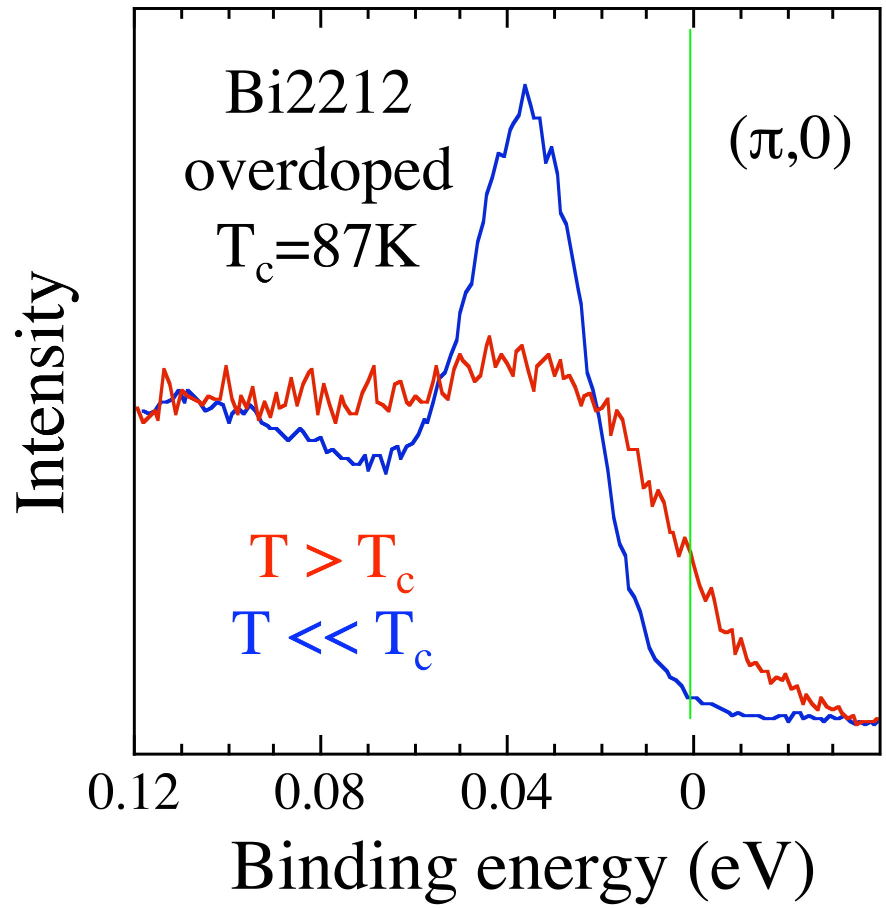
Pseudogaps, Strange Metals, and Coherent Superconductors: The View from ARPES

Mike Norman - Materials Science Div., Argonne Natl. Lab

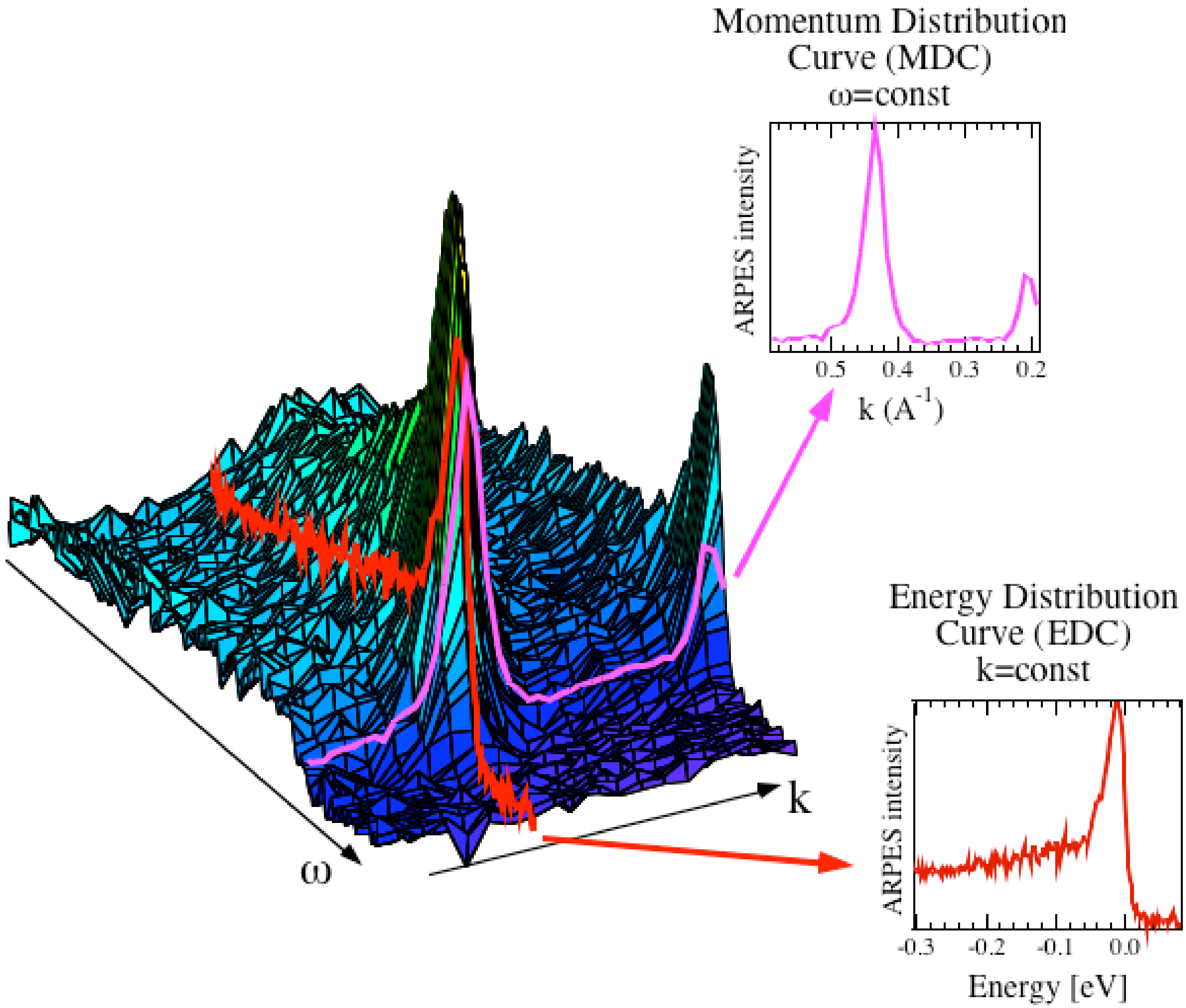


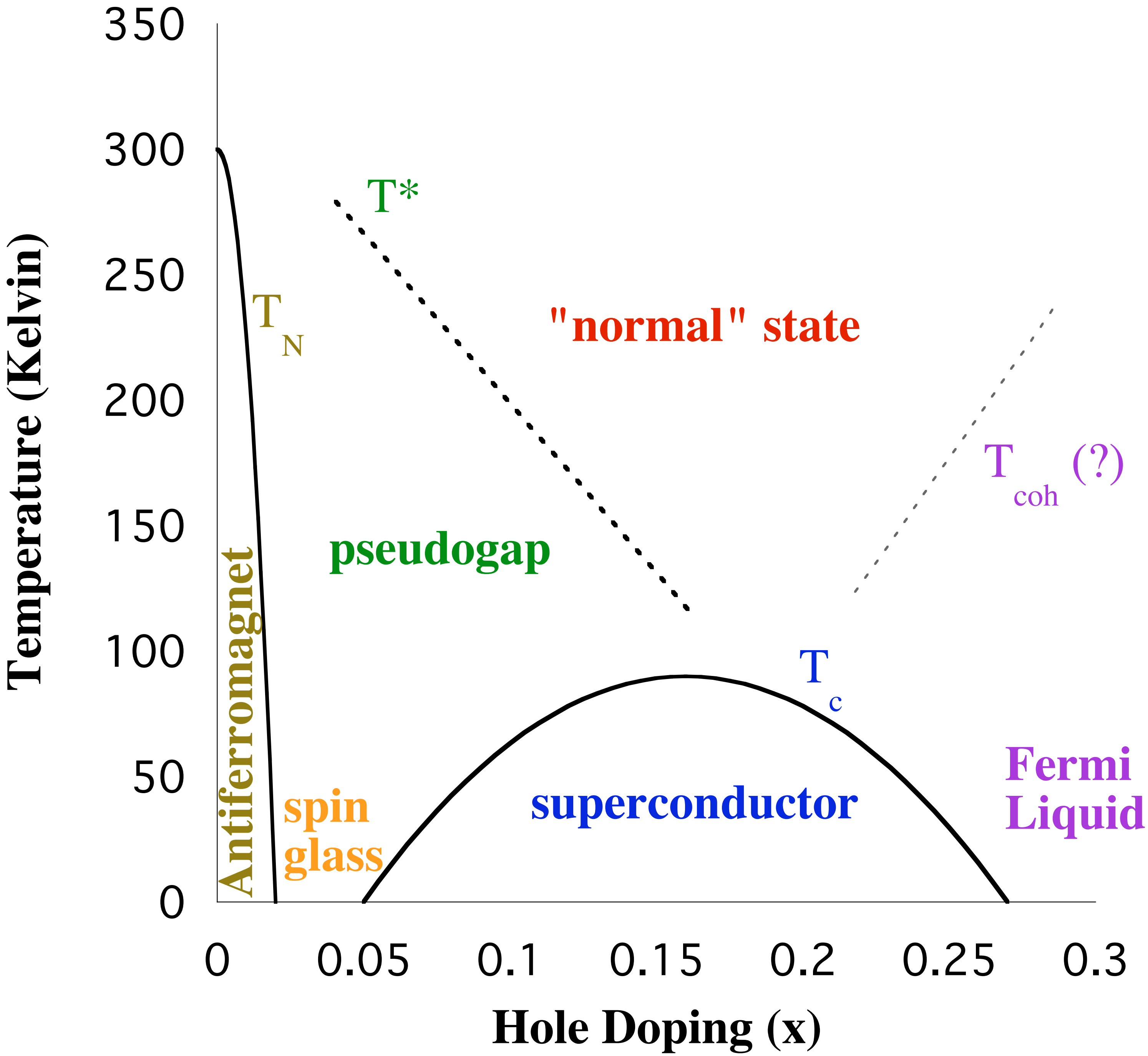
Norman *et al.*
PRL 79, 3506
(1997)

Campuzano *et al.*, cond-mat/0209476
Damascelli *et al.*, RMP 75, 473 (2003)

MPI, Dresden, Apr. 4, 2005

Angle Resolved Photoemission Spectroscopy (ARPES)

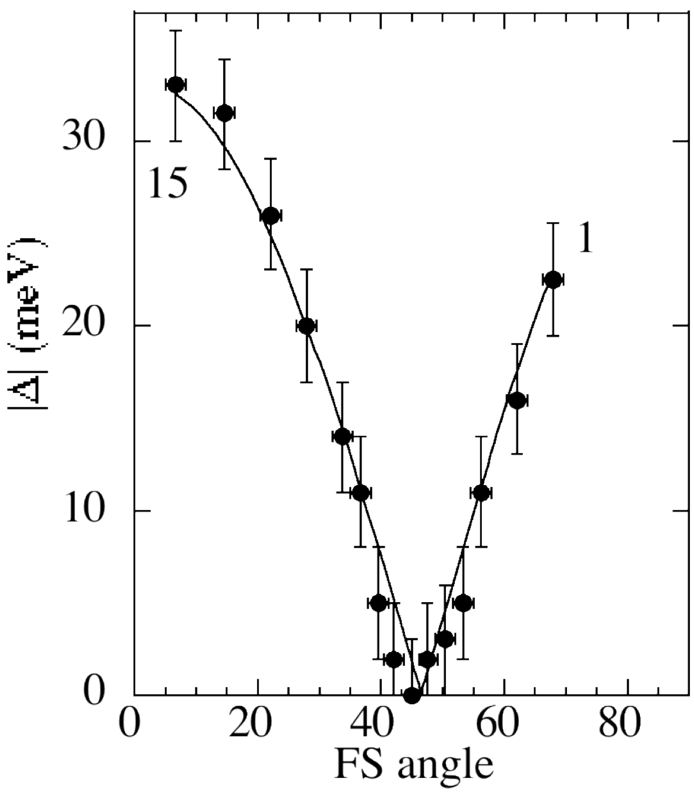


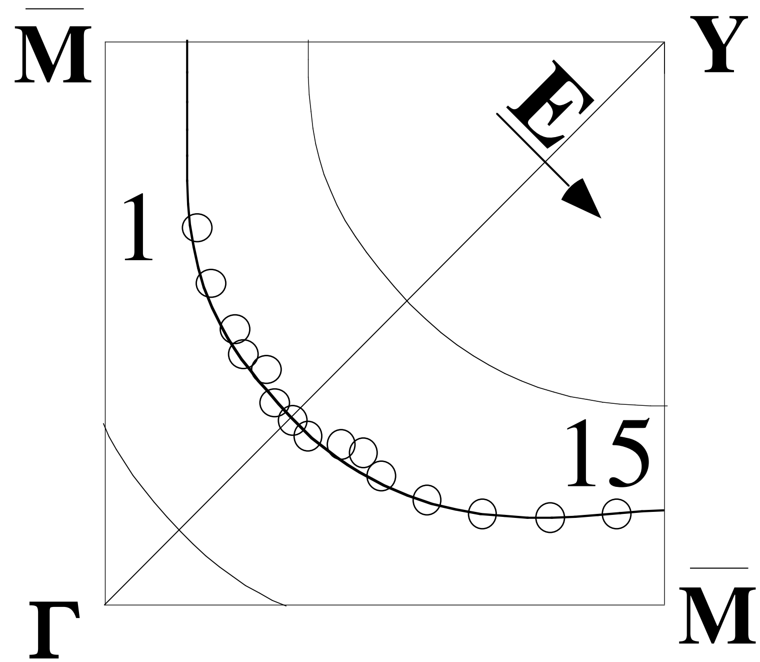

350
300
250
200
150
100
50
0
Temperature (Kelvin)
T*
T
N
"normal" state
T
coh
(?)
pseudogap
Antiferromagnet
T
c
spin
glass
superconductor
Fermi
Liquid
0
0.05
0.1
0.15
0.2
0.25
0.3
Hole Doping (x)

Extraction of the Superconducting Energy Gap

Ding *et al.*, PRL 74, 2784 (1995) & PRB 54, 9678 (1996)

Δ_k --> $\cos(k_x) - \cos(k_y)$ --> Implies near-neighbor pairs

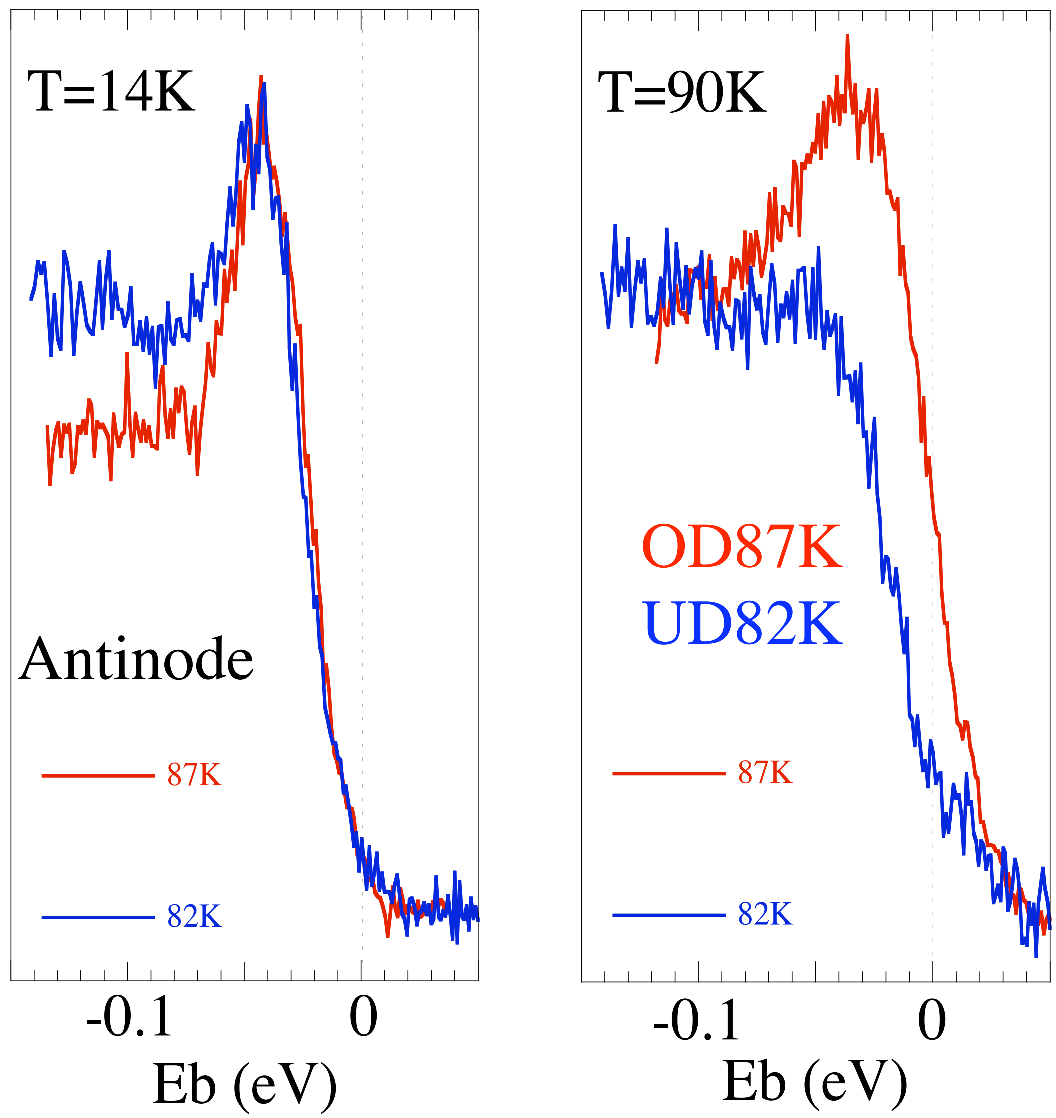


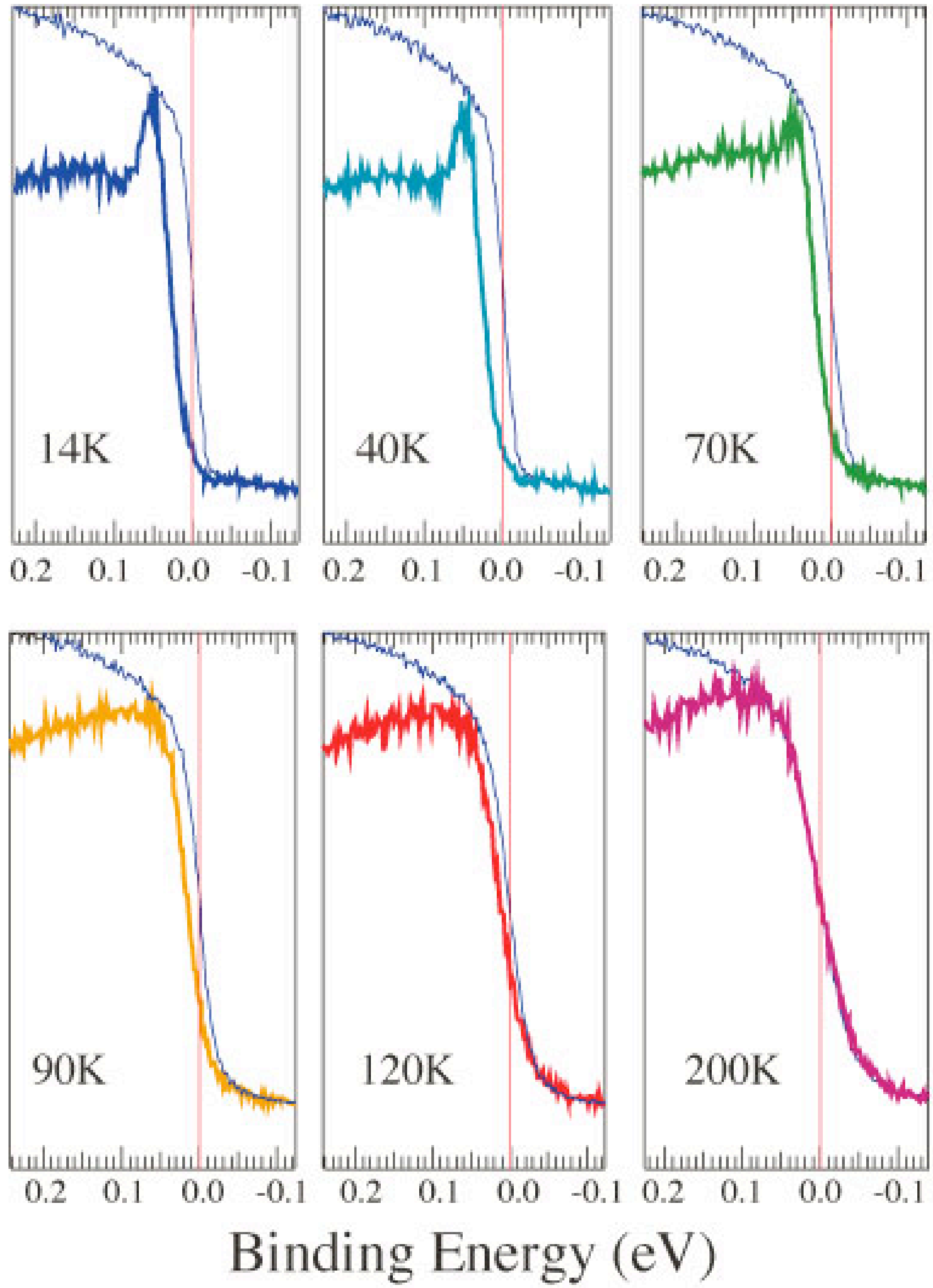


Bi2212
overdoped, T_c=87K
(OD87K)

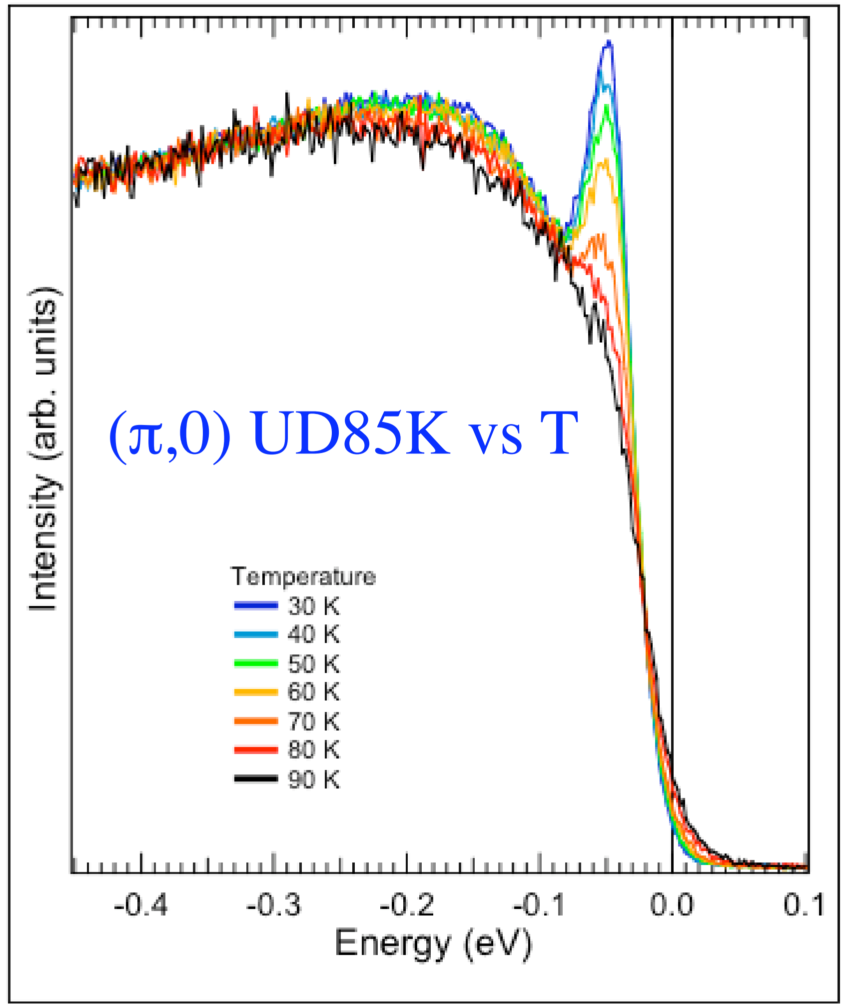
ARPES - Ding *et al.*, Nature 382, 51 (1996)

pseudogap - spectral gap but no coherent peak





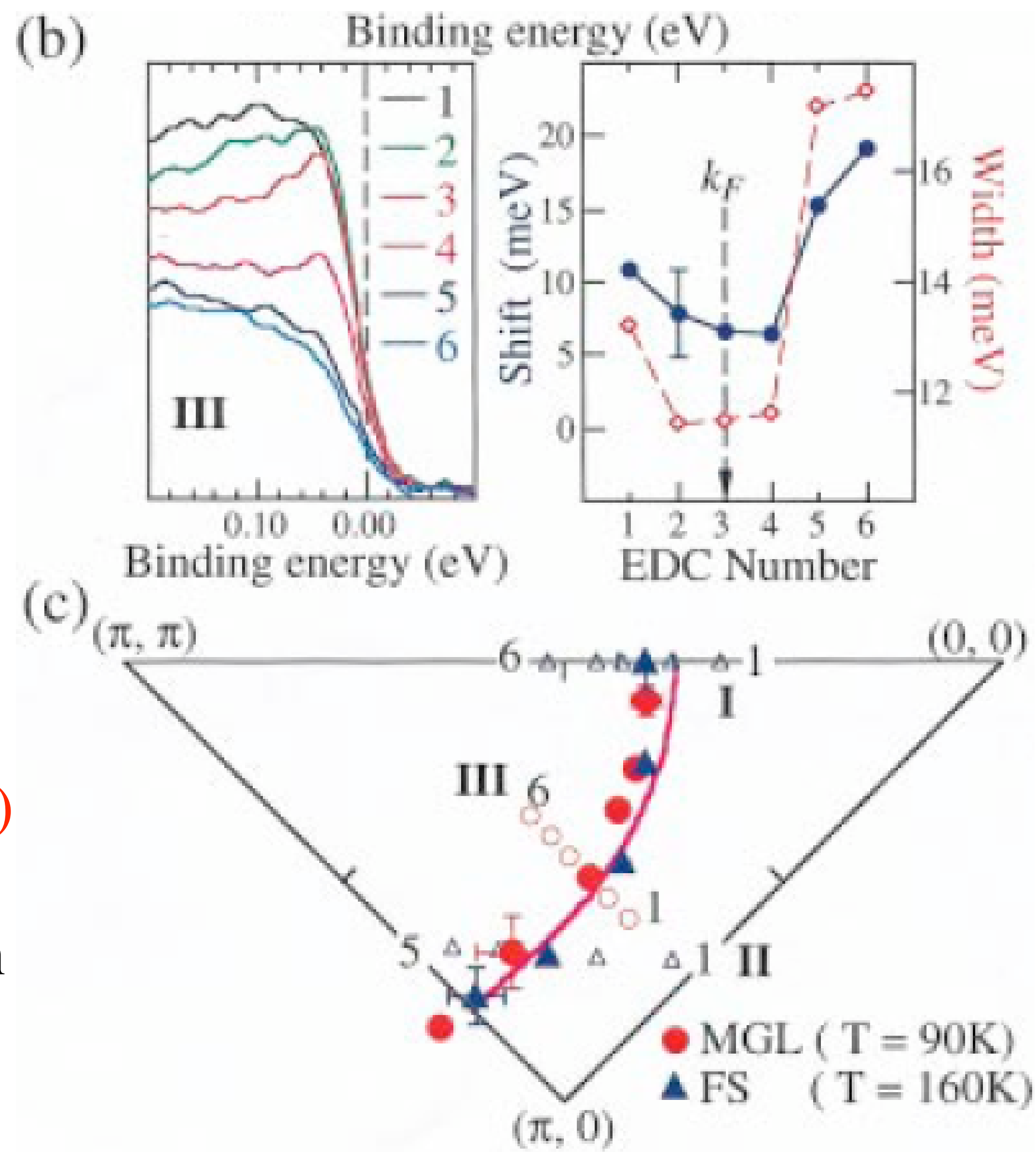
<-- Antinode UD83K vs T



(π,0) UD85K vs T

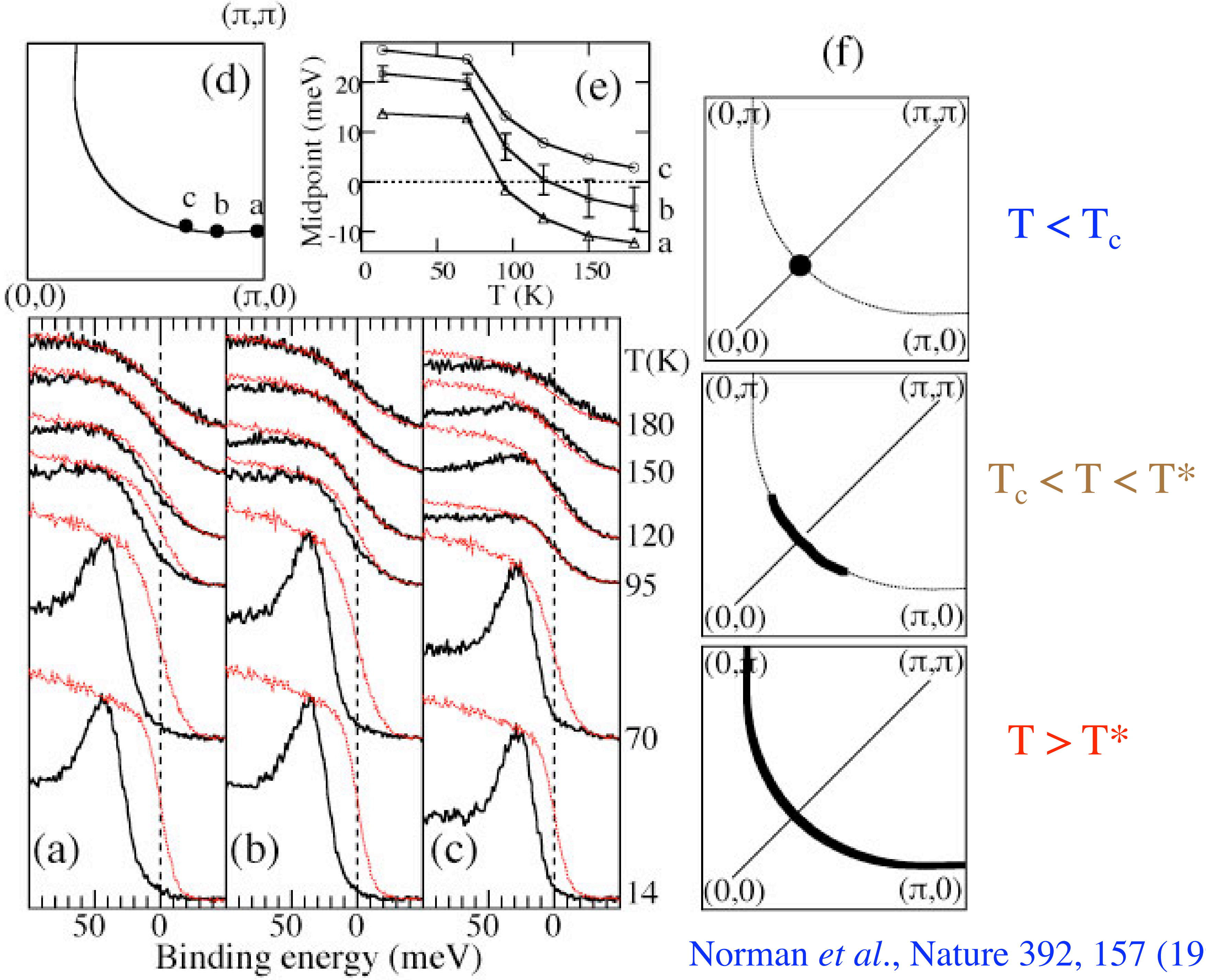
“Fermi surface” in the presence of an energy gap

Ding *et al.*, PRL 78, 2628 (1997)

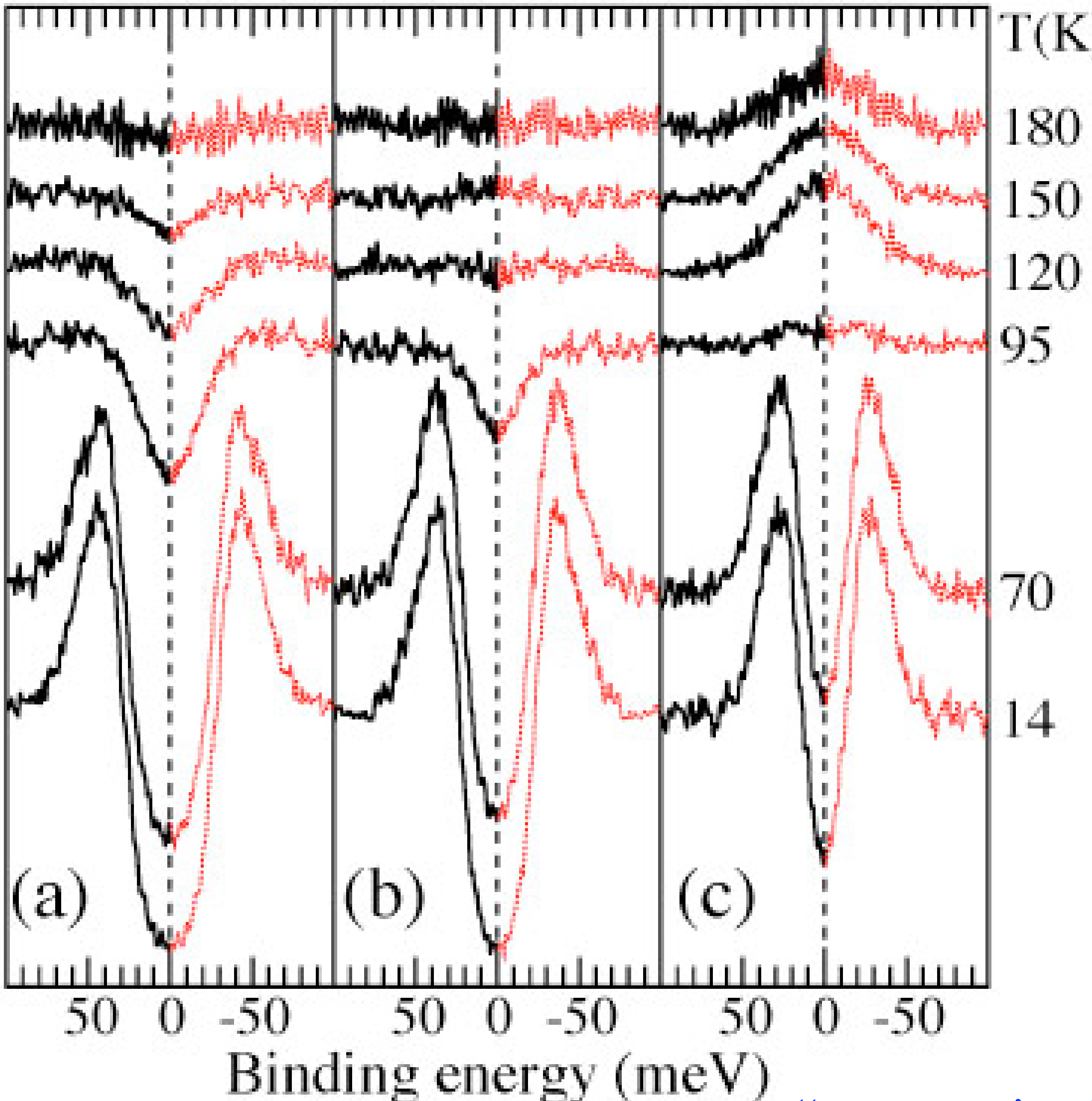


Underlying Fermi surface
for a gapped metal
(minimum gap locus - MGL)

Find maximum in dispersion
along a cut in **k** space

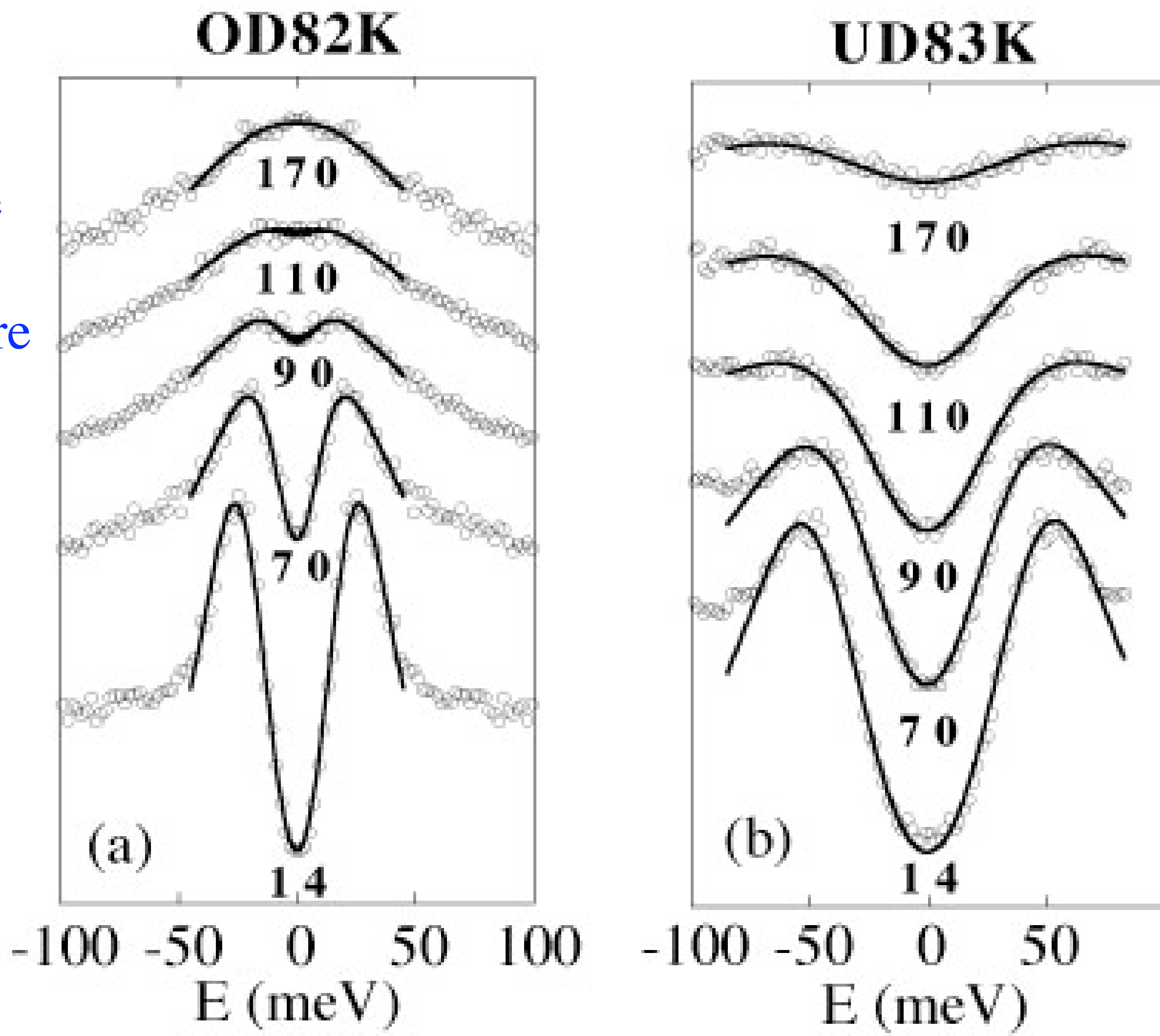


Norman *et al.*, Nature 392, 157 (1998)



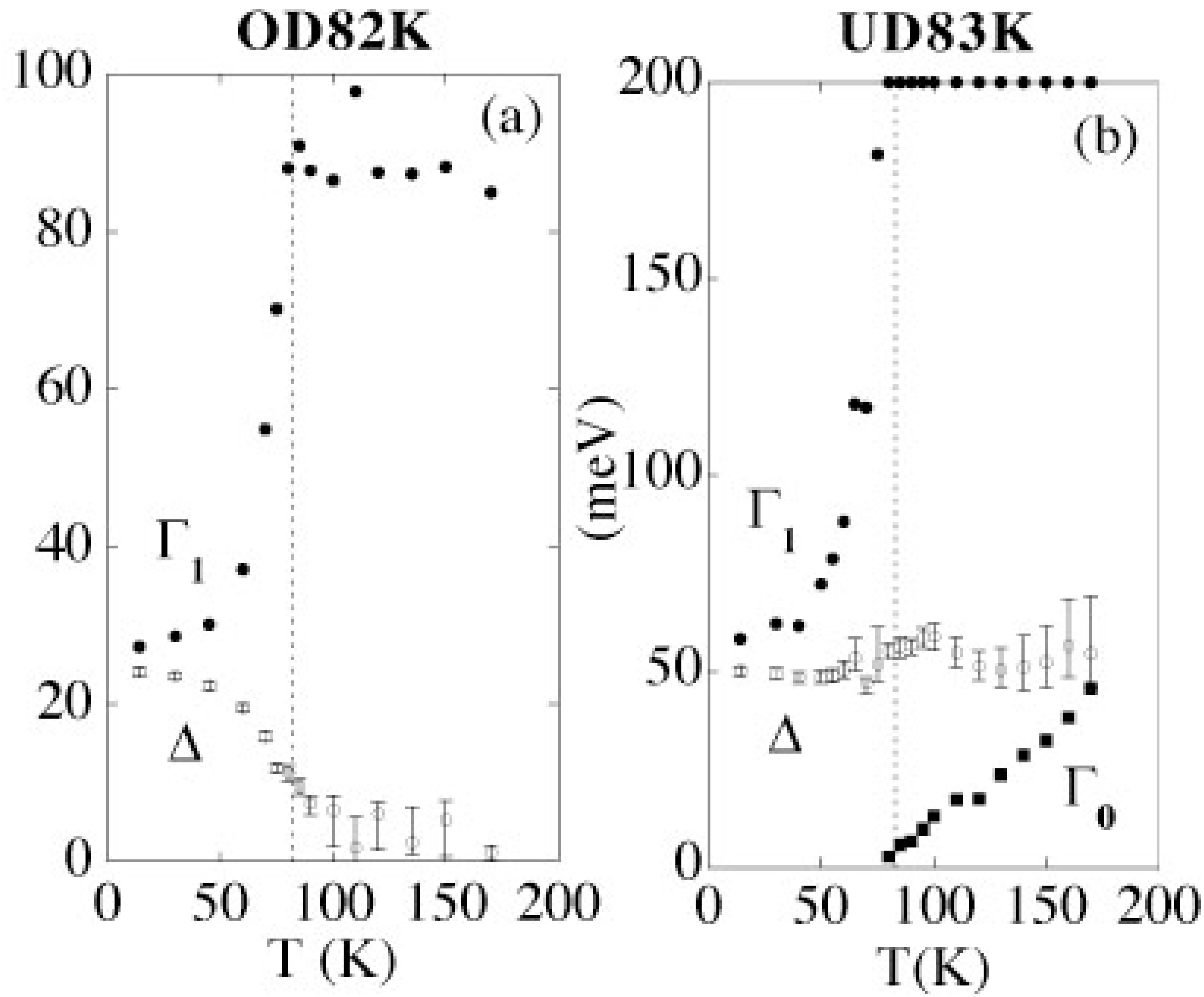
"symmetrized" data vs T

Antinode
vs
temperature

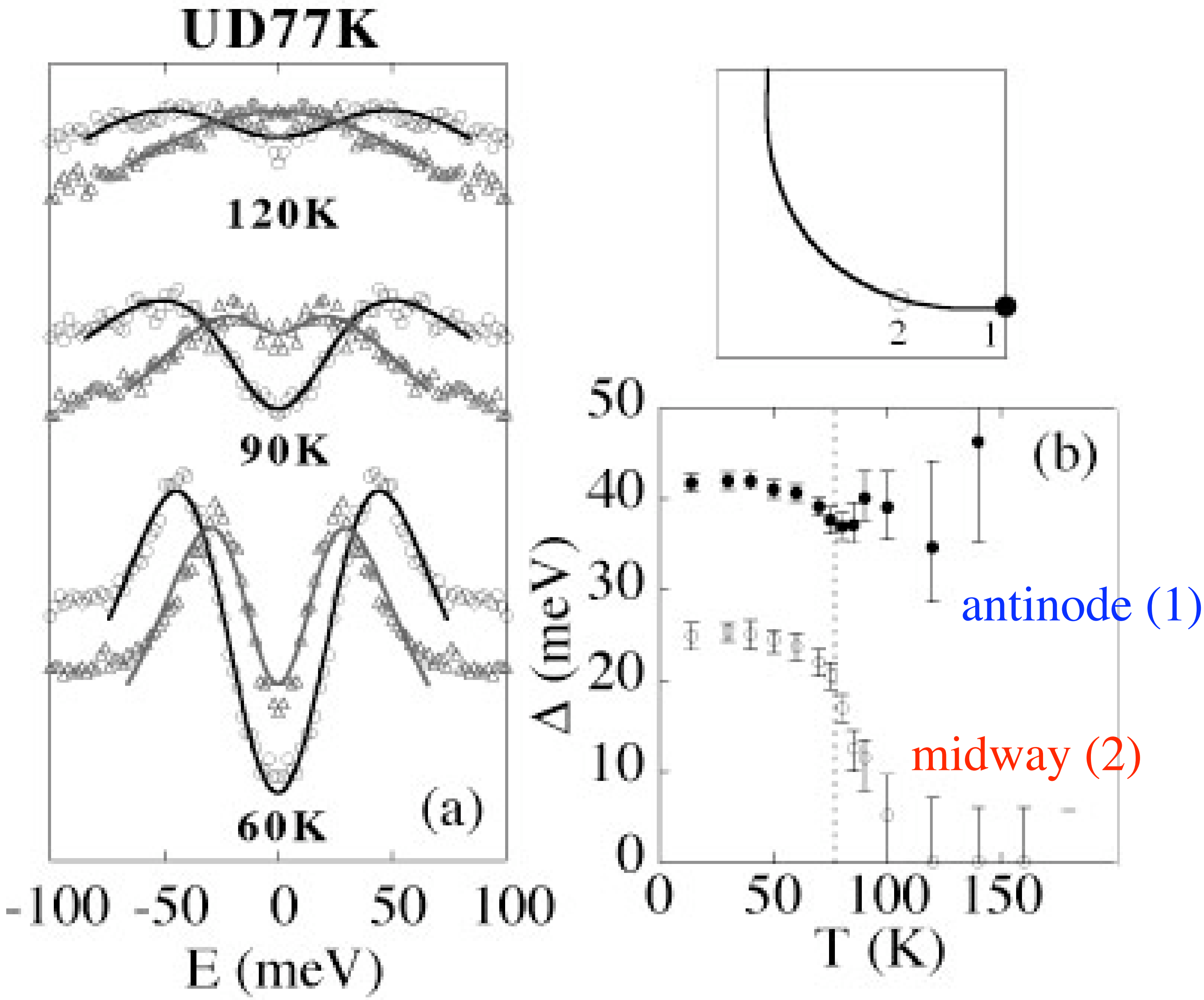


$$\Sigma = -i\Gamma_1 + \Delta^2/(\omega+i\Gamma_0)$$

Norman *et al*., PRB 57, 11093 (1998)



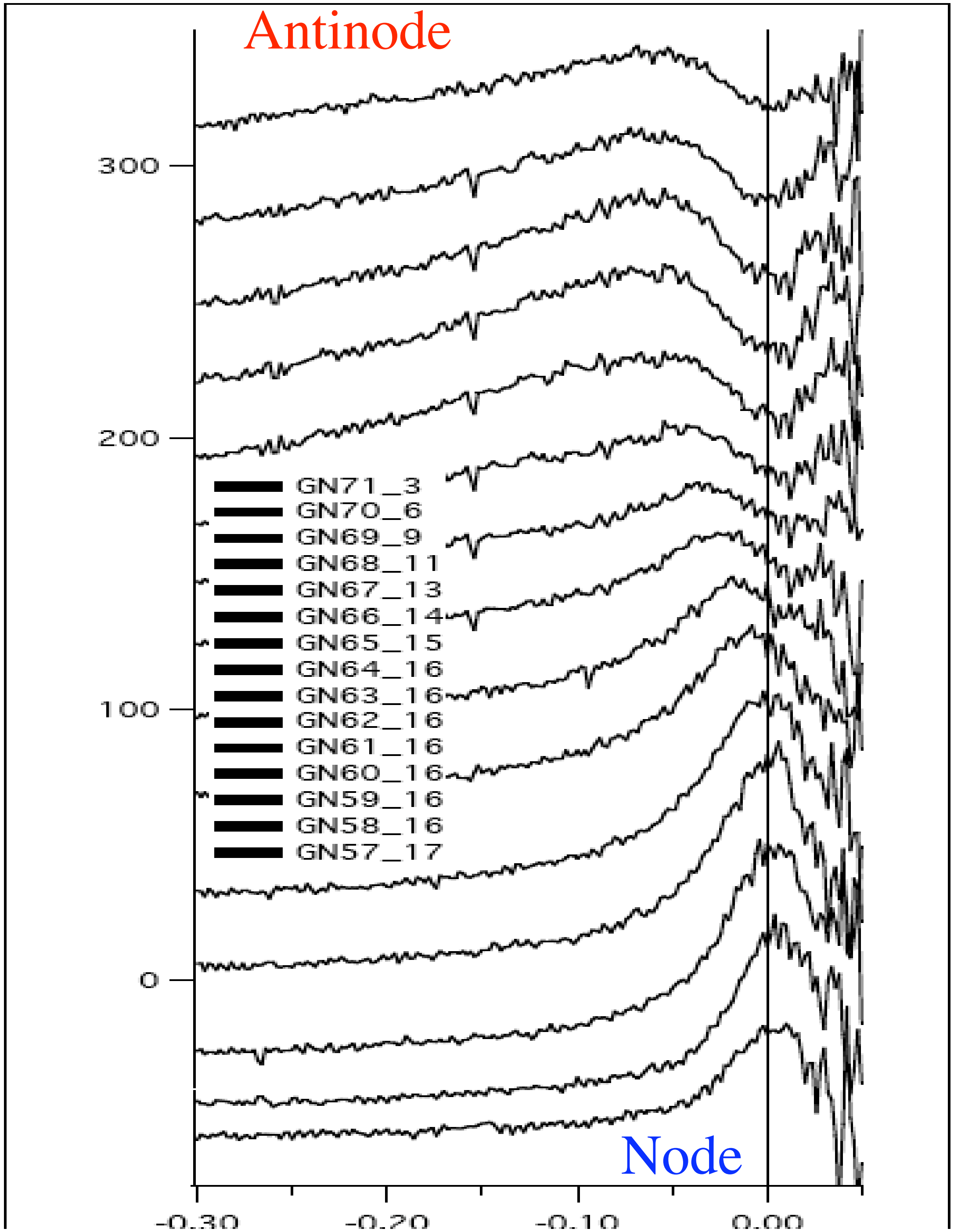
OD82K
UD83K
(a)
(b)
100
80
60
40
20
0
200
150
100
50
0
50
100
150
200
T (K)
T(K)
(meV)
Γ_1
Δ
Γ_1
Δ
Γ_0



UD77K
120K
90K
60K
(a)
-100 -50 0 50 100
E (meV)
2
1
50
40
30
20
10
0
Δ (meV)
(b)
antinode (1)
midway (2)
0 50 100 150
T (K)

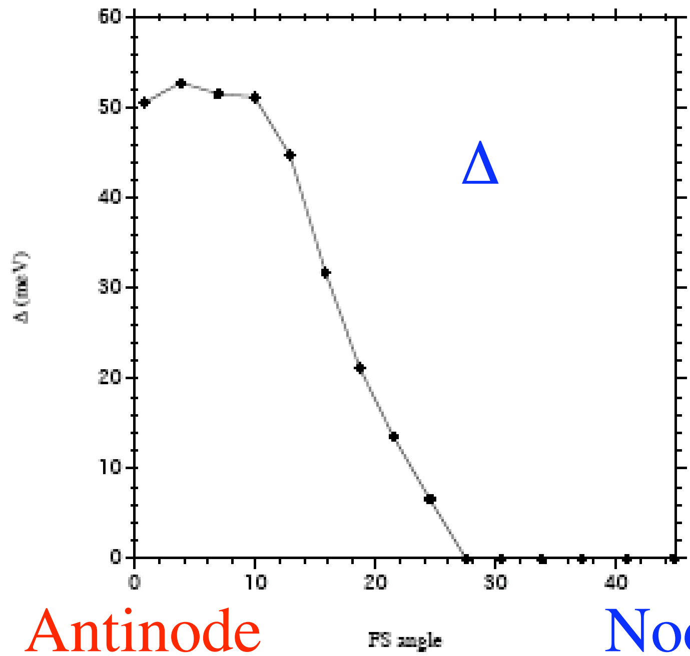
Bi2212
OP90K
T=140K

Fermi function
divided data

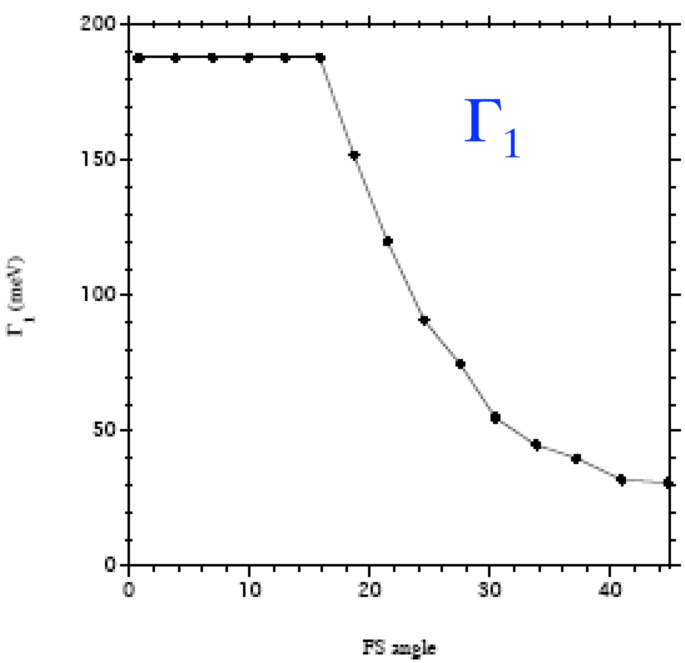


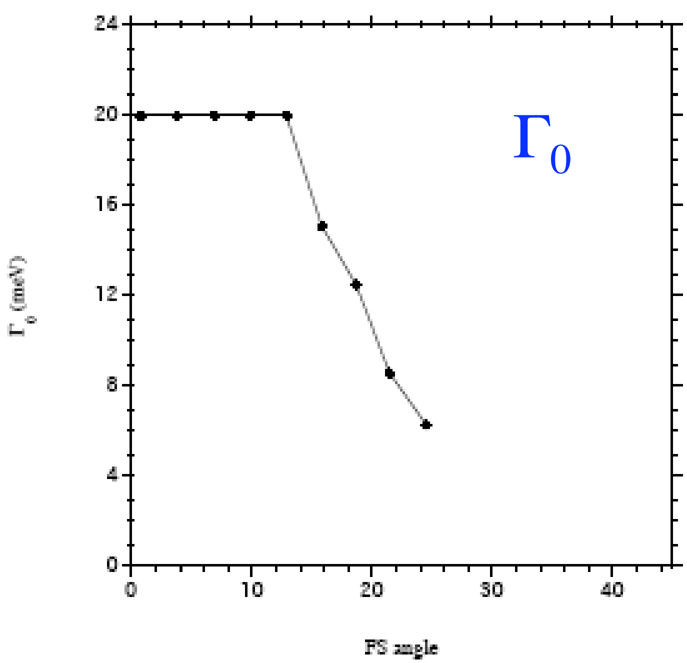
Bi2212 OP90K
T=140K vs
Fermi surface angle

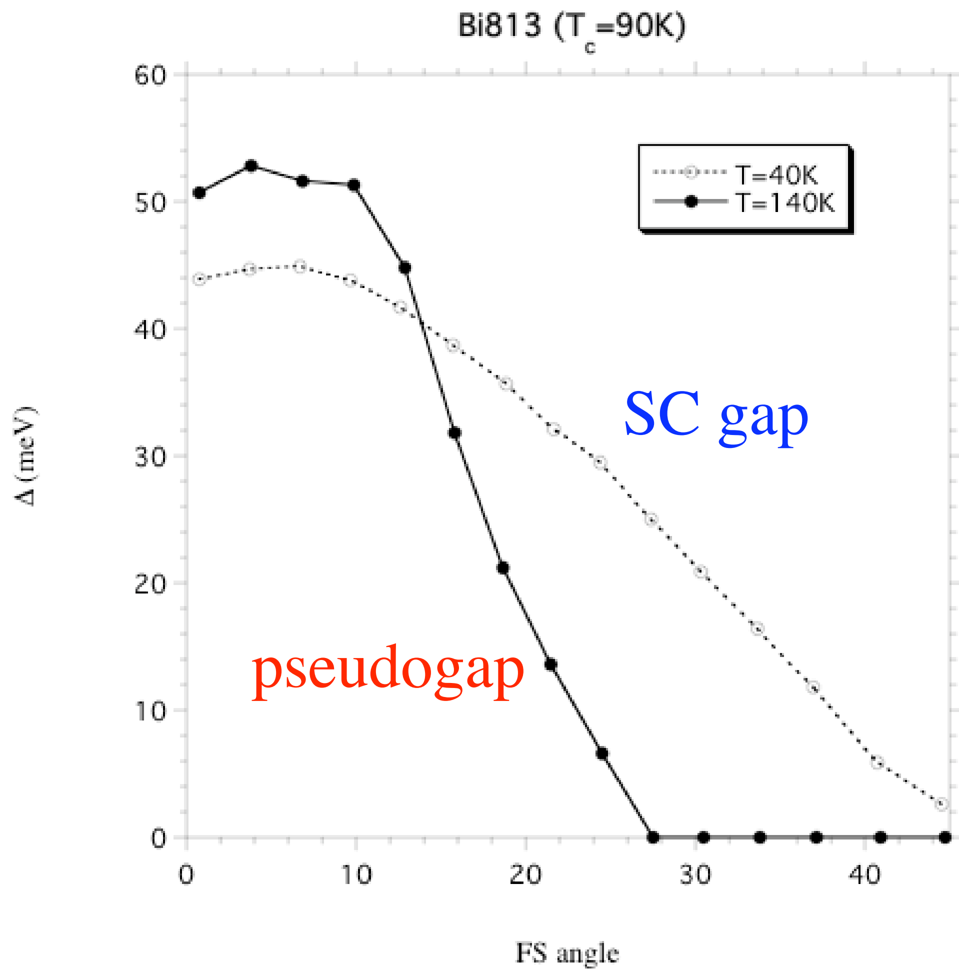
$\Sigma = -i\Gamma_1 + \Delta^2/(\omega + i\Gamma_0)$



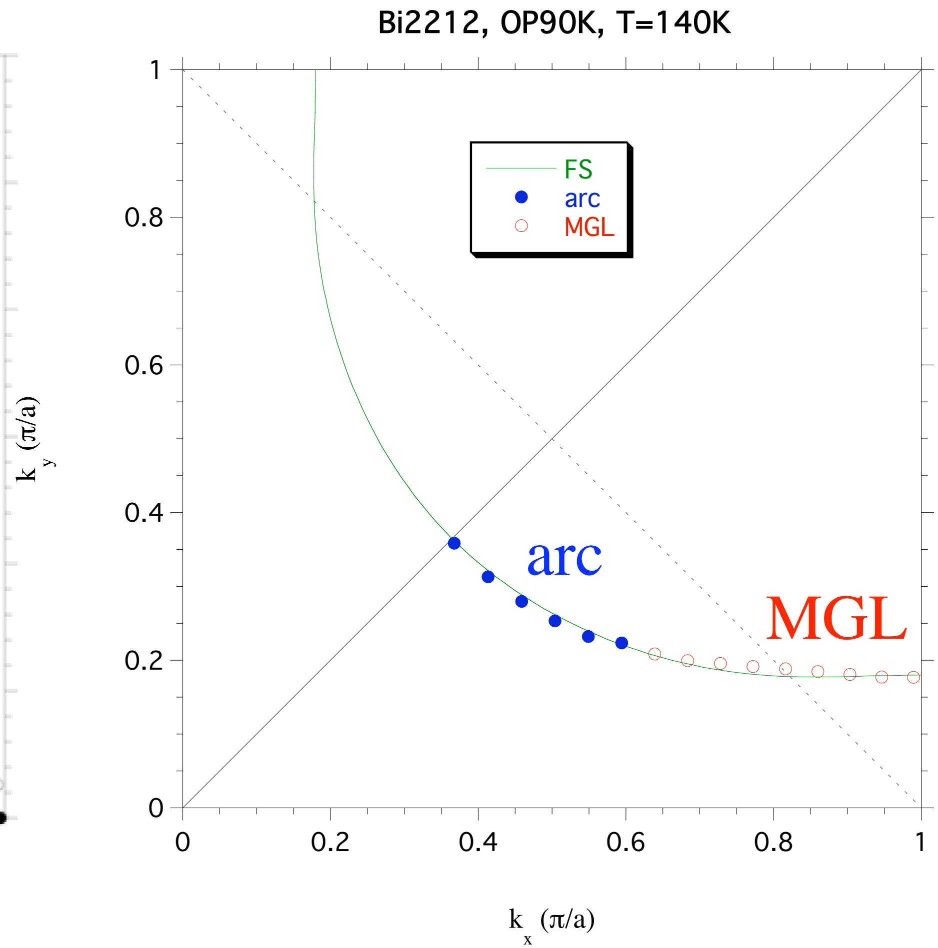
Antinode Node



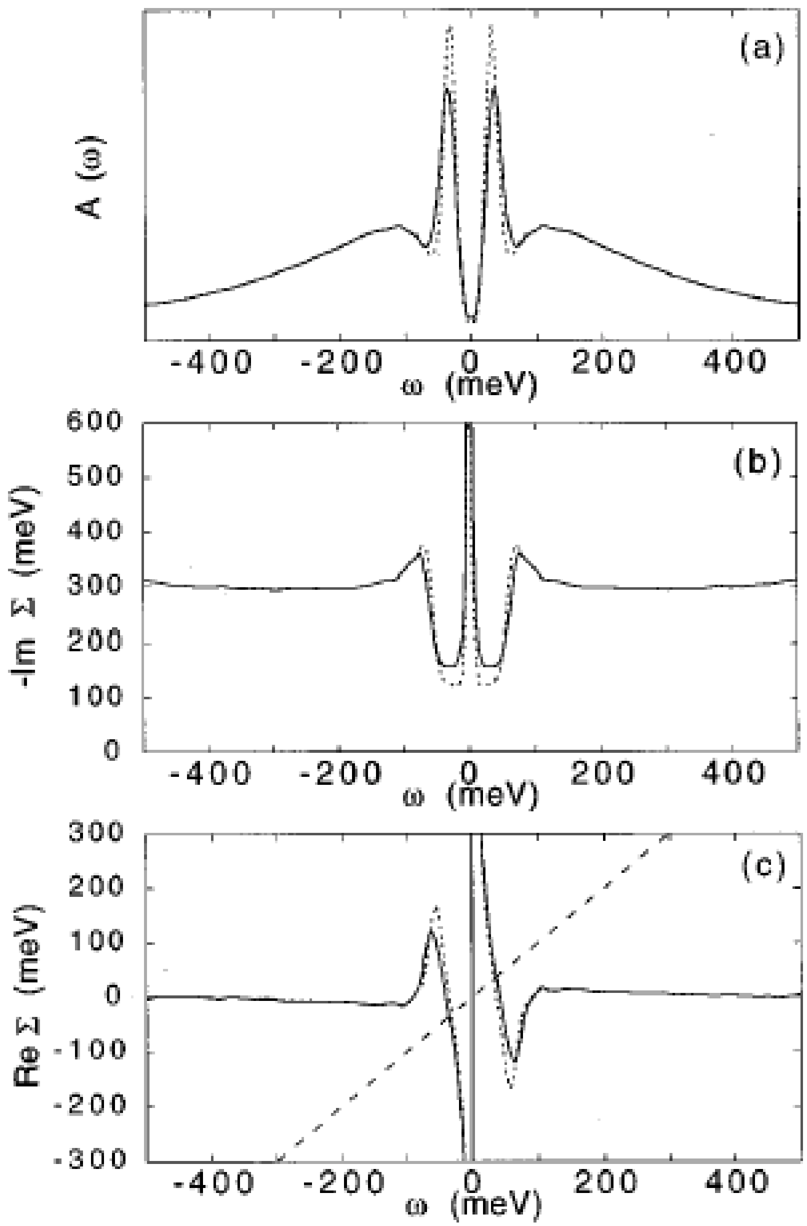




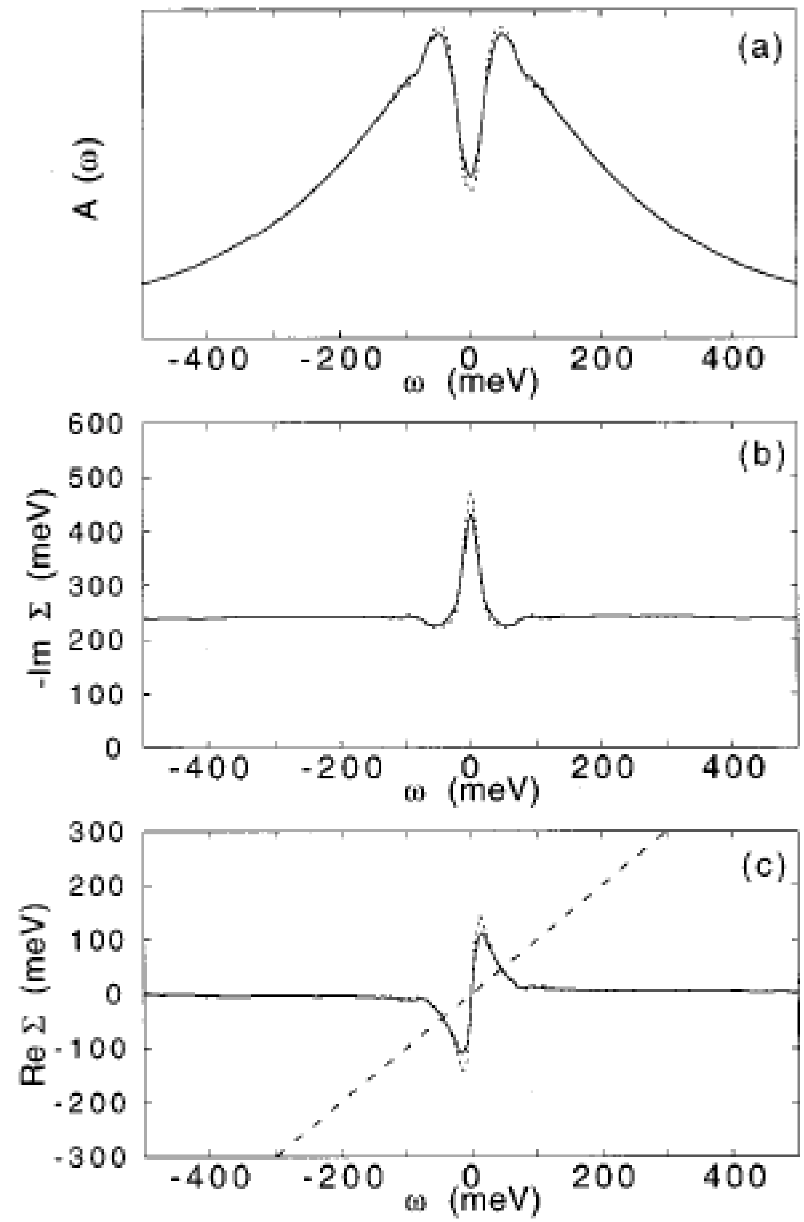
Bi813 (T_c=90K)
T=40K
T=140K
SC gap
pseudogap
Δ (meV)
FS angle



Bi2212, OP90K, T=140K
FS
arc
MGL
arc
MGL
k_y (π/a)
k_x (π/a)



Superconducting Σ at (π,0)

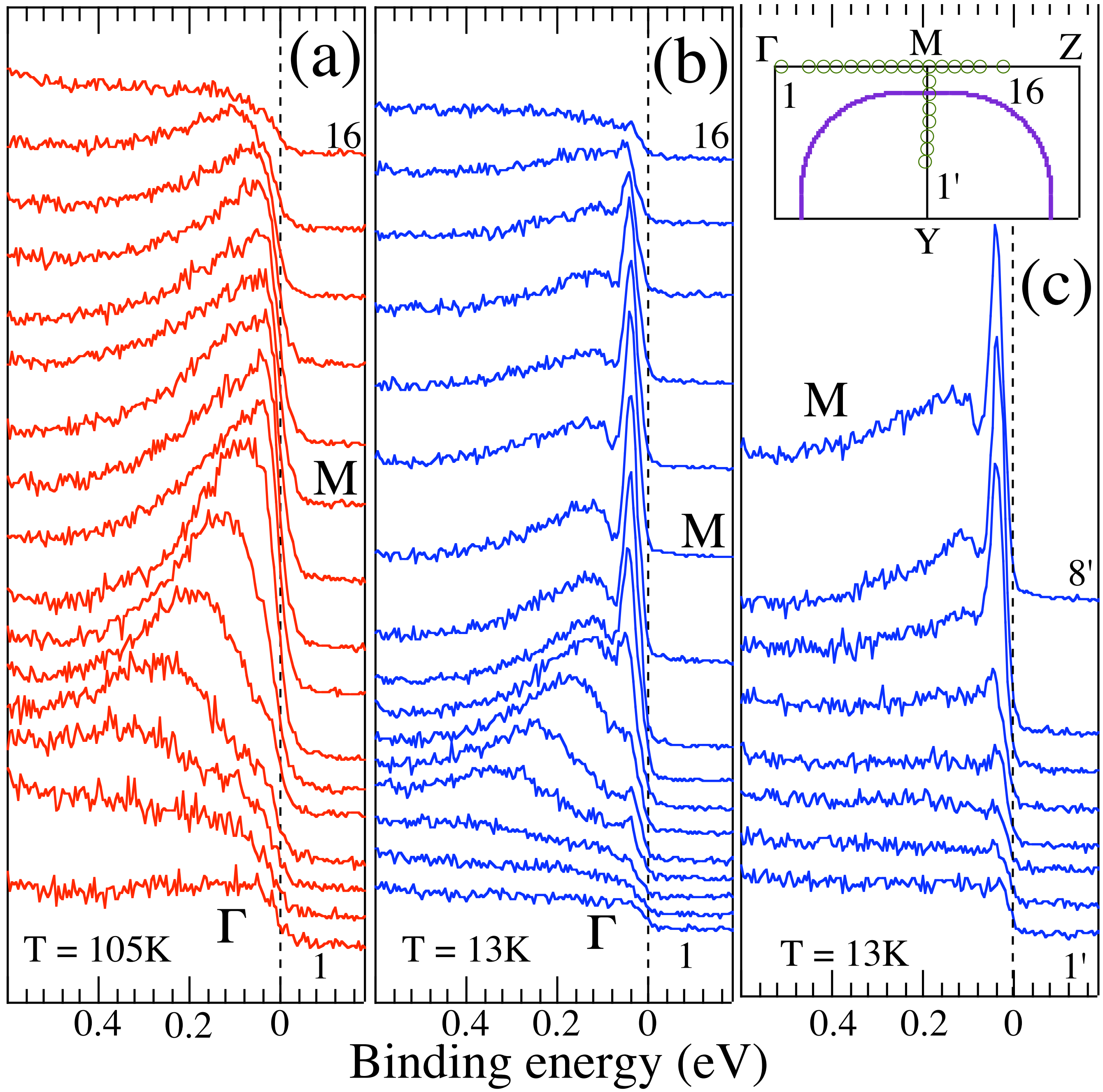


Pseudogap Σ at antinode

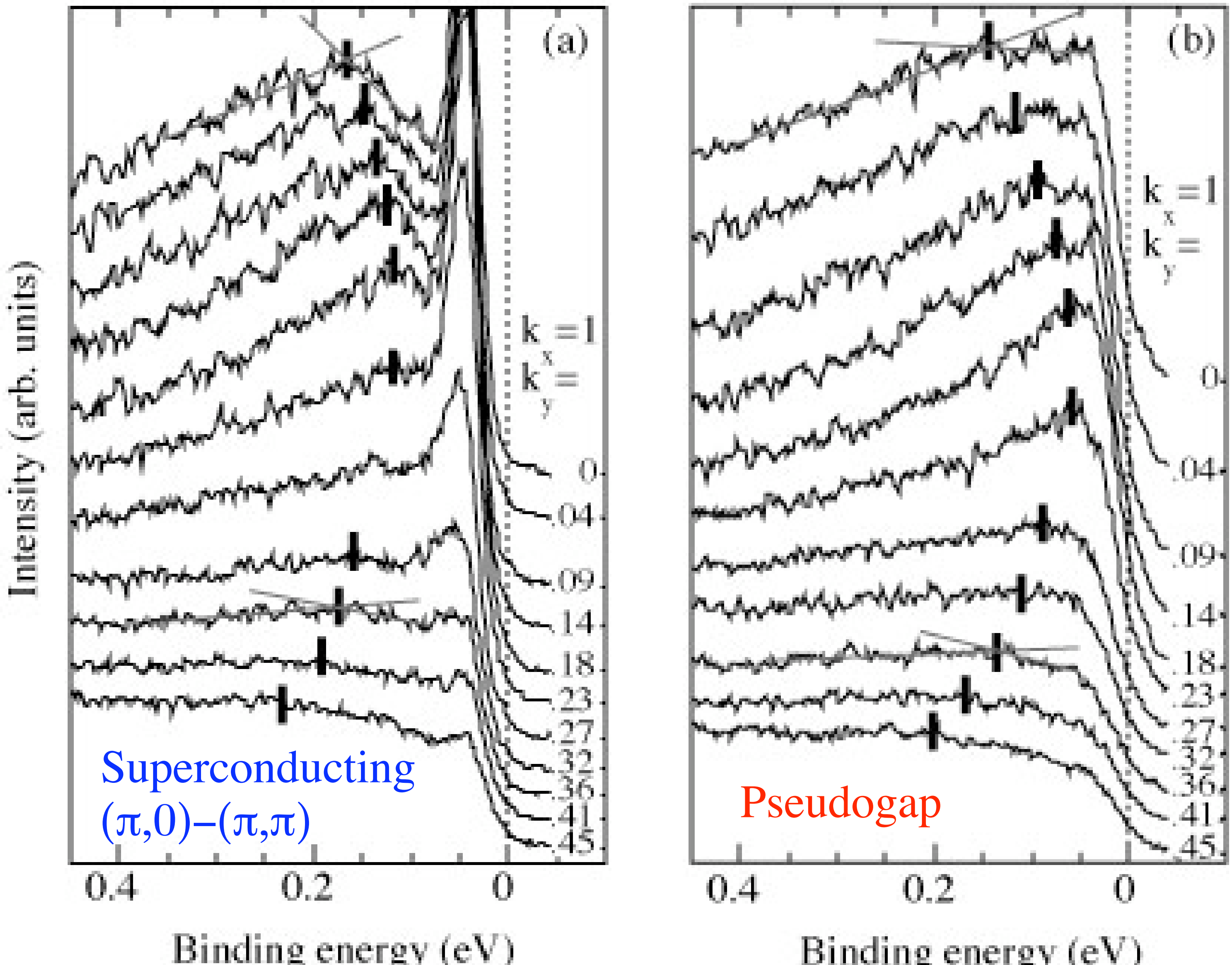
Norman *et al*., PRB 60, 7585 (1999)

Bi2212
OD87K

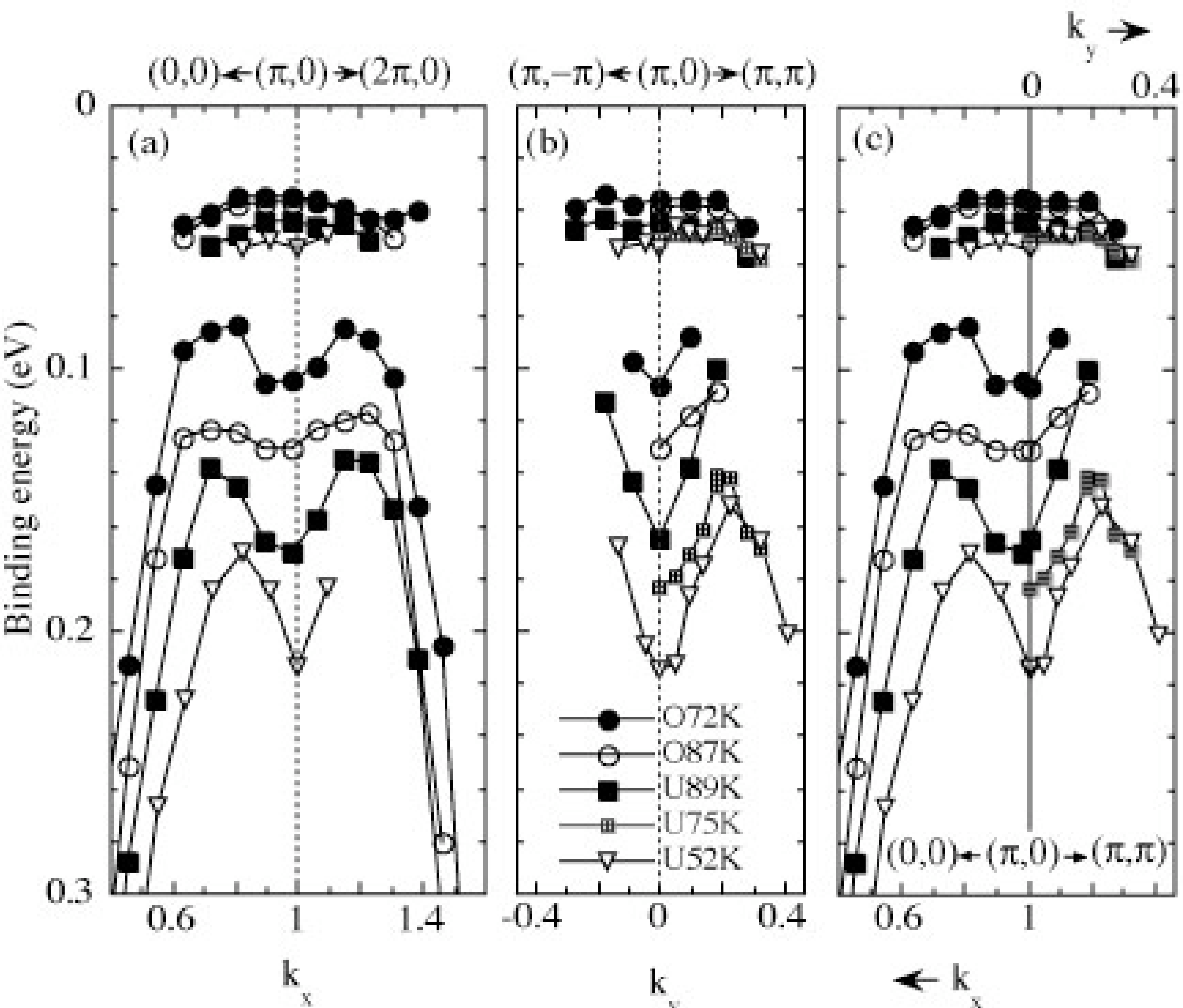
Norman *et al.*
PRL 79, 3506
(1997)



Spectra as a function of **k** above T_c (red) and below T_c (blue)

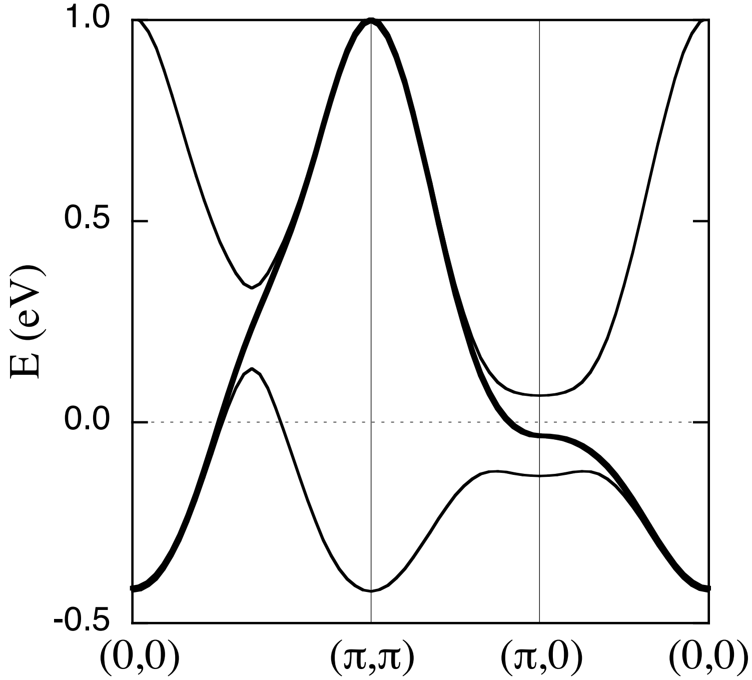


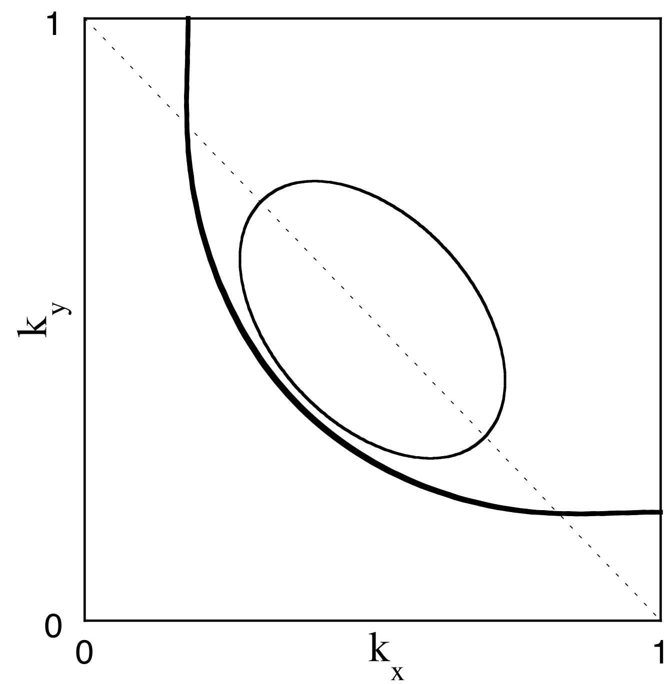
Campuzano *et al*., PRL 83, 3709 (1999)

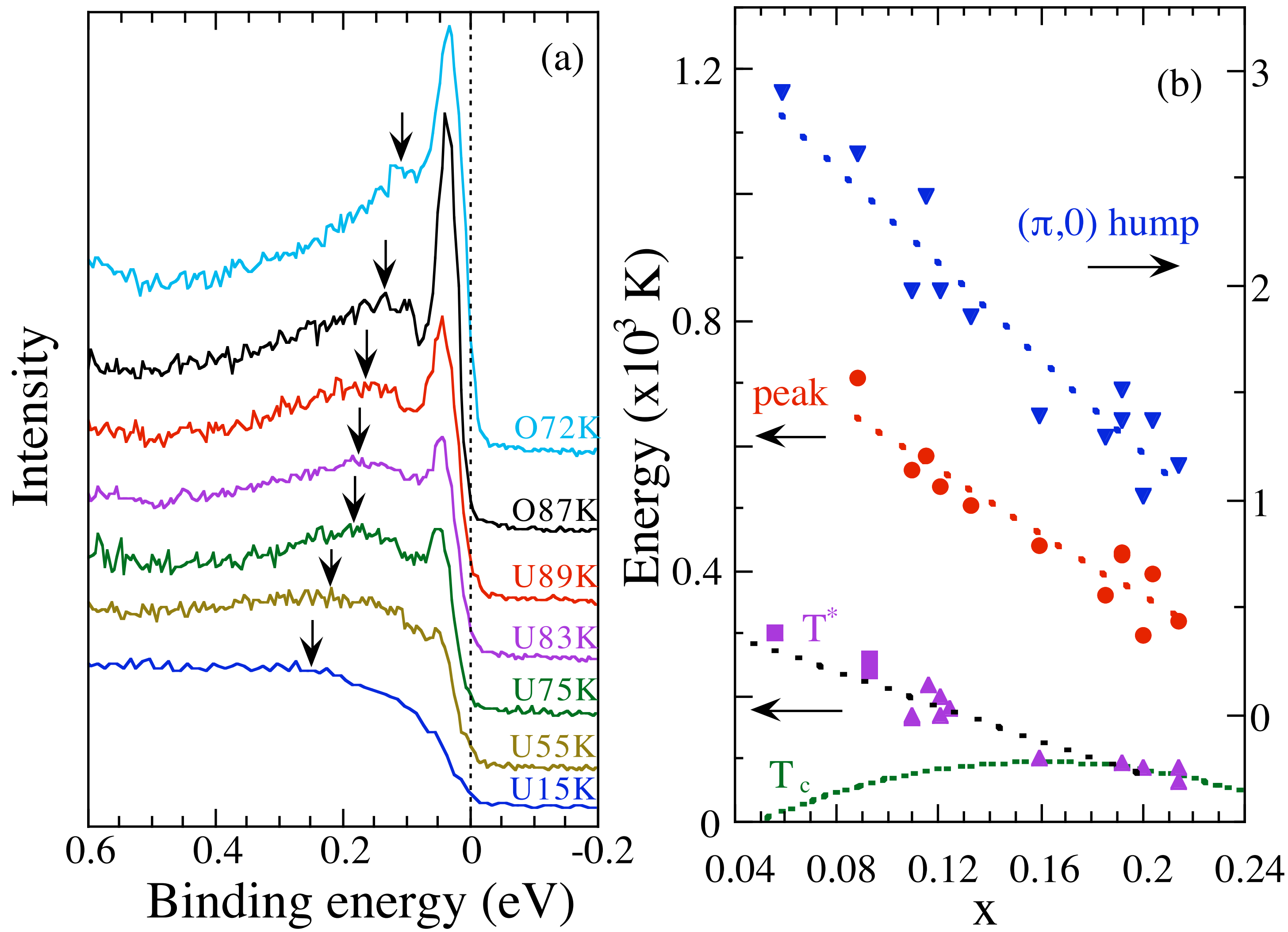


(0,0)←(π,0)→(2π,0)
(π,−π)←(π,0)→(π,π)
k_y →
0
0.4
(a)
(b)
(c)
Binding energy (eV)
0
0.1
0.2
0.3
0.6
1
1.4
-0.4
0
0.4
0.6
1
O72K
O87K
U89K
U75K
U52K
(0,0)←(π,0)→(π,π)
k_x
k_y
← k_x

Hump dispersion is reminiscent of an SDW dispersion with Q=(π,π)

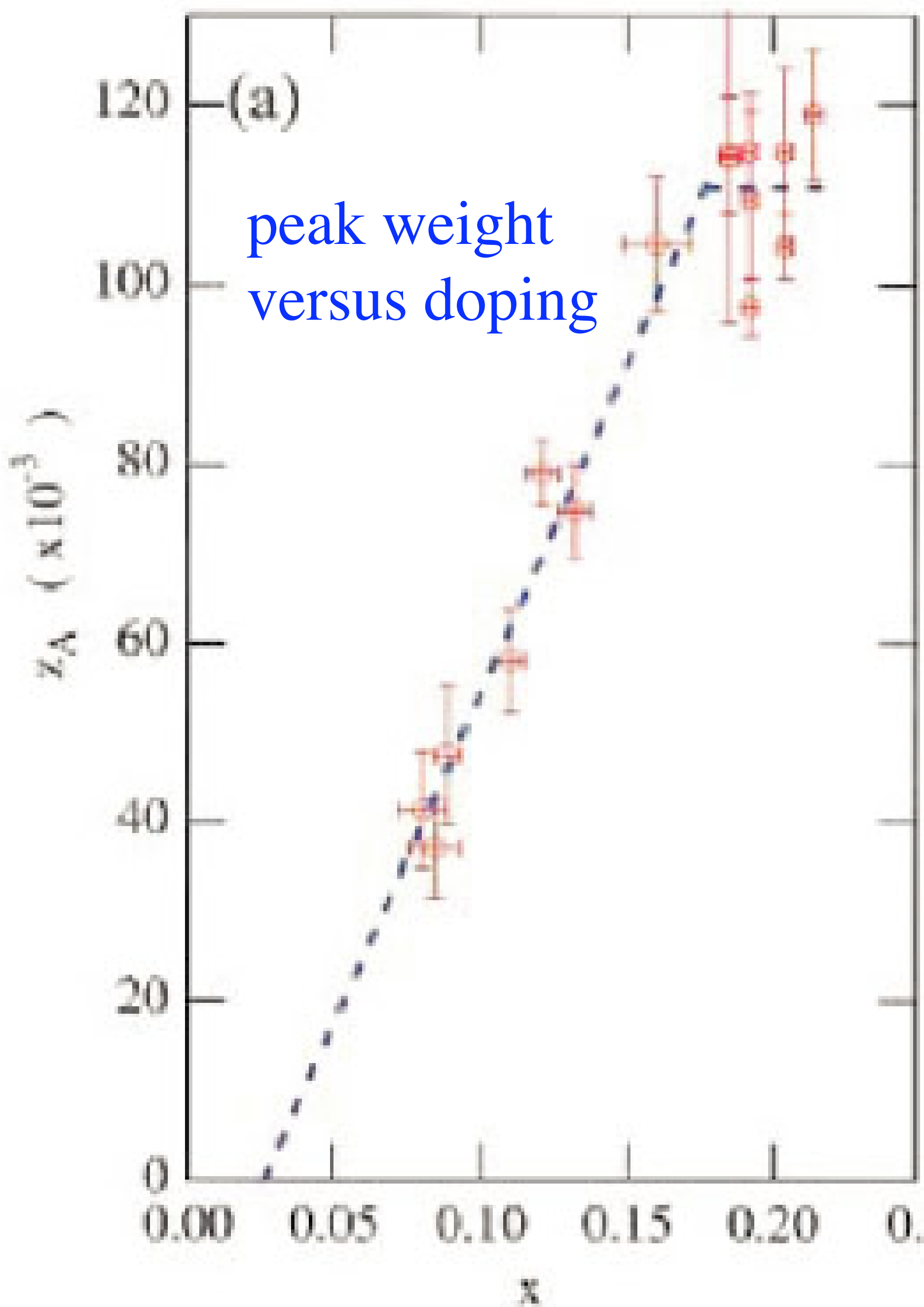




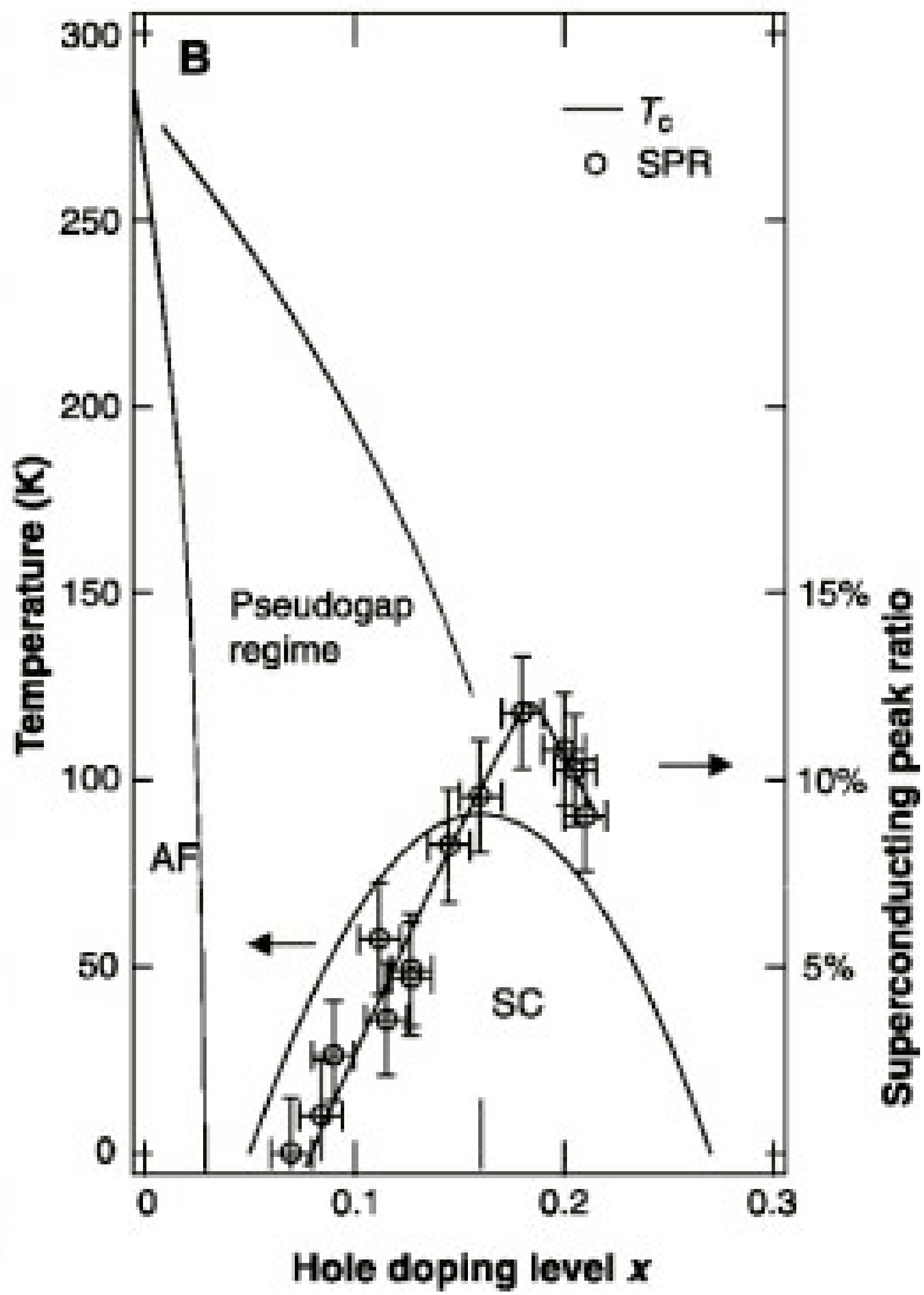


Left - (π,0) spectra versus doping (arrow marks the hump)

Right - Energy scales (peak, hump, T*, T_c) versus doping

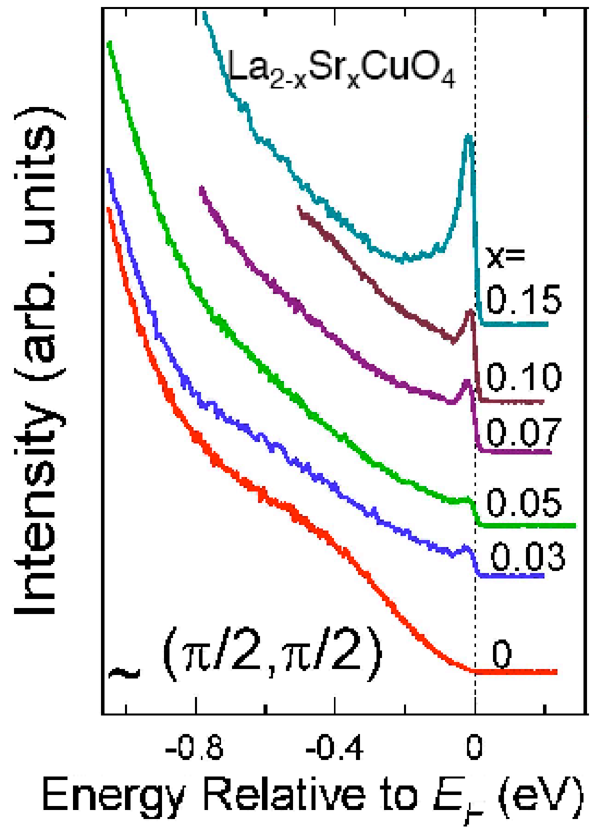


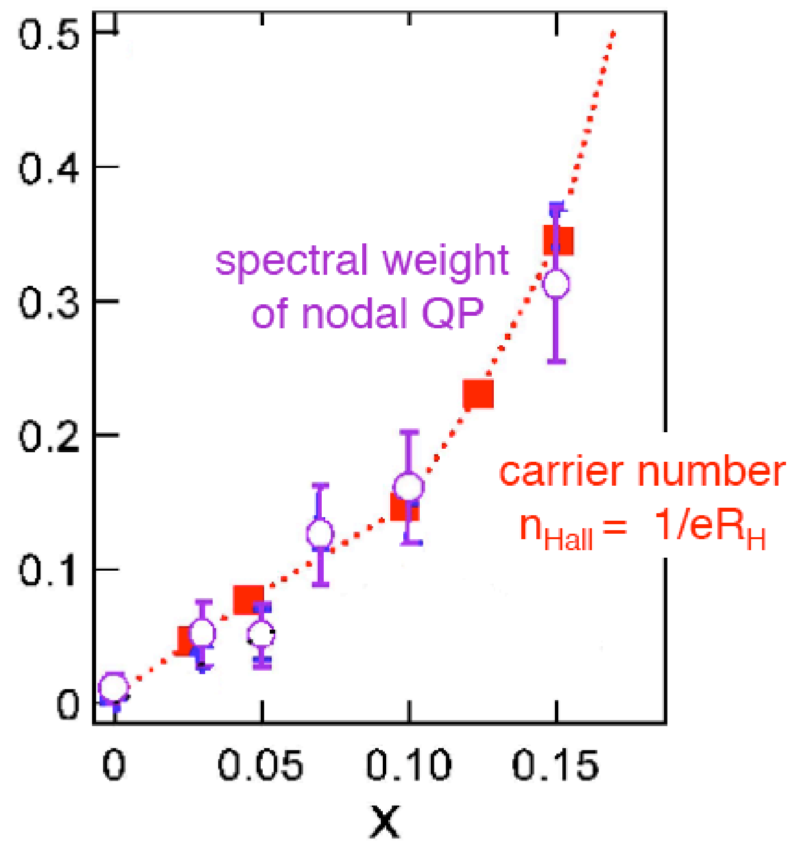
Ding *et al.*, PRL 87, 227001 (2001)



Feng *et al.*, Science 289, 277 (2000)

Spectral weight of nodal quasi-particle ≈ Carrier number ?

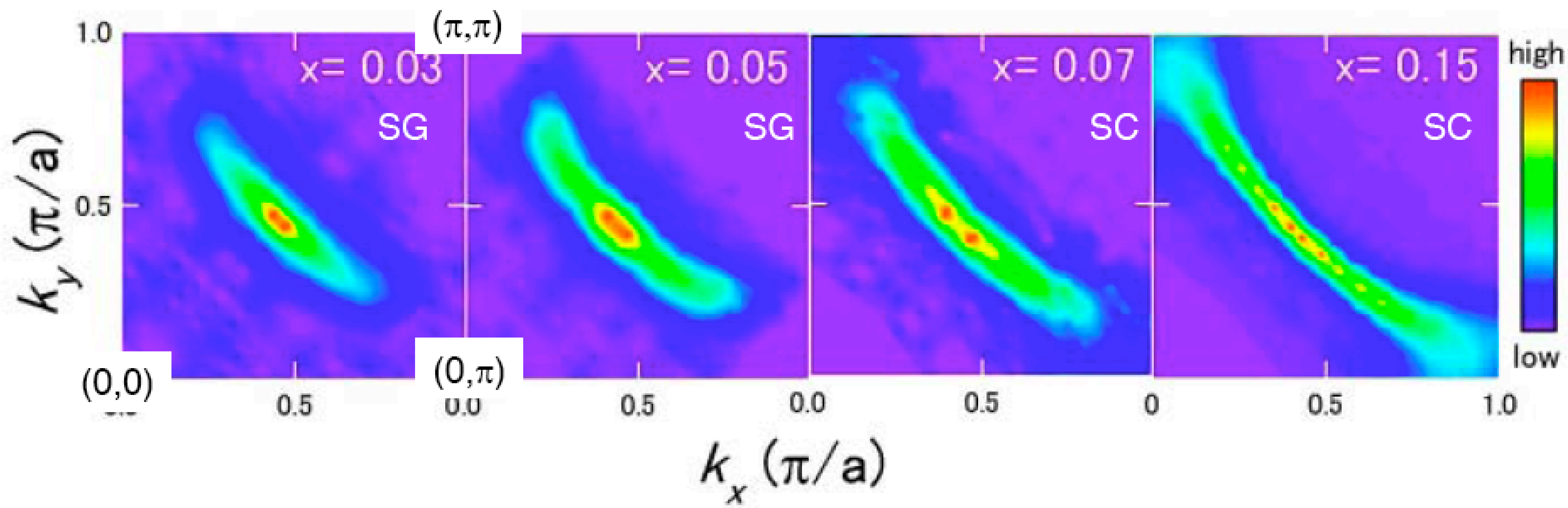




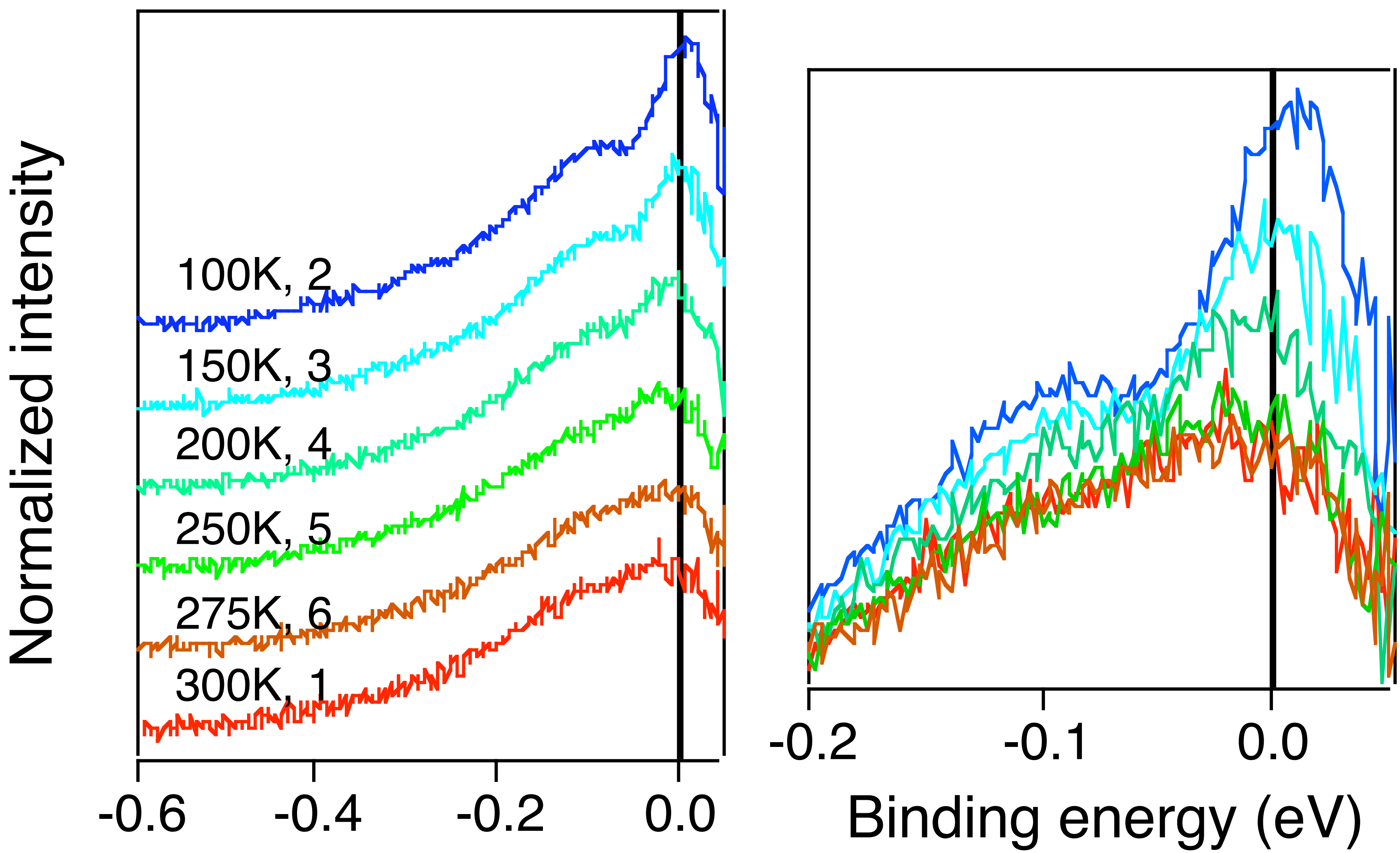
Fujimori - Rio talk - 2003
http://wyvern.phys.s.u-tokyo.ac.jp

Yoshida *et al.*, PRL 91, 027001 (2003)

Fermi "arc" in lightly-doped $La_{2-x}Sr_xCuO_4$

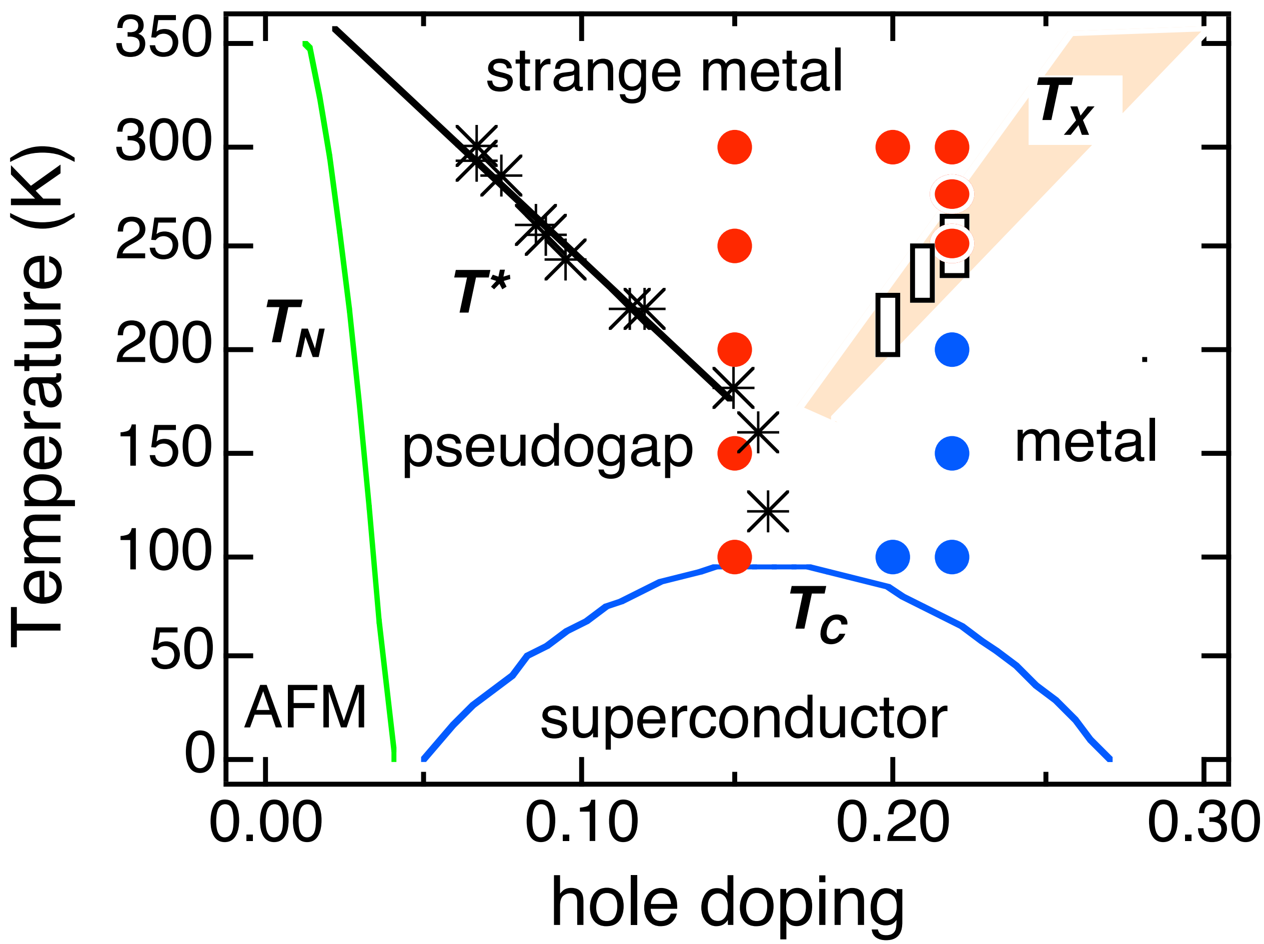


T. Yoshida, thesis, 2001

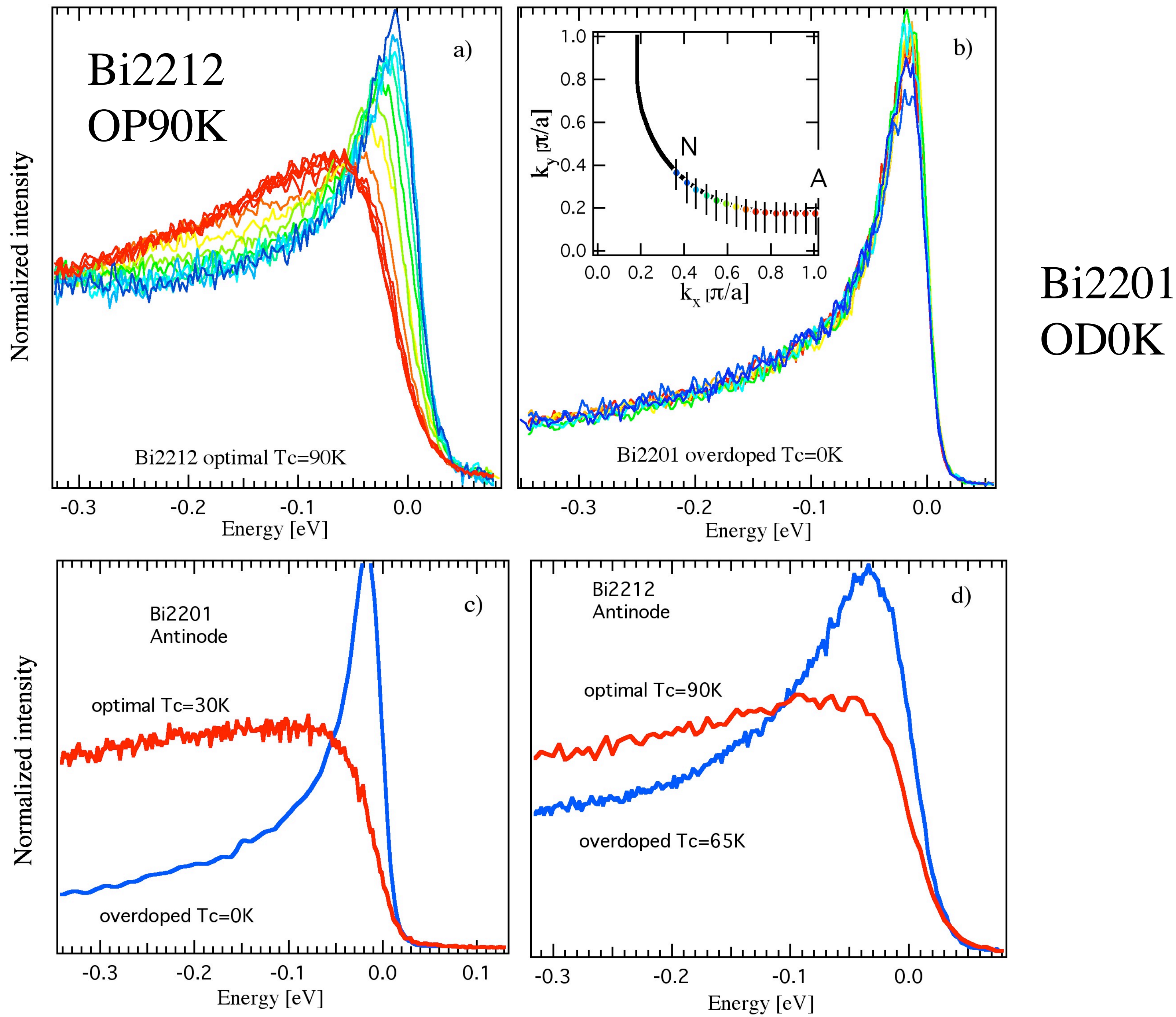


OD52K, T dependence at (π,0)

Kaminski *et al.*, PRL 90, 207003 (2003)

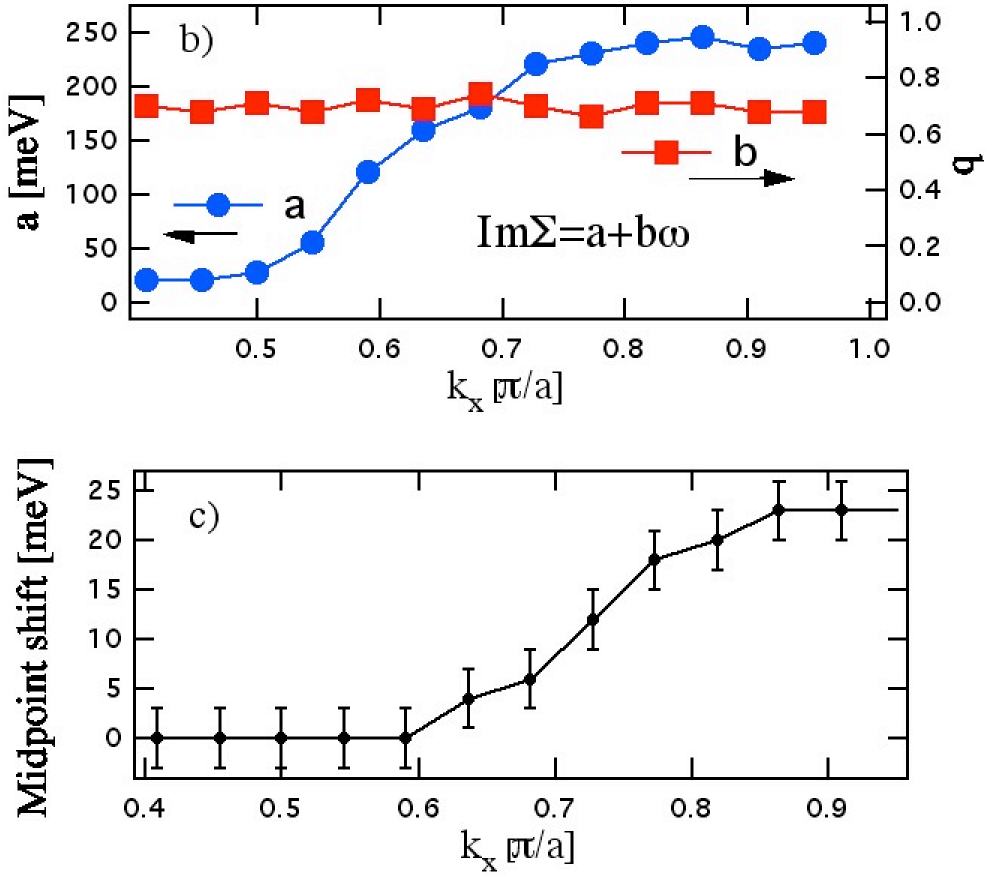


red dots, no bilayer coherence   blue dots, bilayer coherence



Bi2212
OP90K
a)
Bi2212 optimal Tc=90K
Normalized intensity
Energy [eV]
b)
Bi2201 overdoped Tc=0K
N
A
k_y [π/a]
k_x [π/a]
Energy [eV]
Bi2201
OD0K
c)
Bi2201
Antinode
optimal Tc=30K
overdoped Tc=0K
Normalized intensity
Energy [eV]
d)
Bi2212
Antinode
optimal Tc=90K
overdoped Tc=65K
Energy [eV]

$Im\Sigma = a_k + b\omega$, anisotropy of a_k follows that of the pseudogap

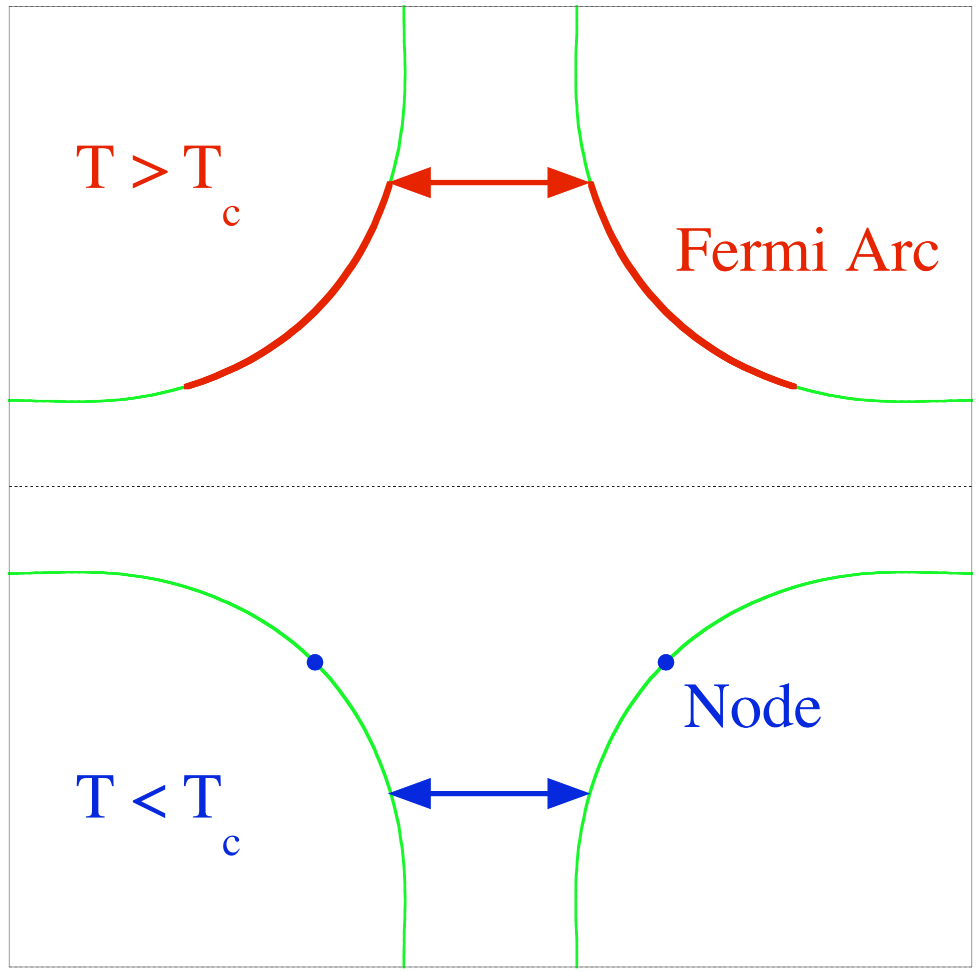


Node Antinode

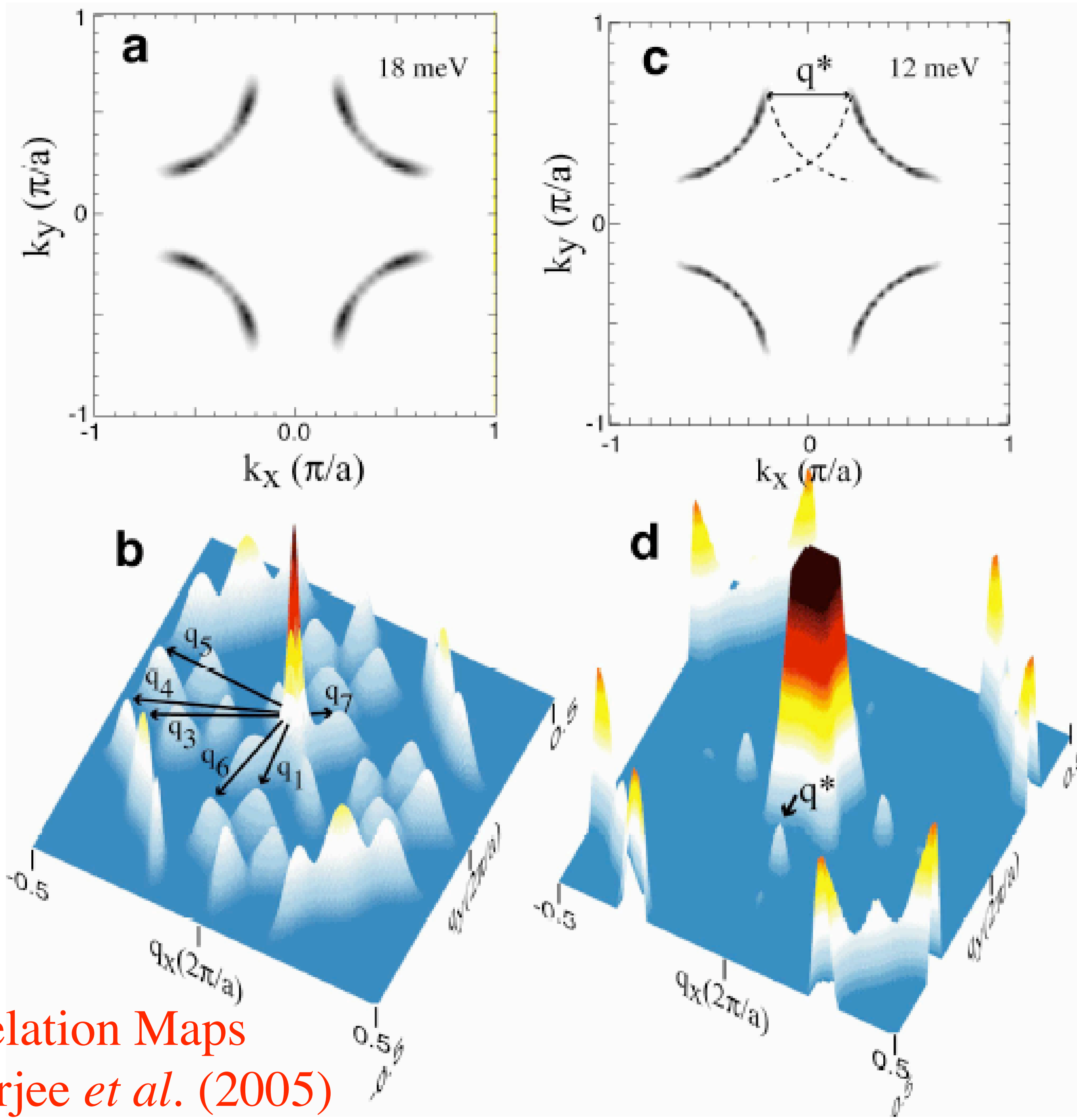
Kaminski *et al.*, Phys. Rev. B 71, 014517 (2005)

STM Fourier wavevector connects the tips of the Fermi arc

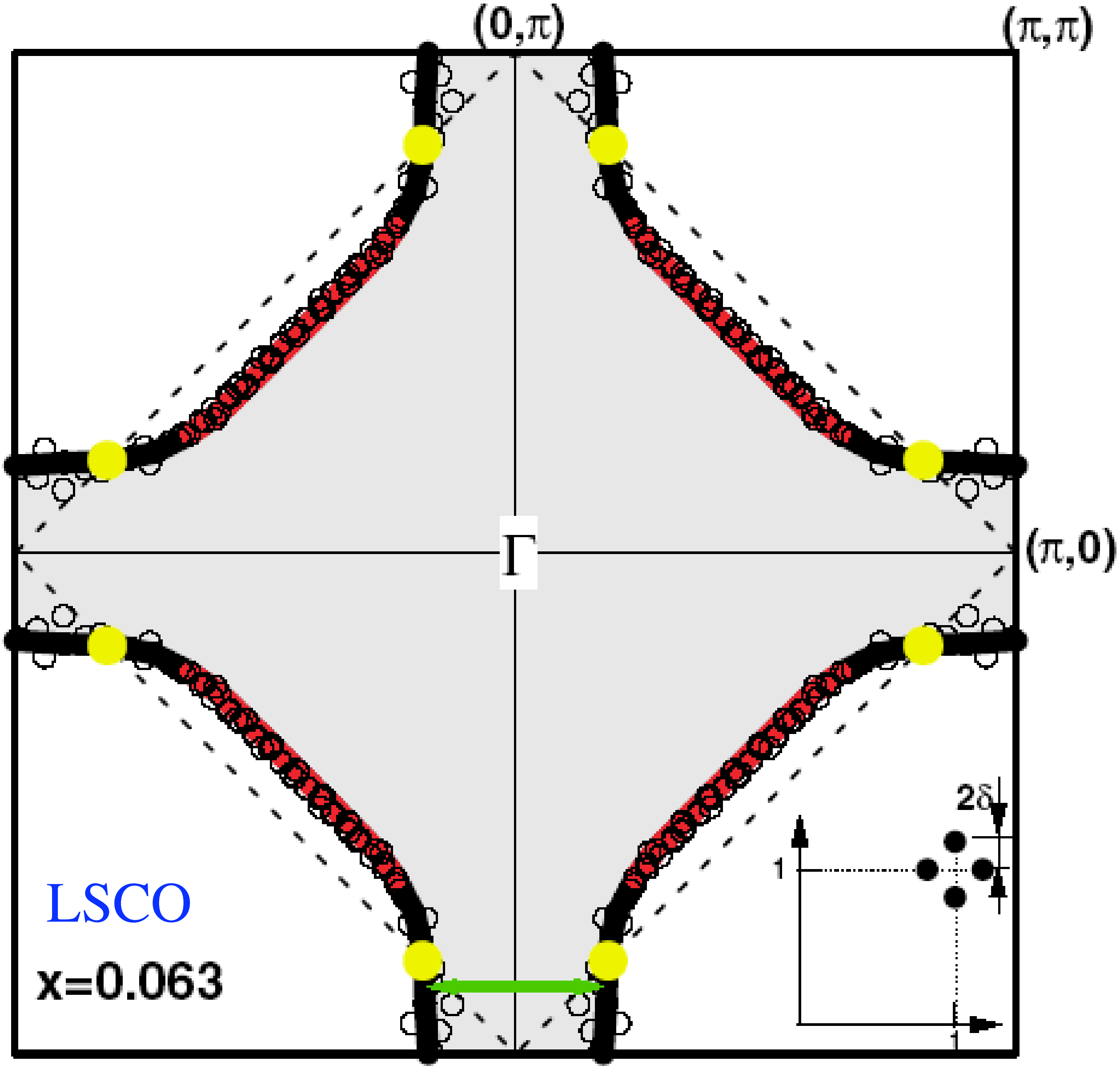
STM data - Vershinin *et al.*, Science 303, 1995 (2004)



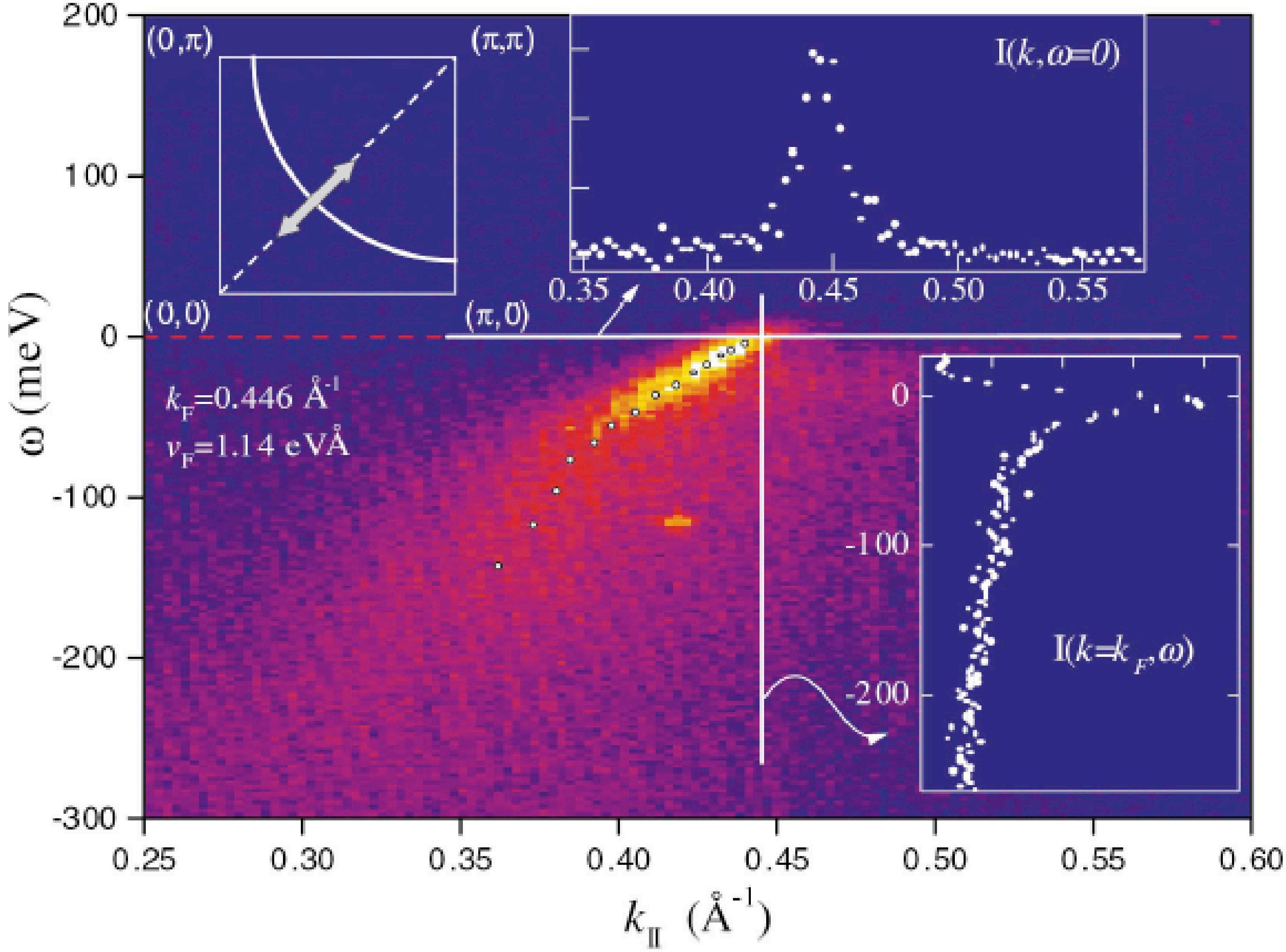
cartoon - Norman, Science 303, 1985 (2004)



Autocorrelation Maps
U. Chatterjee *et al*. (2005)

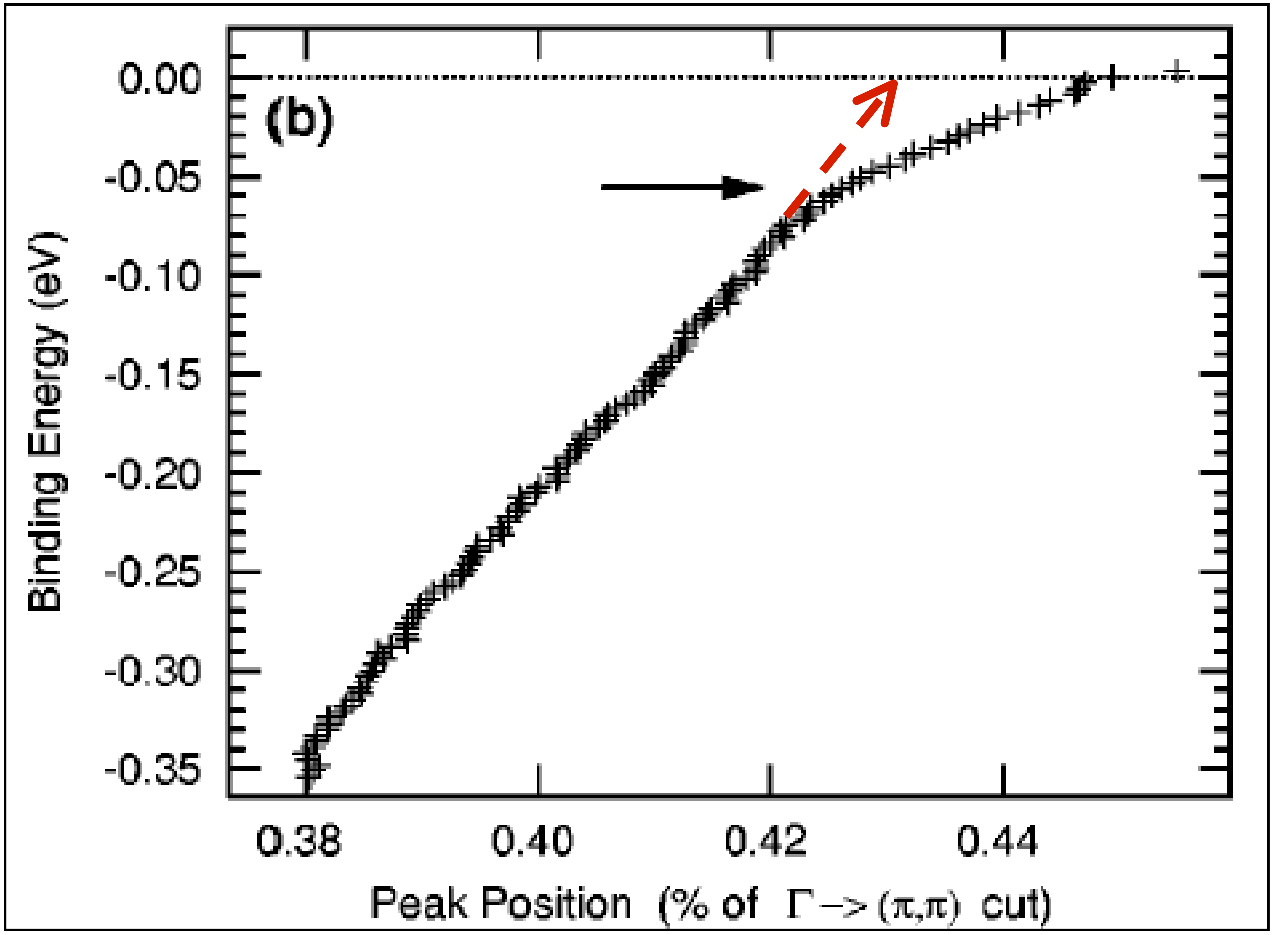


Zhou *et al*., PRL 92, 187001 (2004) --> nested Fermi surface



Valla *et al.*, Science 285, 2110 (1999)

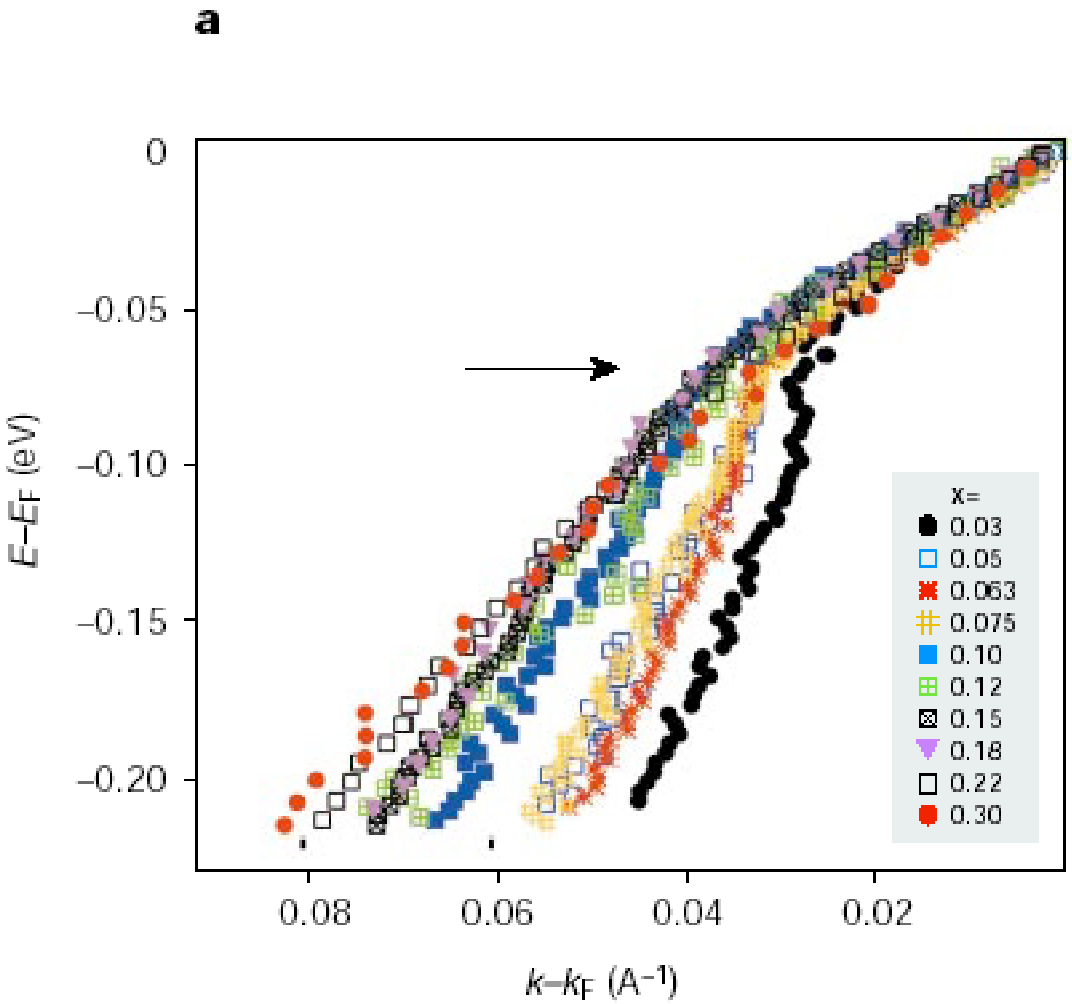
High Energy Dispersion Interpolates to $k < k_F$

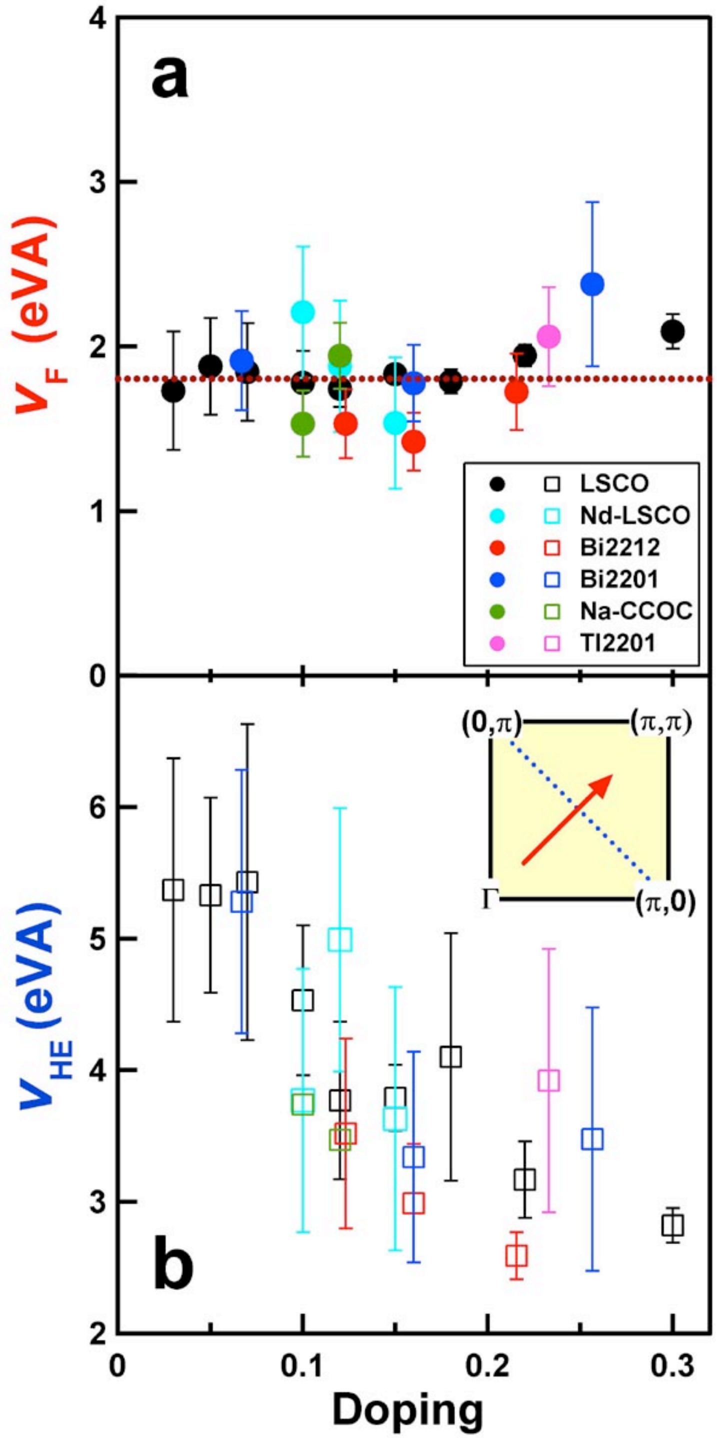


Ronning *et al.*, PRB 67, 165101 (2003)

Doping Independence of Low Energy Nodal Velocity

Zhou *et al.*, Nature 423, 398 (2003)

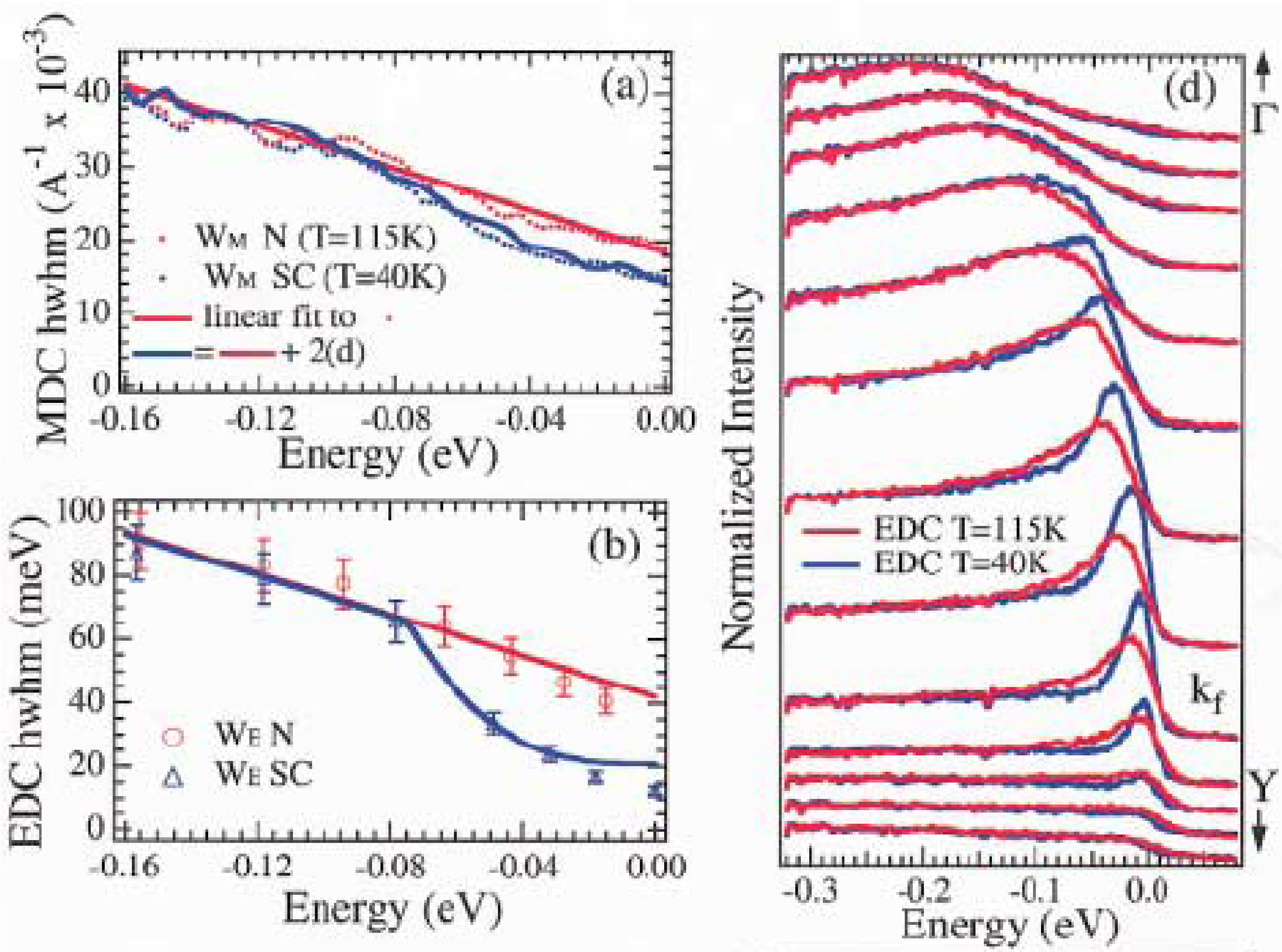




low energy v

high energy v

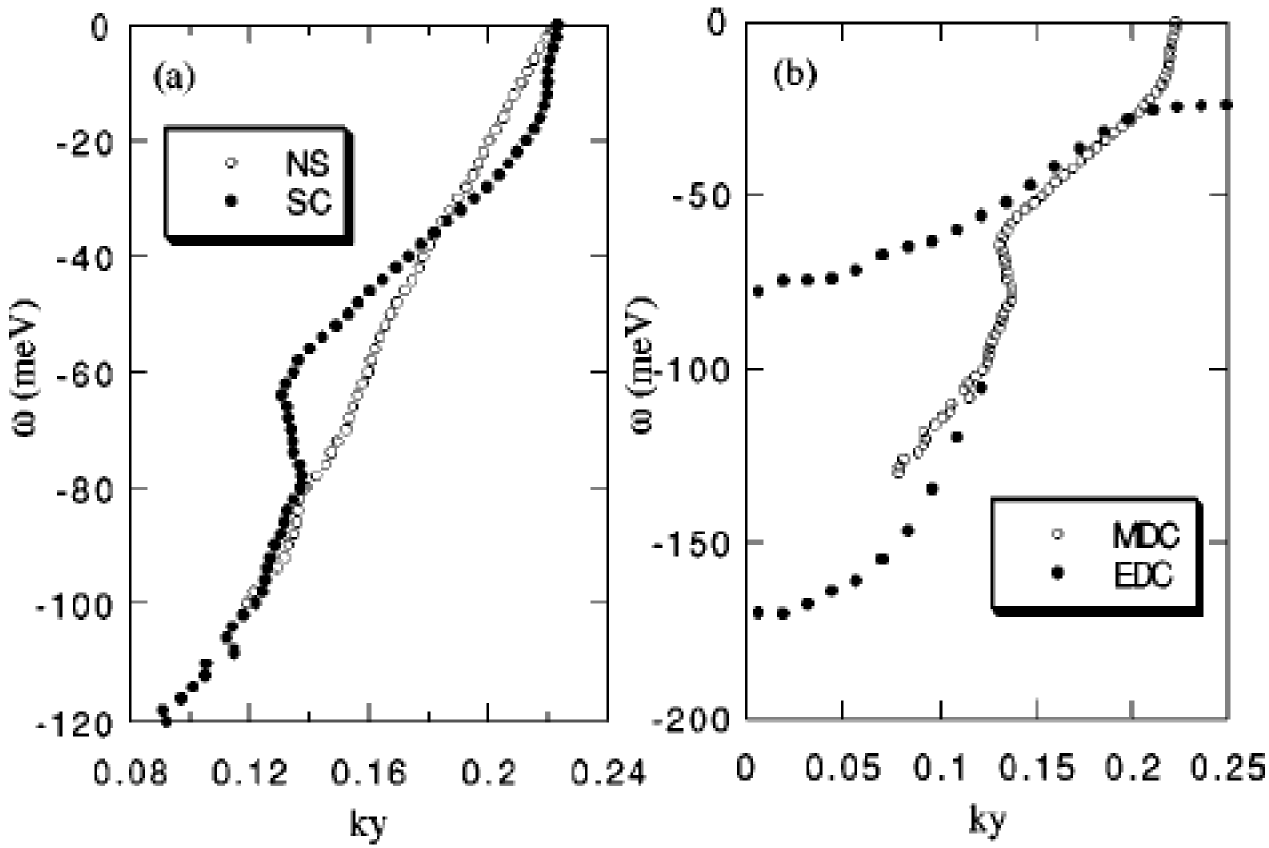
Kaminski *et al.*, PRL 86,1070 (2001) nodal direction MDC and EDC widths



Bi2212
OP90K

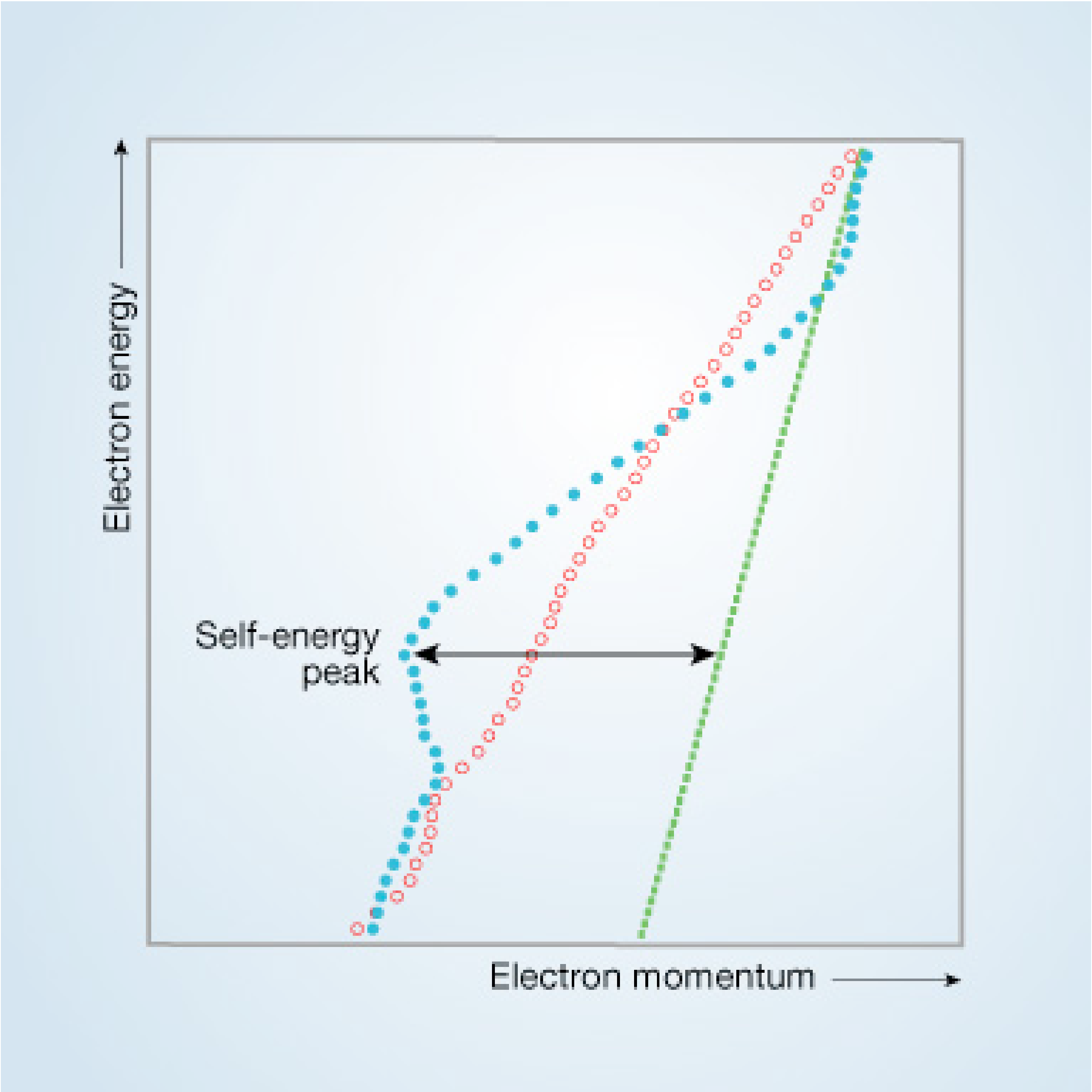
Norman *et al.*, PRB 64, 184508 (2001)

k midway between node and antinode

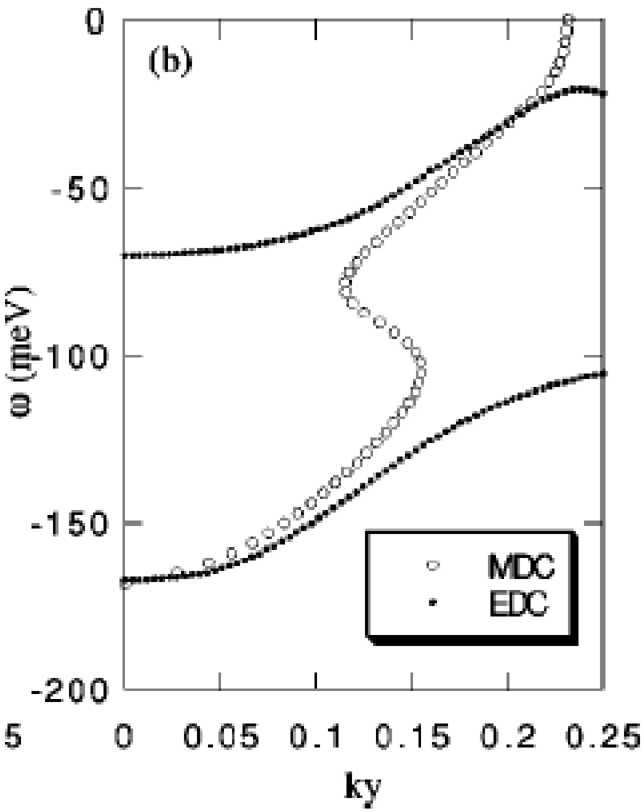


Superconducting MDC dispersion has an S shape (indicates "mode")

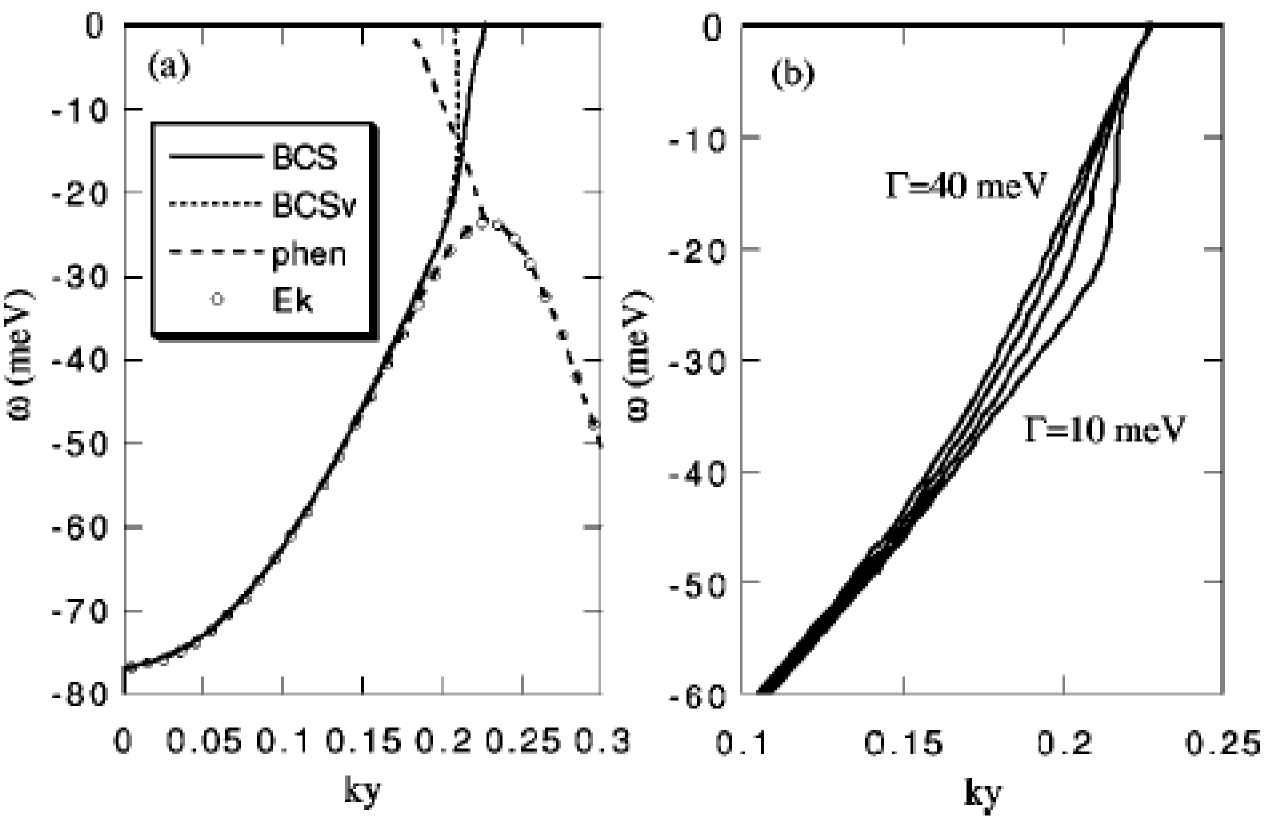
At low energies, MDC dispersion gets steep due to the energy gap



Norman, Nature 427, 692 (2004)   (green is “bare” dispersion)

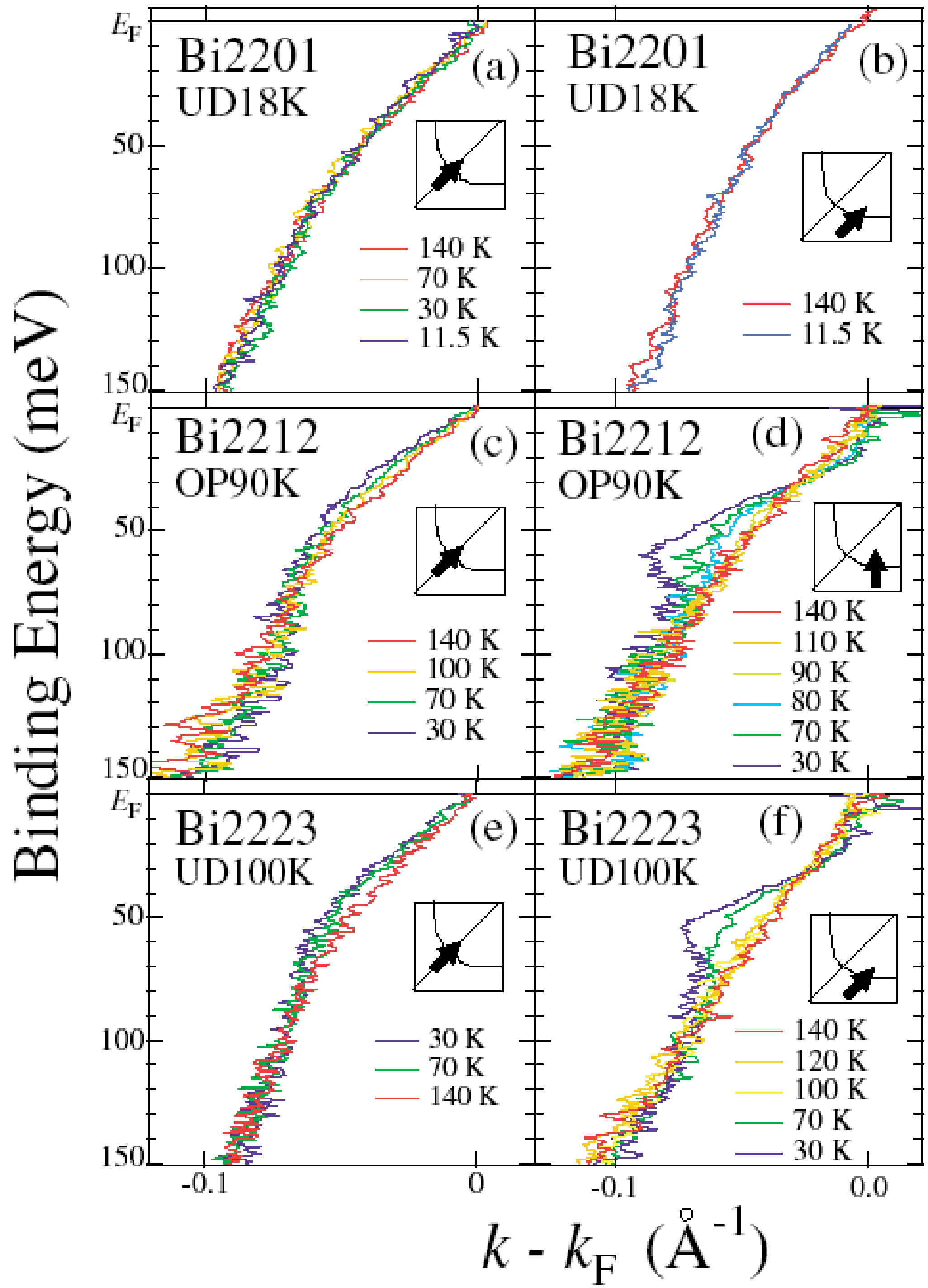


Mode model explains S
Eschrig & Norman
PRL 85, 3261 (2000)

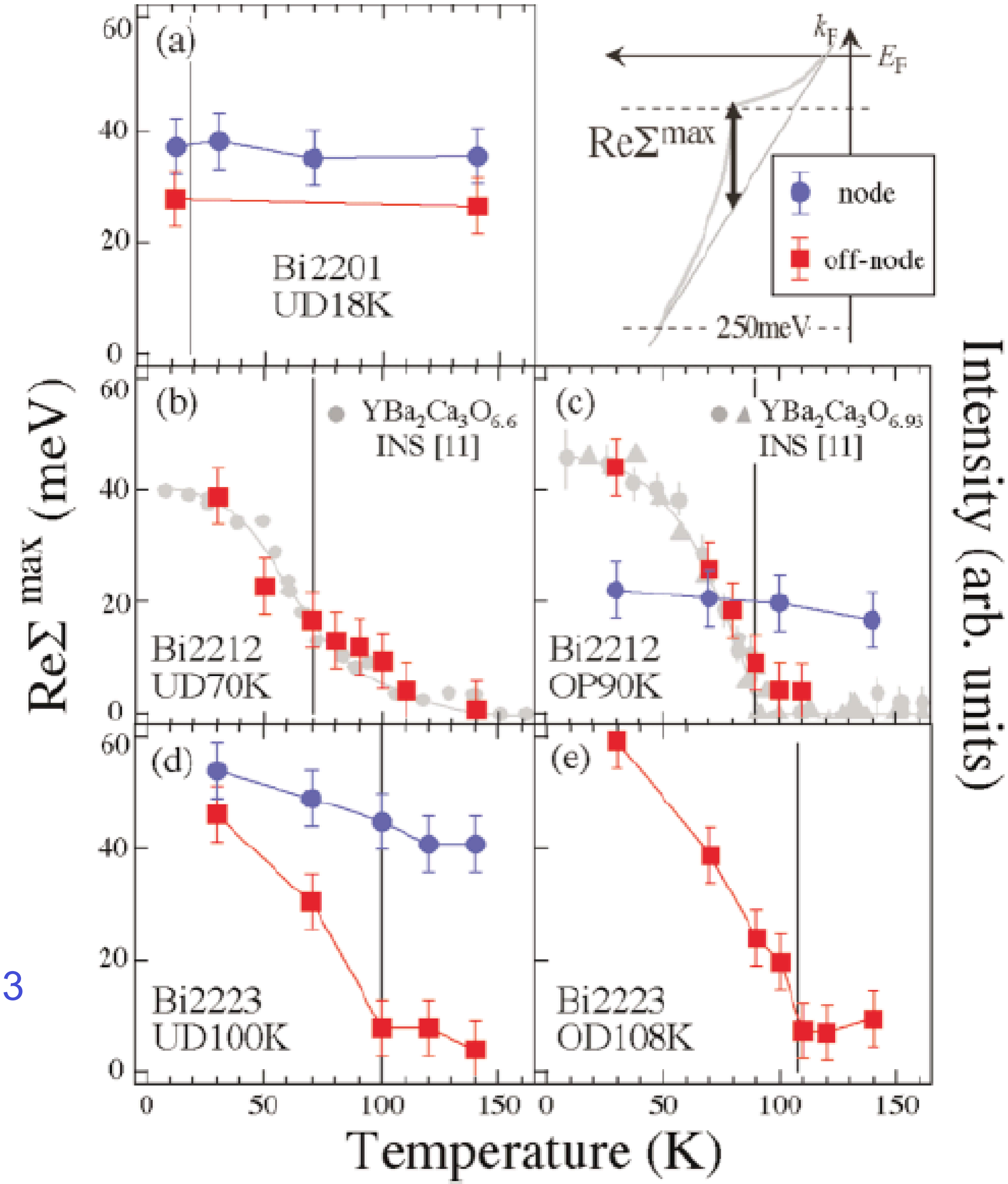


Broadened BCS theory
explains subgap dispersion

MDC dispersion versus **k**, T, and x

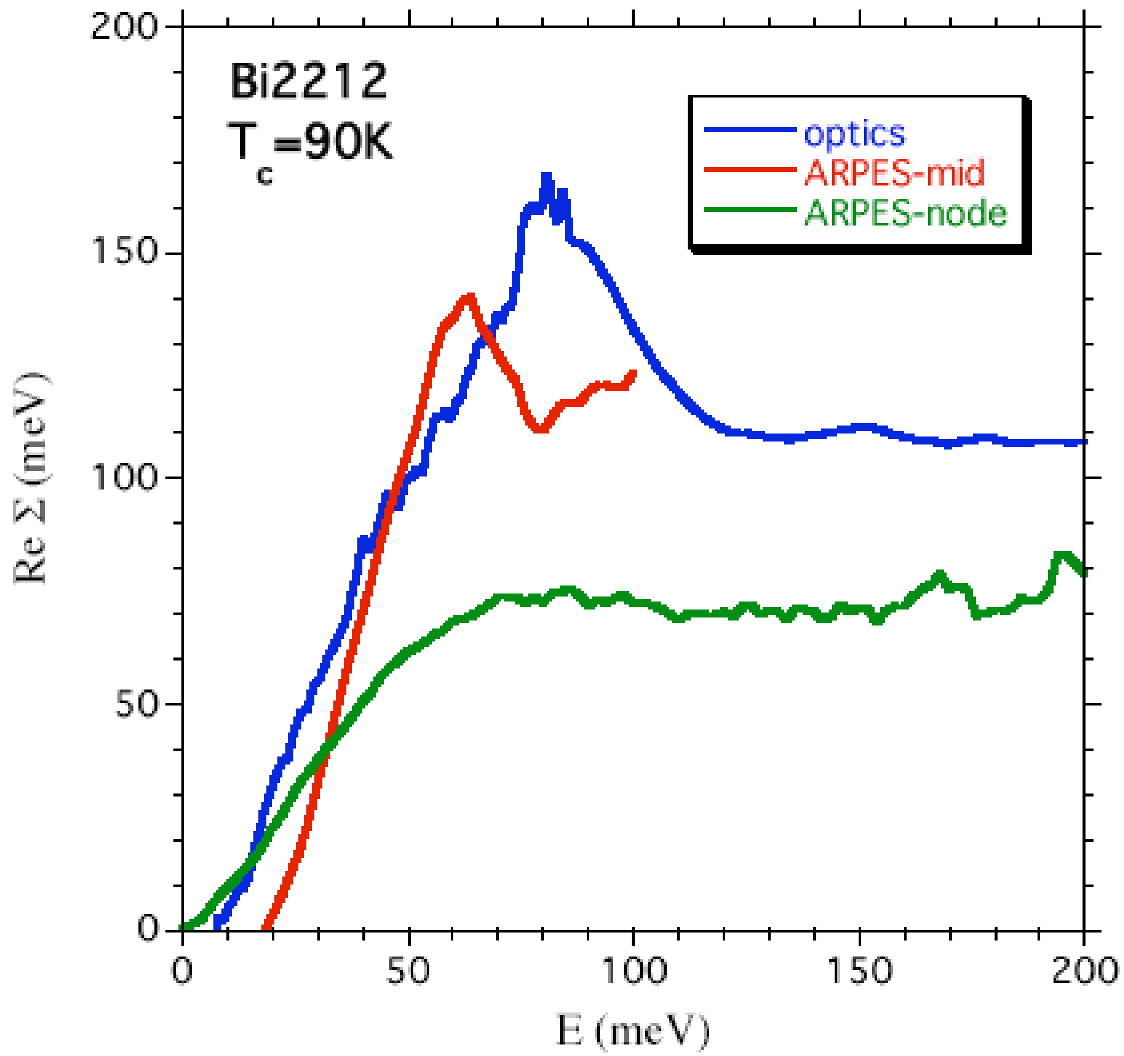


Sato *et al.*,
PRL 91,157003
(2003)



Sato *et al.*
PRL 91, 157003
(2003)

Peak in Optics "Re Σ" is thought to be due to the resonance

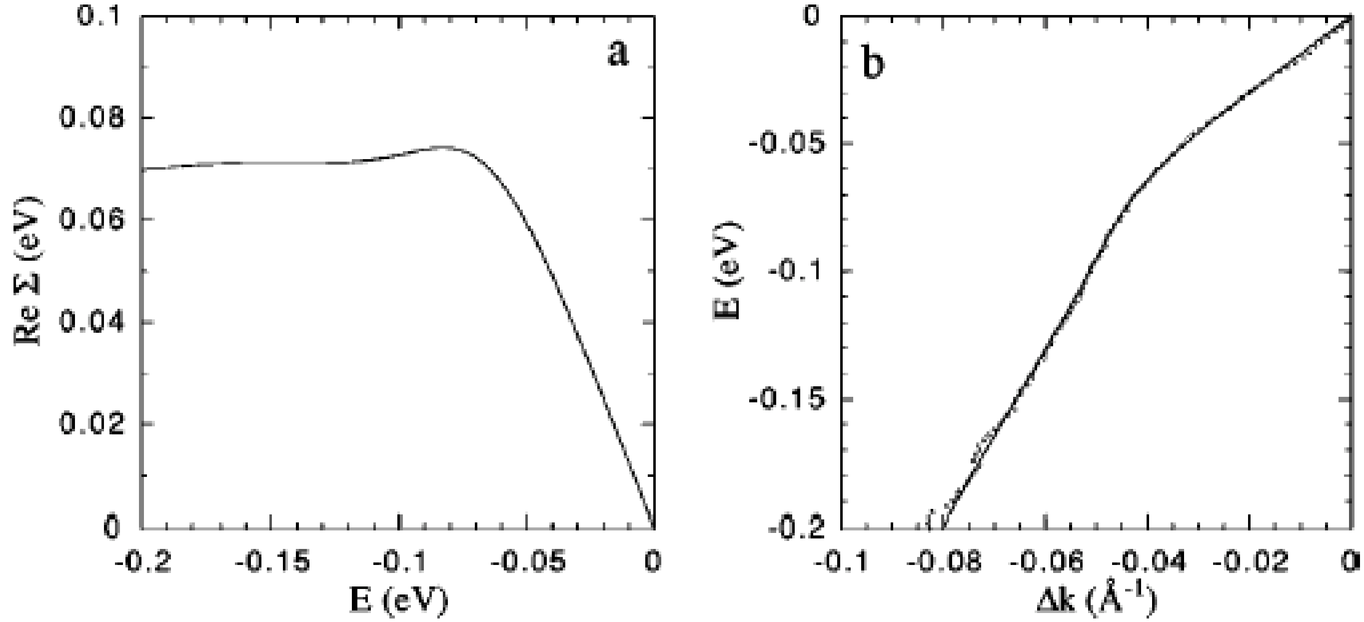


Timusk (optics)

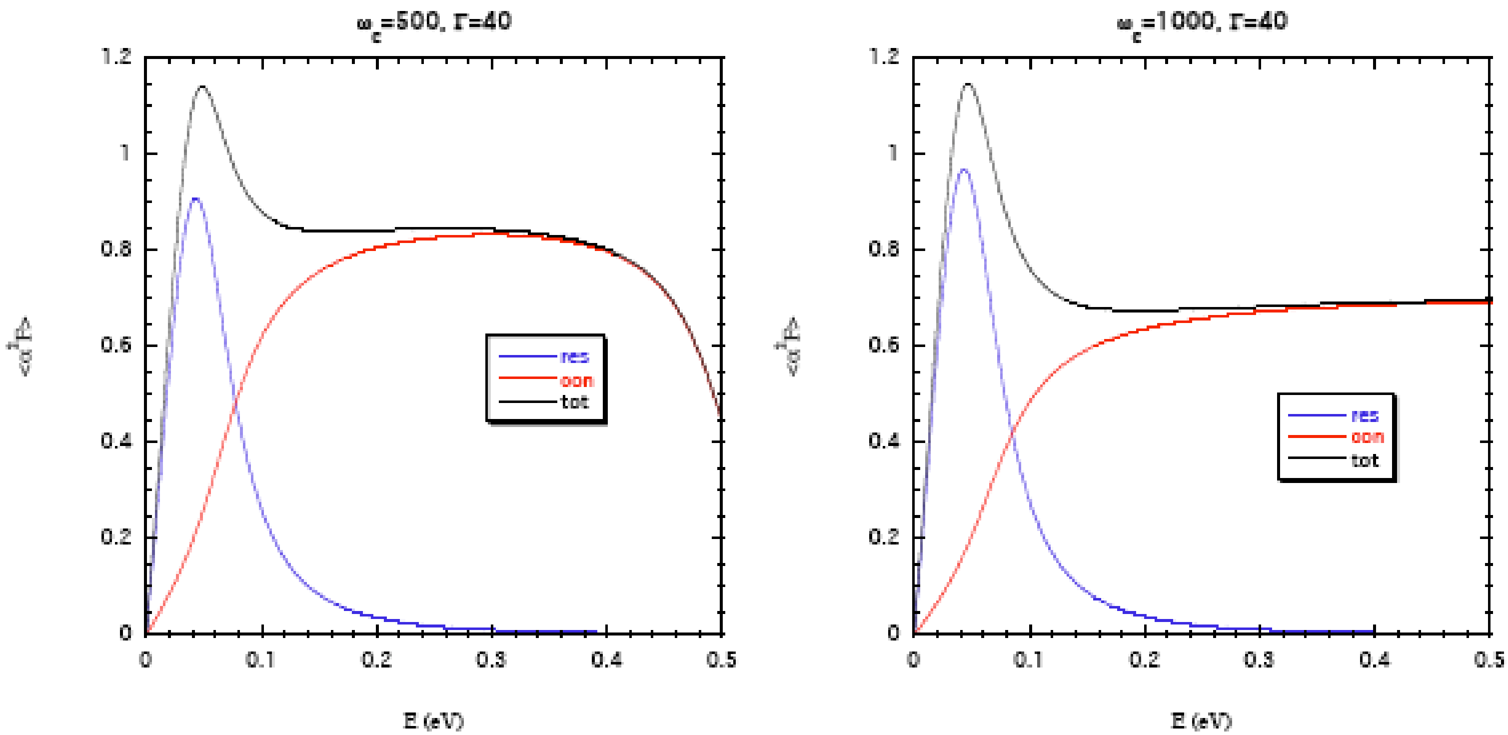
Kaminski (ARPES)

Hwang *et al*., Nature 427, 714 (2004) for optics data

ReΣ

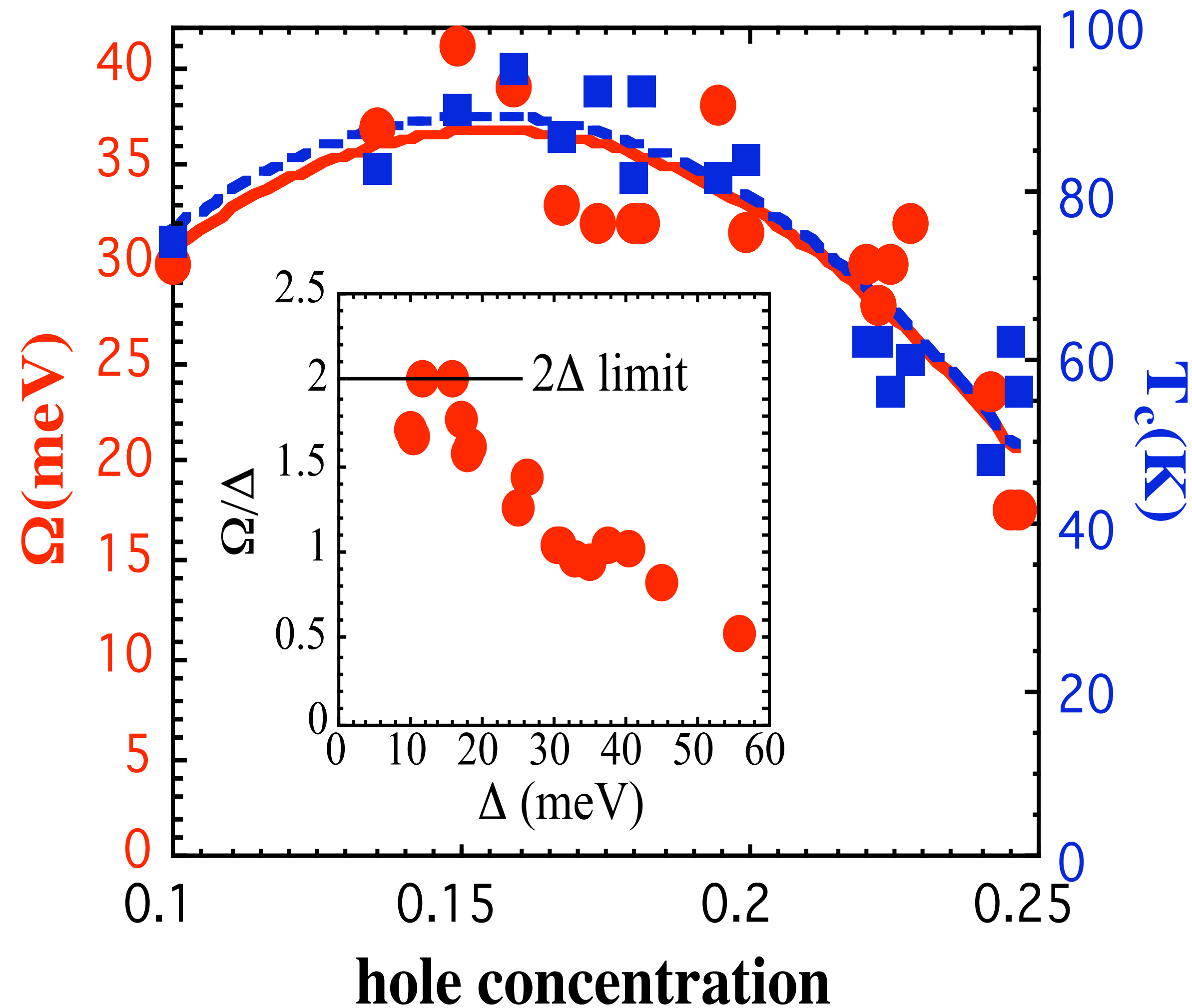


α^2F



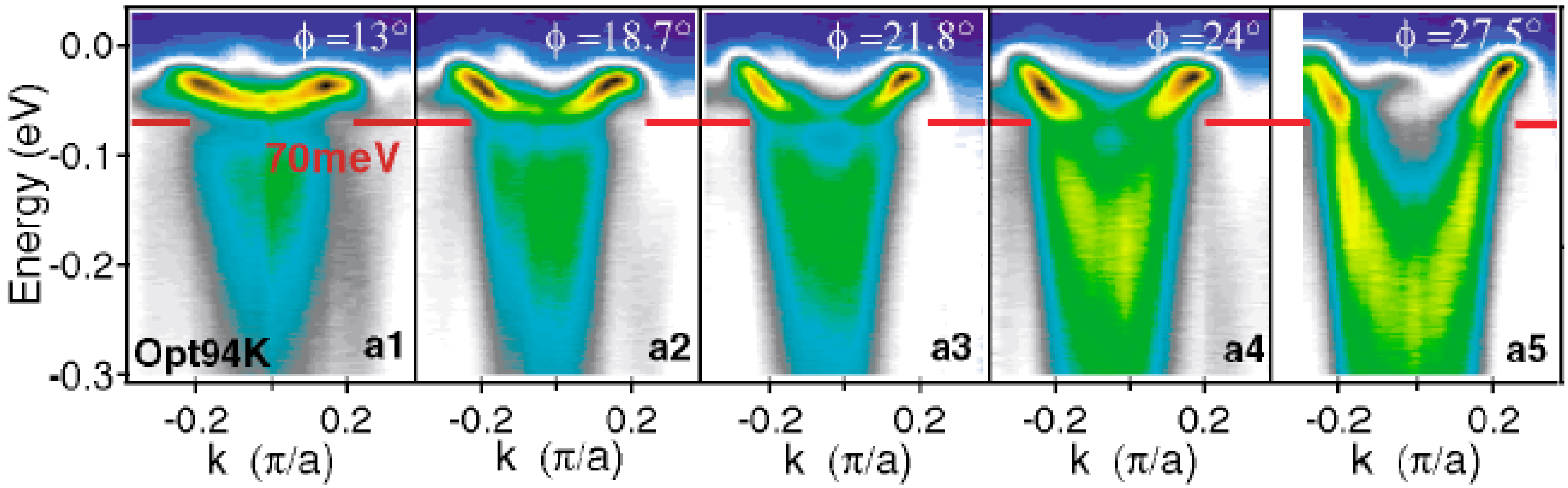
Eschrig & Norman, PRB 67, 144503; Chubukov & Norman, PRB 70, 174505

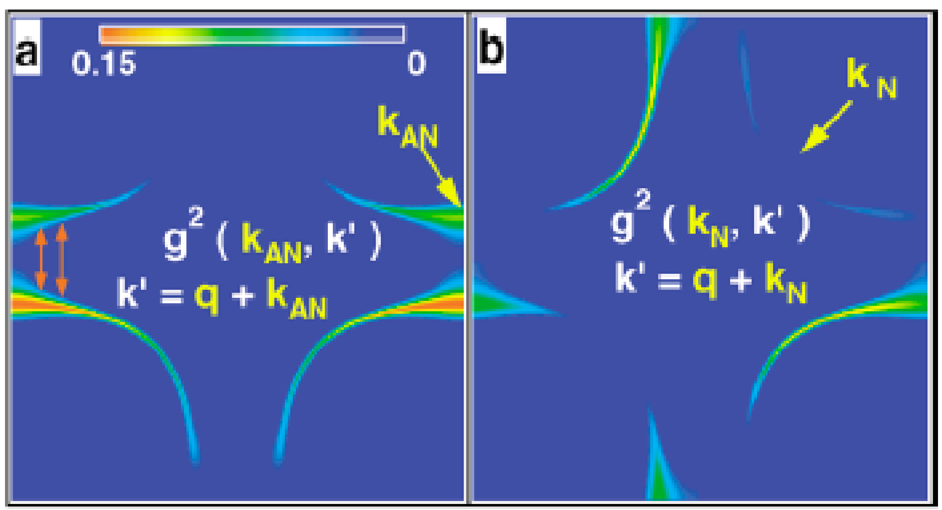
Mode Energy from Tunneling



Zasadzinski *et al.*, PRL 87, 067005 (2001)

B_{1g} phonon?





T. Cuk *et al.*, PRL 93, 117003 (2004)