The Electronic Phase Diagram of the Cuprates

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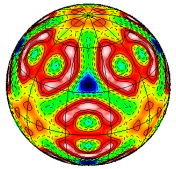
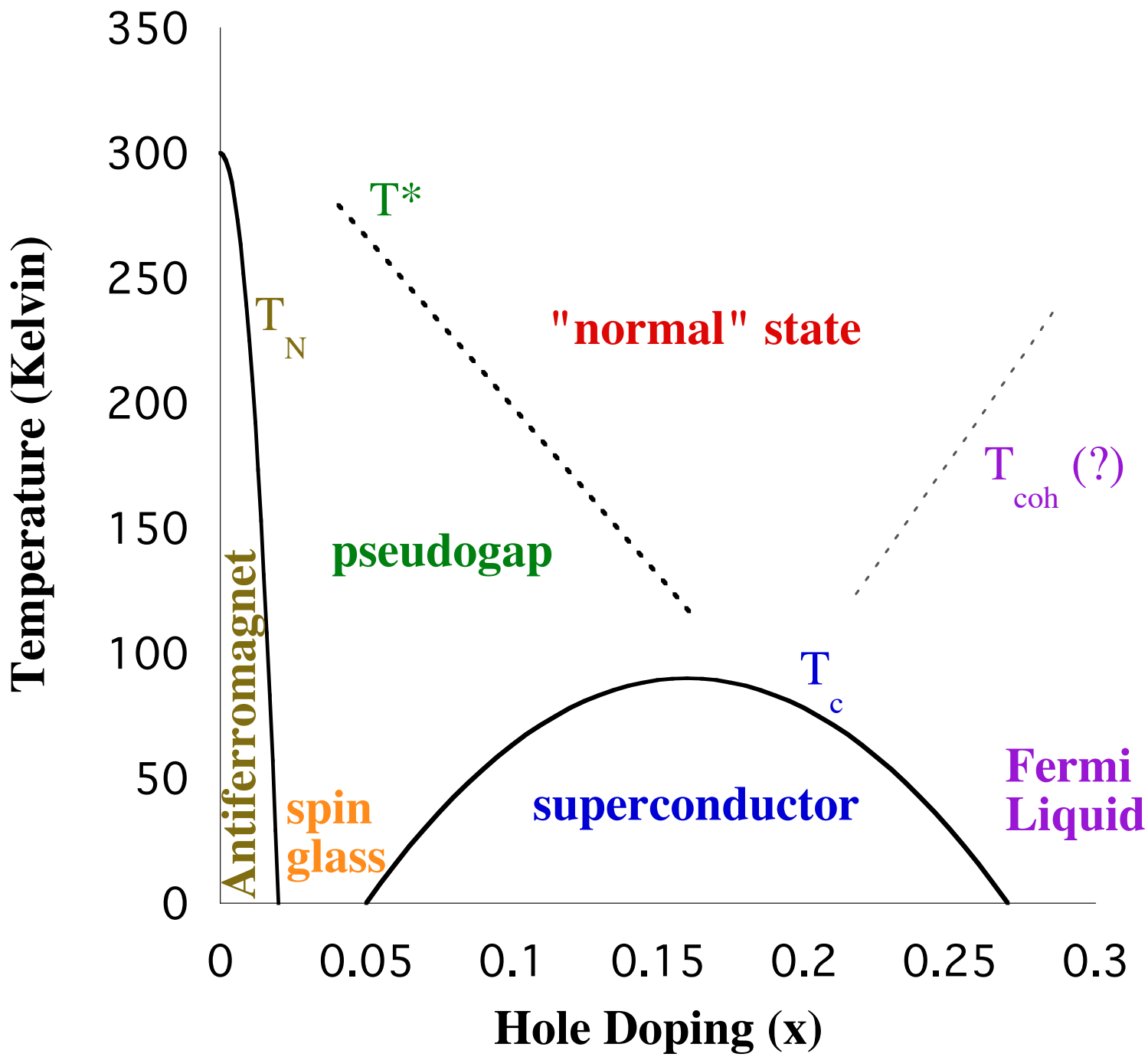


Dresden - Aug. 26, 2010

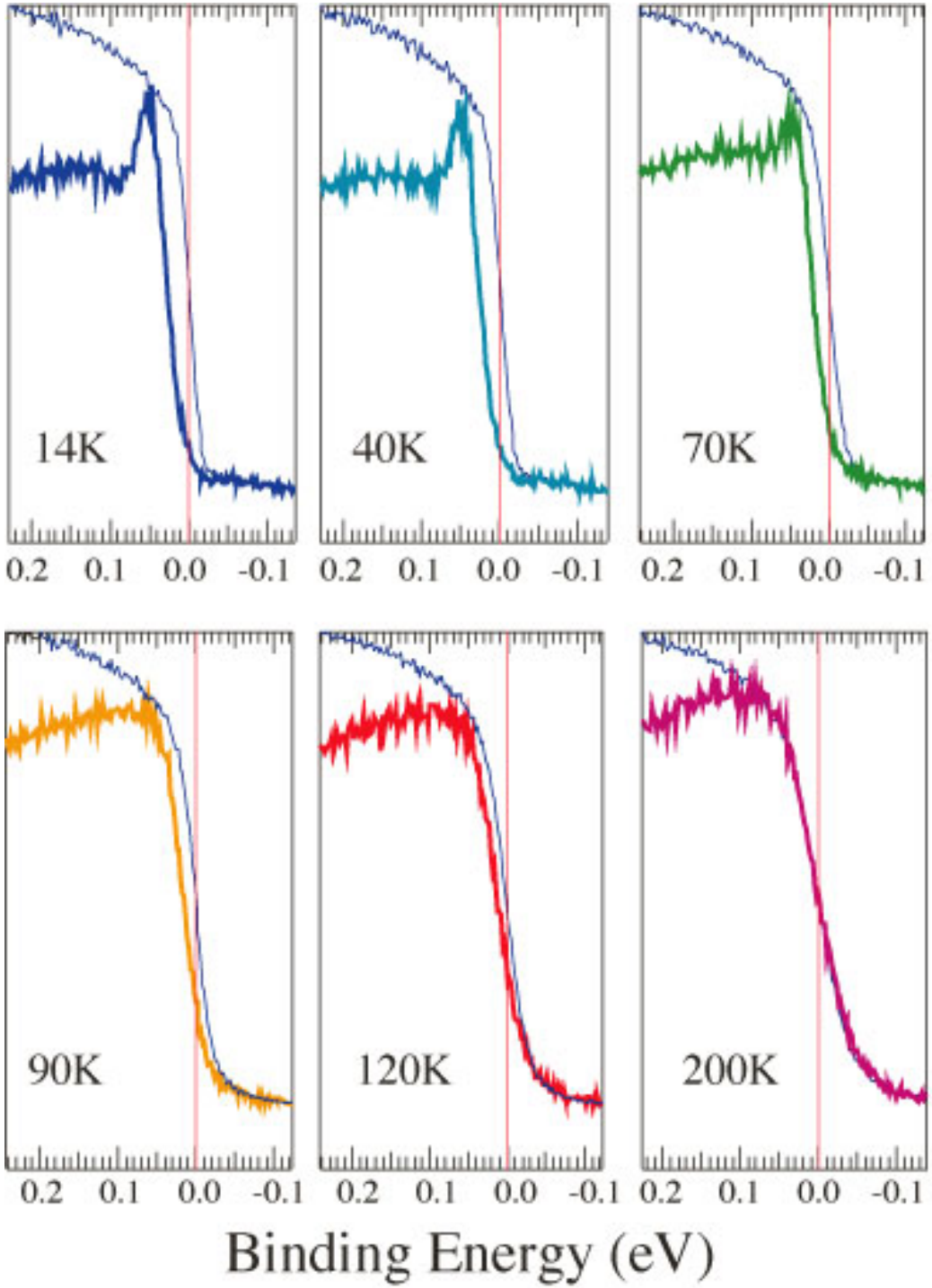

350
300
250
200
150
100
50
0
Temperature (Kelvin)
0
0.05
0.1
0.15
0.2
0.25
0.3
Hole Doping (x)
T*
"normal" state
T N
T coh (?)
pseudogap
T c
Antiferromagnet
spin glass
superconductor
Fermi Liquid

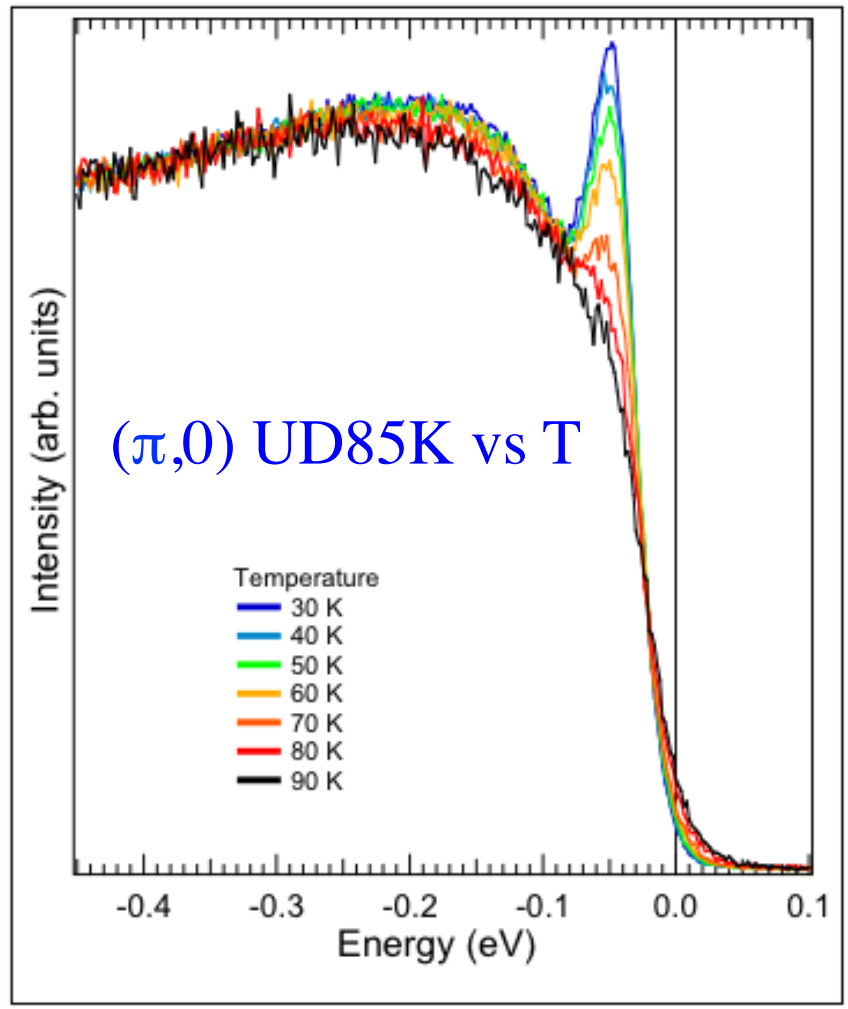
What is the Pseudogap?

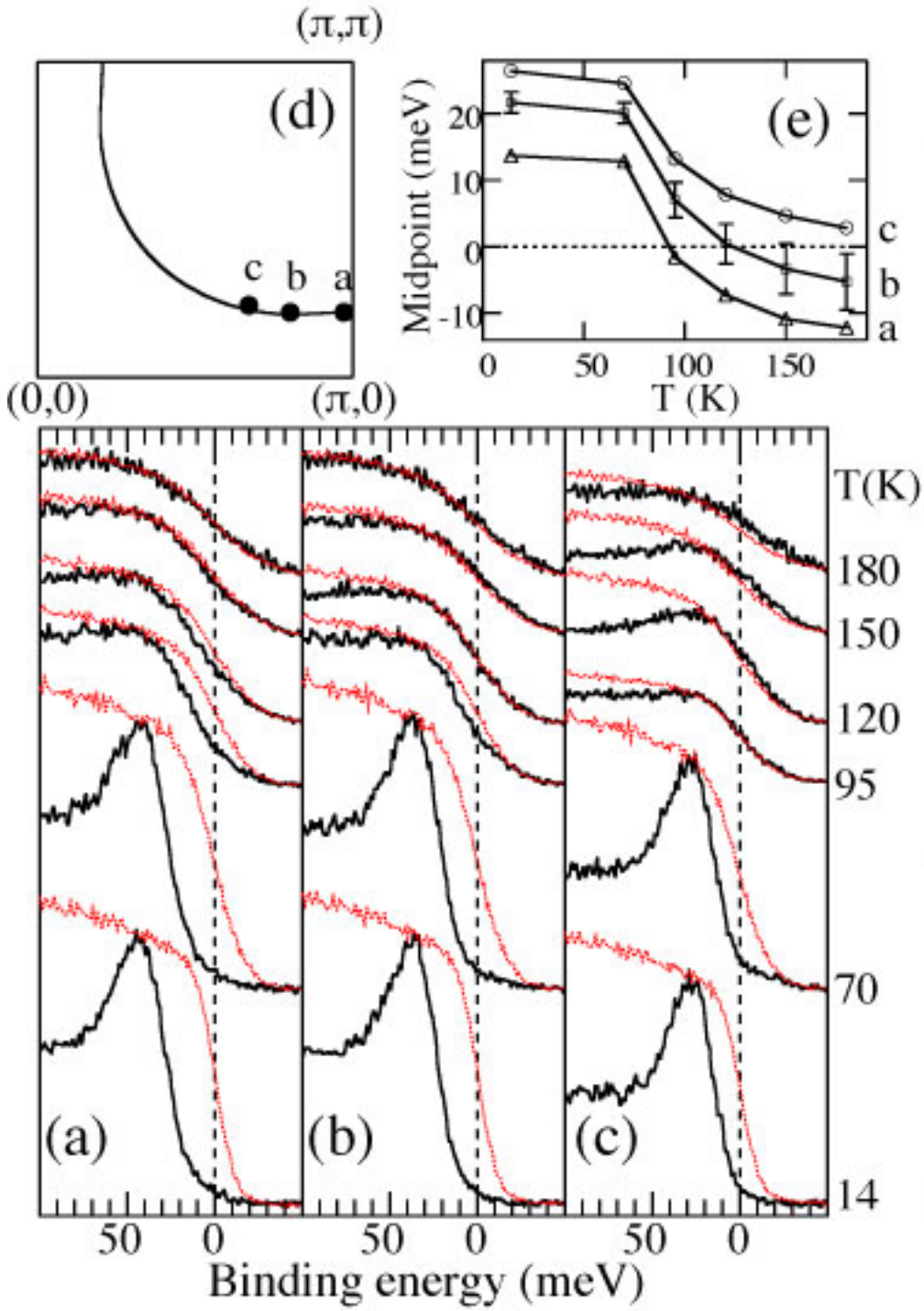
1. Spin singlets
2. Pre-formed pairs
3. Spin density wave
4. Charge density wave
5. d density wave
6. Orbital currents
7. Flux phase
8. Stripes
9. Combination?

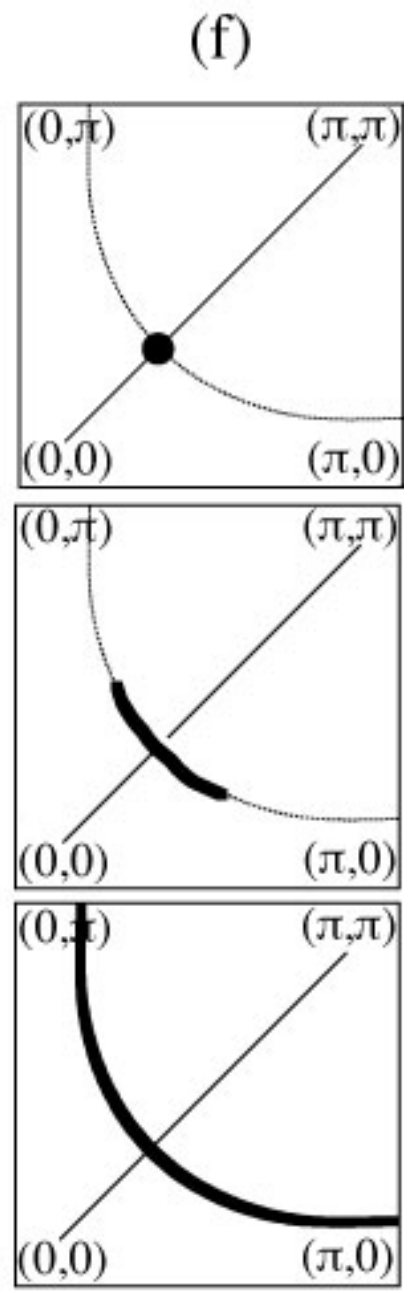
ARPES (Bi2212)

<-- Antinode UD83K vs T







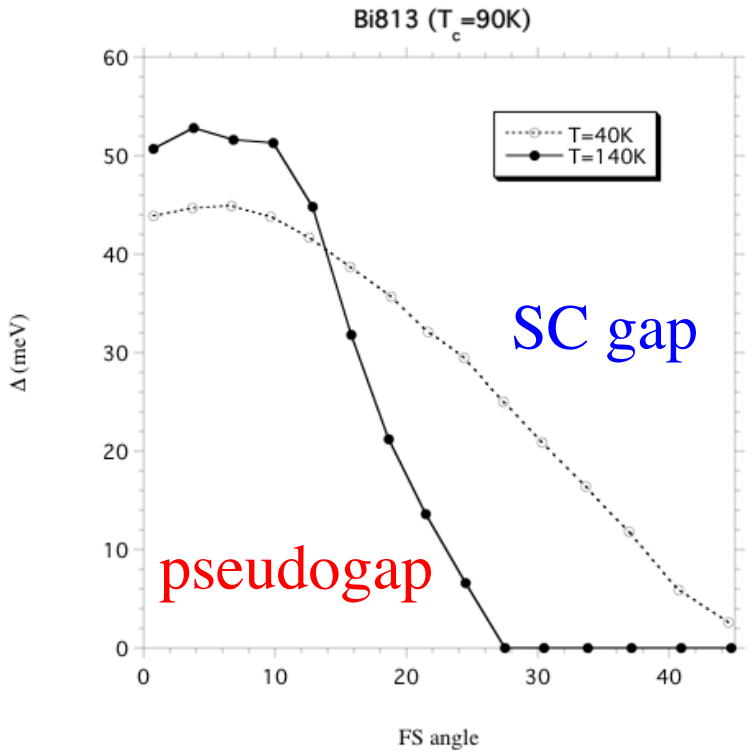


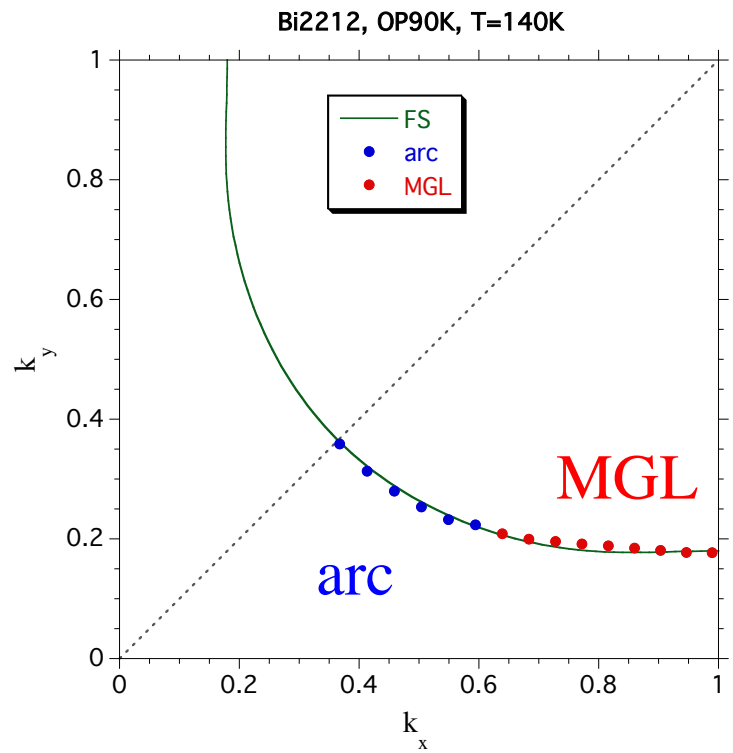
$T < T_c$
(node)

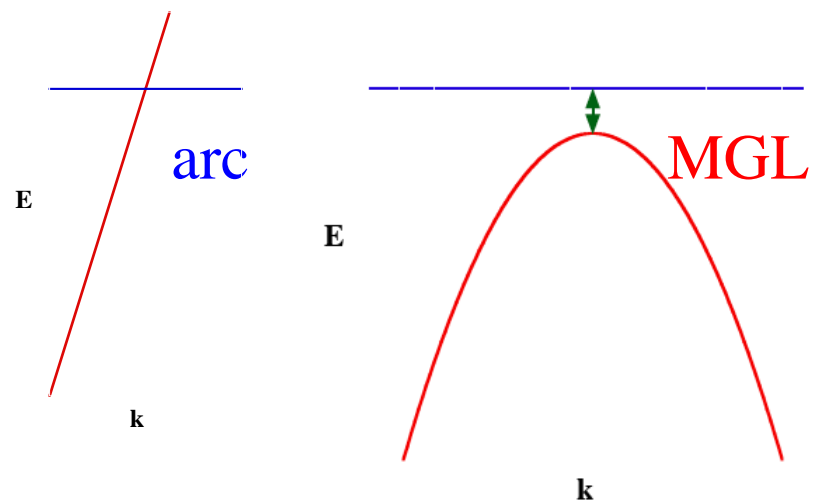
$T_c < T < T^*$
(Fermi arc)

$T > T^*$
(full Fermi surface)

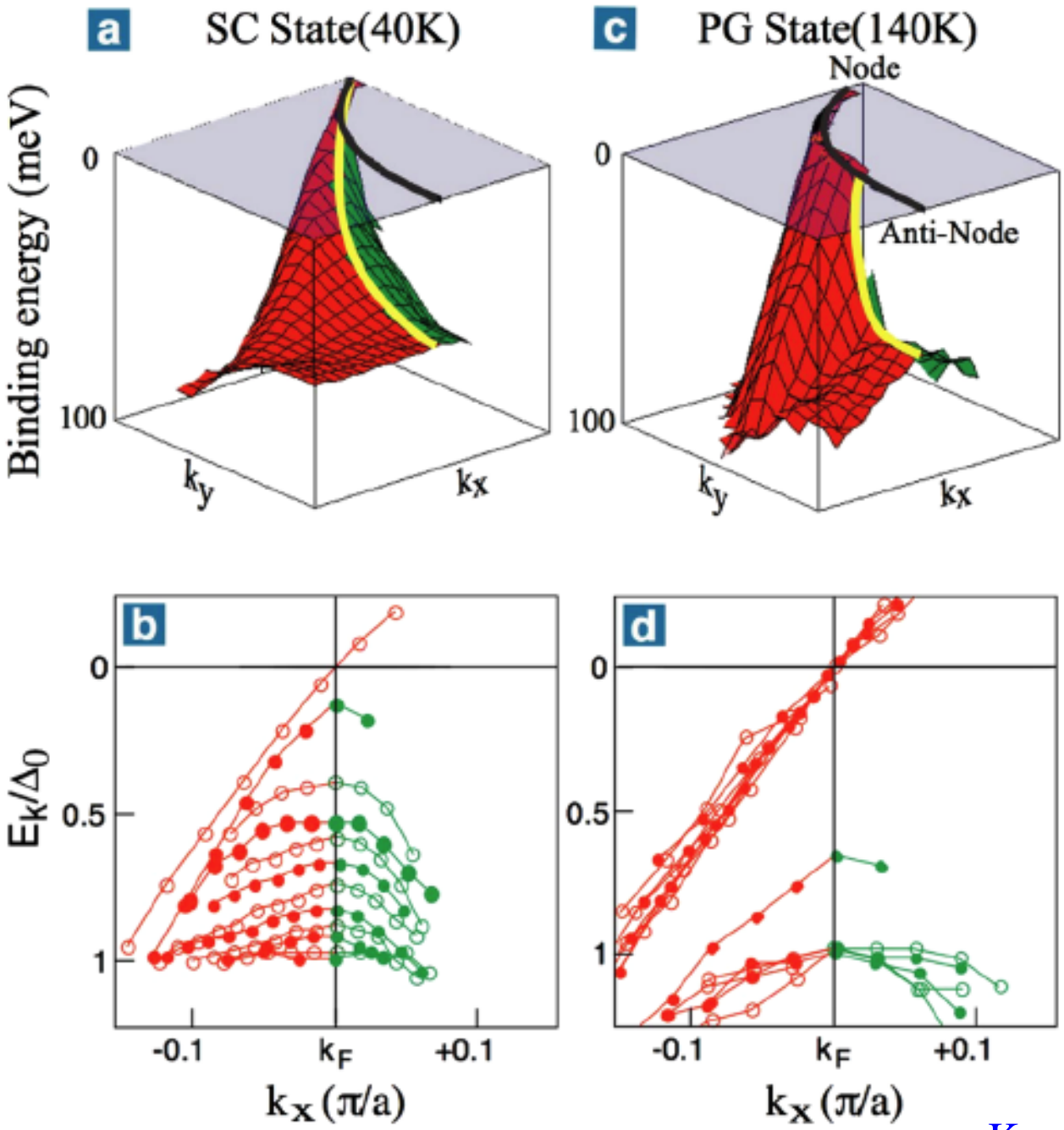
Norman *et al.*, Nature (1998)



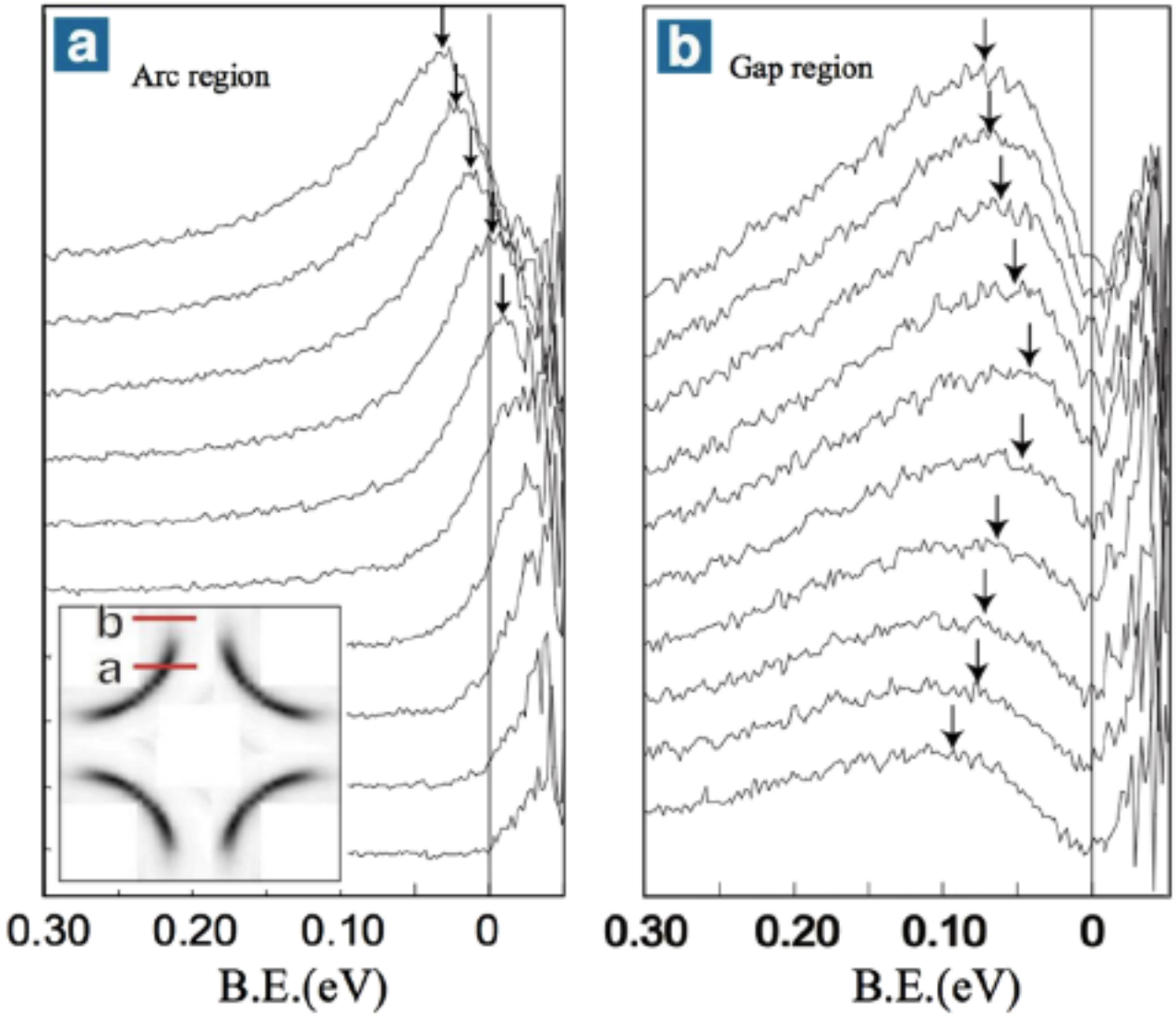




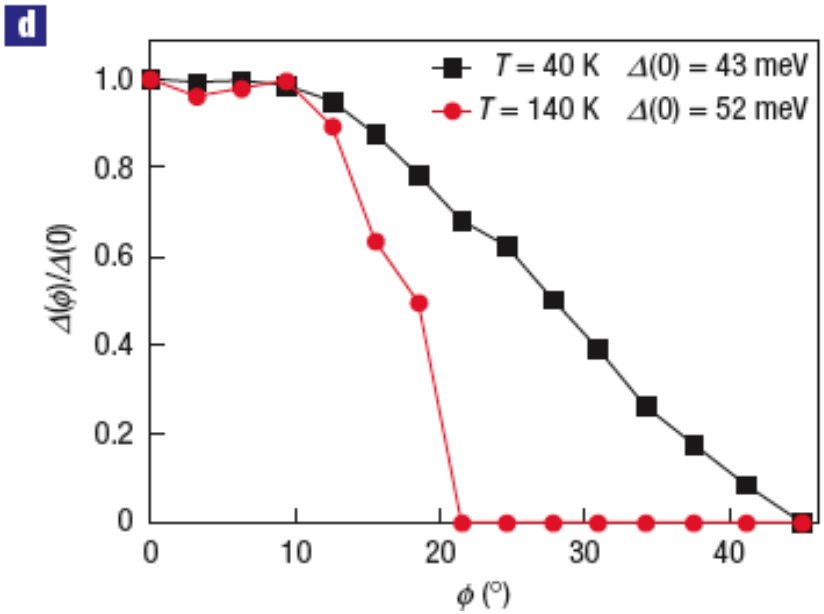
(MGL - minimum gap locus)

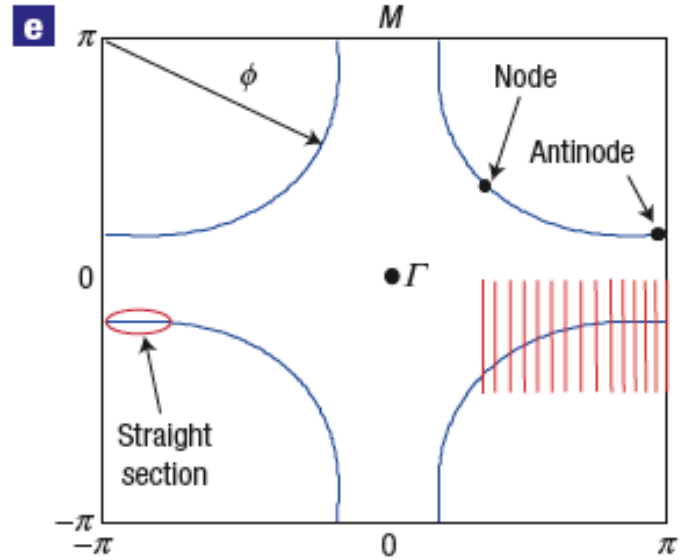


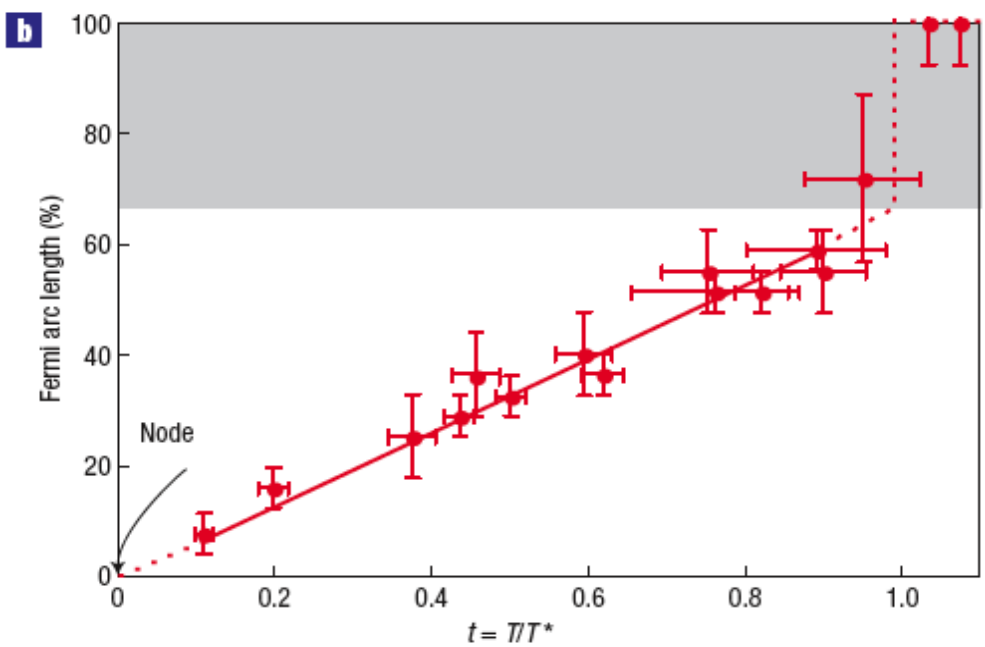
Kanigel *et al*., PRL (2008)

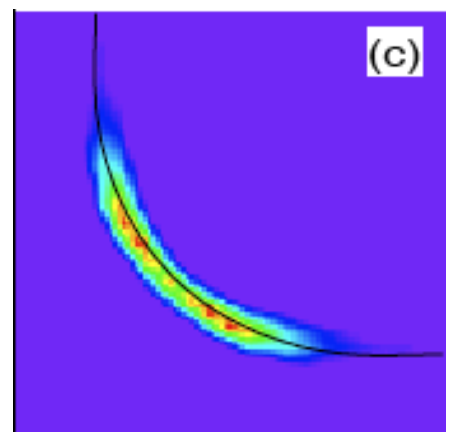

a
Arc region
b
a
0.30
0.20
0.10
0
B.E.(eV)
b
Gap region
0.30
0.20
0.10
0
B.E.(eV)

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



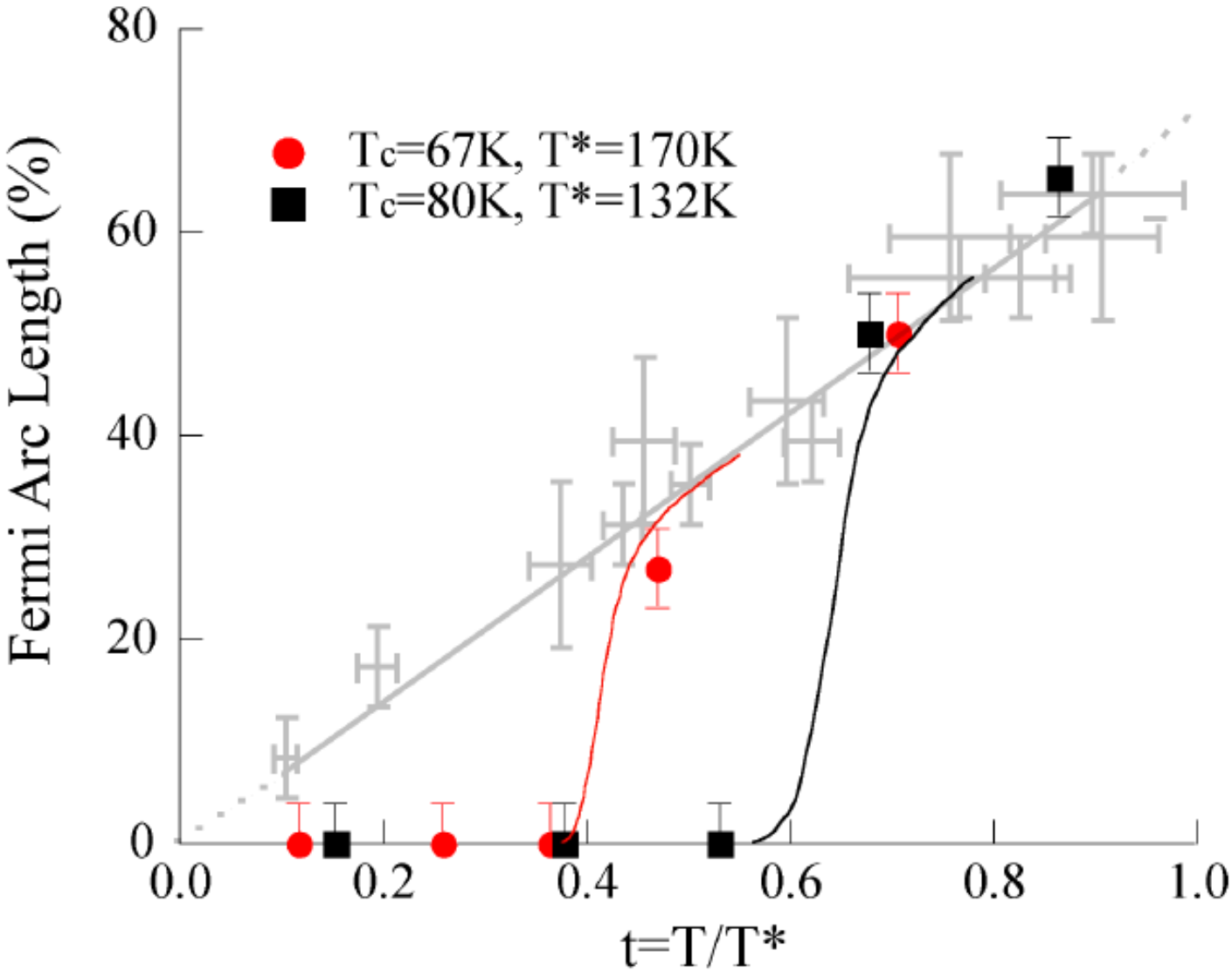






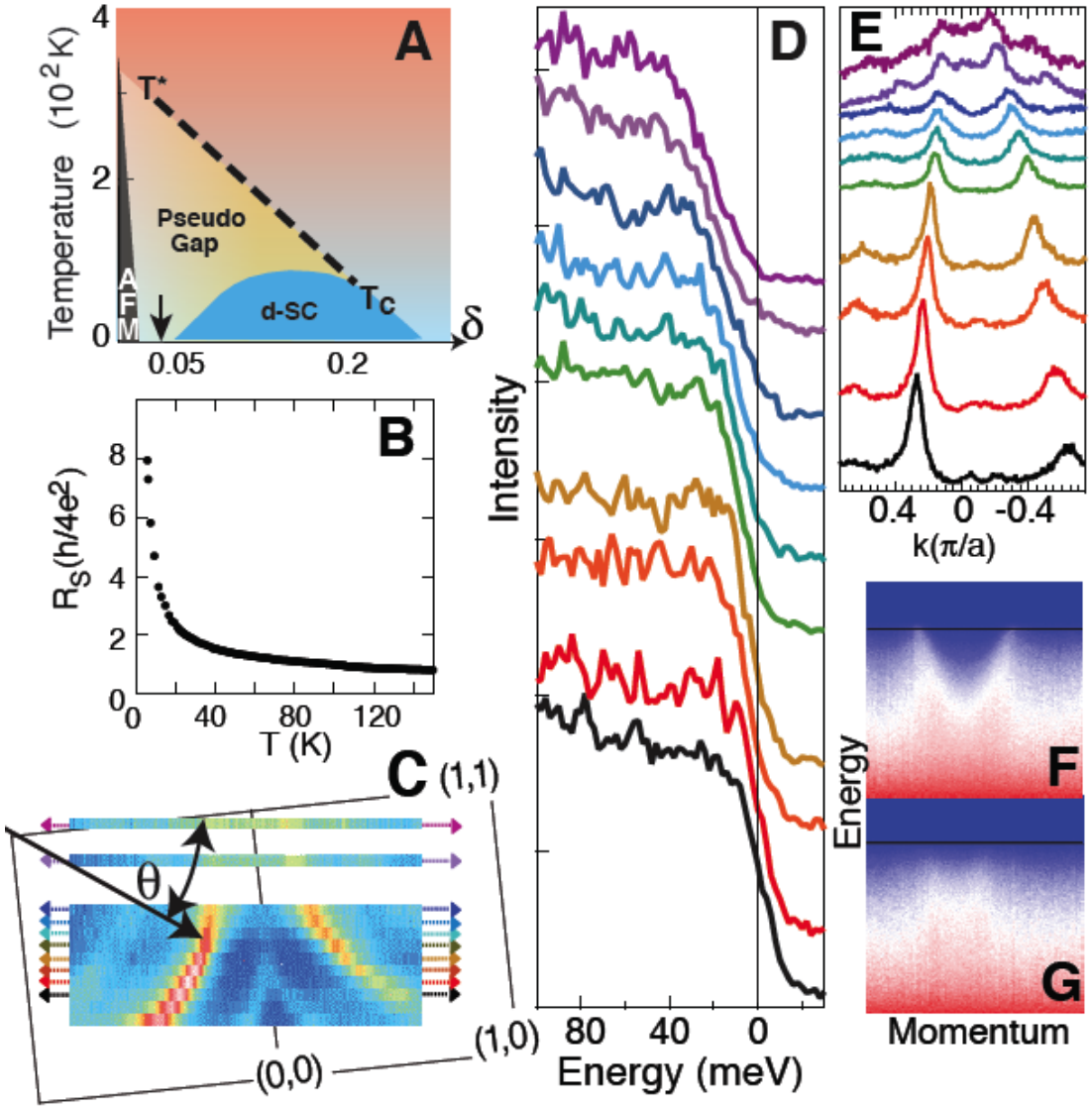
Kanigel *et al.*, Nat. Phys. (2006)

Collapse of Arcs Through T_c



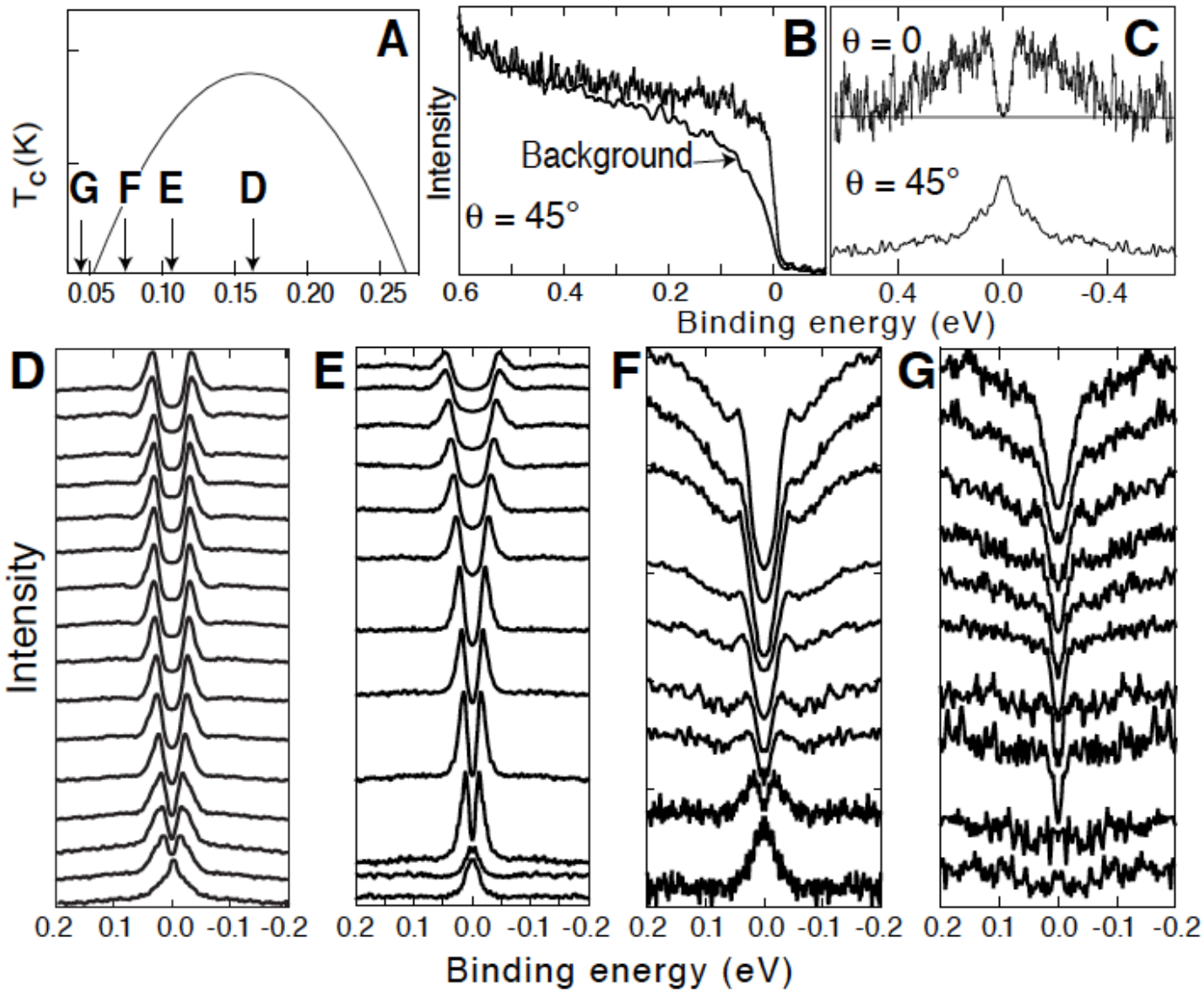
Kanigel *et al.*, PRL (2007)

Insulating Sample - x ~ 0.04

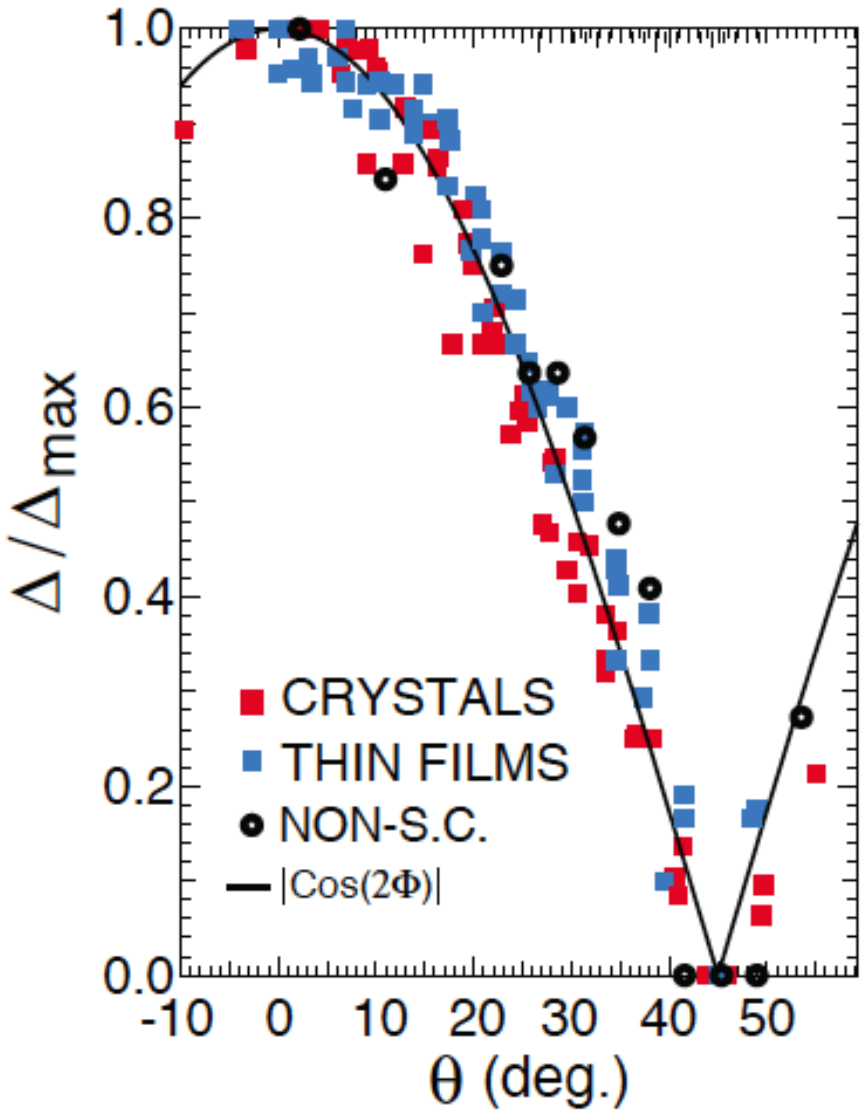


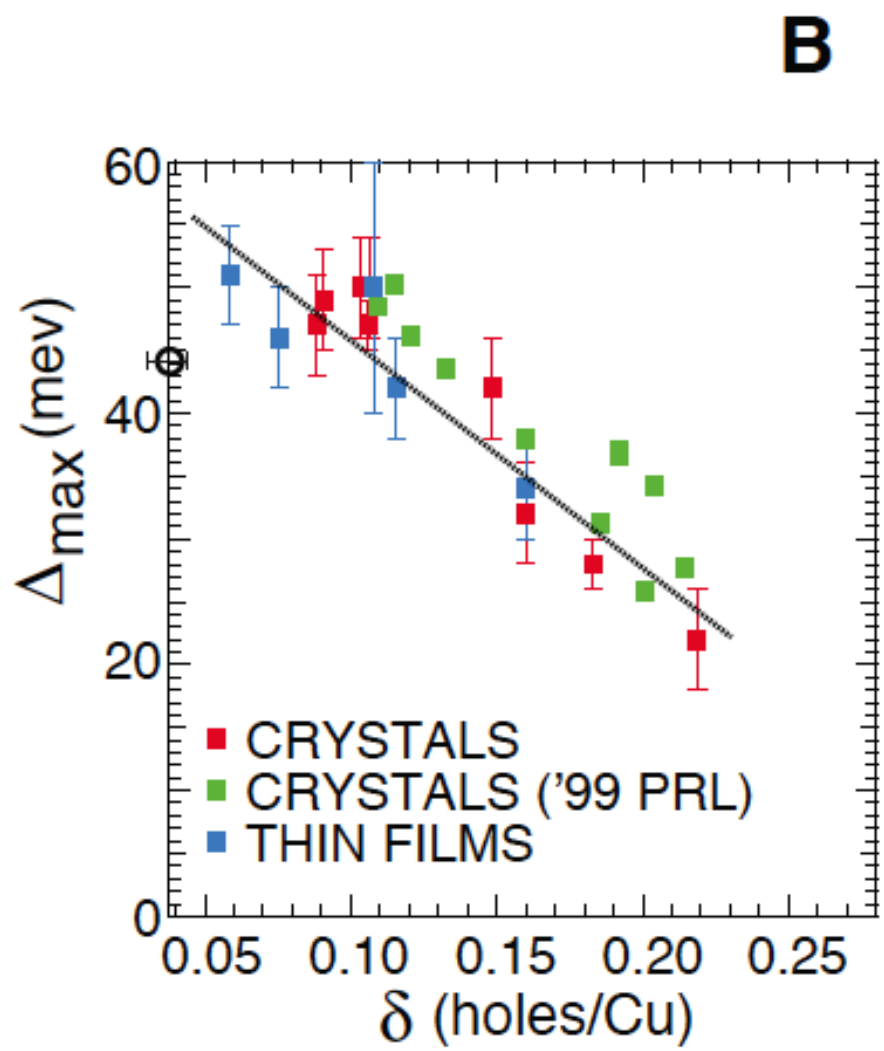
Chatterjee *et al*., Nat. Phys. (2010)

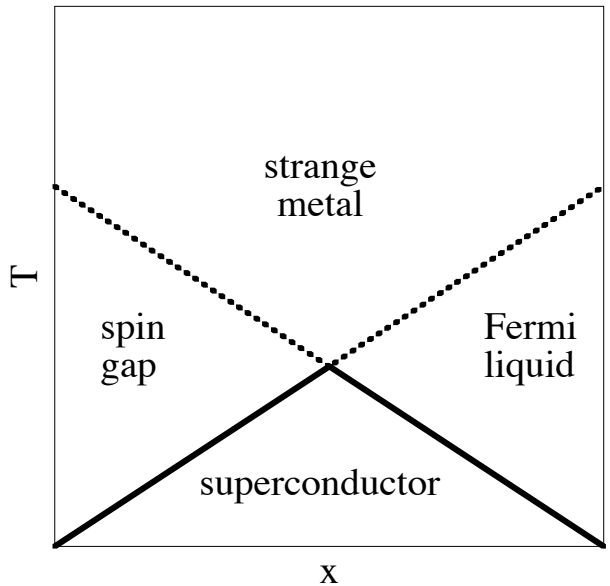
Doping Dependence of the Gap Anisotropy



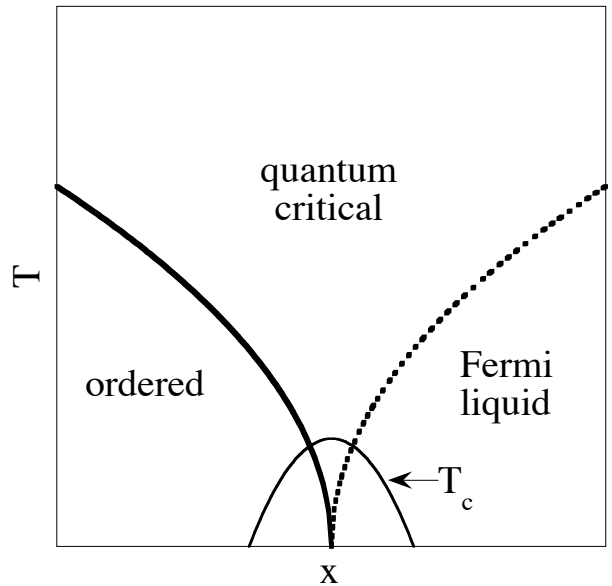
Universal "single gap" behavior





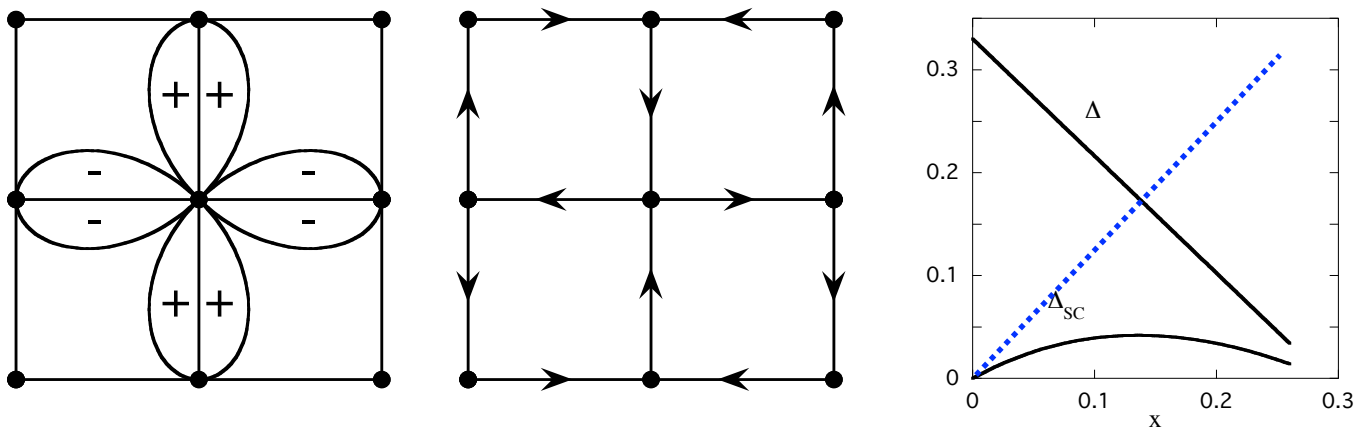


RVB



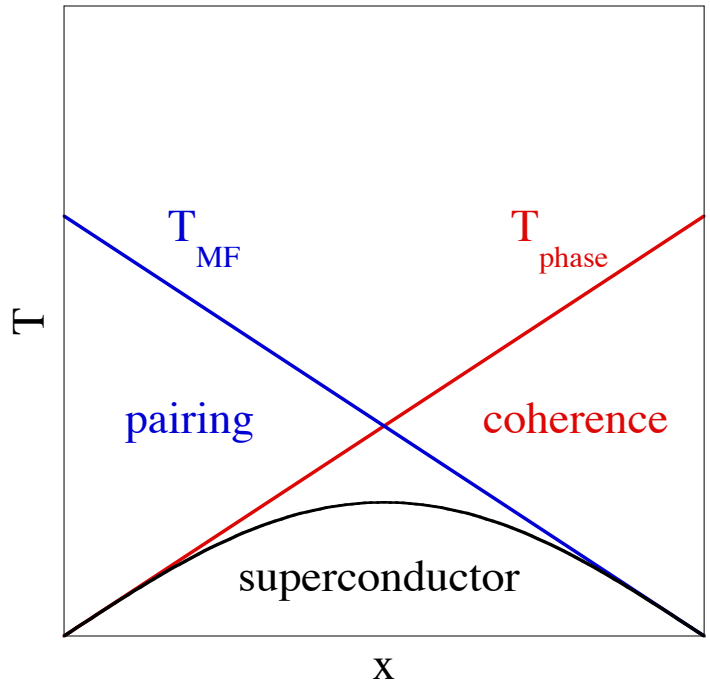
Quantum Critical

RVB Model (Anderson, Lee & Nagaosa, Randeria & Trivedi, etc.)



Pseudogap phase corresponds to a d-wave pairing of spins (left). At half filling, this is quantum mechanically equivalent to a staggered flux state (middle). The spin gap, Δ, is not equivalent to the superconducting order parameter, Δ_{sc} (right).

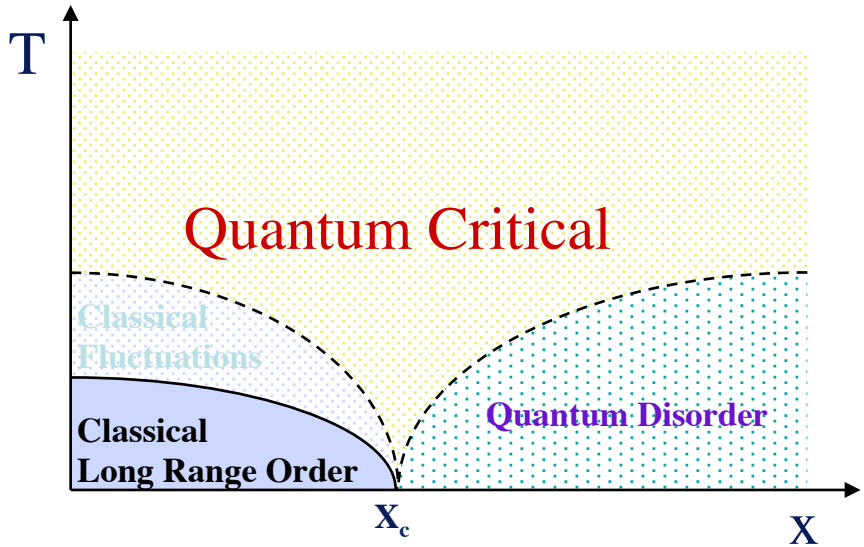
Phase Coherence for Pairs



Pairing occurs below a mean field transition temperature
Coherence occurs below a phase ordering temperature
Superconductivity occurs only below both temperatures

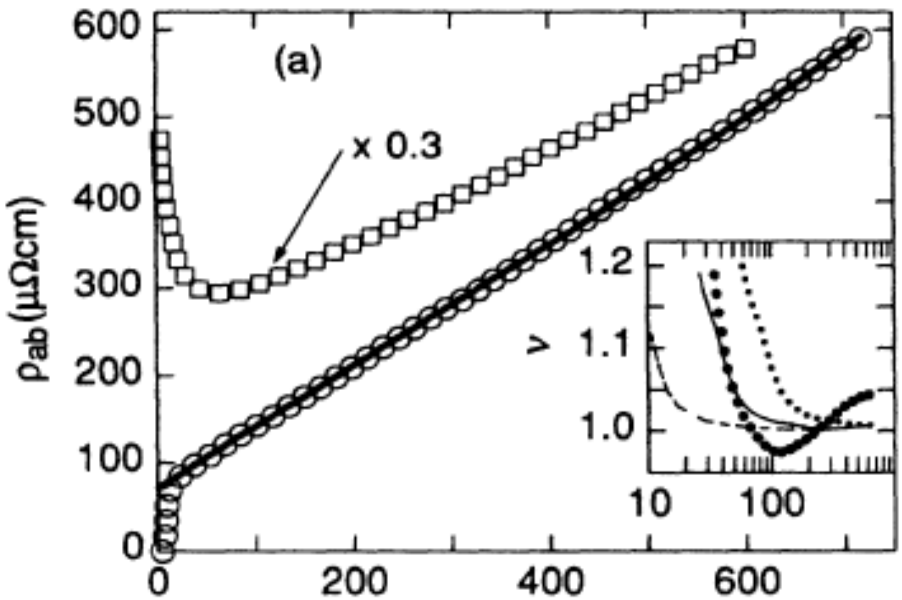
Emery & Kivelson, Nature (1995)

Quantum Critical Scenario



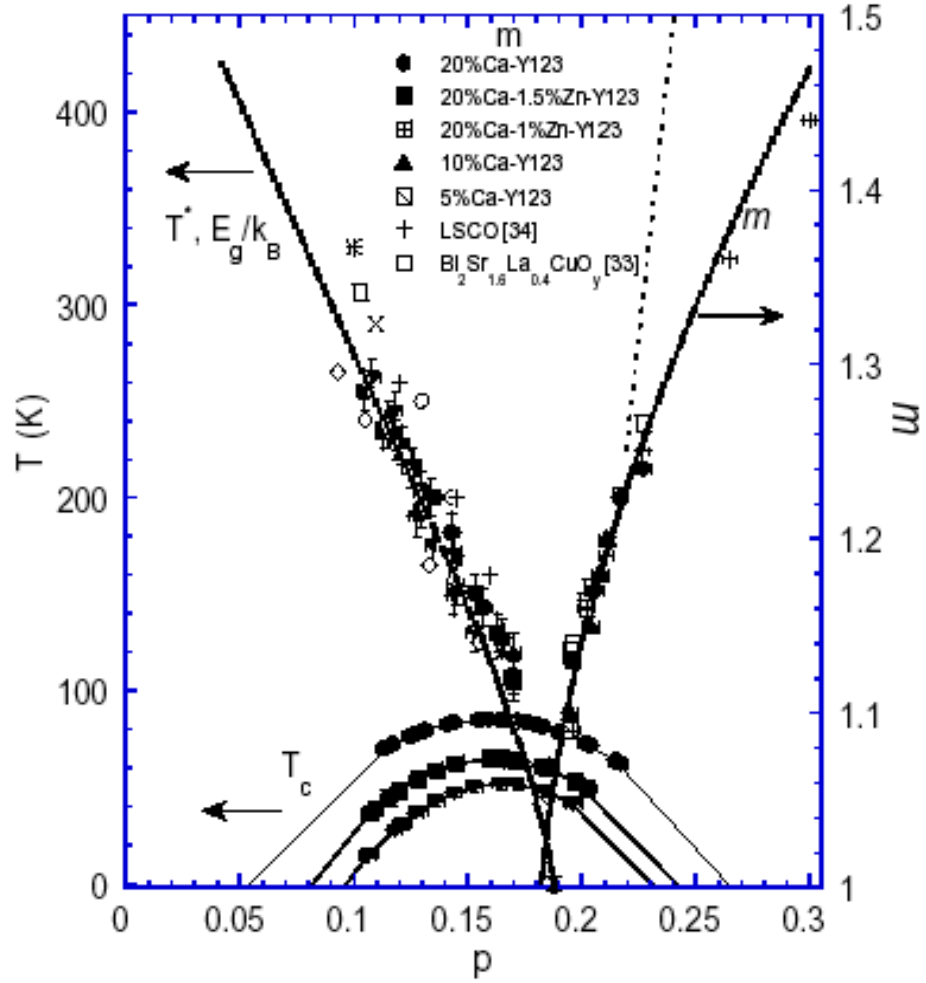
In a quantum critical scenario, an ordered phase exists on one side of the critical point, the corresponding paramagnet (Fermi liquid) is on the other side.

Linear T Resistivity

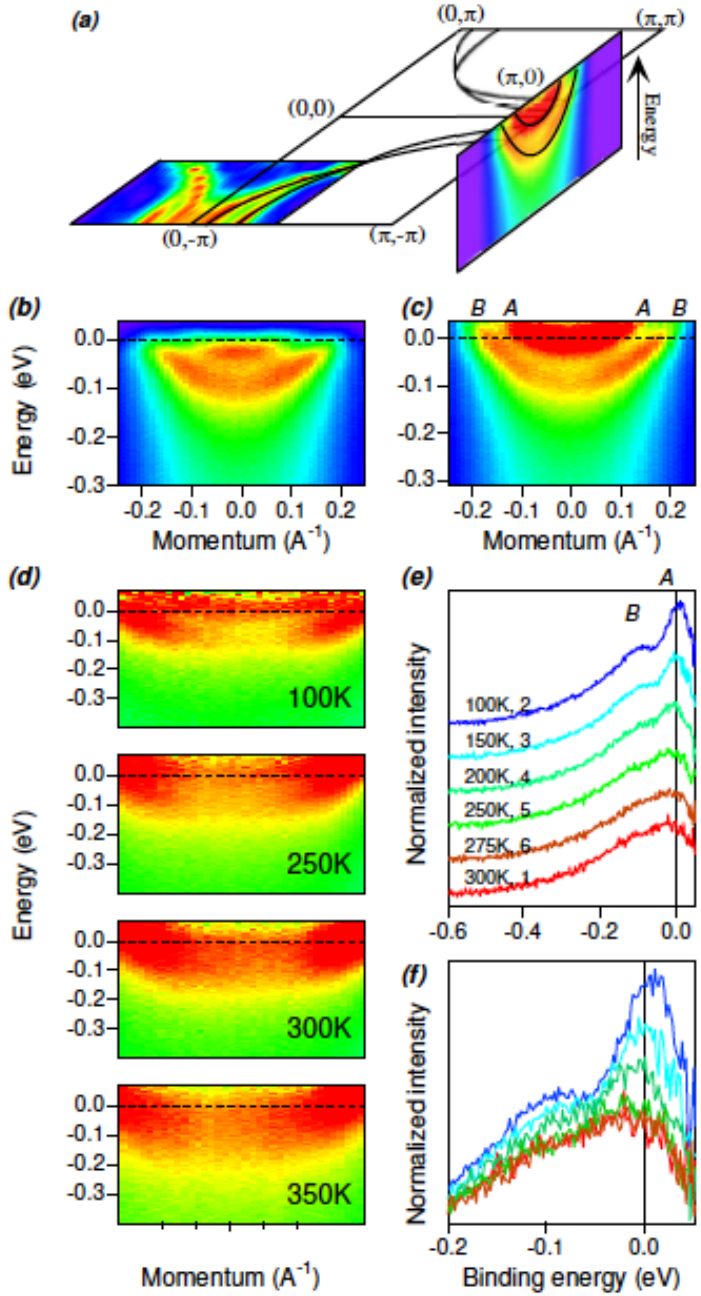


Martin *et al.*, Phys Rev B (1990)

Crossover lines from in-plane transport



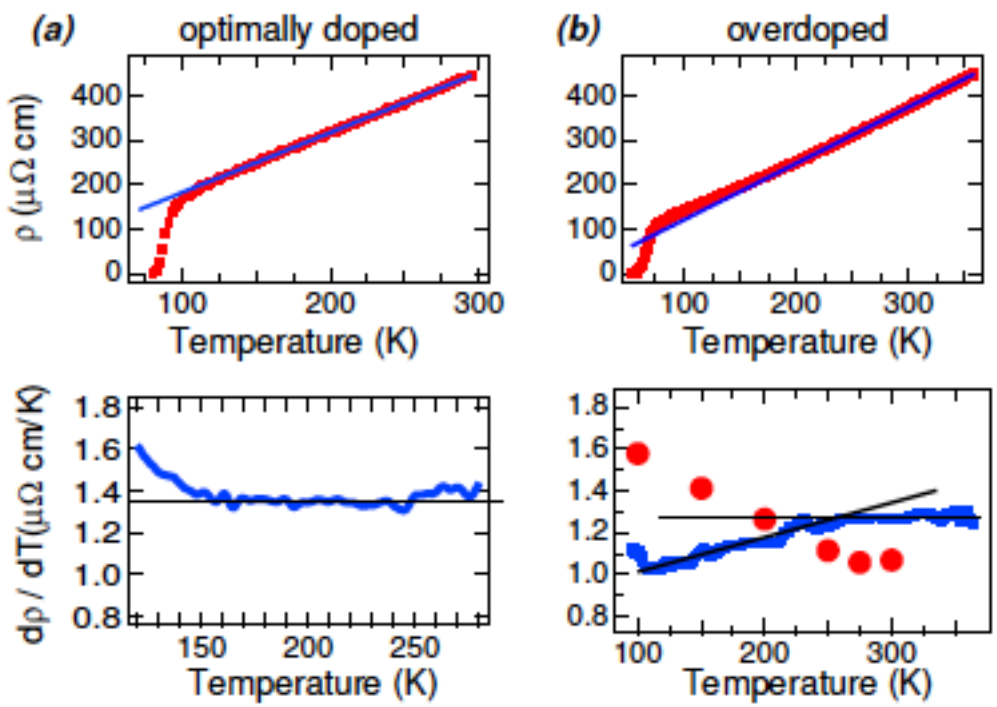
Naqib, Cooper, Tallon, Panagopoulos (Physica C 2003)



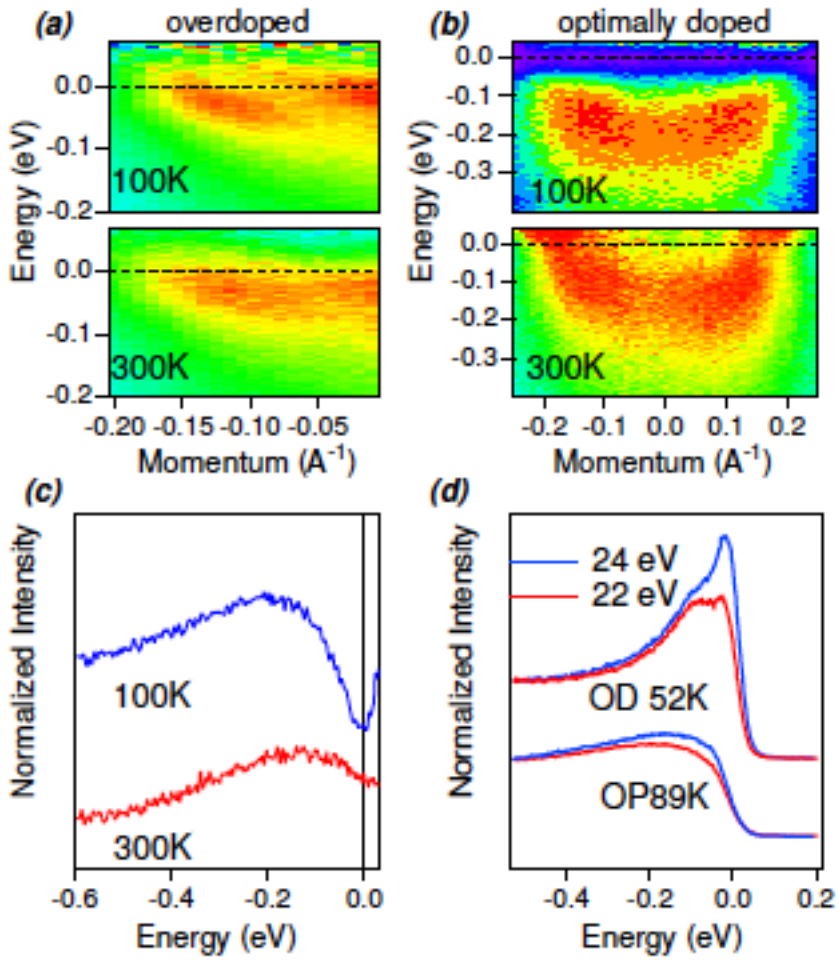
ARPES
OD52K

Kaminski *et al*, PRL (2003)

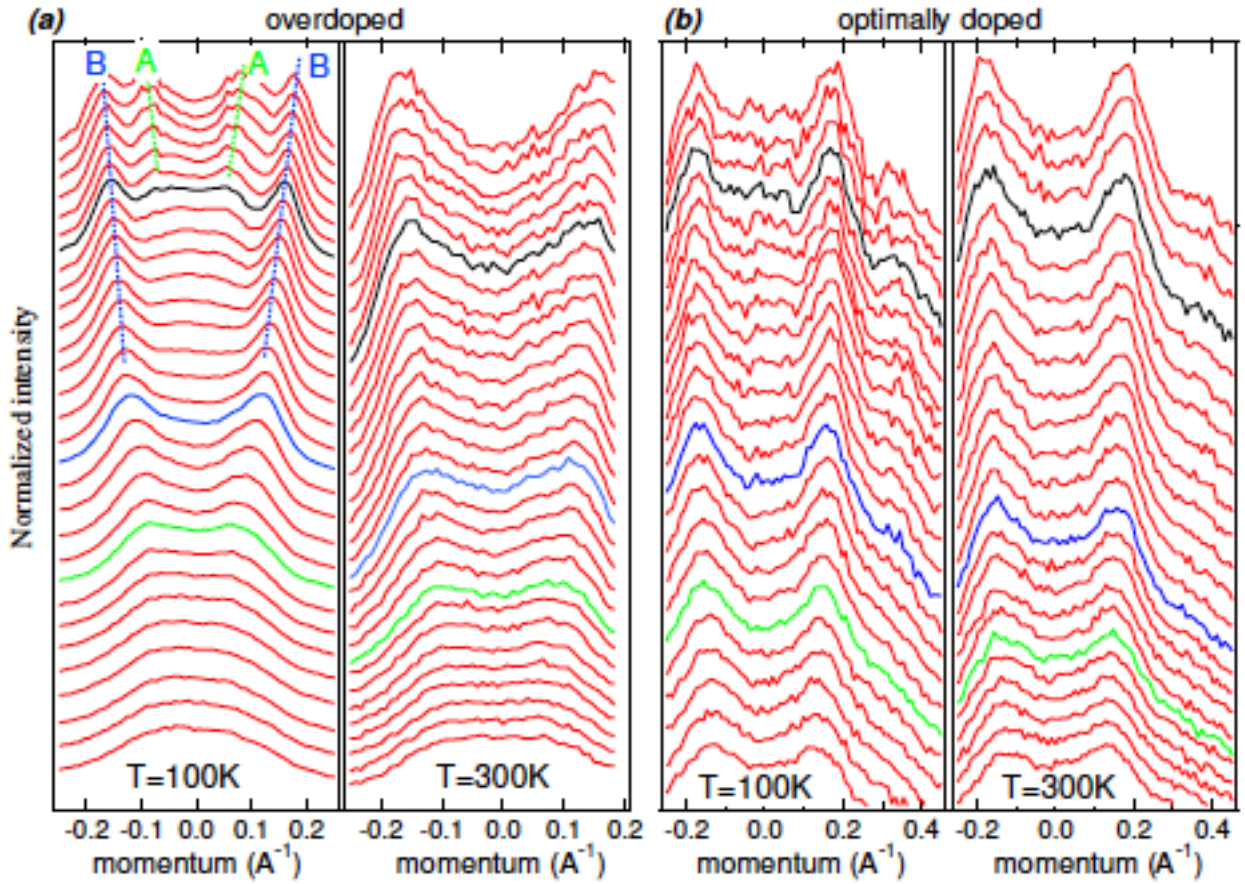
OPT89K OD52K

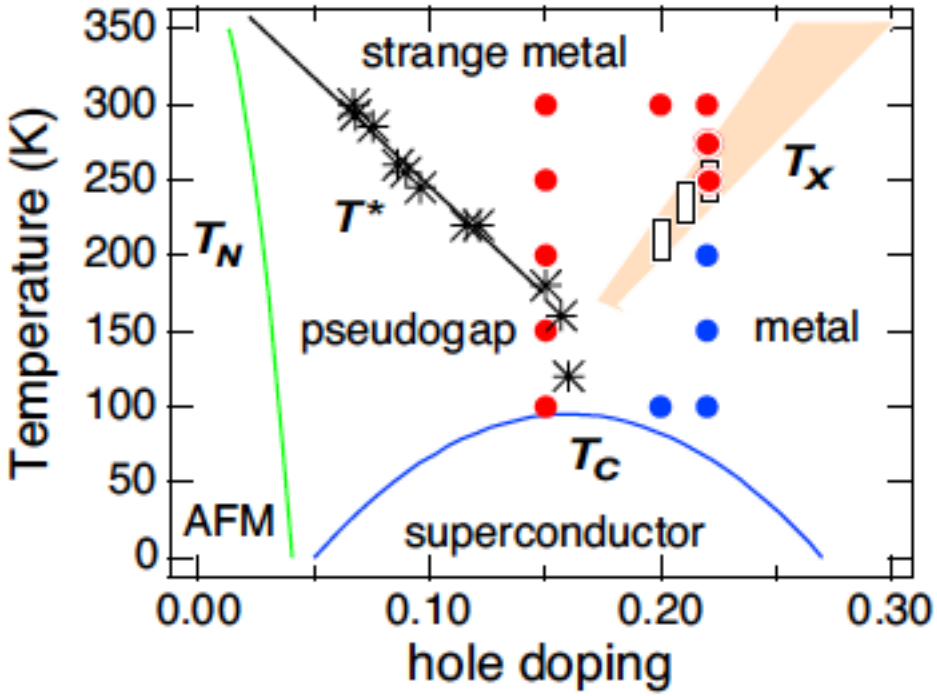


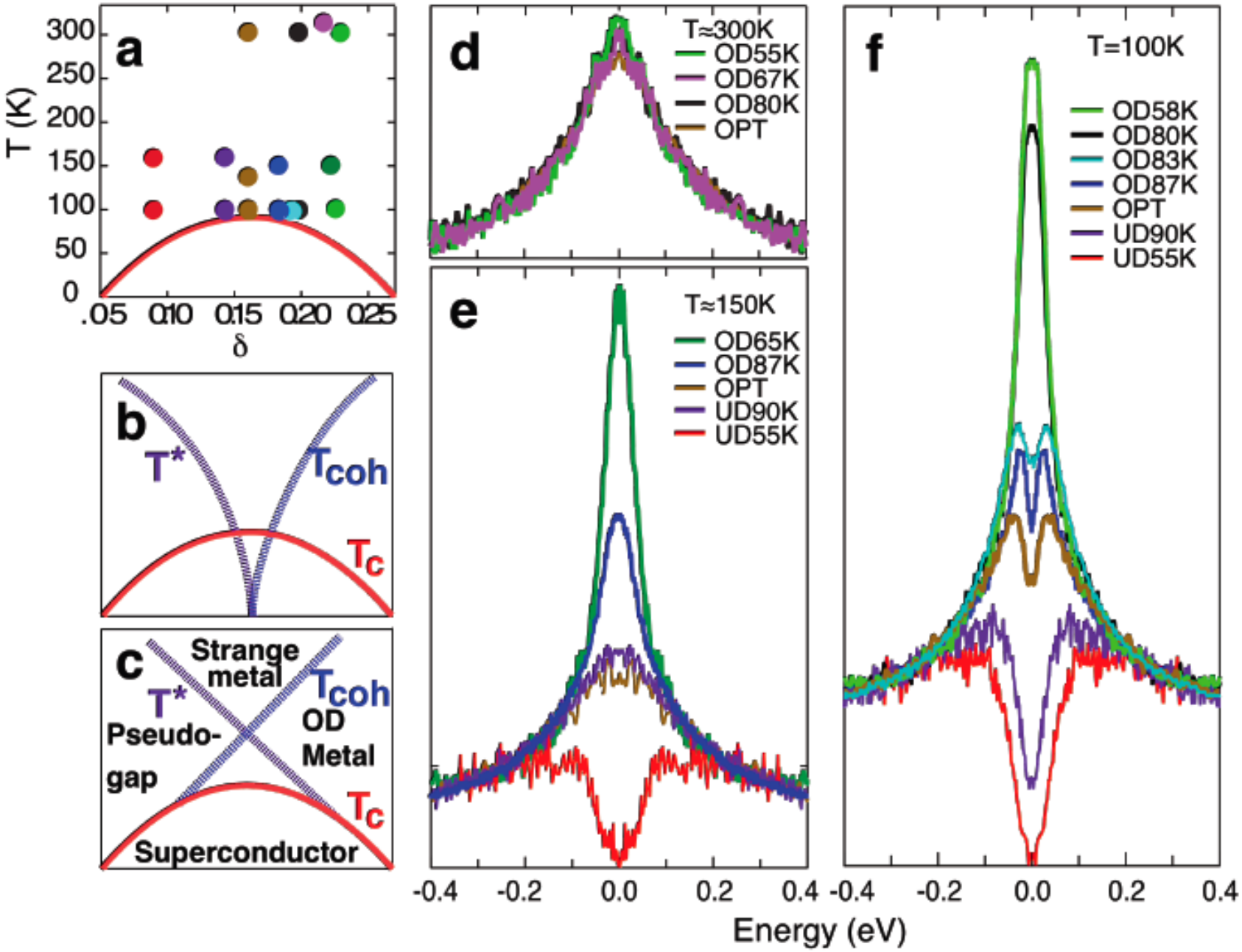
OD75K OPT89K



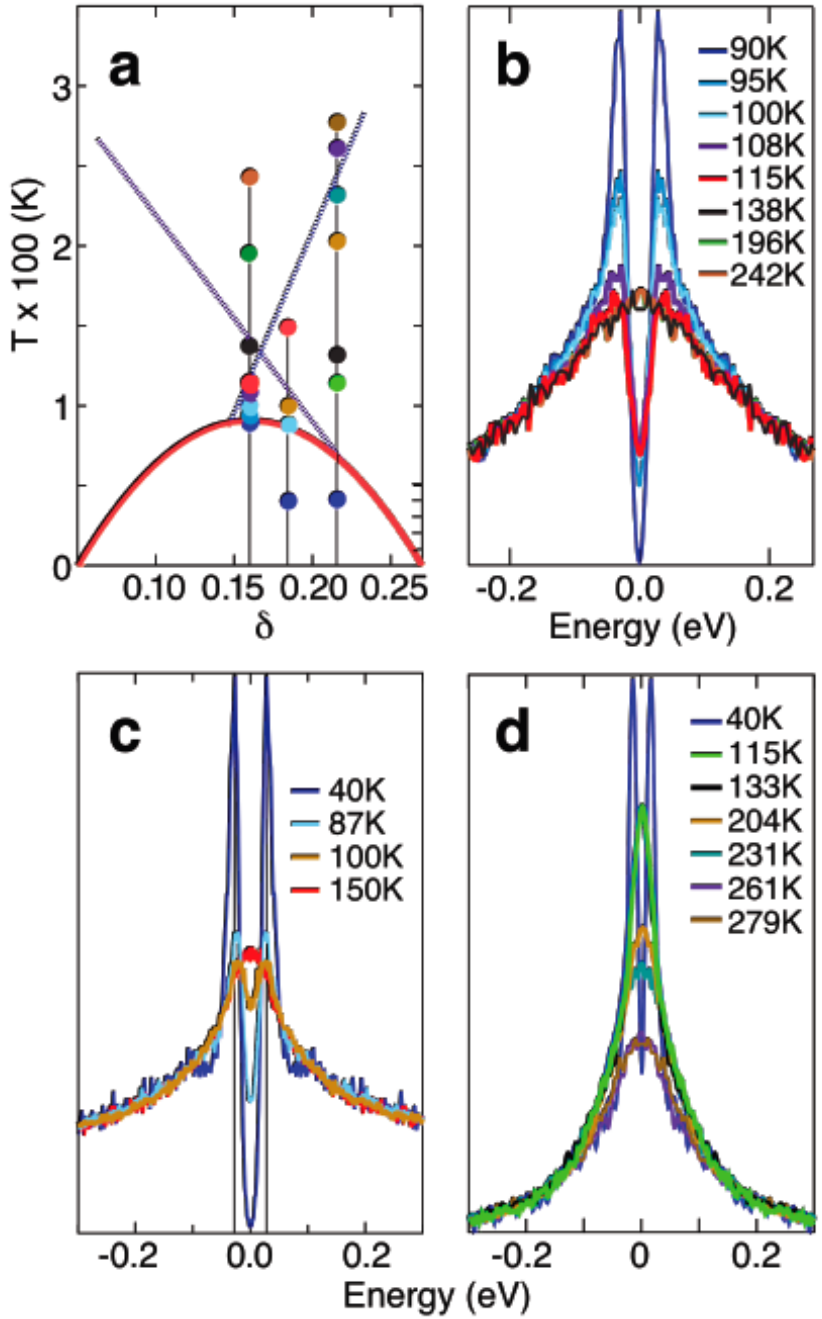
OD52K OPT89K

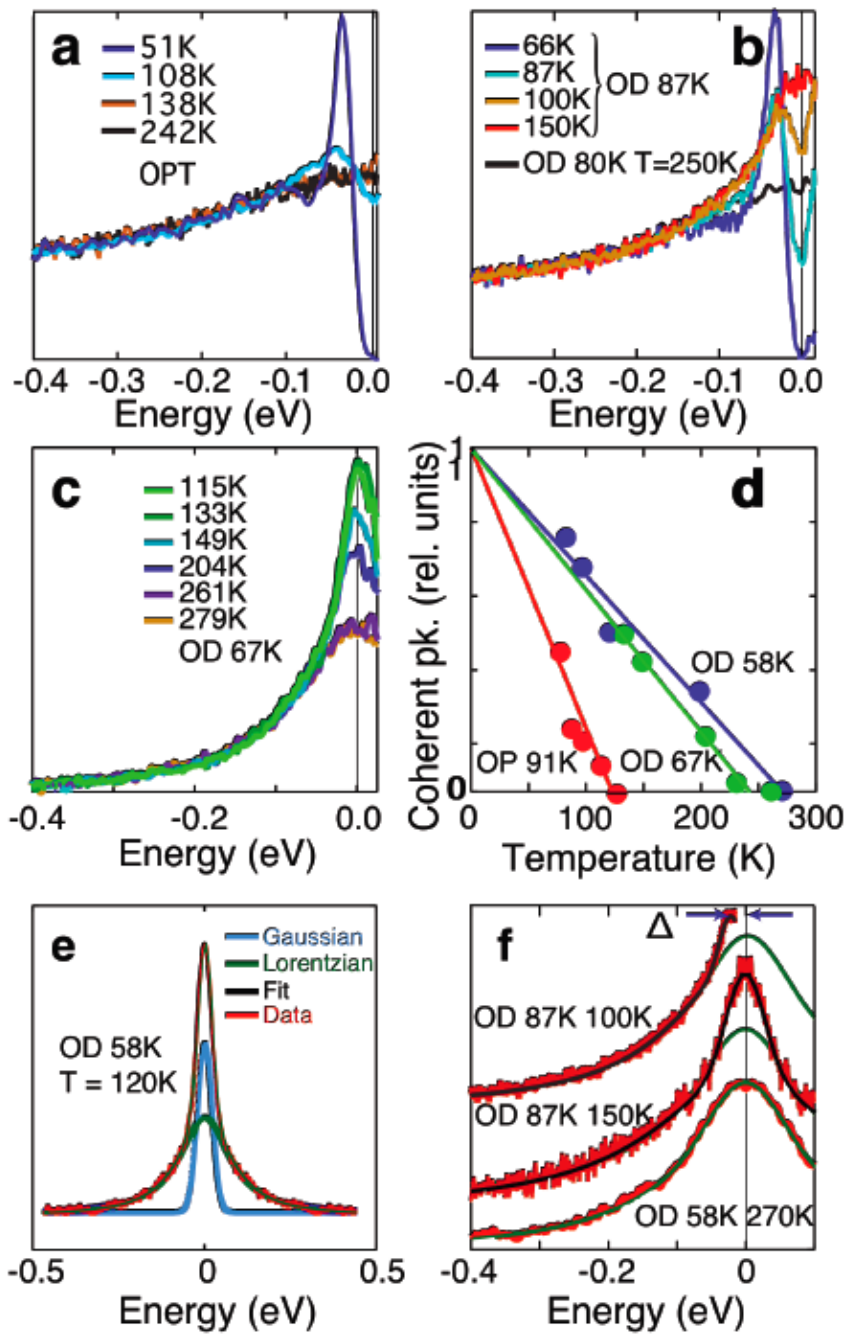


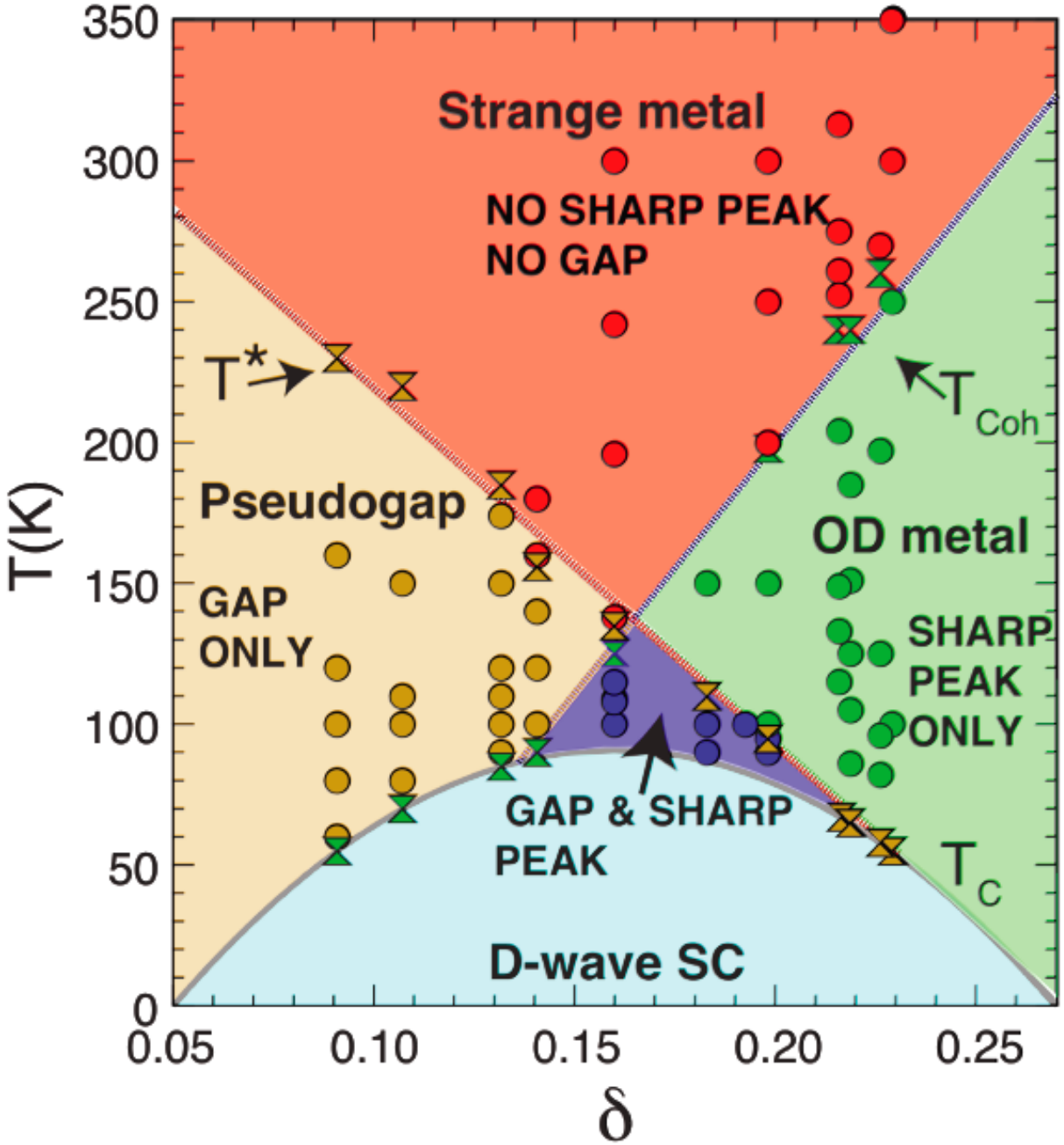

strange metal
T_X
T^*
T_N
pseudogap
metal
T_C
AFM
superconductor
Temperature (K)
hole doping
350
300
250
200
150
100
50
0
0.00
0.10
0.20
0.30



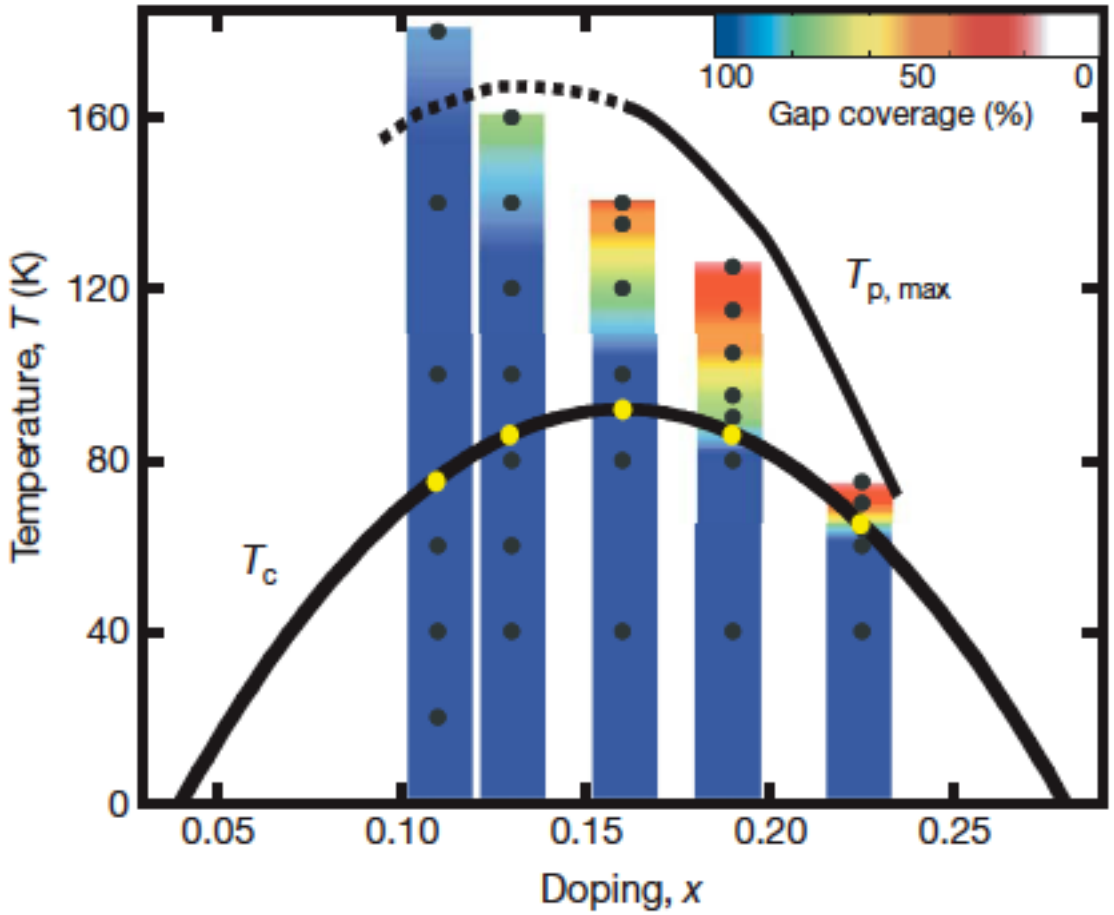
Chatterjee *et al*., unpublished


a
T x 100 (K)
δ
0.10 0.15 0.20 0.25
0
1
2
3
b
90K
95K
100K
108K
115K
138K
196K
242K
-0.2 0.0 0.2
Energy (eV)
c
40K
87K
100K
150K
-0.2 0.0 0.2
d
40K
115K
133K
204K
231K
261K
279K
-0.2 0 0.2
Energy (eV)


a
51K
108K
138K
242K
OPT
-0.4 -0.3 -0.2 -0.1 0.0
Energy (eV)
b
66K
87K
100K
150K
OD 87K
OD 80K T=250K
-0.4 -0.3 -0.2 -0.1 0.0
Energy (eV)
c
115K
133K
149K
204K
261K
279K
OD 67K
-0.4 -0.2 0.0
Energy (eV)
d
Coherent pk. (rel. units)
1
0
OD 58K
OP 91K
OD 67K
0 100 200 300
Temperature (K)
e
Gaussian
Lorentzian
Fit
Data
OD 58K
T = 120K
-0.5 0 0.5
Energy (eV)
f
Δ
OD 87K 100K
OD 87K 150K
OD 58K 270K
-0.4 -0.2 0
Energy (eV)

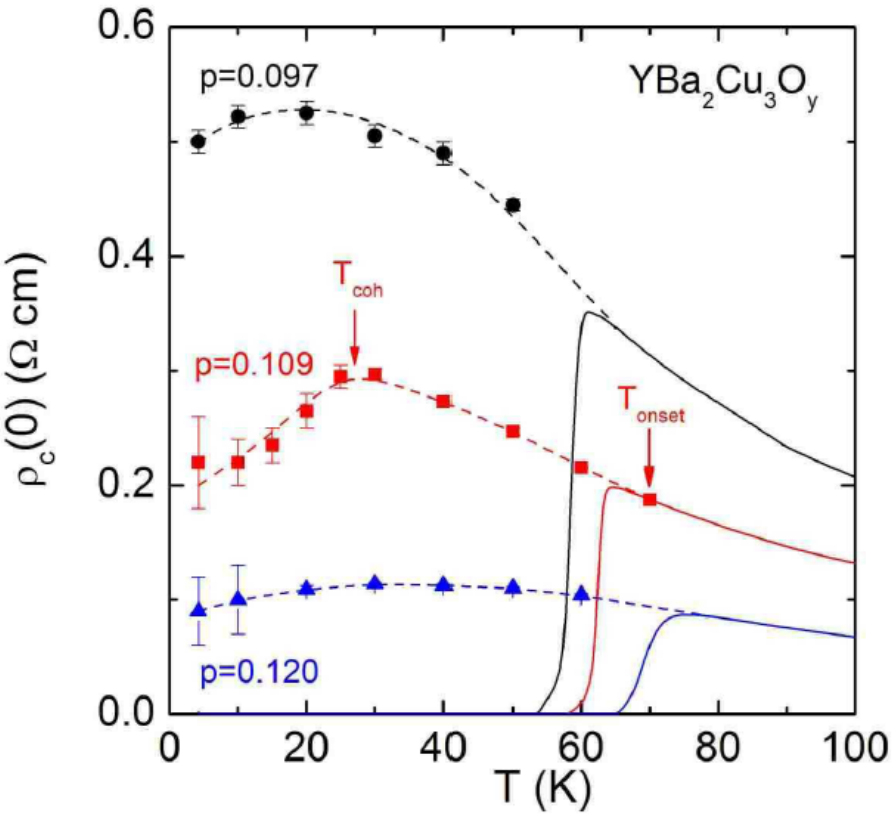

Strange metal
NO SHARP PEAK
NO GAP
T*
Pseudogap
GAP
ONLY
T_Coh
OD metal
SHARP
PEAK
ONLY
GAP & SHARP
PEAK
T_C
D-wave SC
T(K)
δ
350
300
250
200
150
100
50
0
0.05
0.10
0.15
0.20
0.25

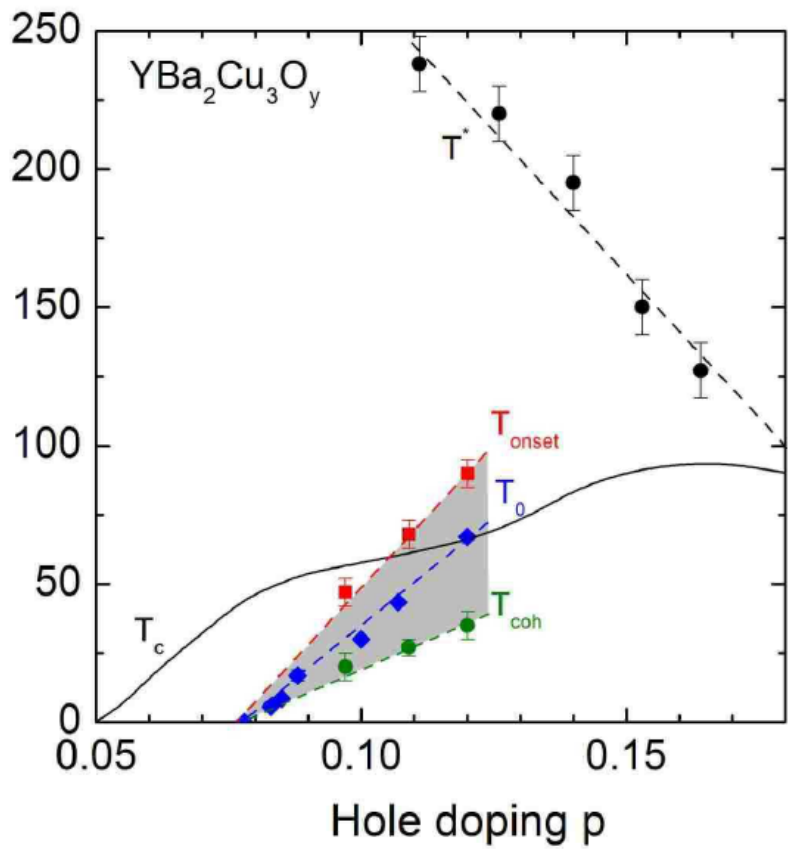
Persistence of Gaps above T_c in STM



Gomes *et al*., Nature (2007)

Coherence in c-axis transport





Vigonolle *et al*., unpublished.