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1957-1

Miniworkshop on Strong Correlations in Materials and Atom Traps

4 - 15 August 2008

Fermi Arcs and Fermi Pockets in Cuprates.

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Fermi Arcs and Fermi Pockets in Cuprates

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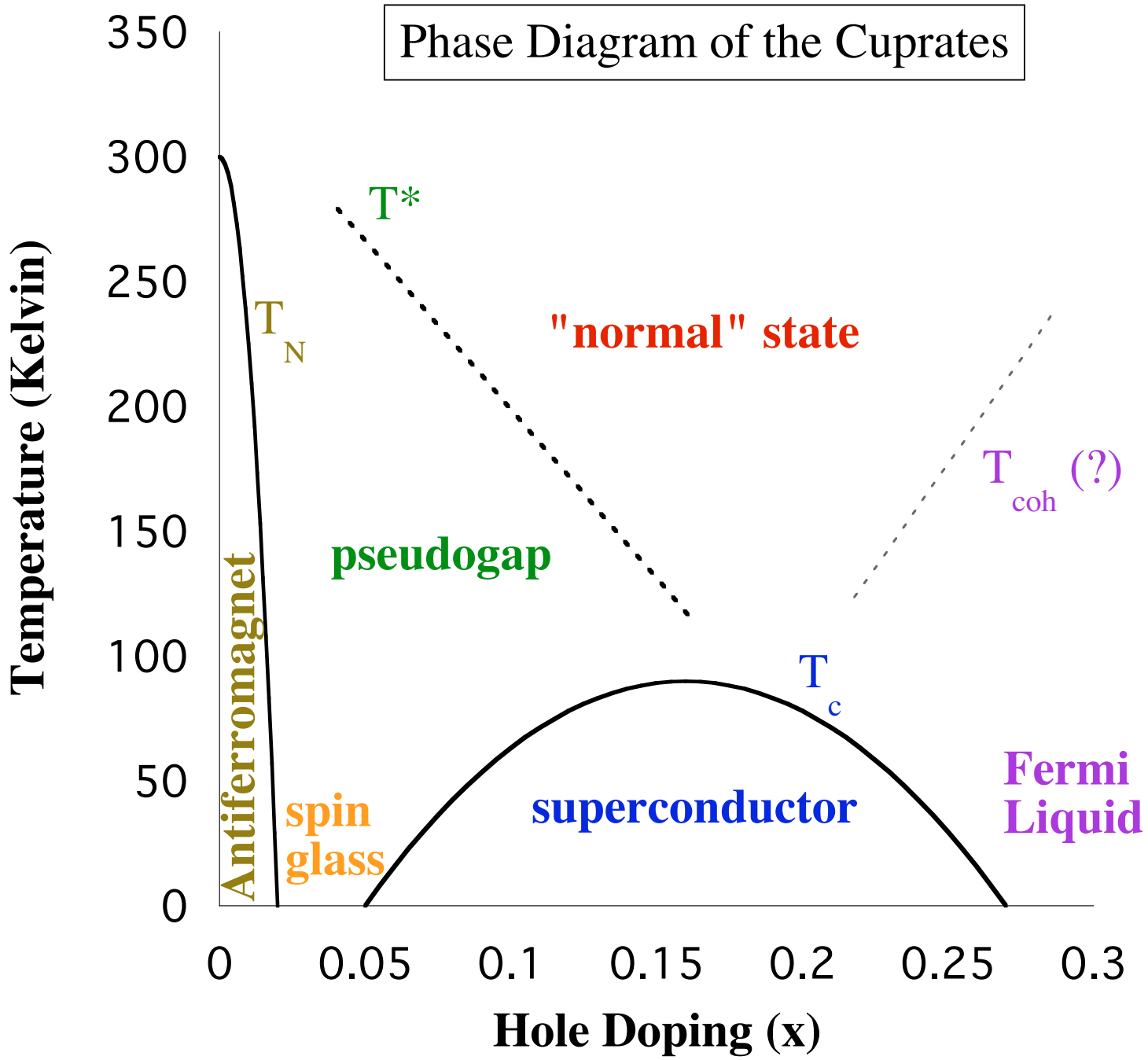
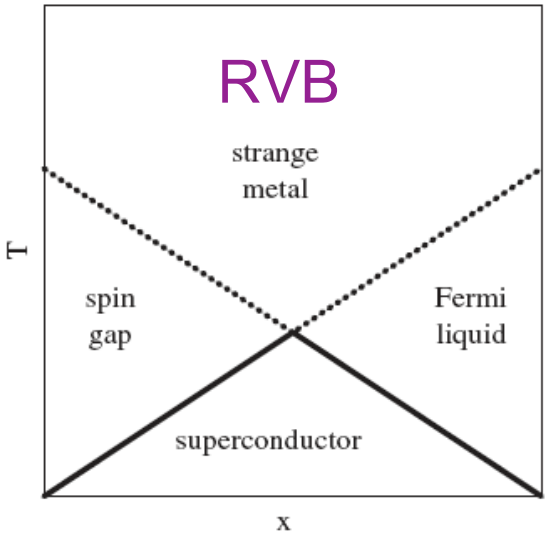
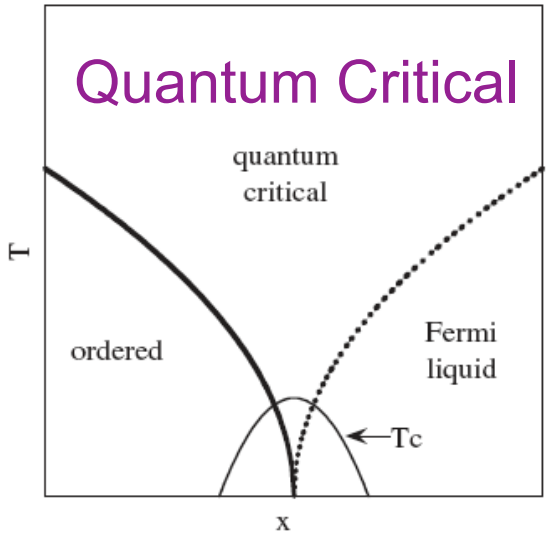
Norman, Kanigel, Randeria, Chatterjee, Campuzano, PRB 76, 174501 (2007)
Millis and Norman, PRB 76, 220503 (2007)

ICTP - Aug. 4, 2008

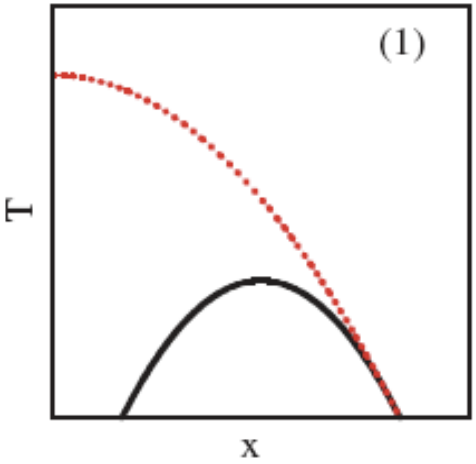

Phase Diagram of the Cuprates
Temperature (Kelvin)
350
300
250
200
150
100
50
0
0
0.05
0.1
0.15
0.2
0.25
0.3
Hole Doping (x)
T*
T N
"normal" state
T coh (?)
pseudogap
T c
Antiferromagnet
spin glass
superconductor
Fermi Liquid

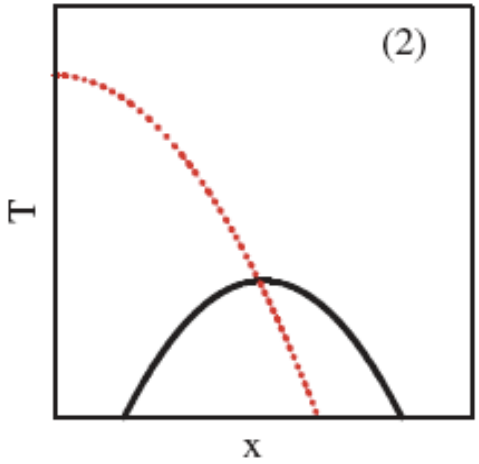
Two Theories of the Phase Diagram

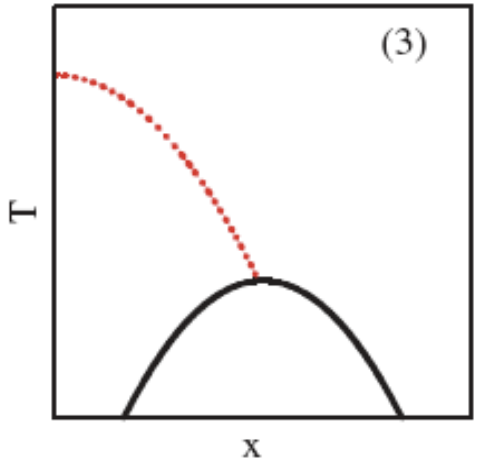




Relation of T* to T_c







Norman, Pines, Kallin, Adv. Phys. (2005)

What is the Pseudogap?

1. Pre-formed pairs
2. Spin density wave
3. Charge density wave
4. d density wave
5. Orbital currents
6. Flux phase
7. Stripes

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

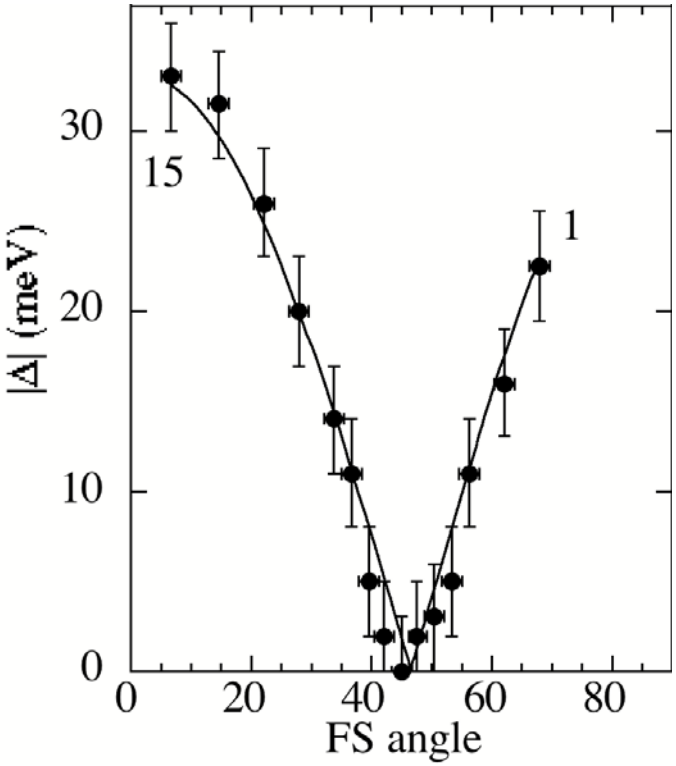
$$I(\mathbf{k},\omega) = c \langle A(\mathbf{k},\omega) f(\omega) \rangle + \text{background}$$ where

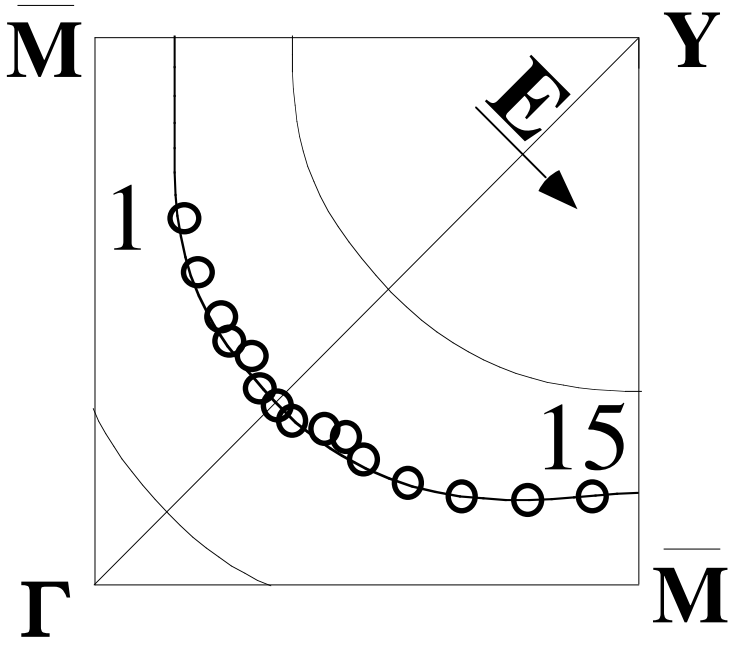
1. A is the single particle spectral function
2. f is the Fermi-Dirac function
3. c is the square of the dipole matrix element (plus intensity normalization)
4. $\langle\ \rangle$ is the convolution with the energy resolution gaussian and sum over the momentum window
5. background is secondaries plus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

Extraction of the Superconducting Energy Gap from ARPES

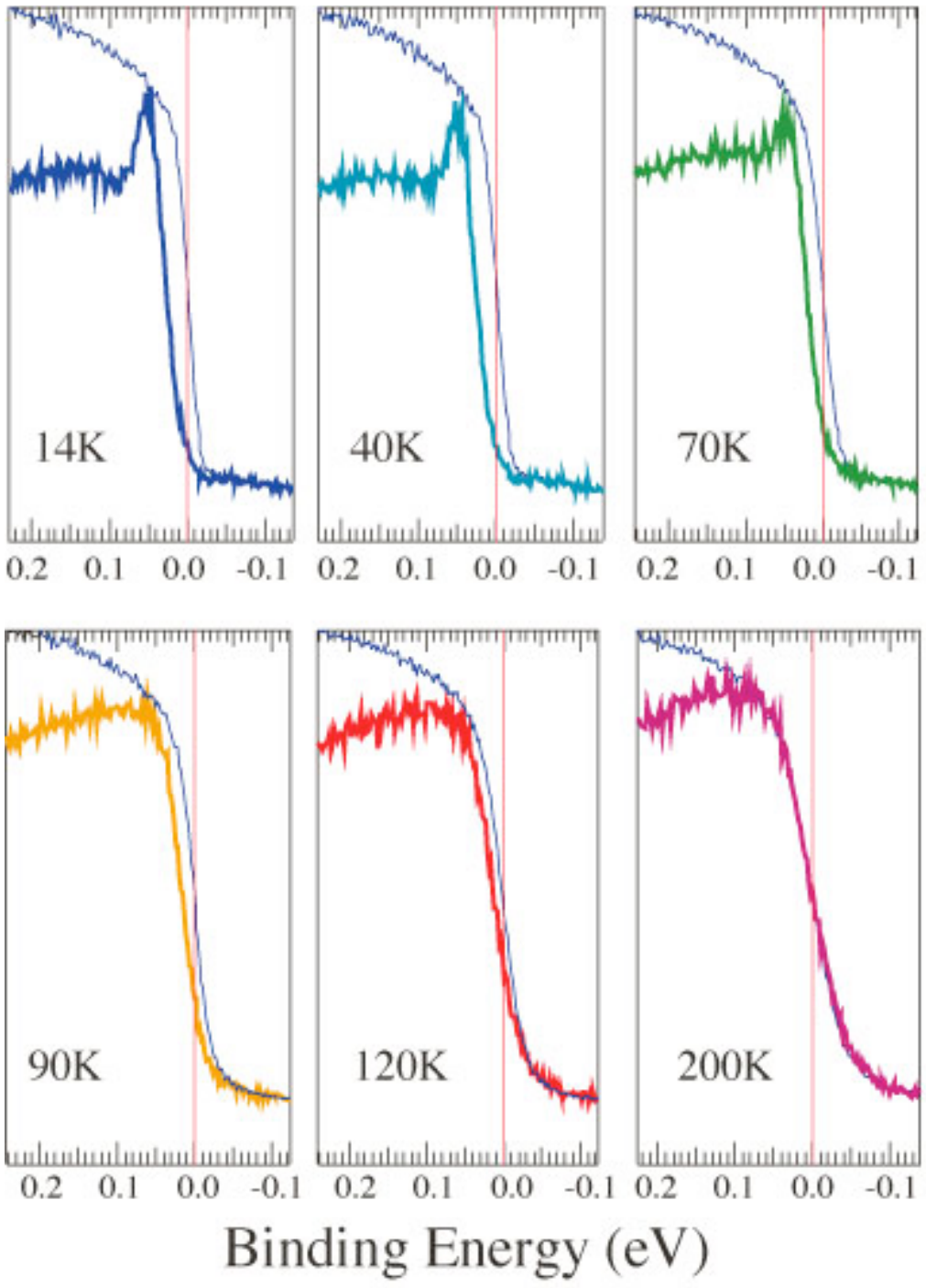
Ding *et al.*, PRL (1995) & PRB (1996)

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

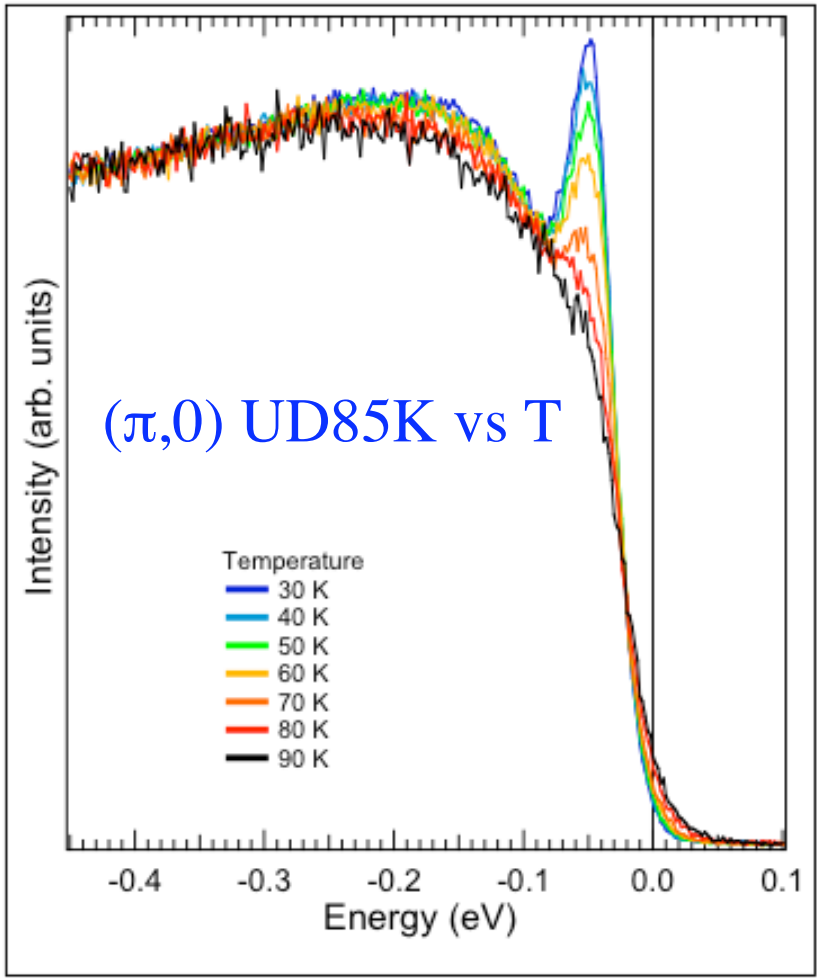


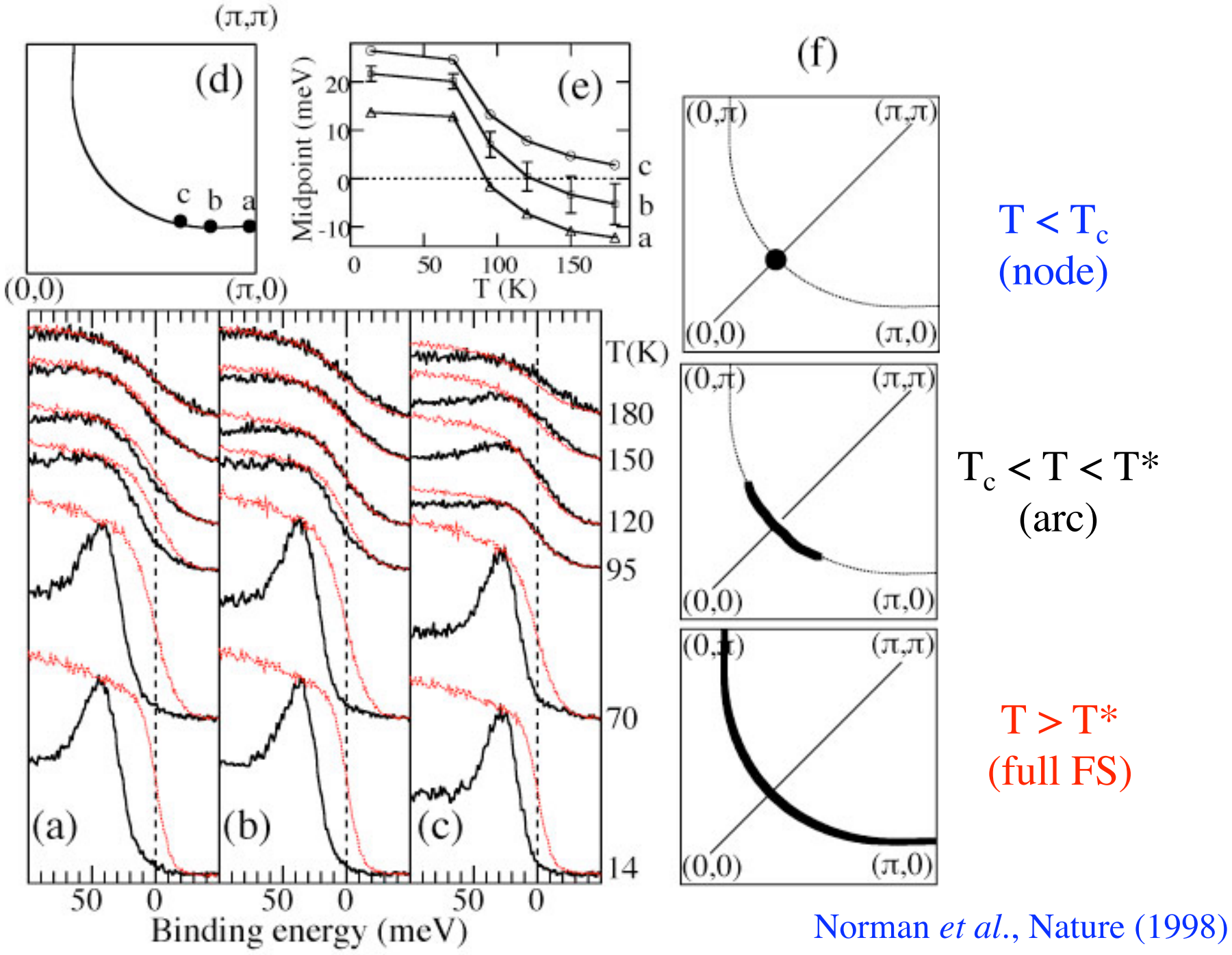


Bi2212
overdoped, T_c=87K
(OD87K)

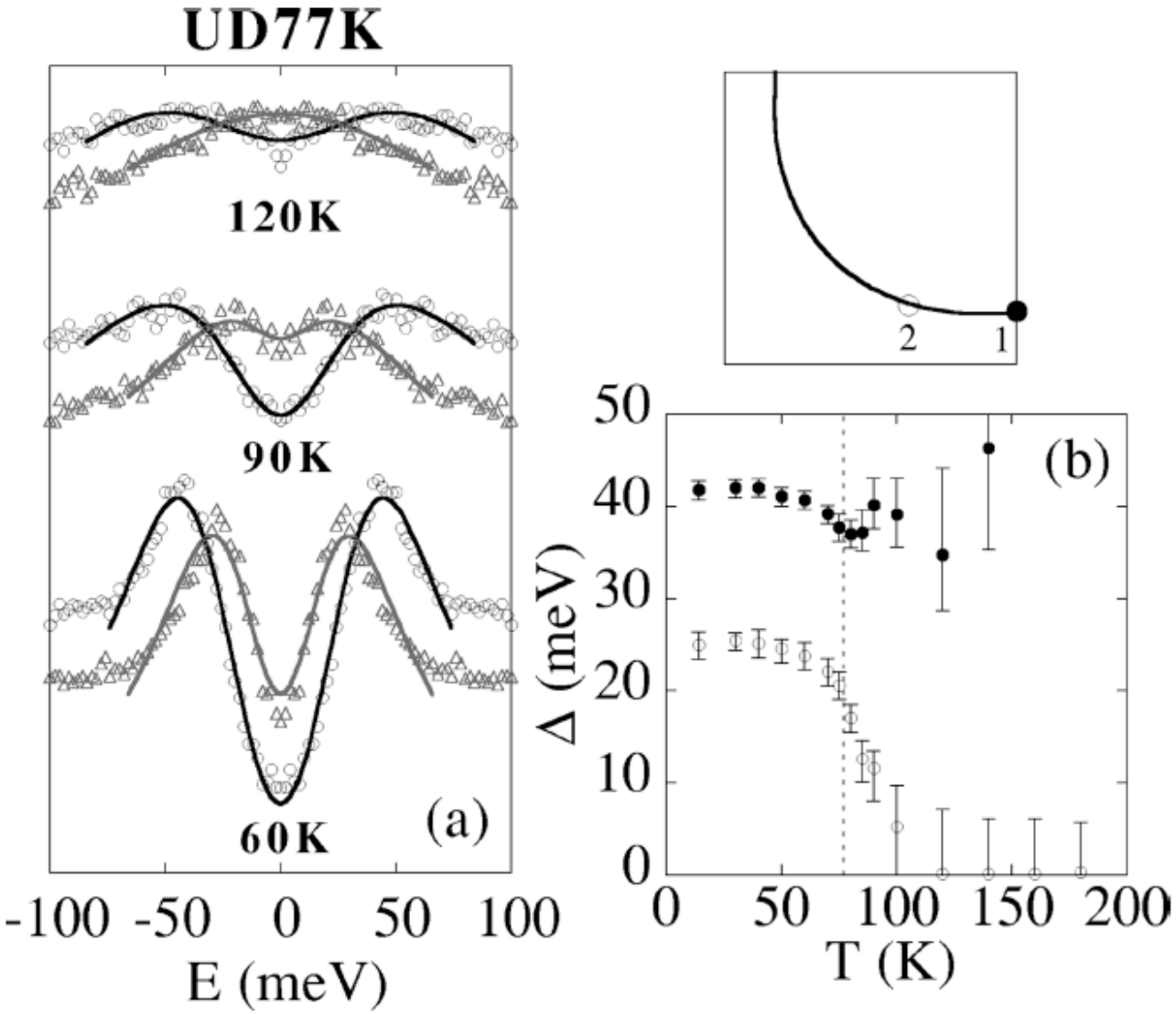


<-- Antinode UD83K vs T




(π,π)
(d)
c b a
(0,0)
(π,0)
(e)
Midpoint (meV)
20
10
0
-10
0
50
100
150
T (K)
c
b
a
(f)
(0,π)
(π,π)
(0,0)
(π,0)
T(K)
180
150
120
95
70
14
(a)
(b)
(c)
50
0
Binding energy (meV)
T < T$_c$
(node)
T$_c$ < T < T*
(arc)
T > T*
(full FS)
Norman *et al.*, Nature (1998)

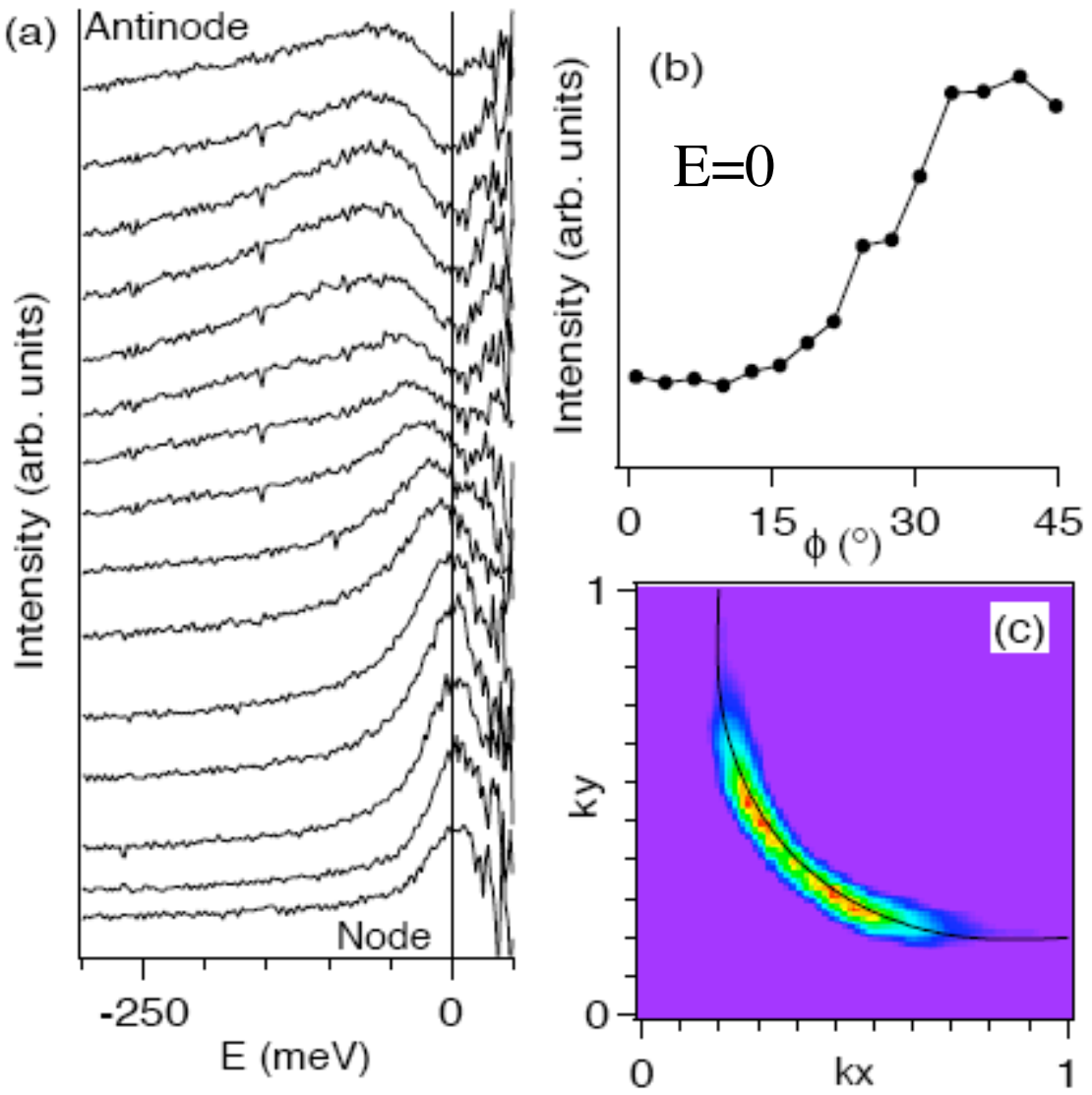
Gap closing with T (2) versus Gap filling with T (1)



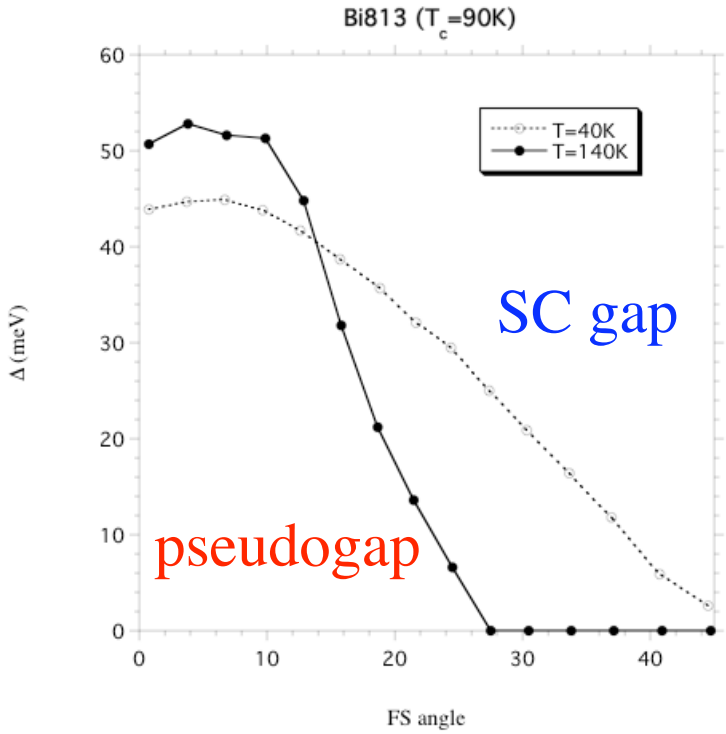
Norman *et al.*, PRB (1998)

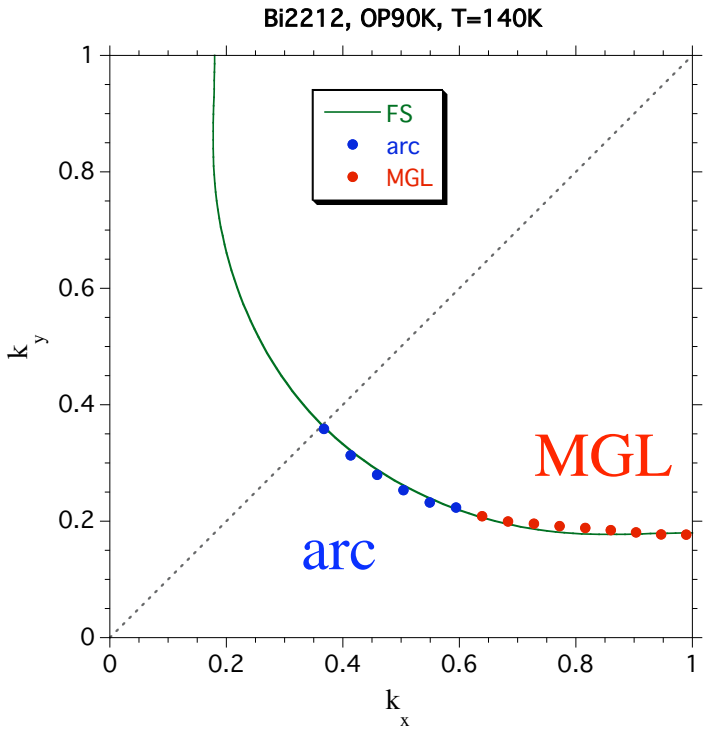
Bi2212
OP90K
T=140K

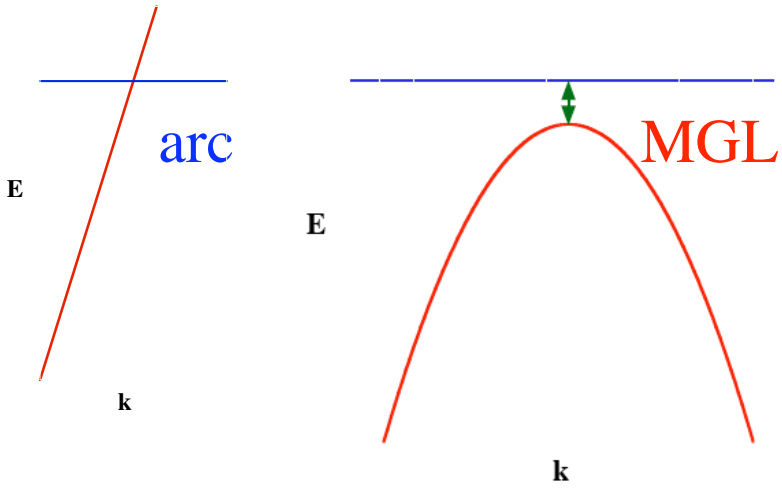
Fermi function divided data along the FS



Norman *et al.*, PRB (2007)

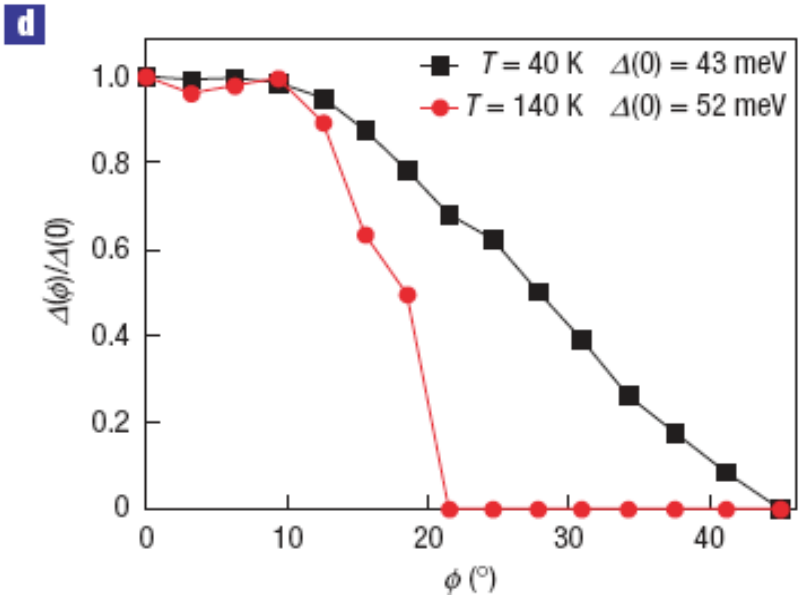


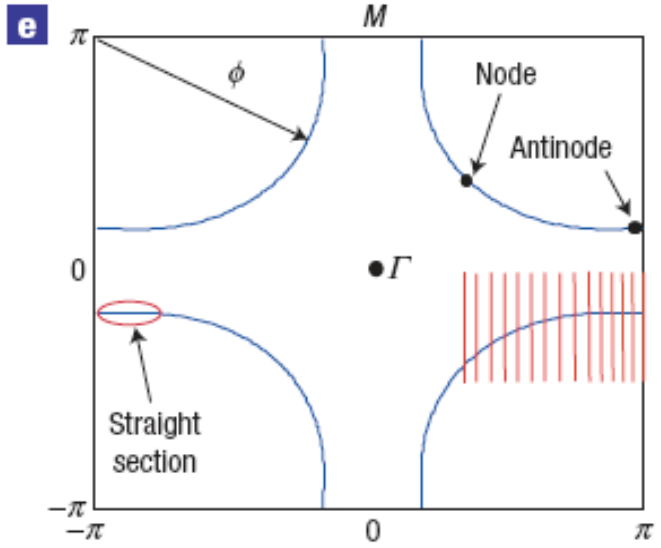


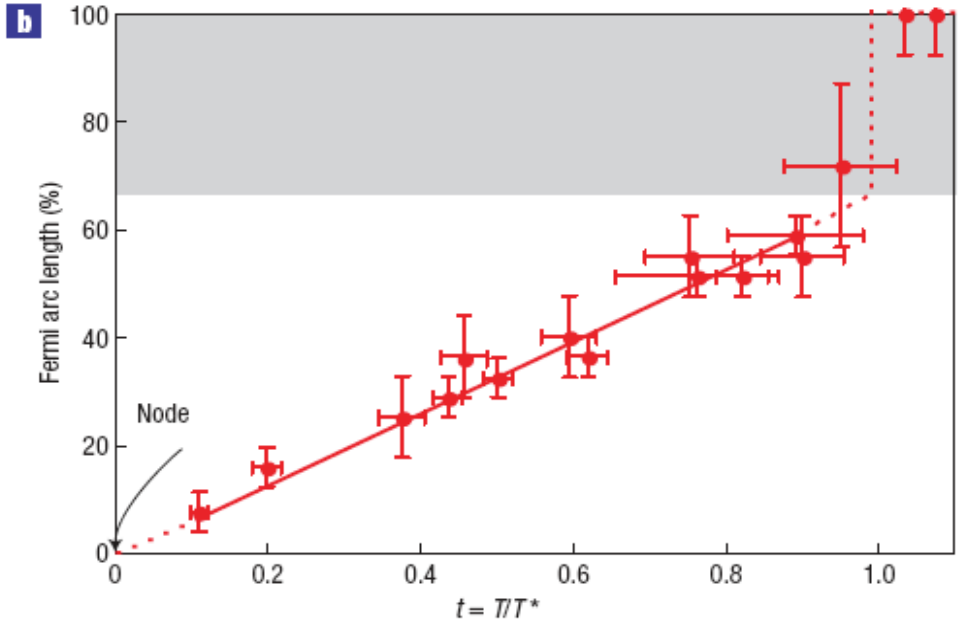


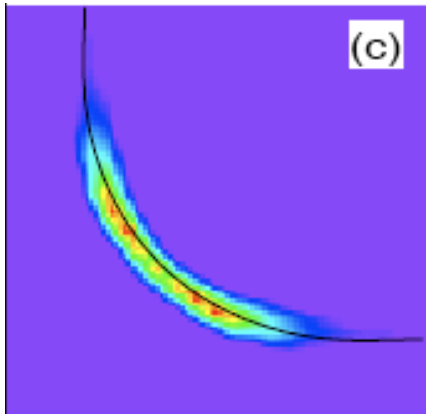
MGL - minimum gap locus

Is the T=0 limit of the pseudogap phase a nodal metal?



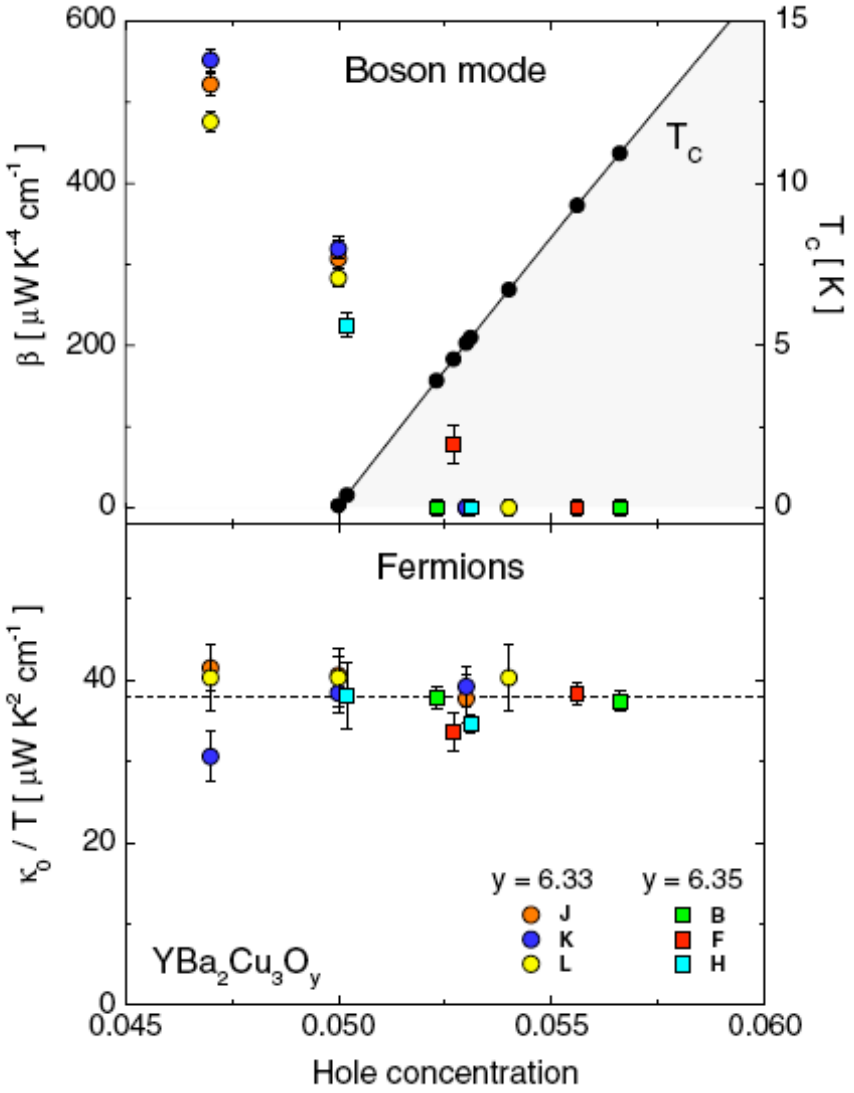






Kanigel *et al.*, Nat. Phys. (2006)

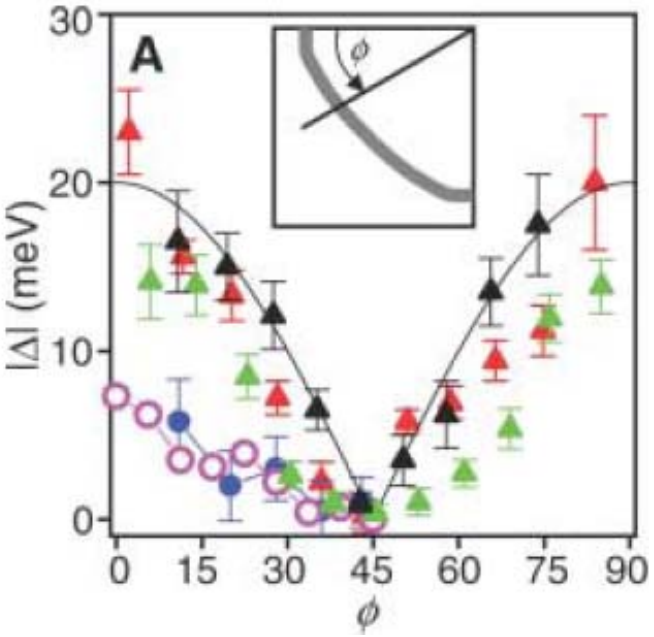
Nodal Liquid Implied by Low T Thermal Conductivity

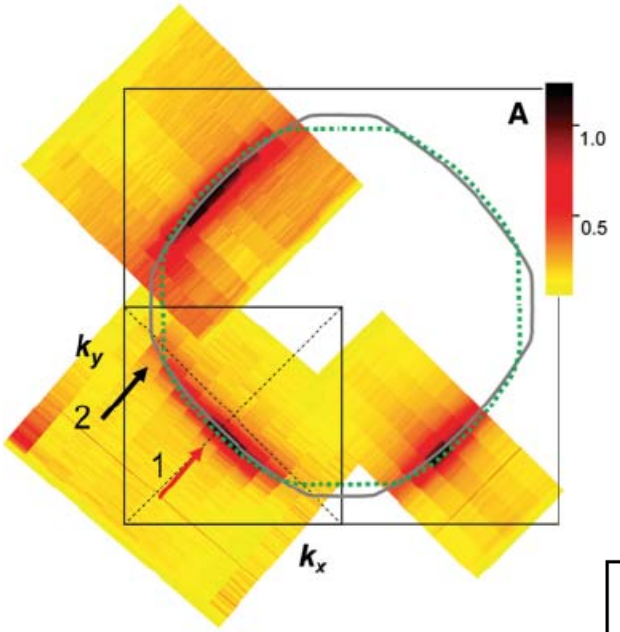


Doiron-Leyraud *et al.*, PRL (2006)

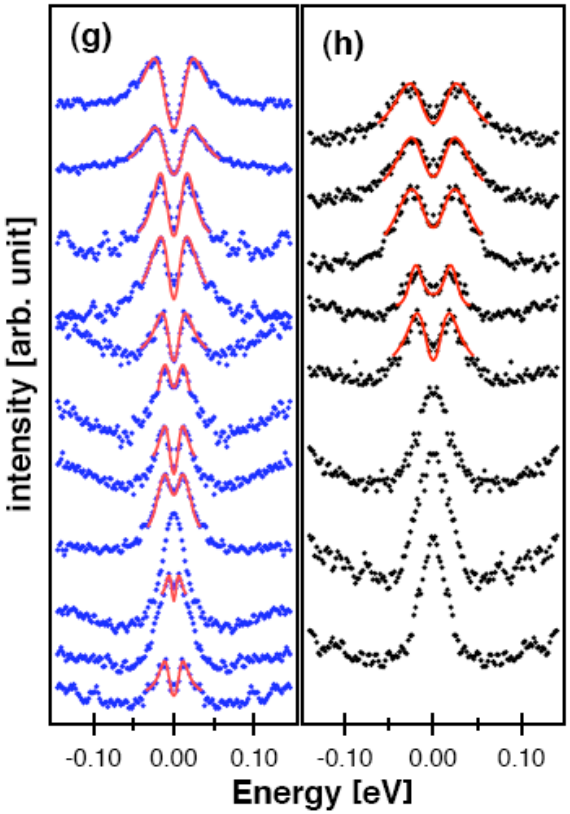
LBCO, x=0.125

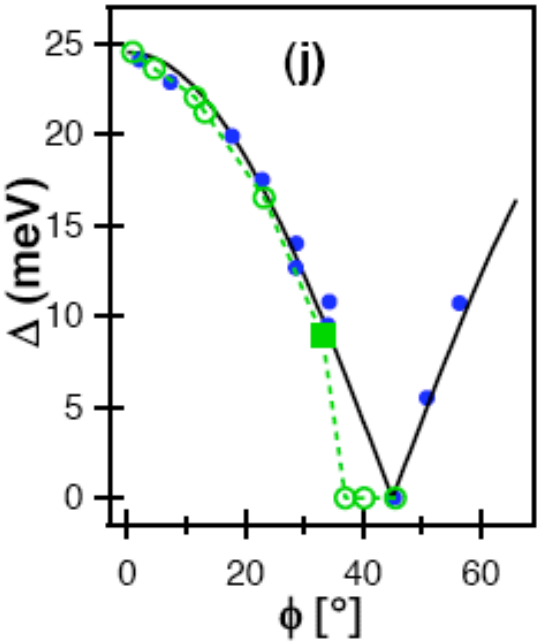
Valla *et al.*, Science (2006)





T=12K T=49K

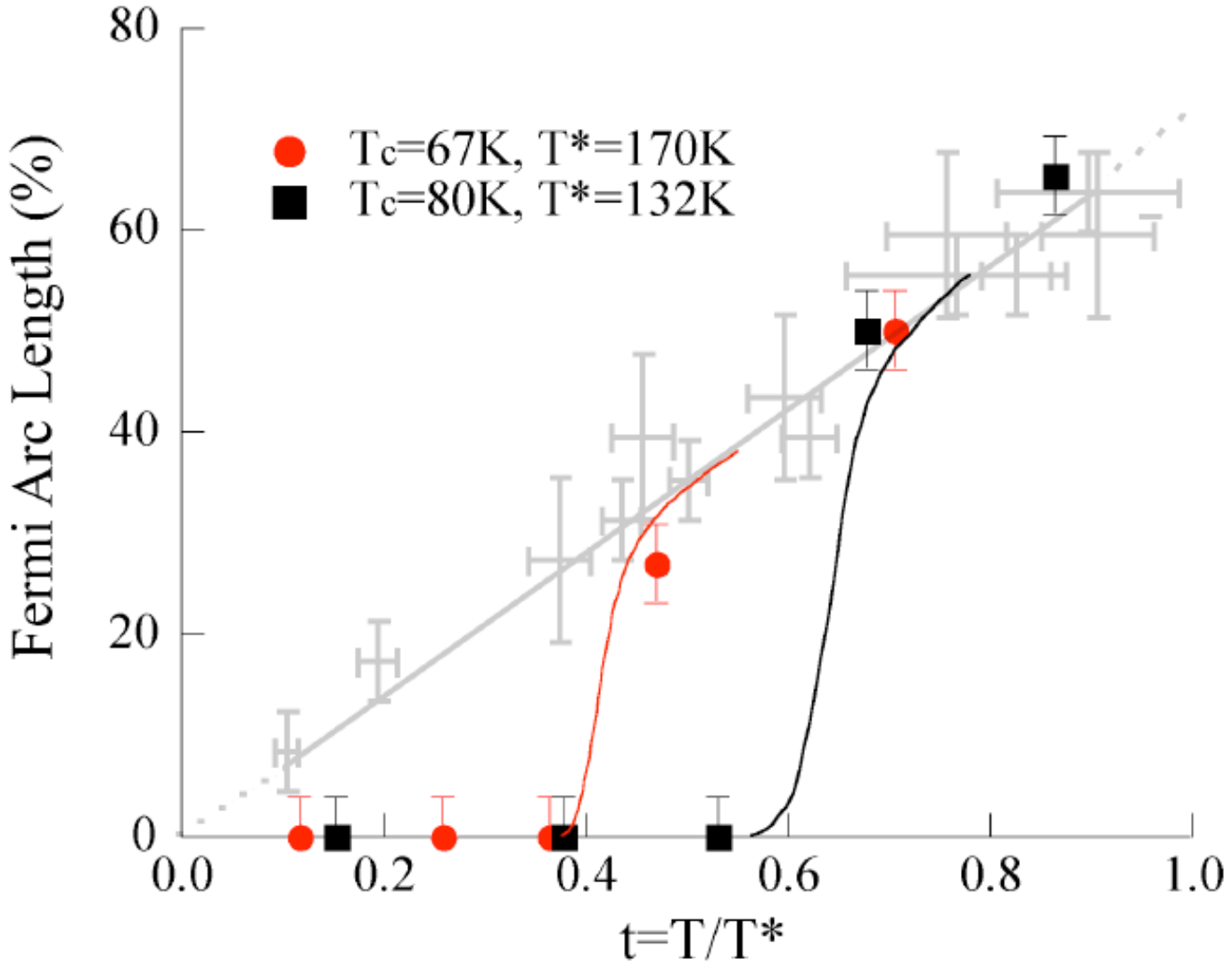




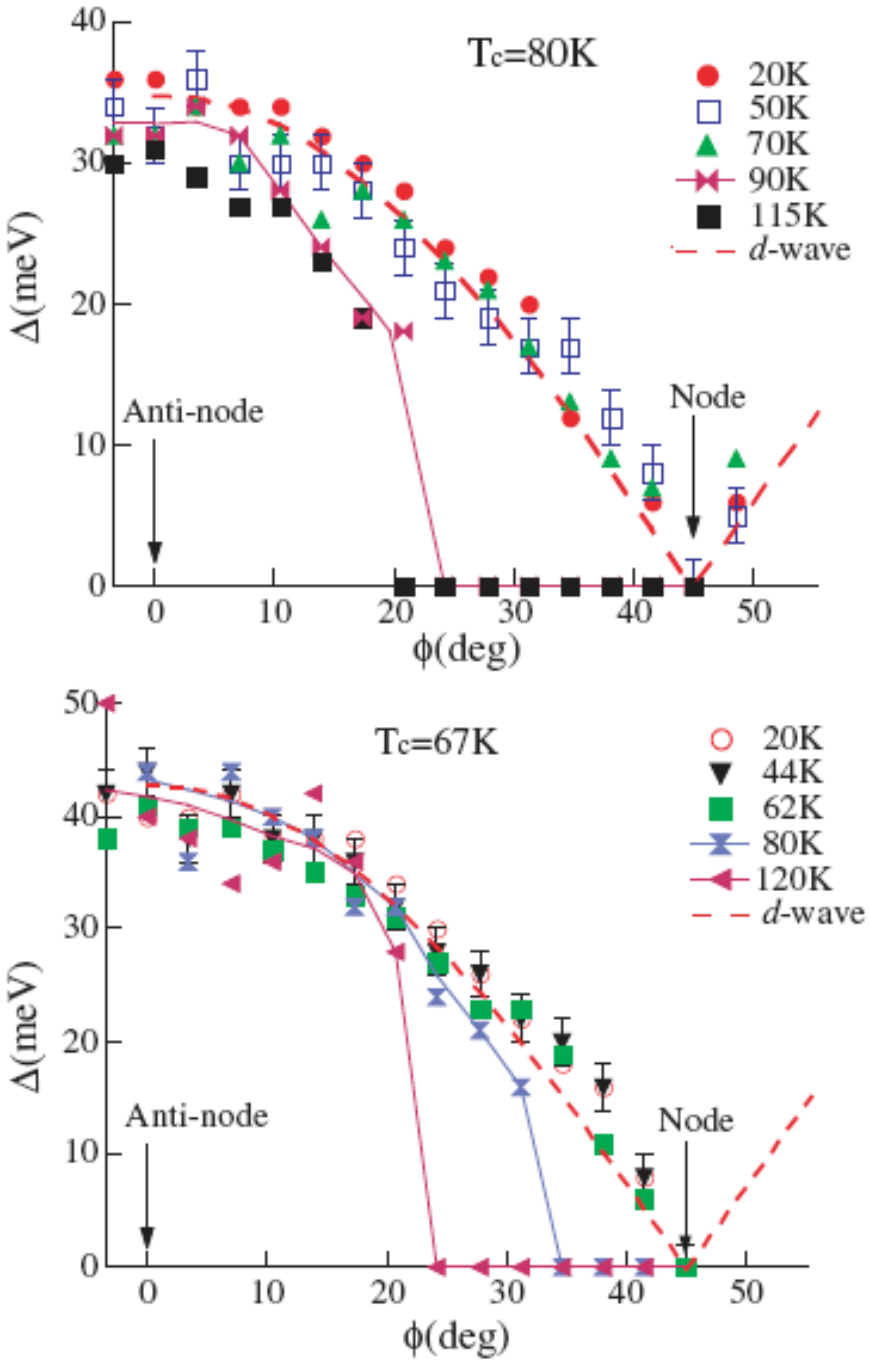
LSCO, x=0.105

Shi *et al.*, PRL (2008)

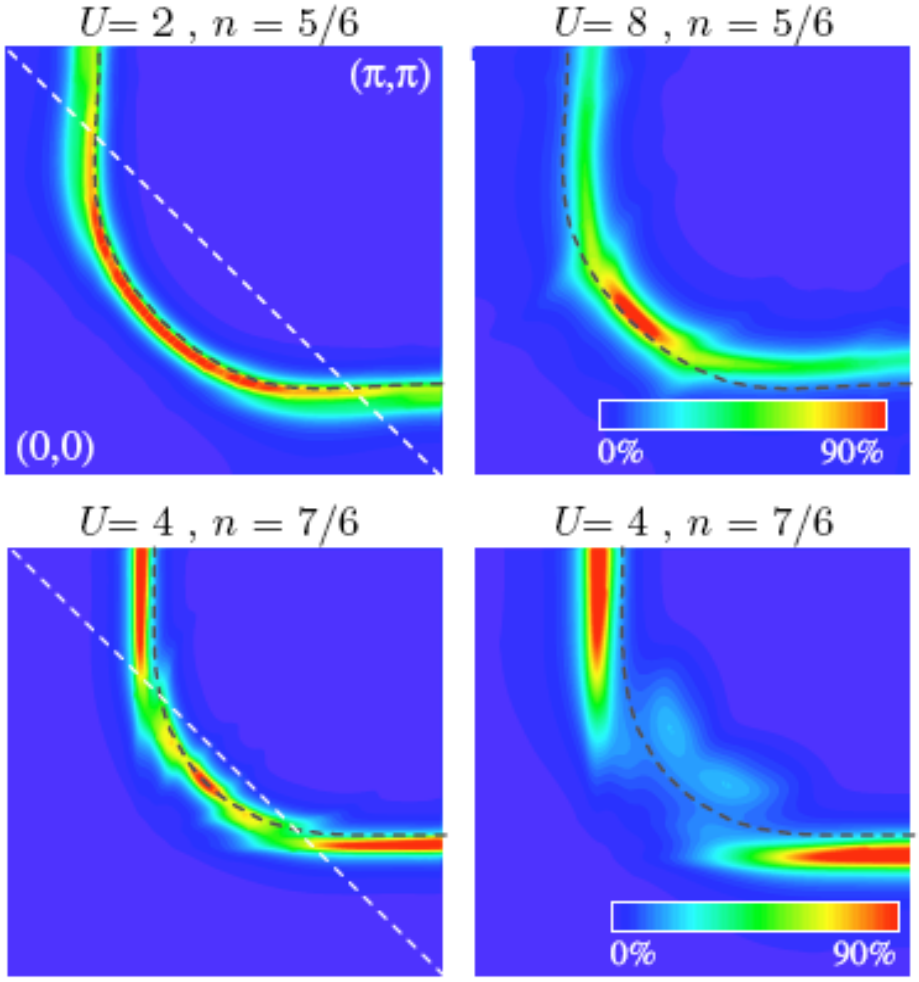
Collapse of Arcs Through T_c



Kanigel *et al.*, PRL (2007)

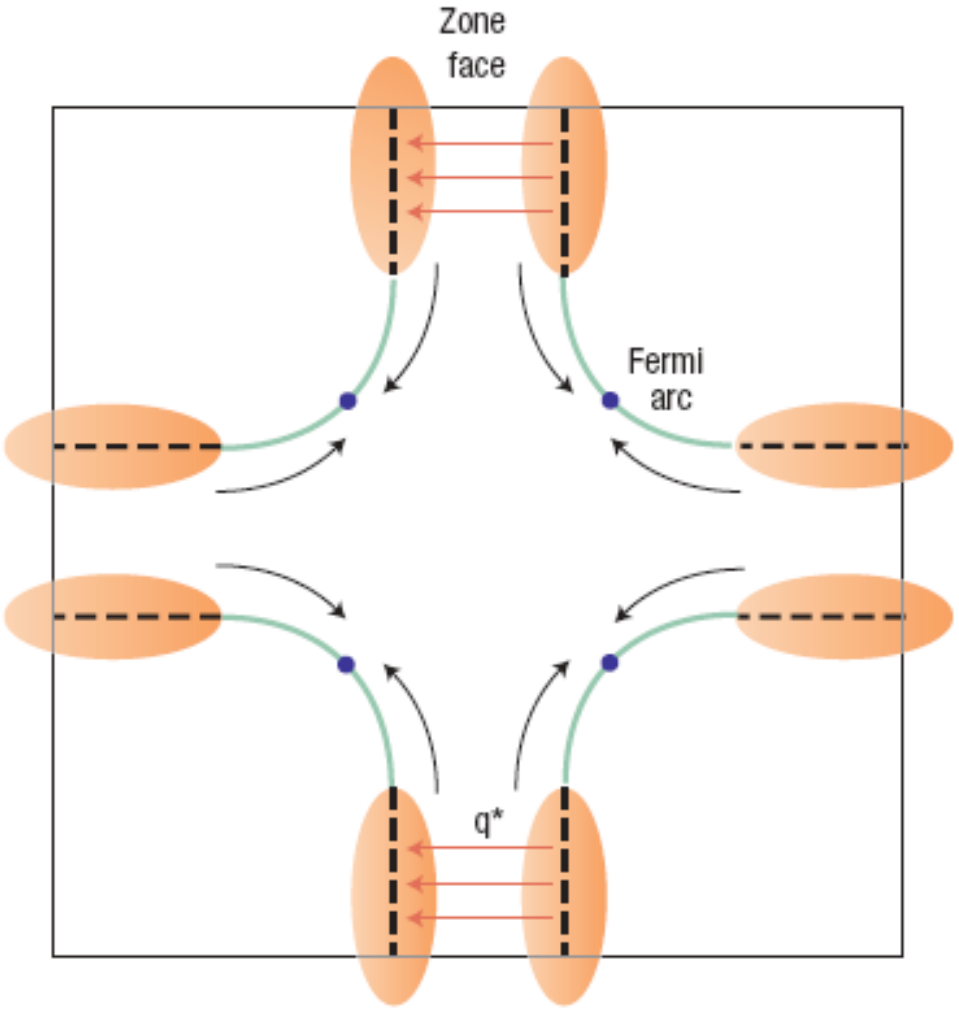

Tc=80K
20K
50K
70K
90K
115K
d-wave
Anti-node
Node
Δ(meV)
ϕ(deg)
Tc=67K
20K
44K
62K
80K
120K
d-wave
Anti-node
Node
Δ(meV)
ϕ(deg)

Dynamical Mean Field Theory (Georges, Kotliar, Tremblay)
Magnetic correlations wipe out parts of the Fermi surface



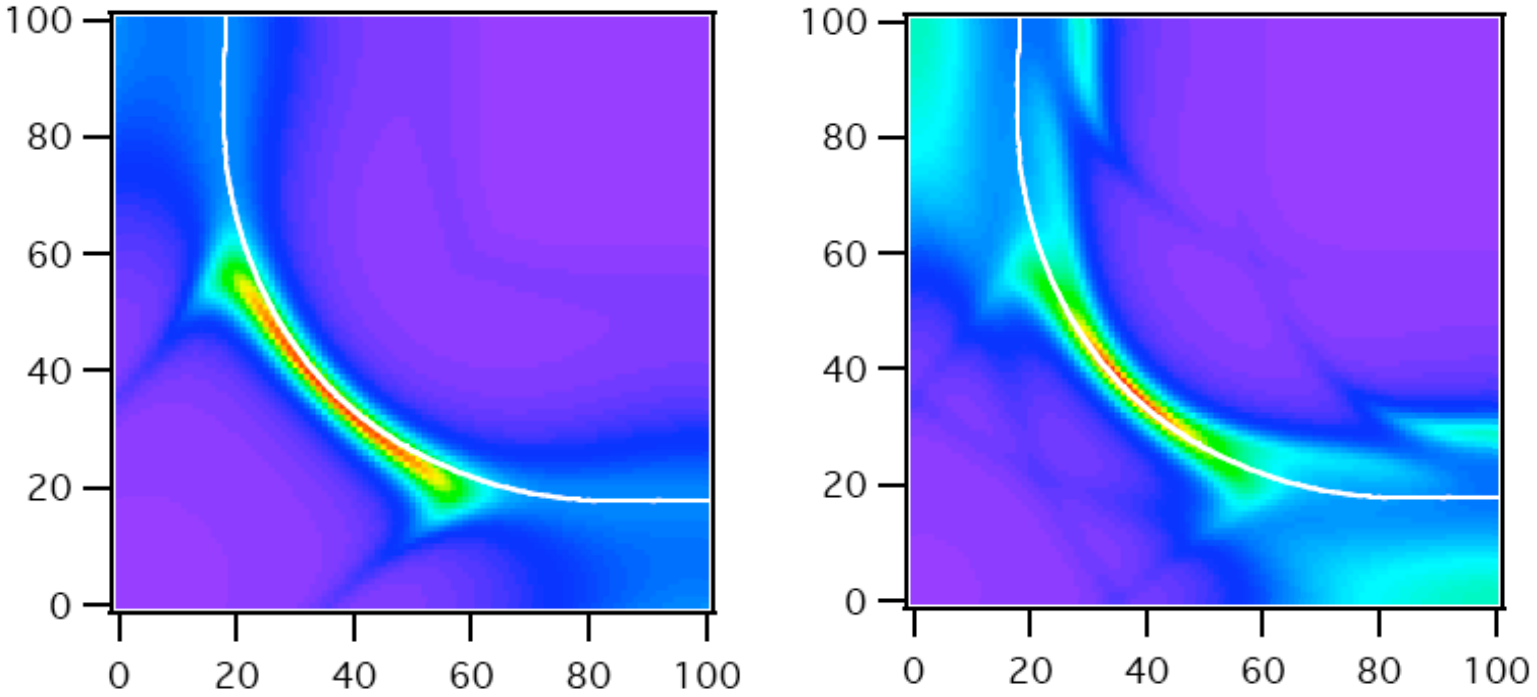
Senechal & Tremblay, PRL (2004)

Charge ordering?



McElroy - Nat. Phys. (2006)

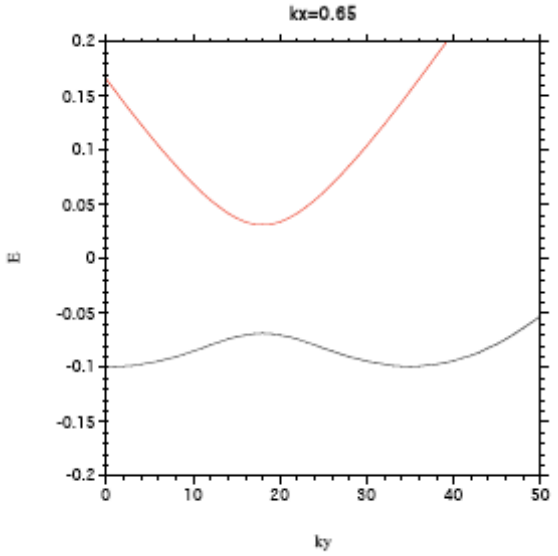
Charge ordering?
q=(0.36,0)π

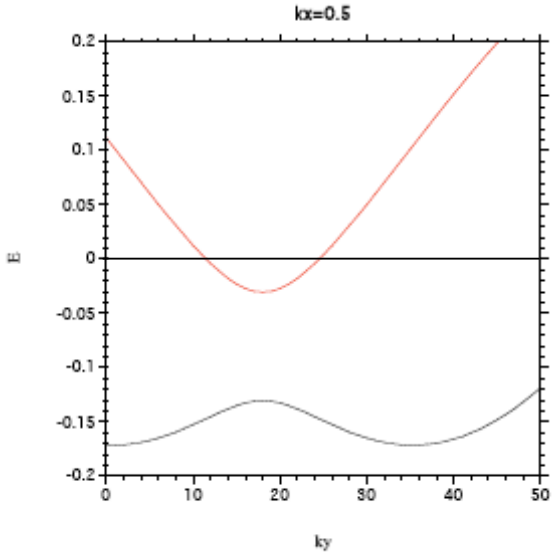


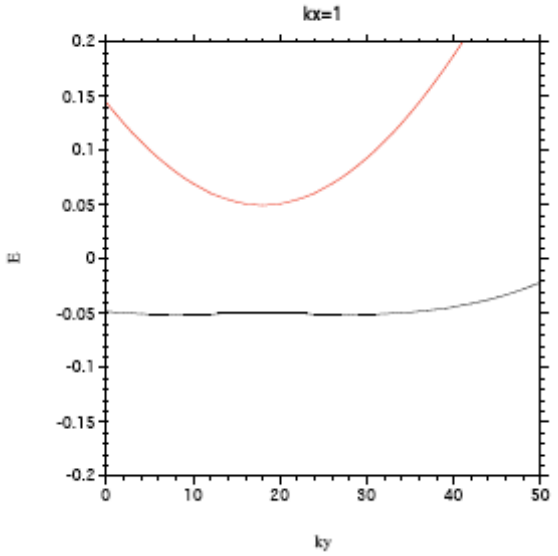
Zero energy intensity maps, left (q) and right (q,-q)

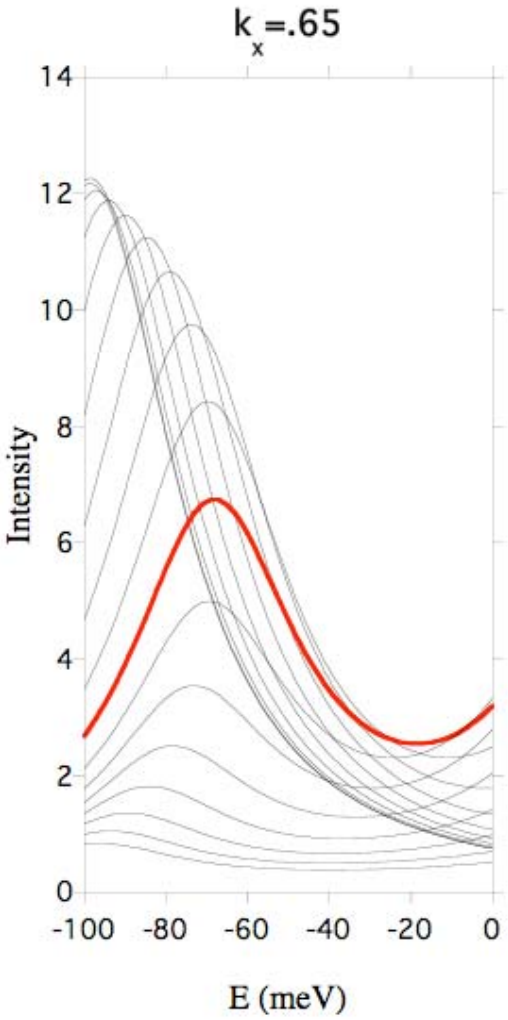
Norman *et al.*, PRB (2007)

Energy gap ***below*** E_F in the 'arc' region for charge ordering scenario

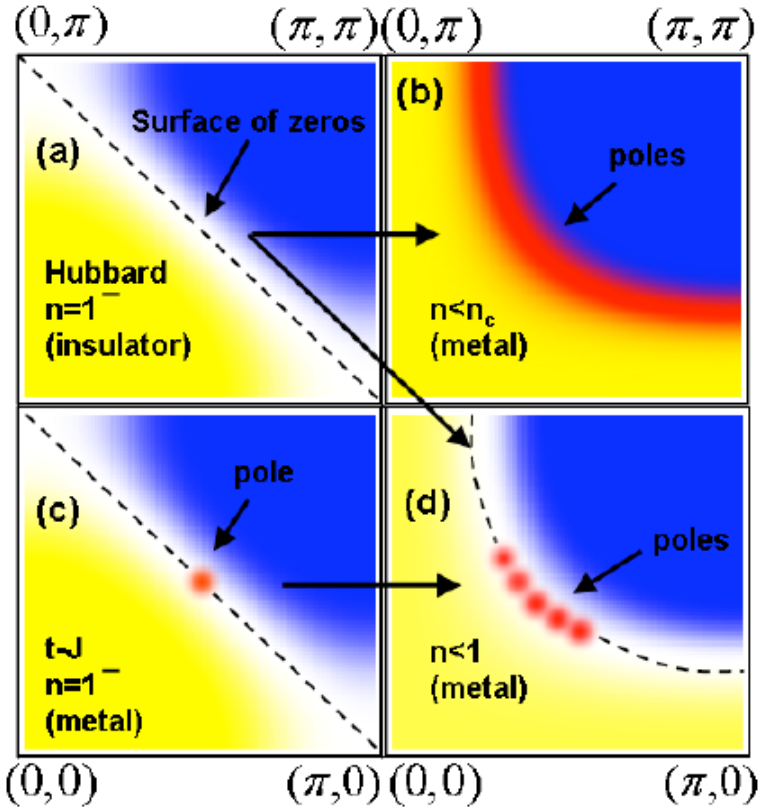




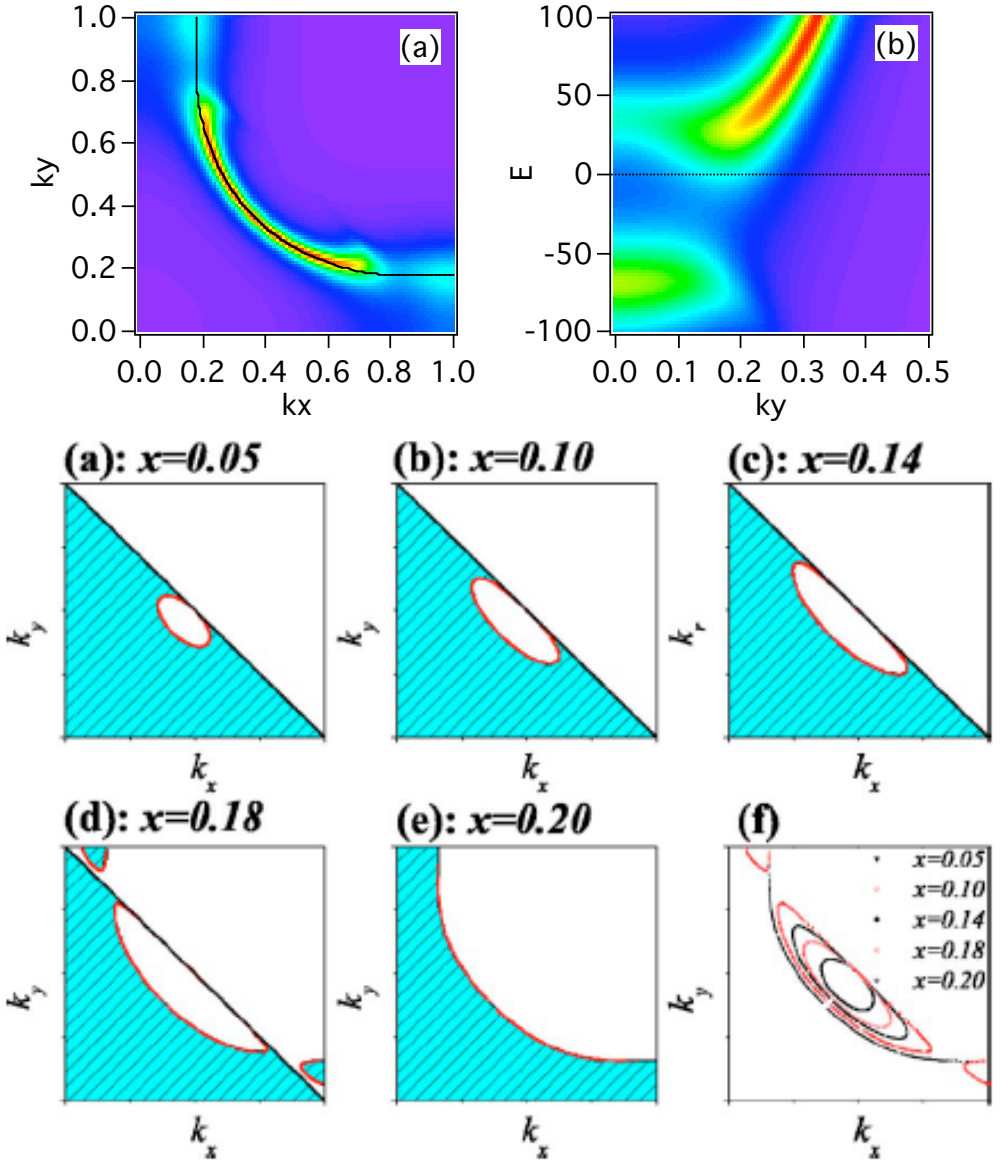




Luttinger Zeros

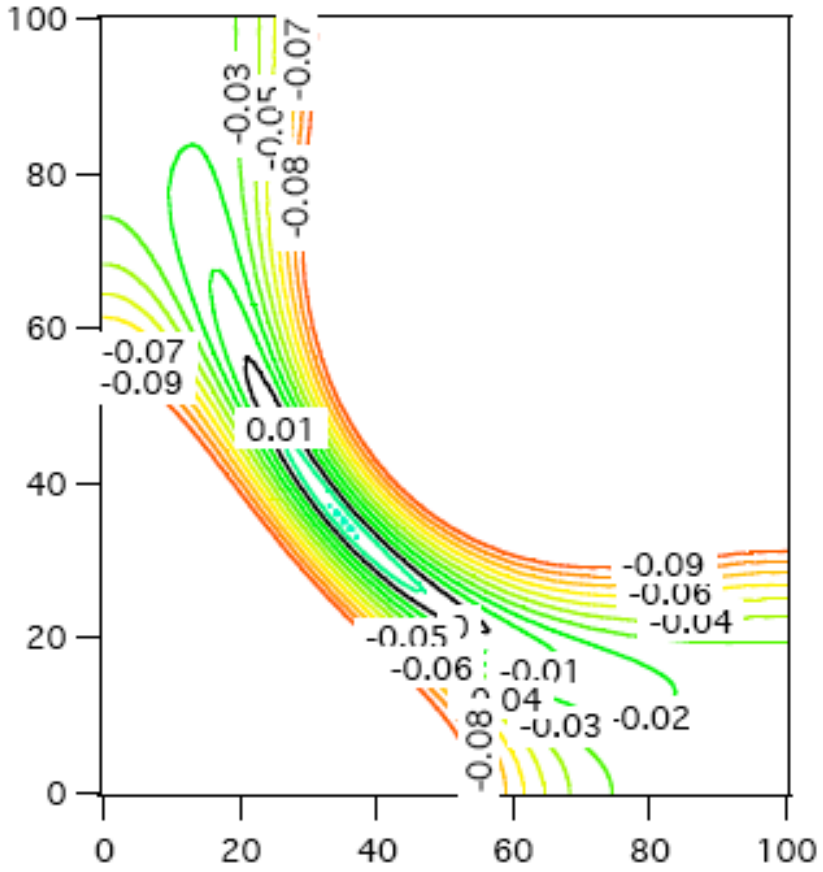


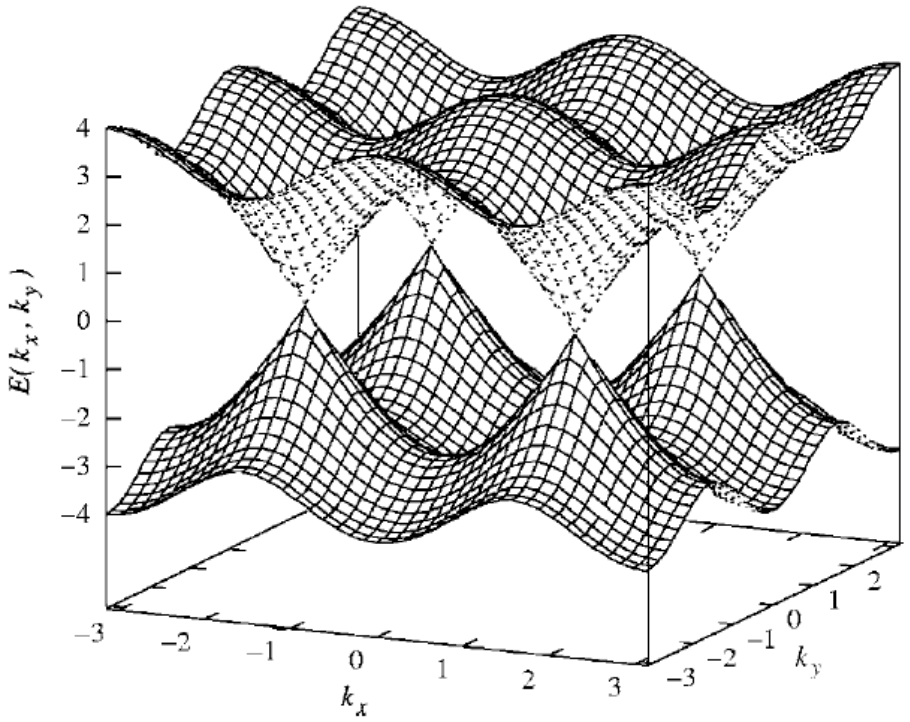
Stanescu, Phillips, Choy, PRB (2007)



Yang, Rice, Zhang, PRB (2006)

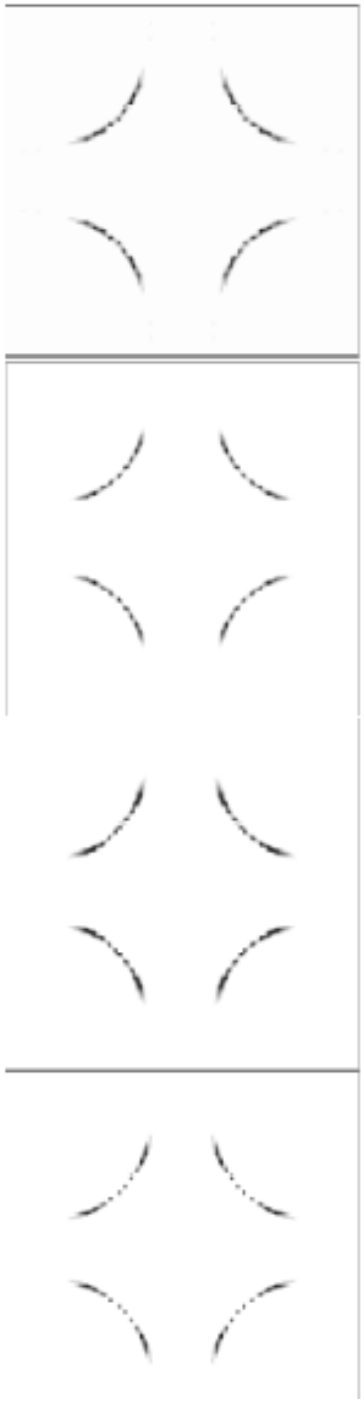
Dispersing Fermi Arcs in the Flux Phase State?

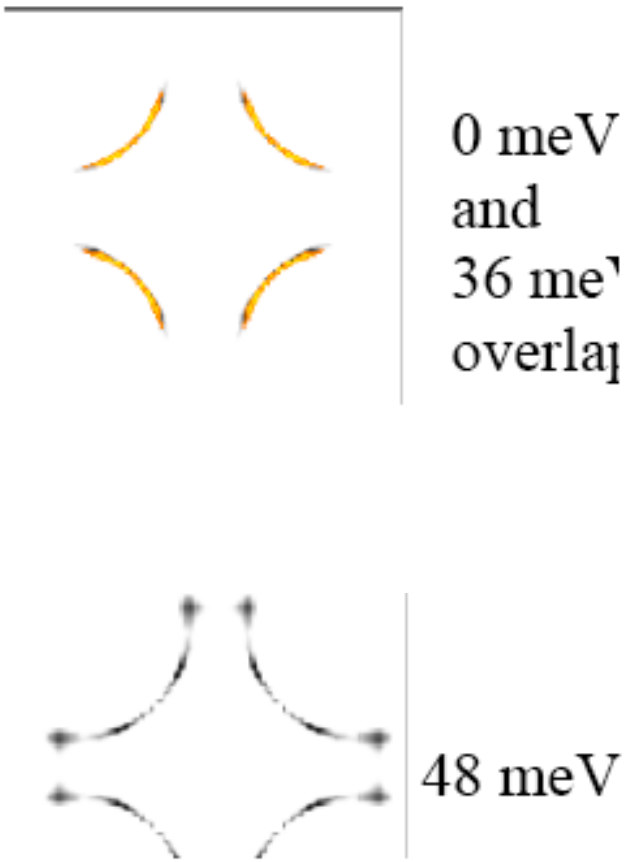




Wen and Lee - PRL (1998)

Fermi arcs appear to be dispersionless

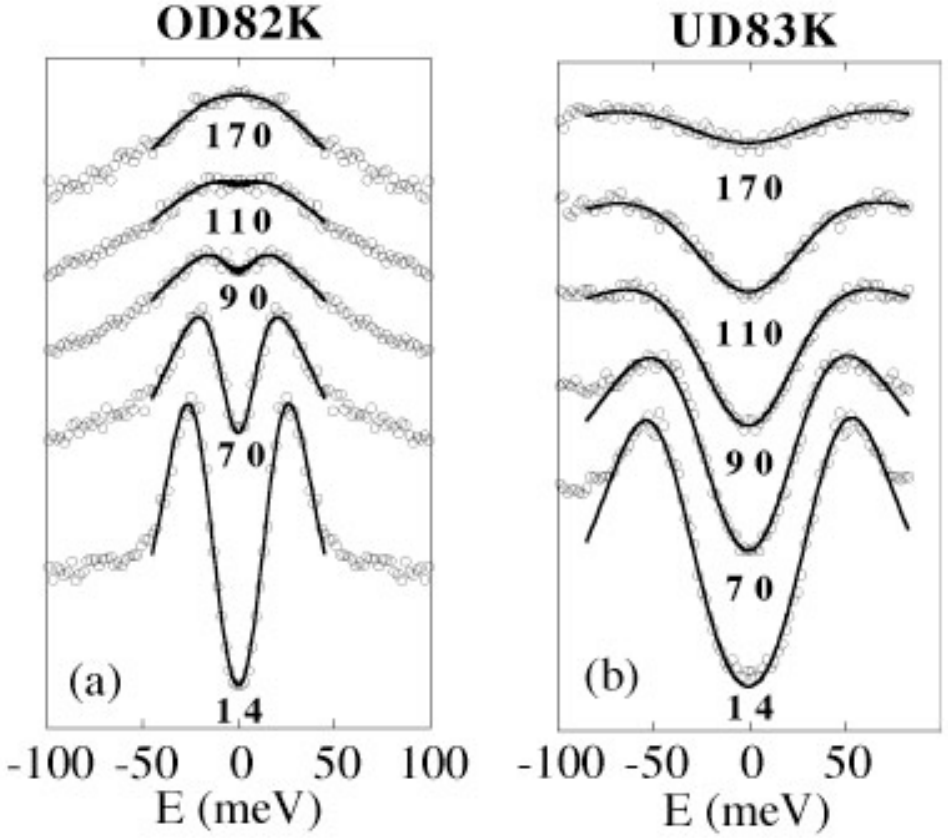




$\Sigma = -i\Gamma_1 + \Delta^2/(\omega+i\Gamma_0)$ where

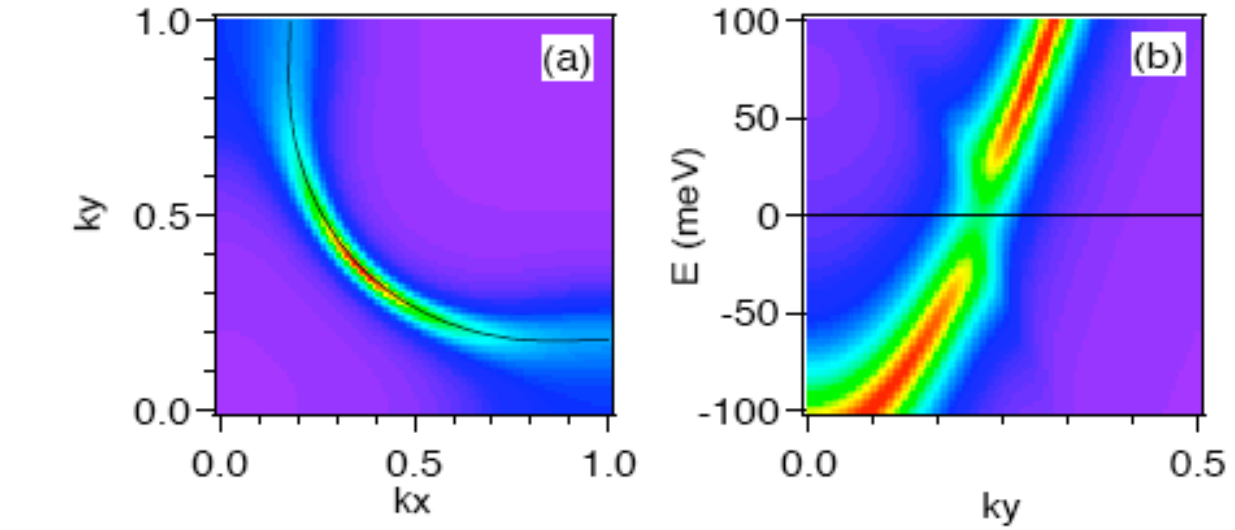
Δ is the gap, Γ_1 the single particle scattering rate and Γ_0 the inverse pair lifetime

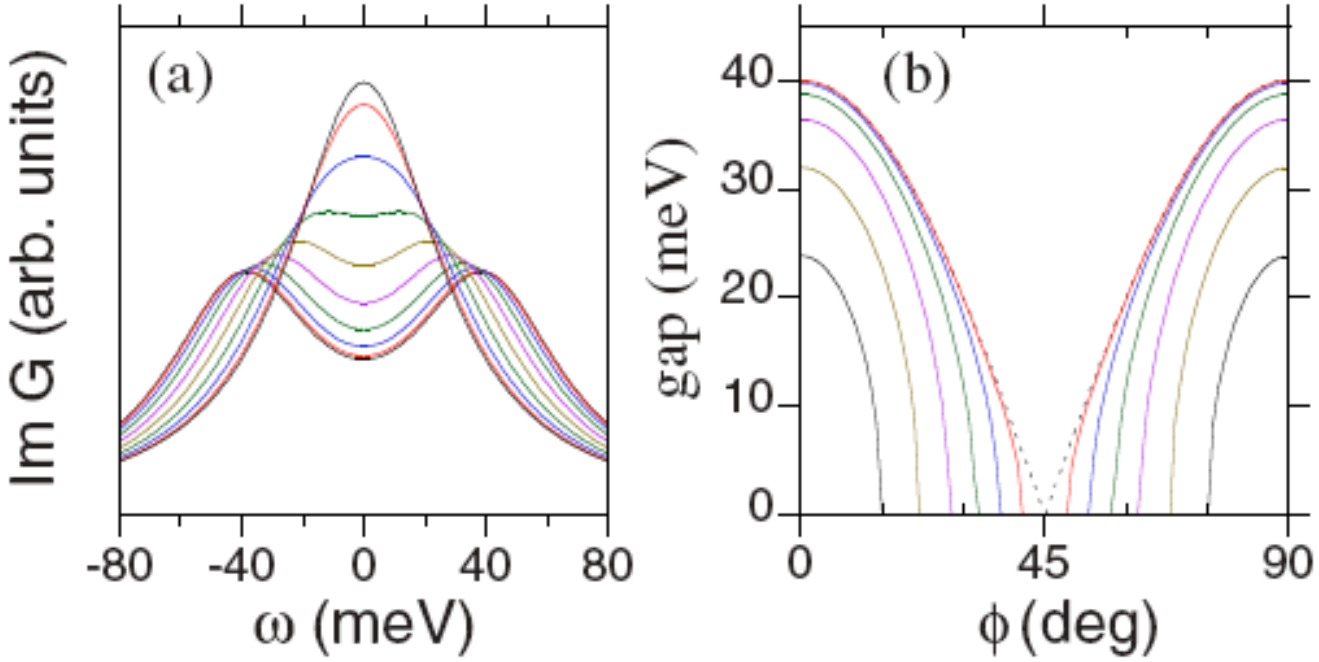
Antinode vs T



Norman *et al.*, PRB (1998)

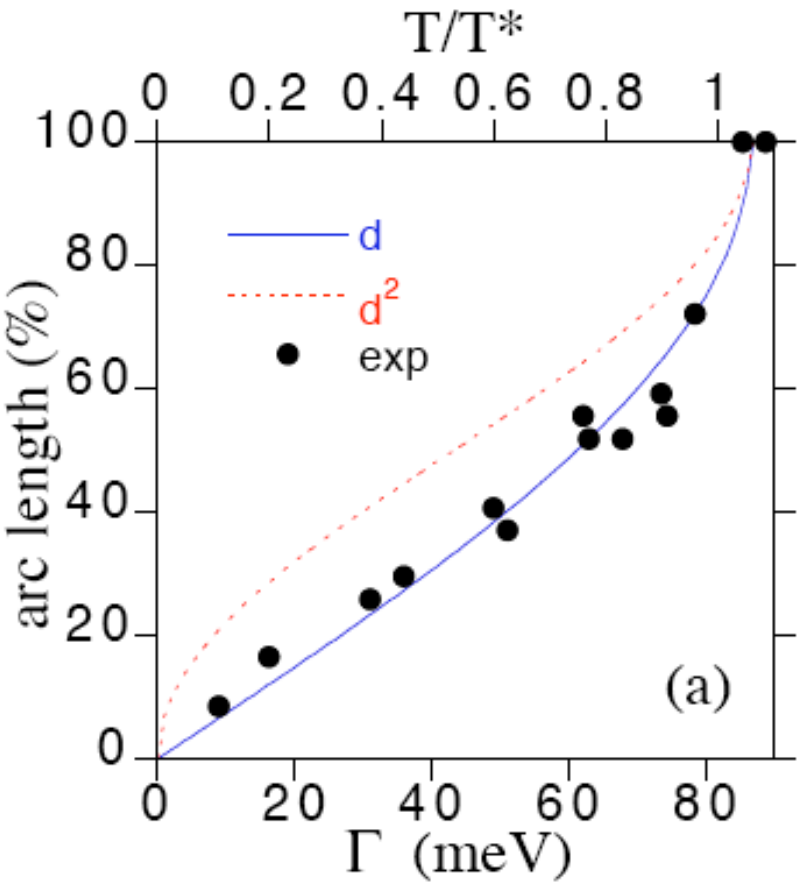
$\Gamma_0 = \Gamma_1$

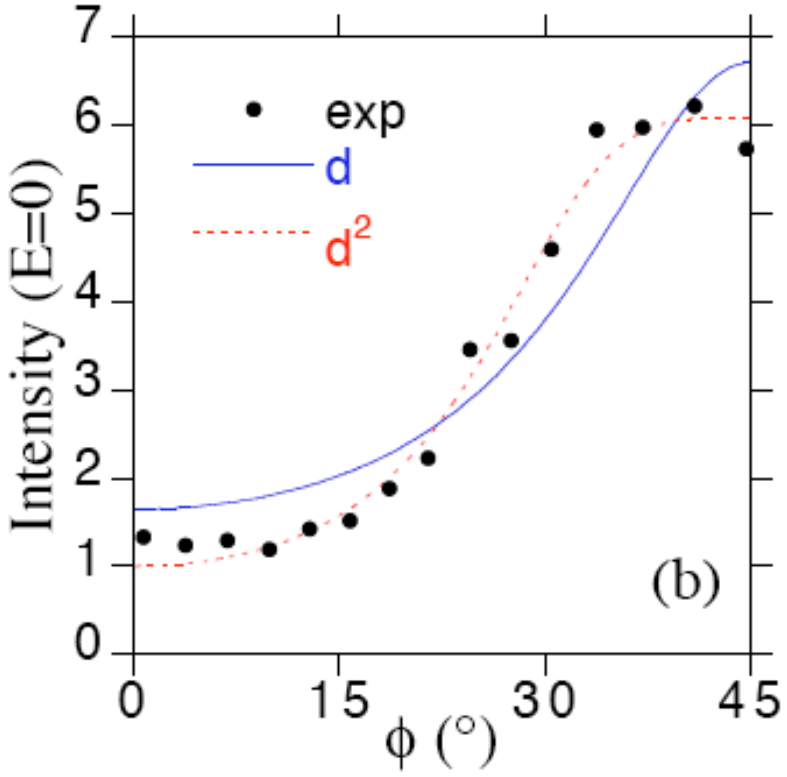




Arc Length is Linear in Γ_0 -> $\Gamma_0 \sim T$ -> Arc Length ~ T

(lifetime broadened d-wave node)



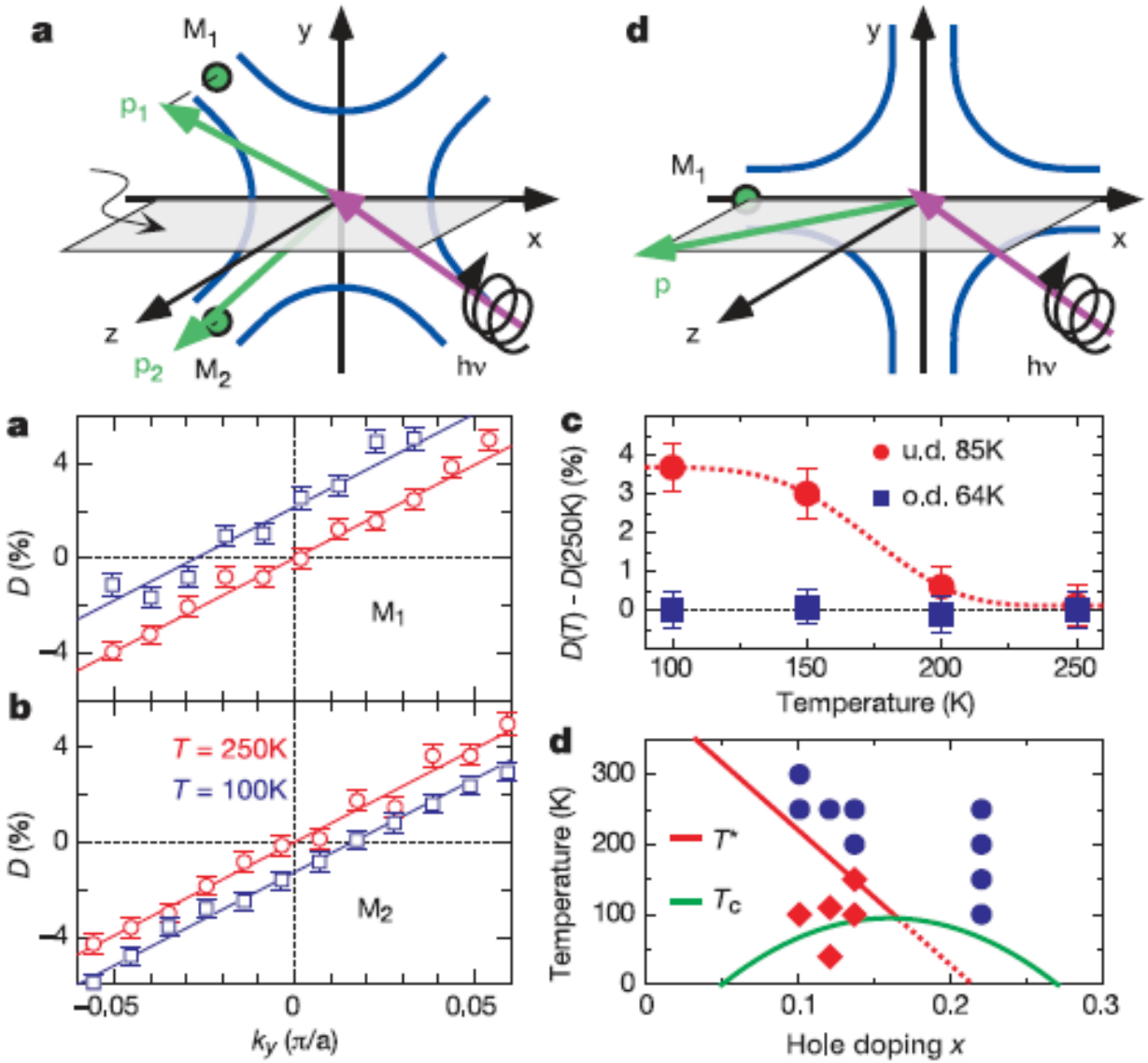


Also explains arc collapse below T_c (Γ_0 -> 0)

SUMMARY of ARPES

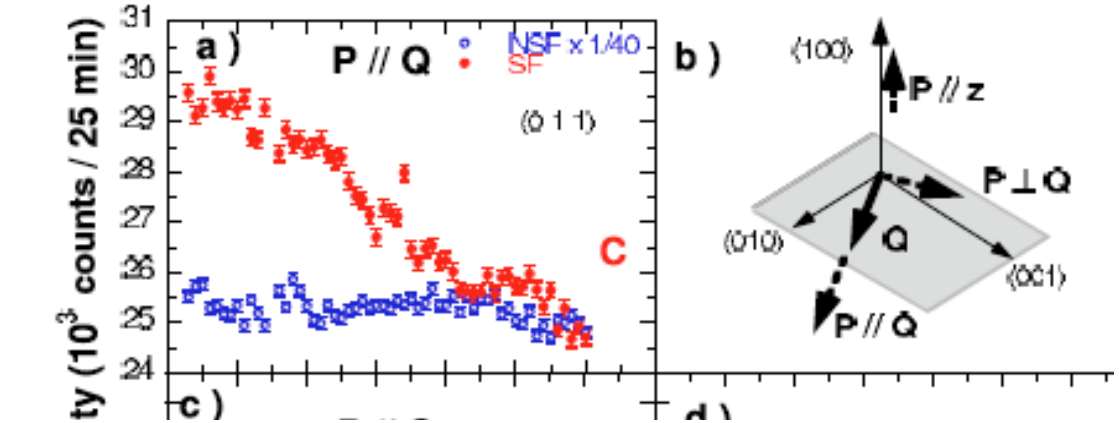
1. Spectroscopic data can be scaled as a function of $T/T^*(x)$
2. Fermi arc length is linear in $T/T^*(x)$
3. No shadow bands are found associated with finite q vector
4. Pseudogap is tied to k_F and E_F implying a q=0 instability
5. The data are consistent with a “fluctuating pairs” model with an inverse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

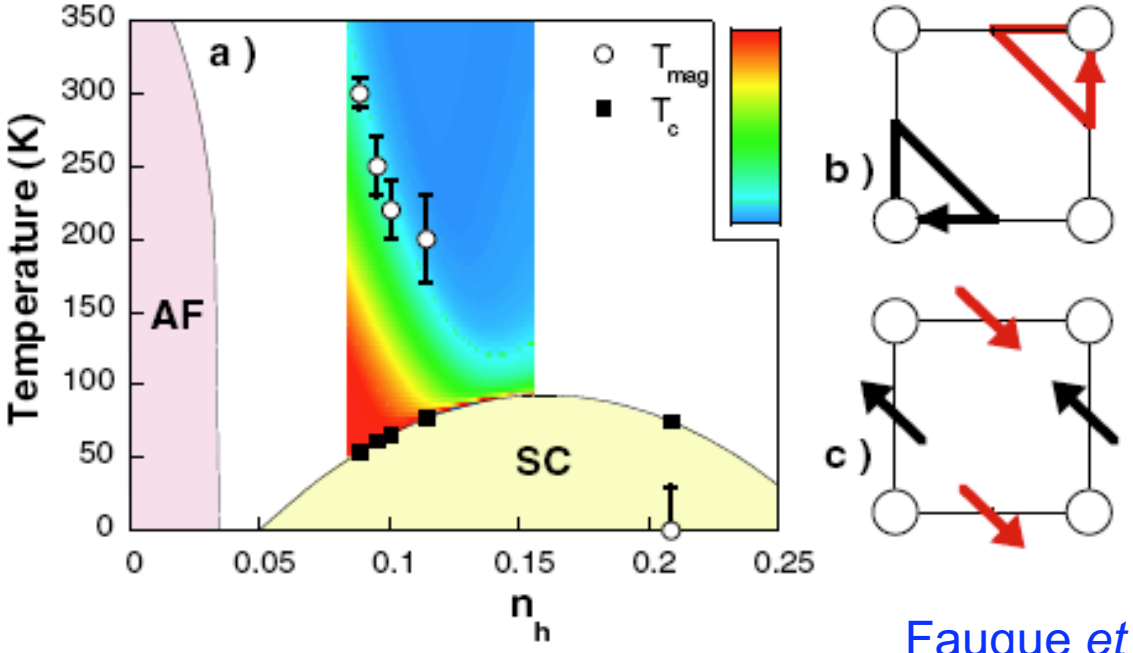
Circular dichroism above T_c in the pseudogap phase?



Kaminski *et al.*, Nature (2002)

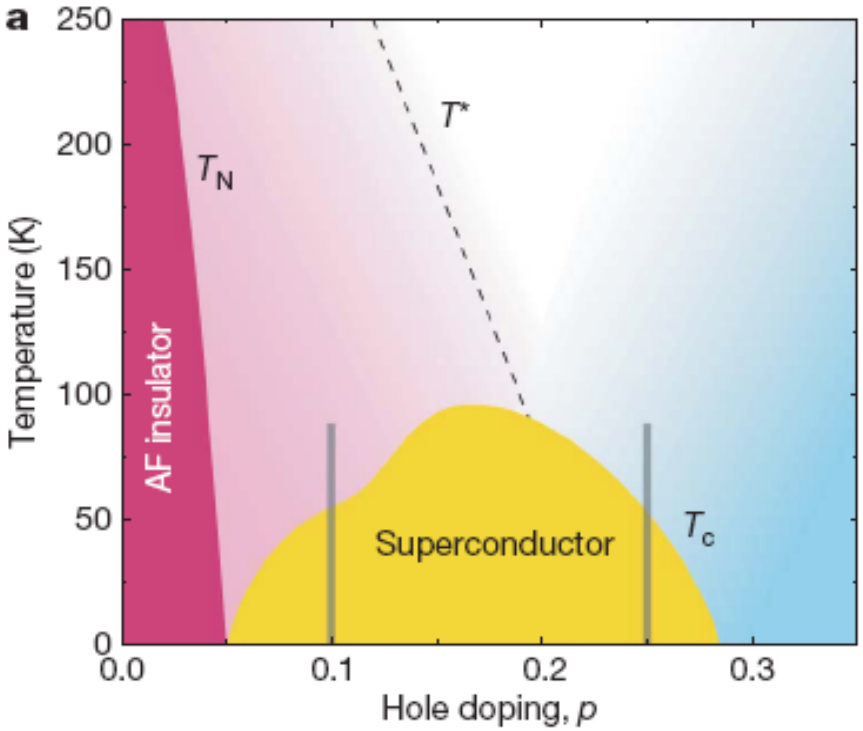
Orbital moments above T_c in the pseudogap phase?

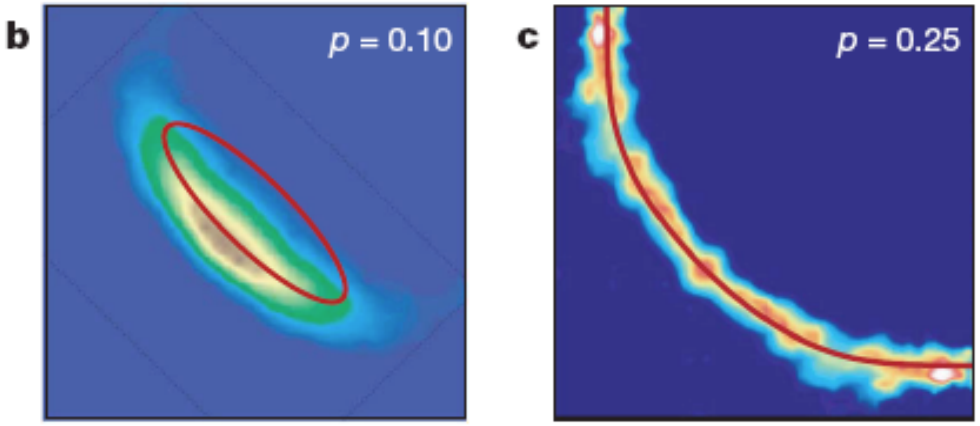




Fauque *et al.*, PRL (2006)

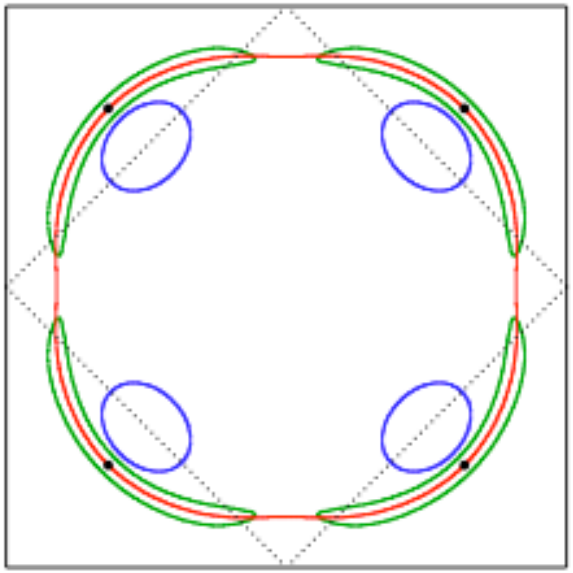
Evolution of the Fermi surface with doping



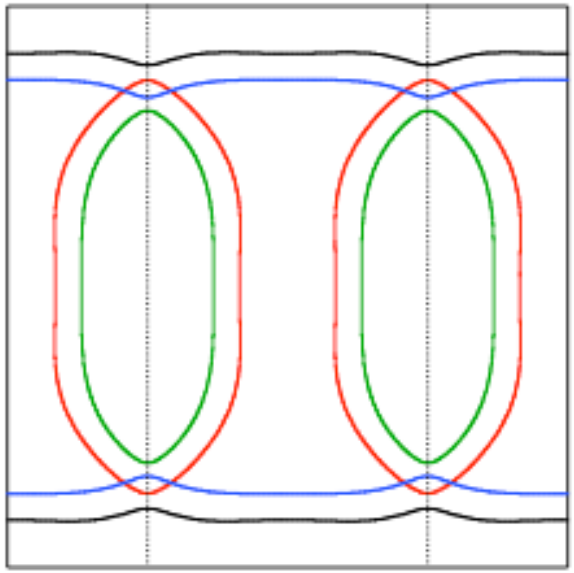


Doiron-Leyraud *et al.*
Nature (2007)

Quantum oscillations measure the areas and masses of extremal orbits of the Fermi surface



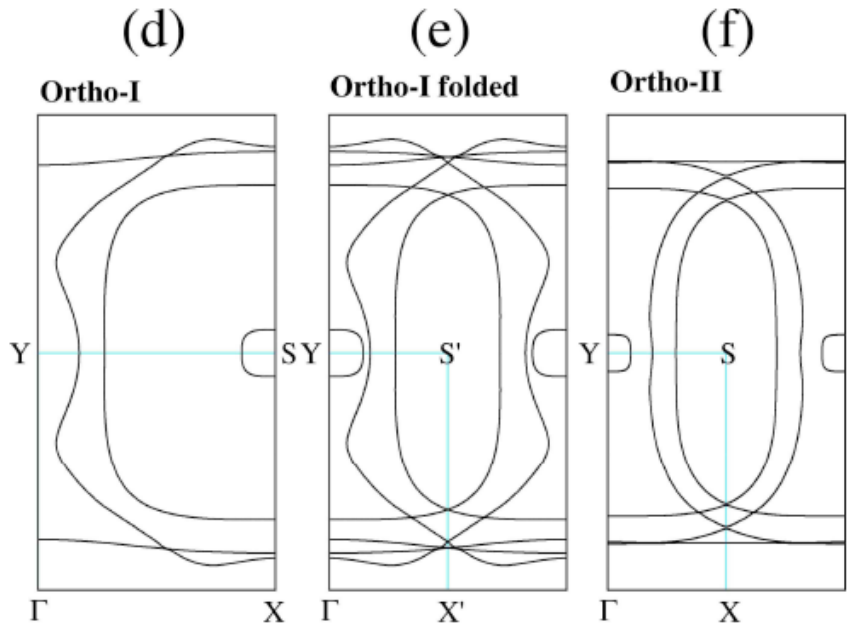
bananas vs pockets



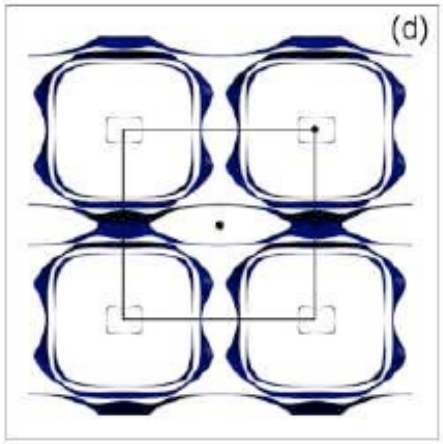
YBCO ortho-II folding

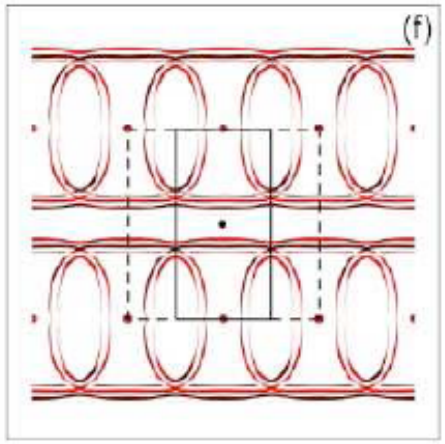
Julian & Norman, Nature N&V (2007)

YBCO - band theory



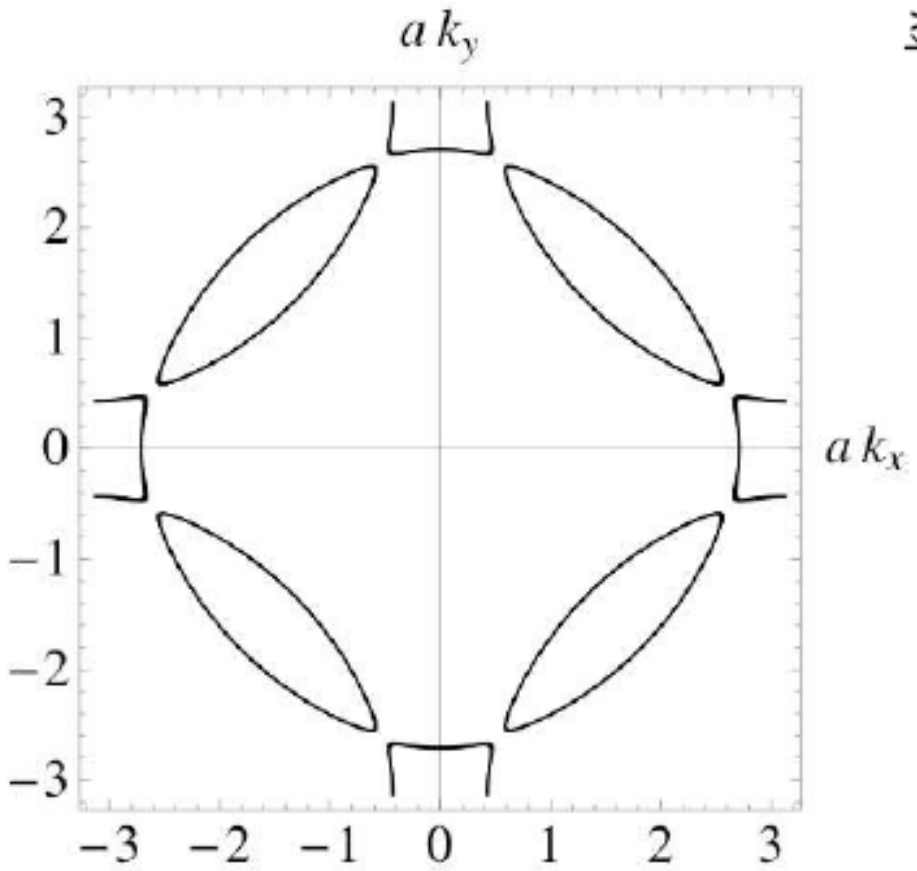
Carrington & Yelland, PRB (2007)

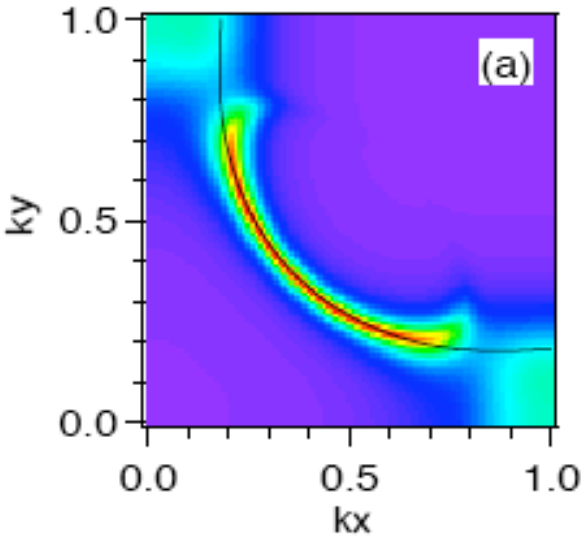




Elfimov, Sawatzky, Damascelli, PRB (2008)

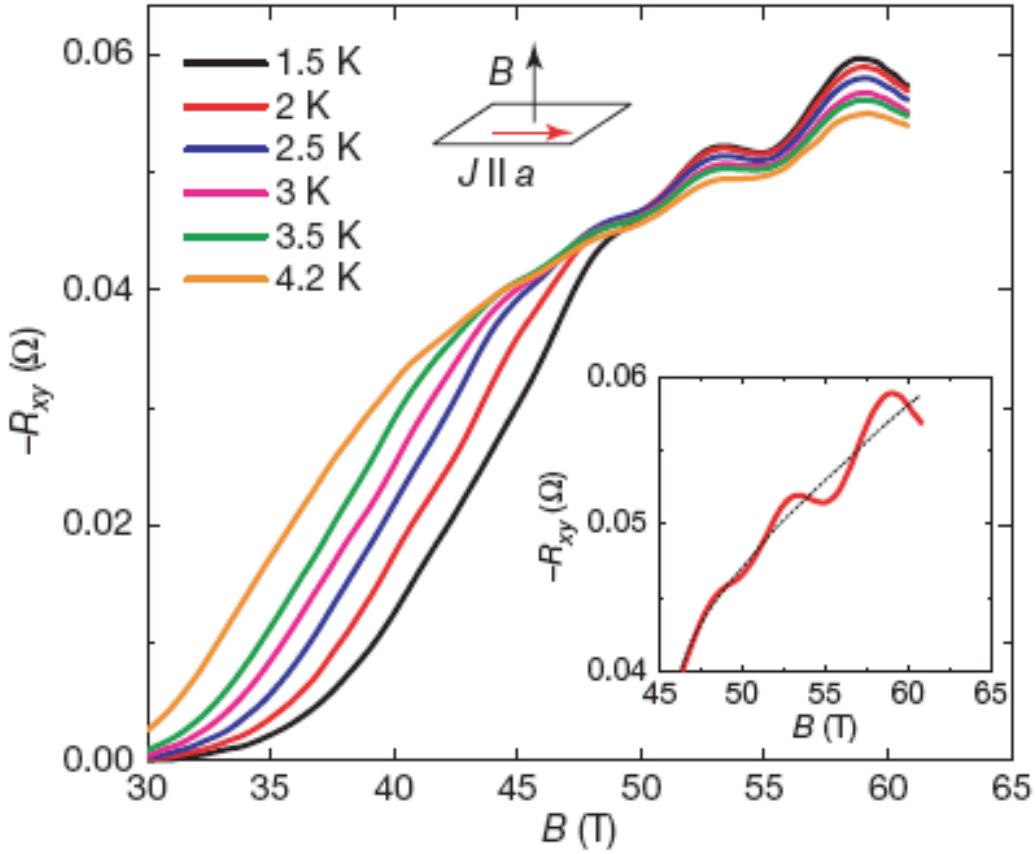
d density wave, q=(π,π)





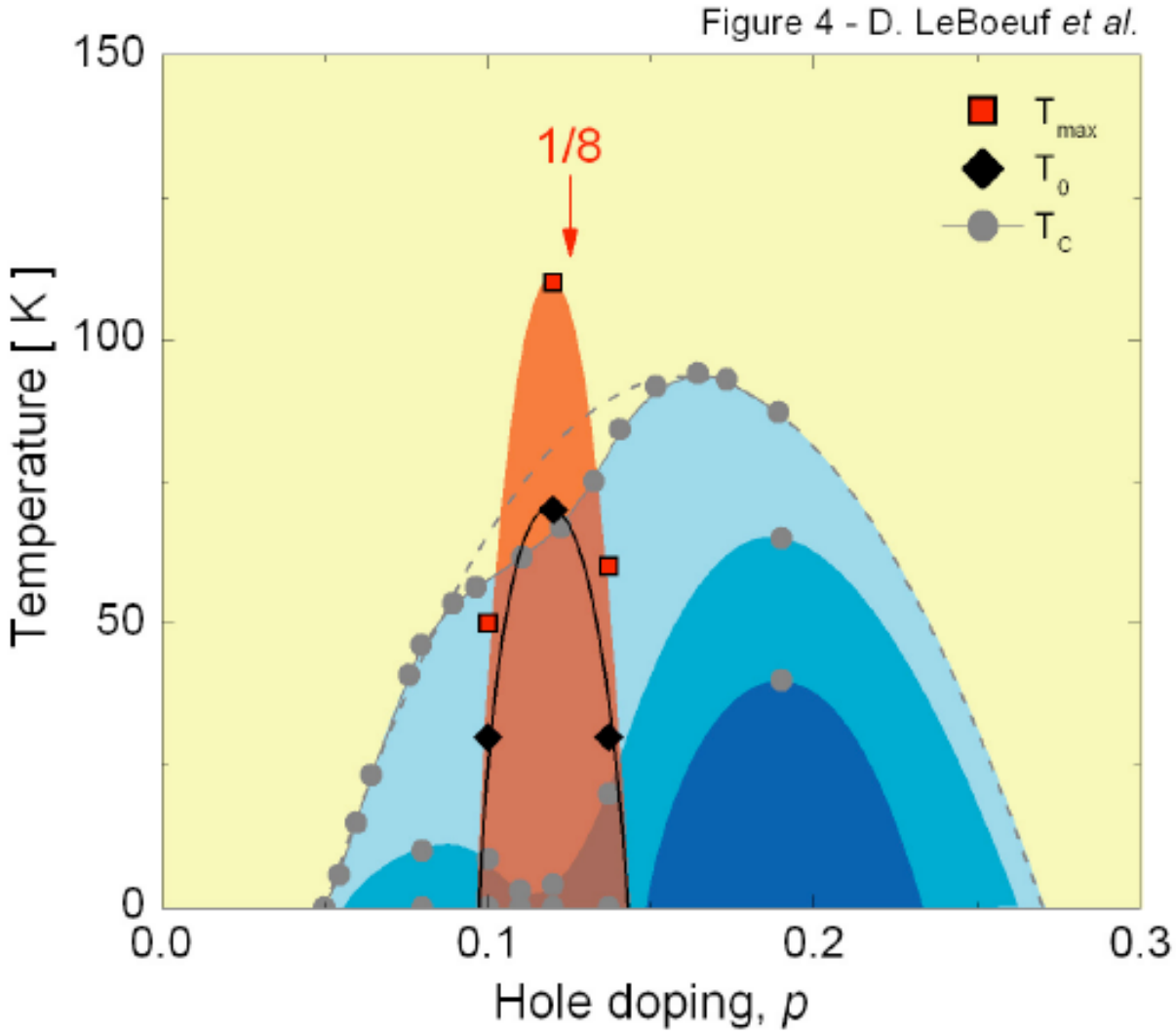
Chakravarty & Kee, PNAS (2008)

Magneto-oscillations in the Hall resistivity
(note that $R_H < 0$)



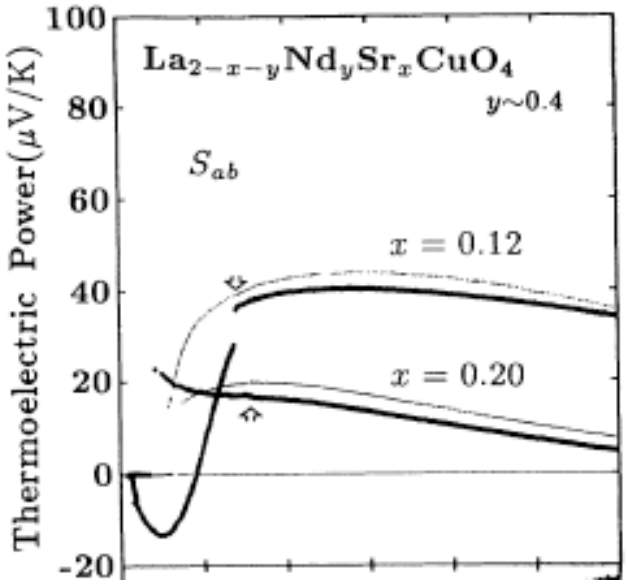
Doiron-Leyraud *et al.*
Nature (2007)

$R_H < 0$ forms a dome around x=1/8

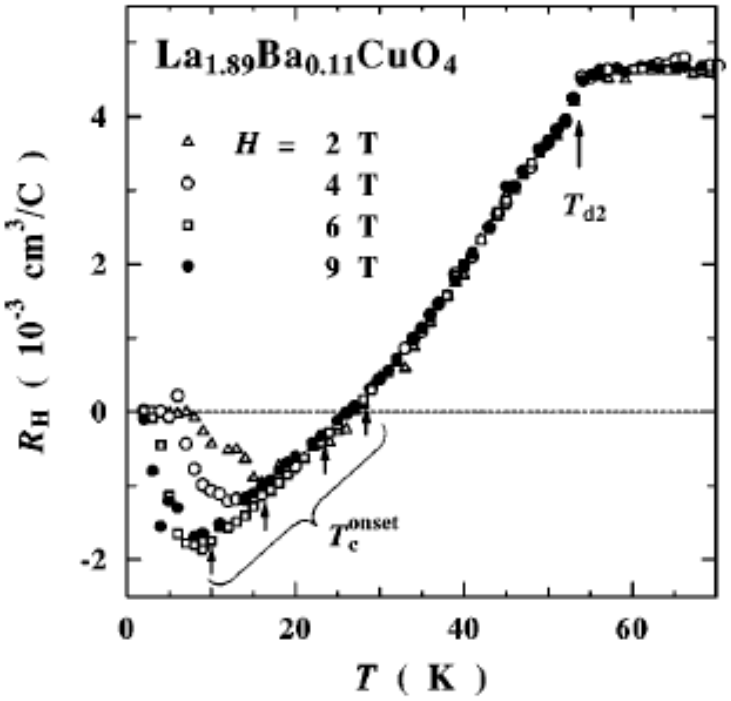


LeBoeuf *et al.*, Nature (2007)

This was also known from earlier studies of
the thermopower and Hall on LSCO & LBCO

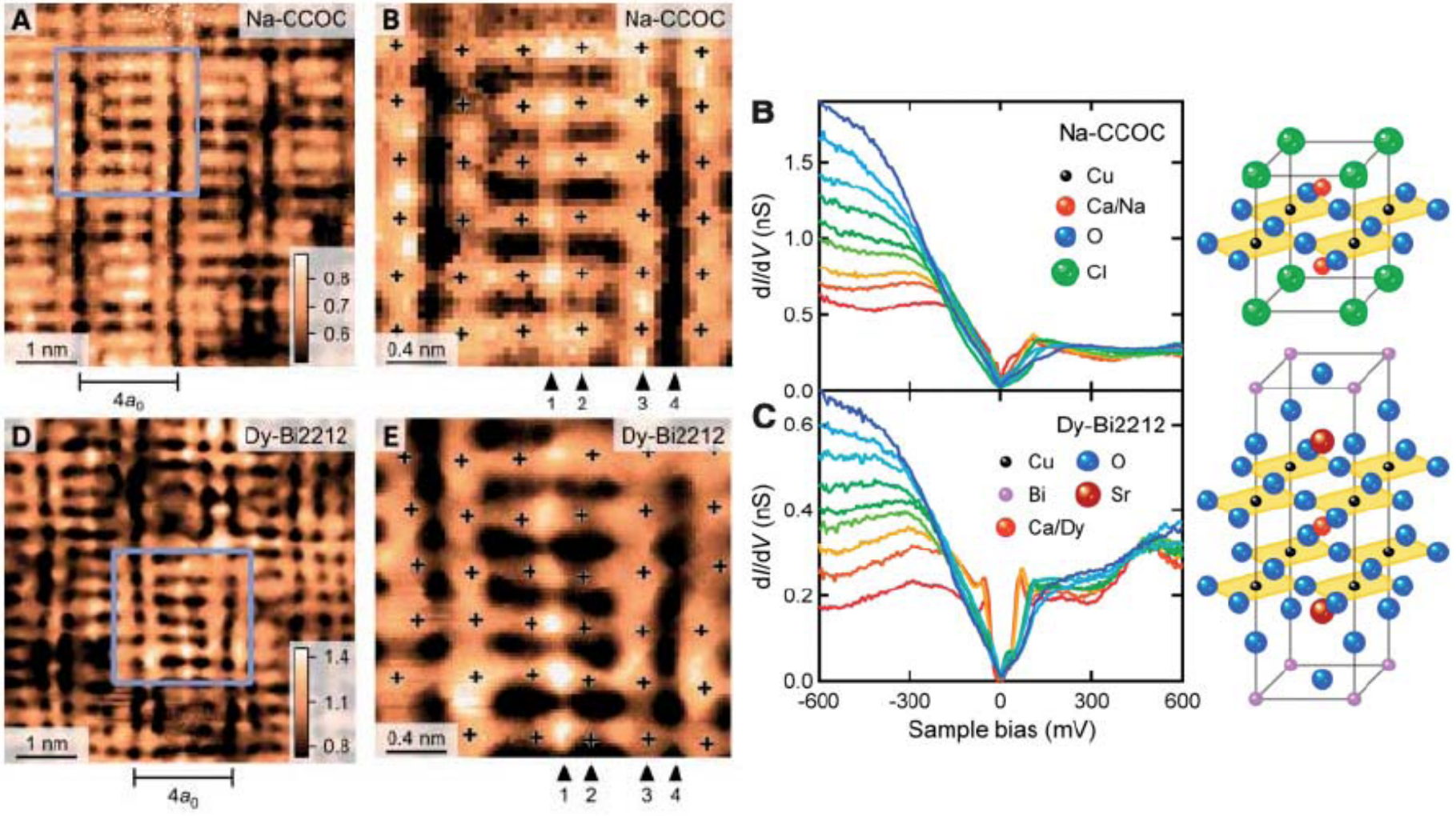


Nakamura & Uchida, PRB (1992)



Adachi, Noji, Koike, PRB (2001)

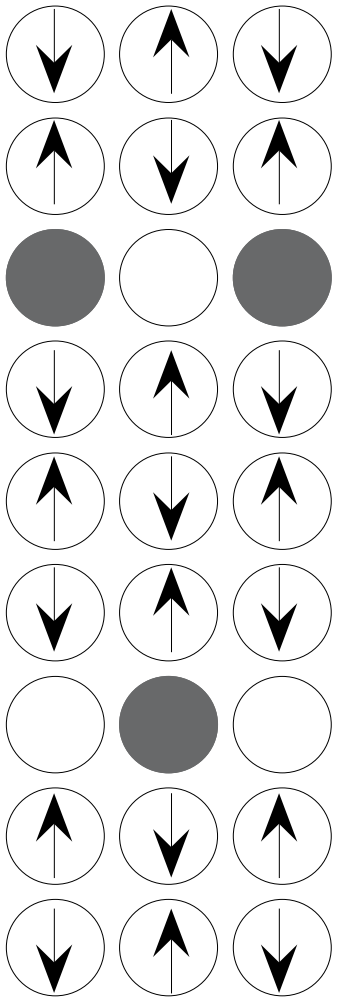
Hole Density shows a “4a period bond centered electronic glass”

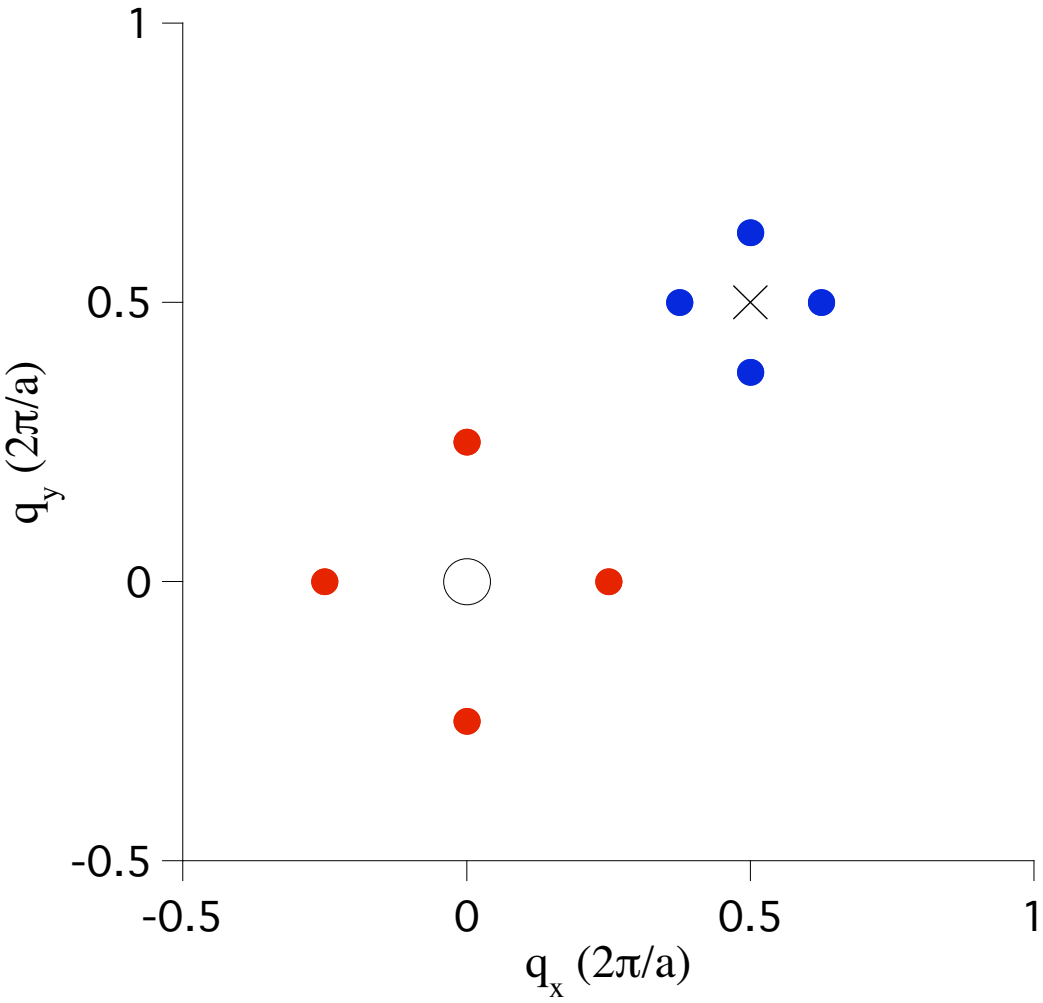


Kohsaka *et al.*, Science (2007)

Antiphase Stripes (Tranquada *et al.* - Nature 1995)

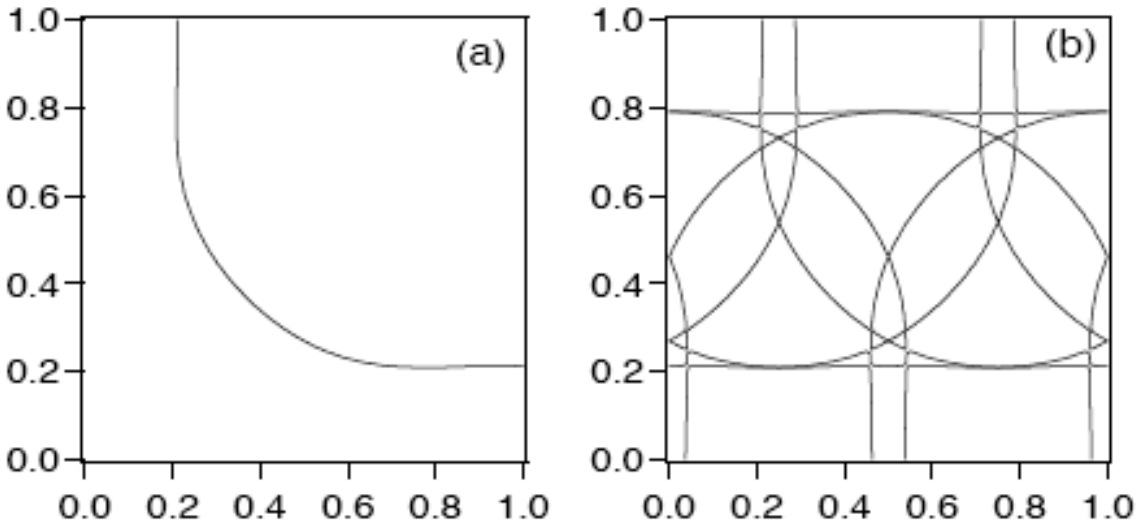
Charge peaks at $(2\delta,0)\pi$, Spin peaks at $(1+\delta,1)\pi$





4 period stripe, q=(0.75,1)π

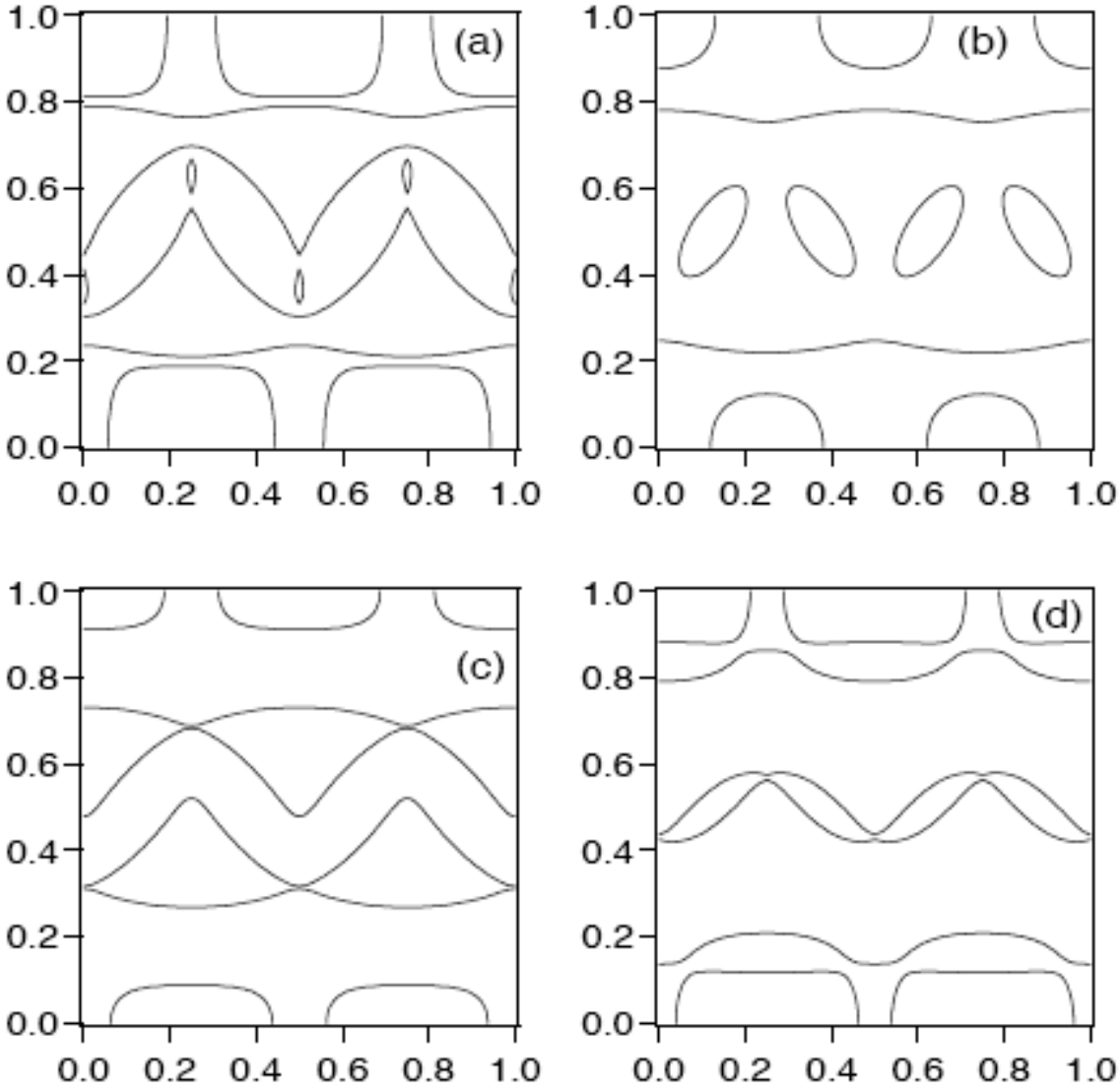
$$\begin{pmatrix}
\varepsilon_k & V_c & 0 & V_c & 0 & V & V & 0 \\
V_c & \varepsilon_{k+(\frac{1}{2},0)} & V_c & 0 & 0 & 0 & V & V \\
0 & V_c & \varepsilon_{k+(1,0)} & V_c & V & 0 & 0 & V \\
V_c & 0 & V_c & \varepsilon_{k+(\frac{3}{2},0)} & V & V & 0 & 0 \\
0 & 0 & V & V & \varepsilon_{k+(\frac{1}{4},1)} & V_c & 0 & V_c \\
V & 0 & 0 & V & V_c & \varepsilon_{k+(\frac{3}{4},1)} & V_c & 0 \\
V & V & 0 & 0 & 0 & V_c & \varepsilon_{k+(\frac{5}{4},1)} & V_c \\
0 & V & V & 0 & V_c & 0 & V_c & \varepsilon_{k+(\frac{7}{4},1)}
\end{pmatrix}$$



V - spin potential, V_c - charge potential

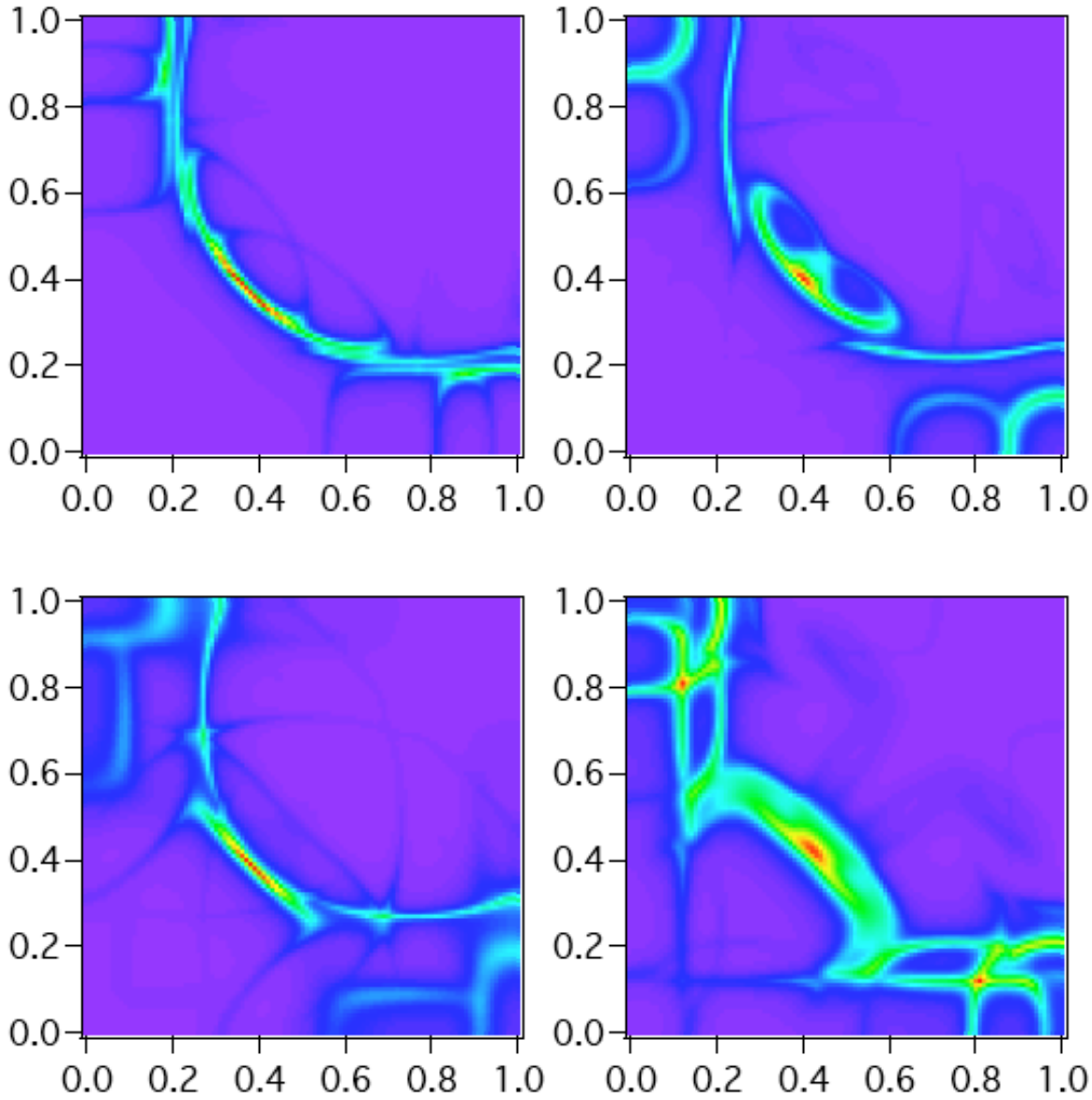
Millis & Norman, PRB (2007)

Electron pockets stable for a large range of potentials

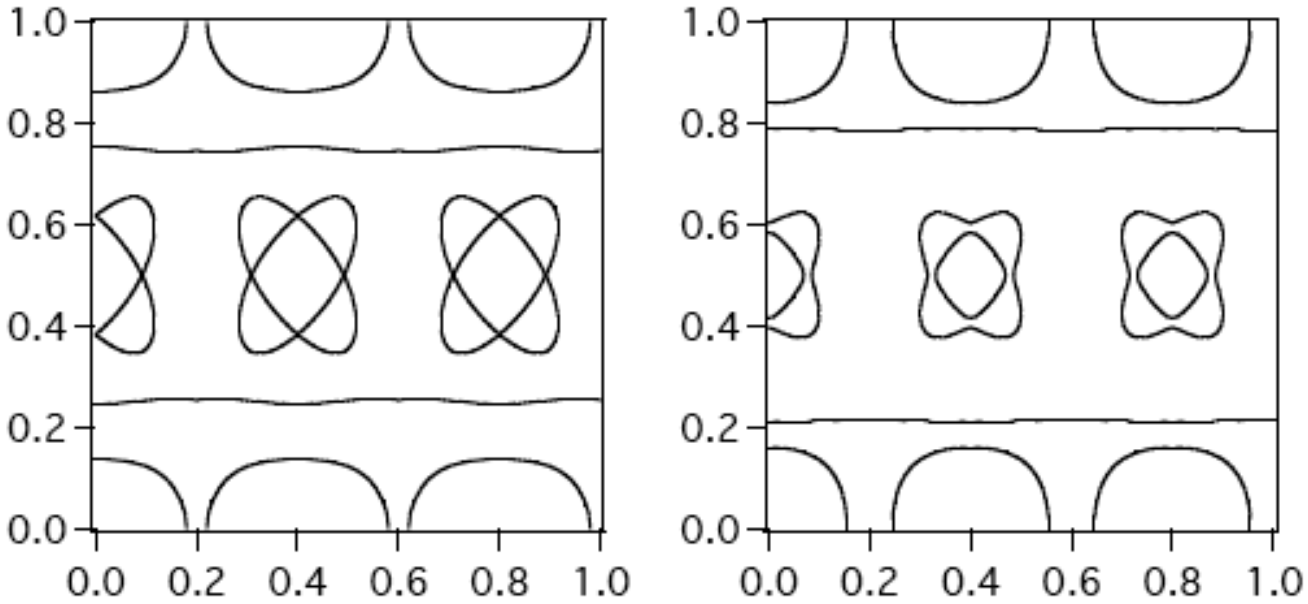


<-- e^- pocket

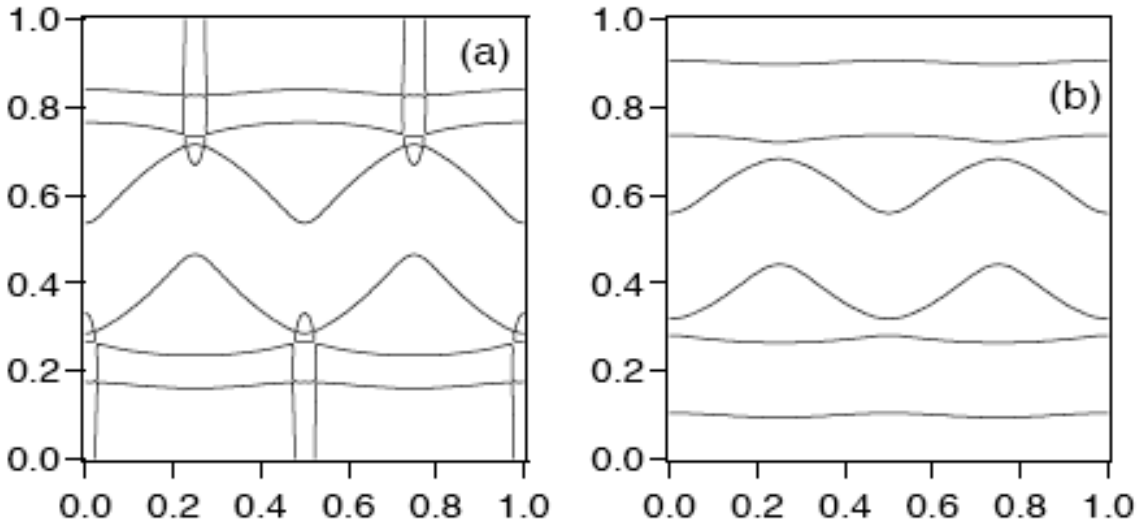
Predicted ARPES intensities from the previous slide



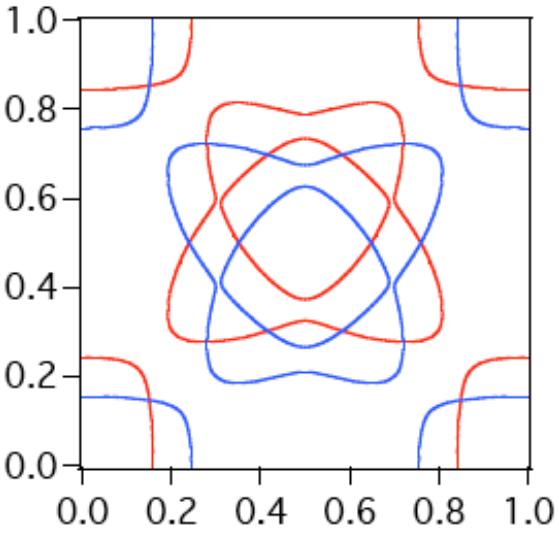
5 period stripe, q=(0.8,1)π



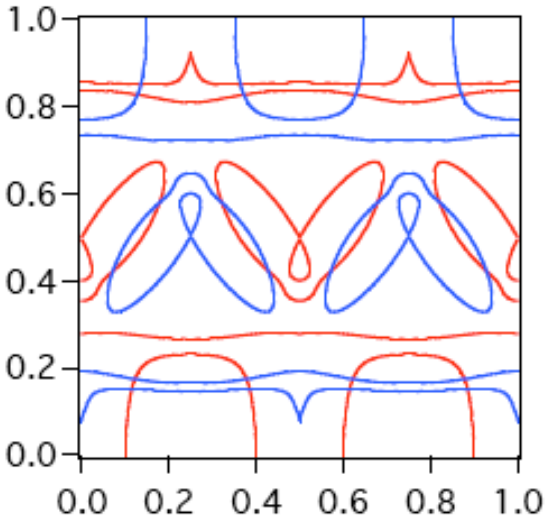
Charge only case (V=0)

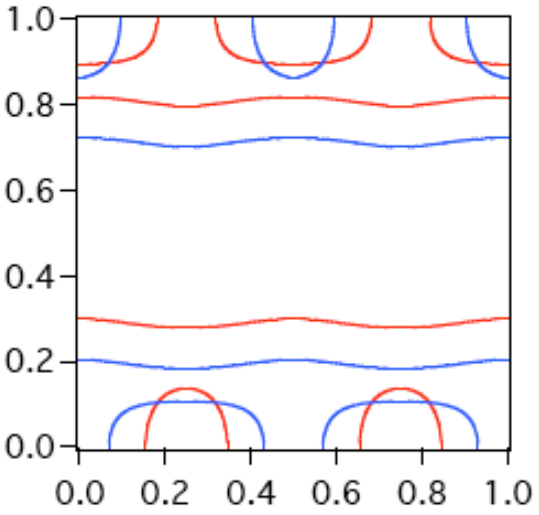


ortho-II + bilayer



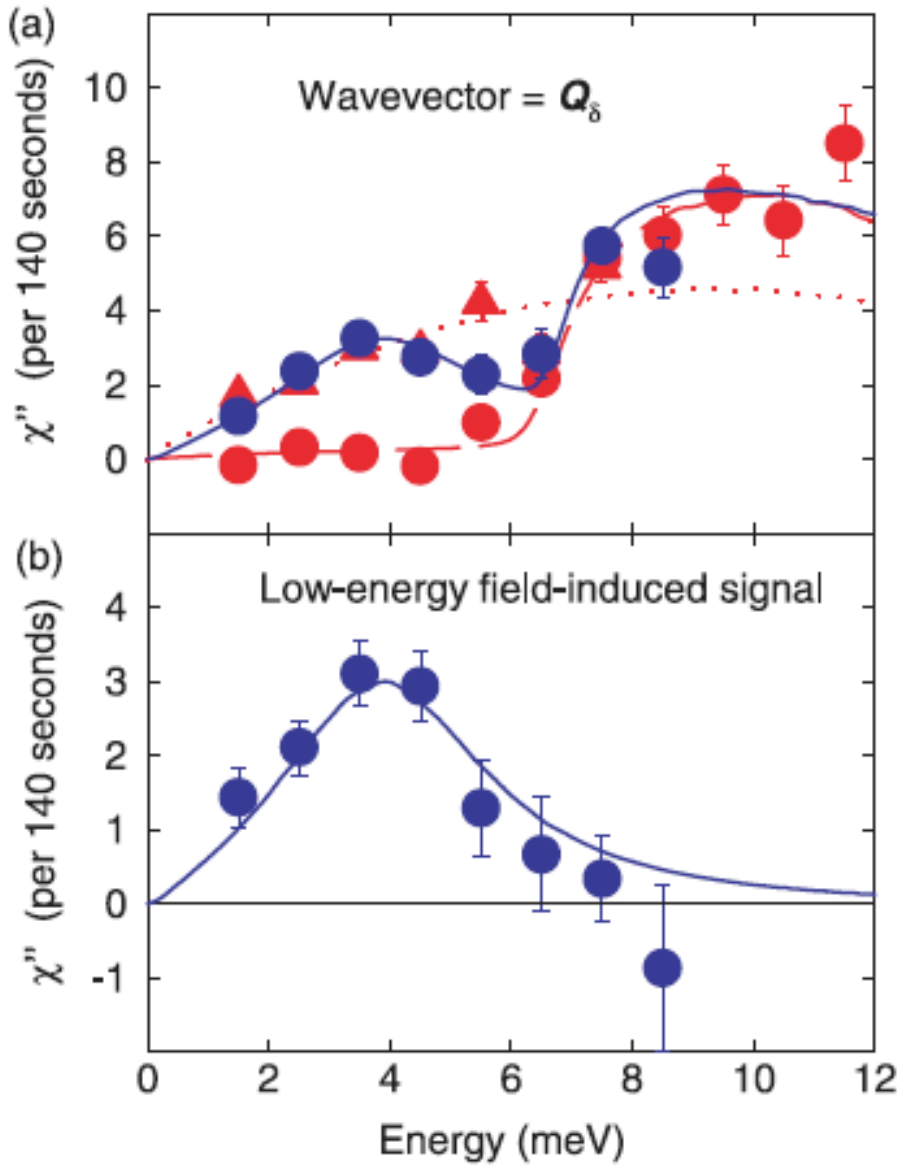
q=(1,1,1)π





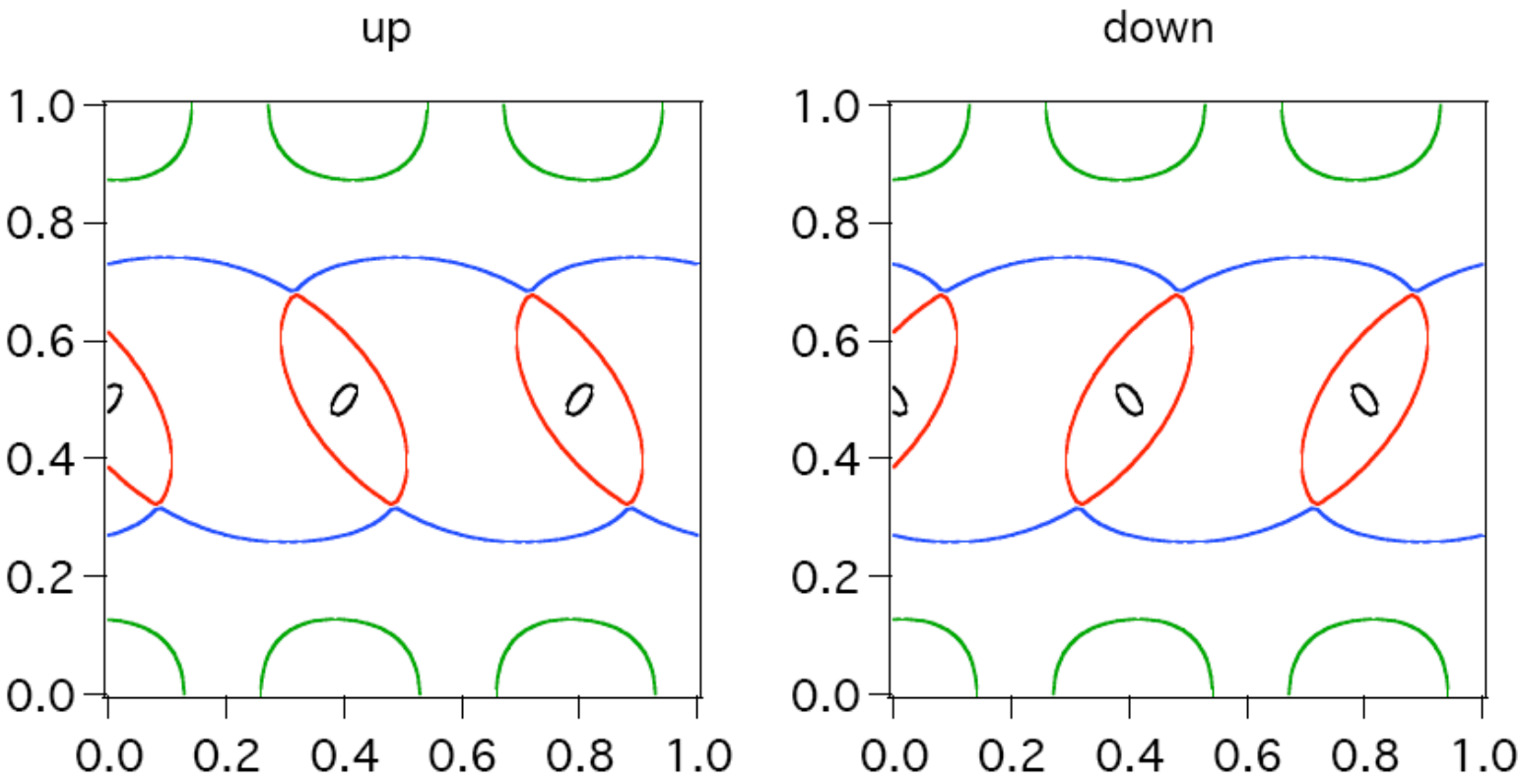
q=(.75,1,1)π

Field Induced SDW in LSCO



Lake *et al.*, Science (2001)

Spiral Spin Density Wave?



Sebastian *et al.*, Nature (2008)

SUMMARY of DHVA

1. A small pocket is observed in ortho-II YBCO and Y248
2. The pocket is electron like
3. It is probably due to a field induced SDW (a spiral?)
4. The relation of arcs to pockets is a subject of continuing debate