Strong Correlations and ARPES: Recent Progress in Theory and Experiment
Dresden, April 4-8, 2005

Understanding thermodynamic and transport properties of underdoped cuprates from ARPES data

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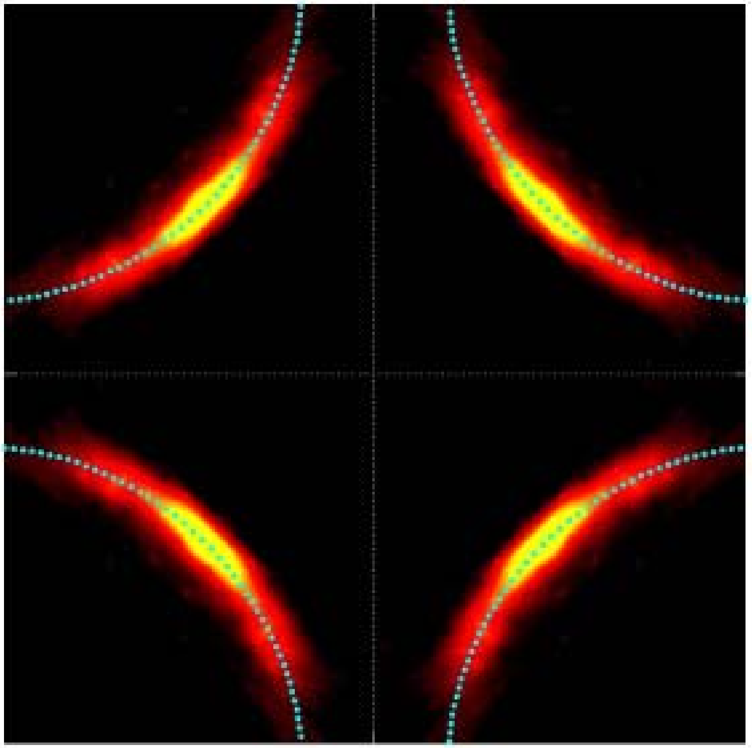
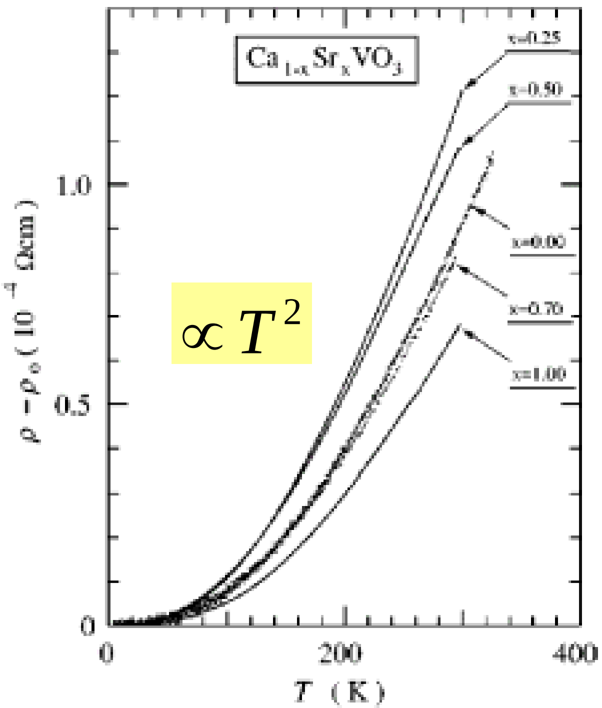


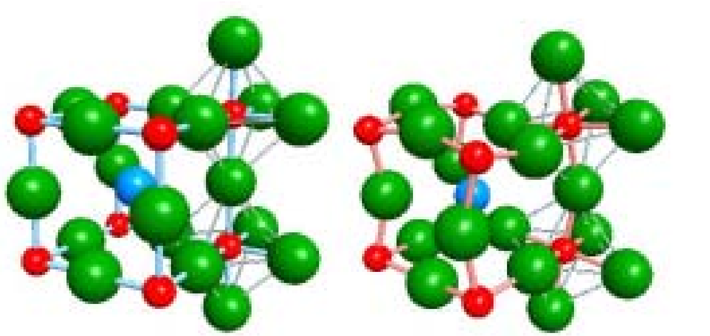
Outline

- Introduction
  - Conventional Fermi liquids
- Pseudogap and Fermi arc
- Thermodynamic properties
  - Electronic specific heats
- Transport properties
  - Doping dependence
  - Impurity effects
- Conclusion

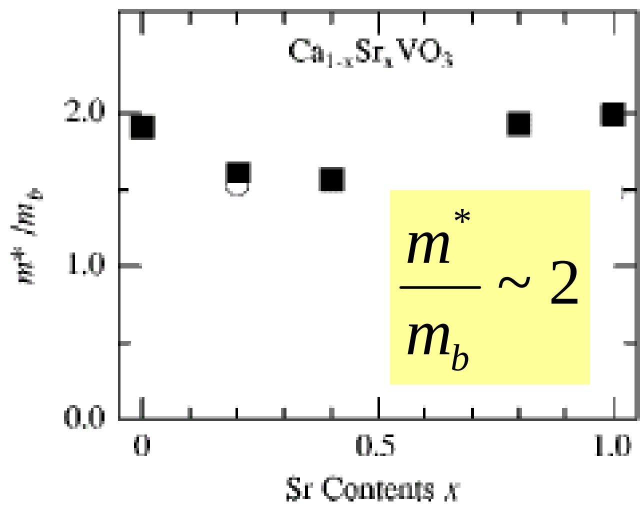
Normal Fermi-liquid systems $SrVO_3$ and $Ca_{1-x}Sr_xVO_3$

Electrical resistivity



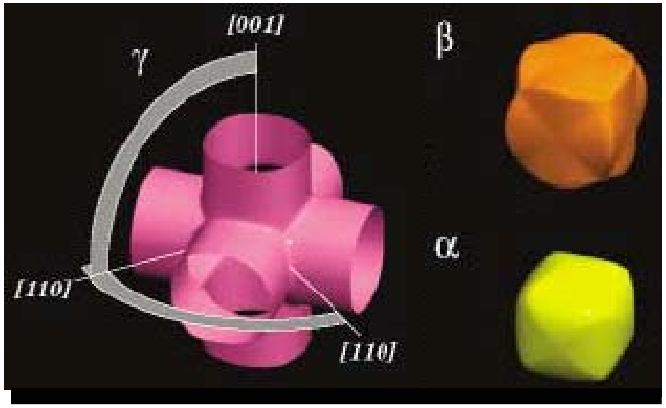


Electronic specific heat



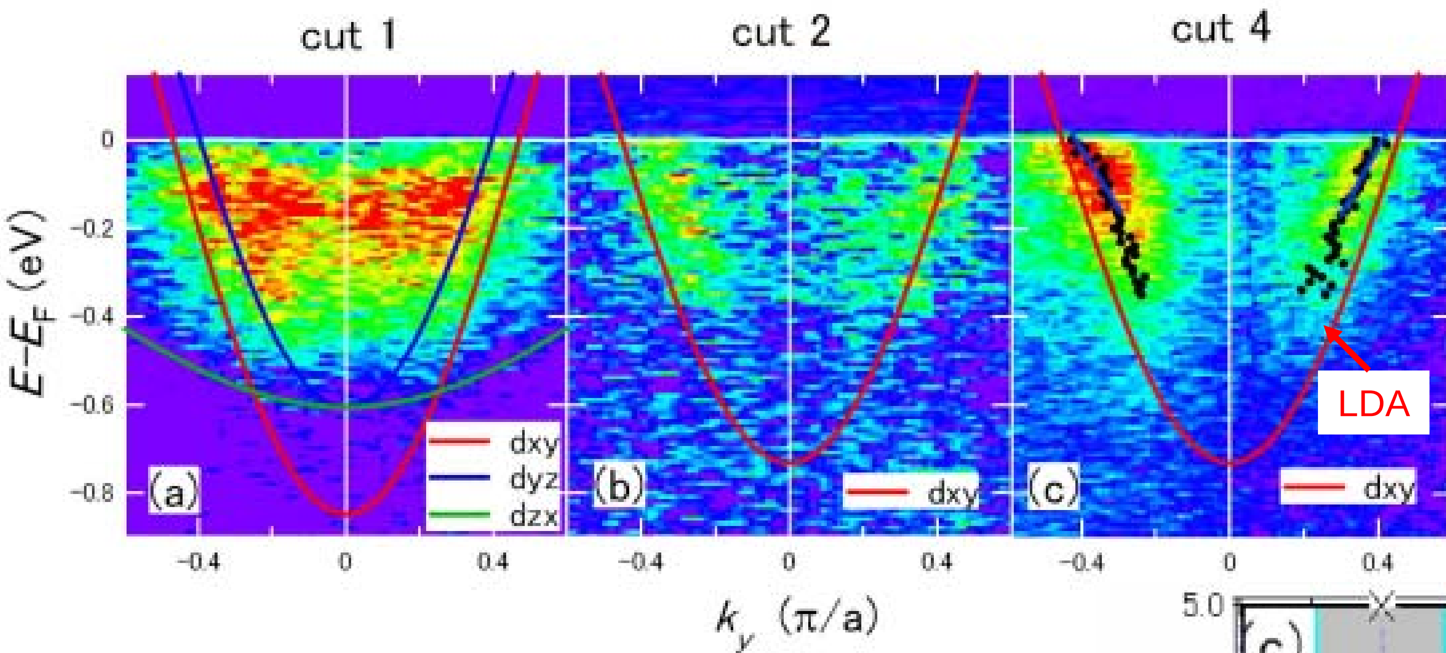
I.H. Inoue et al, PRB 98'

dHvA expt



I. H. Inoue et al., PRL '02

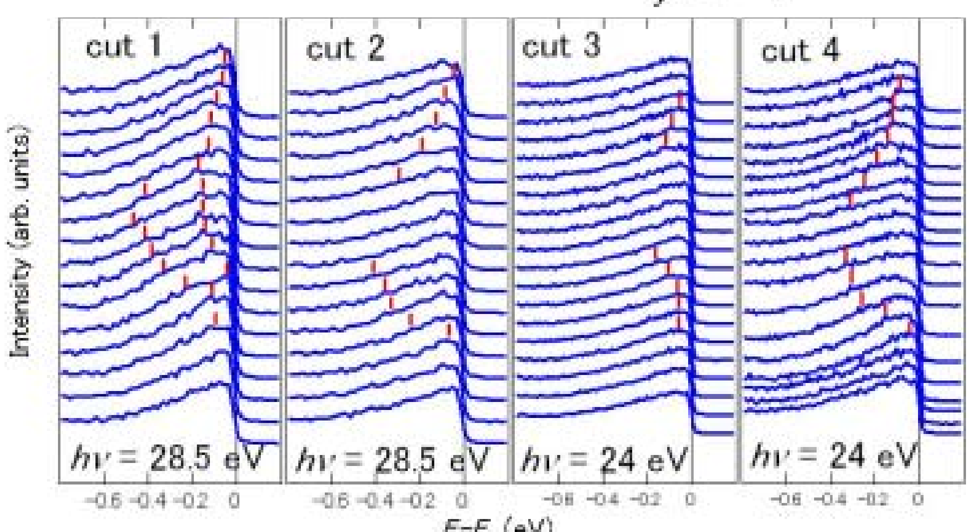
Mass renormalization in ARPES spectra of $SrVO_3$

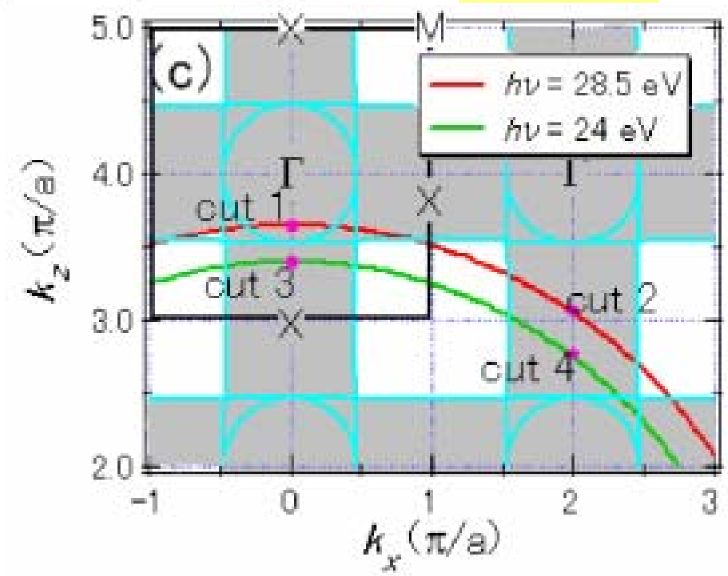


$$\frac{v_F}{v_F^*} = 1.8 \pm 0.2$$

consistent with

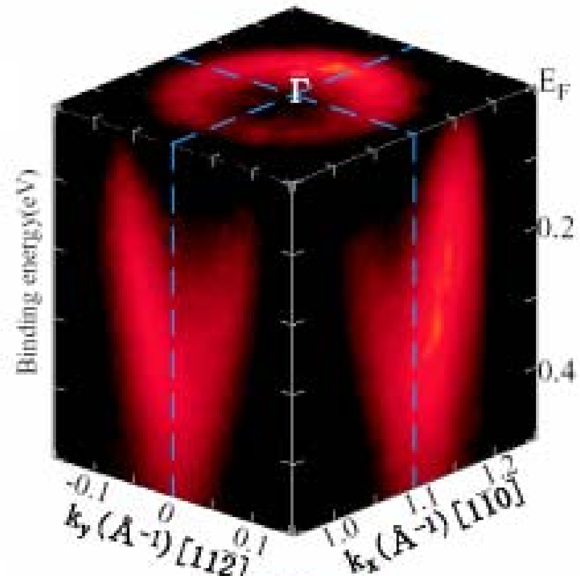
$$\frac{m^*}{m_b} \sim 2$$



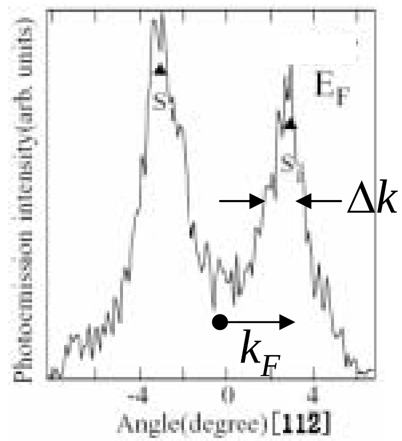


T. Yoshida et al., cond-mat/05

ARPES spectra and transport of 2D free electrons on Si √3×√3-Ag



MDC

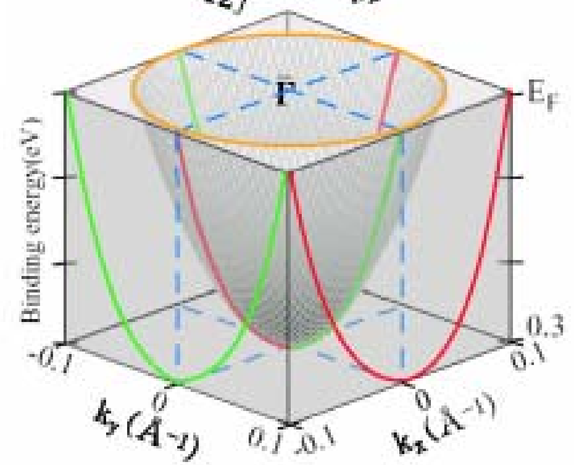


$$\sigma = \frac{ne^2\tau}{m^*} = \frac{e^2 k_F}{h\Delta k}$$

$$n = k_F^2 / 2\pi$$

$$m^* v_F = \hbar v_F$$

$$\tau = l / v_F = 1 / v_F \Delta k$$

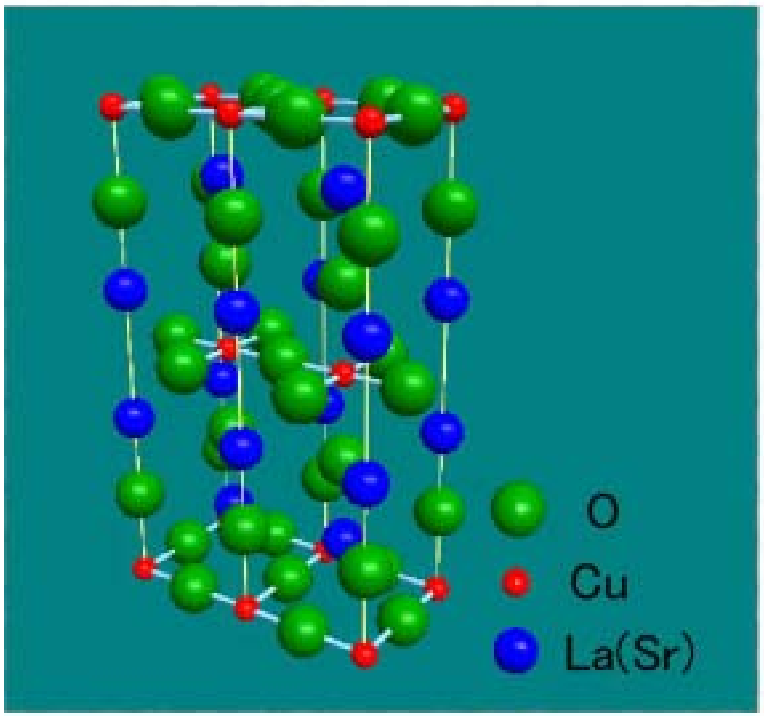


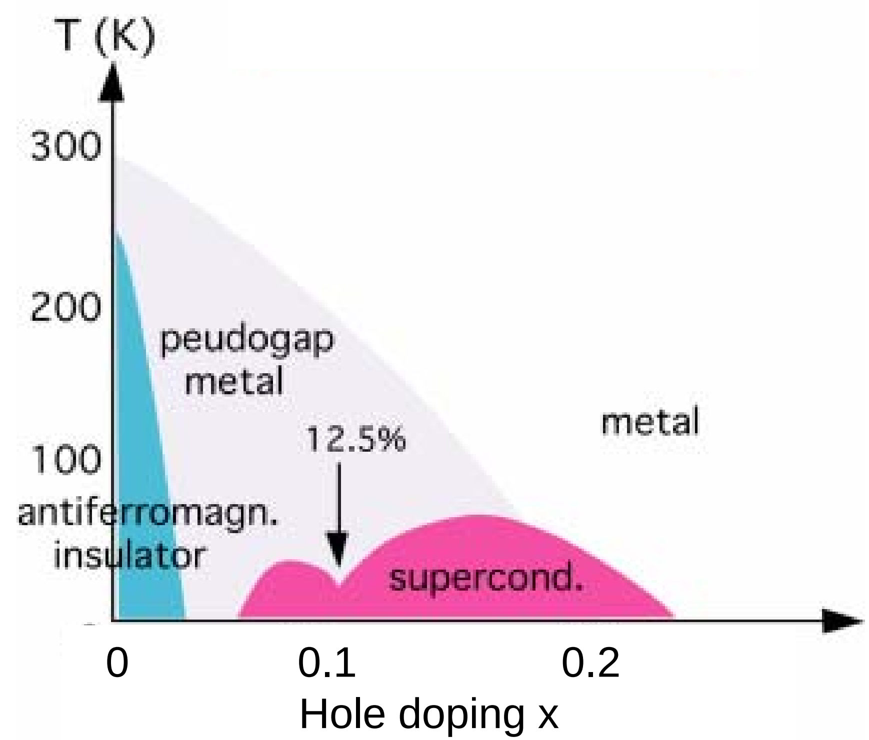
k_F (Å^{-1})	0.10
Δk (Å^{-1})	~0.061
σ_{ARPES} ($10^{-4}\Omega^{-1}$)	~0.65
σ_{tr} ($10^{-4}\Omega^{-1}$)	~0.75

T. Hirahara, I. Matsuda, M. Ueno, S. Hasegawa, Surf. Sci. ’04
PRB, in press

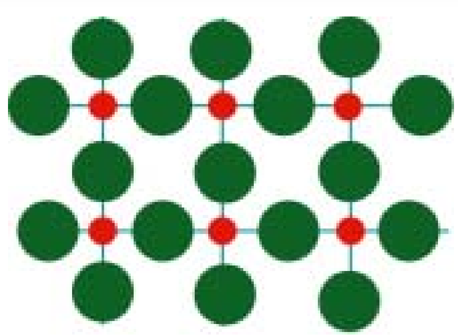
Phase diagram of high-T_C cuprates

$La_{2-x}Sr_xCuO_4$



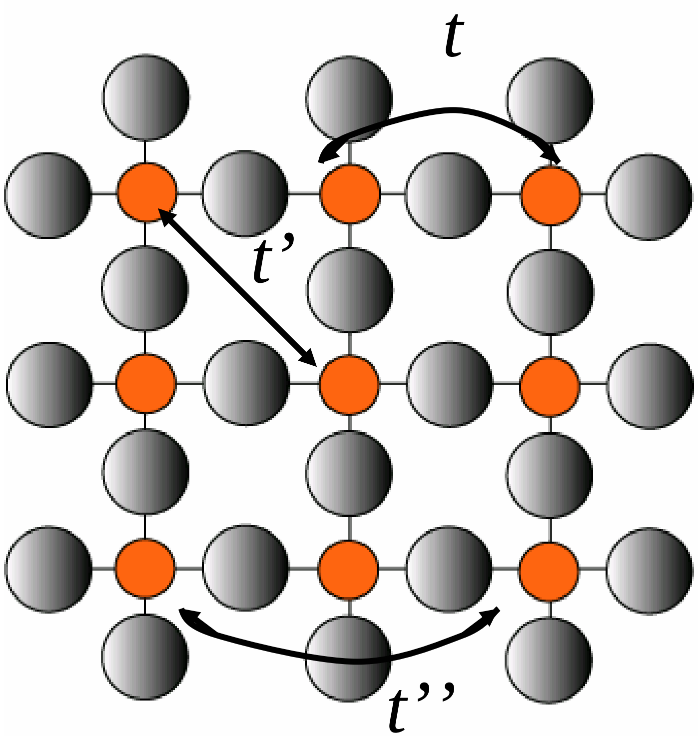


CuO_2 plane

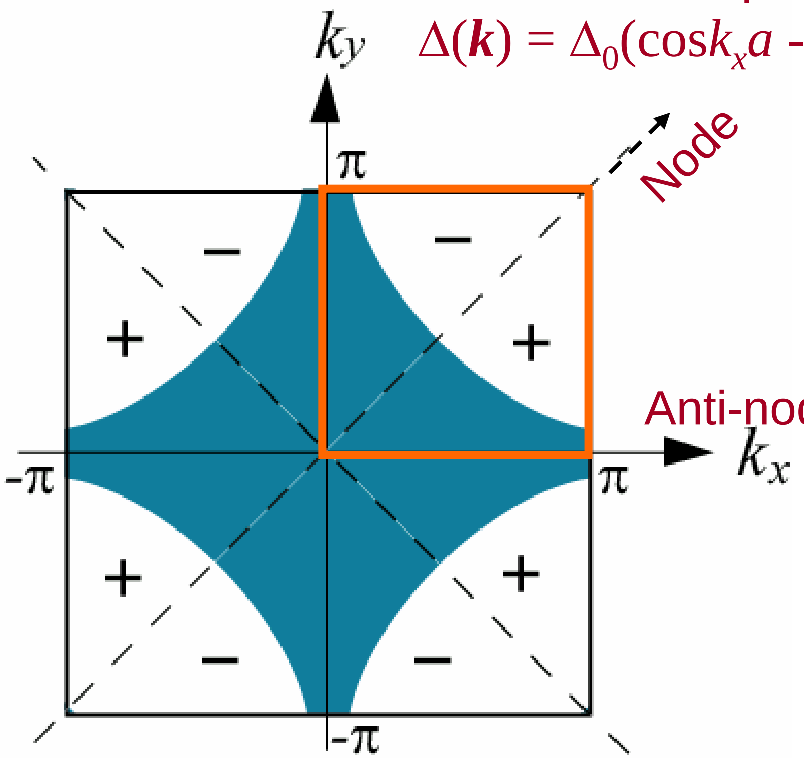


Phase diagram, Fermi surface and *d*-wave gap/pseudogap in high-T_C cuprates

CuO_2 plane



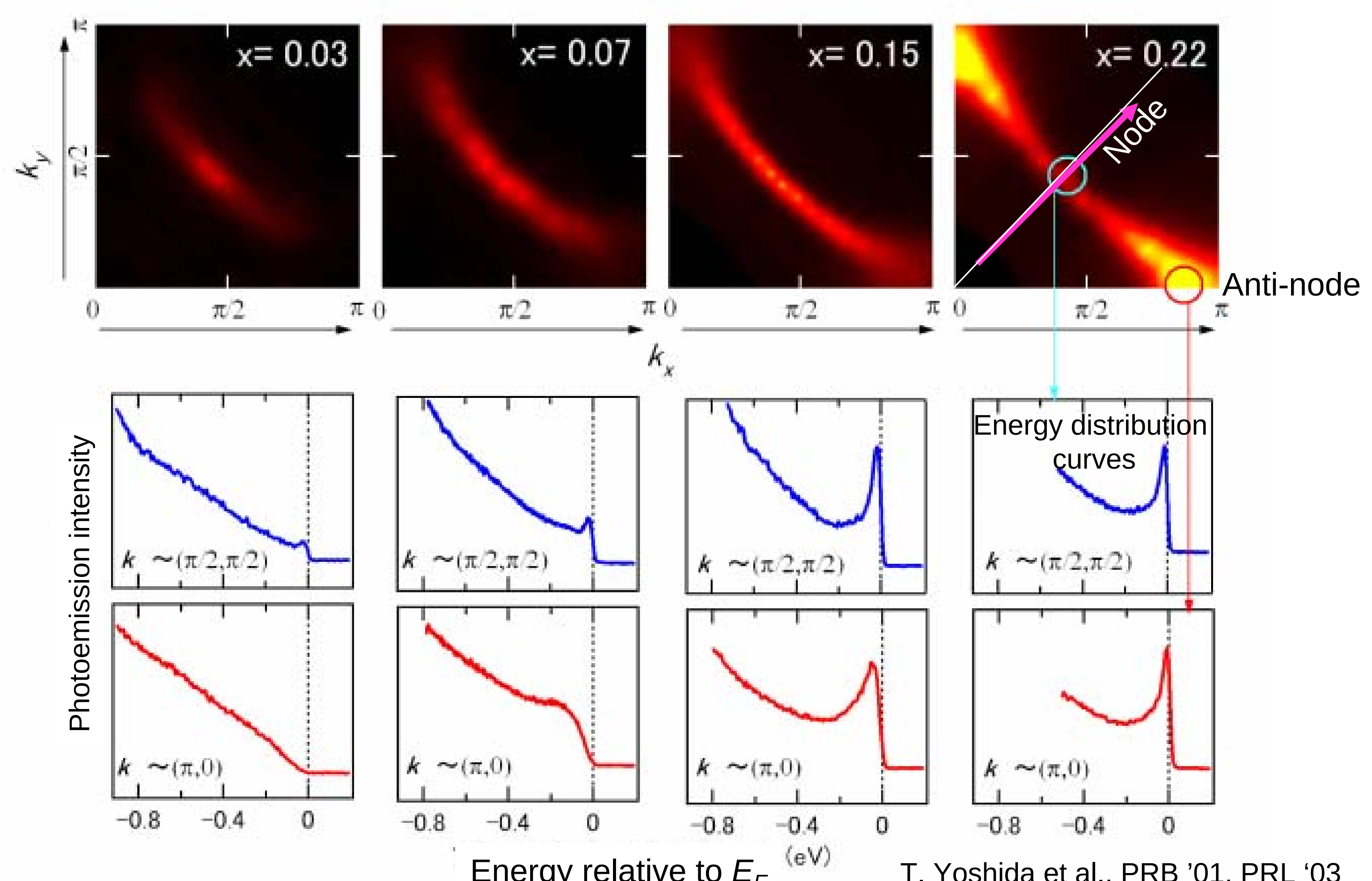
d-wave order parapeter:
$\Delta(\boldsymbol{k}) = \Delta_0(\cos k_x a - \cos k_y a)$



Band structure and Fermi surface:

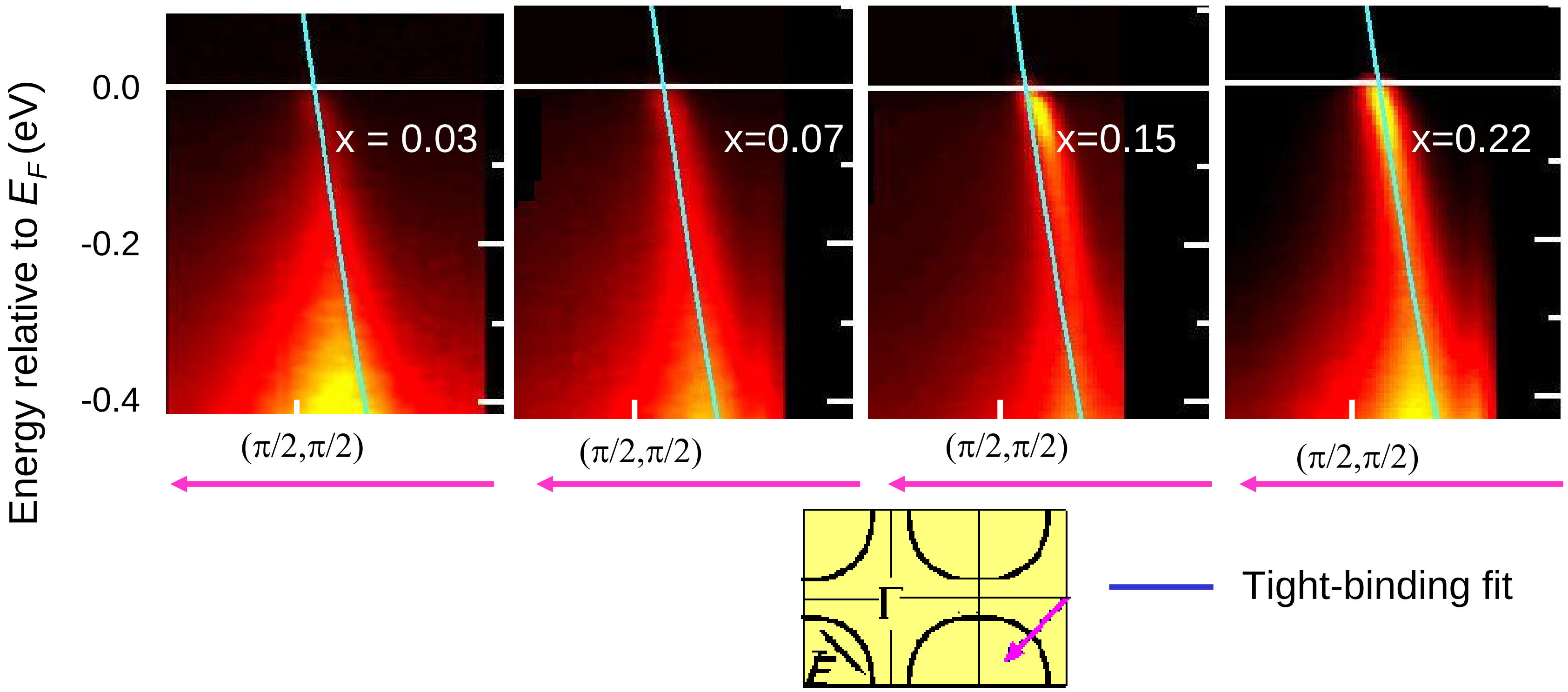
$$E(\boldsymbol{k}) = -2t(\cos k_x a + \cos k_y a)$$
$$- 4t'\cos k_x a \cos k_y a - 2t''(\cos 2k_x a + \cos 2k_y a)$$

Peudogap and Fermi arc in $La_{2-x}Sr_xCuO_4$



T. Yoshida et al., PRB '01, PRL '03

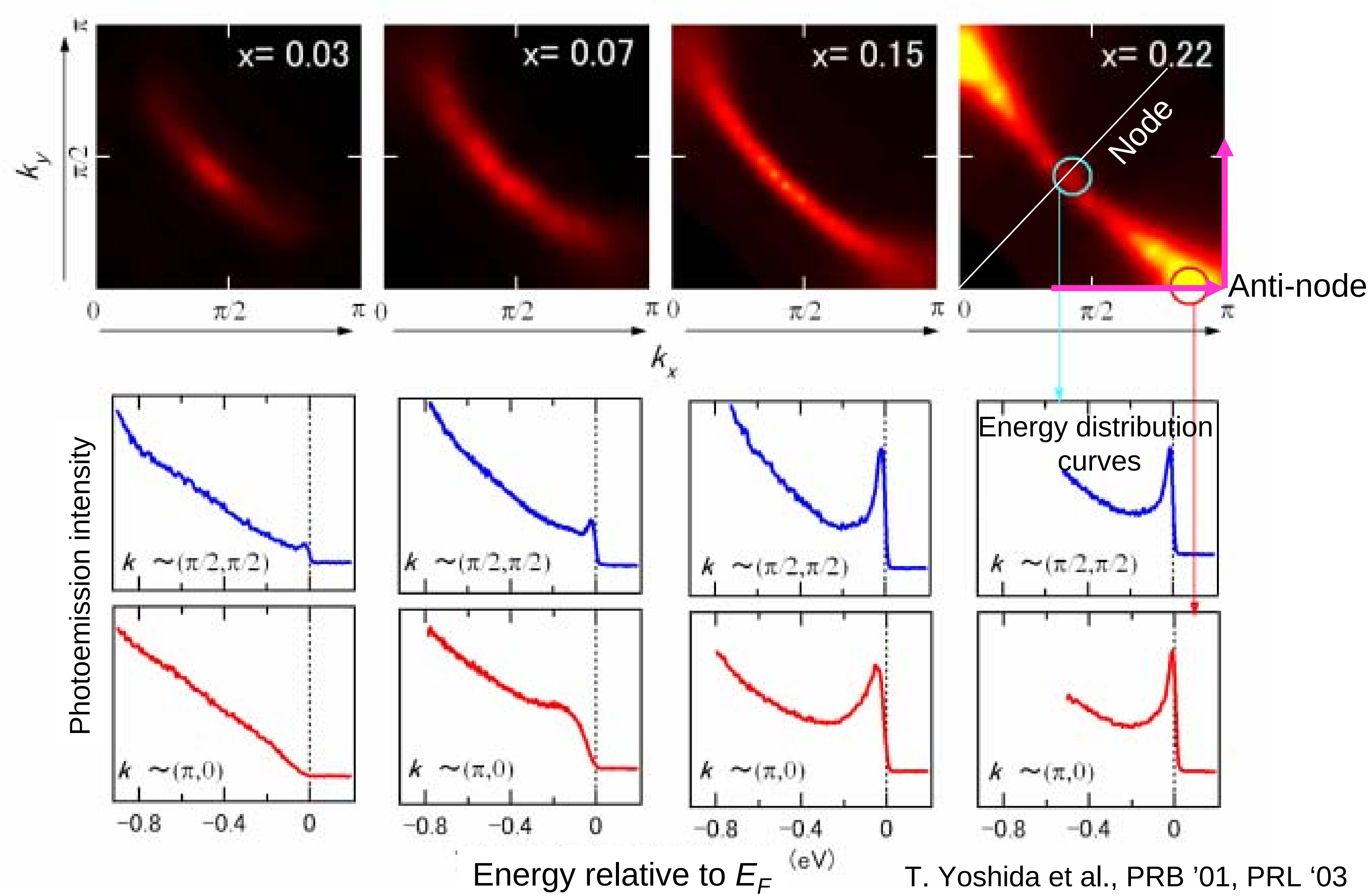
Quasi-particle forming the Fermi arc in the nodal region



Fermi velocity of nodal QP is doping-independent !

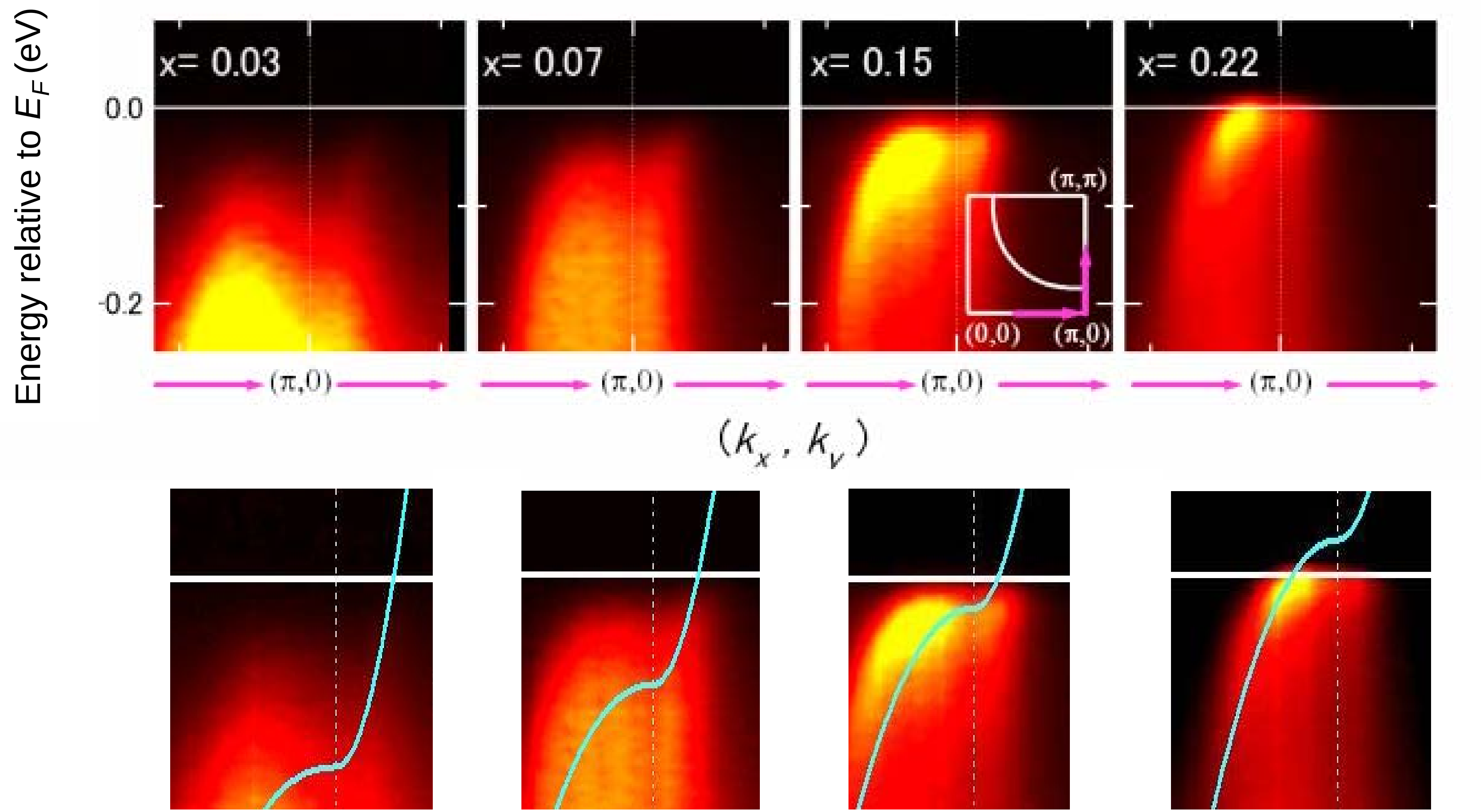
X.J. Zhou et al., Nature '03

Peudogap and Fermi arc in $La_{2-x}Sr_xCuO_4$



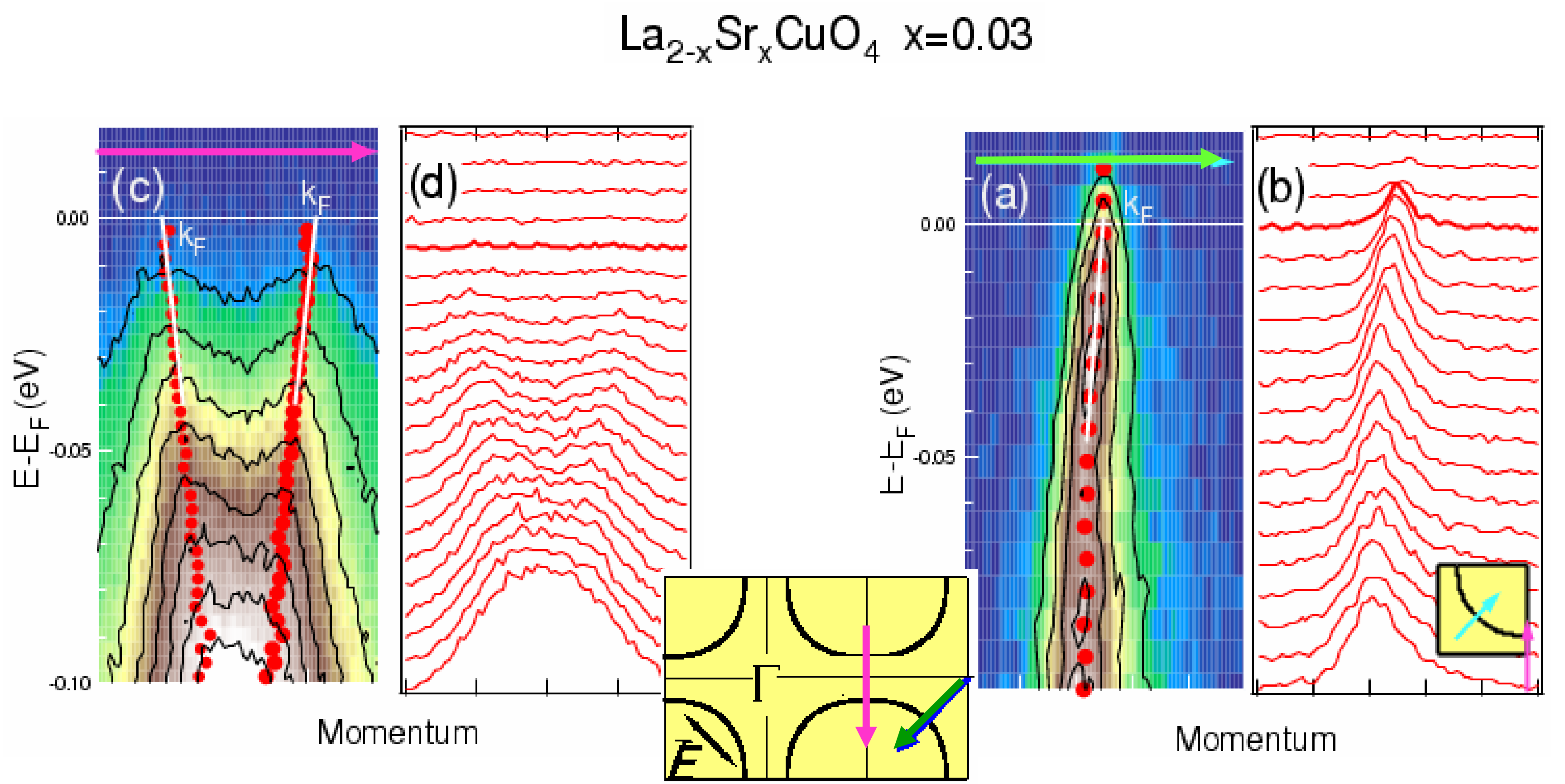
T. Yoshida et al., PRB '01, PRL '03

Peudogap in the anti-nodal region

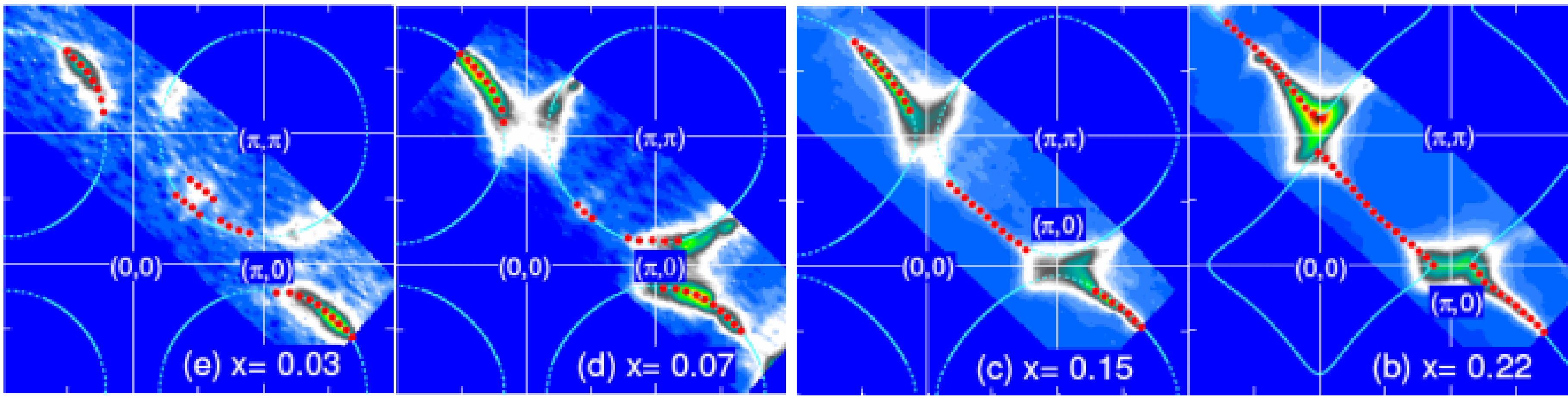


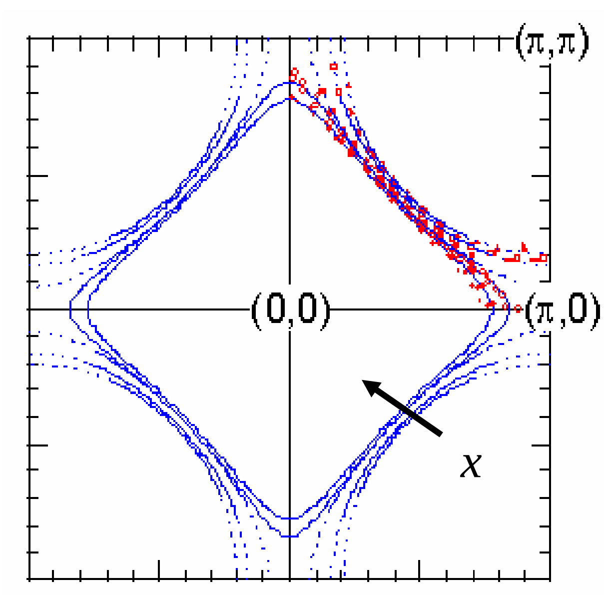
Tight binding fit

"Remnant" Fermi-surface crossing in lightly-doped $La_{2-x}Sr_xCuO_4$



Fermi surface, “remnant” Fermi surface





Tight binding fit: $E(\boldsymbol{k}) = -2t(\cos k_x a + \cos k_y a)$
$- 4t'\cos k_x a \cos k_y a - 2t''(\cos 2k_x a + \cos 2k_y a)$

Tight-binding fit

Intensity peak in k-space

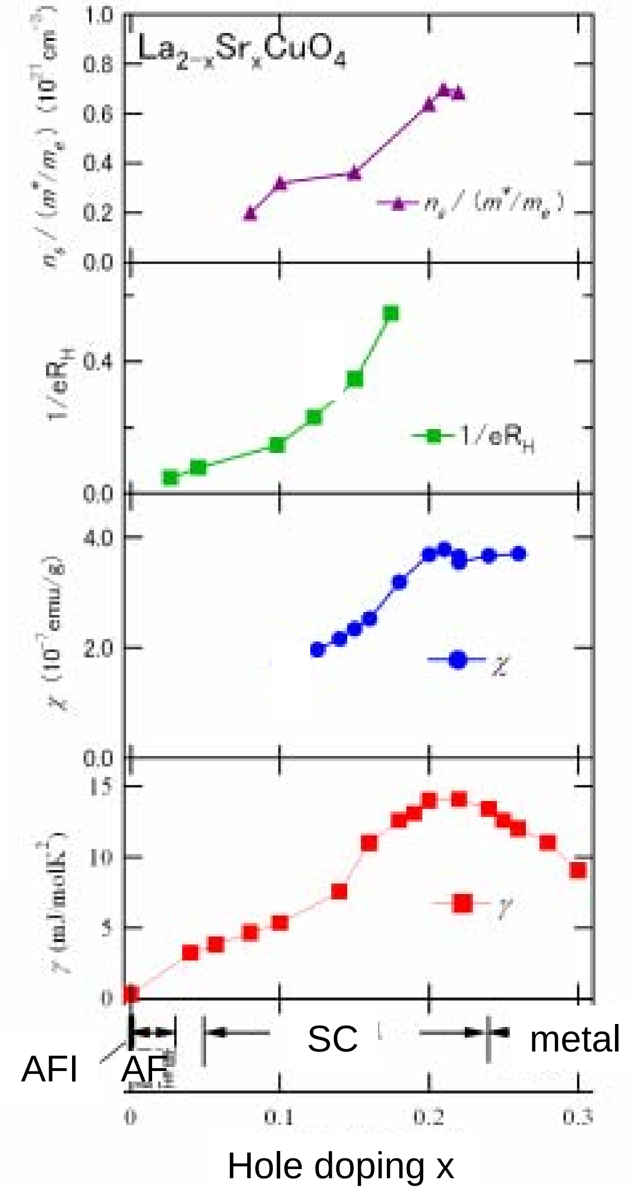
Pseudogap behaviors of $La_{2-x}Sr_xCuO_4$

Superfluid density

Carrier number

Pauli susceptibility

Electronic specific heat



Y.J. Uemura et al., PRL ‘89

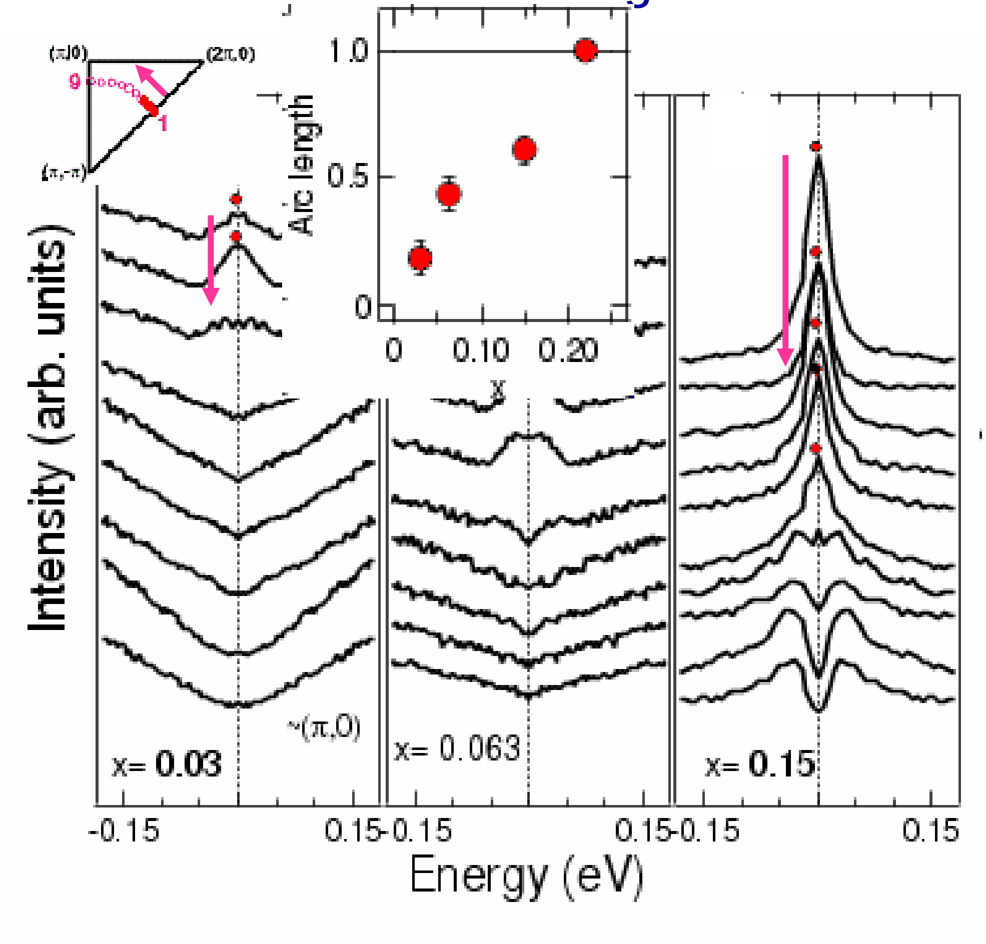
H. Takagi et al., PRB 89

T. Nakano et al., PRB ‘94

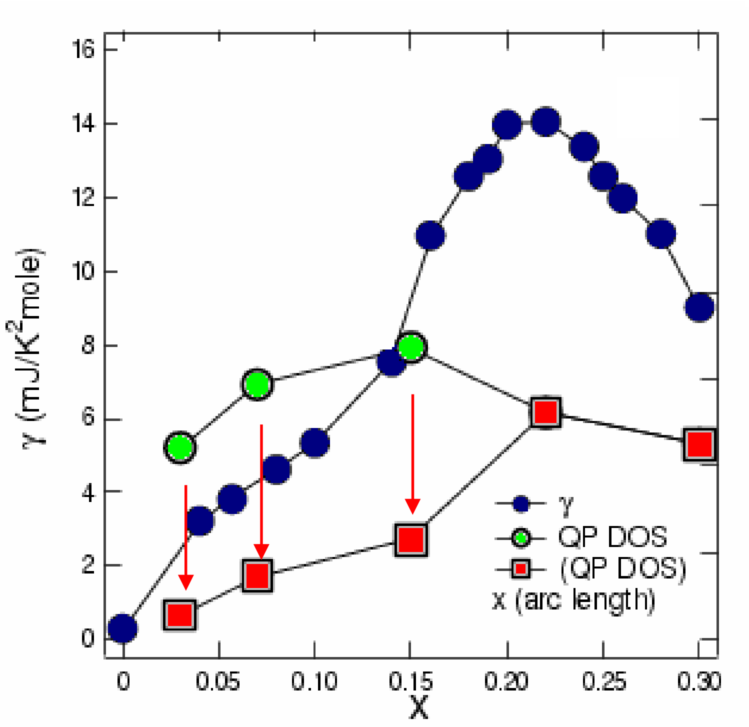
N. Momono et al., JPSJ ‘03

Density of QPs and electronic specific heats

Fermi arc length

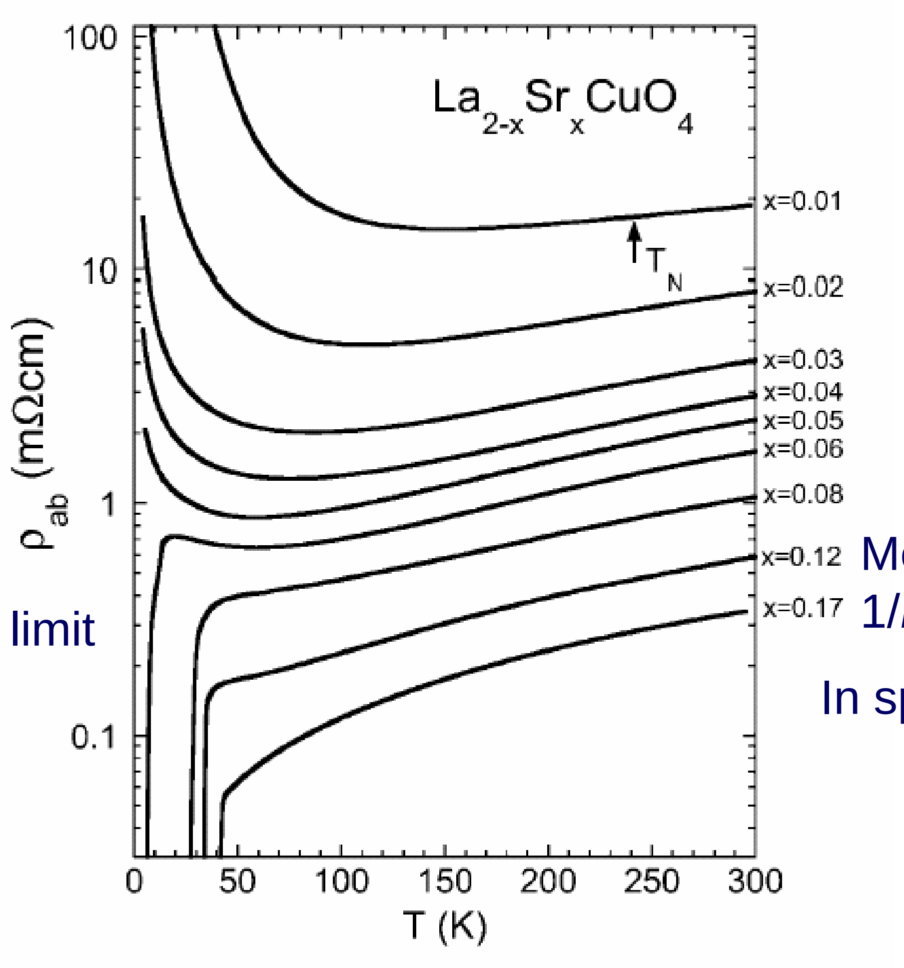


Density of QPs at E_F
compared with specifit heat γ



γ: N. Momono et al., Physica C '94

Unusual metallic transport in lightly-doped cuprates



Ioffe-Regel limit

Metallic resistivity well exceeds the Ioffe-Regel limit: $k_F l \sim 1$

↓

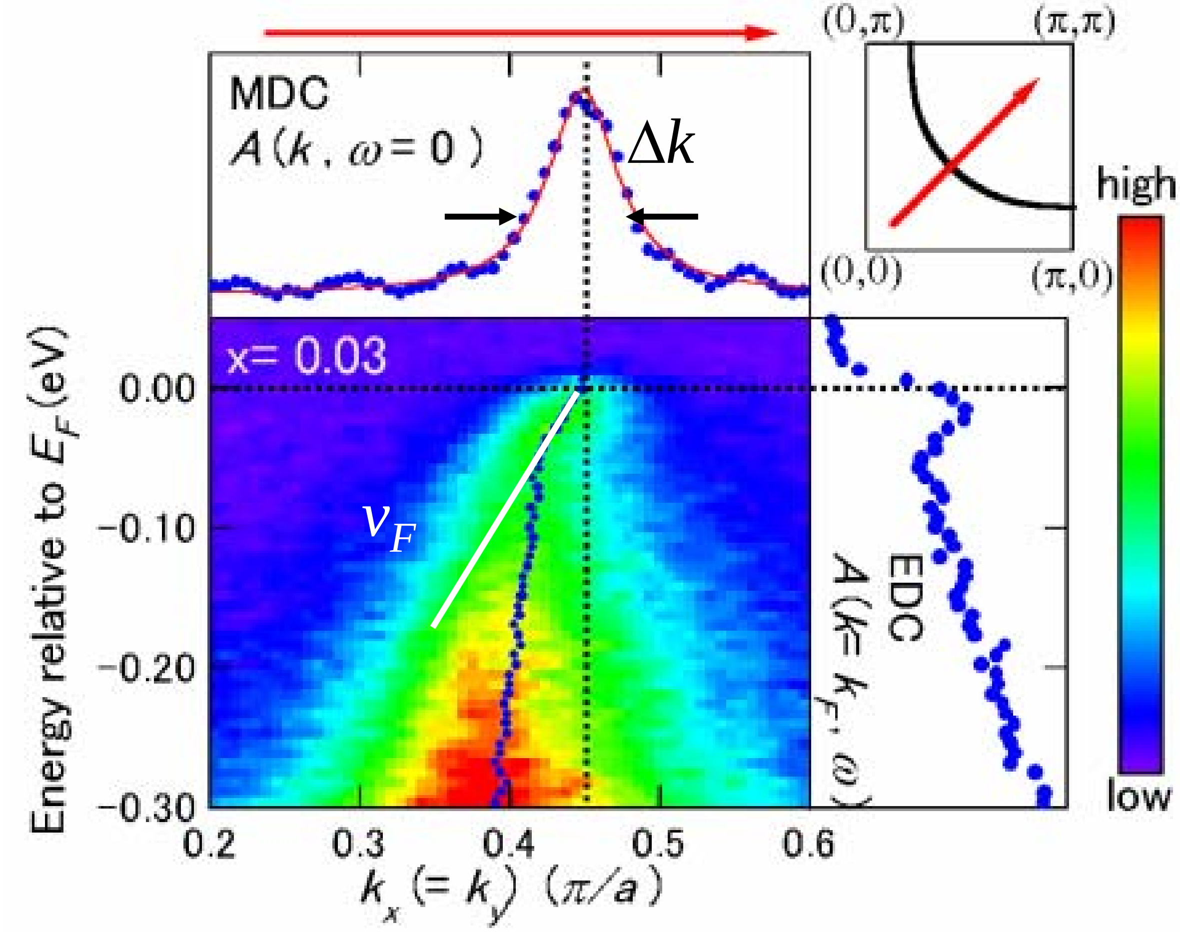
Mean-free path l is shorter than $1/k_F \sim 2$ A ?

In spite of well-defined Fermi surface

Due to pseudogap/Fermi arc

Y. Ando et al. PRL '01

Mean-free path, Fermi velocity and scattering rate from ARPES data



Mean-free path

$l = 1/\Delta k$

Fermi velocity

v_F

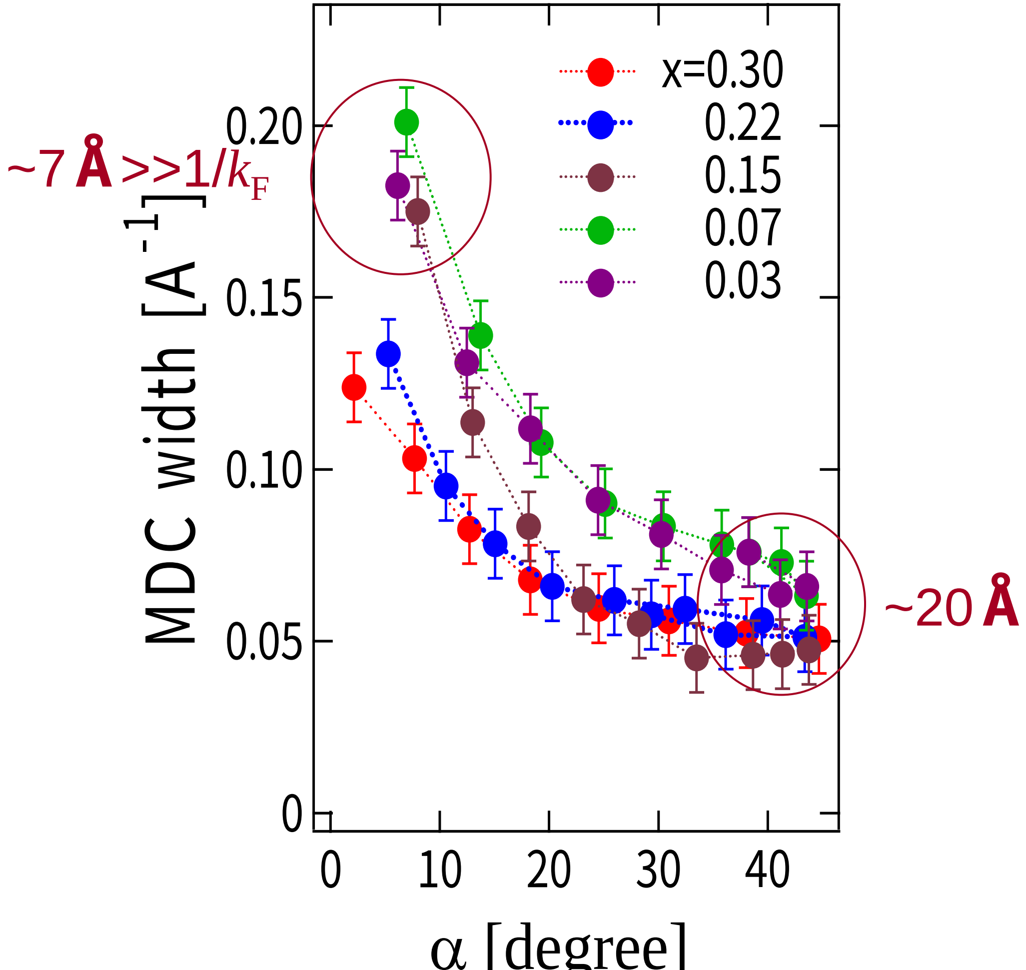
Scattering rate

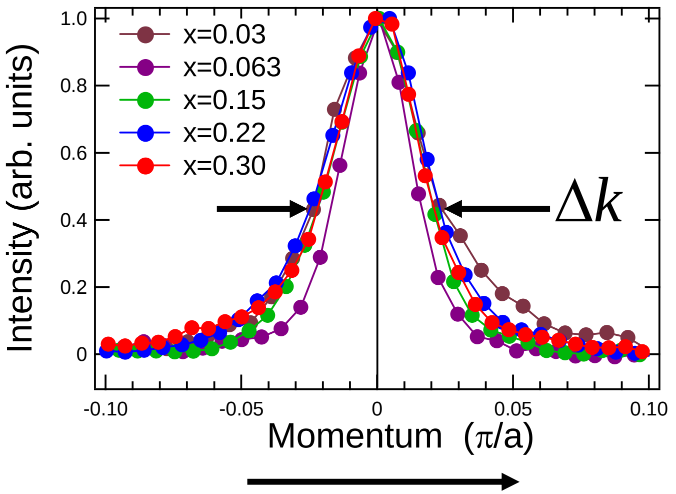
$1/\tau = v_F / l$

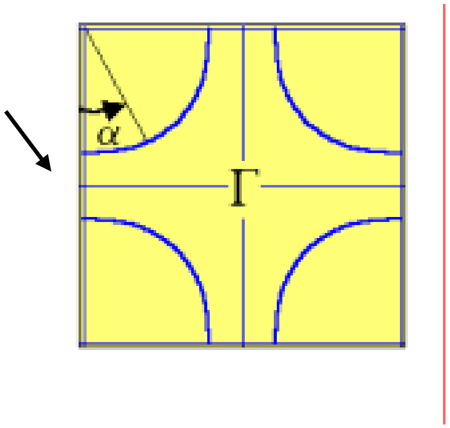
T. Yoshida et al., PRL '03

Doping and momentum dependence of MDC width

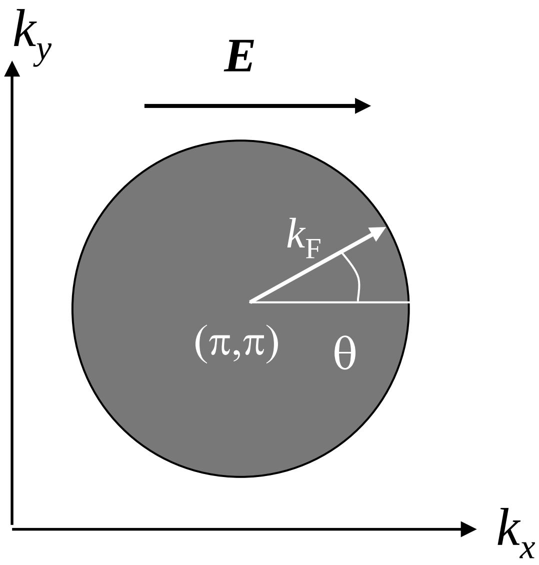
Mean free path $l = 1/\Delta k$







Boltzmann transport

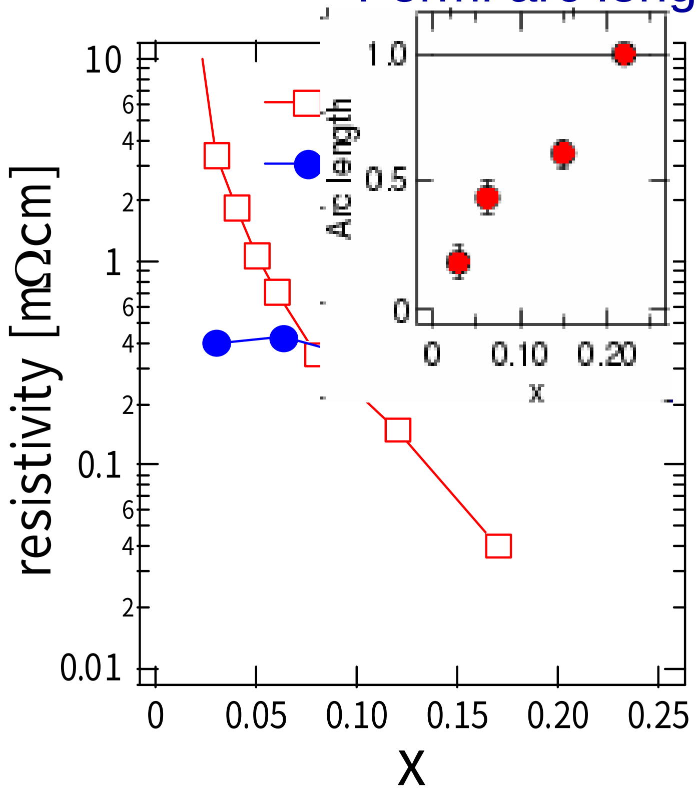


$$\begin{aligned}\sigma &\propto e^2 \int_{\mathrm{FS}} \tau v_x \cos\theta dS \\ &= ne^2 \langle 2\tau v_{\mathrm{F}} \cos^2\theta / k_{\mathrm{F}} \rangle_{\mathrm{FS}} \\ &= ne^2 \langle 2l \cos^2\theta / k_{\mathrm{F}} \rangle_{\mathrm{FS}} \\ &= ne^2 \langle 2 \cos^2\theta / k_{\mathrm{F}} \Delta k \rangle_{\mathrm{FS}}\end{aligned}$$

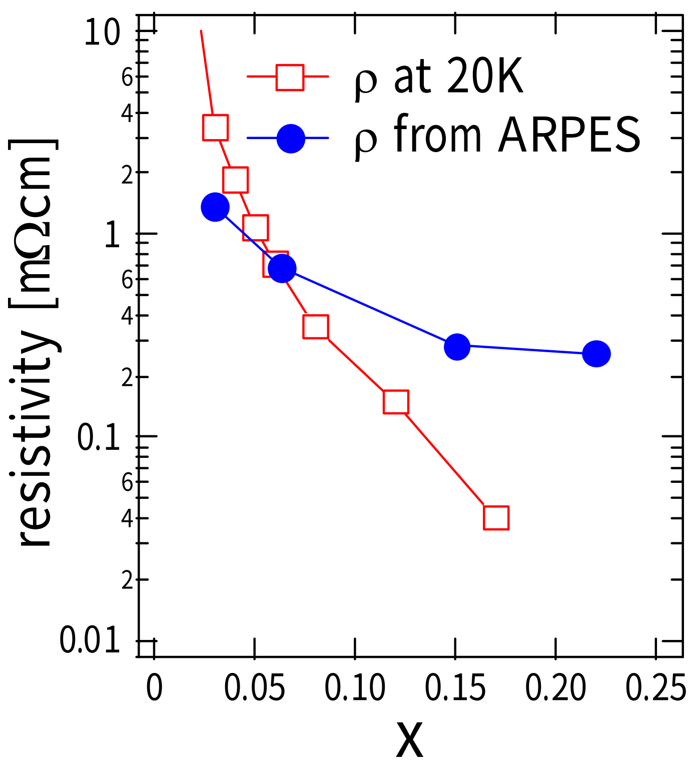
$$\Delta k = 1/\, l$$

Boltzmann transport

Fermi arc length



Resistivity with Fermi arc



- $1/\tau_{ARPES} > 1/\tau_{tr}$
- surface defects ?
- k_z dispersion ?

Summary

- Thermodynamics
  - Density of QPs extracted from ARPES is compared with electronic specific heats.
  - Psuedogap removes part of QPs from E_F.
- Transport
  - ARPES MDC width is compared with DC resistivity (using Boltzmann theory).
  - Pseudogap removes part of charge carriers.
  - ARPES MDC width is generally larger than that expected from transport.
  - ARPES MDC width is consistent with residual resistivity due to Zn impurities.