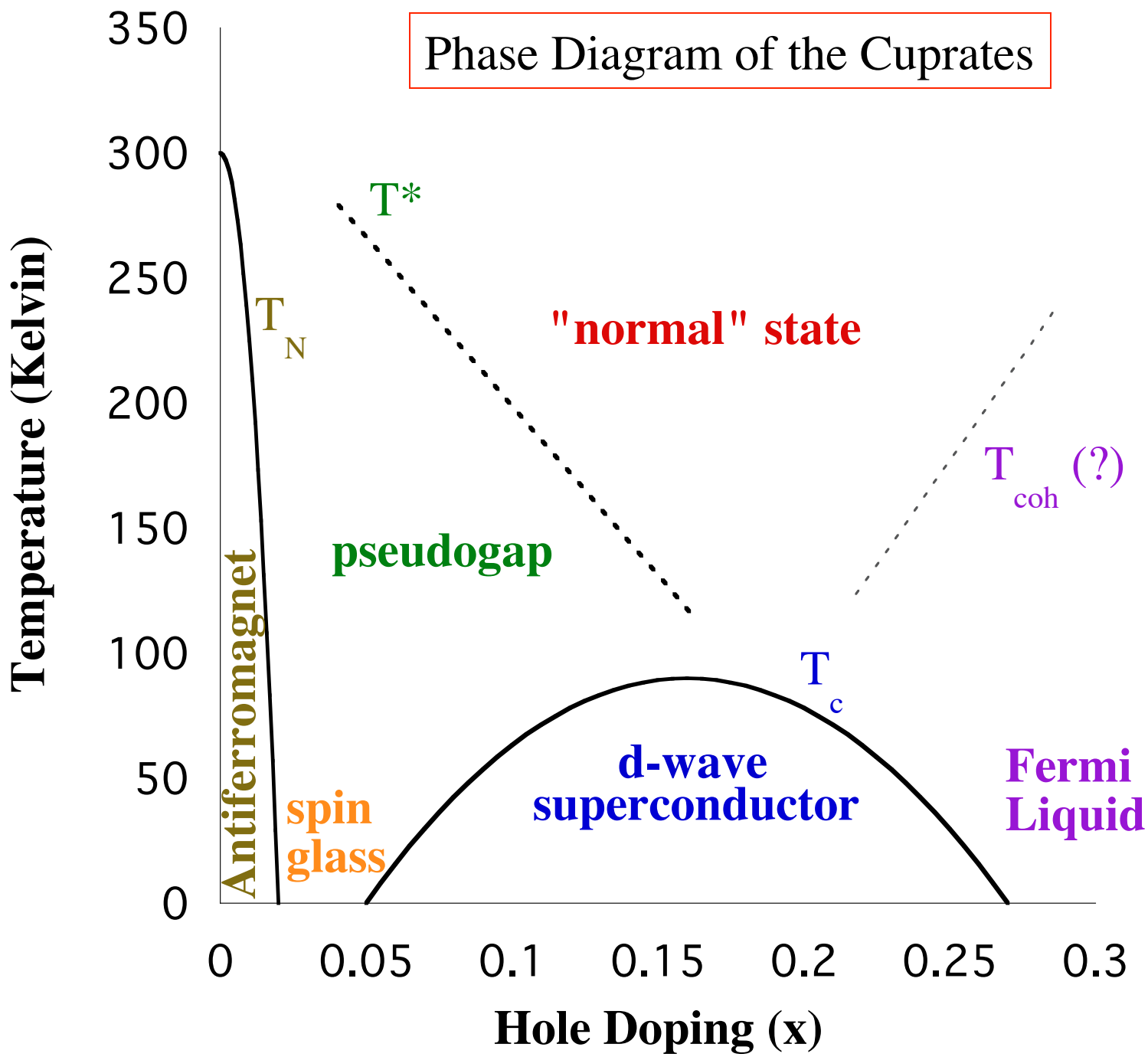
Fermi Surface Reconstruction and the Origin of High Temperature Superconductivity

Mike Norman

Materials Science Division
Argonne National Laboratory
&
Center for Emergent Superconductivity

Physics 3, 86 (2010)

Toulouse – April 5, 2012

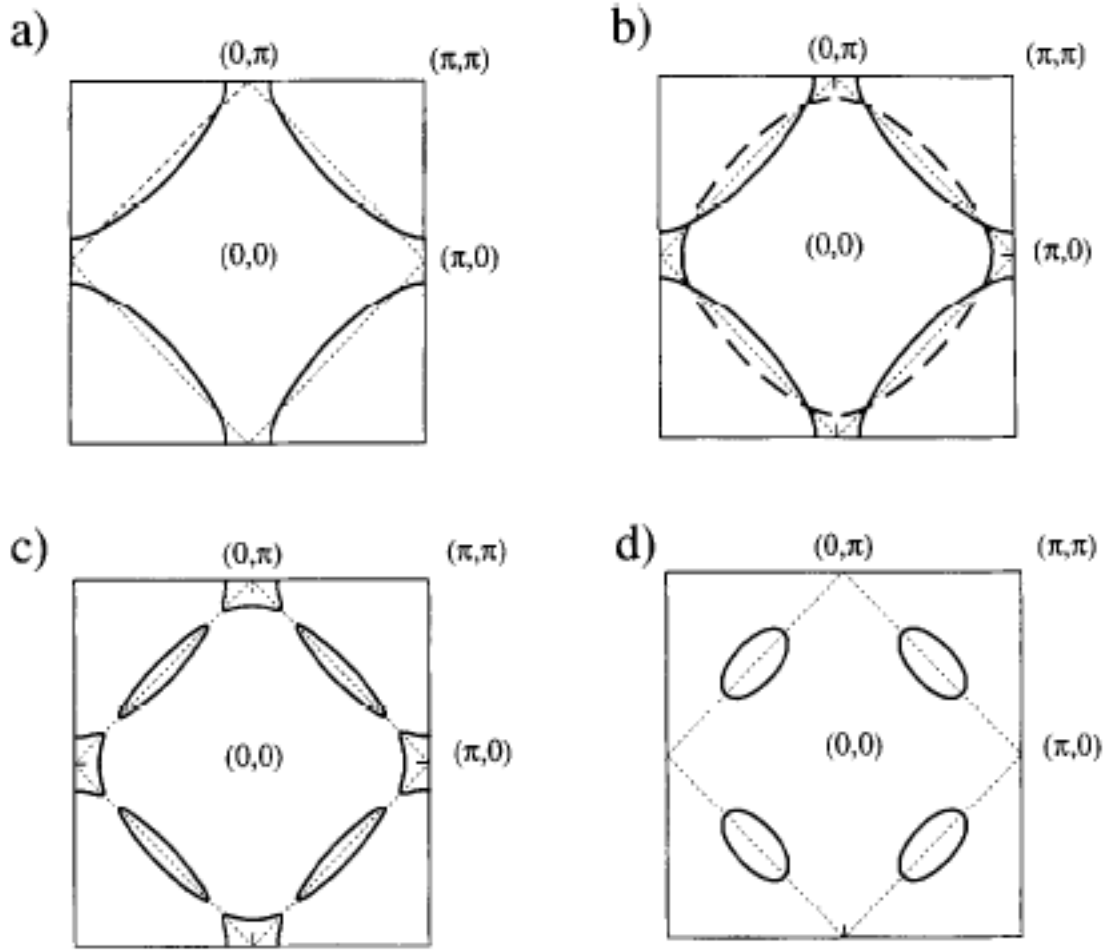

Phase Diagram of the Cuprates
Temperature (Kelvin)
350
300
250
200
150
100
50
0
T*
T N
"normal" state
T coh (?)
pseudogap
T c
Antiferromagnet
spin glass
d-wave superconductor
Fermi Liquid
0
0.05
0.1
0.15
0.2
0.25
0.3
Hole Doping (x)

What is the Pseudogap Due to?

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/nematic
9. Valence bond solid/glass
10. Combination?

Doping a Mott Insulator - x versus 1+x

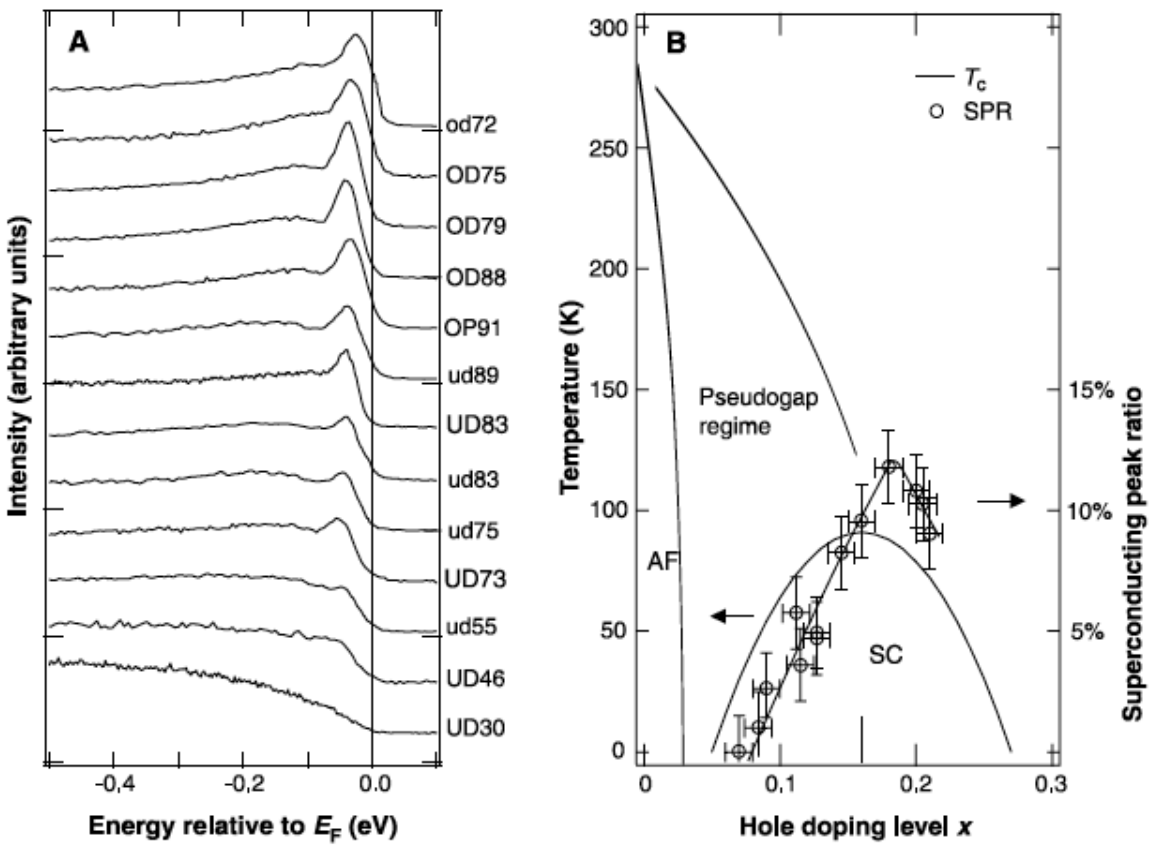
"Slater" approach - AF order causes small pockets around $(\pi/2, \pi/2)$ whose area scales like x, the number of doped holes



Chubukov & Morr
Phys. Reports (1997)

Doping a Mott Insulator - x versus 1+x

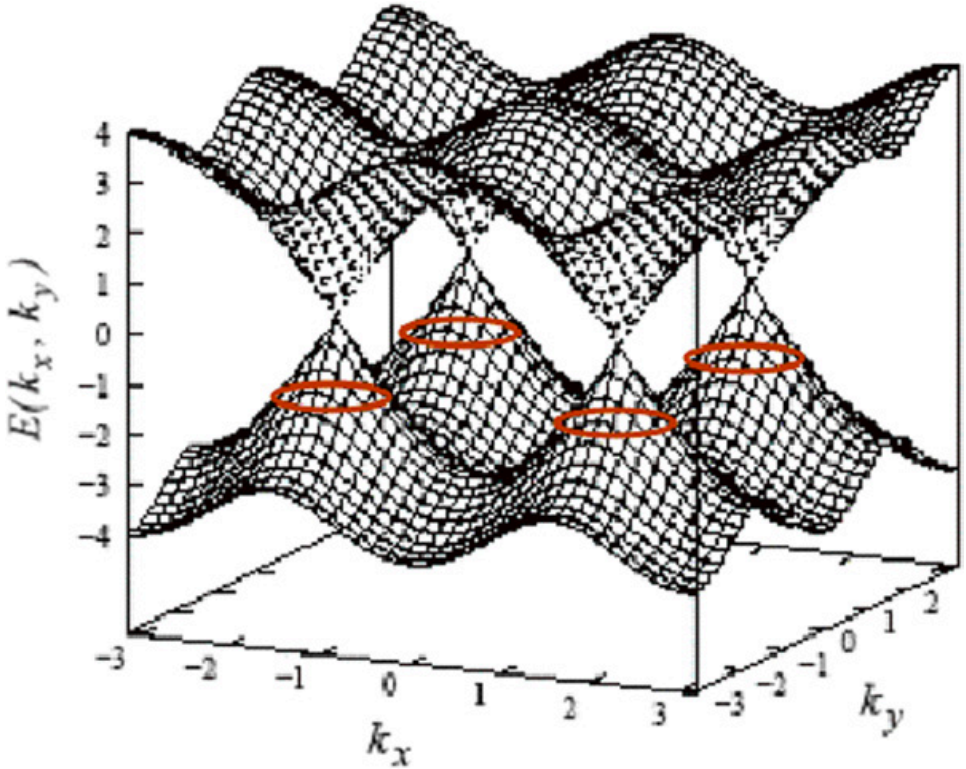
"uniform" RVB approach
large Fermi surface, but spectral weight scales as x

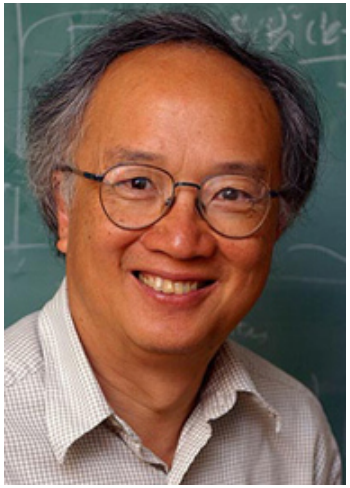


Feng *et al.*, Science (1999)

Doping a Mott Insulator - x versus 1+x

"flux phase" RVB approach
small pockets originating from Dirac cones

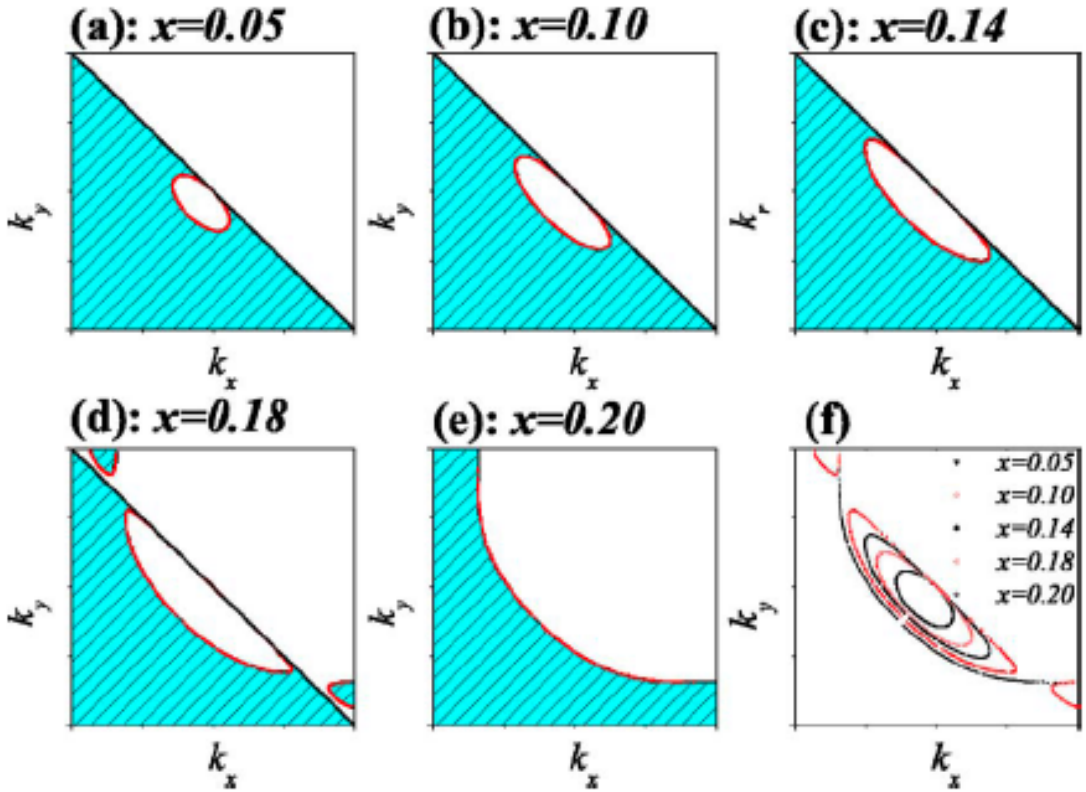




Lee, Rep. Prog. Phys. (2008)

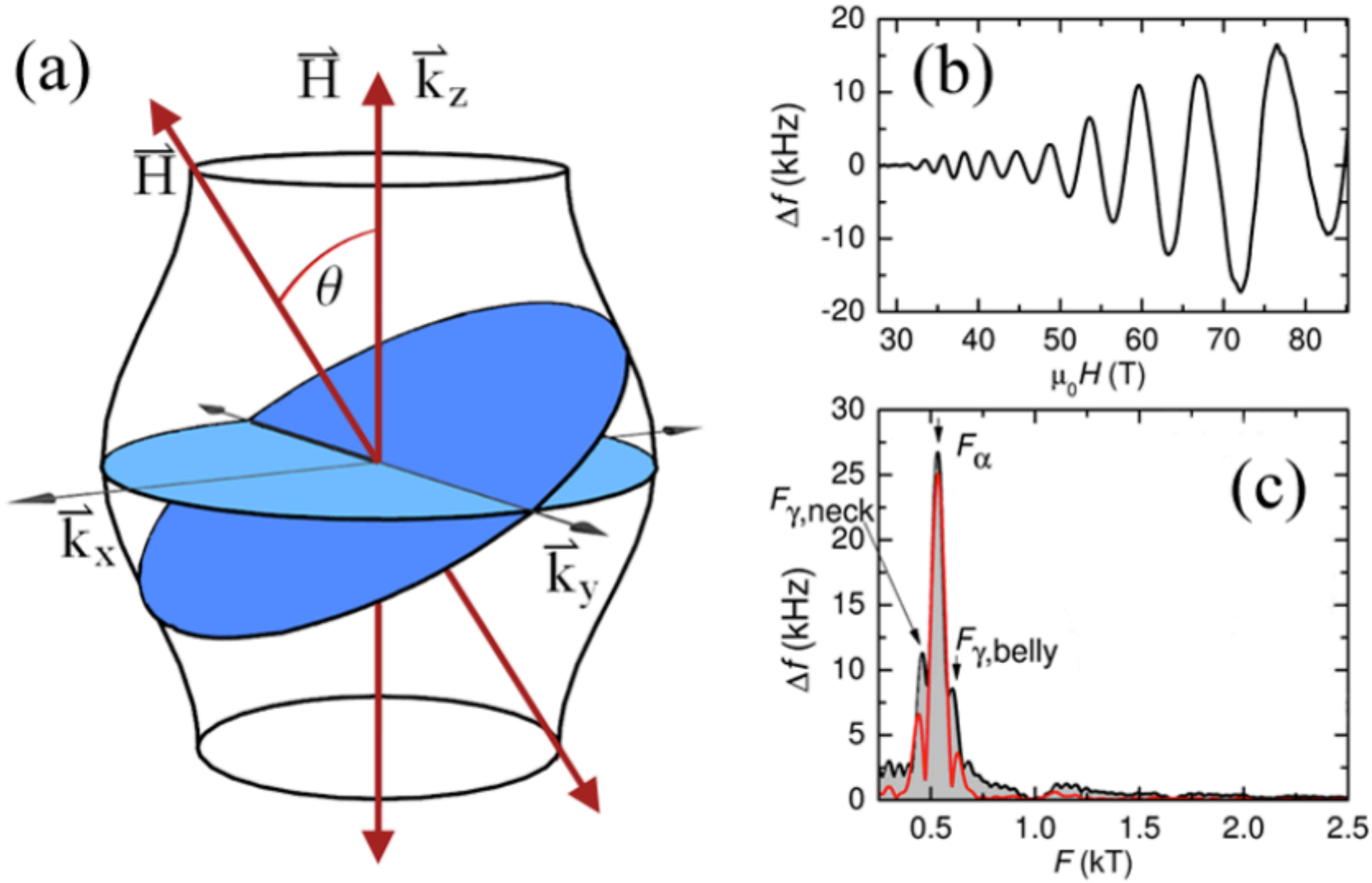
Doping a Mott Insulator - x versus 1+x

"umklapp" RVB approach
large Fermi surface truncated at AF zone boundary



Yang, Rice, Zhang
PRB (2006)

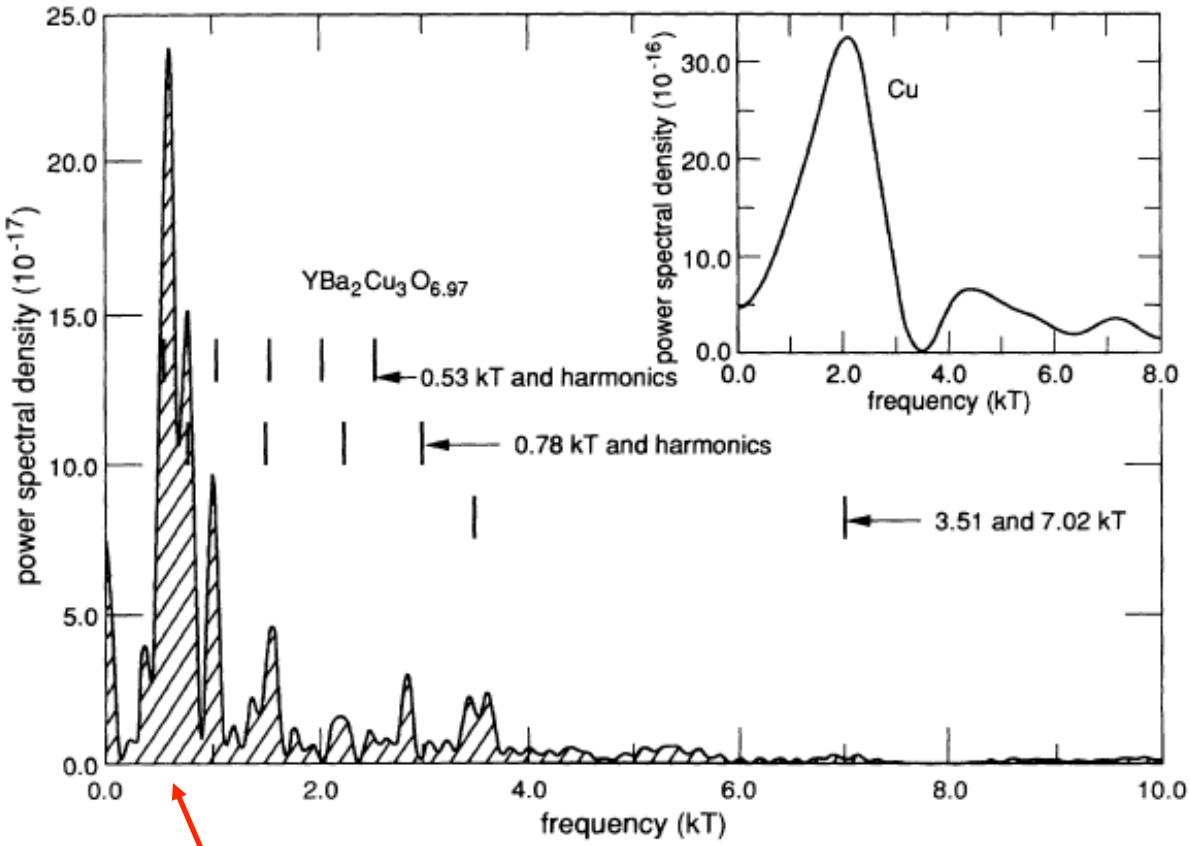
Quantum Oscillations (period determines area of extremal orbit)



(Brad Ramshaw)

Physics 3, 86 (2010)

Quantum Oscillations (the bad old days)

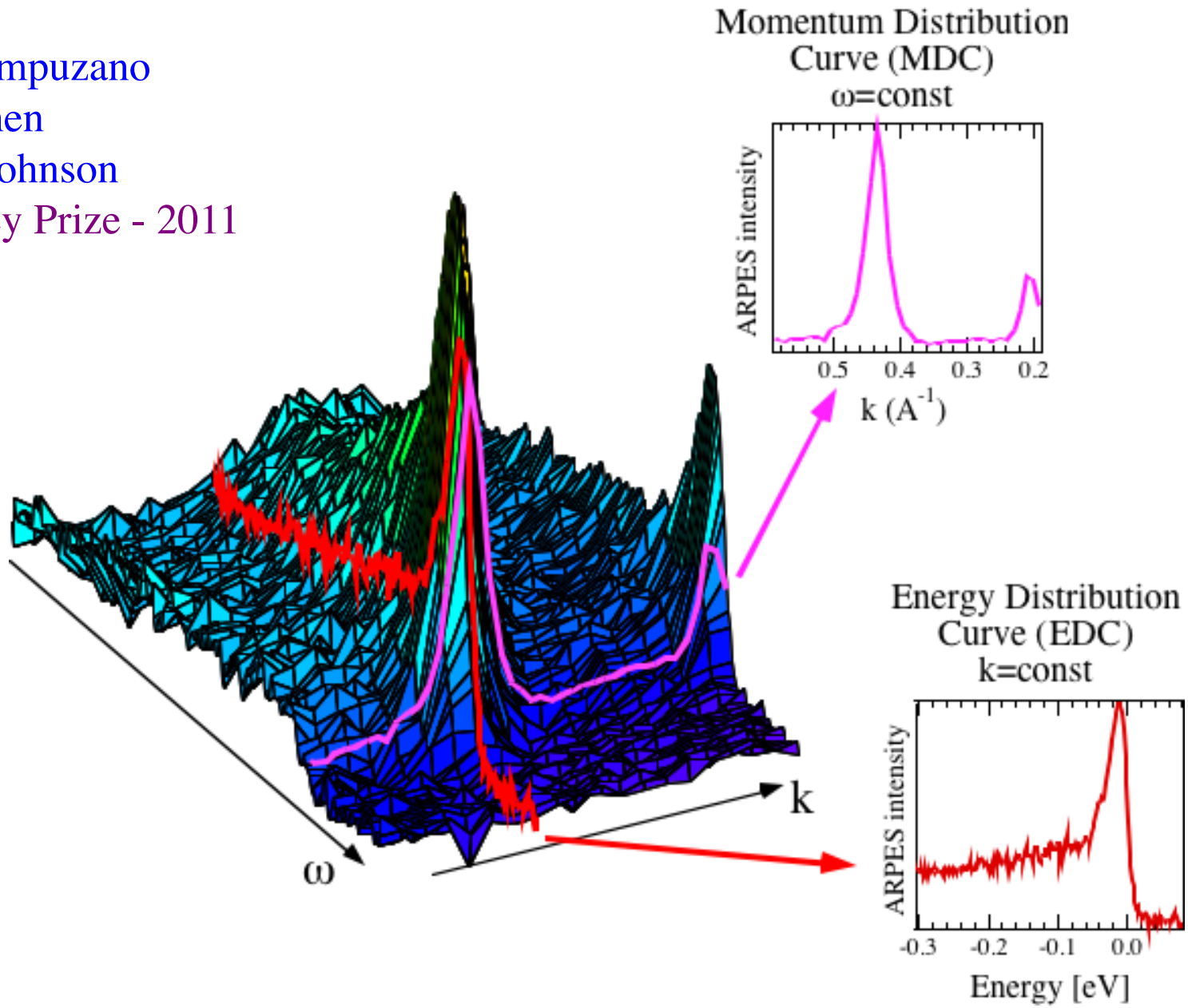


small Fermi surface!

Fowler *et al.*, PRL (1992)
Kito *et al.*, JPCS (1992)
Haanappel *et al.*, JPCS (1993)
but see Springford *et al.*, PRL (1992)

Angle Resolved Photoemission Spectroscopy (ARPES)

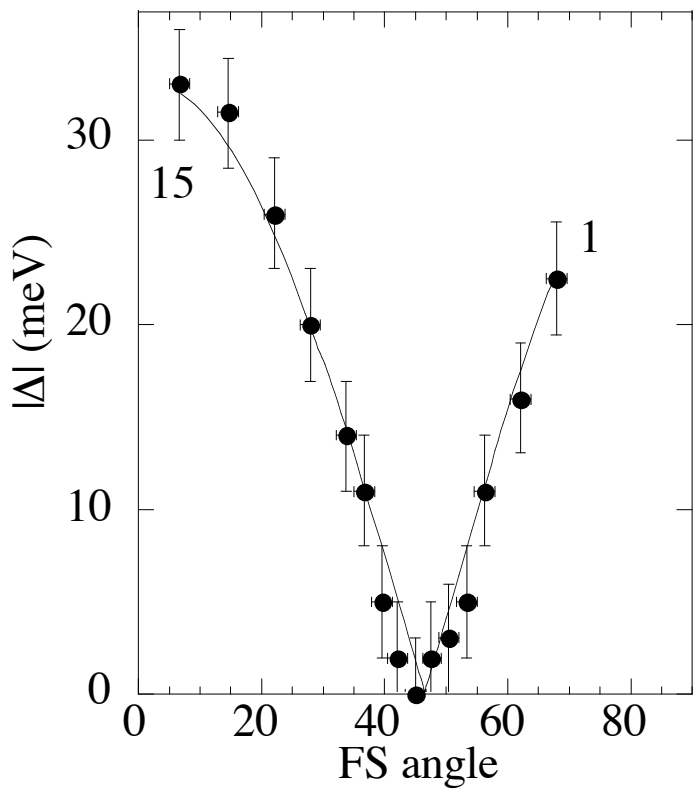
J C Campuzano
Z X Shen
Peter Johnson
Buckley Prize - 2011

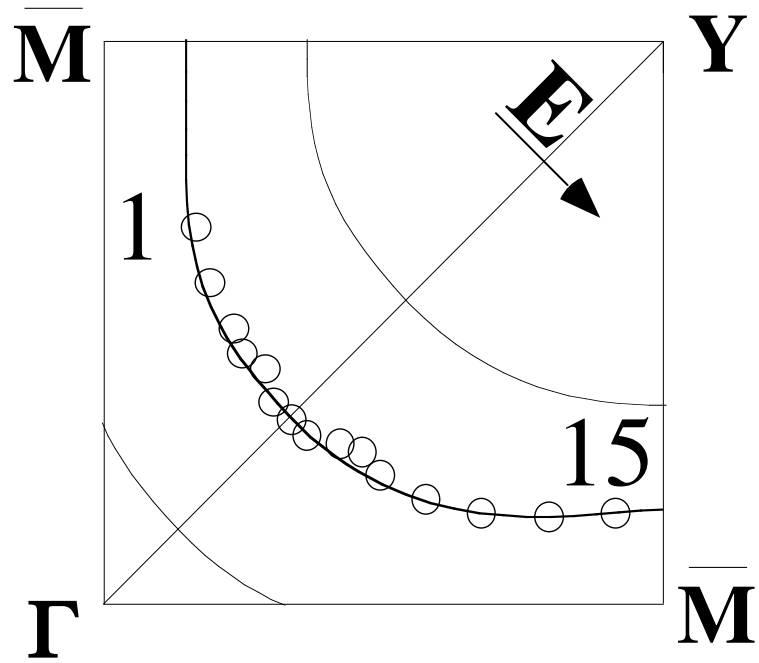


Extraction of the Superconducting Energy Gap from Photoemission

Ding *et al*., PRB (1996) following the pioneering work of Shen *et al*., PRL (1993)

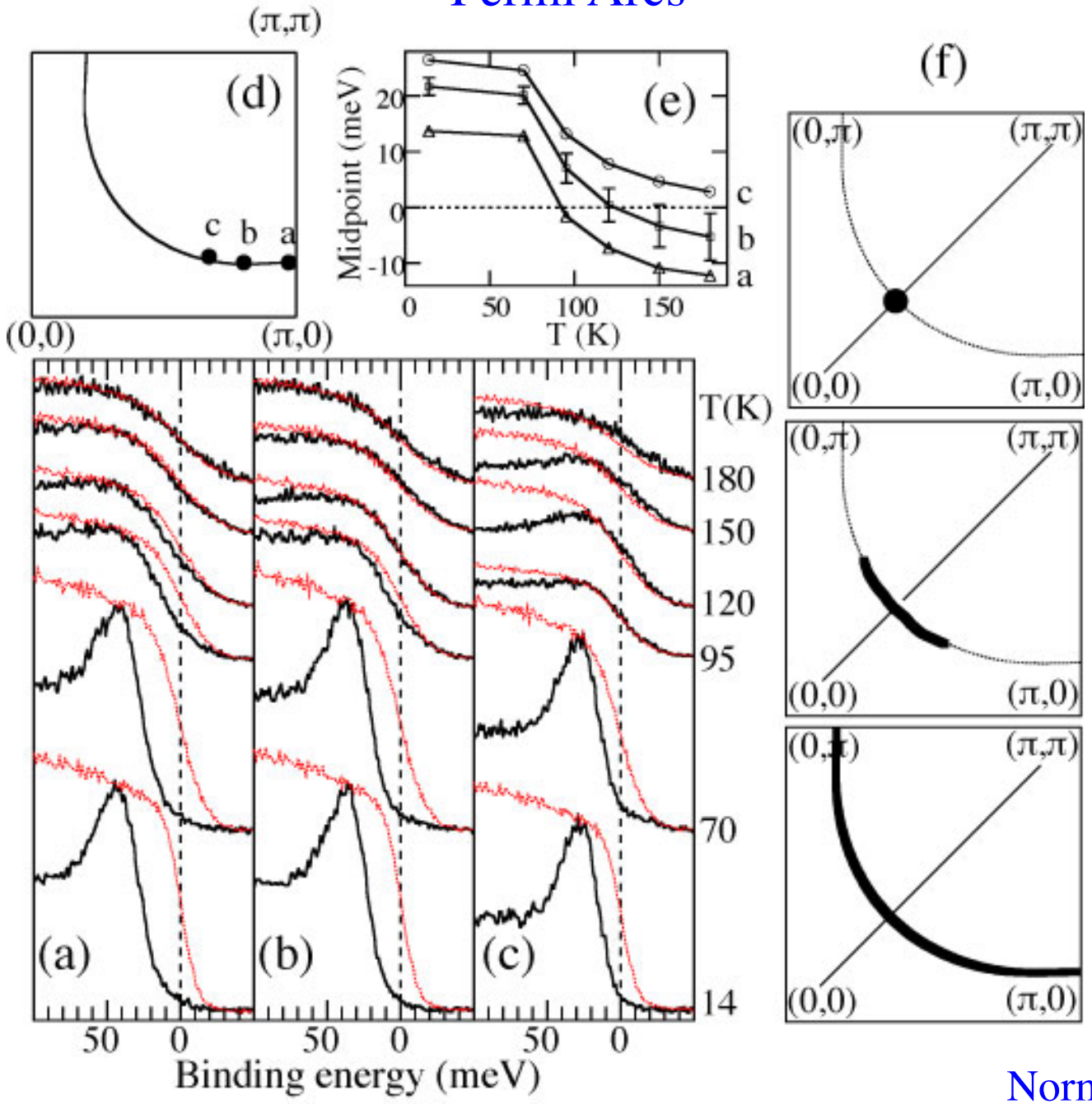
Δ_k --> $\cos(k_x a) - \cos(k_y a)$ --> d-wave energy gap





Bi2212, T_c=87K

Fermi Arcs



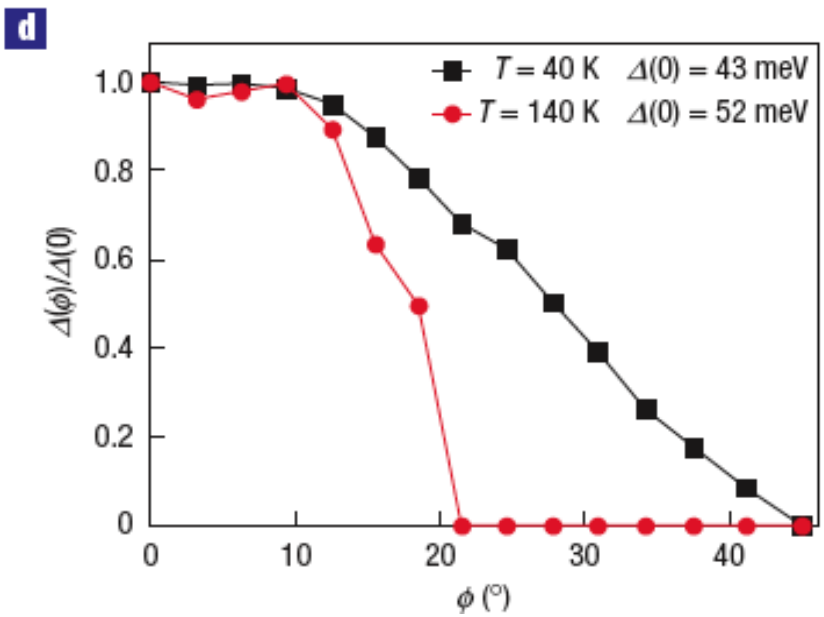
$T < T_c$
(d-wave node)

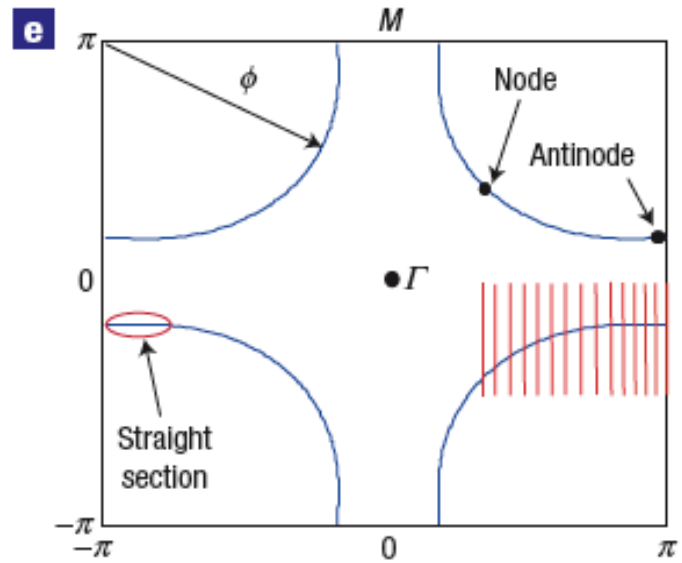
$T_c < T < T^*$
(Fermi arc)

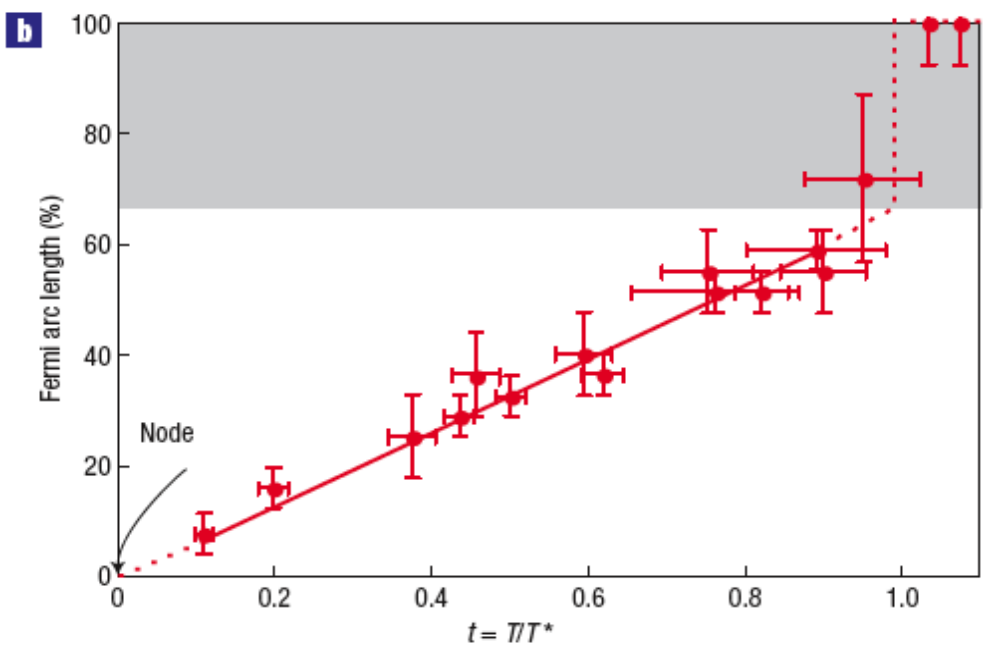
$T > T^*$
(large Fermi surface)

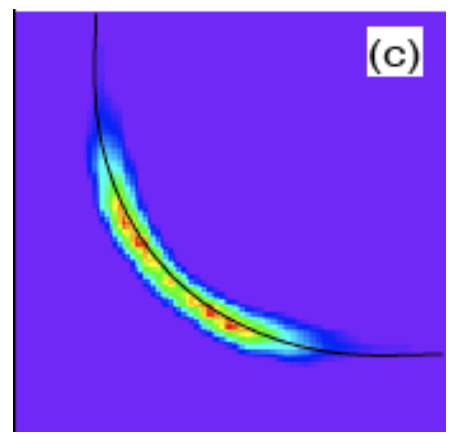
Norman *et al.*, Nature (1998)

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





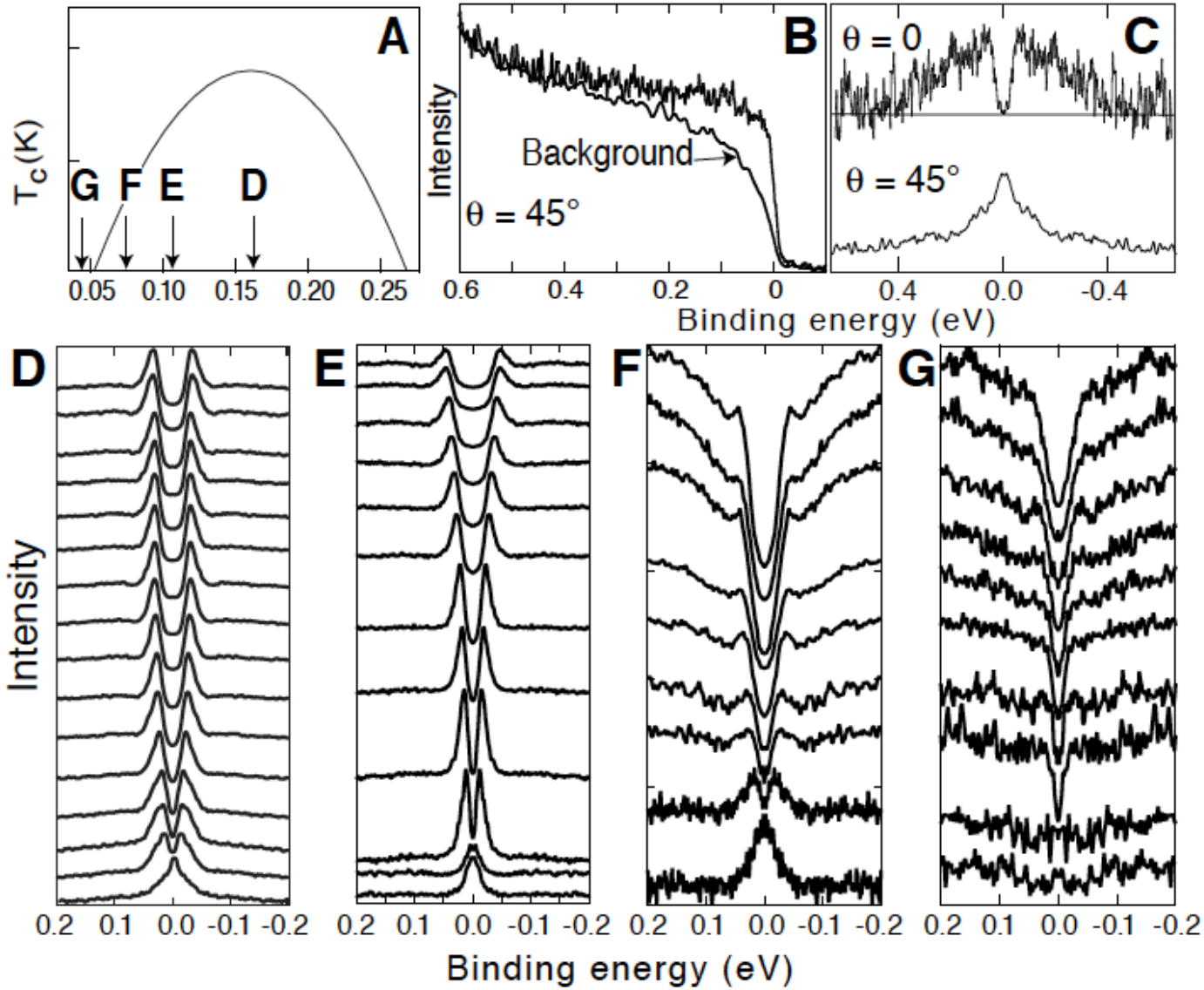




Kanigel *et al.*, Nat. Phys. (2006)

Doping Dependence of the Gap Anisotropy

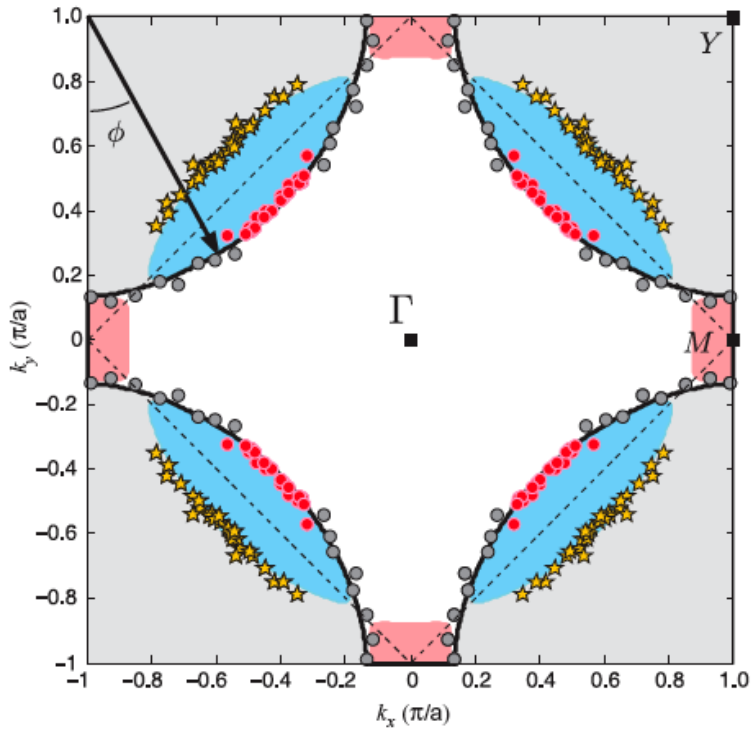
optimal

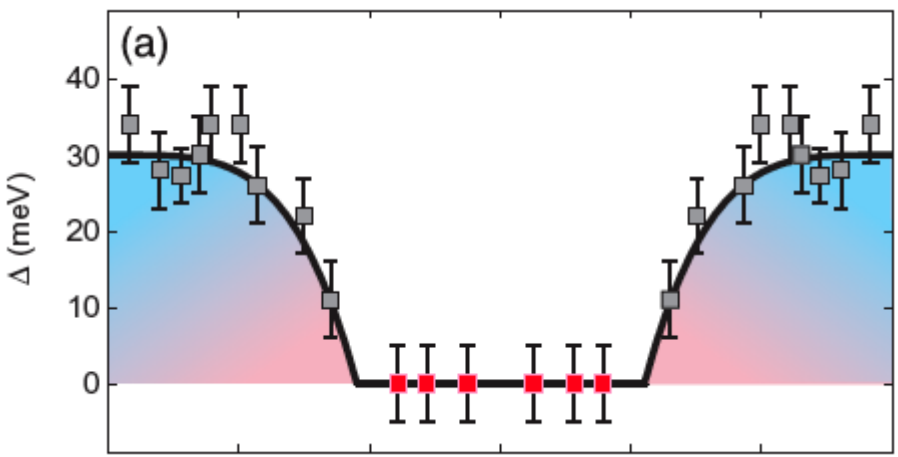


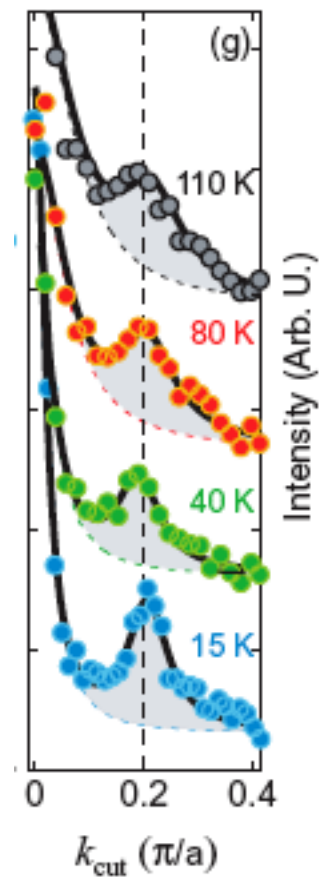
insulator

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

Pocket in Nd-doped LSCO (x=0.12) (structural?)

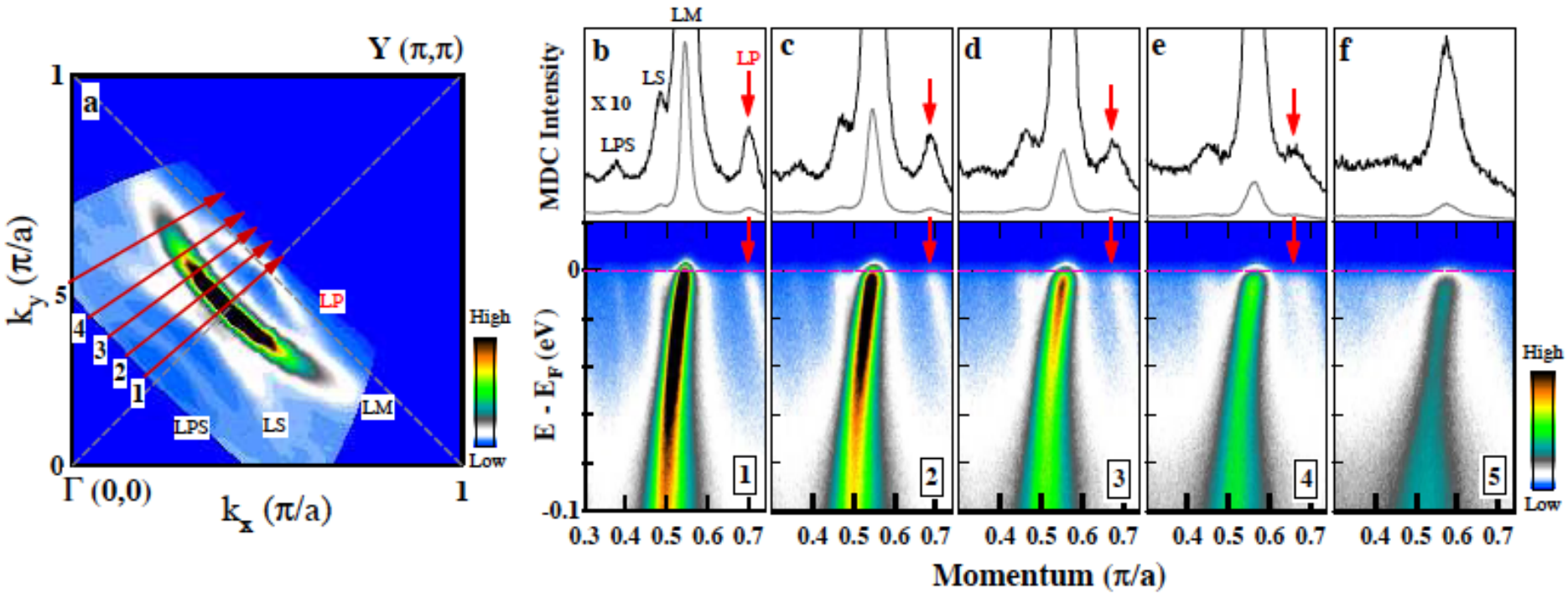






Chang *et al.*, New J. Phys. (2008)

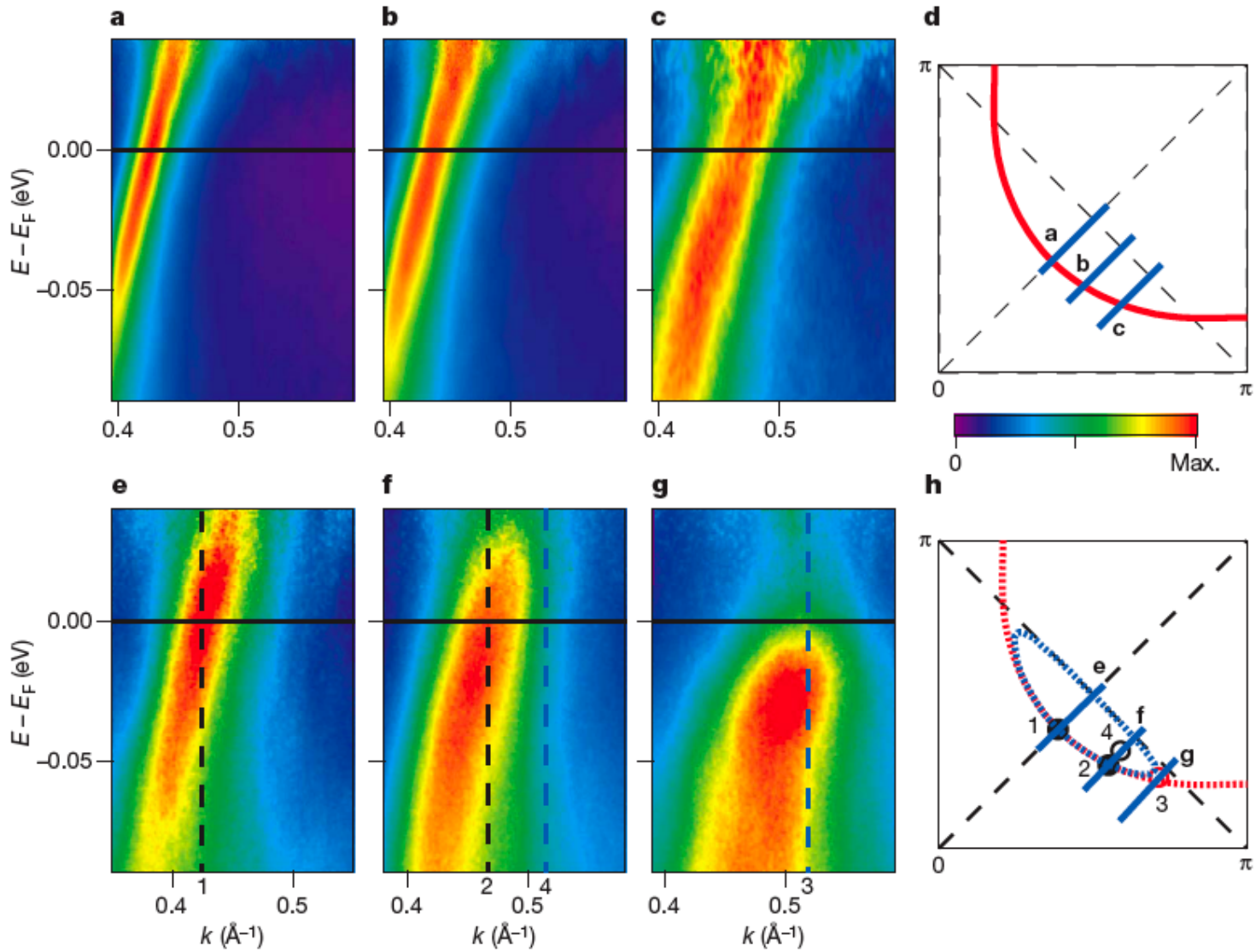
Pocket in La doped Bi2201
(structural?)



Structural? – yes – King *et al*., PRL (2011)

Meng *et al*., Nature (2009)

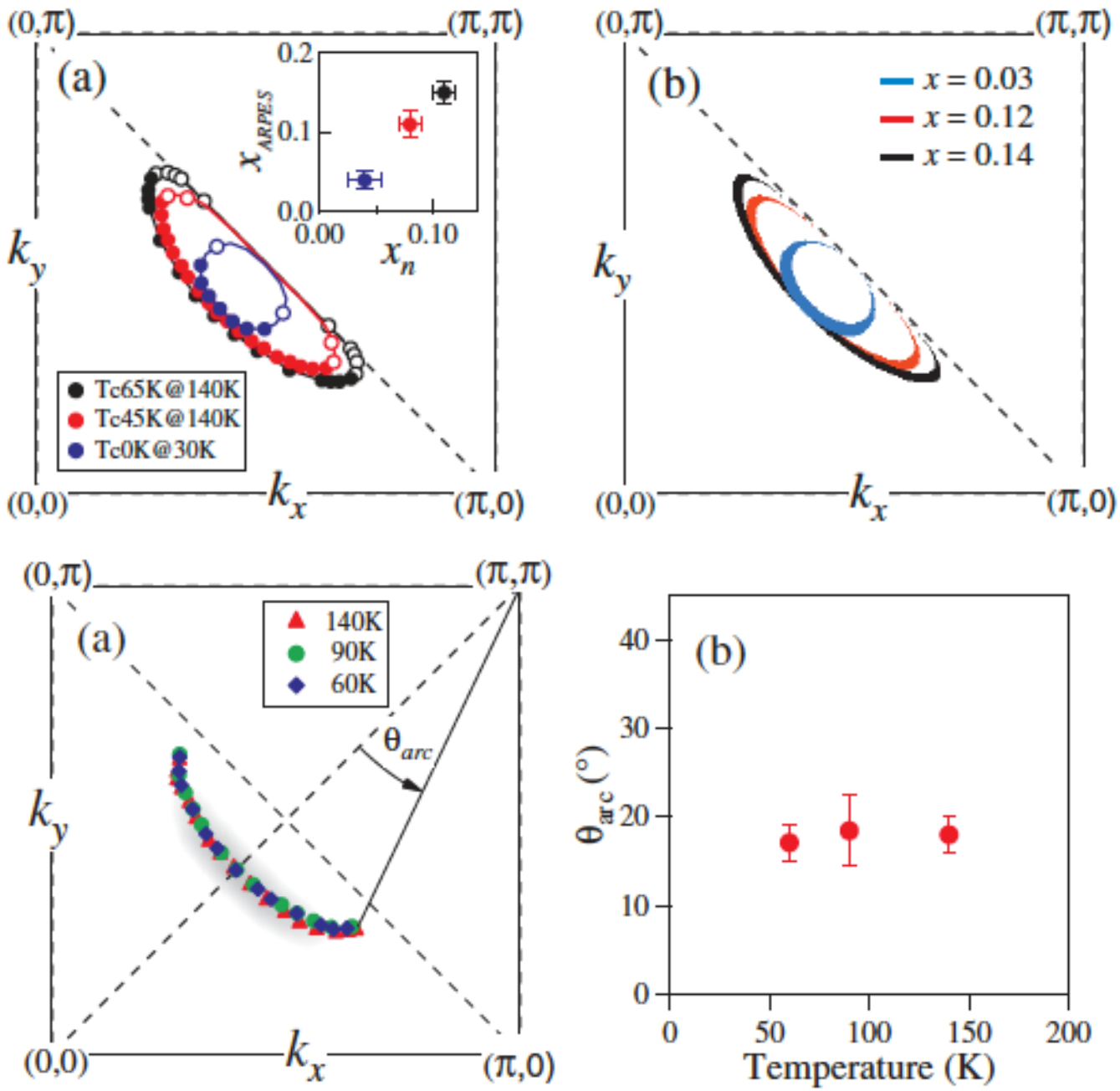
Pocket in Bi2212?



T_c=91K (optimal doped)

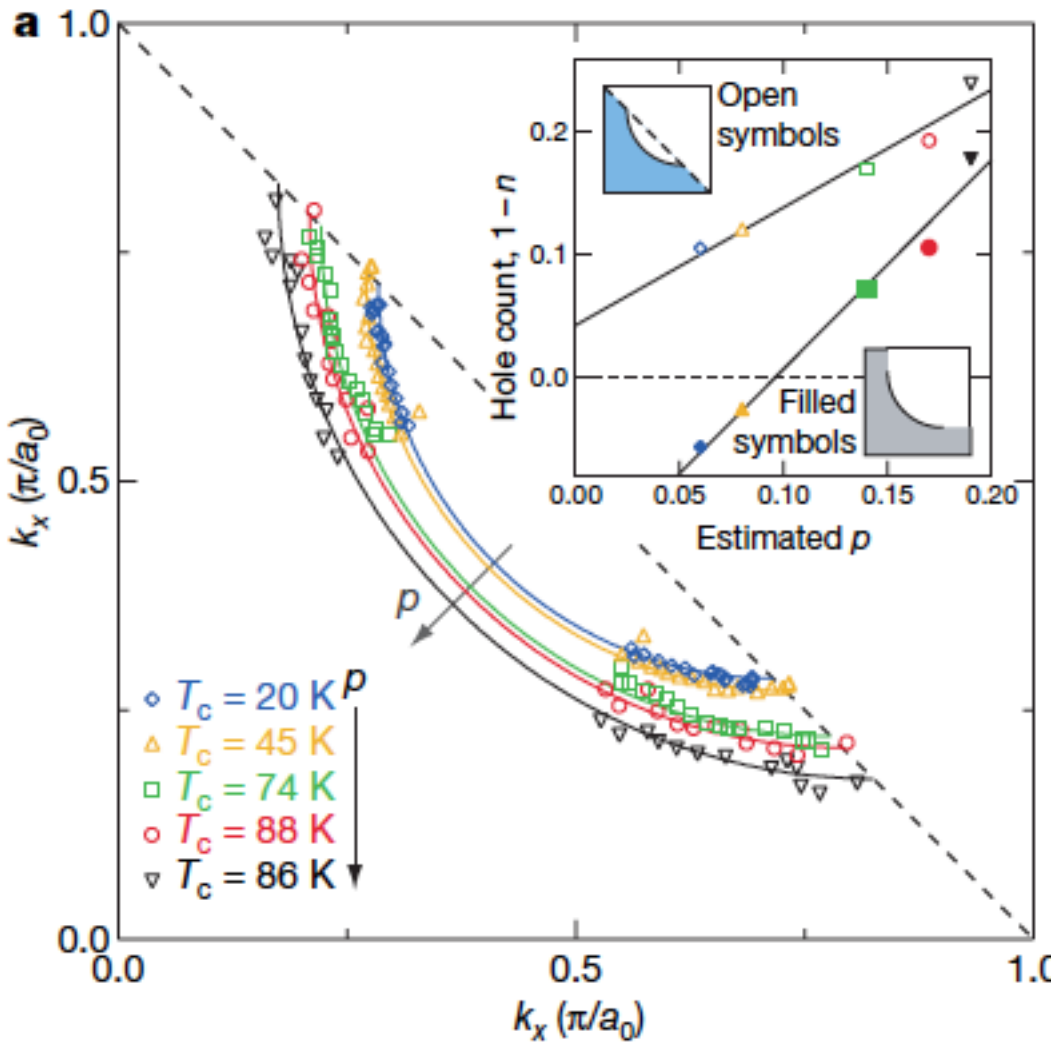
T_c=65K (underdoped)

Yang *et al.*, Nature (2008)

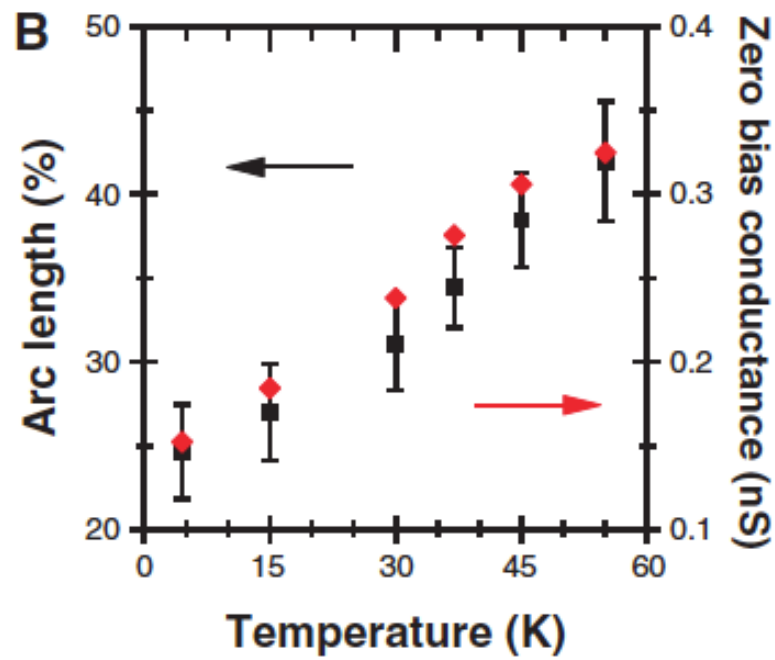


Yang *et al*.
PRL (2011)

Truncation of QPI at the AF zone boundary

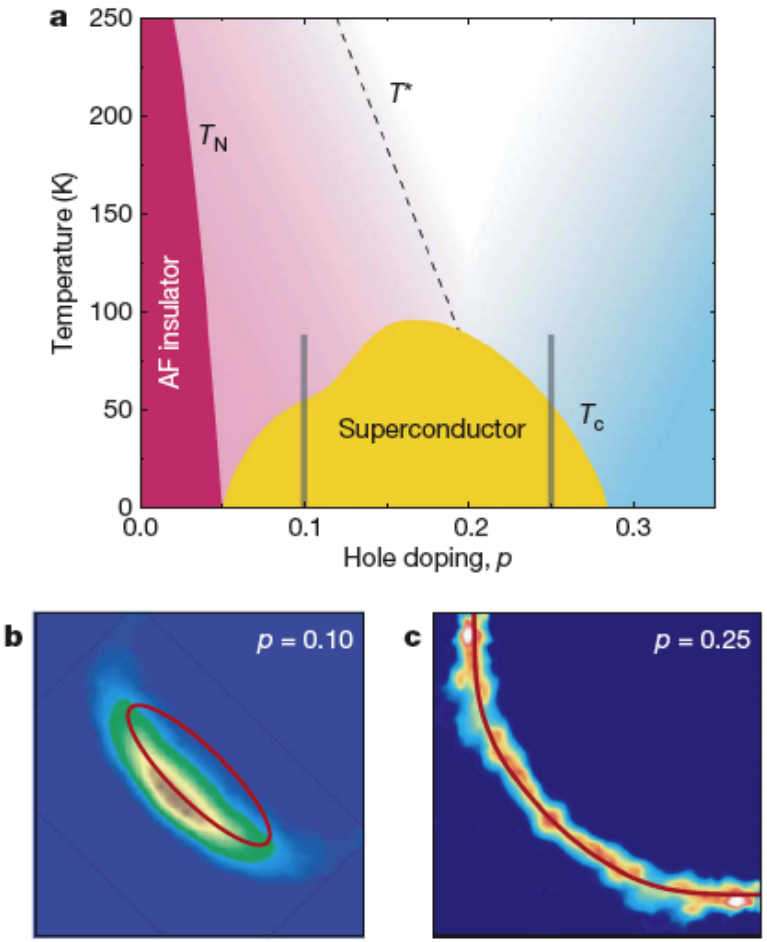


Kohsaka *et al*., Nature (2008)

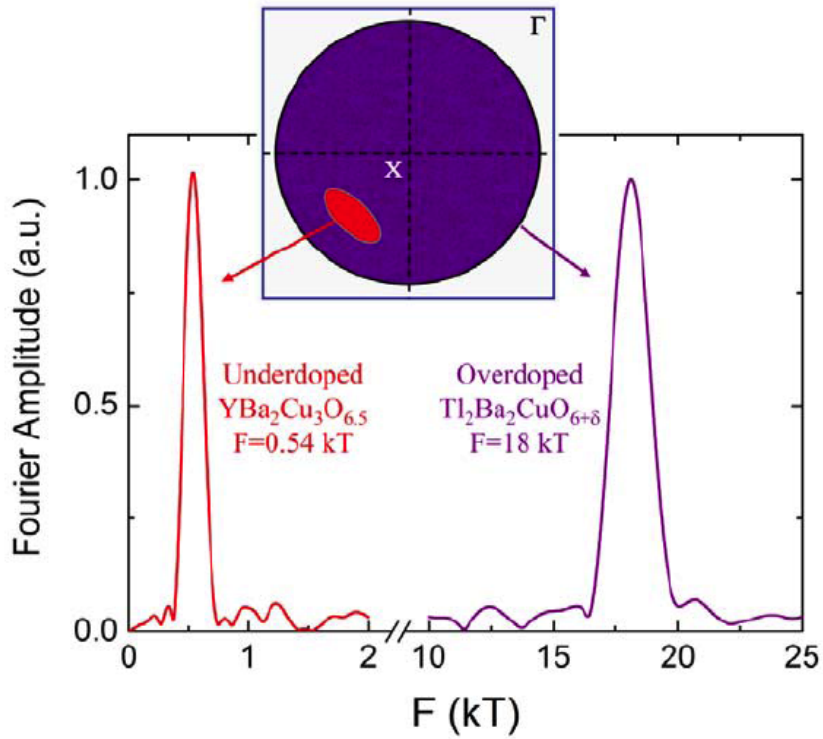


Lee *et al*., Science (2009)

Quantum Oscillations make a comeback (2007)

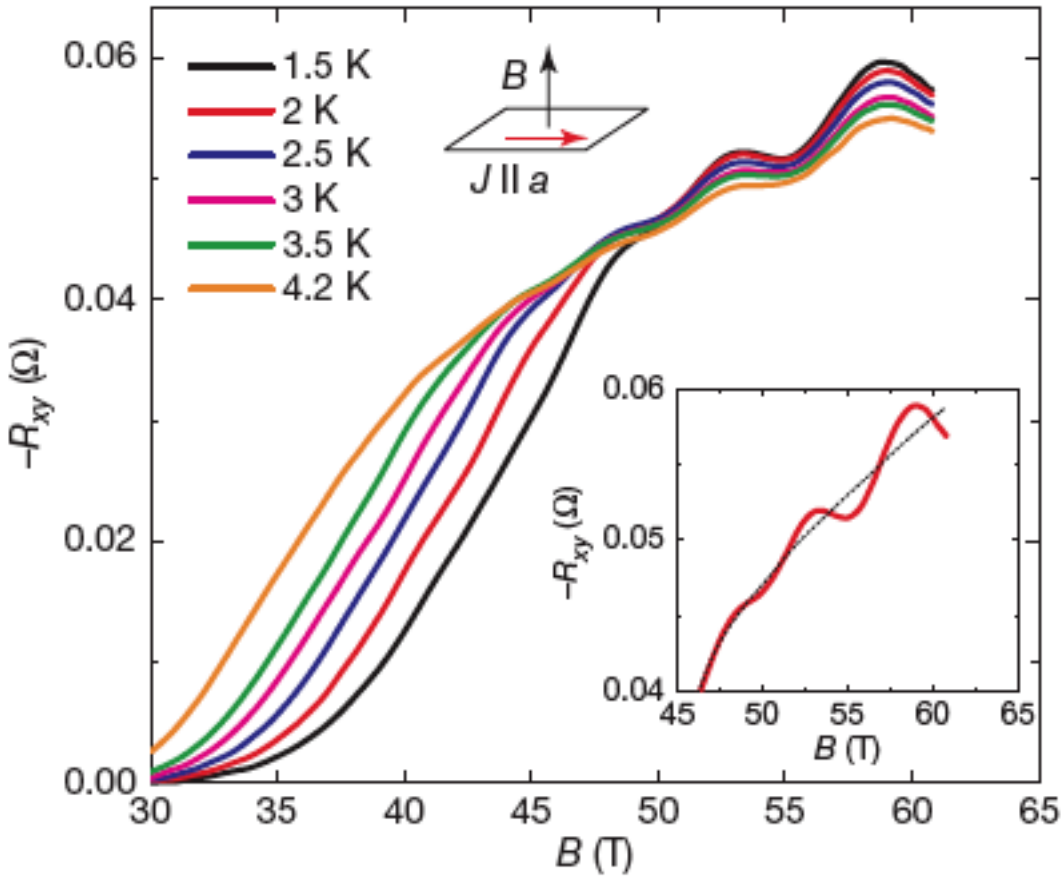


Doiron-Leyraud *et al.*, Nature (2007)
(underdoped - small Fermi surface)



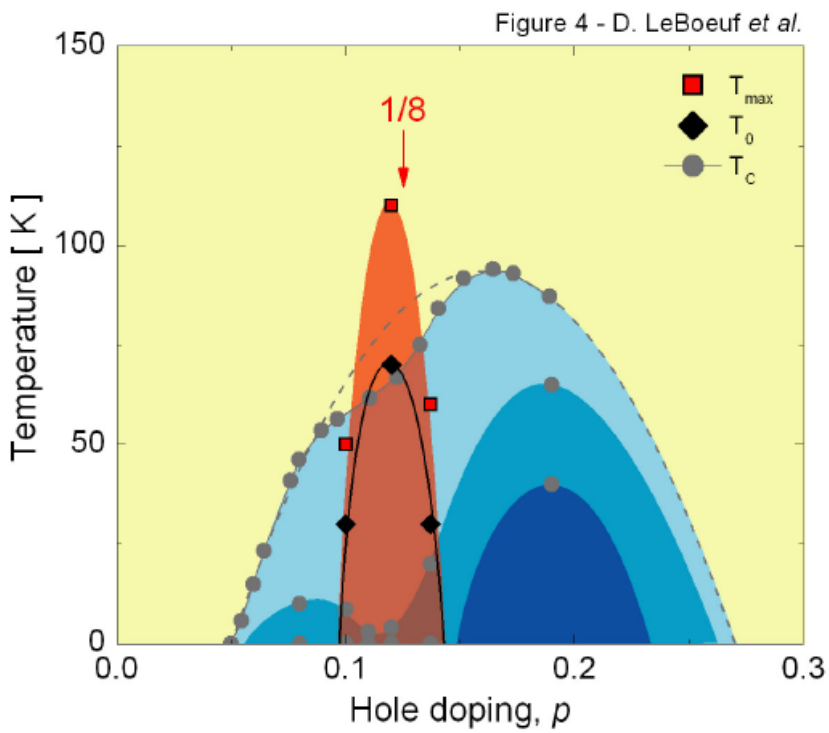
Vignolle *et al.*, Nature (2008)
(overdoped - large Fermi surface)

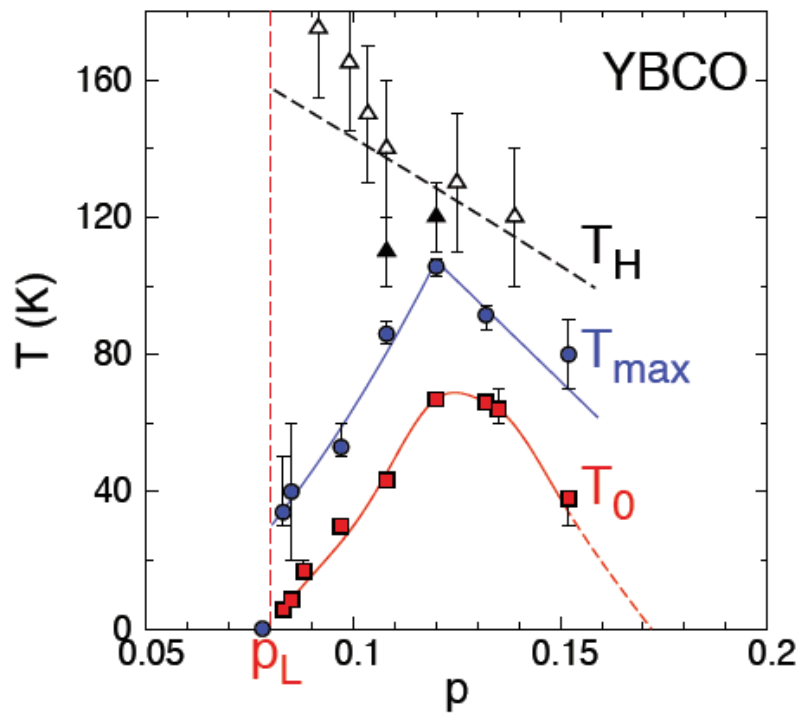
The Hall number is negative!
(electron pockets?)



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

Hall number < 0 in YBCO forms a dome around x=1/8



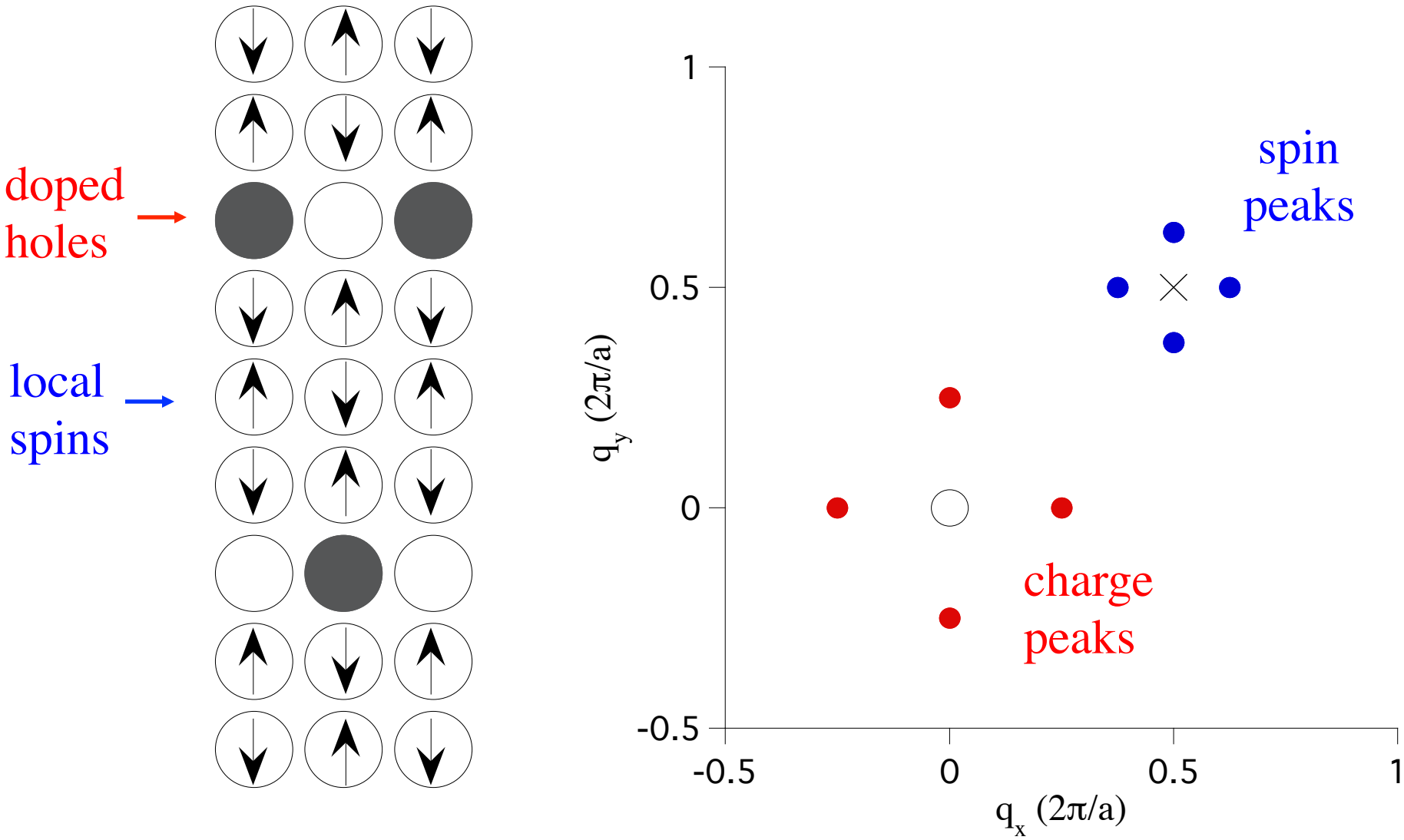


LeBoeuf *et al.*, Nature (2007)

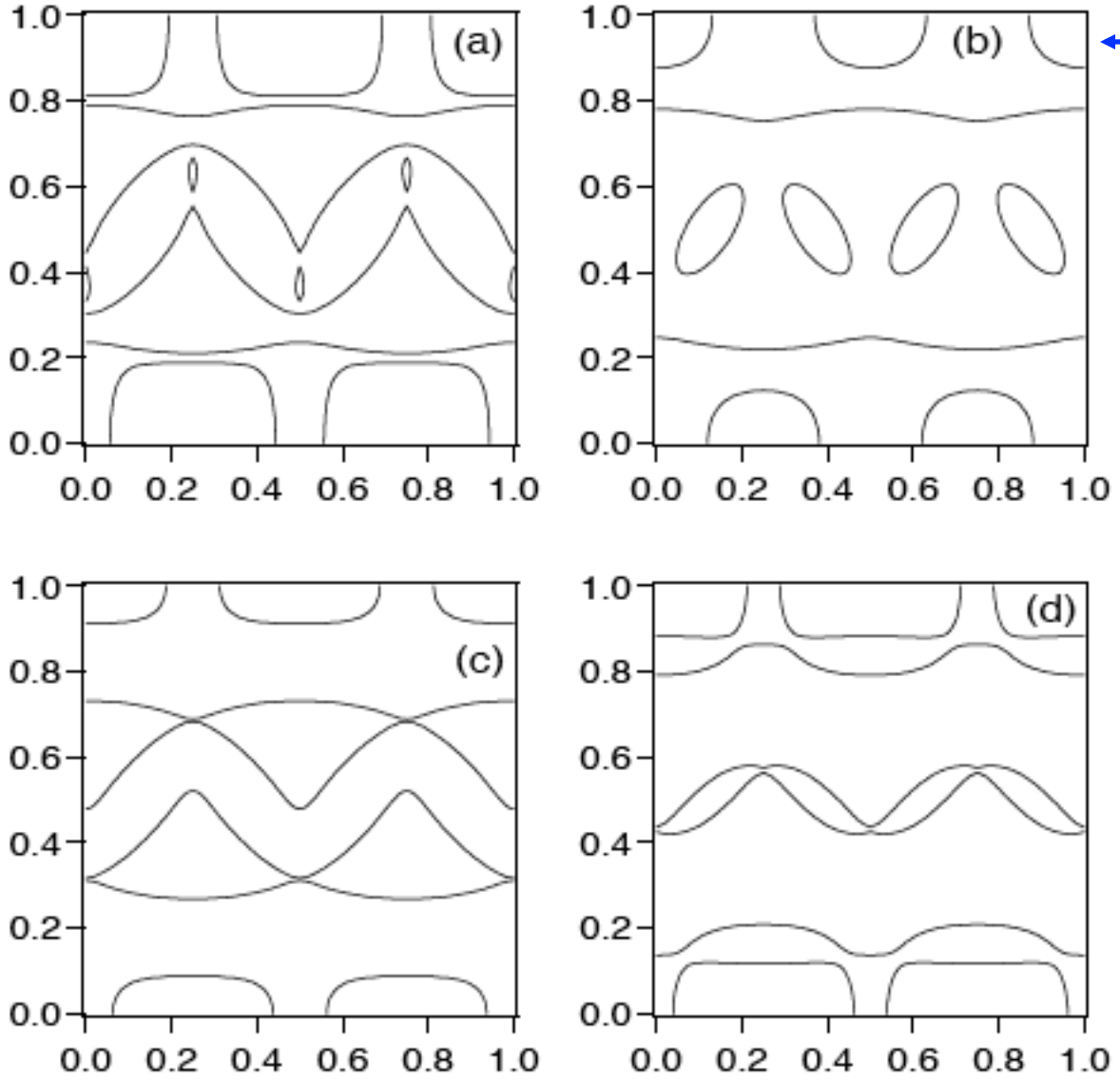
LeBoeuf *et al.*, PRB (2011)

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

Charge peaks at (±2x,0), Spin peaks at (1/2±x,1/2), x~1/8



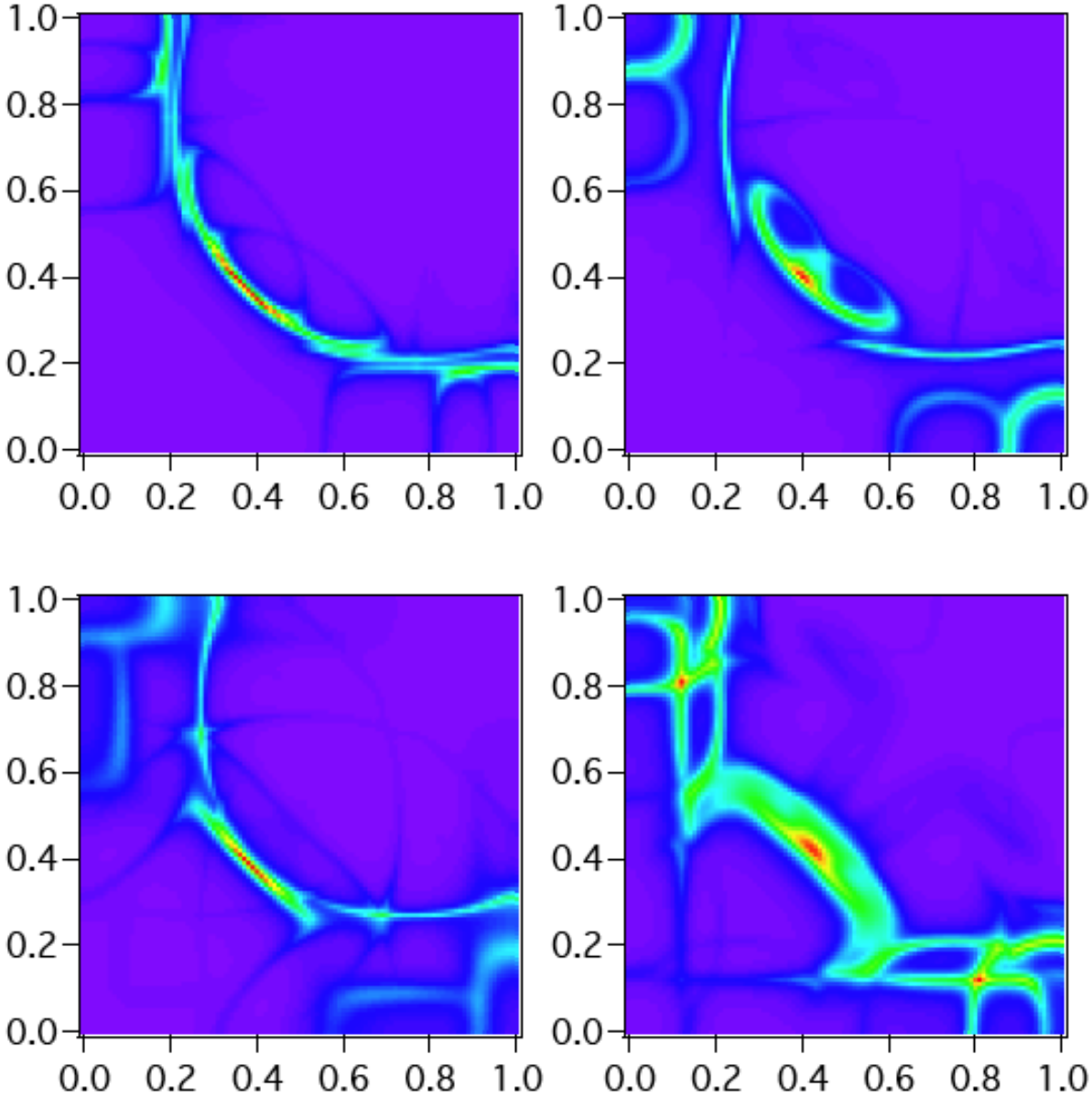
For magnetic stripes, electron pockets are stable for a range of potentials



← e^- pocket

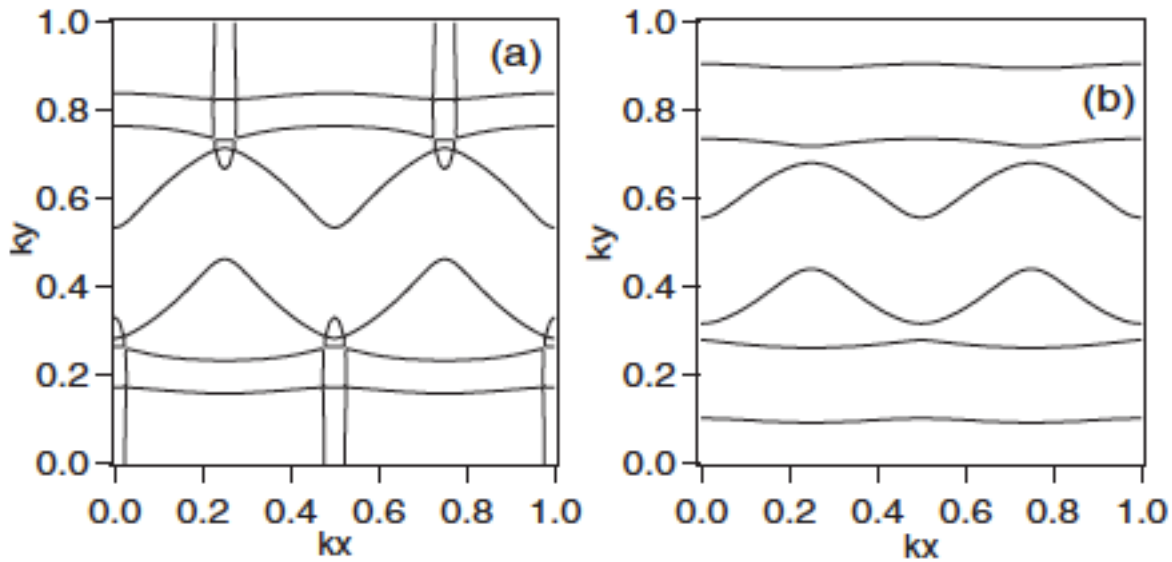
Millis & Norman, PRB (2007)

Are electron pockets consistent with photoemission?



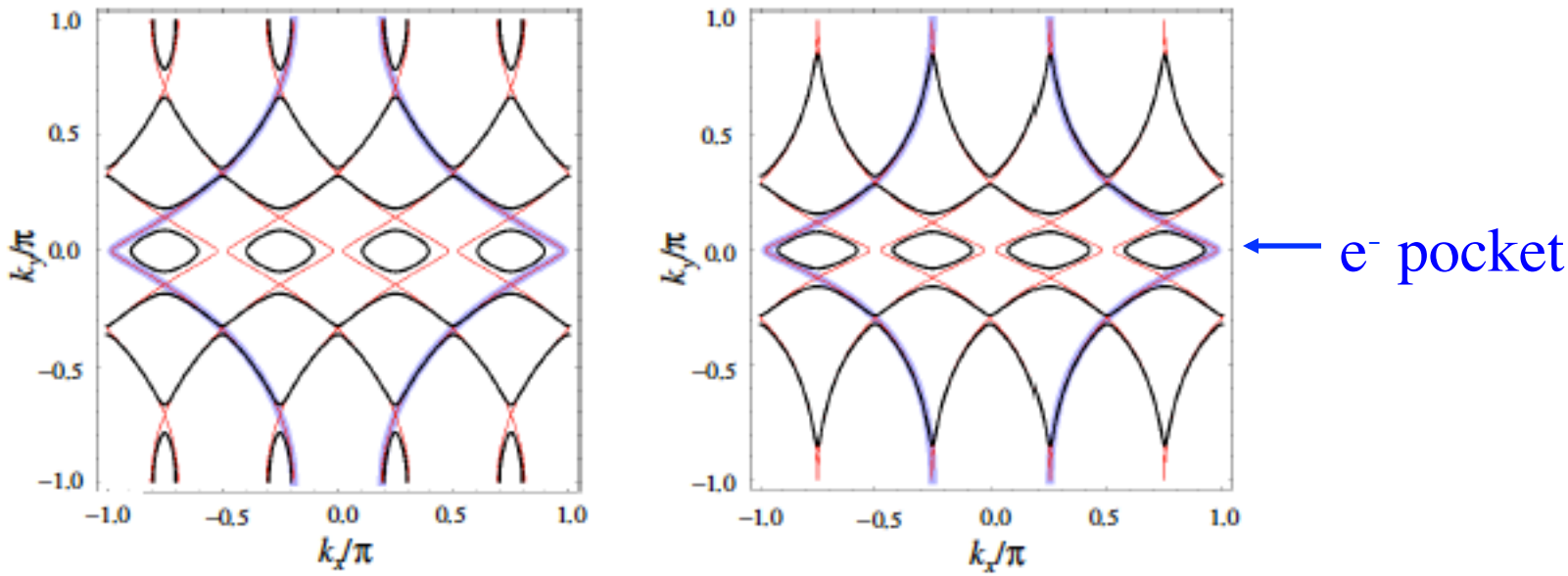
www.aps.org (2009)

For charge only stripes, there are no pockets!



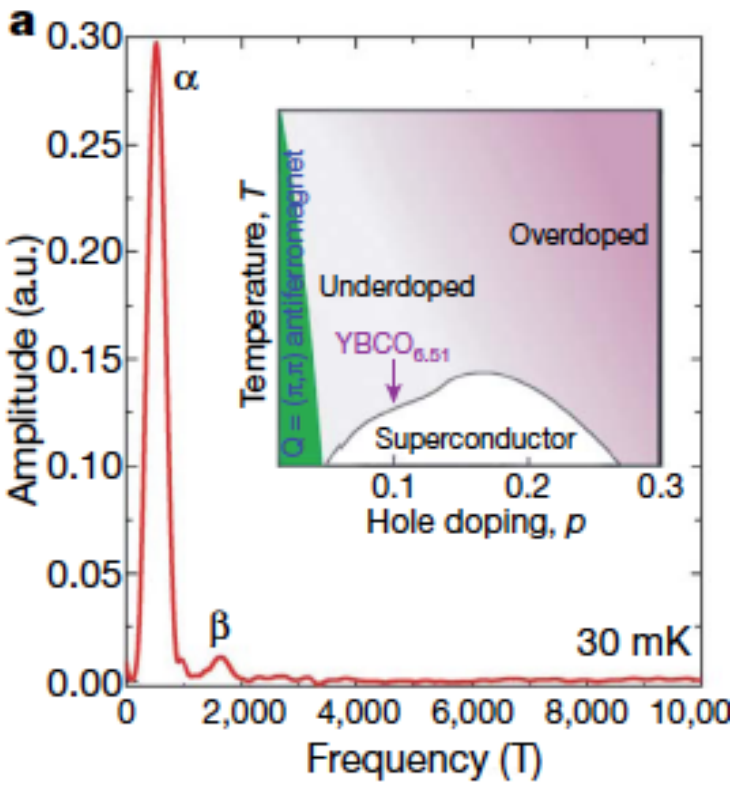
Millis & Norman, PRB (2007)

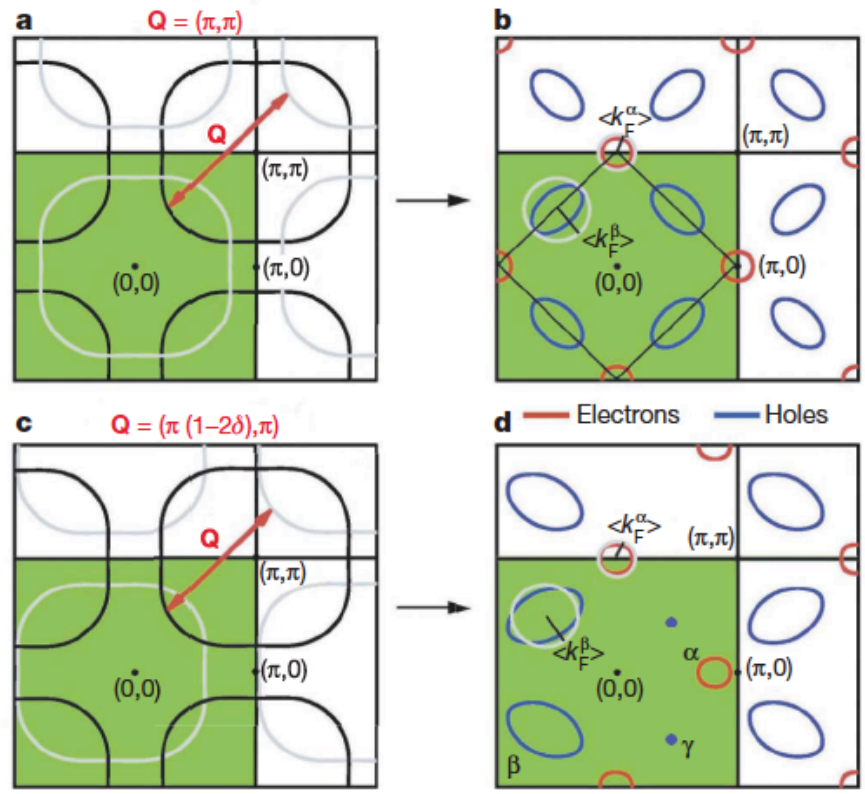
Though strong nematicity can stabilize them



Yao, Lee, & Kivelson, PRB (2011)

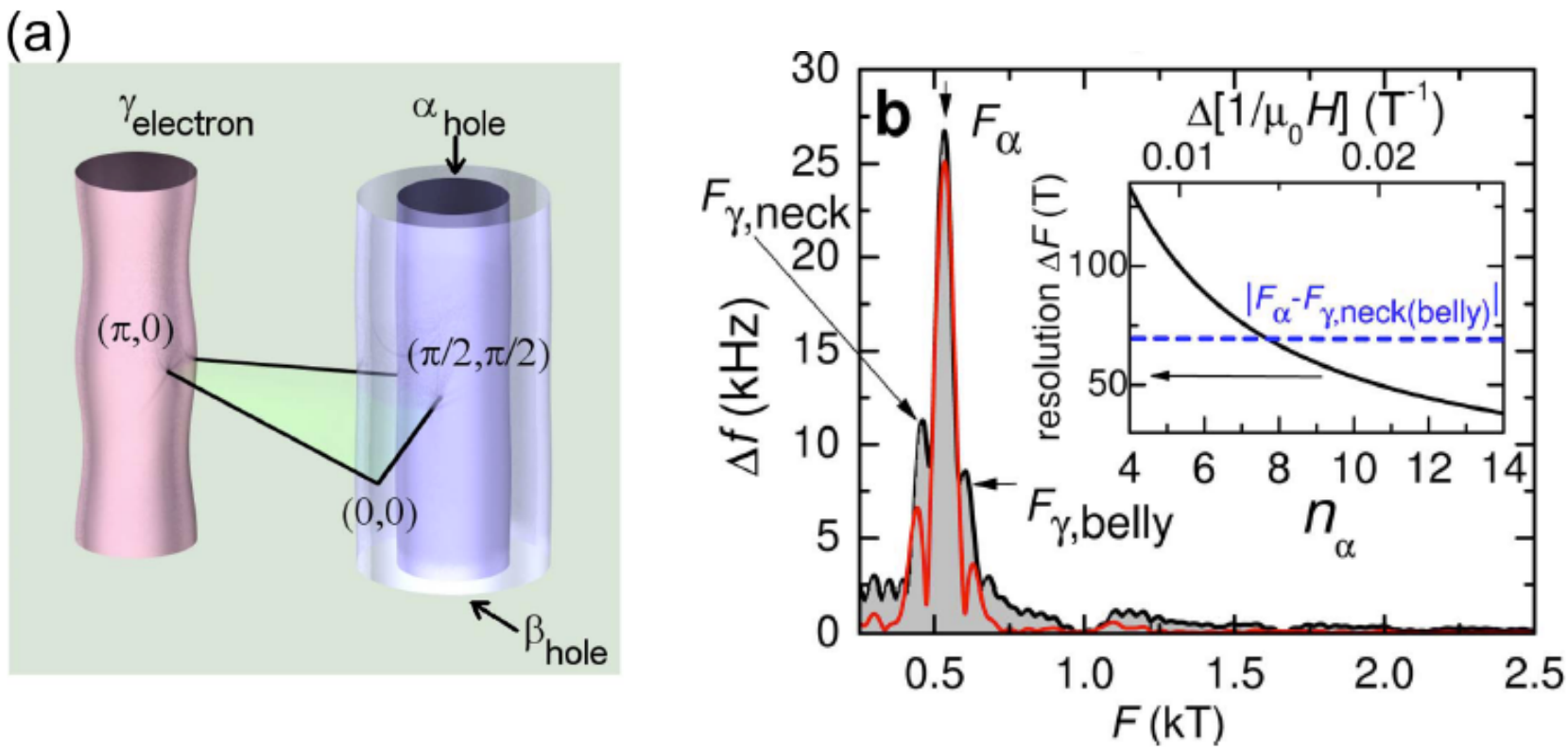
A larger hole Fermi surface (β) from a spin spiral state?





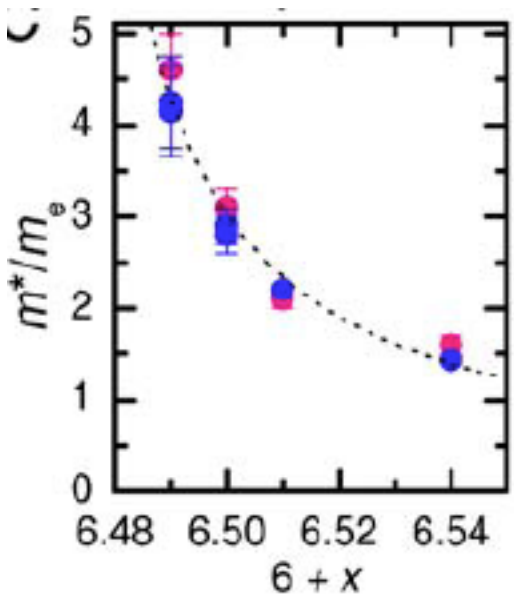
Sebastian *et al.*, Nature (2008)

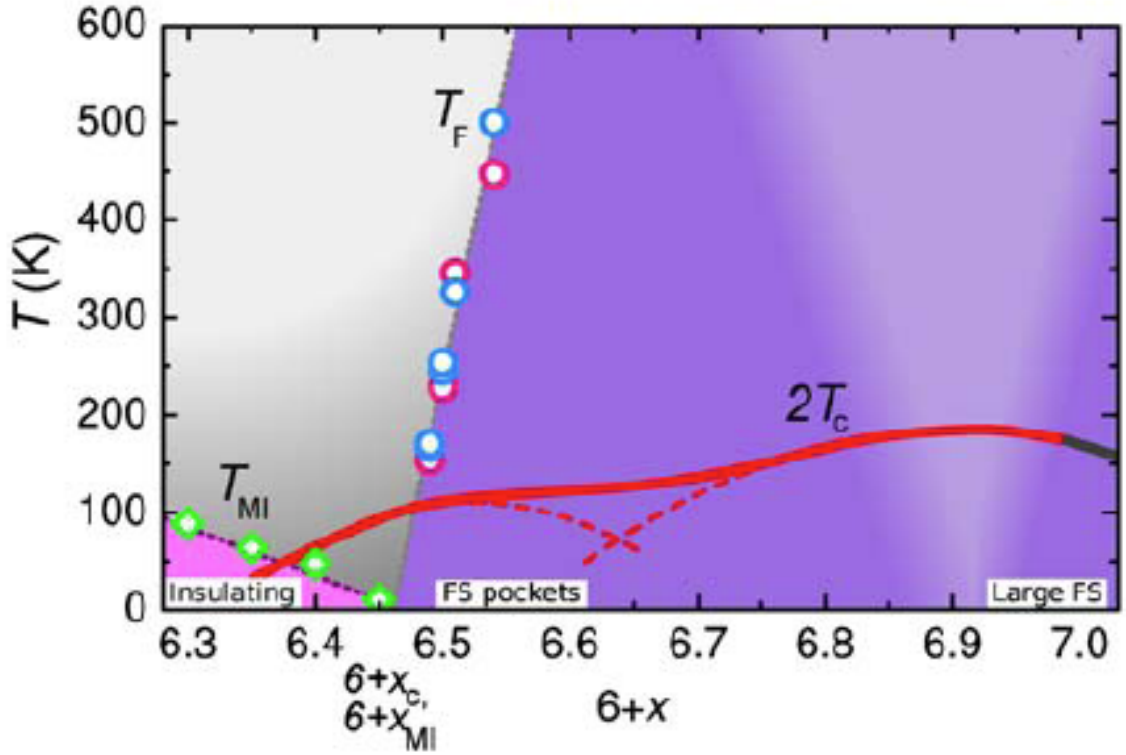
Small electron (warped cylinder), small hole (unwarped cylinder), and larger hole Fermi surfaces?



Sebastian *et al.*, PRB (2010)

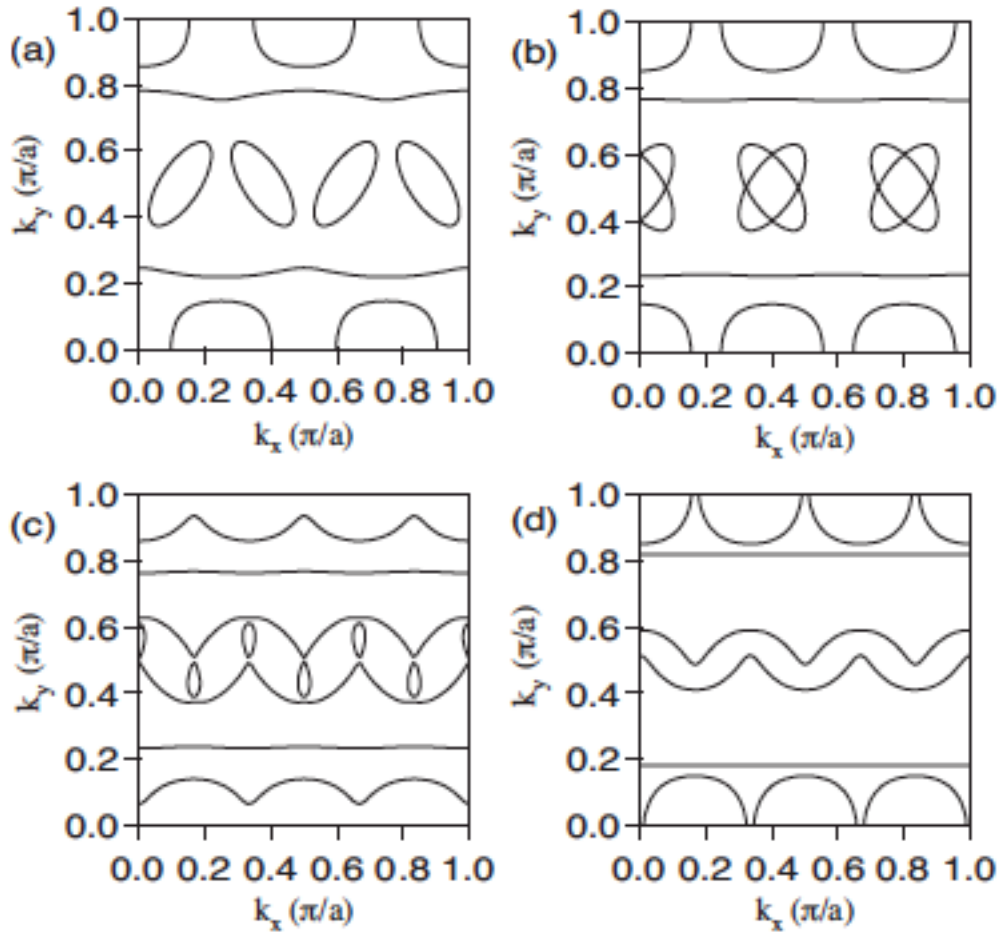
Divergence of cyclotron mass near x=0.09 (exciton instability)?

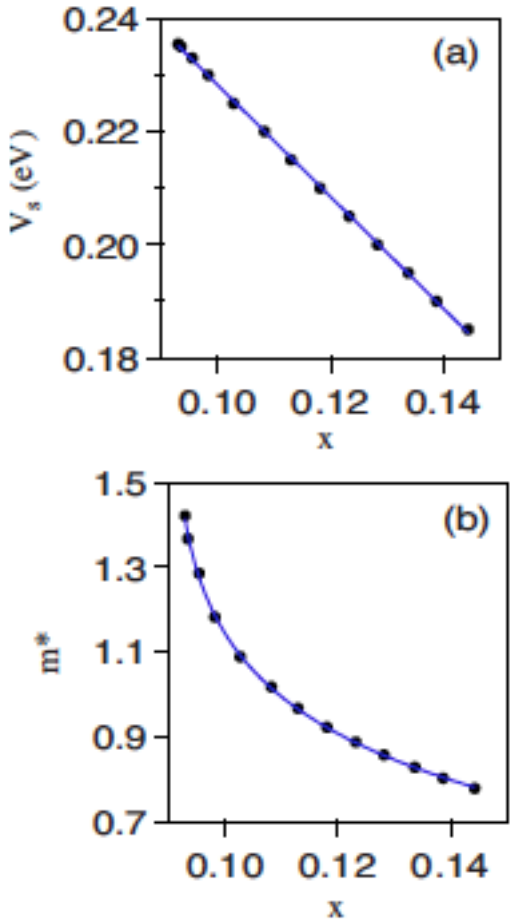




Sebastian *et al*., PNAS (2010)

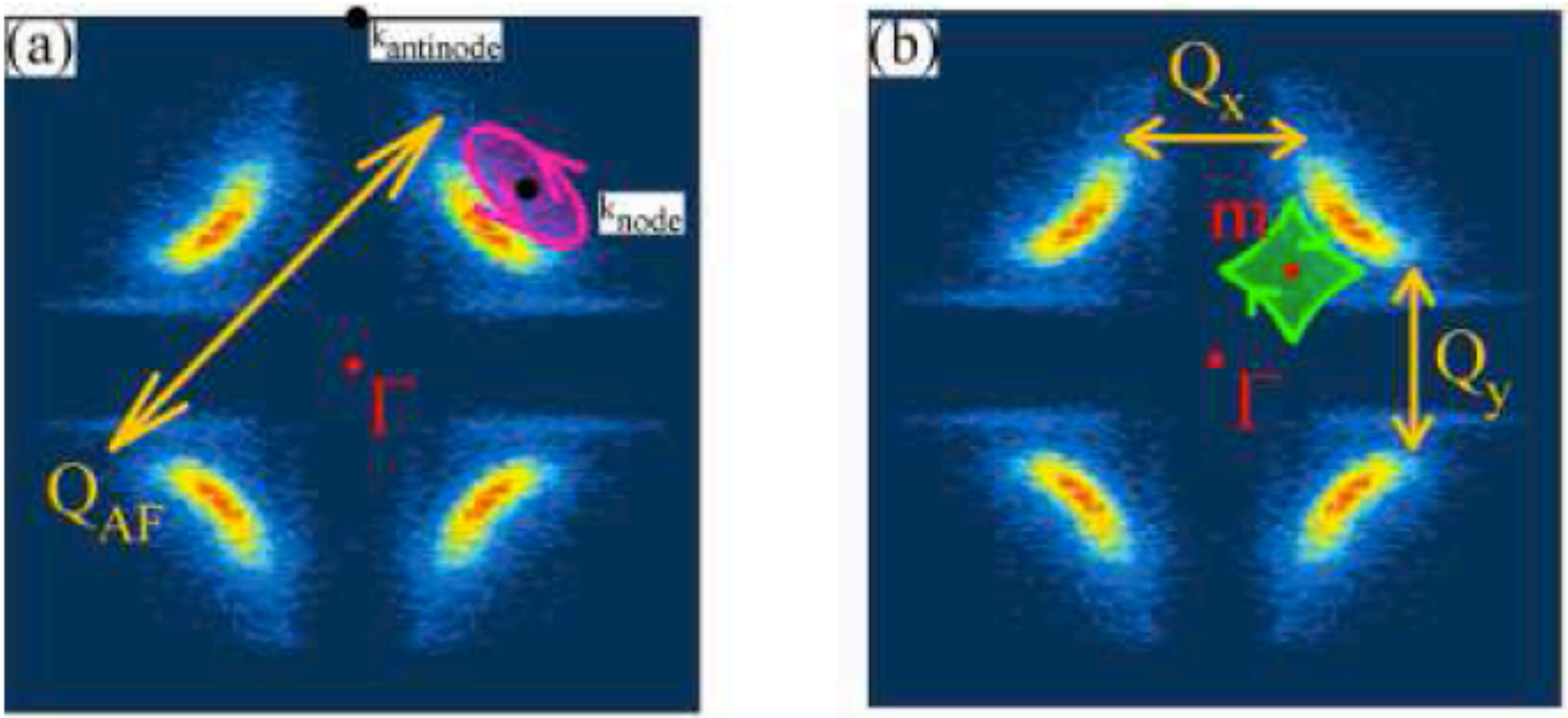
Lifshitz Transition (electron pockets touch) near x=0.09?





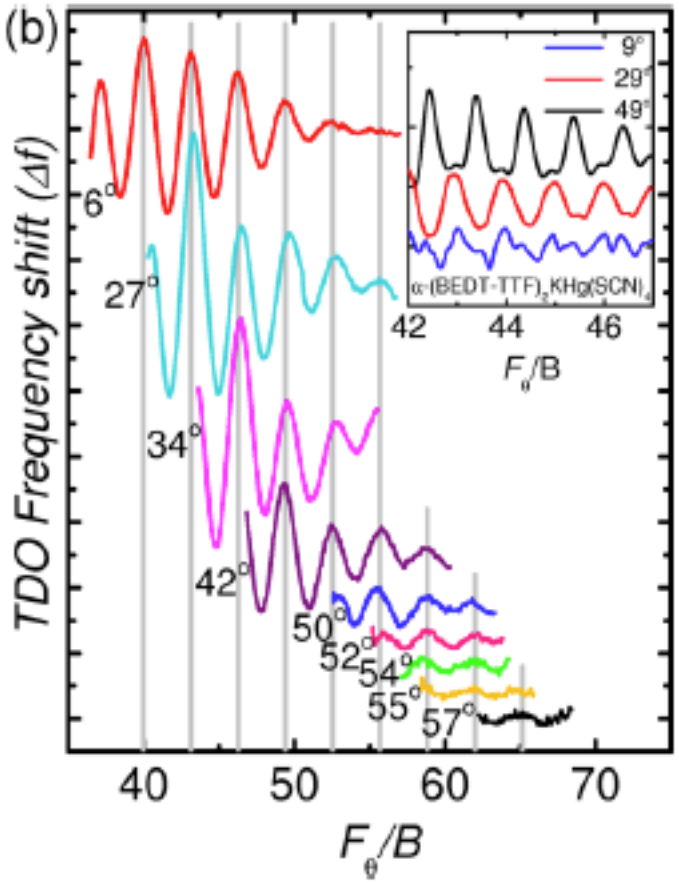
Norman, Lin, & Millis, PRB (2010)

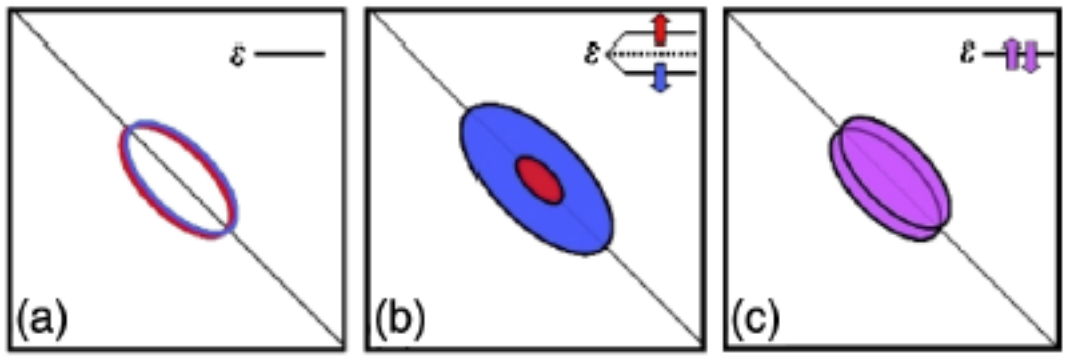
Electron pocket near the node due to checkerboard charge order?



Harrison & Sebastian, PRL (2011)

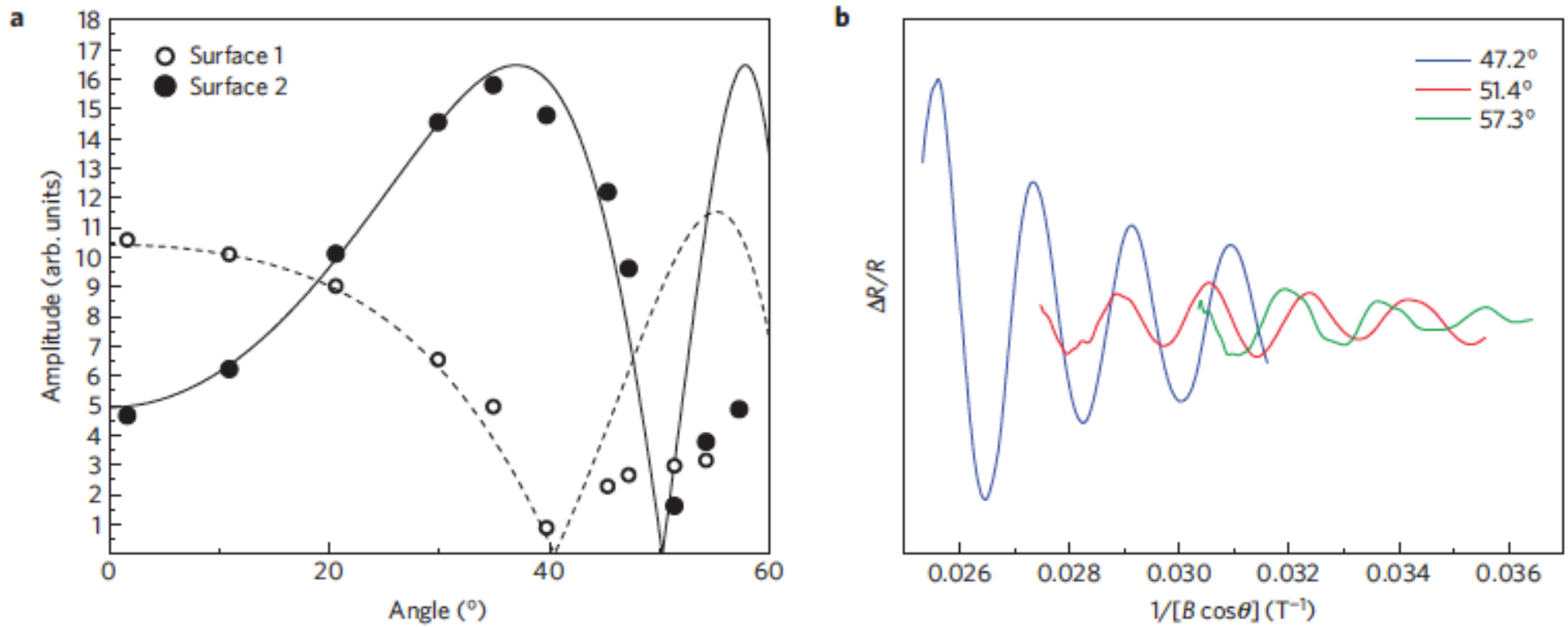
Quenched Zeeman splitting?
(no spin zeros)





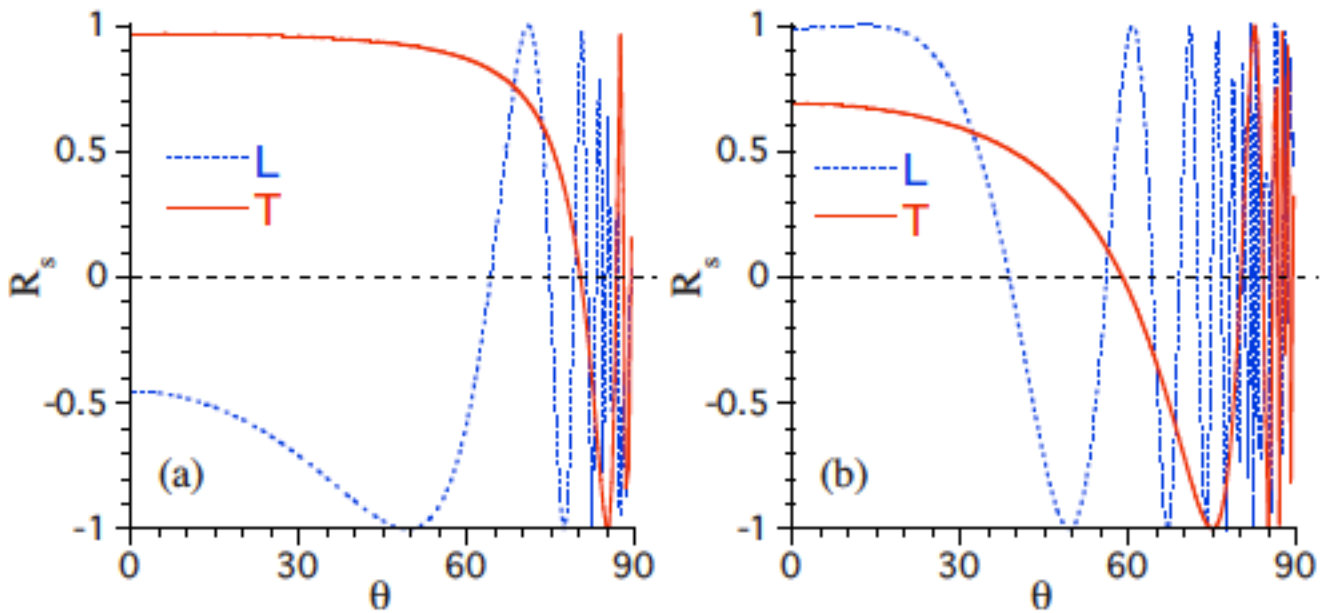
Sebastian *et al.*, PRL (2009)

Full Zeeman splitting?



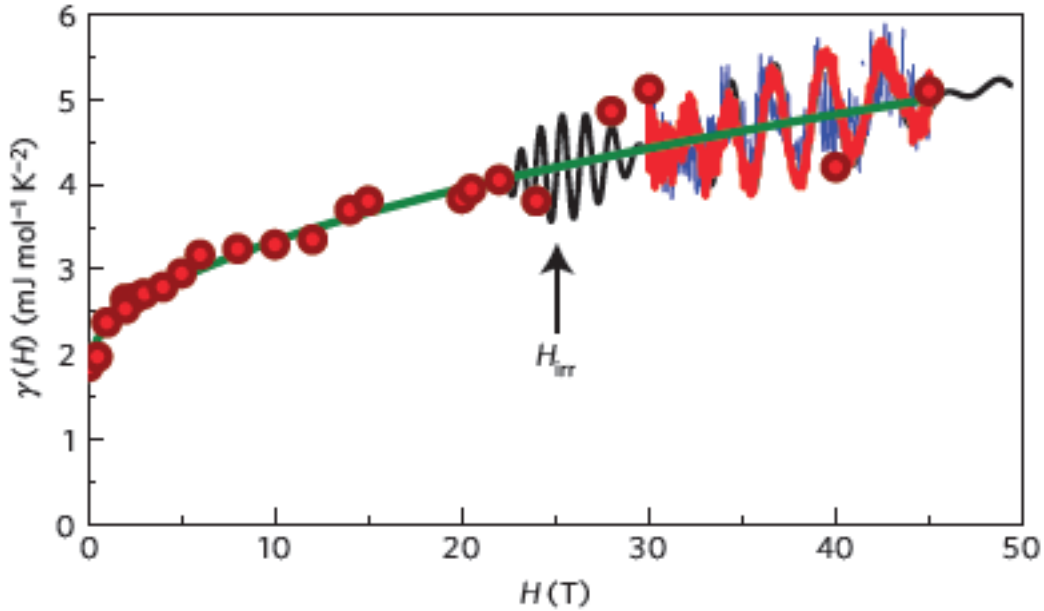
Ramshaw *et al.*, Nat. Phys. (2011)

Longitudinal (L) SDW versus transverse (T) SDW



Norman & Lin, PRB (2010)
following Ramazashvili, PRL (2010)

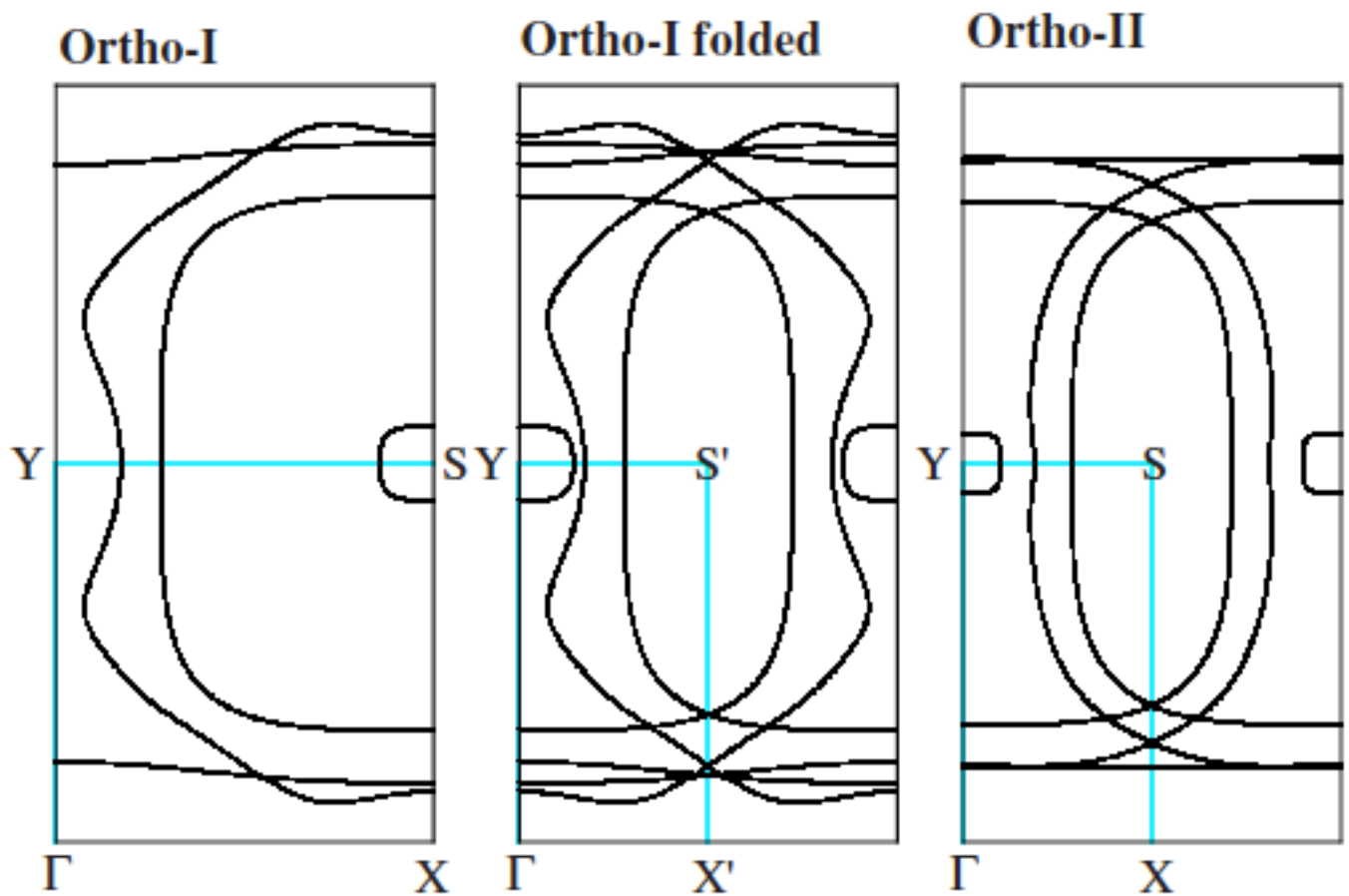
Quantum oscillations in the specific heat



1. $\sqrt{H}$ dependence all the way into the oscillatory region
2. $\gamma(H=0)$ = oscillatory part of γ = one pocket/zone/bilayer

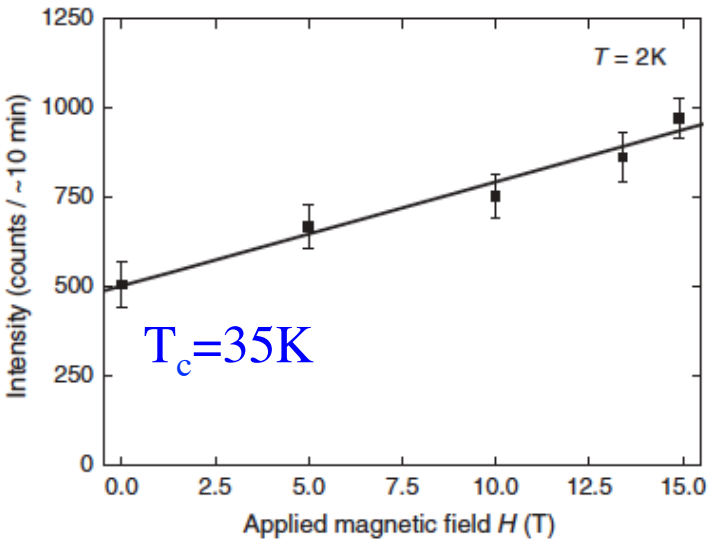
Riggs *et al.*, Nature Phys. (2011)

A pocket is found by band theory near the S/Y points for YBCO (Ortho-I and II), but NOT for Y124

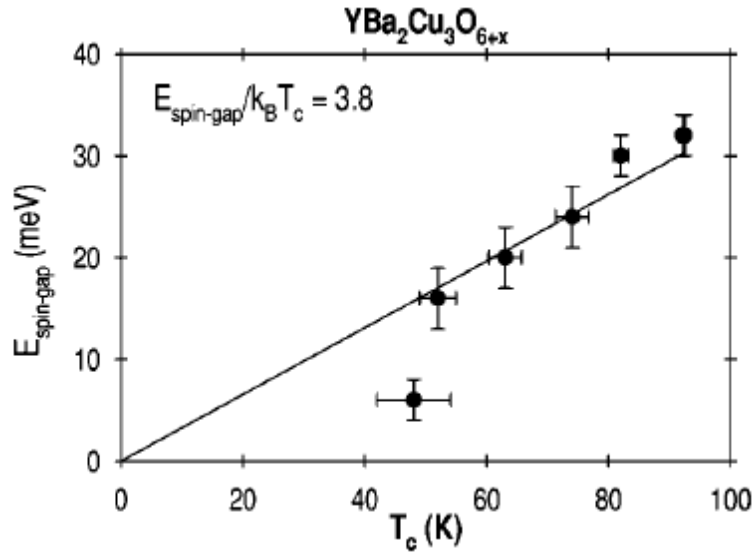


Carrington & Yelland, PRB (2007)

Field induced spin density wave in YBCO?

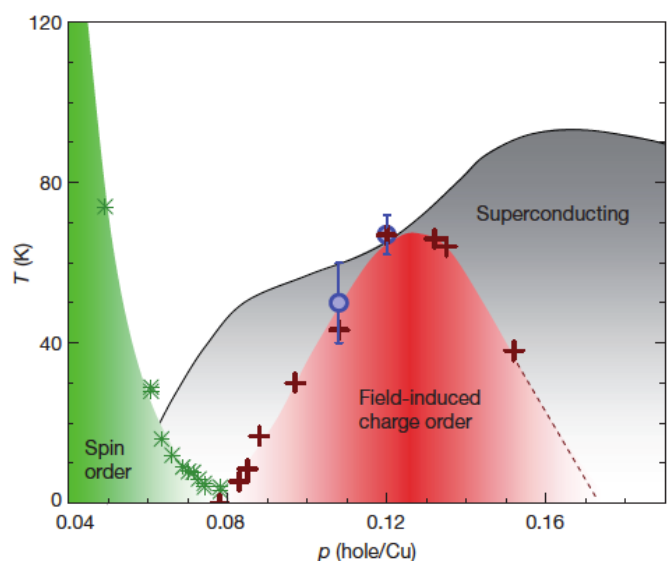


Haug *et al.*, PRL (2009)



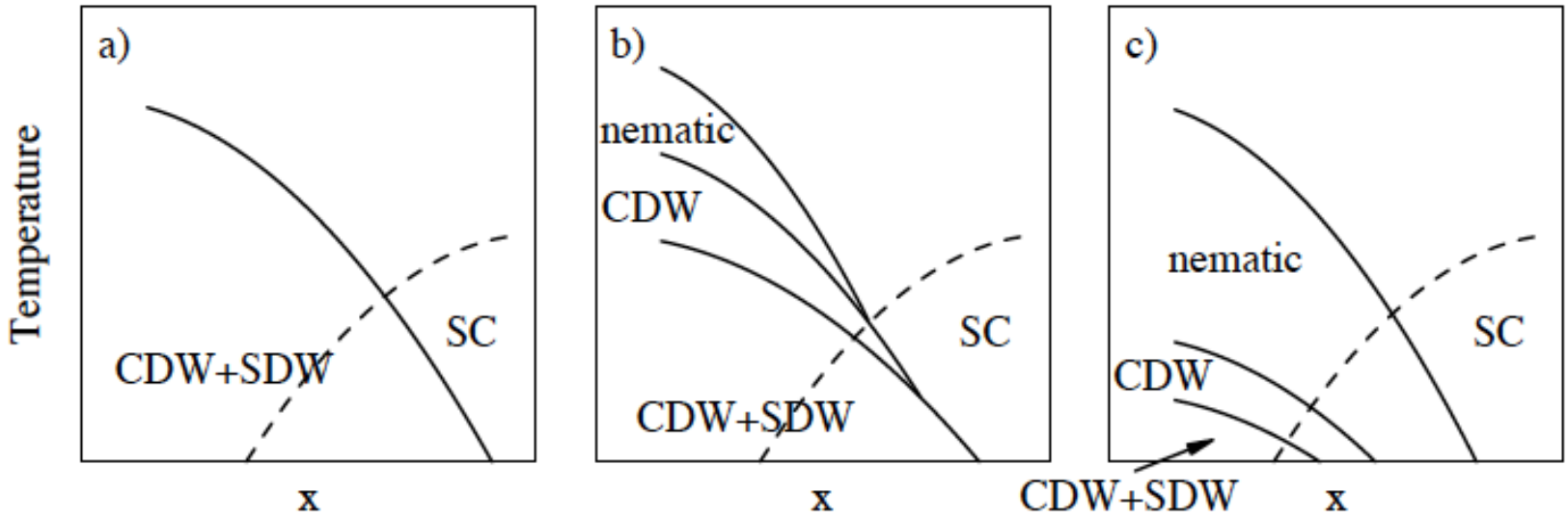
Dai *et al.*, PRB (2001)

Field induced CDW in YBCO?



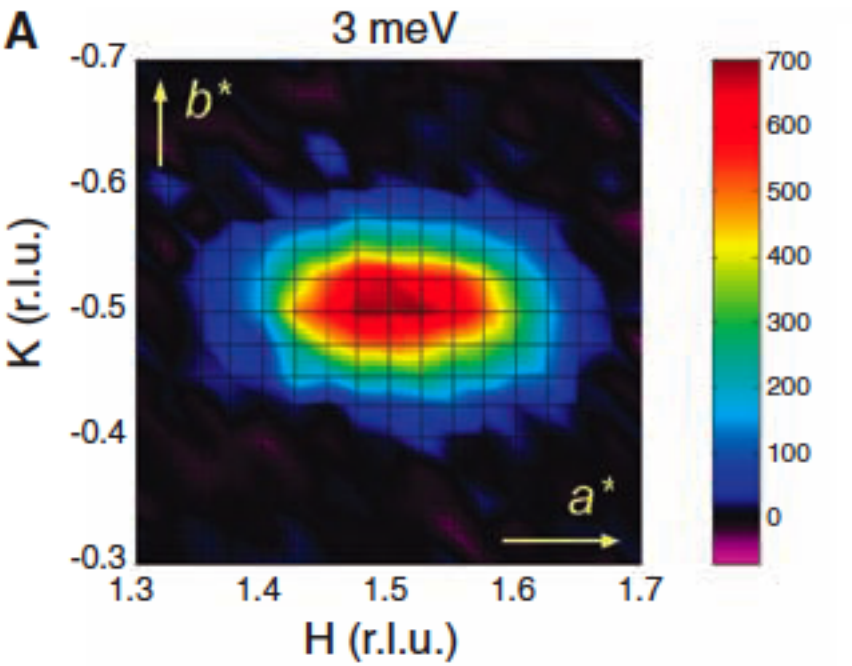
Wu *et al.*, Nature (2011)

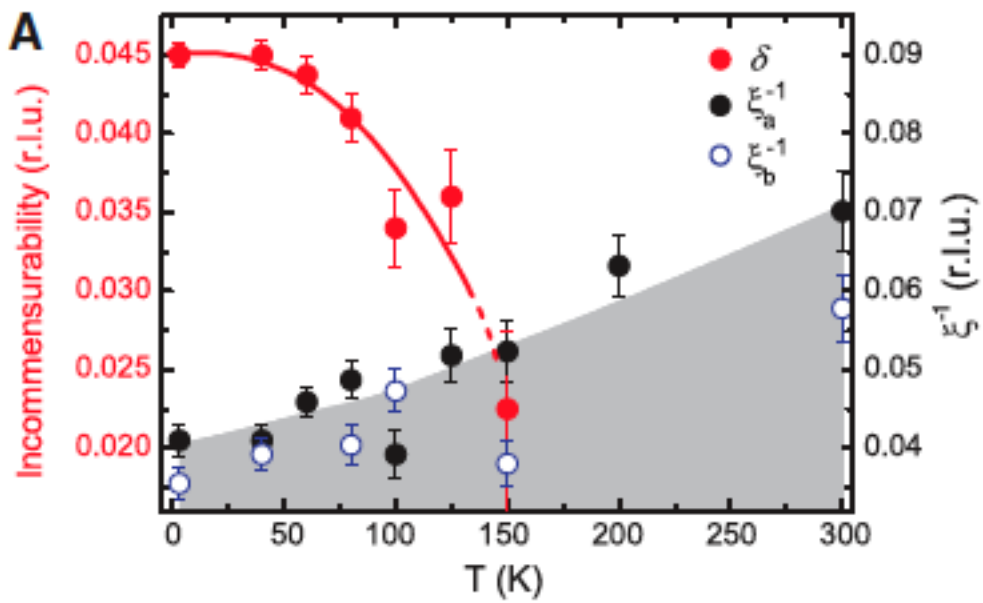
Is the Pseudogap a Nematic Phase?



Vojta, Adv. Phys. (2009)

Nematic Spin Response below T* (a ≠ b)

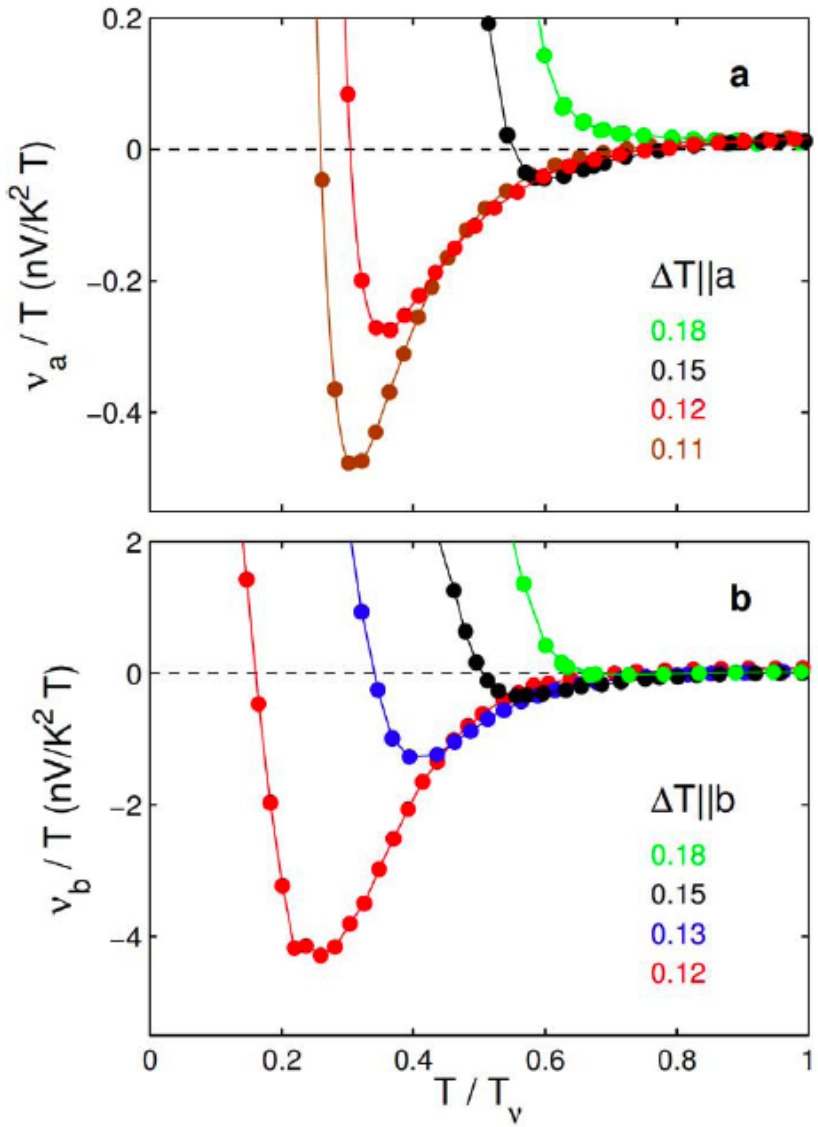


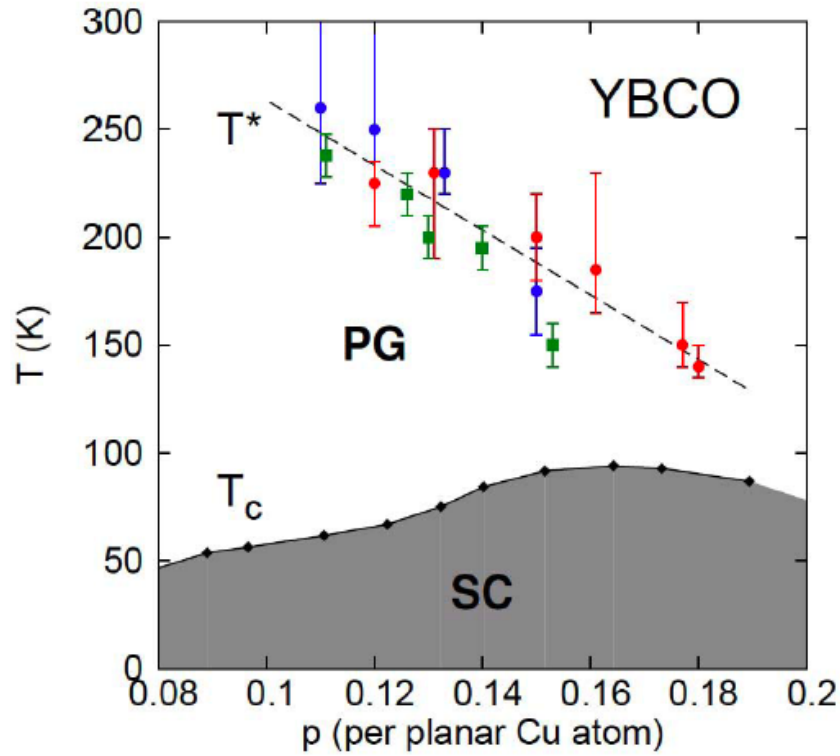


T_c=35K

Hinkov *et al.*, Science (2008)

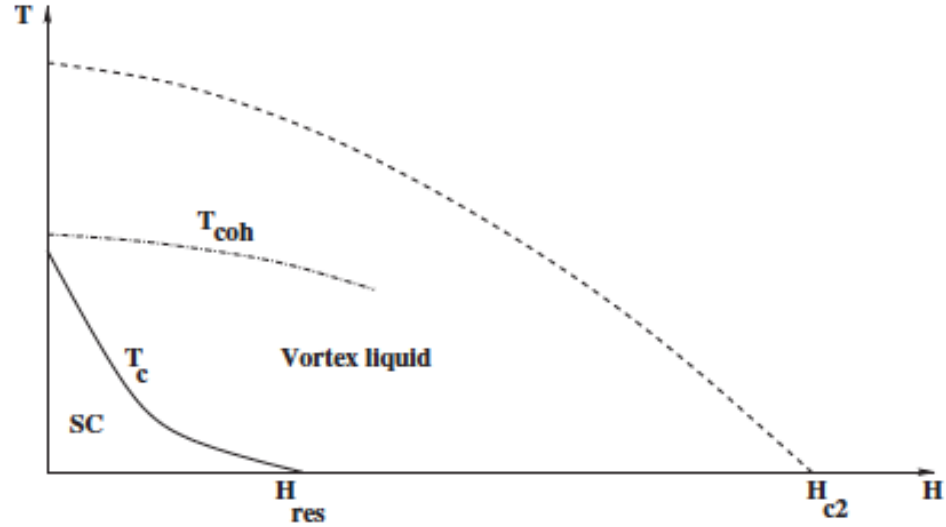
Anisotropic Nernst Signal below T* (a ≠ b)

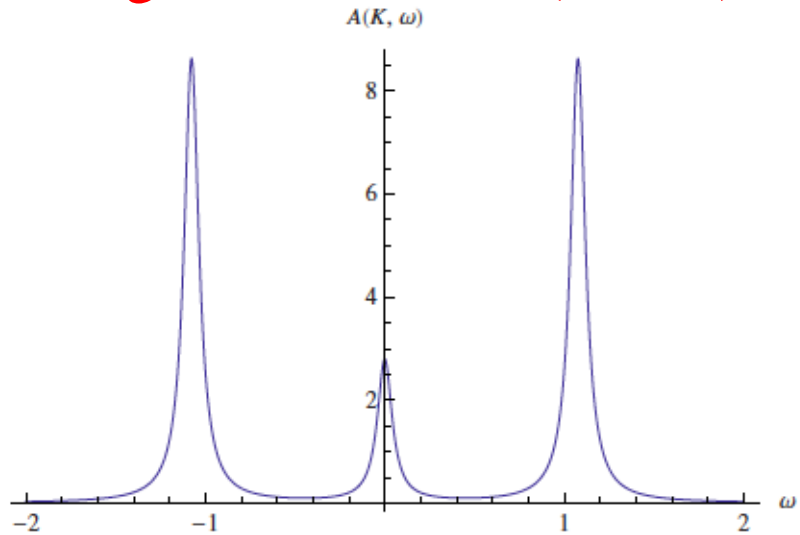


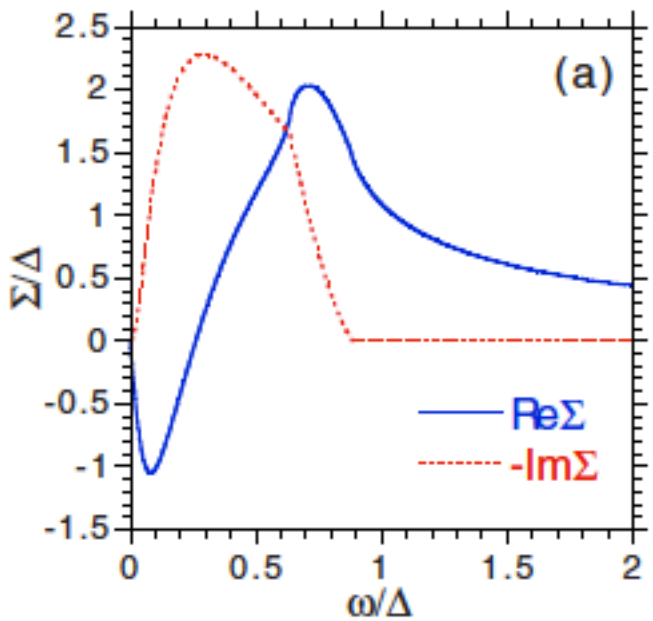


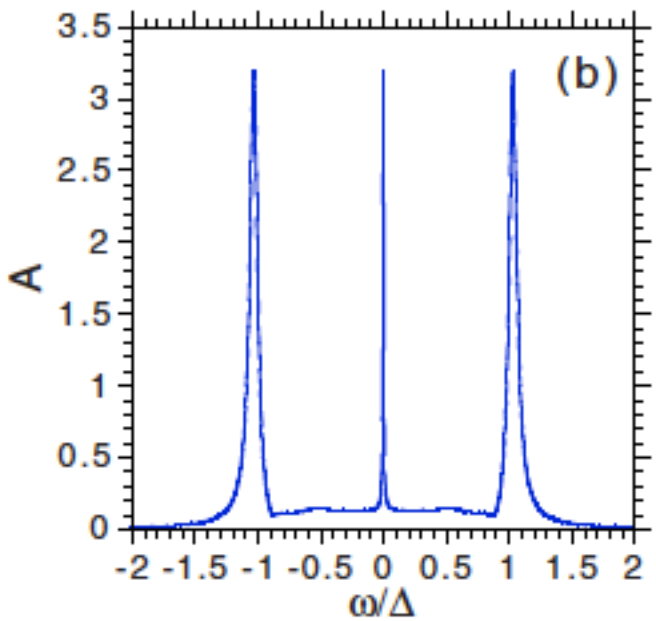
Daou *et al.*, Nature (2010)

Contrasting Low Field/High T (ARPES) & High Field/Low T (dHvA)



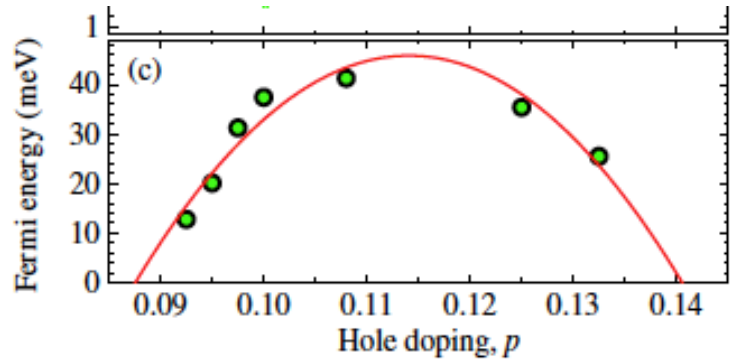






Senthil & Lee, PRB (2009); Micklitz & Norman, PRB (2009)

QUESTIONS



Singleton *et al.*, PRL (2010)

1. What happens for x < 0.09?
2. What happens for x > 0.14?
3. Are the oscillations above the upper critical field?
4. Are electron pockets consistent with ARPES and STM?
5. Is the pseudogap really due to nematic order?
6. What does all of this have to say about the origin of high T_c?