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SMR 1232 - 9

XII WORKSHOP ON
STRONGLY CORRELATED ELECTRON SYSTEMS

17 - 28 July 2000

Recent Photoemission Results from Single Layer Cuprates

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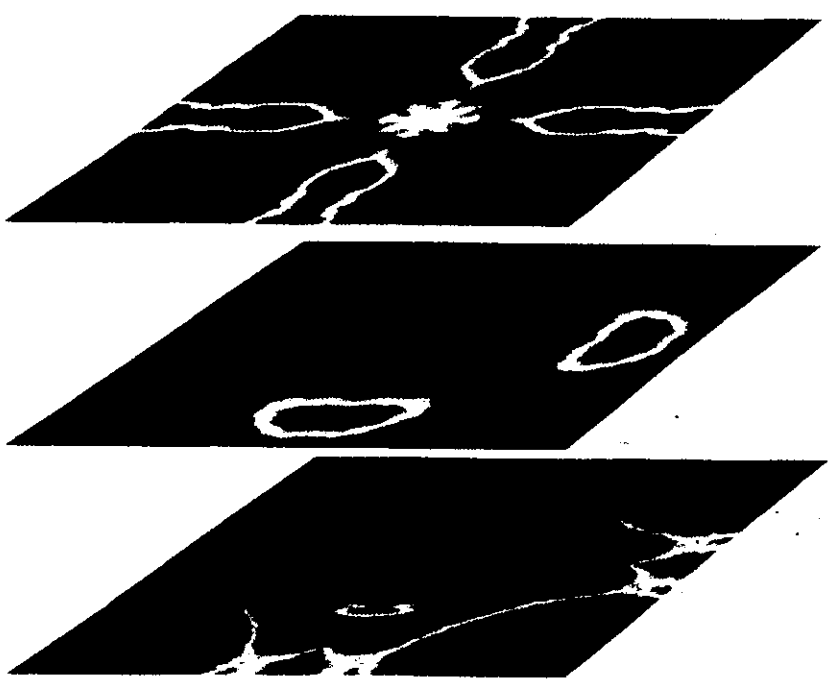
These are preliminary lecture notes, intended only for distribution to participants.

Recent Photoemission Results from Single Layer Cuprates

Zhi-Xun Shen - *Stanford University*



Collaborators

Stanford & ALS: Xingjiang Zhou, N.P. Armitage, F. Ronning, C. Kim, D.H. Lu, S.A. Kellar, P. Bogdanov, A. Lanzara, D.L. Feng, A. Damascelli, K.M. Shen, Z. Hussain

Univ. Of Tokyo: A. Fujimori, A. Ino, T. Yoshida, M. Nakamura, T. Mizokawa

Univ. Of Tokyo: S. Uchida, H. Eisaki, T. Noda (LSCO)

Univ. Of Tokyo: Y. Tokura, Y. Onose, Y. Taguchi (NCCO)

Ames: L.L. Miller (CCOCl)

MIT: R.J. Birgeneau, M. Kastner, B.O. Wells, Y. Kim

Collaborators

Stanford University: X.J. Zhou, D.L. Feng, P. Bogdanov, A. Lanzara, S.A. Kellar, A. Damascelli, D.J. Lu, K.M. Shen

Advanced Light Source: Z. Hussain,

Univ. of Tokyo: A. Fujimori, A. Ino, T. Yoshida, M. Nakamura, T. Mizokawa

Univ. of Tokyo: H. Eisaki, S. Uchida

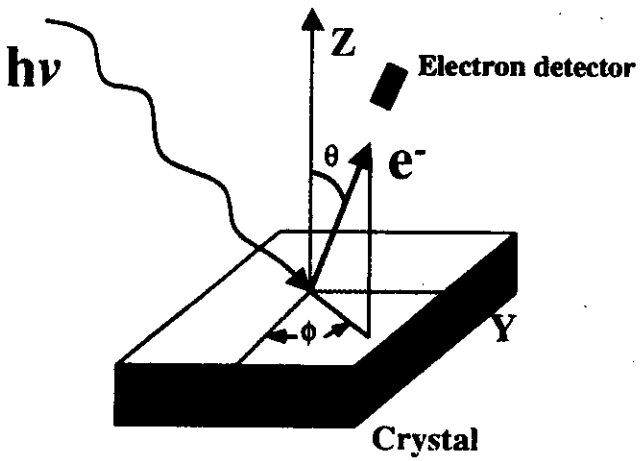
Univ. of Tokyo: K.Kishio, J.-I. Shimoyama

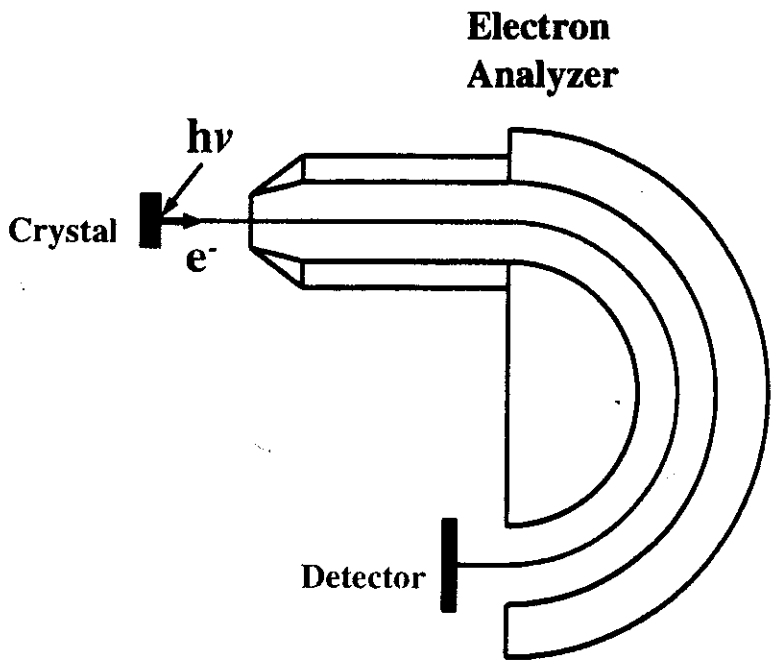
Univ. of New South Wales, G.Gu

Univ. of Tsukuba: R. Yoshizaki

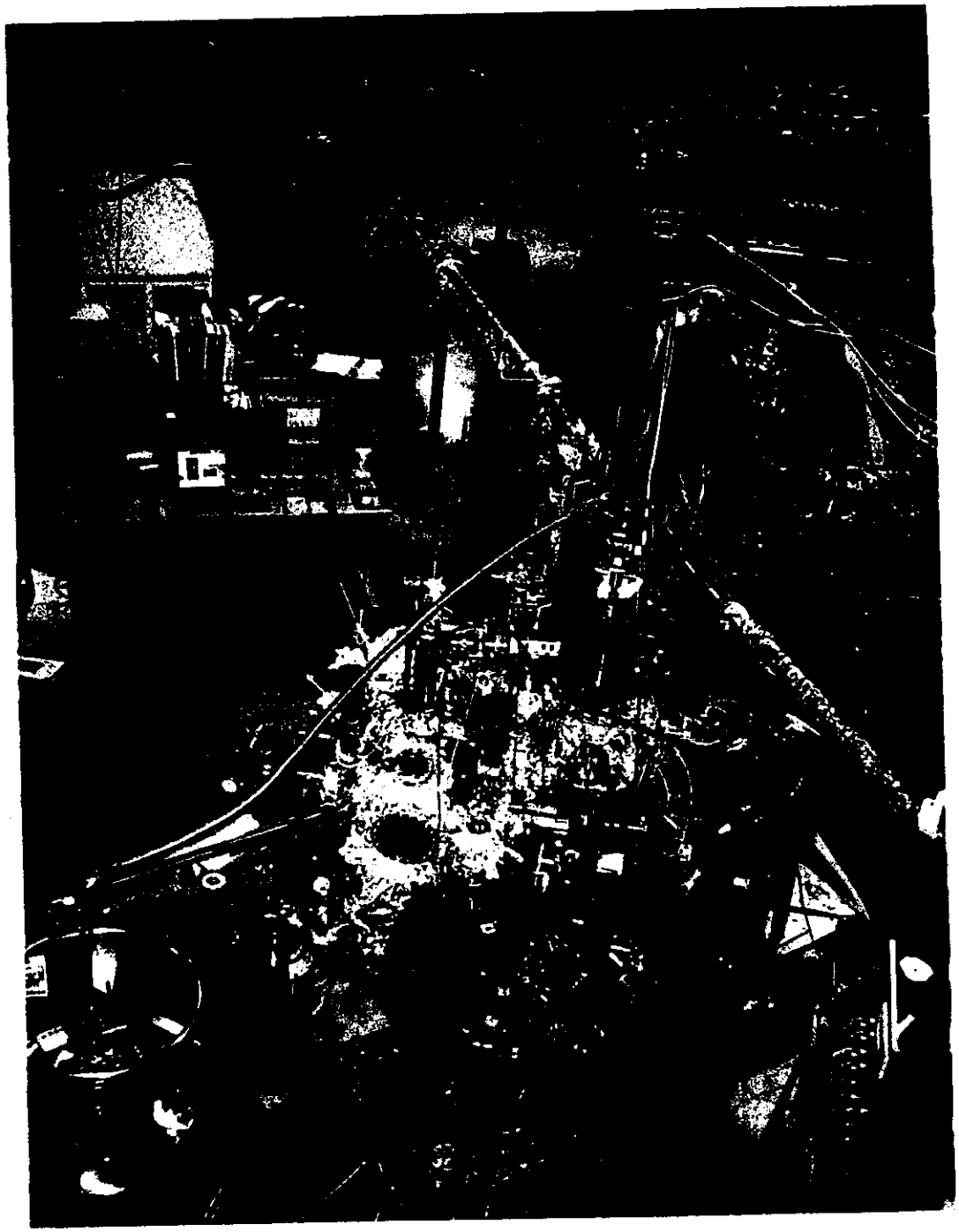
UBC: R. Liang, Doug Bonn, W. Hardy

Angle-Resolved Photoemission





SSRL Beamline 5-4
NIM/SCIENTA System



Outline

- Introduction

- 2212 (YBCO, LSCO) – anti-nodal state
  — Anomalous Signiture of Superfluid in Single Particle Spectral function
  Science, July, 2000

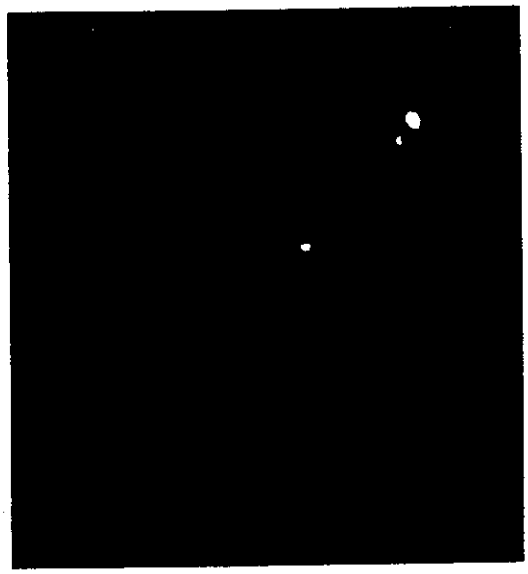
- 2212 (LSCO)
  — Signiture of many-body effect along the nodal direction
  Phys. Rev. Lett. in press

- LSCO — Nd-LSCO
  Electronic Structure of the Stripe phase.
  - Charge gap
  - Spectral weight near $(\pi, 0)$ / Spectral weight Confinement
  - metallic state of static charge ordered state

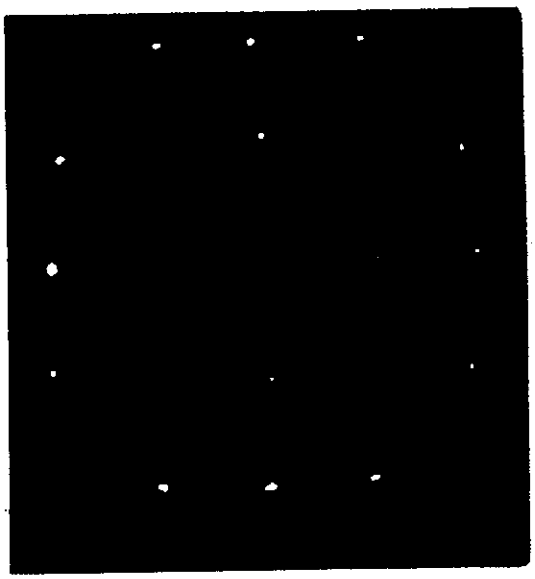
- Electron doped Nd-Ce-Cu-O

- YBCO

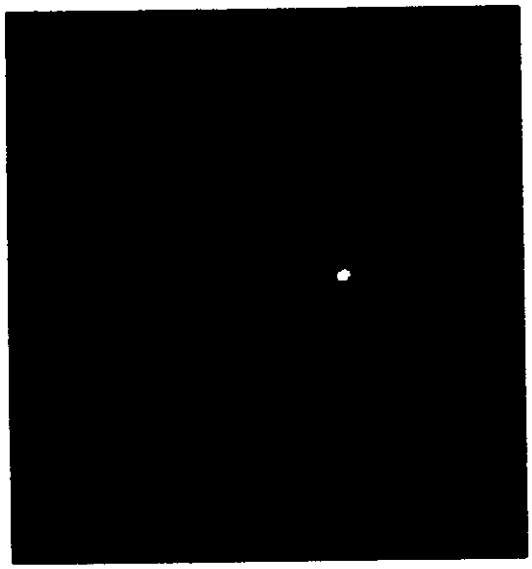
Low Energy Electron Diffraction of Layered Cuprates Cleaved *in situ*



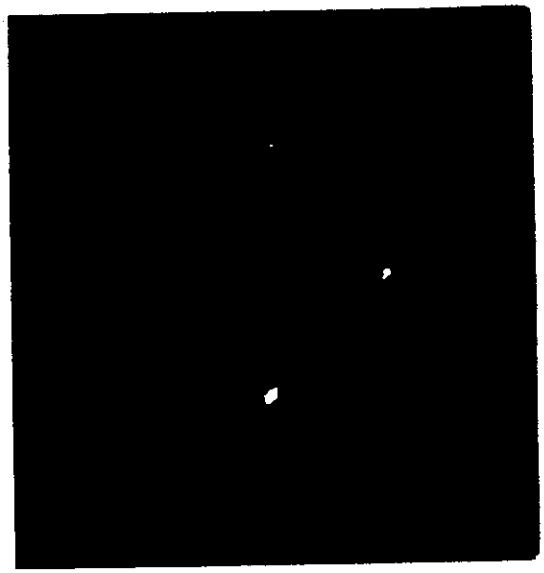
$Bi_2Sr_2CaCu_2O_{8+\delta}$



$YBa_2Cu_3O_{6.92}$

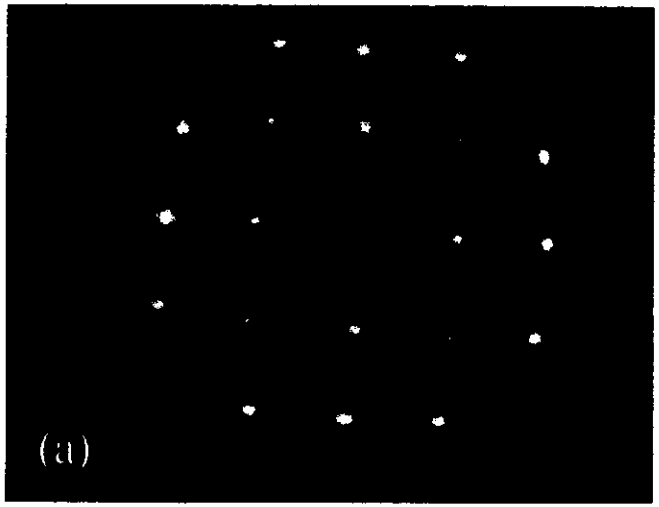


$Nd_{1.85}Ce_{0.15}CuO_4$

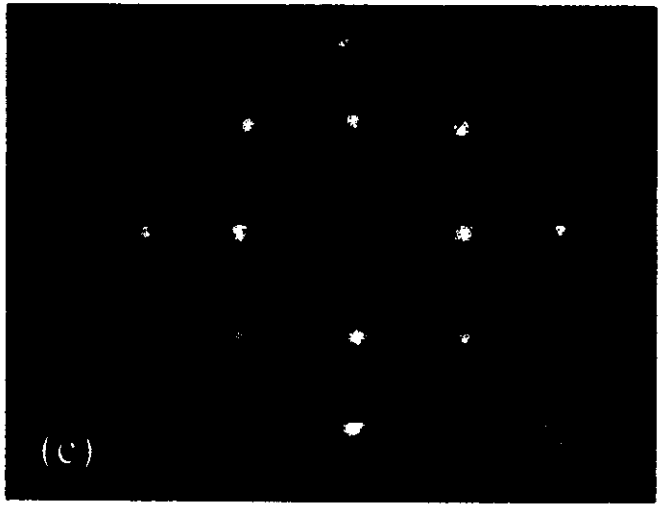


$Ca_2CuO_2Cl_2$

$YBa_2Cu_3O_{6.92}$ (T_c = 93 K)

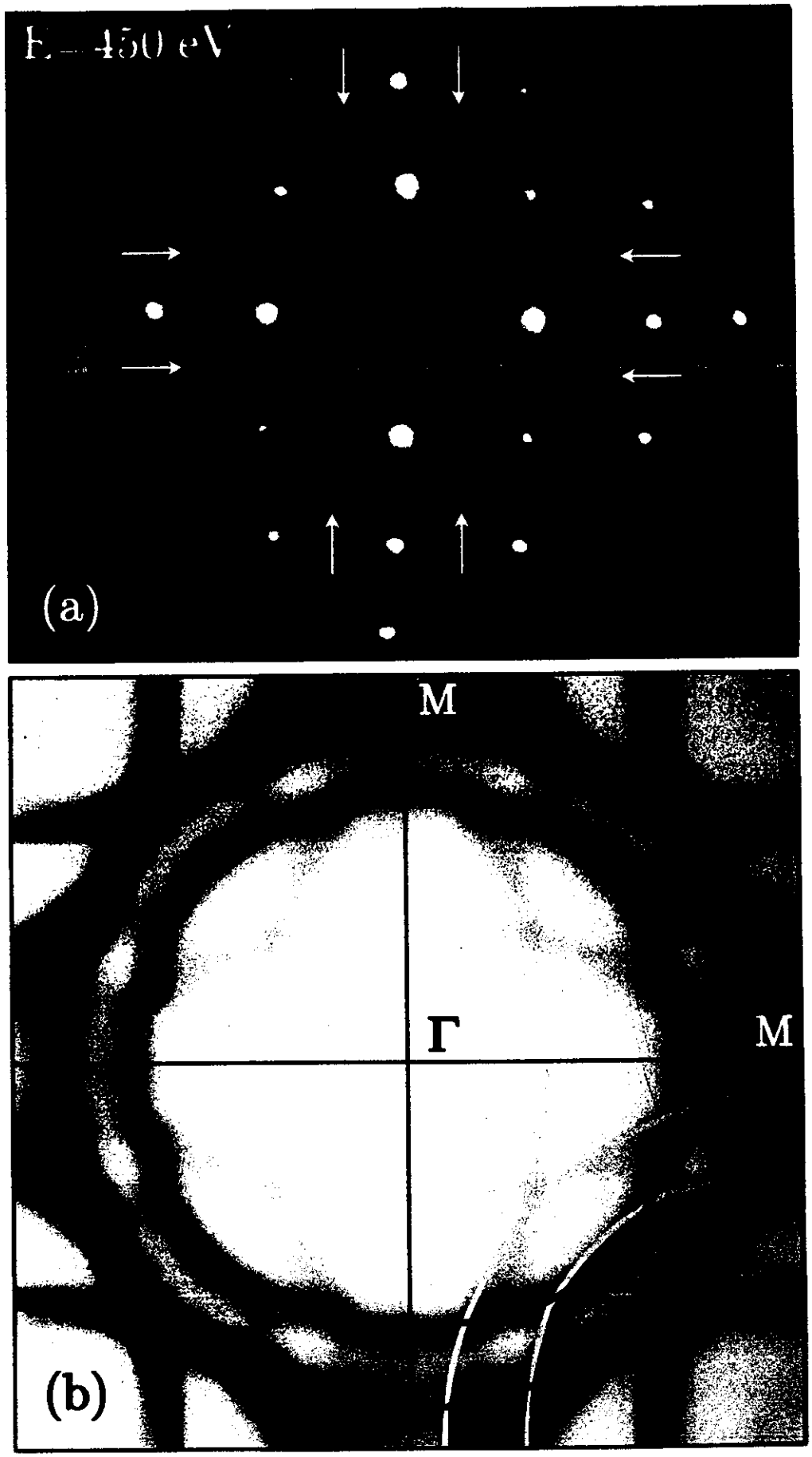


$YBa_2Cu_3O_{6.993}$ (T_c = 88.6 K)

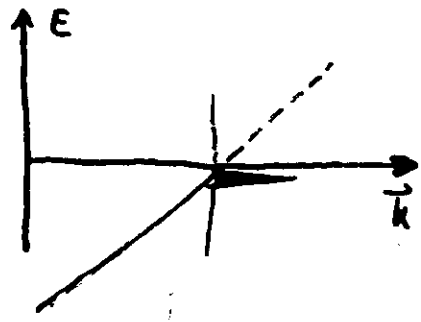


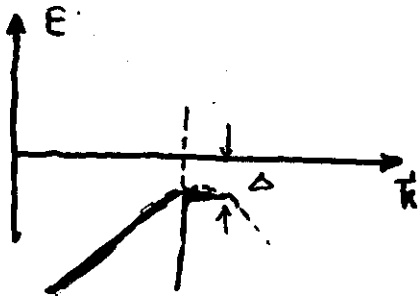
$YBa_2Cu_3O_{6.5}$ (T_c = 56 K)

After warming up


E = 450 eV
(a)
M
Γ
M
(b)

Modification of Single Particle $A(k,\omega)$
due to Superconducting Transition (BCS





Expected:

a) Peak energy shift due to gap

b) Peak intensity modification due to coherence factors u_k^2 & v_k^2.

$u_k^2, v_k^2 \sim \Delta, \varepsilon_k$

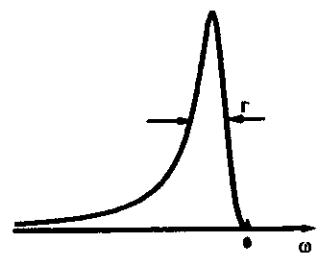
No information about the phase coh

Angle-Resolved Photoemission Spectroscopy

Under sudden approximation:

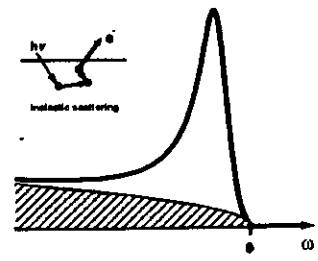
$$\rho(\vec{k},\omega) \propto \mathrm{Im}\ \frac{1}{\omega - \varepsilon_k^0 - \sum(\vec{k},\omega)}$$

$$= \frac{1}{\pi}\frac{\mathrm{Im}\{\sum(\vec{k},\omega)\}}{[E - E_k^0 - \mathrm{Re}\sum(\vec{k},\omega)]^2 + [\mathrm{Im}\sum(\vec{k},\omega)]^2}$$



Real world

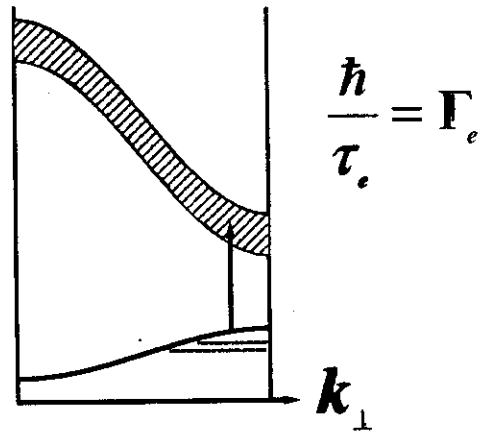
$$|M_{if}(\vec{k},h\nu)|^2 \times [\rho(\vec{k},\omega) + \rho_{inelastic}(\omega)]$$



Cross-section **Instrument resolution Δk and Δω**

Dimensionality:
Effect of Photoelectron lifetime width

$$\Gamma = \Gamma_h + \left|\frac{V_{h\perp}}{V_{e\perp}}\right|\Gamma_e$$



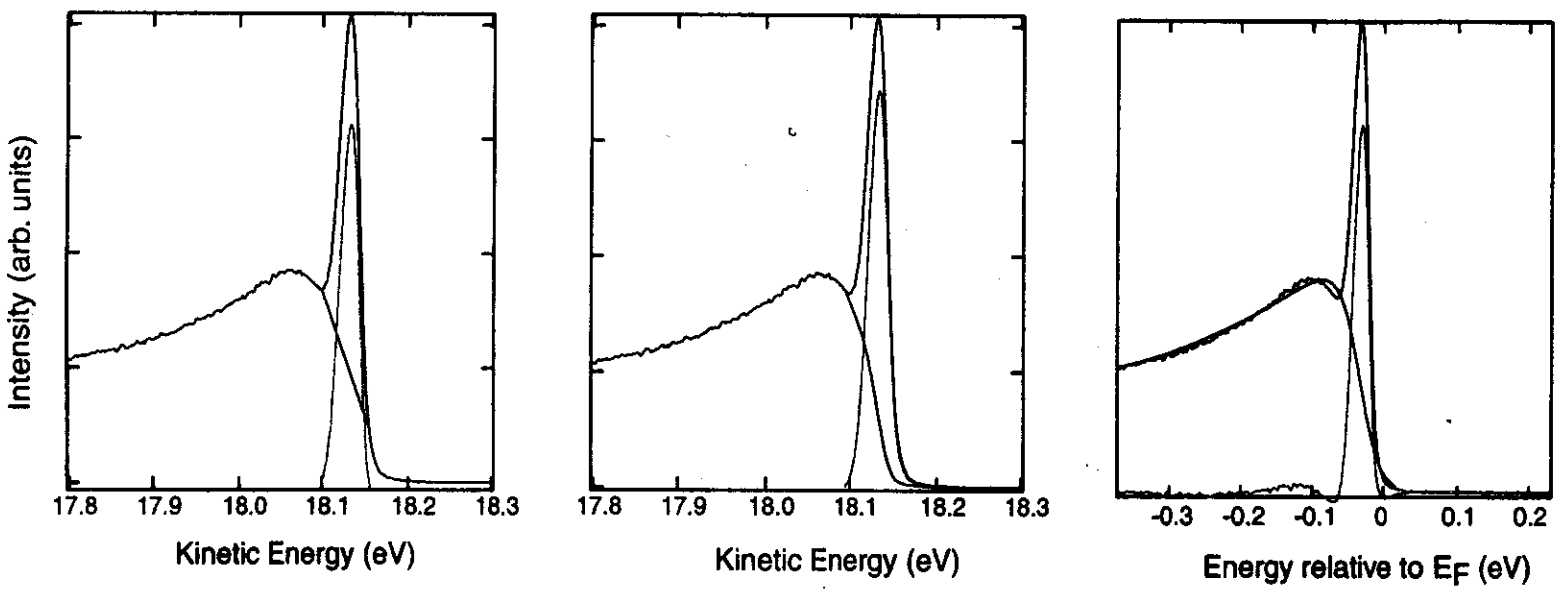
k_Z effect

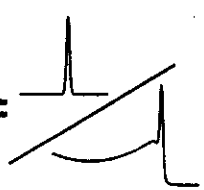
Extracting SPR from spectra-``background subtraction"

Linear background

Integration(Shirley) background

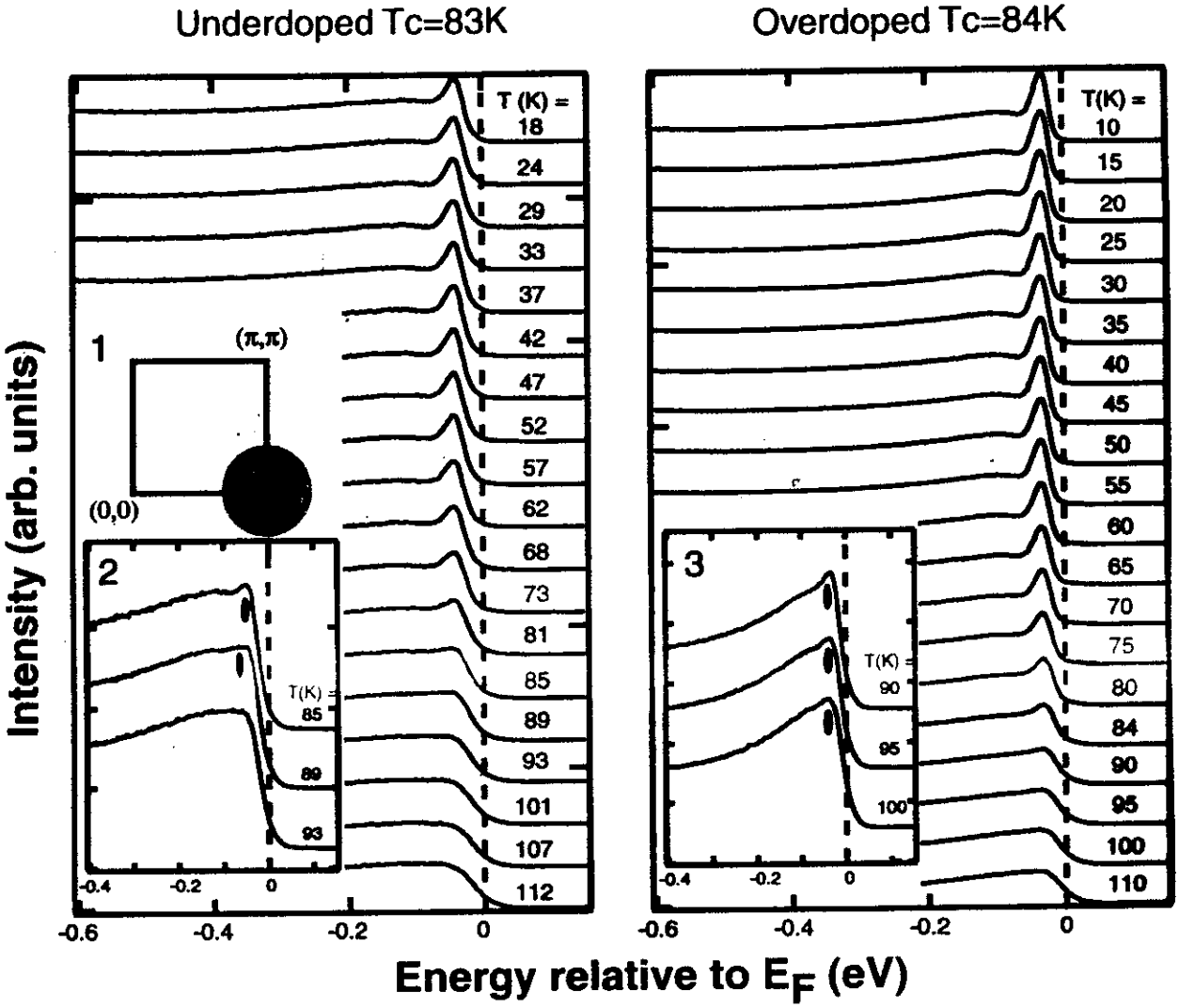
Polynomial background



SPR= 

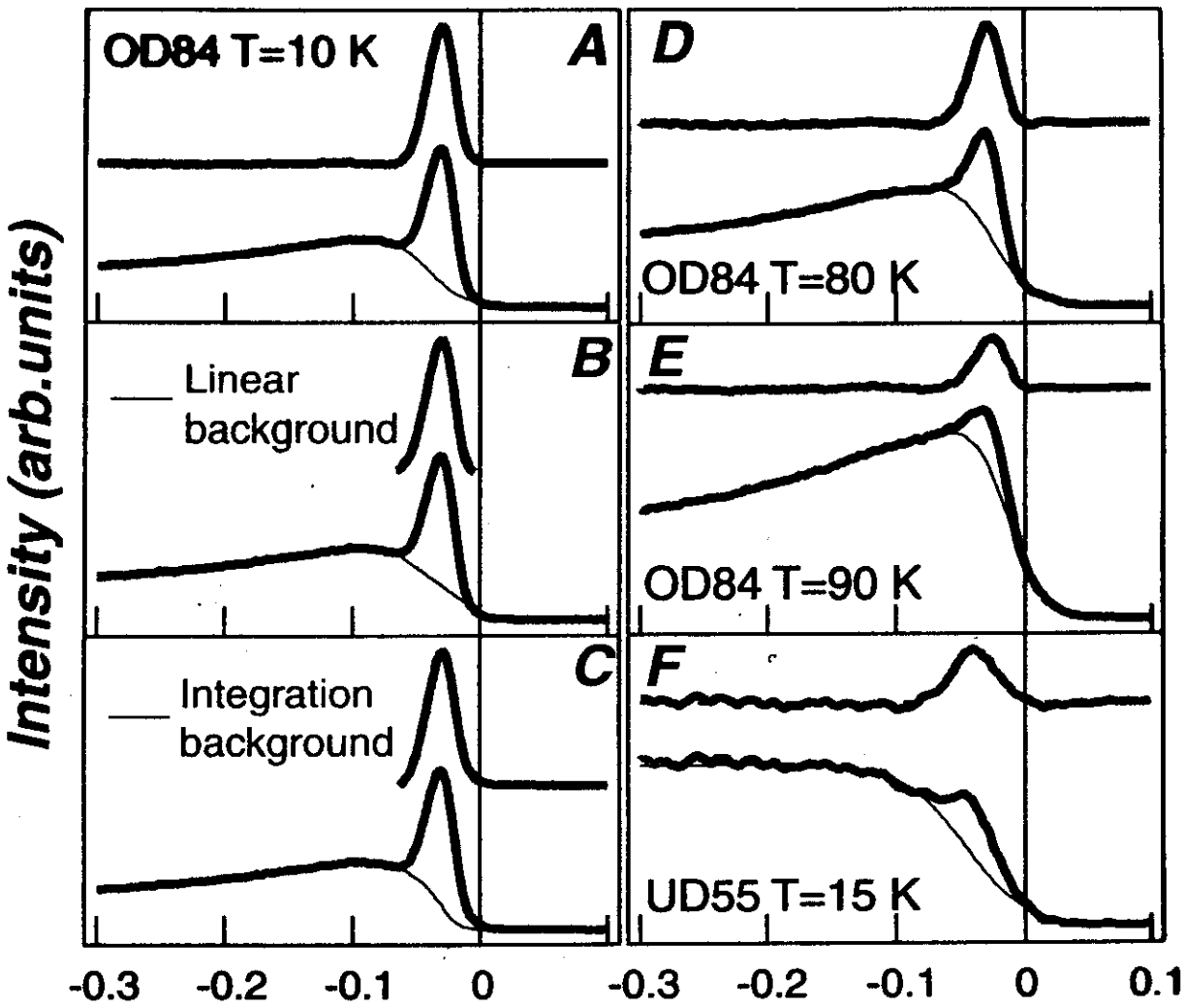
11.3% for linear background
13.6% for Shirley background
11.4% polynomial background

Temperature dependence of ARPES spectrum near (π,0) of the Bi2212 system



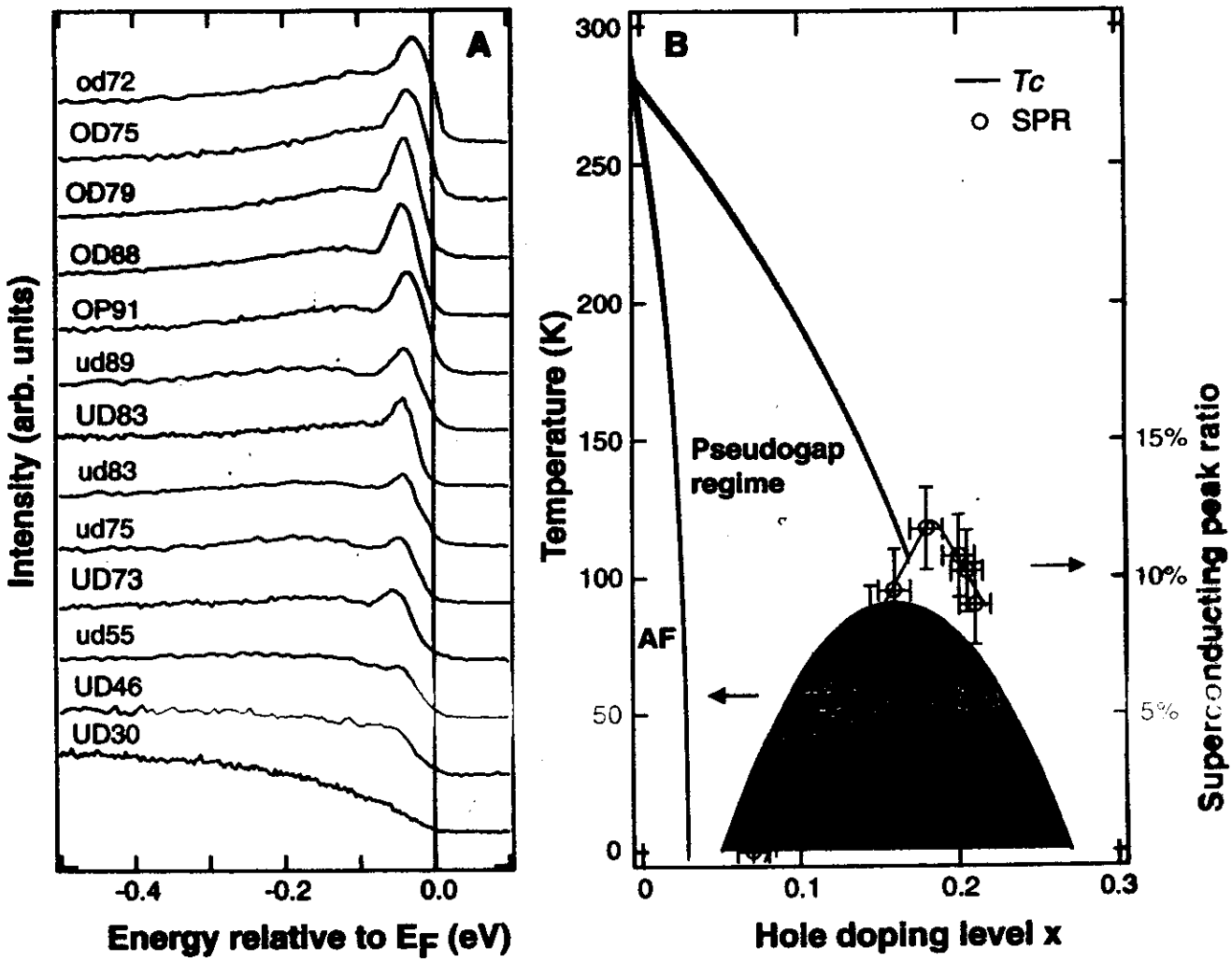
D.L. Feng, Z.-X. Shen
Stanford University

Extracting the superconducting peak



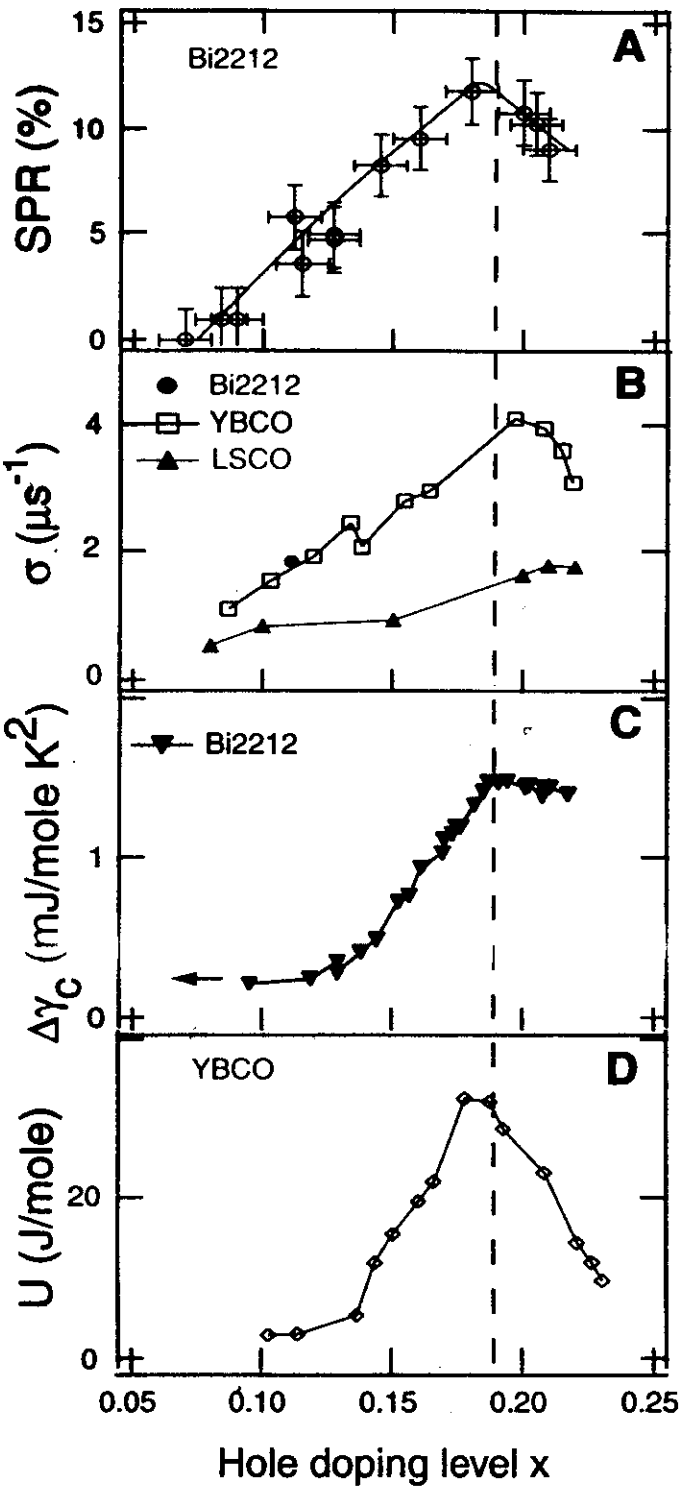
A,D,E,F: fitting the "background" by
$y=a_1\{\exp[(x-a_2)/a_3]+1\}^{-1}[1+a_4(x-a_5)^2]$

D.L.Feng, Z.-X. Shen
Stanford University



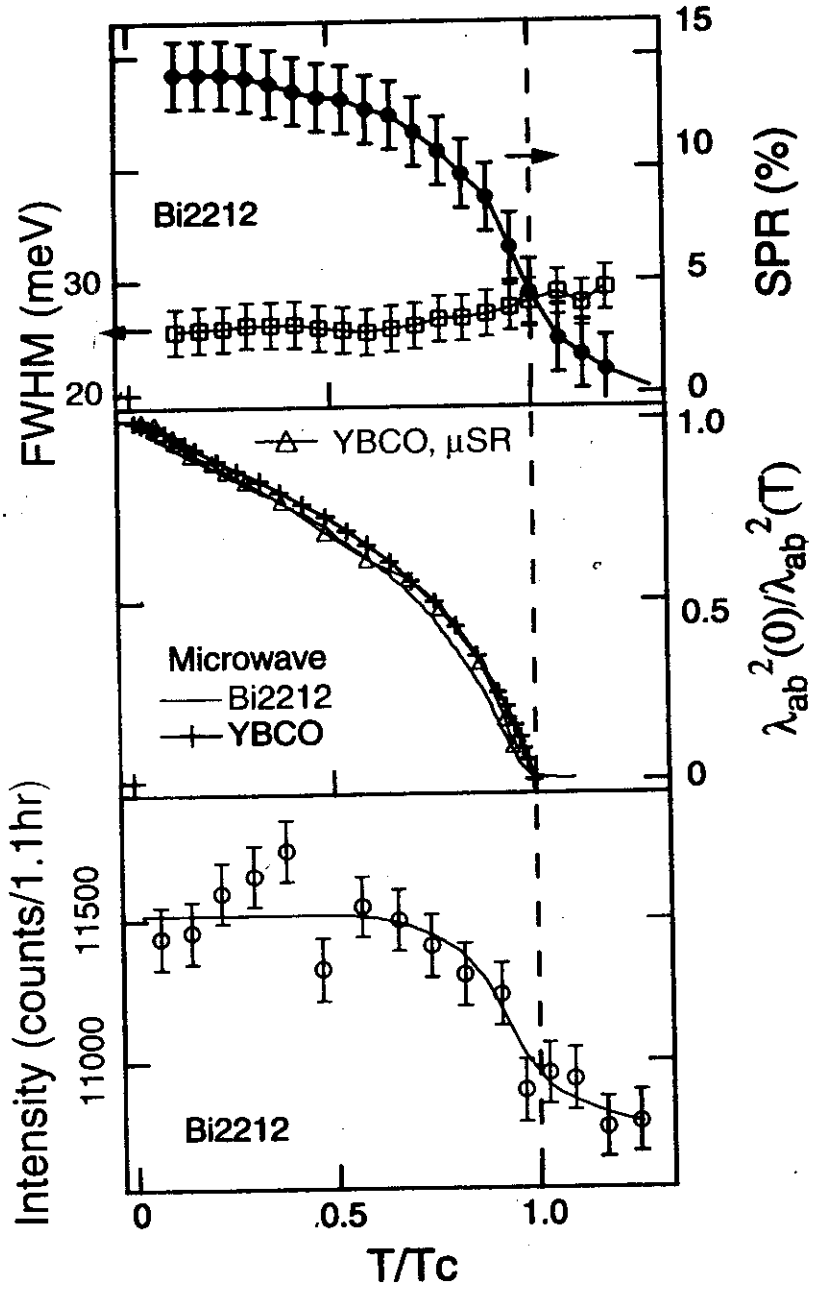
D.L. Feng, Z.-X. Shen
Stanford University

Doping dependence of superconducting state properties

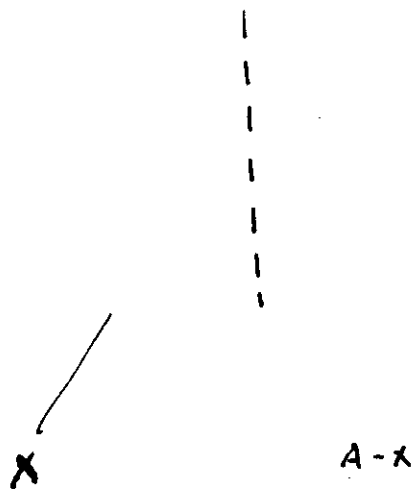


D.L. Feng, Z.-X. Shen
Stanford University

Temperature dependence of various properties

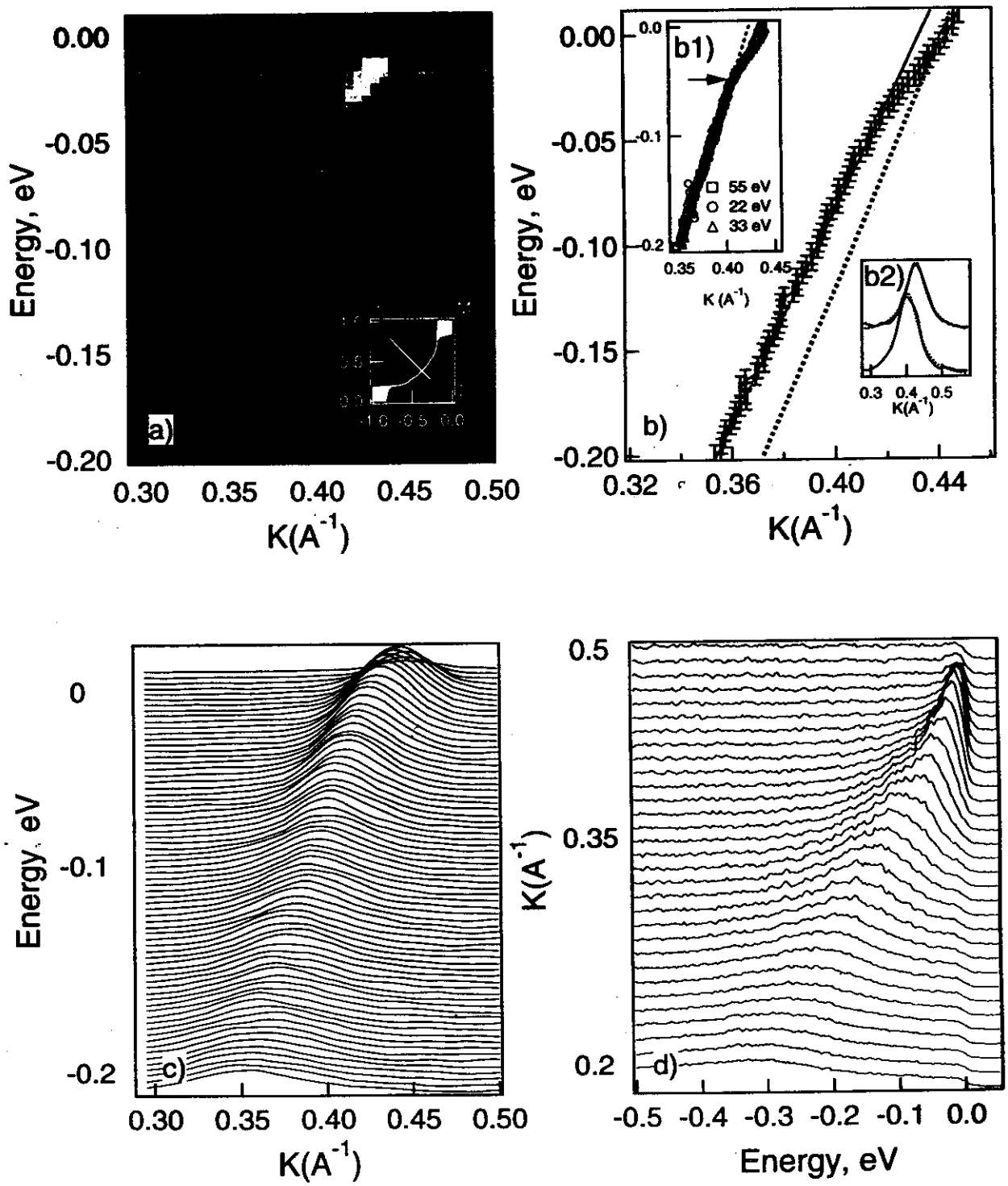


D.L. Feng, Z.-X. Shen
Stanford Univ.

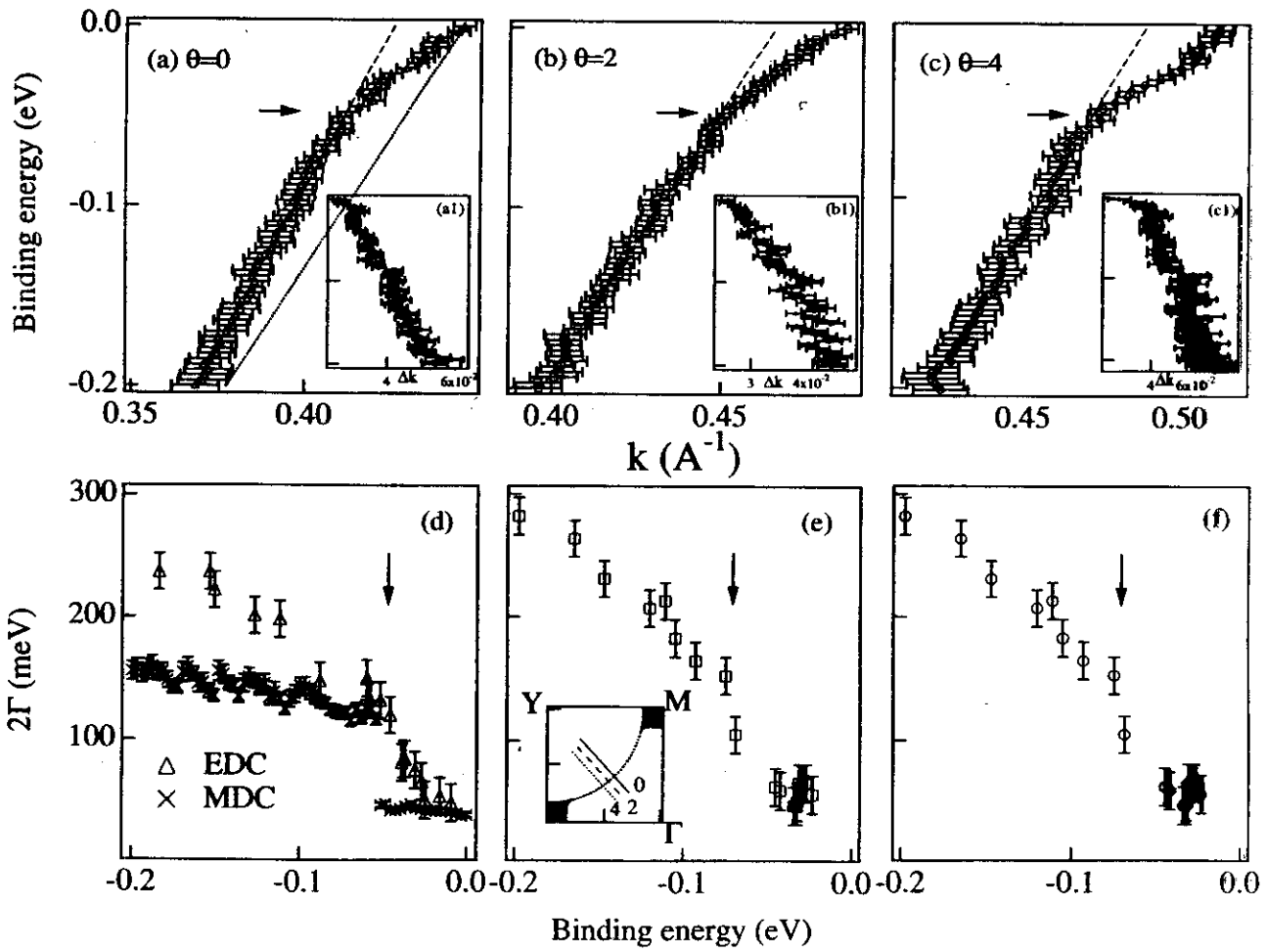


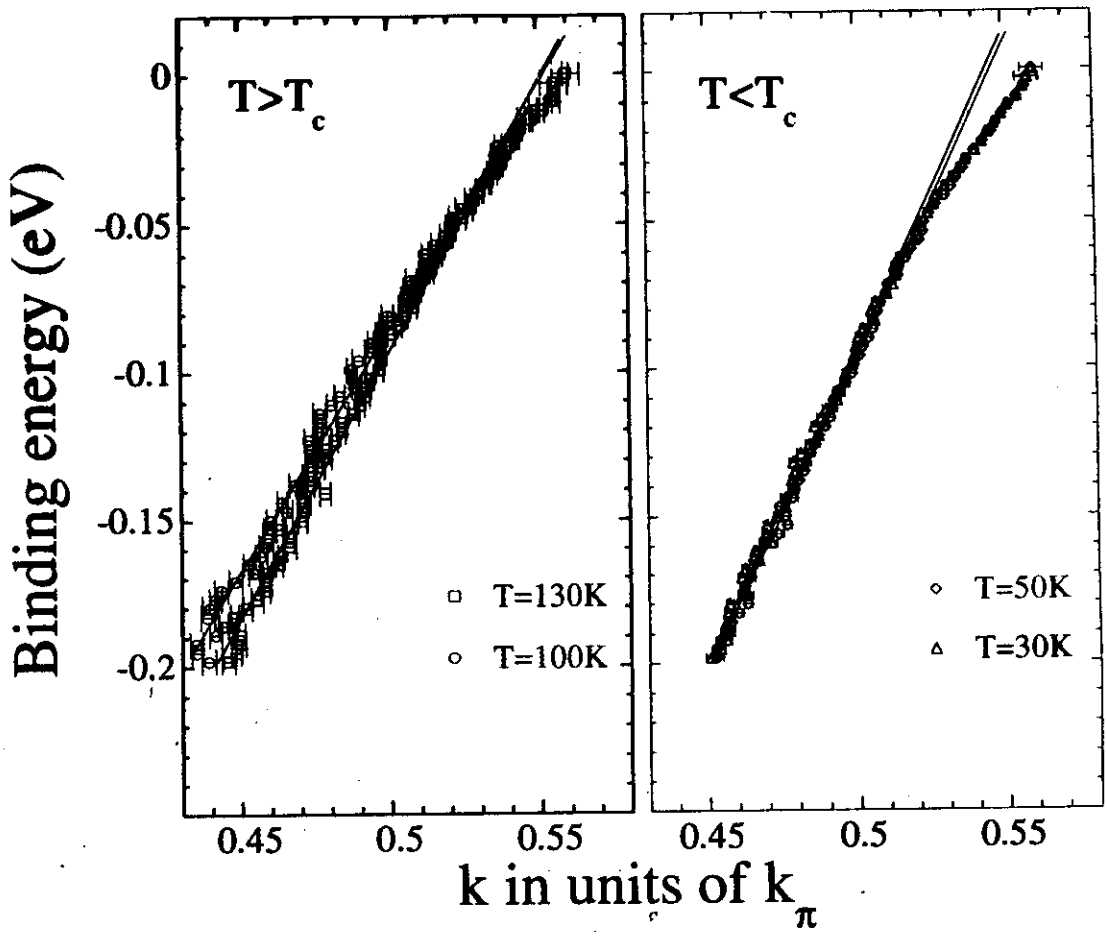
doped property
of Mott insulator

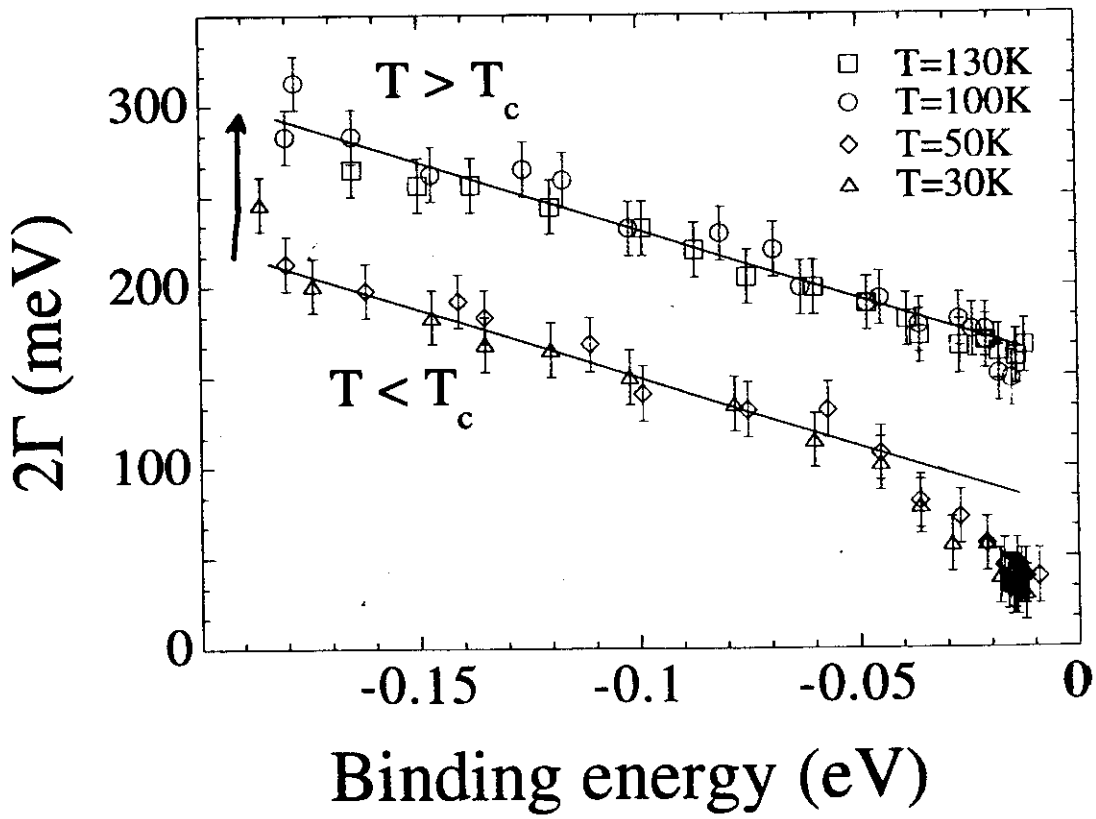
- RVB
- stripes


a)
b)
b1)
b2)
c)
d)
Energy, eV
K(A^{-1})
55 eV
22 eV
33 eV
0.00
-0.05
-0.10
-0.15
-0.20
0.30 0.35 0.40 0.45 0.50
0.32 0.36 0.40 0.44
0
-0.1
-0.2
0.5
0.35
0.2
-0.5 -0.4 -0.3 -0.2 -0.1 0.0

Bogdanov et al. Phys. Rev. Lett. in press



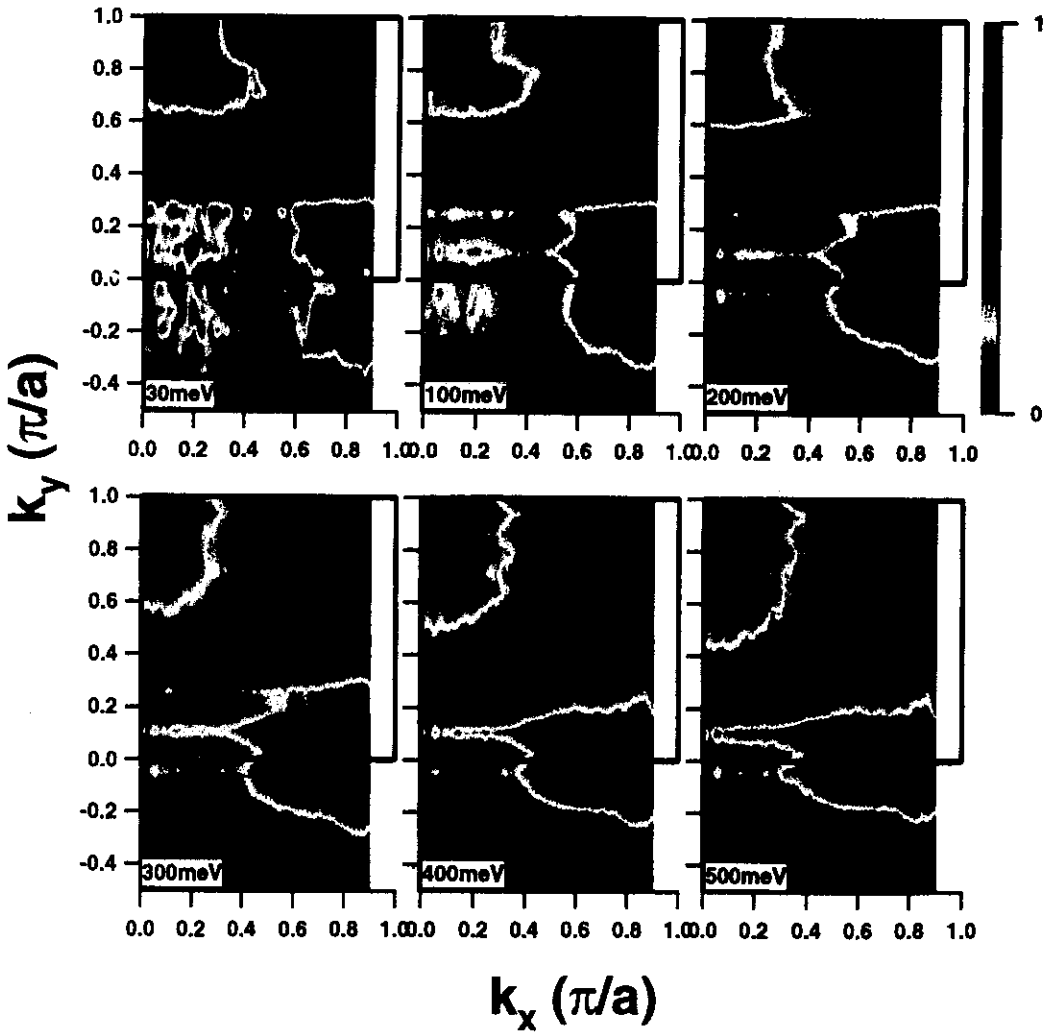

T>T_c
T<T_c
Binding energy (eV)
0
-0.05
-0.1
-0.15
-0.2
T=130K
T=100K
T=50K
T=30K
0.45
0.5
0.55
k in units of k_π


T > T_c
T < T_c
T=130K
T=100K
T=50K
T=30K
2Γ (meV)
300
200
100
0
-0.15
-0.1
-0.05
0
Binding energy (eV)

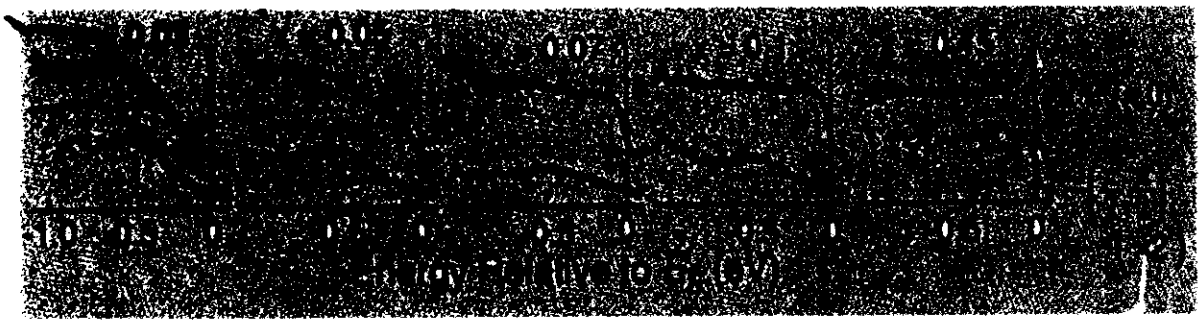
Stanford University

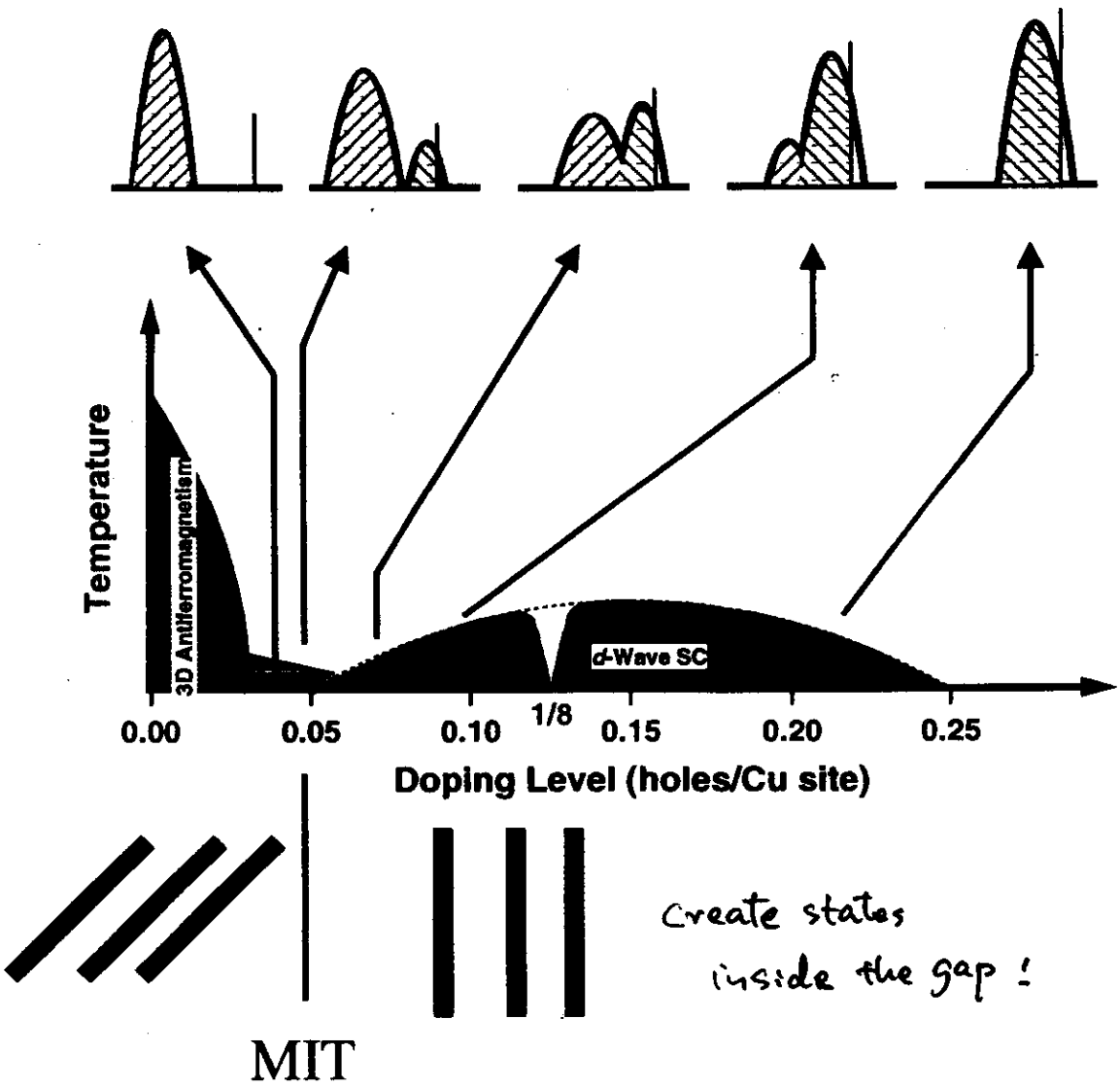
Spectral Weight of $(La_{1.95}Sr_{0.05})CuO_4$ at 20K

Advanced Light Source

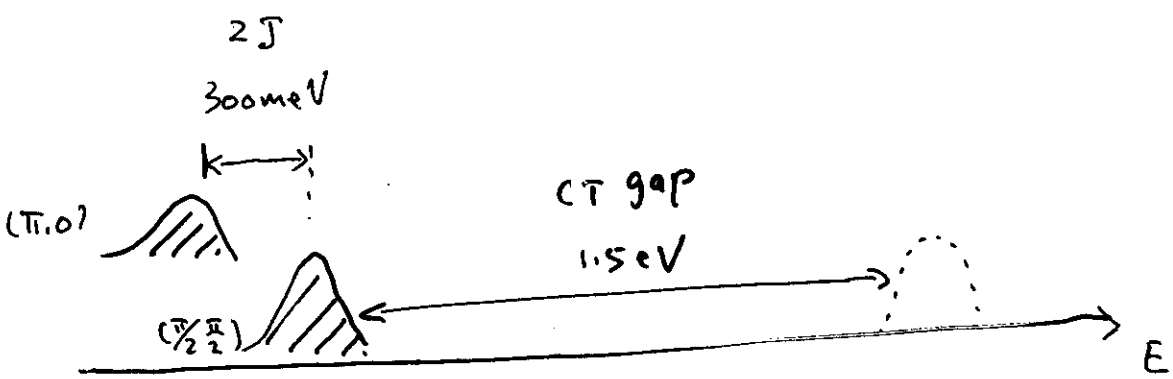


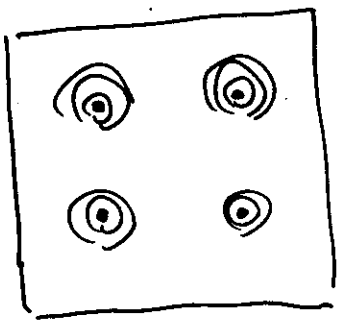
$La_{2-x}Sr_xCuO_4$



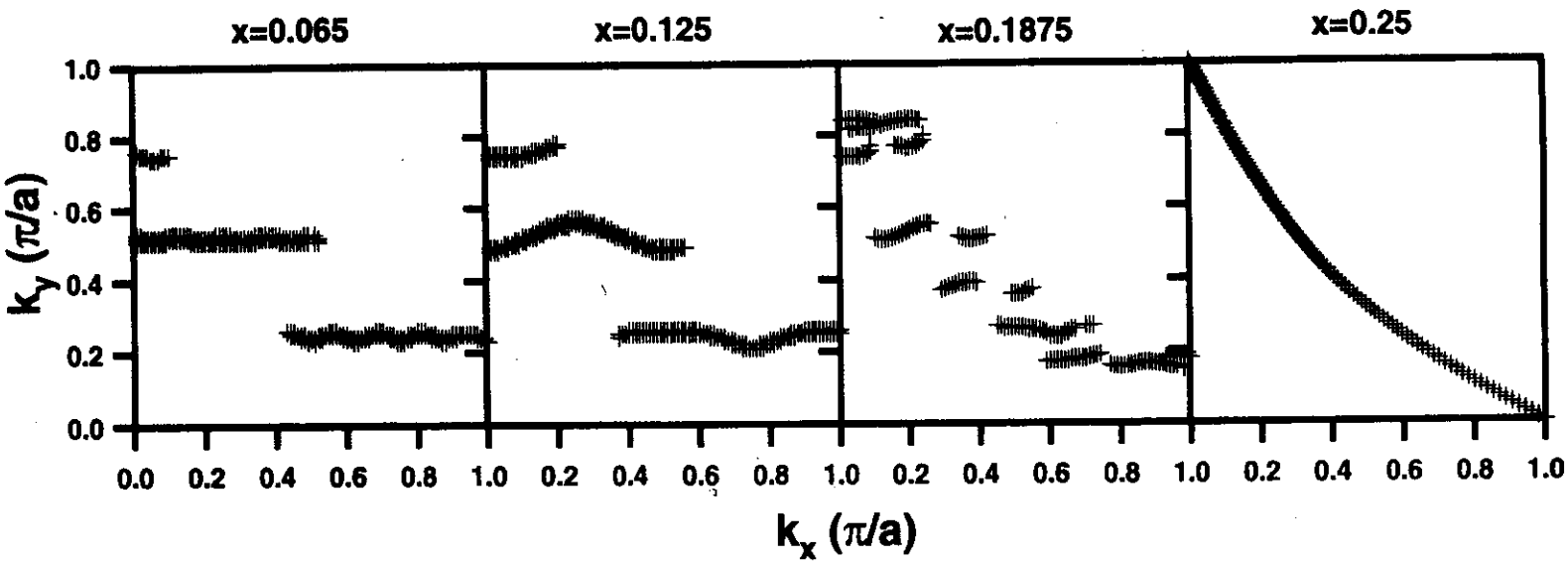


Starting Point:



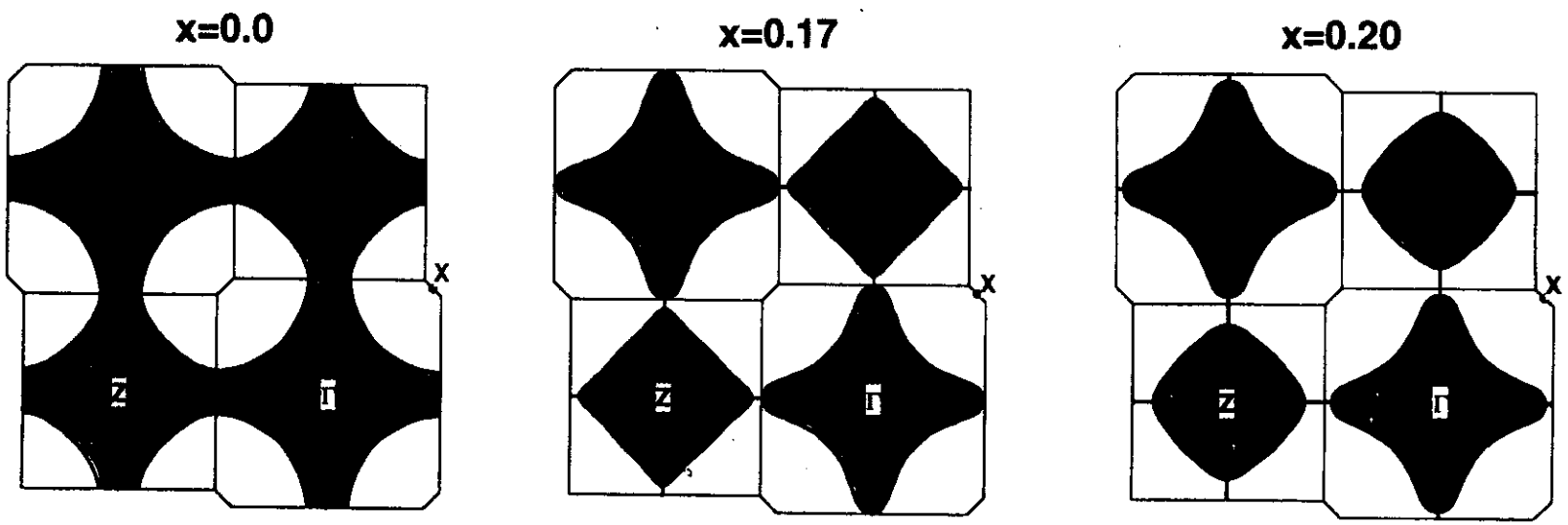


Calculated Fermi Surface in Terms of Stripe Picture



R. S. Markiewicz, cond-mat/9911108

LDA Calculated Fermi Surface of $(La_{2-x}Sr_x)CuO_4$



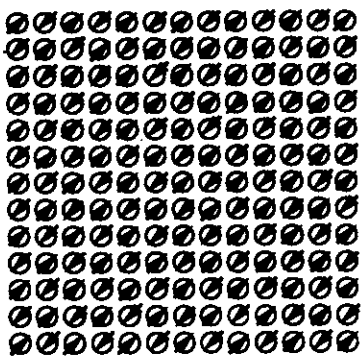
J.-H. Xu et al., Physics Letters A, 120(1987)489.

Doping of CuO_2 Planes

Stanford

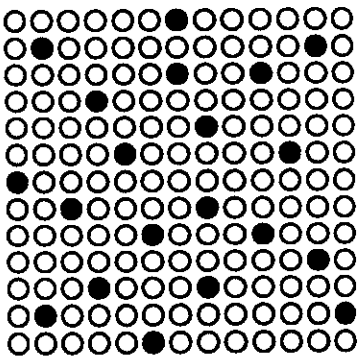
Advanced Light Source

Undoped

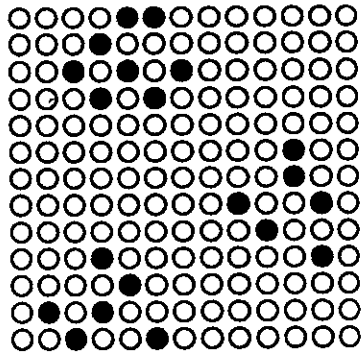


Antiferromagnetic Insulator

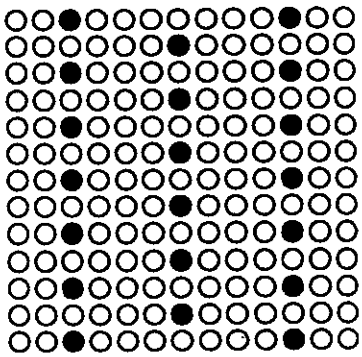
Doped



Random



Phase Seperation



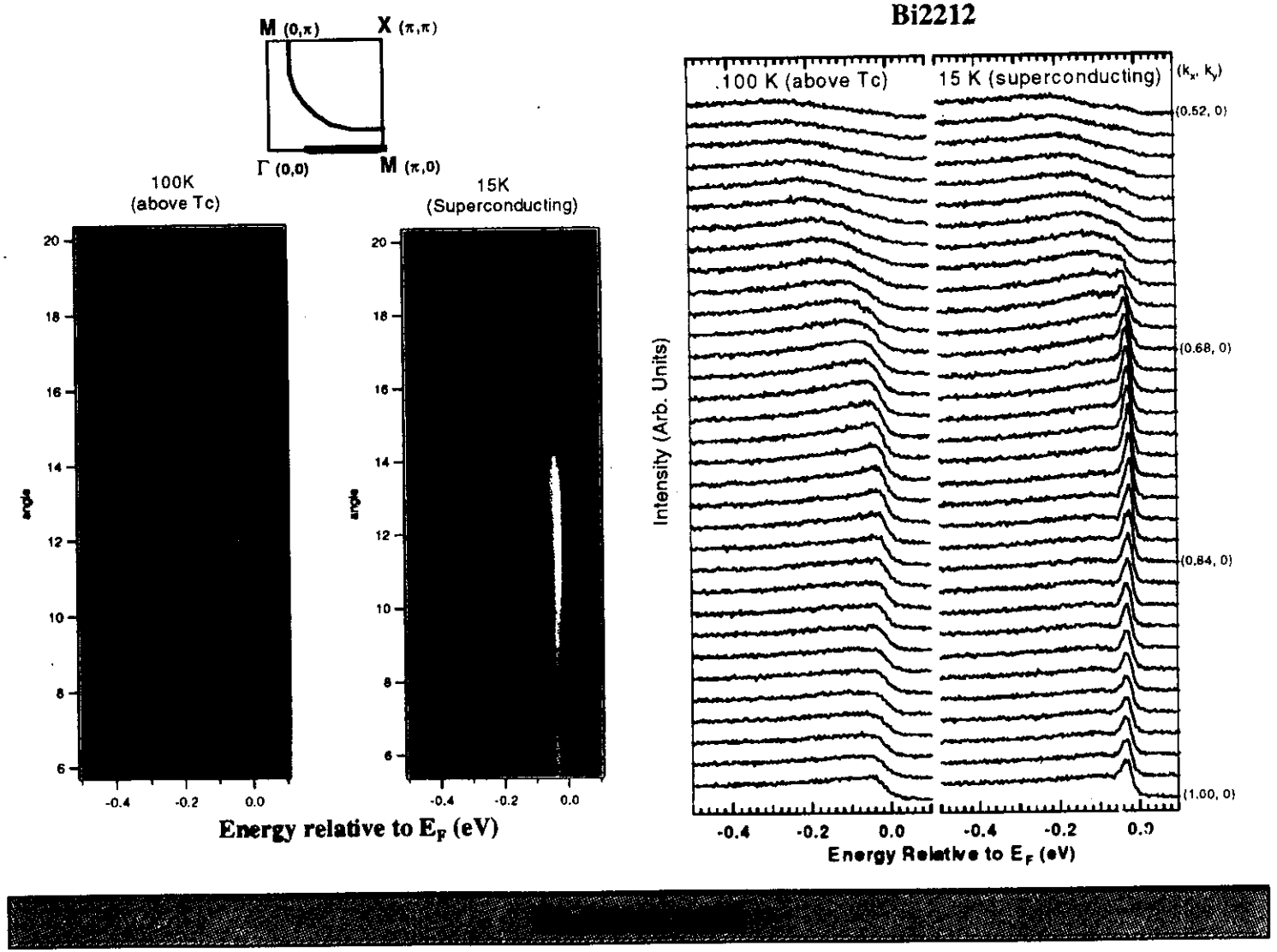
Stripes

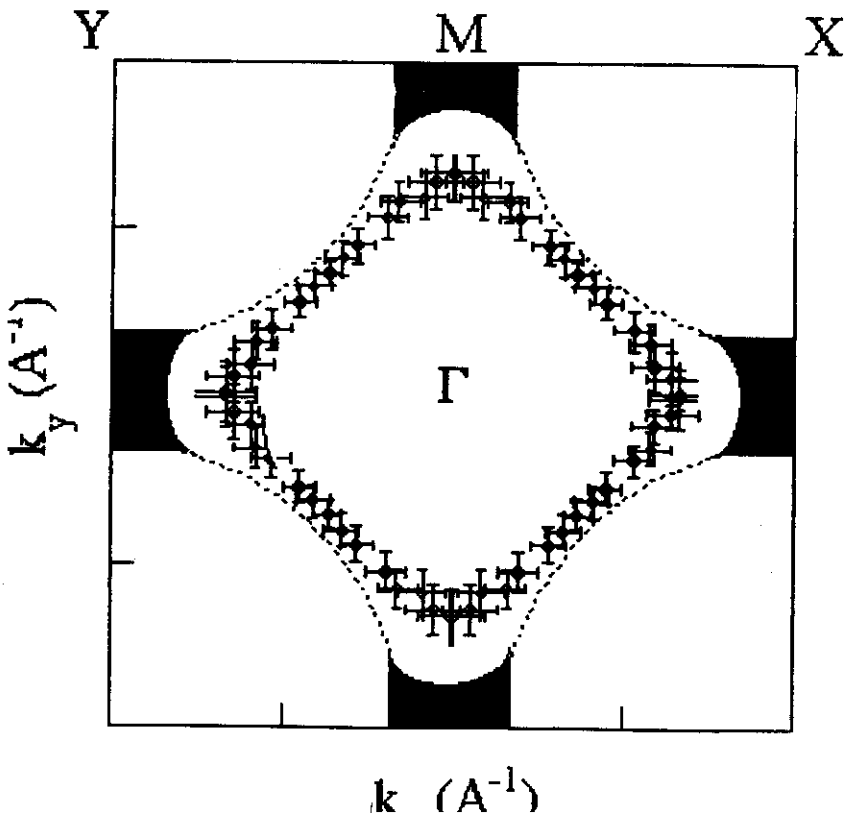
- What is the origin ?

2212 possibilities :

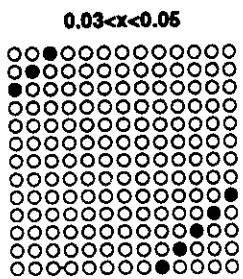
- Phonon
- neutron mode / magnetic excitation
- Superconducting gap
- charge inhomogeneity (charge stripes)
- Two bands (bonding - antibonding)

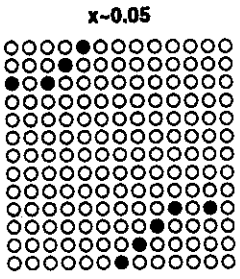
ARPES is Sensitive to Superconductivity

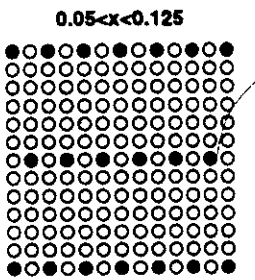


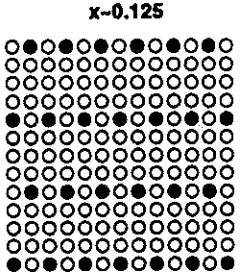

Y
M
X
Γ
k_y (A^{-1})
k (A^{-1})

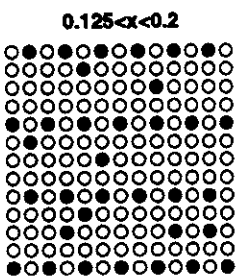
Dynamic Stripes and DOS in $(La_{2-x}Sr_x)CuO_4$

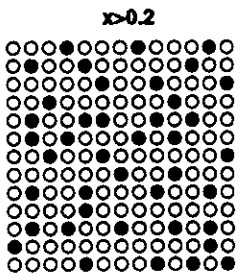








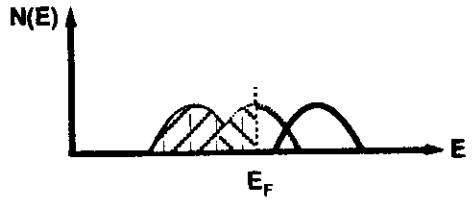




x<5%: **Look like insulator, could be consistent with the diagonal stripe;**

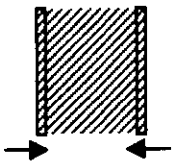
x~5-7%: **Two components visible;**

Stripes well separated

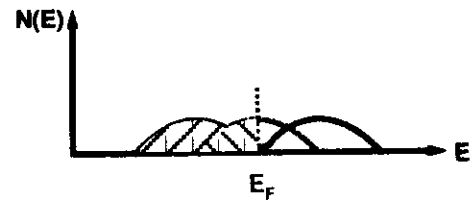


"New state inside gap"

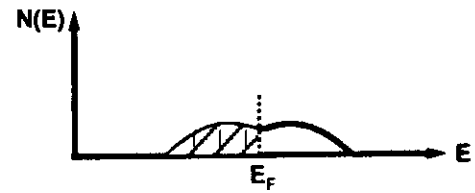
x~10% 12%

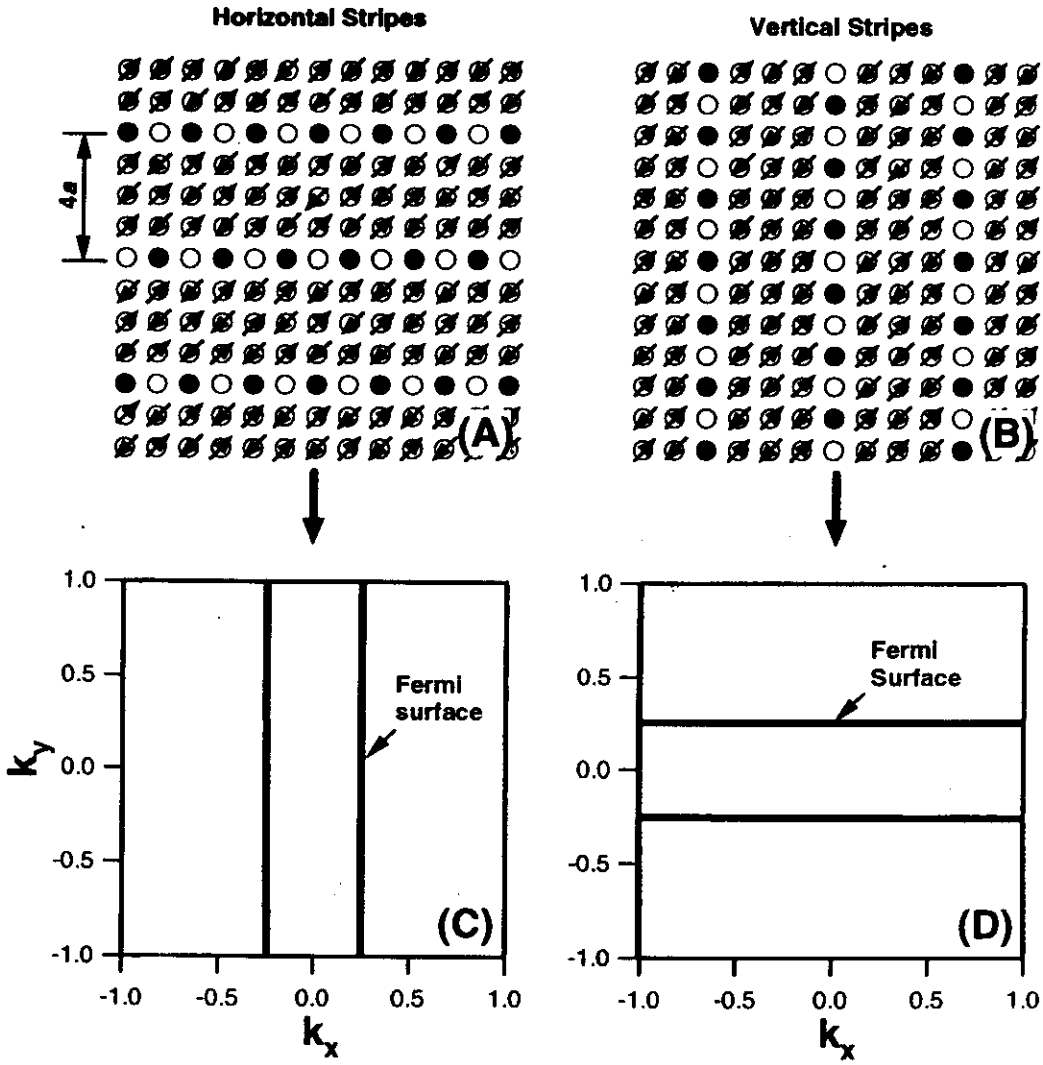


Stripes close to each other



x>=22%

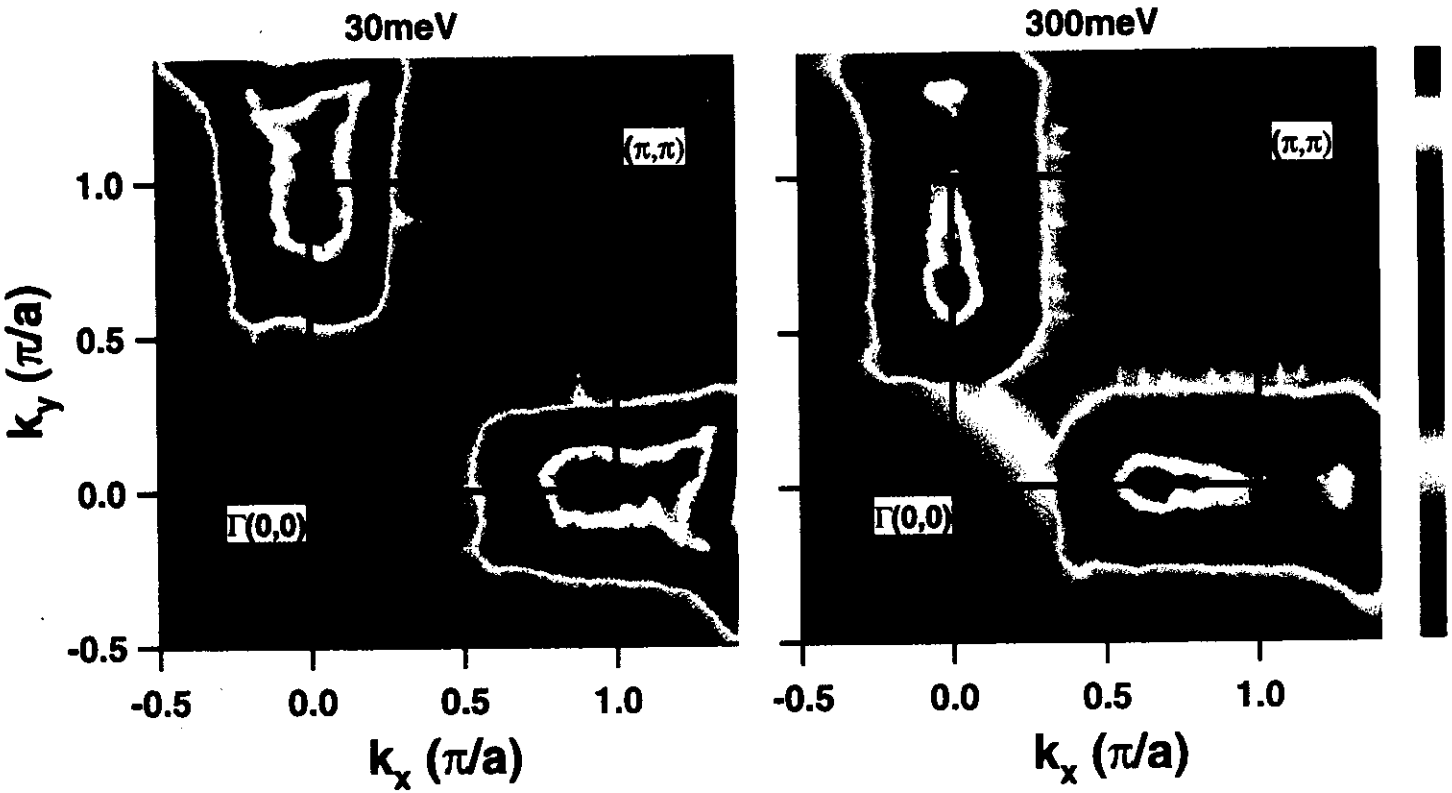



Horizontal Stripes
Vertical Stripes
4a
(A)
(B)
(C)
(D)
Fermi surface
Fermi Surface
1.0
0.5
0.0
-0.5
-1.0
k_y
k_x

Stanford University

Spectral Weight of $(La_{1.3}Nd_{0.6}Sr_{0.1})CuO_4$ at 20K

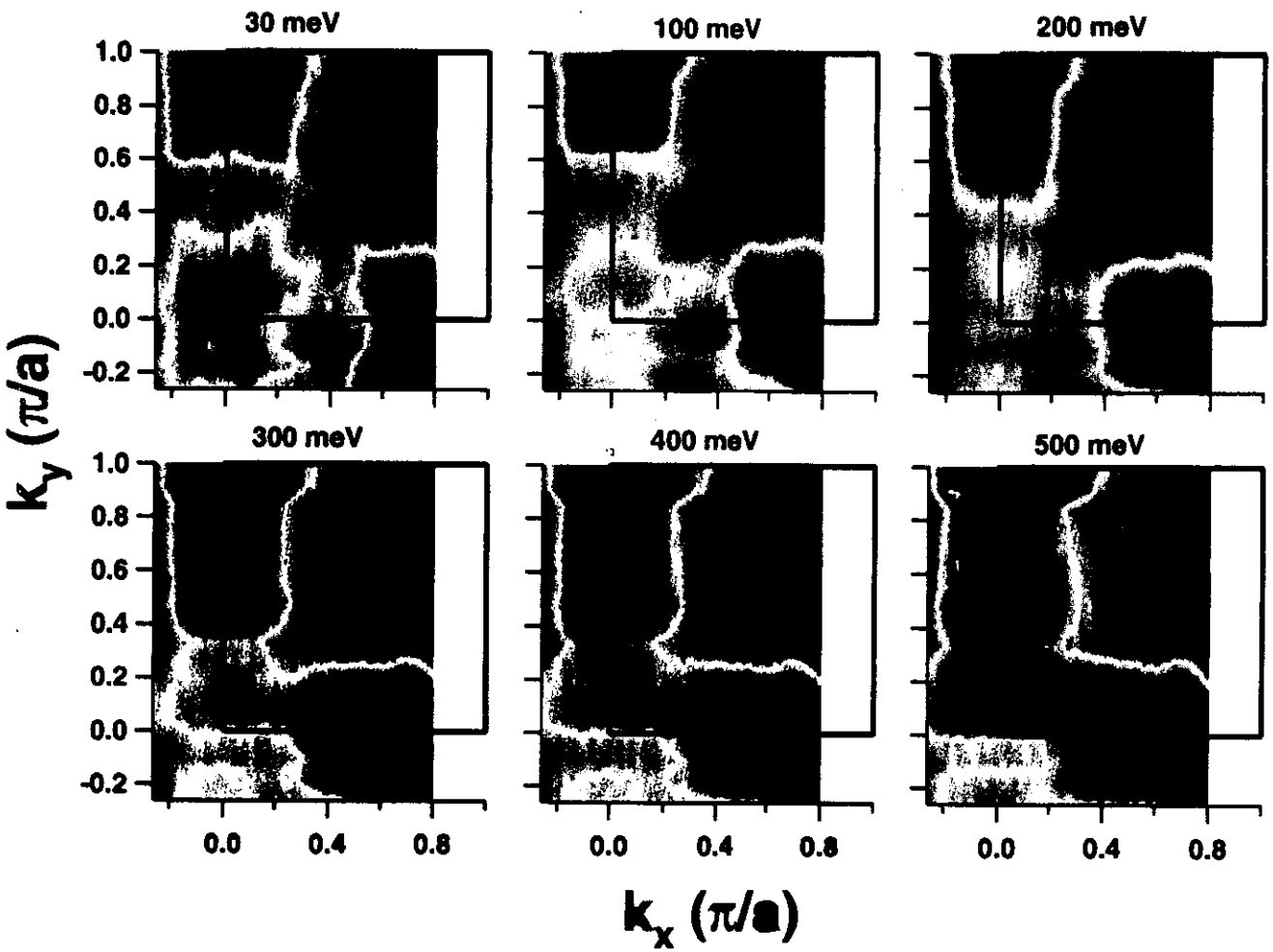
Advanced Light Source

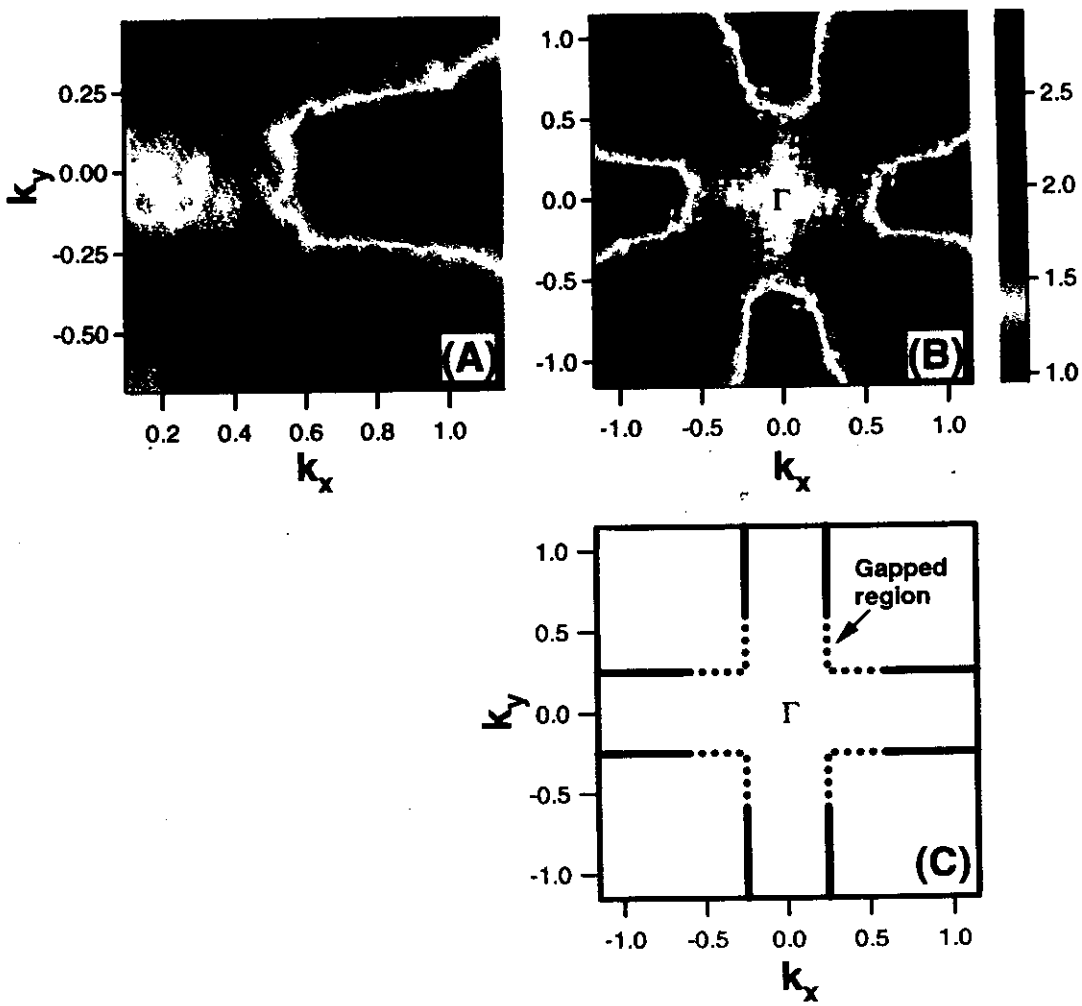


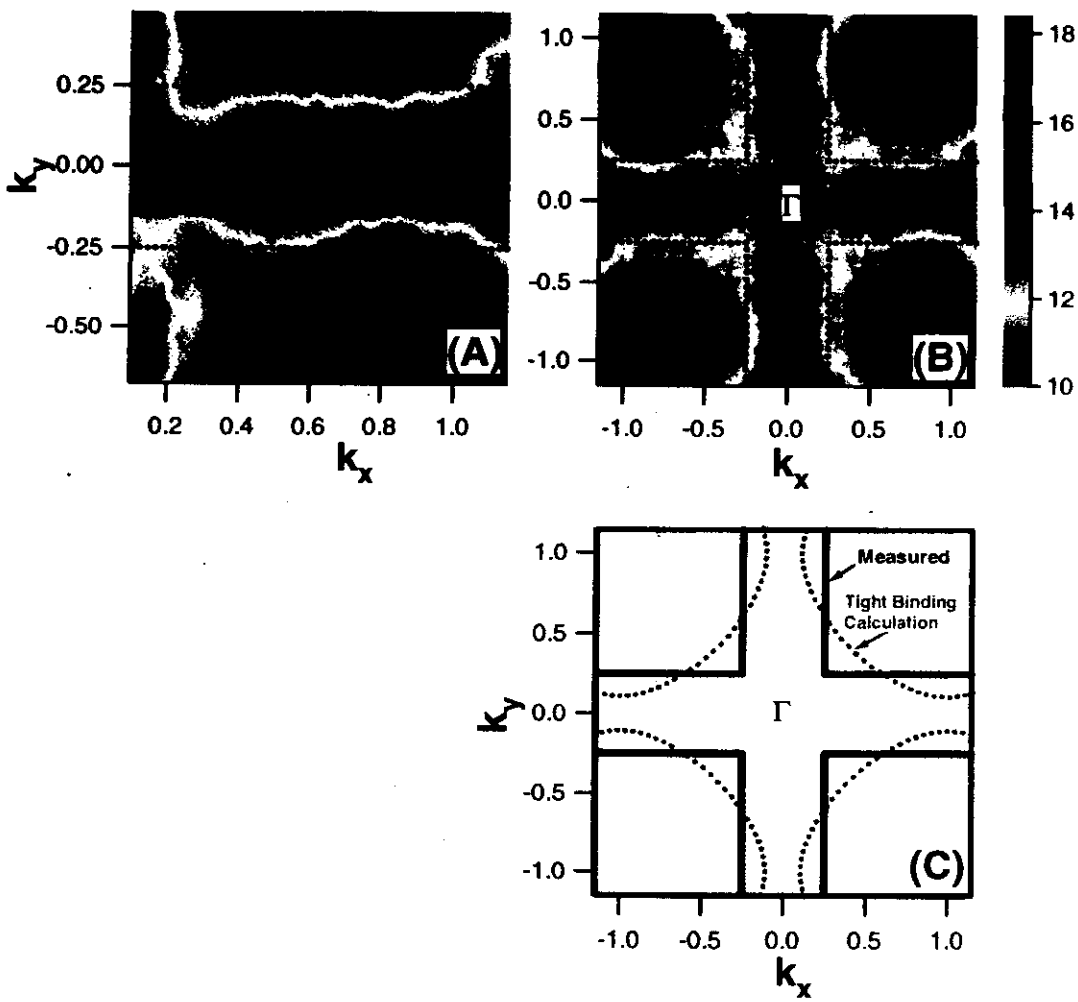
Stanford University

Spectral Weight of $(La_{1.88}Sr_{0.12})CuO_4$ at 20 K

Advanced Light Source

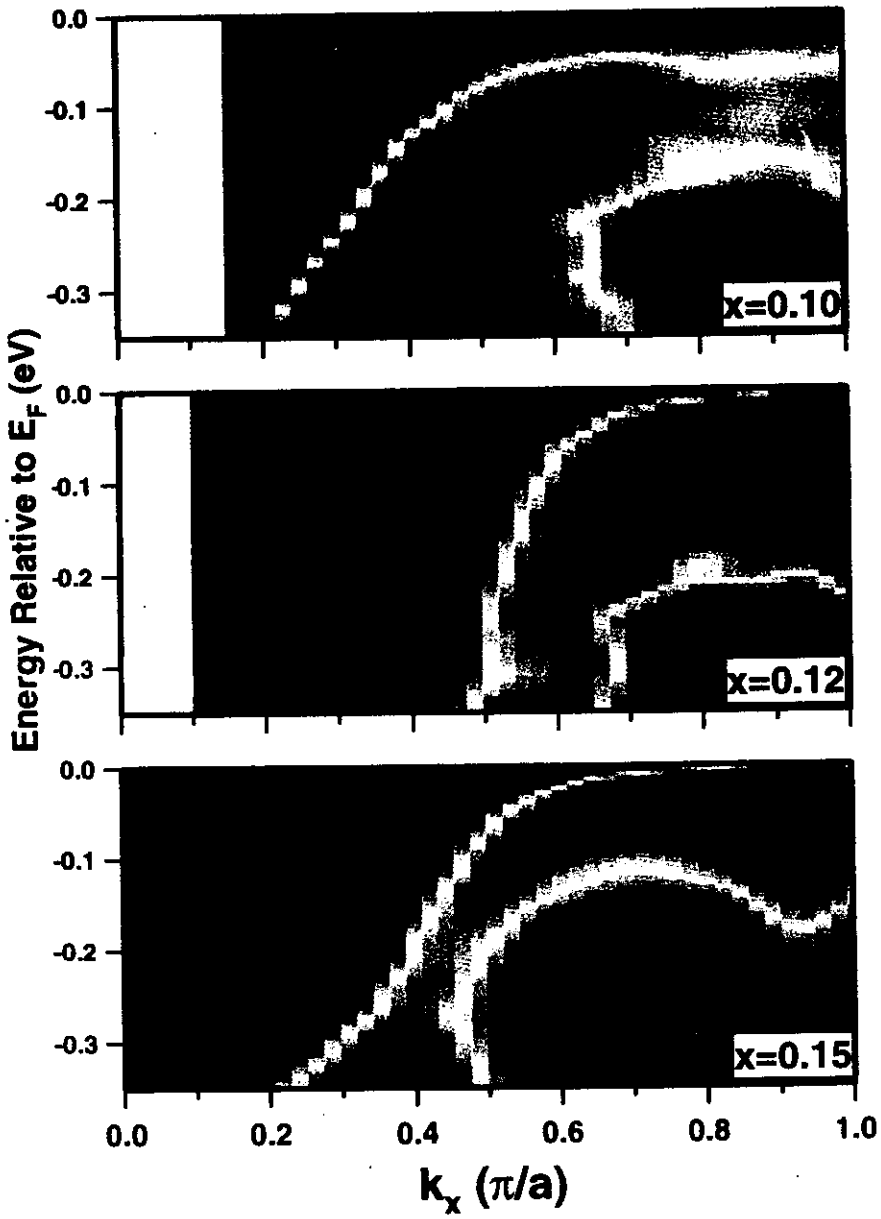



0.25
0.00
-0.25
-0.50
k_y
(A)
0.2
0.4
0.6
0.8
1.0
k_x
1.0
0.5
0.0
-0.5
-1.0
Γ
(B)
-1.0
-0.5
0.0
0.5
1.0
k_x
2.5
2.0
1.5
1.0
1.0
0.5
0.0
-0.5
-1.0
k_y
Gapped region
Γ
(C)
-1.0
-0.5
0.0
0.5
1.0
k_x

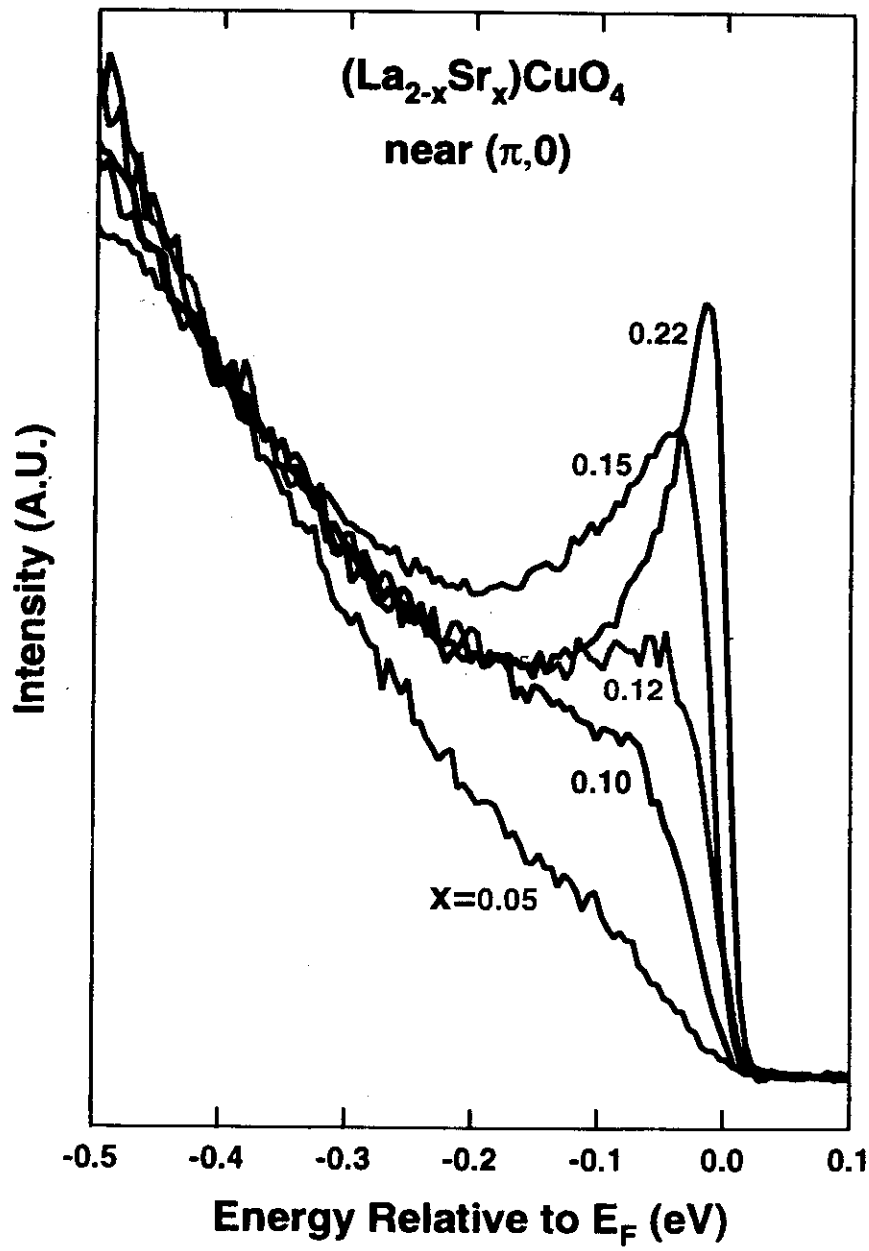

0.25
0.00
-0.25
-0.50
k_y
0.2
0.4
0.6
0.8
1.0
k_x
(A)
1.0
0.5
0.0
-0.5
-1.0
Γ
-1.0
-0.5
0.0
0.5
1.0
k_x
(B)
18
16
14
12
10
Measured
Tight Binding Calculation
1.0
0.5
0.0
-0.5
-1.0
k_y
Γ
(C)
-1.0
-0.5
0.0
0.5
1.0
k_x

Dispersion along (0, 0) to (π, 0) for $(La_{1.4-x}Nd_{0.6}Sr_x)CuO_4$ at 15 K

Advanced Light Source



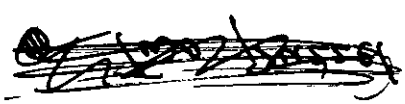
ARPES Spectra of $(La_{2-x}Sr_x)CuO_4$ near $(\pi,0)$ at 20K



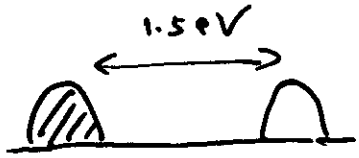
Two Puzzles (Zhou et al. 99)

① Why $(\pi, 0)$ region behaves like that of BSCCO ?

② Why one sees ~~such~~ a strong dispersion for motion transverse to stripes ?



- Key Points.

a) 

charge gap is important,
aspects of it may survive
in certain cases ?
"in gap state" universal ?

b) It is related to the "flat band" near
$(\pi, 0)$.

c) distinction between stripe & chain

chain

stripe
" transverse
hopping still
possible "

$W \sim t$

$W \sim J$

d) metallic state in static charge ordered compound.
— suprise to me !