The Abdus Salam
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Miniworkshop on
New States of Stable and Unstable Quantum Matter
(14 - 25 August 2006)

The Nodal Metal in Cuprates: A New State of Matter?

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

Trieste, Aug. 21, 2006

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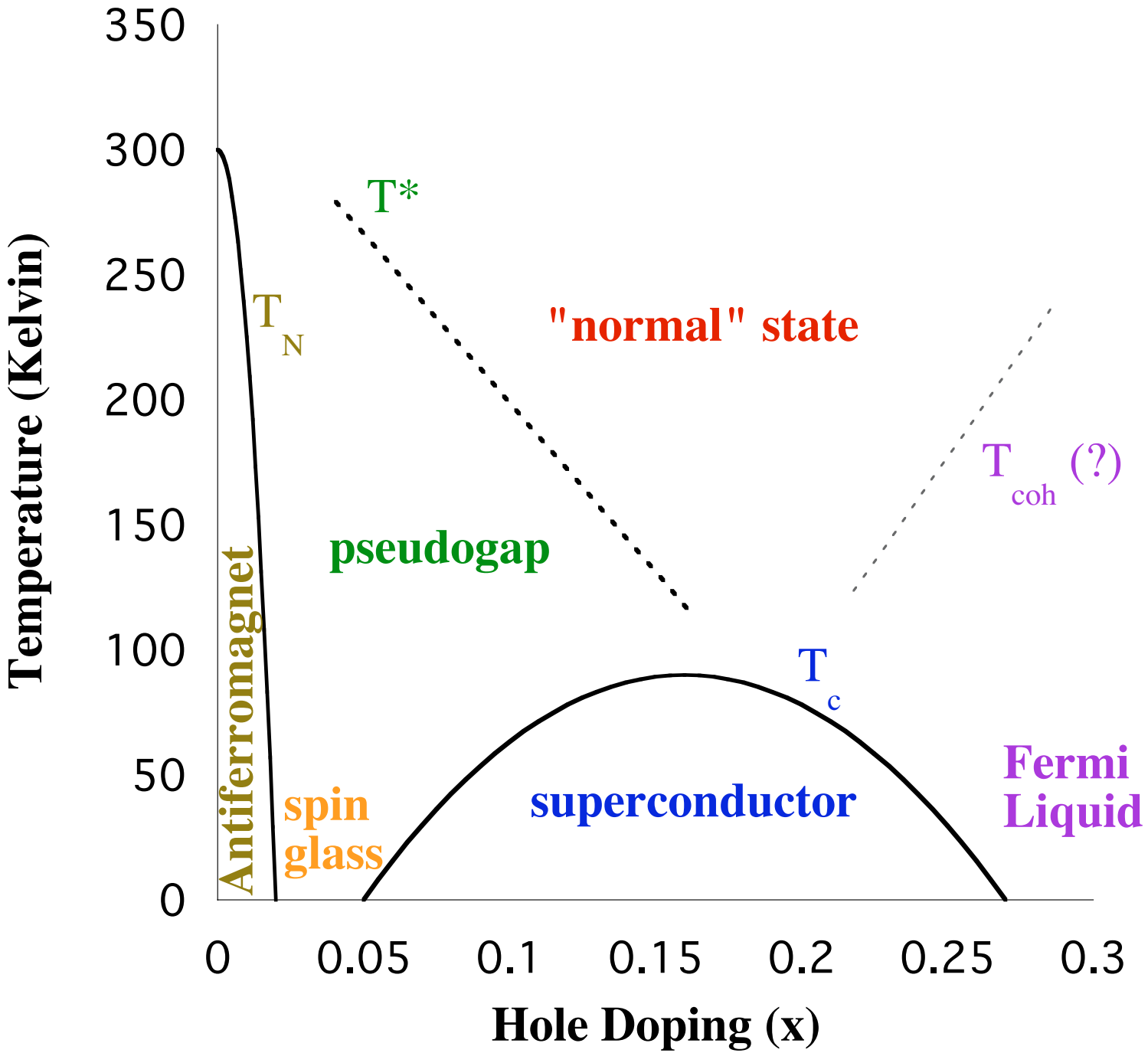
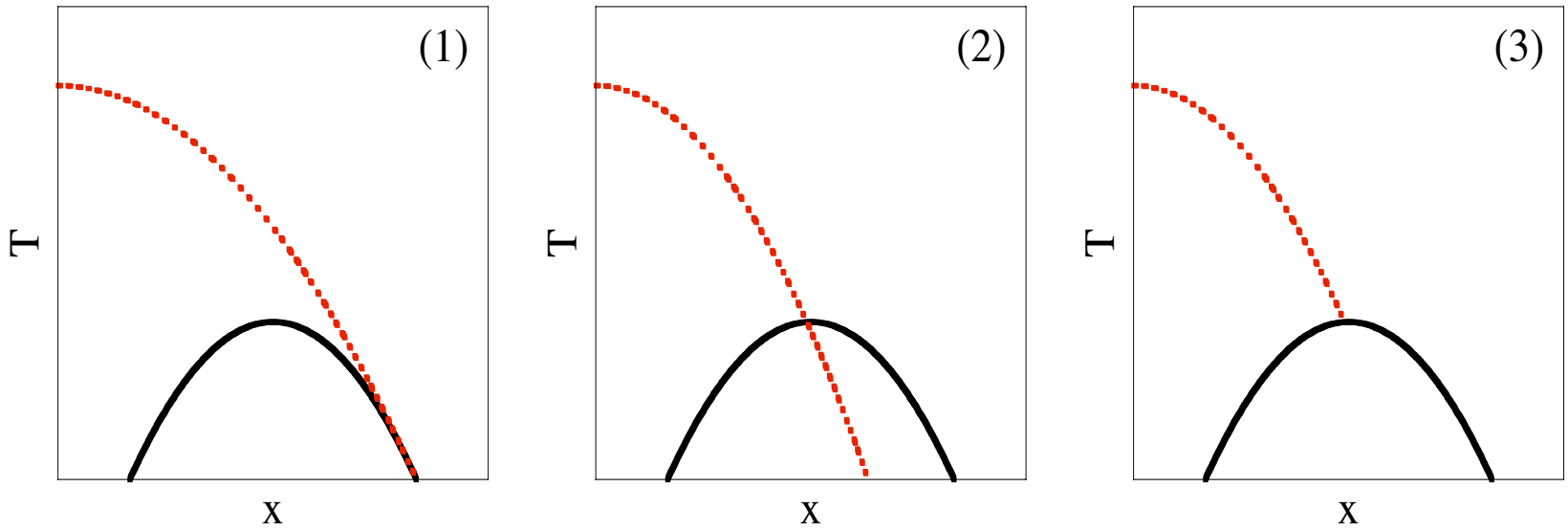
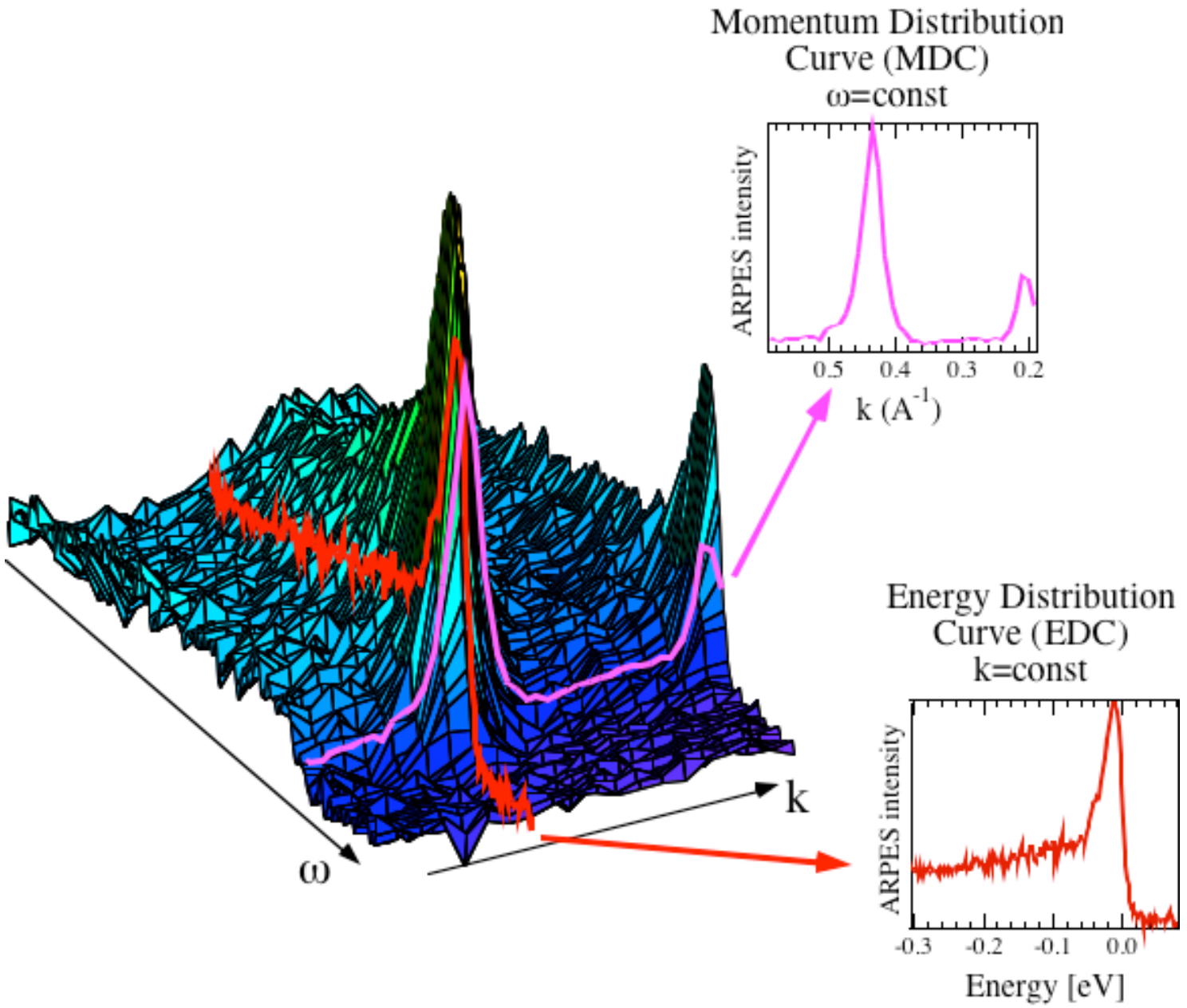

Temperature (Kelvin)
350
300
250
200
150
100
50
0
0
0.05
0.1
0.15
0.2
0.25
0.3
Hole Doping (x)
T*
T N
"normal" state
T coh (?)
pseudogap
T c
Antiferromagnet
spin glass
superconductor
Fermi Liquid



Norman, Pines, Kallin - Advances in Physics 54, 715 (2005)

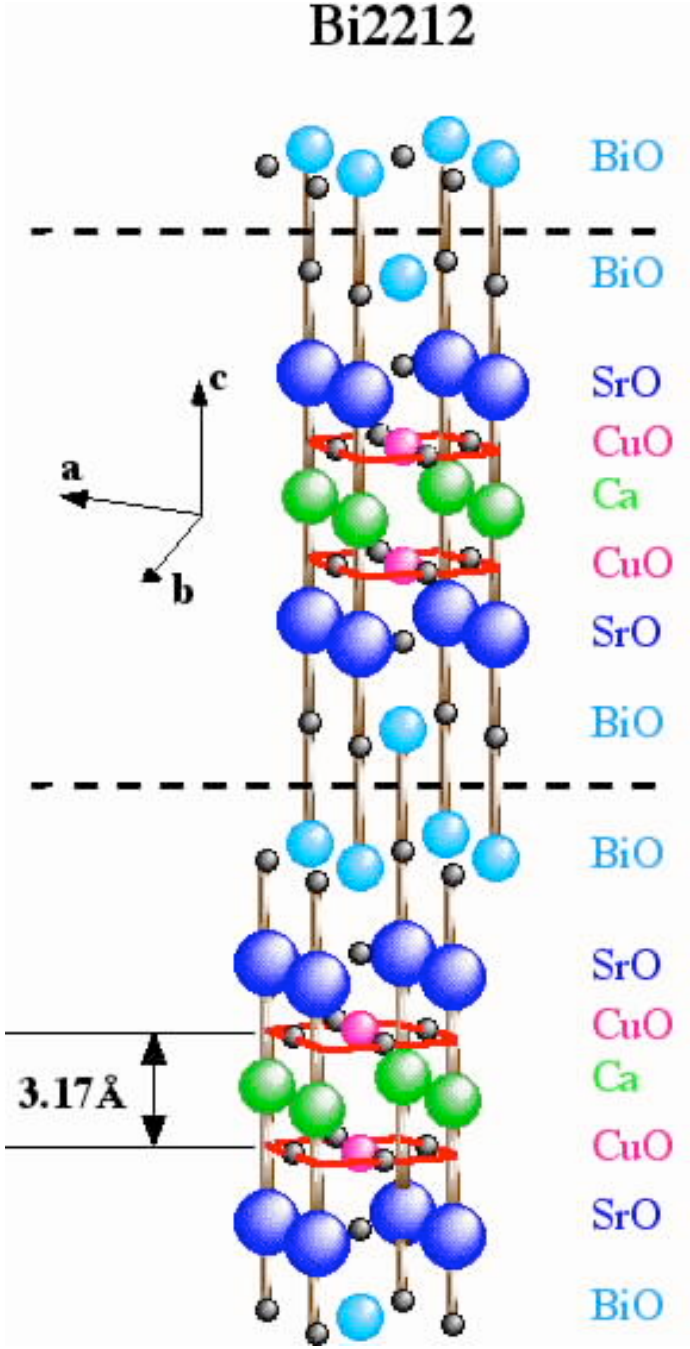
Angle Resolved Photoemission Spectroscopy (ARPES)



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

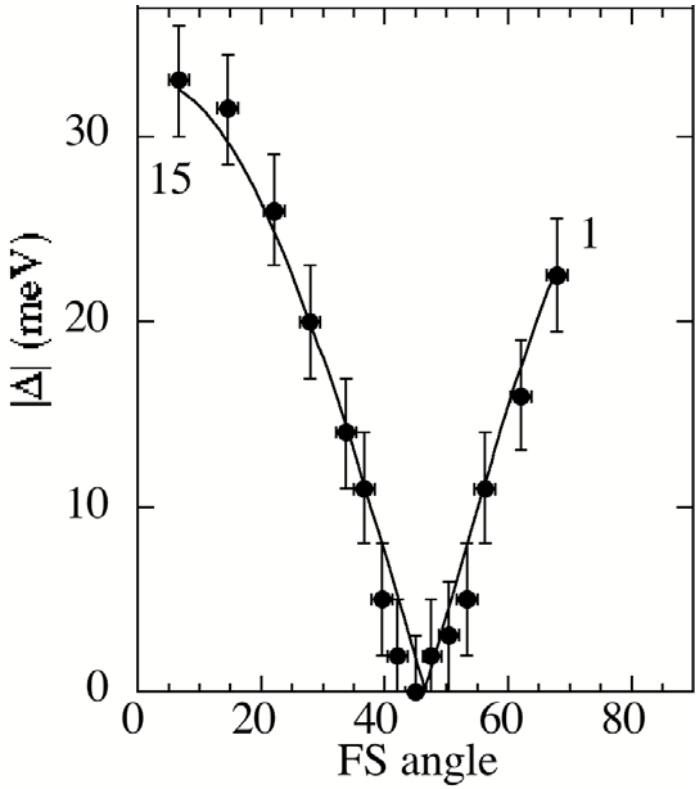
1. A is the single particle spectral function
2. f is the Fermi-Dirac function
3. c is the square of the dipole matrix element (plus intensity normalization)
4. $\langle\ \rangle$ is the convolution with the energy resolution gaussian and sum over the momentum window
5. background is secondaries plus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

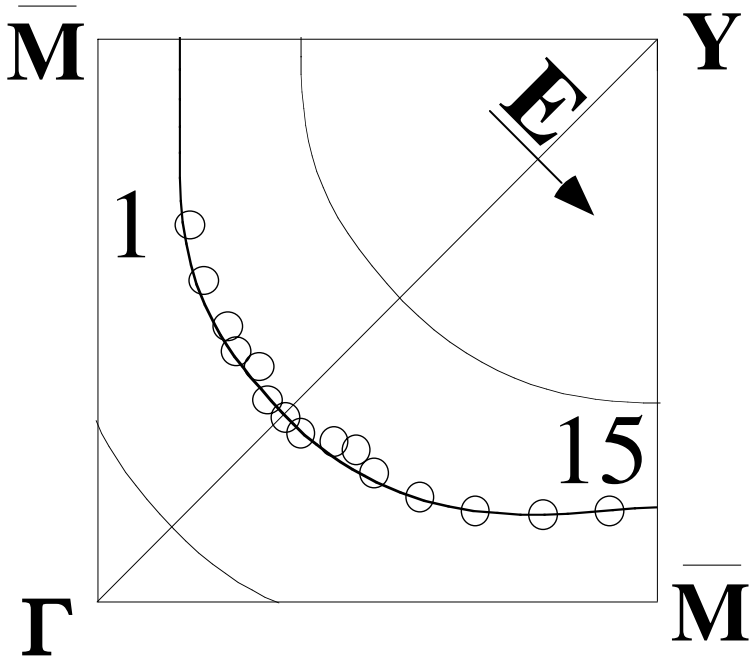

Bi2212
BiO
BiO
SrO
CuO
Ca
CuO
SrO
BiO
BiO
SrO
CuO
Ca
CuO
SrO
BiO
c
a
b
3.17Å

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

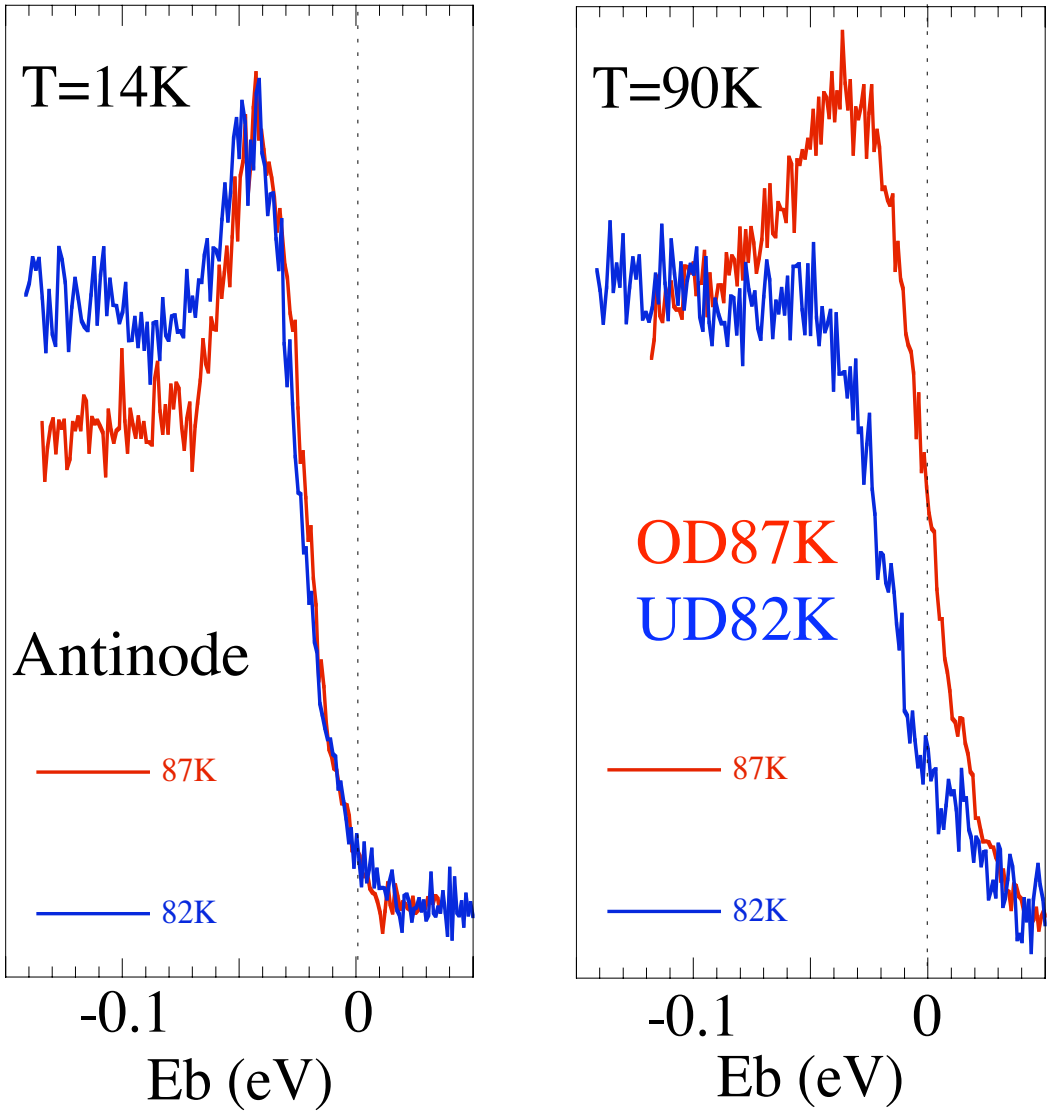


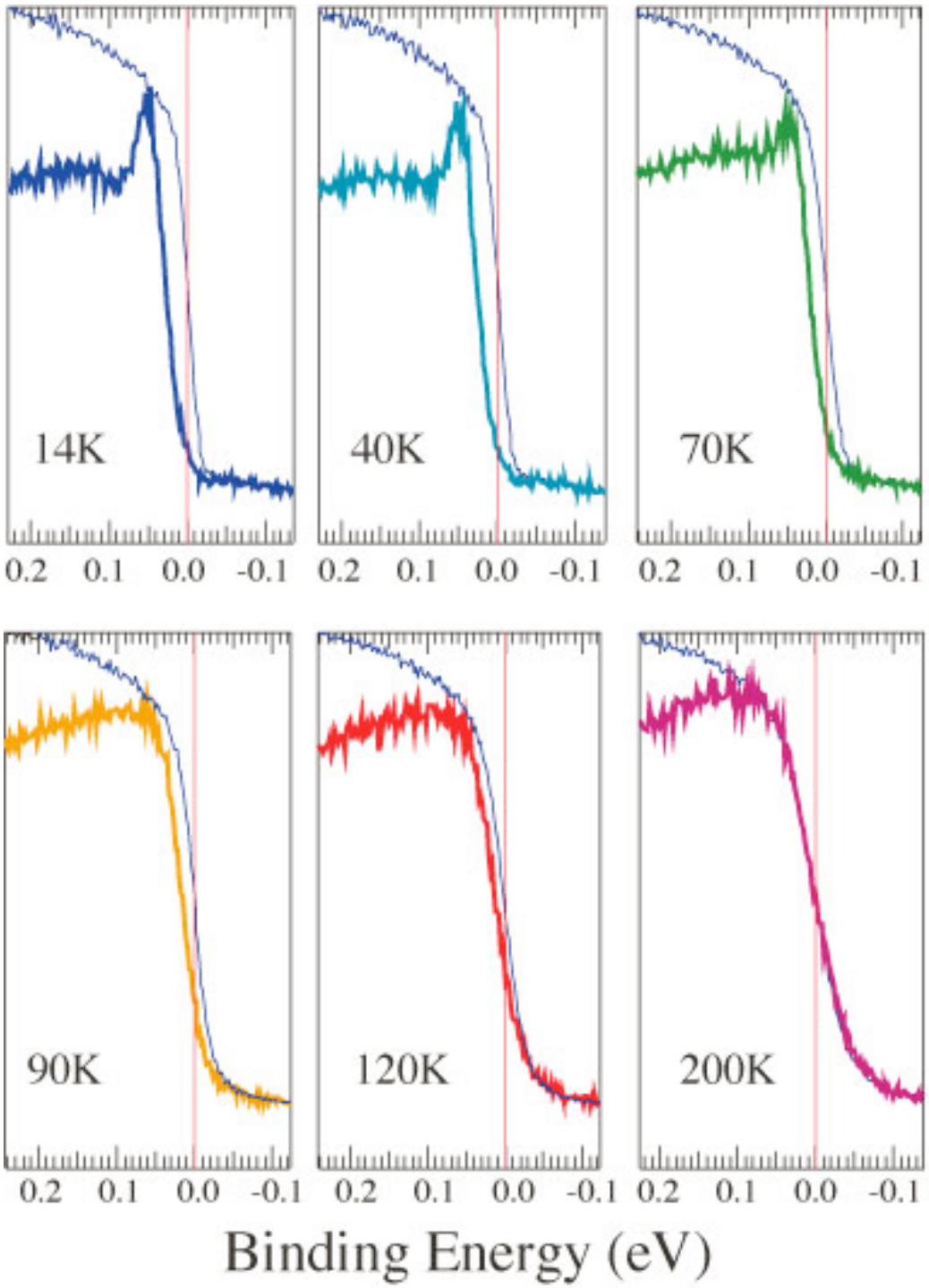


Bi2212
overdoped, T_c=87K
(OD87K)

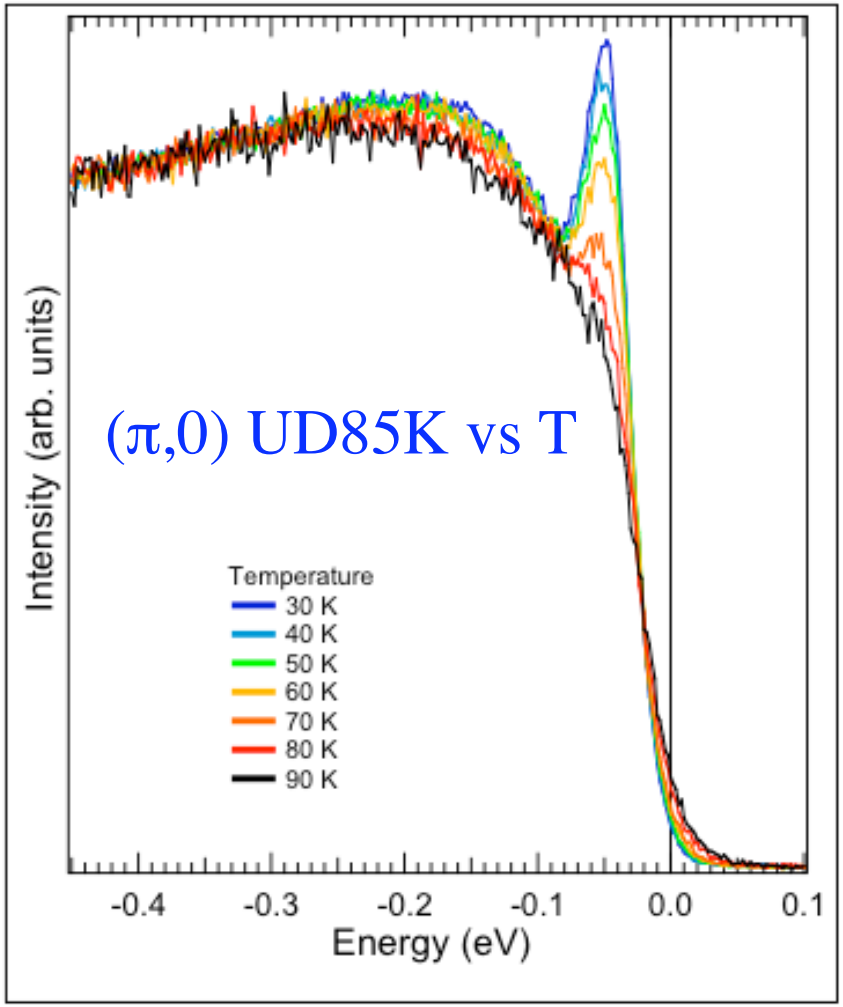
ARPES - Ding *et al.*, Nature 382, 51 (1996)

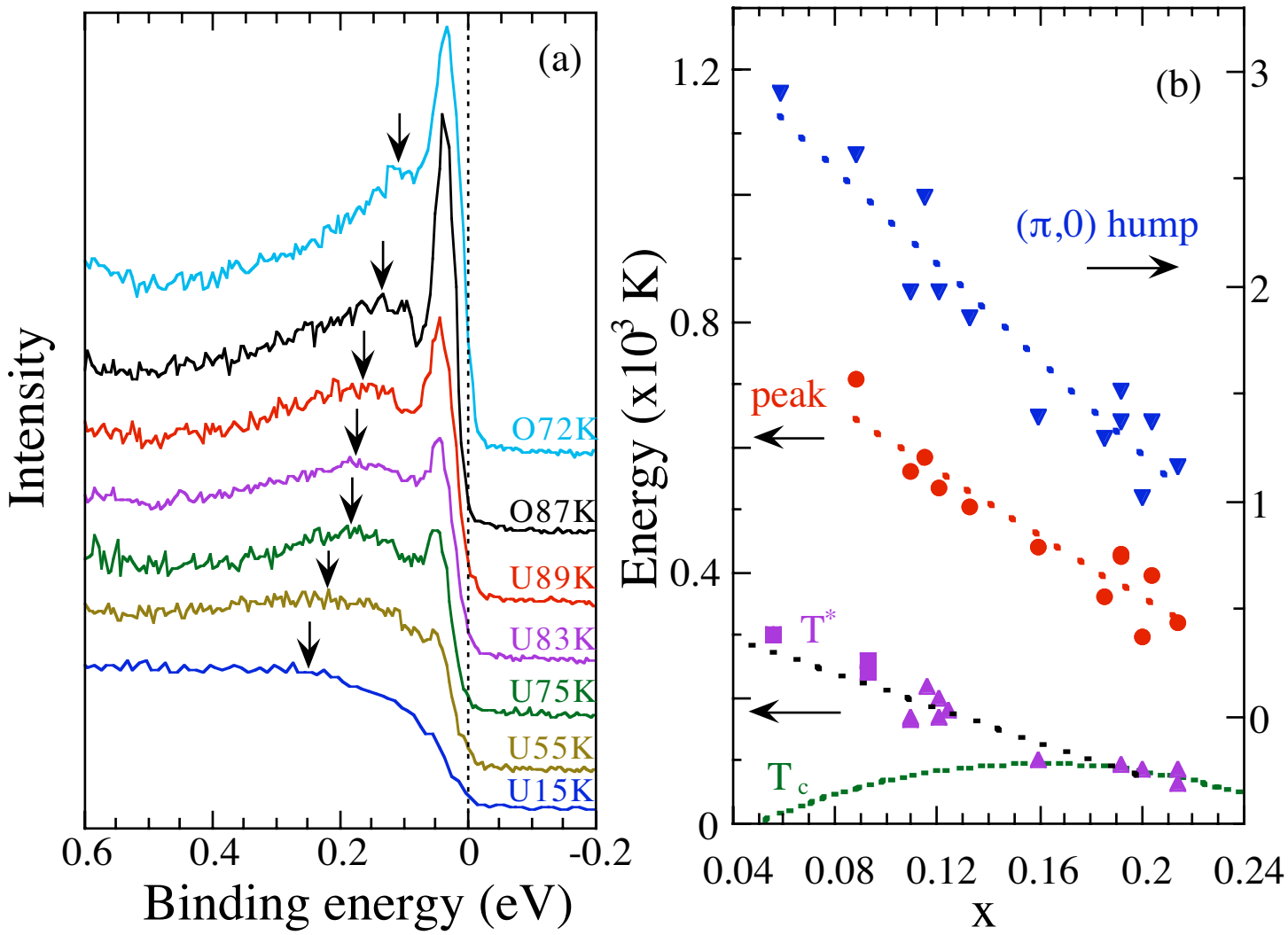
pseudogap - spectral gap but no coherent peak





<-- Antinode UD83K vs T





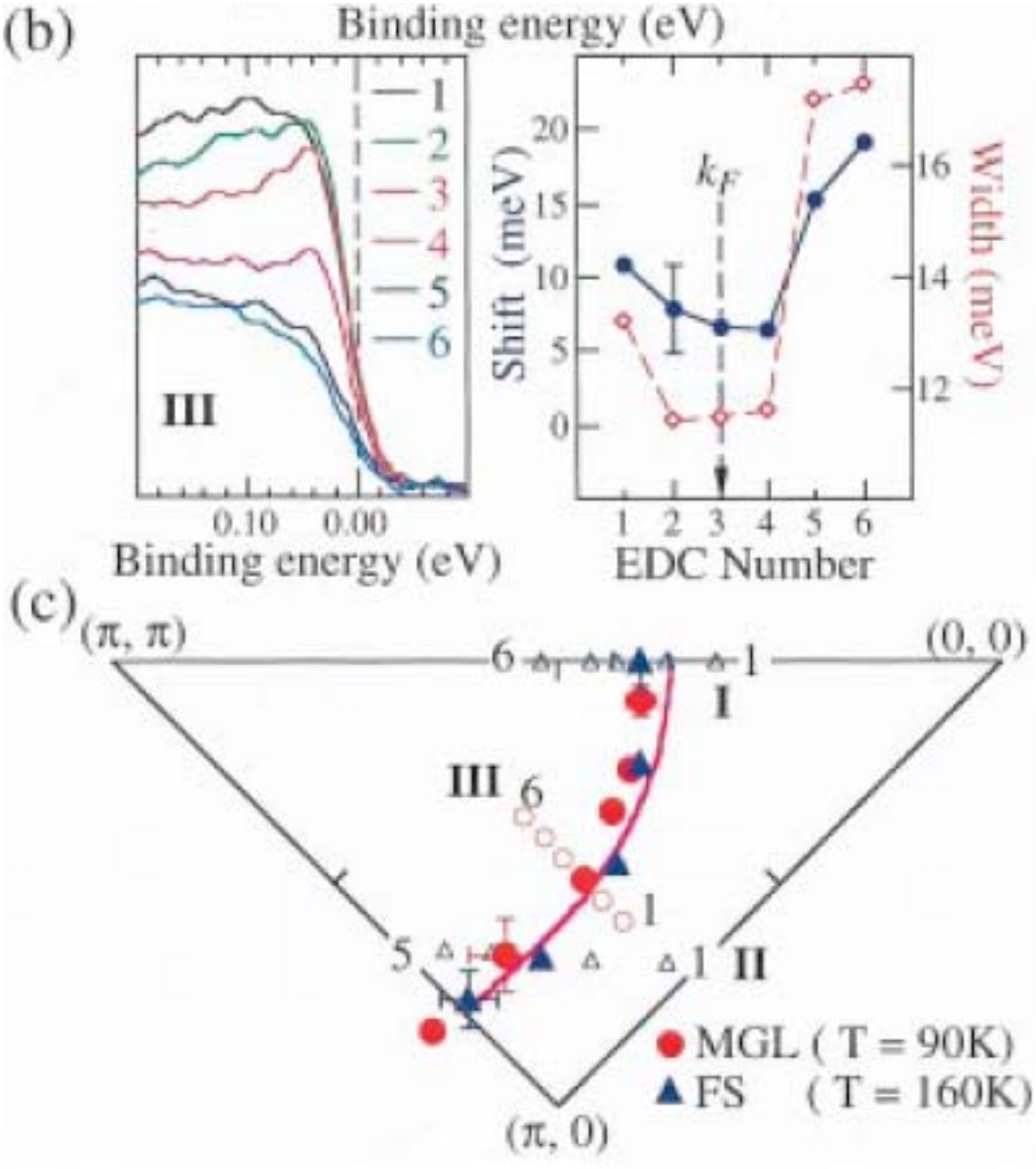
Left - (π,0) spectra versus doping (arrow marks the hump)

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

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

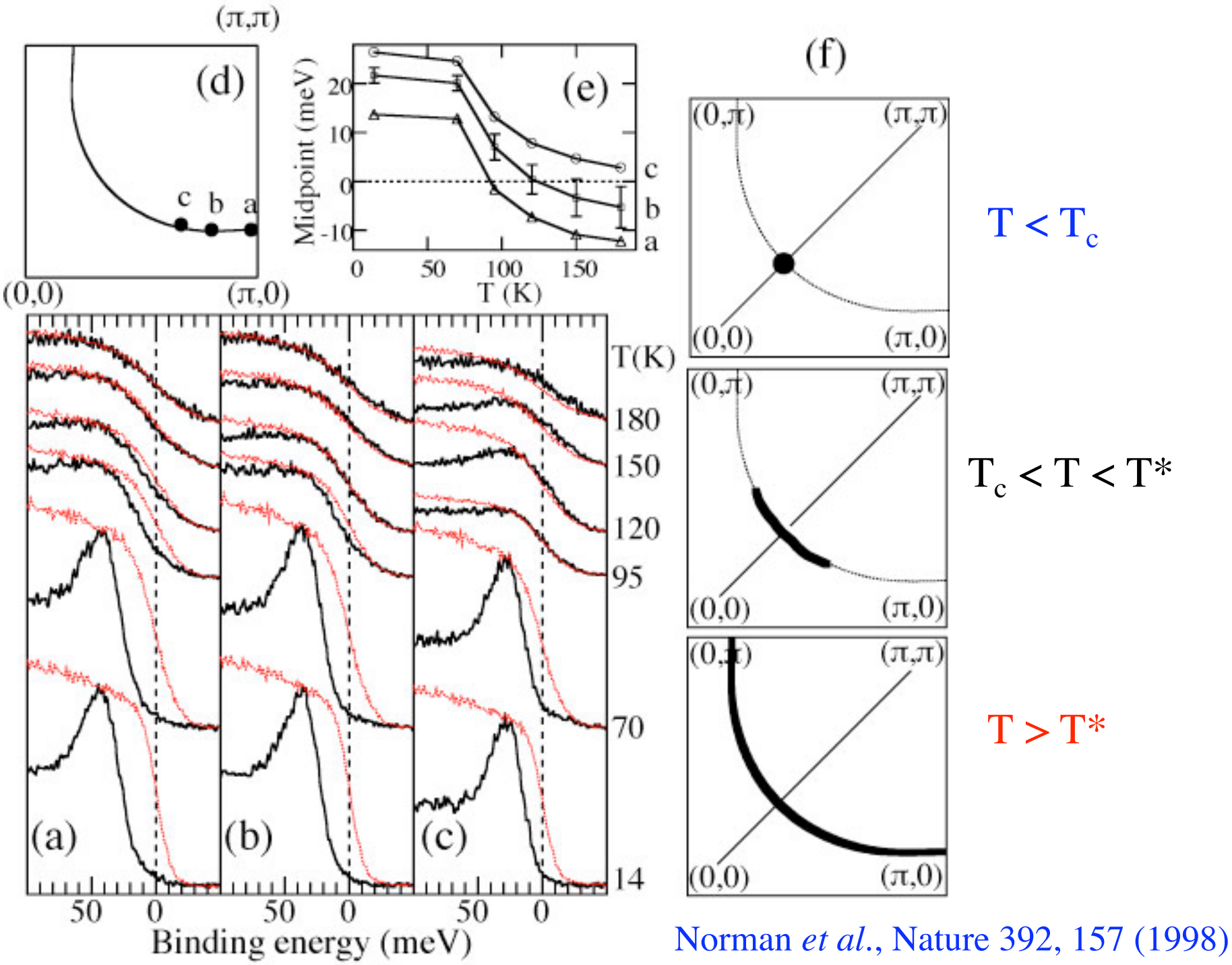
"Fermi surface" in the presence of an energy gap

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

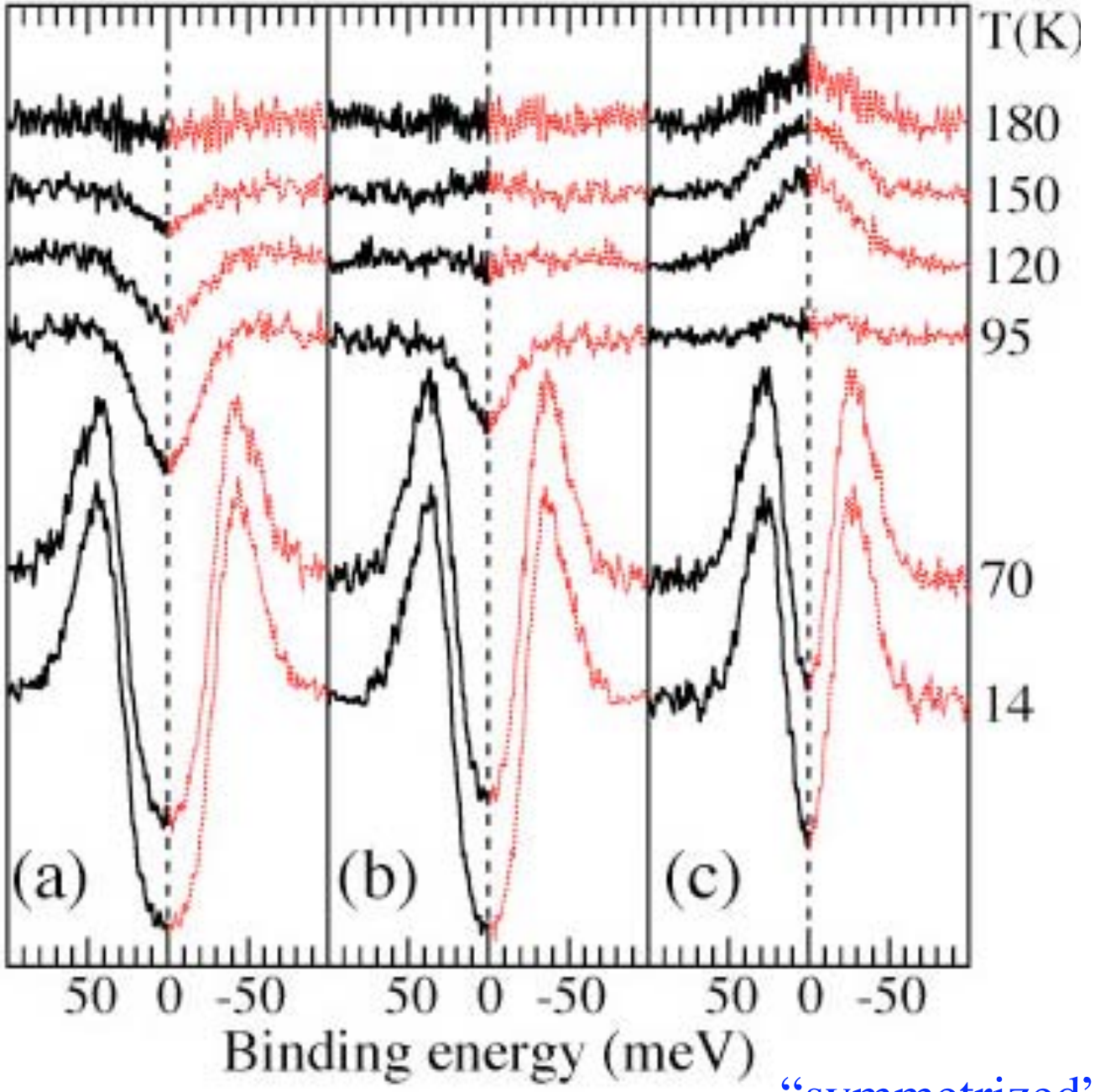


Underlying Fermi surface
for a gapped metal
(minimum gap locus - MGL)

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

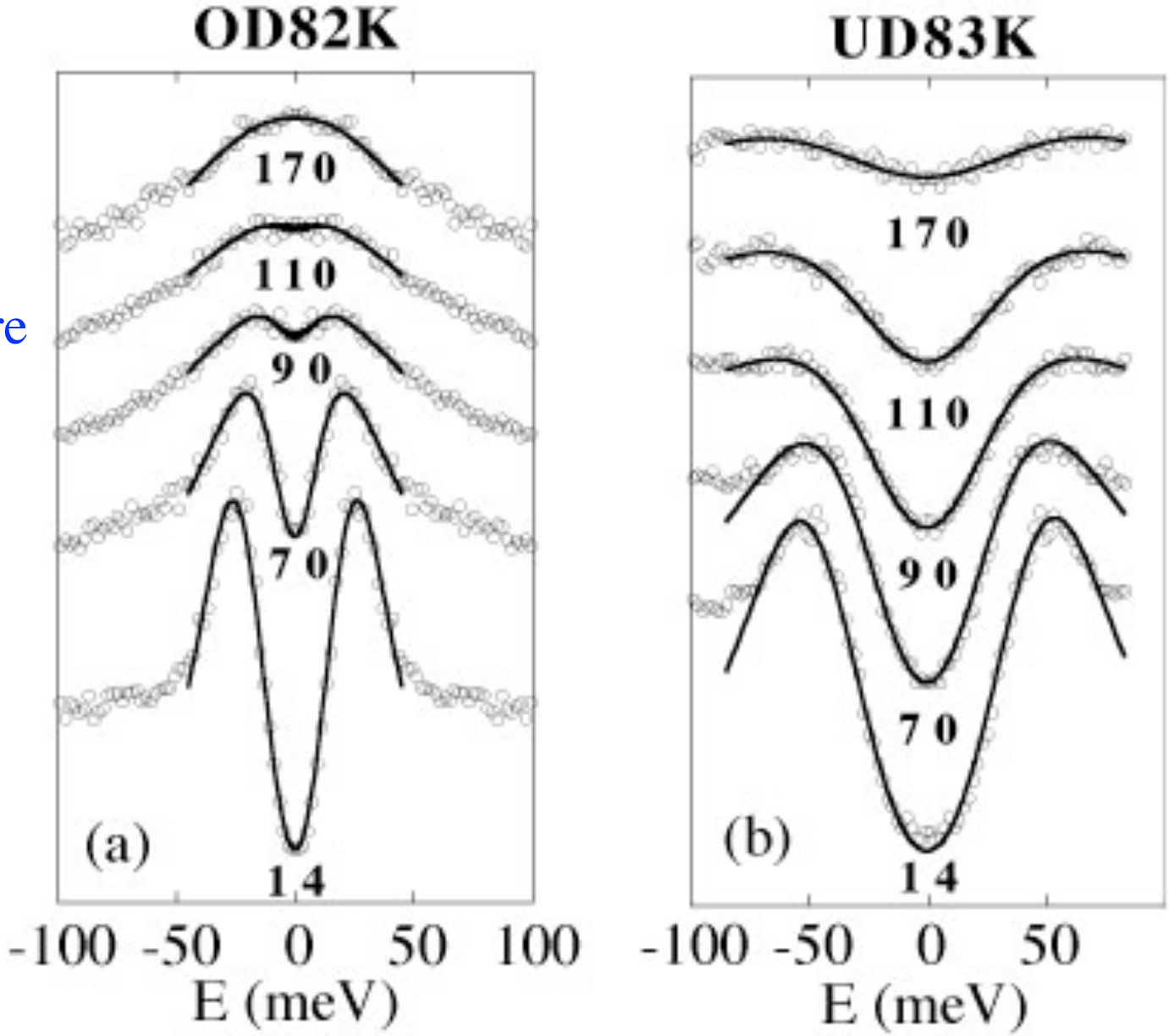


Norman *et al.*, Nature 392, 157 (1998)



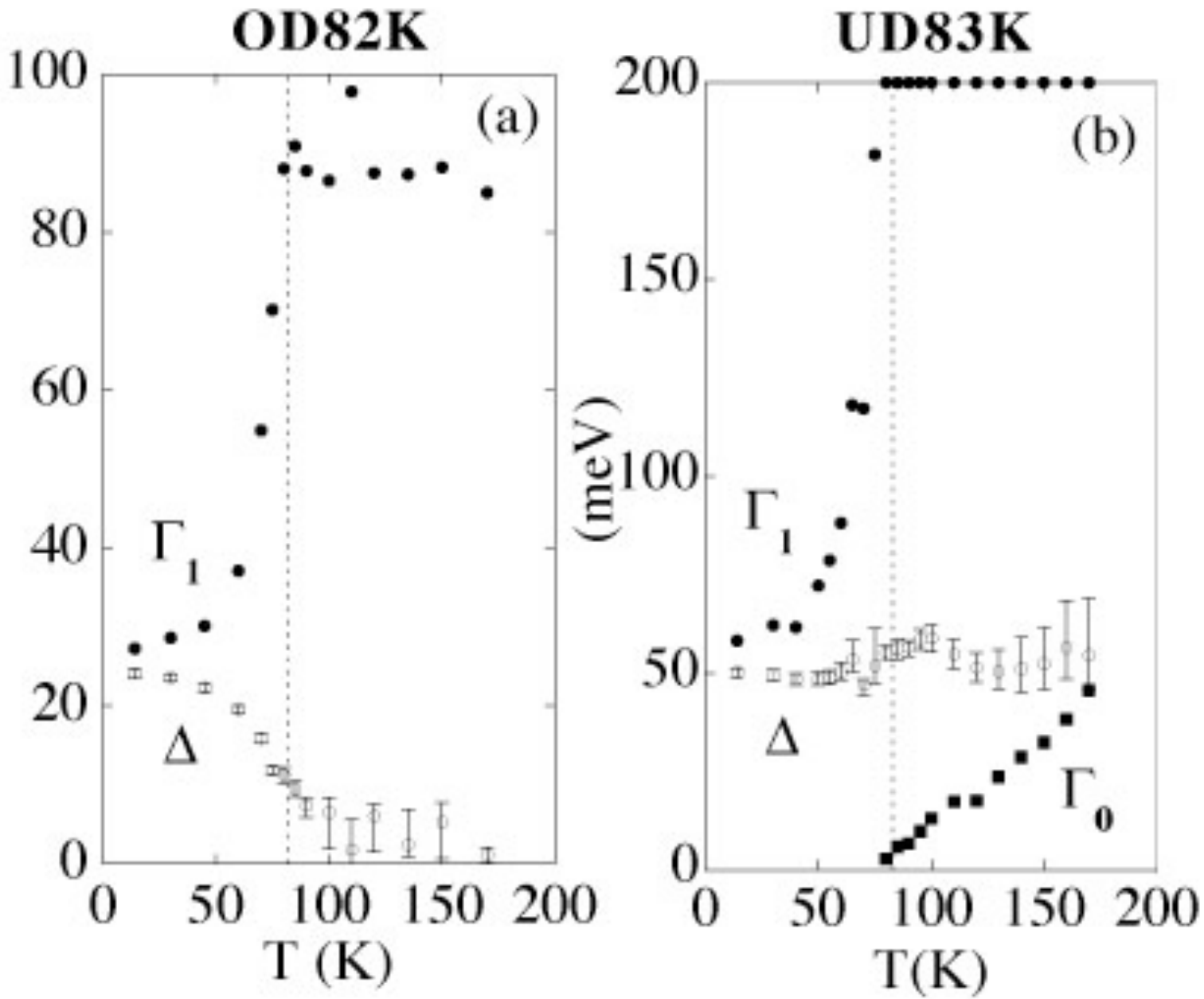
"symmetrized" data vs T

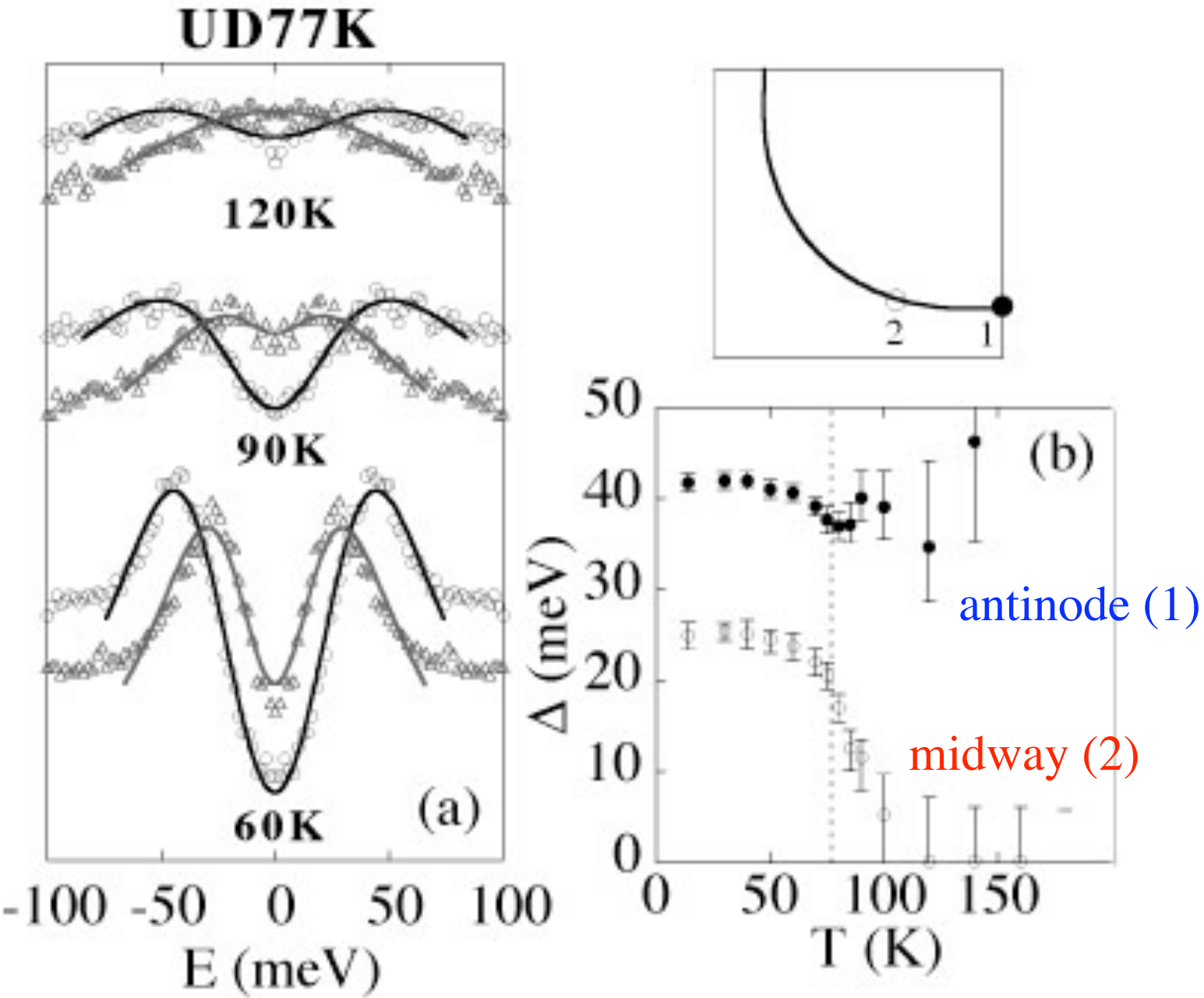
Antinode
vs
temperature



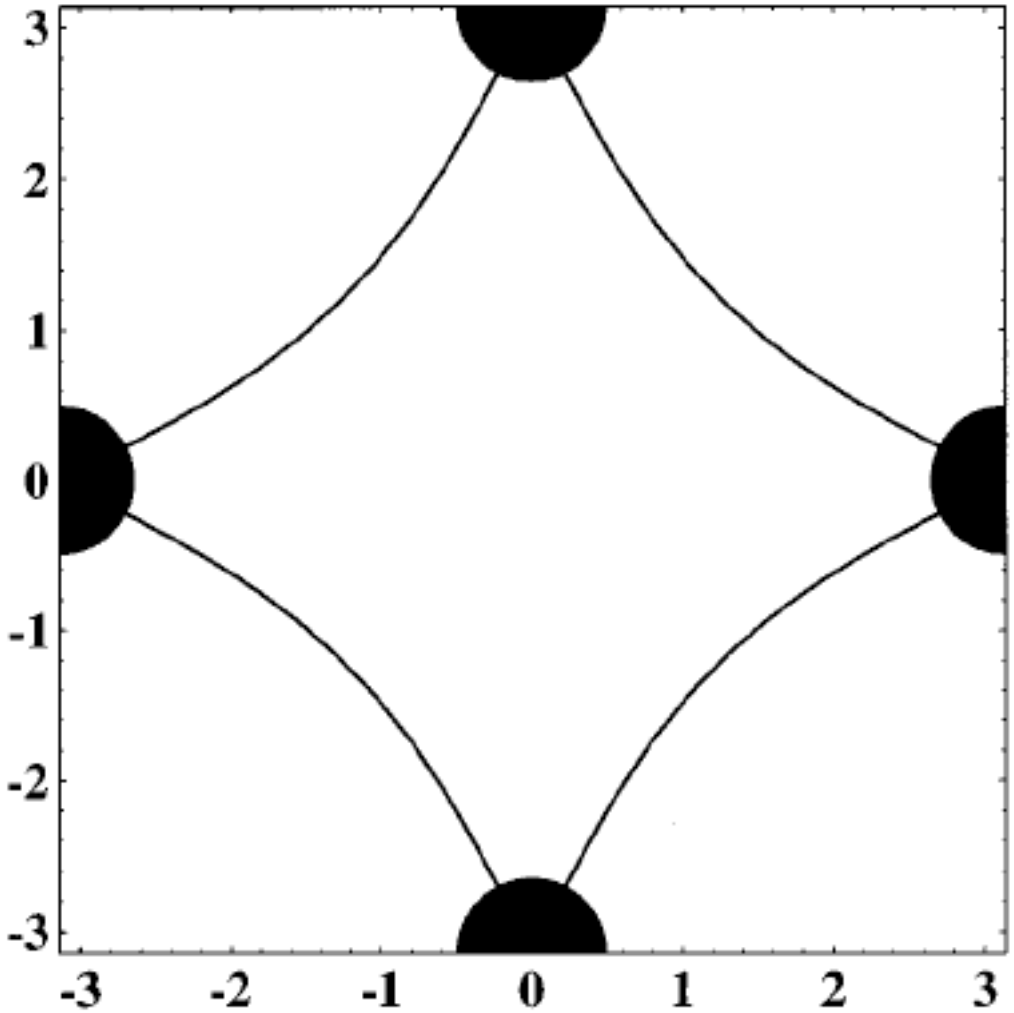
$\Sigma = -i\Gamma_1 + \Delta^2/(\omega+i\Gamma_0)$

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


OD82K
(a)
100
80
60
40
20
0
Γ1
Δ
0
50
100
150
200
T (K)
UD83K
(b)
200
150
100
50
0
(meV)
Γ1
Δ
Γ0
0
50
100
150
200
T(K)


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)

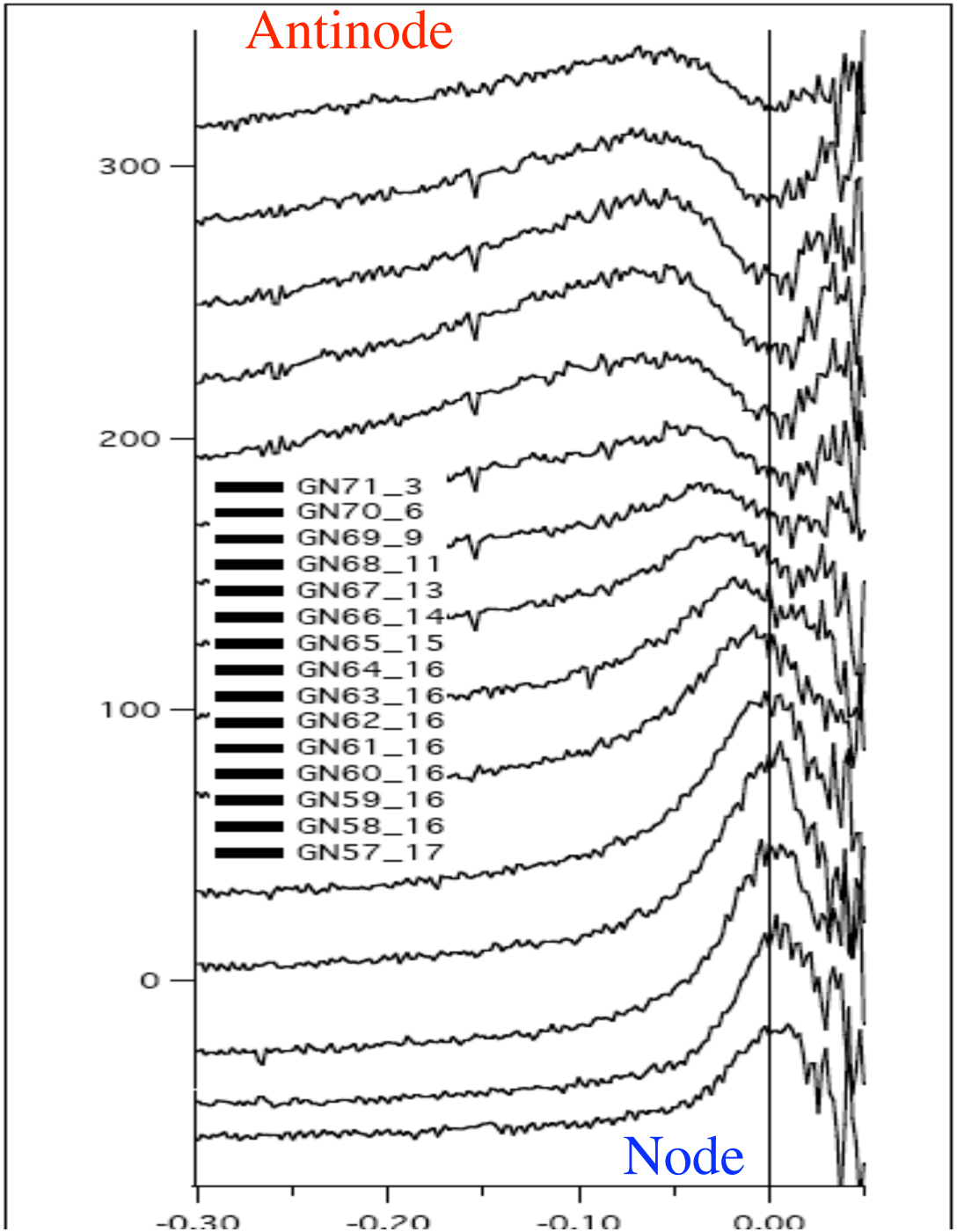
Arcs Connecting Pseudogapped Regions



Geshkenbein, Ioffe, Larkin - Phys Rev B 55, 3173 (1997)

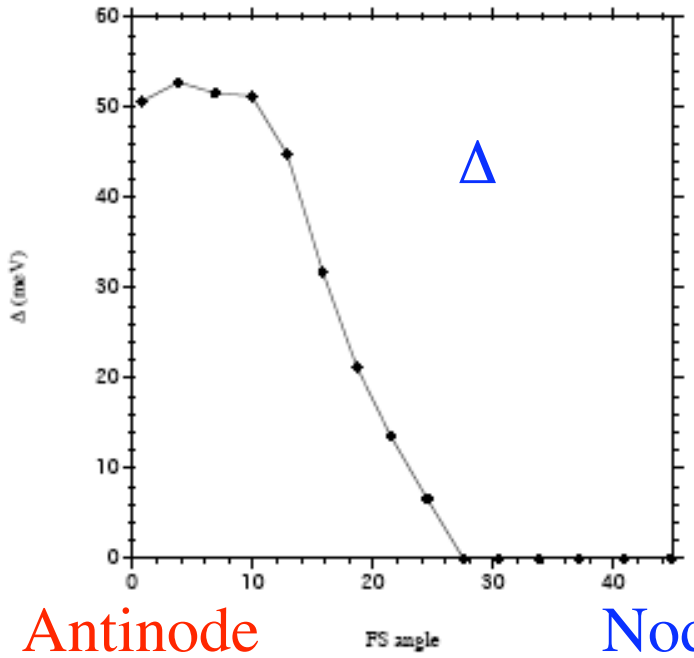
Bi2212
OP90K
T=140K

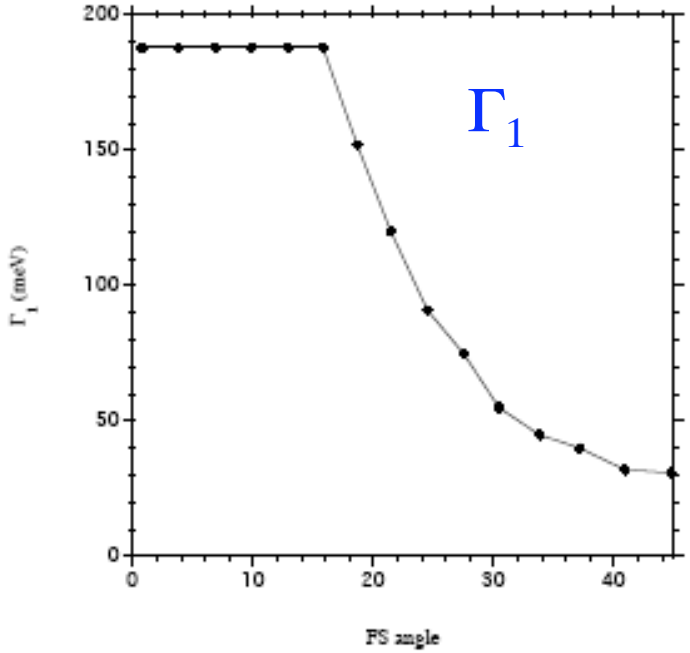
Fermi function
divided data

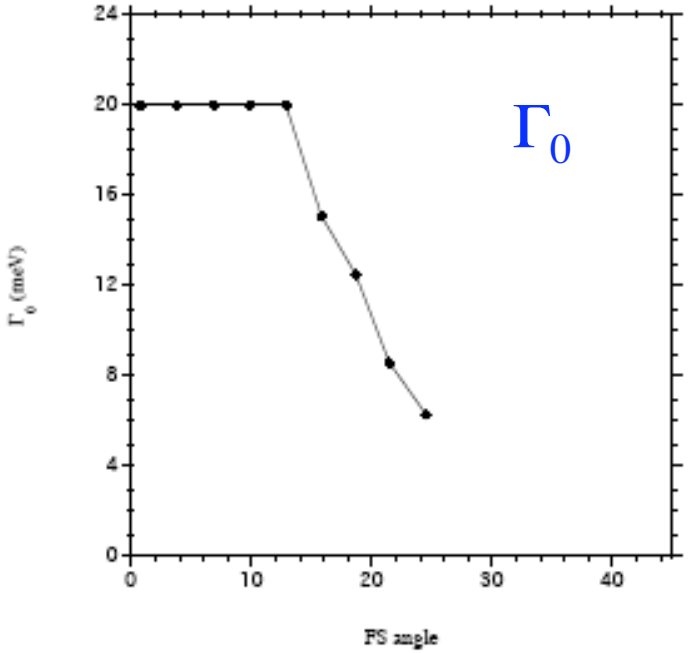


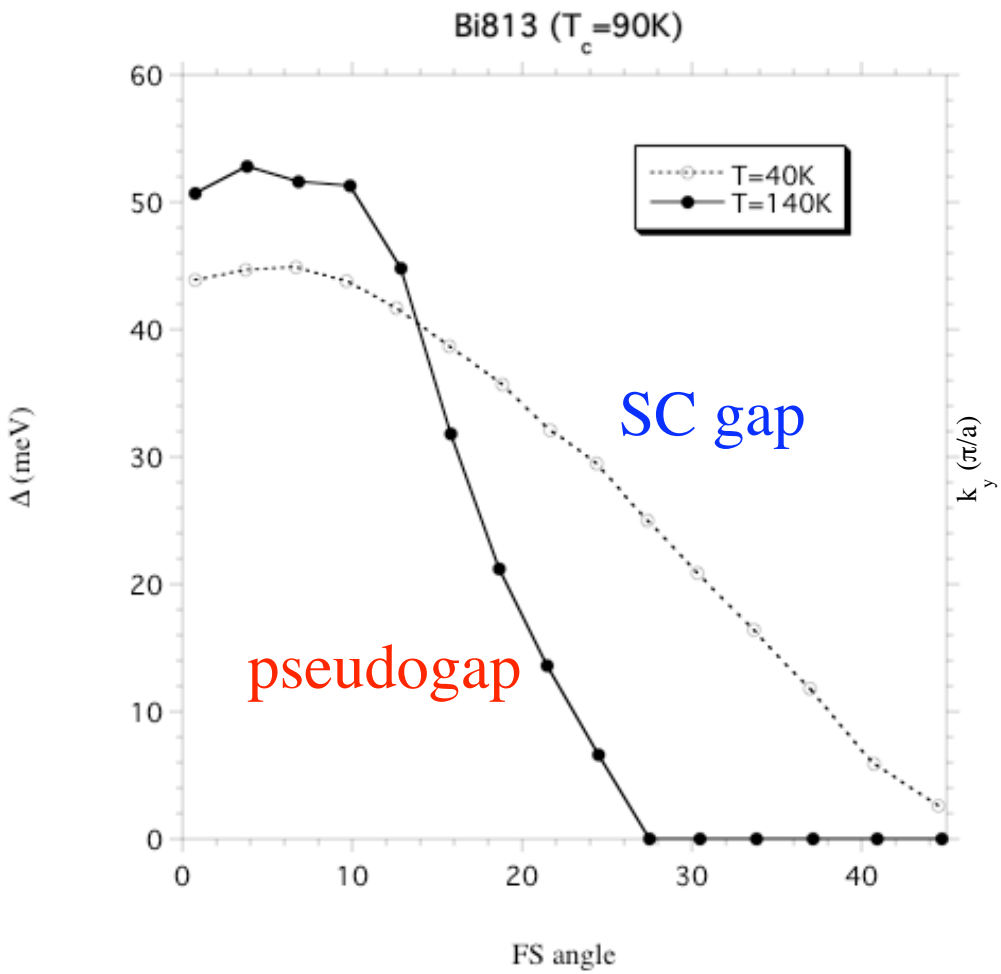
Bi2212 OP90K
T=140K vs
Fermi surface angle

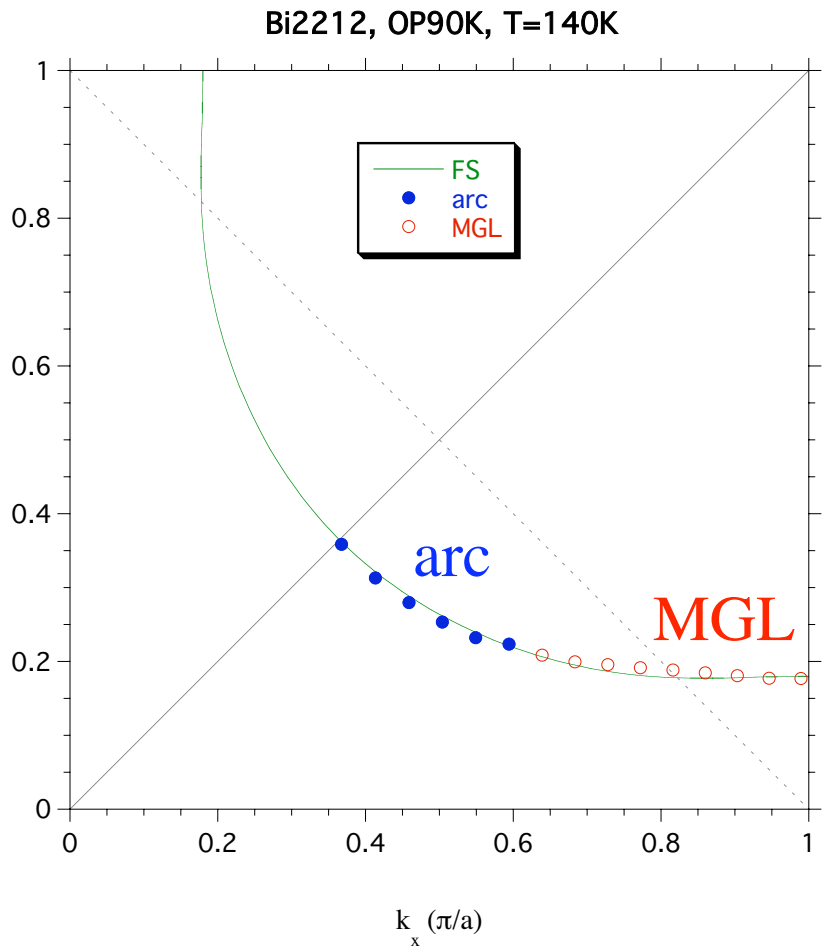
$\Sigma = -i\Gamma_1 + \Delta^2/(\omega + i\Gamma_0)$





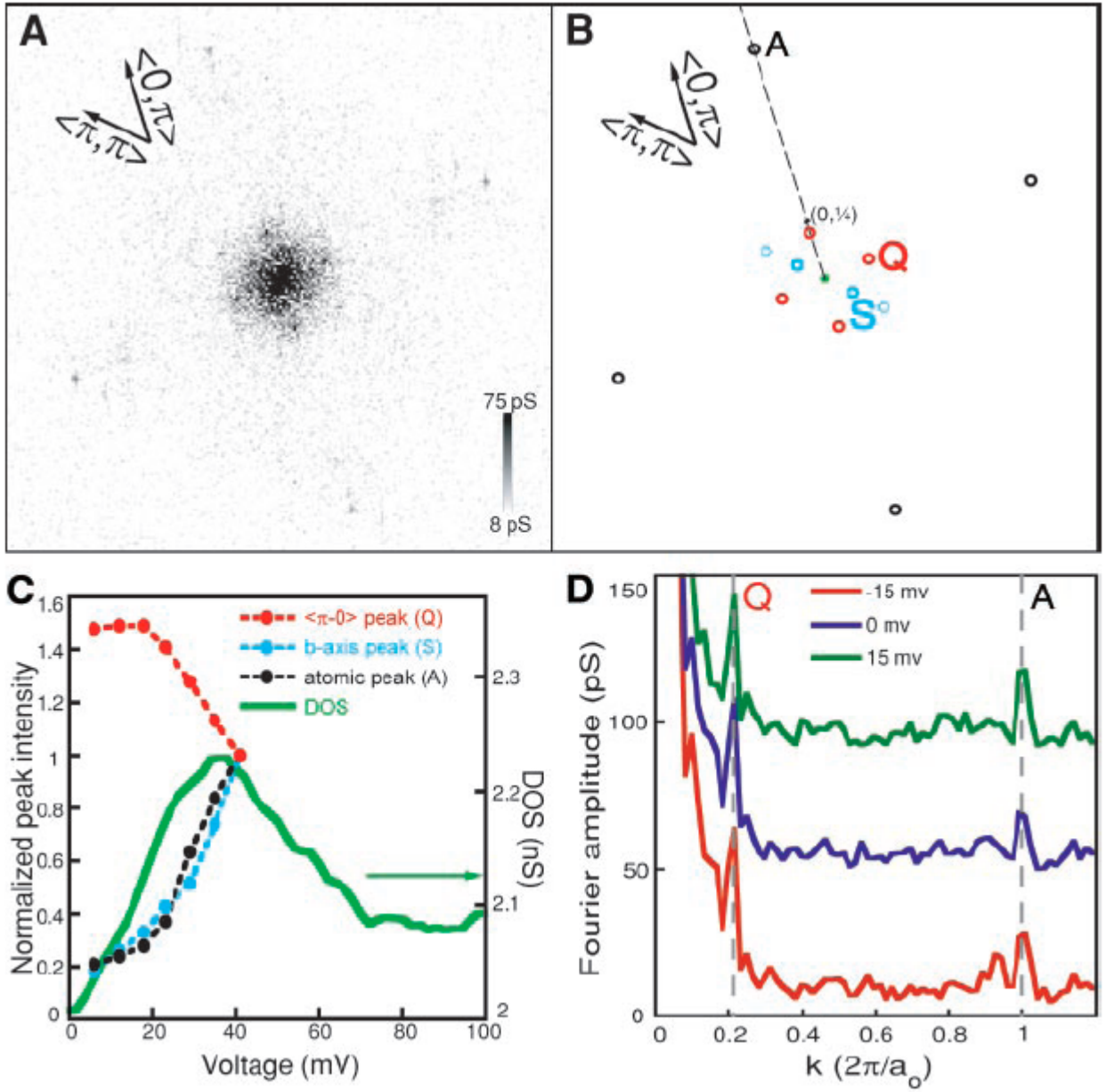



Bi813 (T_c=90K)
T=40K
T=140K
SC gap
pseudogap
Δ (meV)
FS angle
0
10
20
30
40
50
60

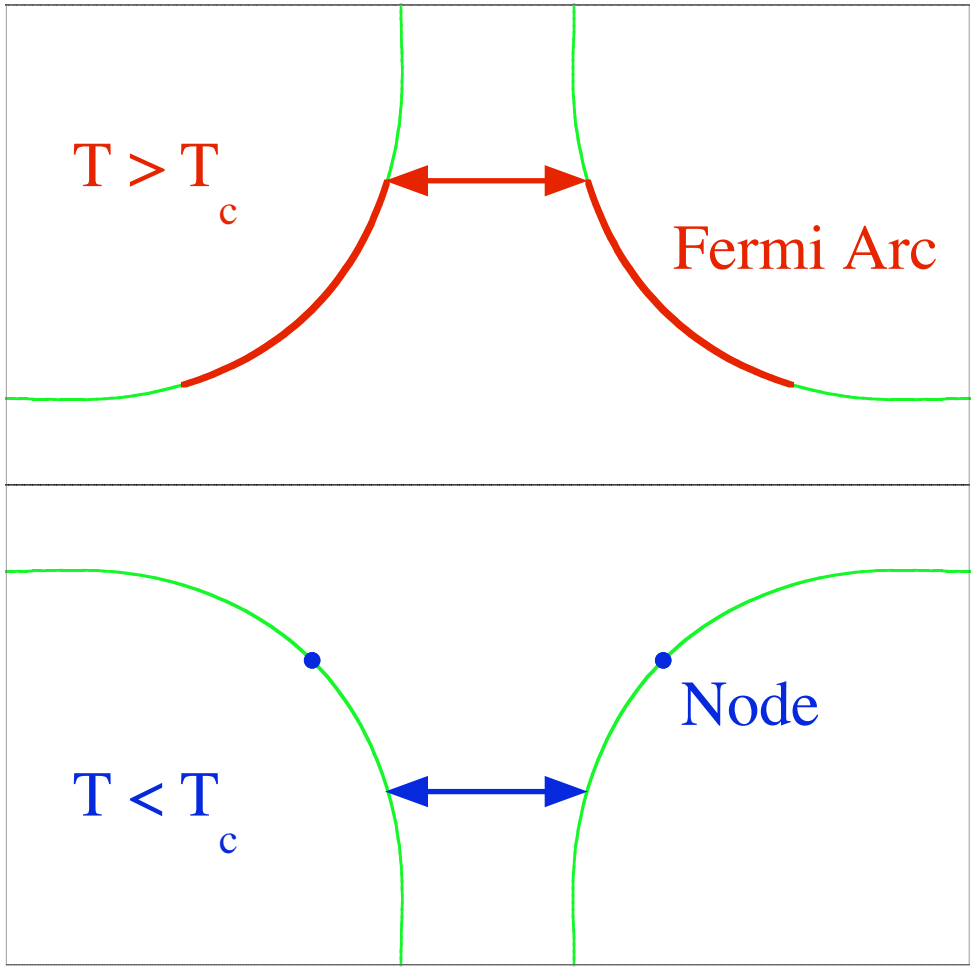

Bi2212, OP90K, T=140K
FS
arc
MGL
arc
MGL
k_y (π/a)
k_x (π/a)
0
0.2
0.4
0.6
0.8
1

Non-dispersive FT-STM peaks in the pseudogap state

Vershinin *et al.*, Science 303, 1995 (2004) - Charge ordering?

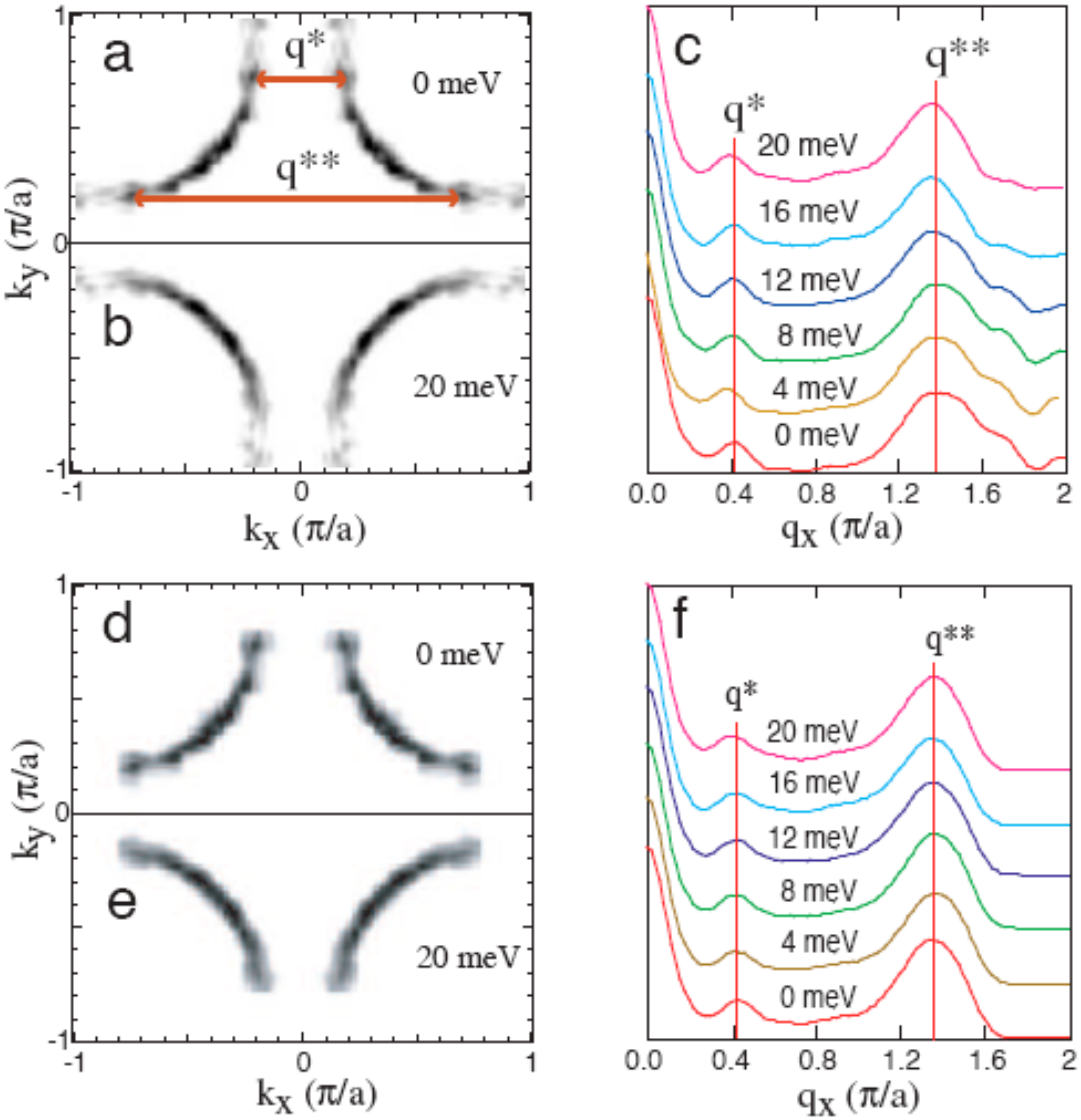


STM Fourier wavevector connects the tips of the Fermi arc

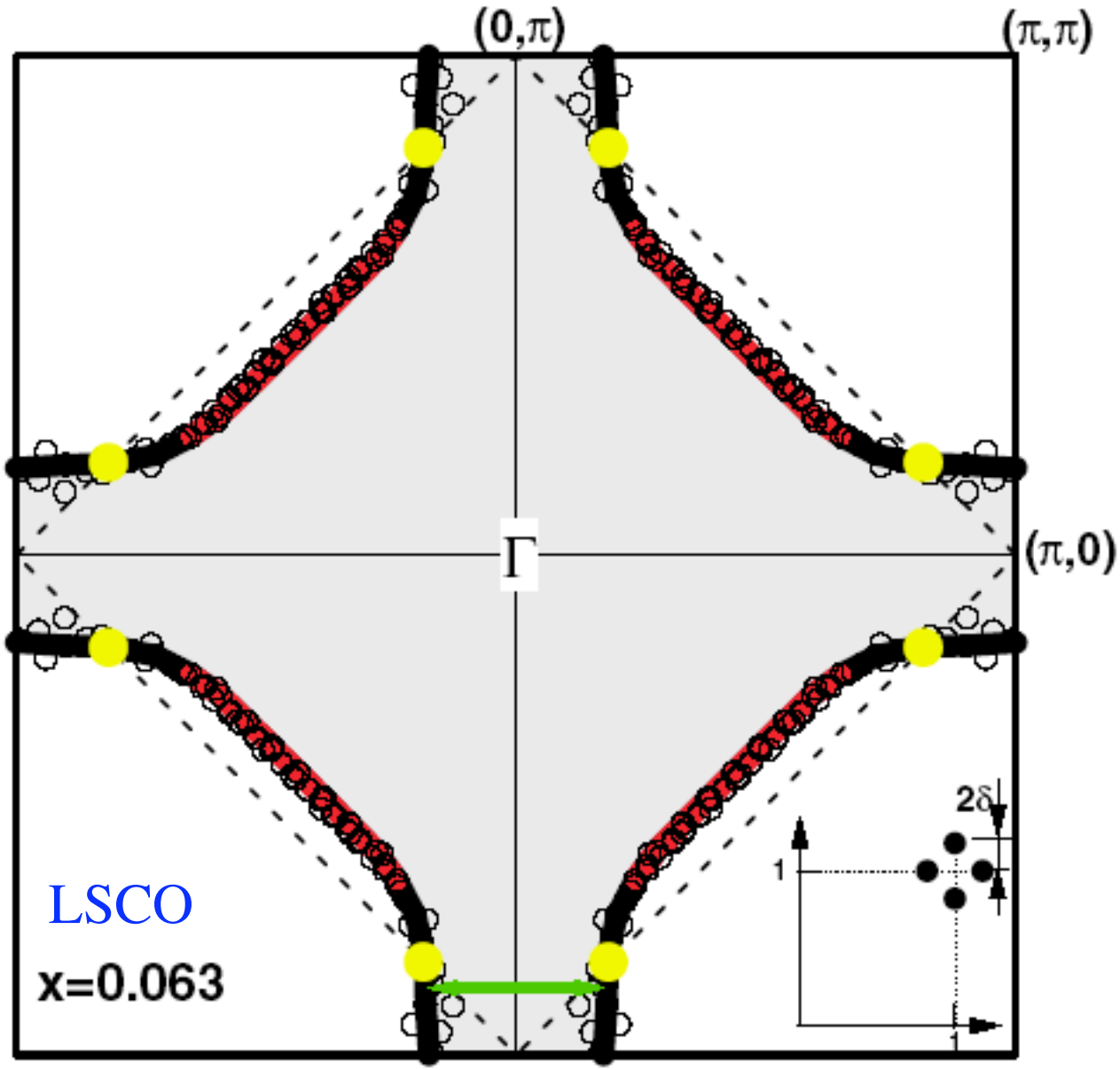


cartoon - Norman, Science 303, 1985 (2004)

ARPES autocorrelation sees this wavevector



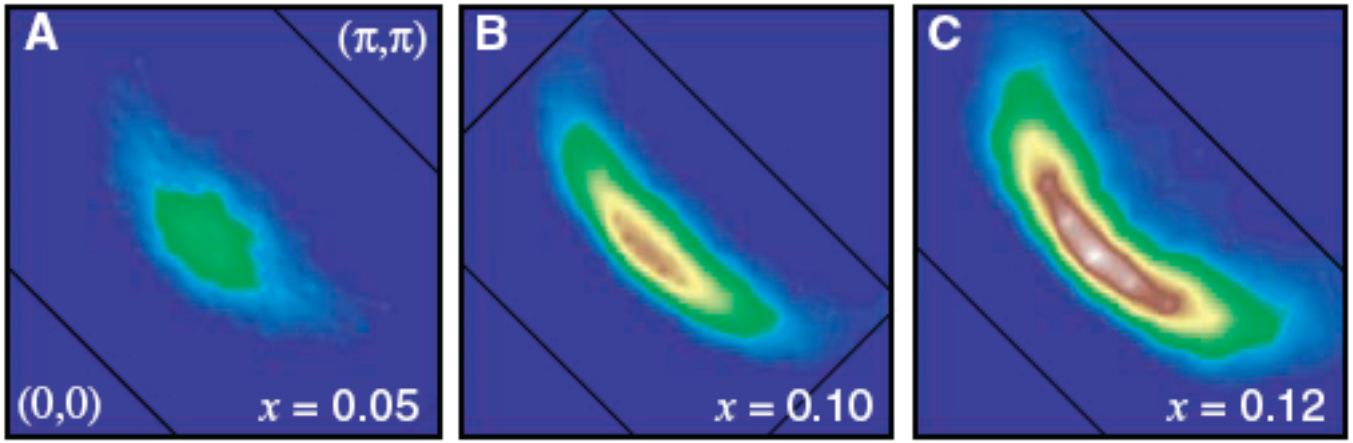
Chatterjee *et al.*, Phys. Rev. Lett. 96, 107006 (2006)

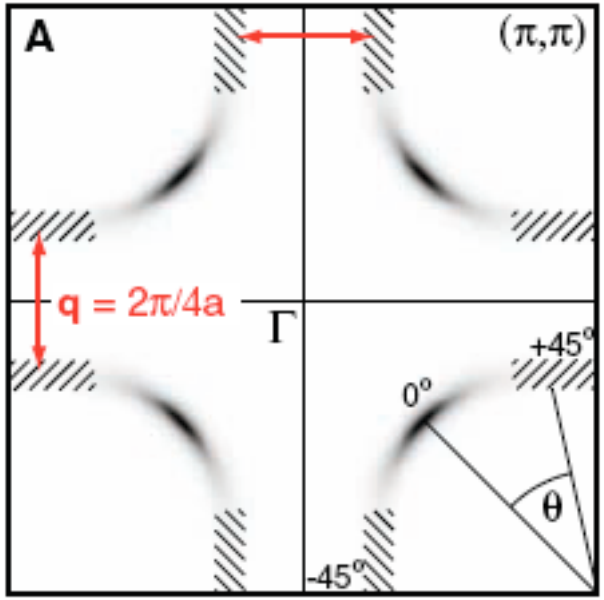


Zhou *et al.*, PRL 92, 187001 (2004) --> nested Fermi surface in LSCO

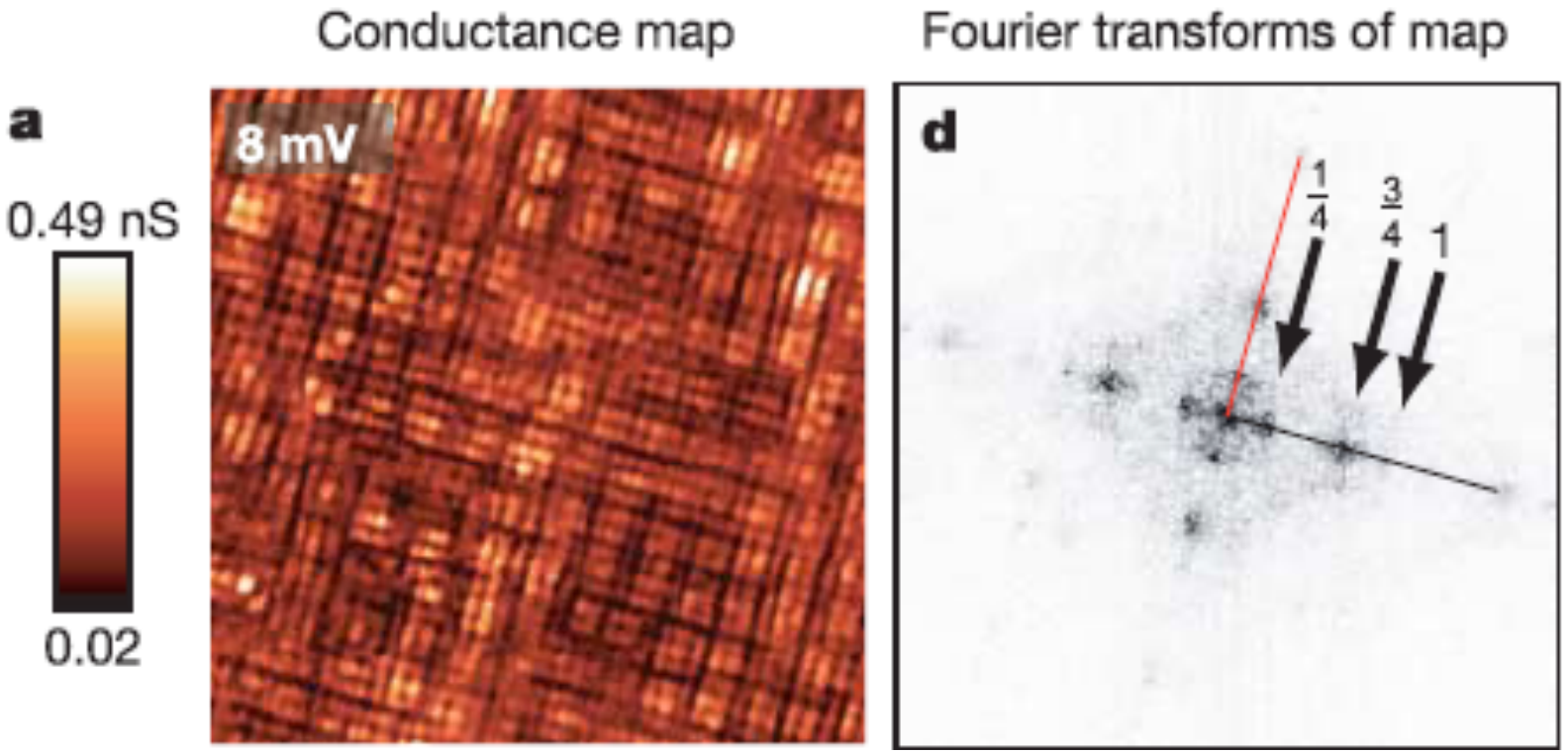
Antinodal Charge Ordering in $Ca_{2-x}Na_xCuO_2Cl_2$

Shen *et al*, Science 307, 901 (2005)



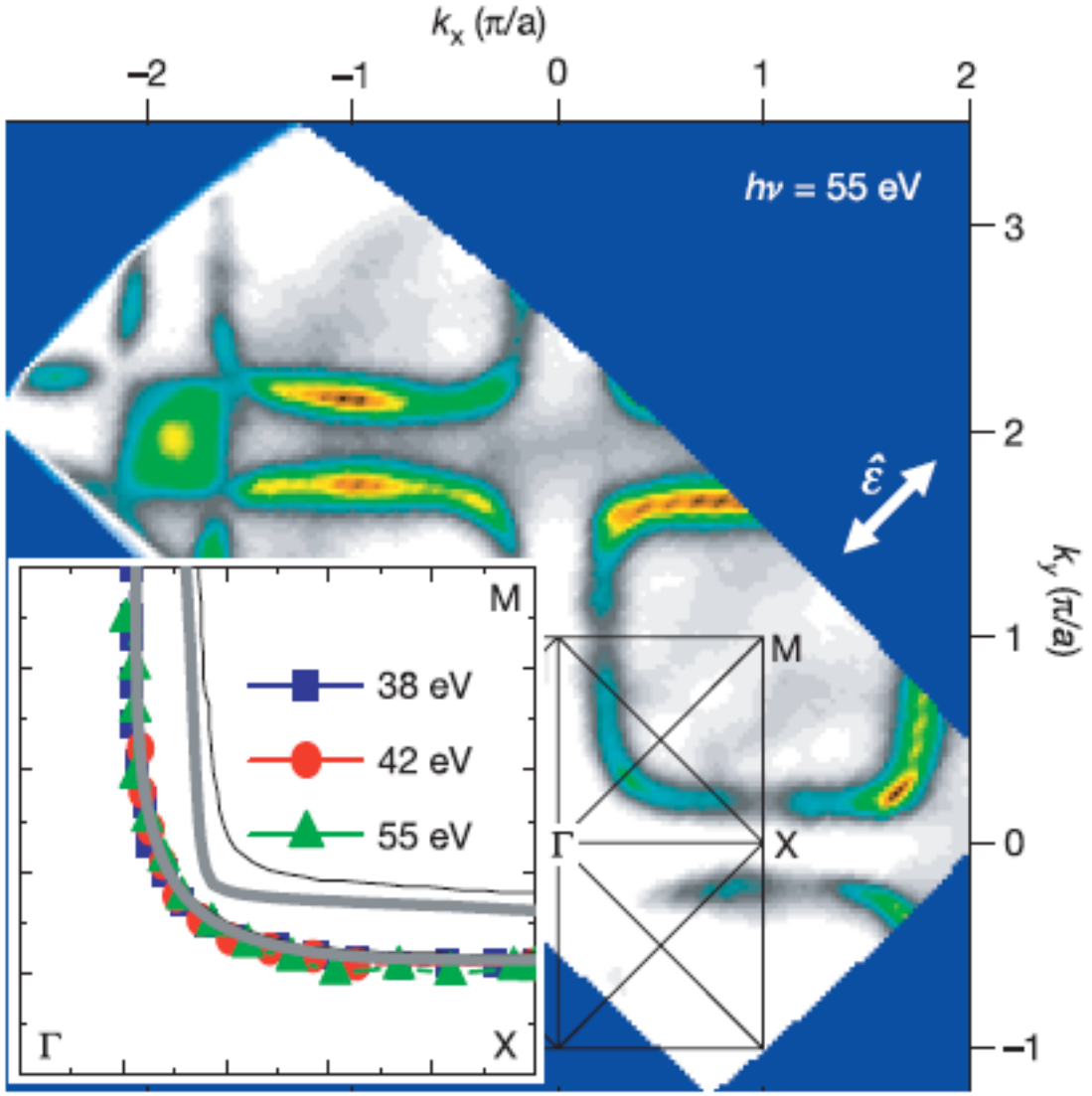


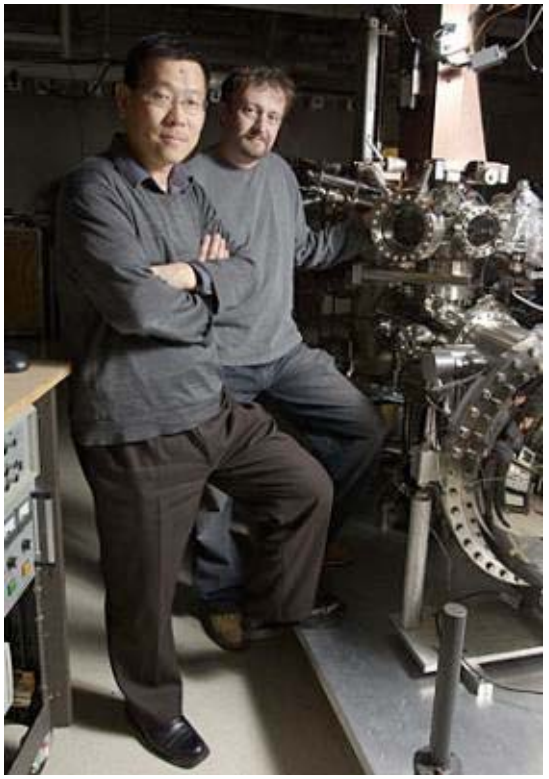
‘Checkerboard’ Charge Ordering in $Ca_{2-x}Na_xCuO_2Cl_2$



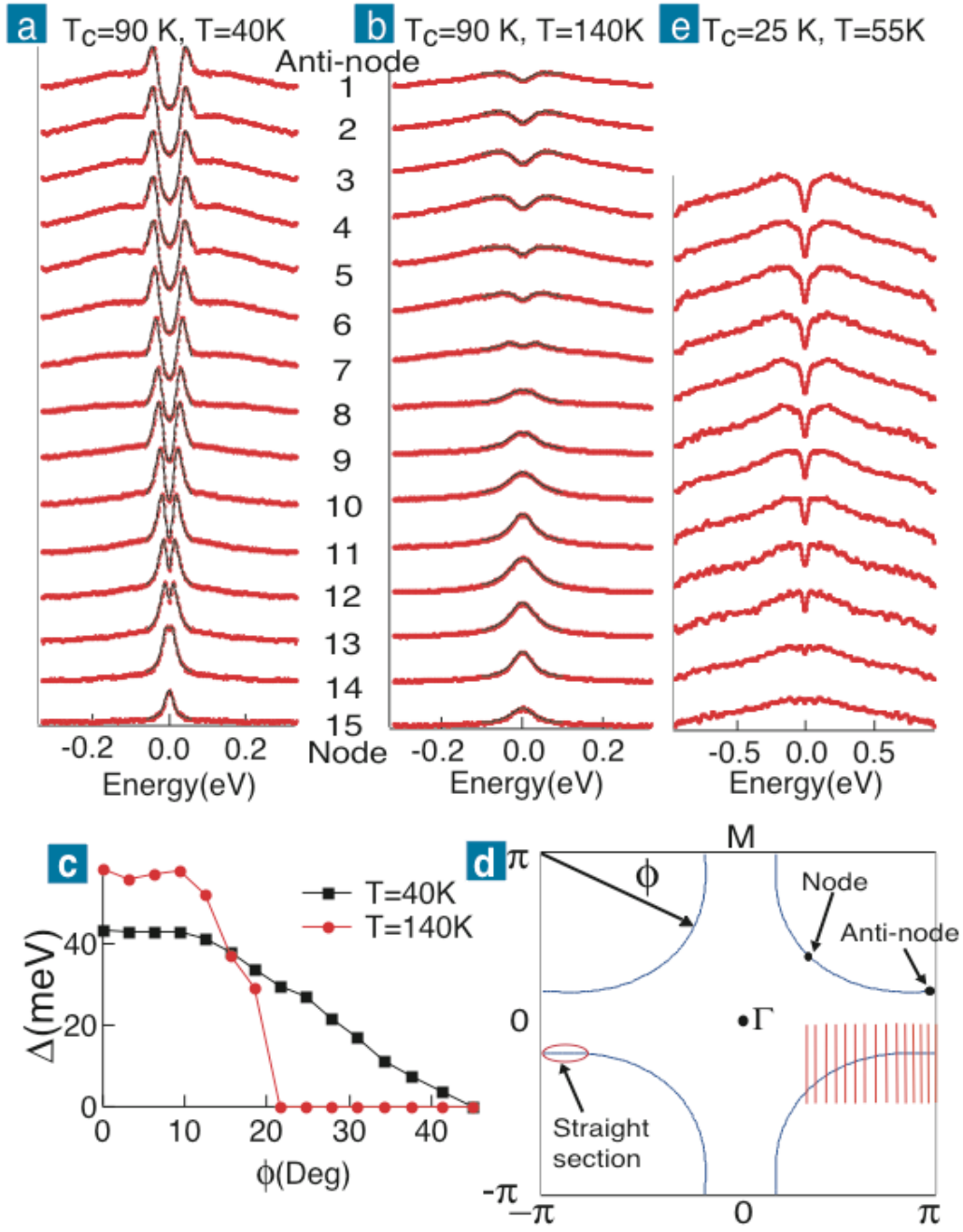
Hanaguri *et al*, Nature 430, 1001 (2004)

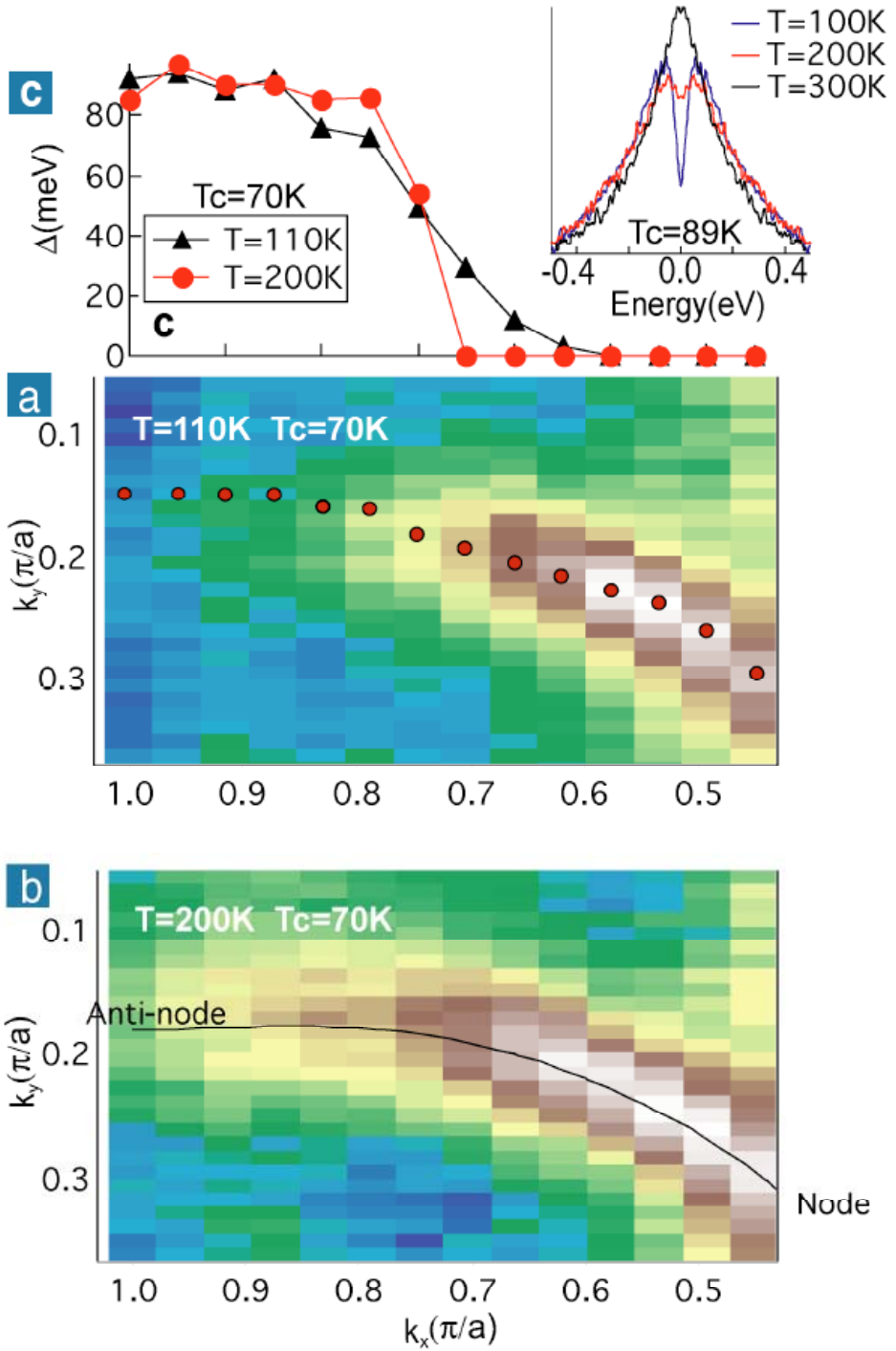
Experiments debunk 'pseudogap' role in superconductivity

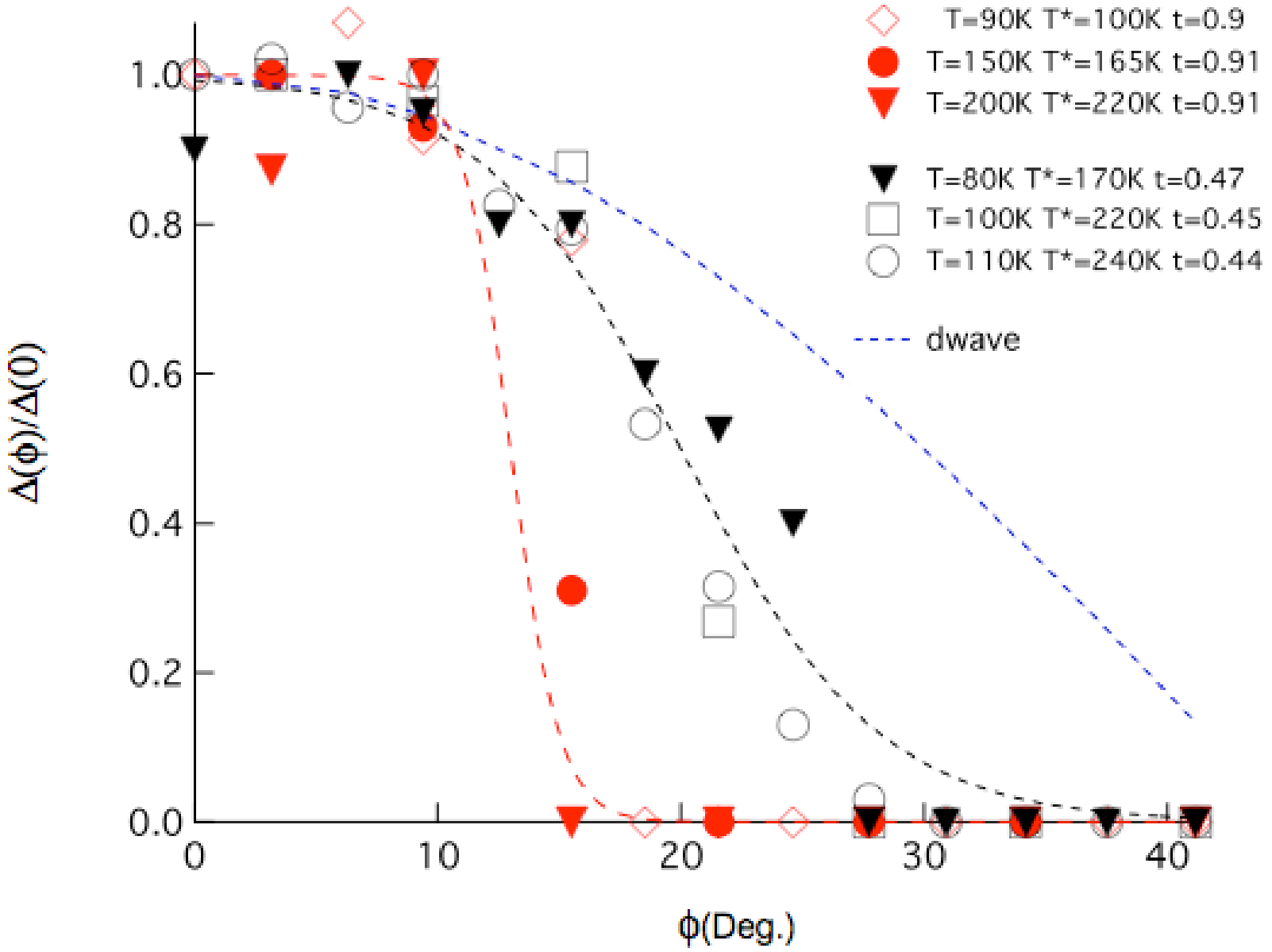


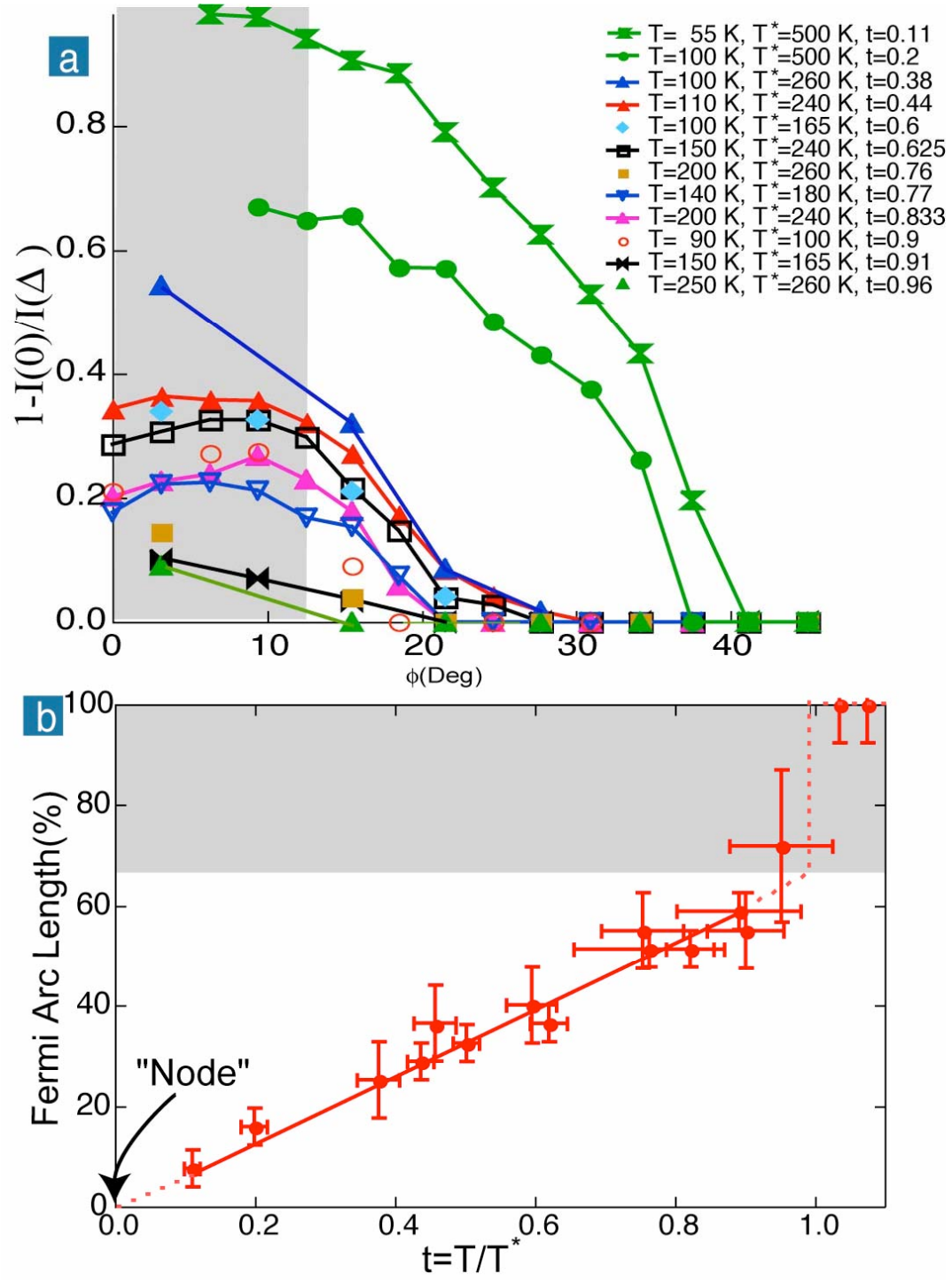


Pseudogap in Manganites - Mannella *et al.*, Nature 438, 474 (2005)

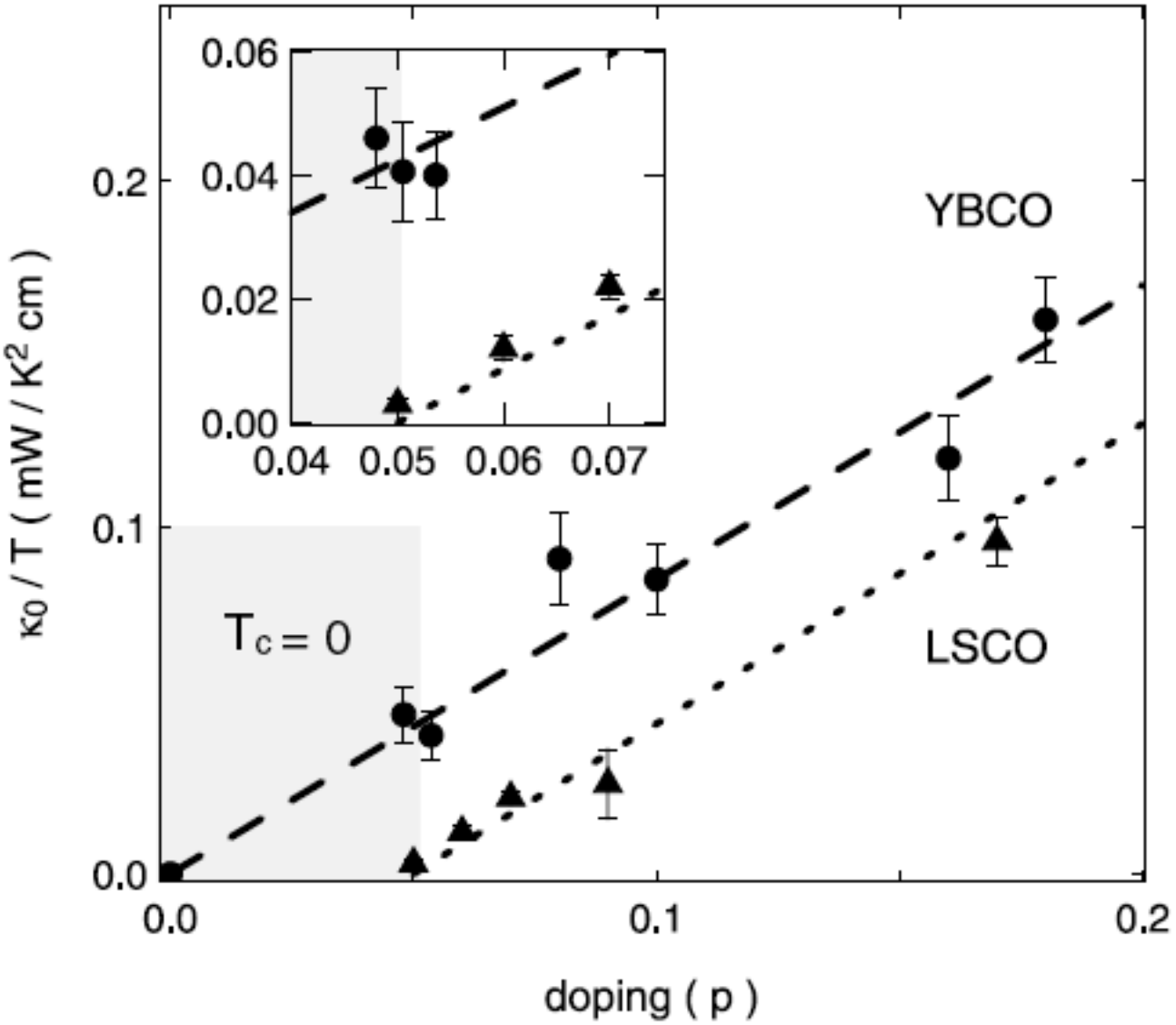

a
T_C=90 K, T=40K
b
T_C=90 K, T=140K
e
T_C=25 K, T=55K
Anti-node
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
Node
-0.2 0.0 0.2
Energy(eV)
-0.2 0.0 0.2
Energy(eV)
-0.5 0.0 0.5
Energy(eV)
c
T=40K
T=140K
Δ(meV)
40
20
0
0 10 20 30 40
ϕ(Deg)
d
M
π
ϕ
Node
Anti-node
0
•Γ
Straight
section
-π
−π
0
π


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

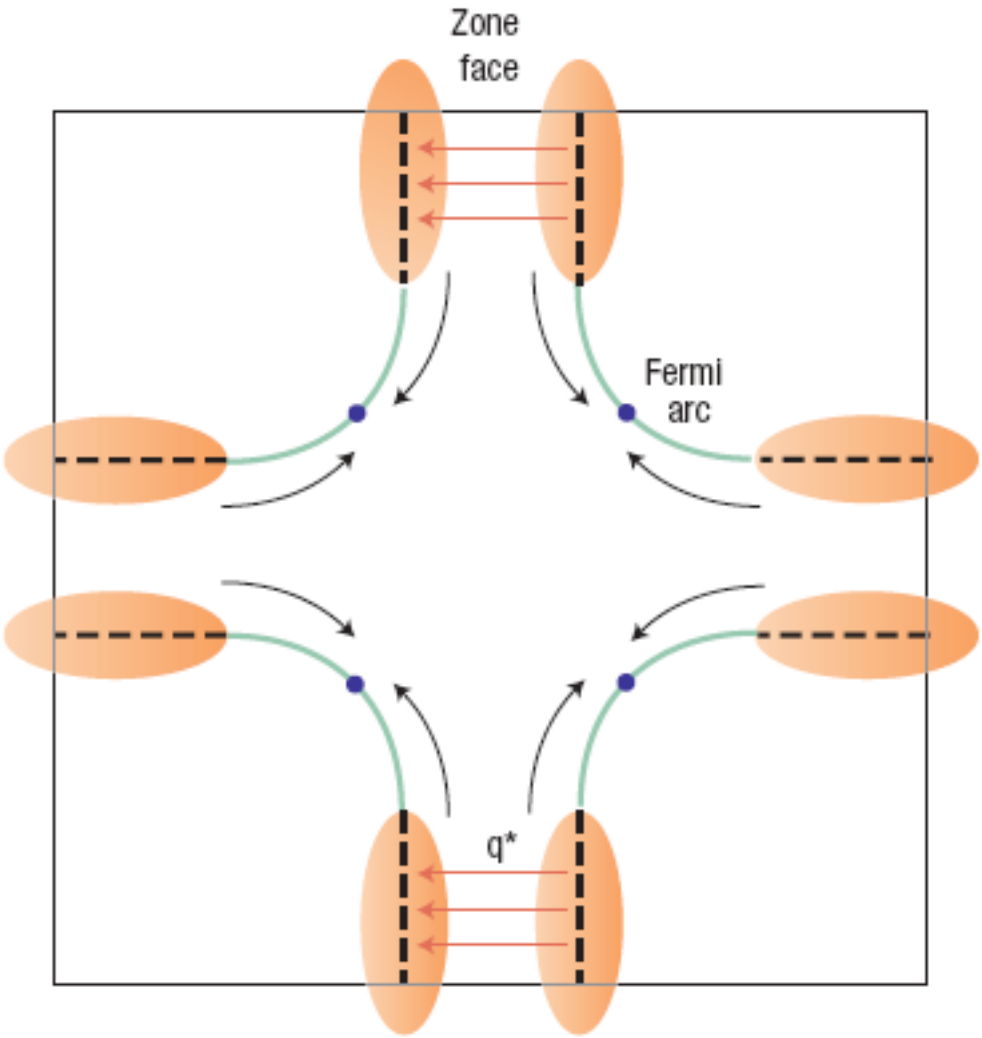

a
T= 55 K, T*=500 K, t=0.11
T=100 K, T*=500 K, t=0.2
T=100 K, T*=260 K, t=0.38
T=110 K, T*=240 K, t=0.44
T=100 K, T*=165 K, t=0.6
T=150 K, T*=240 K, t=0.625
T=200 K, T*=260 K, t=0.76
T=140 K, T*=180 K, t=0.77
T=200 K, T*=240 K, t=0.833
T= 90 K, T*=100 K, t=0.9
T=150 K, T*=165 K, t=0.91
T=250 K, T*=260 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



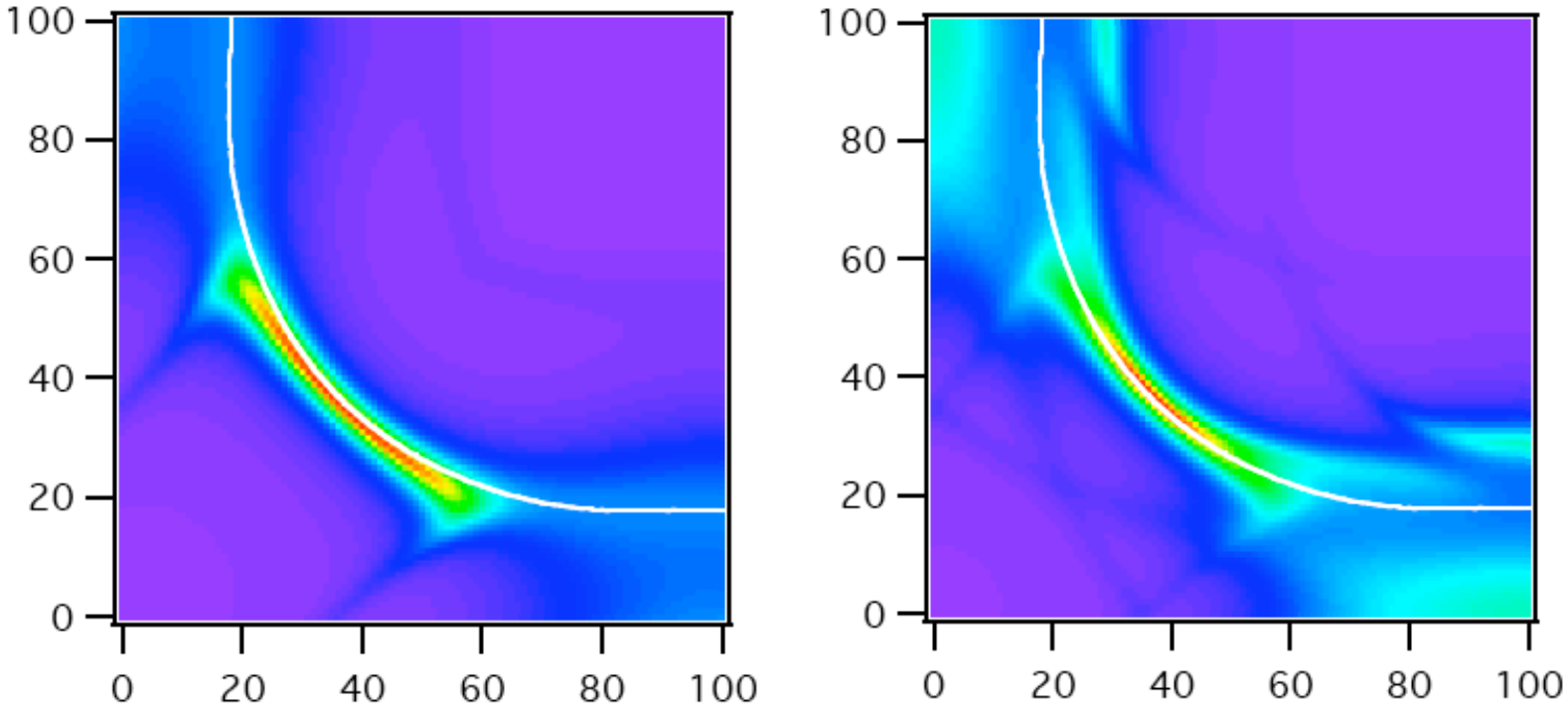
Sutherland *et al*, PRL 94, 147004 (2005)

Charge ordering?



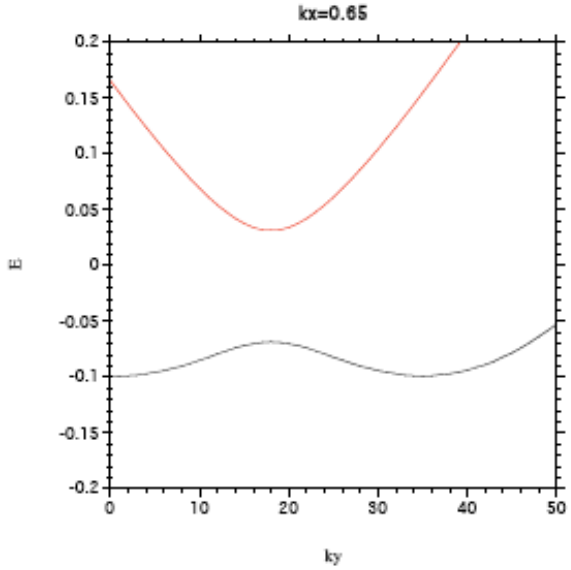
Kyle McElroy - Nature Physics 2, 441 (2006)

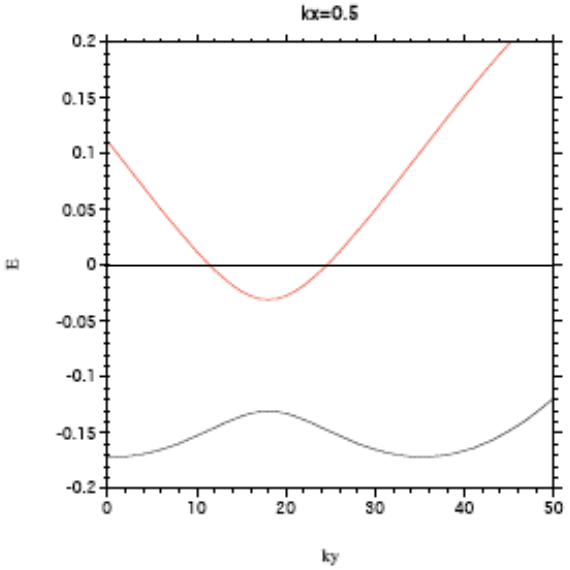
Charge ordering?

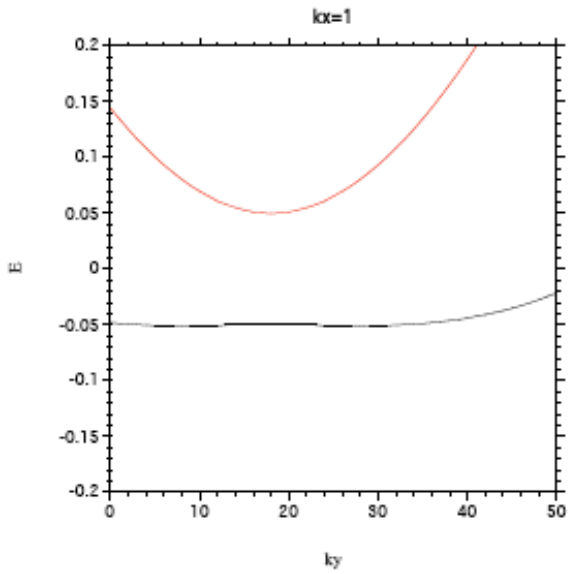


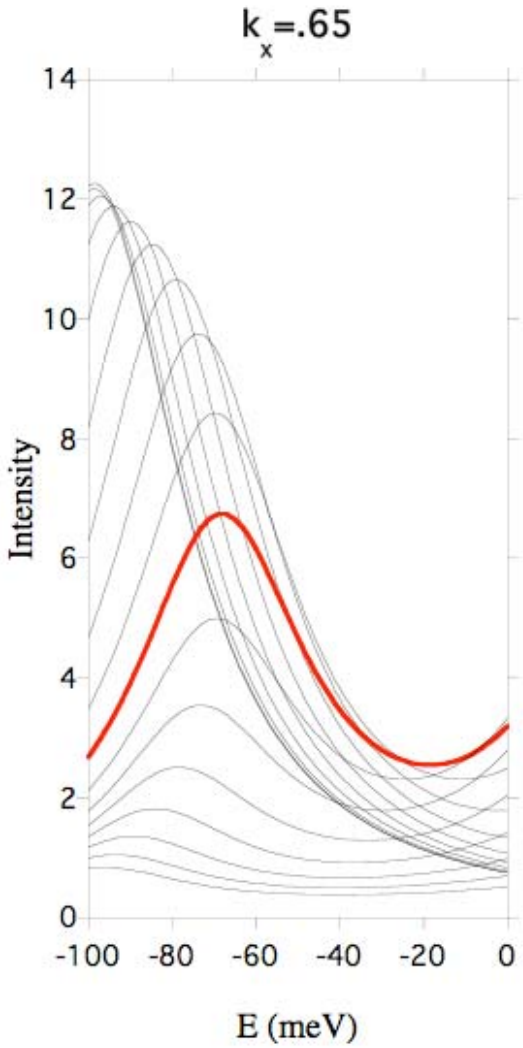
Zero energy intensity maps, left (q) and right (q,-q)

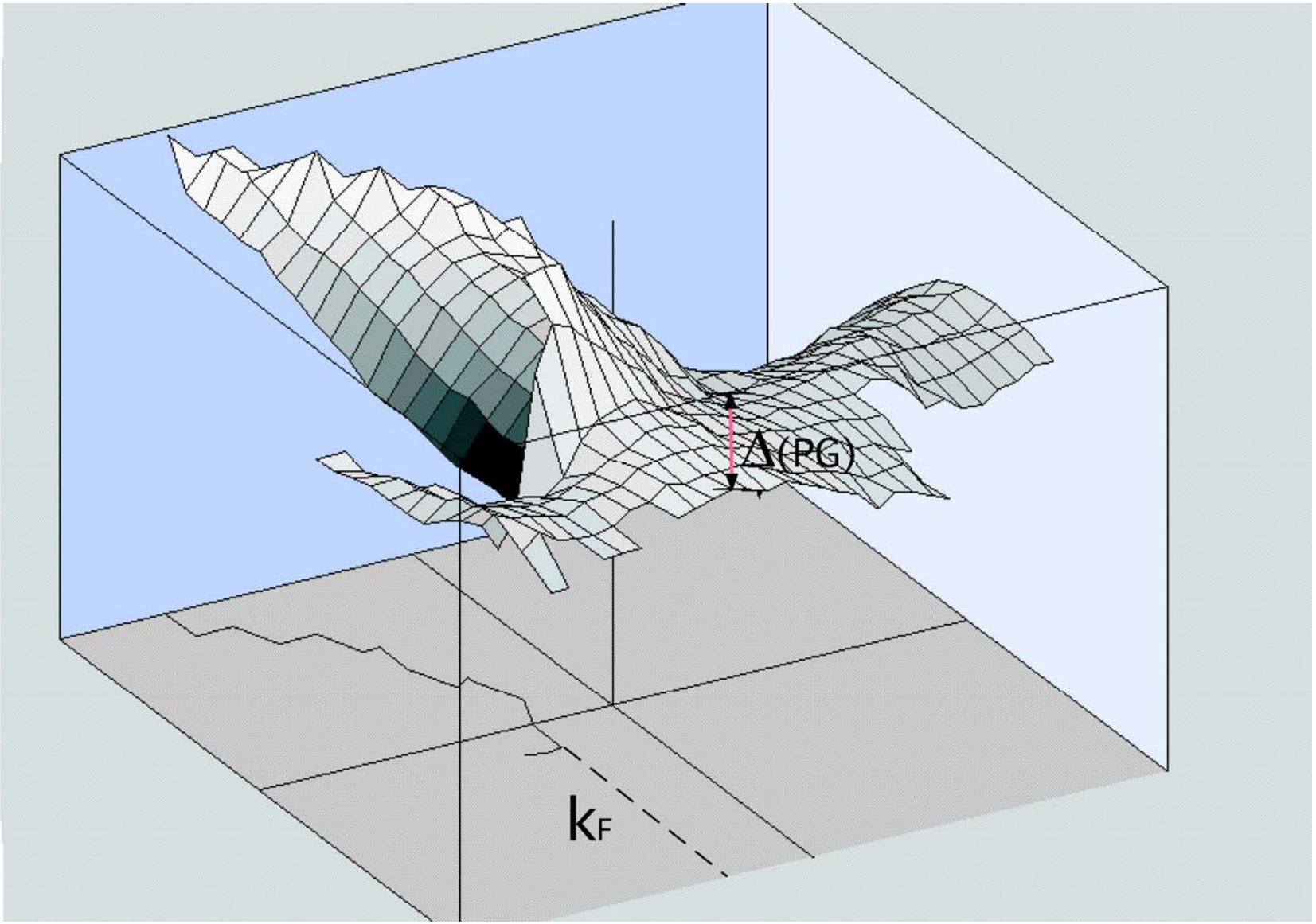
Energy gap below E_F in the 'arc' region for charge ordering at finite q



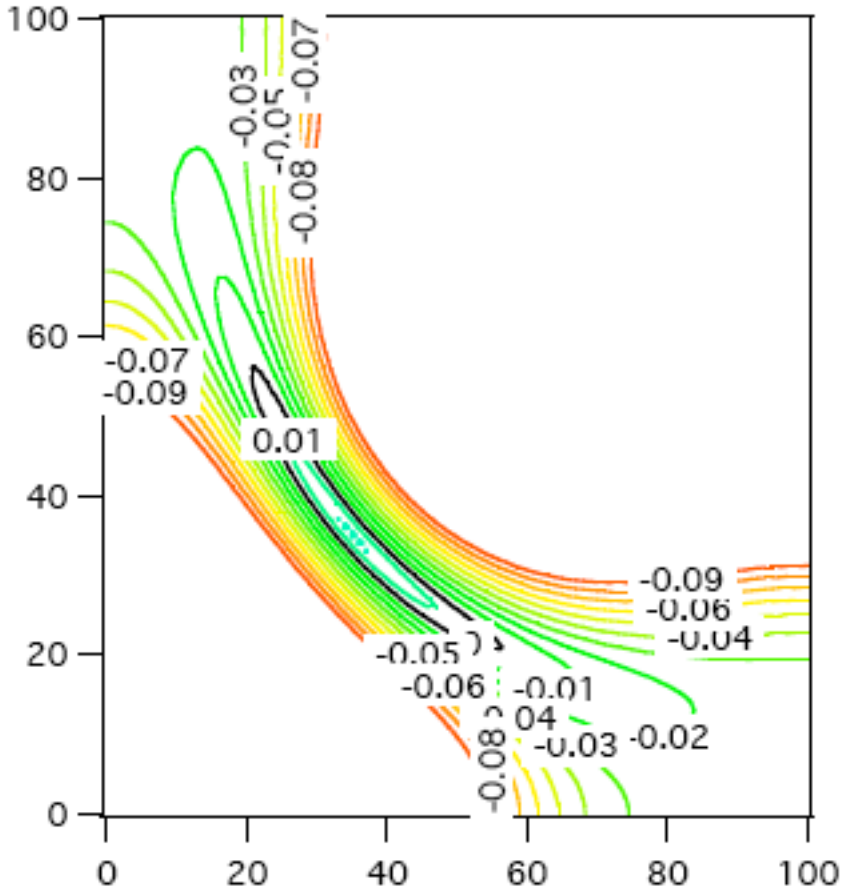


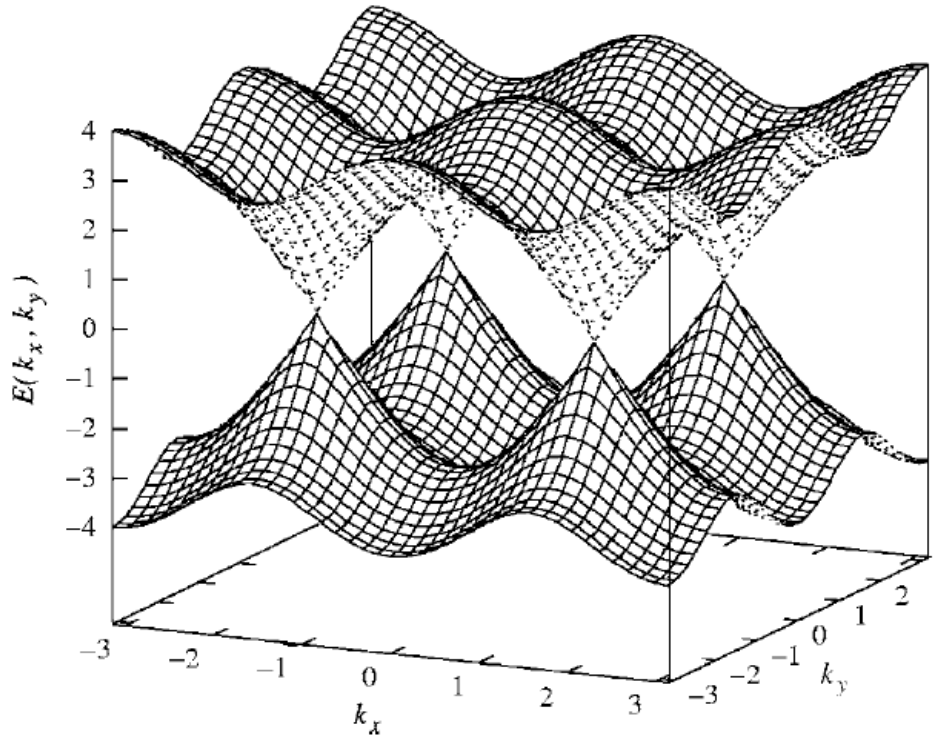





Δ(PG)
k_F

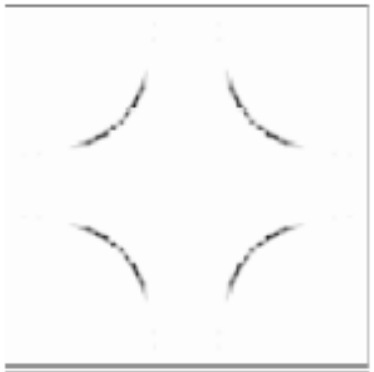
Dispersing Fermi Arcs in the Flux Phase State





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

Fermi arcs dispersionless



0 meV

12 meV

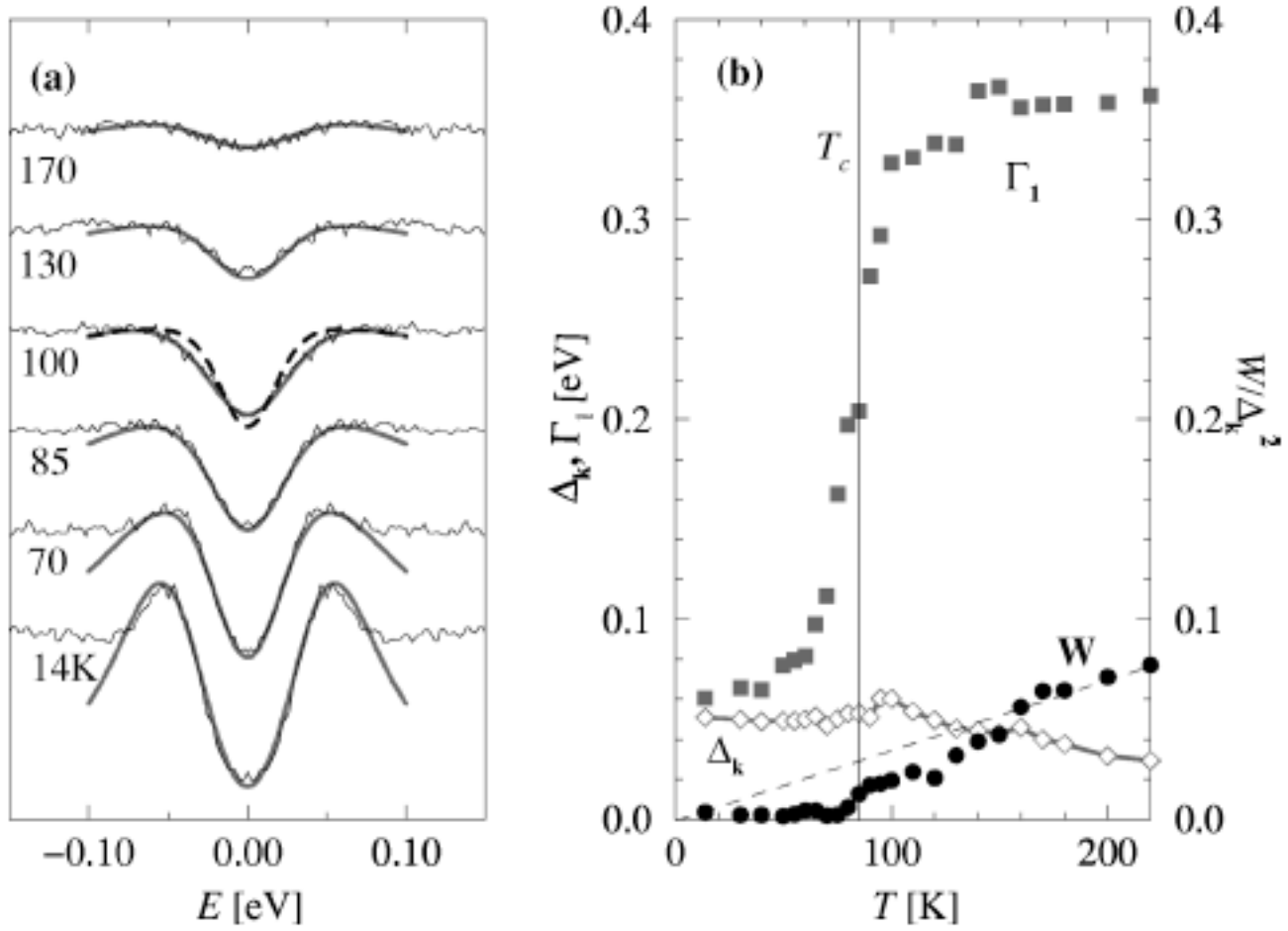
24 meV

36 meV

0 meV
and
36 me
overla

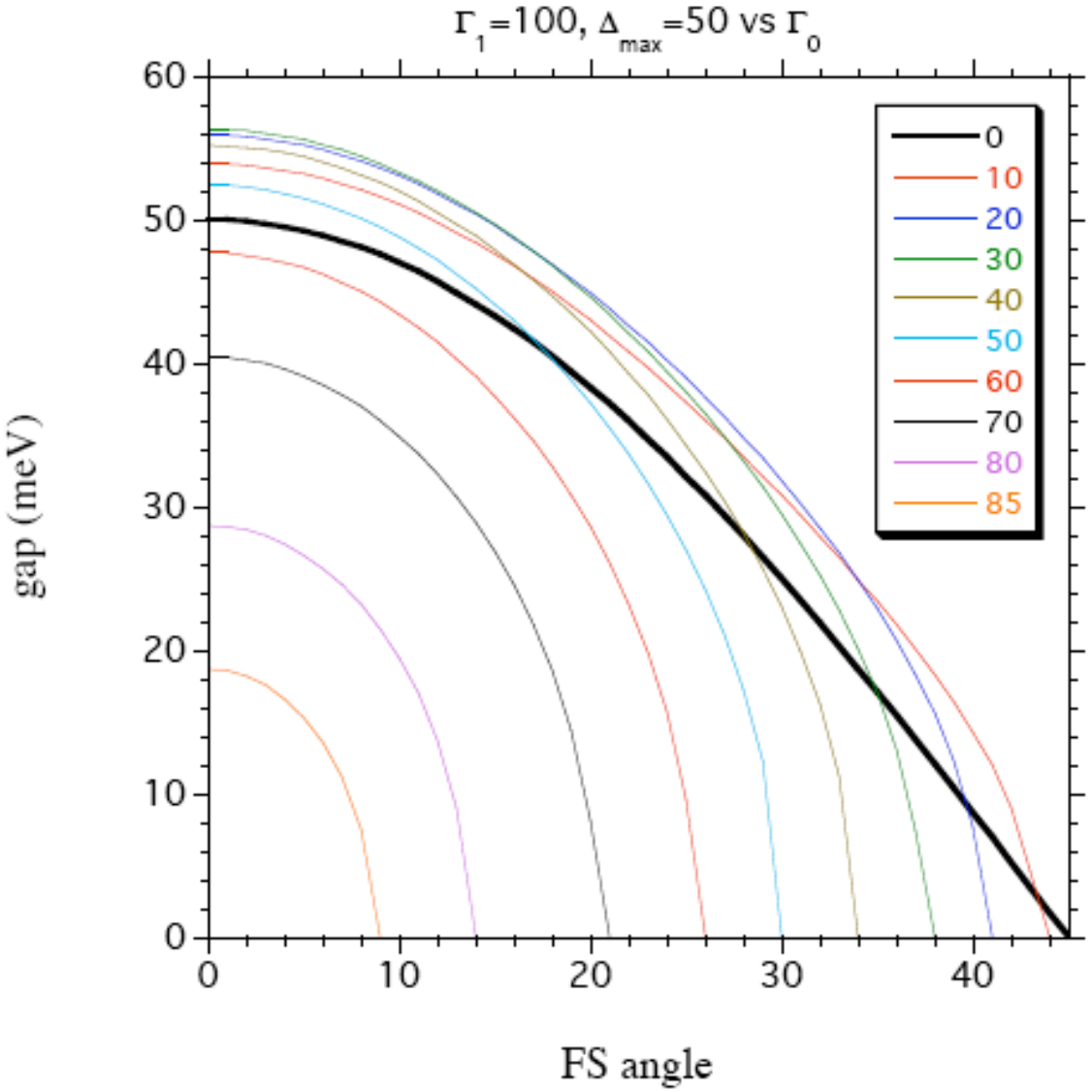
48 meV

Phase Fluctuations above T_c

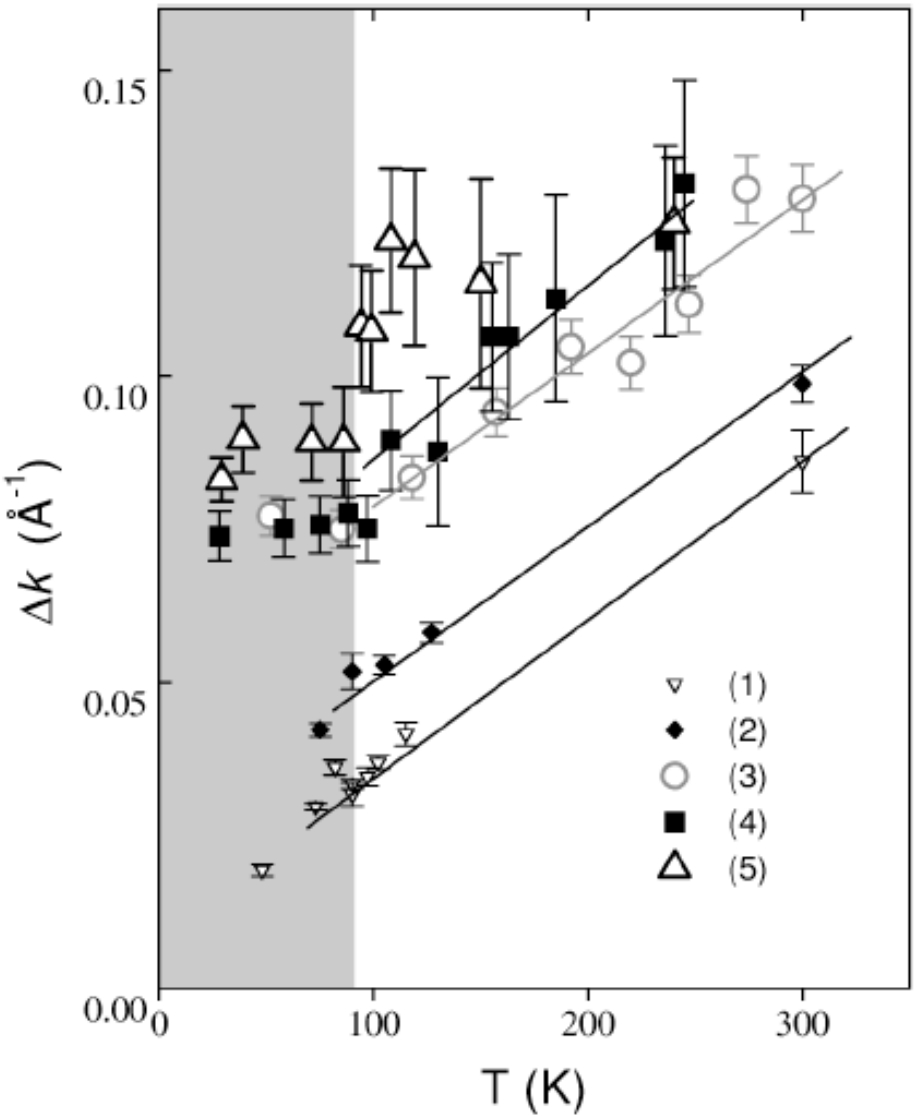


Franz and Millis, Phys Rev B 58, 14572 (1998)

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

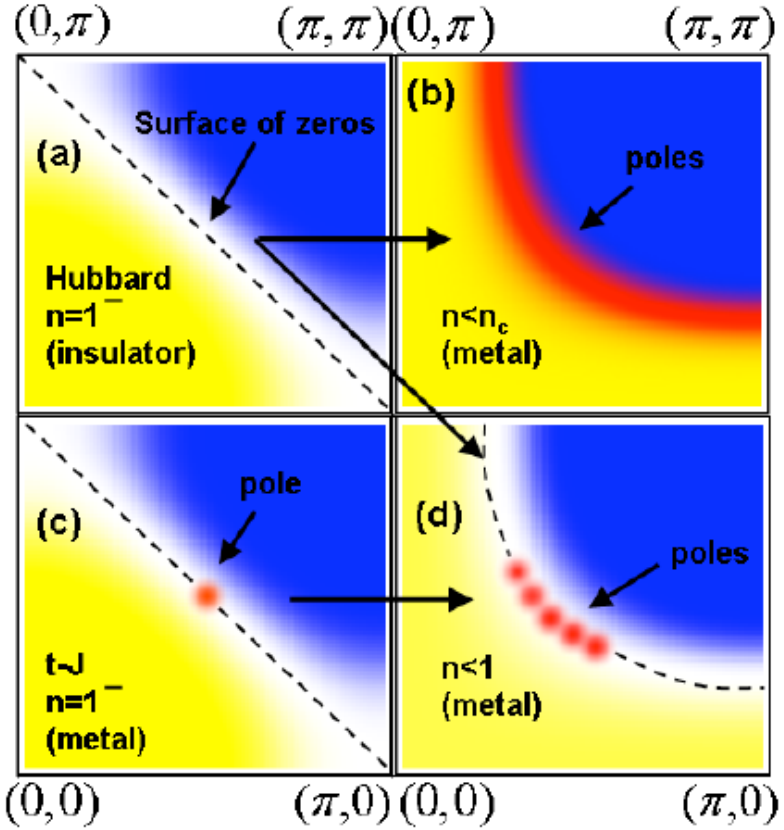


Linear T scattering rate (Marginal Fermi Liquid)

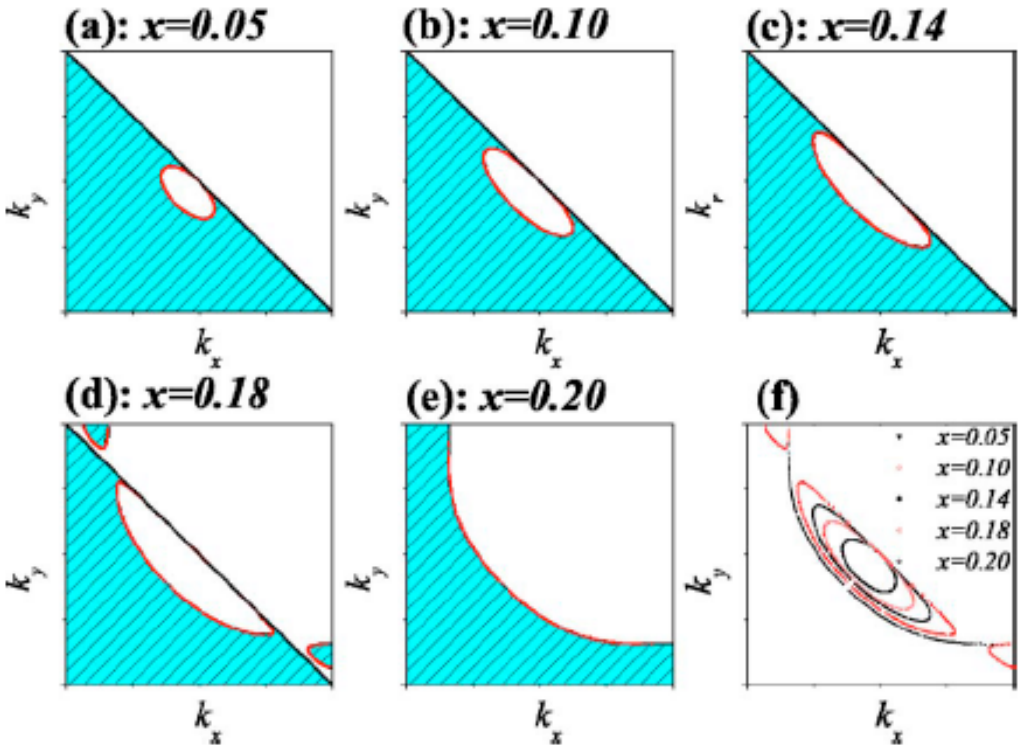


Valla *et al*, Phys Rev Lett 85, 828 (2000)

Luttinger Zeros



Stanescu, Phillips, Choy
cond-mat/0602280



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

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