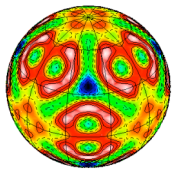
The Nodal Metal in Cuprates
A New State of Matter?

Mike Norman

Materials Science Division
Argonne National Laboratory

Kanigel *et al*., Nature Physics 2, 447 (2006)



Russia - June 27, 2007

The Team

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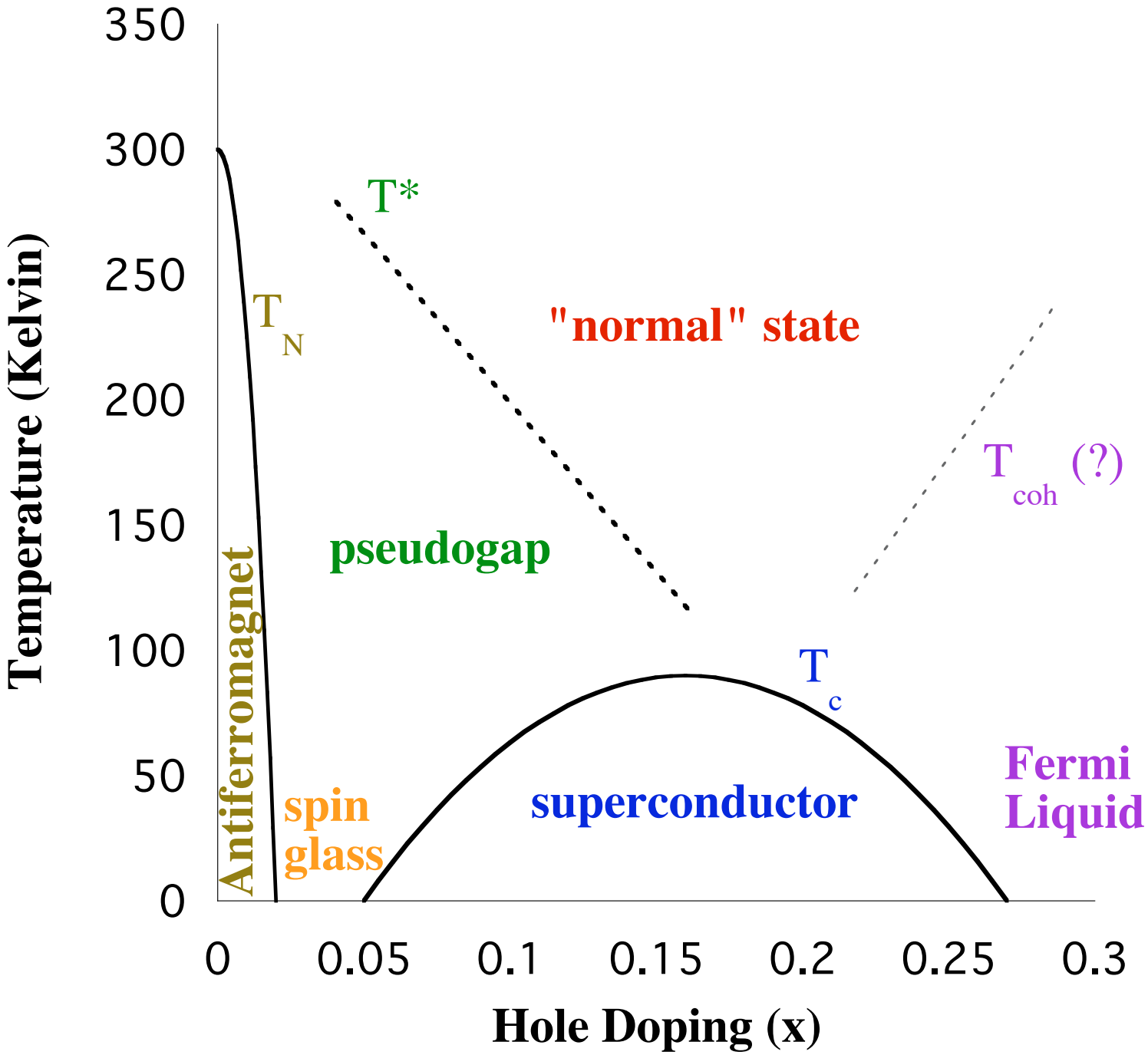
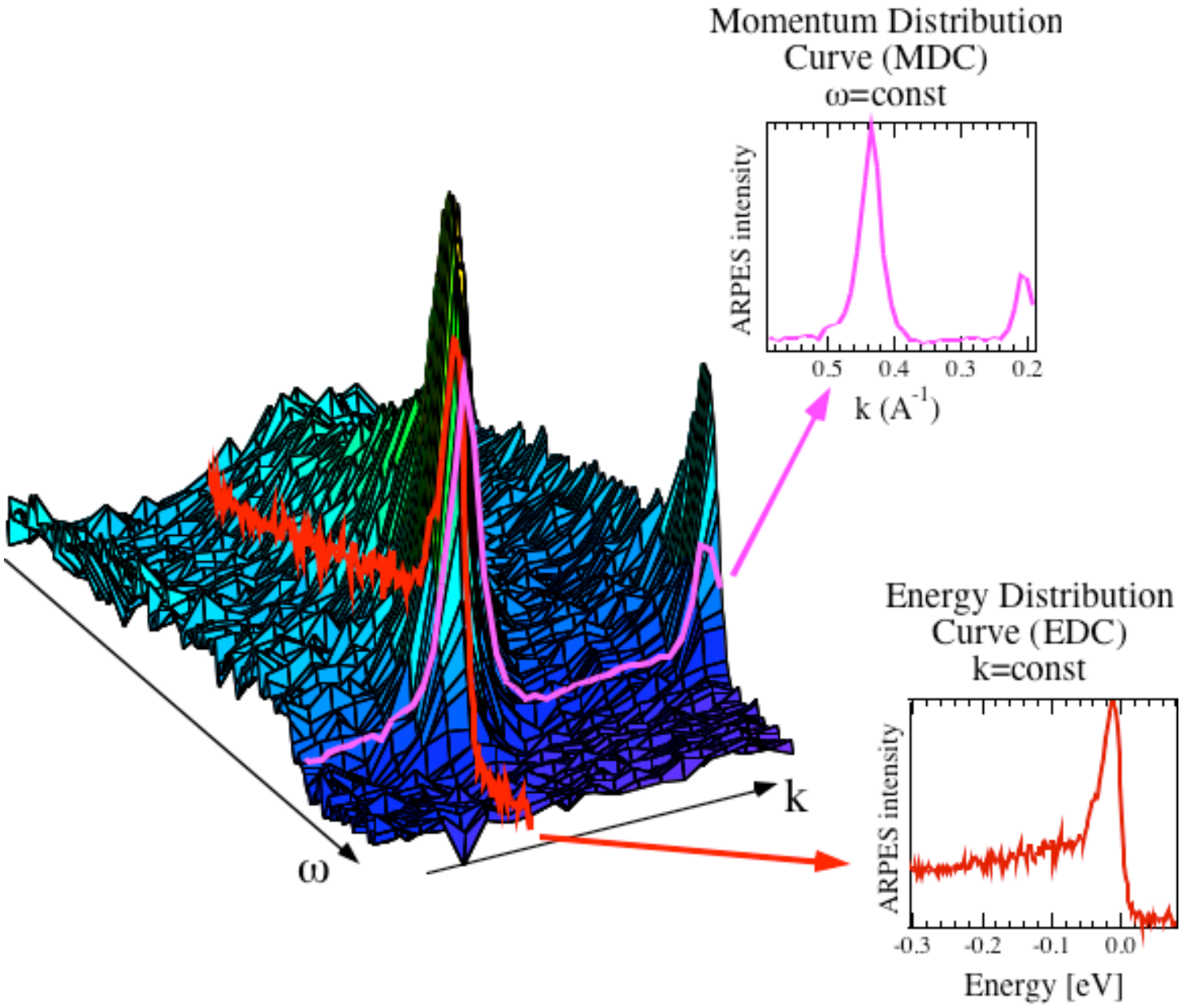

Temperature (Kelvin)
350
300
250
200
150
100
50
0
0
0.05
0.1
0.15
0.2
0.25
0.3
Hole Doping (x)
T*
T N
"normal" state
T coh (?)
pseudogap
T c
Antiferromagnet
spin glass
superconductor
Fermi Liquid

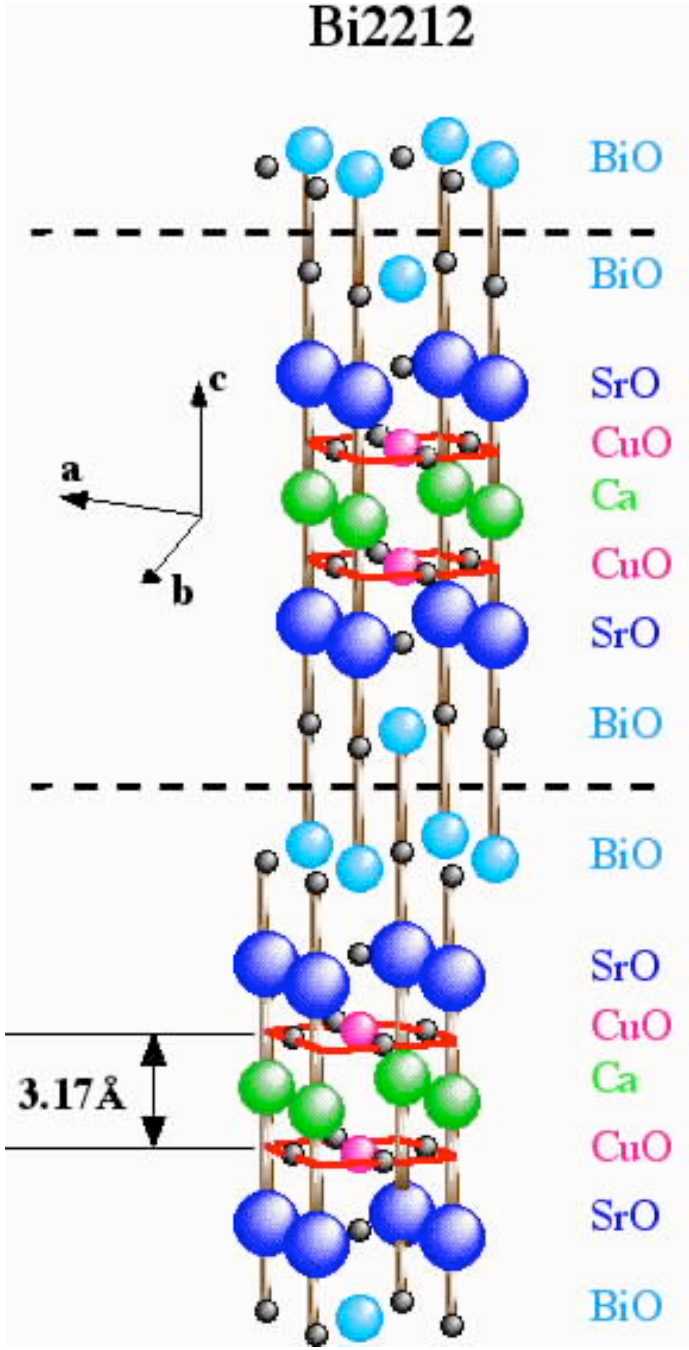
Angle Resolved Photoemission Spectroscopy (ARPES)



Assuming the "sudden approximation", ARPES in 2D systems measures the single particle spectral function

$$I(\mathbf{k},\omega) = c\,\langle A(\mathbf{k},\omega) f(\omega)\rangle + \text{background}$$ where

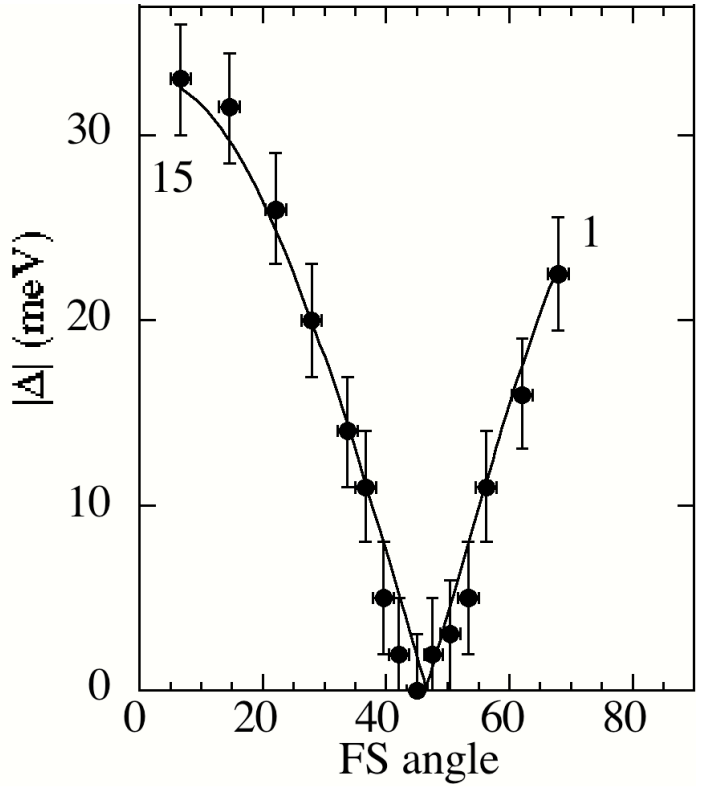
1. A is the single particle spectral function
2. f is the Fermi-Dirac function
3. c is the square of the dipole matrix element (plus intensity normalization)
4. $\langle\ \rangle$ is the convolution with the energy resolution gaussian and sum over the momentum window
5. background is secondaries plus other contributions

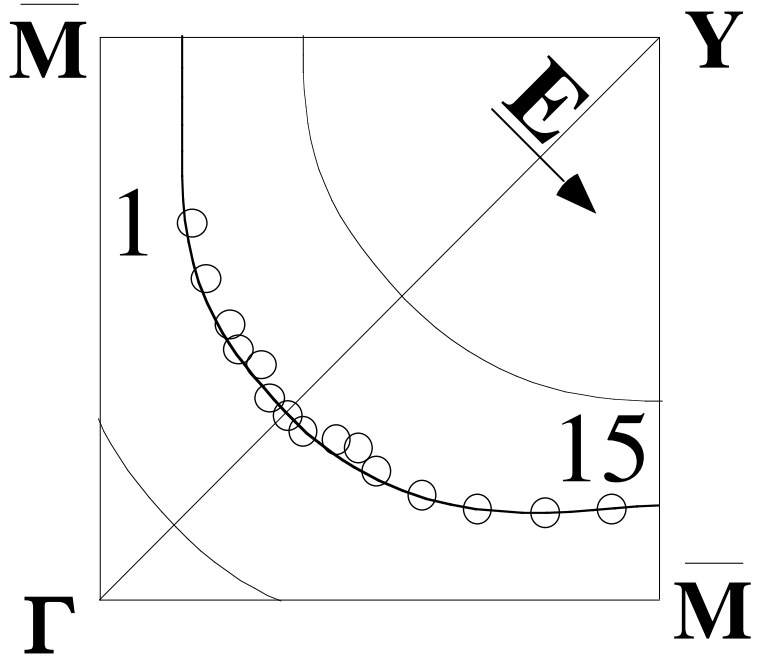

Bi2212
BiO
BiO
SrO
CuO
Ca
CuO
SrO
BiO
BiO
SrO
CuO
Ca
CuO
SrO
BiO
c
a
b
3.17Å

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

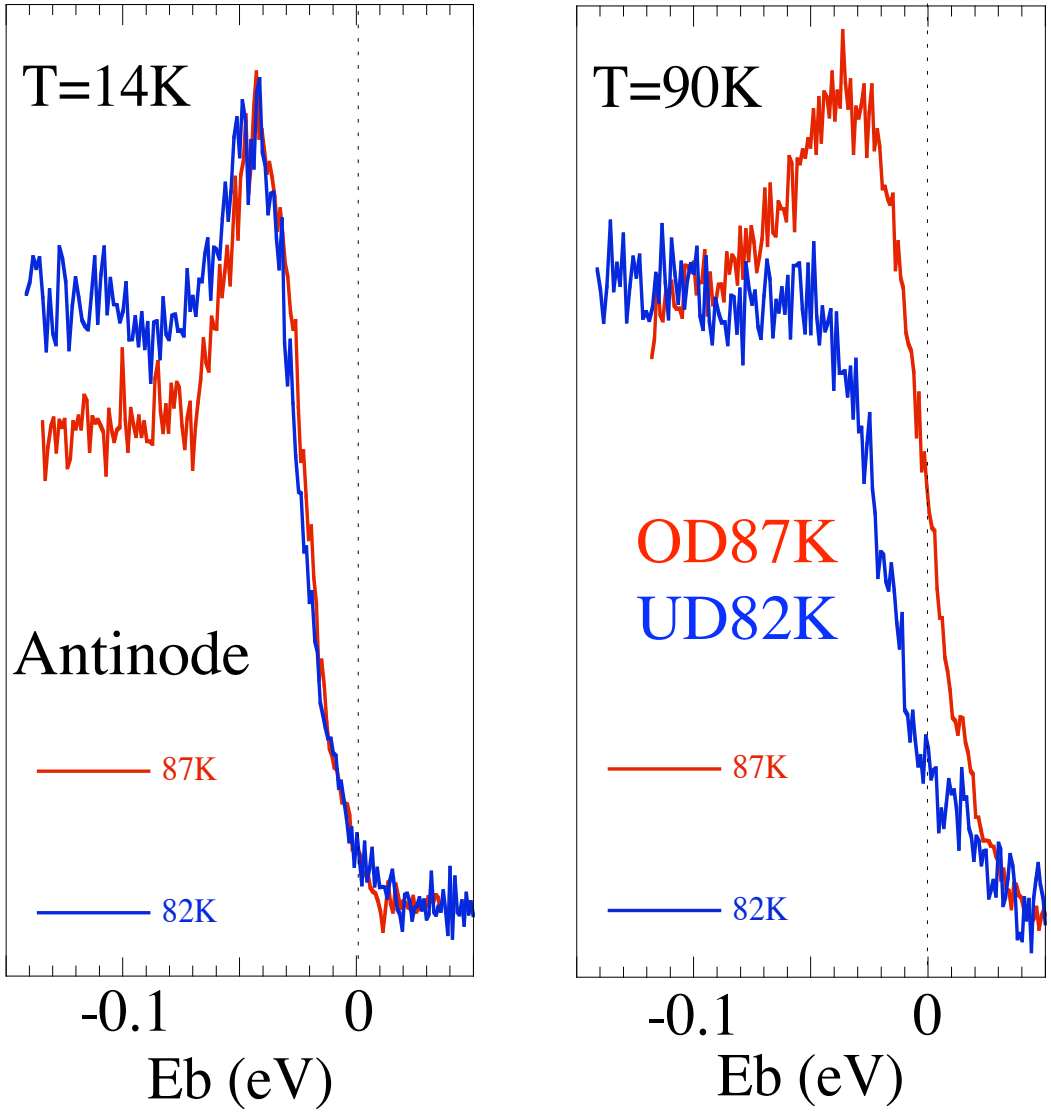


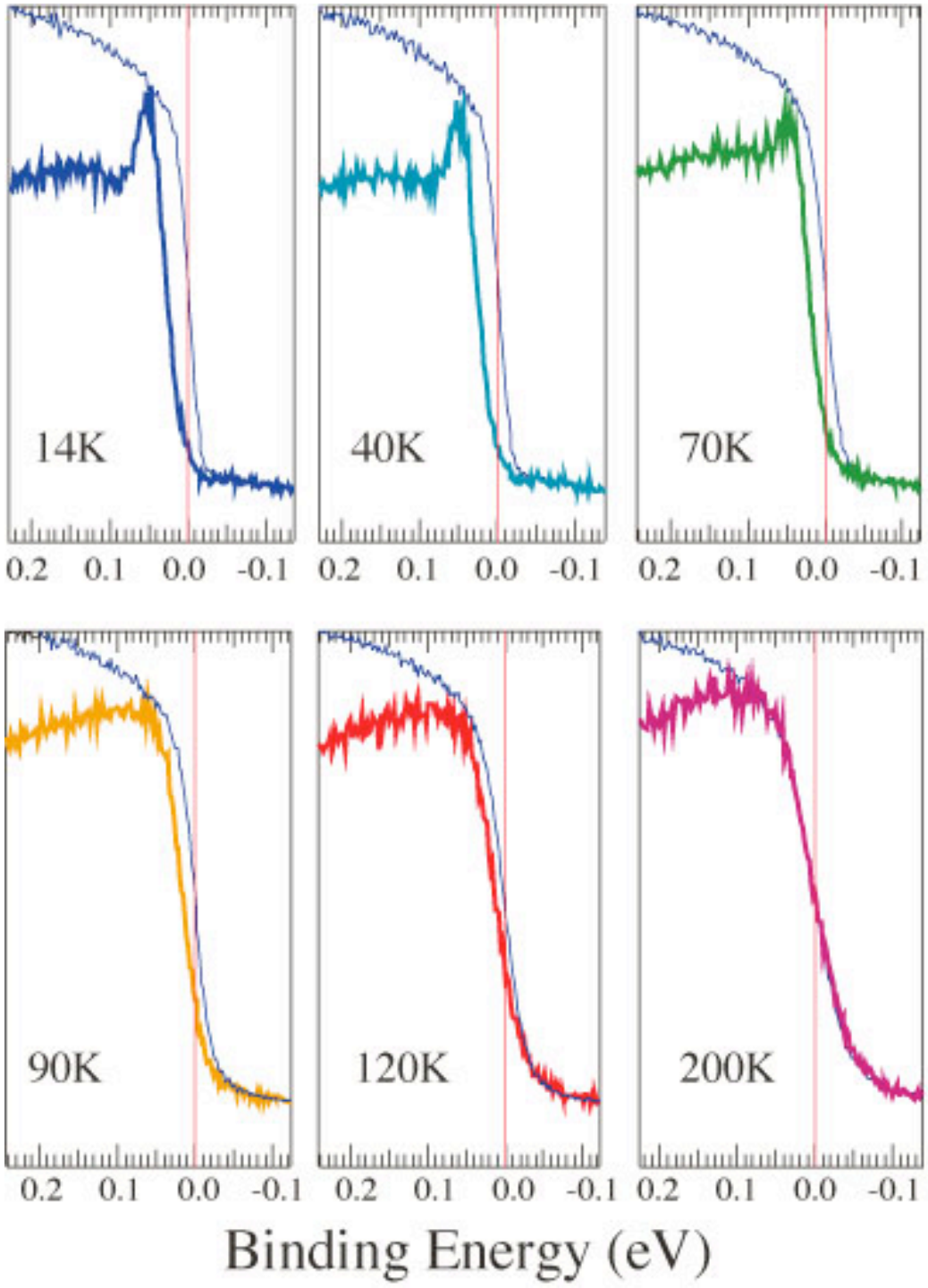


Bi2212
overdoped, T_c=87K
(OD87K)

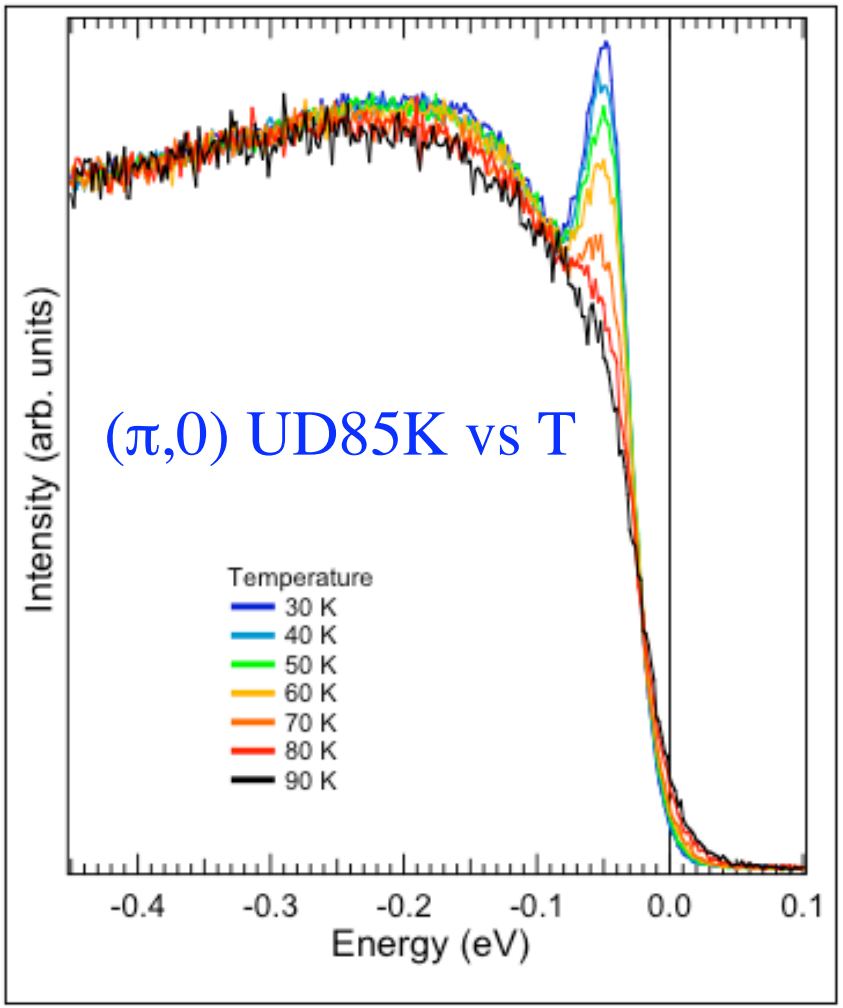
ARPES - Ding *et al.*, Nature 382, 51 (1996)

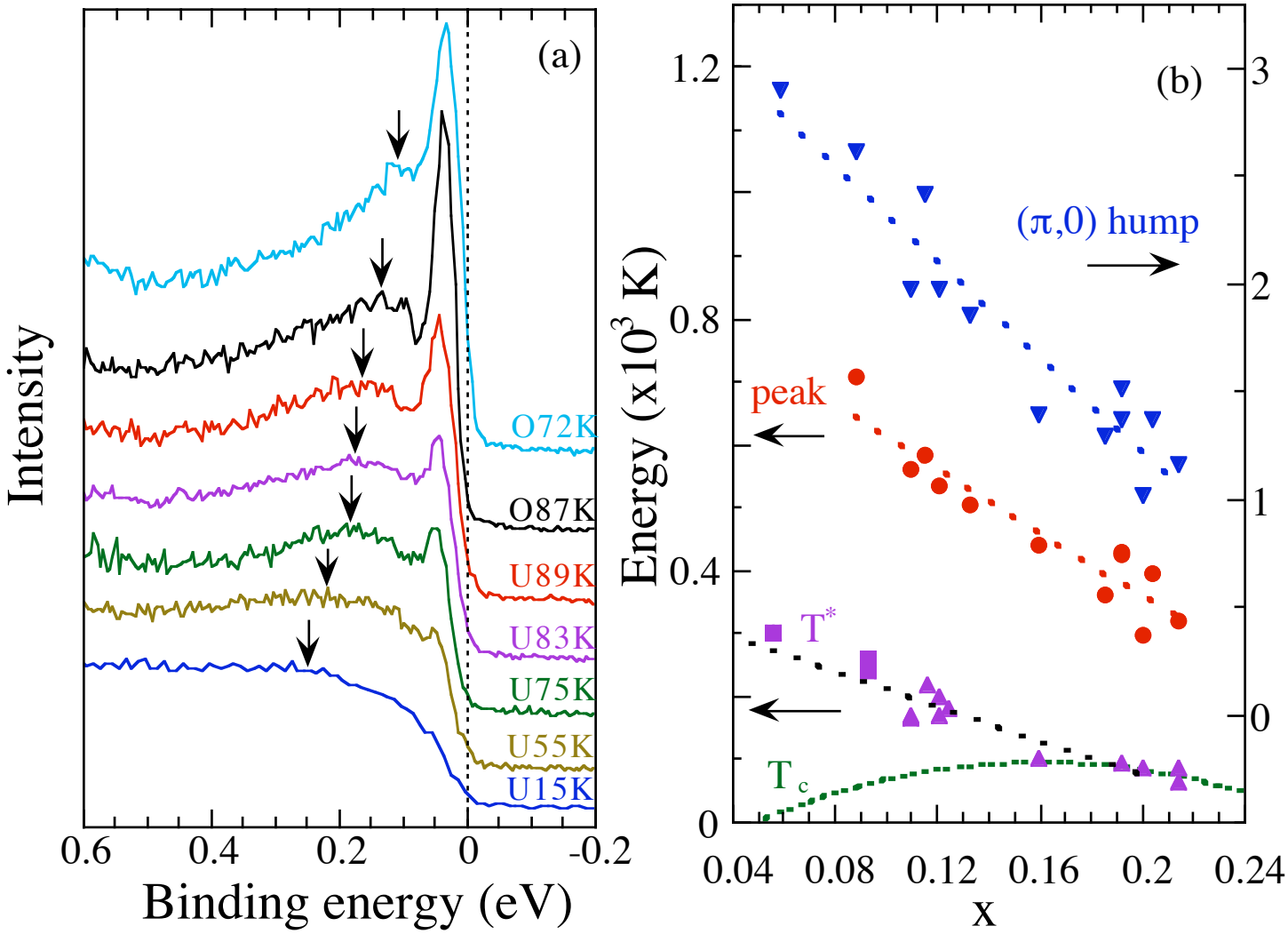
pseudogap - spectral gap but no coherent peak





<-- Antinode UD83K vs T

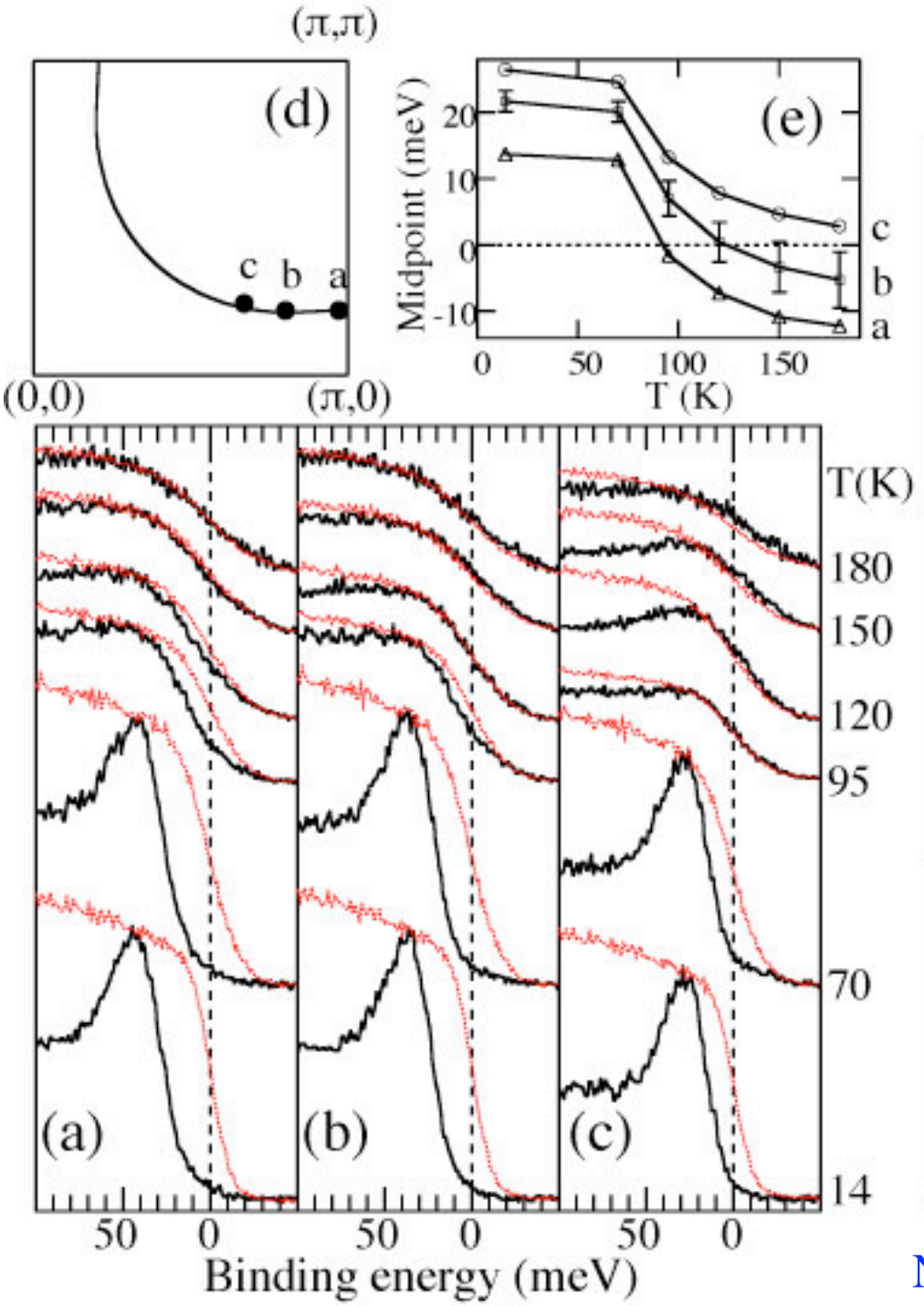


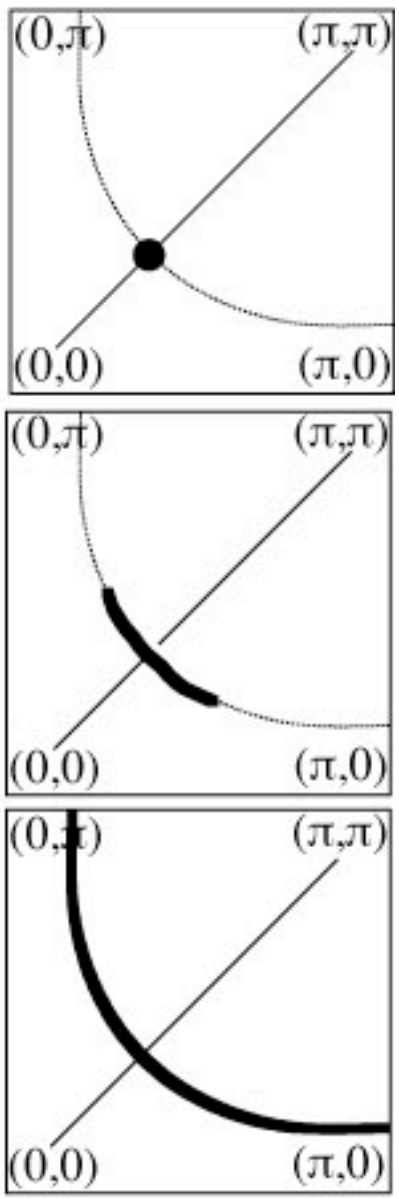


Left - (π,0) spectra versus doping (arrow marks the hump)

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

Campuzano *et al.,* Phys Rev Lett 83, 3709 (1999)



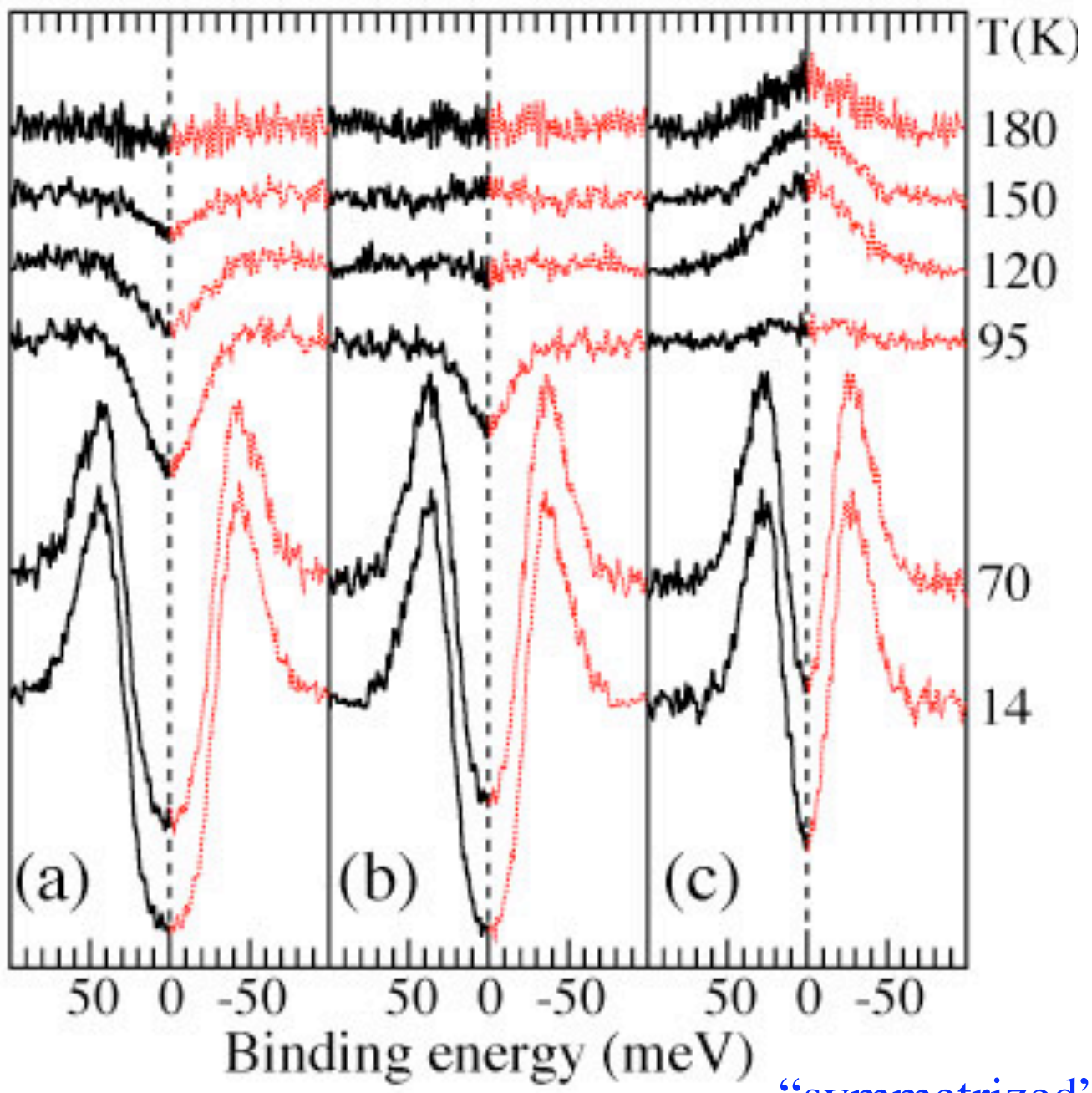


$T < T_c$

$T_c < T < T^*$

$T > T^*$

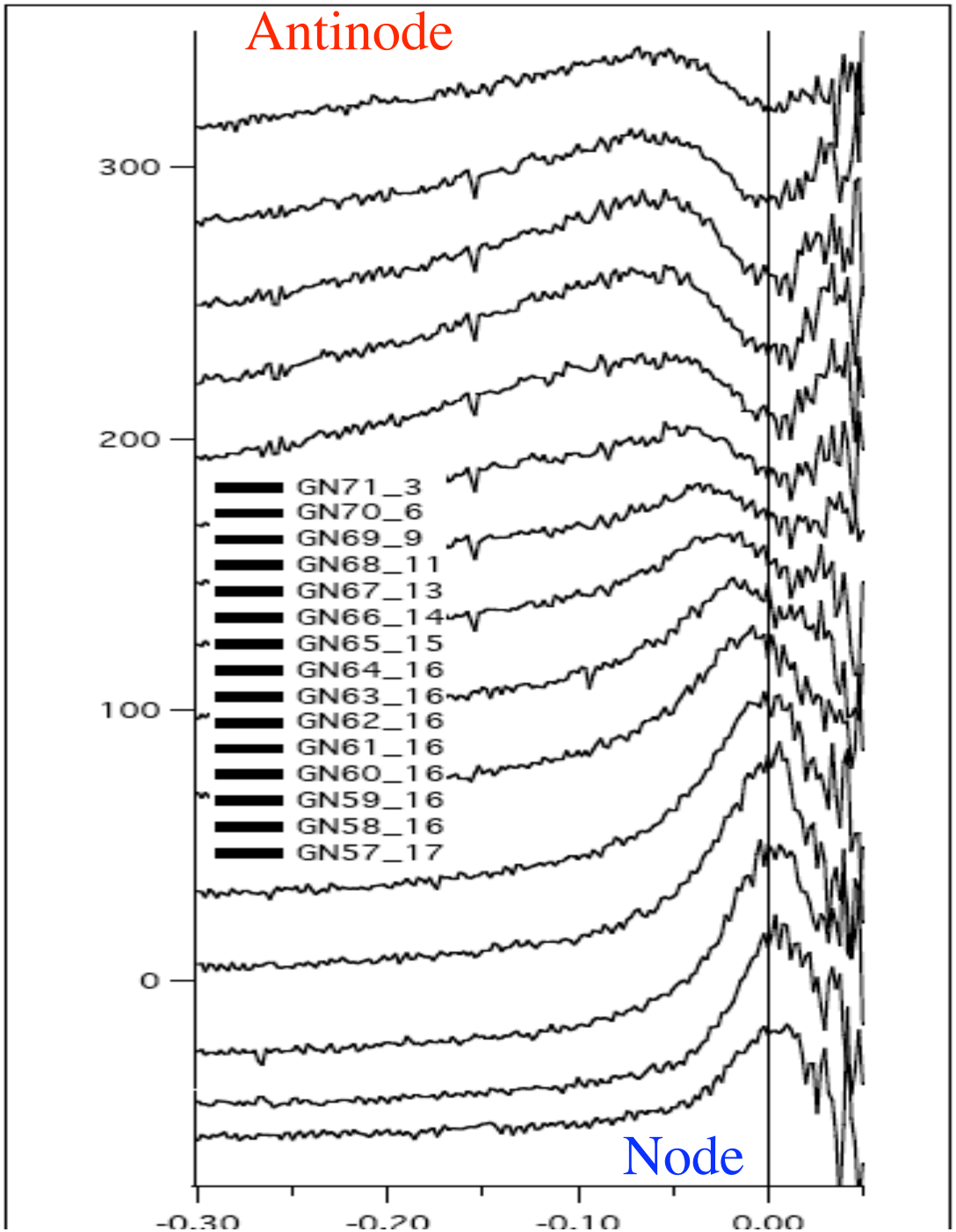
Norman *et al.*, Nature 392, 157 (1998)

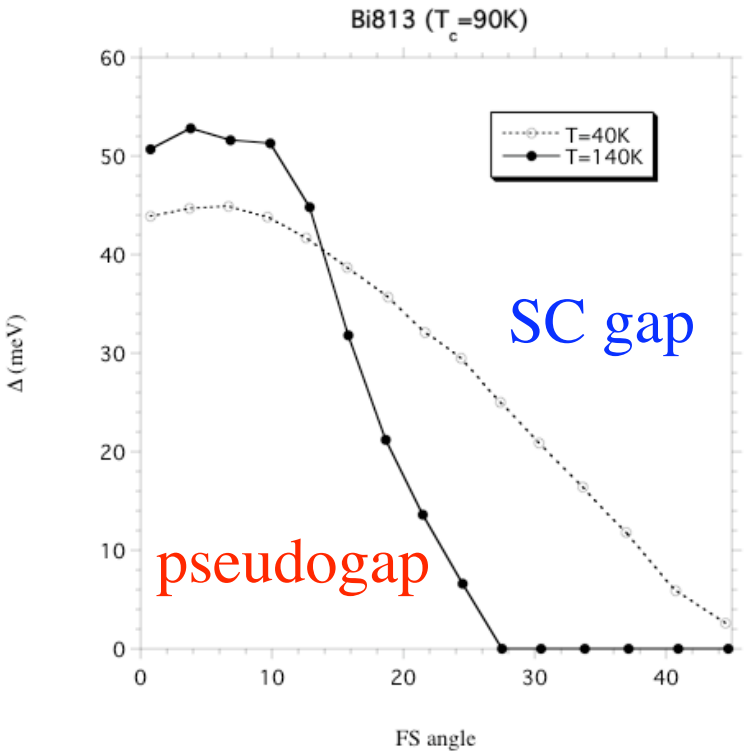


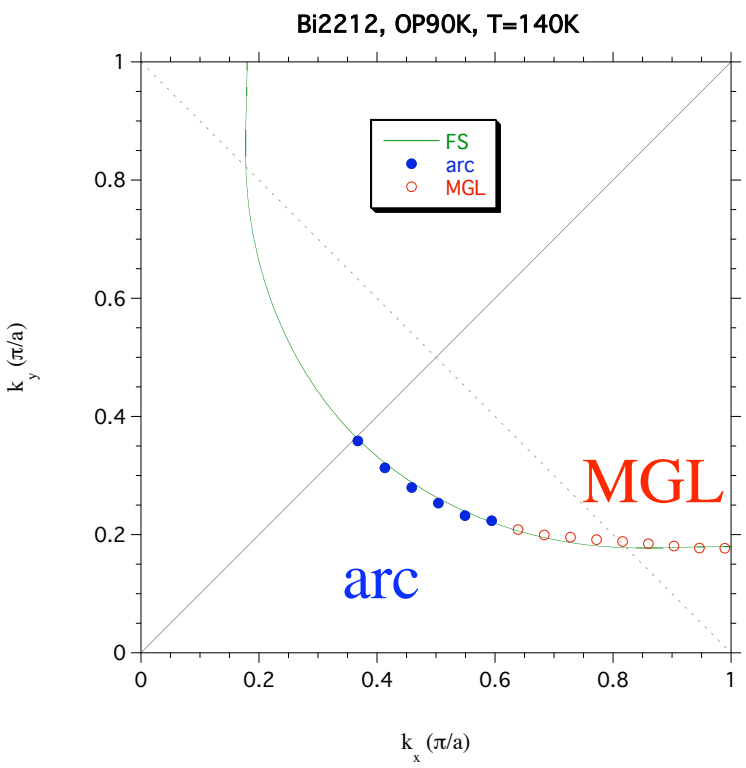
"symmetrized" data vs T

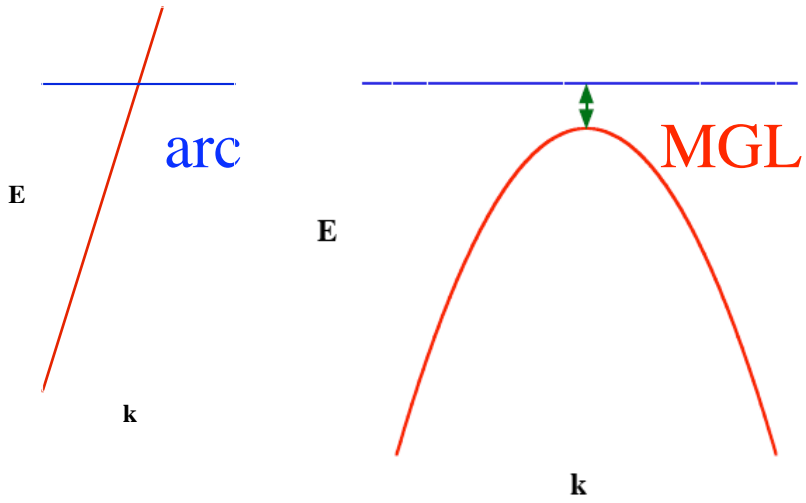
Bi2212
OP90K
T=140K

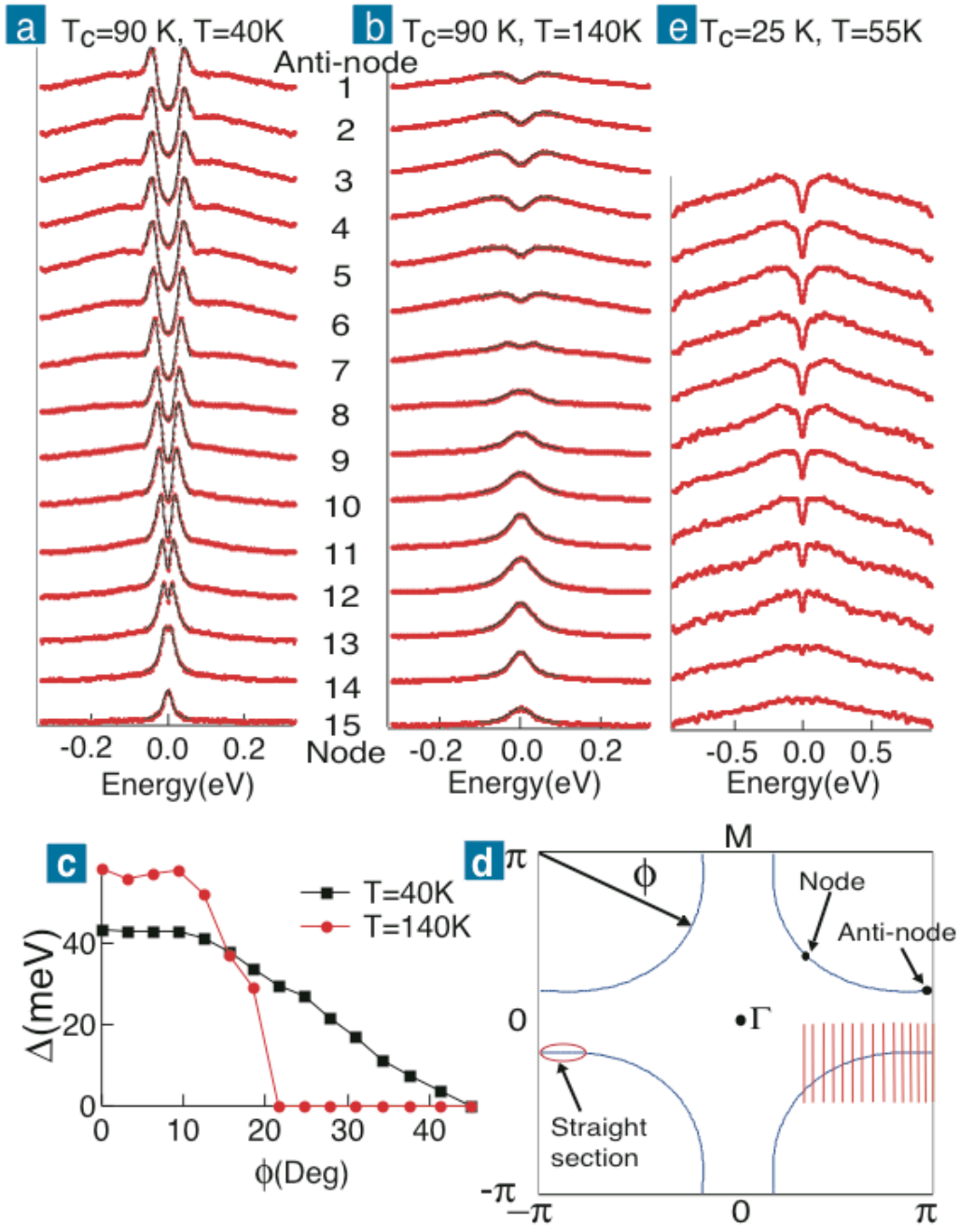
Fermi function
divided data

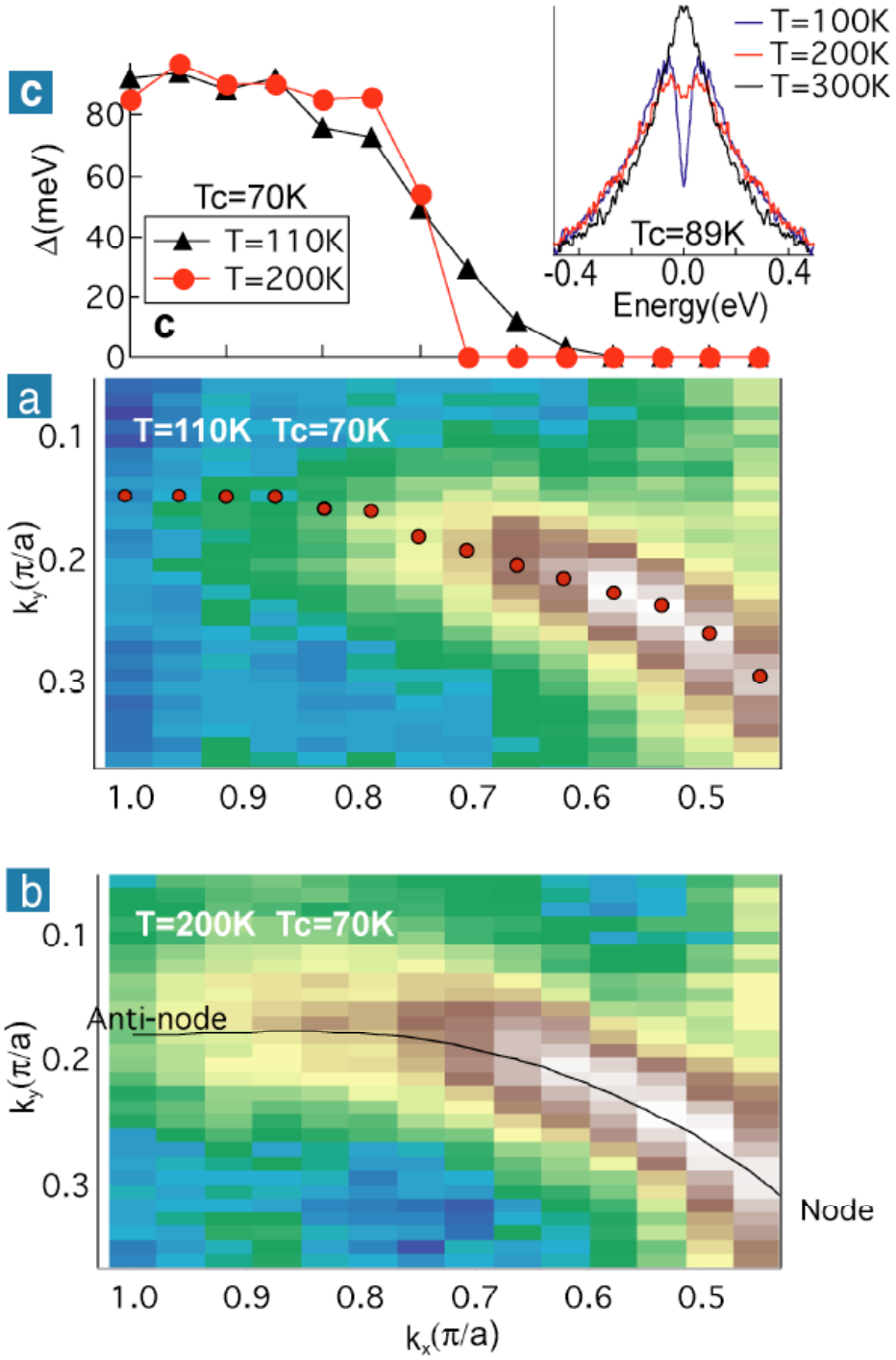


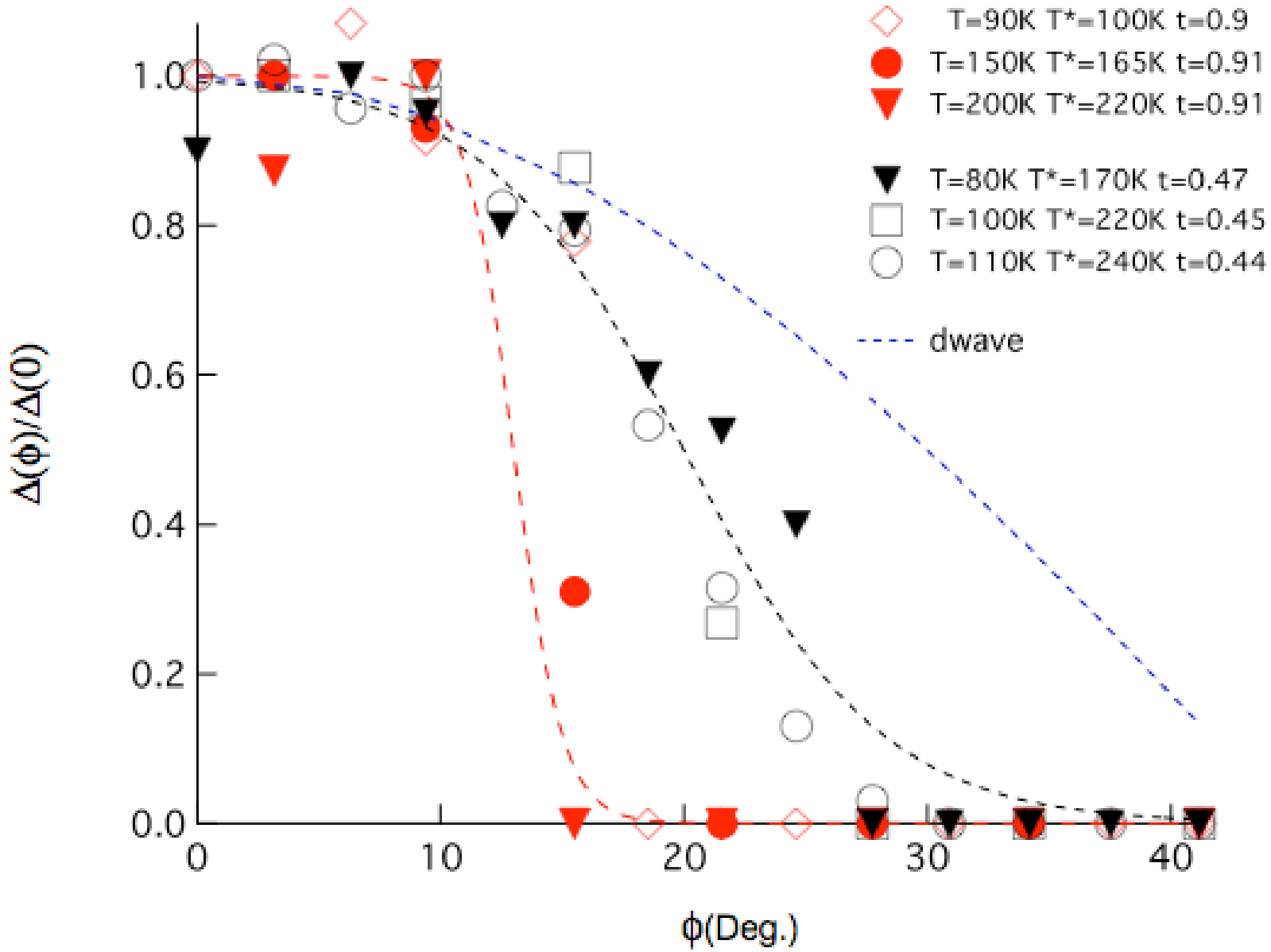

Bi813 (T_c=90K)
T=40K
T=140K
SC gap
pseudogap
Δ (meV)
FS angle

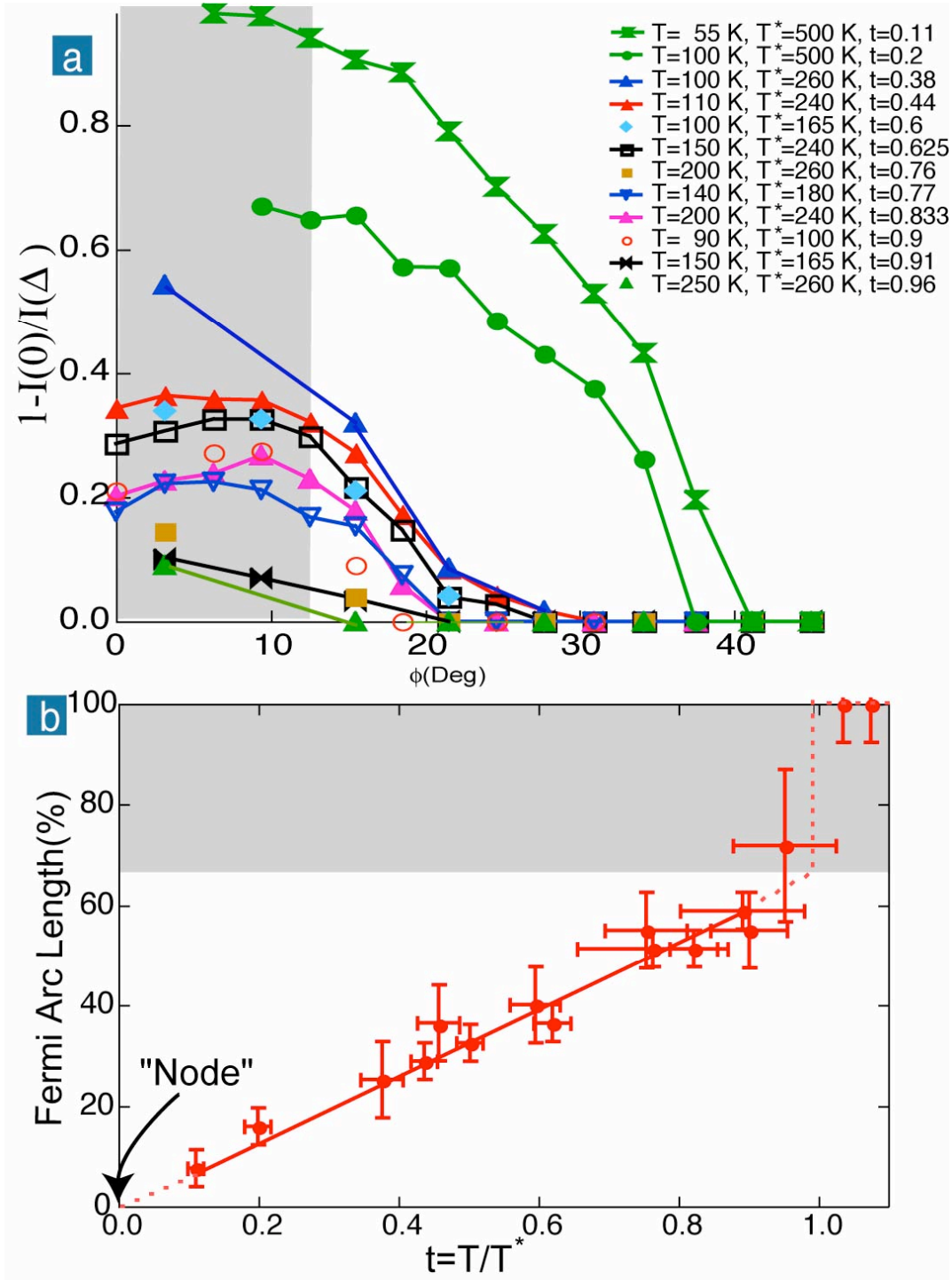

Bi2212, OP90K, T=140K
FS
arc
MGL
MGL
arc
k_y (π/a)
k_x (π/a)


arc
E
k
MGL
E
k

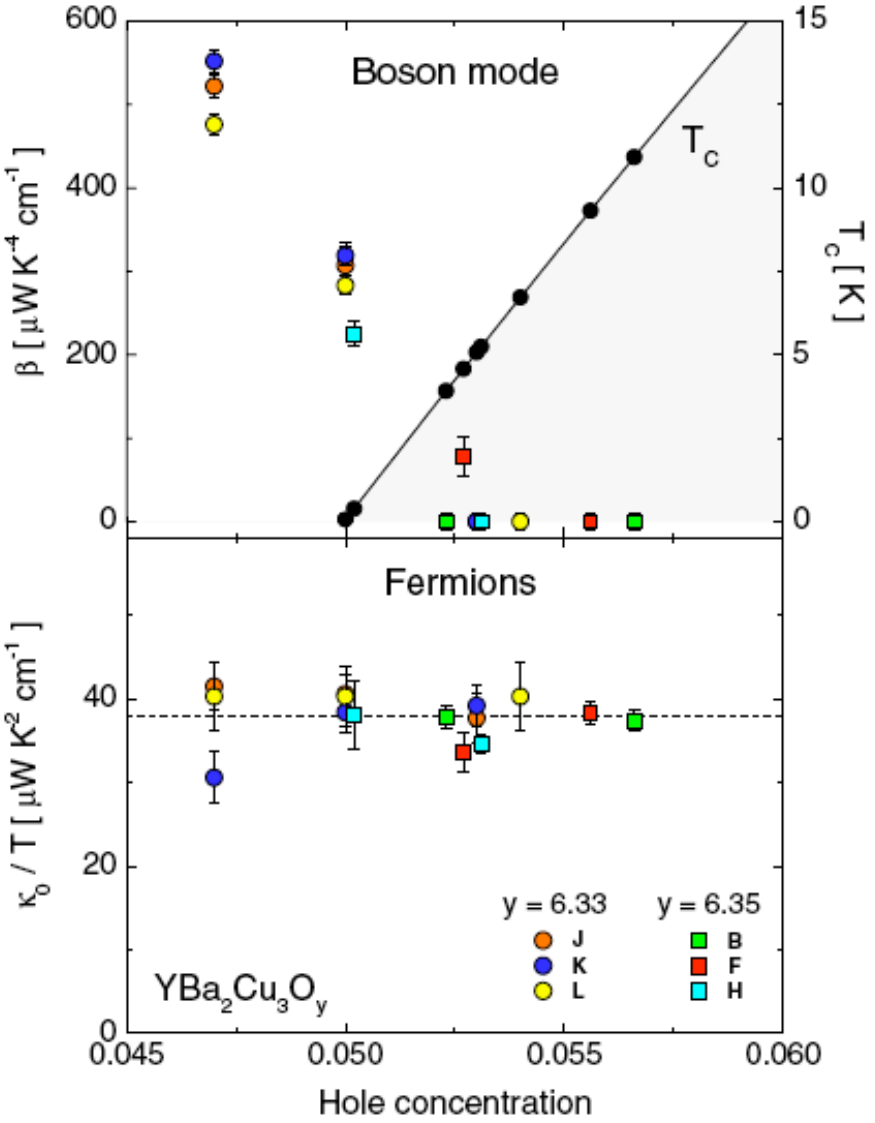

a
Tc=90 K, T=40K
b
Tc=90 K, T=140K
e
Tc=25 K, T=55K
Anti-node
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Node
-0.2 0.0 0.2
Energy(eV)
-0.2 0.0 0.2
Energy(eV)
-0.5 0.0 0.5
Energy(eV)
c
T=40K
T=140K
Δ(meV)
40
20
0
0 10 20 30 40
ϕ(Deg)
d
M
π
ϕ
Node
Anti-node
0
•Γ
Straight
section
-π
−π
0
π


c
Δ(meV)
80
60
40
20
0
Tc=70K
T=110K
T=200K
c
T=100K
T=200K
T=300K
Tc=89K
-0.4
0.0
0.4
Energy(eV)
a
T=110K Tc=70K
0.1
0.2
0.3
k_y(π/a)
1.0
0.9
0.8
0.7
0.6
0.5
b
T=200K Tc=70K
Anti-node
Node
k_x(π/a)


T=90K T*=100K t=0.9
T=150K T*=165K t=0.91
T=200K T*=220K t=0.91
T=80K T*=170K t=0.47
T=100K T*=220K t=0.45
T=110K T*=240K t=0.44
dwave
Δ(ϕ)/Δ(0)
ϕ(Deg.)
0.0
0.2
0.4
0.6
0.8
1.0
0
10
20
30
40

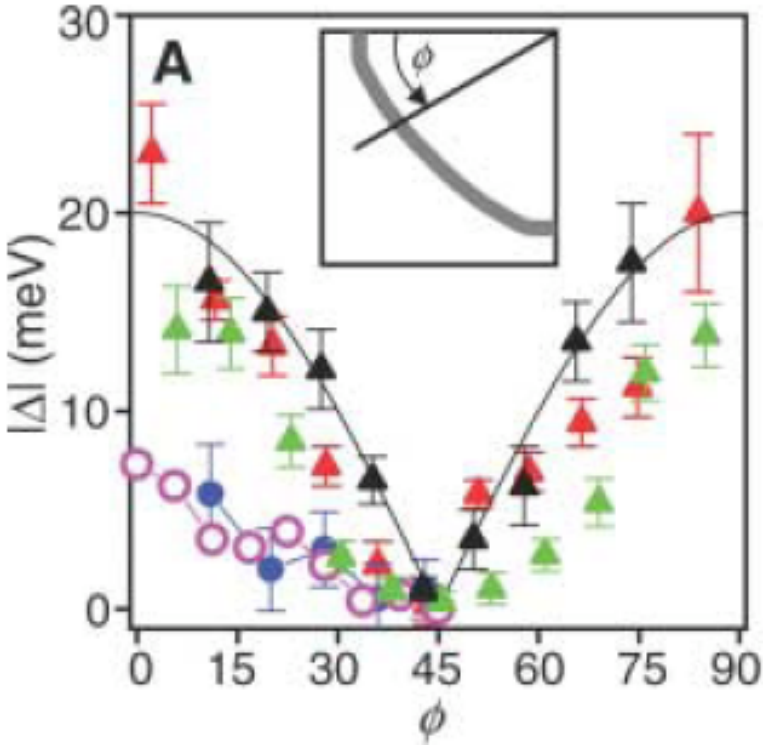

a
T= 55 K, T*=500 K, t=0.11
T=100 K, T*=500 K, t=0.2
T=100 K, T*=260 K, t=0.38
T=110 K, T*=240 K, t=0.44
T=100 K, T*=165 K, t=0.6
T=150 K, T*=240 K, t=0.625
T=200 K, T*=260 K, t=0.76
T=140 K, T*=180 K, t=0.77
T=200 K, T*=240 K, t=0.833
T= 90 K, T*=100 K, t=0.9
T=150 K, T*=165 K, t=0.91
T=250 K, T*=260 K, t=0.96
1-I(0)/I(Δ)
0.0
0.2
0.4
0.6
0.8
0
10
20
30
40
ϕ(Deg)
b
Fermi Arc Length(%)
0
20
40
60
80
100
"Node"
0.0
0.2
0.4
0.6
0.8
1.0
t=T/T*

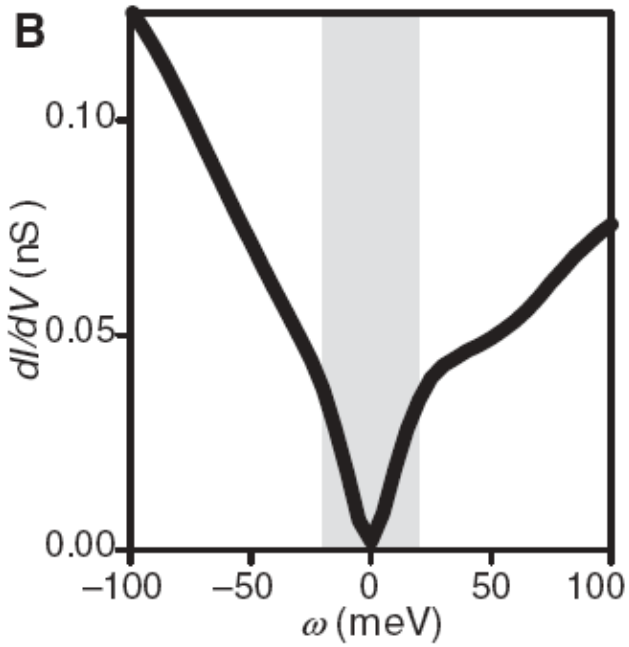
Nodal Liquid Implied by Low T Thermal Conductivity

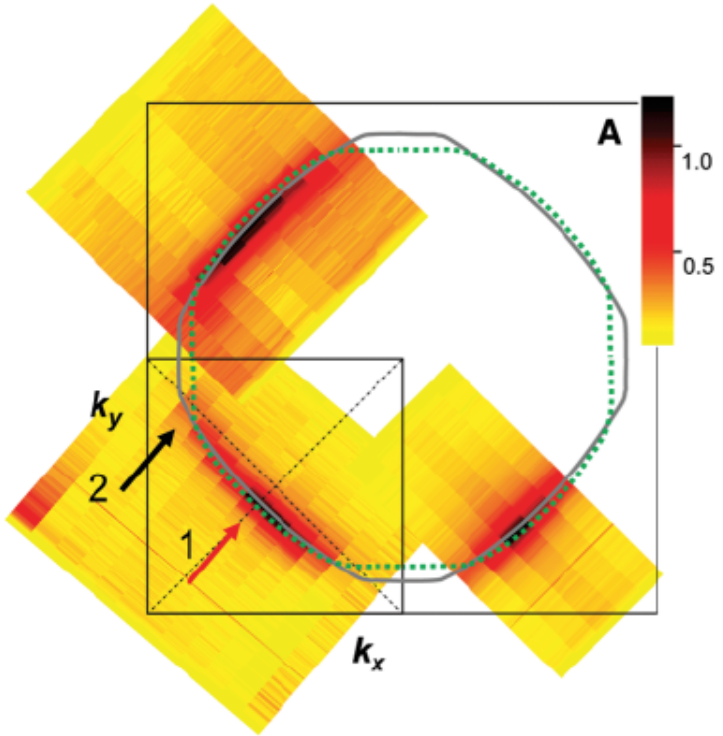


Doiron-Leyraud *et al*, PRL 97, 207001 (2006)

1/8 doped LBCO

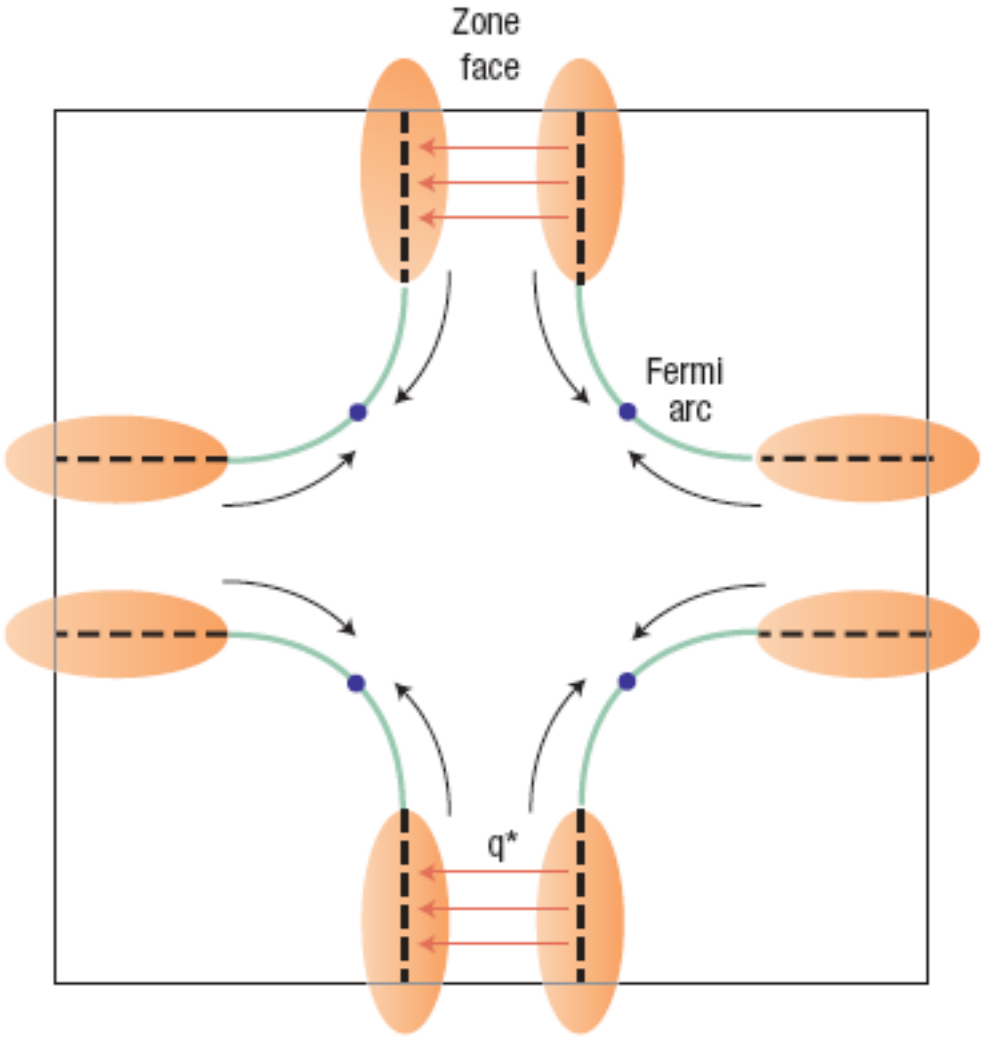






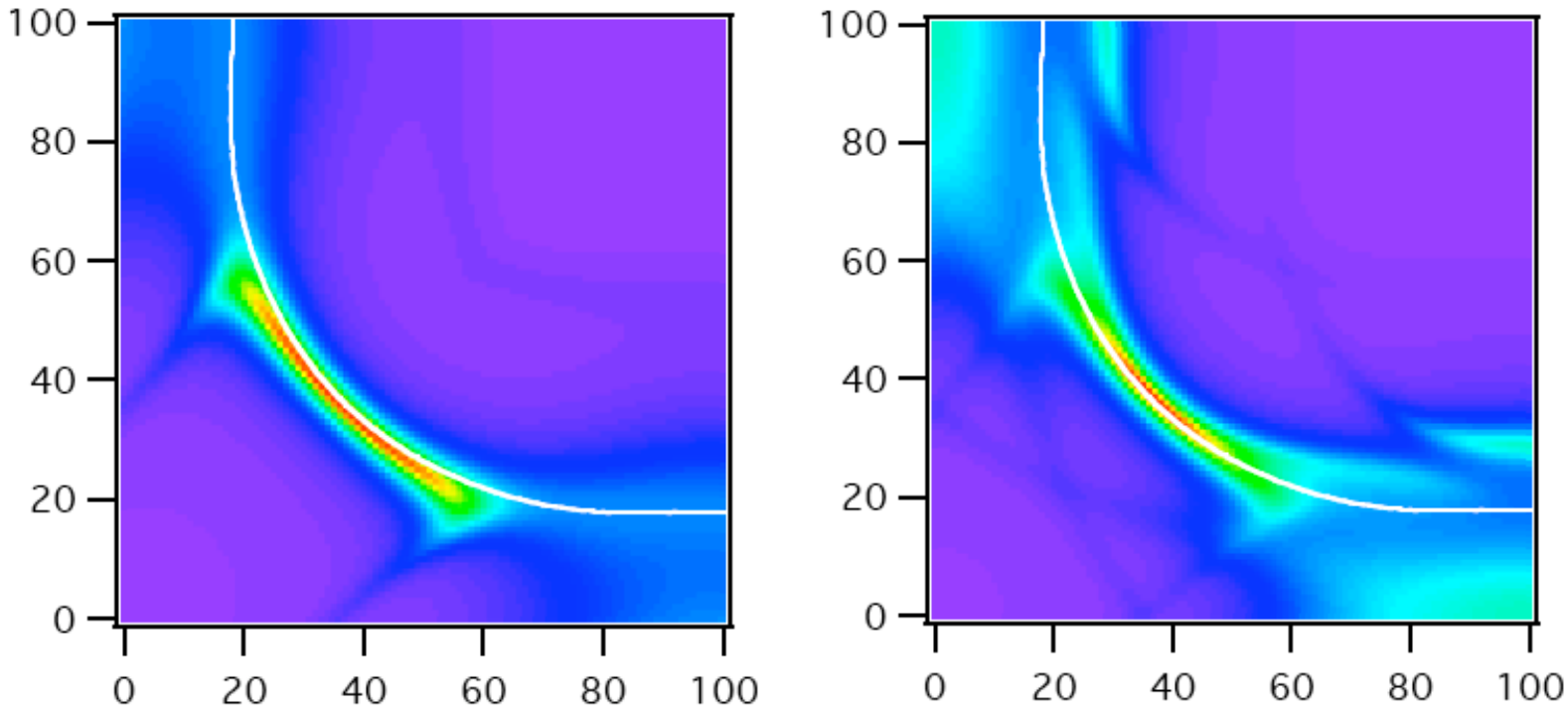
Valla *et al.*,
Science 314, 1914 (2006)

Charge ordering?



Kyle McElroy - Nature Physics 2, 441 (2006)

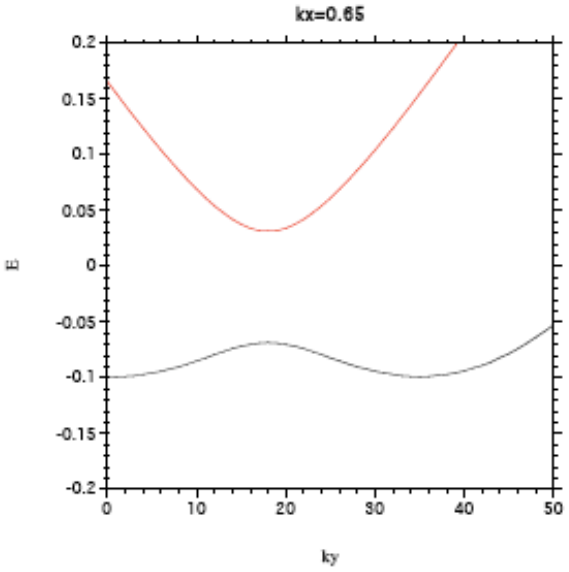
Charge ordering?

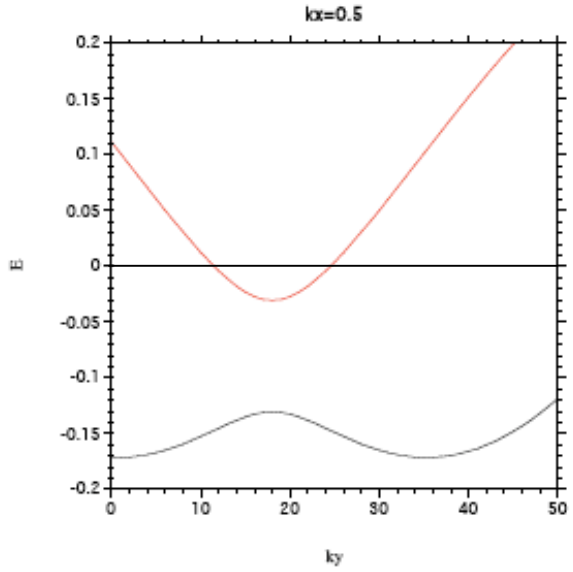


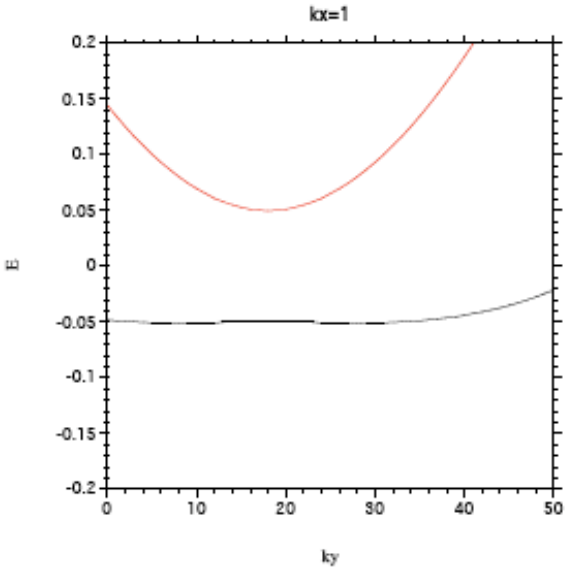
Zero energy intensity maps, left (q) and right (q,-q)

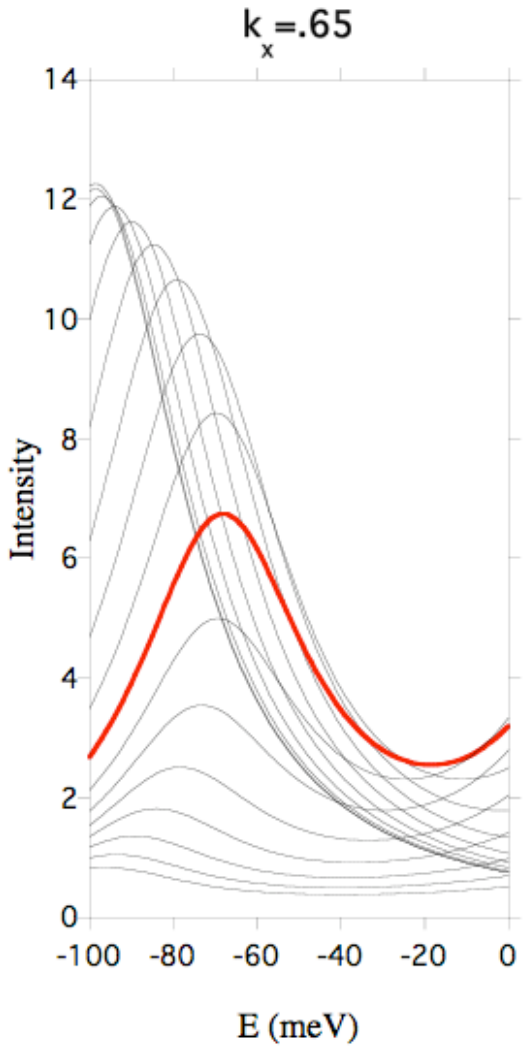
Norman *et al.*, unpublished

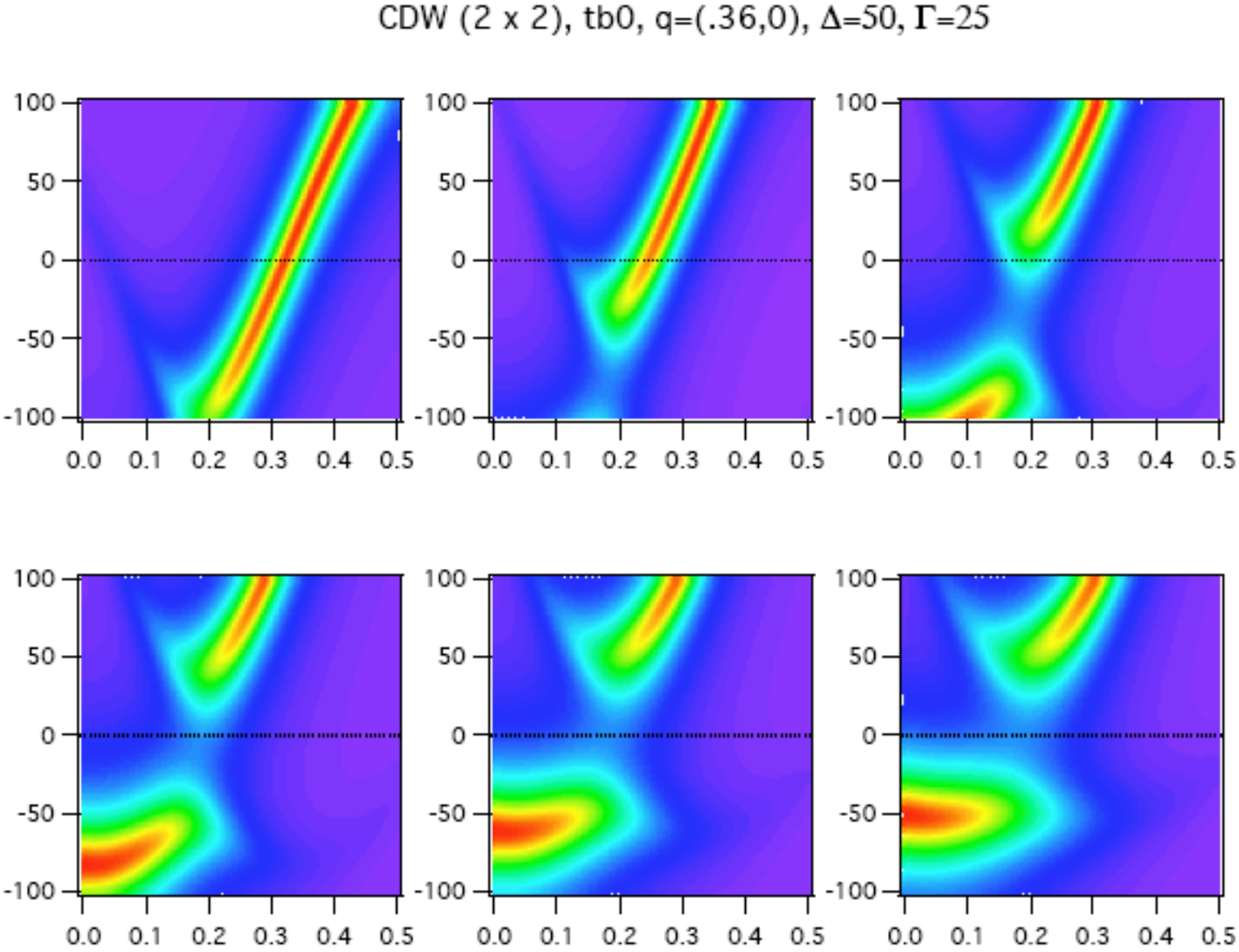
Energy gap below E_F in the 'arc' region for charge ordering at finite q

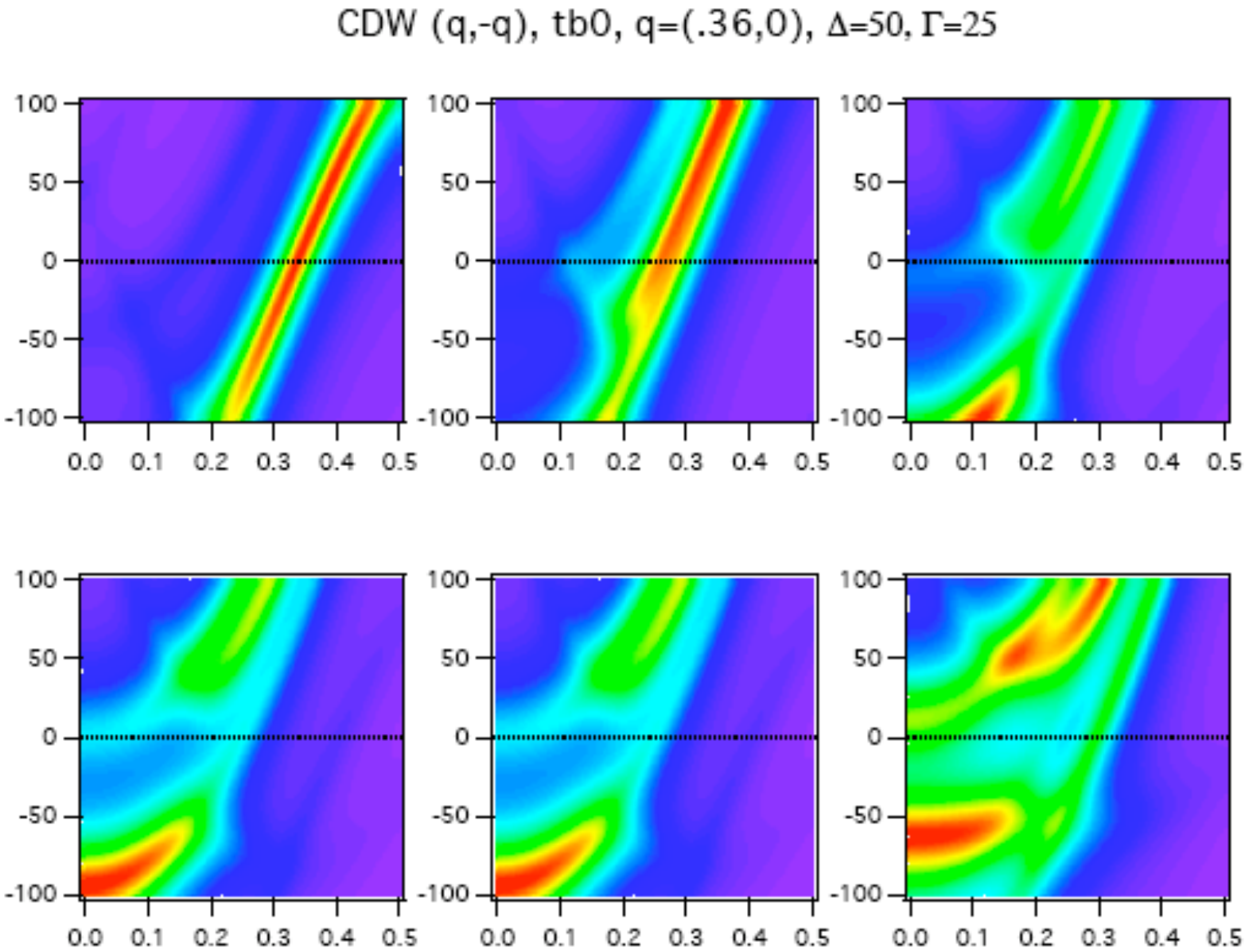




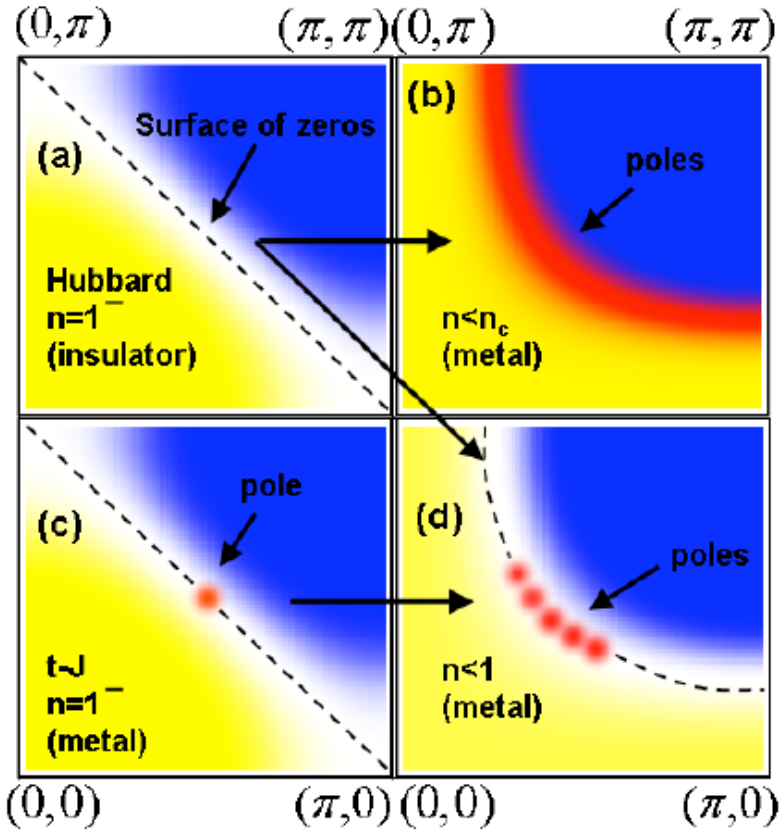




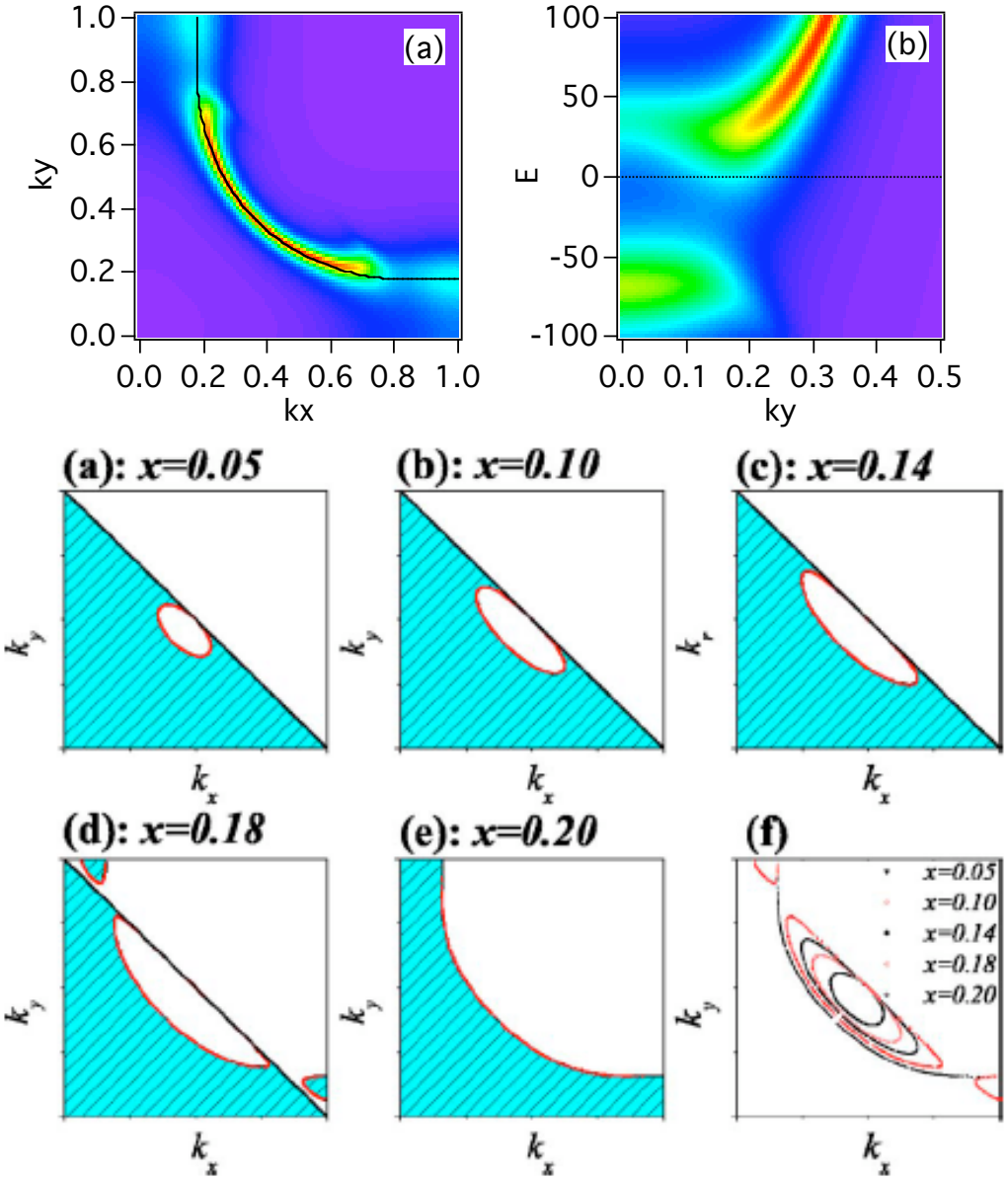

CDW (2 x 2), tb0, q=(.36,0), Δ=50, Γ=25
100
50
0
-50
-100
0.0
0.1
0.2
0.3
0.4
0.5


CDW (q,-q), tb0, q=(.36,0), Δ=50, Γ=25
100
50
0
-50
-100
0.0
0.1
0.2
0.3
0.4
0.5

Luttinger Zeros

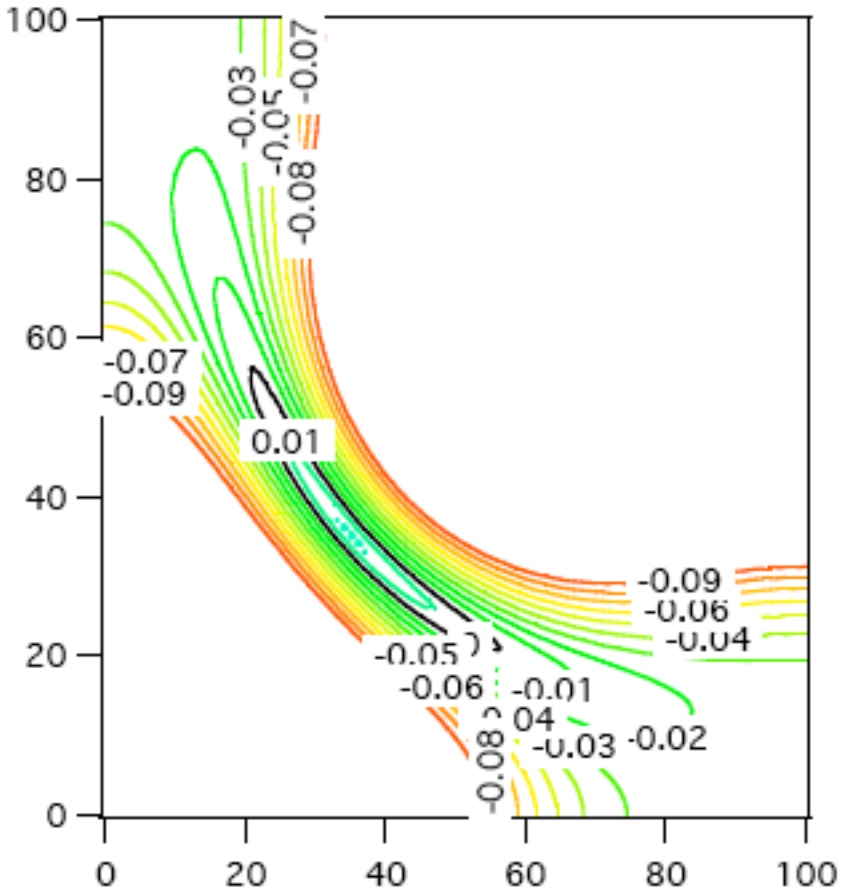


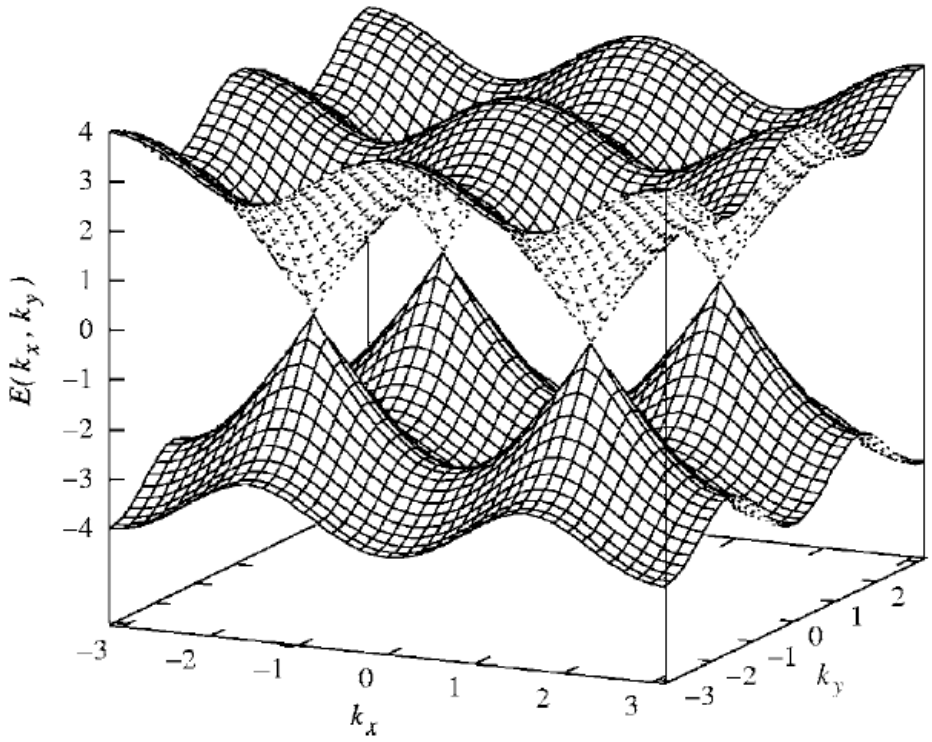
Stanescu, Phillips, Choy
cond-mat/0602280



Yang, Rice, Zhang
Phys Rev B 73, 174501 (2006)

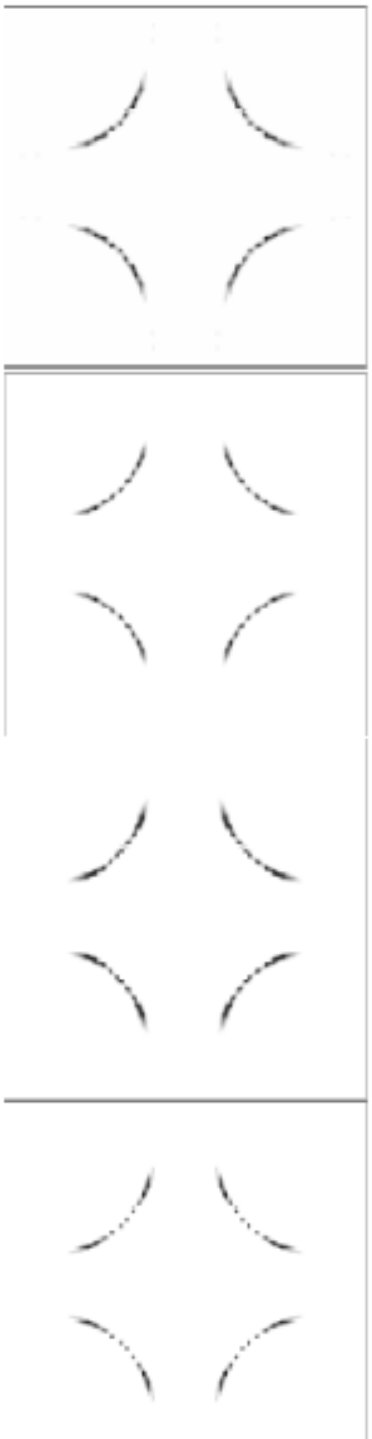
Dispersing Fermi Arcs in the Flux Phase State?

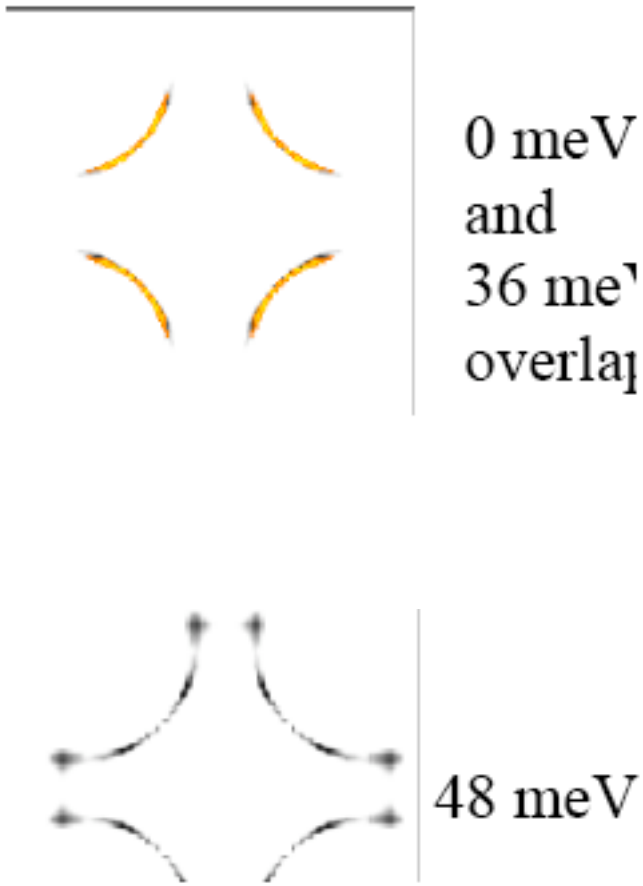




Wen and Lee - Phys Rev Lett 80, 2193 (1998)

Fermi arcs are dispersionless

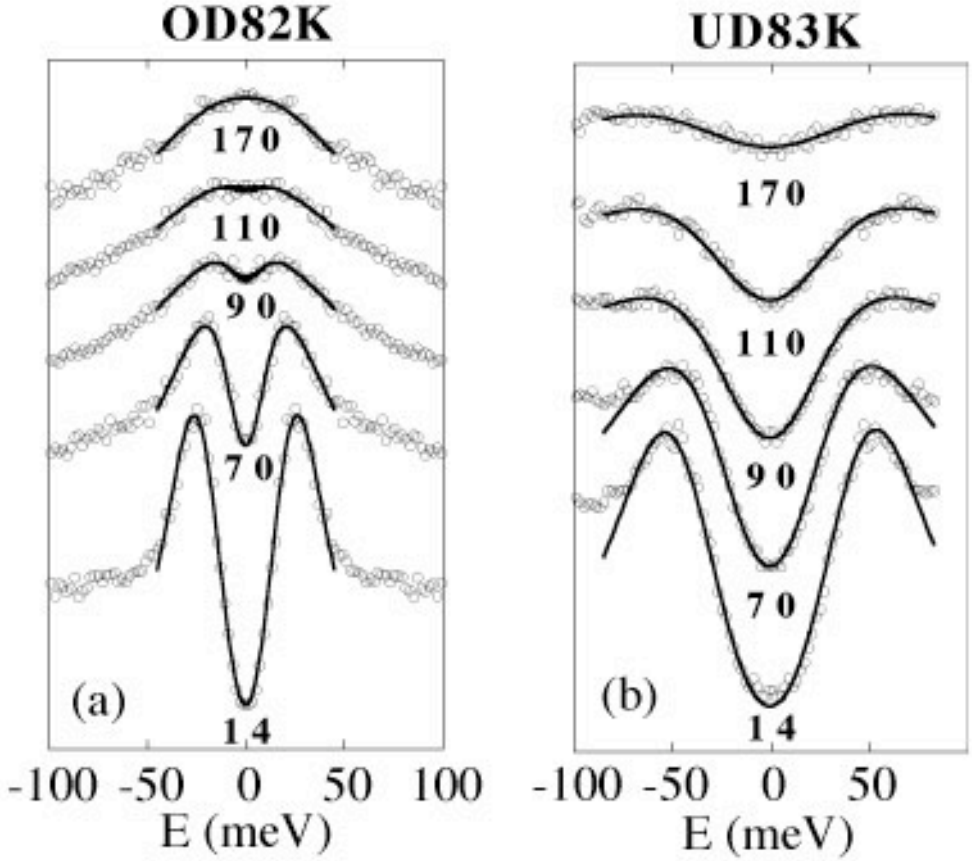




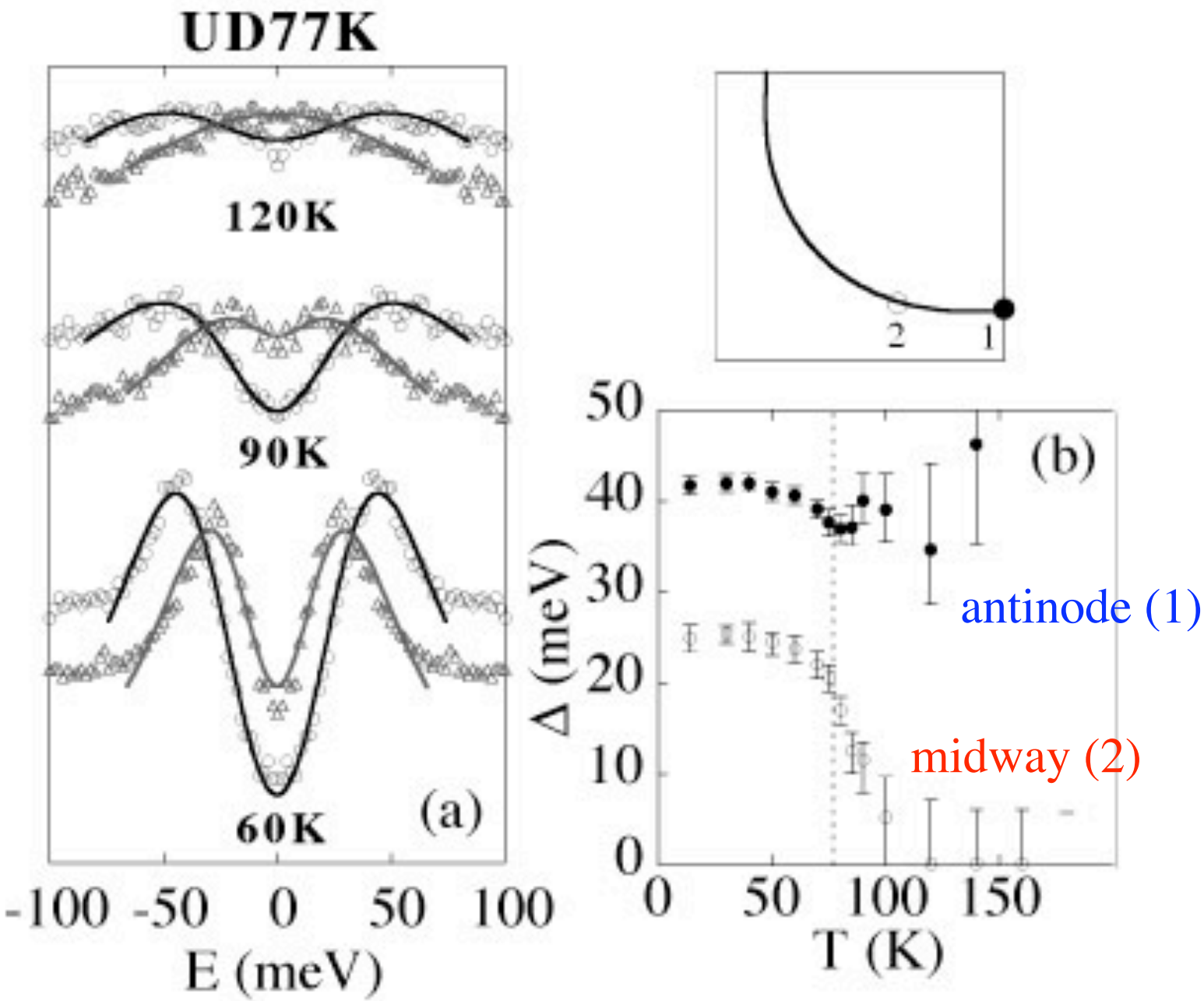
$\Sigma = -i\Gamma_1 + \Delta^2/(\omega+i\Gamma_0)$ where

Δ is the gap, Γ_1 the single particle scattering rate and Γ_0 the inverse pair lifetime

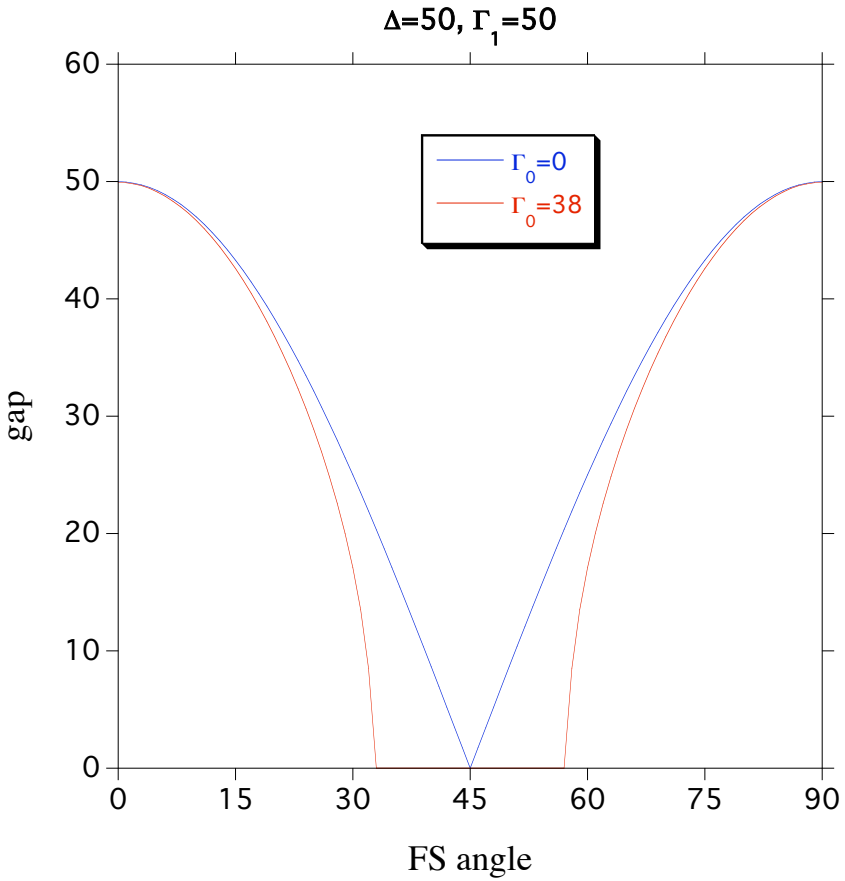
Antinode vs T

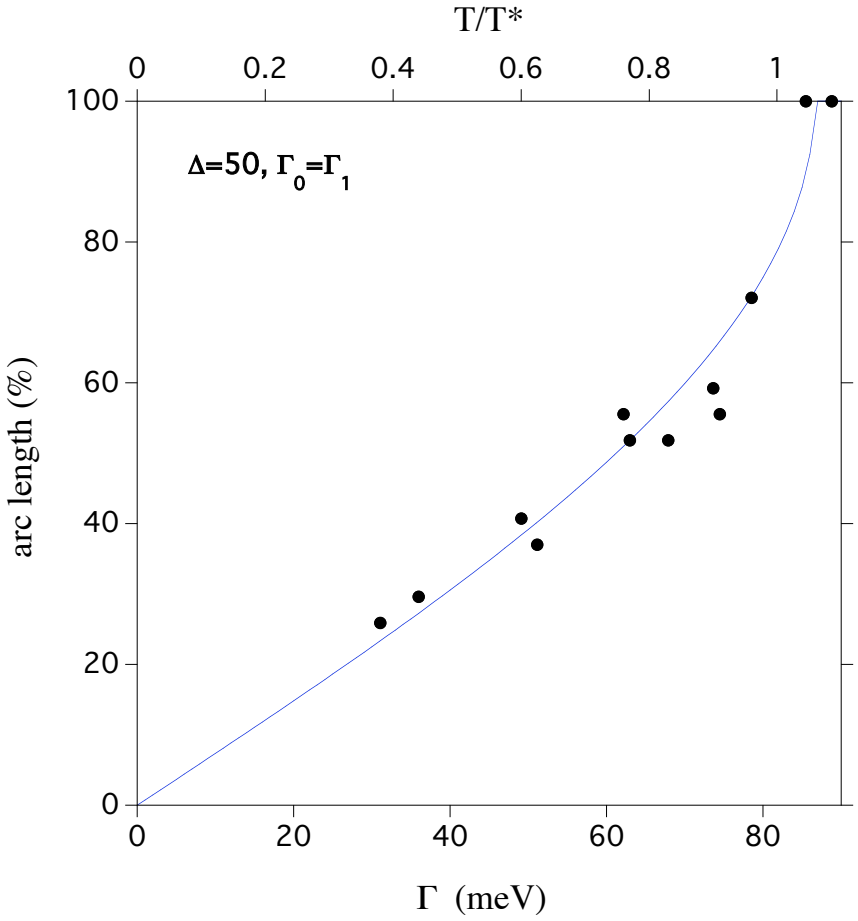


Norman *et al.*, Phys Rev B 57, 11093 (1998)


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

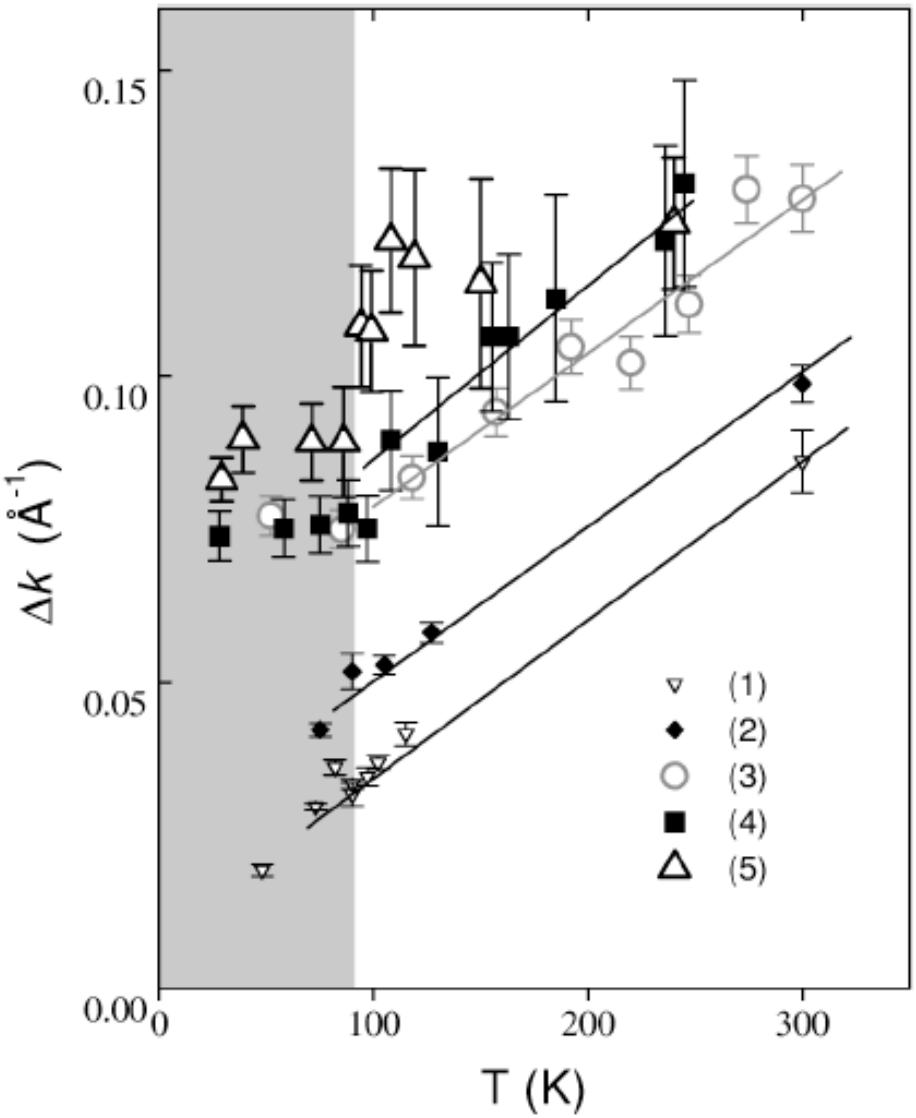
Arc Length is Linear in Γ_0 -> $\Gamma_0 \sim T$ -> Arc Length ~ T





Also explains arc collapse below T_c (Γ_0 -> 0)

Linear T scattering rate (Marginal Fermi Liquid)



Valla *et al*, Phys Rev Lett 85, 828 (2000)

SUMMARY

1. Spectroscopic data can be scaled as a function of T/T*(x)
2. Fermi arc length is linear in T
3. Pseudogap appears to distort in shape as a function of T
4. No shadow bands are found associated with finite q vector
5. Pseudogap is tied to k_F and E_F implying a q=0 instability
6. The data are consistent with a “fluctuating pairs” model