The Abdus Salam
International Centre for Theoretical Physics

2157-12

**Workshop on Principles and Design of Strongly Correlated Electronic Systems**

*2 - 13 August 2010*

# Competing Ground States in Cuprates: Disentangling Cooper-pair Formation above Tc from the Pseudogap State

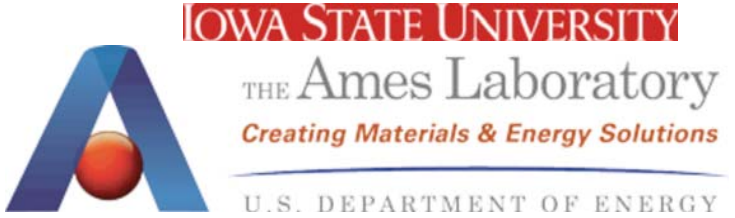
Adam KAMINSKI

*Ames Laboratory and Iowa State University*
*U.S.A.*

# Competing ground states in cuprates: disentangling Cooper-pair formation above $T_c$ from the pseudogap state

Adam Kamiński
Ames Laboratory and Iowa State University

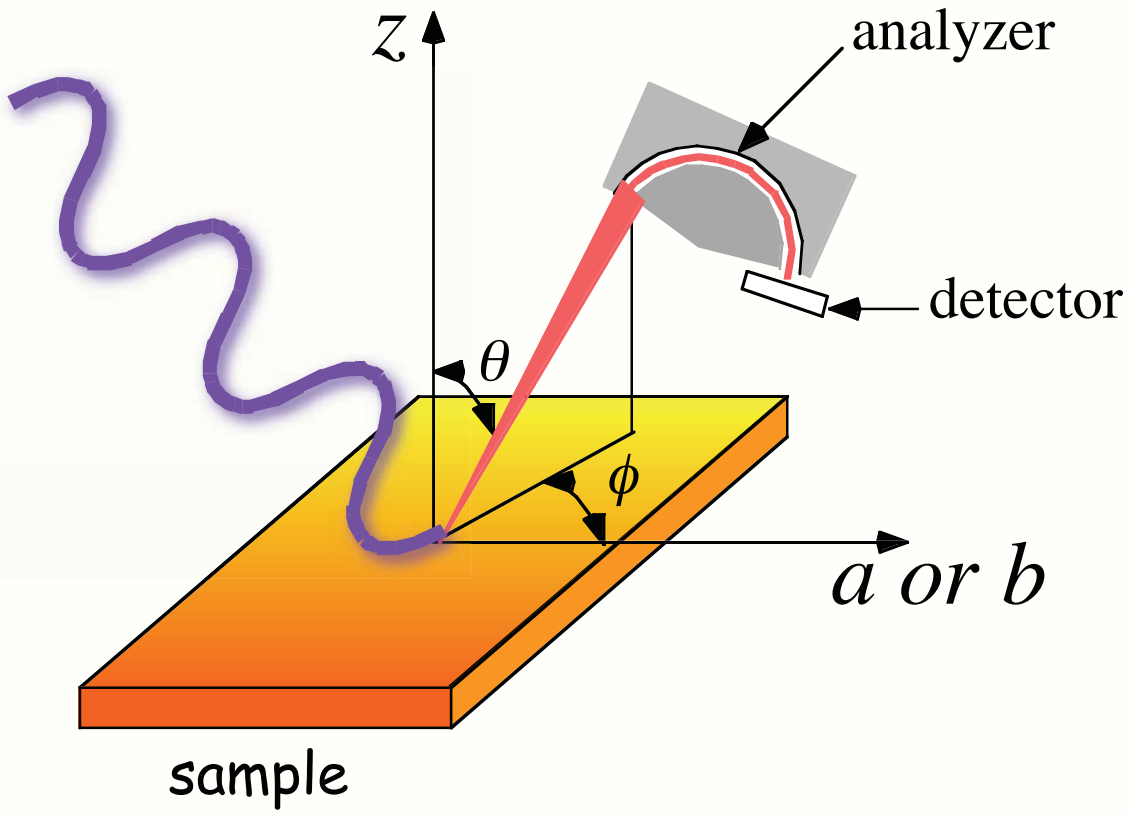
Funded by:
Office for Basic Energy Sciences
US Department of Energy

## Collaborators:

| | |
|---|---|
| Ames Laboratory and<br>Iowa State University | Takeshi Kondo, Jörg Schmalian<br>Ari Palczewski |
| Brookhaven National Lab | Genda Gu, J. S. Wen, Z. J. Xu |
| Paul Scherrer Institut: | Rustem Khasanov |
| Nagoya University: | Tsunehiro Takeuchi, Yoichiro Hamaya |
| Universität Zürich: | S. Strassle, H. Keller |

# Angle Resolved Photoemission Spectroscopy




We need:

binding energy - $E_b$

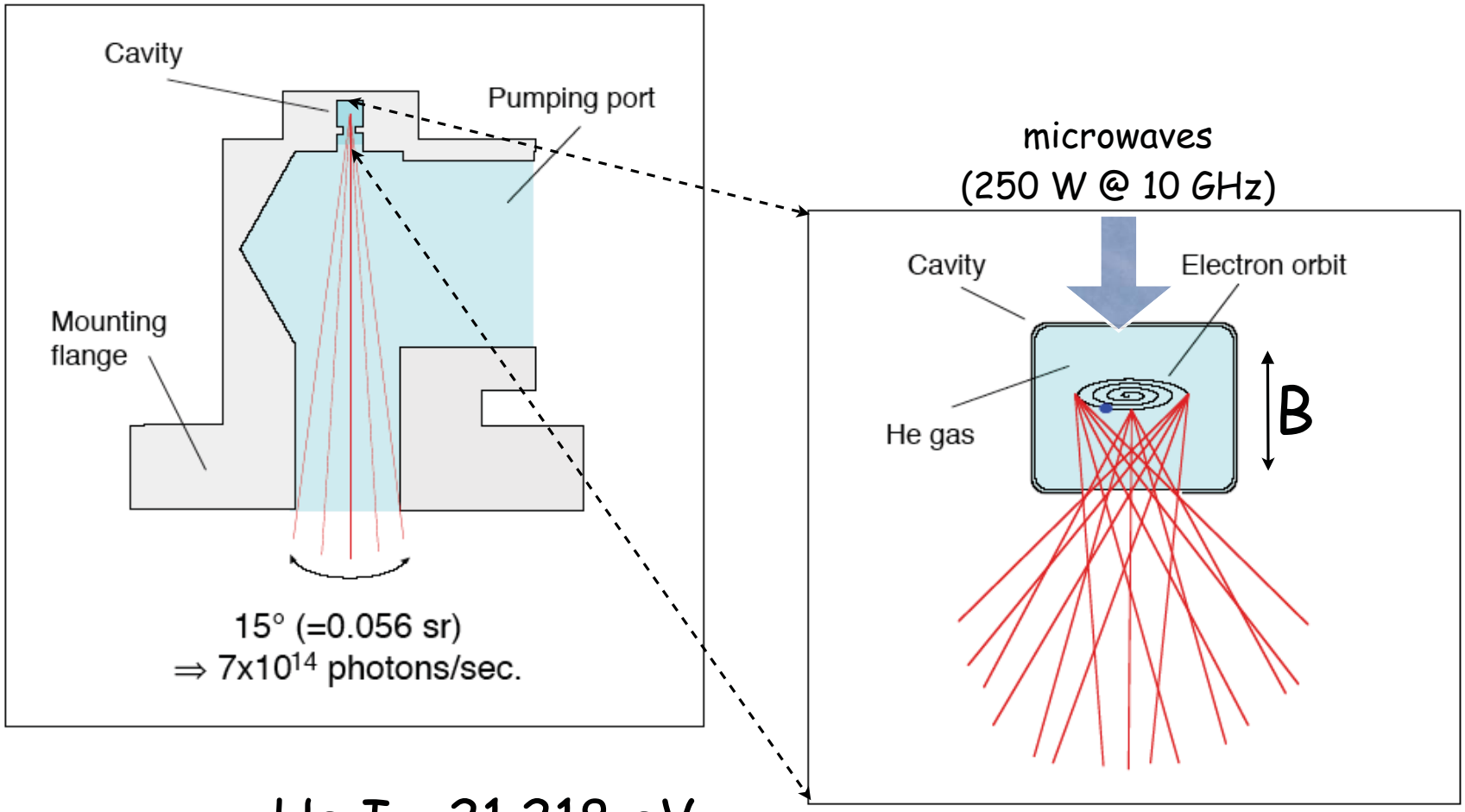
initial momentum - $k^i$

$$E_b = E - h\nu + W$$

$$k^i_{||} = k^f_{||} = \sqrt{2mE/\hbar^2}\sin\theta$$

$$k^i_{\perp} = k^f_{\perp} - G = \sqrt{2mE/\hbar^2}\cos\theta - G$$

# Helium ECR lamp

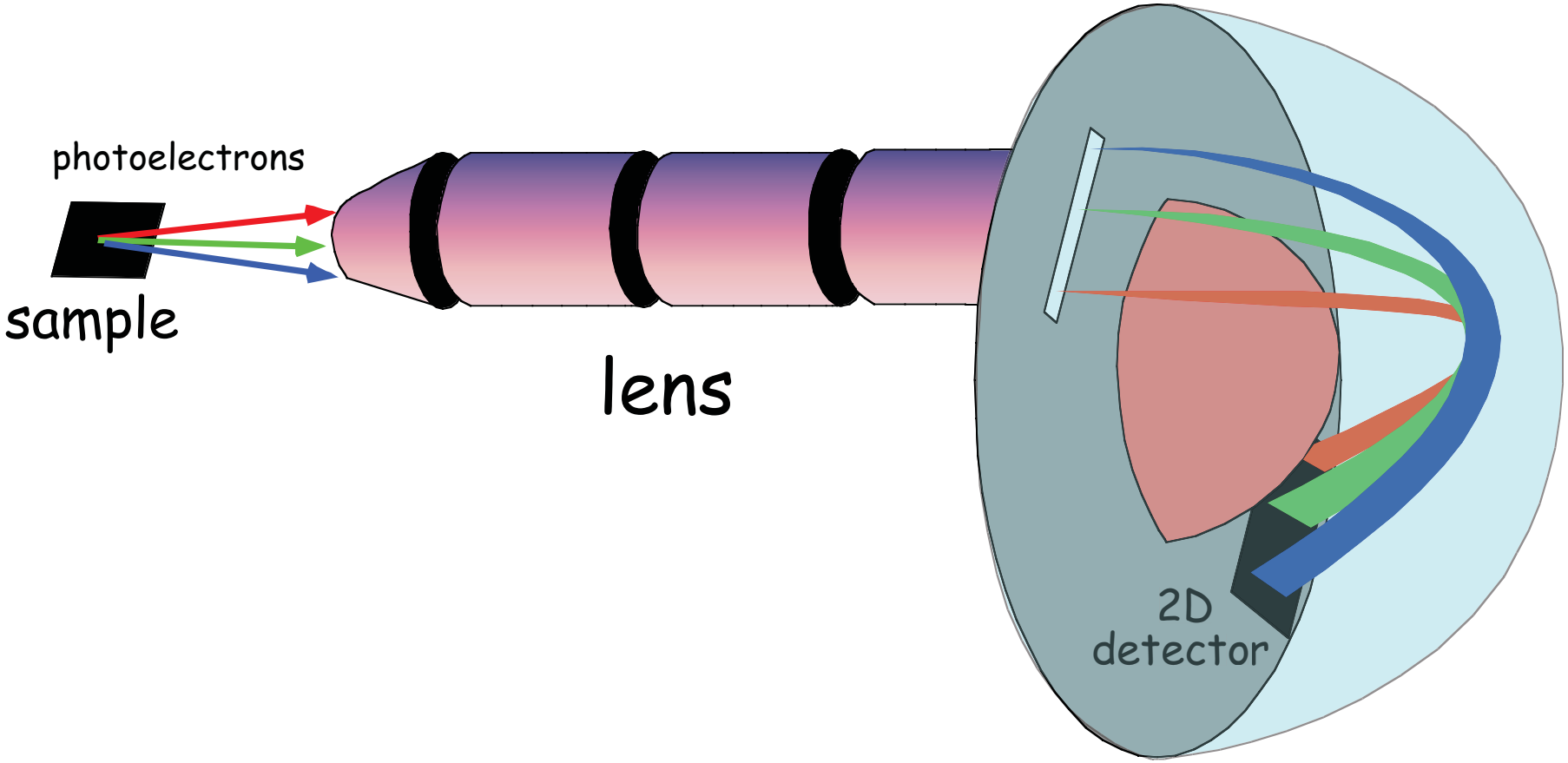



He I - 21.218 eV

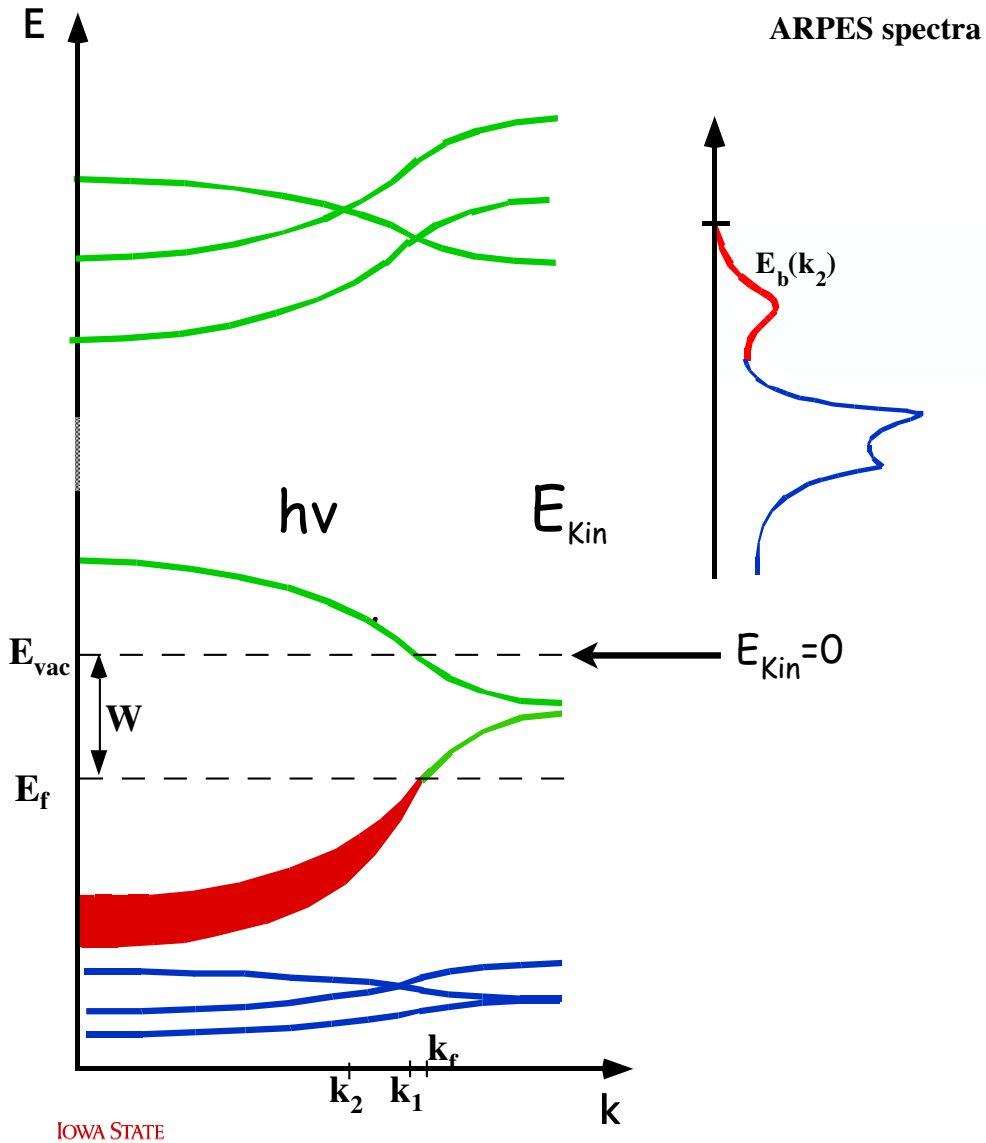
He I - 23.087 eV

He II - 40.823 eV

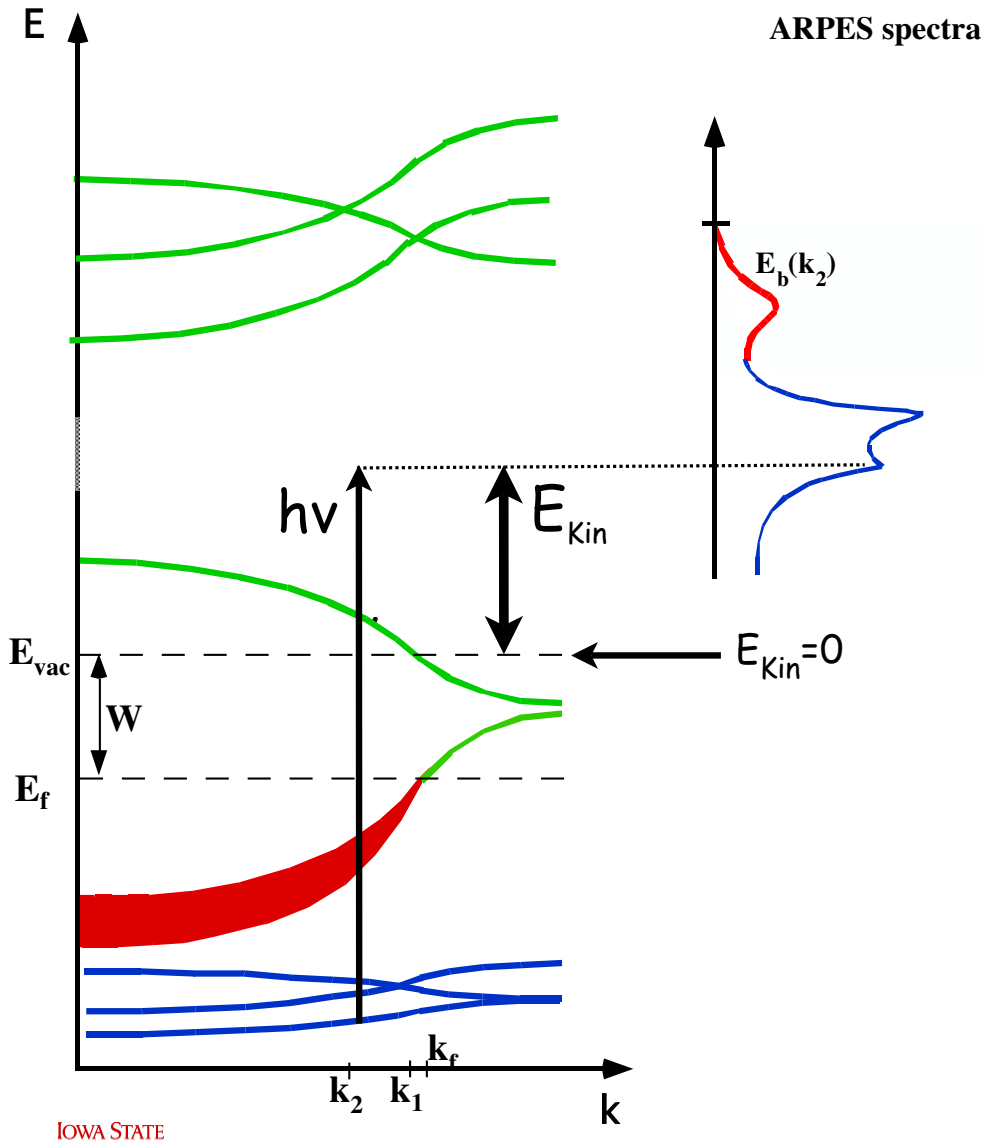
# Electron analyzer



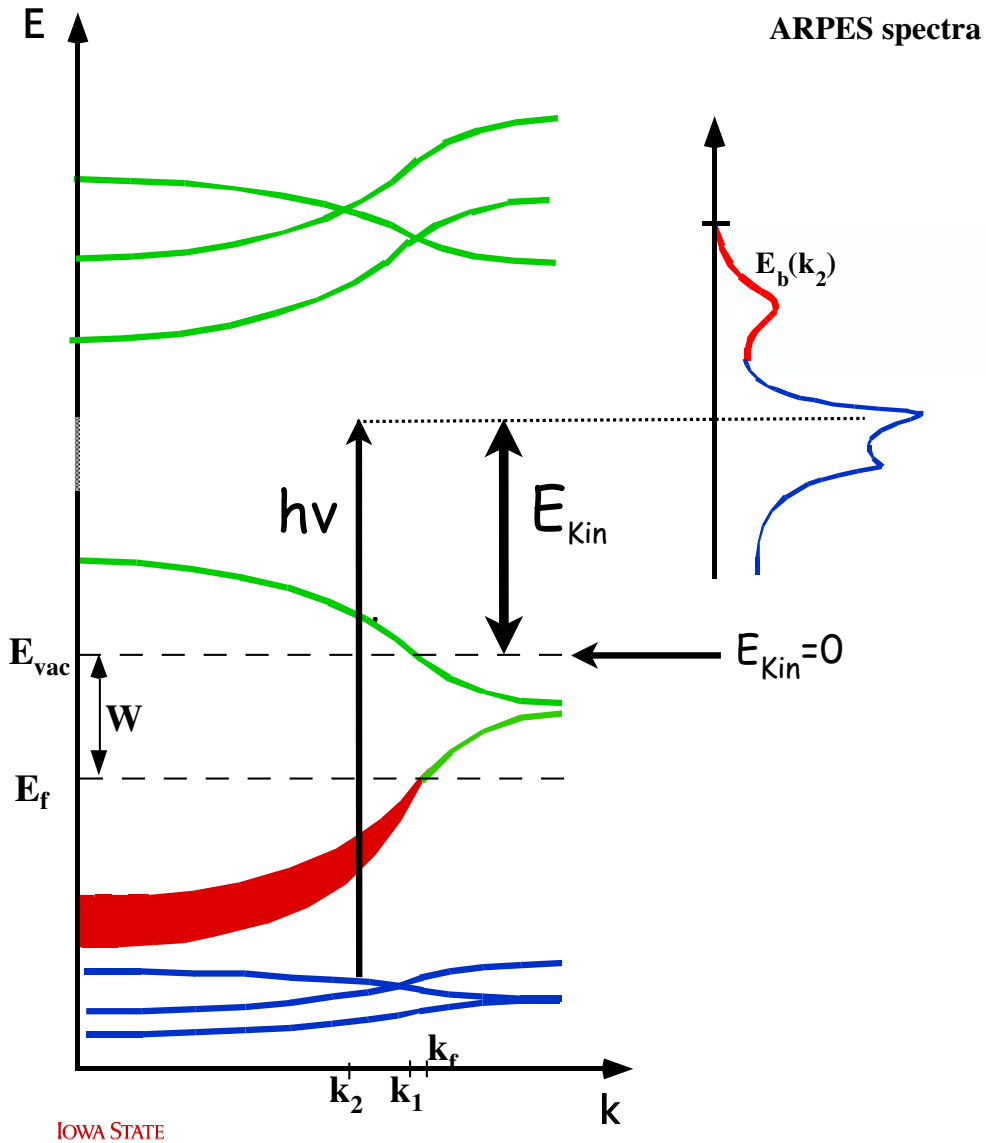
## Electronic structure



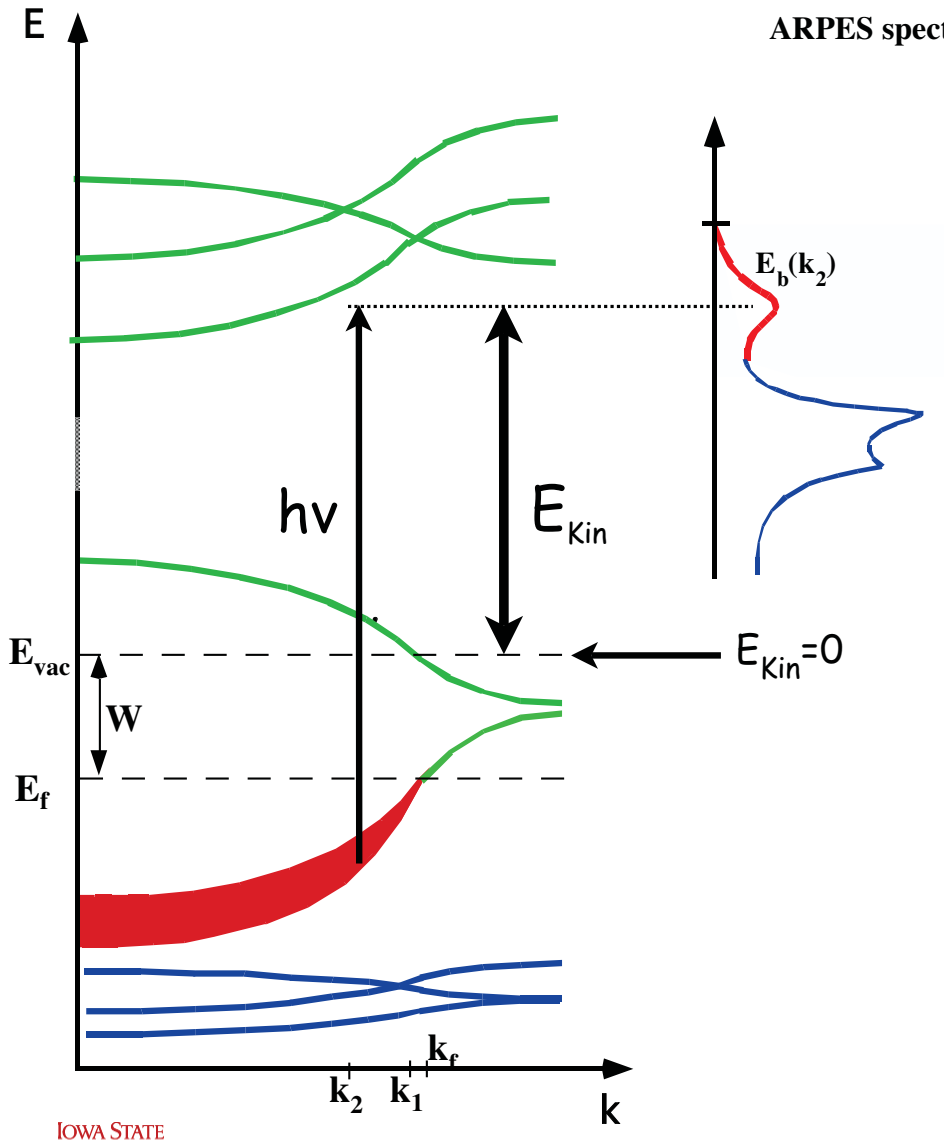
## Electronic structure



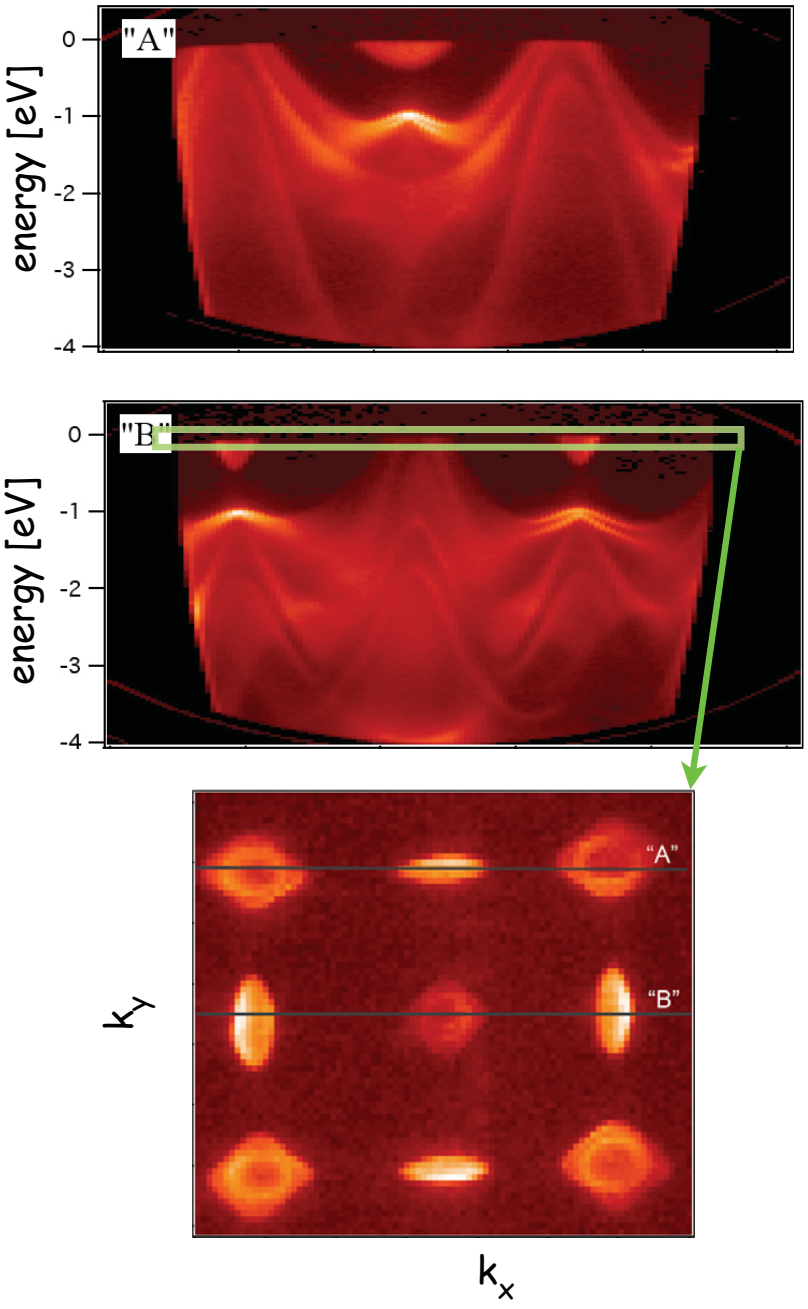
## Electronic structure



## Electronic structure

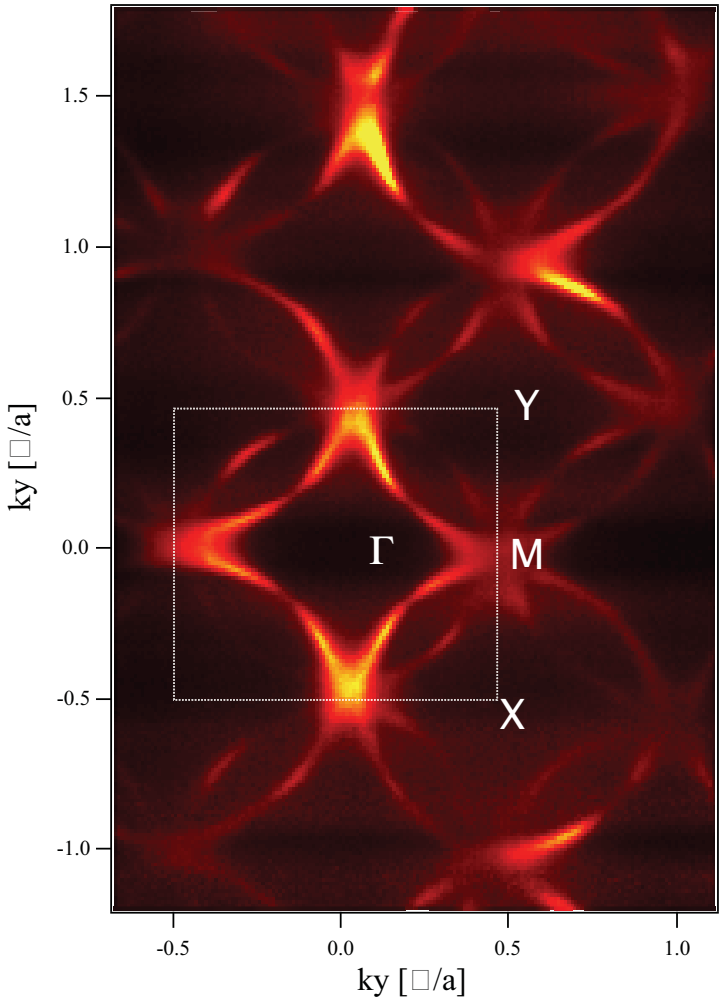



ARPES spectra

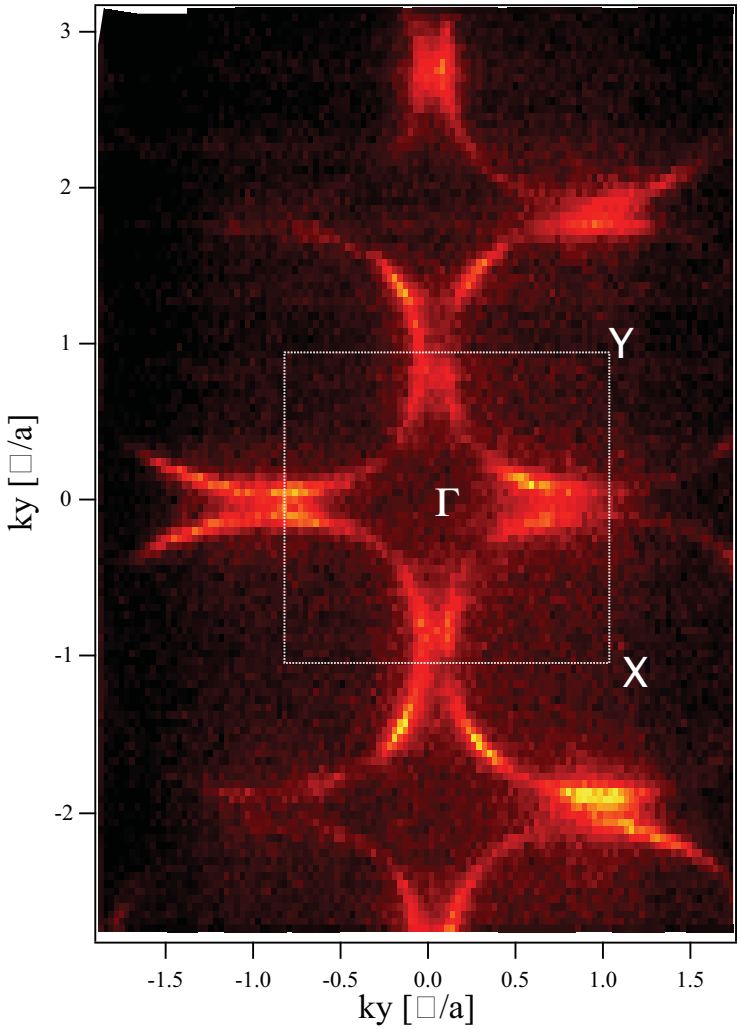


# Fermi surface of high temperature superconductor

$Bi_2Sr_2Cu_1O_{6+x}$ (Tc=35K)



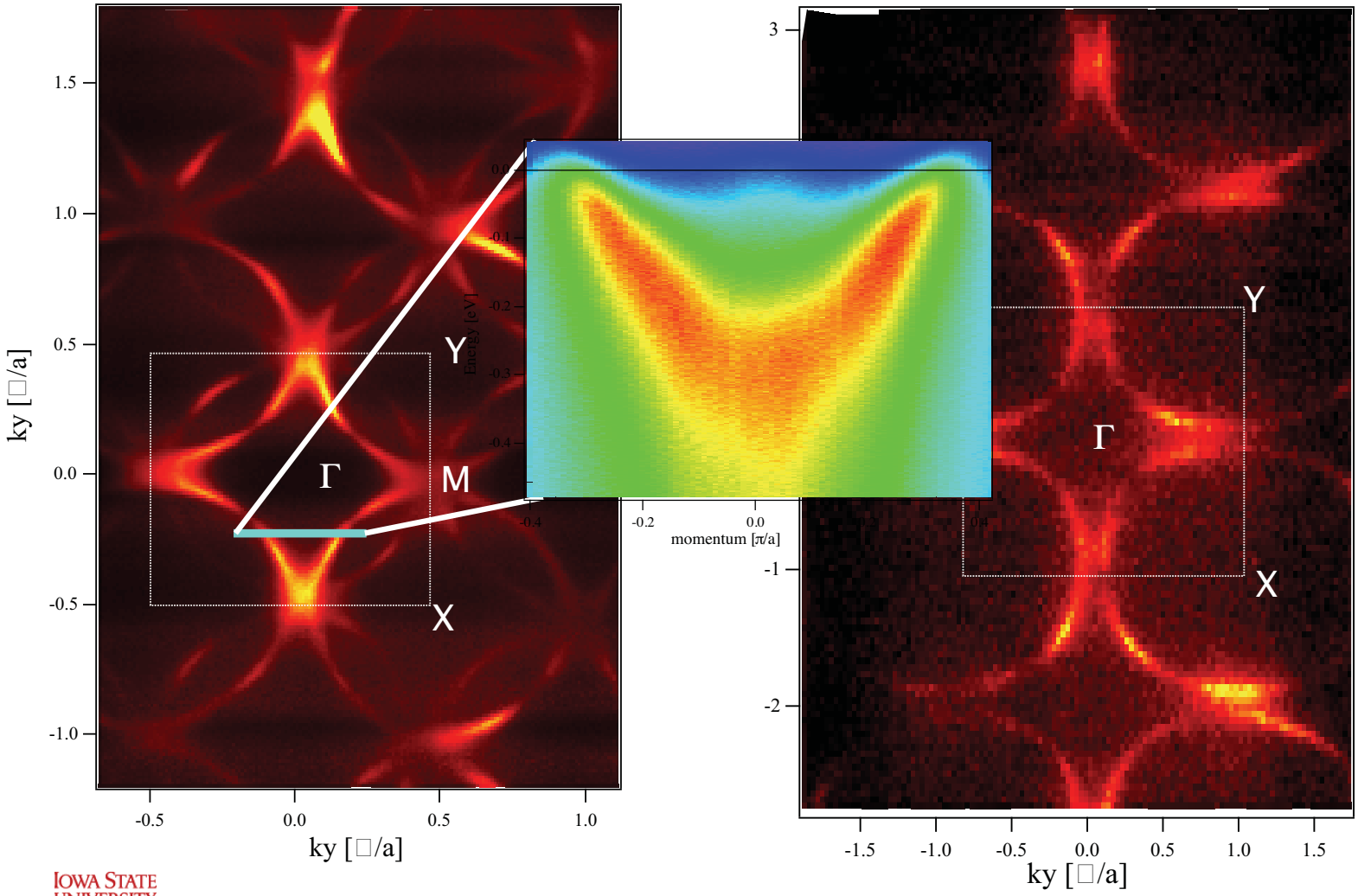

$Tl_2Ba_2Cu_1O_{6+x}$(Tc=90K)




IOWA STATE UNIVERSITY
AMES LABORATORY

# Fermi surface of high temperature superconductor

$Bi_2Sr_2Cu_1O_{6+x}$ (Tc=35K)




$Tl_2Ba_2Cu_1O_{6+x}$ (Tc=90K)

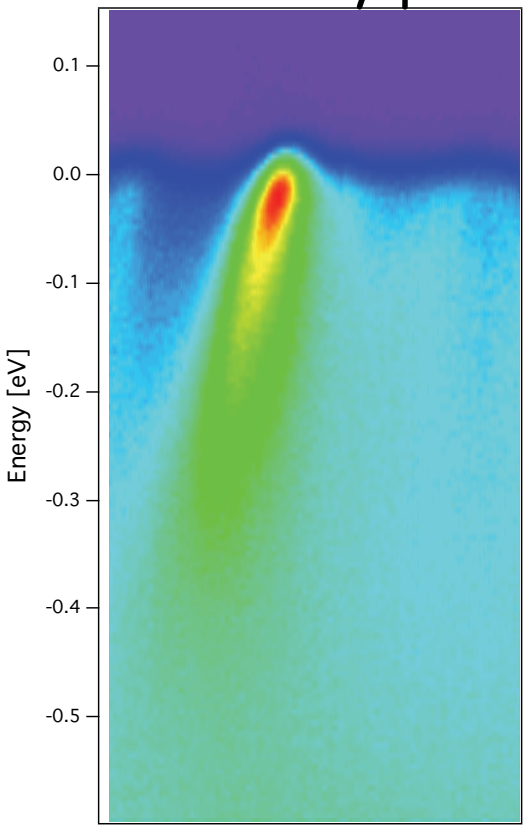
# ARPES intensity

$$I = \langle \Psi_i | \mathbf{A}\cdot\mathbf{p} | \Psi_f \rangle^2 A(k,\omega) f(\omega)$$

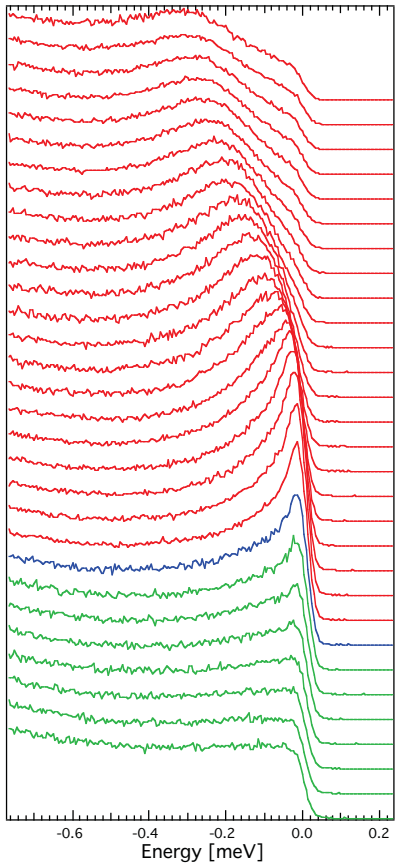
symmetry of $\Psi$

electronic structure + interactions

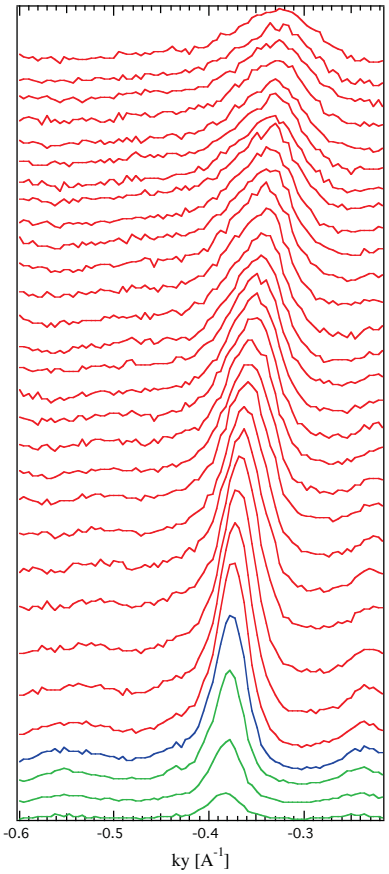
Intensity plot

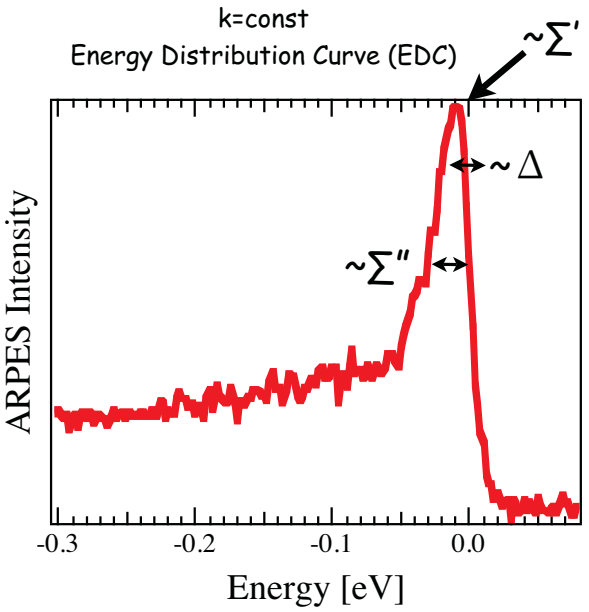


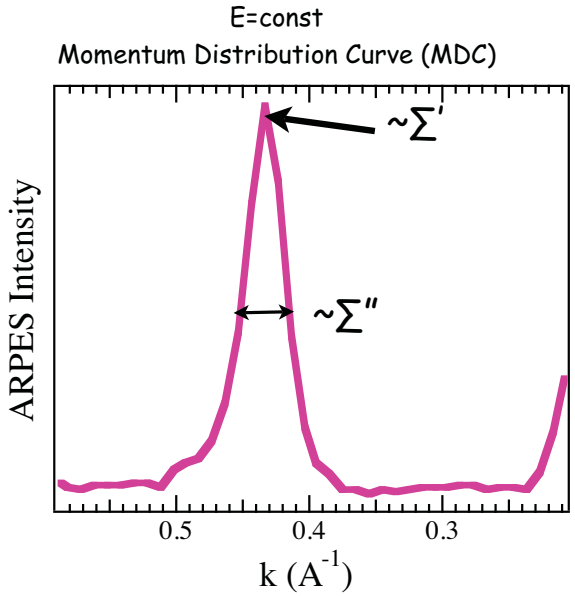

EDC




MDC

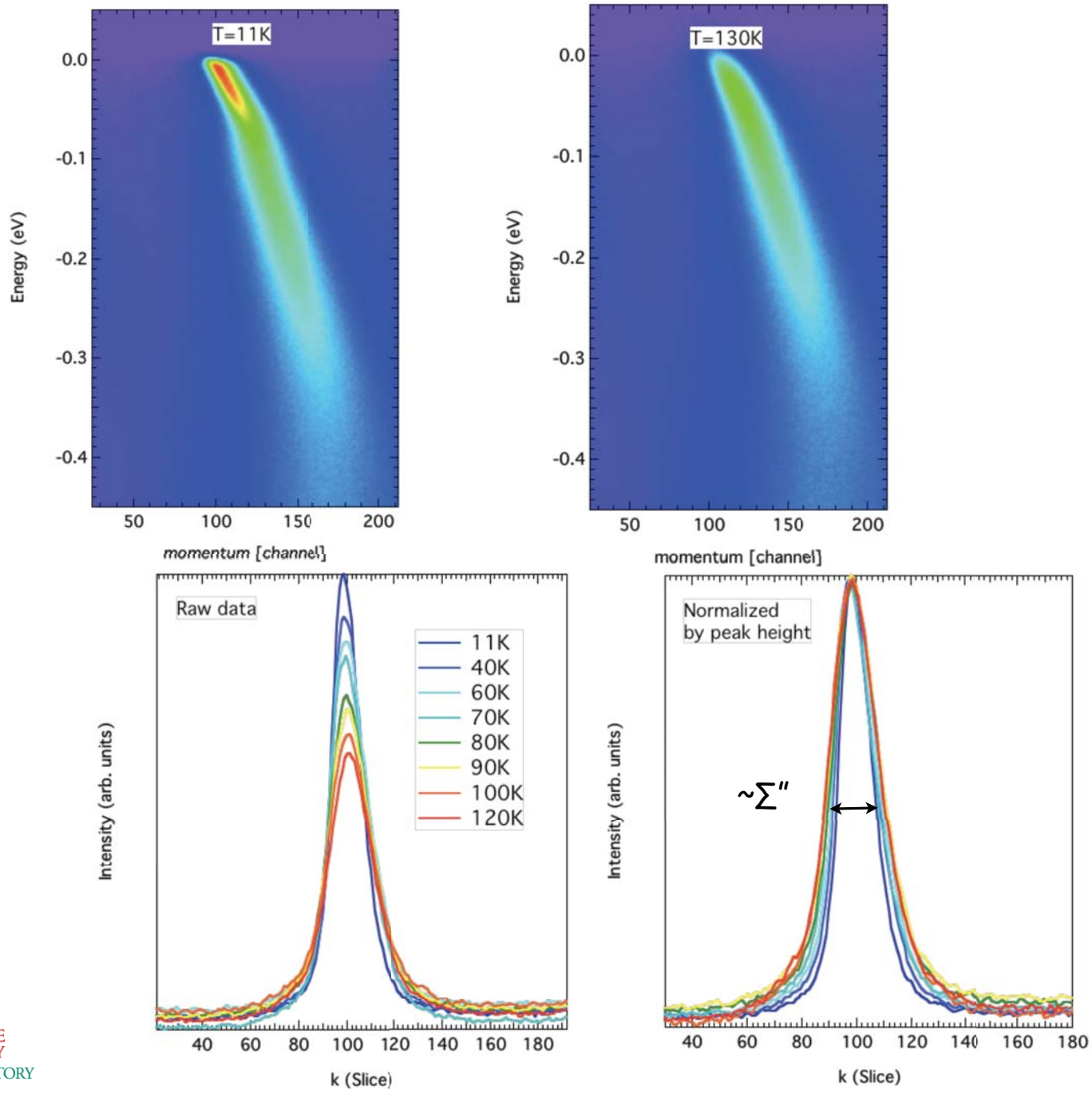


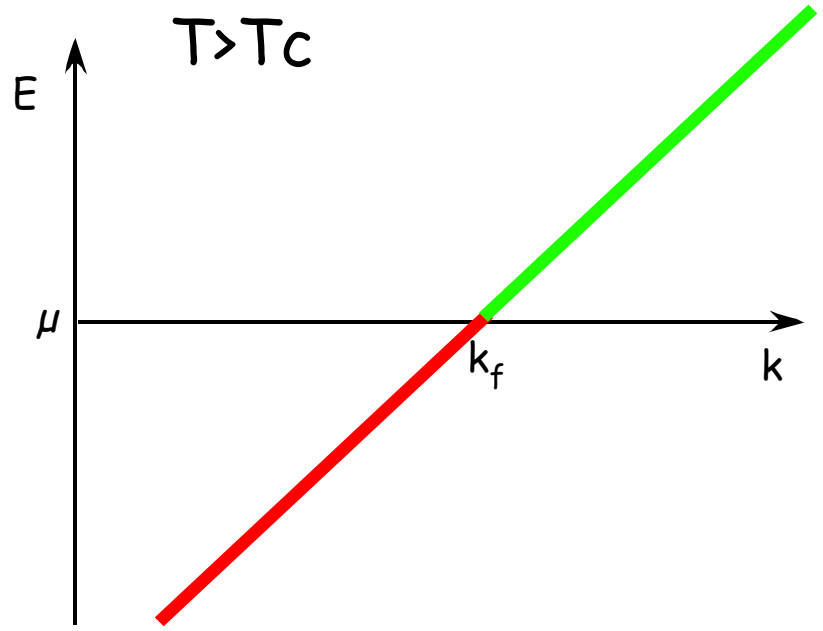





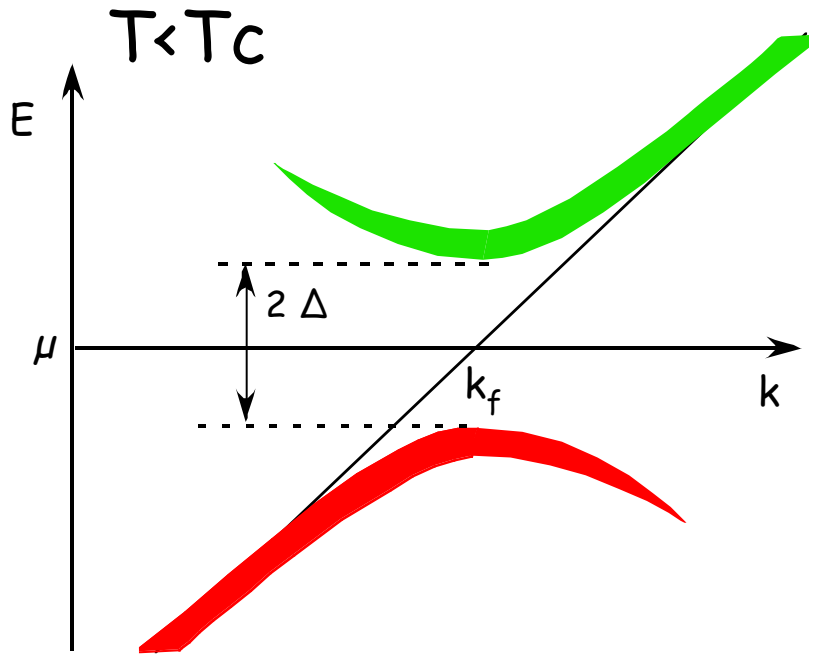
IOWA STATE UNIVERSITY
AMES LABORATORY

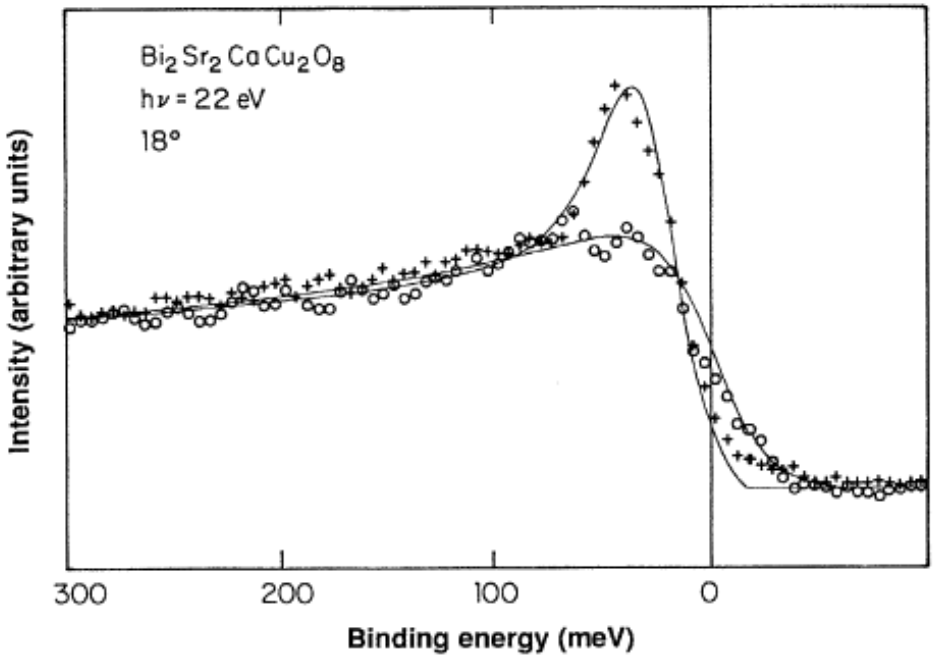

T=11K
T=130K
Energy (eV)
0.0
-0.1
-0.2
-0.3
-0.4
50
100
150
200
momentum [channel]
Raw data
Normalized
by peak height
11K
40K
60K
70K
80K
90K
100K
120K
Intensity (arb. units)
~Σ"
40
60
80
100
120
140
160
180
k (Slice)

# Superconducting energy gap



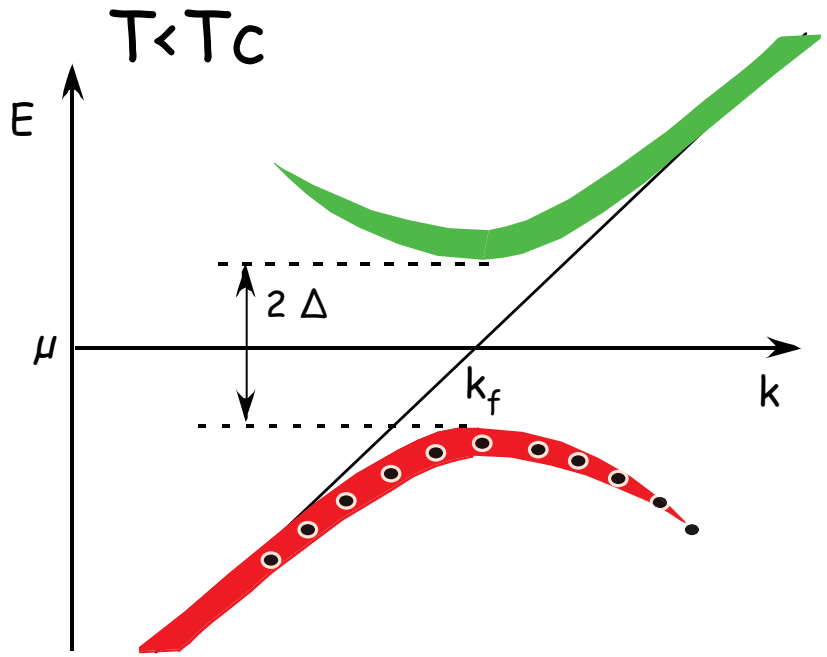
# Superconducting energy gap

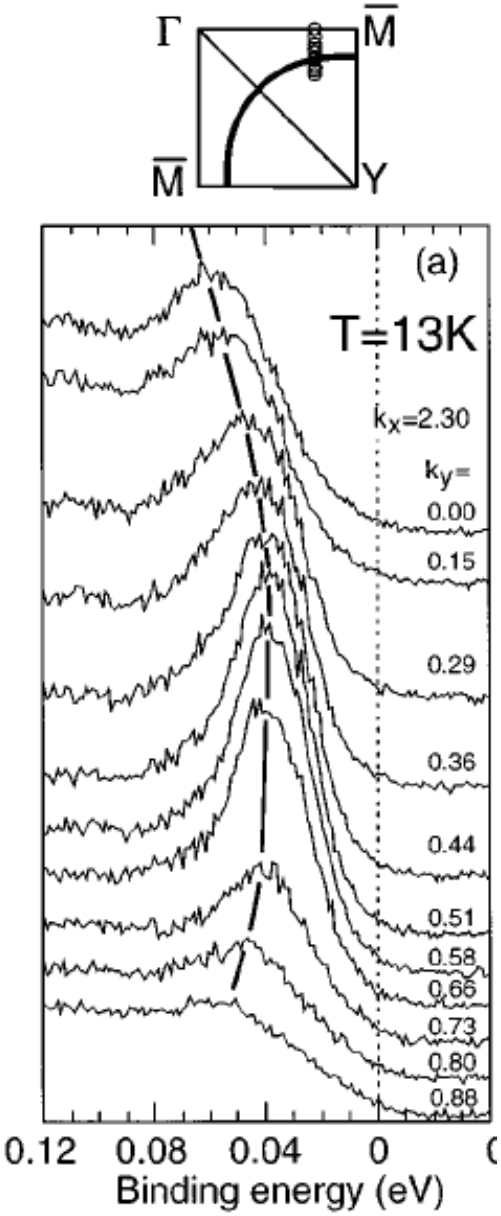



C. G. Olson *et al.,* Science **245,** 731-733 (1989)

# Superconducting energy gap

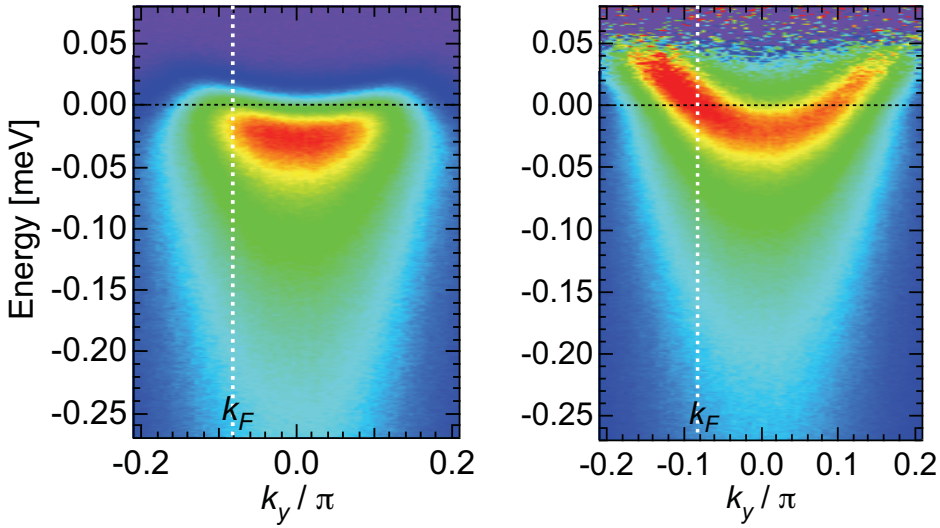


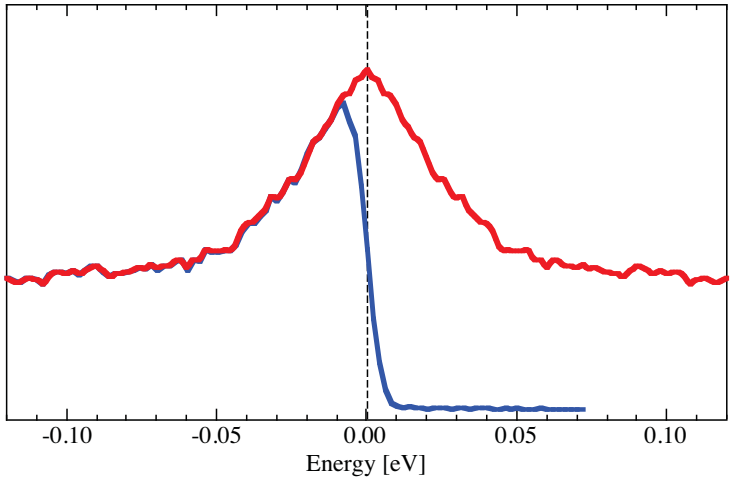
# Divide or symmetrize?

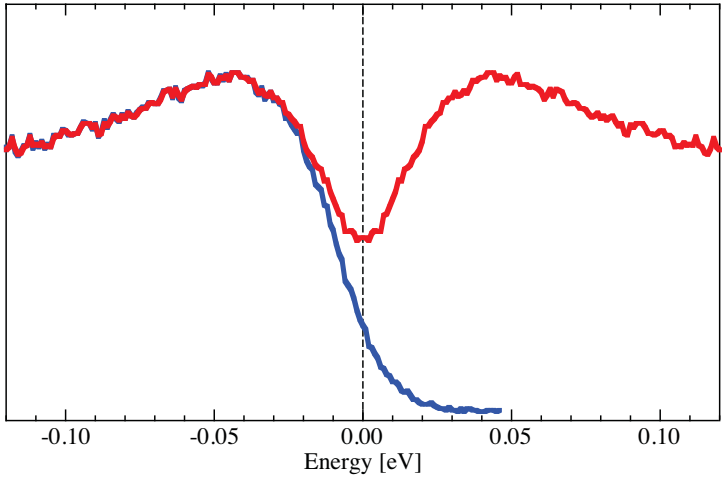
$$I \sim A(k,\omega) f(\omega)$$

$$f(-\omega) = 1-f(\omega)$$



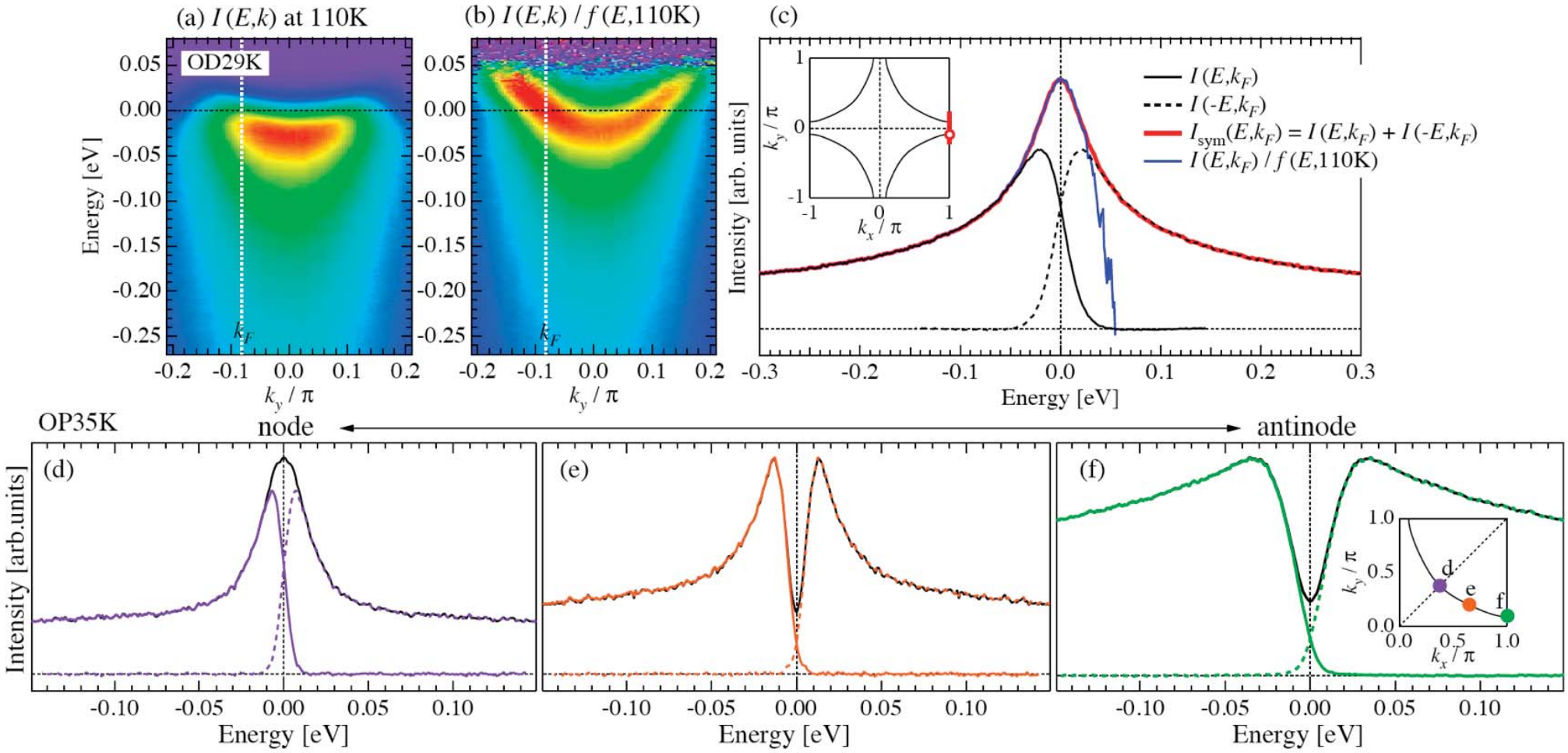

$$S \sim A(k_f,\omega) f(\omega)+A(k_f,-\omega) f(-\omega) = A(k_f,\omega)$$

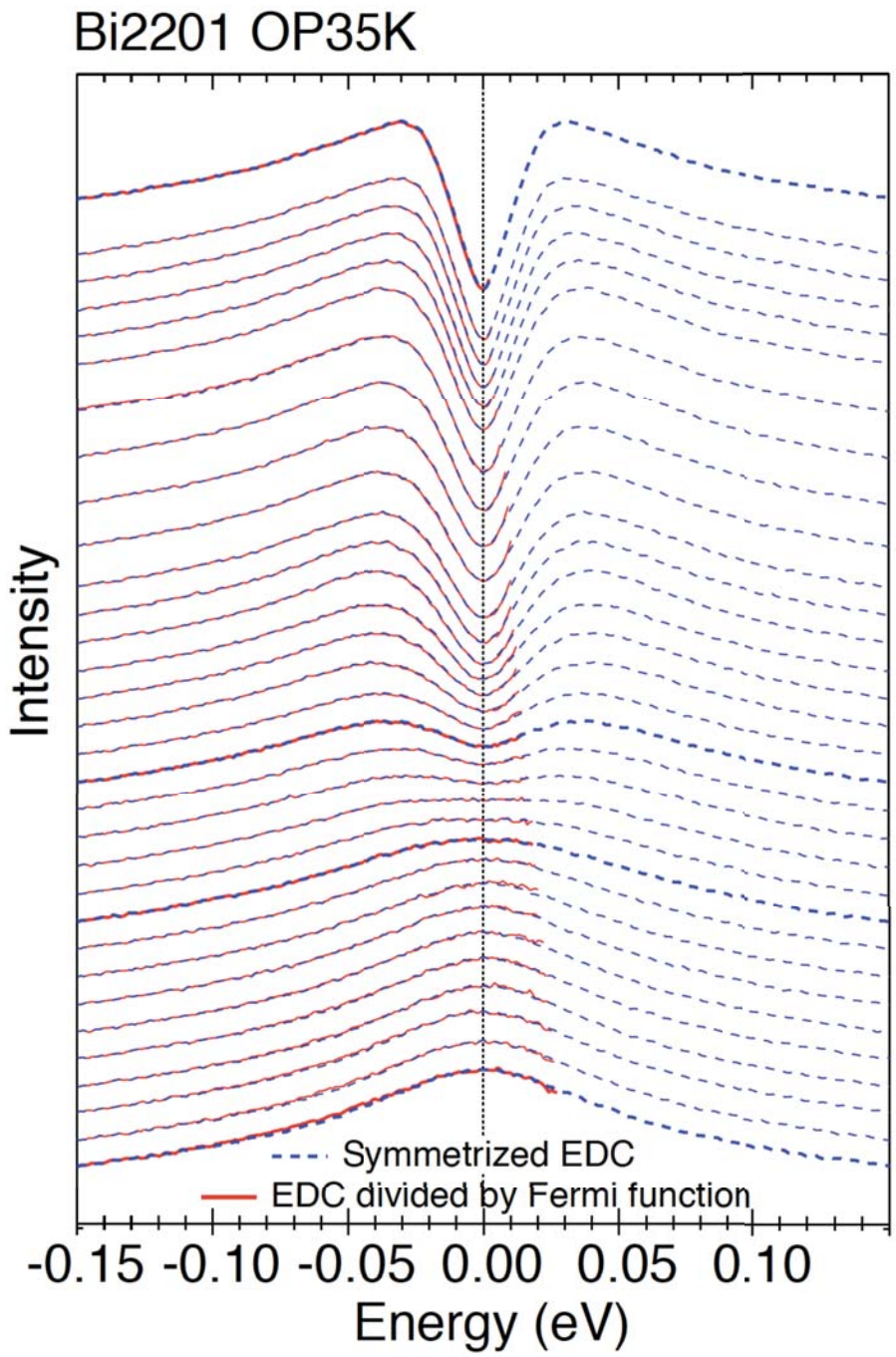



M. R. Norman et al., *Nature* **392**, 157 (1998)

# Details of symmetrization procedure





# High precision lab-based ARPES system

Energy resolution: ~1 meV

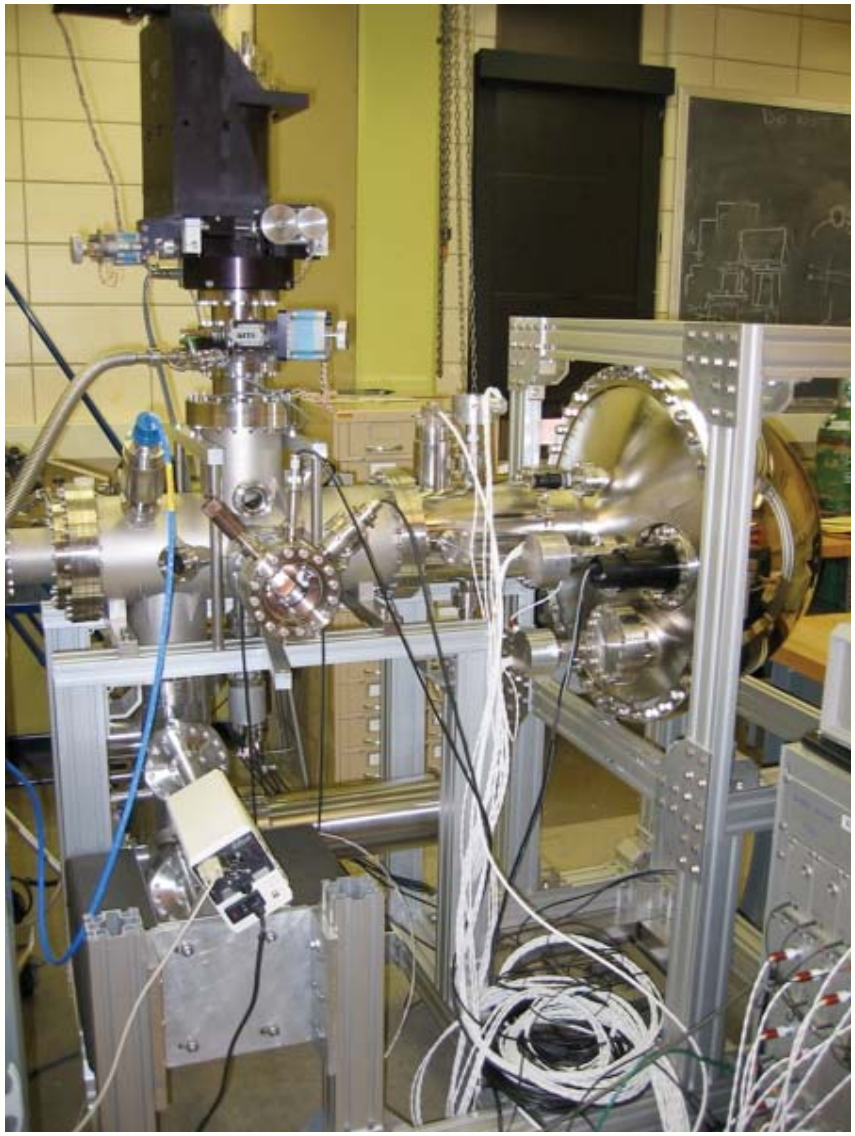
Angular resolution: 0.1 deg.

UV source: $10^{13}$ photons/sec.

Sample positioning:~1$\mu$m

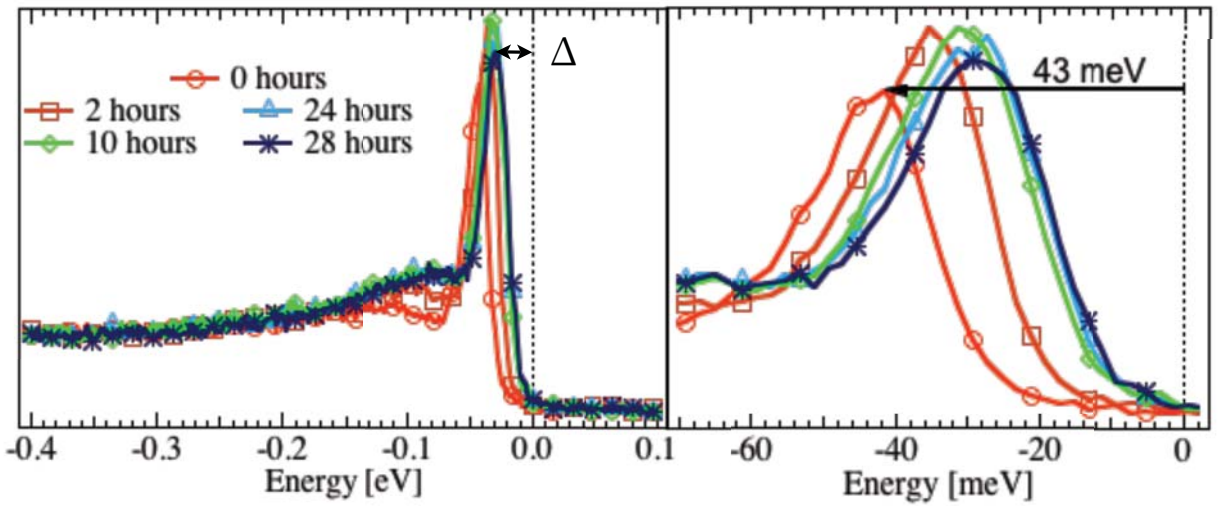
Ability to perform quantitative measurements of spectral intensity

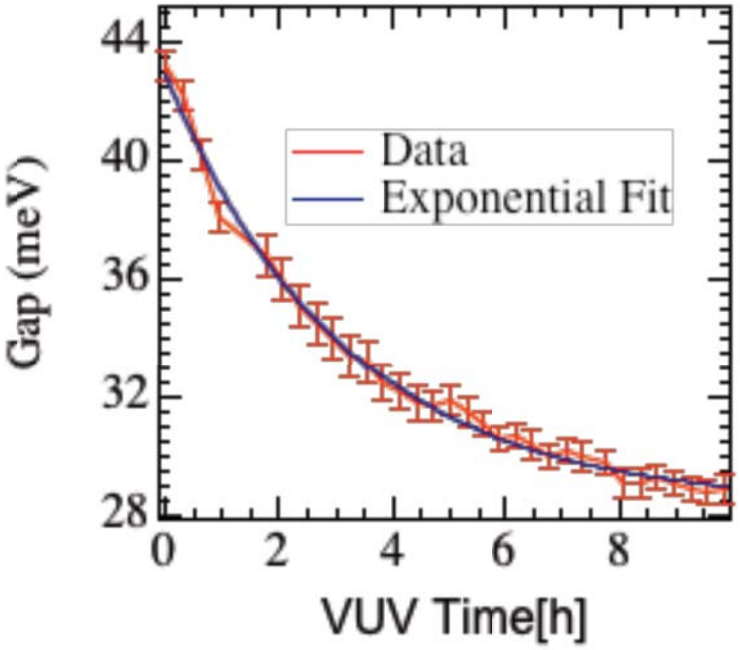
<u>Sample lifetime (Bi2212) ~ 2 weeks</u>



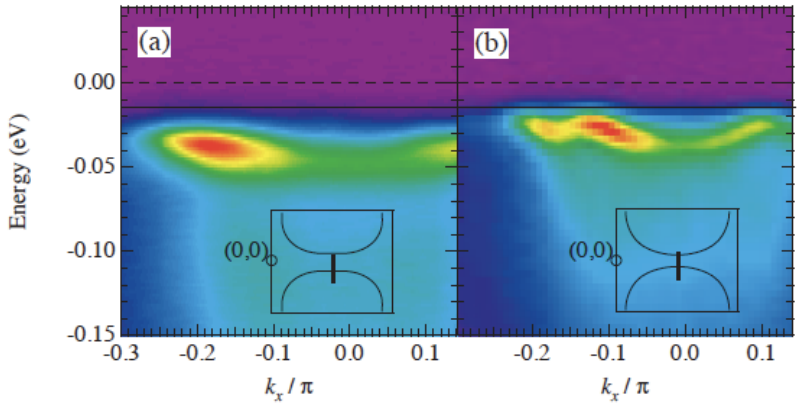
# Sample aging due to $CO_2$ absorption when vacuum is less than perfect

OP Bi2212 Tc=95K



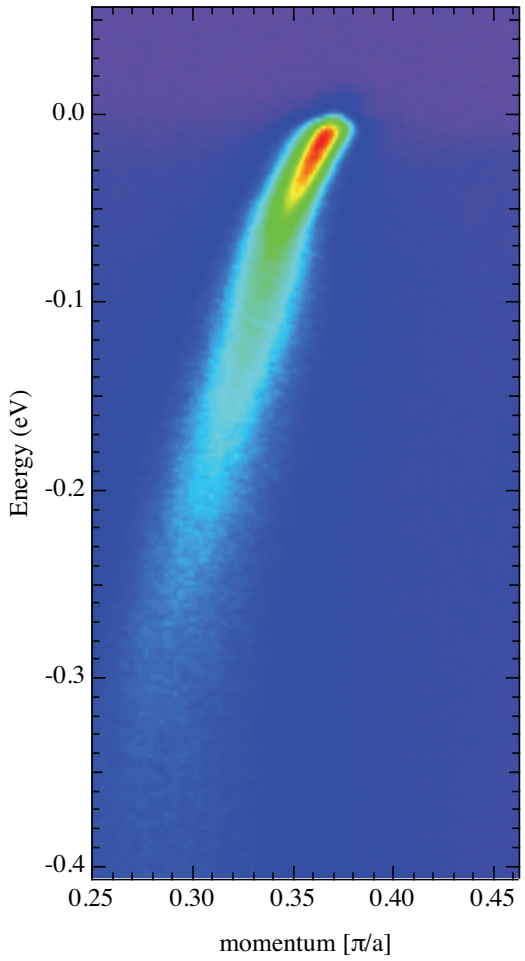

as cleaved 24 hours later



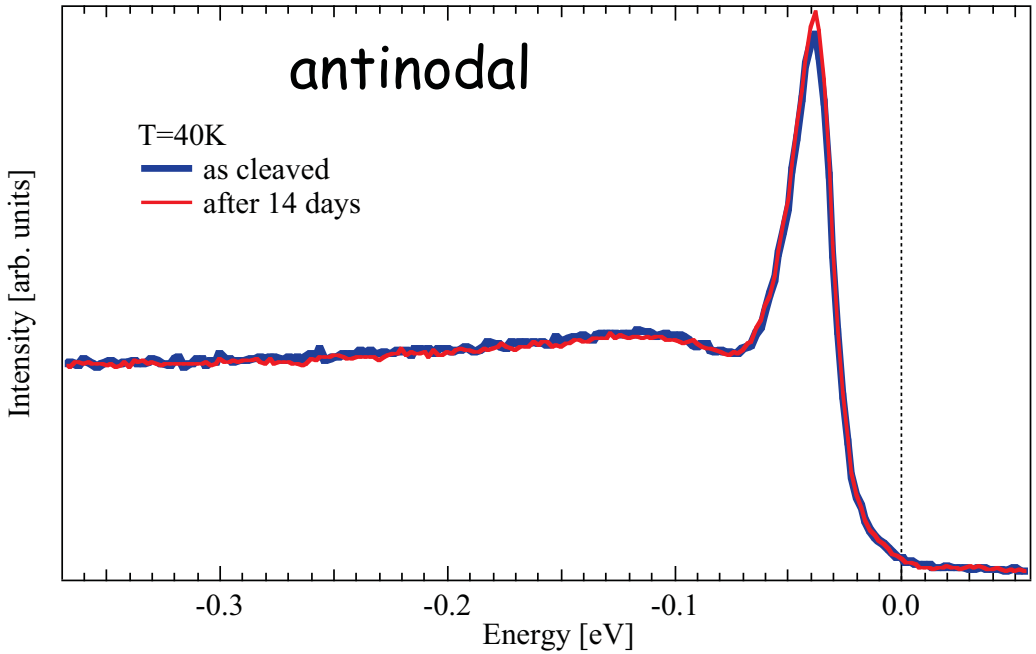

A. Palczewski et al.,
Phys. Rev. B **81**, 104521 (2010)

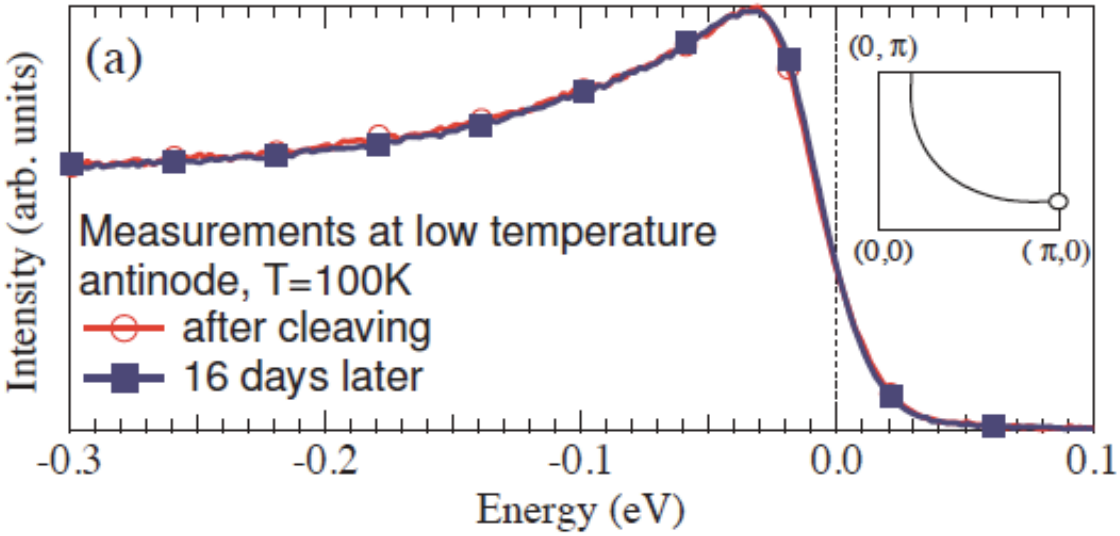
# Benchmark: optimally doped Bi2212

nodal data




antinodal

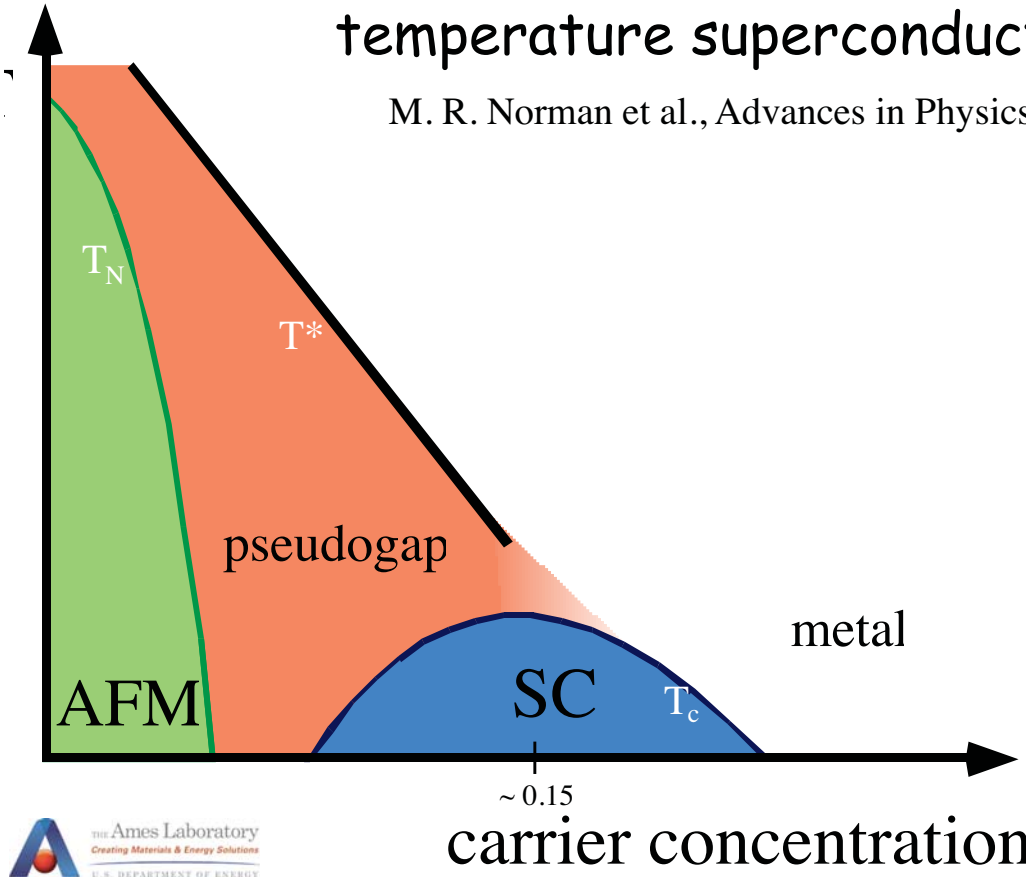


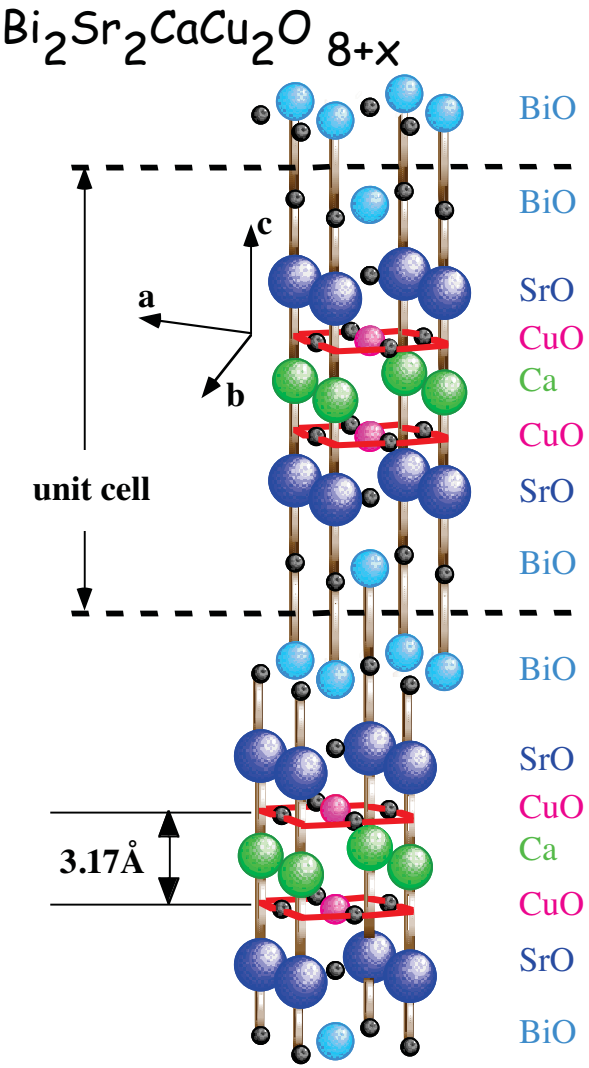



# Phase diagram of cuprates

The pseudogap: friend or foe of high temperature superconductivity?

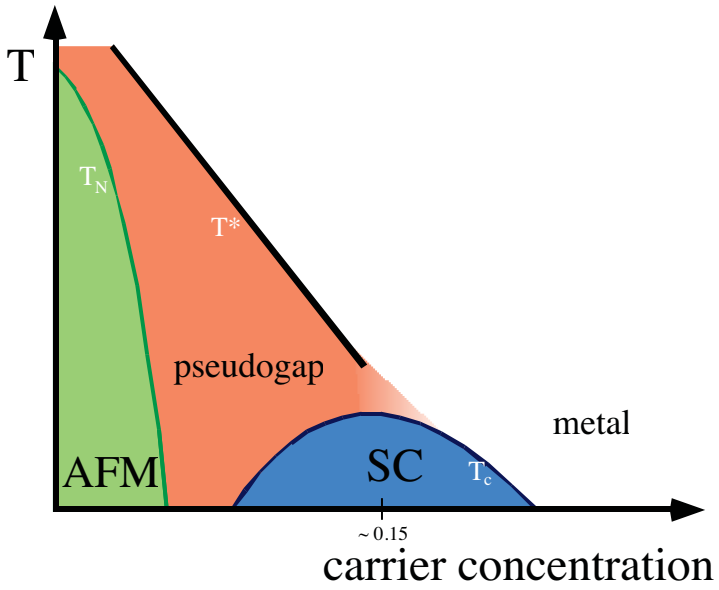
M. R. Norman et al., Advances in Physics, 54:8, 715 (2005)



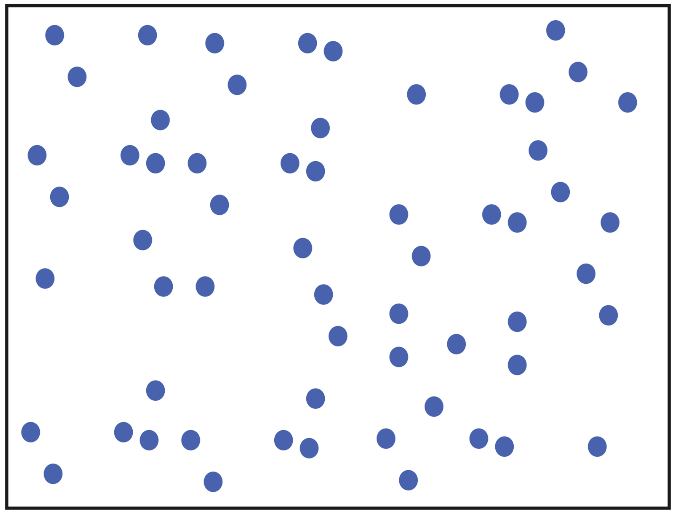



# Possible origin of the pseudogap: pre-formed pair scenario

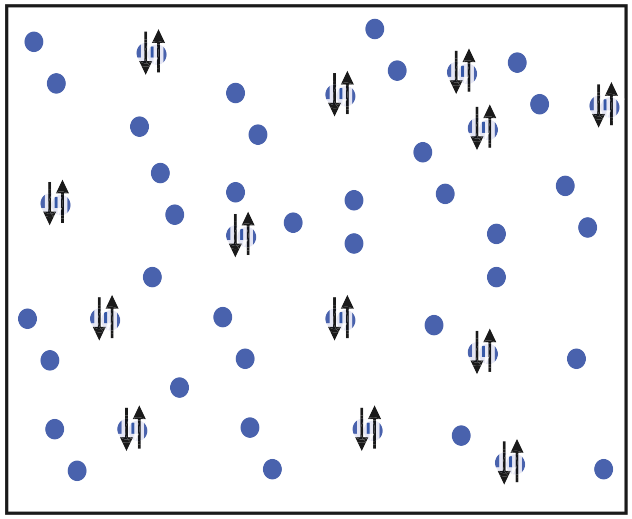
Emery and Kivelson



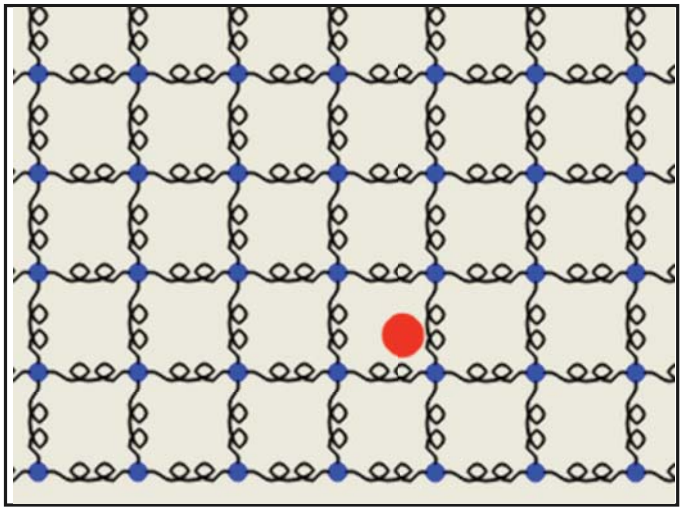

$T>T^*$



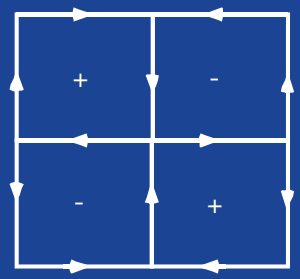
$T^*>T>T_c$



$T<T_c$



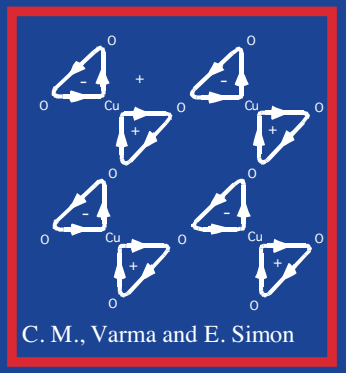
# Possible origin of the pseudogap: ordered state



T. C. Hsu, J. B. Marston, I. Affleck,
*Phys. Rev.* B **43**, 2866 (1991)

S. Chakravarty et al.,
*Phys. Rev. B* **63**, 094503 (2001)

C. M., Varma,
*Phys. Rev.* B **55**, 14554 (1997).



C. M., Varma and E. Simon

Charge Density Wave

Ordered Dimer State

L. Balents, et al.. *Phys. Rev. B* (2005)

Neutron scattering:
H. A. Mook et al. PRB (2002, 2004)

Quantum oscillations:
N. Doiron-Leyraud et al. Nature (2007)
D. LeBoeuf et al. Nature (2007)
S. Sebastian et al. Nature (2008)

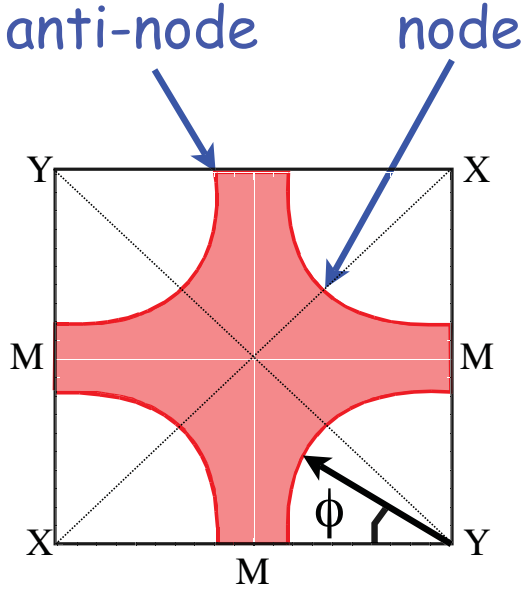
Dichroism in ARPES:
A. Kaminski et al. Nature (2002)

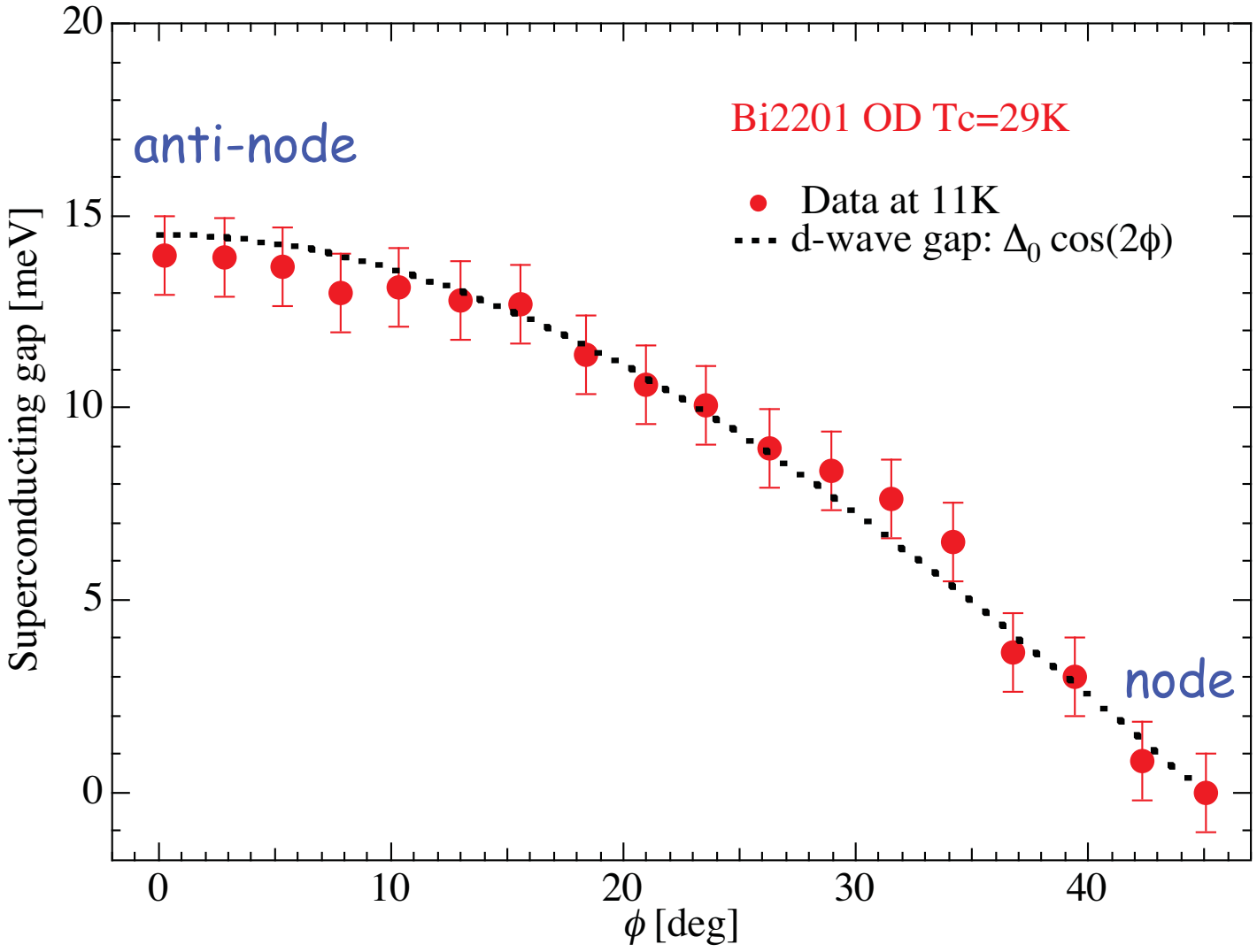
Neutron scattering
B. Fauqué et al. PRL (2006)
H. A. Mook et al. arXiv: 0802.3620
Y. Li et al. arXiv: 0805.2959

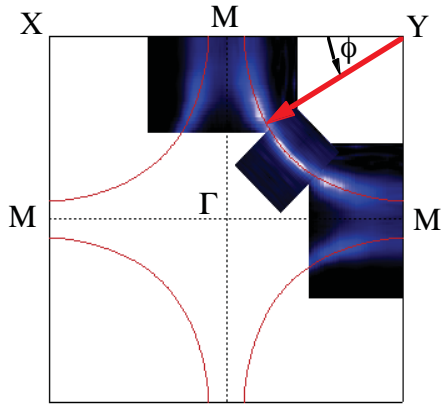
Kerr effect:
J. Xia et al. PRL (2008)

STM:
W. D. Wise et al.
Nature Physics
(2008)

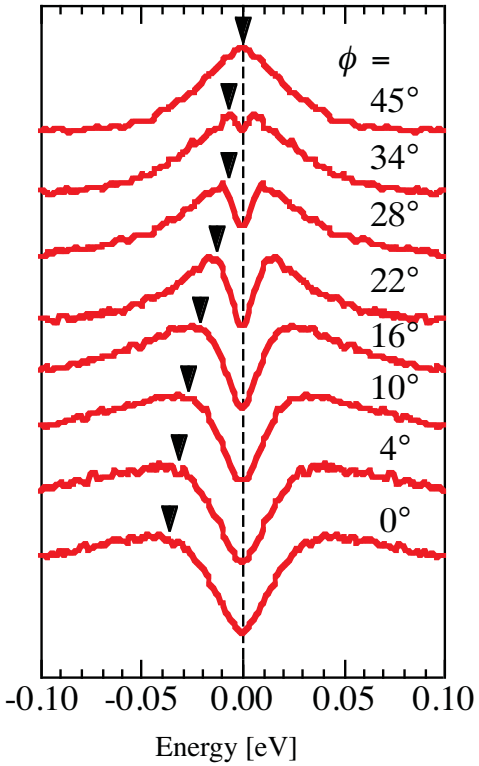
# d-wave superconducting order parameter

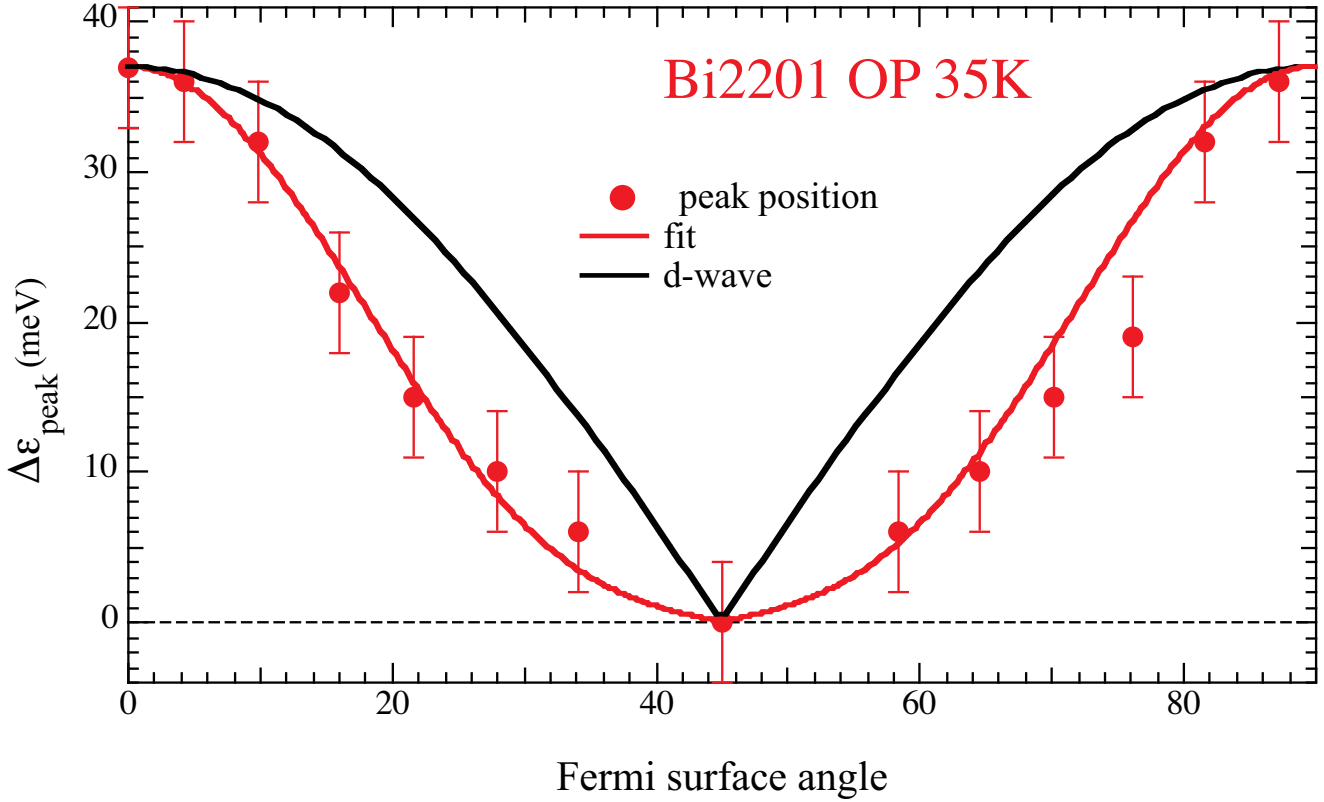




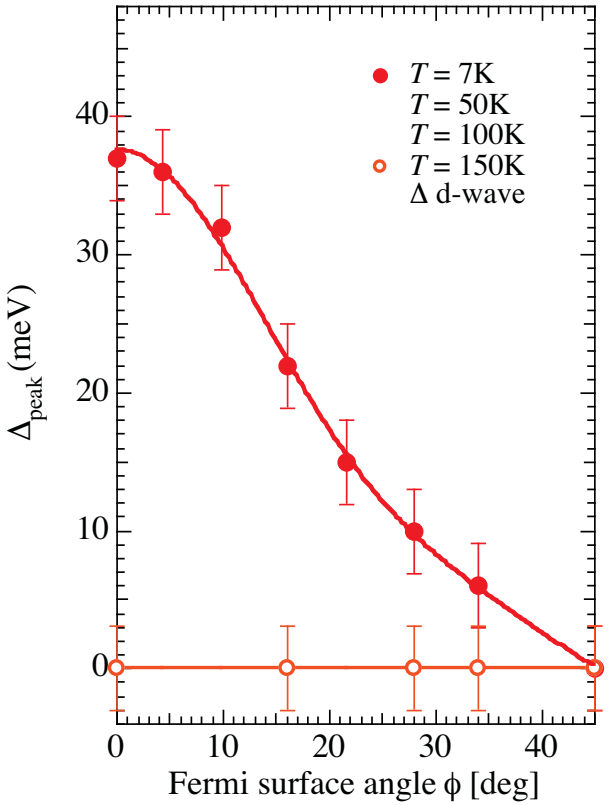

# At lower carrier concentration there is strong deviation of the spectral gap from d-wave symmetry

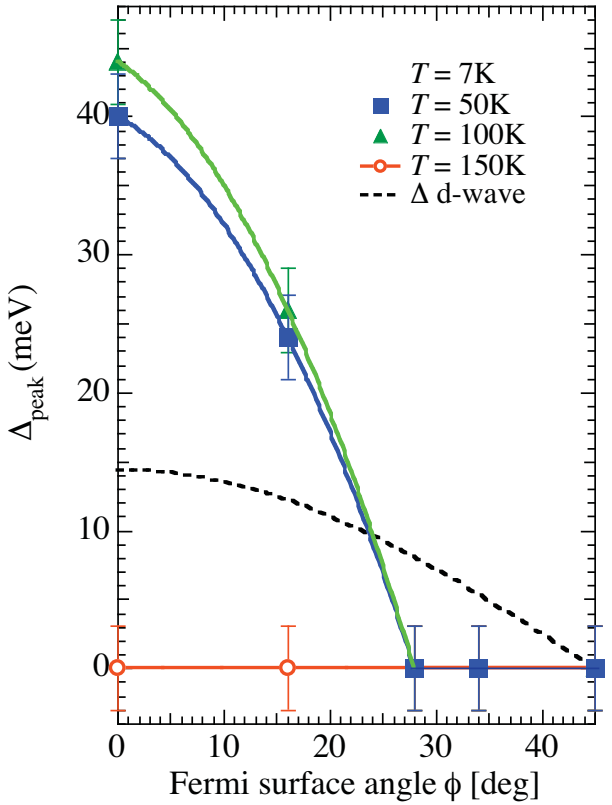



T. Kondo et al., Phys. Rev. Lett. **98**, 267004 (2007)

# How can we understand this deviation?

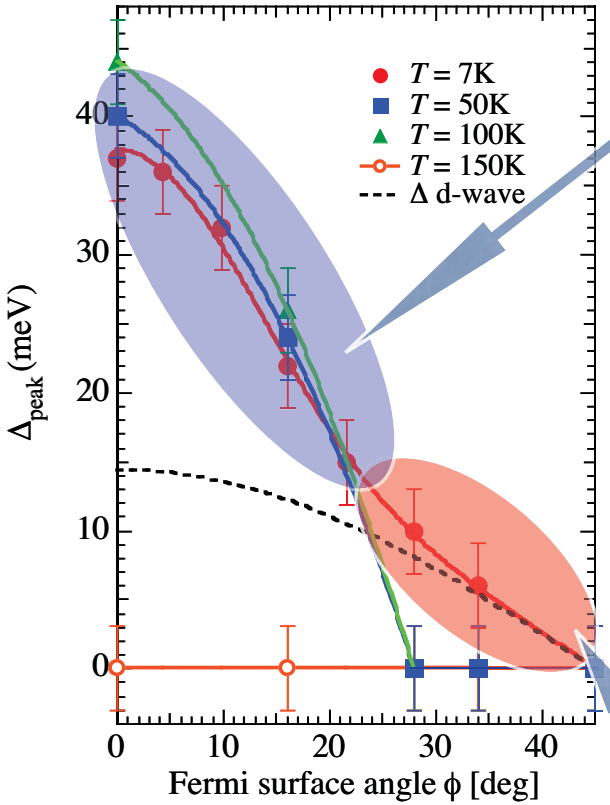


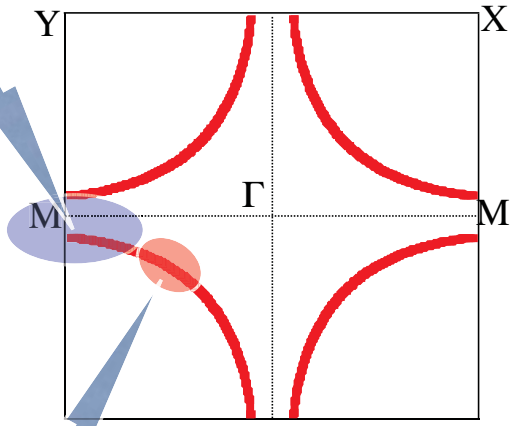




T. Kondo et al.,
Phys. Rev. Lett. **98**, 267004 (2007)

# How can we understand this deviation?

pseudogap



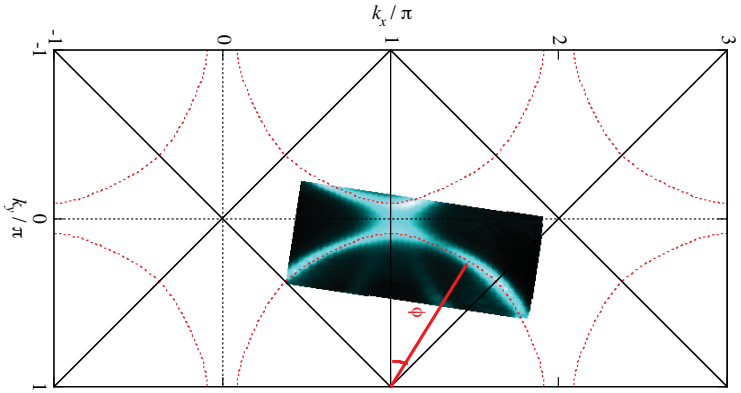

superconducting gap

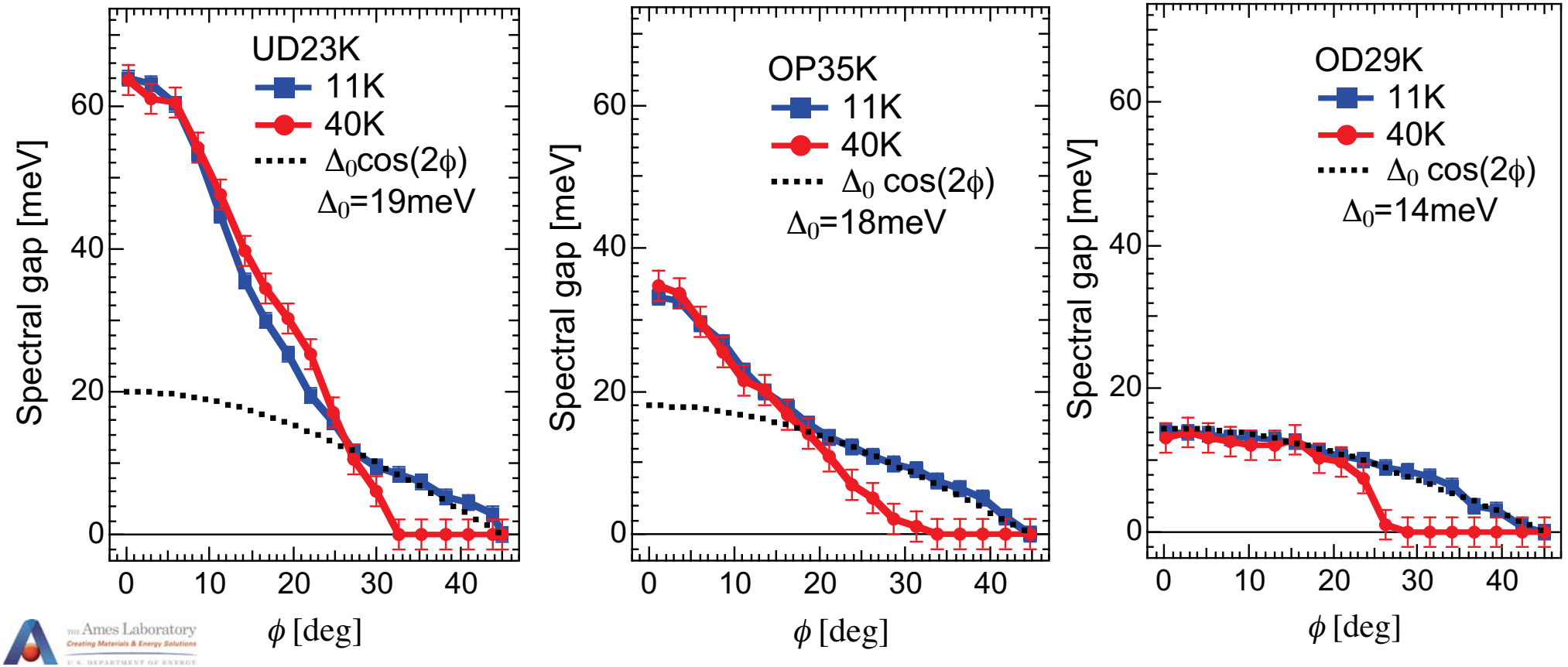
T. Kondo et al.,
Phys. Rev. Lett. **98**, 267004 (2007)

# Spectral gap has two components


Le Tacon, M. *et al. Nature Physics* **2**, 537–543 (2006).
Tanaka, K. et al. *Science* **314**, 1910–1913 (2006).
Lee, W. S. et al. *Nature* **450**, 81–84 (2007).
Boyer, M. C. *et al. Nature Physics* **3**, 802–806 (2007).

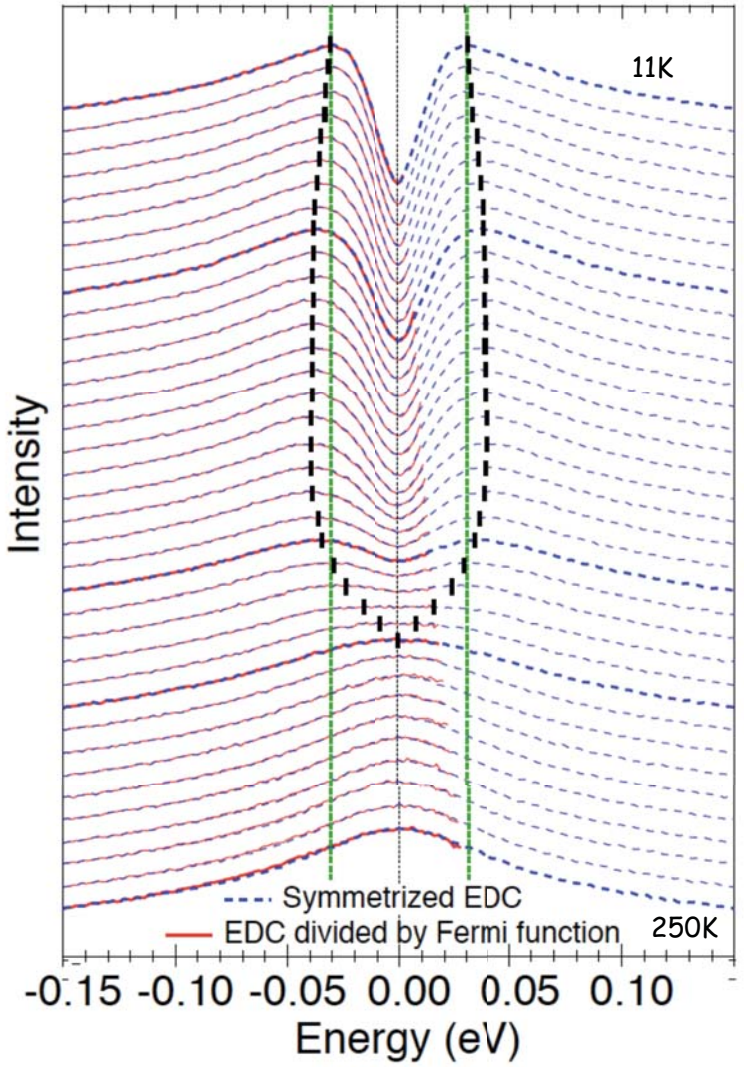
# Doping and momentum dependence of the spectral gap

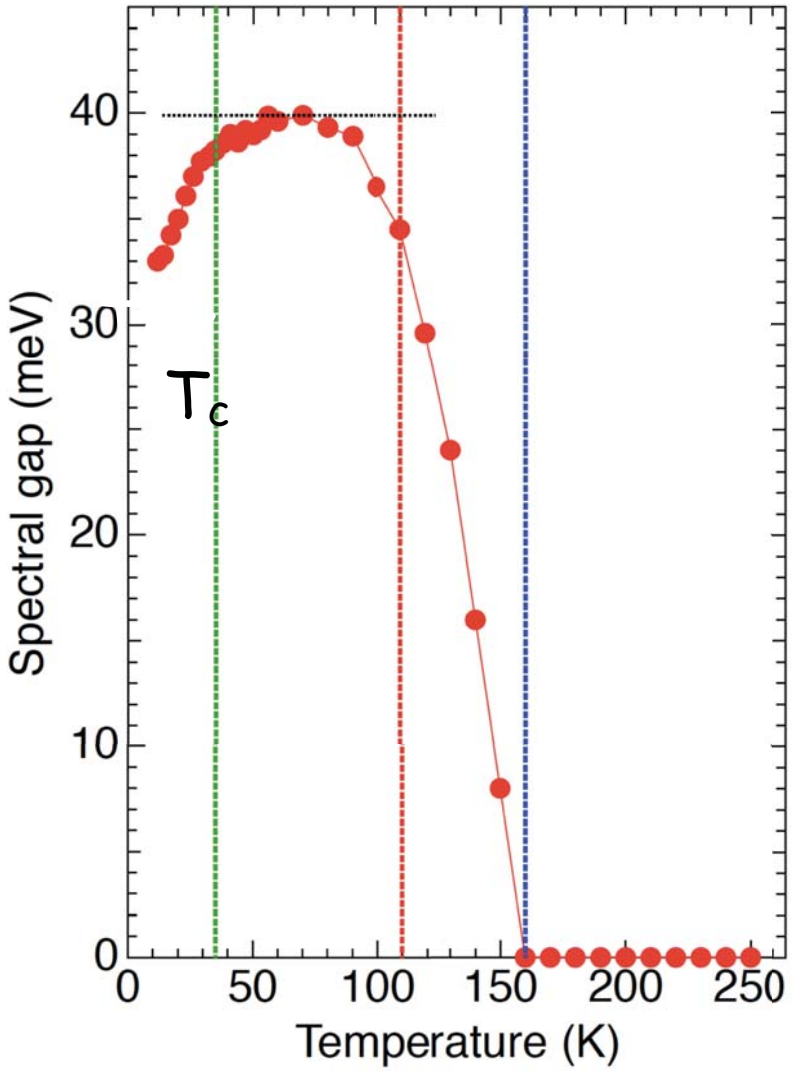


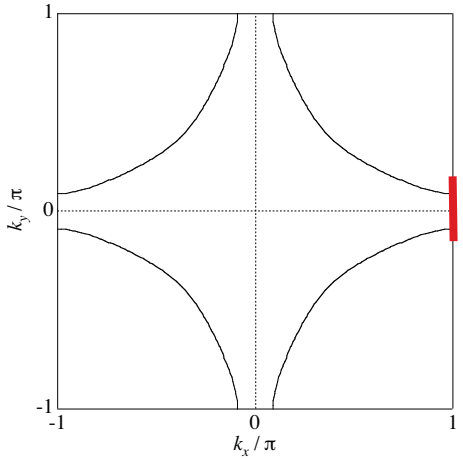



# Spectral gap has "unusual" temperature dependence"

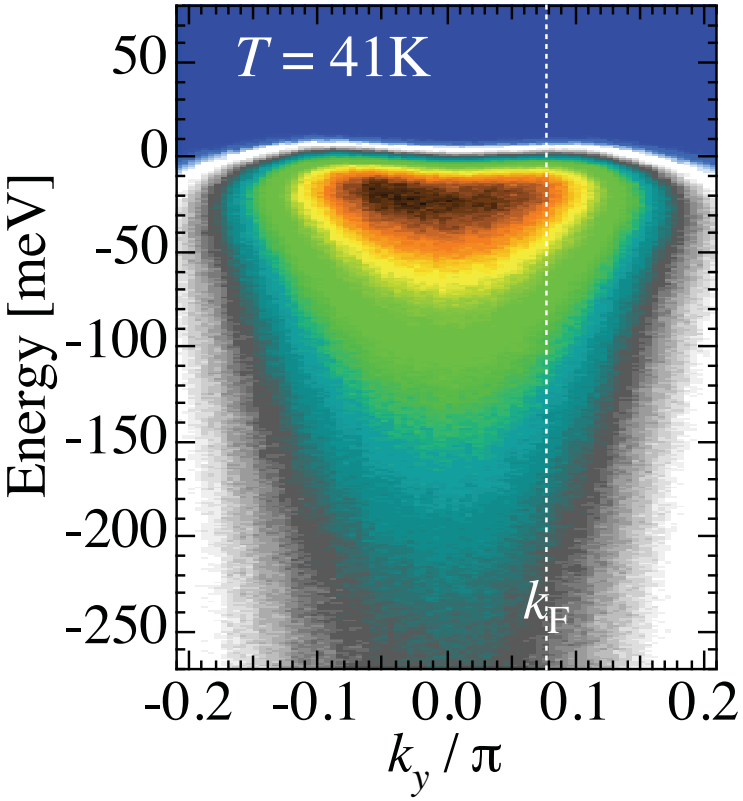
## Antinode

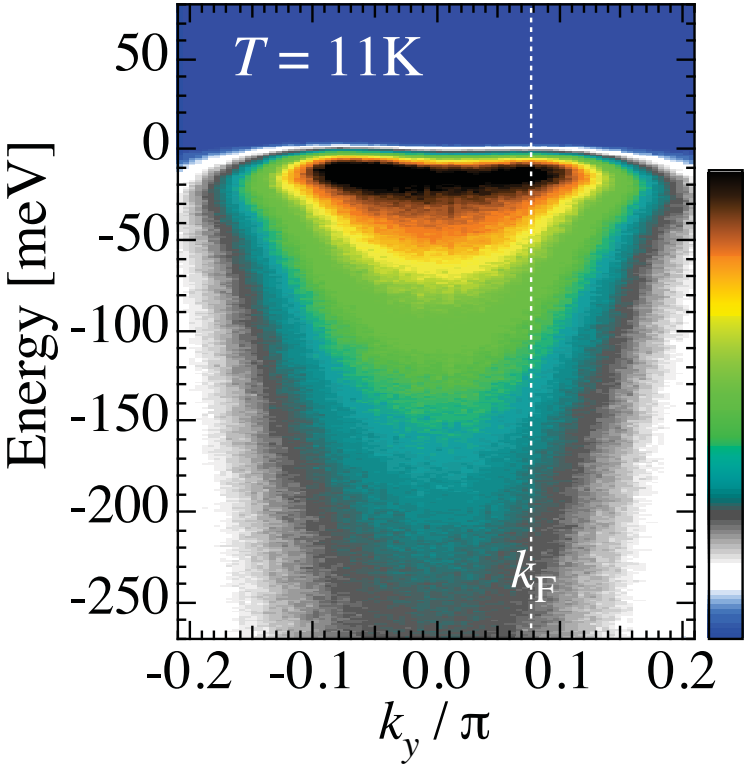


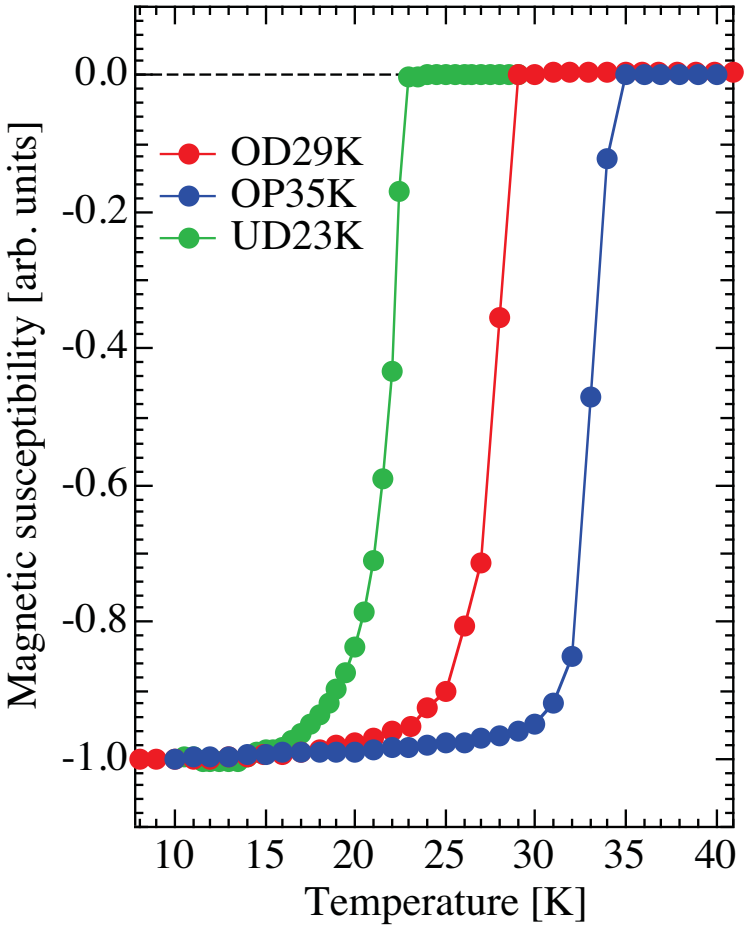


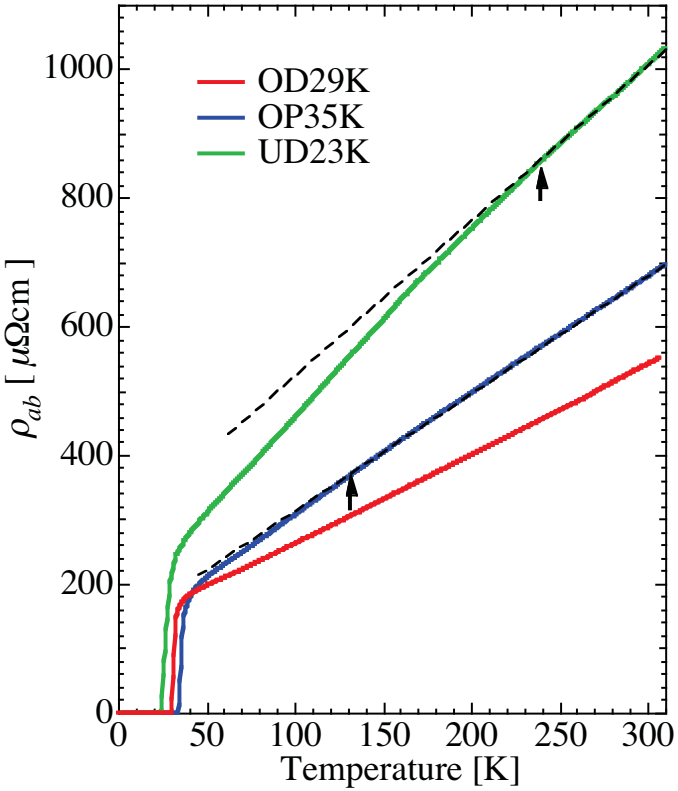

# We need to study spectral weighs!

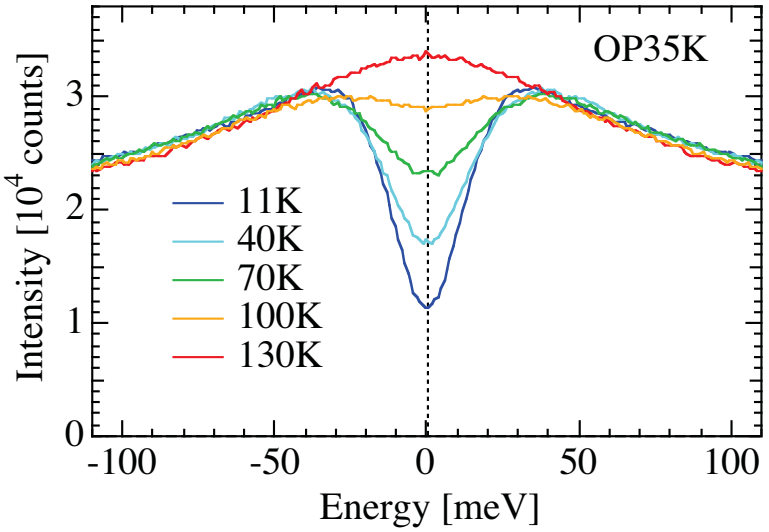


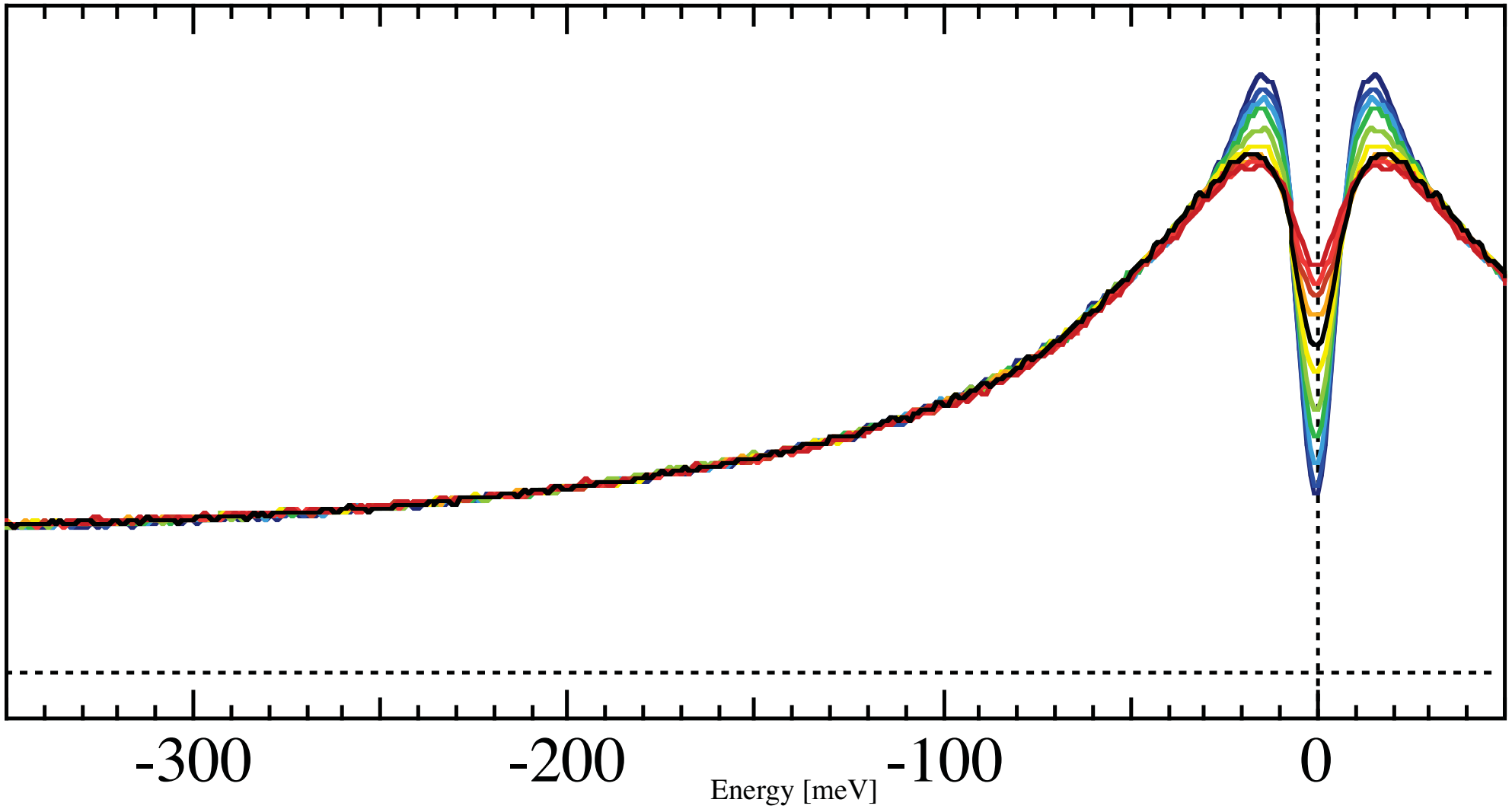
# Set of high quality, well characterized Bi2201 samples



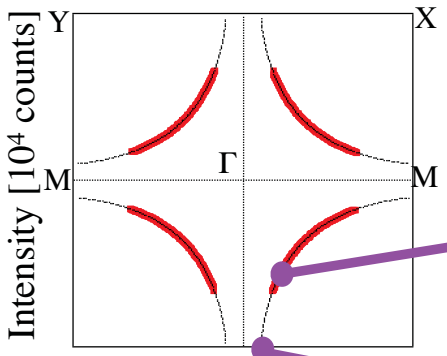



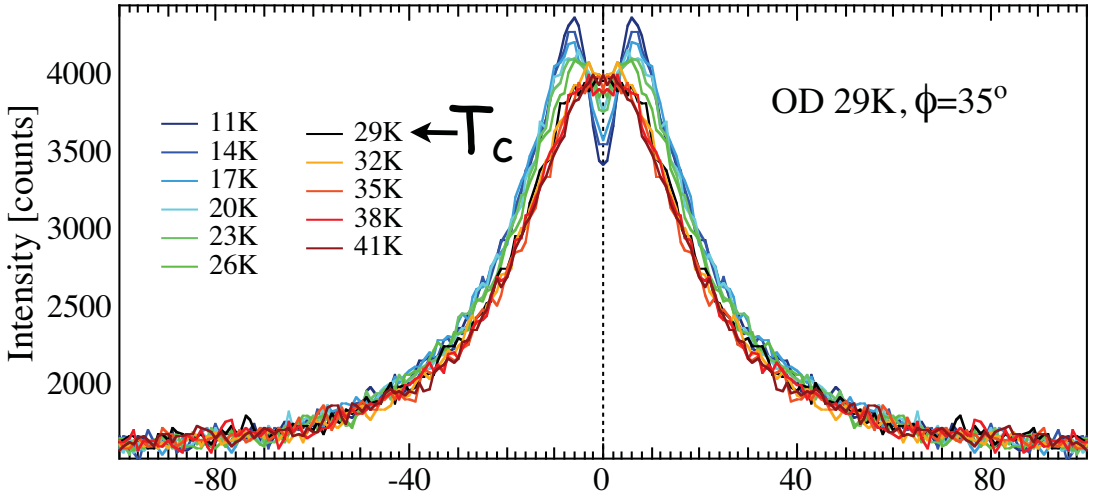



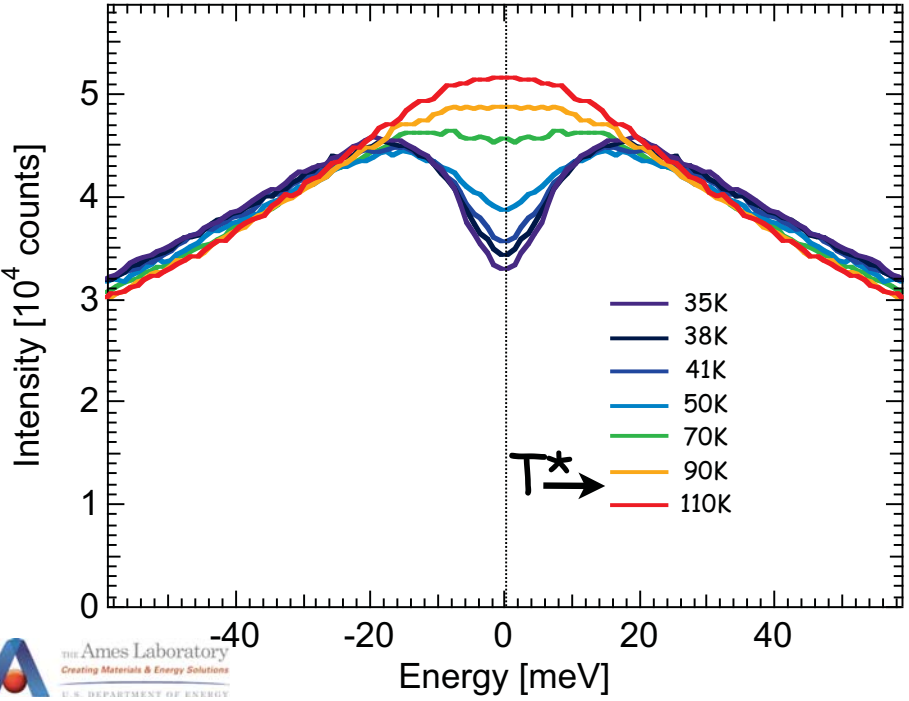
# Temperature dependence at antinode T=11K ...110K

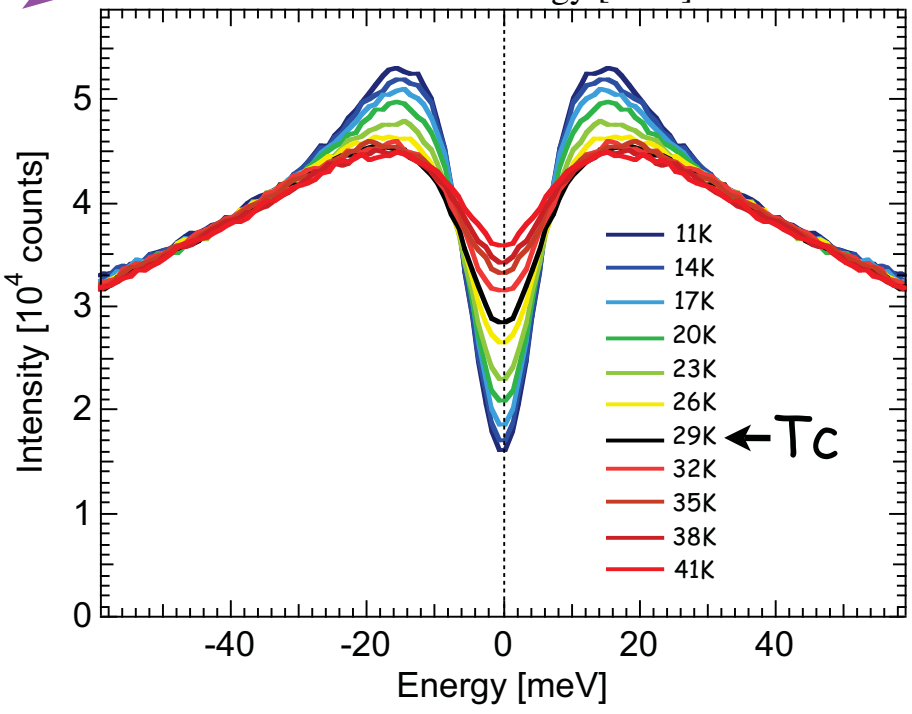


# Spectral changes across $T_c$ and T* at antinode

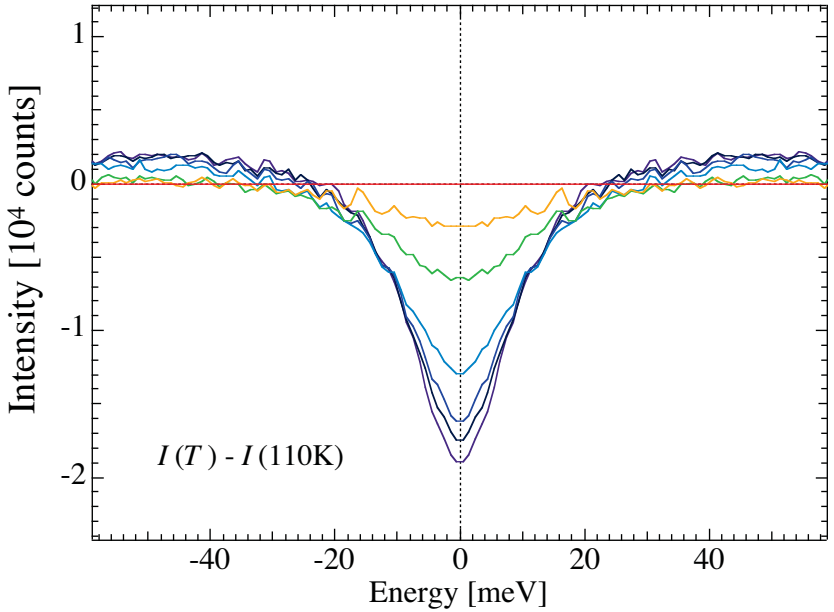


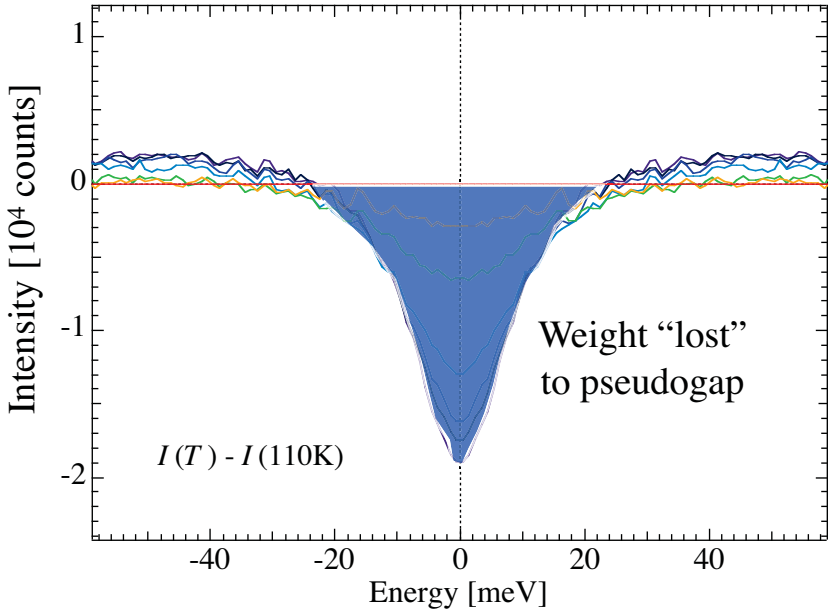



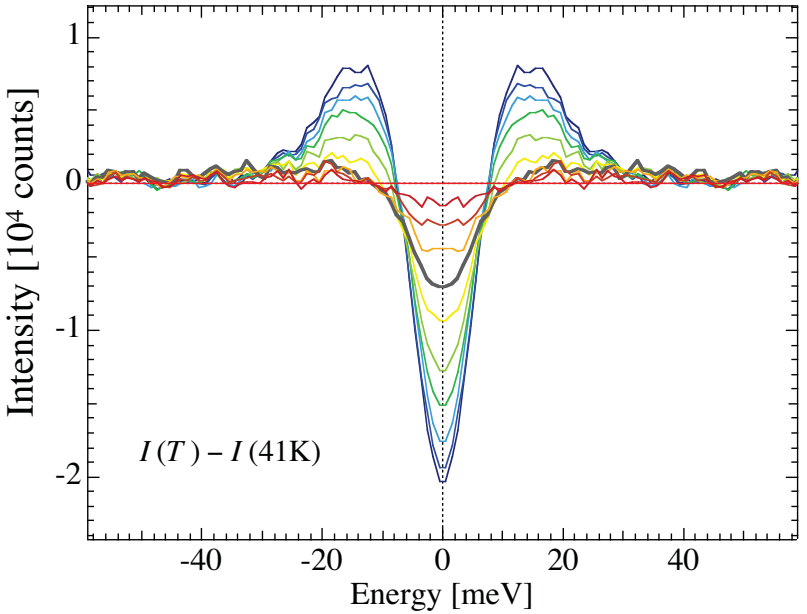



# Temperature dependence of SC and PG spectral weights

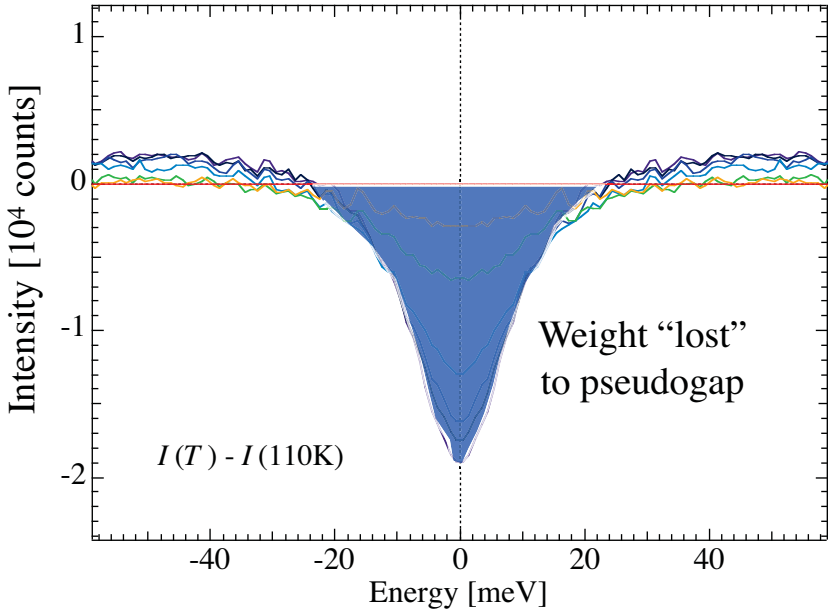


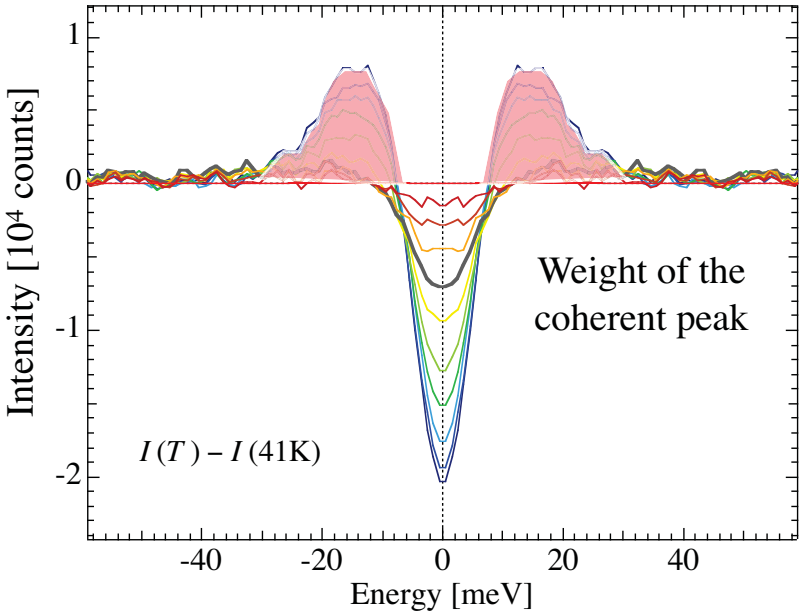
# Temperature dependence of SC and PG spectral weights

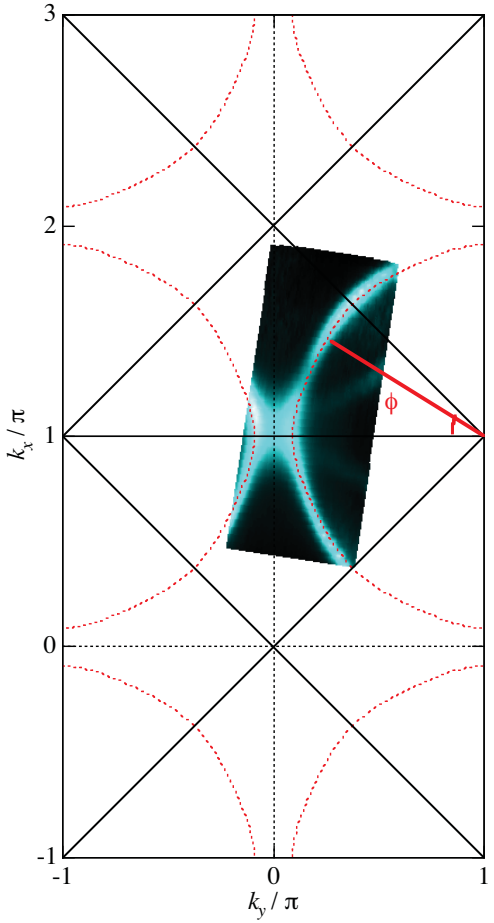


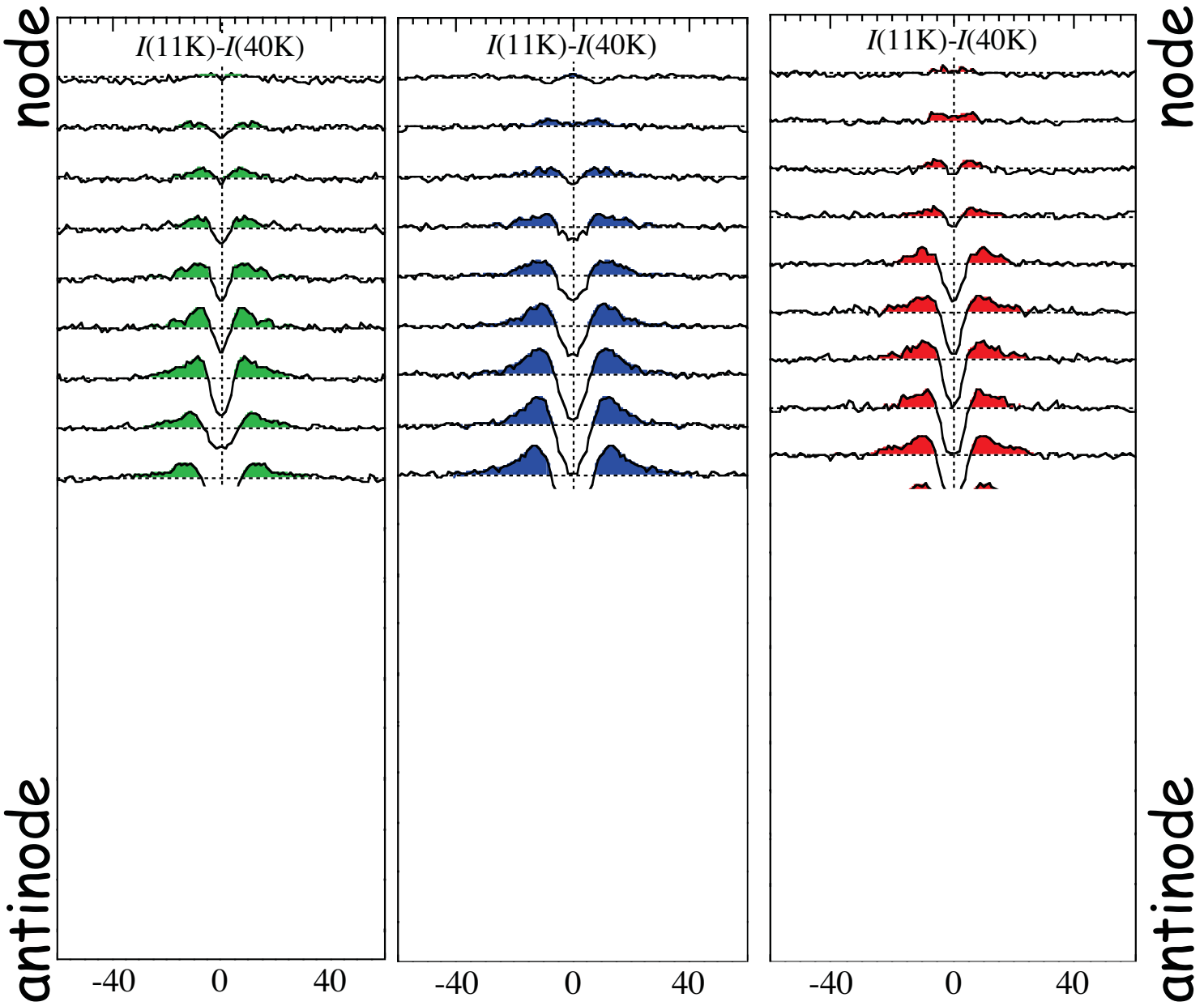



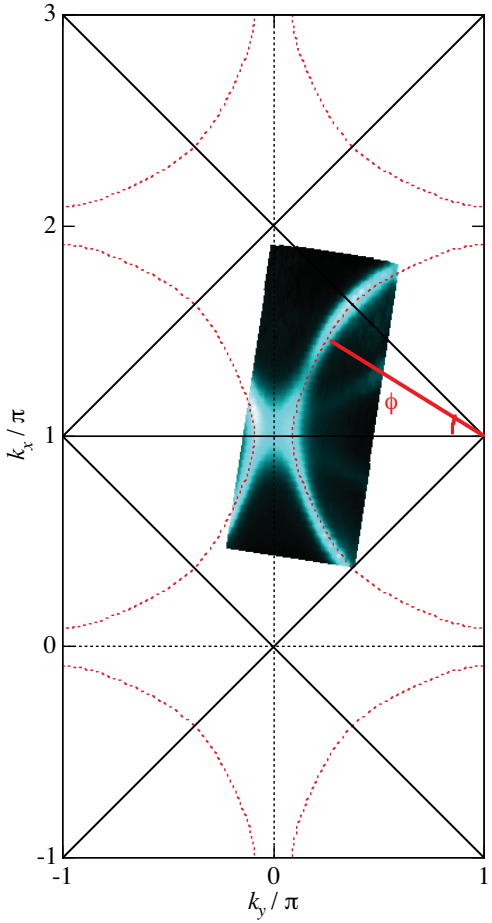
# Temperature dependence of SC and PG spectral weights

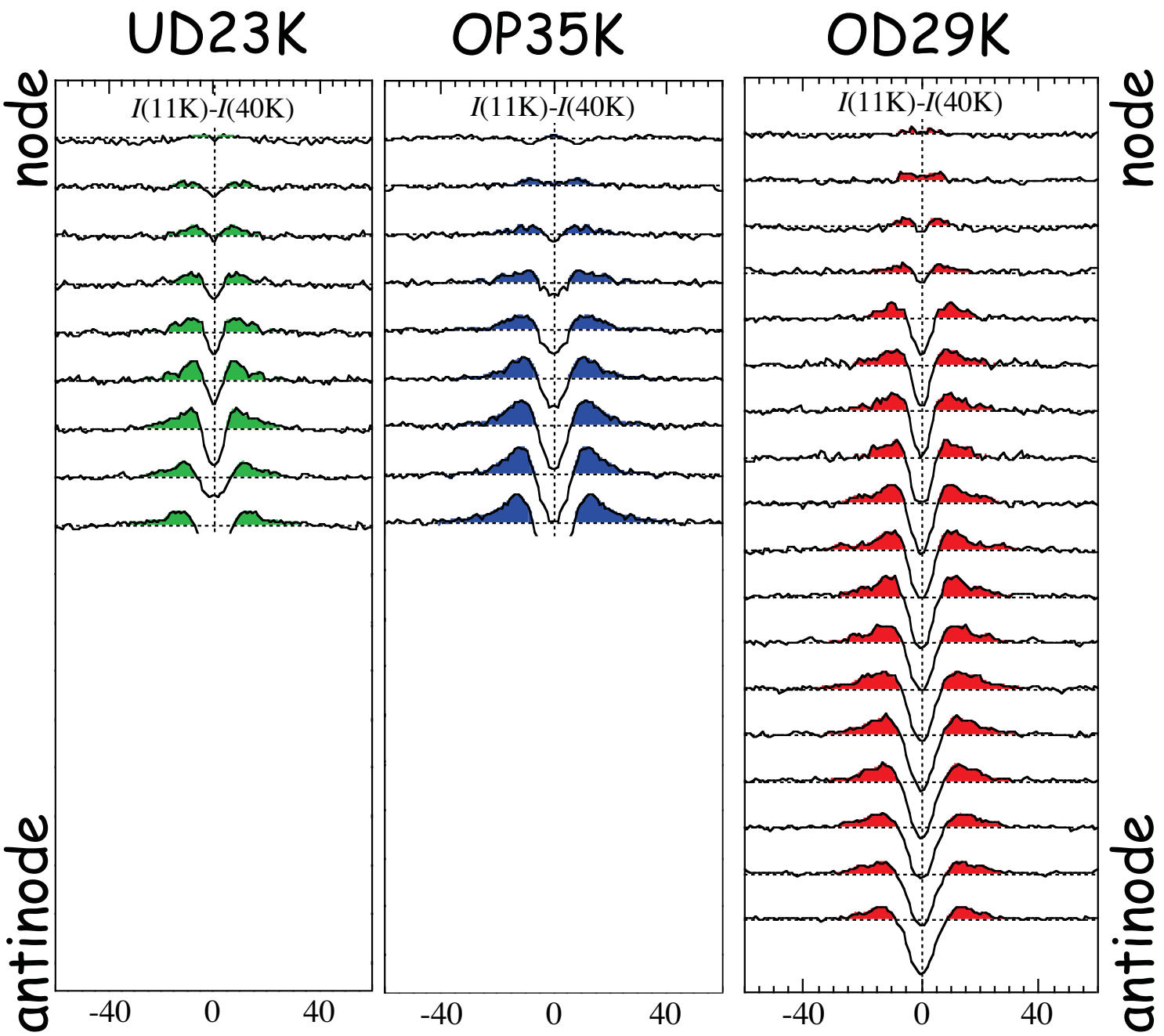


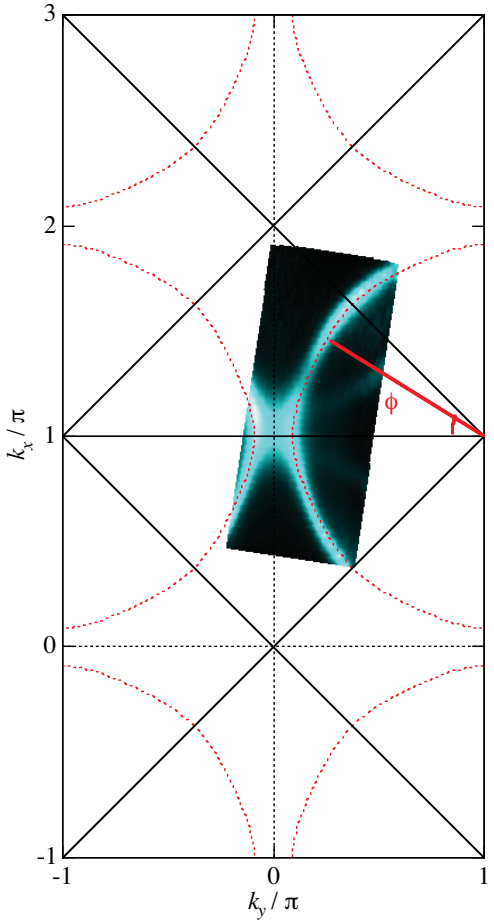



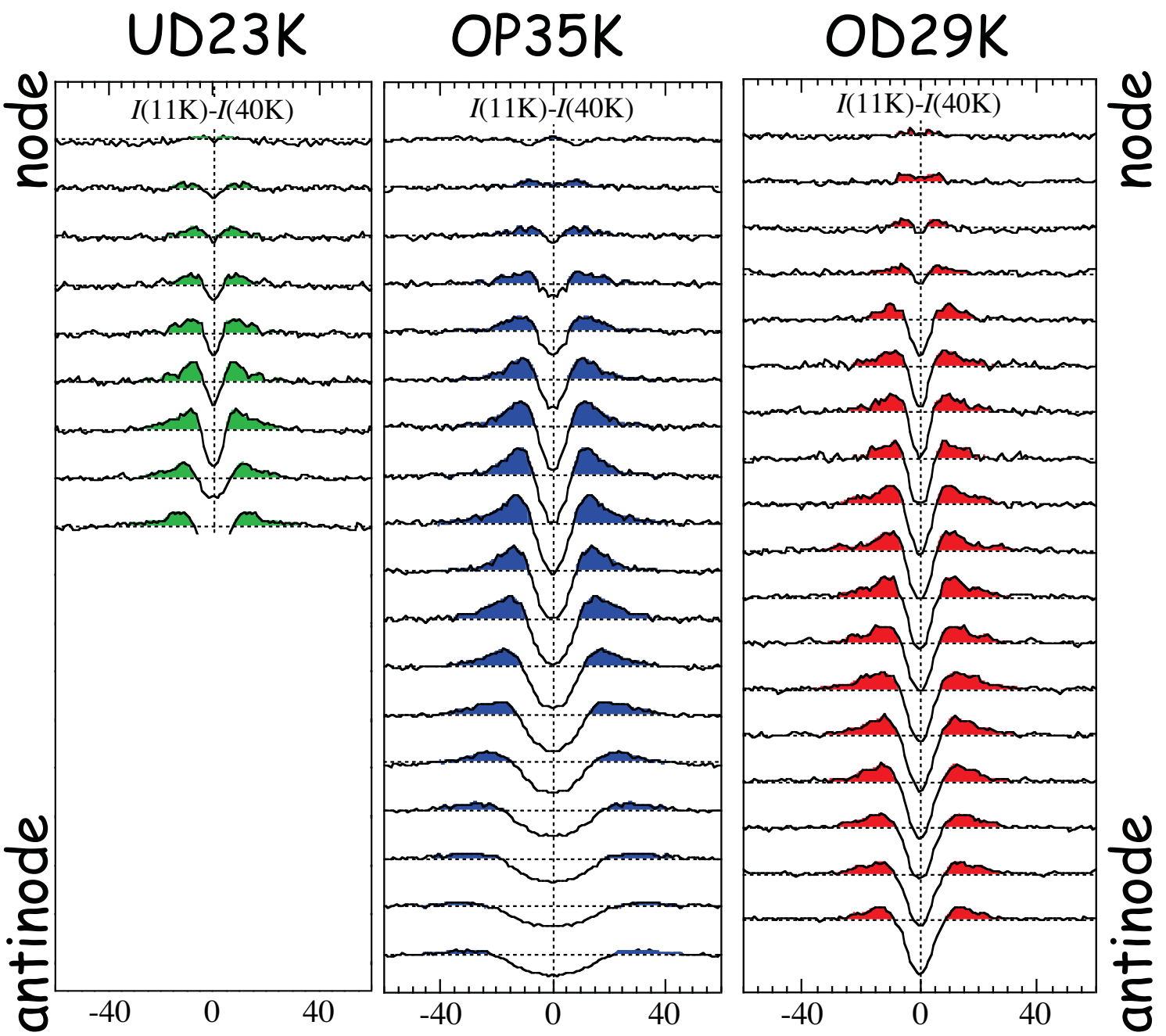


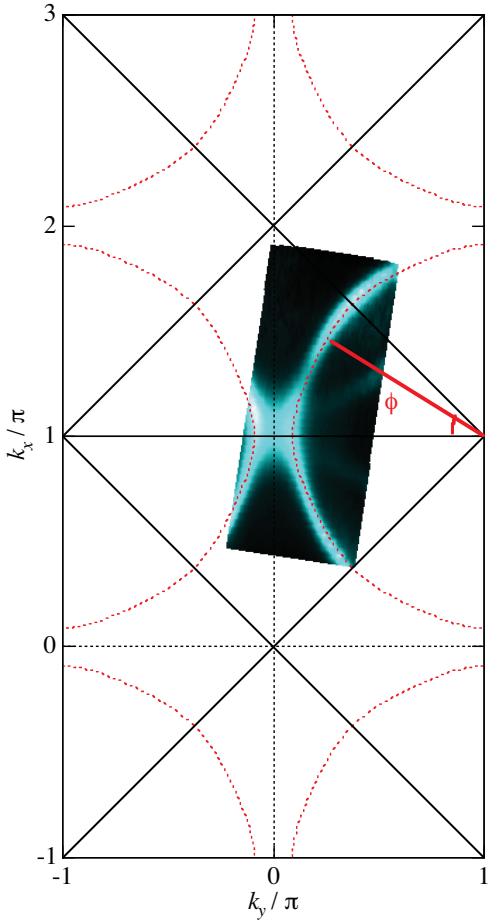



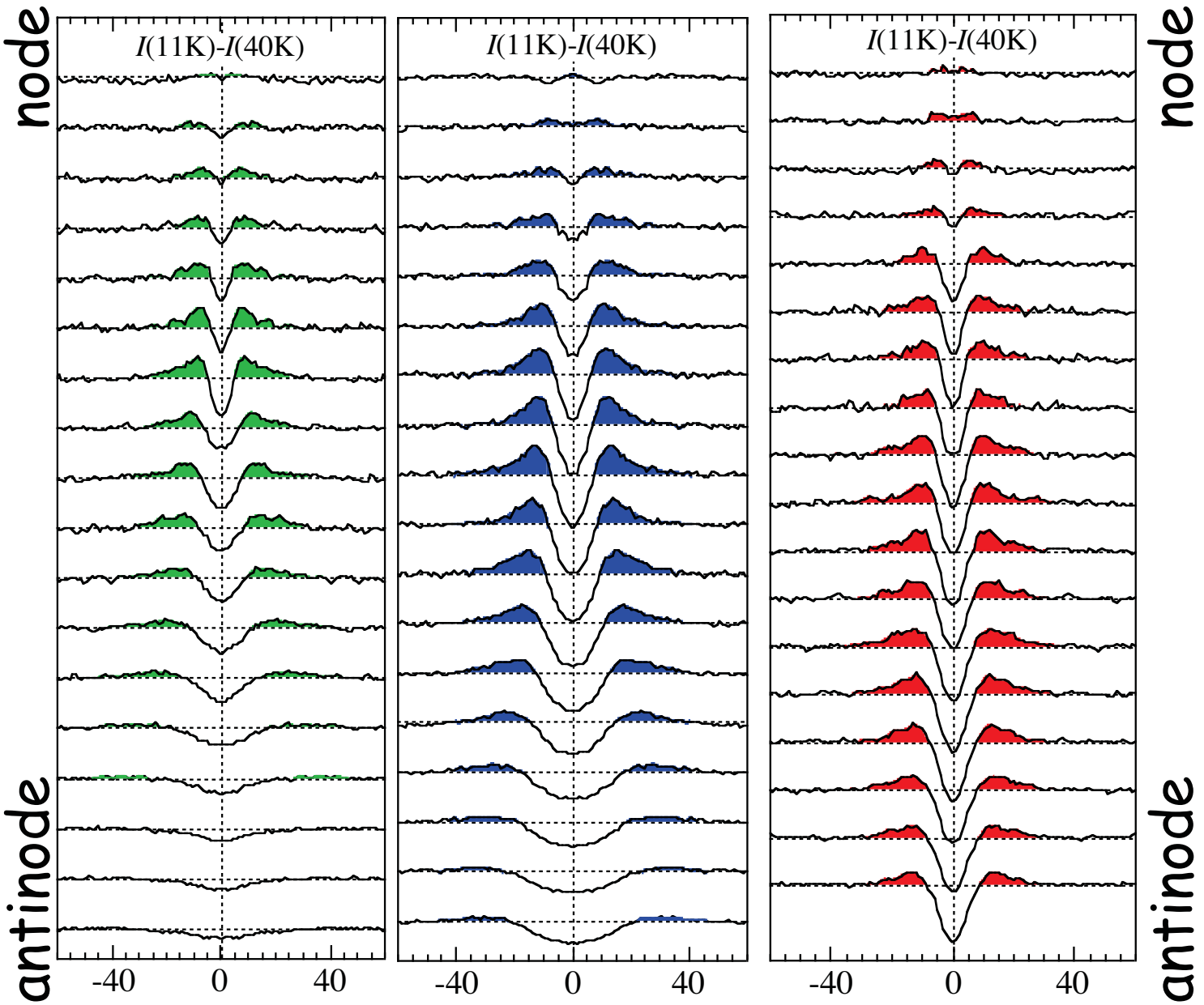


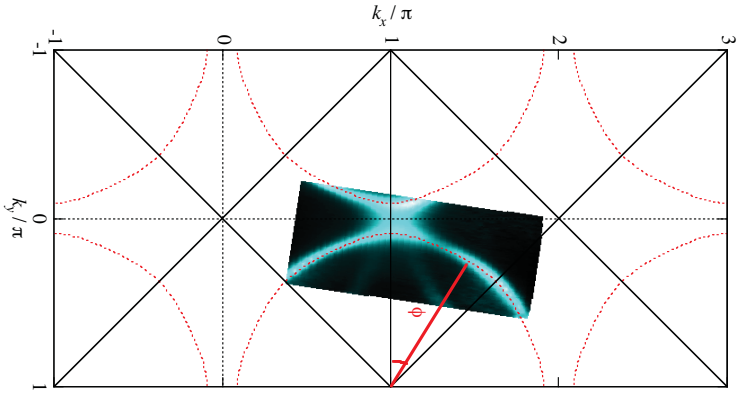


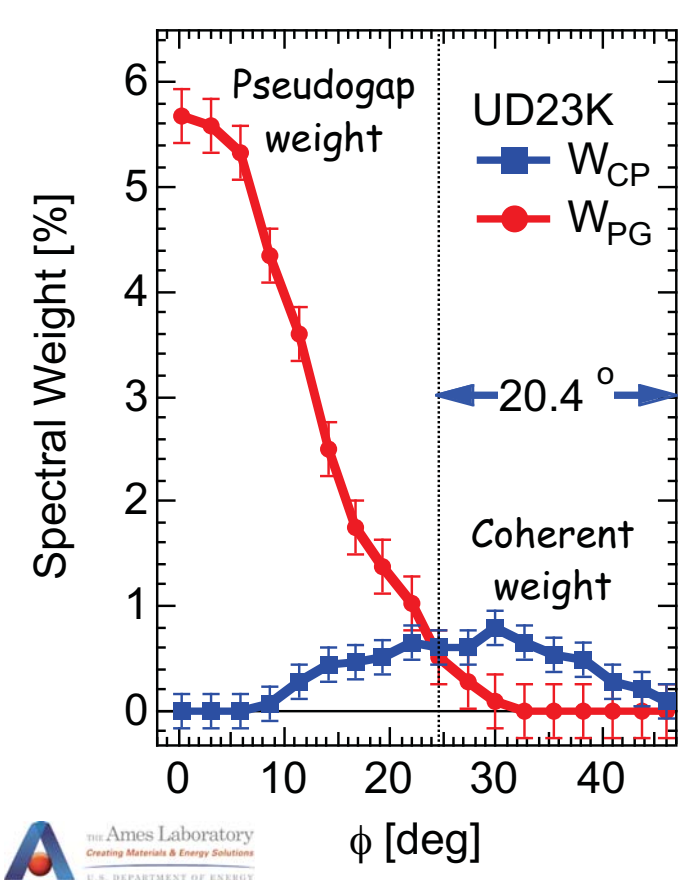



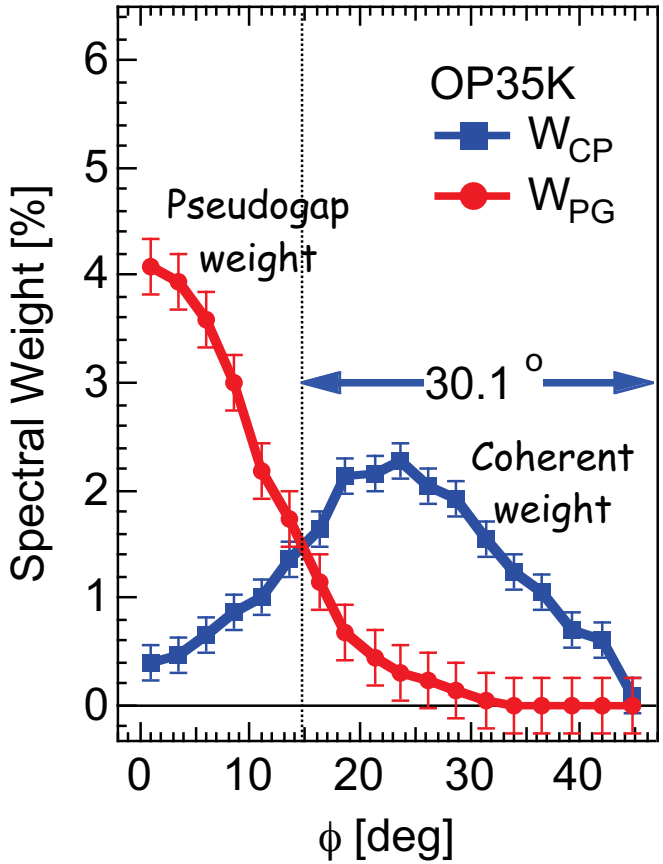


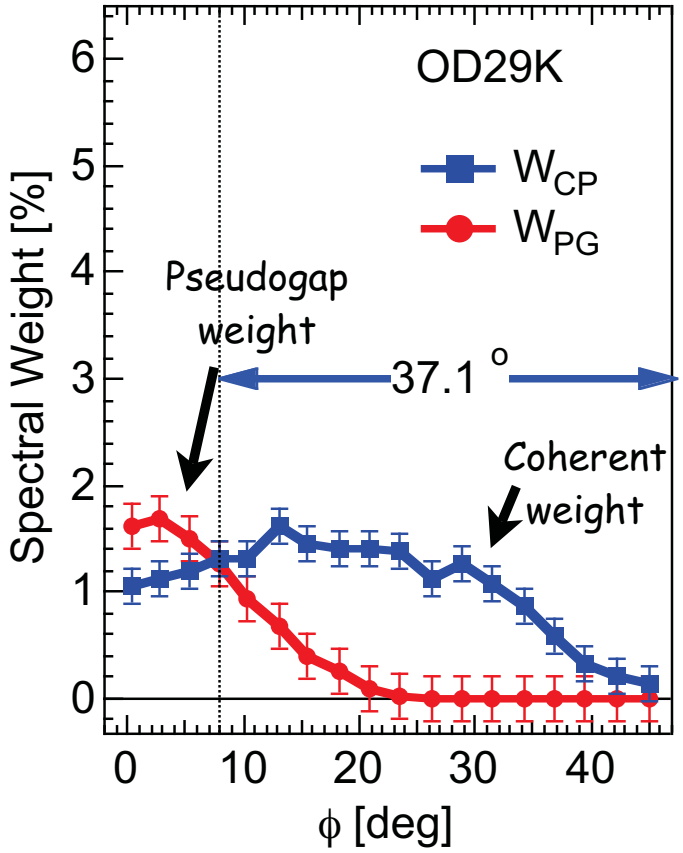



# Doping and momentum dependence of the spectral weights

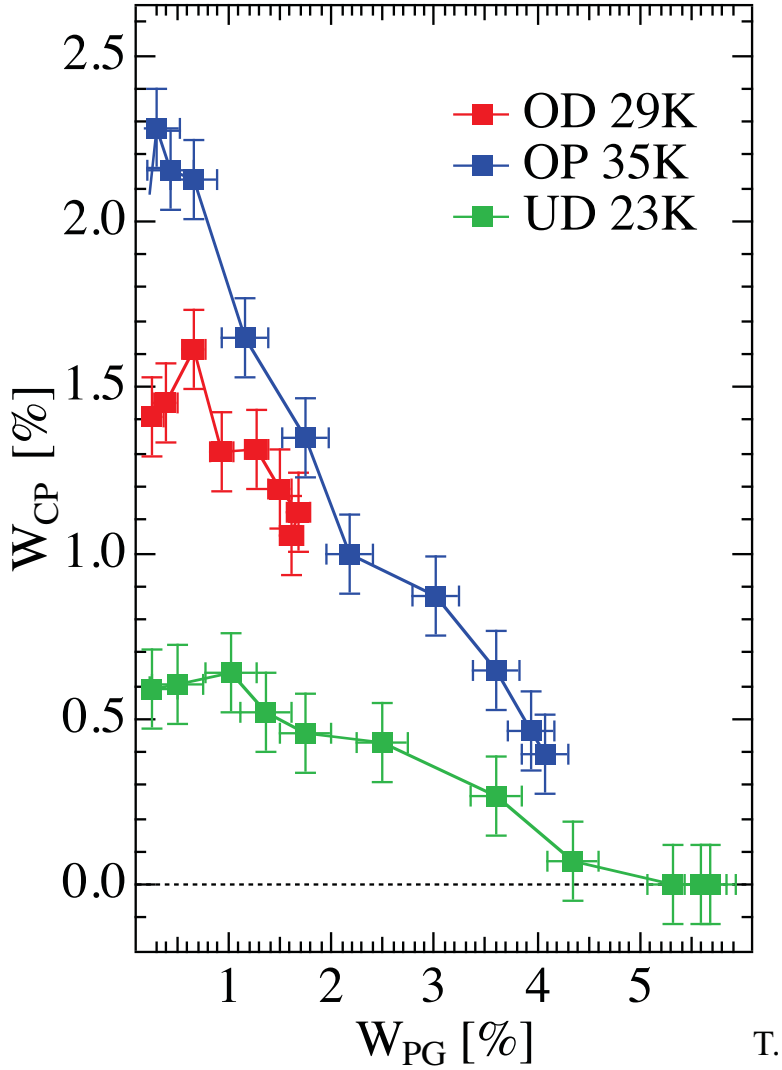


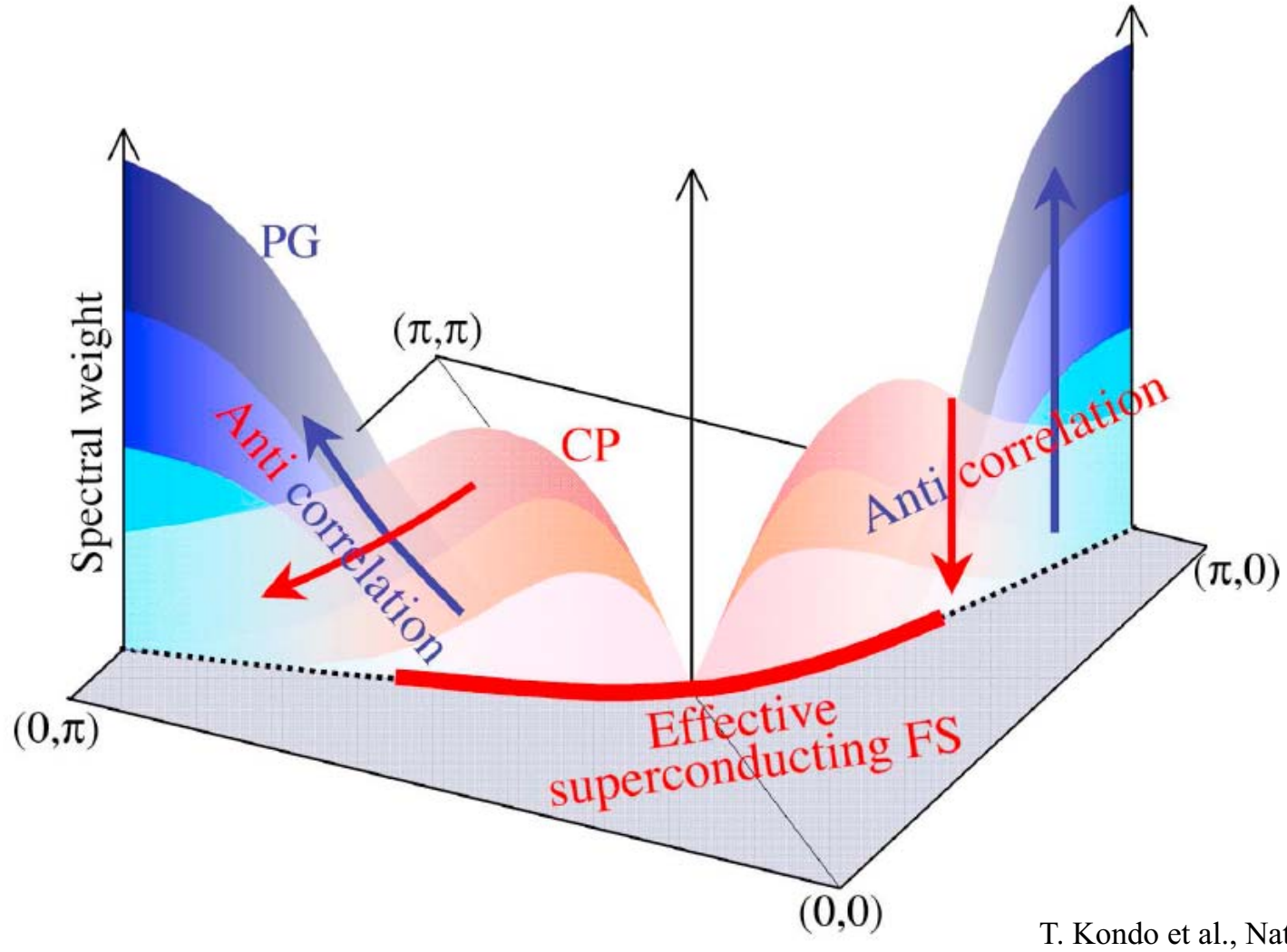



# Weight of the coherent peak and weight lost to the pseudogap are anti-correlated



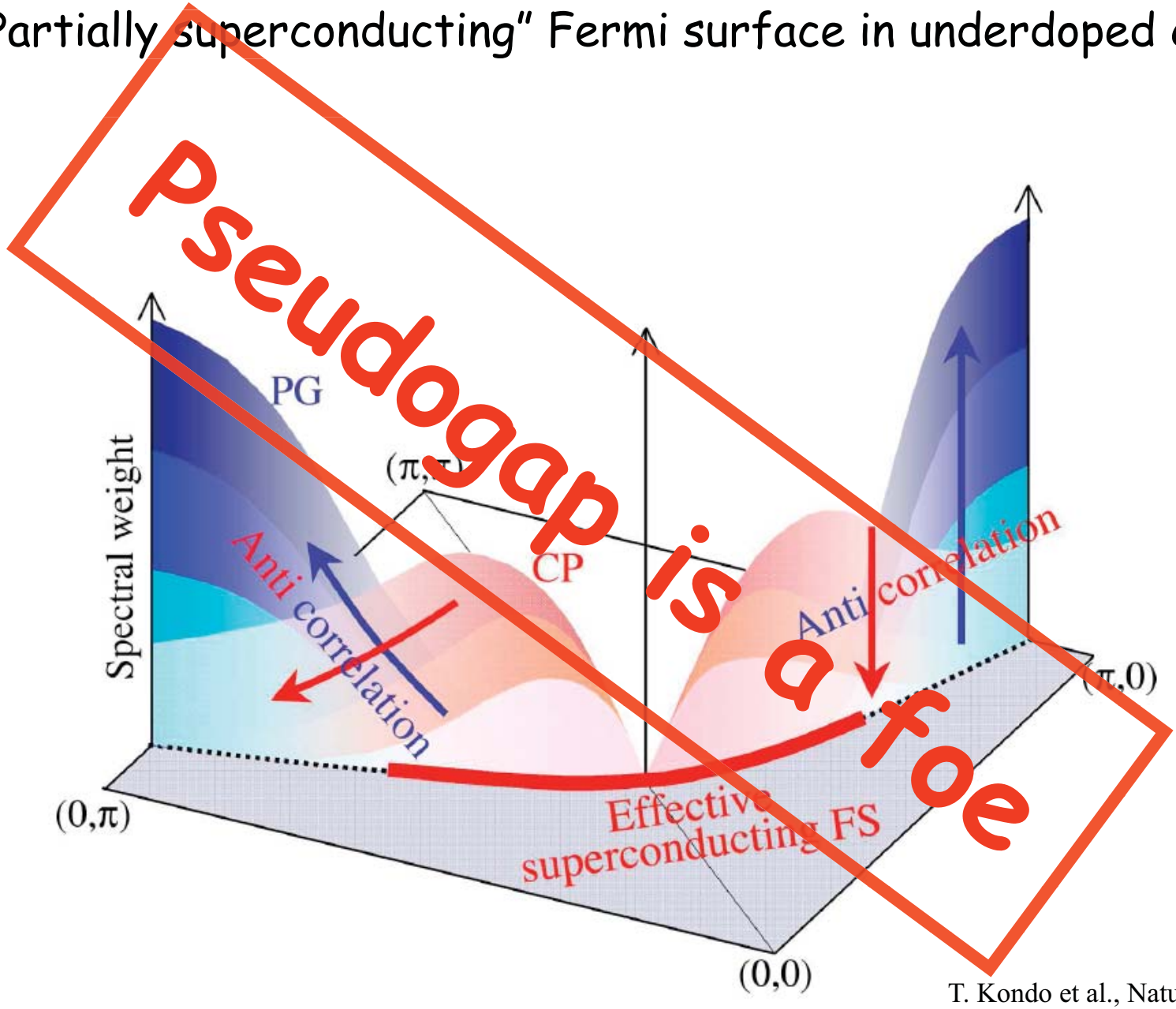

T. Kondo et al., Nature **457**, 295 (2009)

# "Partially superconducting" Fermi surface in underdoped cuprates



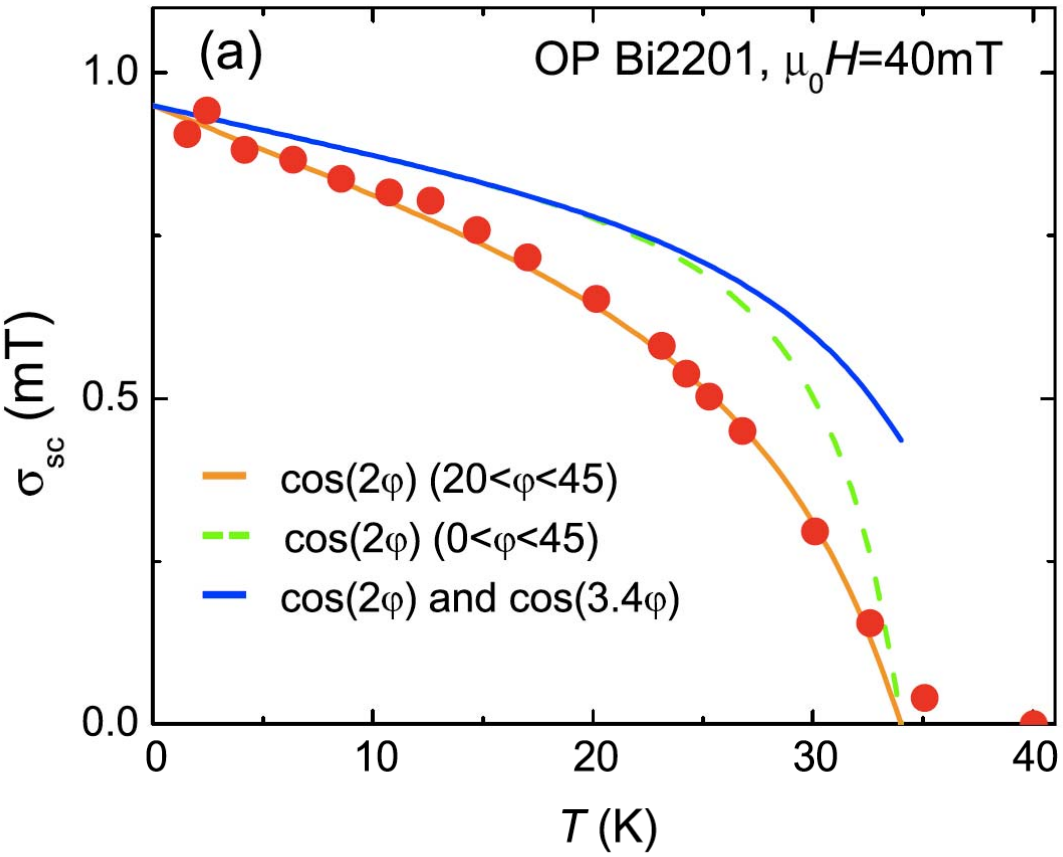

T. Kondo et al., Nature **457**, 295 (2009)

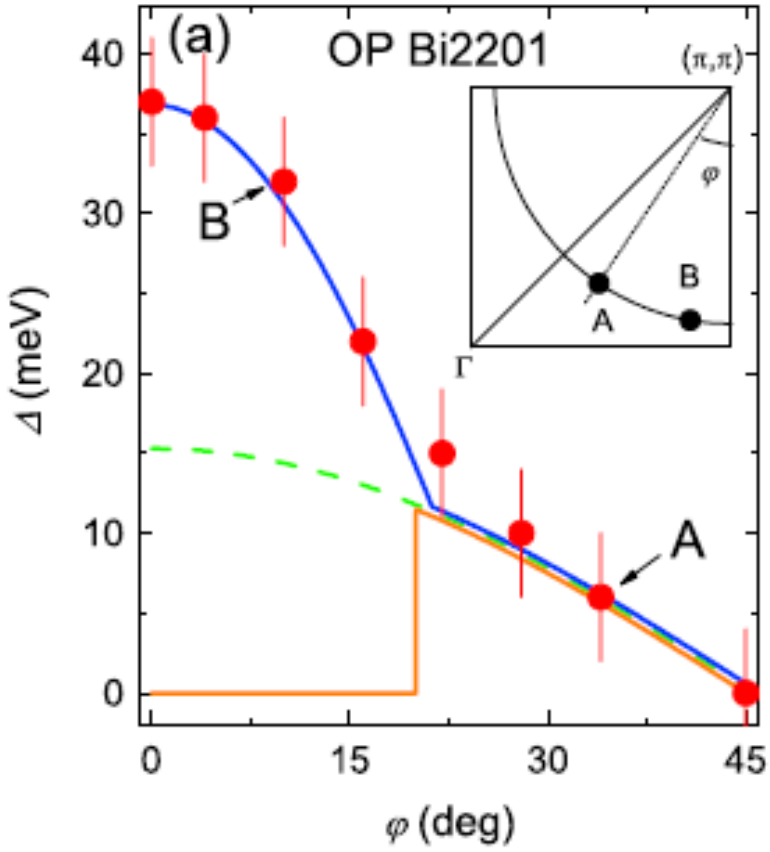
"Partially superconducting" Fermi surface in underdoped cuprates




T. Kondo et al., Nature **457**, 295 (2009)

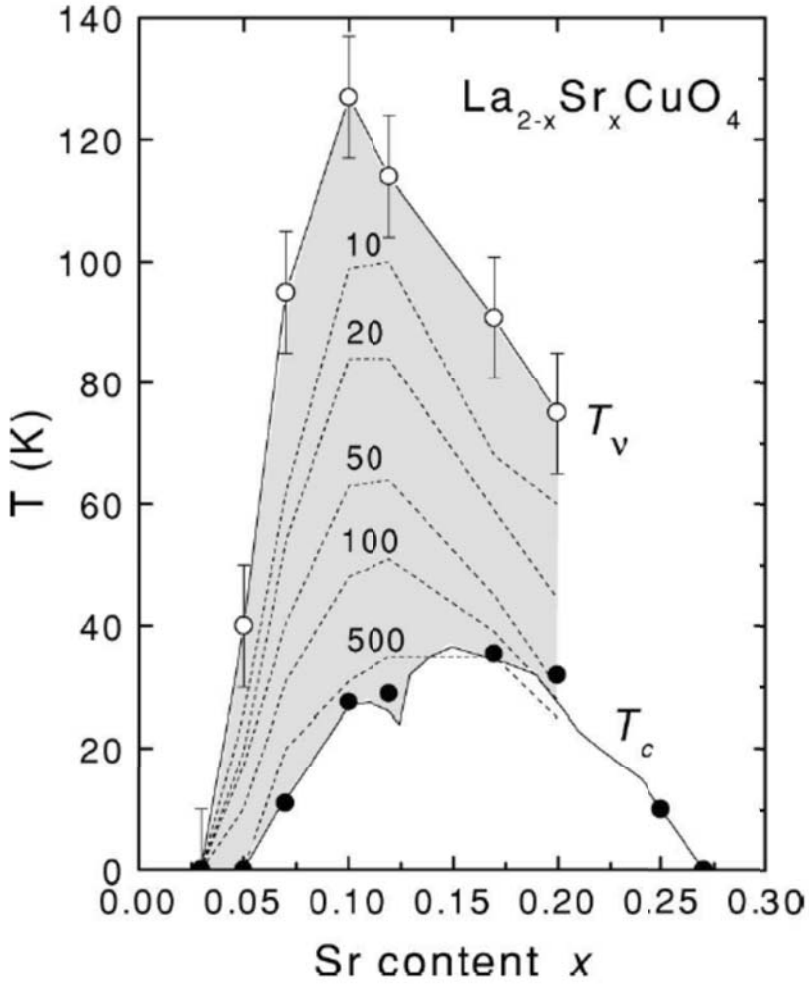
# Superfluid density measured by $\mu$SR

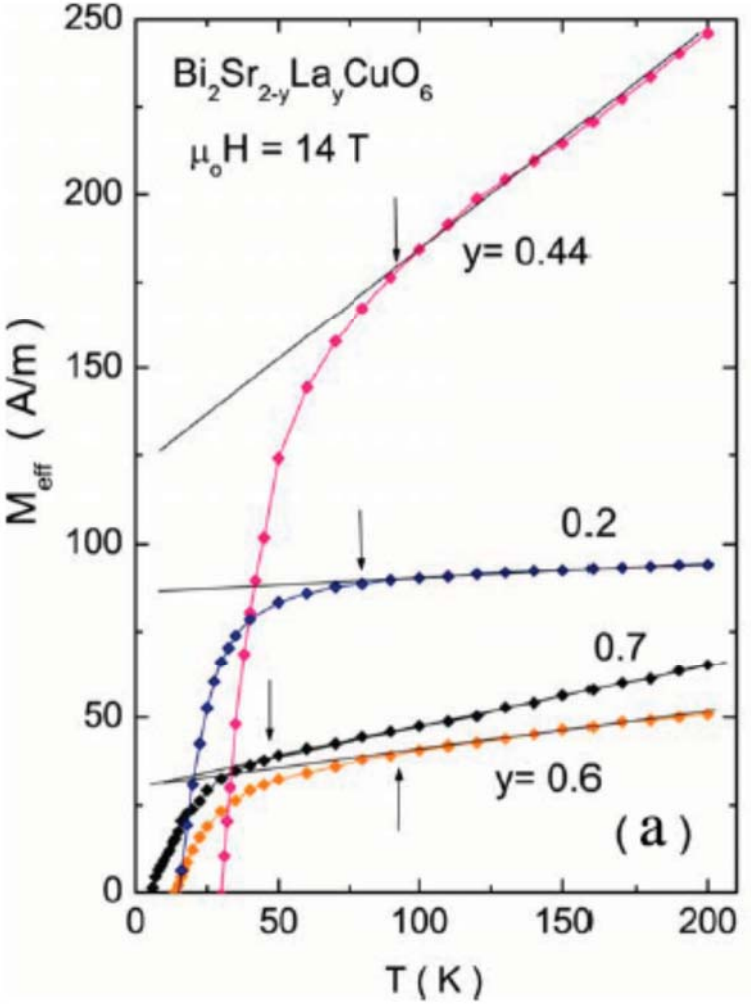



R. Khasanov et al., Phys. Rev. Lett. **101**, 227002

..one problem: Nerst effect and magnetization measurements detect pairing above Tc...

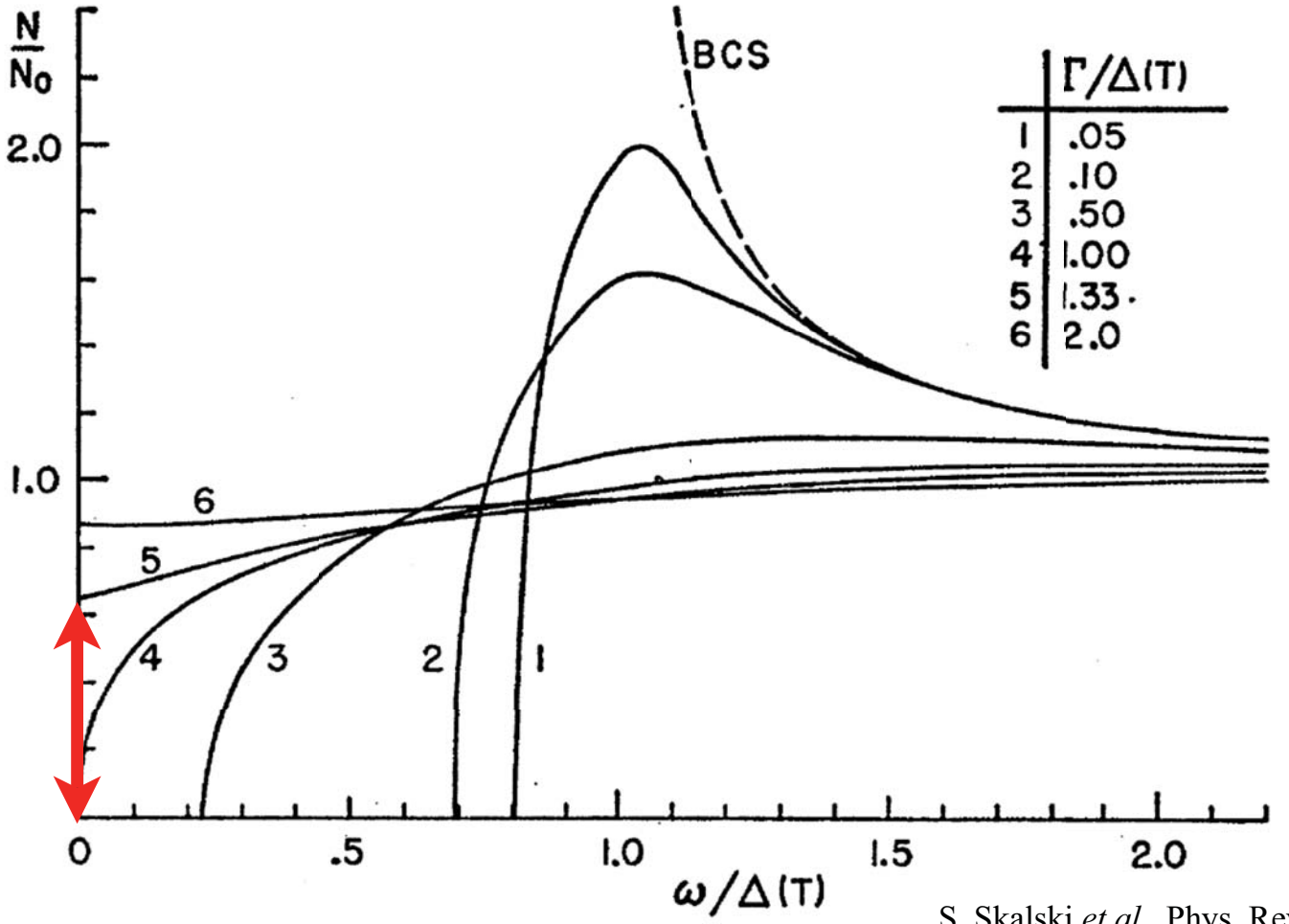



Wang, Y. *et al*. Phys. Rev. B **64**, 224519 (2001)

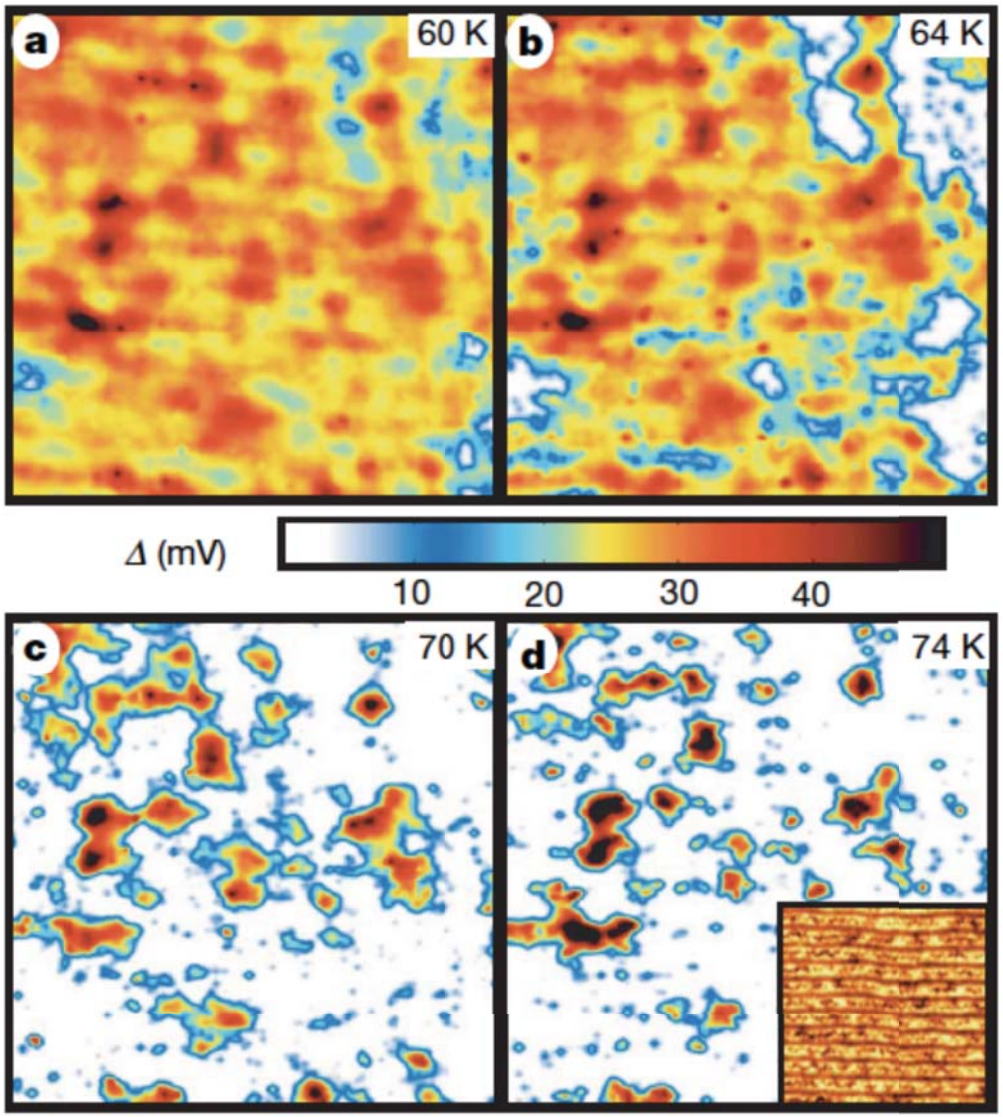
Lu Li, *et al*. Phys. Rev. B **81**, 054510 (2010)

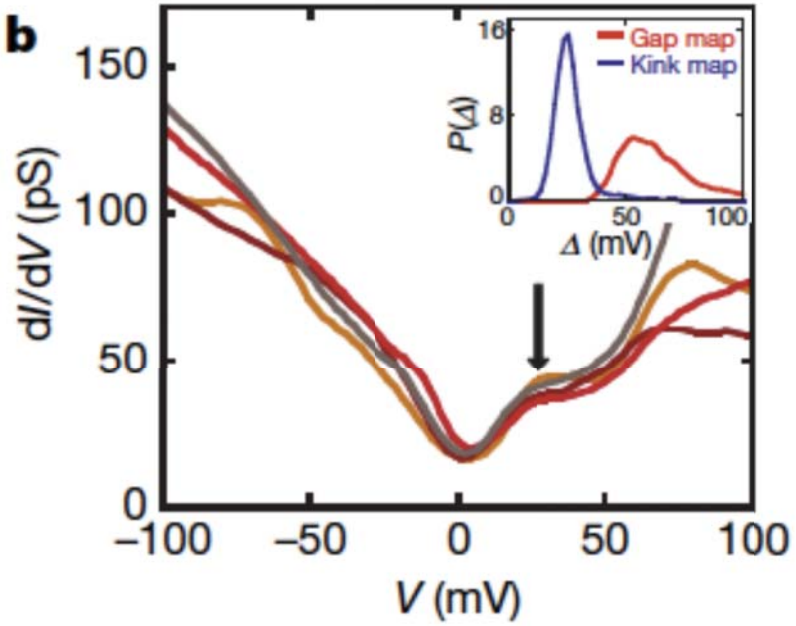
# Density of states at $E_f$ - $D(E_f)$ is well aware of pairing gap and pair breaking




S. Skalski *et al.*, Phys. Rev. 136, A1500 (1062)

# Superconducting patches above Tc in STM data

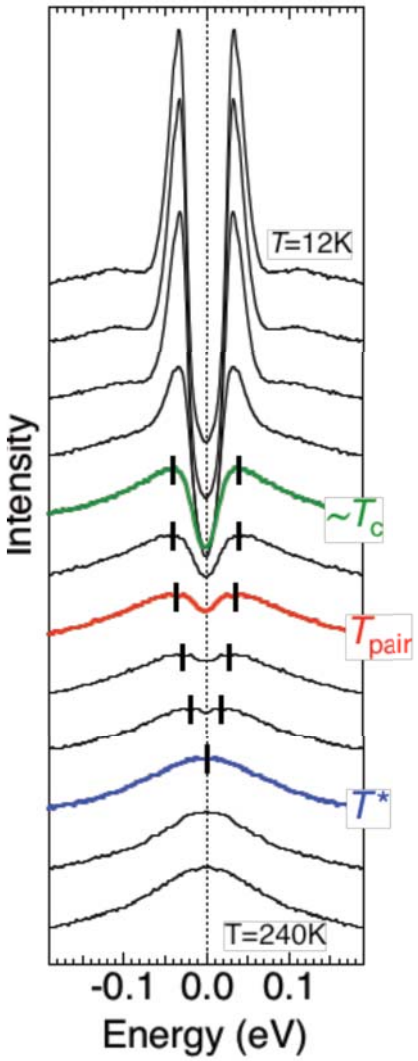


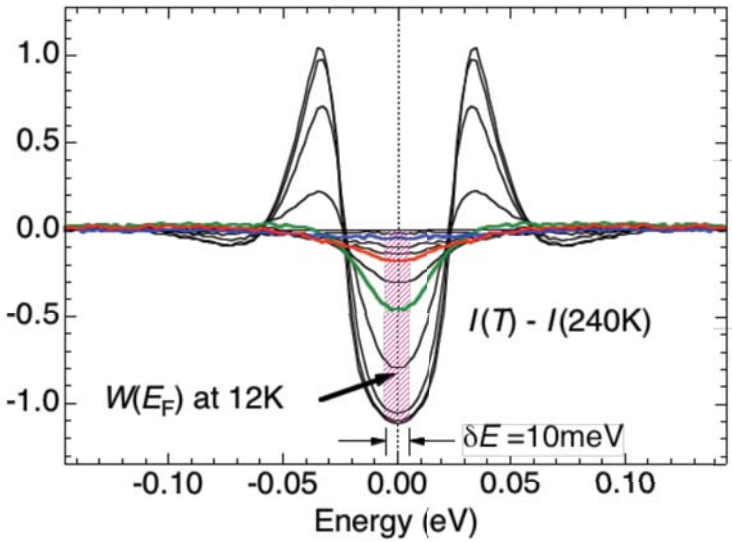



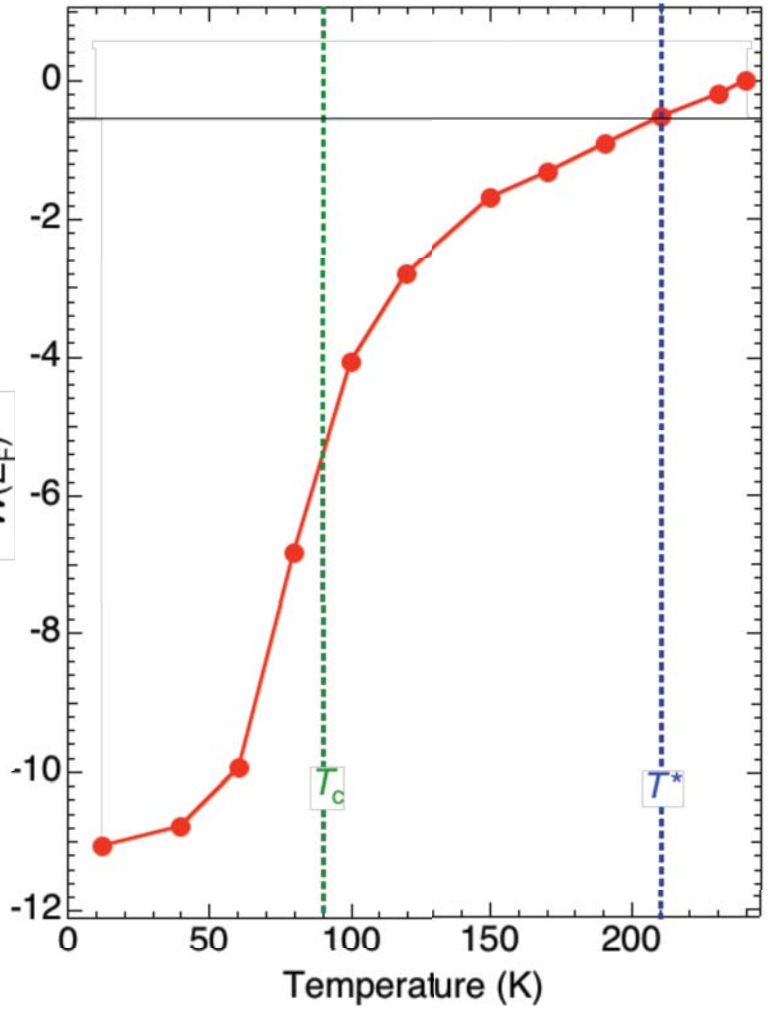

K. Gomez. *et al*. Nature **447**, 569 (2007)

# Quantitative studies of spectral weight at $E_f$

## OP Bi2212 Tc=95K



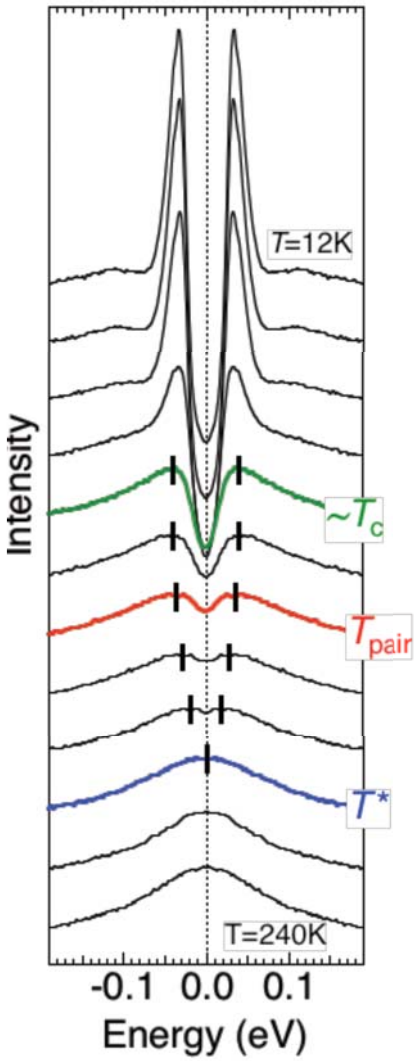



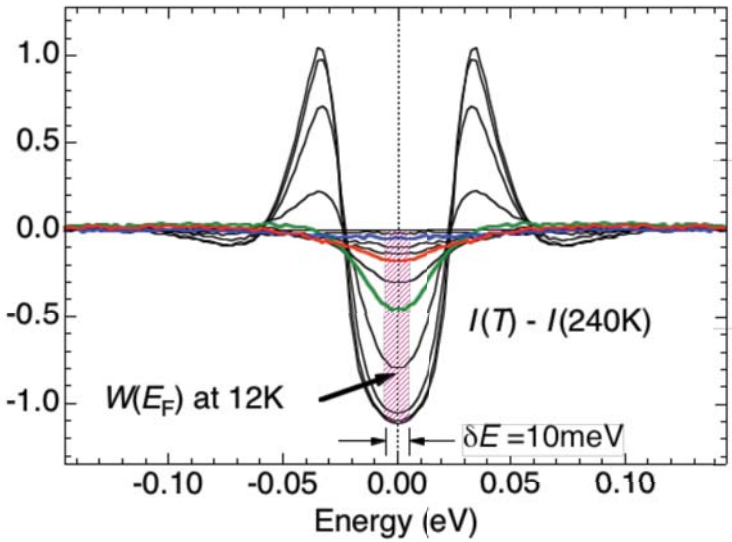



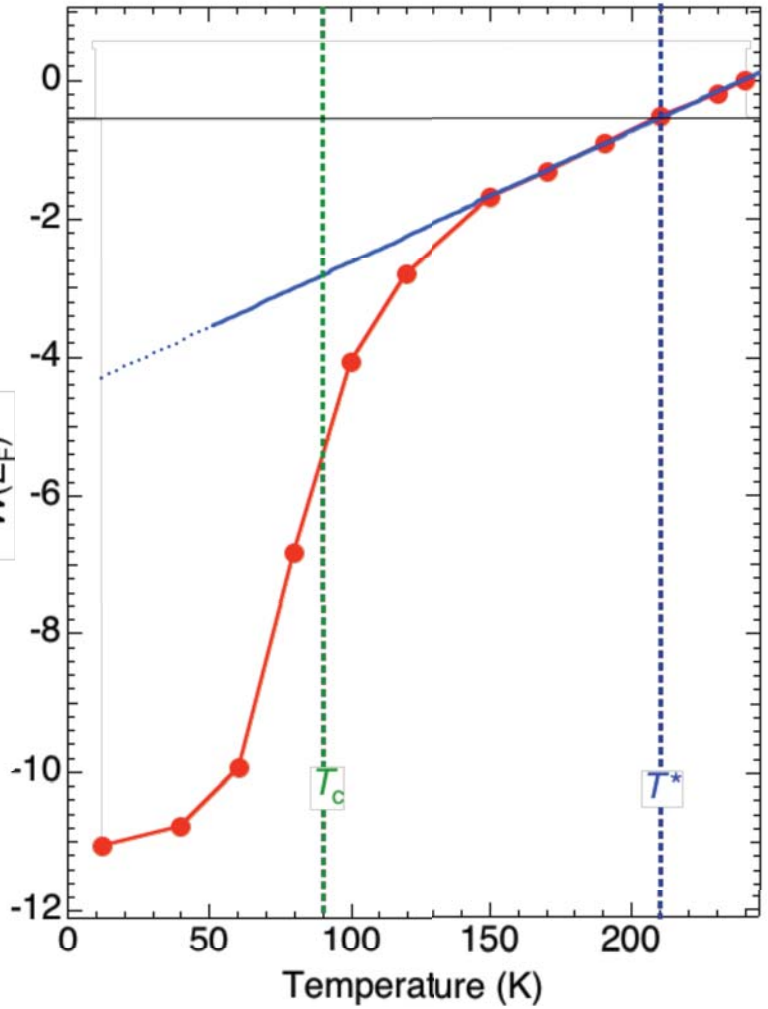

T. Kondo *et al*., arXiv:1005.5309

# Quantitative studies of spectral weight at $E_f$

## OP Bi2212 Tc=95K



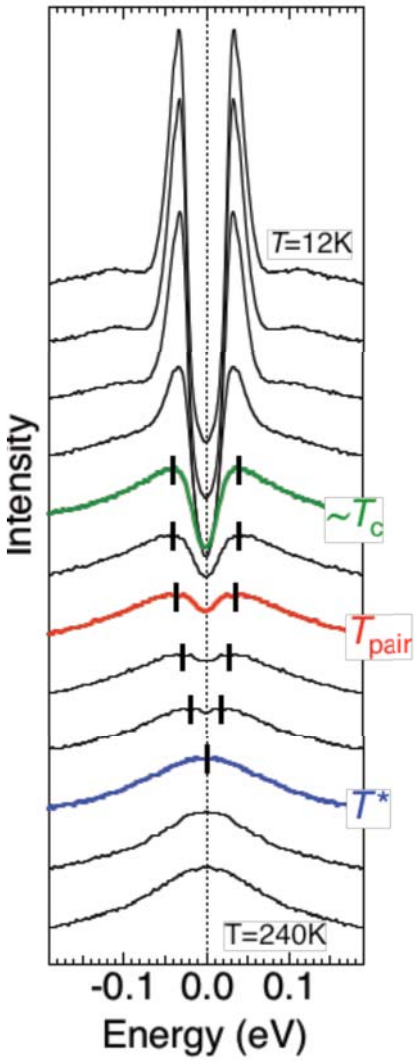



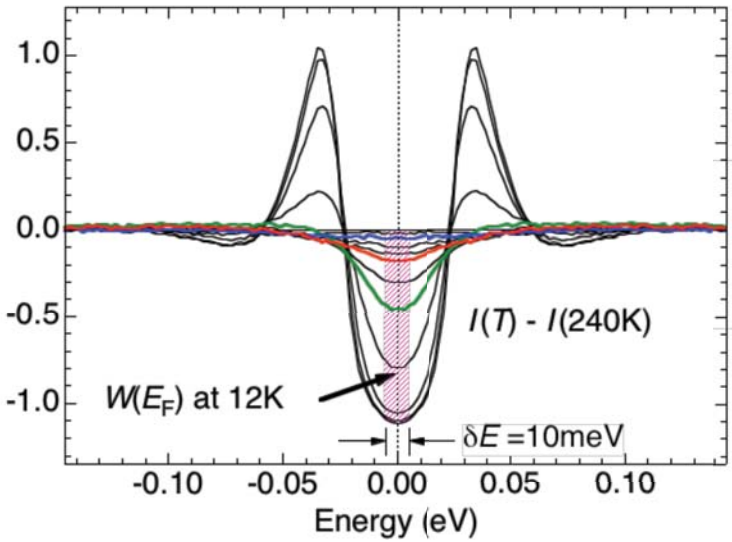



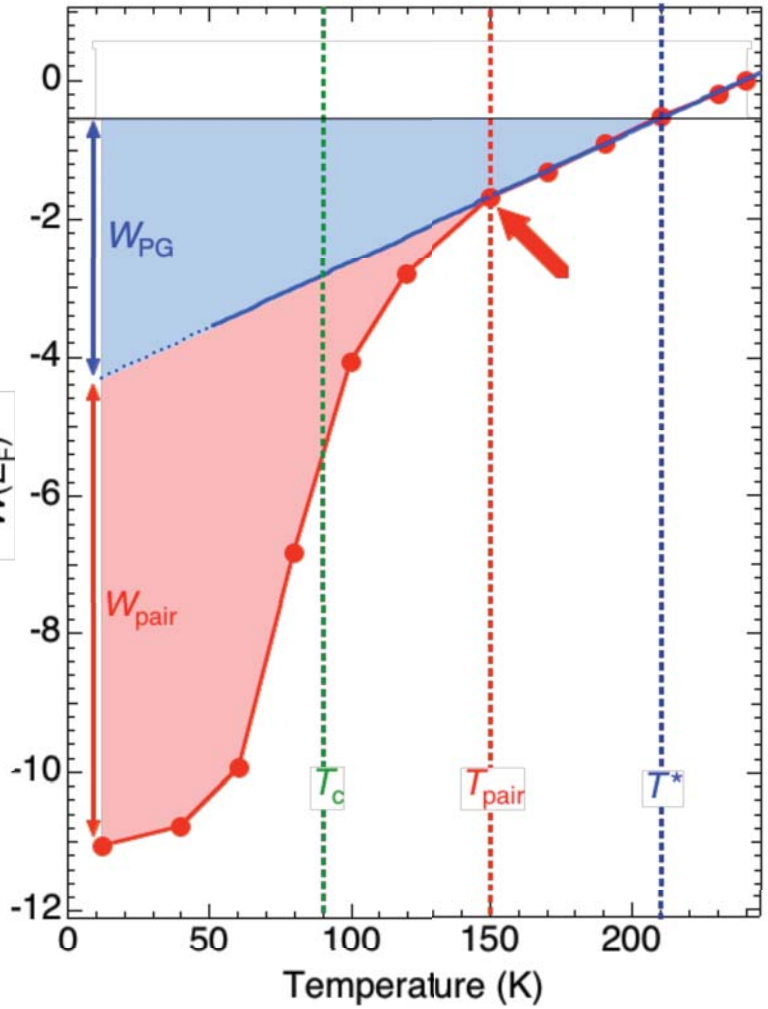

T. Kondo *et al*., arXiv:1005.5309

# Quantitative studies of spectral weight at $E_f$

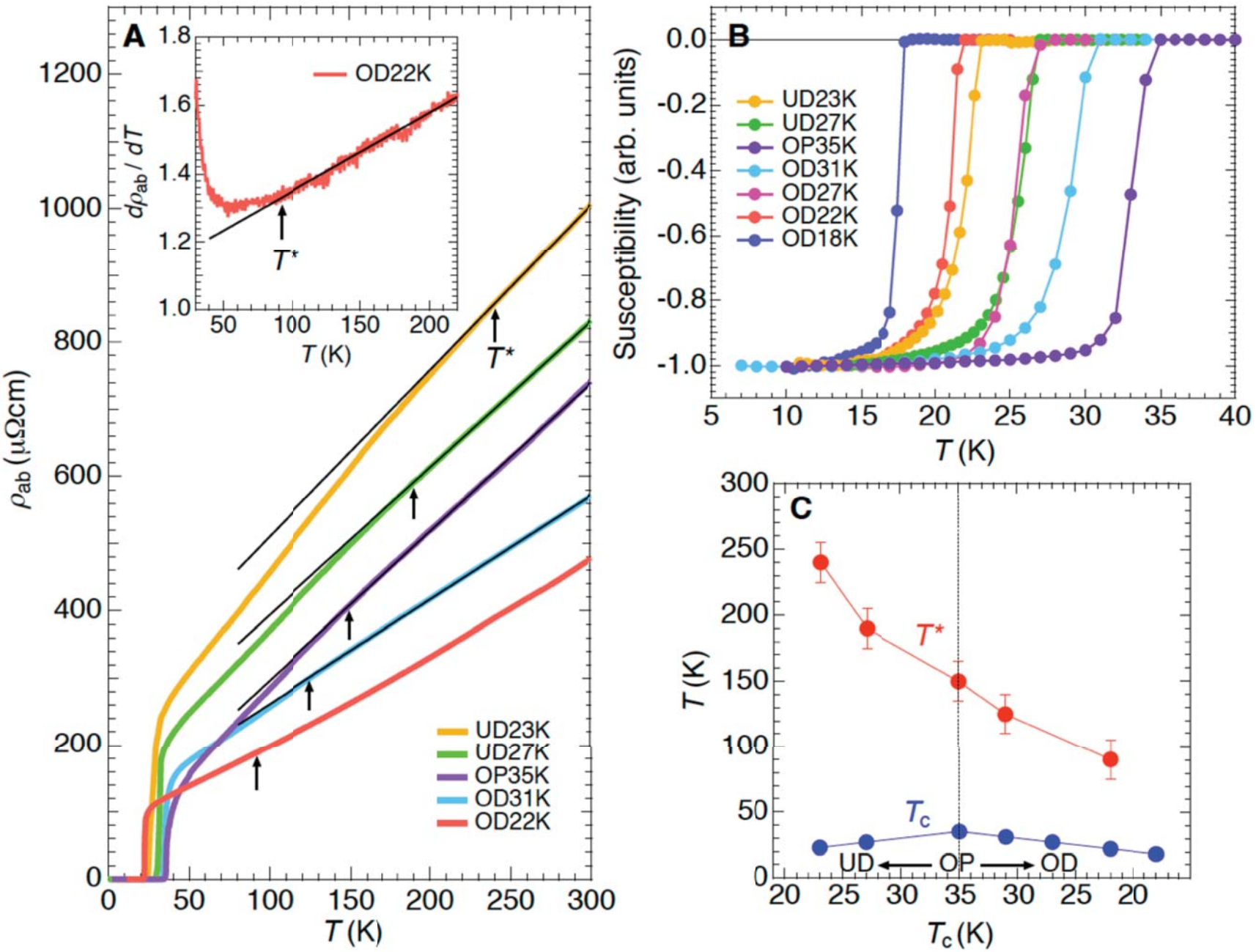
## OP Bi2212 Tc=95K



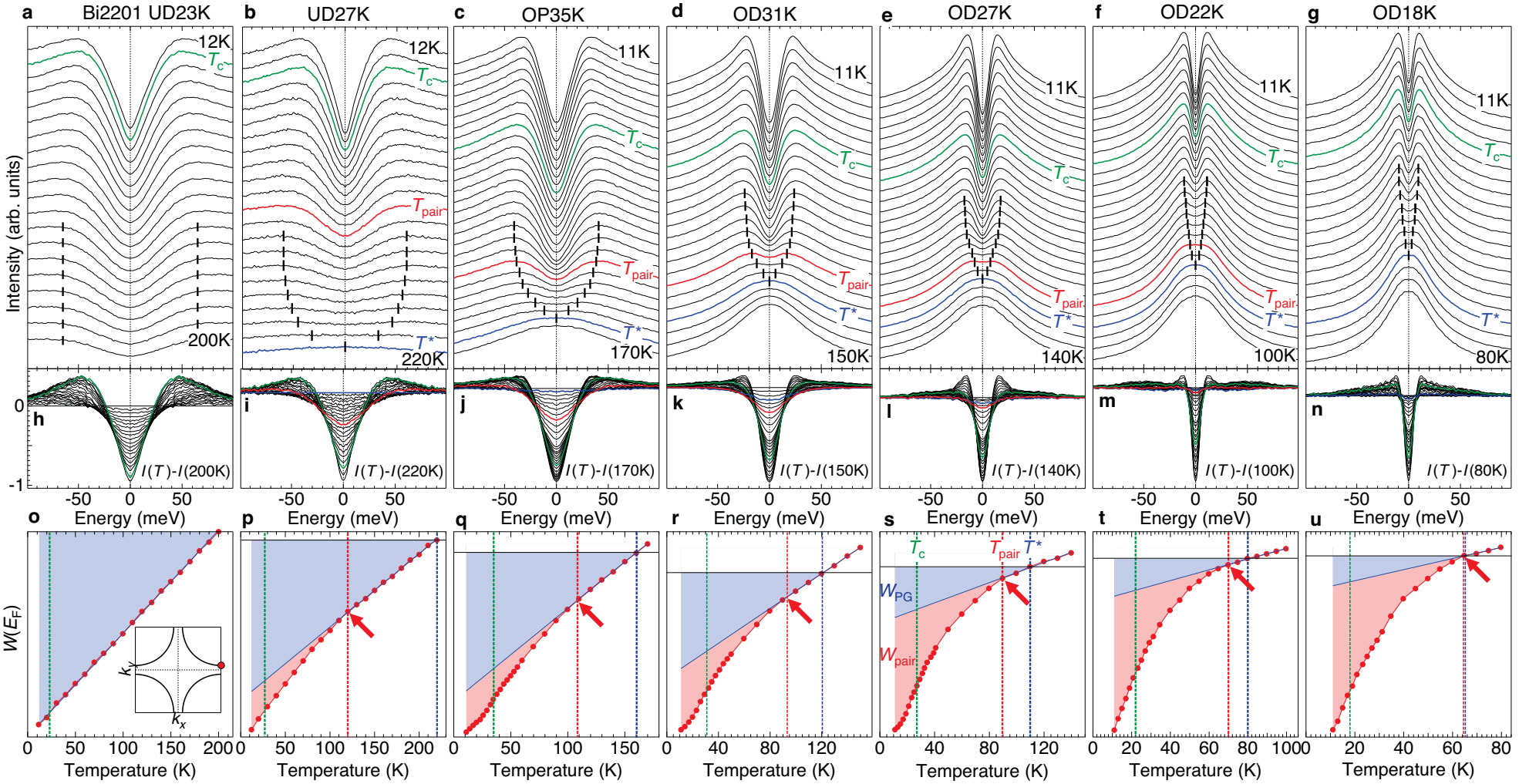



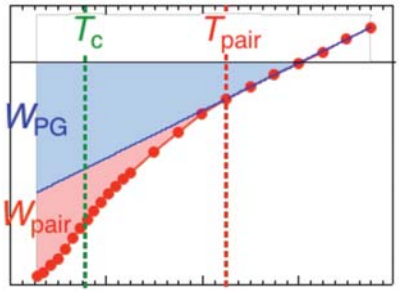

T. Kondo *et al.*, arXiv:1005.5309



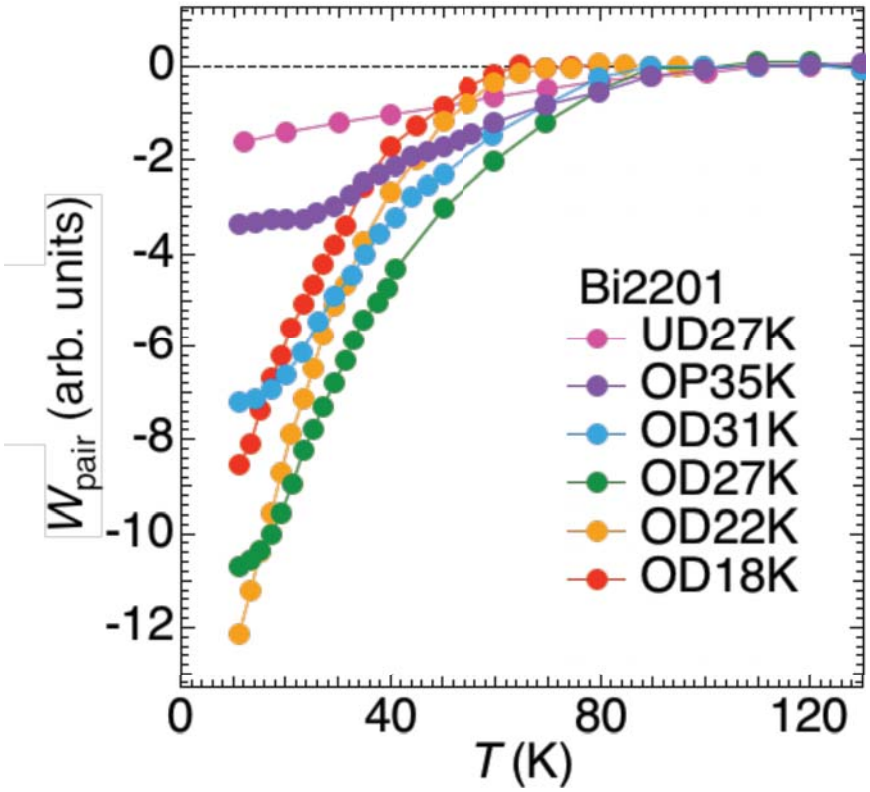
# Doping dependence of the $W_{PG}$ and $W_{pair}$: Bi2201

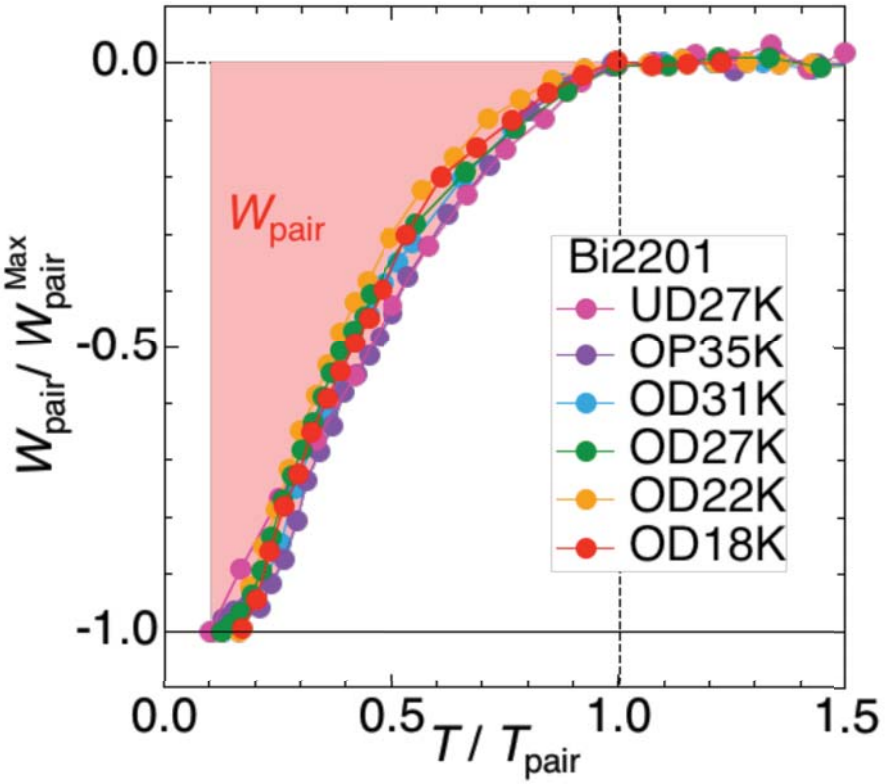


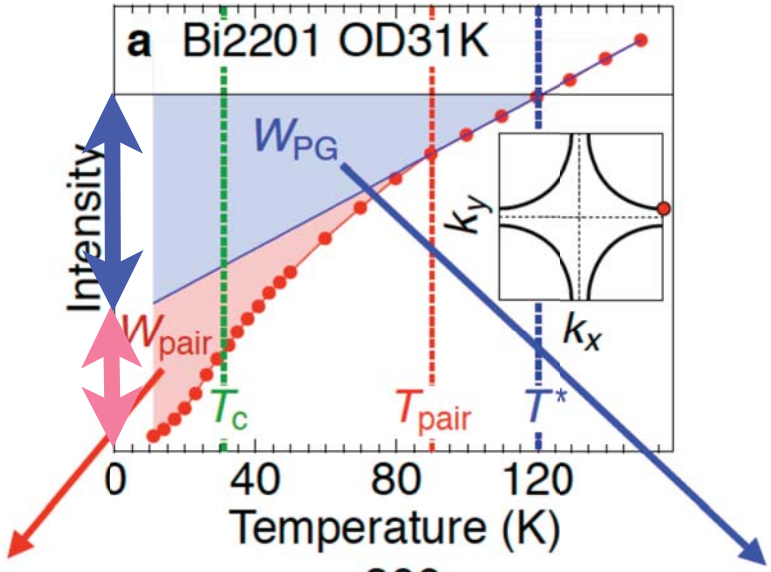

T. Kondo *et al.*, arXiv:1005.5309

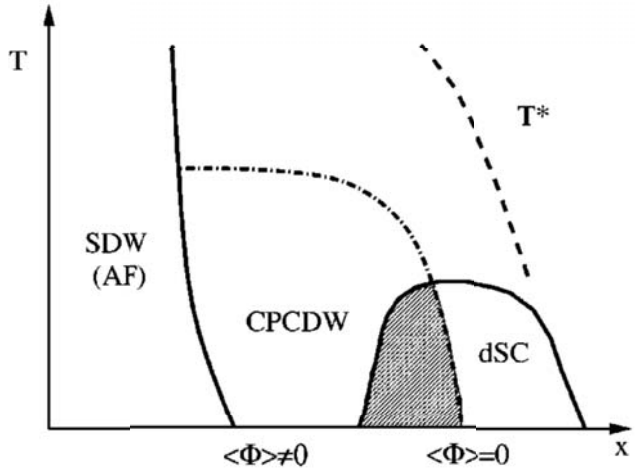



# Universal scaling of $W_{pair}$ w.r.t. $T_{pair}$

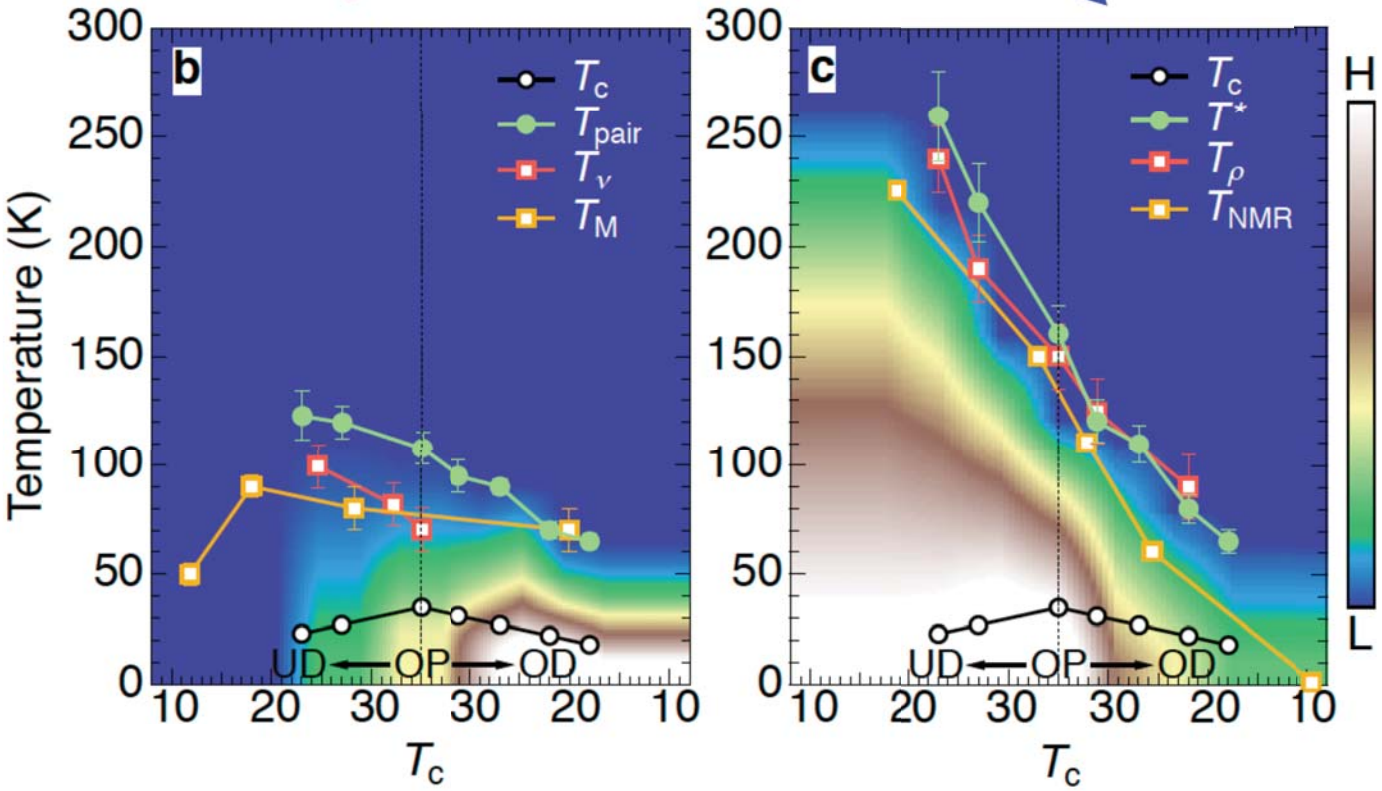





A. Melikyan *et al.* Phys. Rev. B 71, 214511 (2005)




$T_{NMR}$ G. Zheng *et al.*, Phys. Rev. Lett. **94**, 047006 (2005).

$T_m$ Lu Li, *et al.* Phys. Rev. B 81, 054510 (2010)

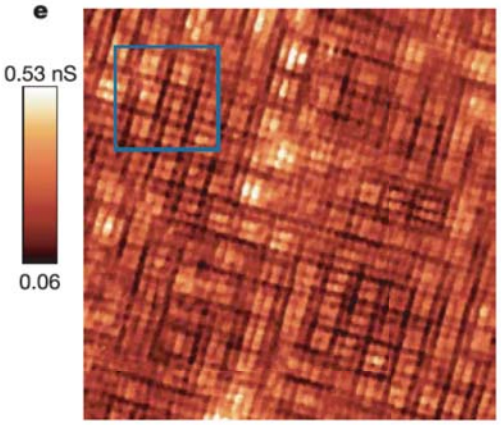
$T_v$ Wang, Y. *et al.* Phys. Rev. B **64**, 224519 (2001)

ARPES

$T^*$
$T_{pair}$ T. Kondo *et al.*, arXiv:1005.5309

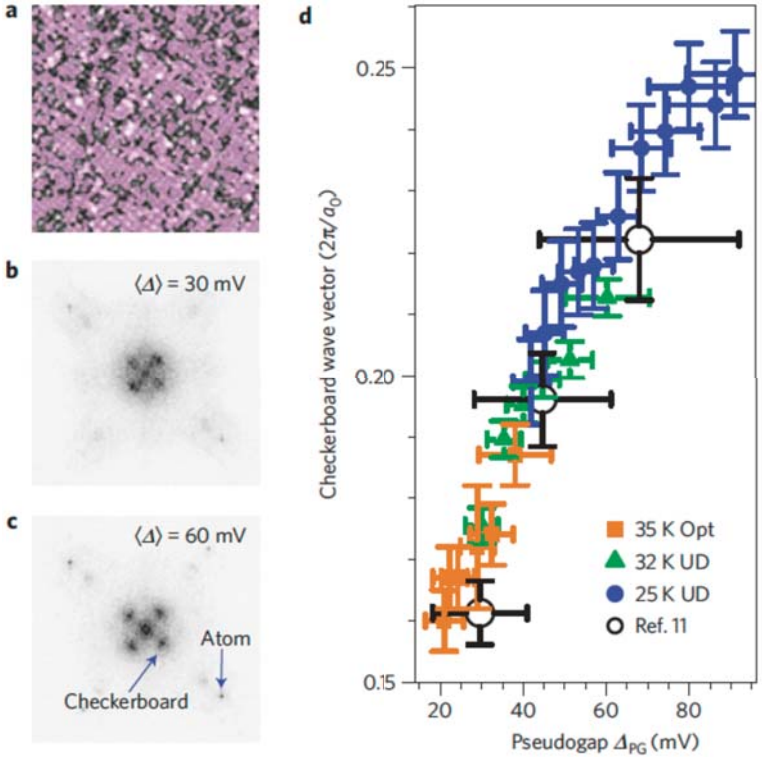
# Pseudogap = "checkerboard" order?

$Ca_{2-x}Na_xCuO_2Cl_2$




T. Hanaguri *et al*., Nature **430**, 1001-1005 (2004)

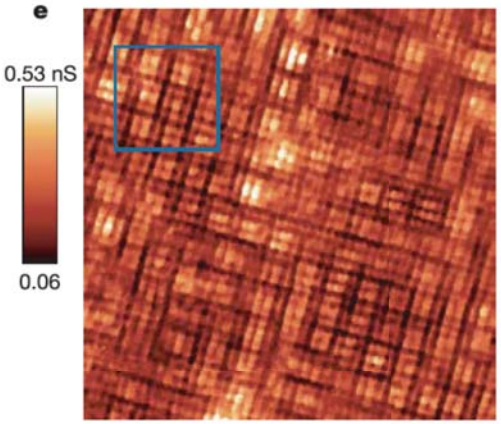
Bi2201




Wise *et al*., Nat. Phys. 5, 213-216 (2009)

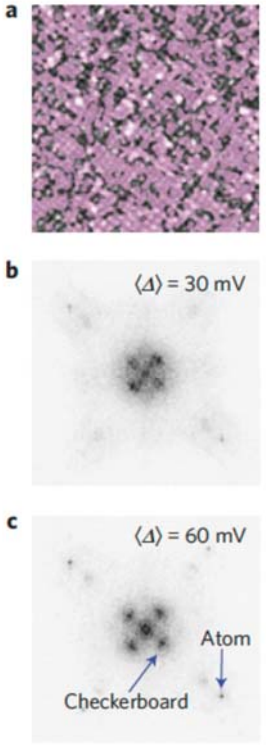
# Pseudogap = "checkerboard" order?

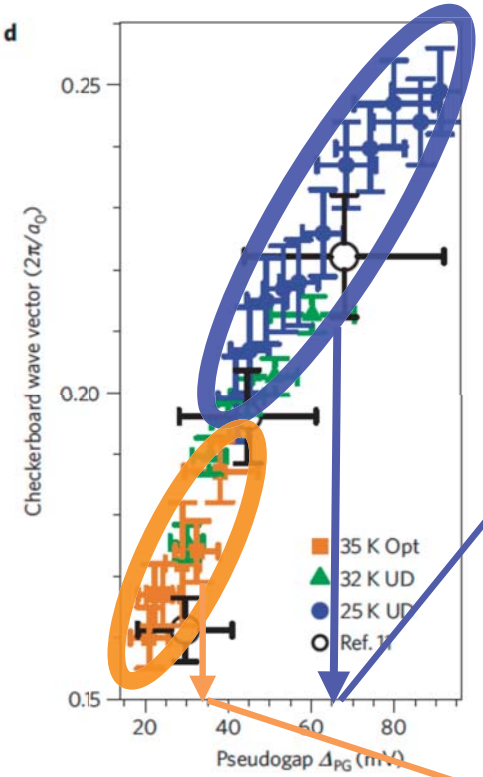
$Ca_{2-x}Na_xCuO_2Cl_2$



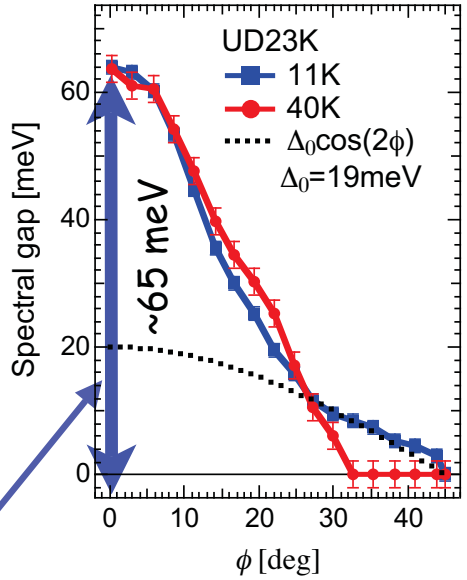

T. Hanaguri *et al.*, Nature **430**, 1001-1005 (2004)

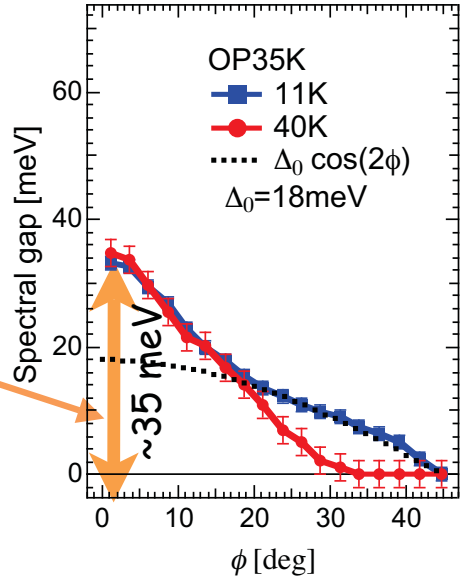
Bi2201




Wise *et al.*, Nat. Phys. 5, 213-216 (2009)




T. Kondo et al., Nature **457**, 295 (2009)

# Conclusions

- pseudogap is a state that coexists and competes with superconductivity
- energy scale associated with pseudogap is similar to one of the checker board order observed in STM
- quantitative ARPES approach revealed new spectroscopic temperature scale $T_{pair}$ associated with pairing and different from the pseudogap temperature T*: $T_c << T_{pair} << T^*$
- there is indeed a pre-formed pair state in cuprates, but it is not directly related to the pseudogap