The Abdus Salam
International Centre
for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2357-7

Innovations in Strongly Correlated Electronic Systems: School and Workshop

6 - 17 August 2012

Arcs versus Pockets to d-wave or not to d-wave, that is the question

Mike NORMAN

Materials Science Division, Argonne National Laboratory &
Center for Emergent Superconductivity
Argonne
USA.

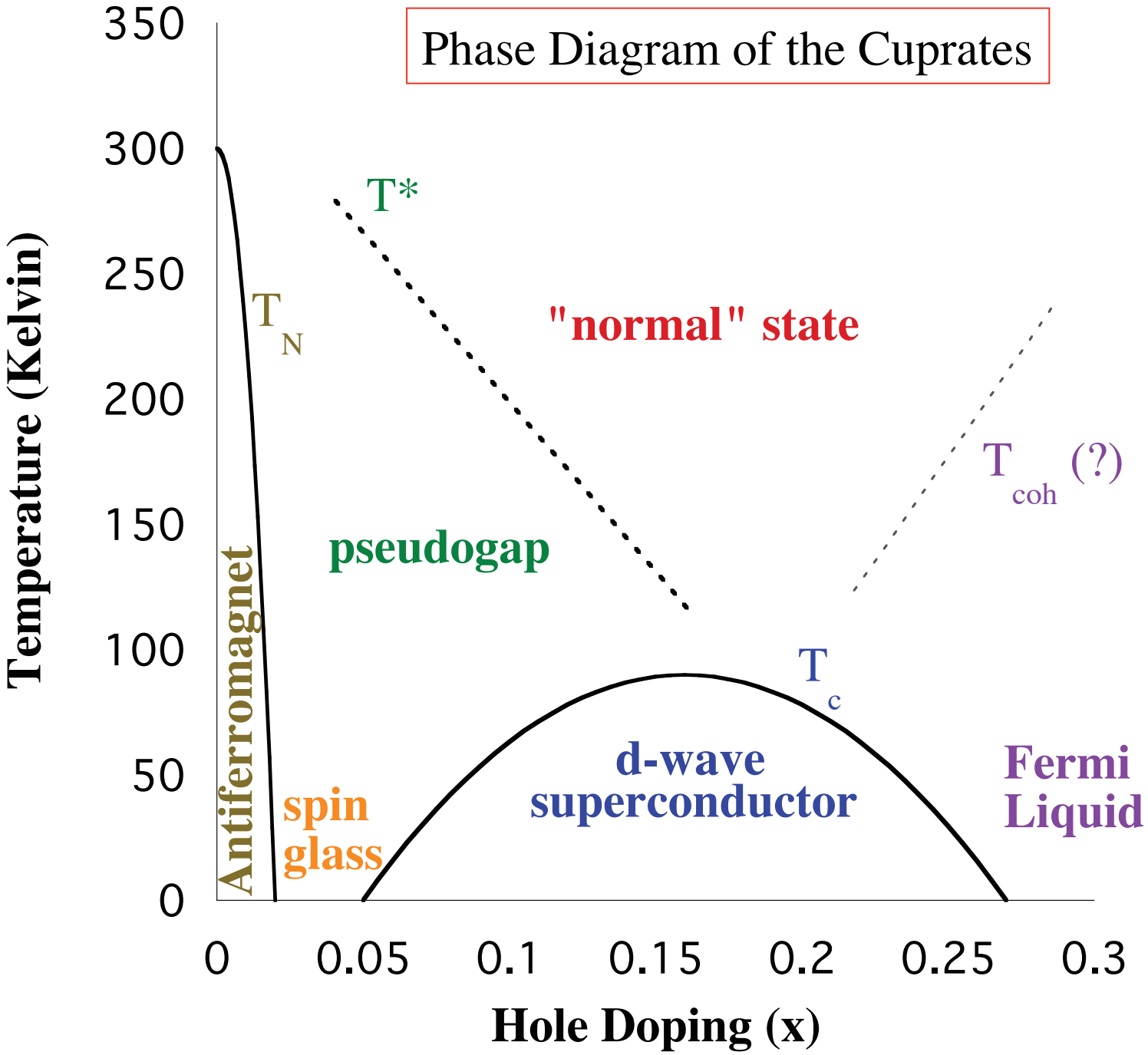
Strada Costiera, 11 - 34151 - Trieste - Italy • Tel. +39 0402240111 • Fax. +39 040224163 • sci_info@ictp.it • www.ictp.it
ICTP is governed by UNESCO, IAEA, and Italy, and it is a UNESCO Category 1 Institute

Arcs versus Pockets
To d-wave or not to d-wave, That is the question

Mike Norman

Materials Science Division
Argonne National Laboratory
&
Center for Emergent Superconductivity

Trieste – August 13, 2012

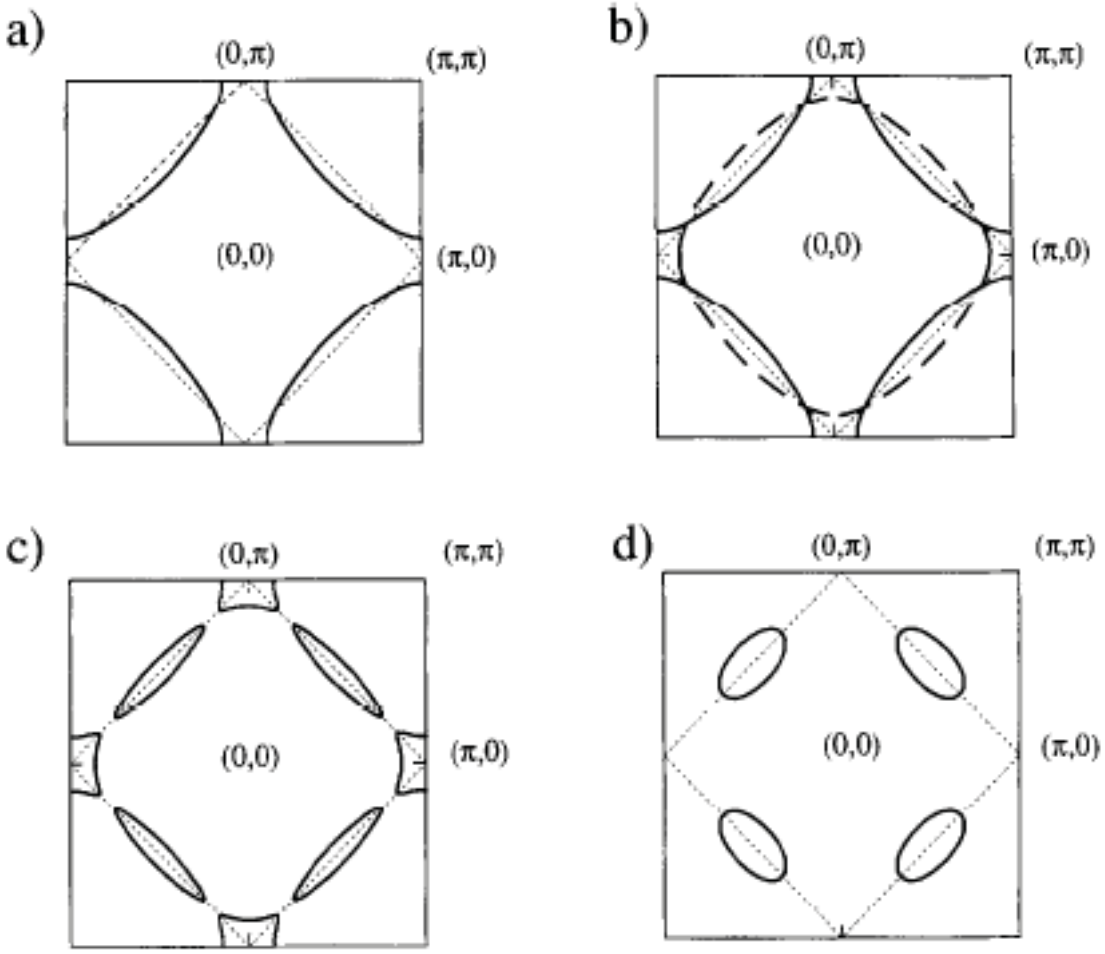

Phase Diagram of the Cuprates
Temperature (Kelvin)
350
300
250
200
150
100
50
0
0
0.05
0.1
0.15
0.2
0.25
0.3
Hole Doping (x)
T*
T N
"normal" state
T coh (?)
pseudogap
T c
Antiferromagnet
spin glass
d-wave superconductor
Fermi Liquid

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

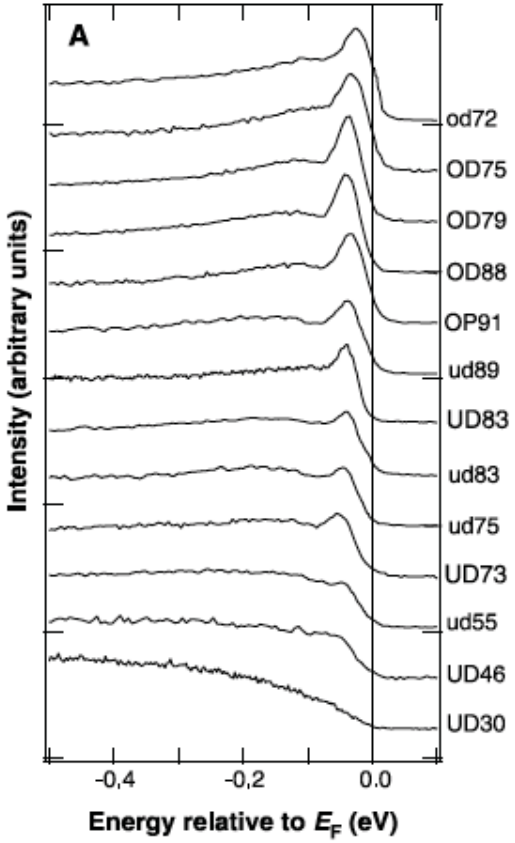
"Slater" approach - AF order causes small pockets around $(\pi/2, \pi/2)$ whose area scales like x, the number of doped holes

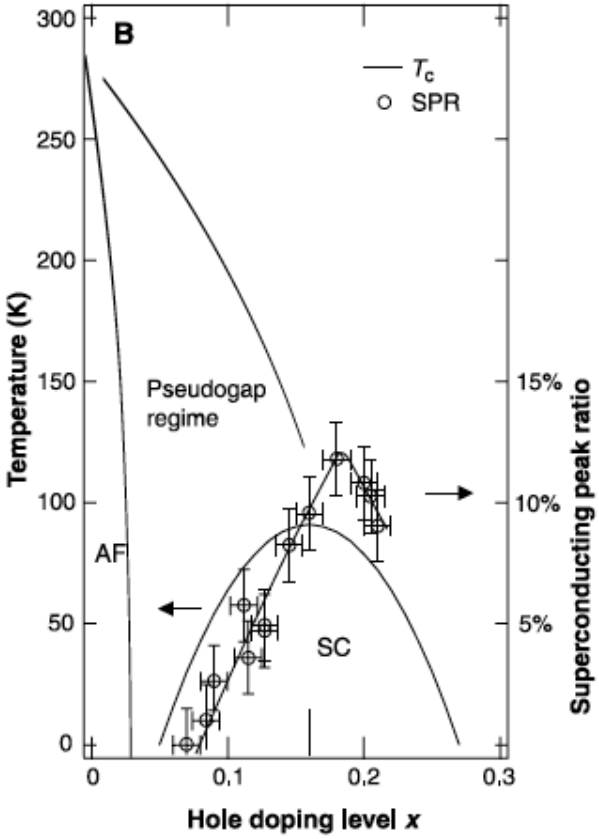


Chubukov & Morr
Phys. Reports (1997)

Doping a Mott Insulator - x versus 1+x

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

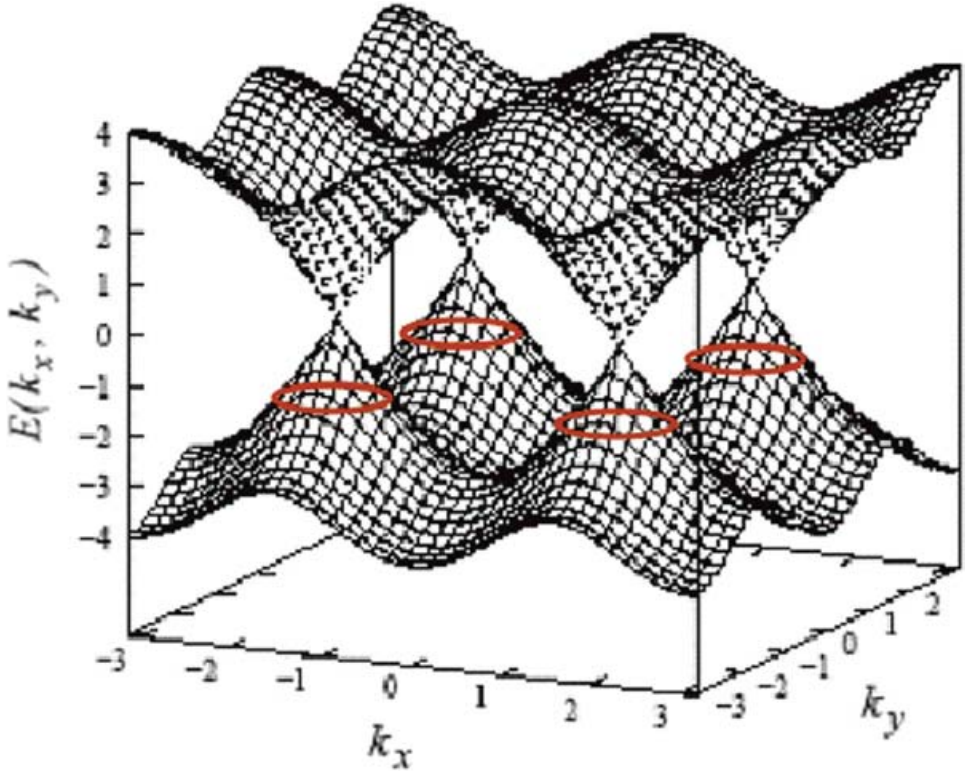




Feng *et al.*, Science (1999)

Doping a Mott Insulator - x versus 1+x

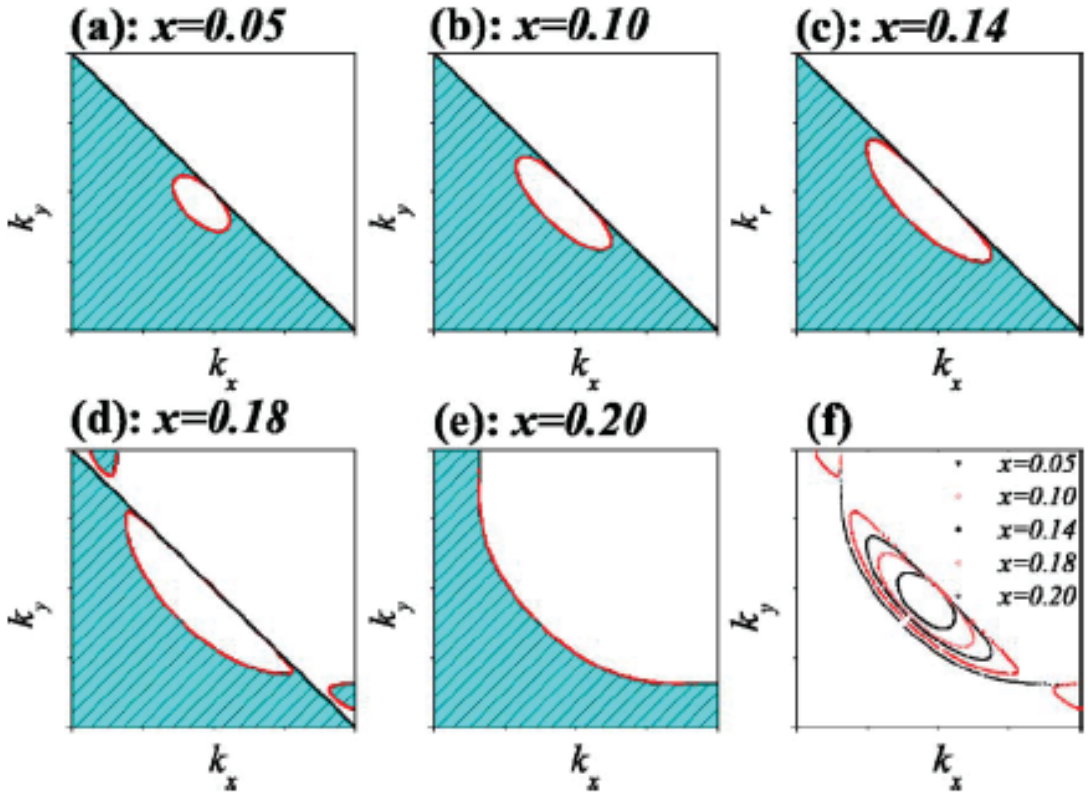
"flux phase" RVB approach (Lee)
small pockets originating from Dirac cones



Lee, Rep. Prog. Phys. (2008)

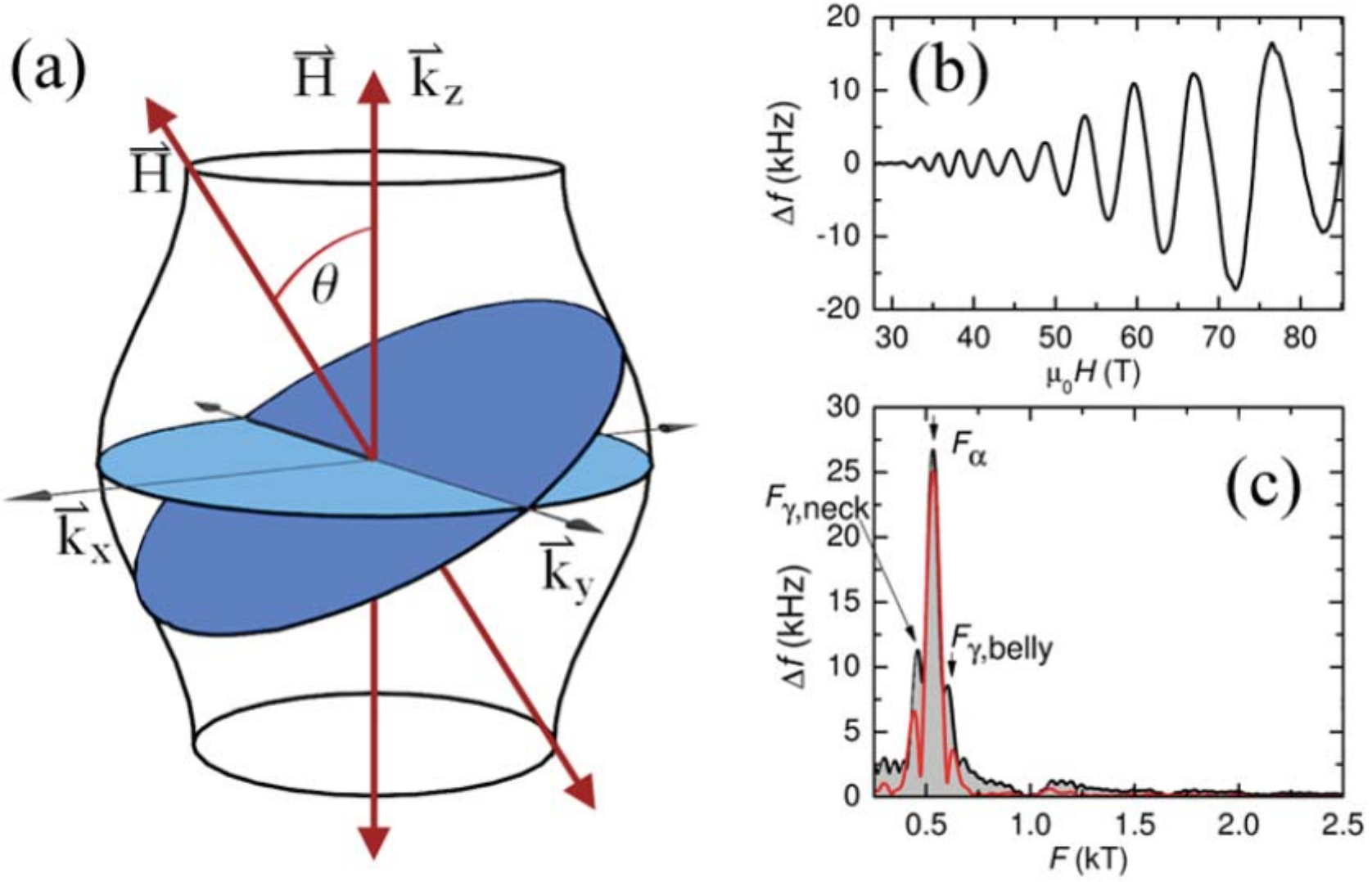
Doping a Mott Insulator - x versus 1+x

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



Yang, Rice, Zhang
PRB (2006)

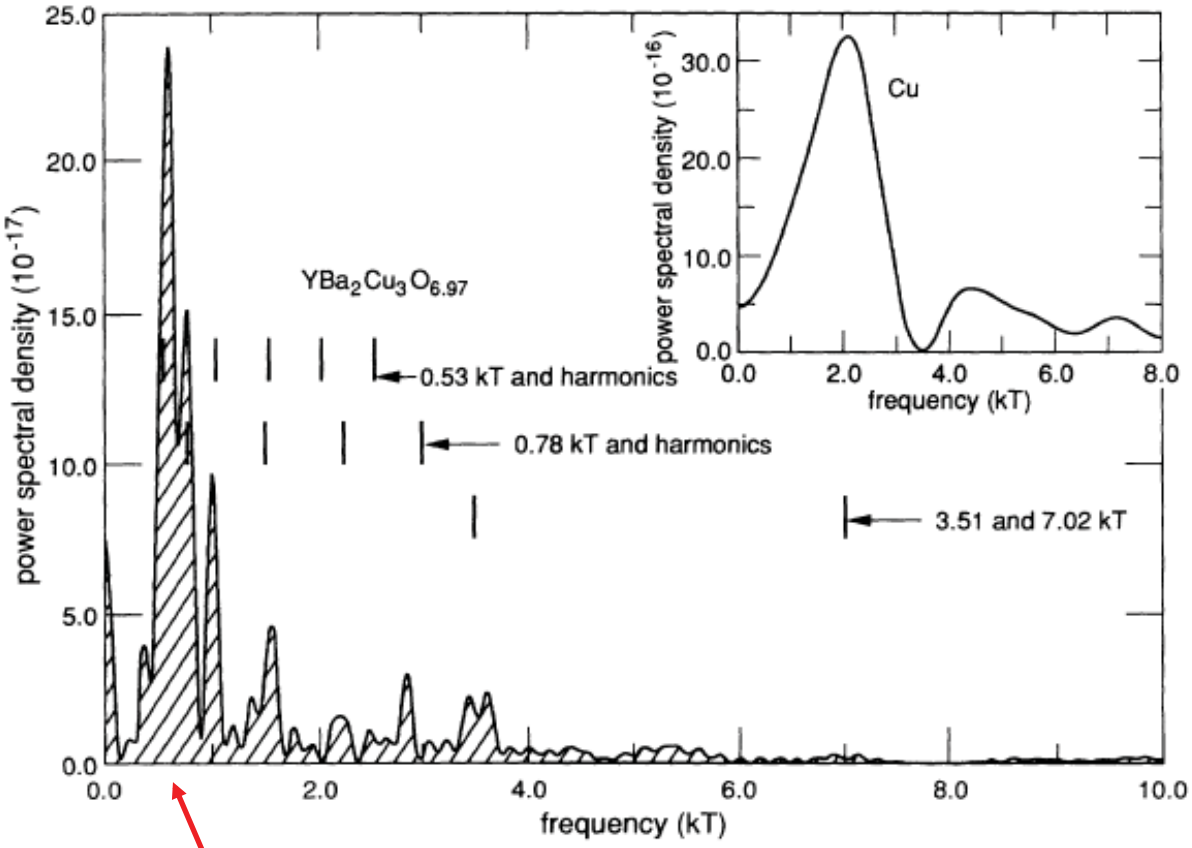
Quantum Oscillations (period determines area of extremal orbit)



(Brad Ramshaw)

Physics 3, 86 (2010)

Quantum Oscillations (the bad old days)

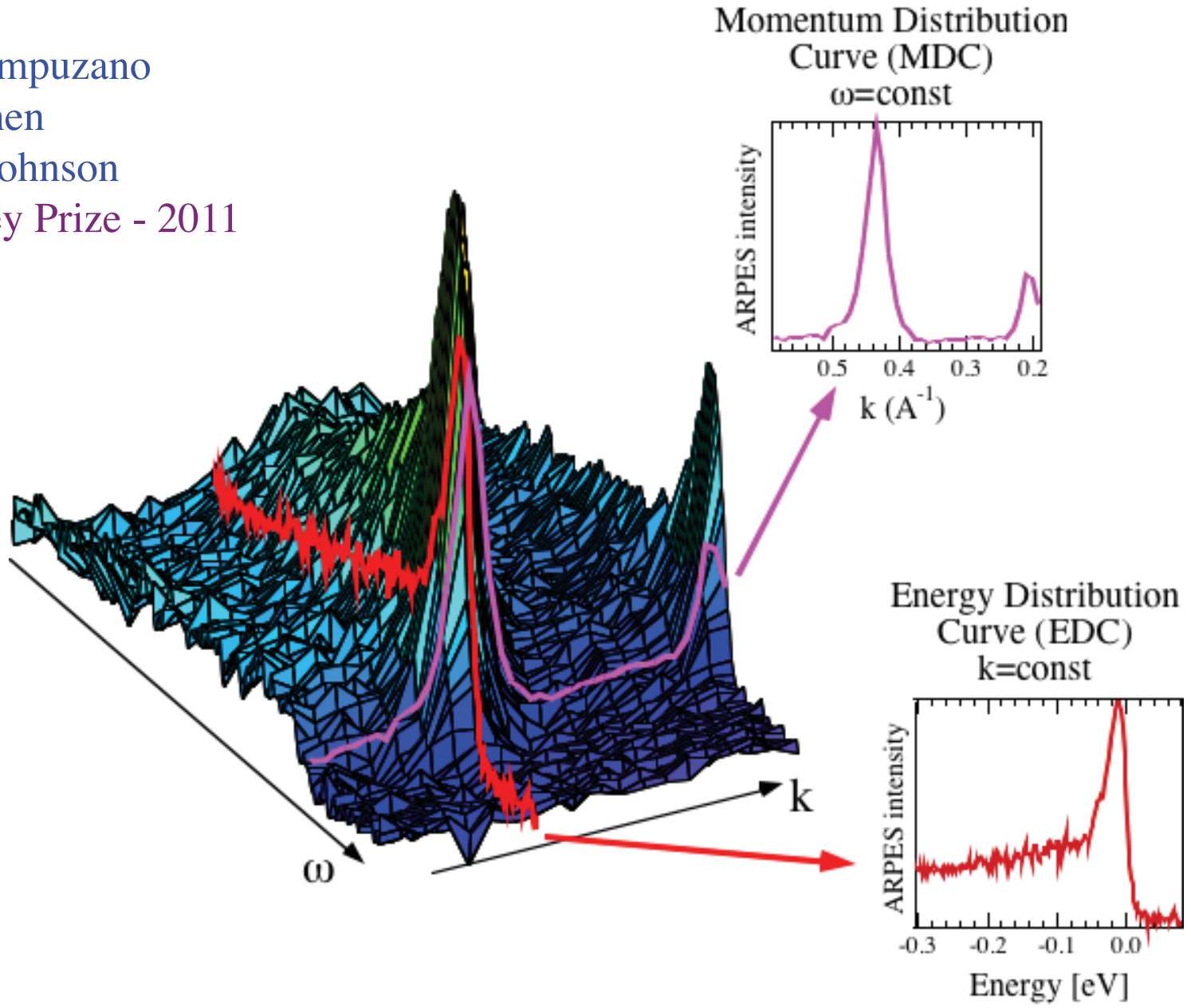


small Fermi surface!

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)

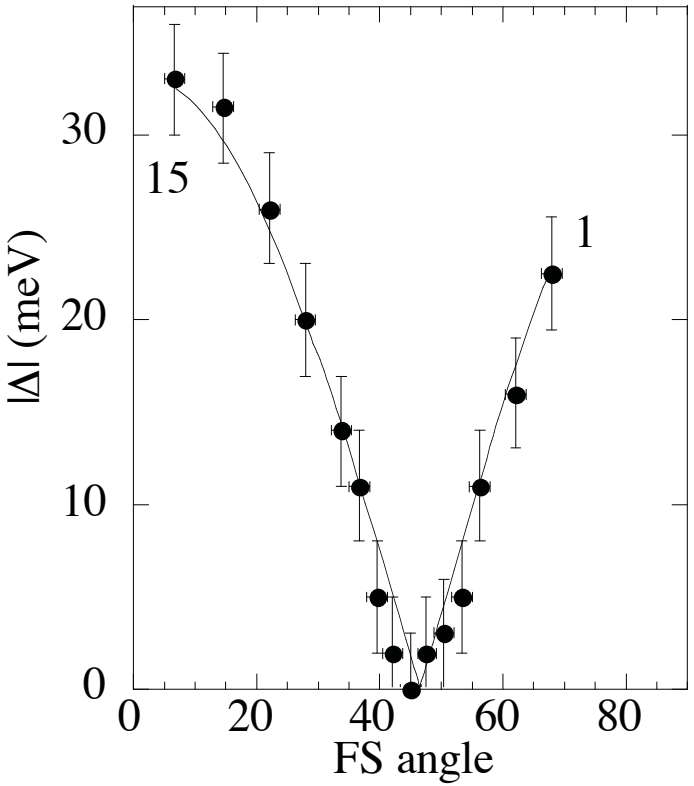
J C Campuzano
Z X Shen
Peter Johnson
Buckley Prize - 2011

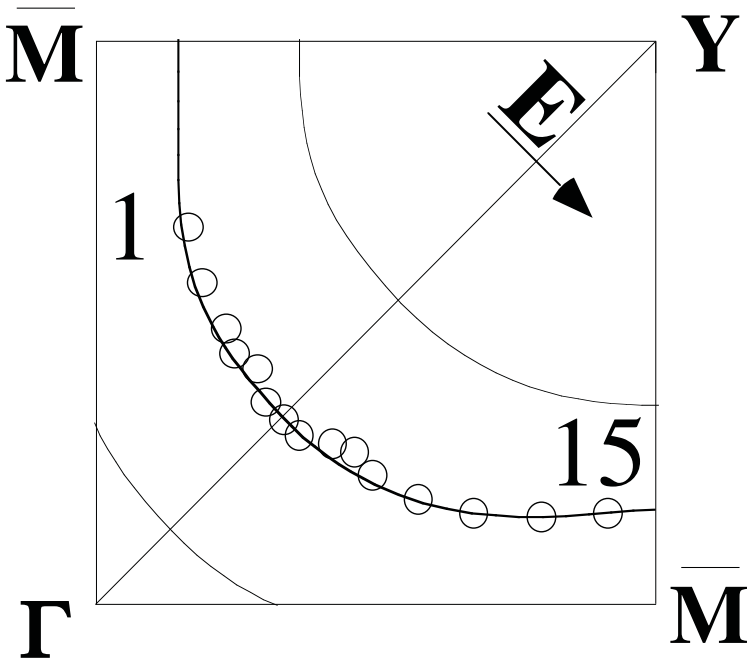


Extraction of the Superconducting Energy Gap from Photoemission

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

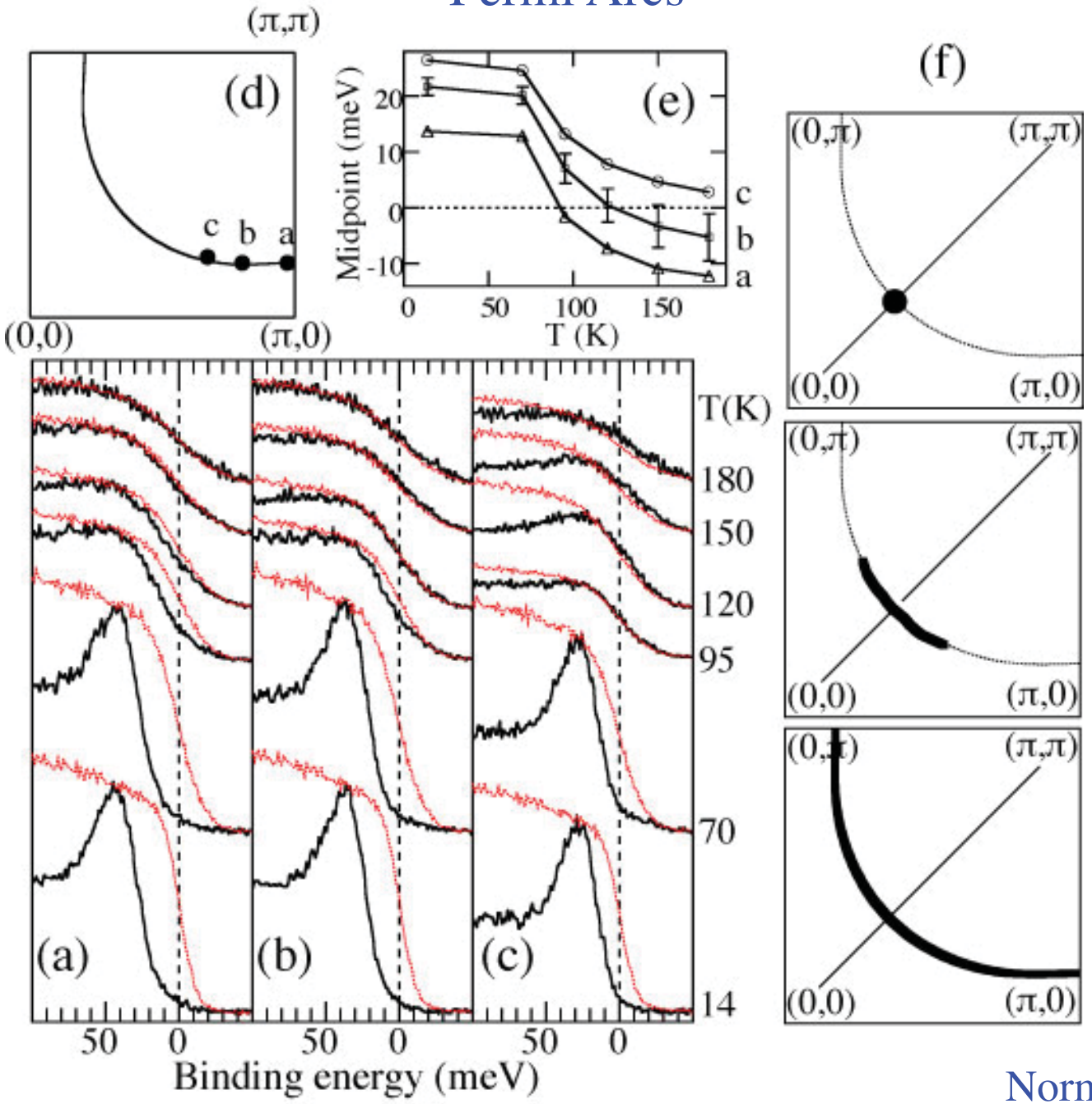
Δ_k --> $\cos(k_x a) - \cos(k_y a)$ --> d-wave energy gap





Bi2212, T_c=87K

Fermi Arcs



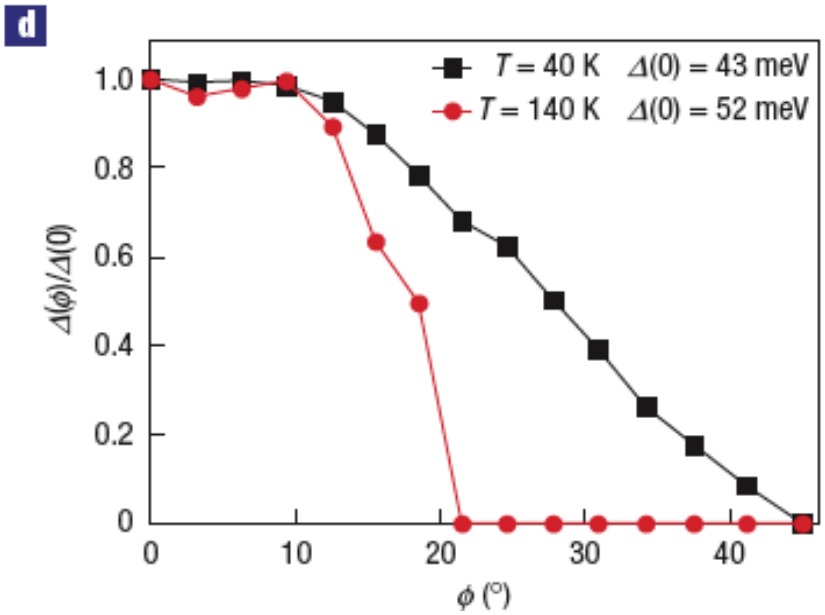
$T < T_c$
(d-wave node)

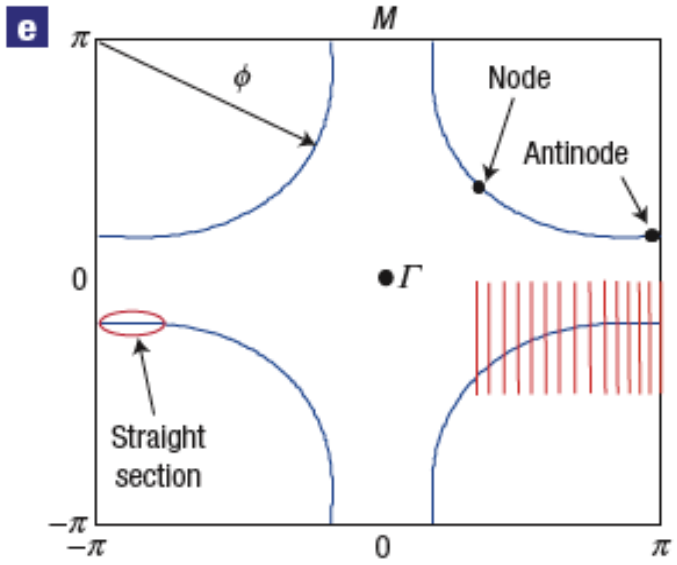
$T_c < T < T^*$
(Fermi arc)

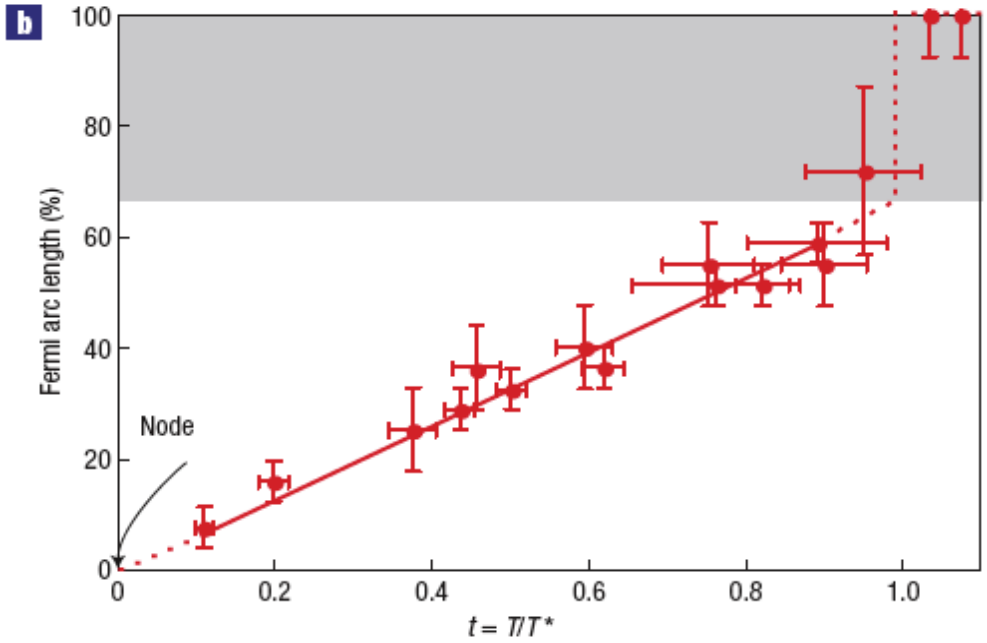
$T > T^*$
(large Fermi surface)

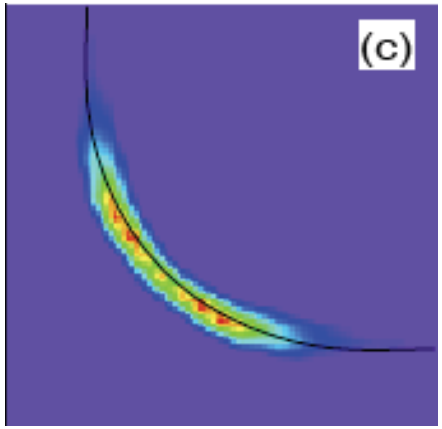
Norman *et al.*, Nature (1998)

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



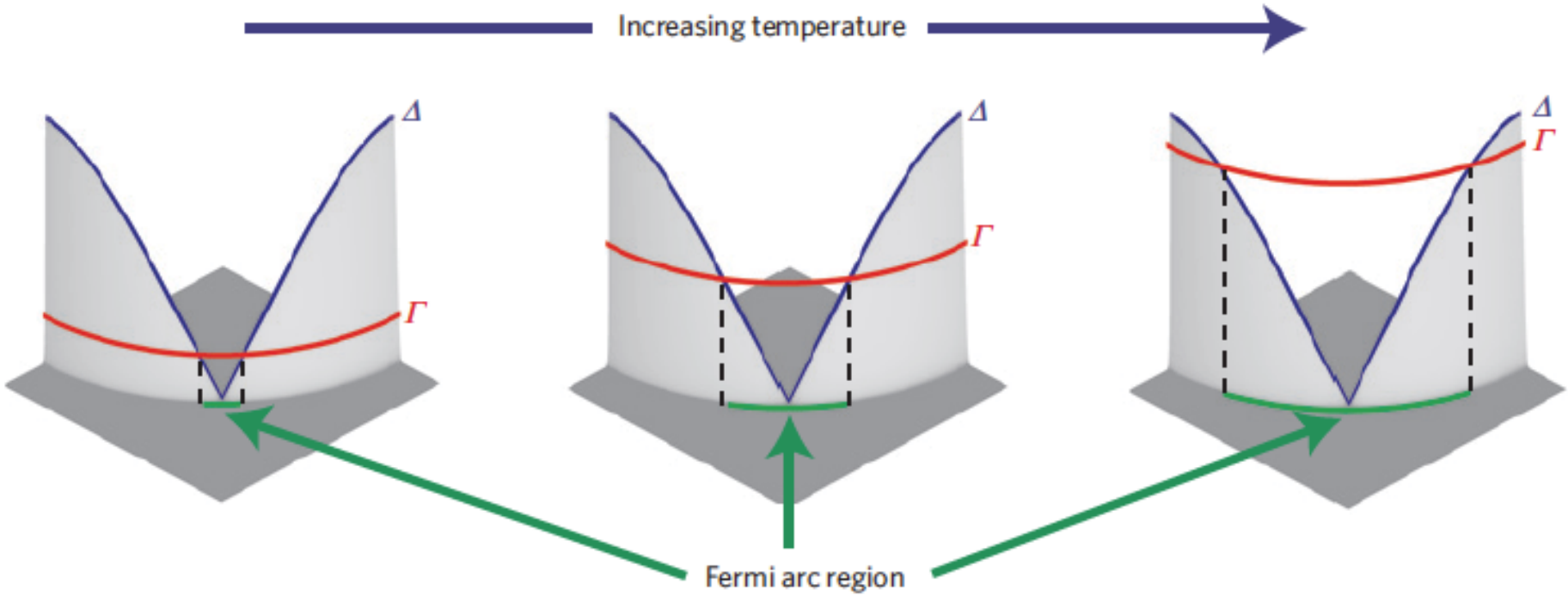






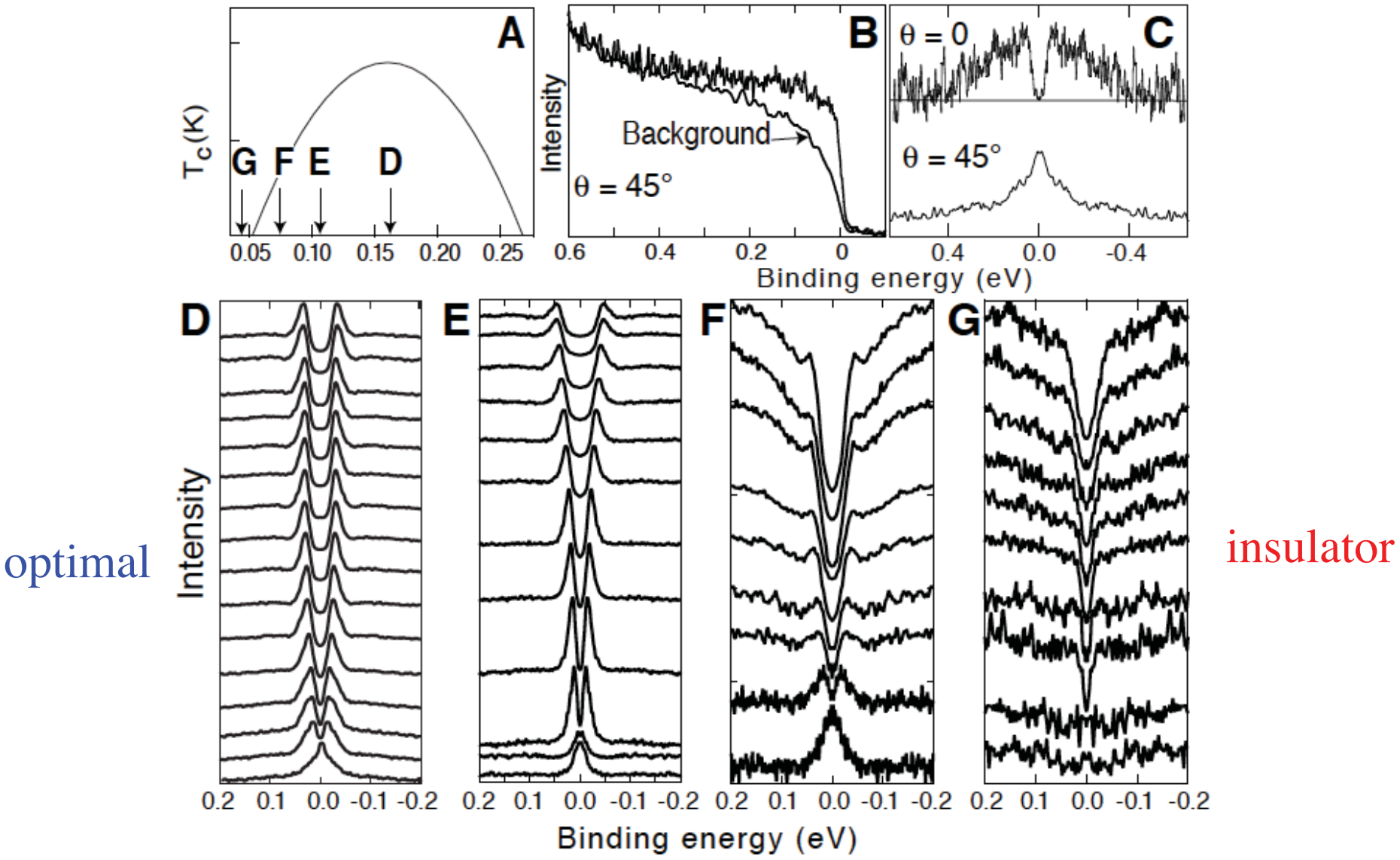
Kanigel *et al.*, Nat. Phys. (2006)

T dependent arcs also found by Dessau's group based on constructing an angle resolved density of states



Reber *et al*., Nat. Phys. (2012)

Doping Dependence of the Gap Anisotropy

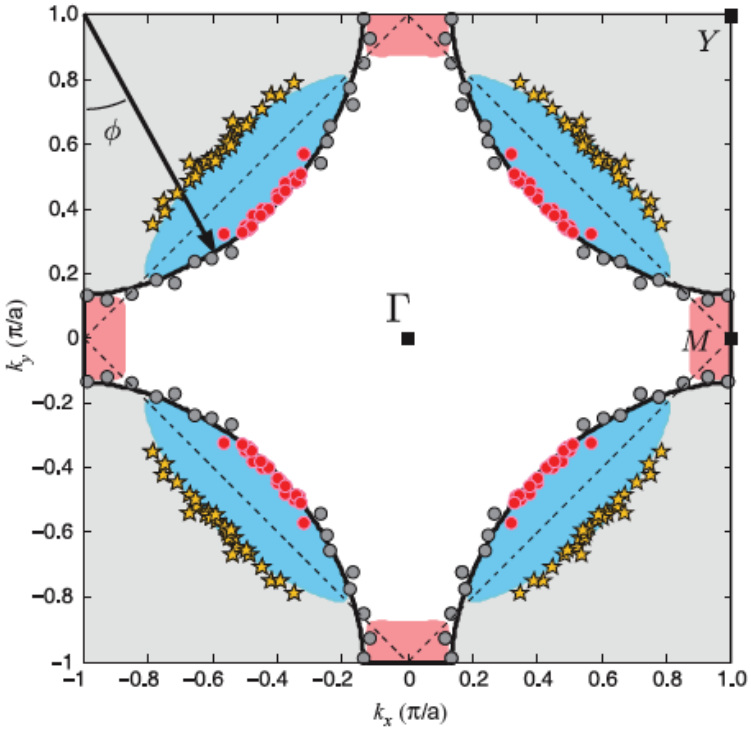


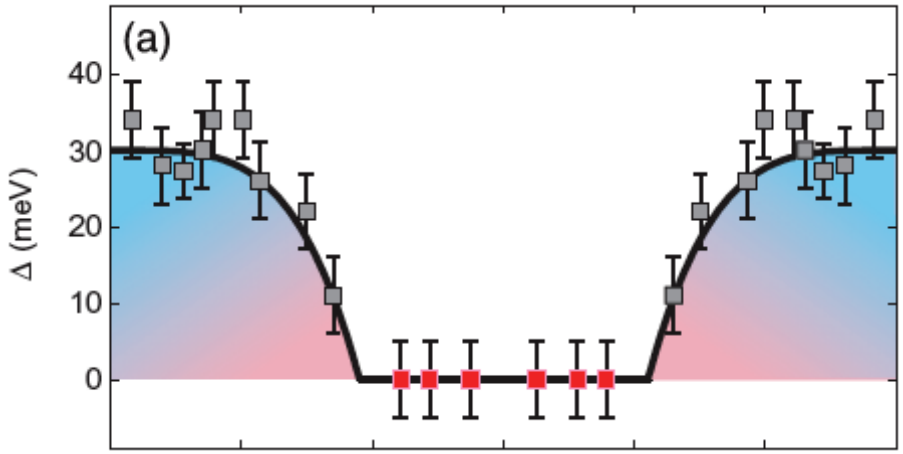
optimal

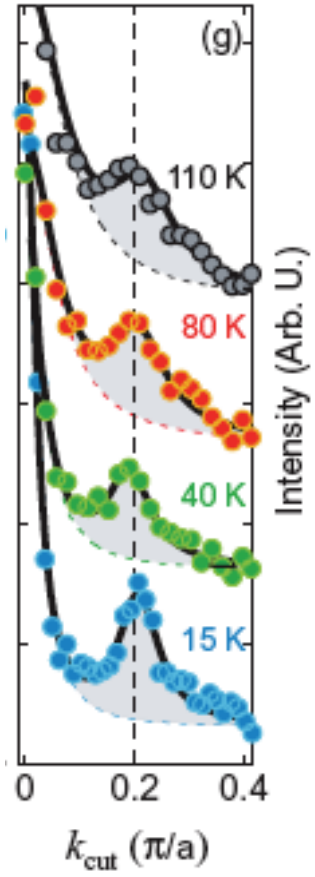
insulator

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

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

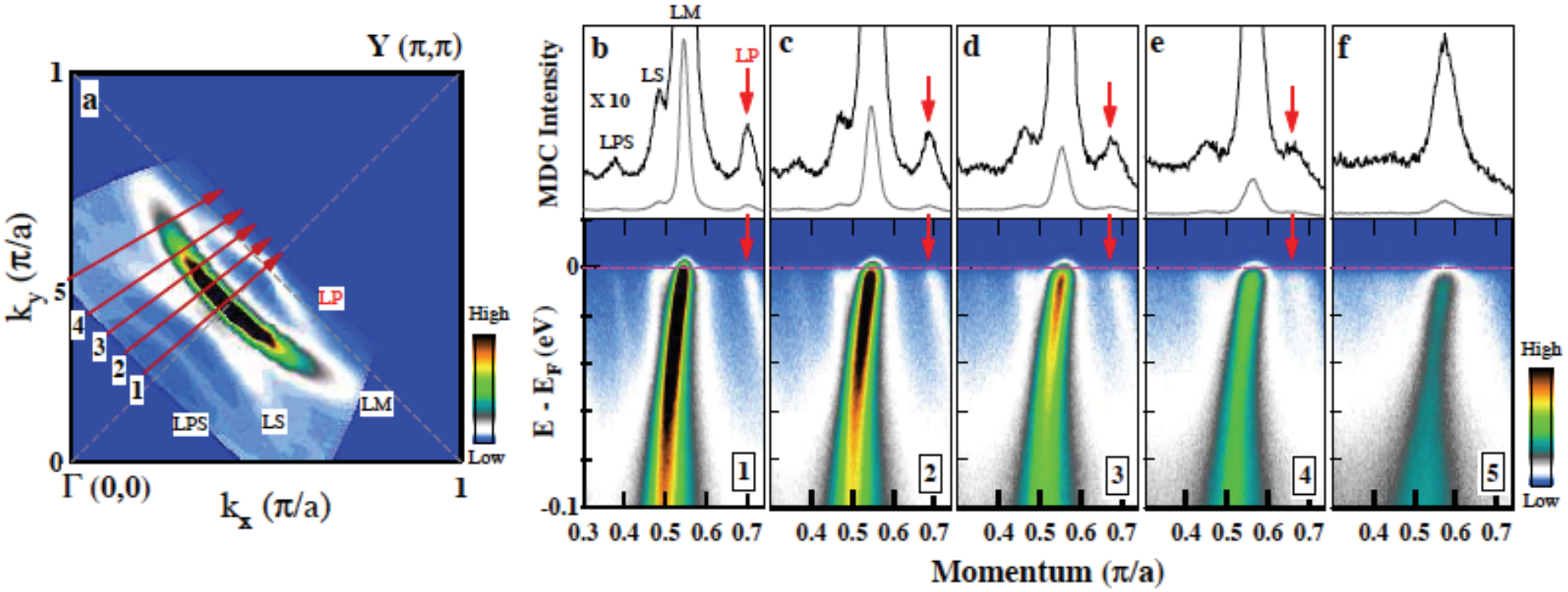






Chang *et al*., New J. Phys. (2008)

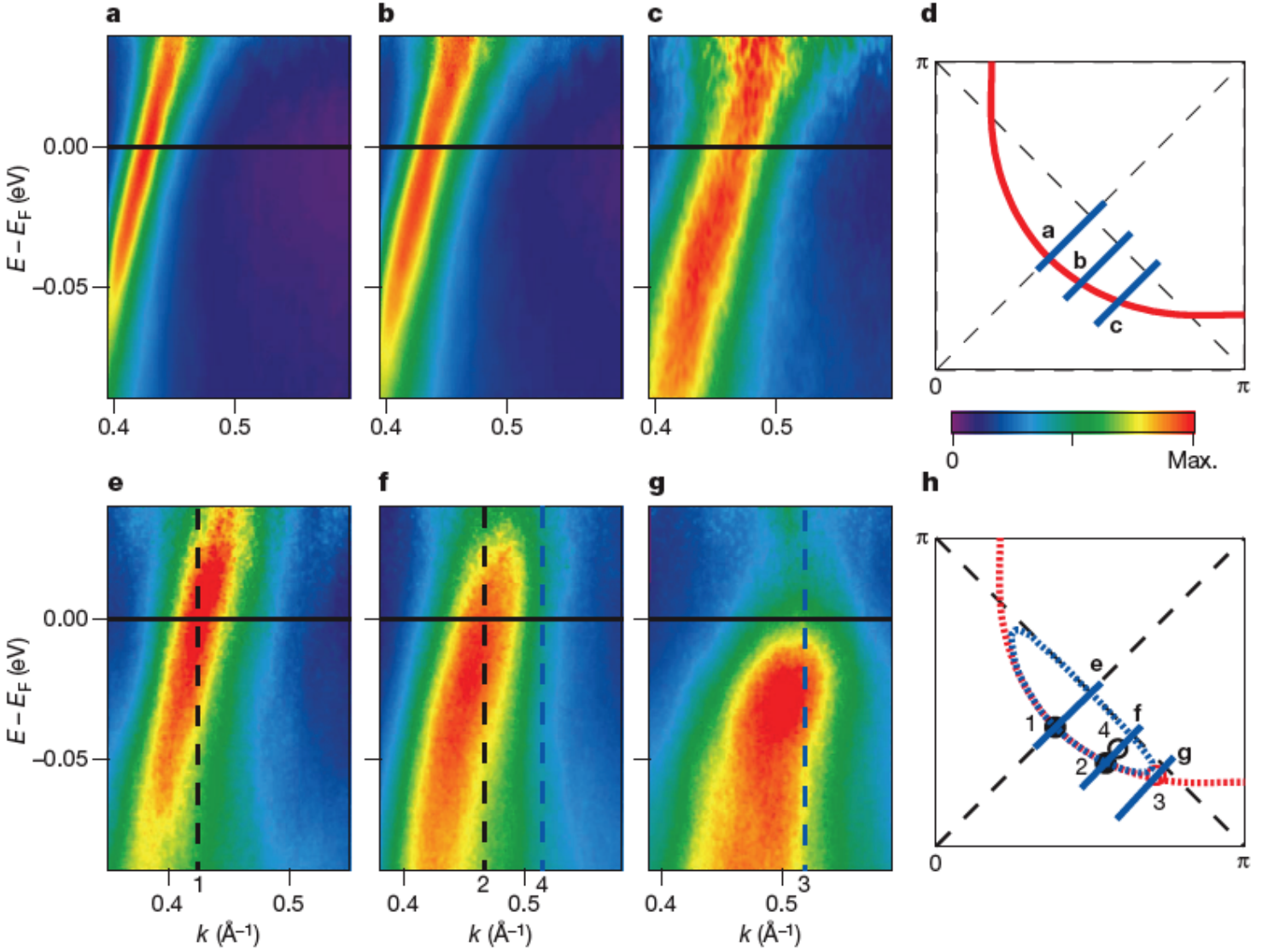
Pocket in La doped Bi2201 (structural?)



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

Meng *et al.*, Nature (2009)

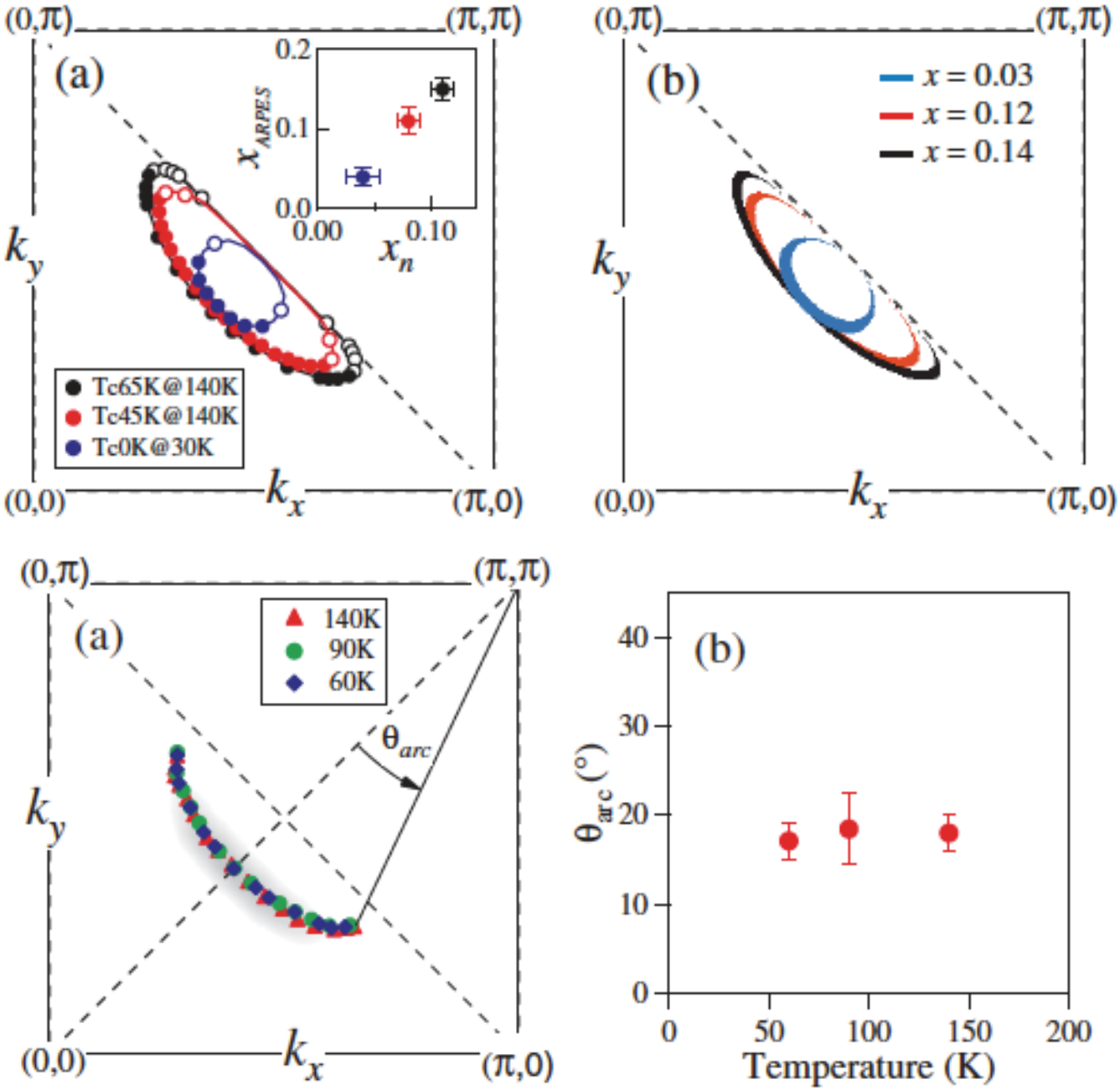
Pocket in Bi2212?



T_c=91K (optimal doped)

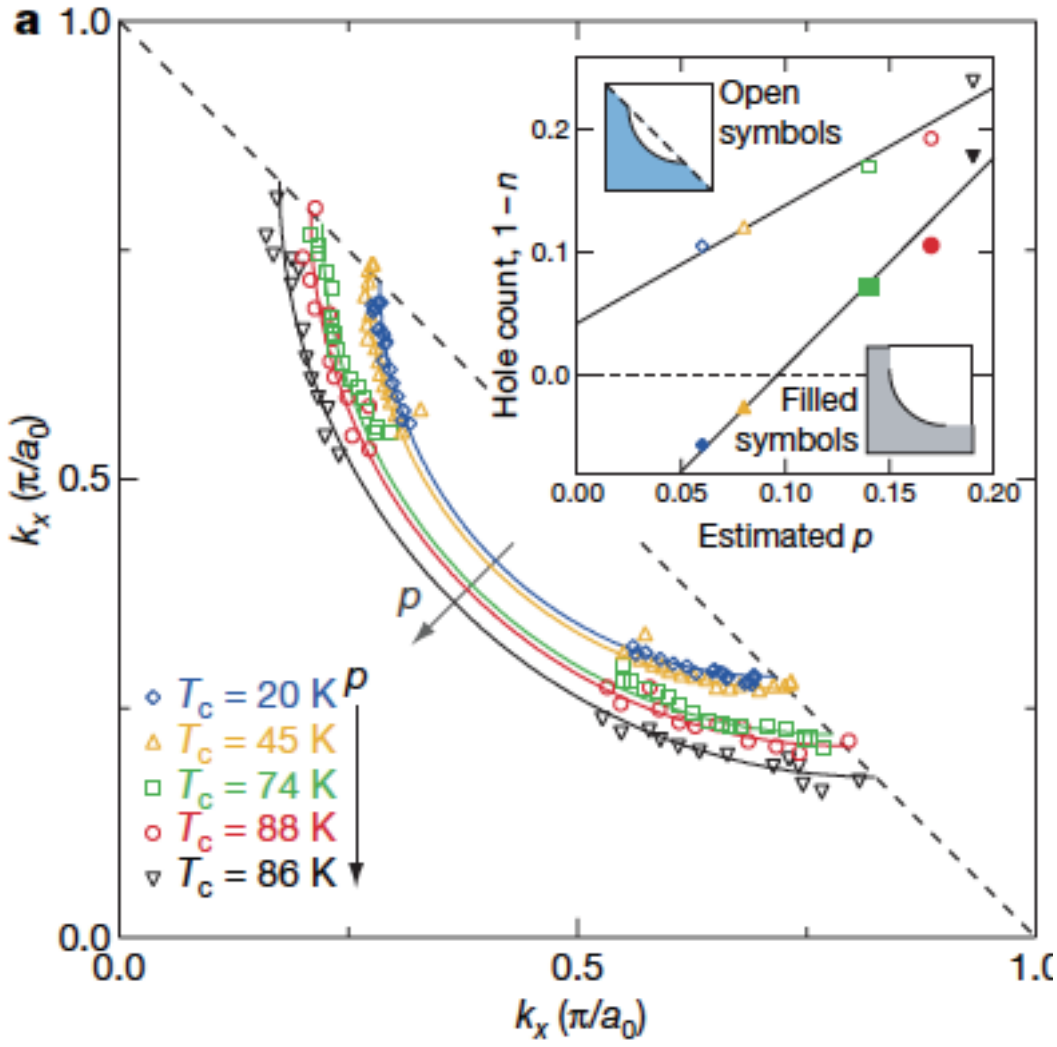
T_c=65K (underdoped)

Yang *et al.*, Nature (2008)

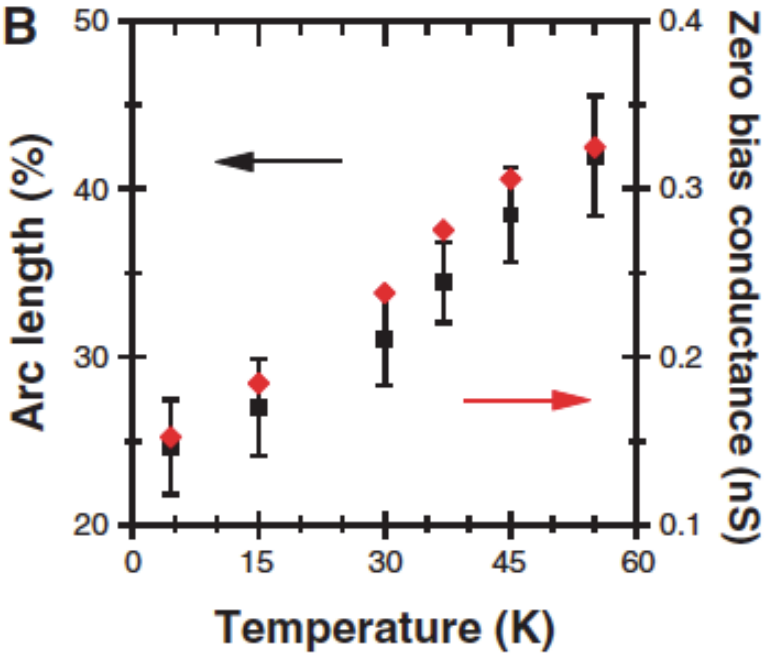


Yang *et al*.
PRL (2011)

Truncation of Quasiparticle Inteference at the AF zone boundary

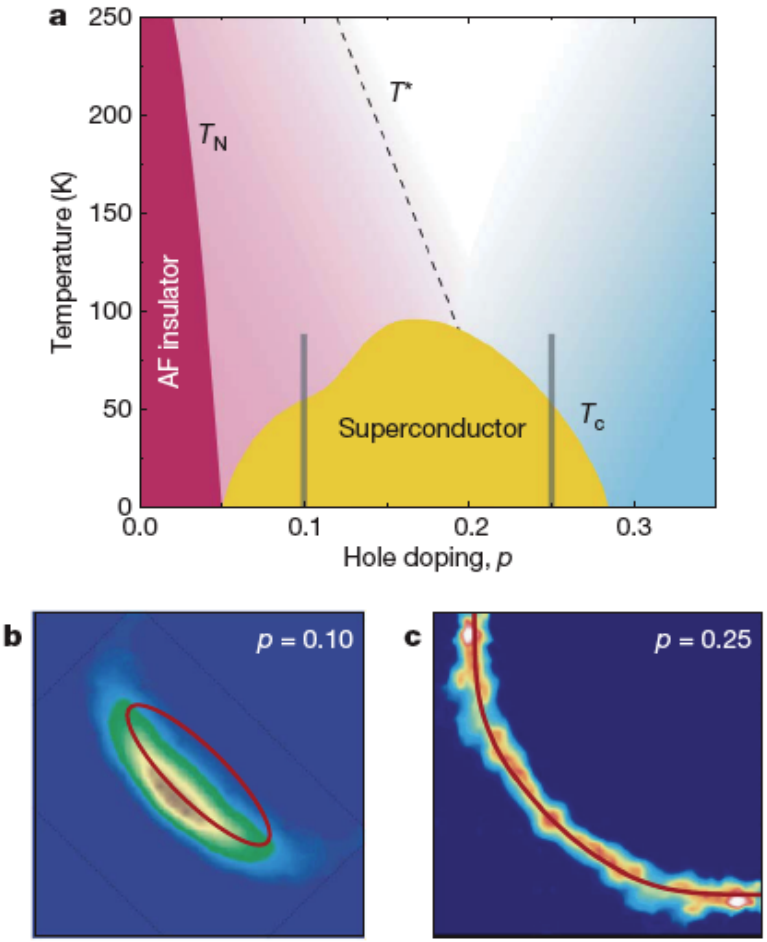


Kohsaka *et al*., Nature (2008)

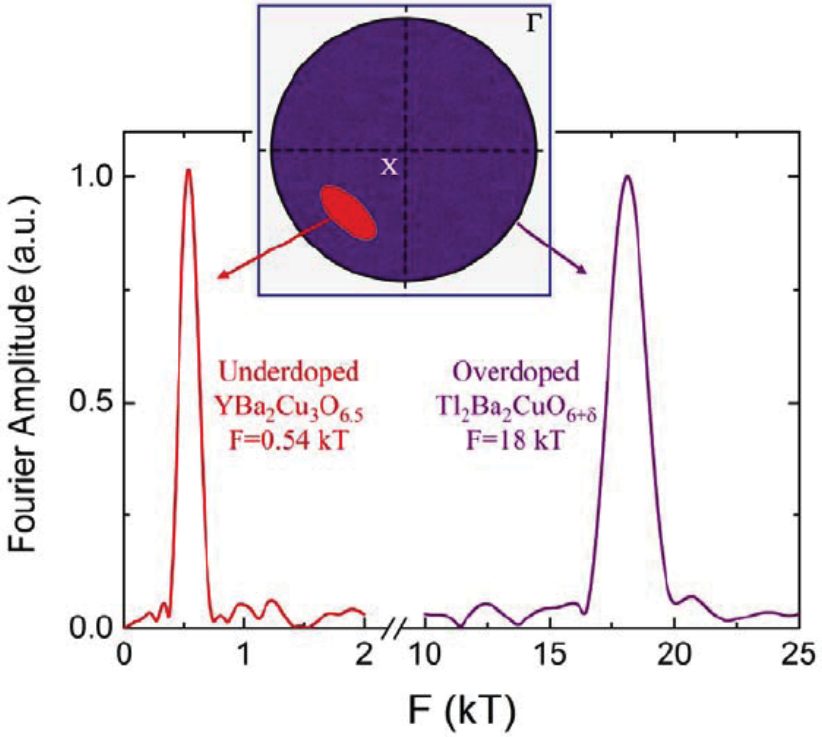


Lee *et al*., Science (2009)

Quantum Oscillations make a comeback (2007)

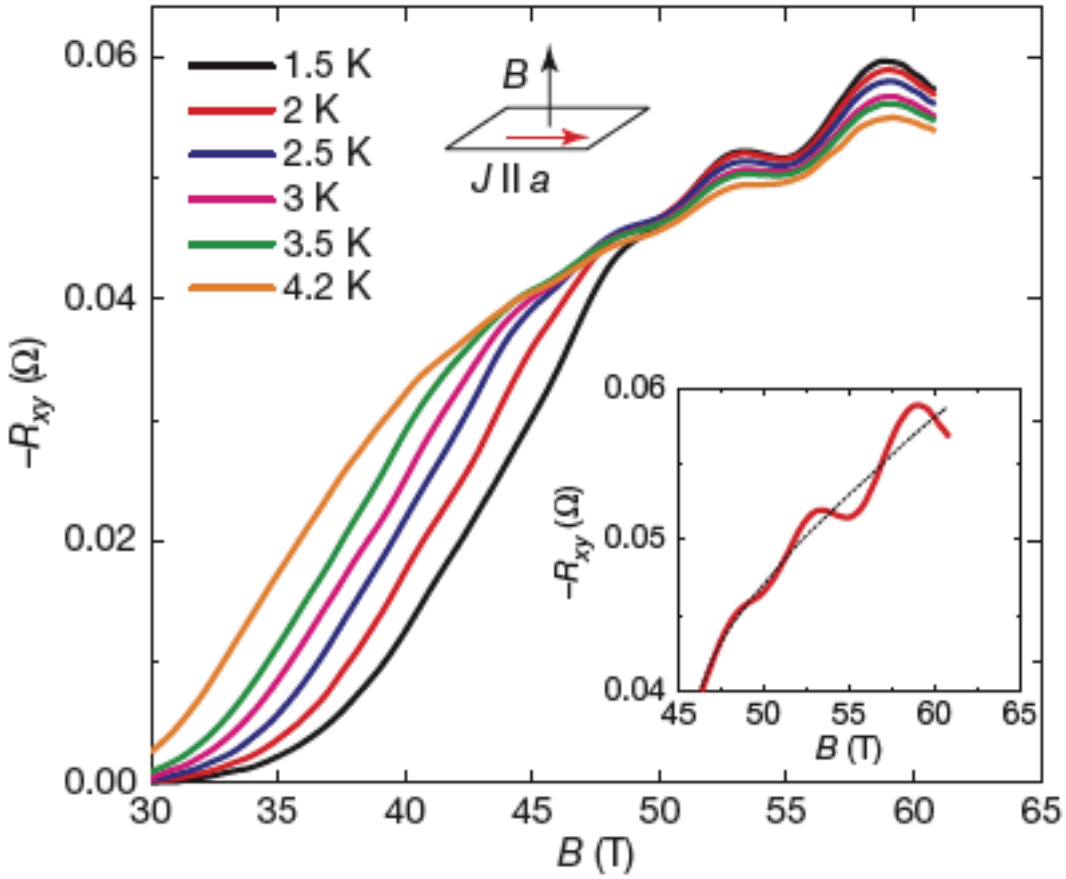


Doiron-Leyraud *et al.*, Nature (2007)
(underdoped - small Fermi surface)



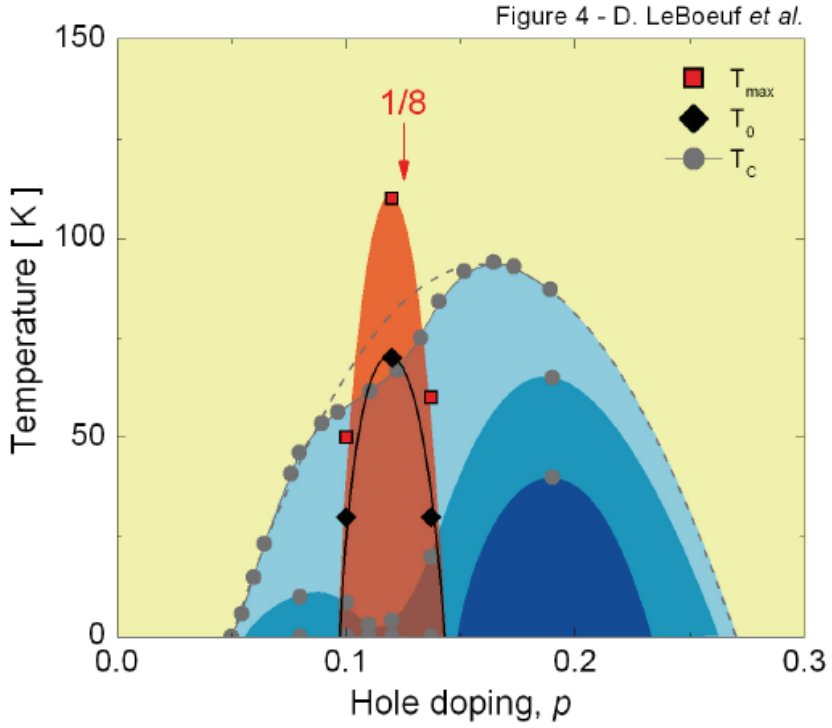
Vignolle *et al.*, Nature (2008)
(overdoped - large Fermi surface)

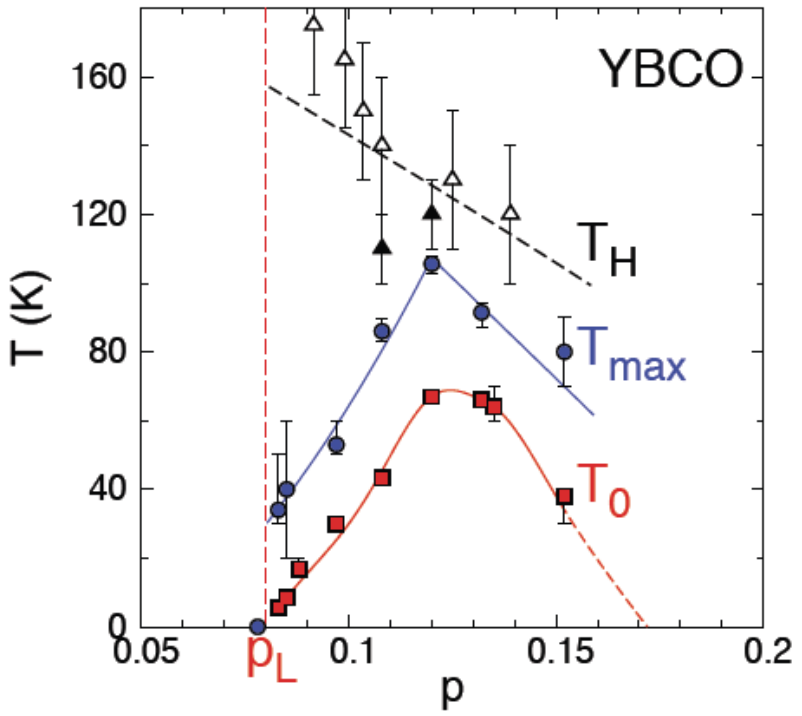
The Hall number is negative!
(electron pockets?)



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

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



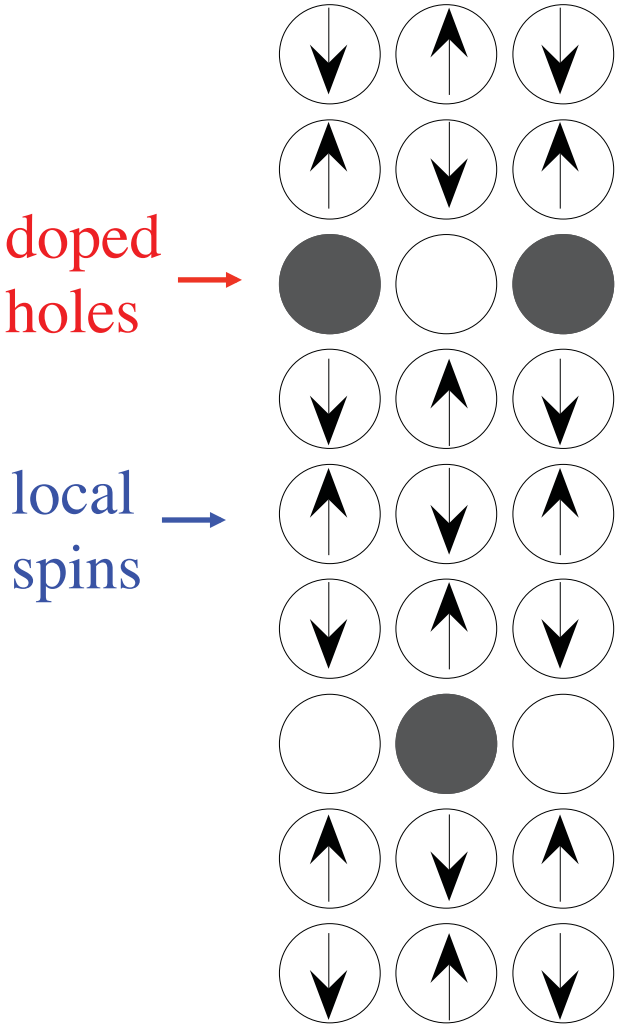


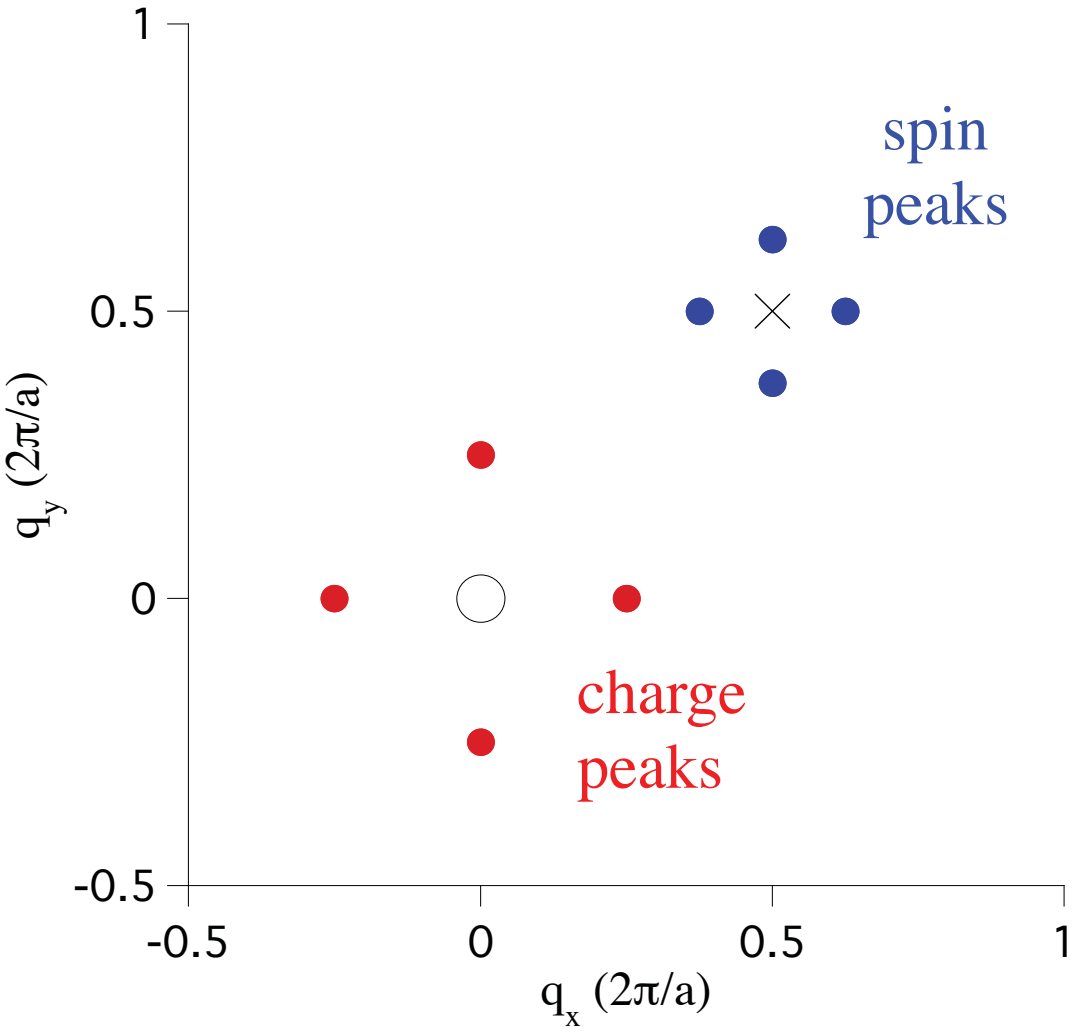
LeBoeuf *et al.*, Nature (2007)

LeBoeuf *et al.*, PRB (2011)

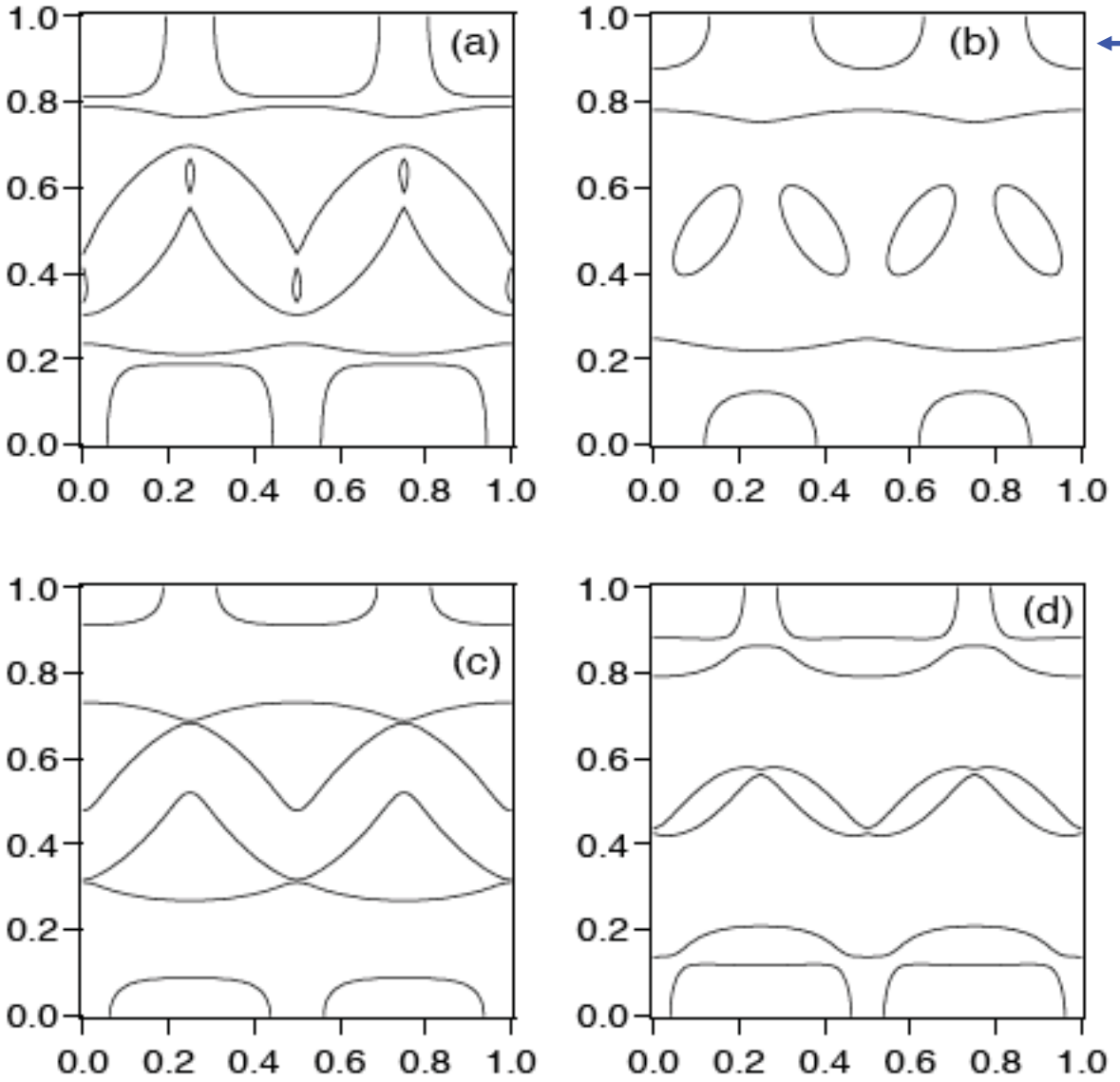
Antiphase Stripes - Tranquada *et al.* - Nature (1995)

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





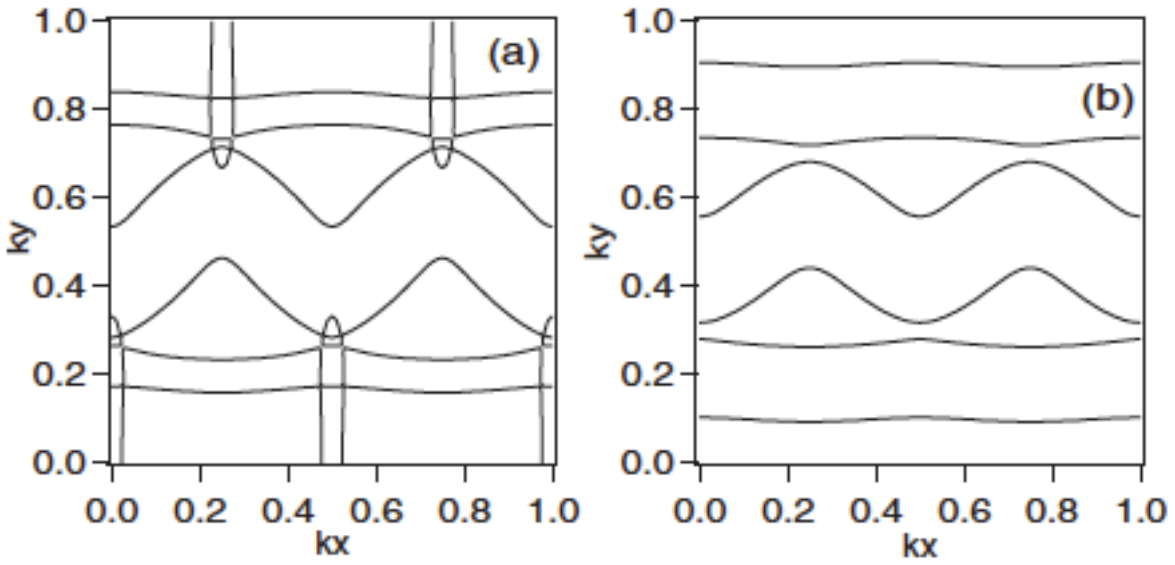
For magnetic stripes, electron pockets are stable for a range of potentials



← e^- pocket

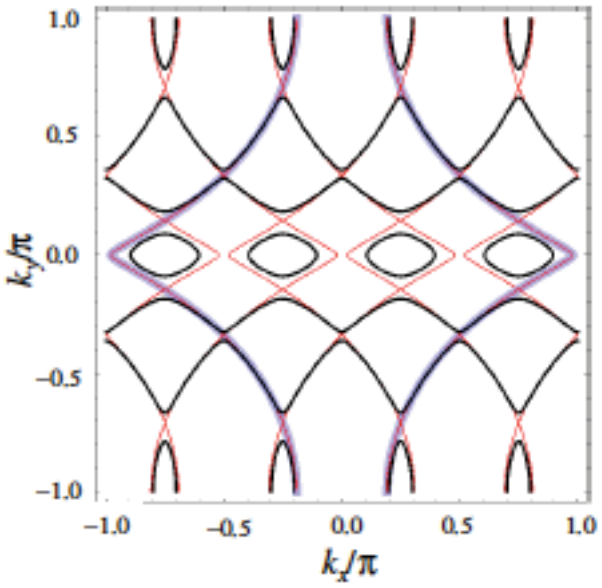
Millis & Norman, PRB (2007)

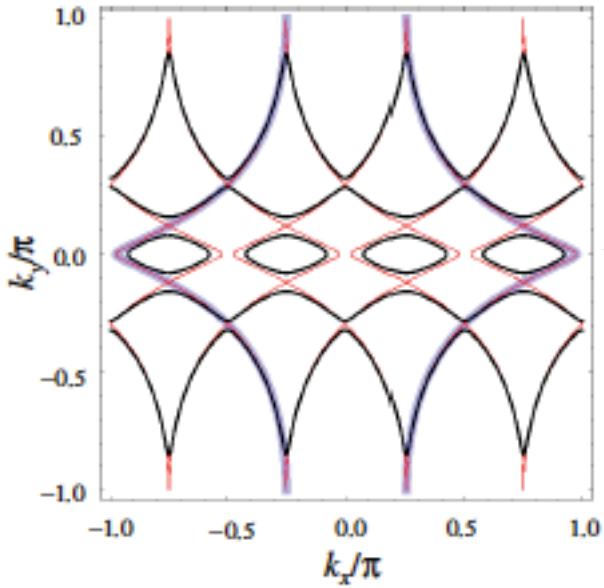
For charge only stripes, there are no pockets!



Millis & Norman, PRB (2007)

Though strong nematicity can stabilize them

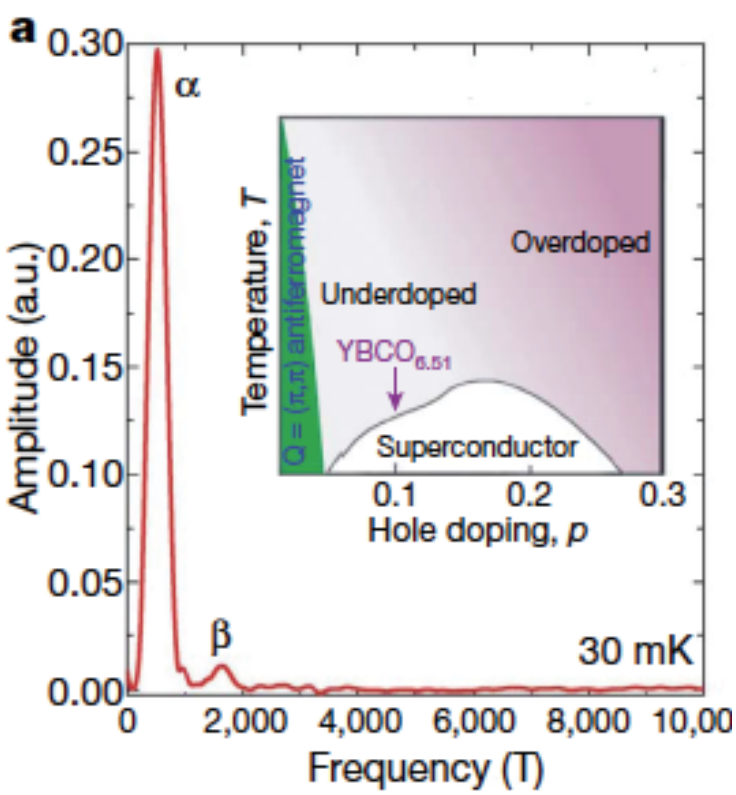


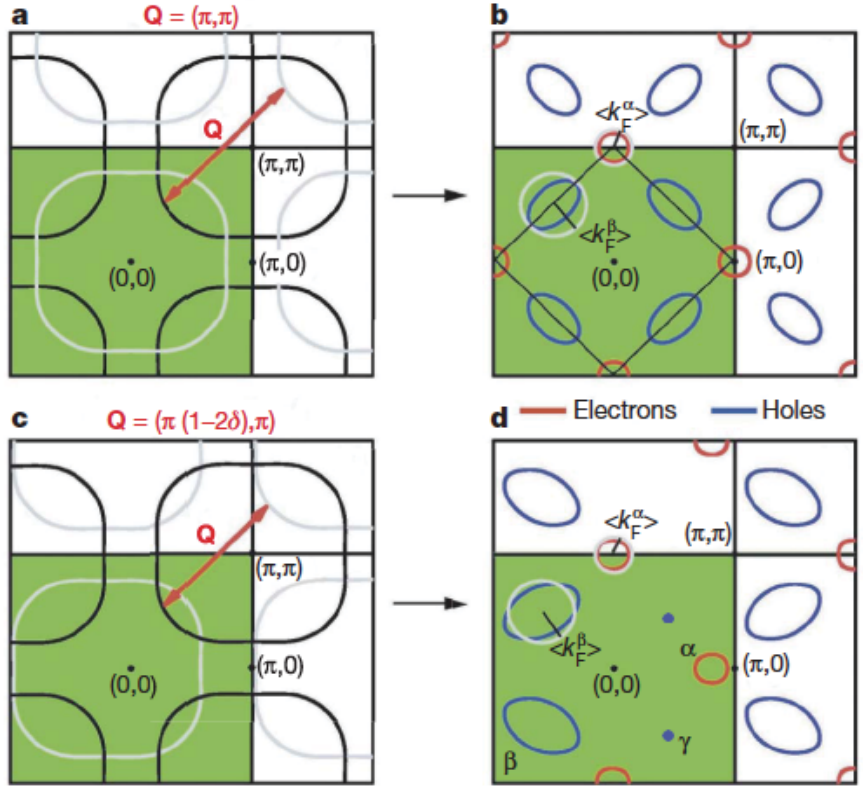


← e^- pocket

Yao, Lee, & Kivelson, PRB (2011)

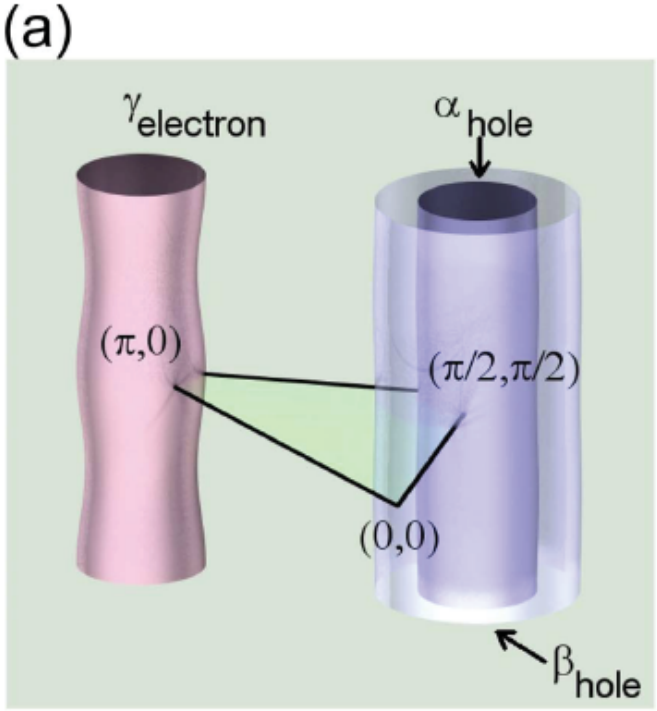
A larger hole Fermi surface (β) from a spin spiral state?

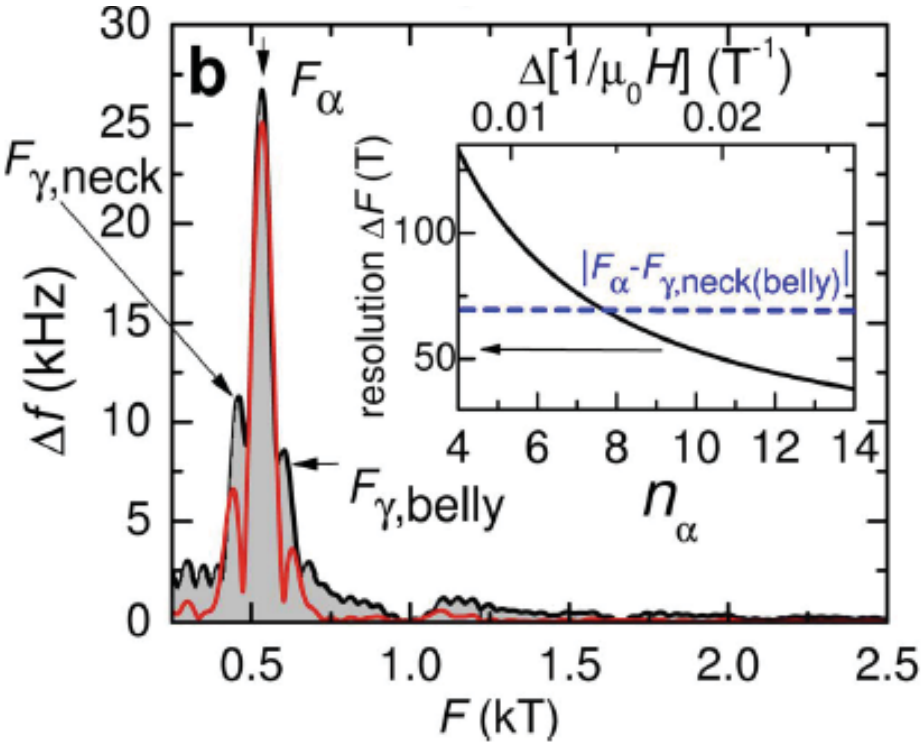




Sebastian *et al*., Nature (2008)

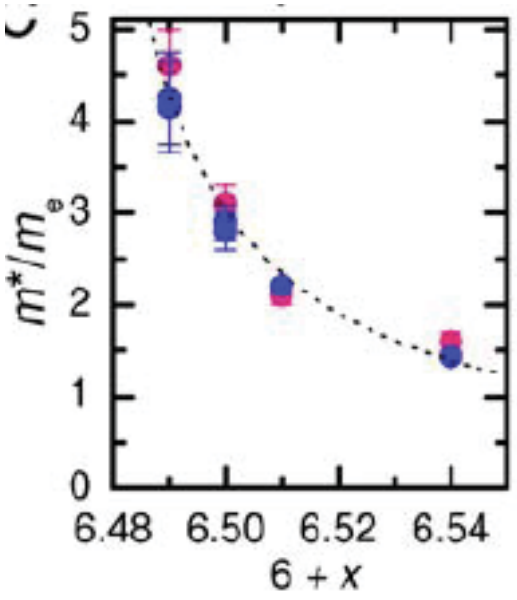
Small electron (warped cylinder), small hole (unwarped cylinder), and larger hole Fermi surfaces?

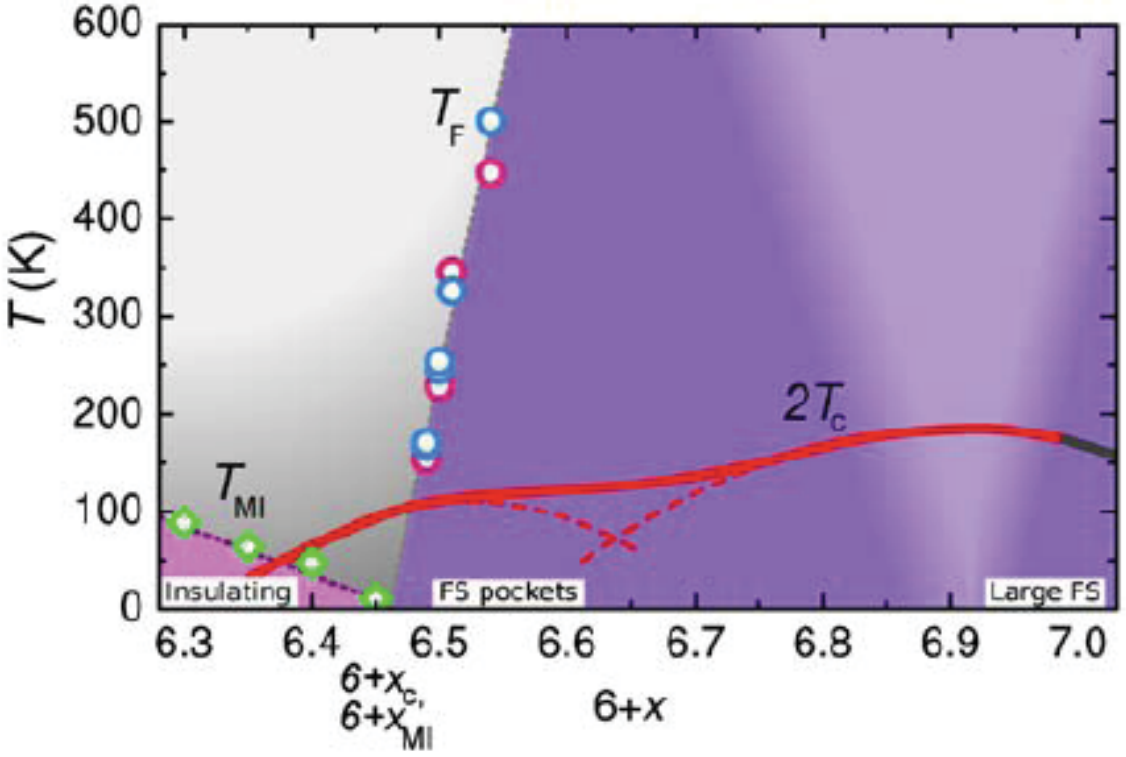




Sebastian *et al.*, PRB (2010)

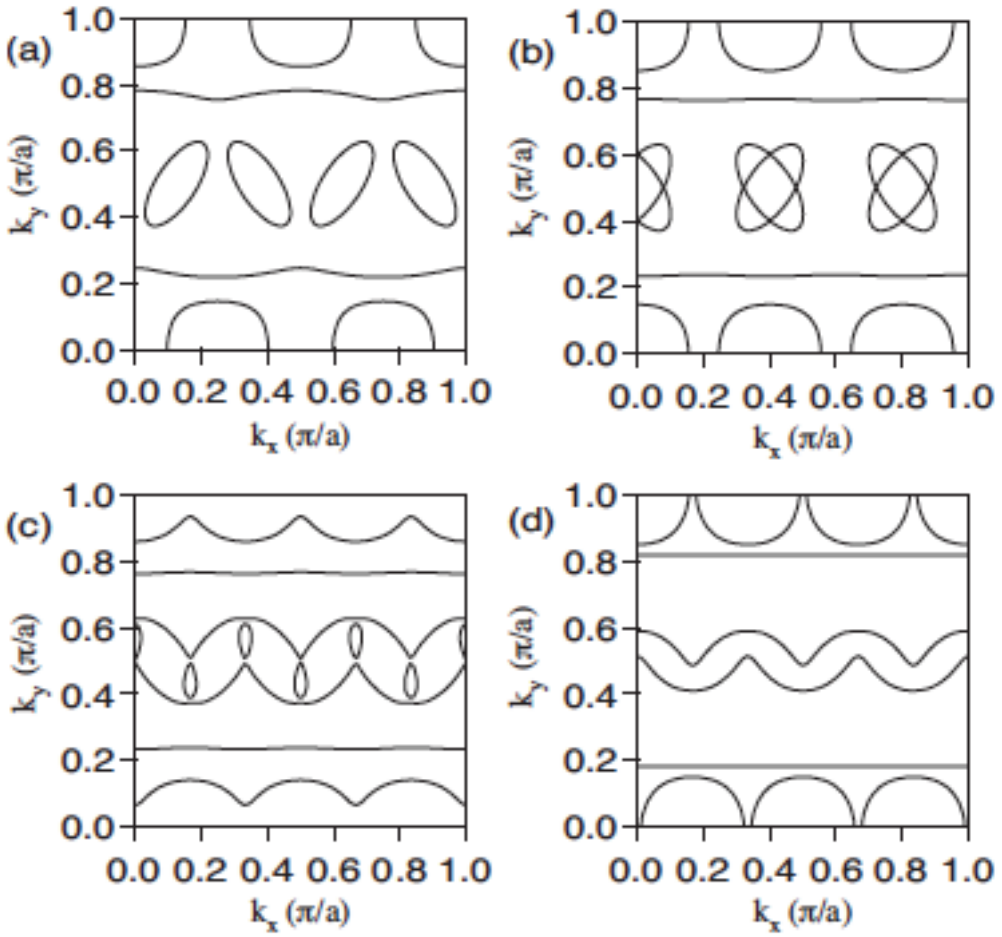
Divergence of cyclotron mass near x=0.09 (exciton instability)?

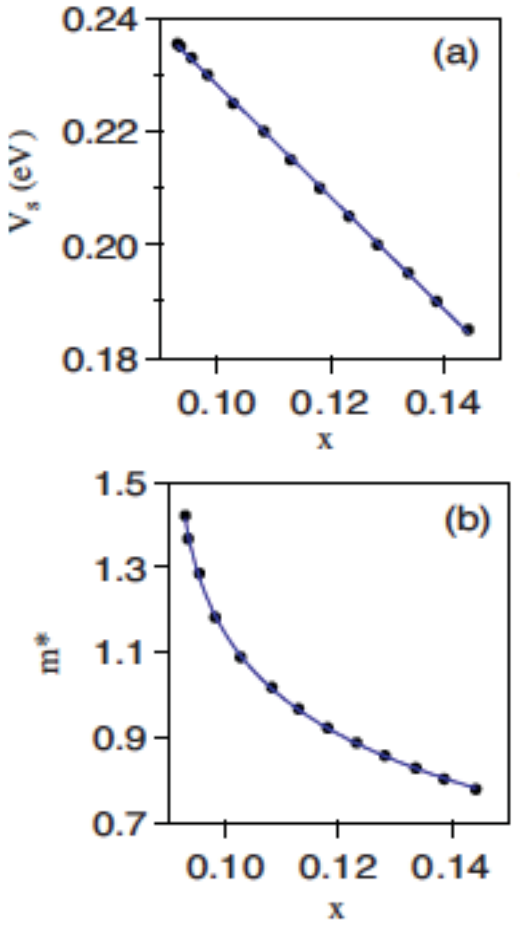




Sebastian *et al*., PNAS (2010)

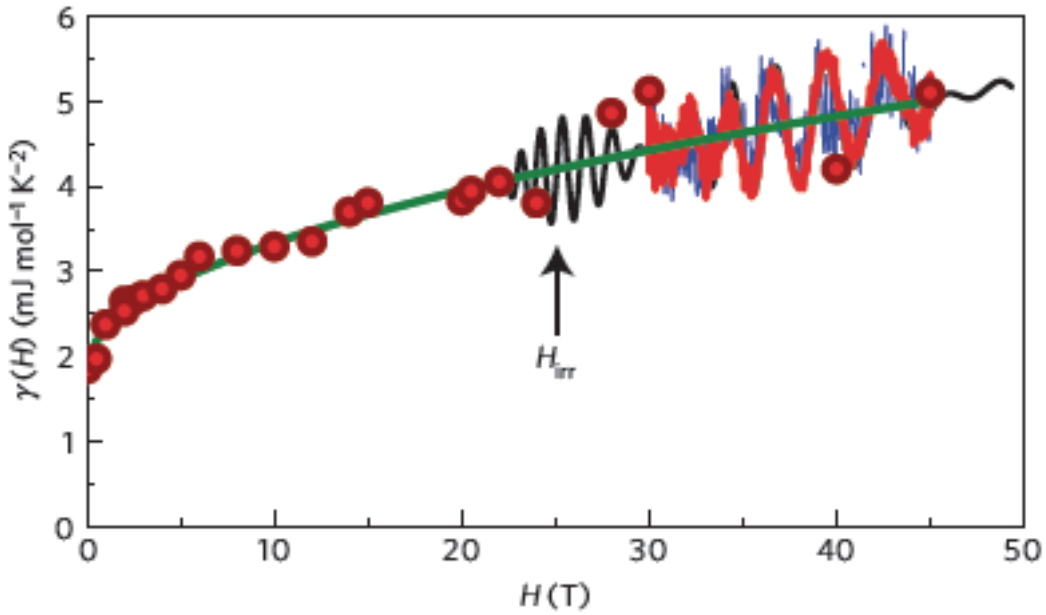
Lifshitz Transition (electron pockets touch) near x=0.09?





Norman, Lin, & Millis, PRB (2010)

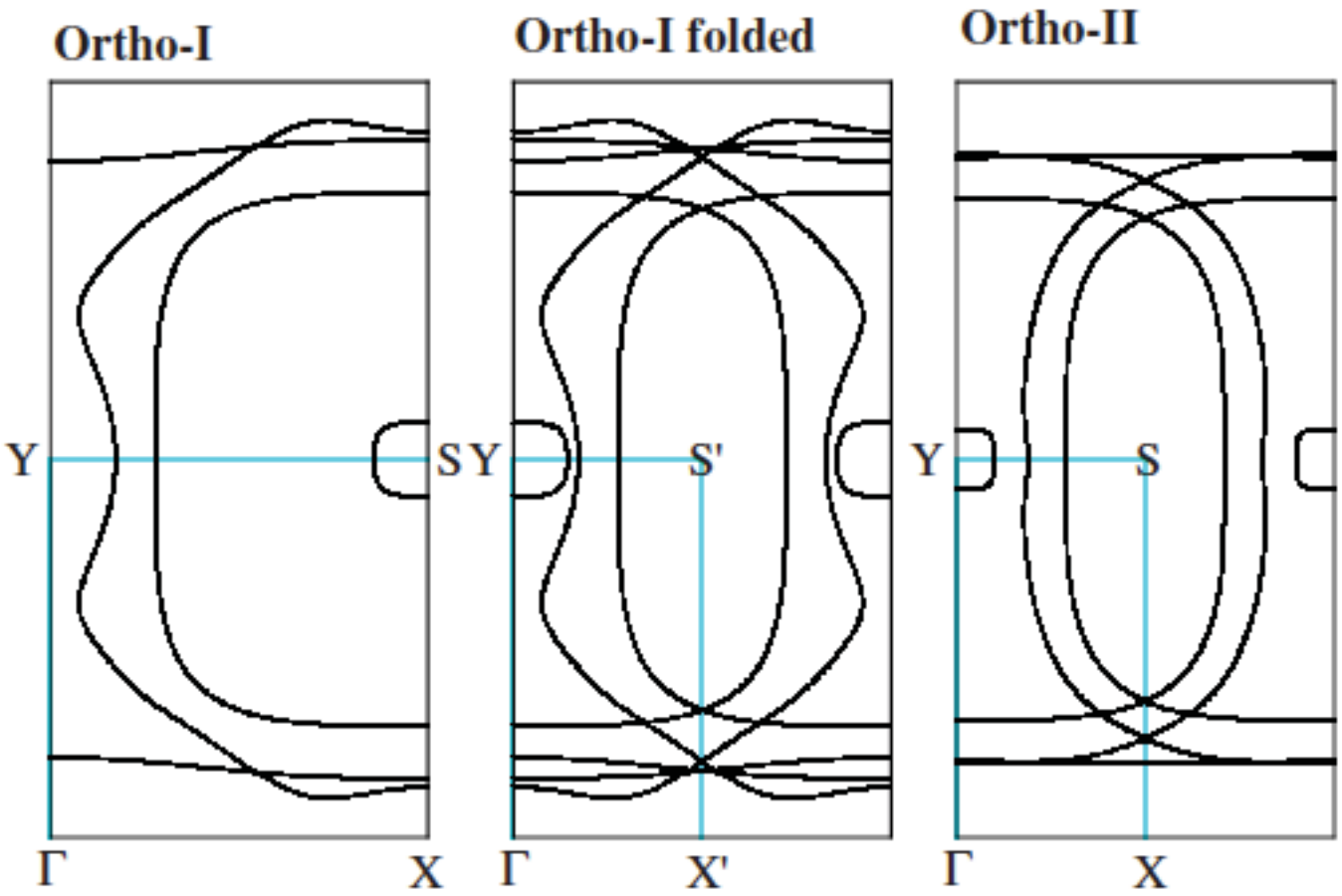
Quantum oscillations in the specific heat



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

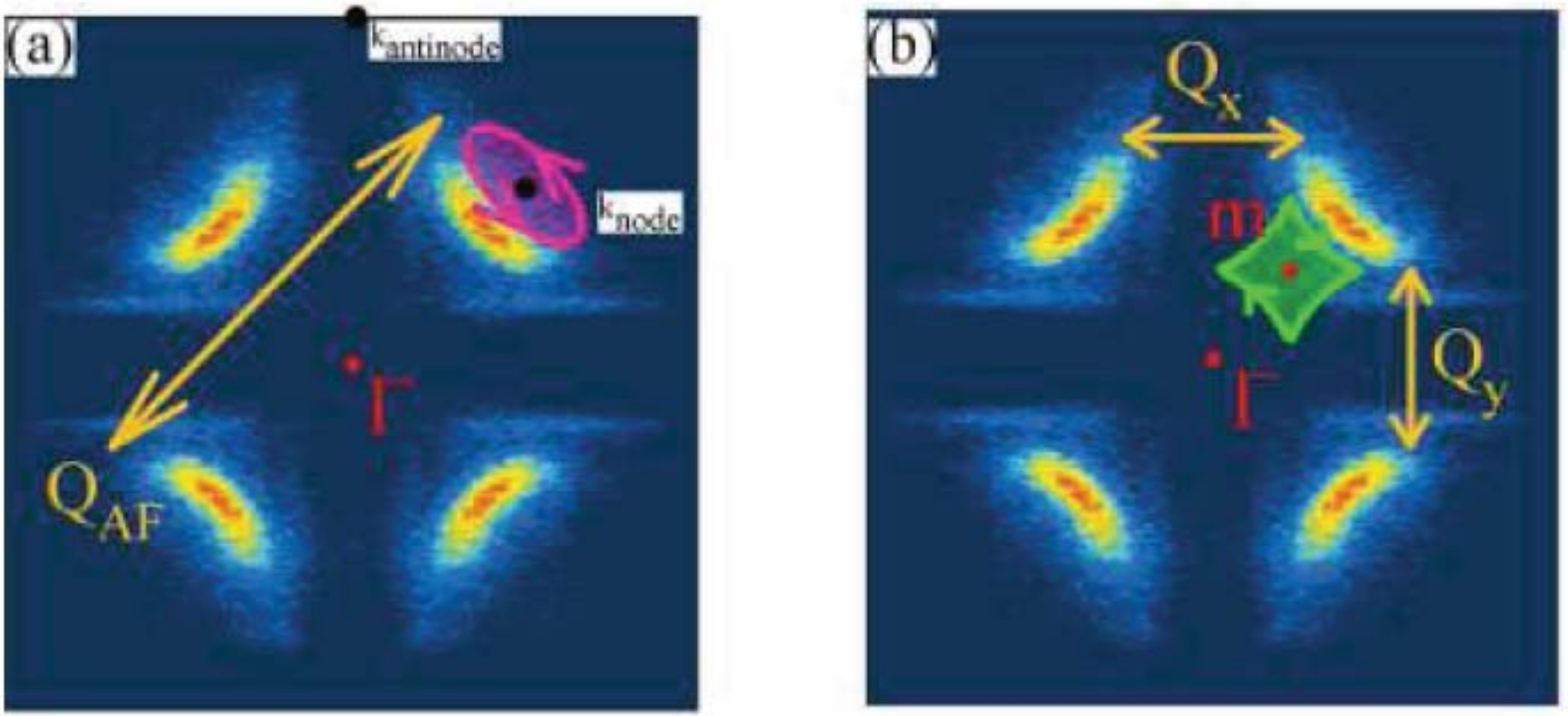
Riggs *et al.*, Nature Phys. (2011)

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



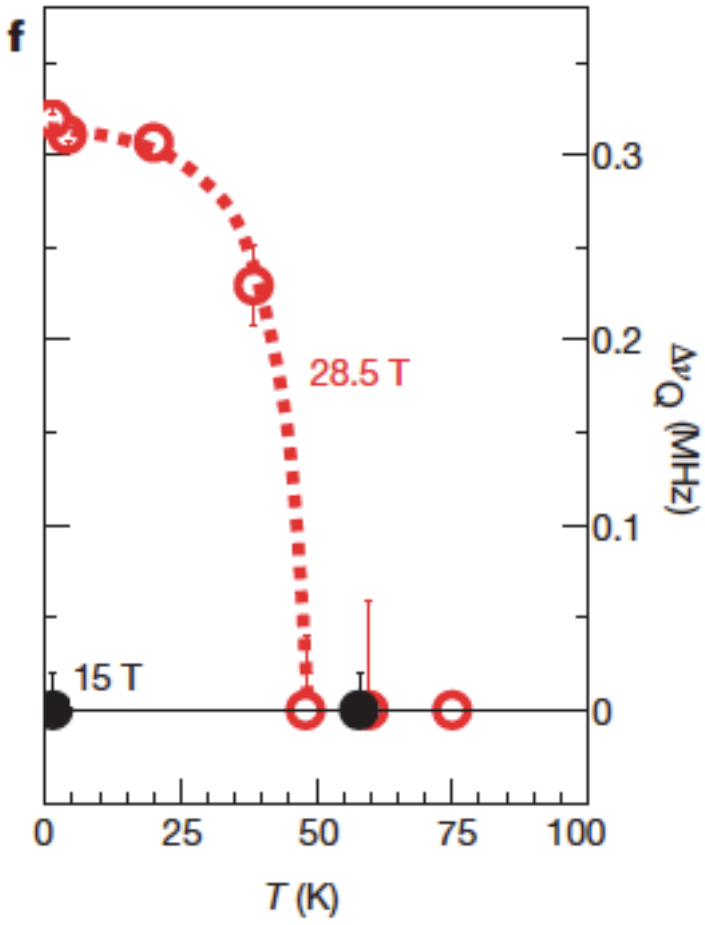
Carrington & Yelland, PRB (2007)

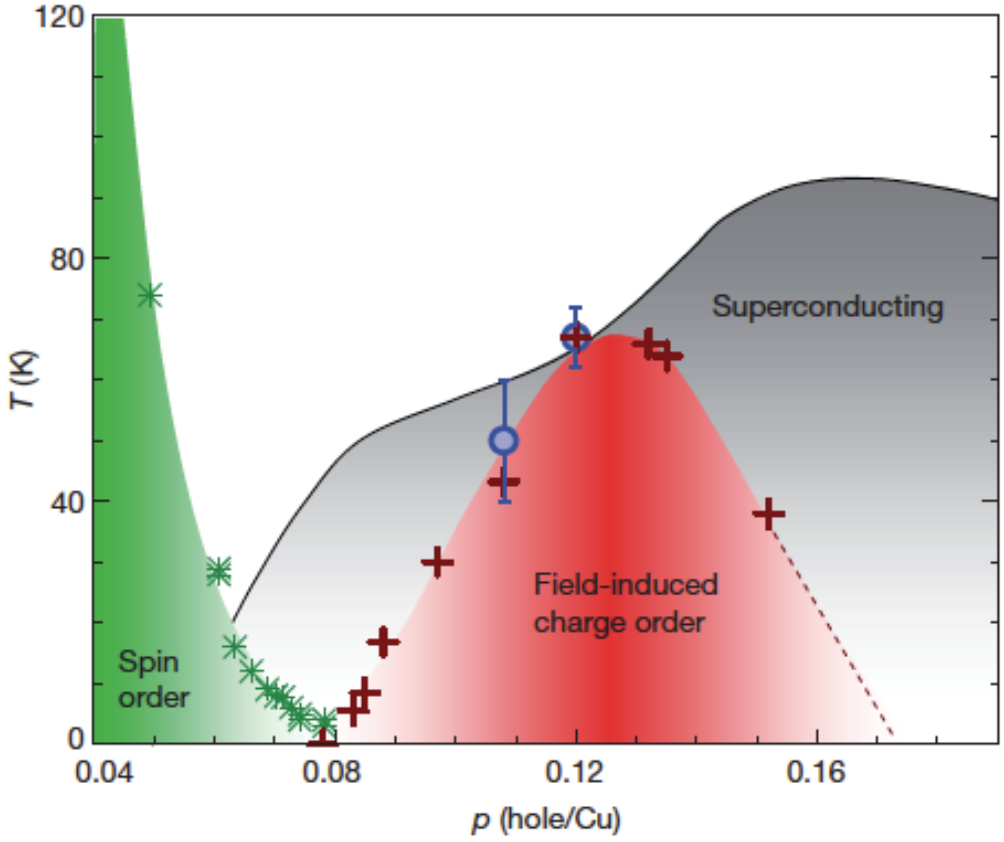
Electron pocket near the node due to checkerboard charge order?



Harrison & Sebastian, PRL (2011)

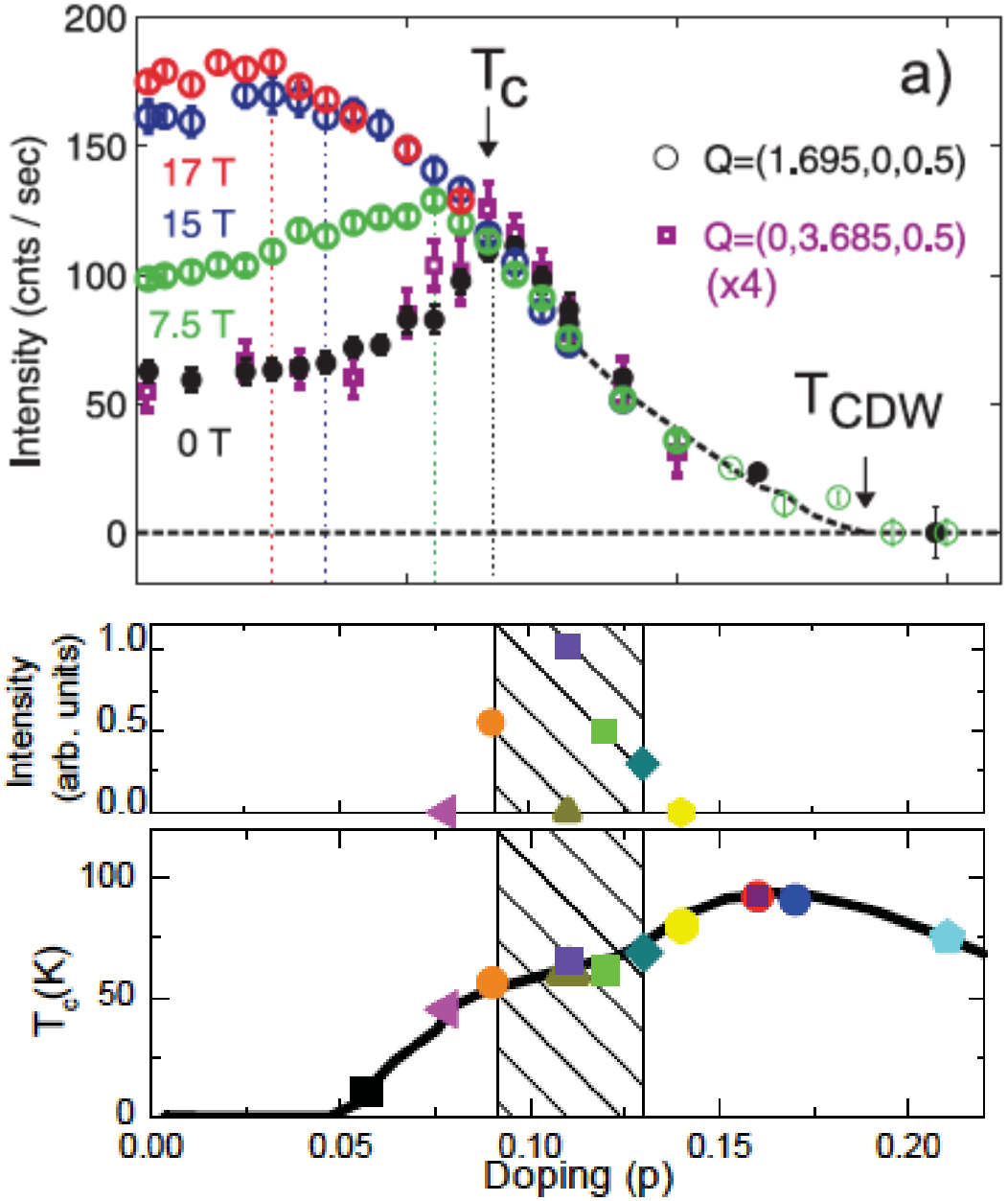
Field induced charge density wave in YBCO?





Wu *et al*., Nature (2011)

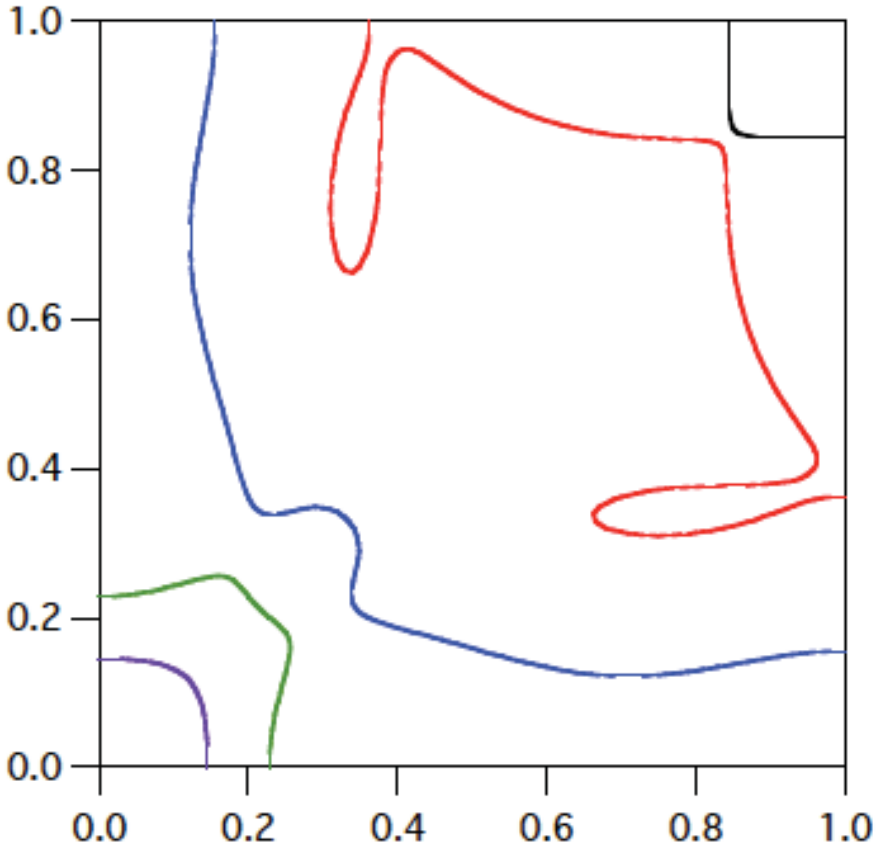
Recent evidence for checkerboard charge order in YBCO from x-ray data

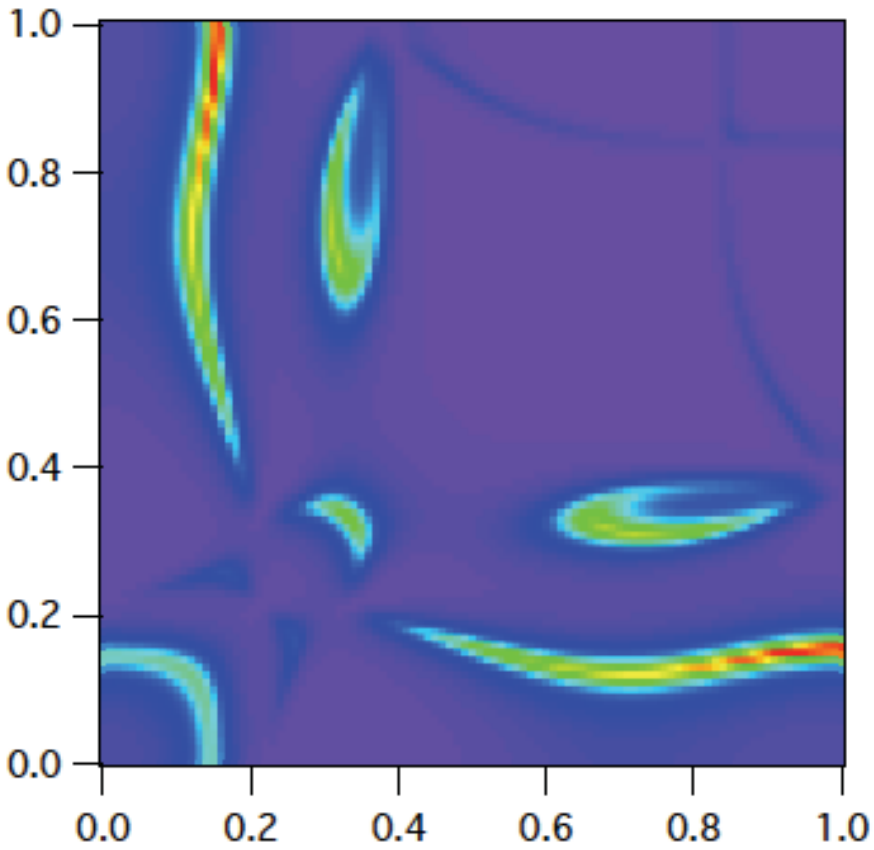


Chang *et al.*,
arXiv (2012)

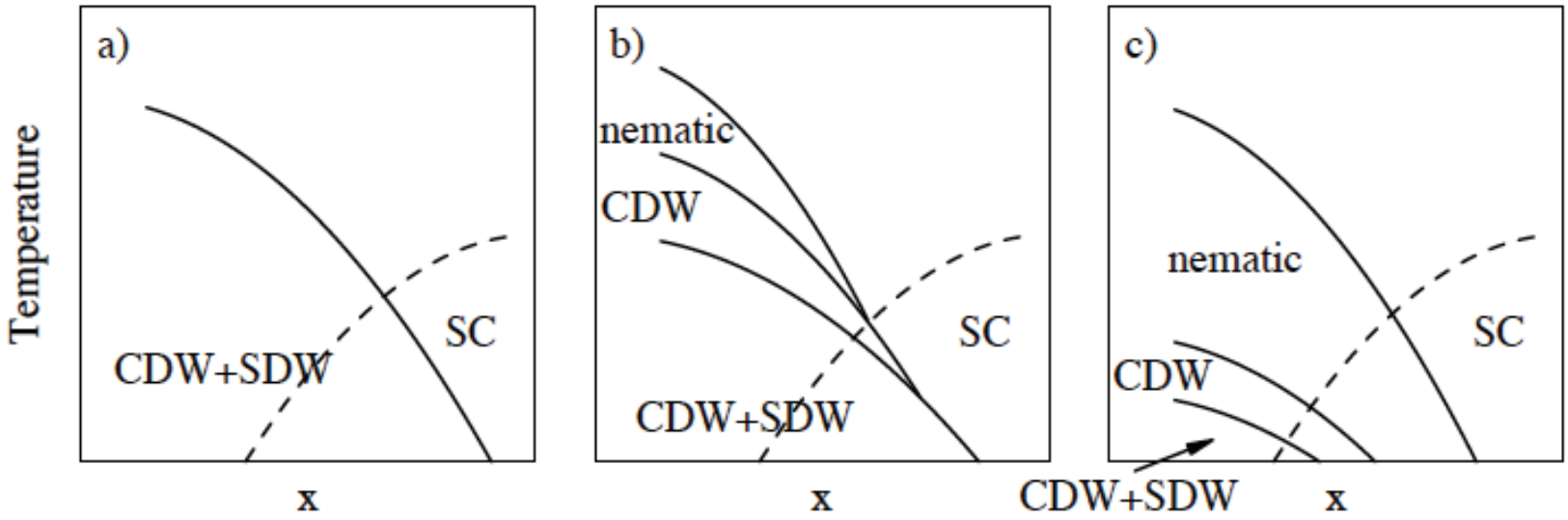
Ghiringhelli *et al.*,
arXiv (2012)

Such order gives rise to a Γ centered electron pocket,
but this is unlike what is seen in ARPES



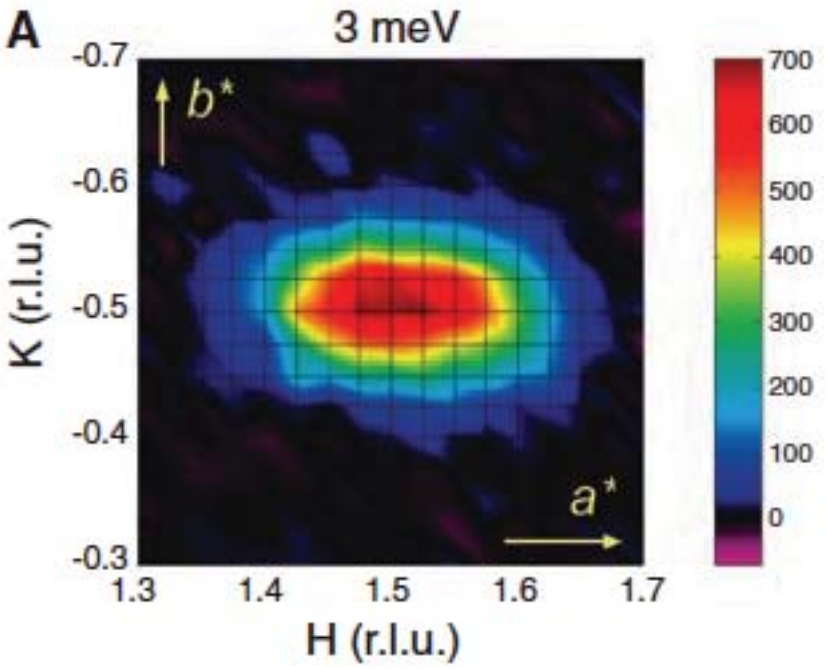


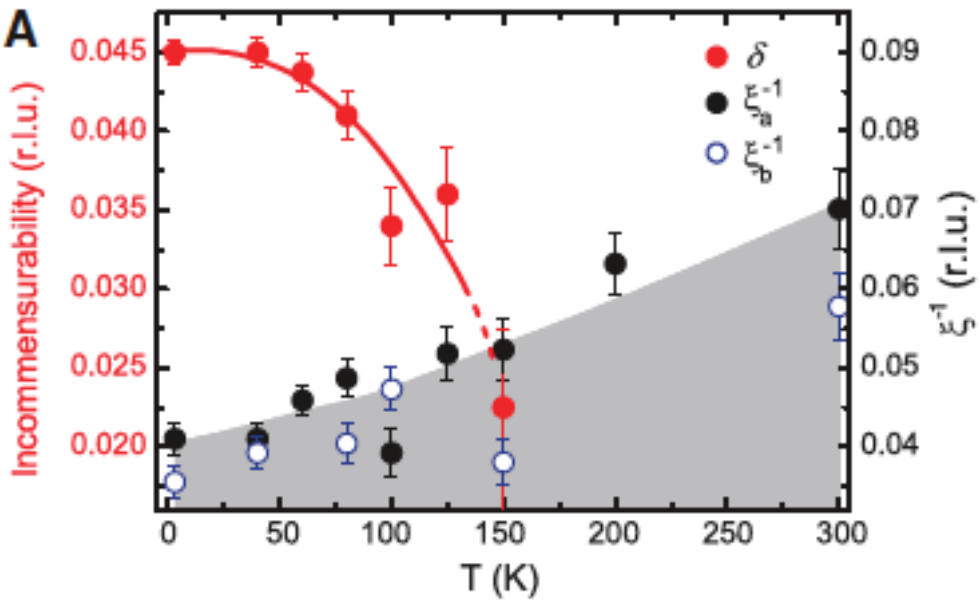
Is the Pseudogap a Nematic Phase?



Vojta, Adv. Phys. (2009)

Nematic Spin Response below T* (a ≠ b)

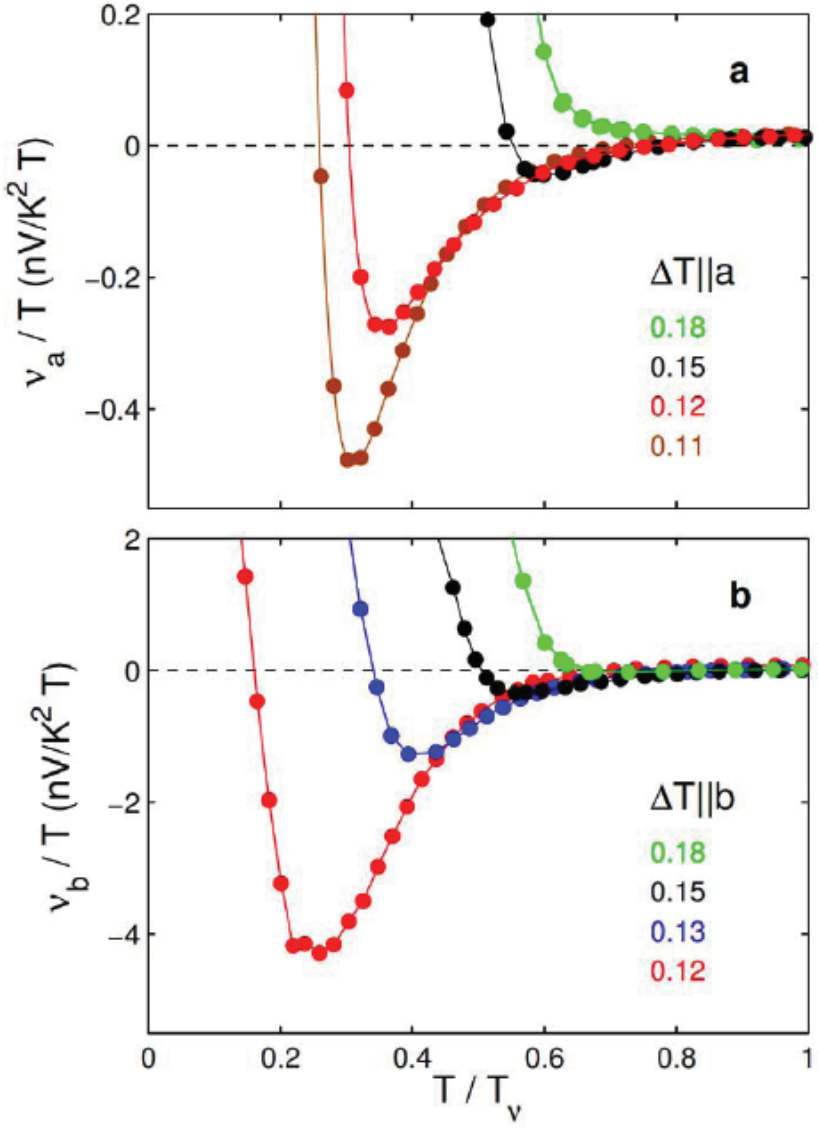


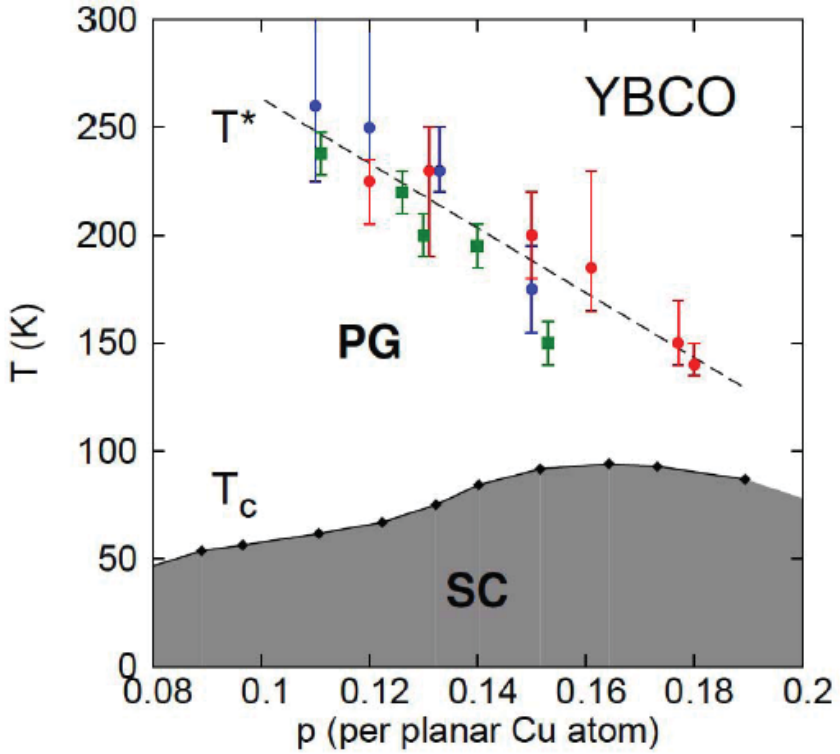


T_c=35K

Hinkov *et al*., Science (2008)

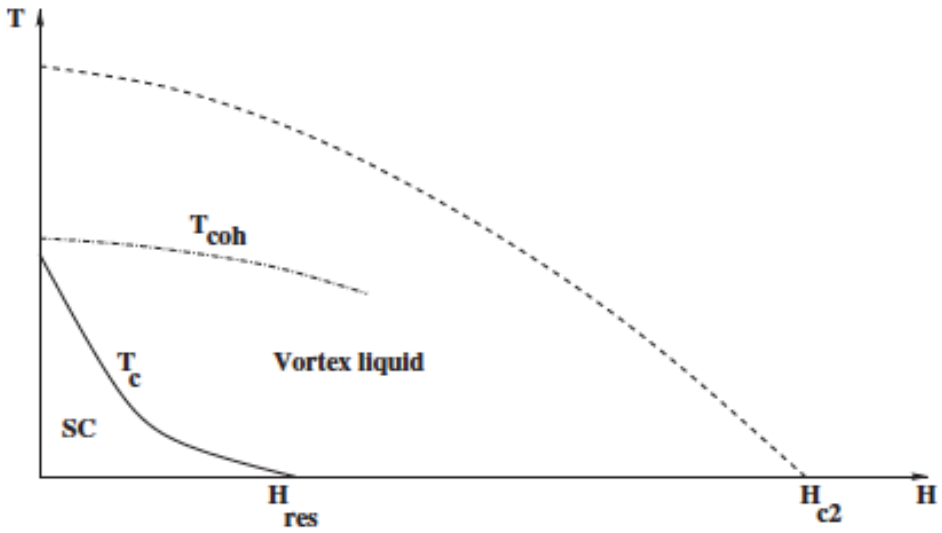
Anisotropic Nernst Signal below T* (a ≠ b)

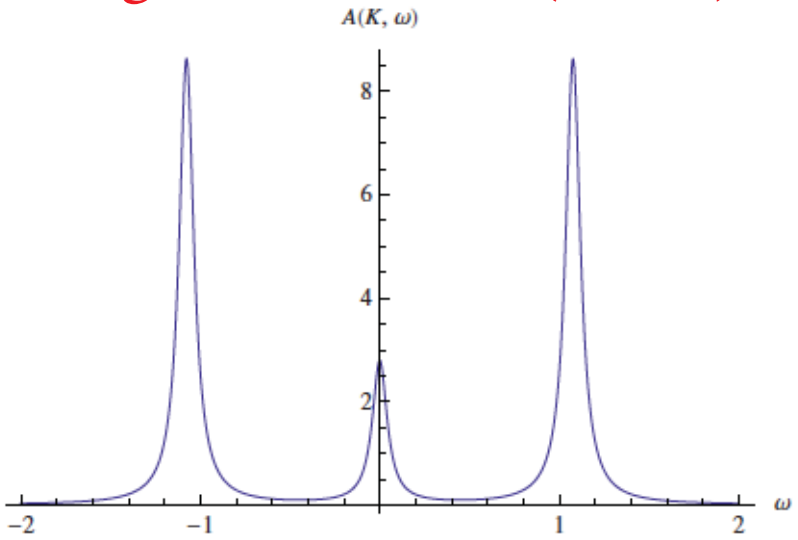


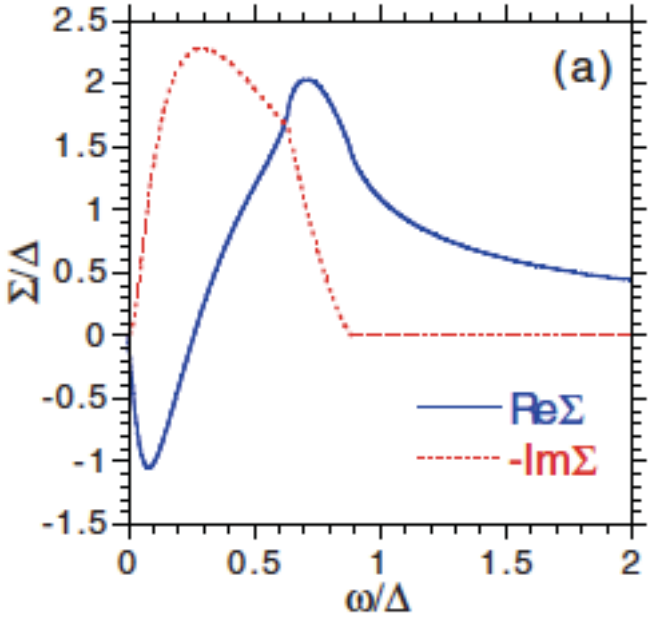


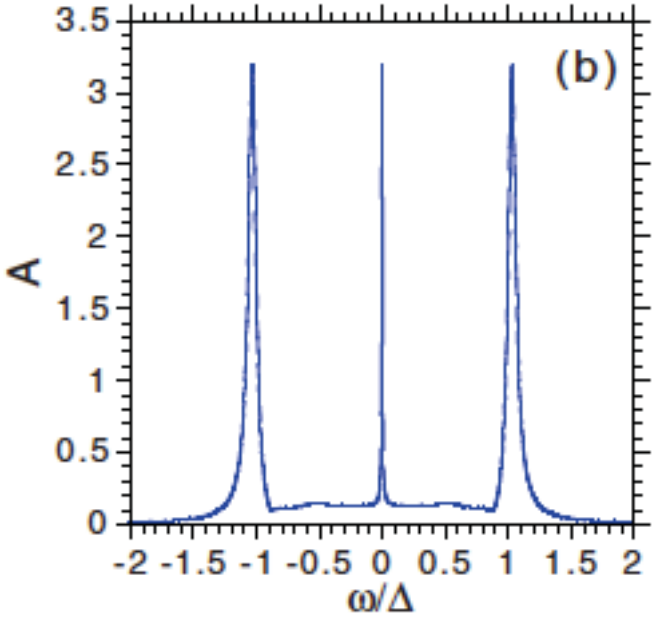
Daou *et al*., Nature (2010)

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









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

QUESTIONS

1. Are there electron pockets due to checkerboard charge order?
2. Are electron pockets consistent with ARPES and STM?
3. Is this an “epi” phenomenon?
4. Are there “arcs” due to a d-wave spin liquid phase?
5. What does all of this have to say about the origin of high T_c?