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*2 - 13 August 2010*

**Correlation Between Spin Fluctuations and Pairing in Electron-doped Cuprates**

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University of Maryland  
College Park  
U.S.A.*

# Correlation between Spin fluctuations and Pairing in Electron-doped Cuprates

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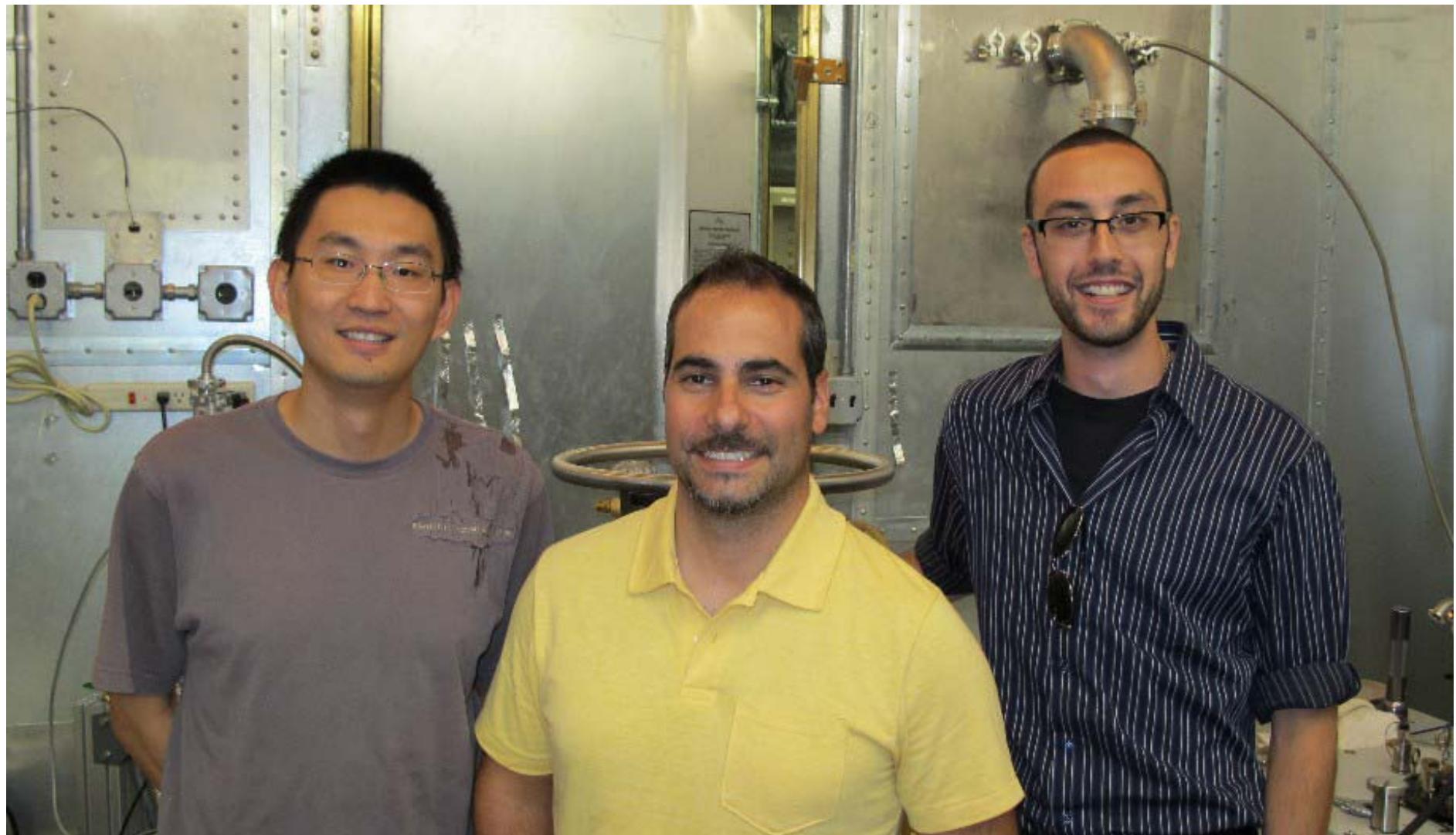
With: Kui Jin, N. P. Butch, K. Kirshenbaum, P. Bach and  
Johnpierre Paglione

ICTP Workshop, Trieste 11 August 2010

Research partially  
supported by the NSF



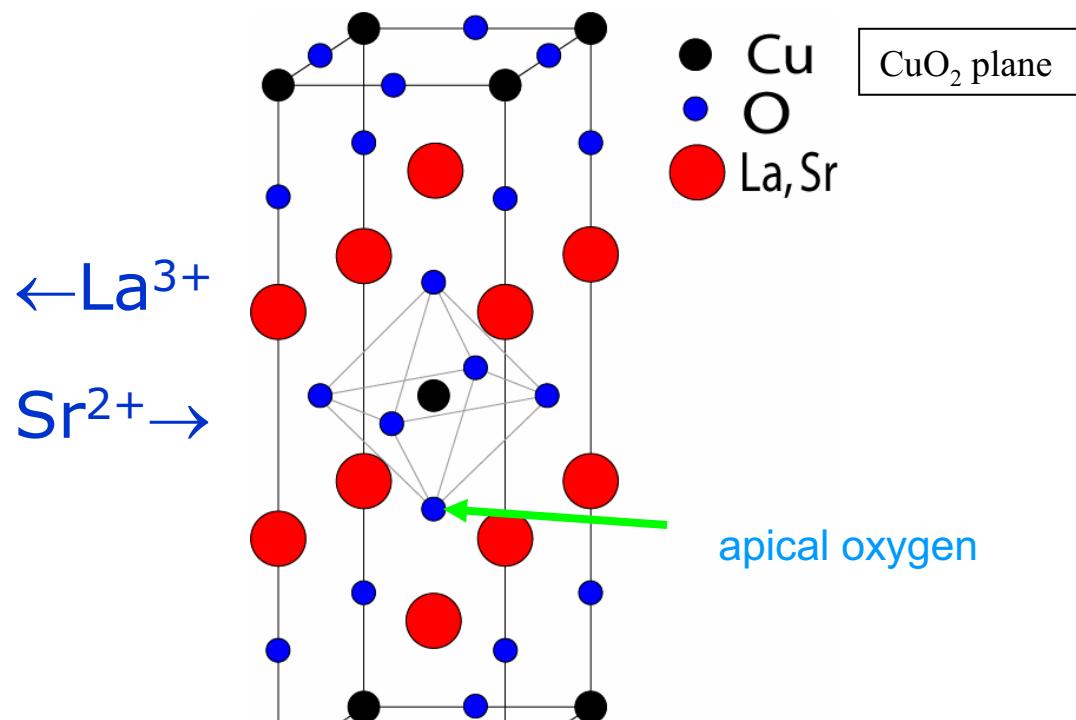
UNIVERSITY OF  
**MARYLAND**



Kui Jin

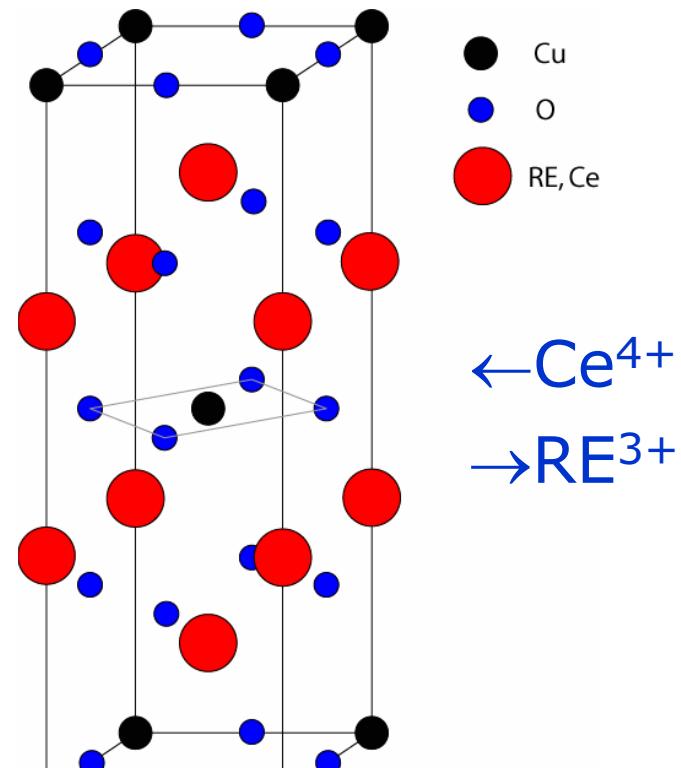
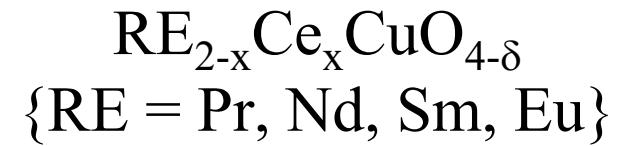
Johnpierre Paglione

Kevin Kirshenbaum



LSCO  
 $a = 3.79\text{\AA}$   
 $c = 13.19\text{\AA}$

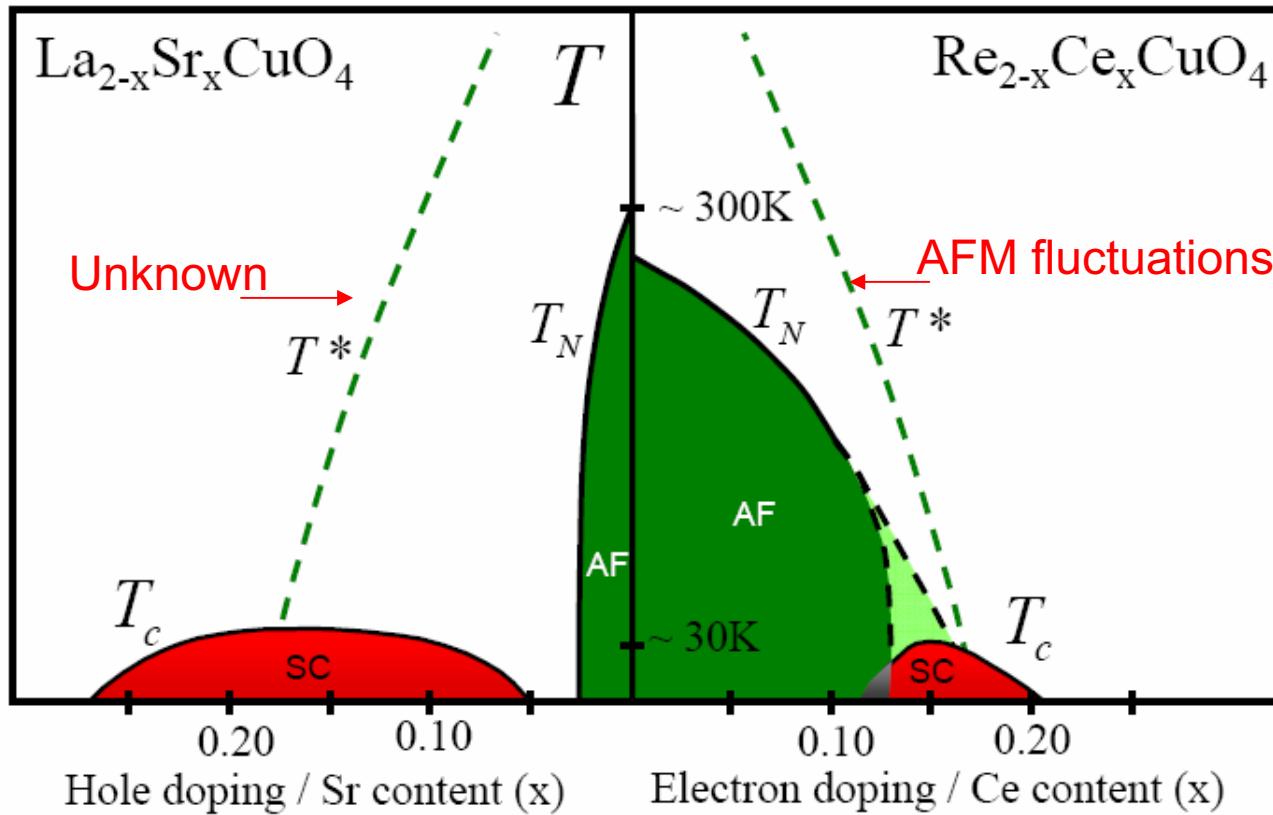
Hole-doped



PCCO  
 $a = 3.95\text{\AA}$   
 $c = 12.13\text{\AA}$

Electron-doped

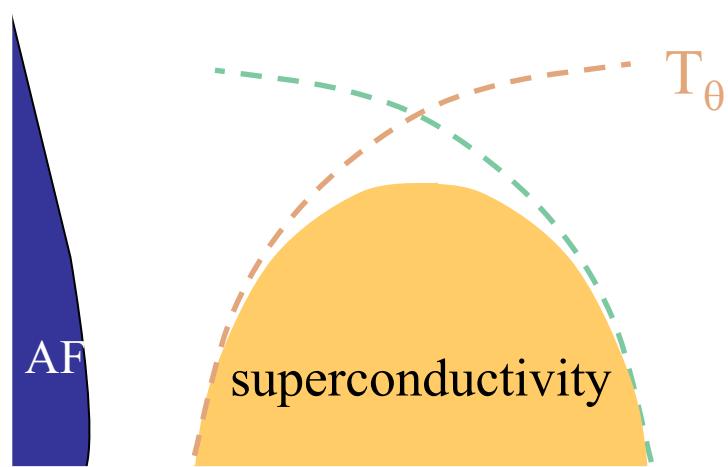
# Phase diagram of the cuprates



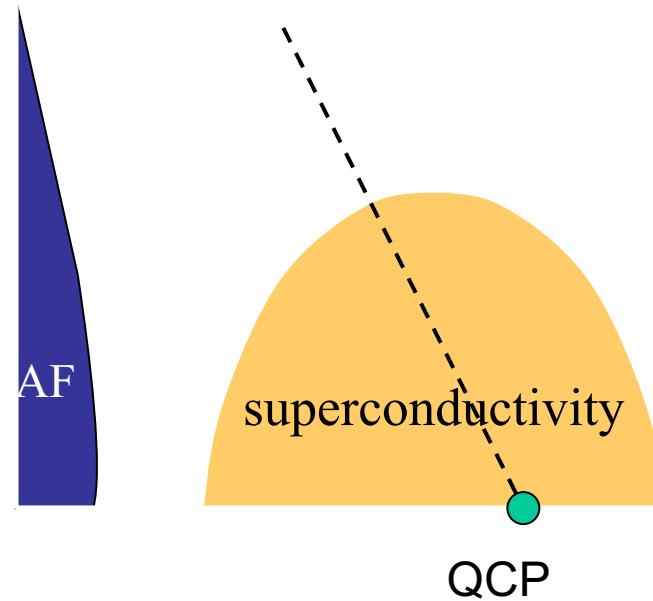
N.P. Armitage, P.Fournier and R.L. Greene, *to appear in RMP*  
Motoyama, et al. *Nature 445*, 186 (2007)

# Two theoretical approaches for the High $T_c$ cuprates

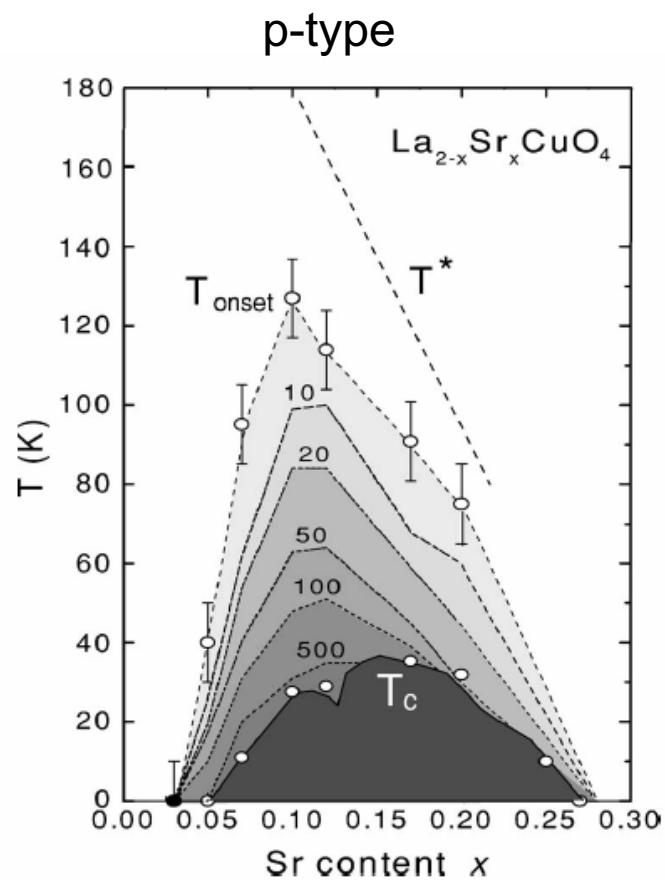
*Pairing and Phase fluctuations*



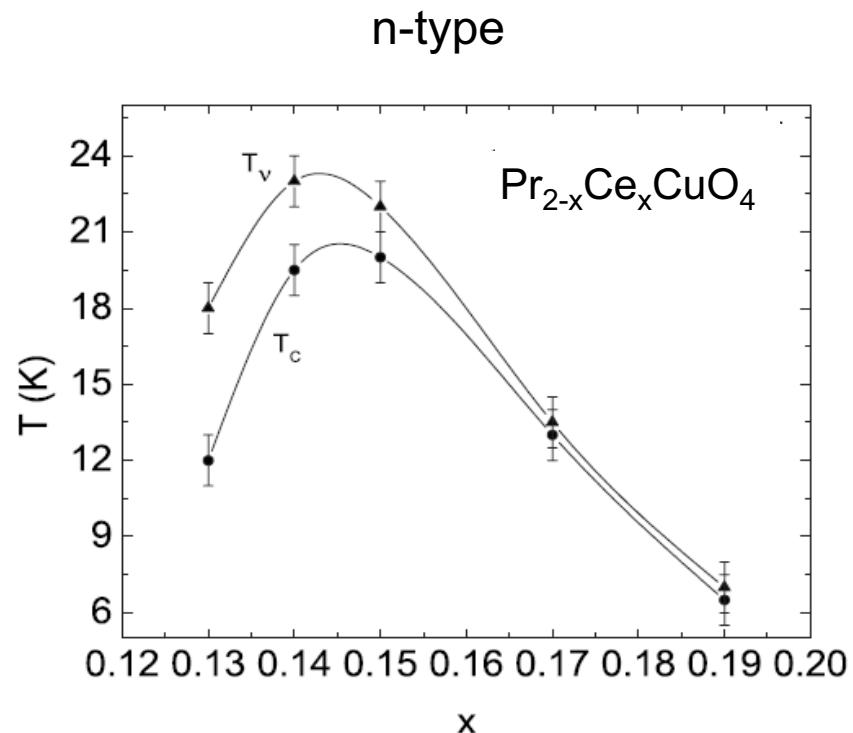
*Competing orders*



# Phase Fluctuations in Cuprate Superconductors



Wang et al., PRB 73, 024510 (2006)



P. Li and R. L. Greene, PRB 76, 174512 (2007)

# Polar Kerr-Effect Measurements of the High-Temperature $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$ Superconductor: Evidence for Broken Symmetry near the Pseudogap Temperature

Jing Xia,<sup>1,2</sup> Elizabeth Schemm,<sup>1,2</sup> G. Deutscher,<sup>3</sup> S. A. Kivelson,<sup>1,2</sup> D. A. Bonn,<sup>4</sup> W. N. Hardy,<sup>4</sup> R. Liang,<sup>4</sup> W. Siemons,<sup>2,5</sup> G. Koster,<sup>2,5</sup> M. M. Fejer,<sup>6</sup> and A. Kapitulnik<sup>1,2,6</sup>

PRL 100, 127002 (2008)

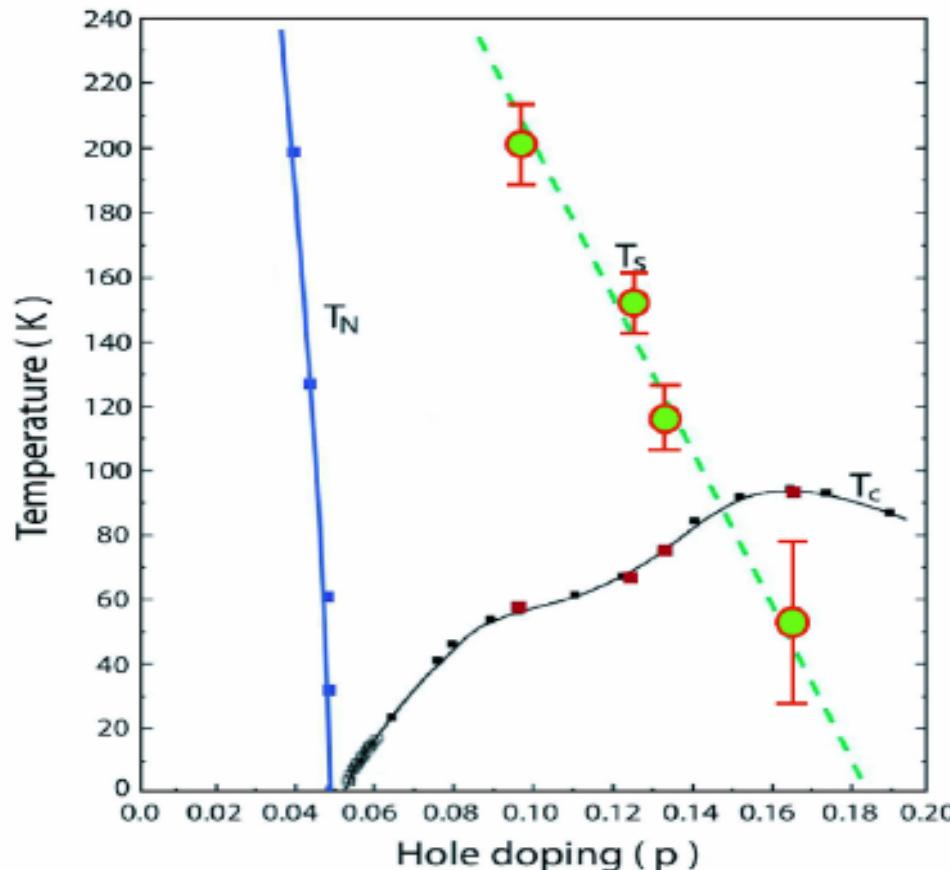
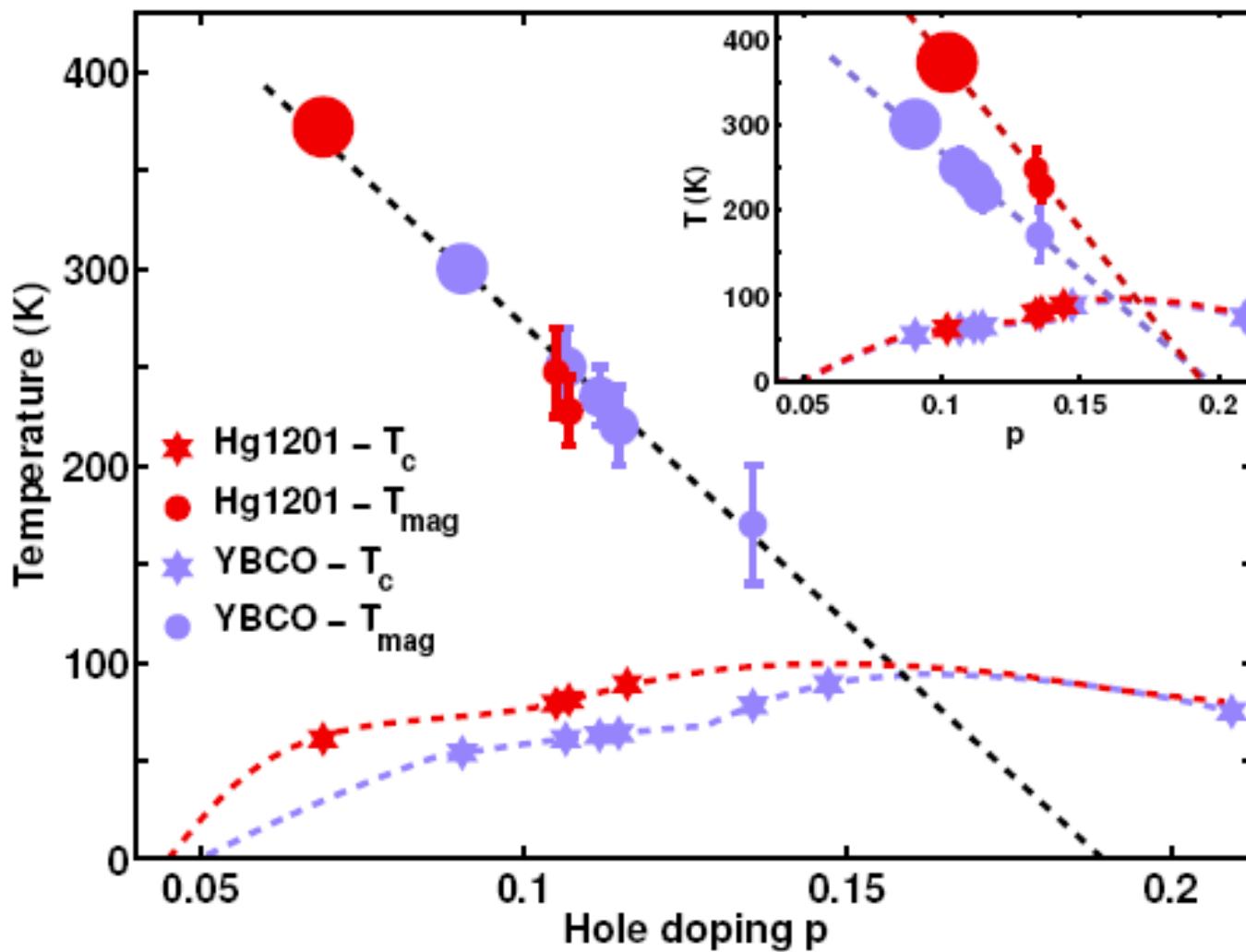


FIG. 1 (color online). The onset of the Kerr-effect signal,  $T_s$  (circles), and  $T_c$  (red squares) for the  $\text{YBa}_2\text{Cu}_3\text{O}_{6+x}$  samples reported in this Letter. Also shown are  $T_c(p)$  (from [12]) and  $T_N(p)$  (from [22]).

# Novel Magnetic Order with Broken Time-reversal Symmetry

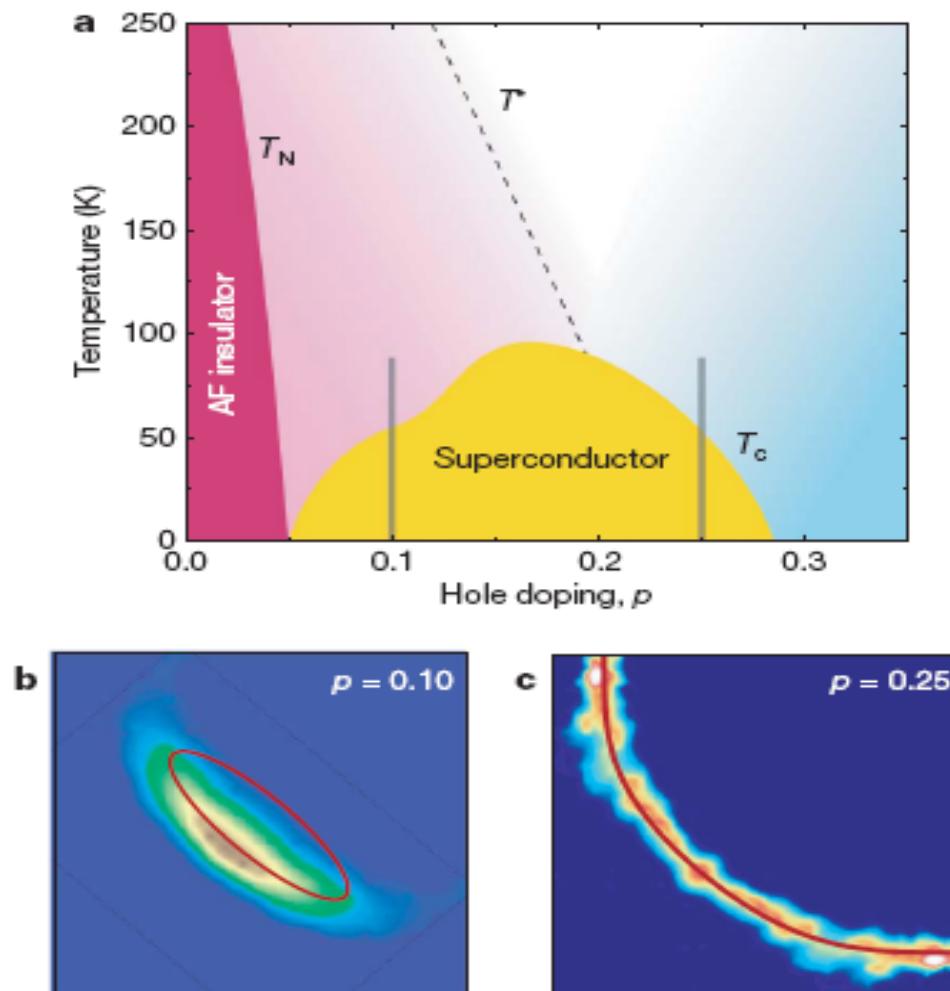
Li et al., Nature 455, 372 (08)



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

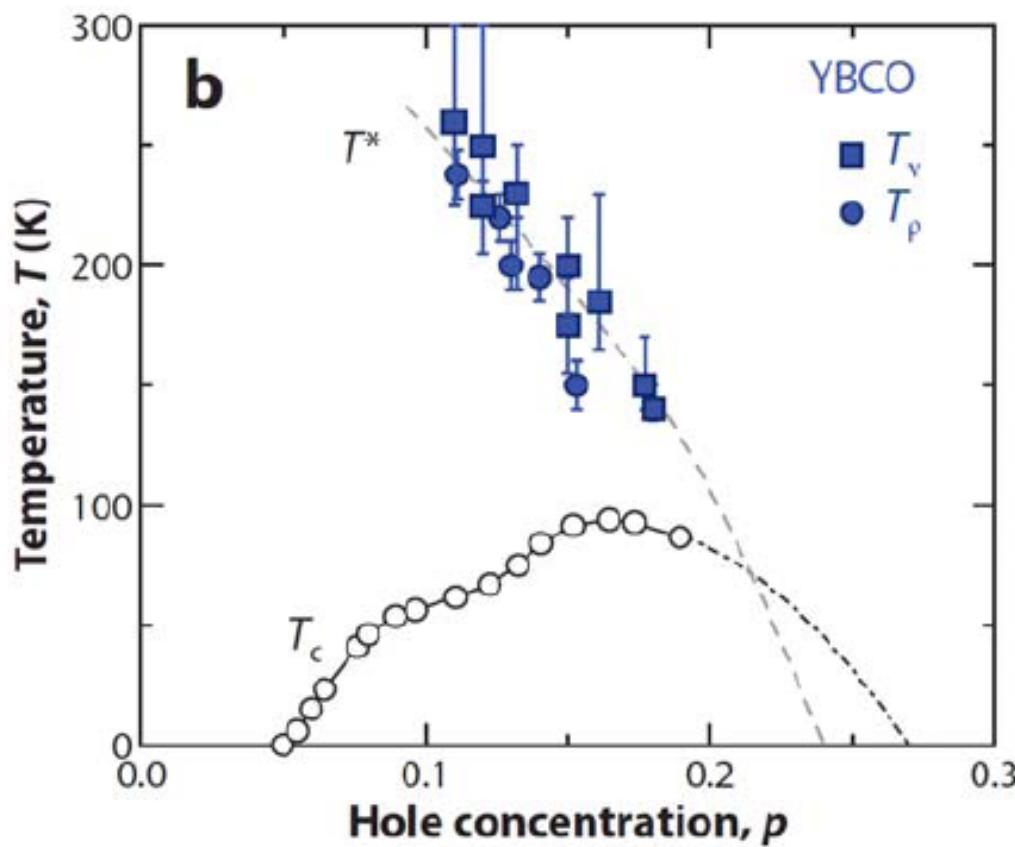
Nicolas Doiron-Leyraud<sup>1</sup>, Cyril Proust<sup>2</sup>, David LeBoeuf<sup>1</sup>, Julien Levallois<sup>2</sup>, Jean-Baptiste Bonnemaison<sup>1</sup>, Ruixing Liang<sup>3,4</sup>, D. A. Bonn<sup>3,4</sup>, W. N. Hardy<sup>3,4</sup> & Louis Taillefer<sup>1,4</sup>

Nature 447, 565 (2007)



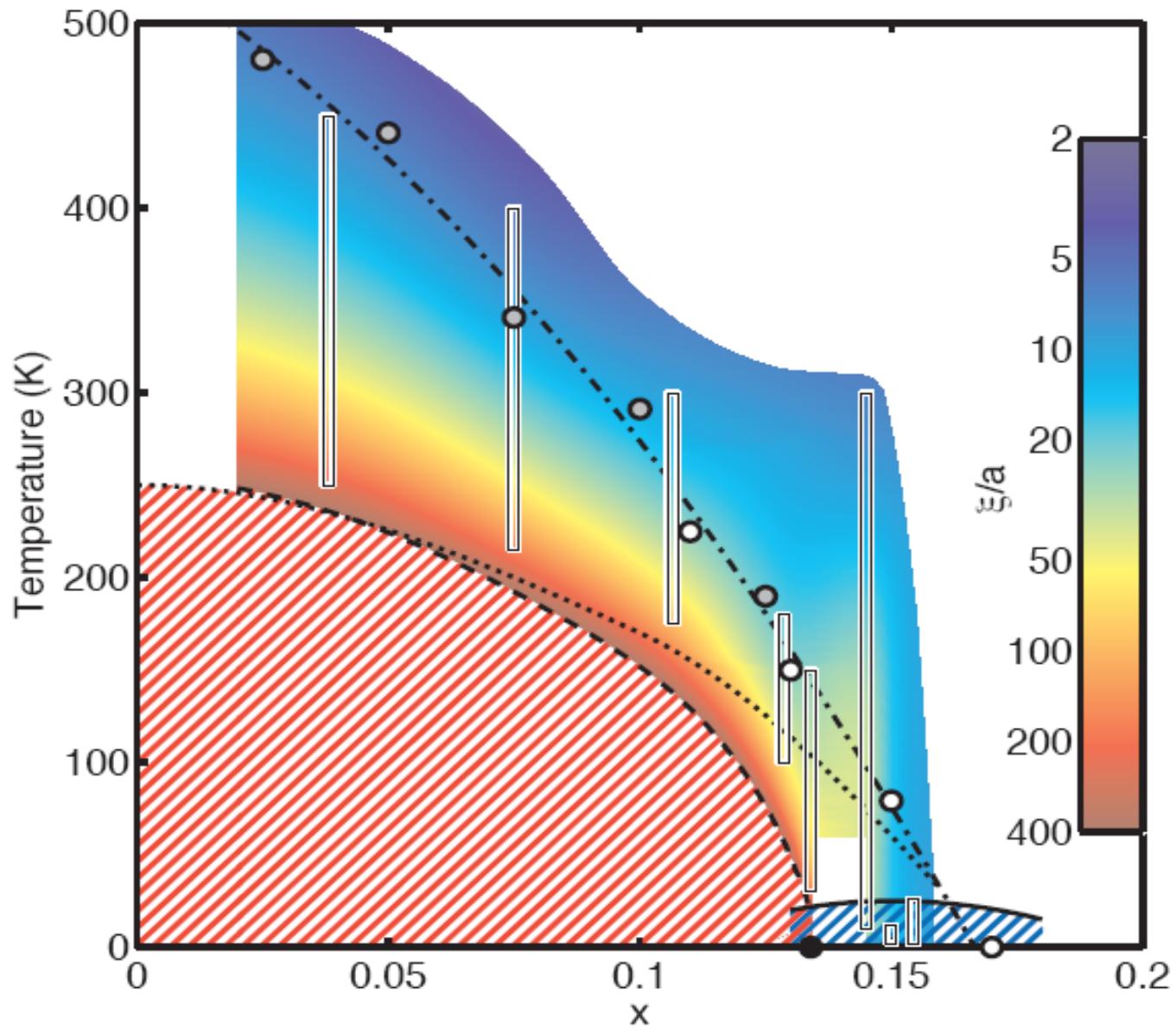
# Broken rotational symmetry in the pseudogap phase of a high- $T_c$ superconductor

Daou et al., Nature 463, 519 (2010)



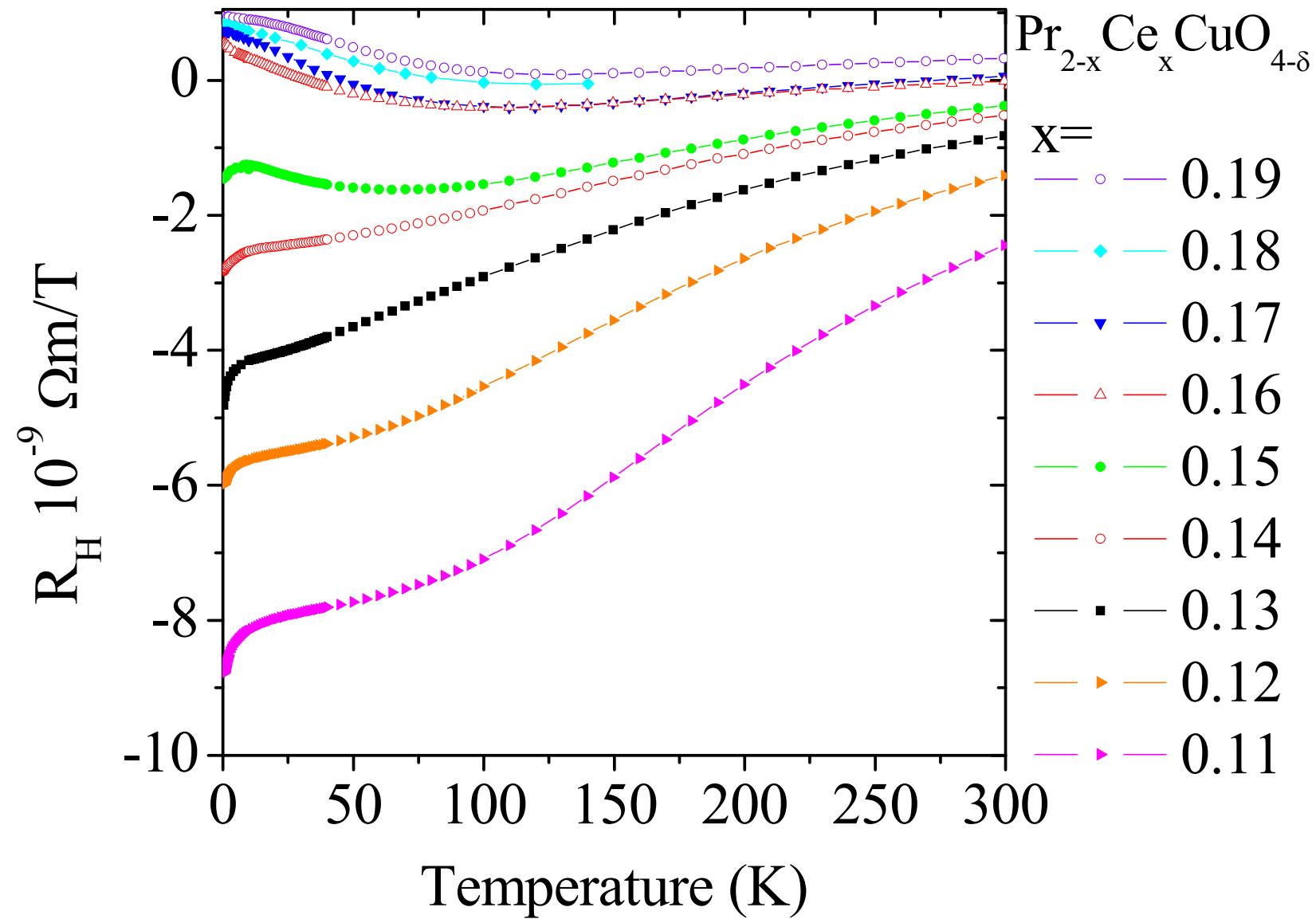
# Neutron Scattering from $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$ (NCCO)

Motoyama et al., Nature 445, 186 (2007)

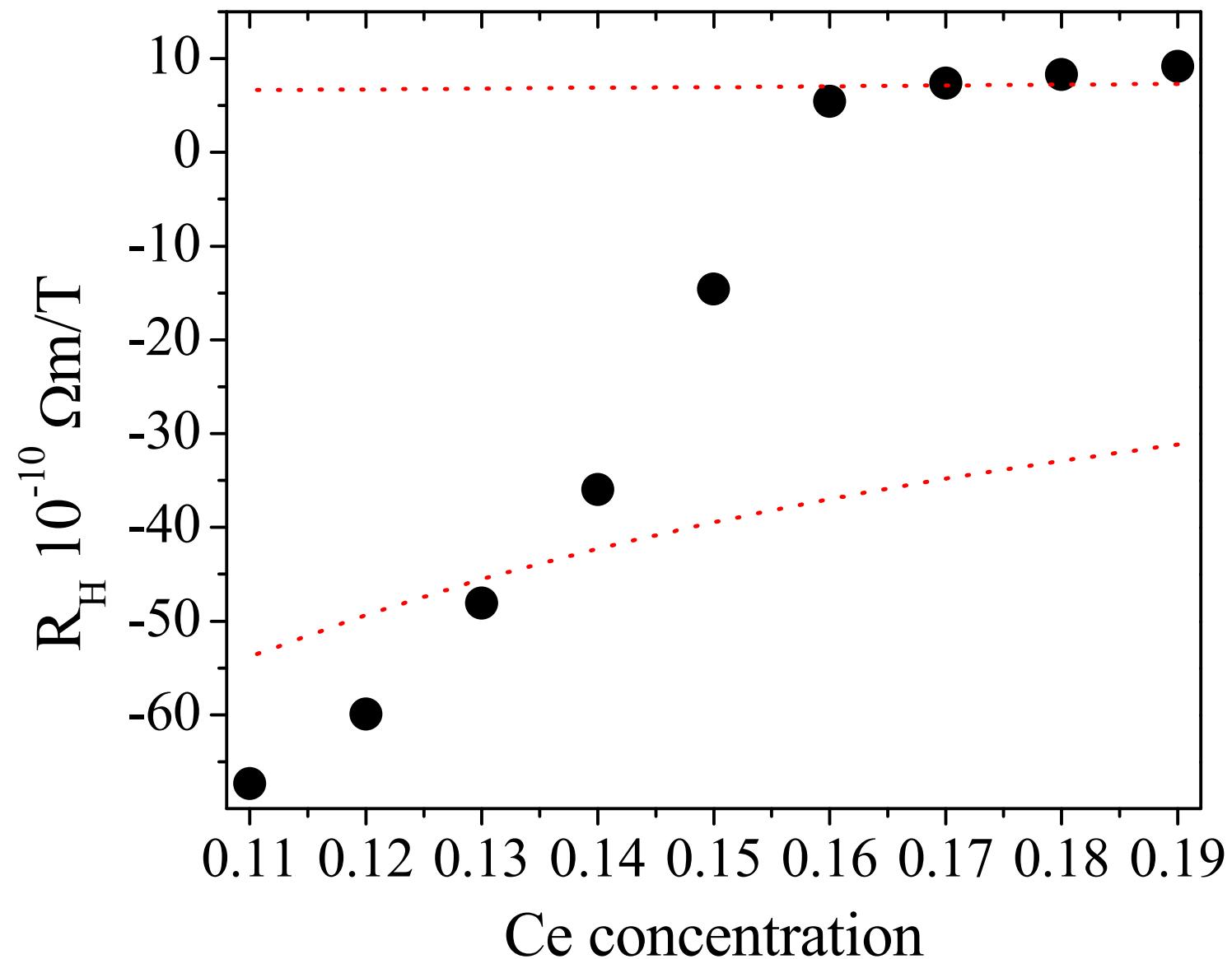


## Hall Effect

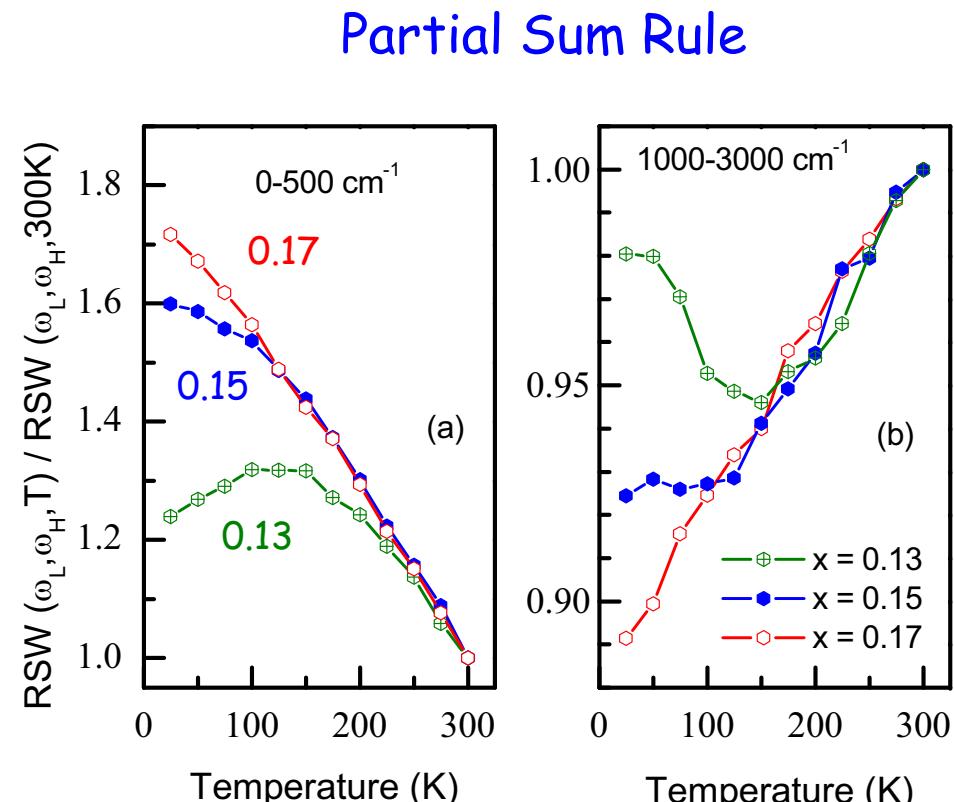
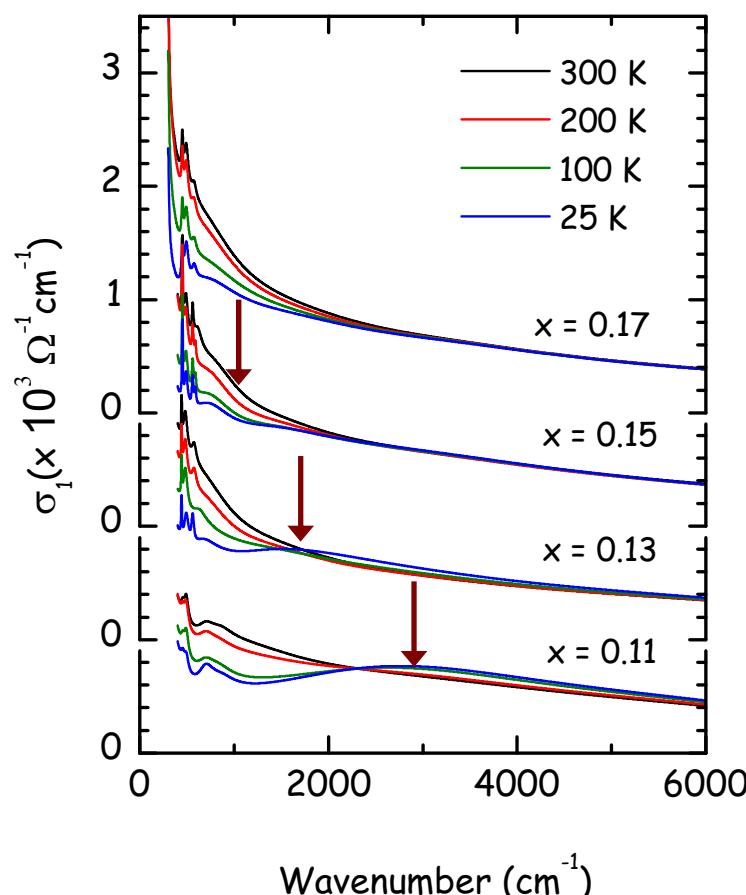
Dagan et al. PRL 2004



$R_H$  at 350mK



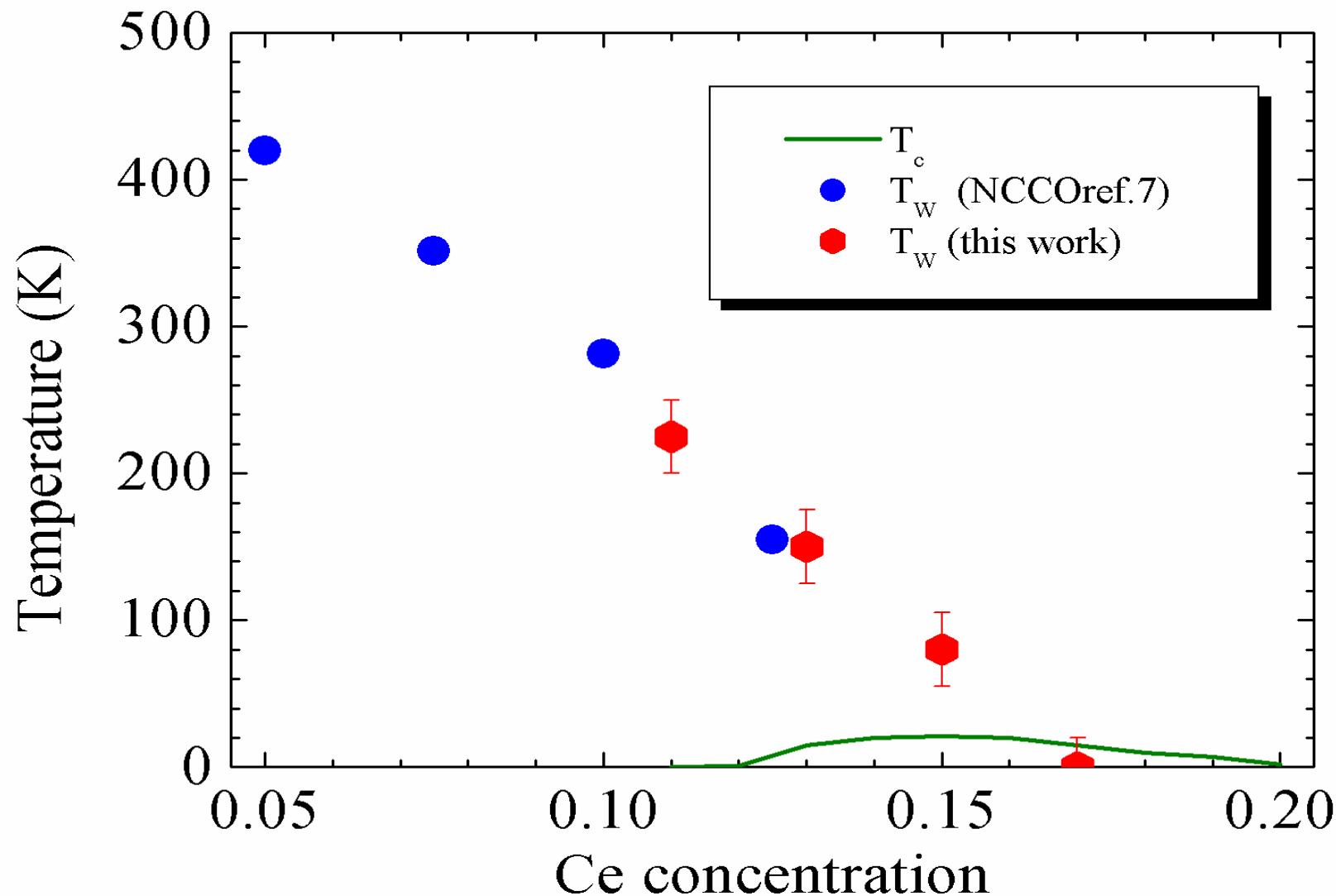
# Optical Conductivity & Normal State Gap in Pr<sub>2-x</sub>Ce<sub>x</sub>CuO<sub>4</sub> (PCCO)



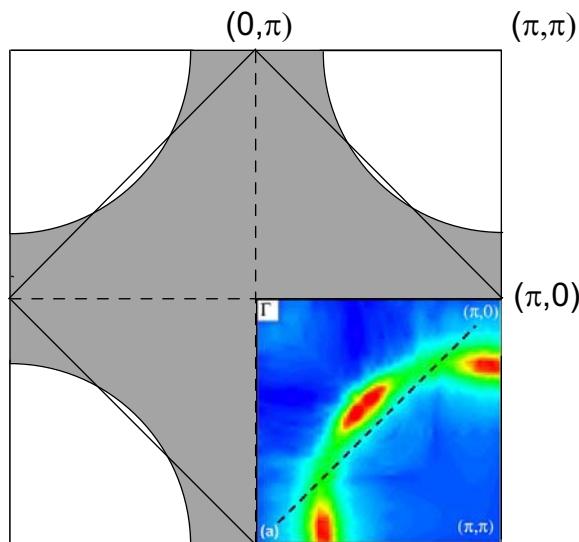
Spectral weight transfer to higher energy

Zimmers et al. (ESPCI)

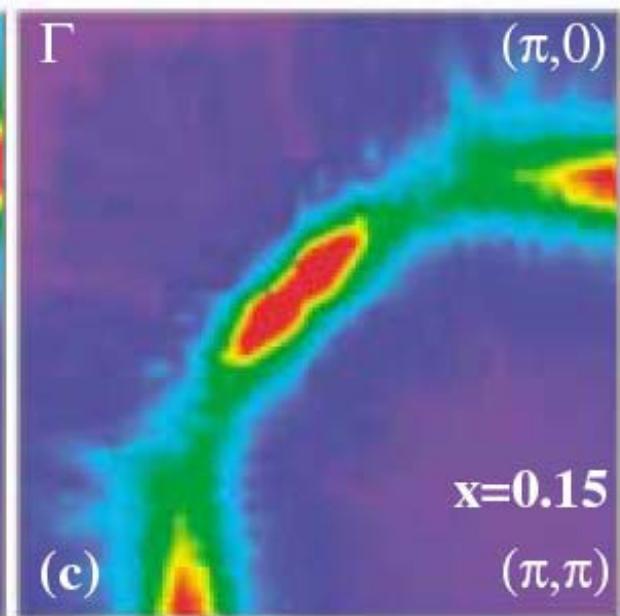
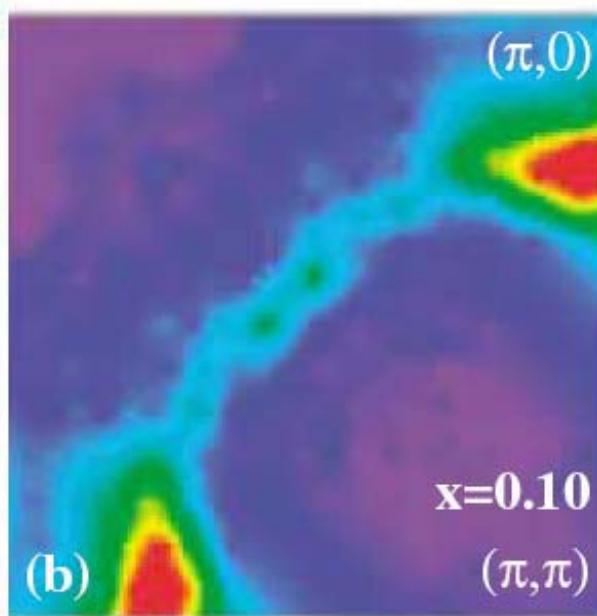
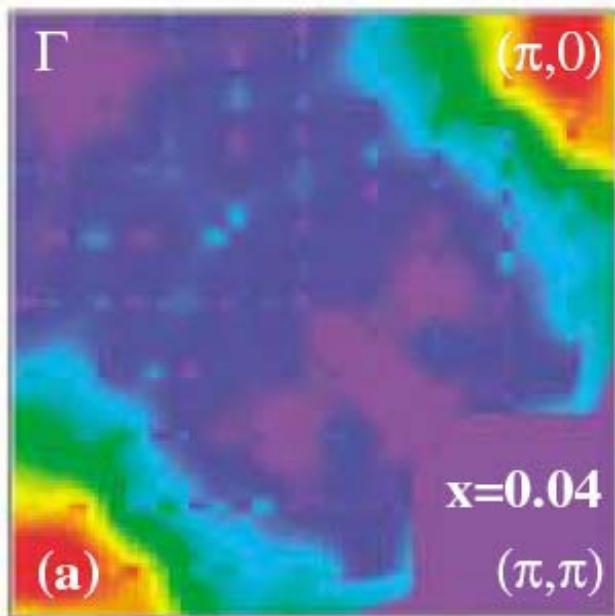
Europhys. Lett 70, 225 (2005)



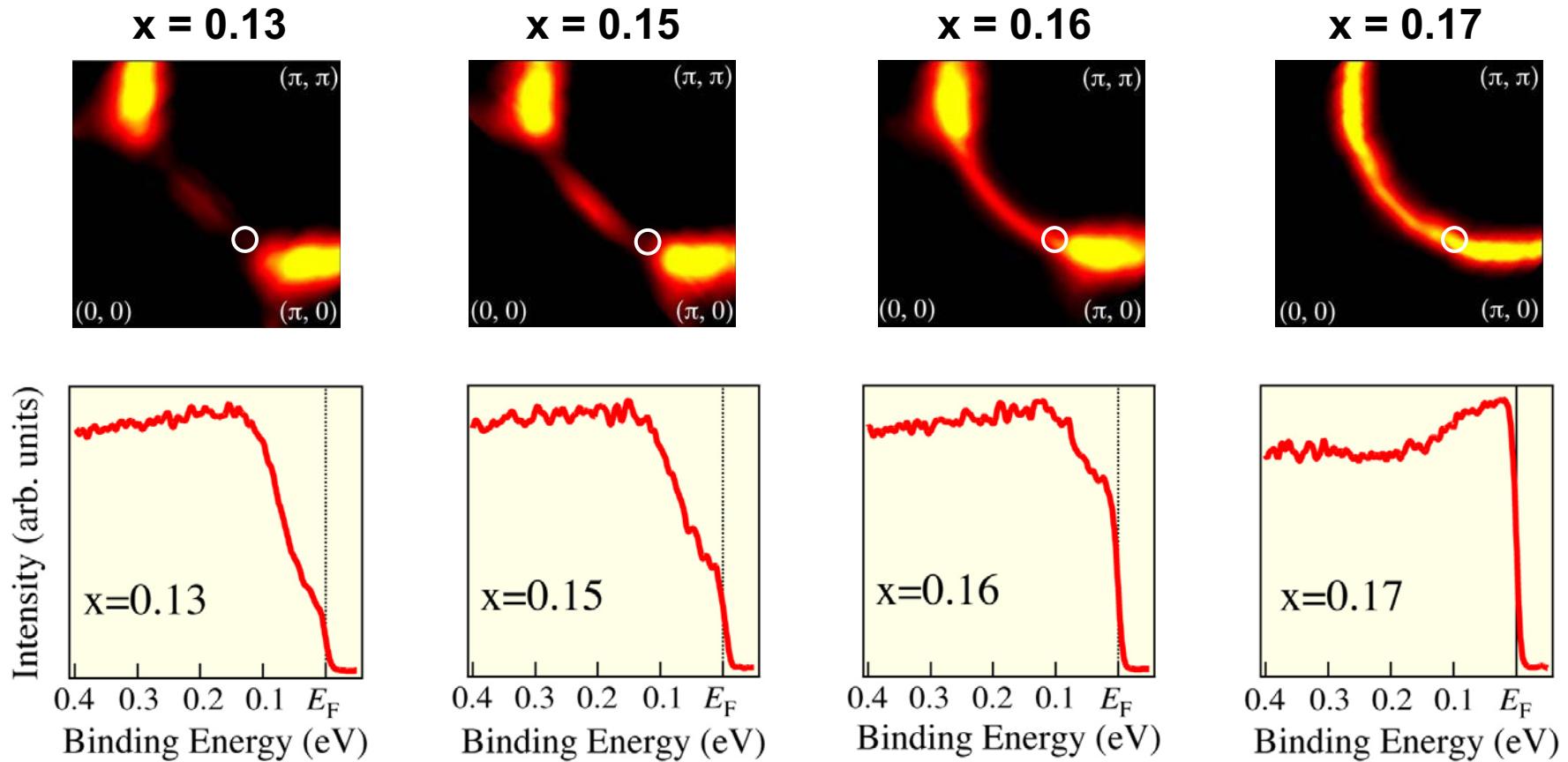
# Fermi surface: $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$



N.P. Armitage *et. al.*  
*PRL* **86** 1126 (2001),  
*PRL* **88**, 257001 (2002).



# Doping dependence of ARPES spectrum at the hot spot in NCCO at 30K



Matsui et al., PRB 75, 224514 (07)

# Shubnikov-de Haas Oscillations in $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_4$ for $x = 0.15-0.17$

Helm et al., PRL 103, 157002 (09)

These results suggest  $(\pi/a, \pi/a)$  reconstruction of the FS for  $x < 0.17$

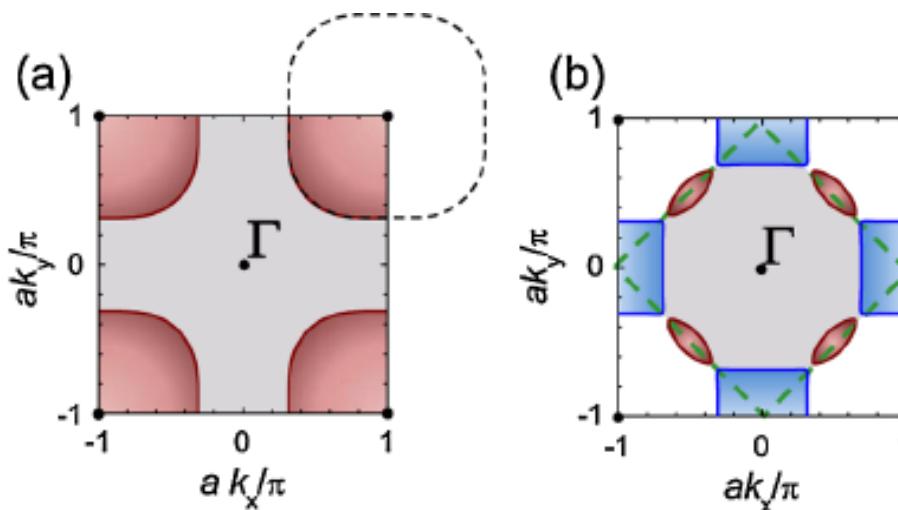


FIG. 4 (color online). (a) Single-component Fermi surface with a cross-sectional area equal to  $\approx 41\%$  of the first Brillouin zone corresponding to  $x = 0.17$ . The dashed line shows the large closed orbit, in the extended zone representation, responsible for the SdH oscillations. (b) Reconstructed Fermi surface comprising one electron and two hole pockets in the reduced Brillouin zone (dashed line). The hole pockets are responsible for the slow oscillations observed on the  $x = 0.15$  and 0.16 crystals.

# Spin density wave model explains

Optics:

Lin and Millis, PRB 72, 224517 (05)

Hall effect:

Lin and Millis, PRB 72, 214506 (05)

Nernst effect

Hackl and Sachdev, PRB 79, 235124 (09)

Also ARPES and SdH oscillations

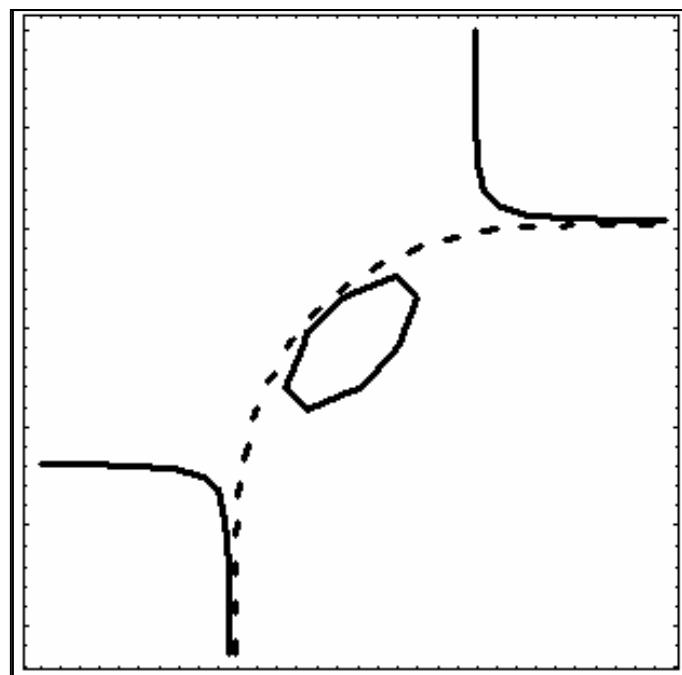
$$\varepsilon_{\mathbf{k}} = -2t(\cos ak_x + \cos ak_y) + 4t' \cos ak_x \cos ak_y - 2t''(\cos 2ak_x + \cos 2ak_y) + \mu, \quad t = 0.38 \text{ eV}, t' = 0.32t, t'' = 0.5t'$$

$$\varepsilon_{\mathbf{k}}^{\pm} = \frac{\varepsilon_{\mathbf{k}} + \varepsilon_{\mathbf{k}+\mathbf{Q}}}{2} \pm \sqrt{\left(\frac{\varepsilon_{\mathbf{k}} - \varepsilon_{\mathbf{k}+\mathbf{Q}}}{2}\right)^2 + \Delta^2}. \quad (3)$$

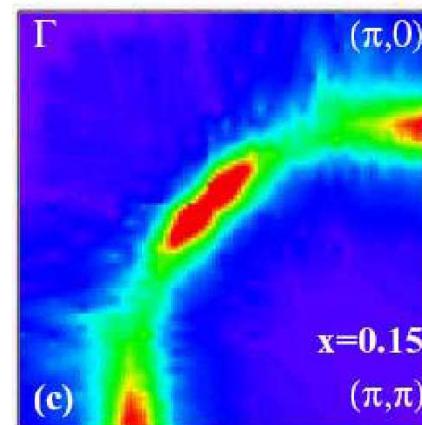
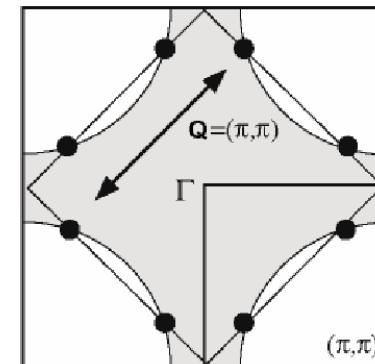
Here,  $\mathbf{Q} = (\pi/a, \pi/a)$  is the superstructure wave vector and  $\Delta$  is the energy gap between the lower and upper bands determined by the strength of the superstructure potential.

# Spin Density Wave in PCCO

$\Gamma$

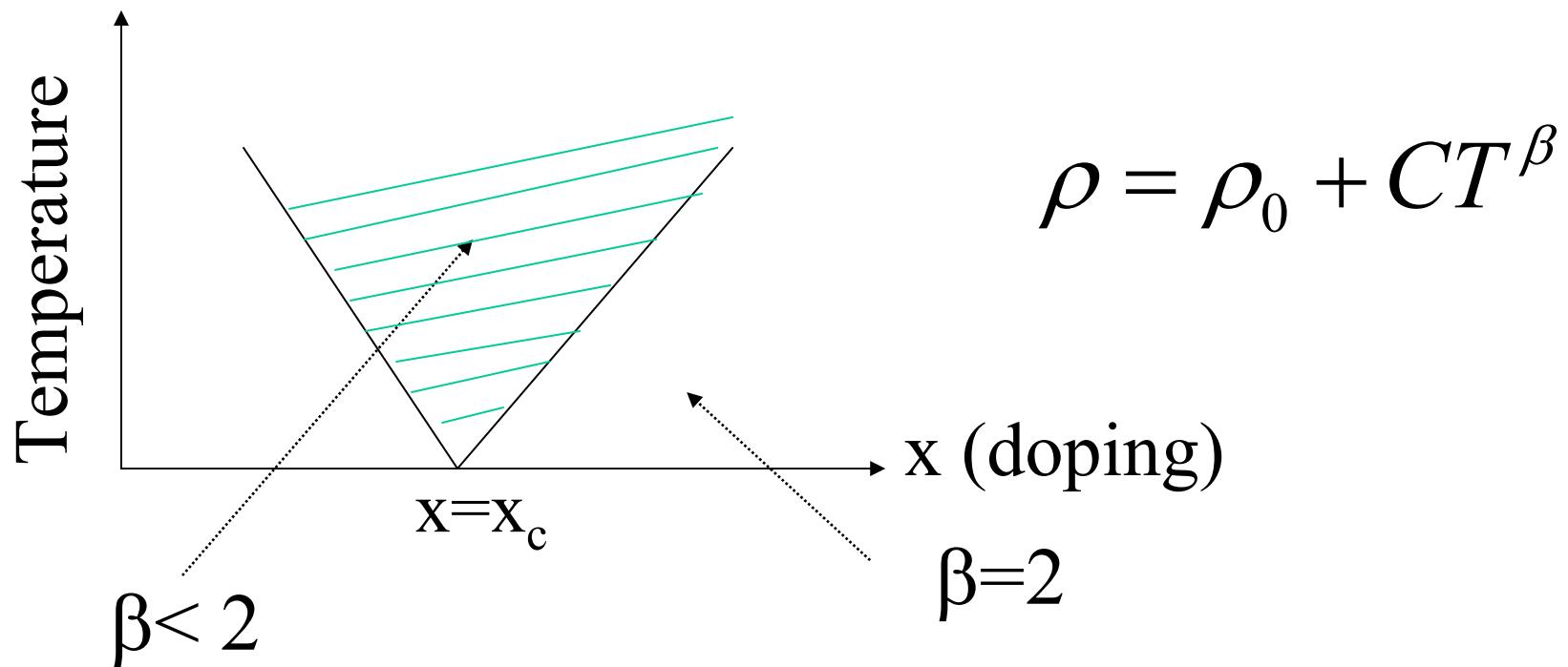


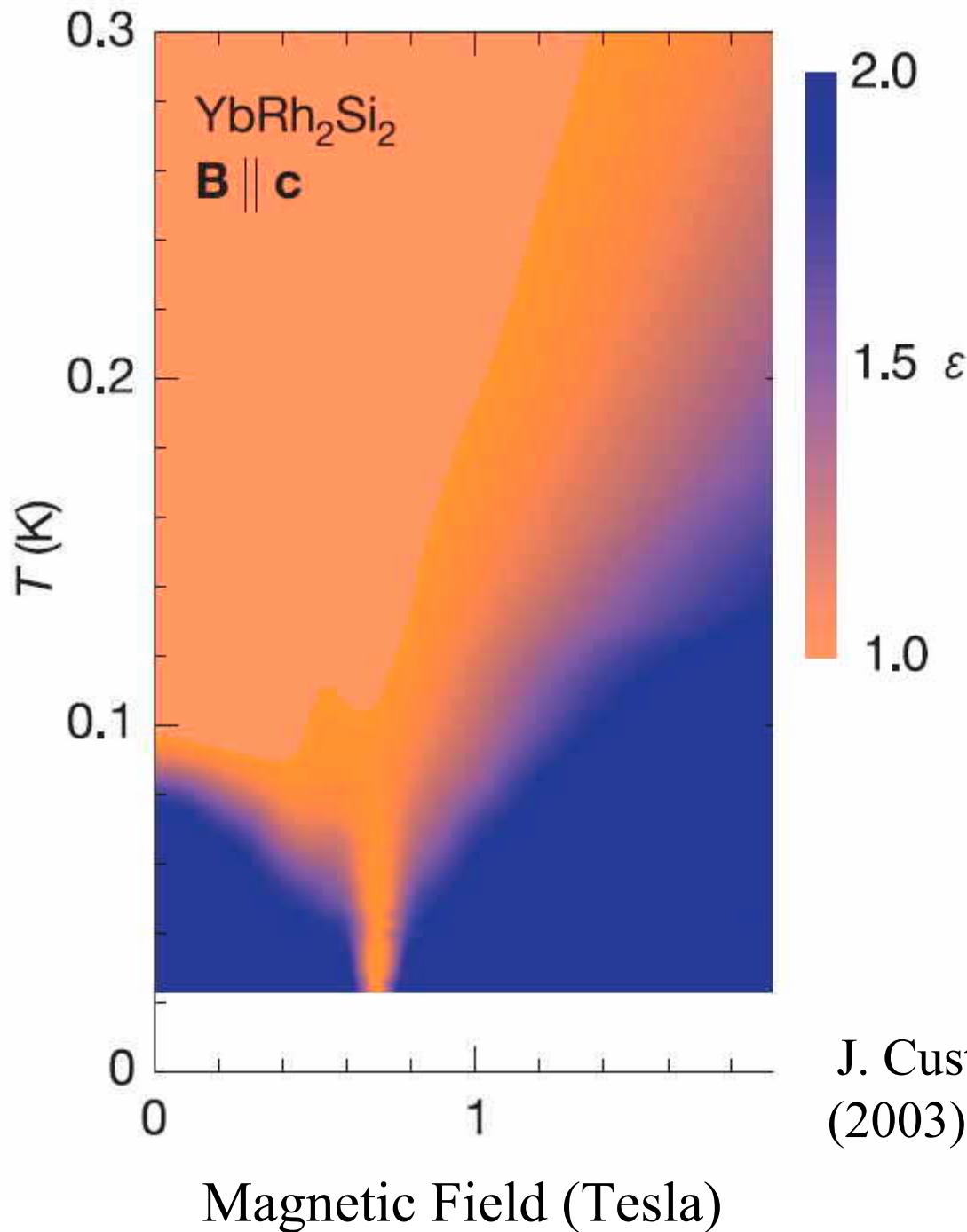
$(\pi,\pi)$



$x=0.15$

# Expected behavior for resistivity near an AFM QCP

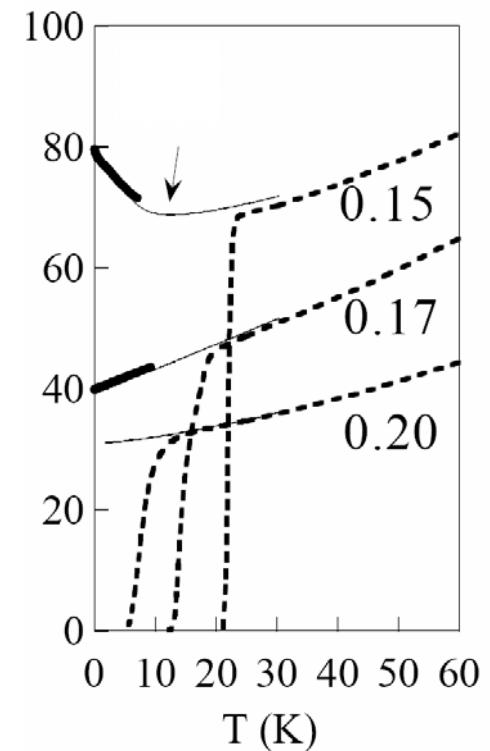
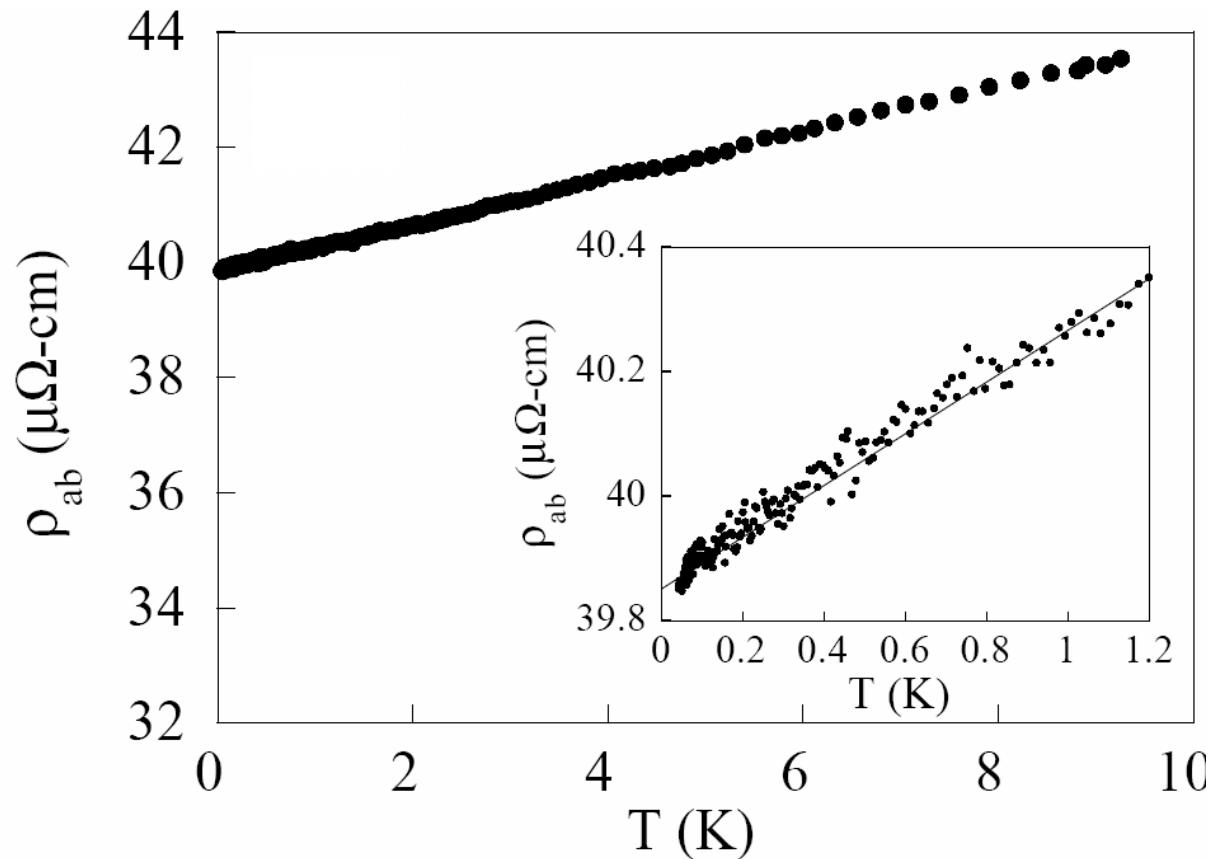




Example of  
AFM to PM  
Quantum  
phase  
transition

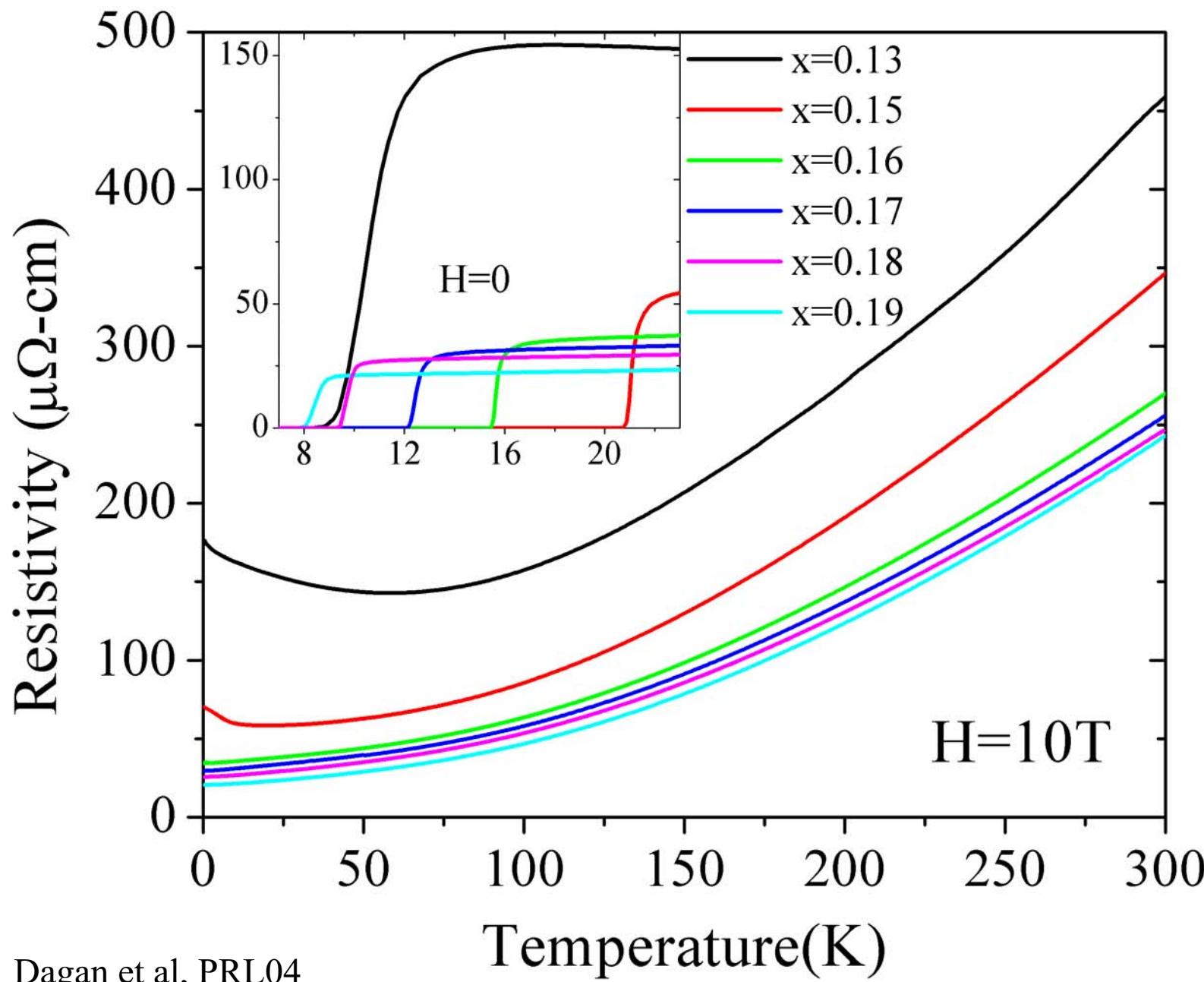
J. Custers *et al.*, Nature, **424**, 524  
(2003).

# Resistivity linear with temperature at a critical doping in PCCO

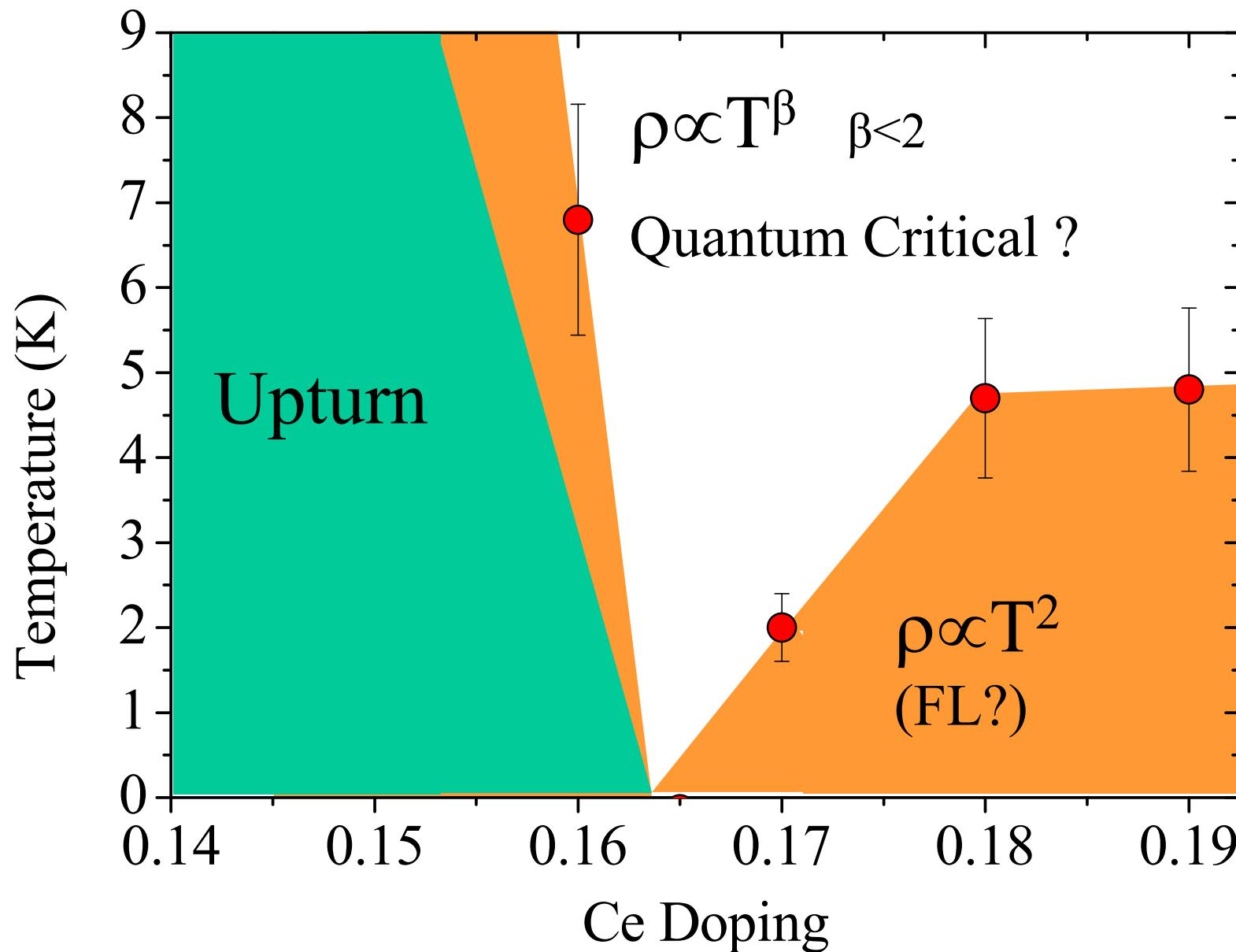


P. Fournier *et al.*, Phys. Rev. Lett. **81**, 4720 (1998).

# **ab-plane resistivity of $\text{Pr}_{2-x}\text{Ce}_x\text{CuO}_4$**

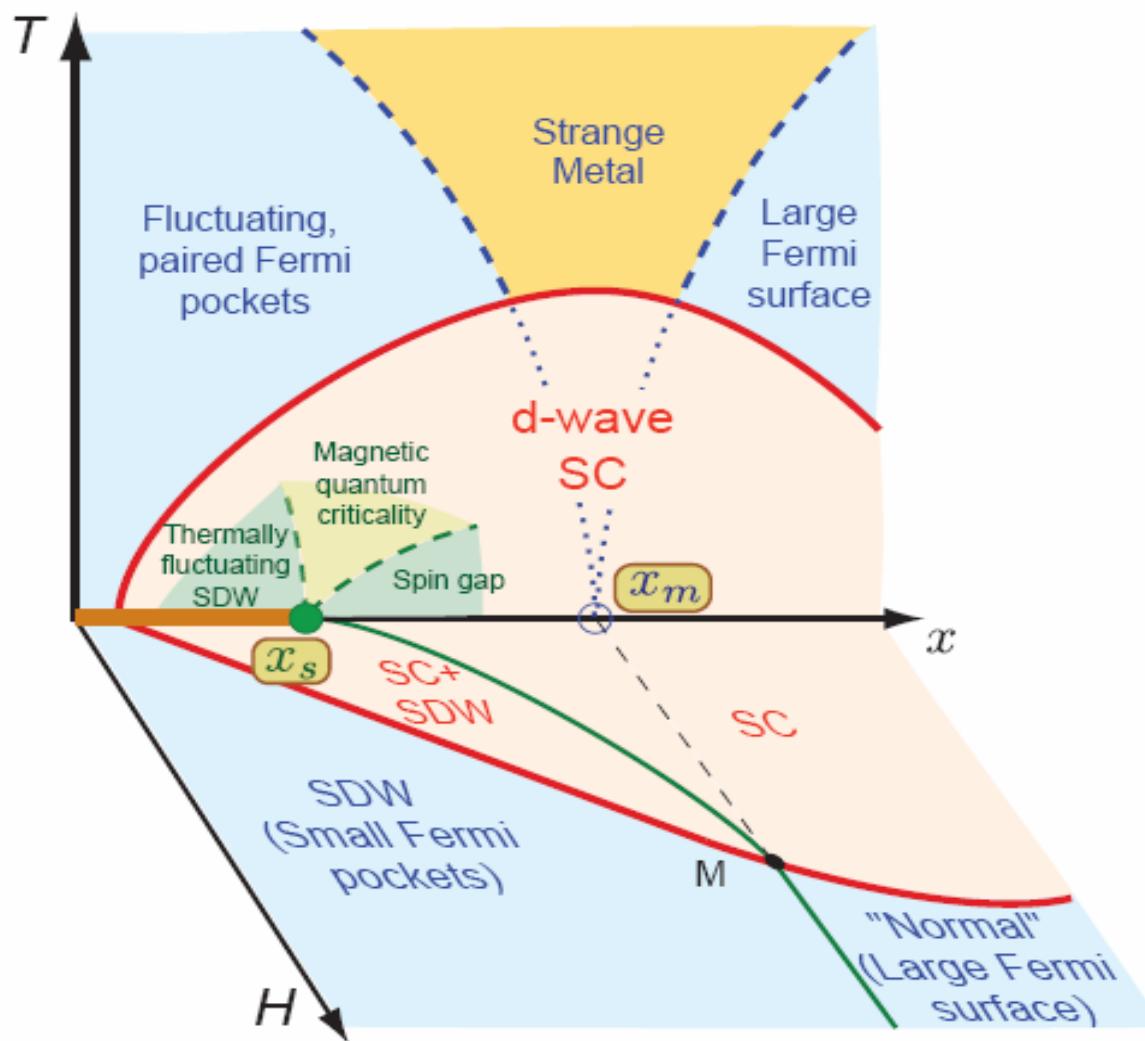


# PCCO Phase Diagram at 10T



Dagan et al, PRL 92, 167001(2004)

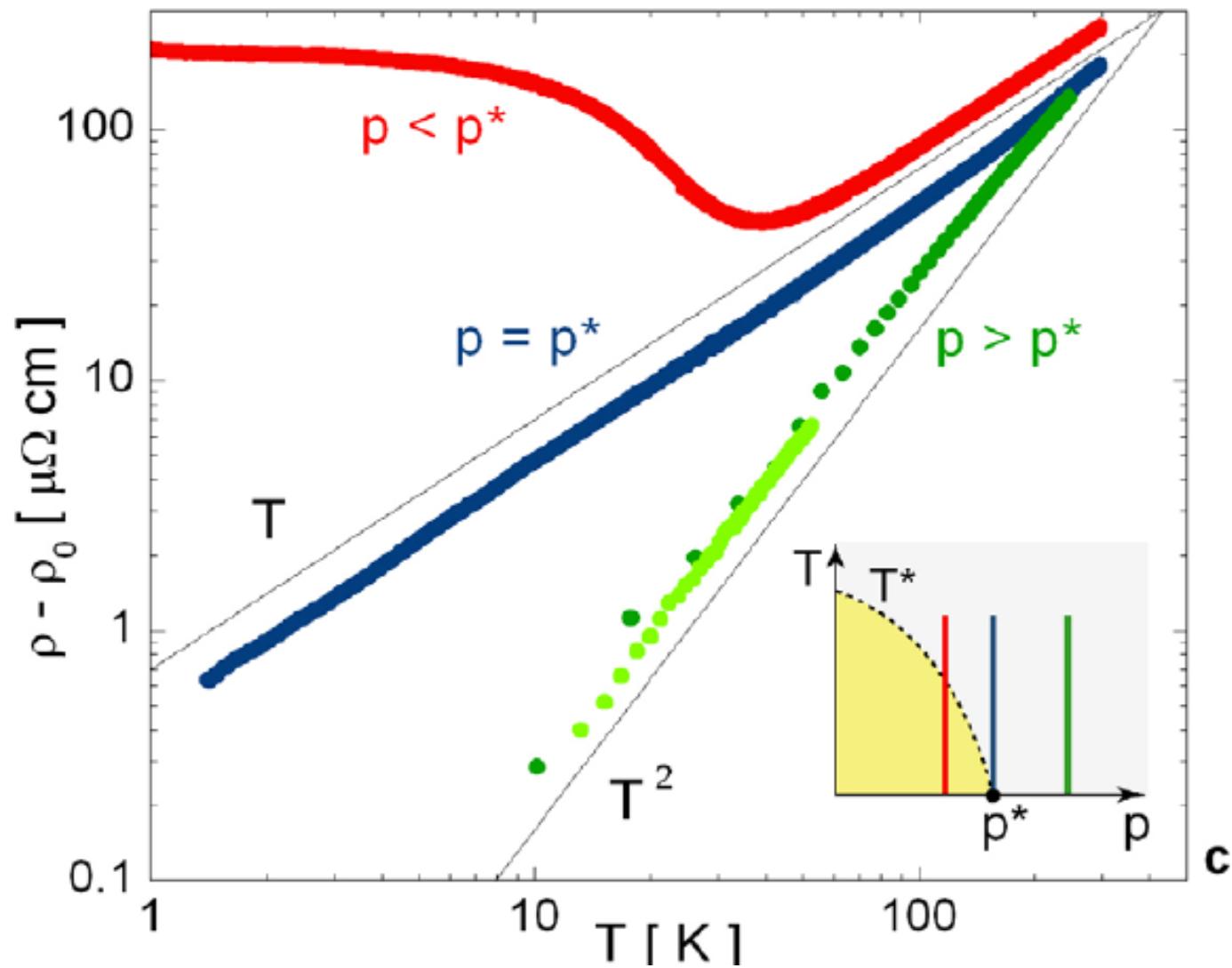
## Sachdev Phase Diagram: see arXiv:0910.0846



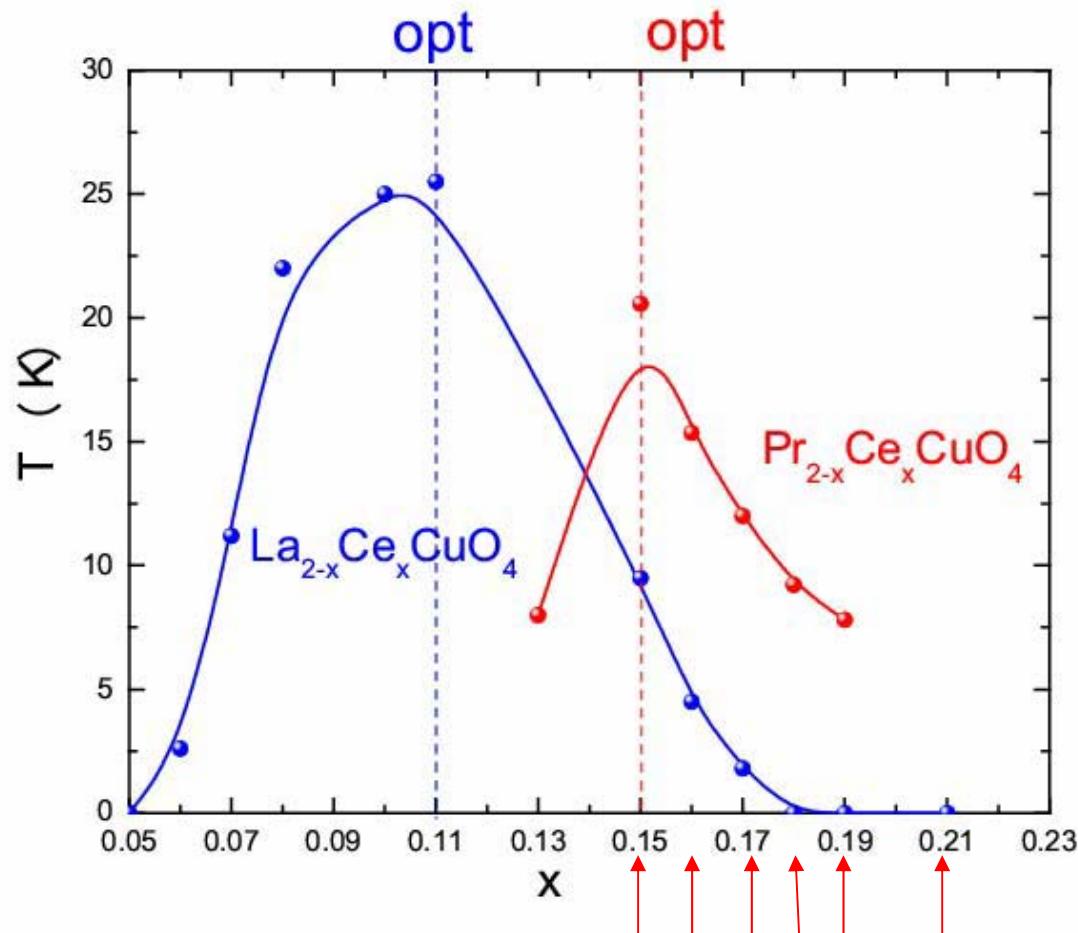
# Linear- $T$ resistivity and change in Fermi surface at the pseudogap critical point of a high- $T_c$ superconductor

$\text{La}_{1.6-x}\text{Nd}_{0.4}\text{Sr}_x\text{CuO}_4$

Daou et al., PRB 79, 180505 (09)

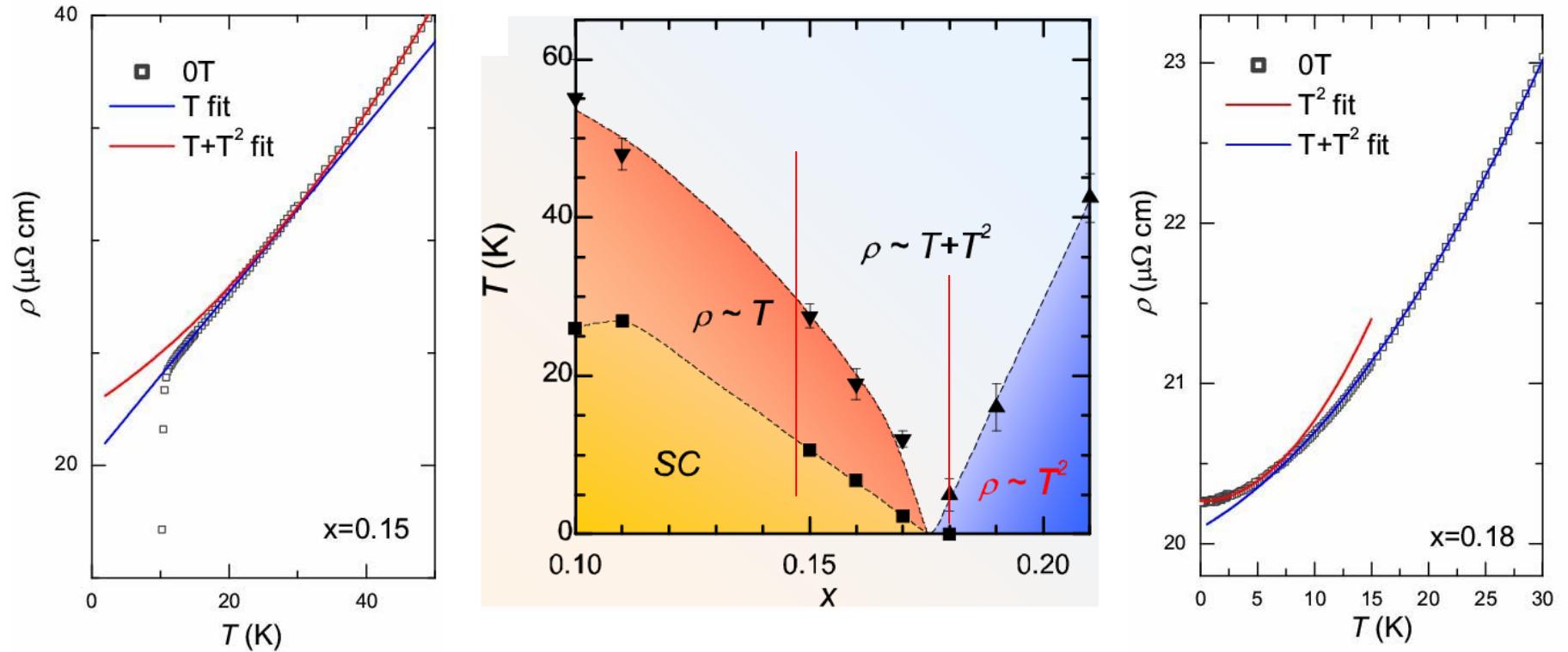


# Study resistivity in overdoped $\text{La}_{2-x}\text{Ce}_x\text{CuO}_4$ (LCCO) & $\text{Pr}_{2-x}\text{Ce}_x\text{CuO}_4$ (PCCO) films



- LCCO: stable over a wide overdoped range; non-SC metallic phase
- LCCO: ab-plane resistivity measured from 20 mK -60 K and 0-17 Tesla

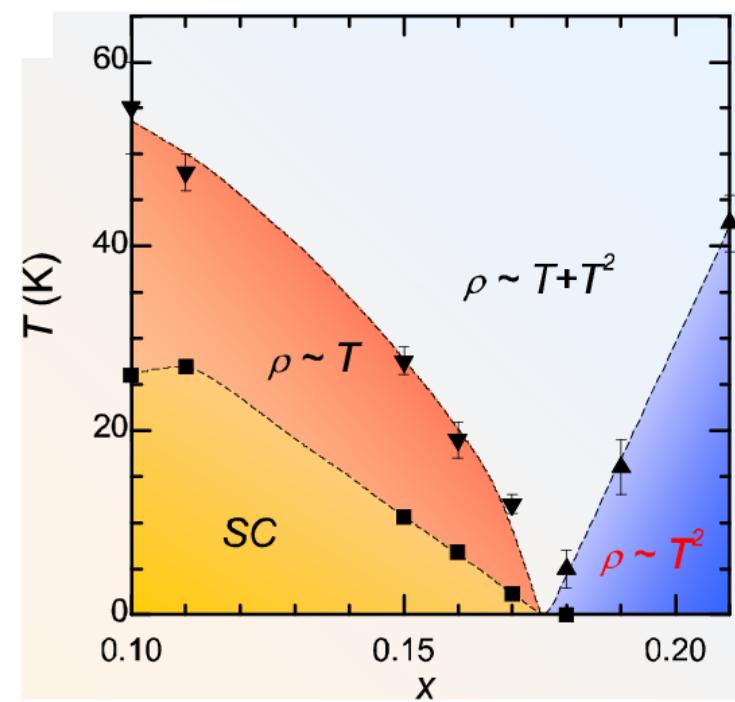
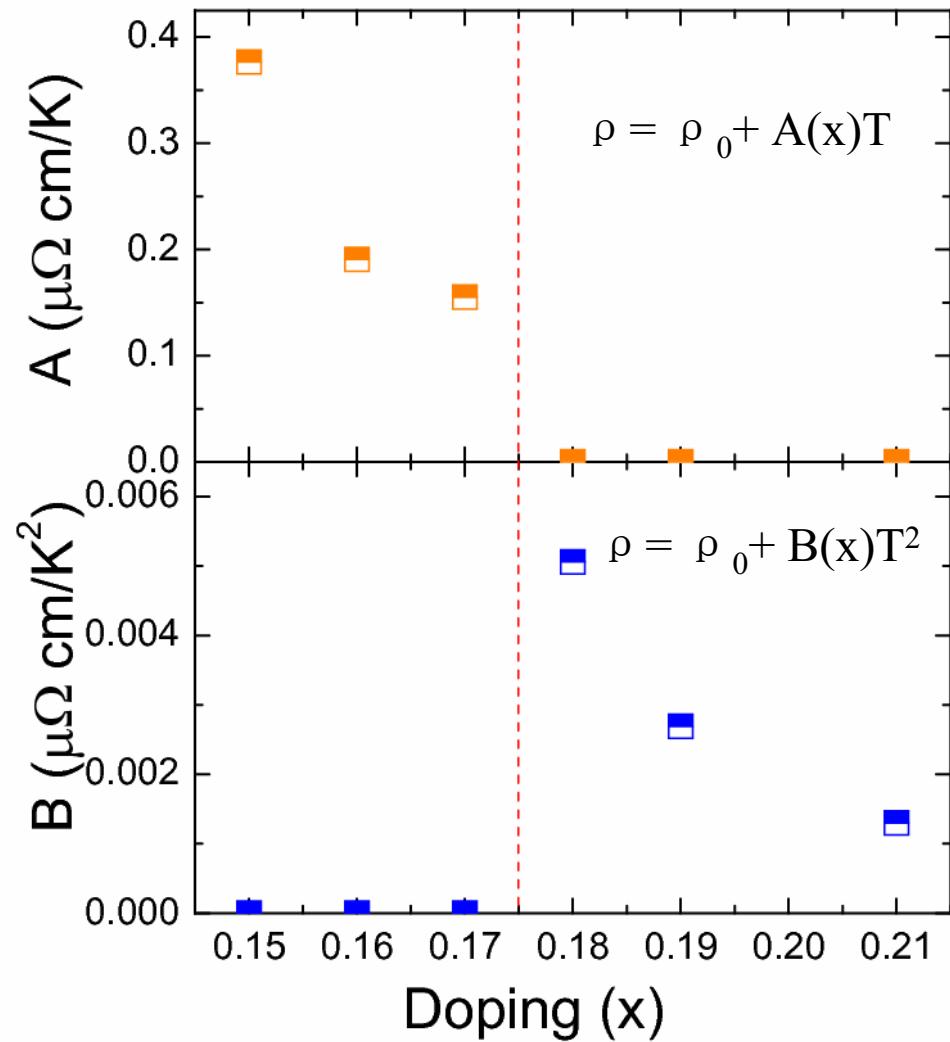
# (T, x) of LCCO in zero field



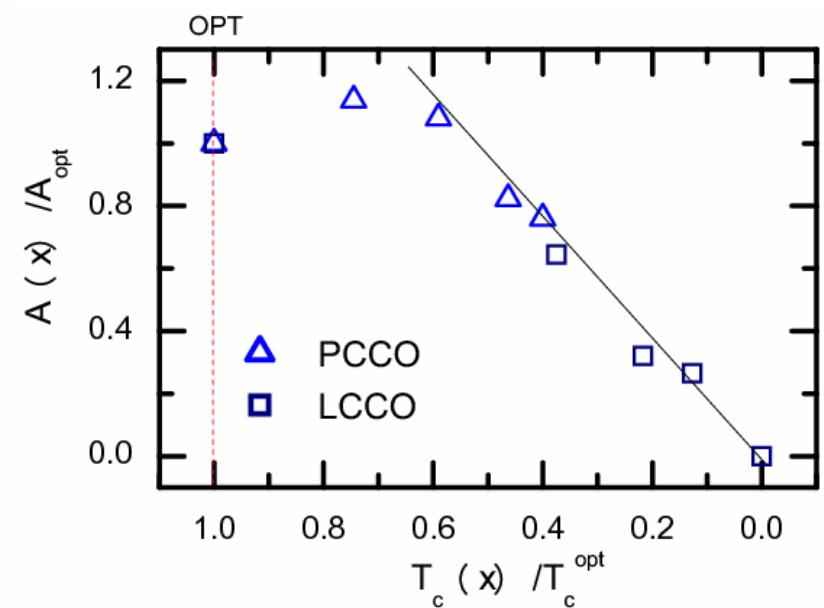
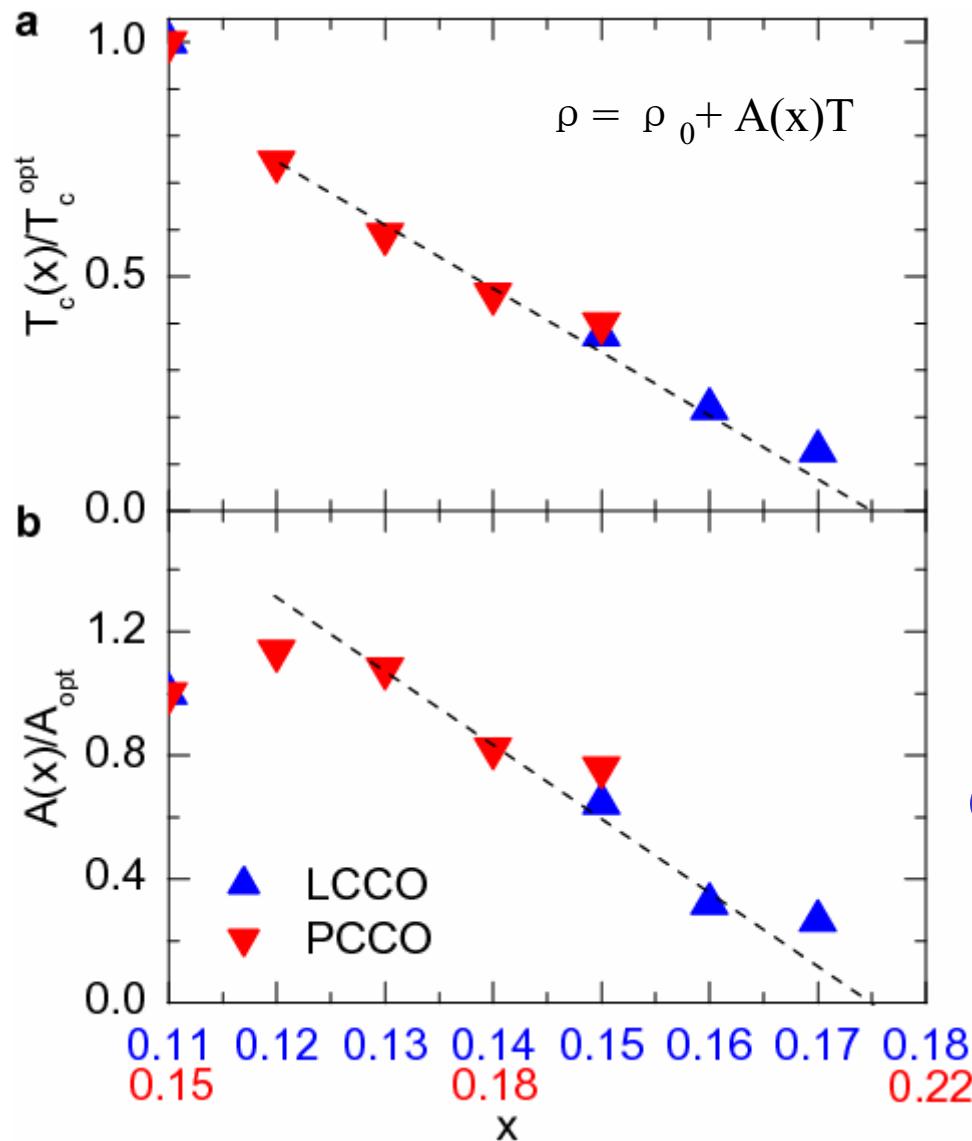
$$\rho \sim T: \rho = \rho_0 + A(x)T; \quad \rho \sim T^2: \rho = \rho_0 + B(x)T^2;$$

$$\rho \sim T + T^2: \rho = \rho_0 + A^*(x)T + B^*(x)T^2 \quad \text{or} \quad \rho = \rho_0 + C(x)T^n \text{ with } 1 < n < 2$$

# LCCO: coefficients in zero field

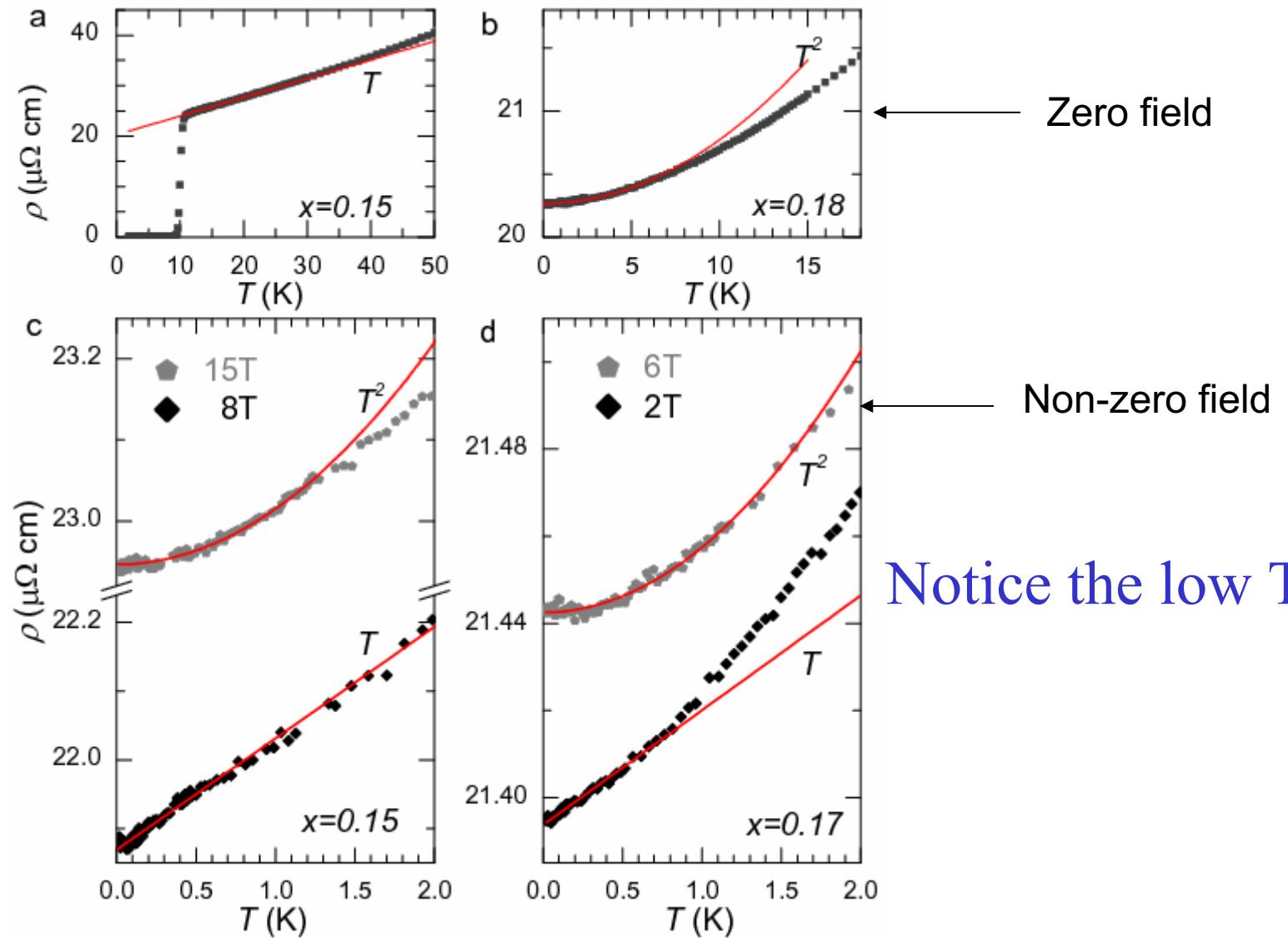


# LCCO and PCCO: normalized $T_c$ and $A(x)$ in zero field

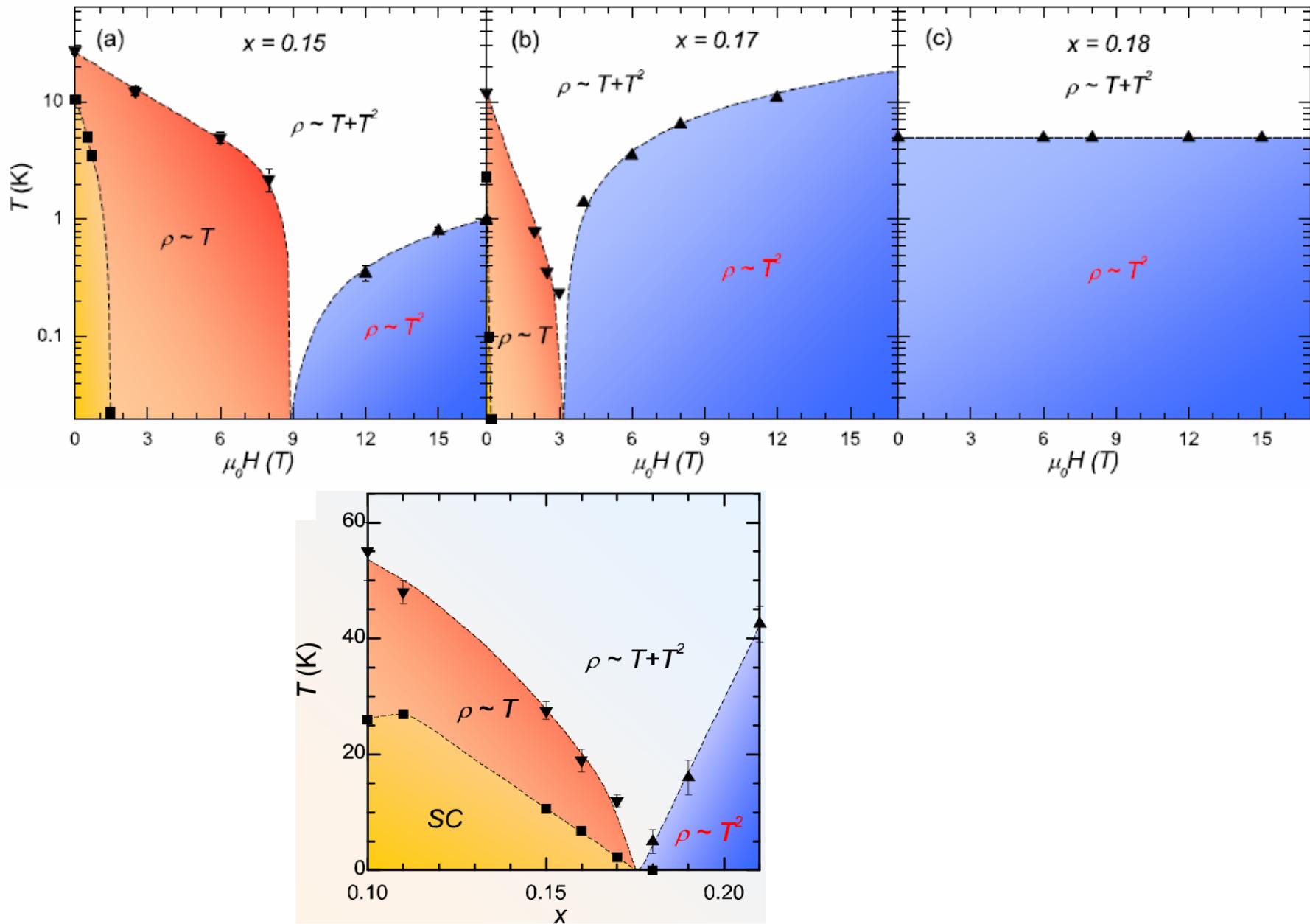


Conclusion: strong correlation  
between linear in  $T$  scattering  
and pairing

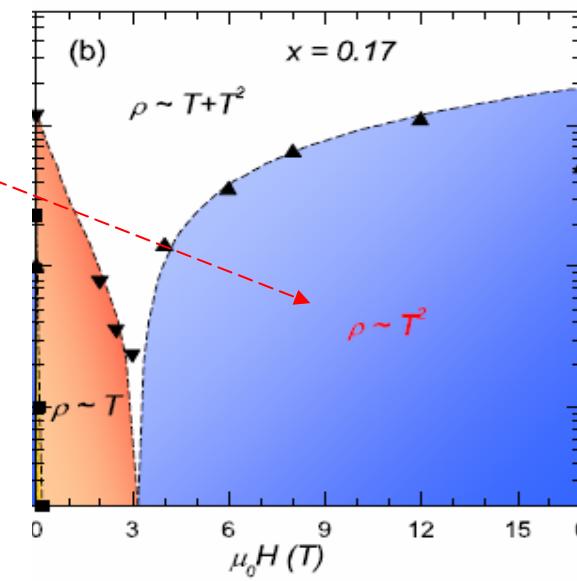
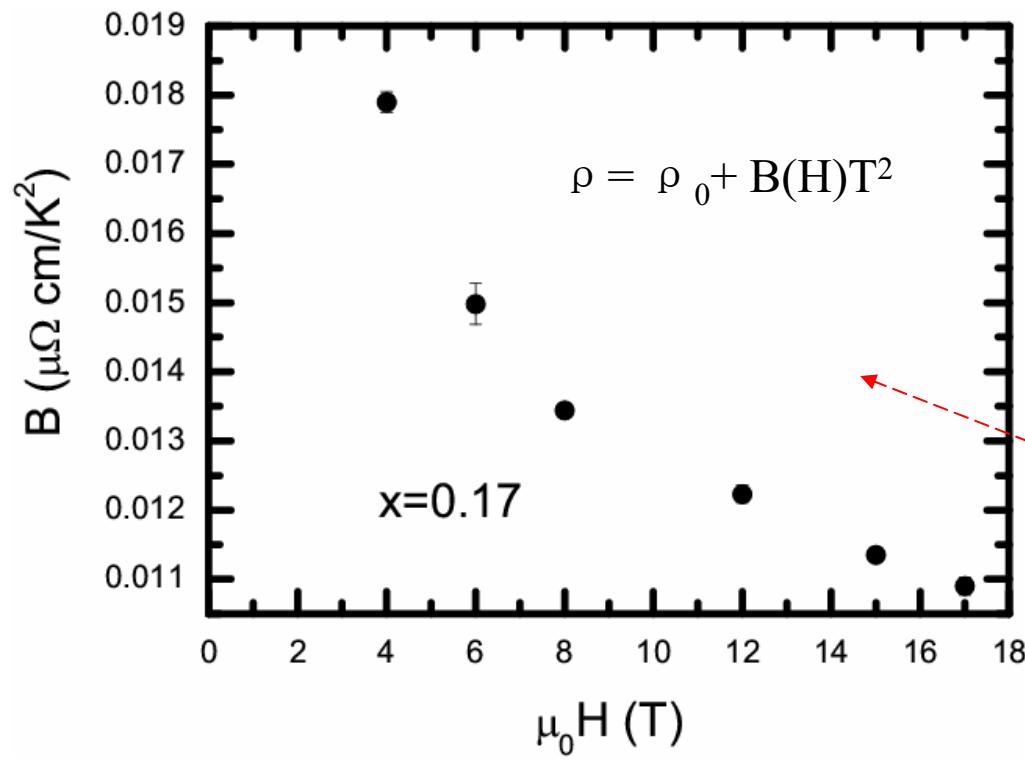
# What happens in a magnetic field?



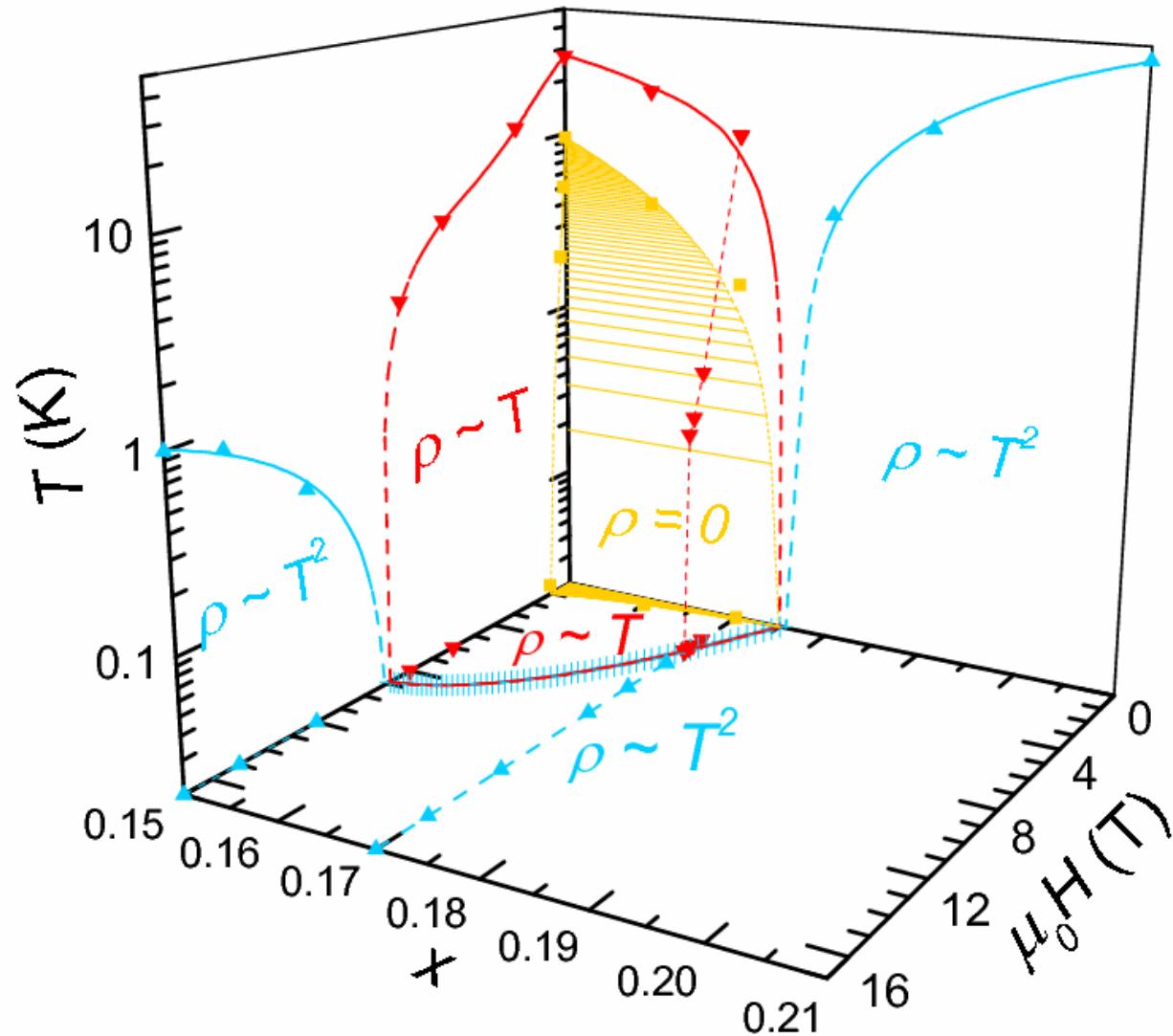
# $(T, H)$ of LCCO with $x=0.15, 0.17$ , and $0.18$



## B vs H in the Fermi-liquid regime for $x = 0.17$ (LCCO)

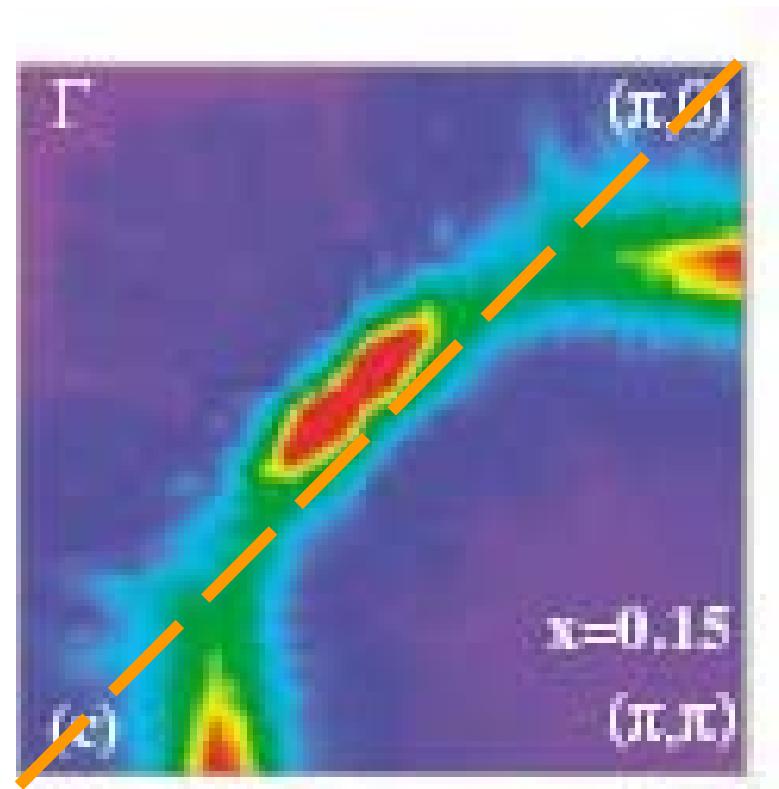


# 3D phase diagram of $\text{La}_{2-x}\text{Ce}_x\text{CuO}_4$



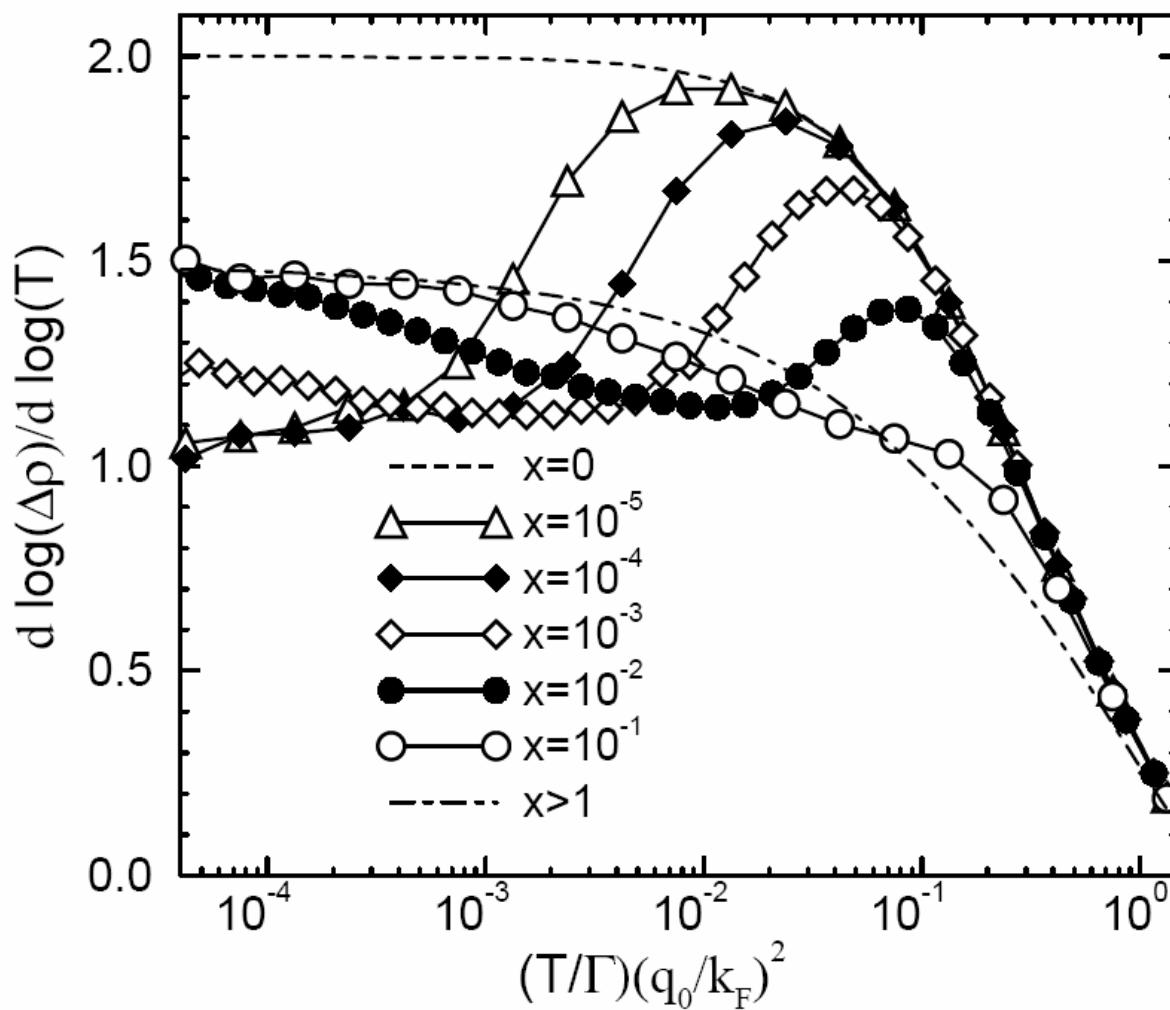
# What's the origin of the T-linear resistivity?

Scattering from  $(\pi, \pi)$  commensurate SDW fluctuations?



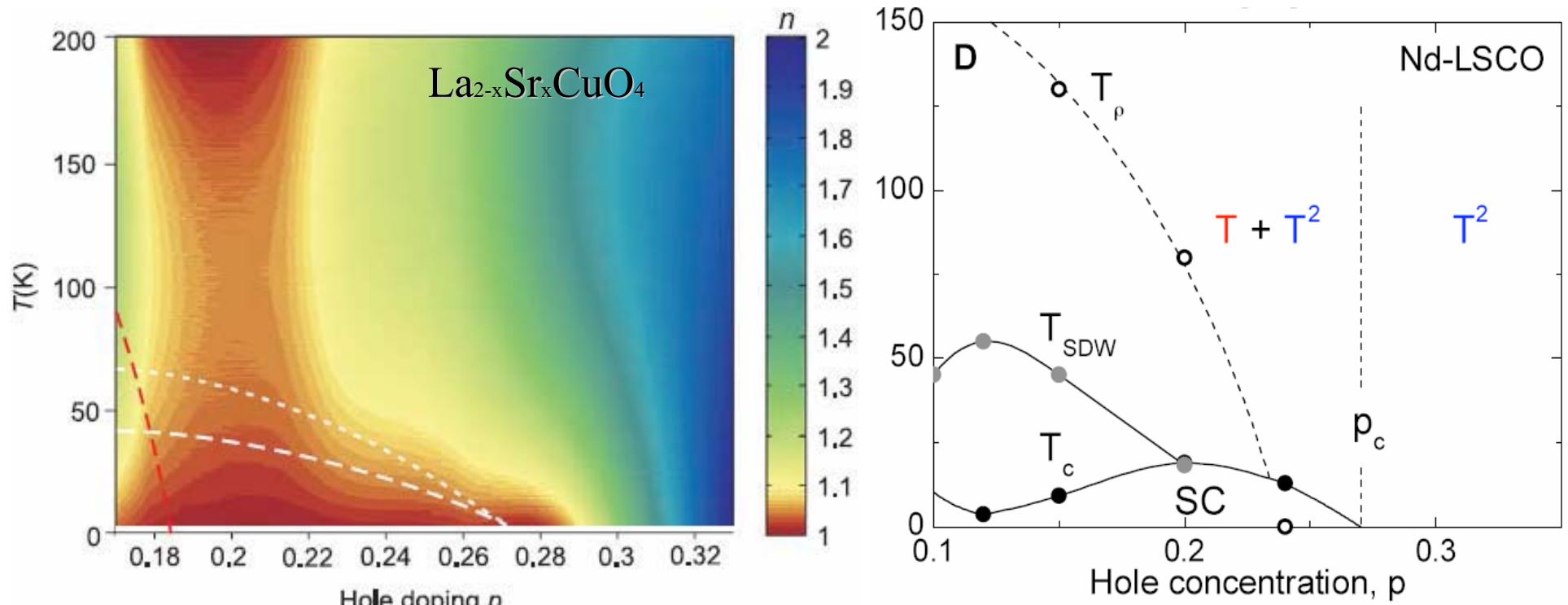
- T. Moriya and K. Ueda *Adv. Phys.* **49**, 555 (2000).  
N. P. Armitage *et.al.* *Phys. Rev. Lett.* **88**, 257001 (2002).  
B. Kyung, *et.al.* *Phys. Rev. Lett.* **93**, 147004 (2004).  
N.P. Armitage, P.Fournier and R.L. Greene, arXiv 0905.2931 (2009)  
C. Bourbonnais and A. Sedeiki, *et.al.* *Phys. Rev. B* **80**, 085105 (2009).

# Resistivity exponent at AFM QCP: effect of disorder



A. Rosch, Phys. Rev. B 62, 4945 (2000)

# Hole-doped cuprate results



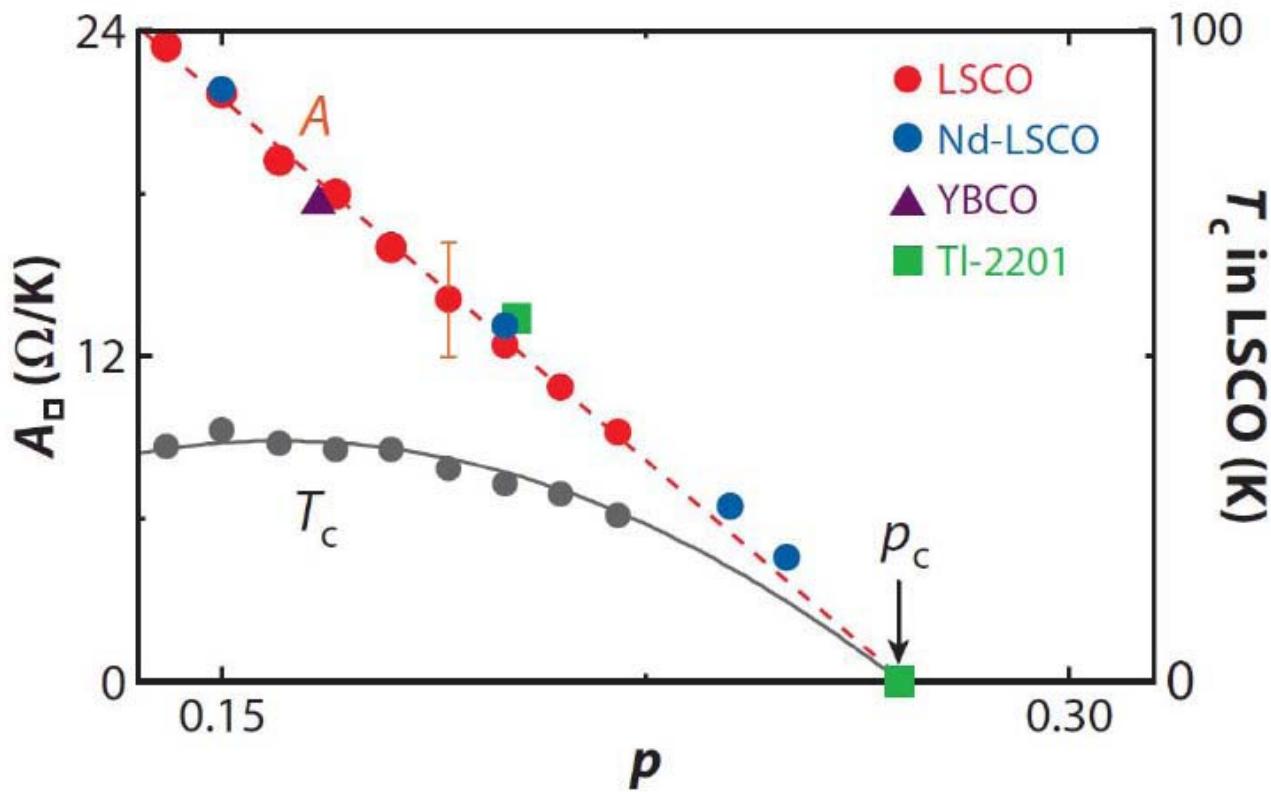
R. A. Cooper, et al. *Science* **323**, 603 (2009)

N. Doiron-Leyraud, et al. *arXiv.0905.0964* (2009)

**T-linear resistivity also related to  $T_c$**

# Correlation of $A$ and $T_c$ in hole-doped cuprates

L. Taillefer arXiv:1003.2972



## Summary and Conclusions

- For n-type cuprates one finds a QCP under the SC dome, resulting from reconstruction of large hole-like FS.
- Reconstruction is caused by commensurate AFM (SDW).
- Pseudogap temperature  $T^*$  marks the onset of short range AFM correlations. QCP is the doping where  $T^*$  goes to zero.
- At QCP, resistivity is perfectly linear in temperature as T goes to zero (10K to 35mK).
- The strength of the linear in T resistivity is found to scale with  $T_c$ , both above  $T_c$  in zero field and at very low T in a magnetic field.
- This direct empirical correlation strongly suggests that pairing and linear in T scattering have a common origin, most likely AFM/SDW spin fluctuations.