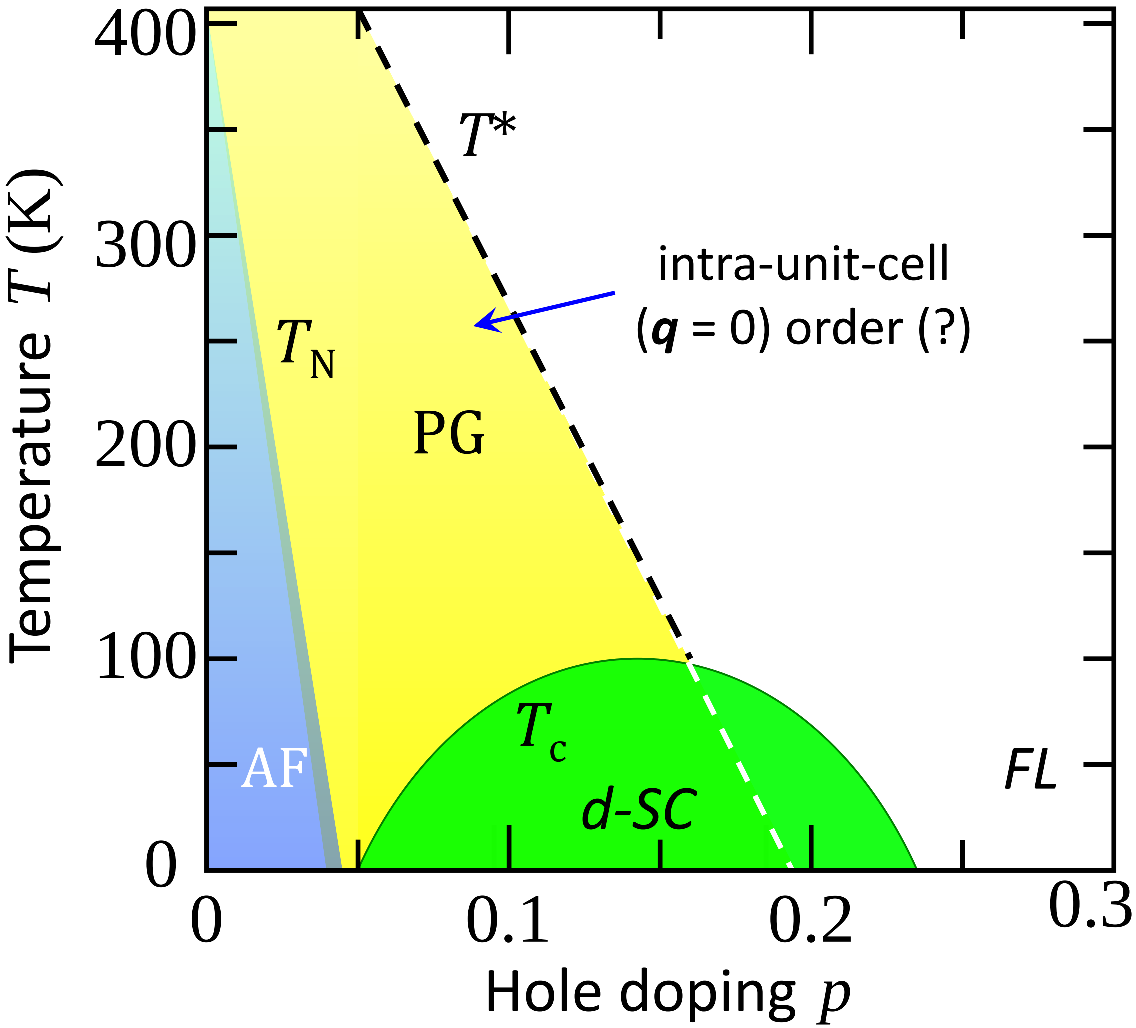
Hole Pairs (PDW) in the PG State ?

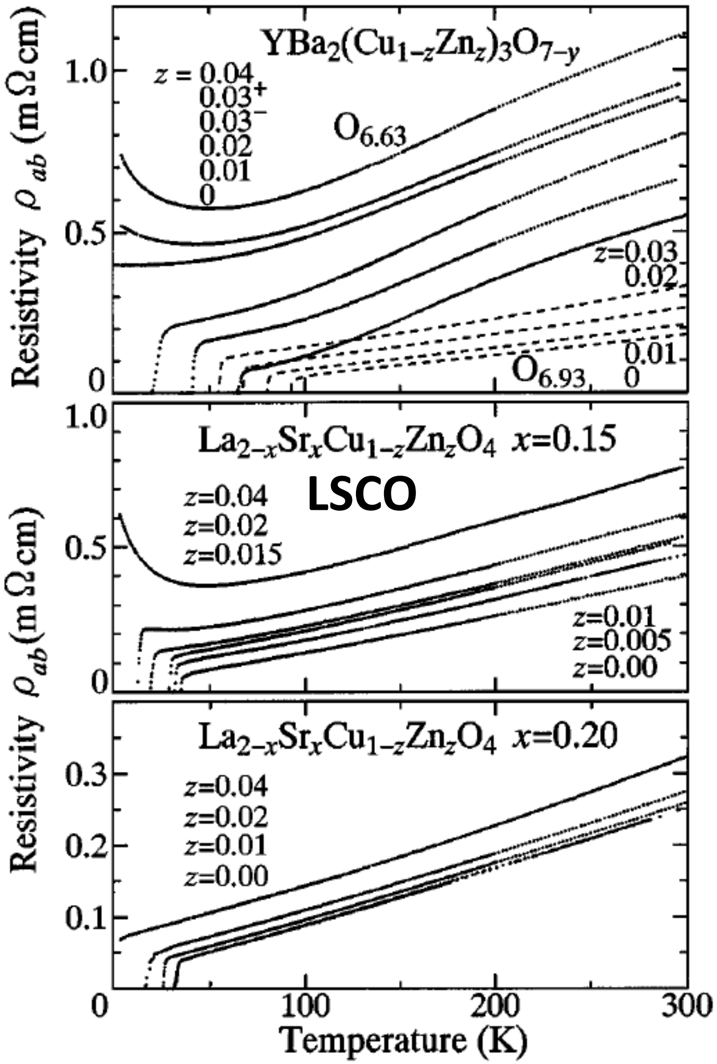


S. Uchida

Univ. of Tokyo
AIST (Tsukuba)
IOP-CAS (Beijing)

1. Residual resistivity produced by untary scatterers: Zn in cuprates

YBCO (M.K. Wu)



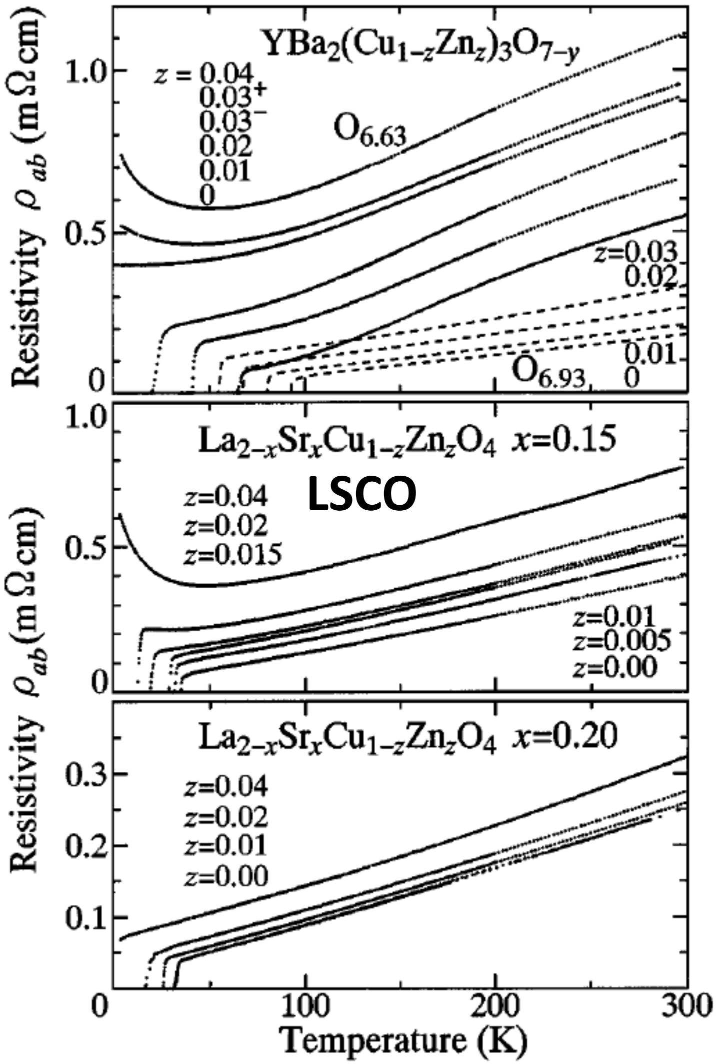
$$\rho_0^{2D} = 4(\hbar/e^2)\,(n_i/n)\,\sin^2\delta_0$$

the unitarity limit ($\delta_0 = \pi/2$)

Y. Fukuzumi, SU *et al.*, PRL **76**, 5654 (1996).

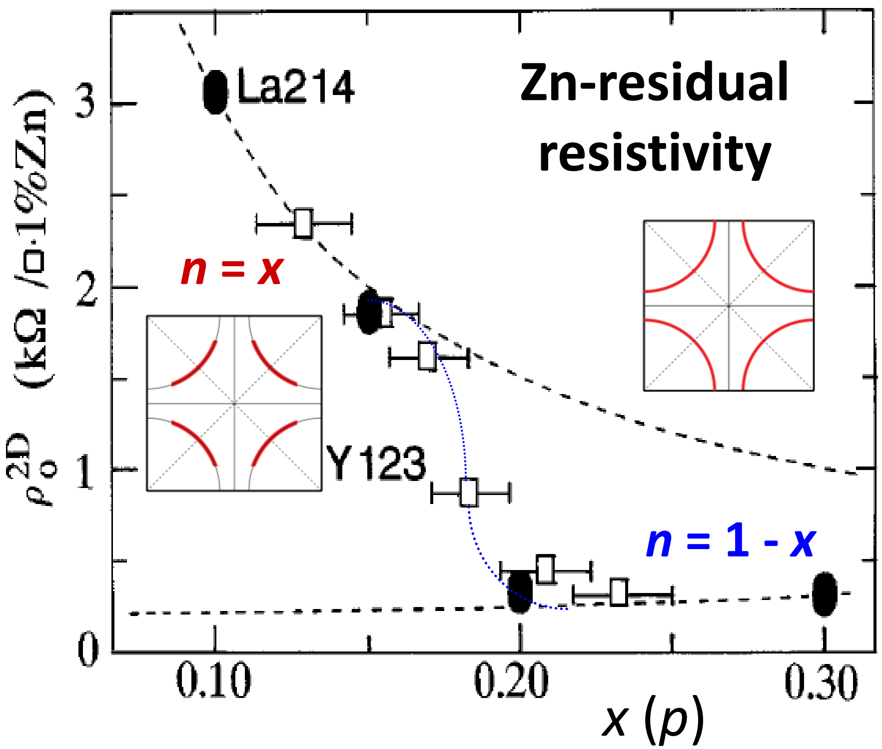
1. Residual resistivity produced by untary scatterers: Zn in cuprates

YBCO (M.K. Wu)



$$\rho_0^{2D} = 4(\hbar/e^2)(n_i/n)\sin^2\delta_0$$

the unitarity limit ($\delta_0 = \pi/2$)



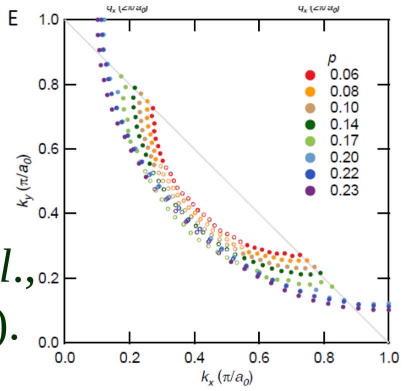
Y. Fukuzumi, SU *et al.*, PRL **76**, 5654 (1996).

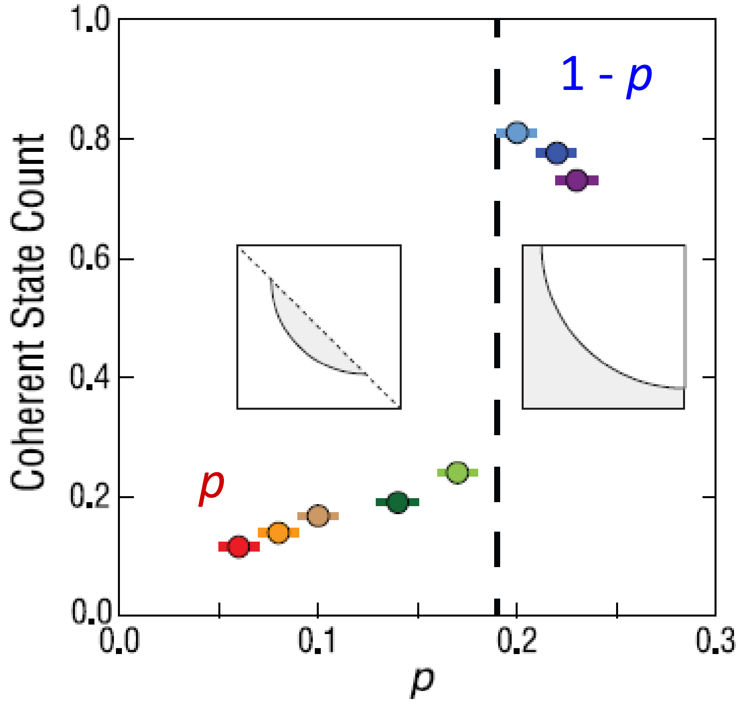
Transformation of the Fermi arc (small Fermi surface) to a large Fermi surface at p ~ 0.2

SI-STM:
"Bogoliubov arc"

Bi2212

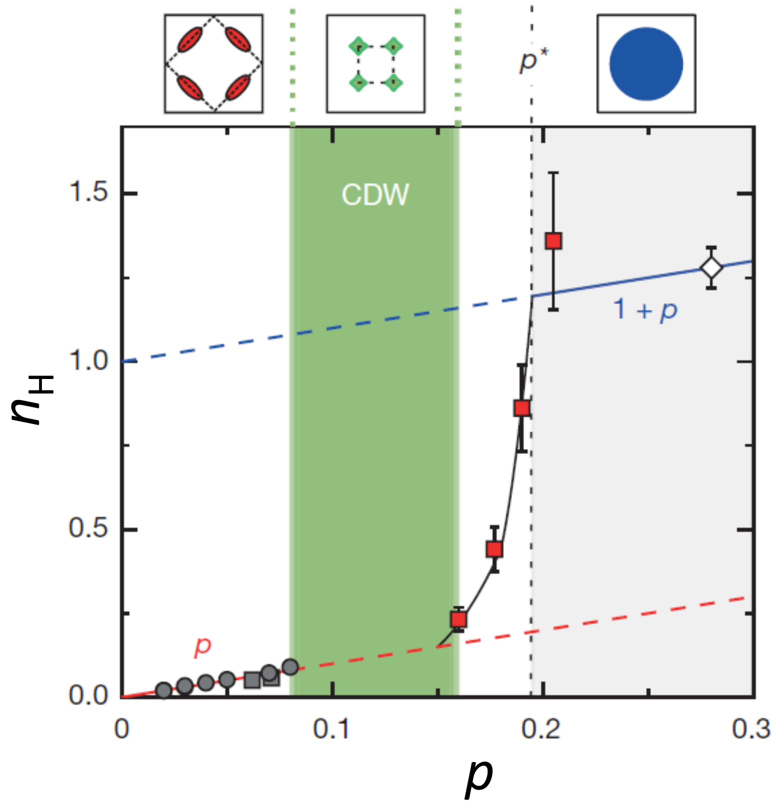
K. Fujita, J.C. Davis *et al.*, Science **344**, 612 (2014).





High-*B* Hall effect

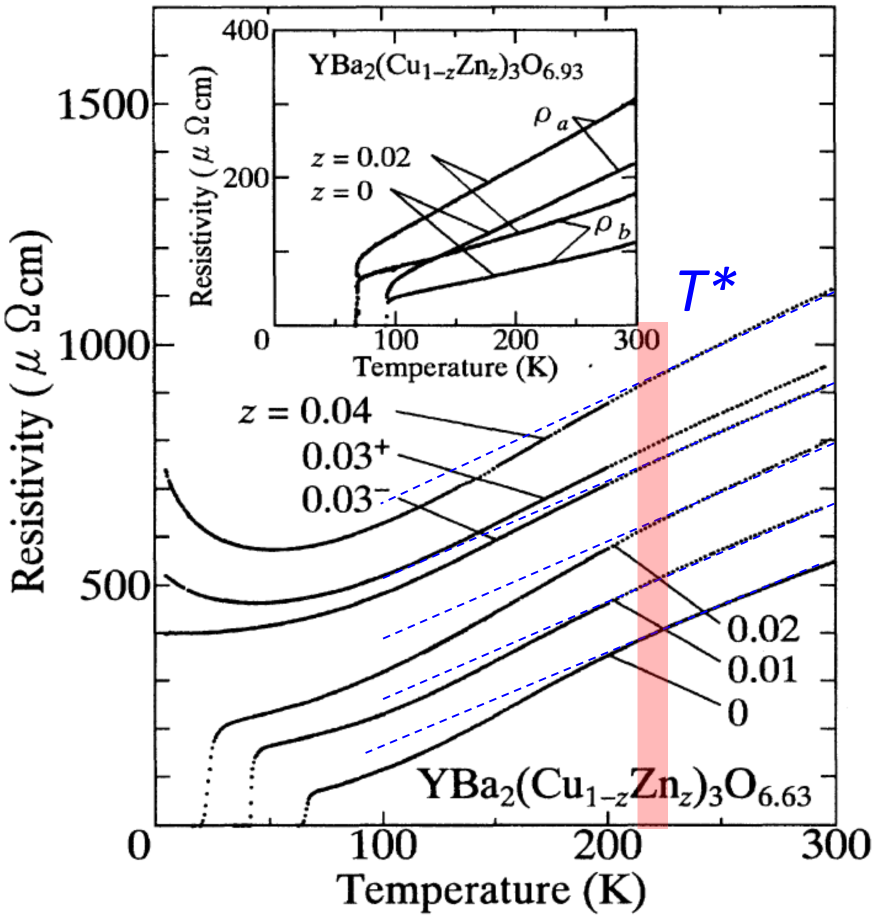
YBCO

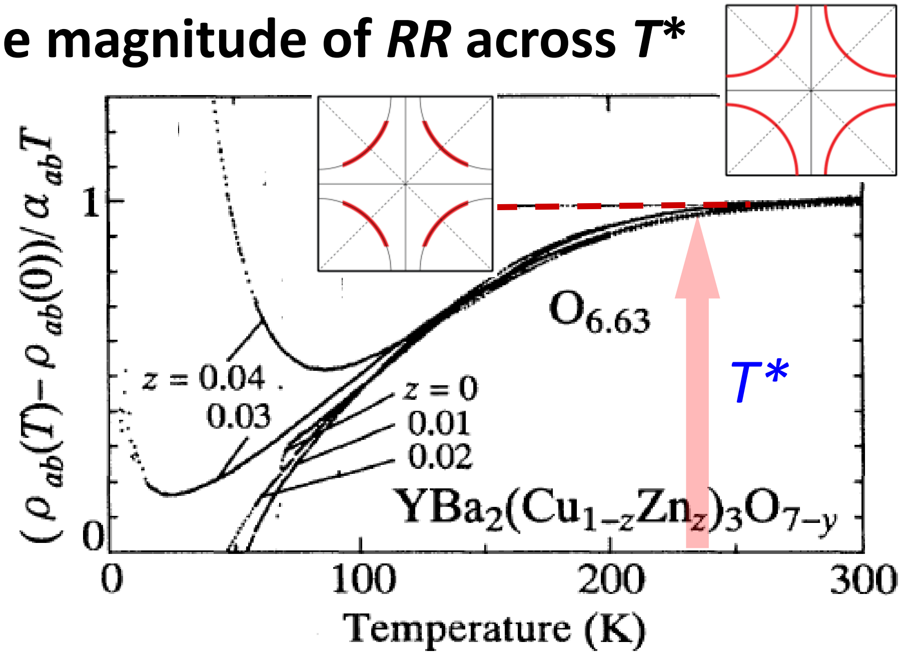


S. Badoux, L. Taillefer *et al.*, Nature **531**, 210 (2016).

1. Residual resistivity produced by untary scatterers: Zn in cuprates

No significant change in the magnitude of *RR* across *T**





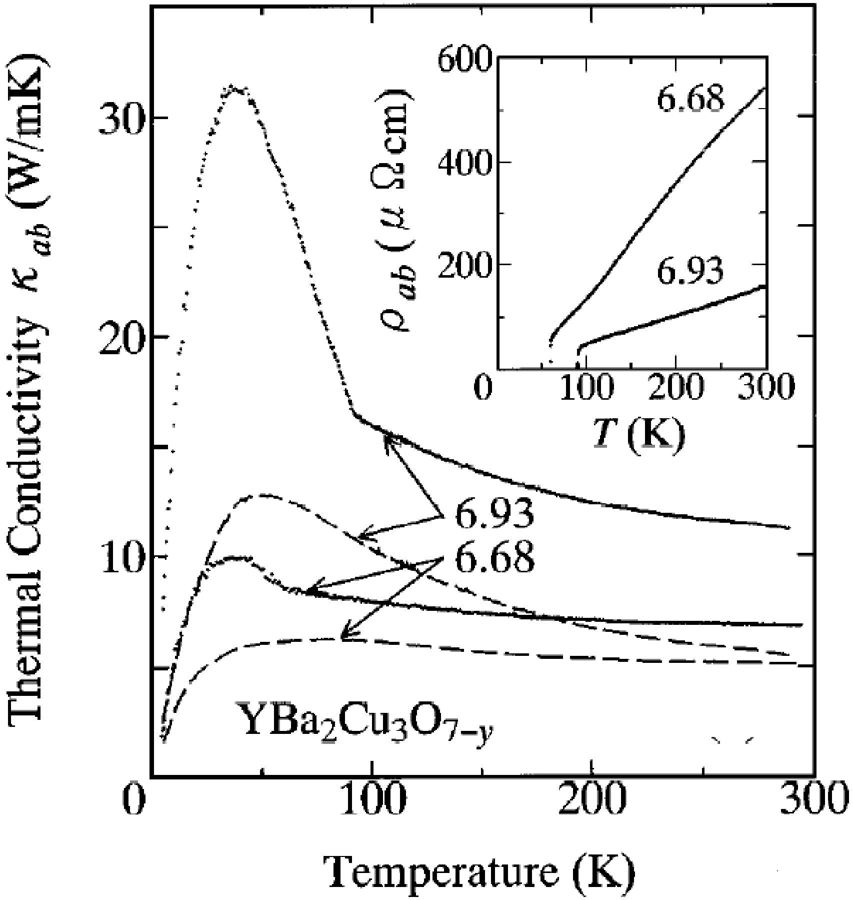
$$\rho_0^{2D} = 4(\hbar/e^2)\,(n_i/n)\,\sin^2\delta_0$$

the unitarity limit ($\delta_0 = \pi/2$)

Y. Fukuzumi, K. Mizuhashi, K. Takenaka, SU, PRL **76**, 5654 (1996).

2. Electronic thermal conductivity: Lorenz number

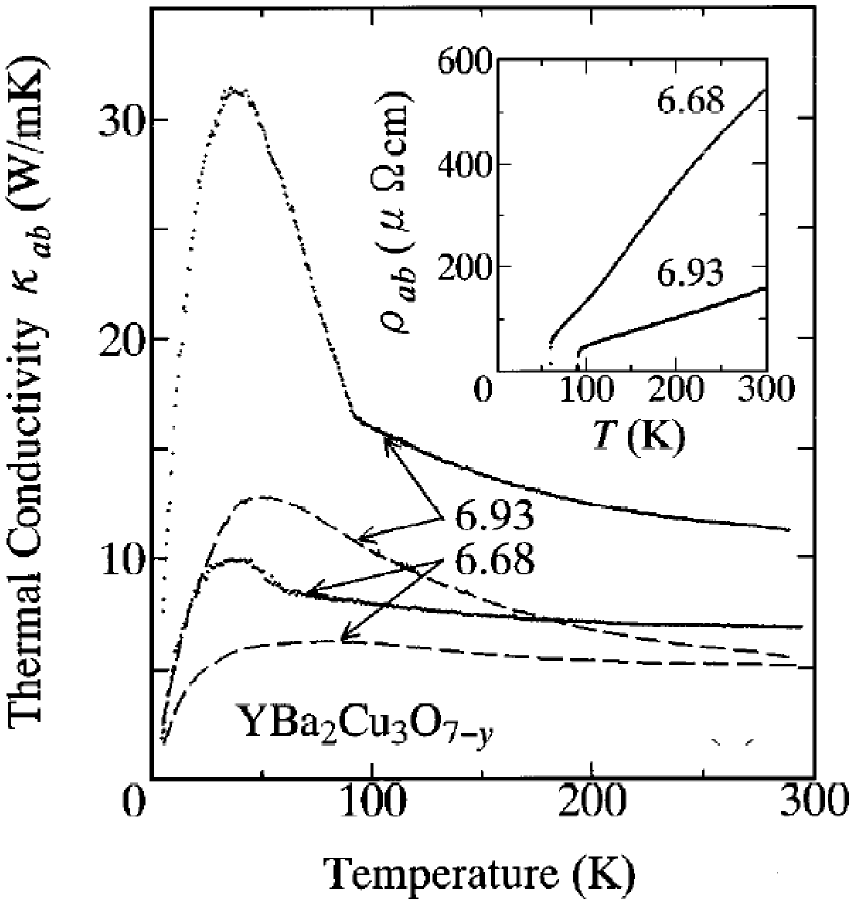
$$L = \kappa/\sigma T = (\pi^2/3)\,(k_B/e)^2 \longrightarrow L^* = (\pi^2/3)\,(k_B/2e)^2 = L/4$$



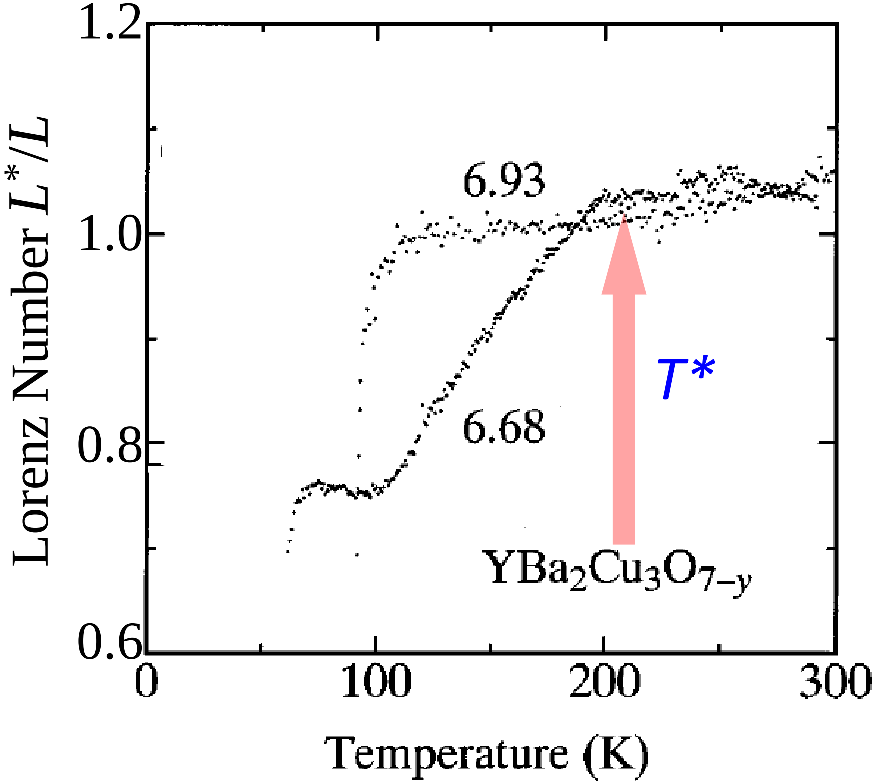
K. Takenaka, SU *et al.*, PRB **56**, 5654 (1997).

2. Electronic thermal conductivity: Lorenz number

$$L = \kappa / \sigma T = (\pi^2/3)\,(k_B/e)^2 \rightarrow L^* = (\pi^2/3)\,(k_B/2e)^2 = L/4$$



Large ambiguity in the phonon contribution



K. Takenaka, SU *et al.*; PRB **56**, 5654 (1997).

Various signatures of Pair Formation above Tc

1) Transverse Josephson plasmon above T_c

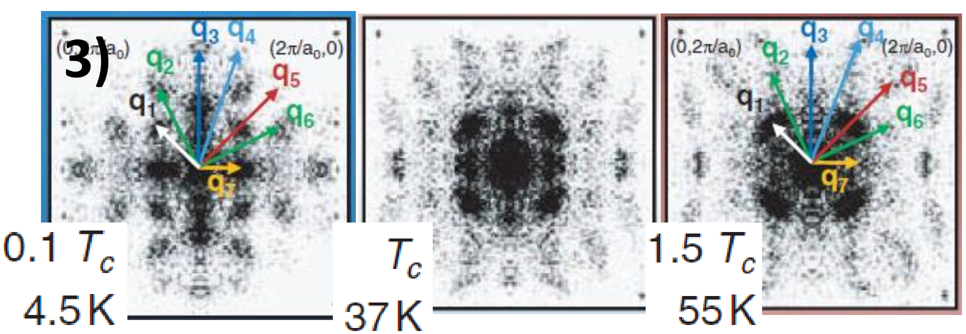
A. Dubroka, C. Bernhard, PRL **106**, 047006 (2011)

2) Diamagnetic signal above T_c / Vortex Nernst effect

Z.A. Xu, N.P. Ong, SU, Nature **406**, 486 (2000)

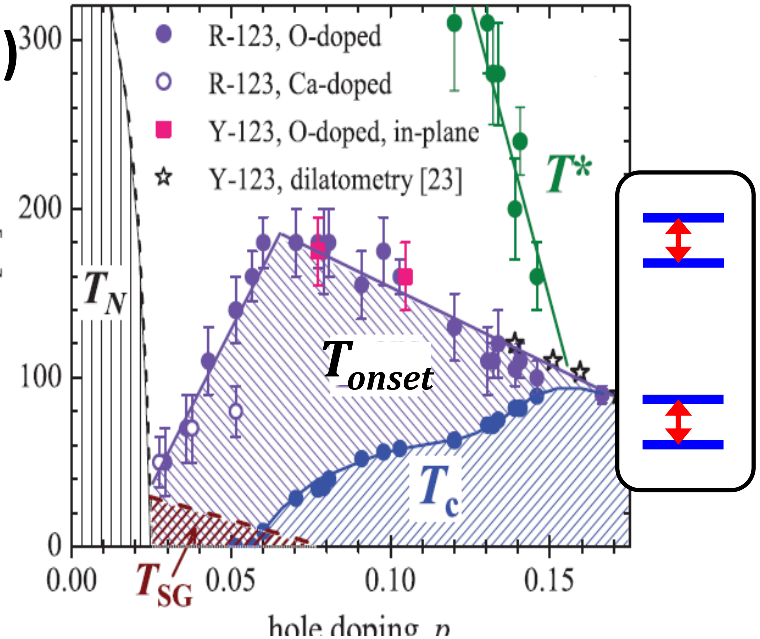
3) Bogoliubov QP interference above T_c

3)

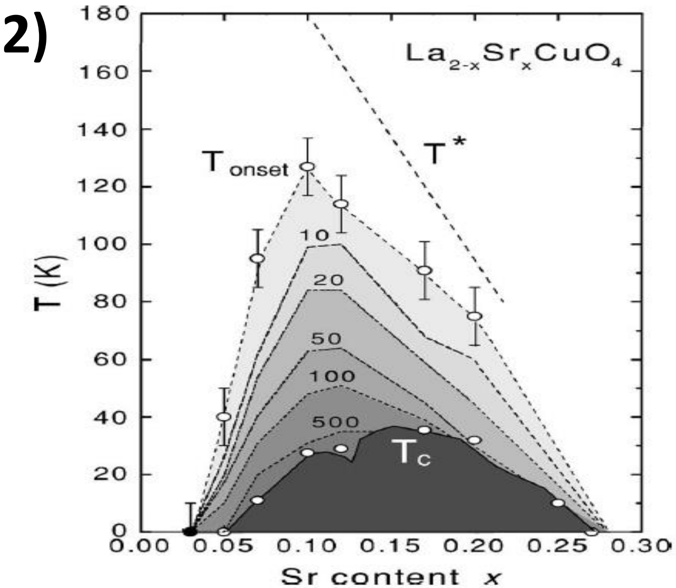


Jhinhwang Lee *et al.*, Science **325**, 1099 (2009)

1)



2)



Various signatures of Pair Formation above Tc

1) Transverse Josephson plasmon above T_c

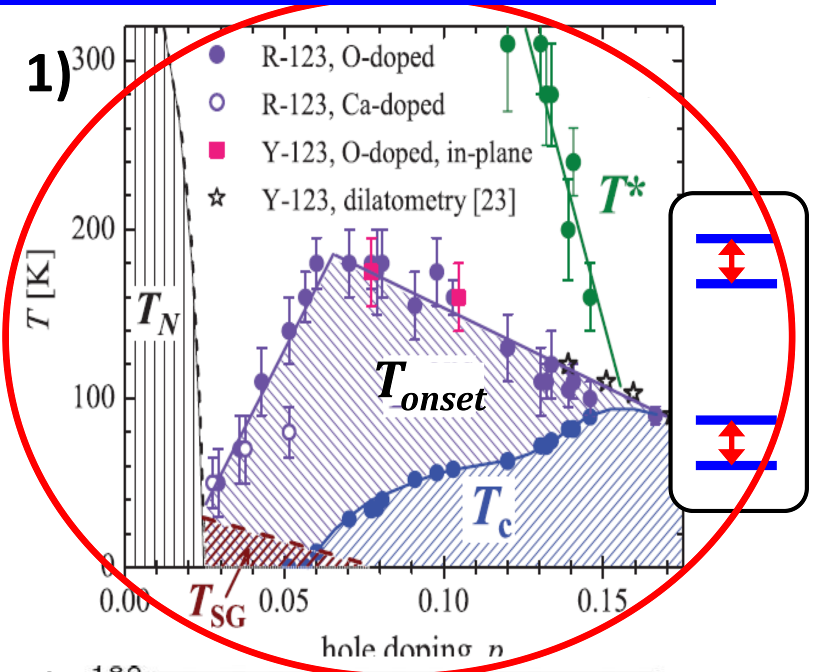
A. Dubroka, C. Bernhard, PRL **106**, 047006 (2011).

2) Diamagnetic signal above T_c / Vortex Nernst effect

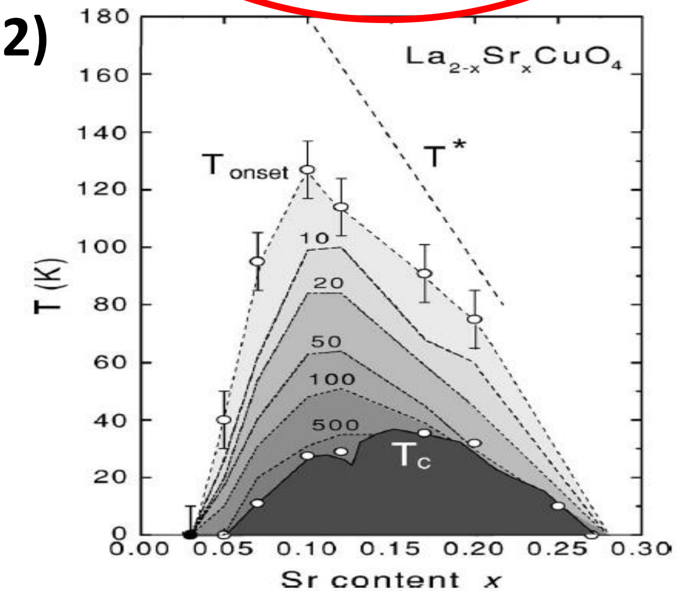
Z.A. Xu, N.P. Ong, SU, Nature **406**, 486 (2000).

3) Bogoliubov QP interference above T_c

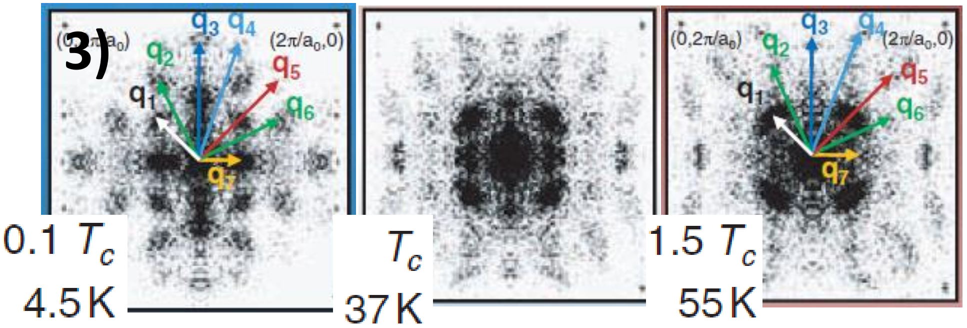
1)



2)



3)

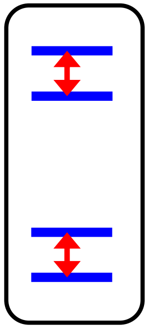


Jhinhwang Lee *et al.*, Science **325**, 1099 (2009).

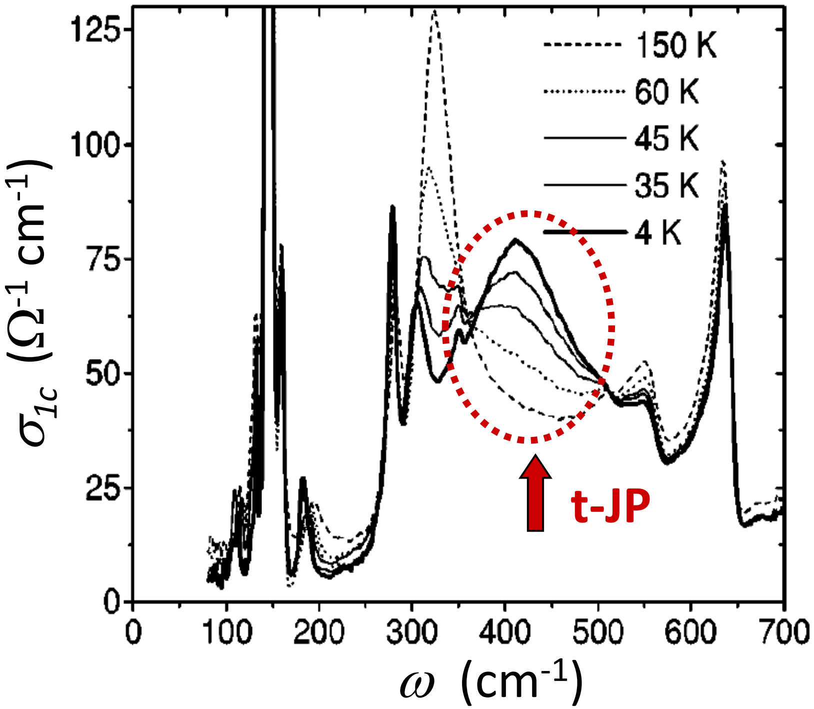
Intra-bilayer Josephson plasma mode persists above T_c

Emergence of a transverse Josephson plasma (t-JP) mode at T_{onset}, well above T_c:

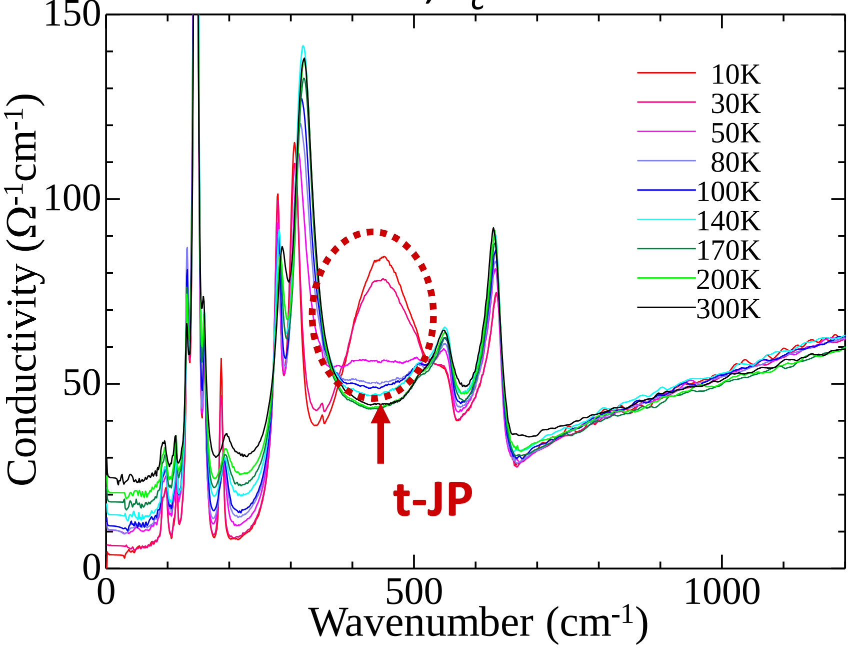
Establishment of intra-bilayer phase coherence



YBCO6.5, T_c = 58 K



YBCO6.6, T_c = 62 K

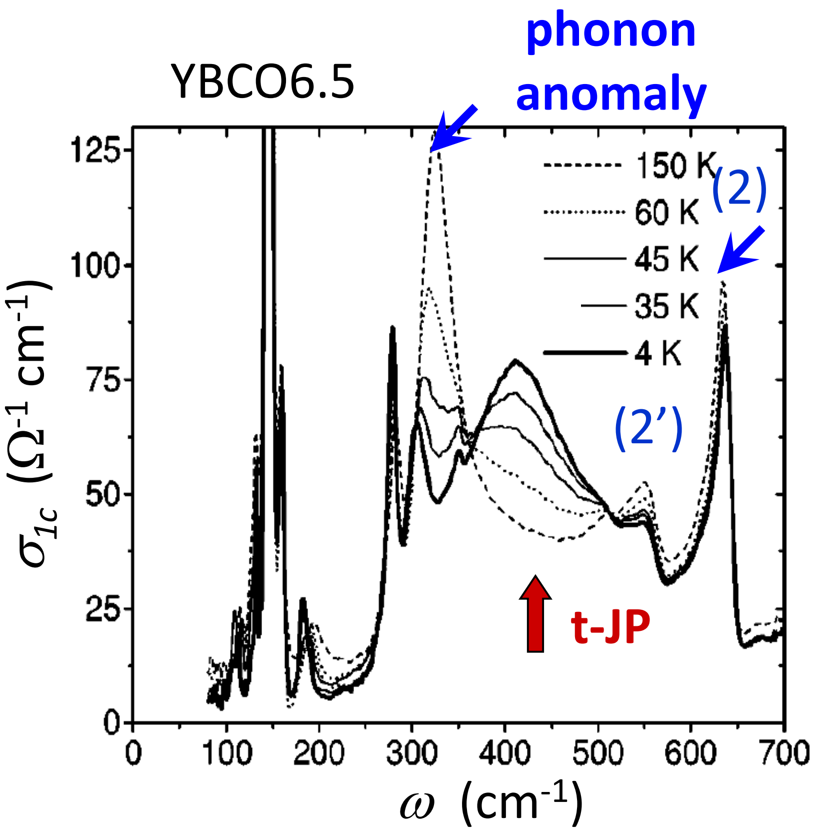


A. Dubroka, C. Bernhard *et al.*, PRL **106**, 047006 (2011).

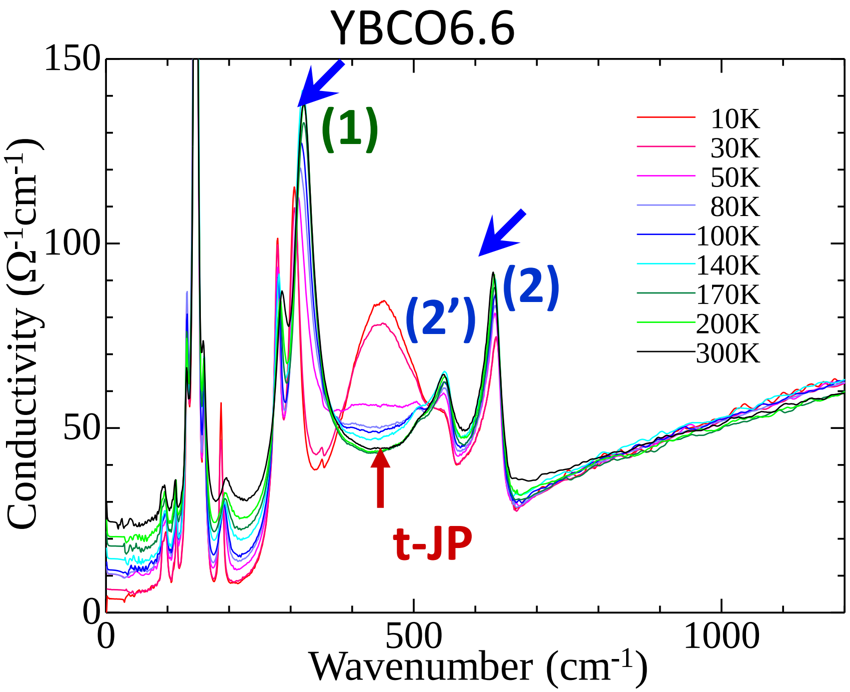
K.M. Kojima, M. Nakajima, S. Tajima, SU, *unpublished results*.

Anomalous optical phonon modes

Weights of two optical phonon modes decrease with lowering *T*, associated with the development of t-JP

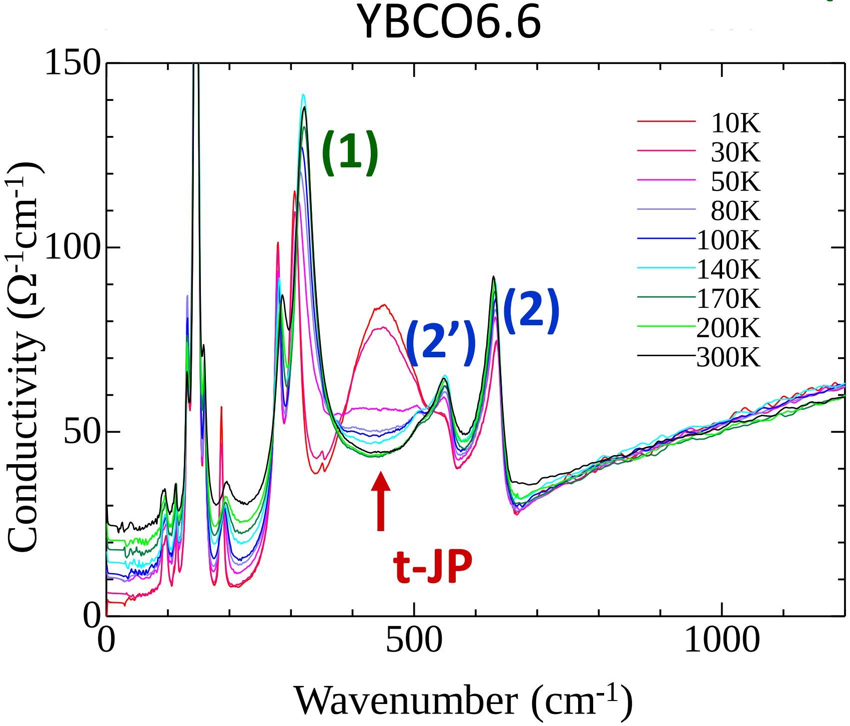


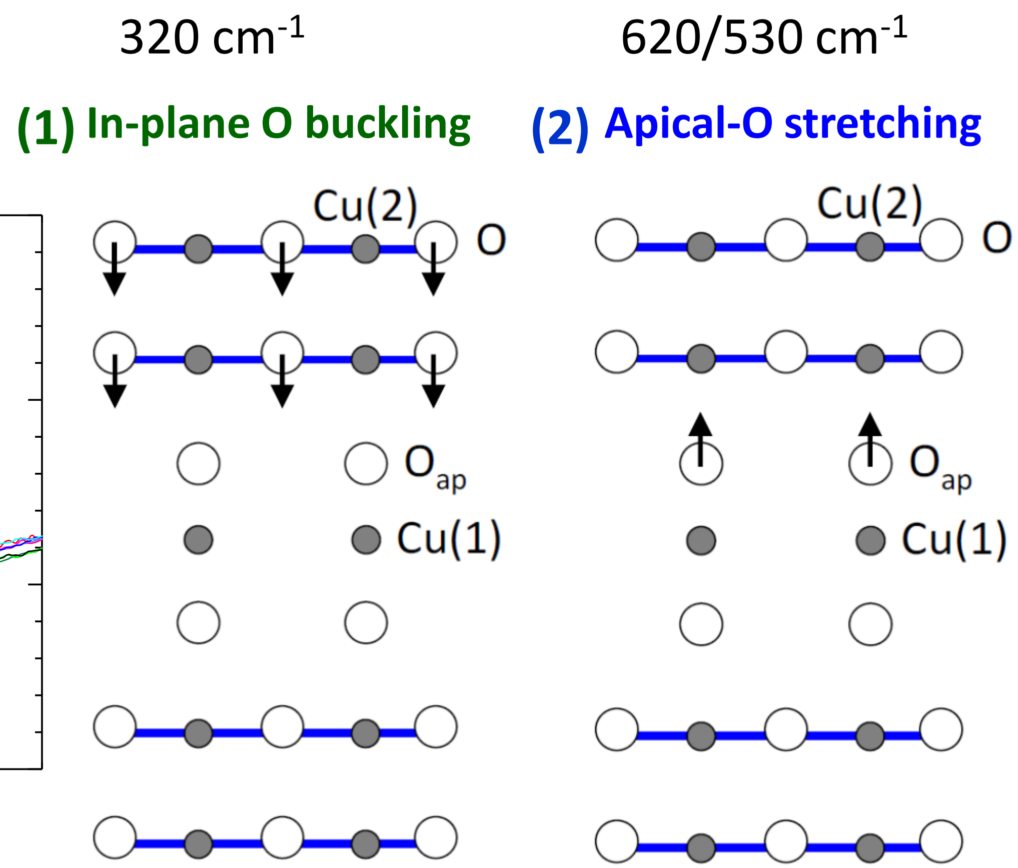
A. Dubroka, C. Bernhard *et al.*, PRL **106**, 047006 (2011).



K.M. Kojima, M. Nakajima, S. Tajima, SU, *unpublished results*.

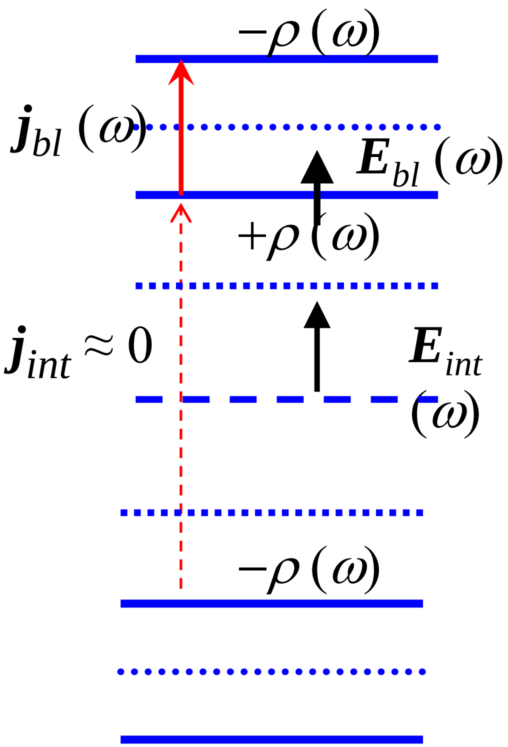
Phonon anomalies associated with the development of t-JP

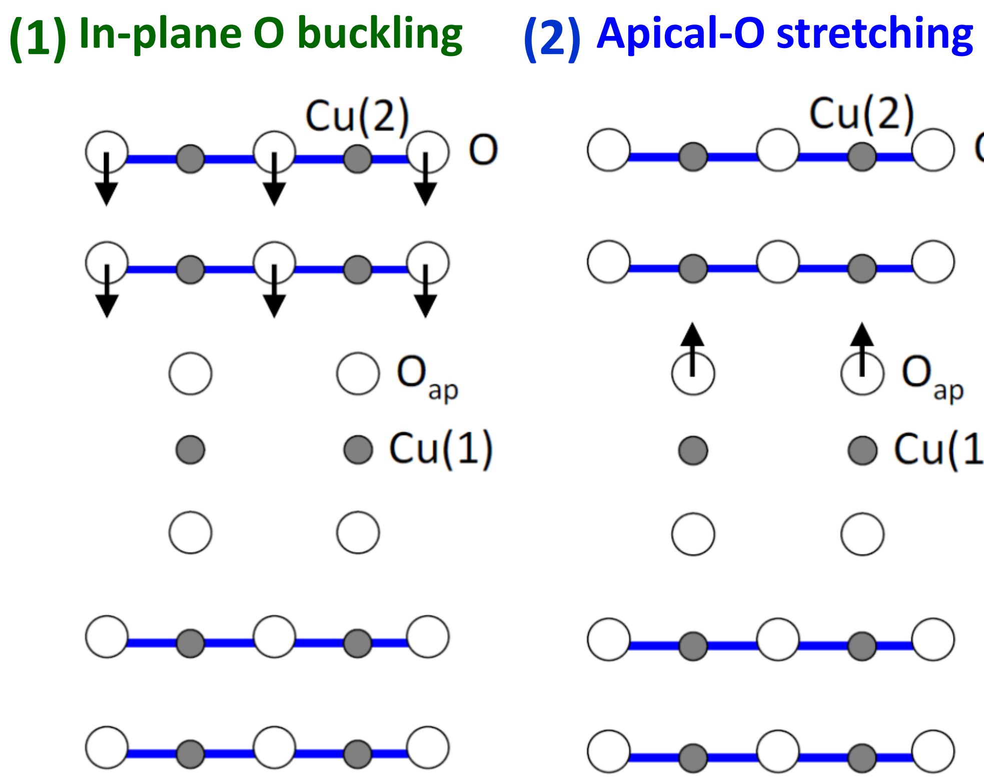




Phonon anomalies associated with the development of t-JP

The phonon anomalies can be explained by changes of the local electric fields acting on the ions upon the onset of intra-bilayer Josephson tunneling.

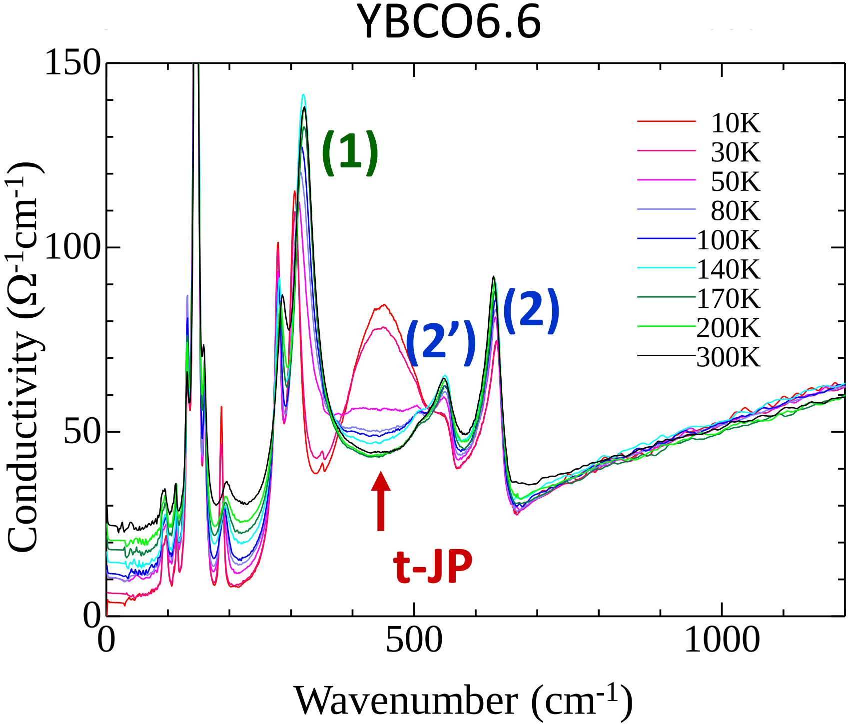


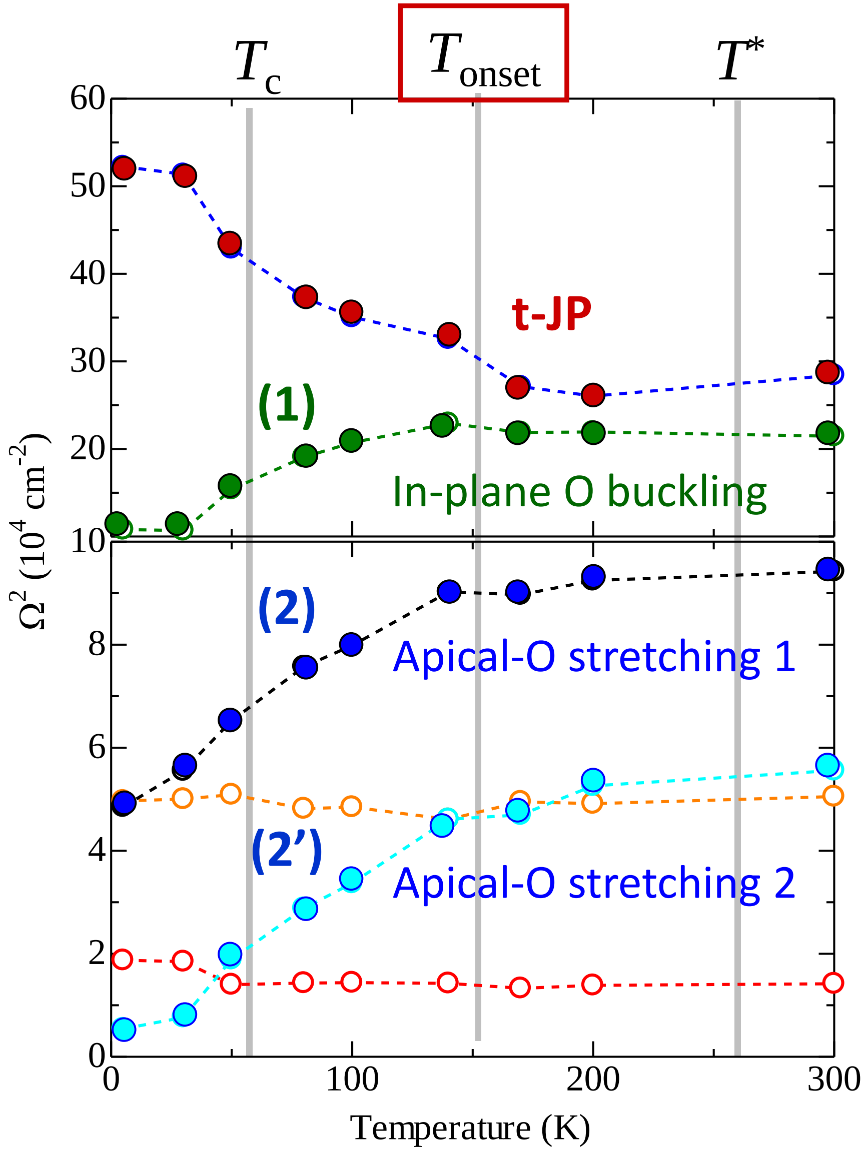


D. Munzar, C. Bernhard *et al.*, Solid State Commun. **112**, 365 (1999).

A.V. Boris, D. Munzar *et al.*, PRL **89**, 277001 (2002).

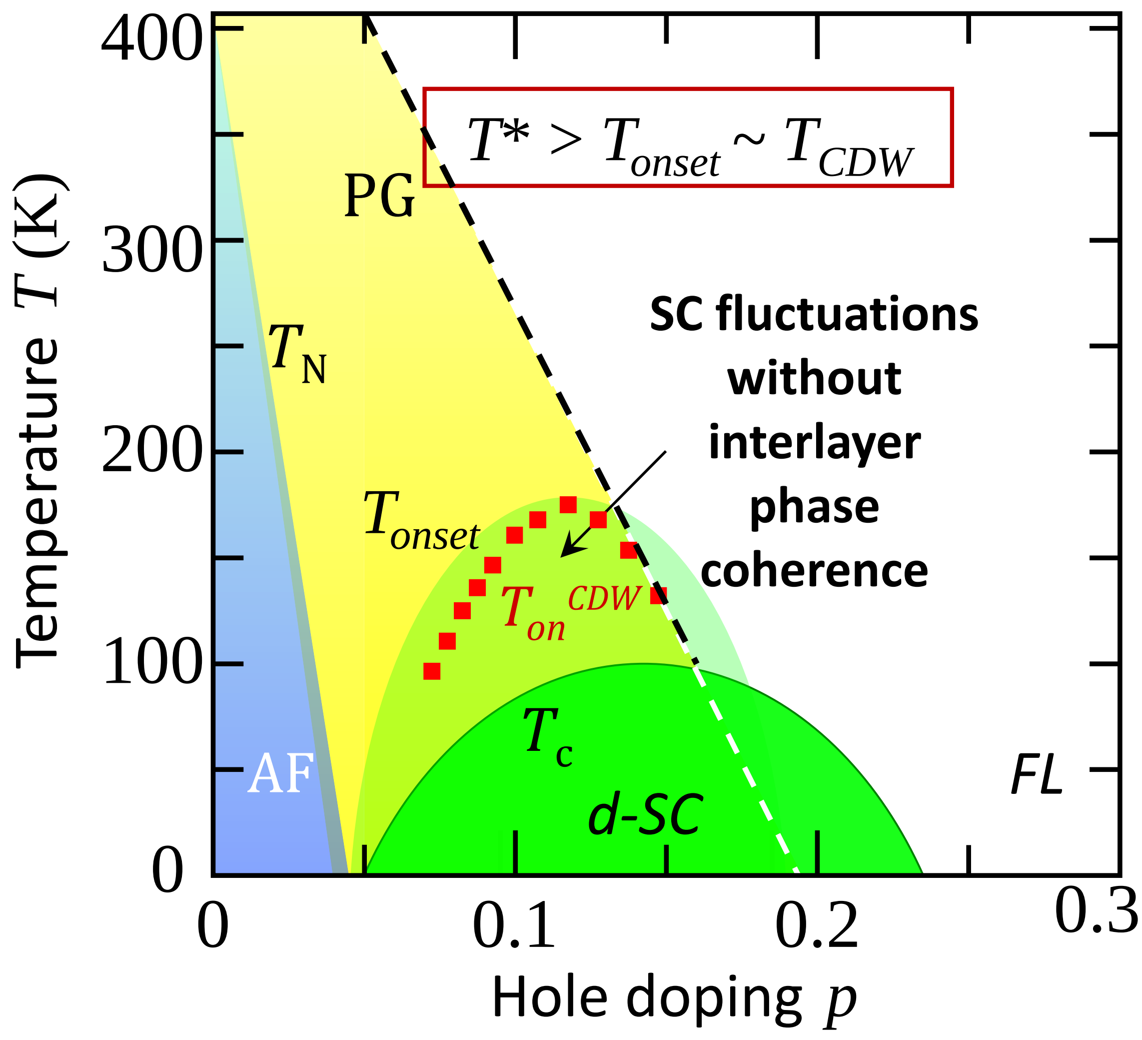
t-JP & phonon anomaly in the bilayer cuprate





K.M. Kojima, M. Nakajima, S. Tajima, SU, *unpublished results*.

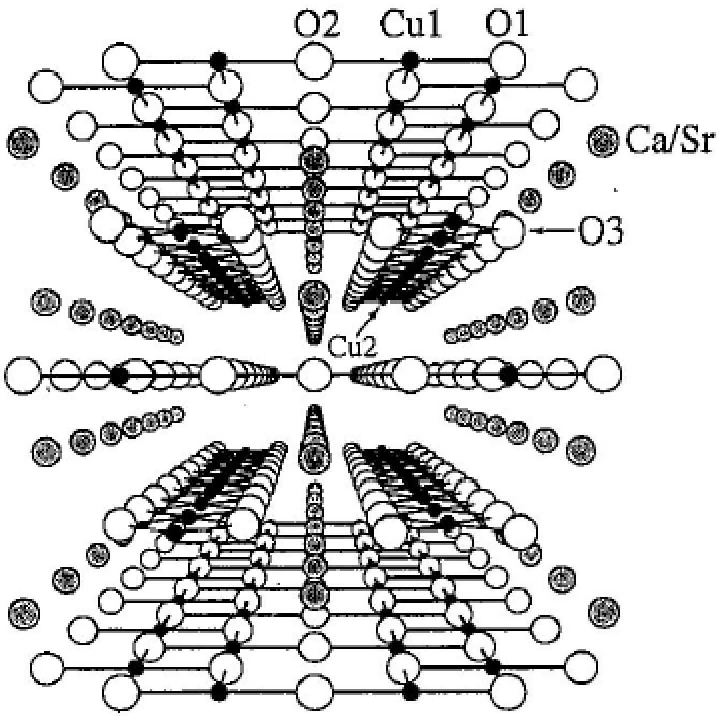
T_{onset} ~ T_{CDW} < T* in underdoped cuprates

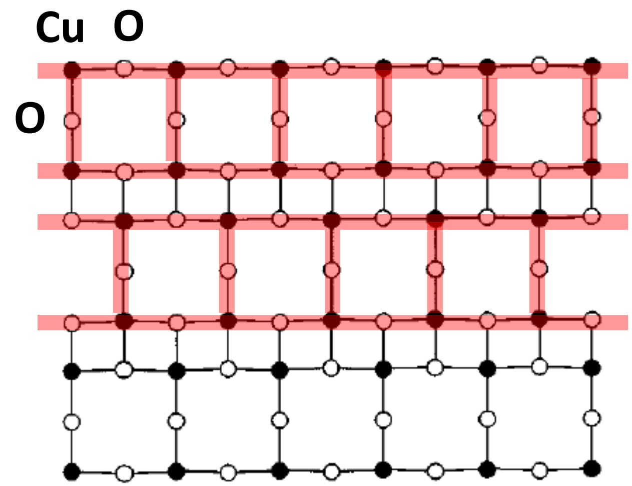


M. Hücker *et al.*, PRB **90**, 054513 (2014).

Pair formation and charge order (CDW) in hole-doped two-leg ladder cuprate

$Sr_{14-x}Ca_xCu_{24}O_{41}$





Pseudogap (spin gap)

Hole pairs

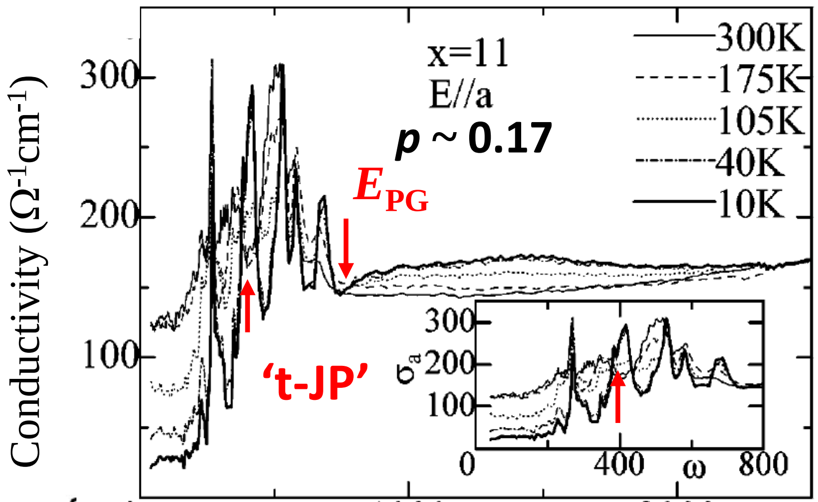
Charge order (PDW)

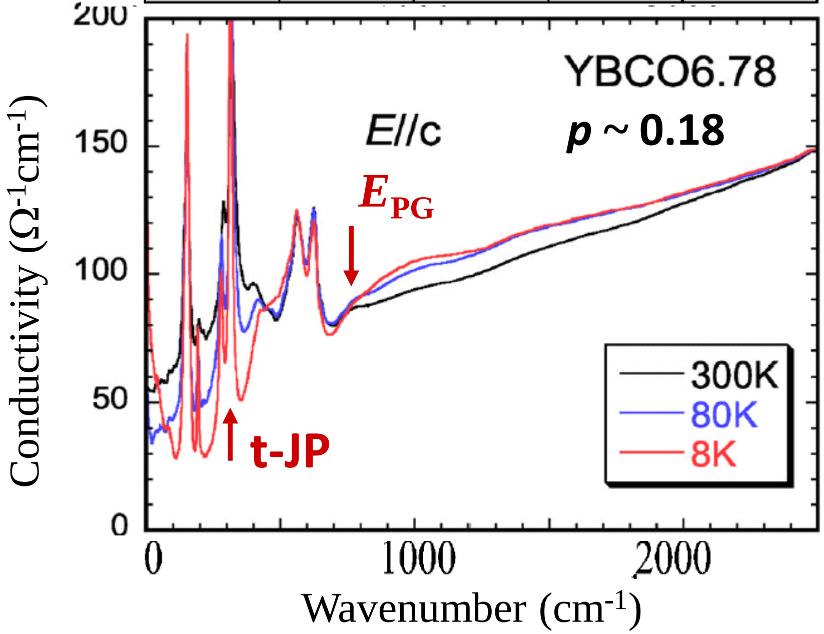
Phonon anomaly

Superconductivity @ *P*

T.M. Rice, K.Y. Tang, F.C. Zhang, Rep. Prog. Phys. **75**, 061502 (2012).

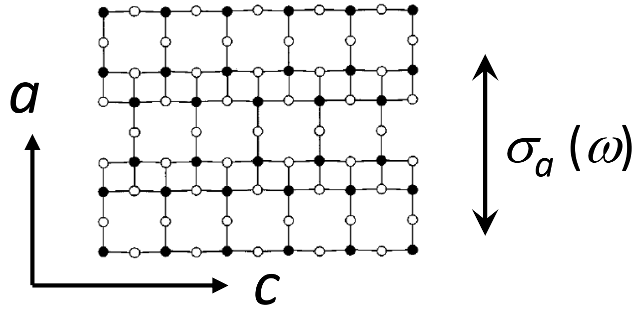
Similarity of the optical spectrum between bilayer cuprate and two-leg ladder cuprate





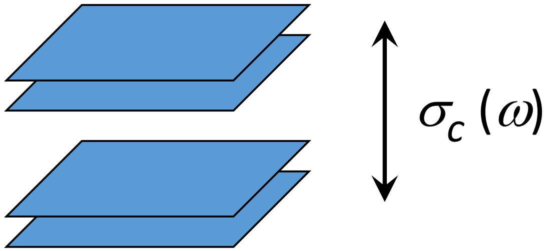
$Sr_3Ca_{11}Cu_{24}O_{41}$

T_c= 0 K, T_{PG} ~ 200 K



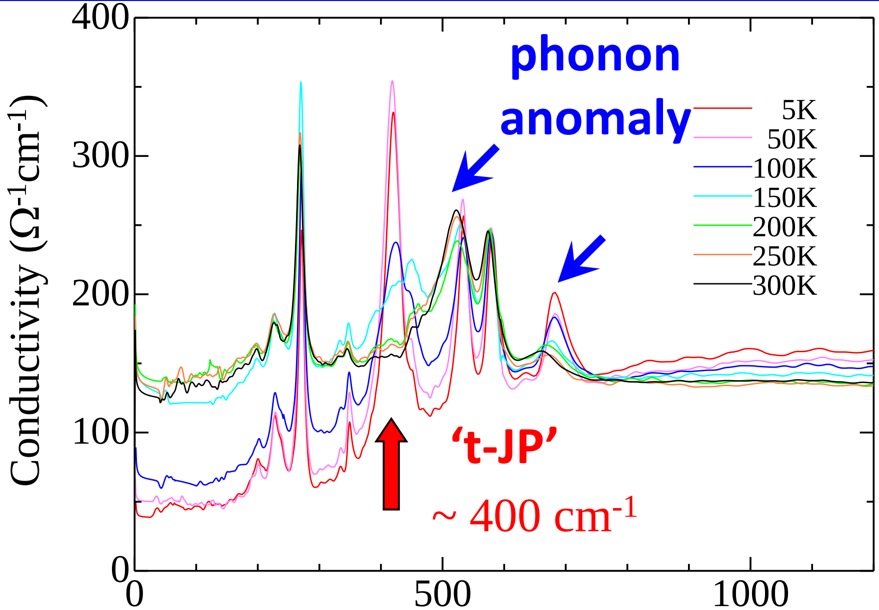
$YBCO_{6.78}$

T_c= 80 K, T^*~ 180 K

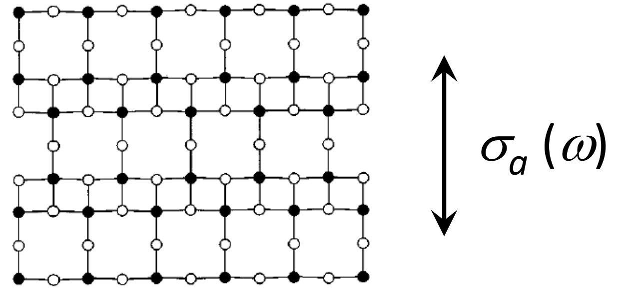


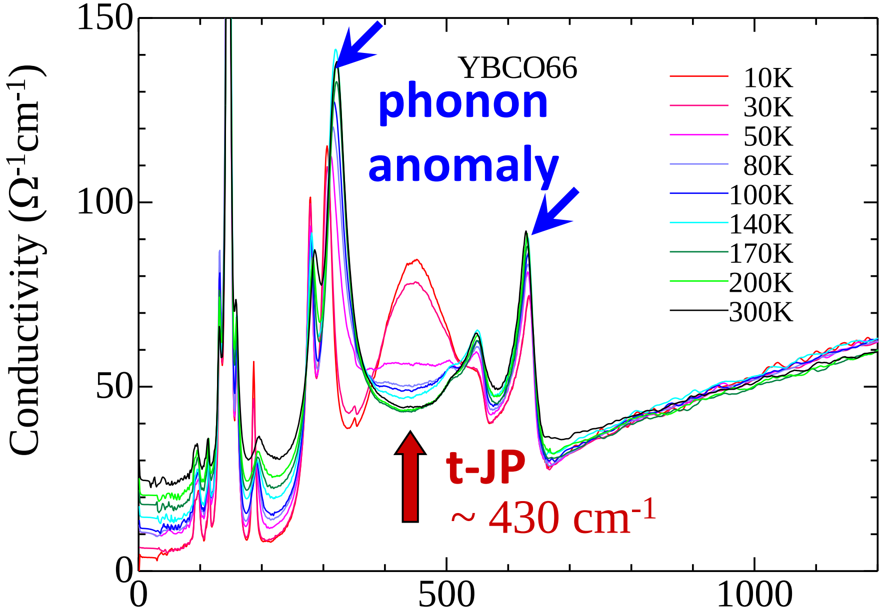
K.M. Kojima, M. Nakajima, S. Tajima, SU, *unpublished results*.

Transverse Josephson plasma & phonon anomaly

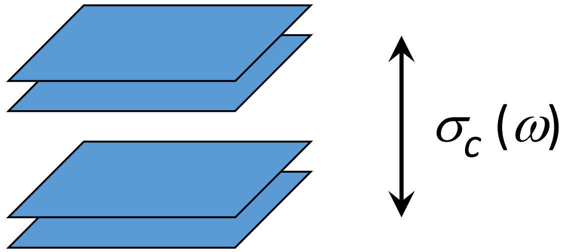


2-leg ladder cuprate:
$Sr_3Ca_{11}Cu_{24}O_{41}$



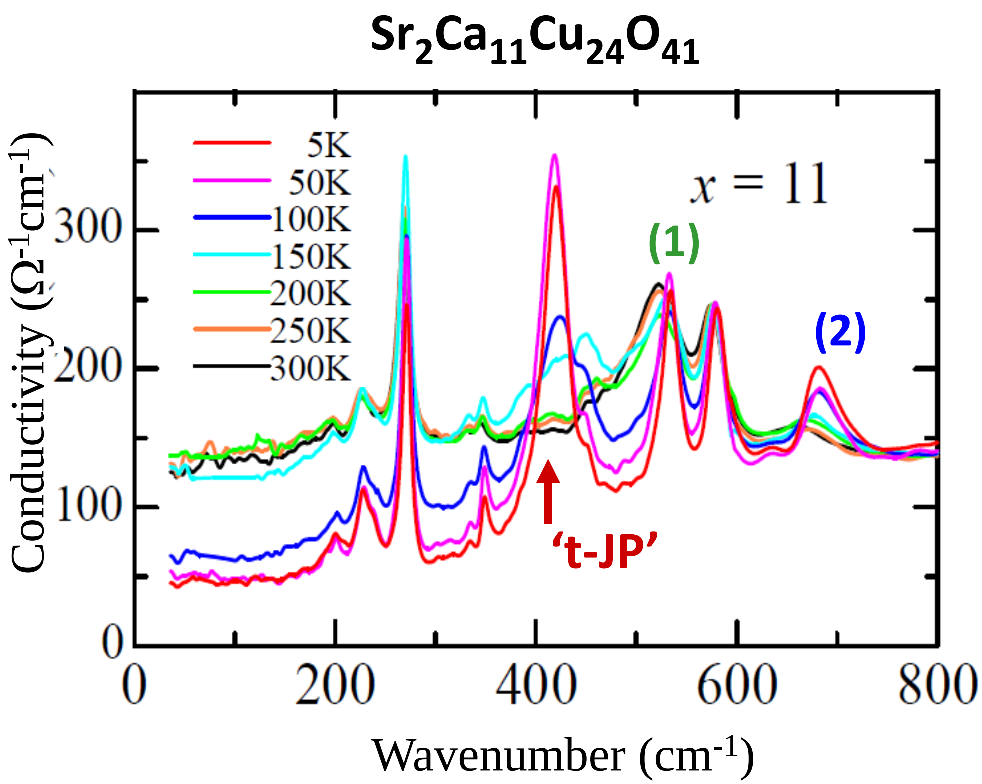


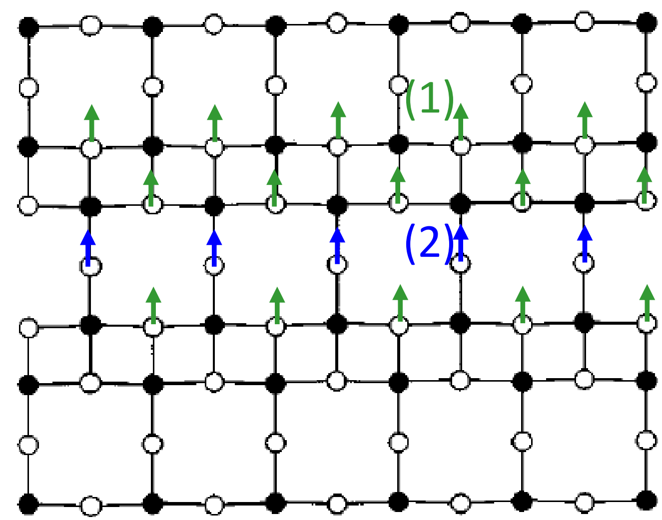
Underdoped cuprate:
YBCO6.6



T. Osafune, SU, S. Tajima *et al.*; PRL **82**, 5654 (1999).

Phonon modes showing an anomaly in the ladder cuprate

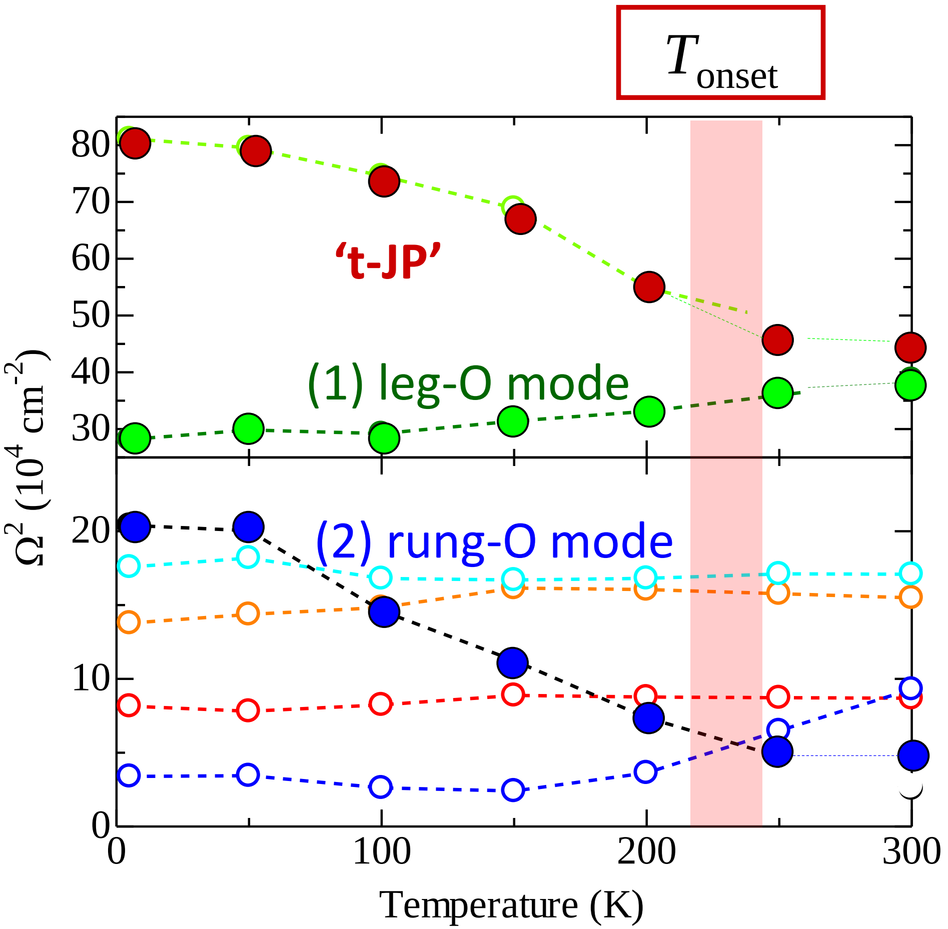


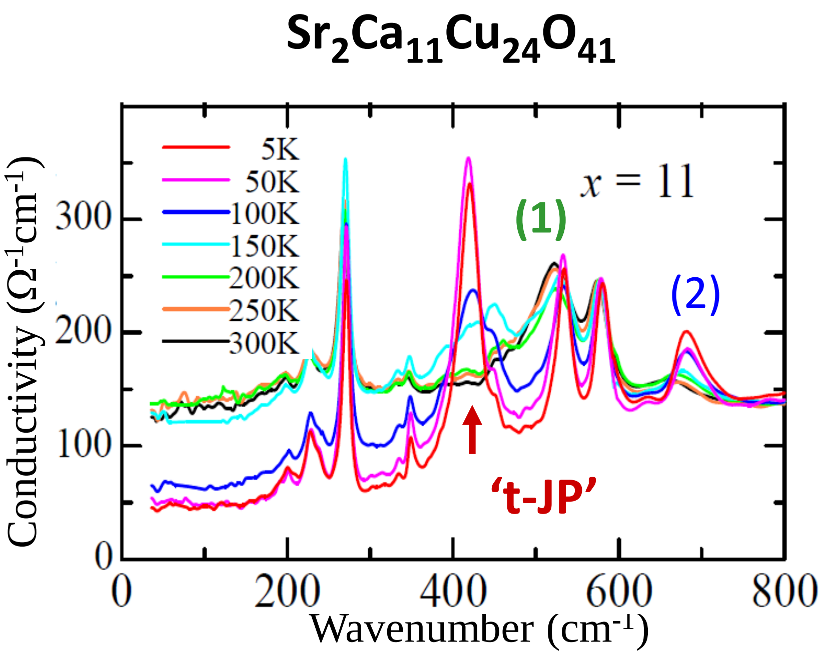


520 cm^{-1} **(1):** leg-O phonon (chain-O buckling)

630 cm^{-1} **(2):** rung-O phonon ('apical'- O)

Onset of t-JP & phonon anomaly

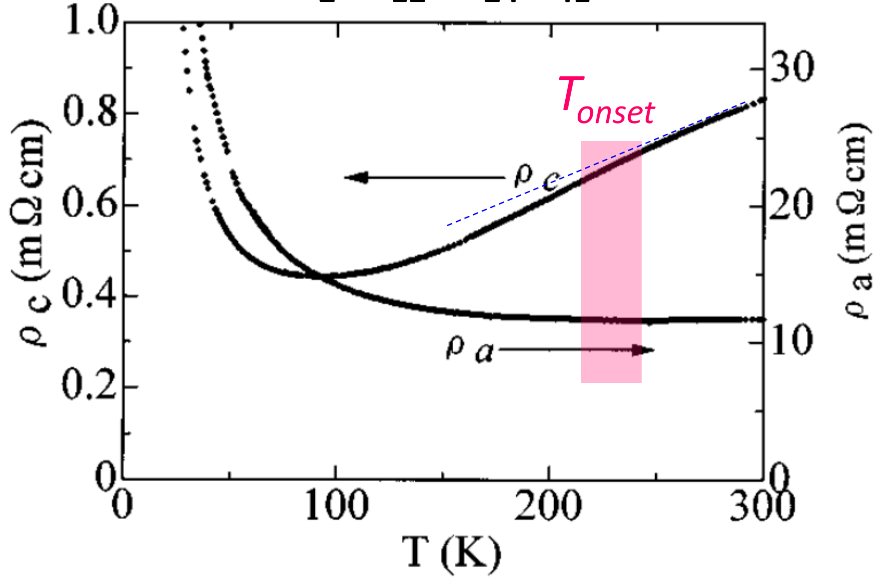


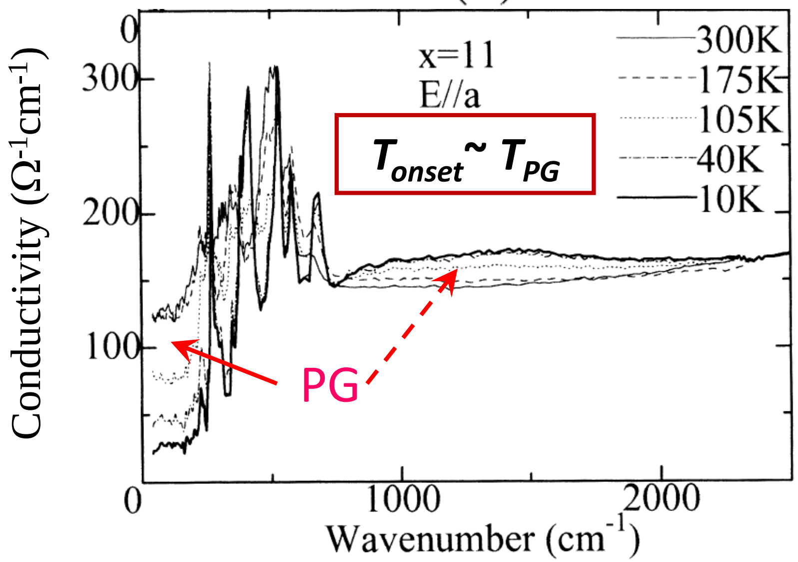


K.M. Kojima, M. Nakajima, S. Tajima,
SU, *unpublished results*.

Onset temperature of t-JP & phonon anomaly

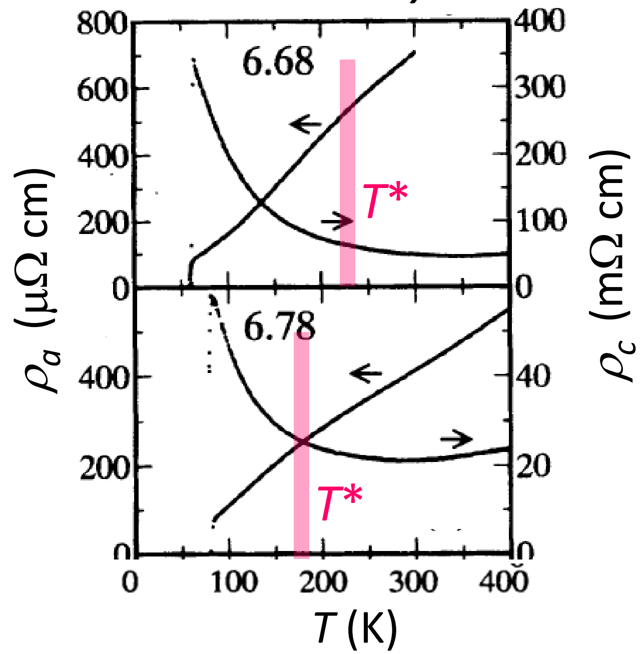
$Sr_2Ca_{12}Cu_{24}O_{41}$





T. Osafune, SU, S. Tajima *et al.*; PRL **82**, 5654 (1999).

$YBa_2Cu_3O_y$

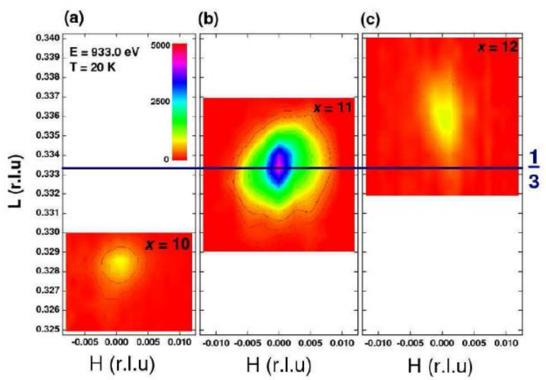


K. Takenaka, H. Takagi, SU, PRB **50**, 6534(R) (1994).

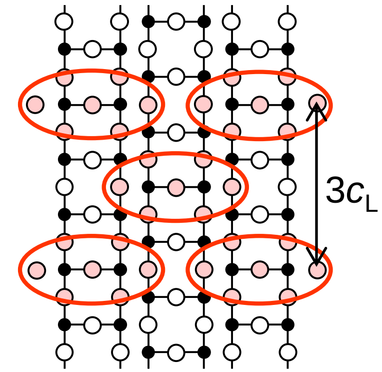
Charge (hole-pair) order in two-leg ladder cuprate

A. Rusydi, P. Abbamonte *et al.*, Phys. Rev. Lett. **97**, 016403 (2006).

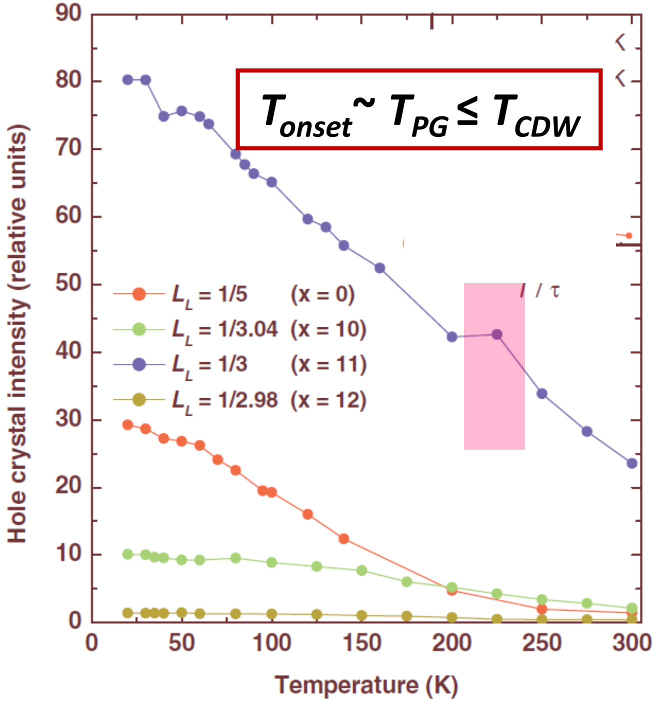
$Sr_{14-x}Ca_xCu_{24}O_{41}$

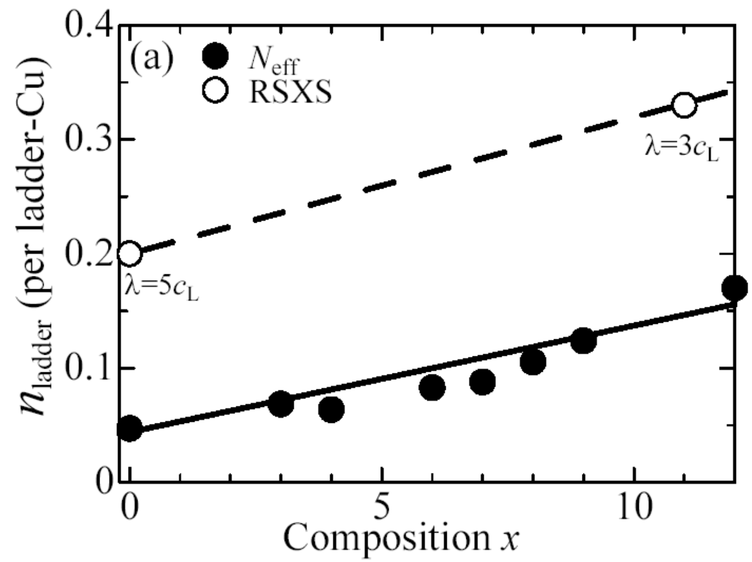


$x \sim 11$



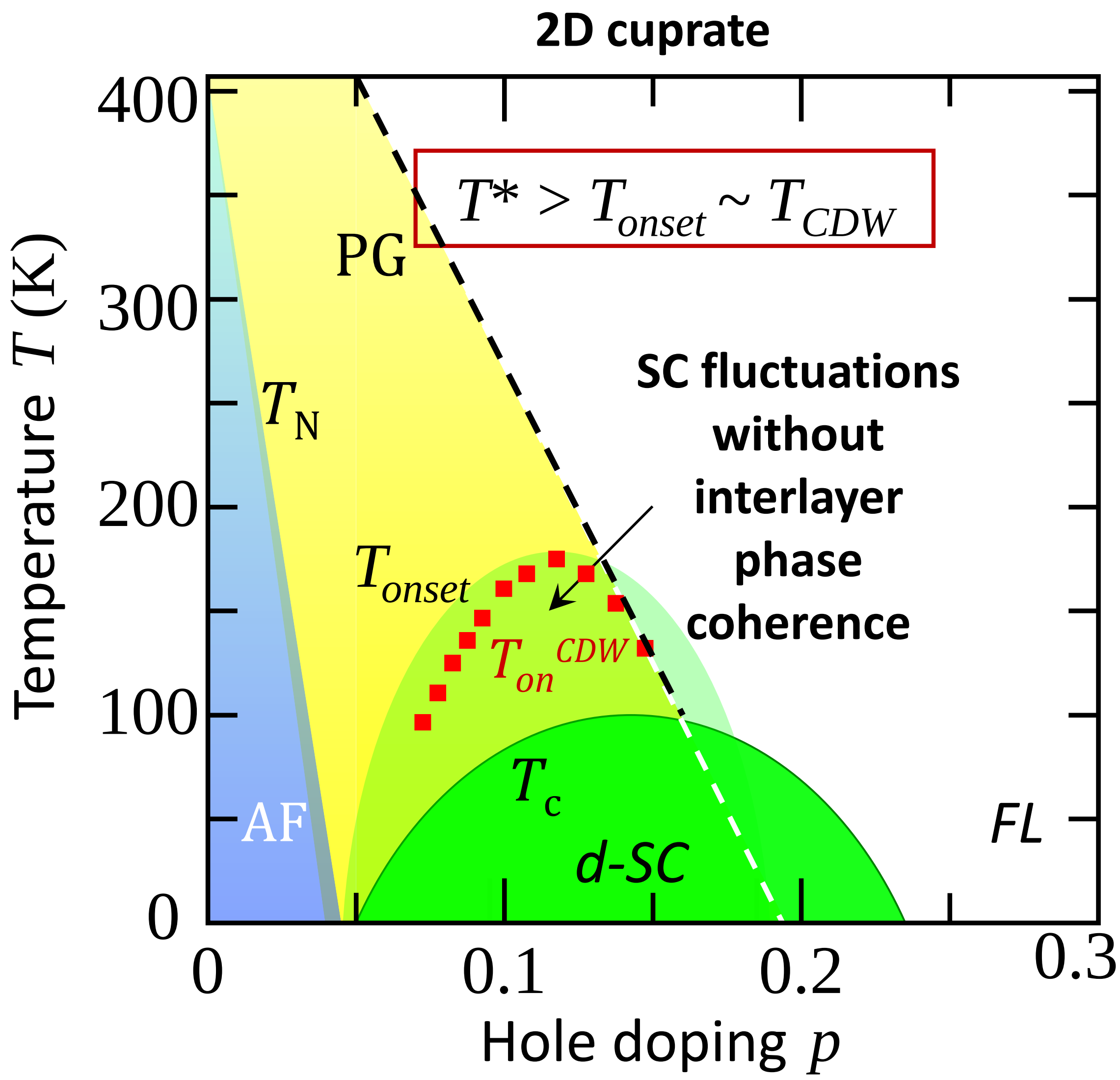
$n = 1/3$





T. Osafune, N. Motoyama, H. Eisaki, SU; PRL **78**, 1980 (1997).

Underdoped cuprate vs Ladder cuprate



Two-leg ladder cuprate

$T_{PG} \sim T_{onset} \gtrsim T_{CDW}$

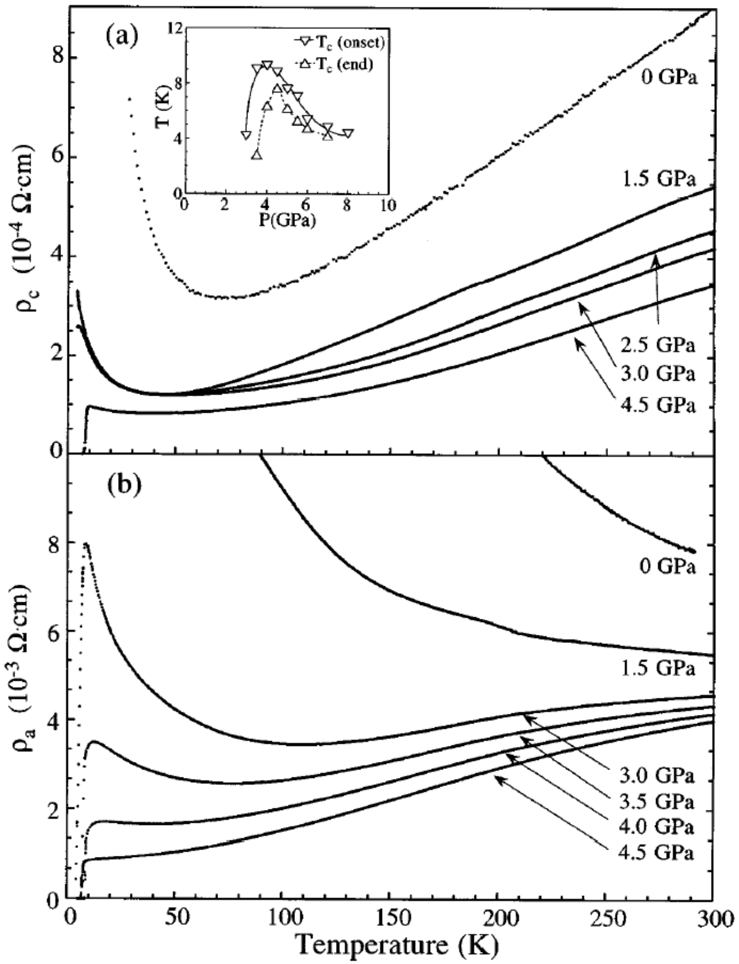
M. Hücker *et al*., PRB **90**, 054513 (2014).

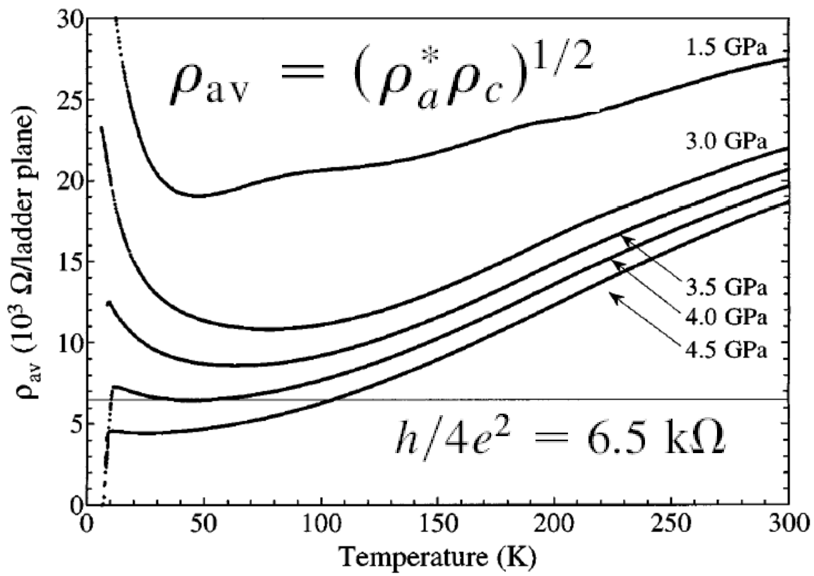
Congratulations to KITS,
Fu-Chun Zhang, Jiang-Ping Hu,
and other members

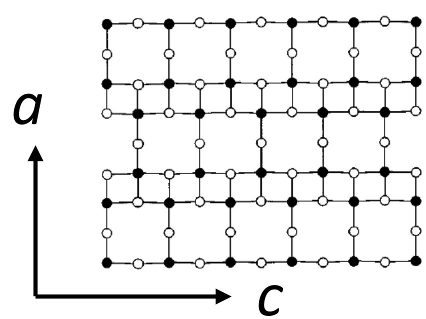
Pressure-Induced Dimensional Crossover and Superconductivity in the Hole-Doped Two-Leg Ladder Compound $Sr_{14-x}Ca_xCu_{24}O_{41}$

T. Nagata,[1] M. Uehara,[1] J. Goto,[1] J. Akimitsu,[1] N. Motoyama,[2] H. Eisaki,[2] S. Uchida,[2] H. Takahashi,[3] T. Nakanishi,[3] and N. Môri[4]

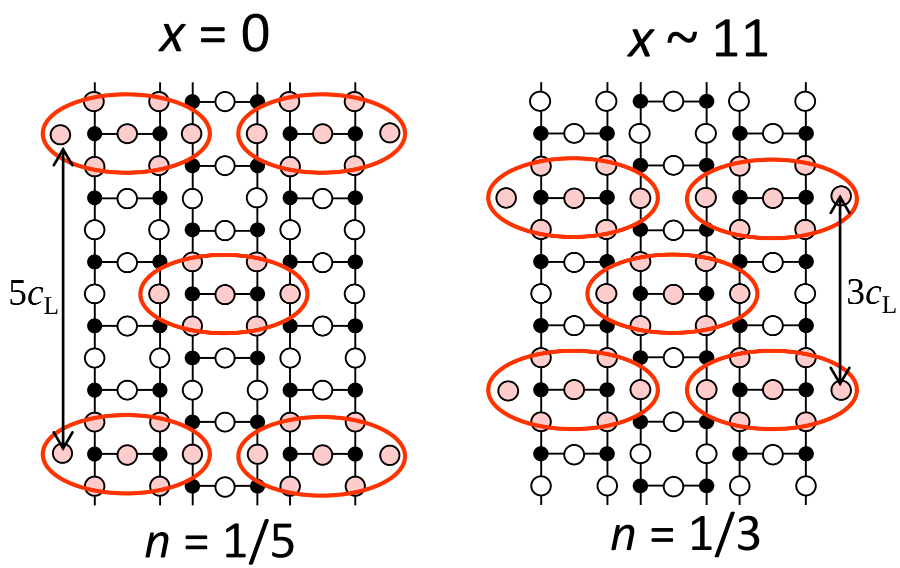
Phys. Rev. Lett. **58**, 758 (2002).

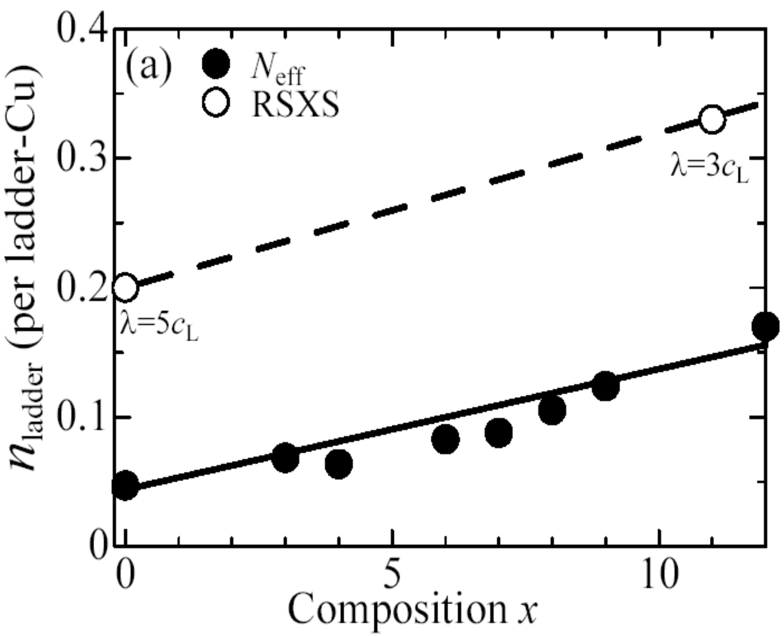






Controversy in the doped hole density





T. Osafune, N. Motoyama, H. Eisaki, SU; PRL **78**, 1980 (1997).

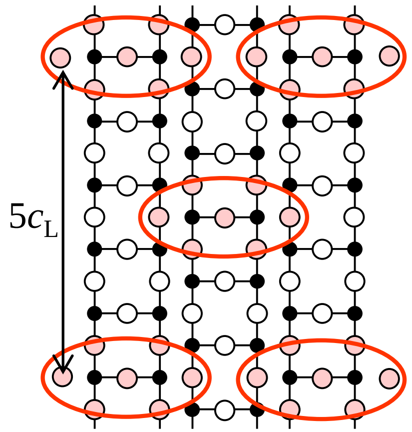
A. Rusydi, P. Abbamonte *et al.*, Phys. Rev. Lett. **97**, 016403 (2006).

K. Wohlfeld, A. Oles, G.A. Sawatzky, PRB **75**, 180501(R) (2007).

J. Almeida, G. Roux, D. Poilblanc, PRB **82**, 041102(R) (2010).

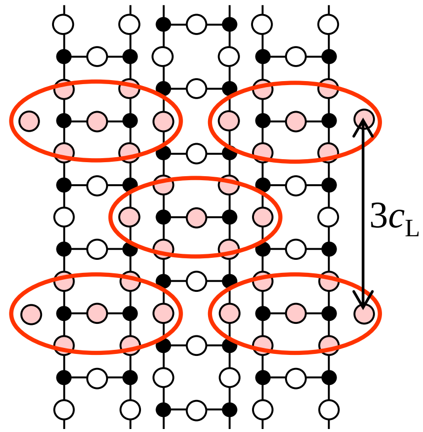
Controversy in the doped hole density

$x = 0$

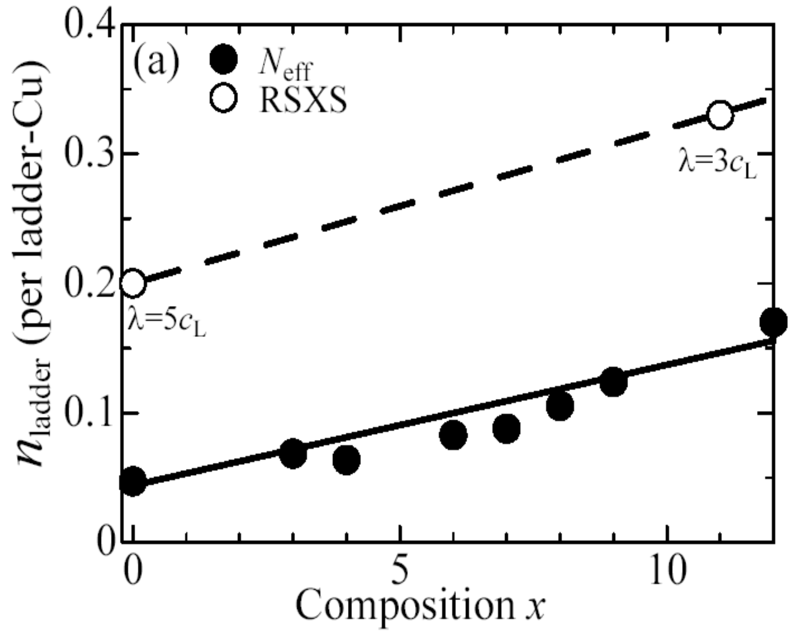


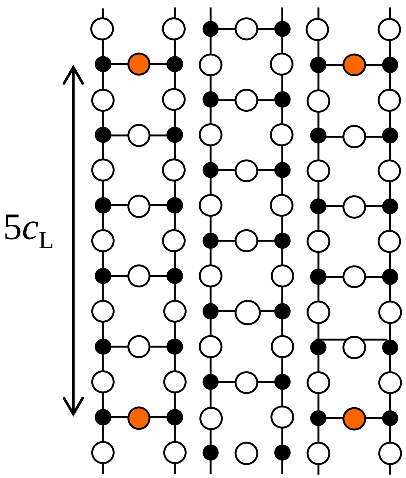
$n = 1/5$

$x \sim 11$

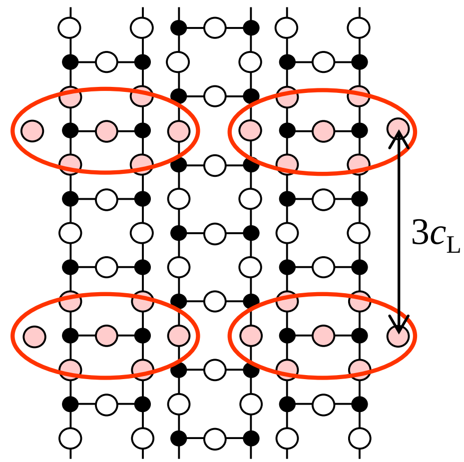


$n = 1/3$





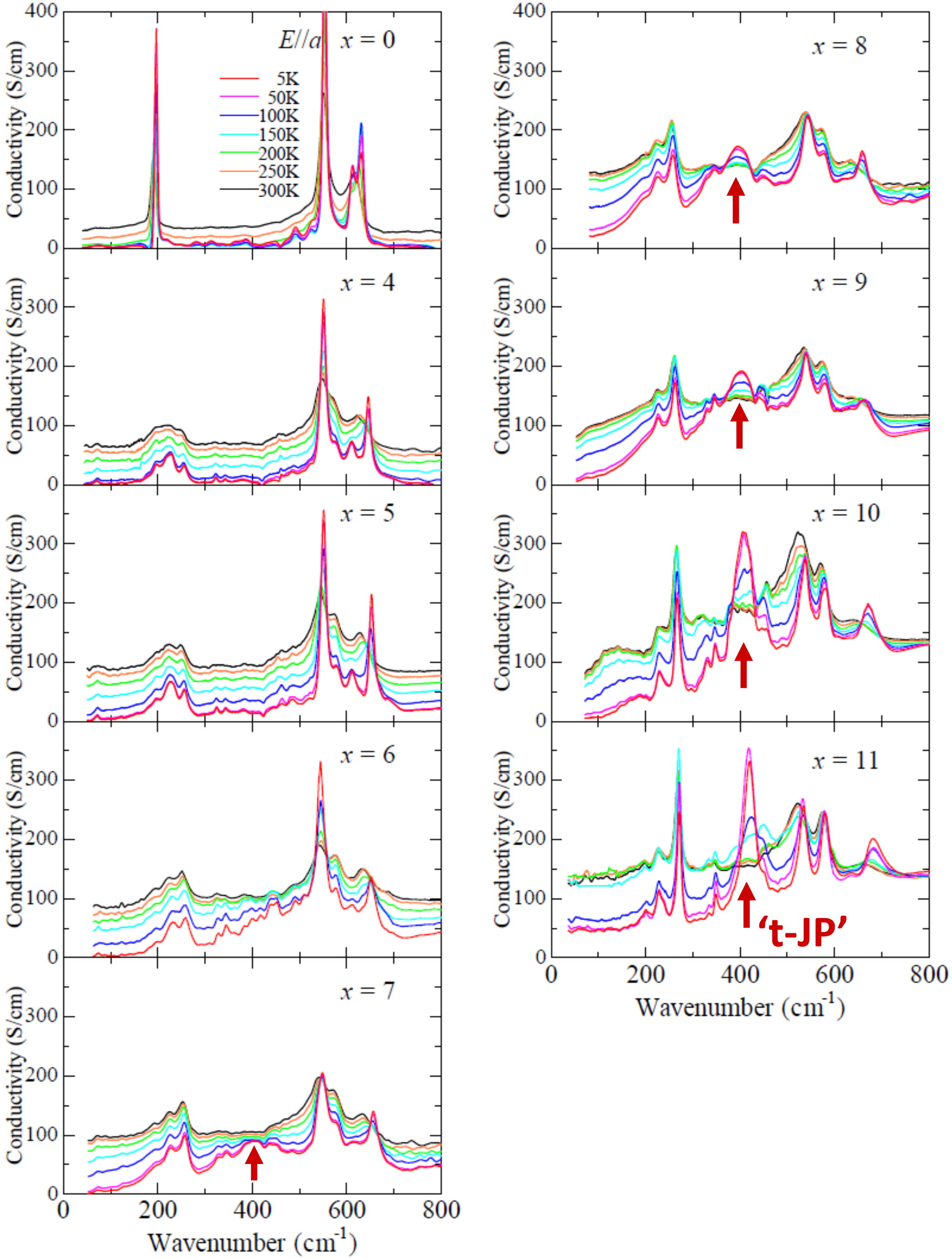
$n \approx 1/20$

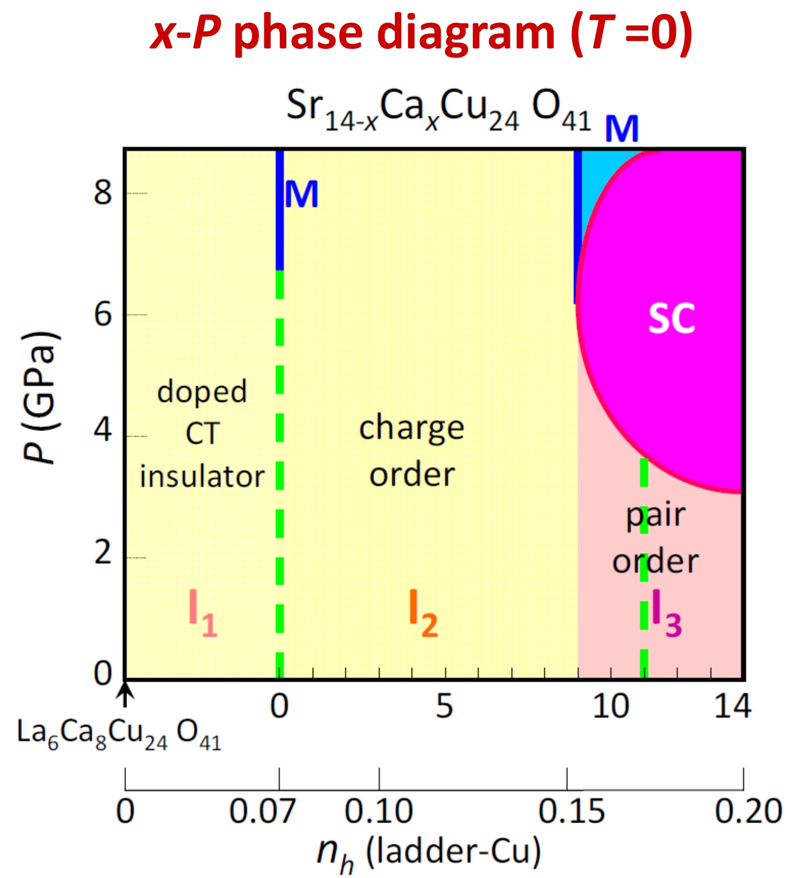


$n \approx 1/6$

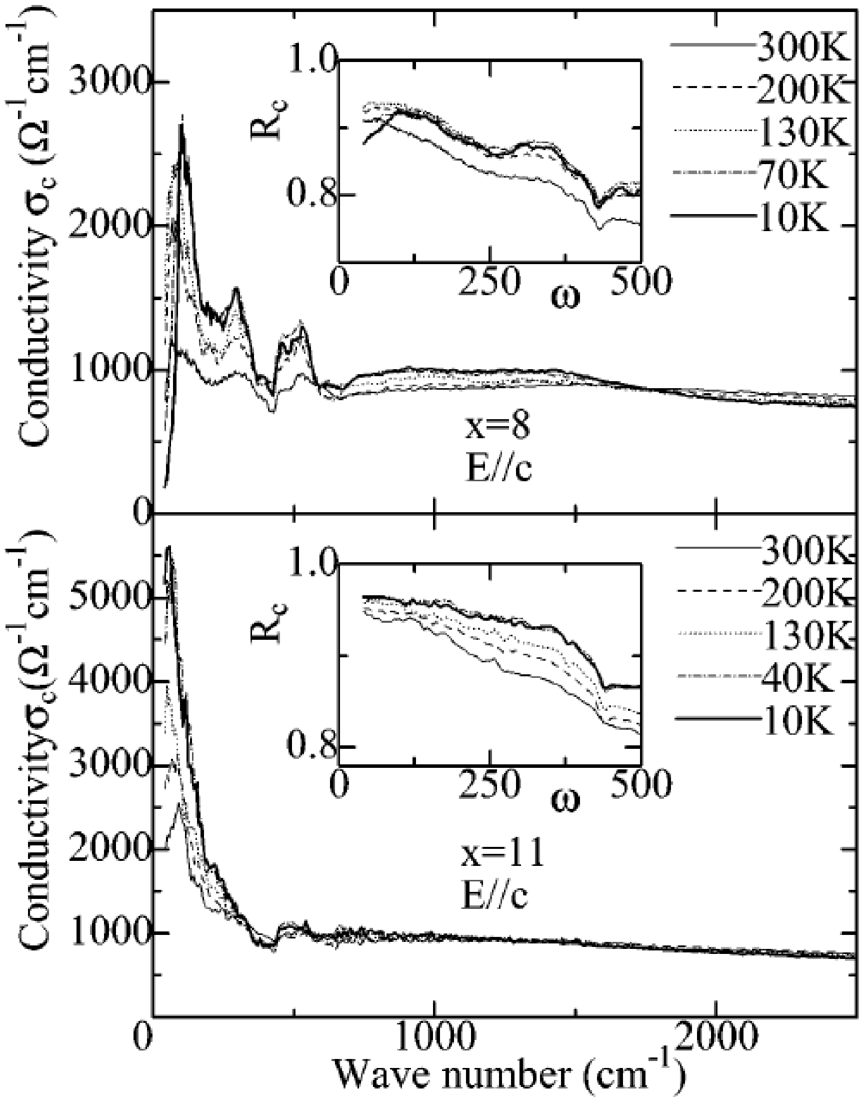
Y. Fujimaki, M. Nakajima, SU;
unpublished

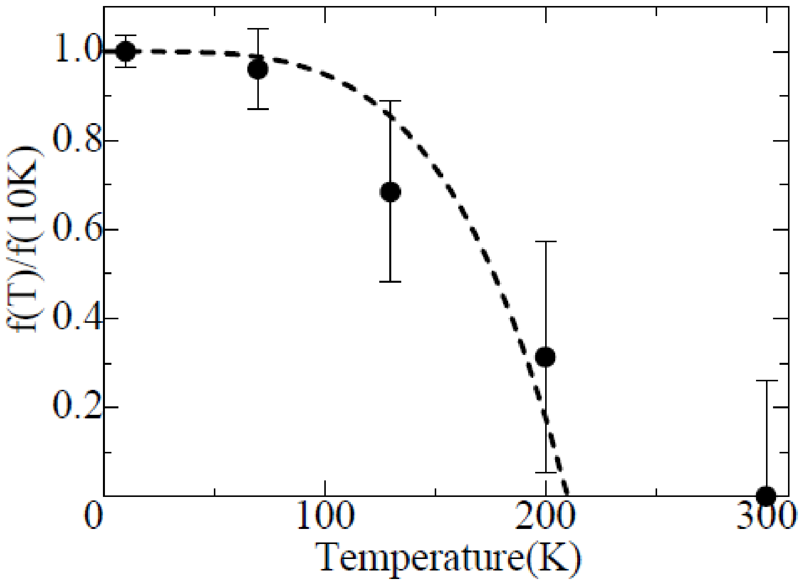
t-JP & phonon anomaly are observed for highly hole-doped 14-24-41





Spectroscopic signature of the charge order





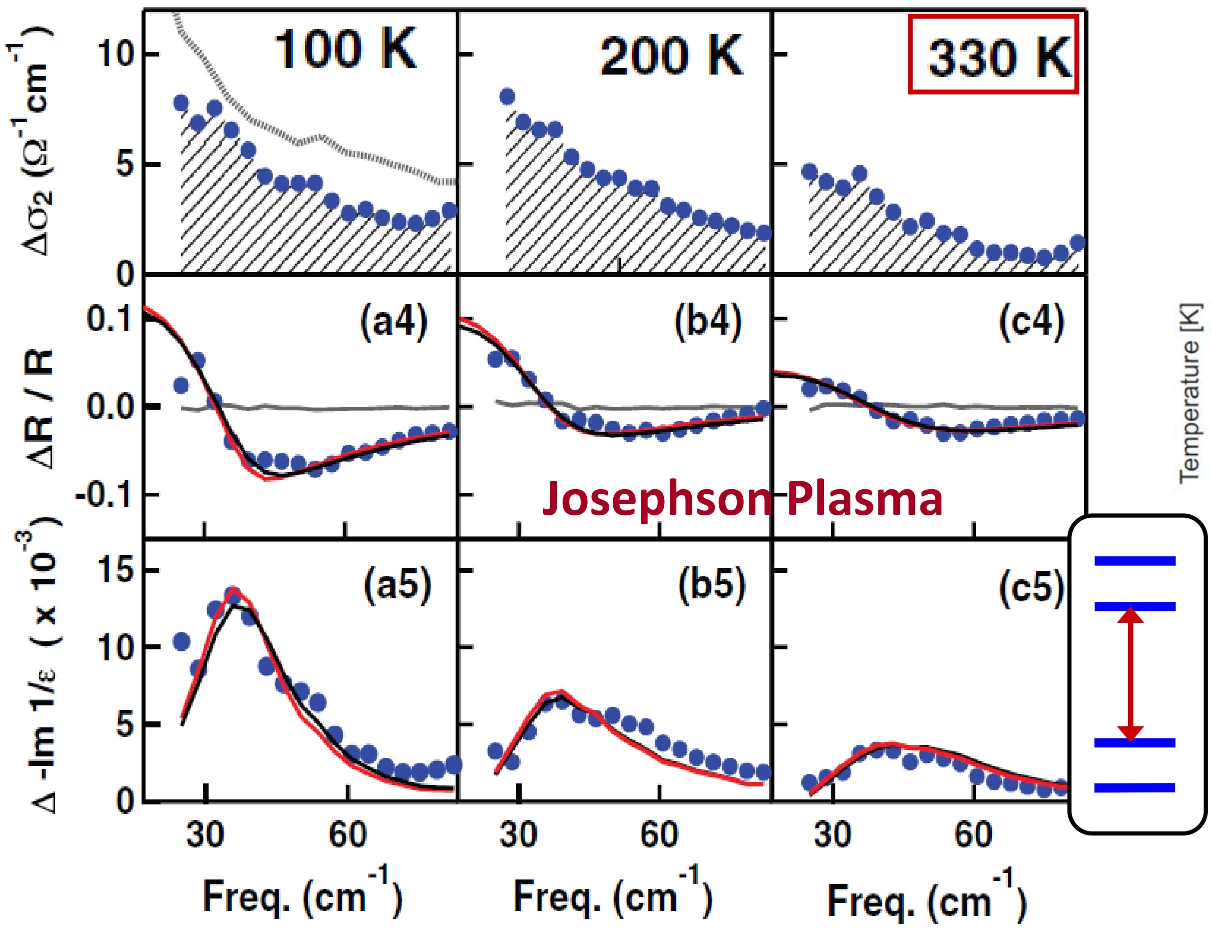
T. Osafune, SU, S. Tajima *et al.*; PRL **82**, 5654 (1999).

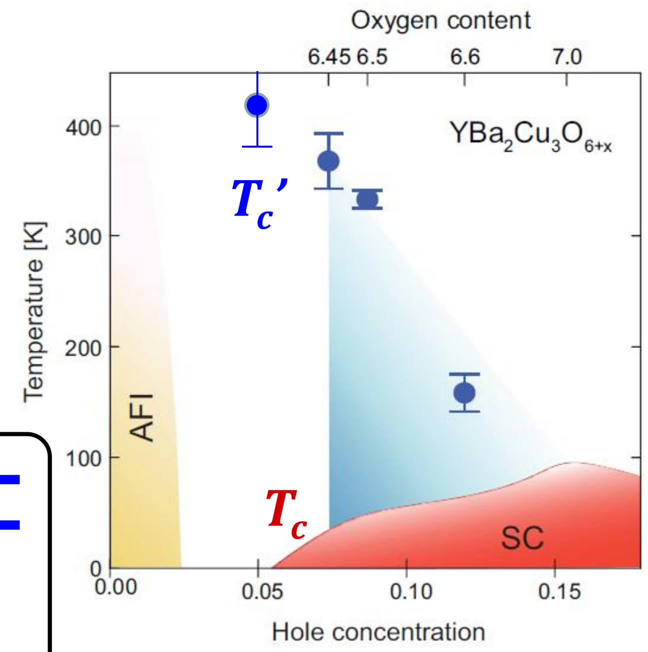
Transient SC-Tc'(p) follows T*(p).

S. Kaiser, A.Cavalleri *et al.*; PRB **89**, 184516 (2014).
C.R. Hunt, A.Cavalleri *et al.*; PRB **94**, 224303 (2016).

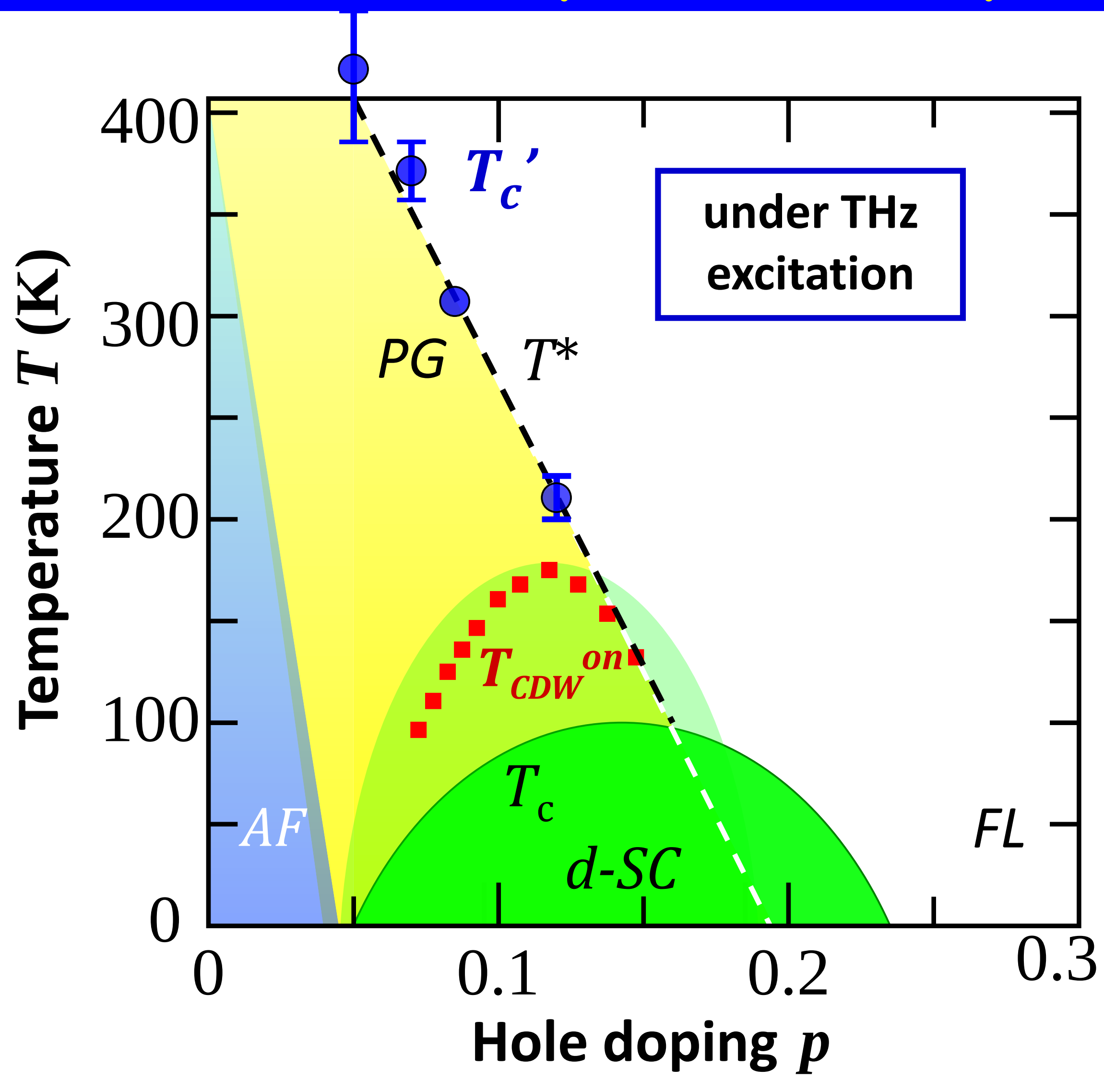
Interbilayer coherence is transiently established.

YBCO6.45 excited by ~ 20 THz pulsed laser



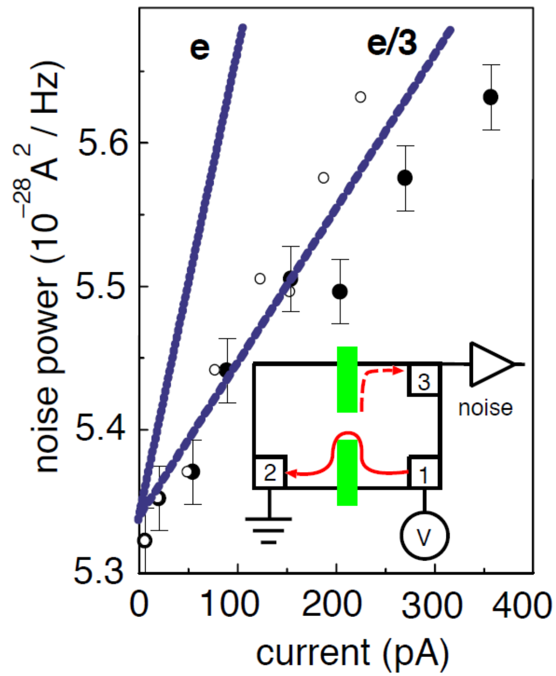


Transient Tc'(p) follows T*(p).

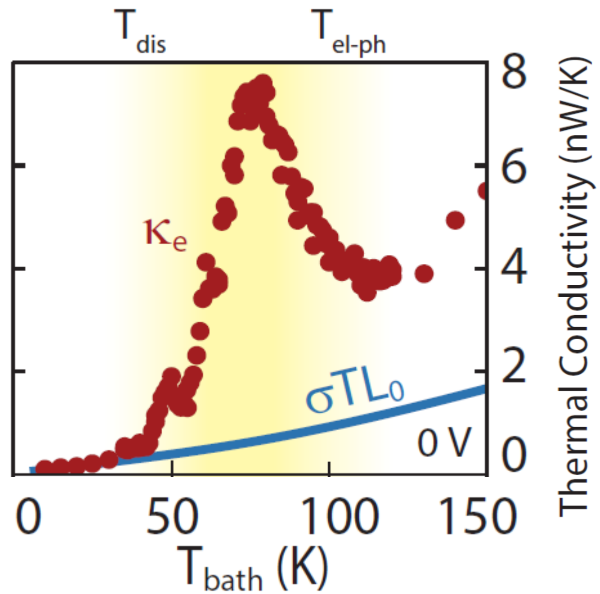


Quantum Shot Noise & Johnson Noise

GaAs/GaAlAs or Graphene



Graphene



Quantum shot noise results from the discreteness of the current-carrying charges, and so is proportional to the charge of the quasiparticles.

Johnson noise thermometry measures electronic thermal conductivity, and can test the Wiedemann-Franz law.

V.J. Goldman, B. Su;
Science **267**, 5200 (1995).

J. Crossno, P. Kim *et al.*,
Science **351**, 1058 (2016).