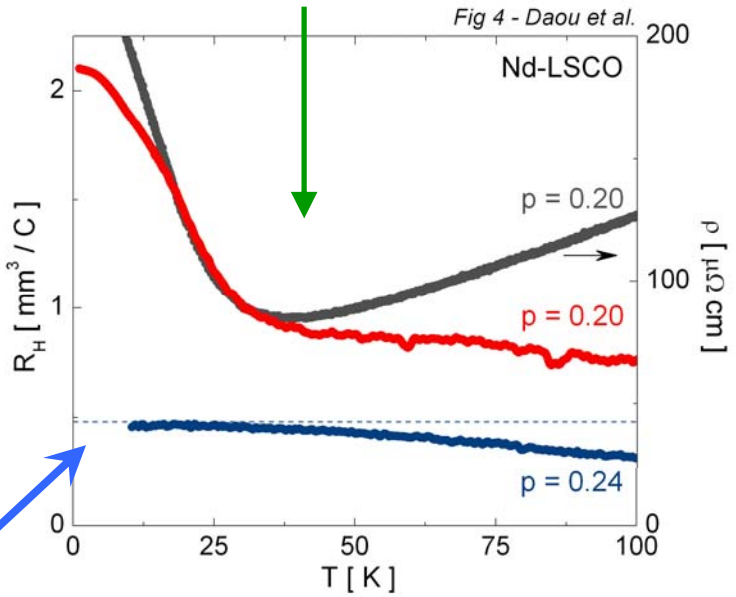
R. Daou *et al*. (2008)

Fermi surface transformation in Nd-LSCO





T_{NQR}

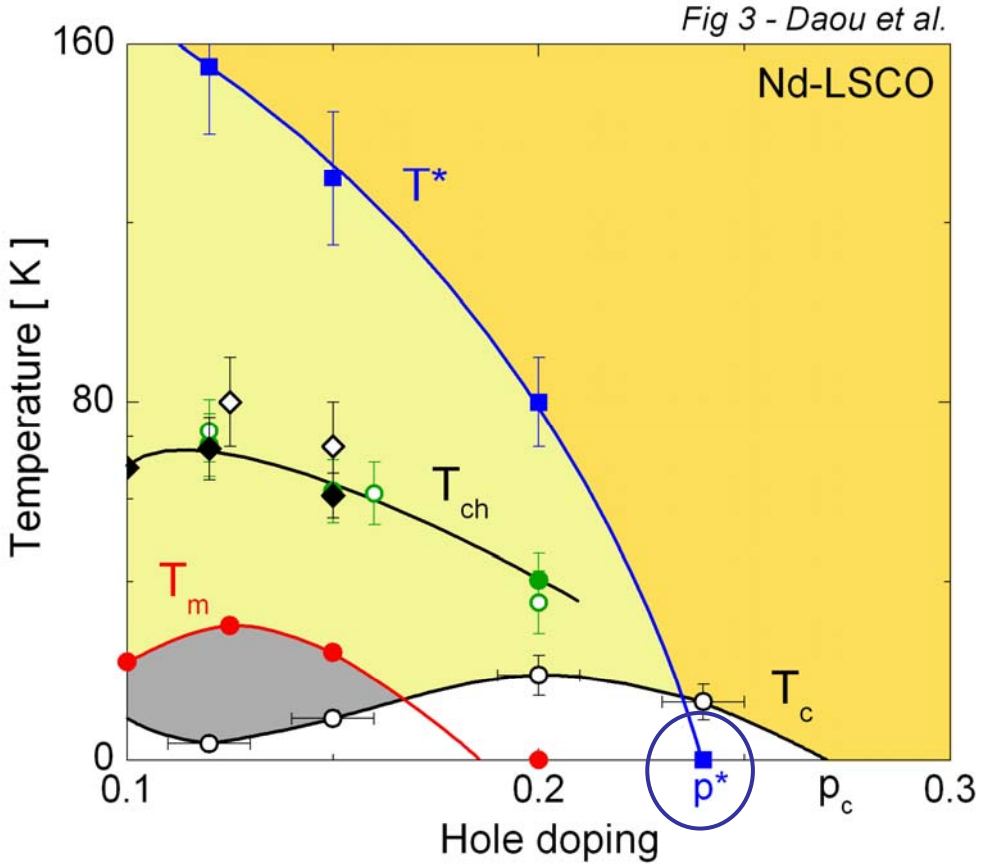


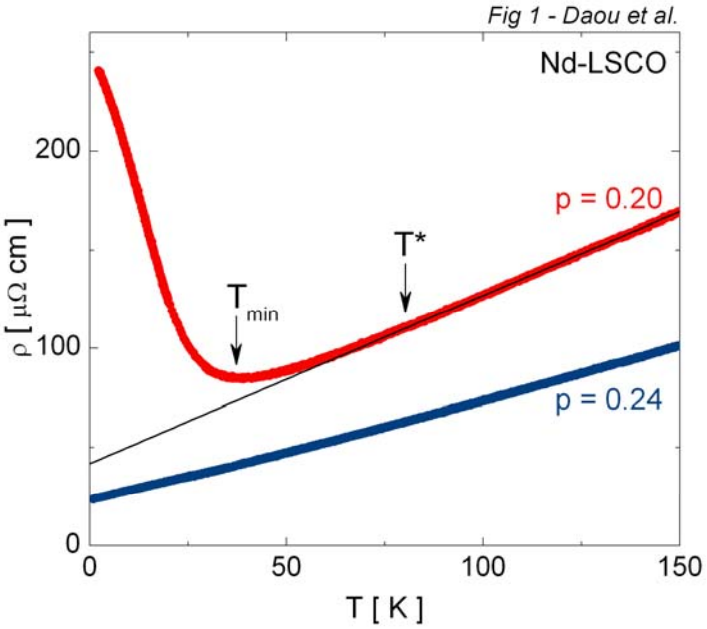
Cause of FS change :

“stripe” order

R. Daou *et al*. (2008)

Quantum Critical Point in Nd-LSCO

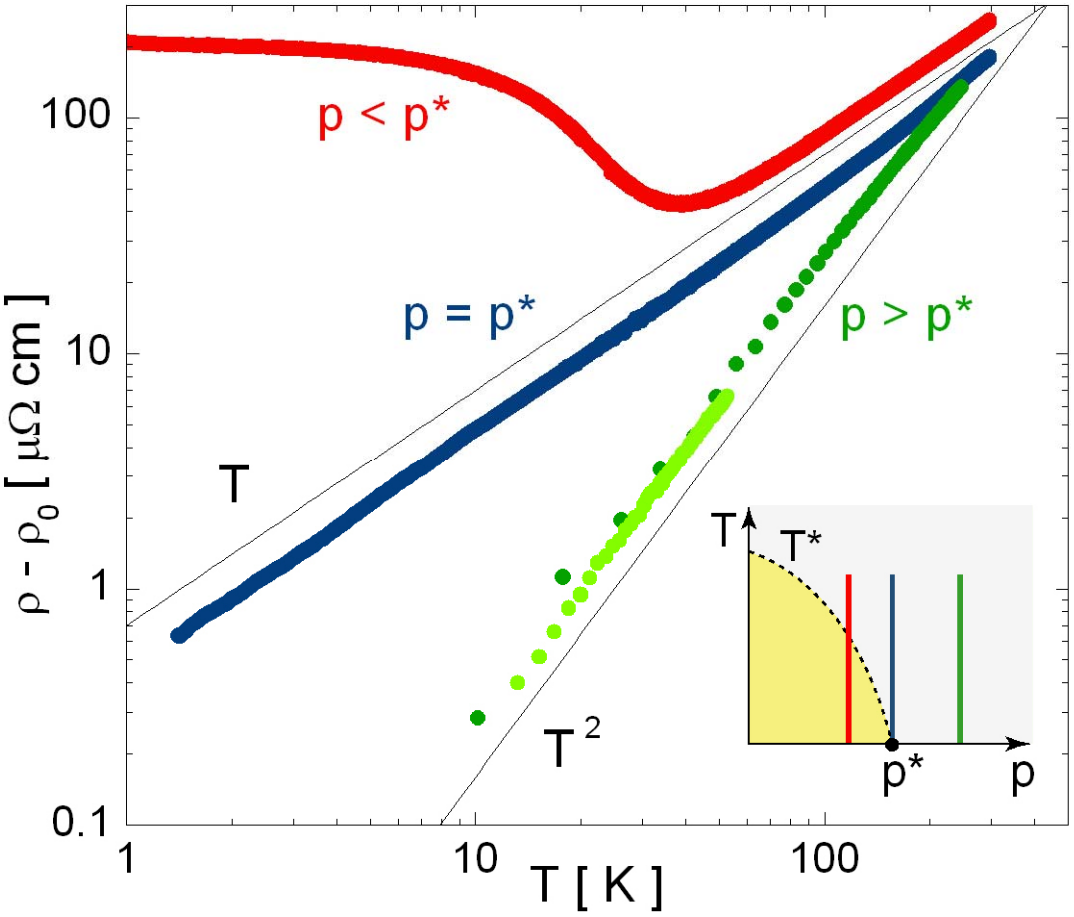


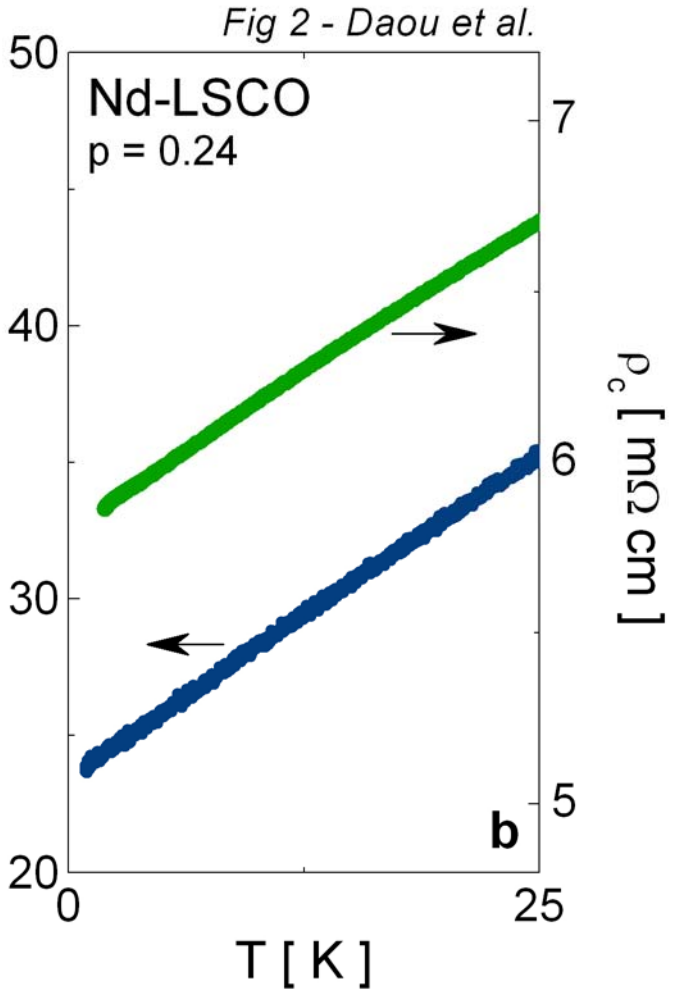


→ ***Quantum critical point***

R. Daou *et al*. (2008)

Quantum criticality in Nd-LSCO





***p* = 0.3** : LSCO from Nakamae *et al*., PRB 2003

→ Three regimes of quantum criticality

R. Daou *et al*. (2008)

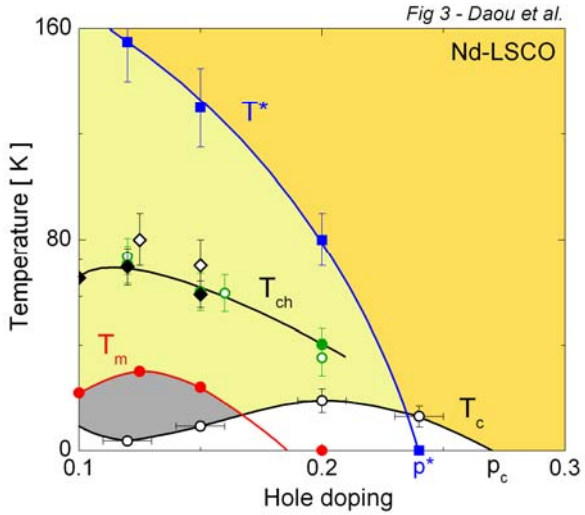
Summary – Part II

Nd-LSCO

Fermi surface reconstruction
by “stripe” order

Quantum critical point inside SC region

Pseudogap phase = “stripe” phase



Summary – Part II

Nd-LSCO

Fermi surface reconstruction
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Quantum critical point inside SC region

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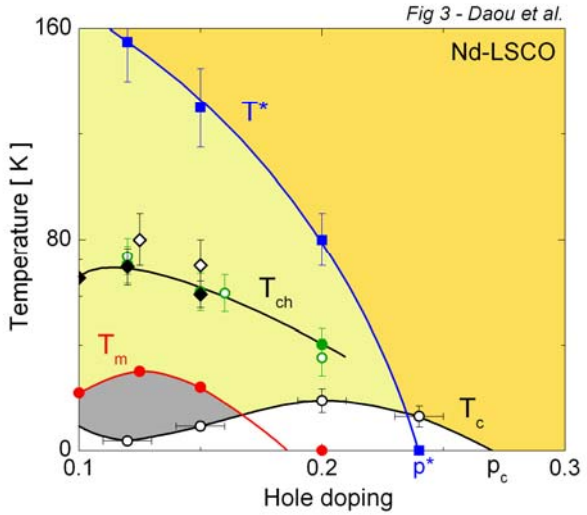
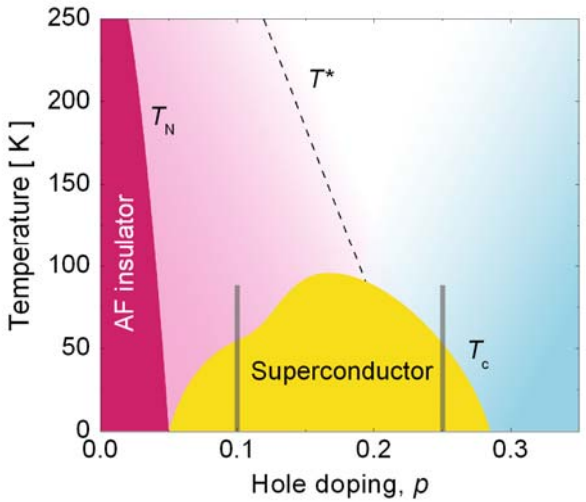


YBCO

Similar : T^*, R_H drop, $\rho \sim T$, T_c dip, …

Pseudogap phase = fluctuating stripes ?



The End