ARPES part II

Adam Kamiński

Ames Laboratory and Iowa State University

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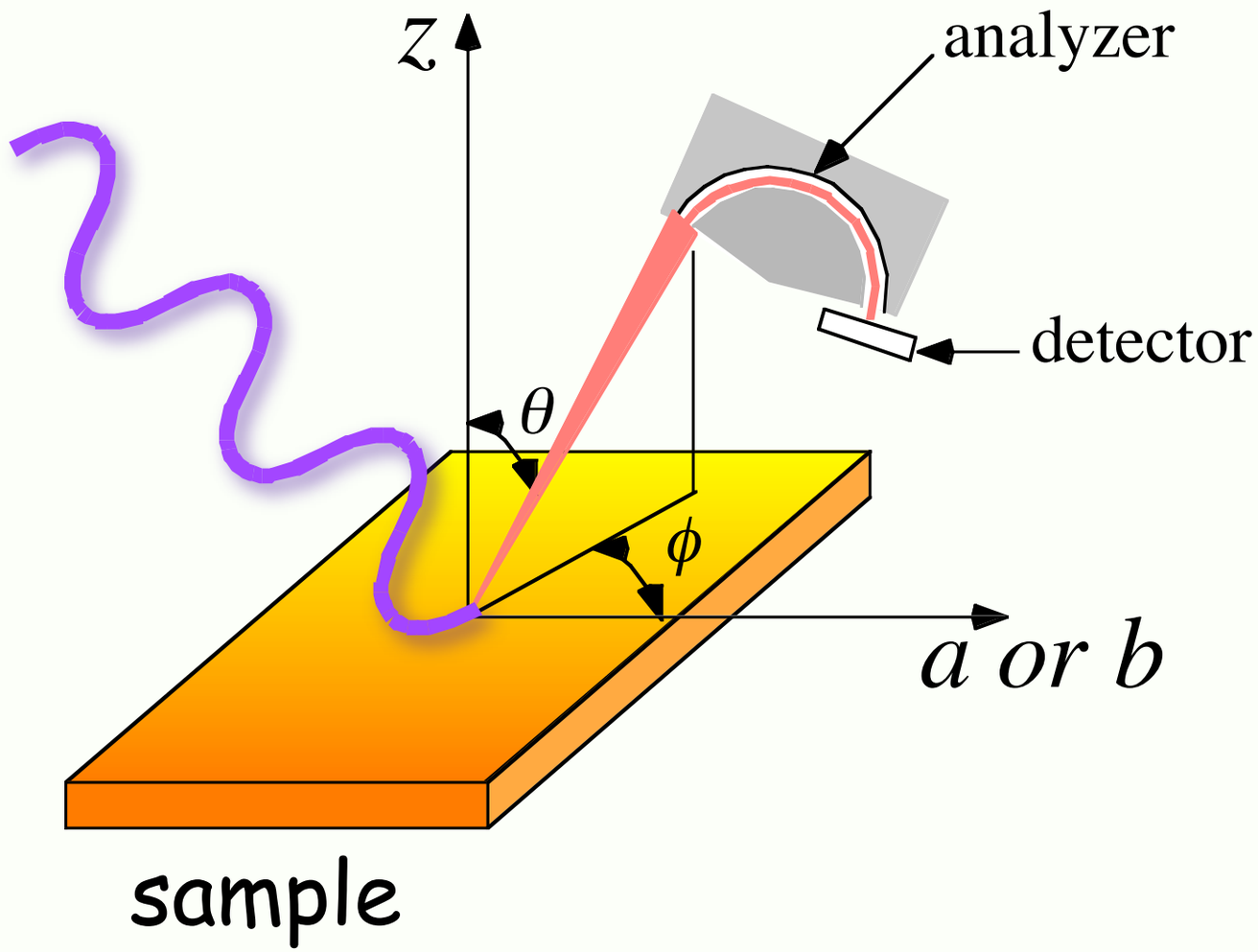
ARPES experiment



We need:

binding energy - E_b

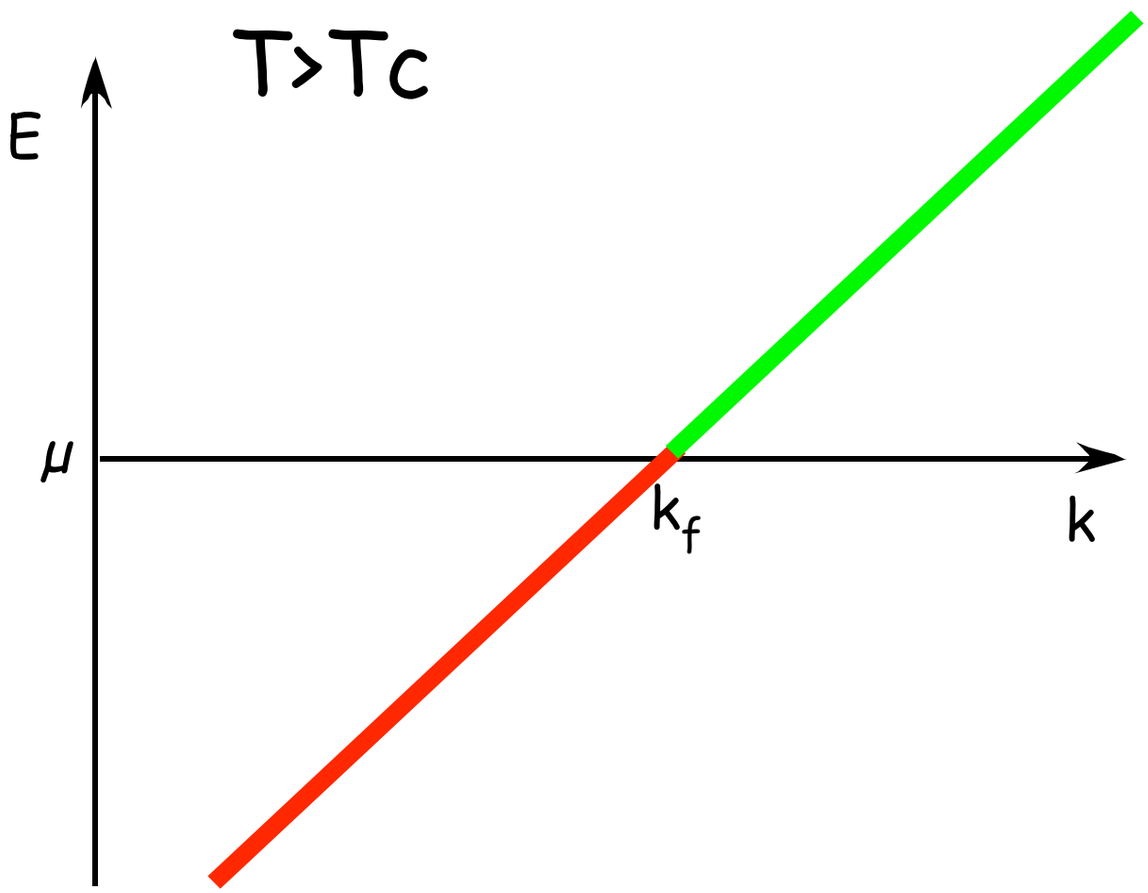
initial momentum - k^i

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

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

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

Energy gaps (superconducting etc...)



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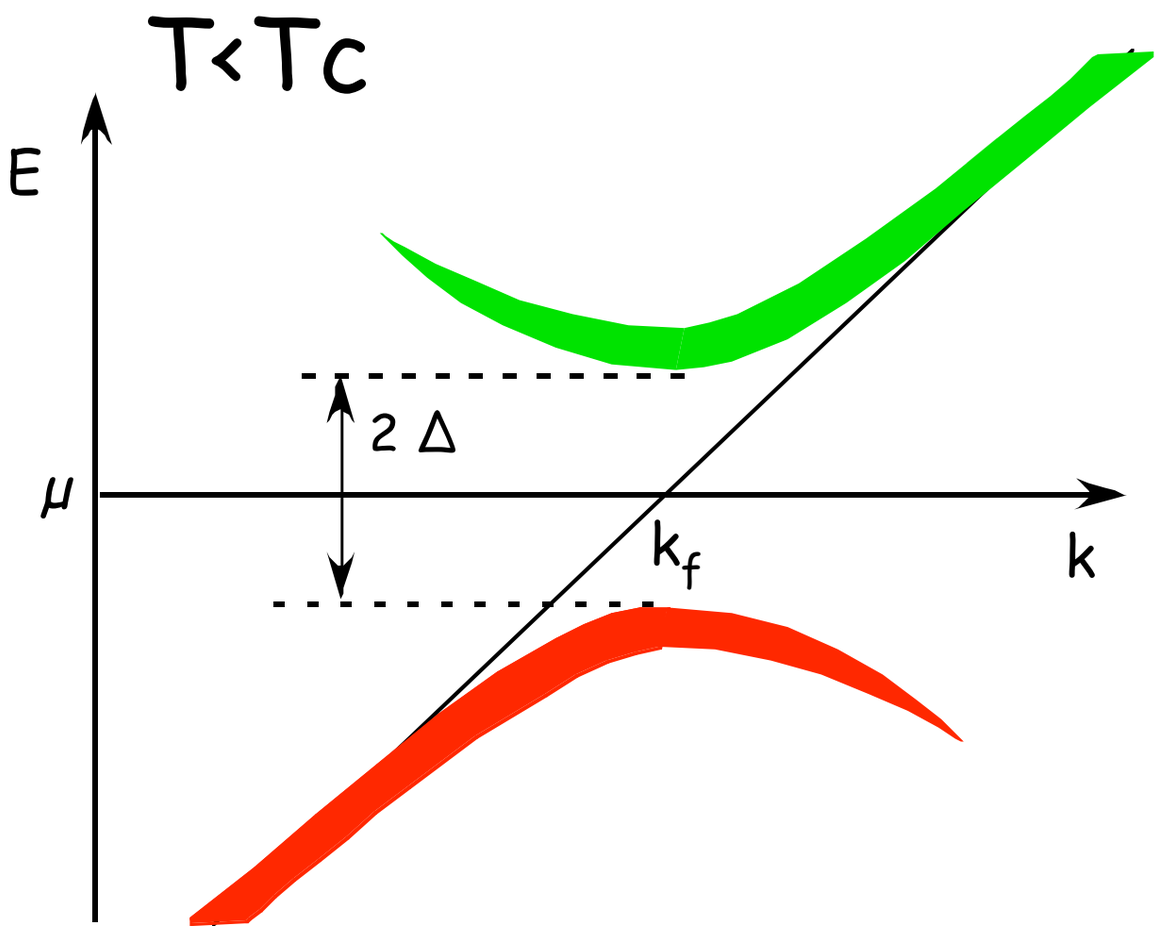

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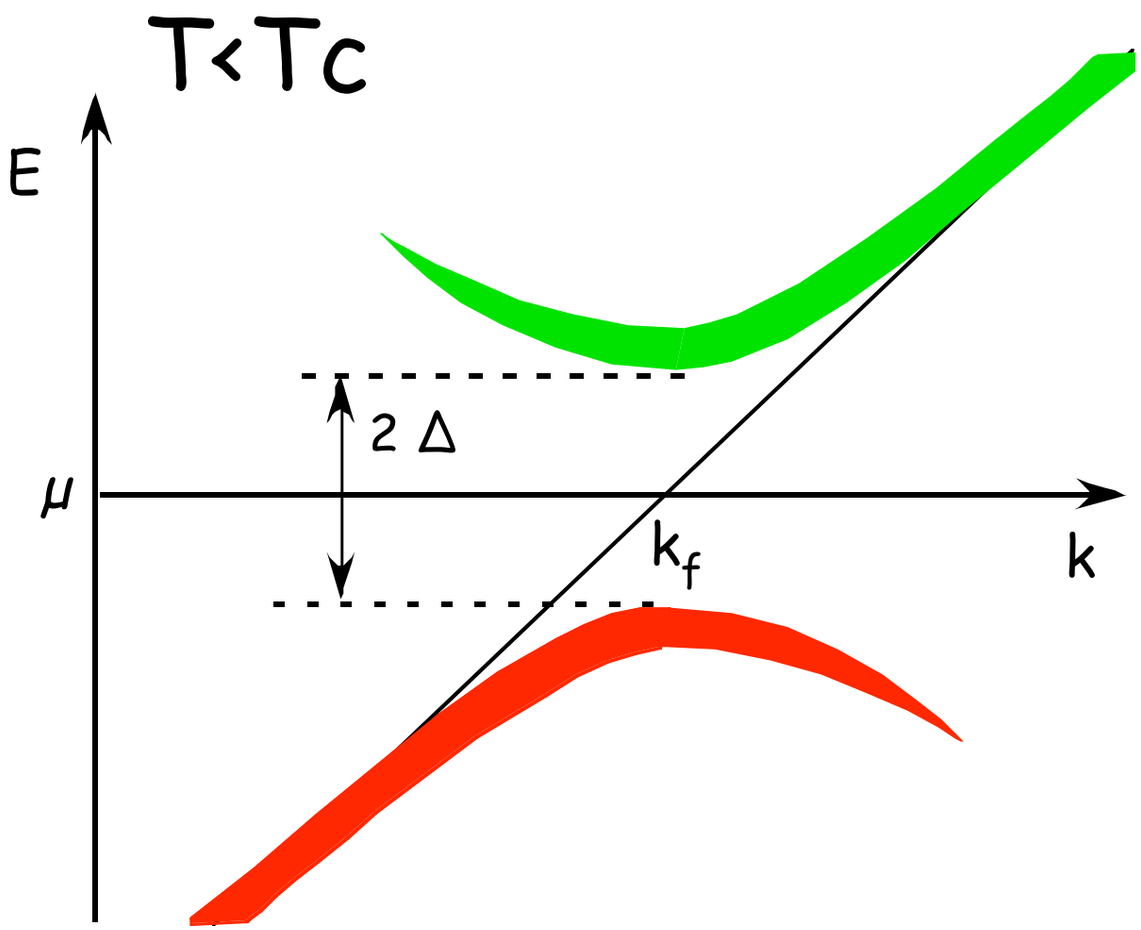
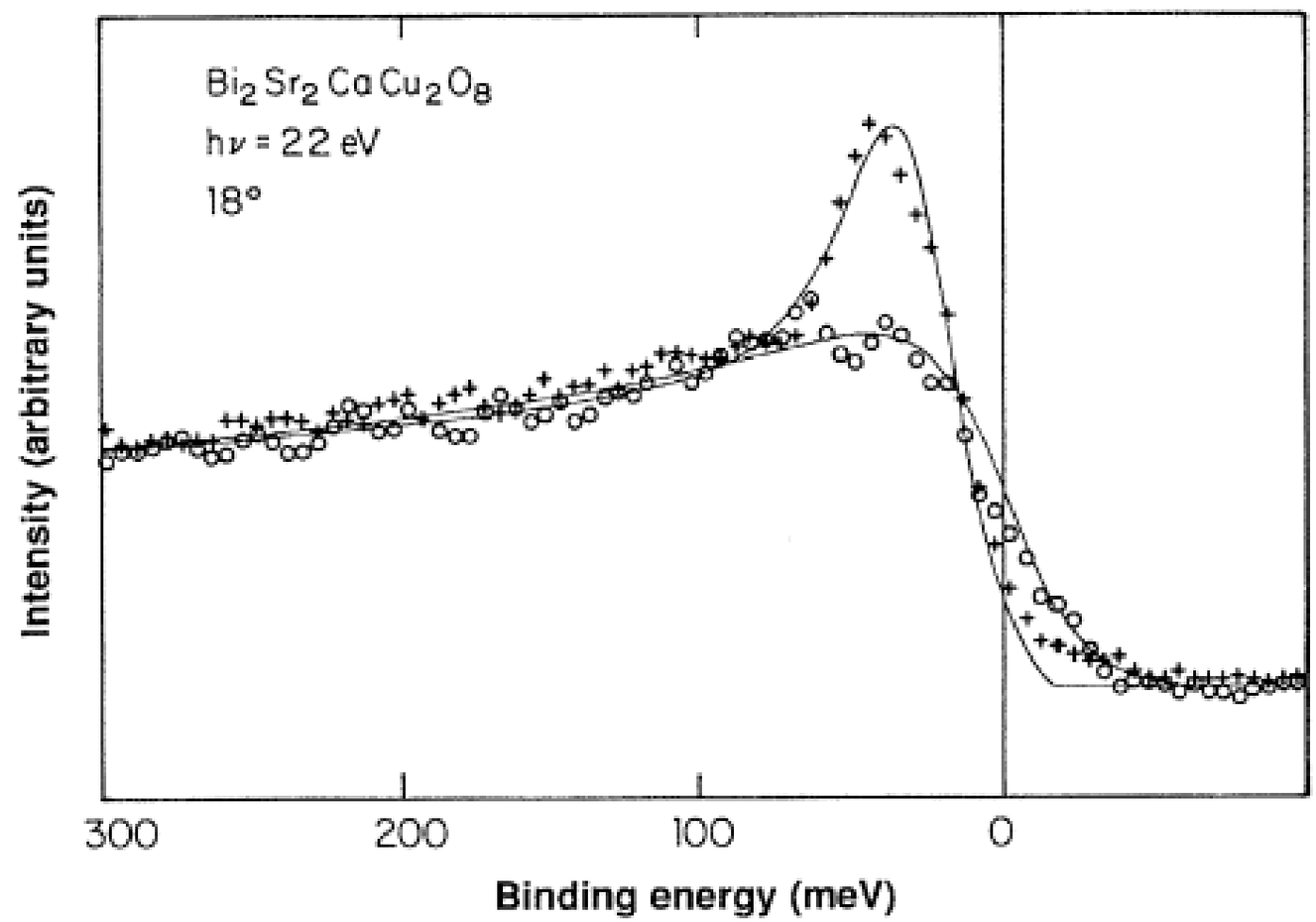
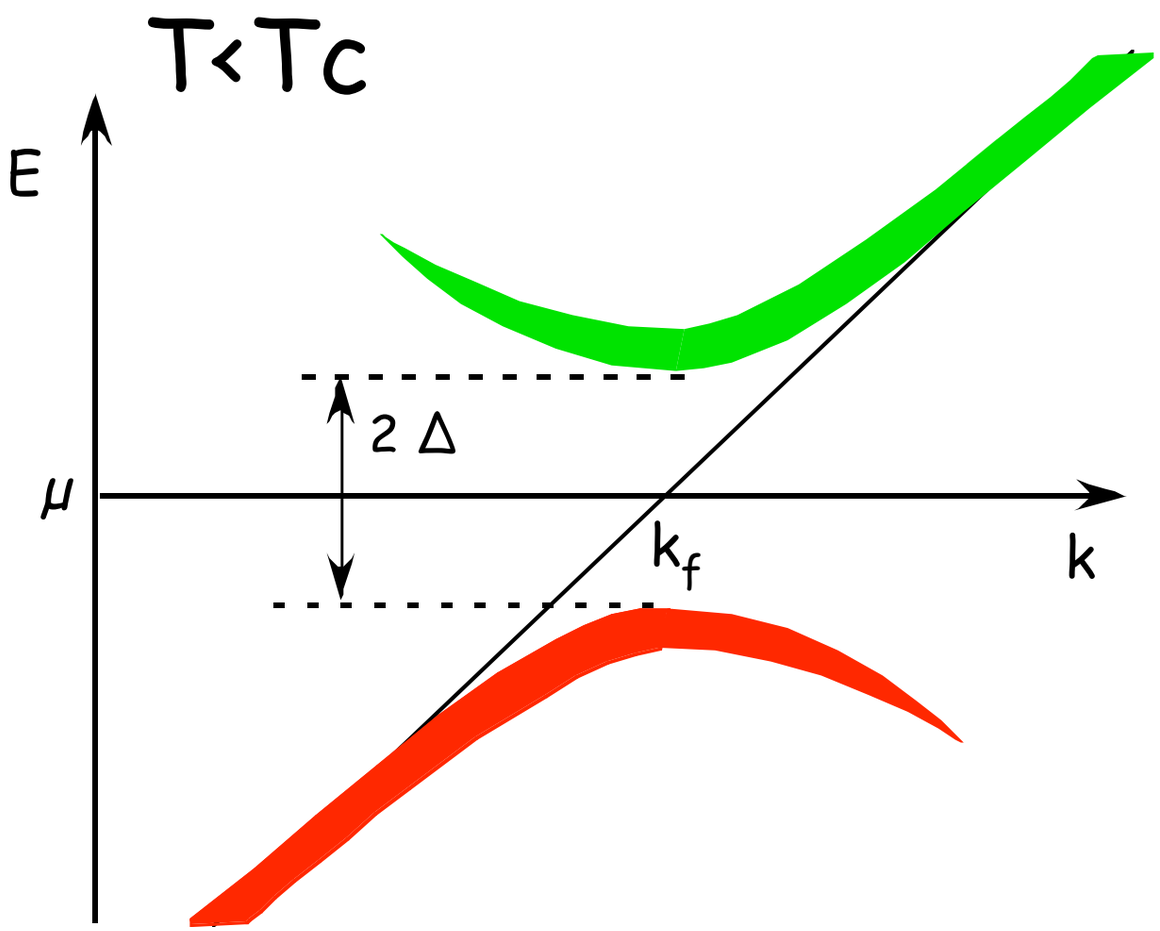
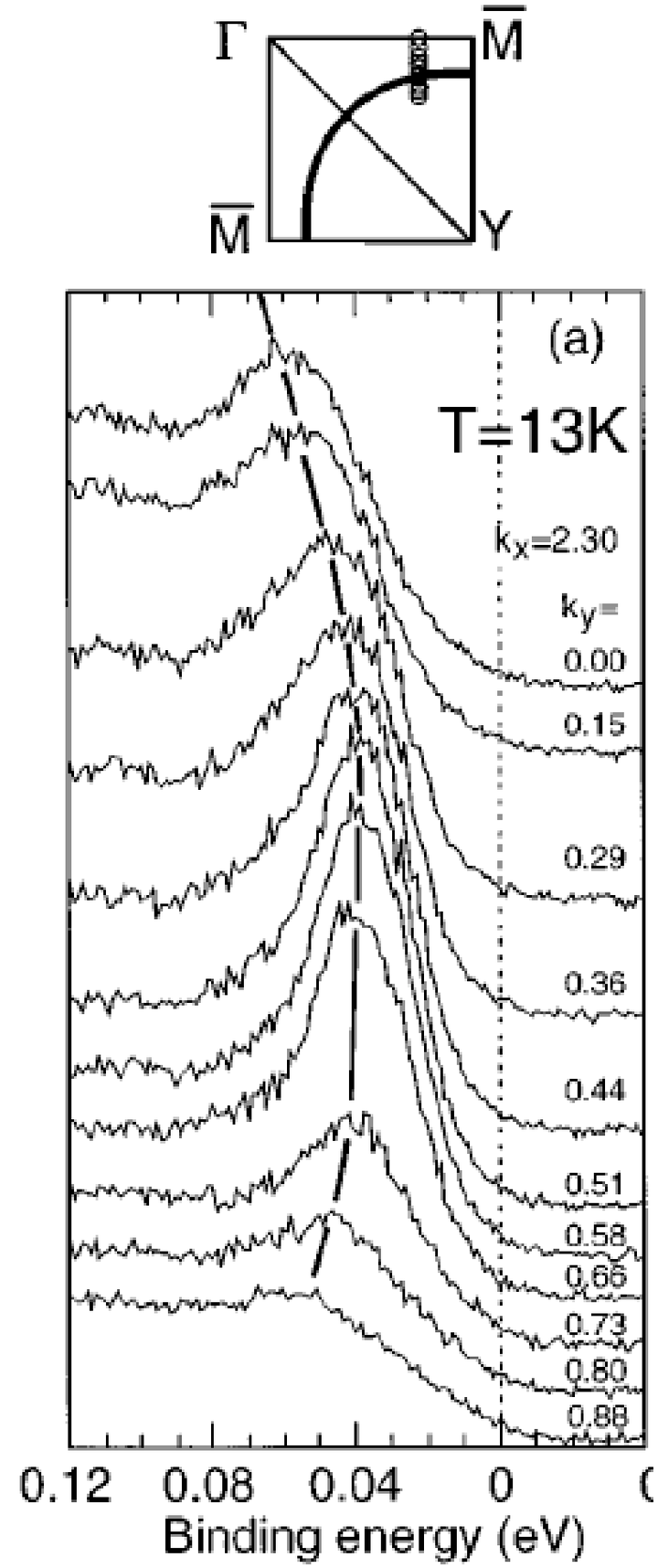


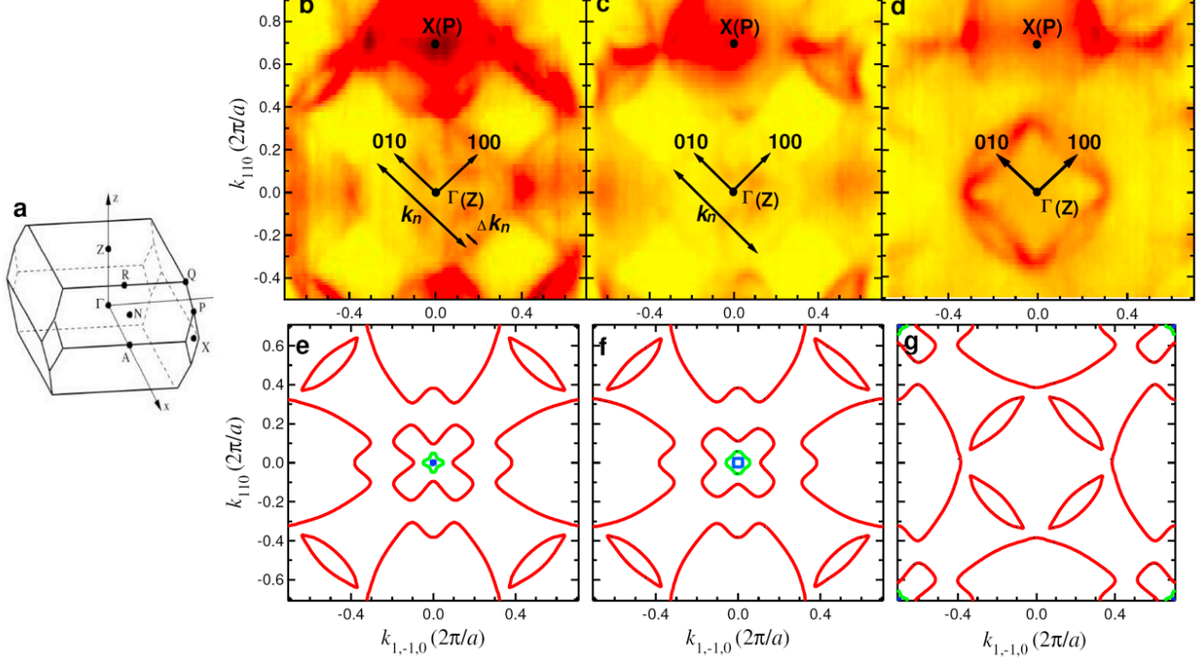


C. G. Olson *et al.,* Science **245,** 731-733 (1989)

Energy gaps (superconducting etc...)

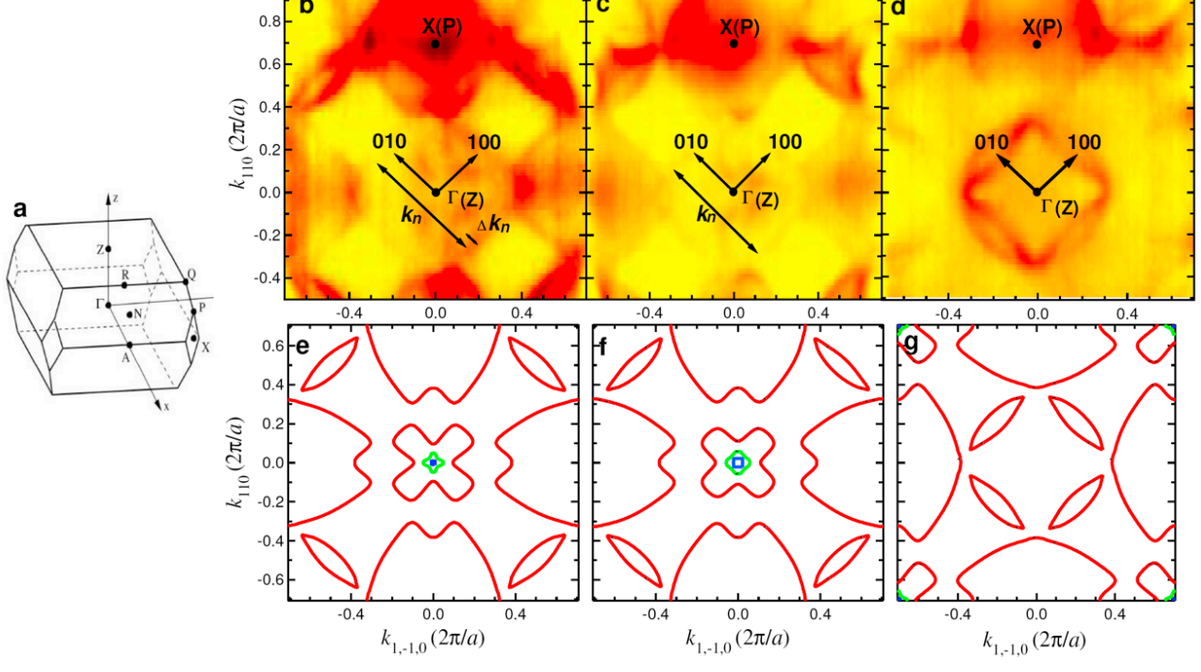


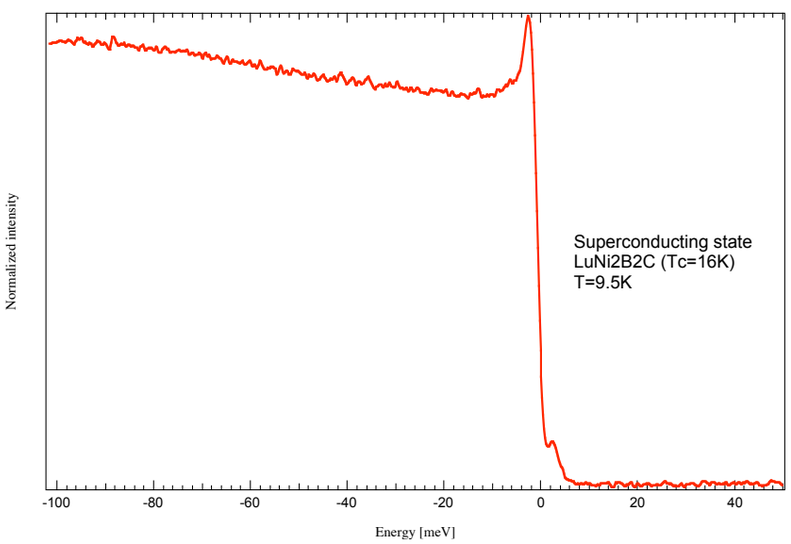




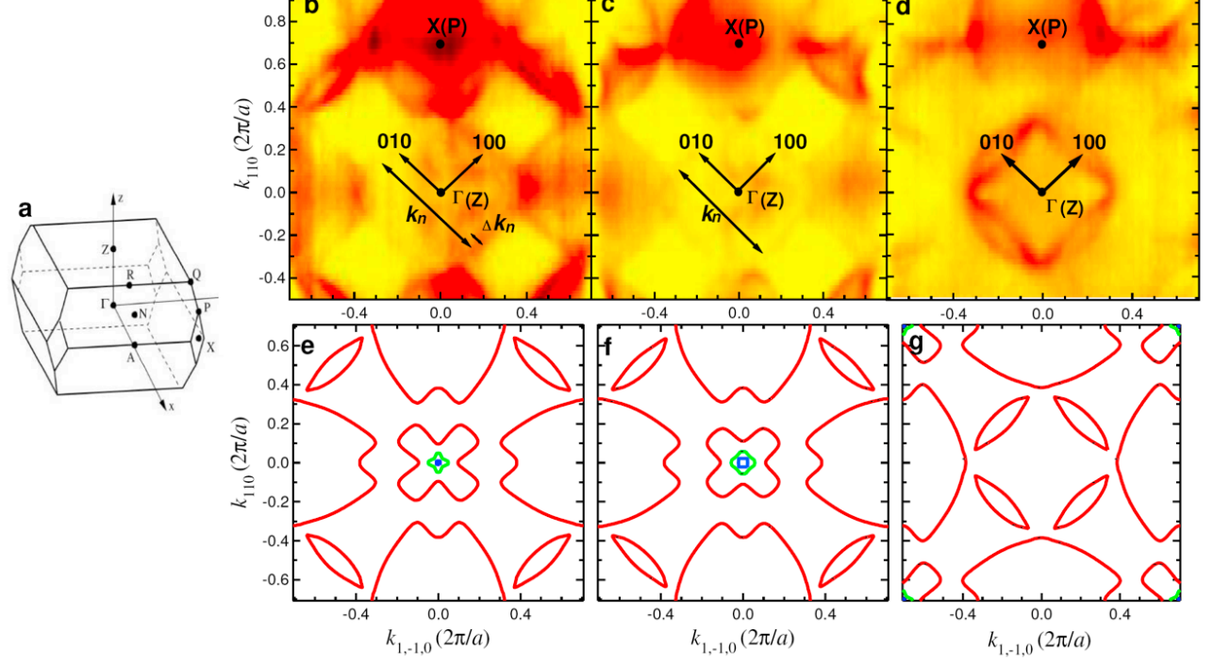
RNi_2B_2C

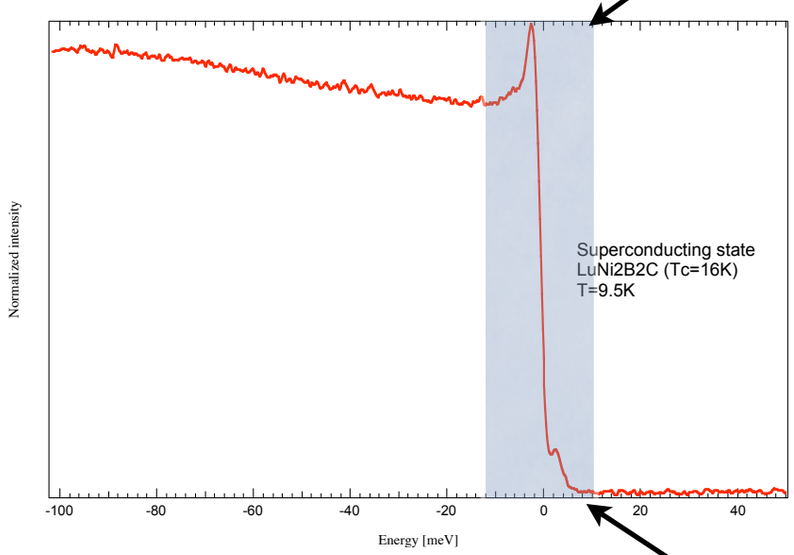
RNi_2B_2C

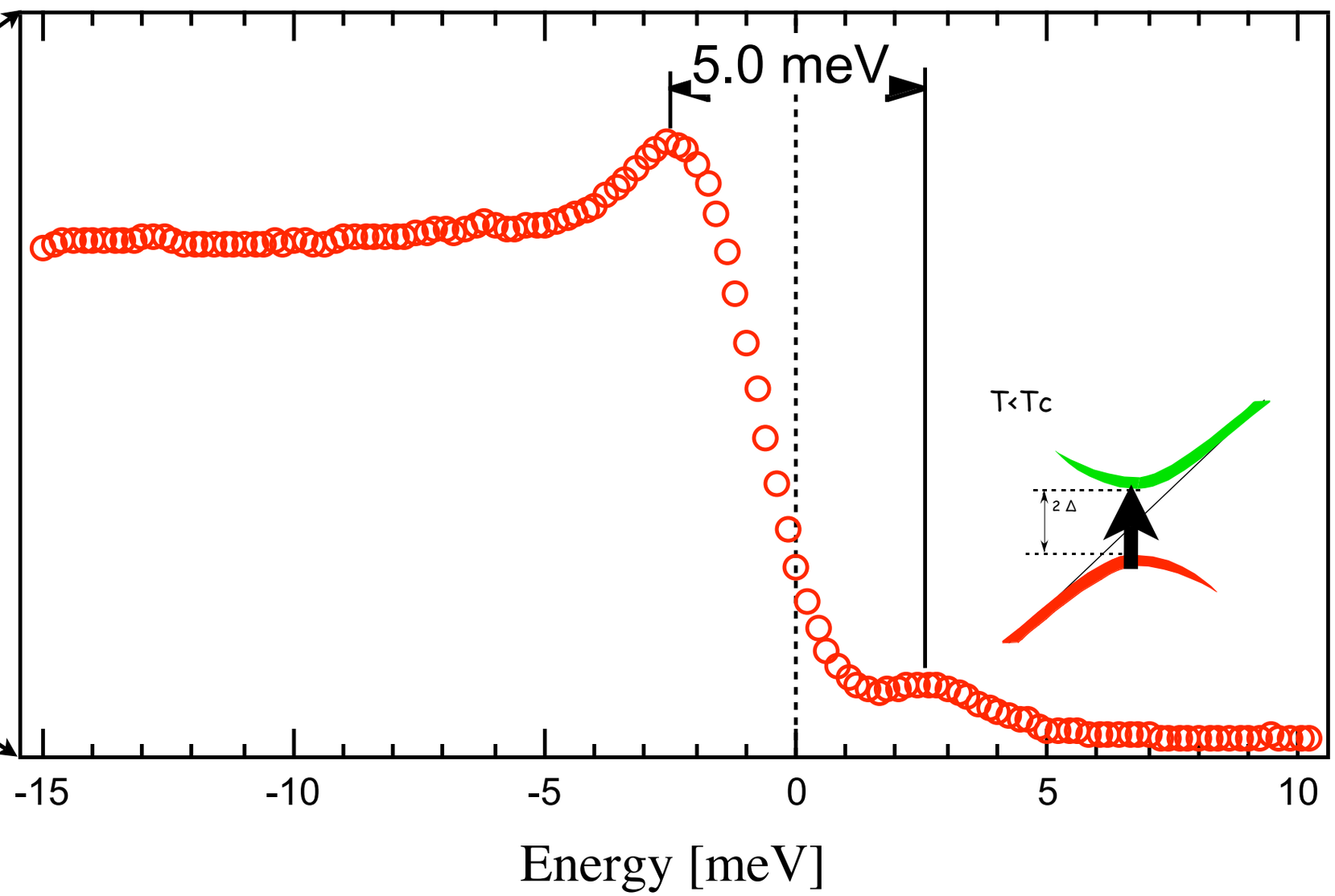

a
b
c
d
e
f
g
X(P)
010
100
Γ(Z)
k_n
Δk_n
k_{110} $(2\pi/a)$
$k_{1,-1,0}$ $(2\pi/a)$


Normalized intensity
Energy [meV]
Superconducting state
LuNi2B2C (Tc=16K)
T=9.5K

RNi_2B_2C







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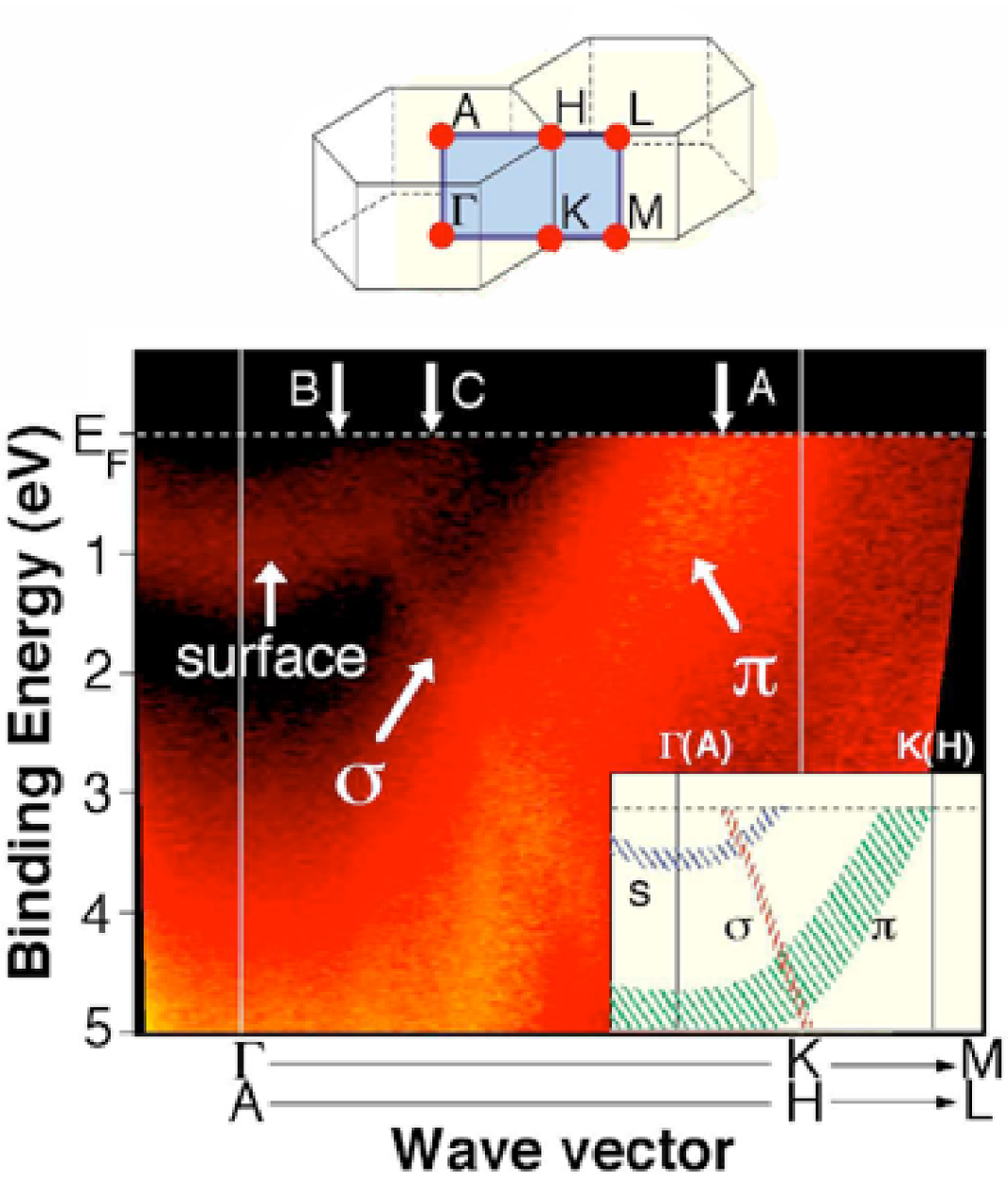
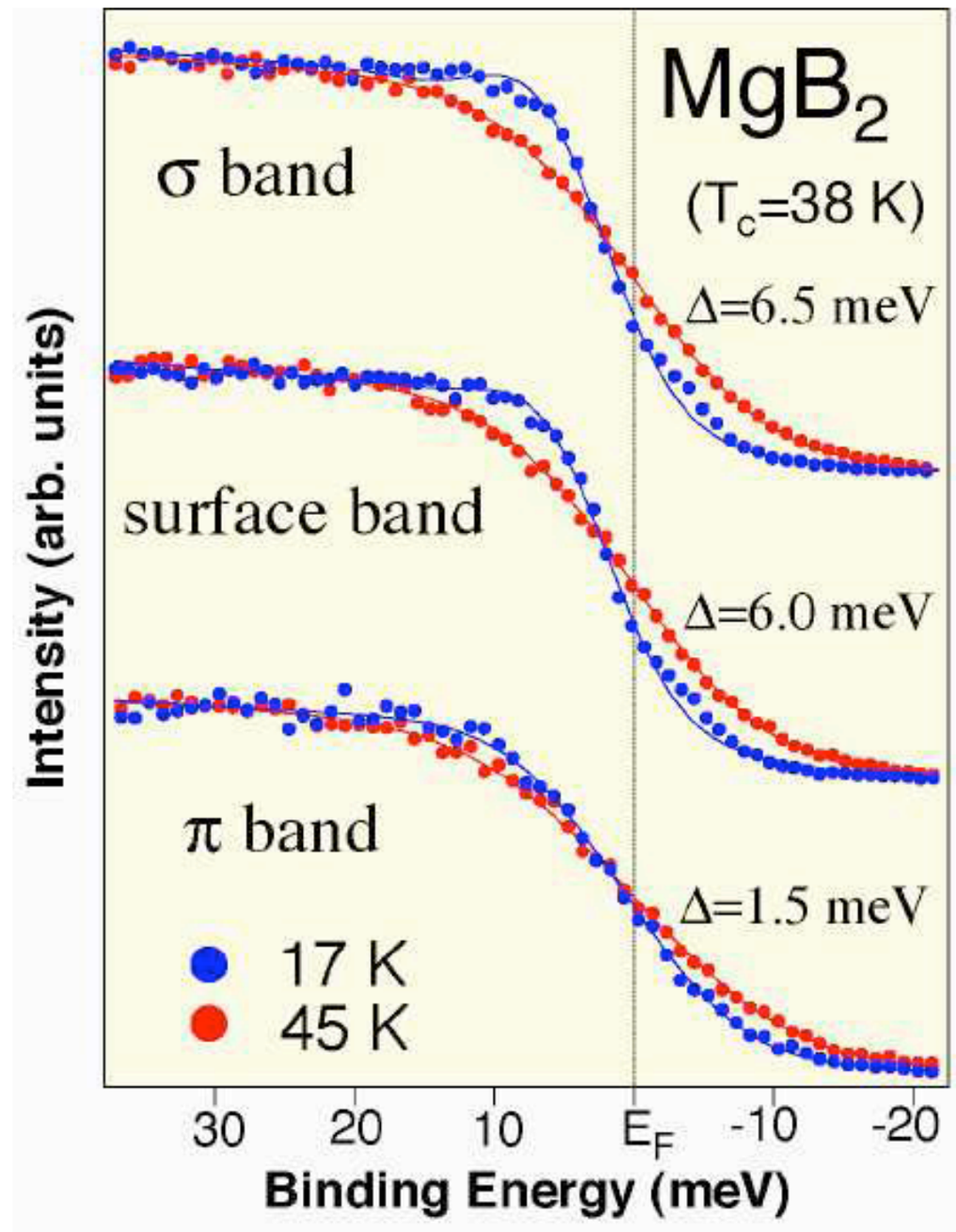
P. Starowicz et al., PRB **77** 134520 (2008)

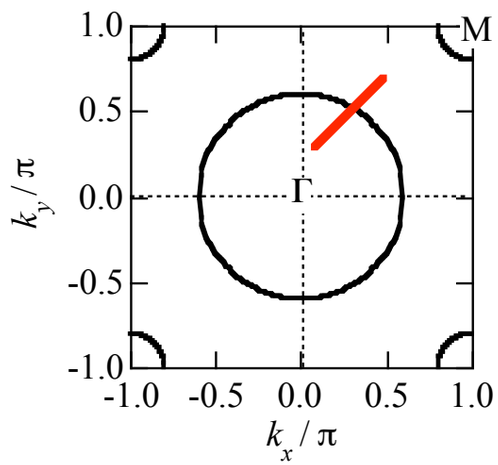
Two band superconductivity in MgB_2

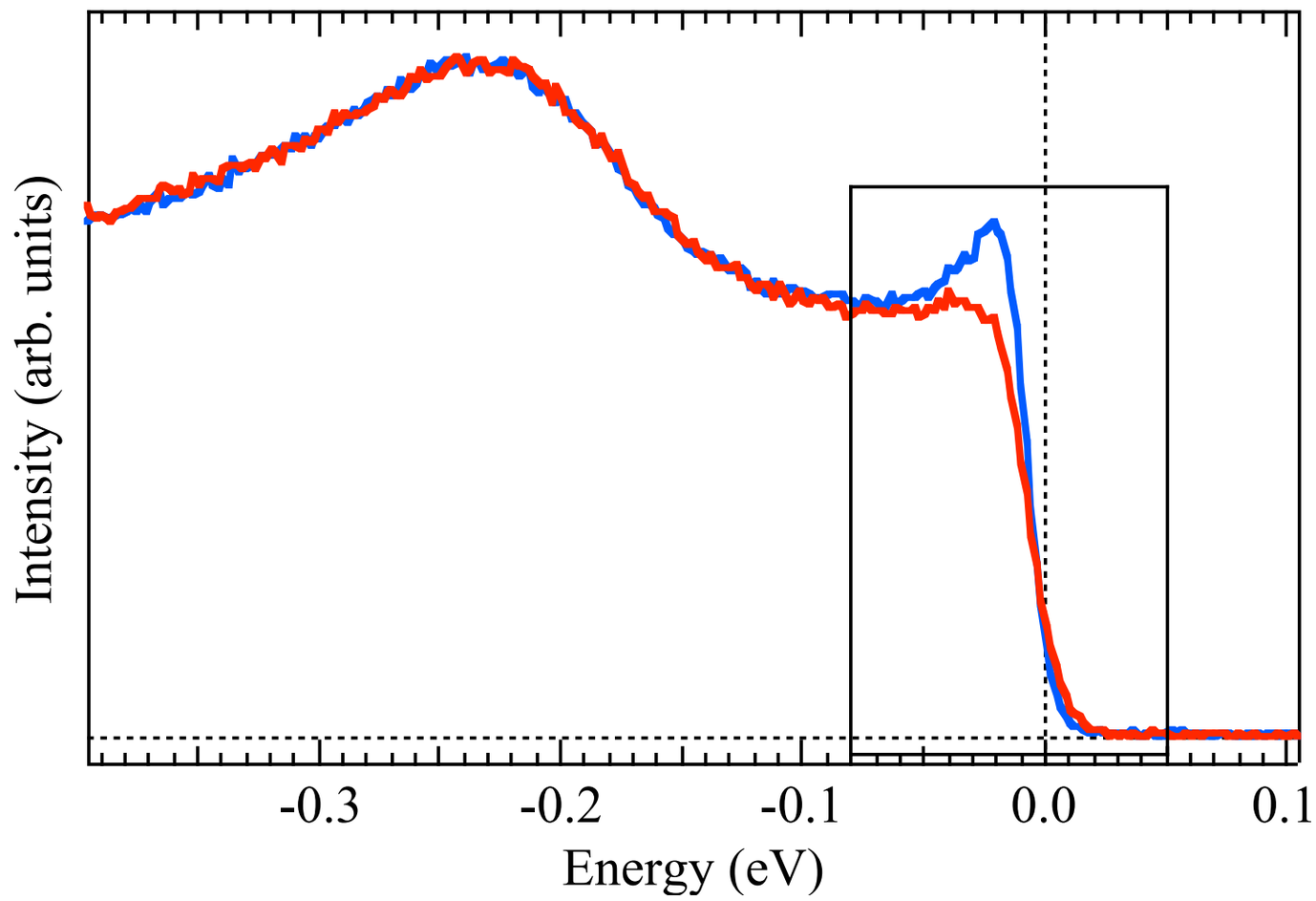


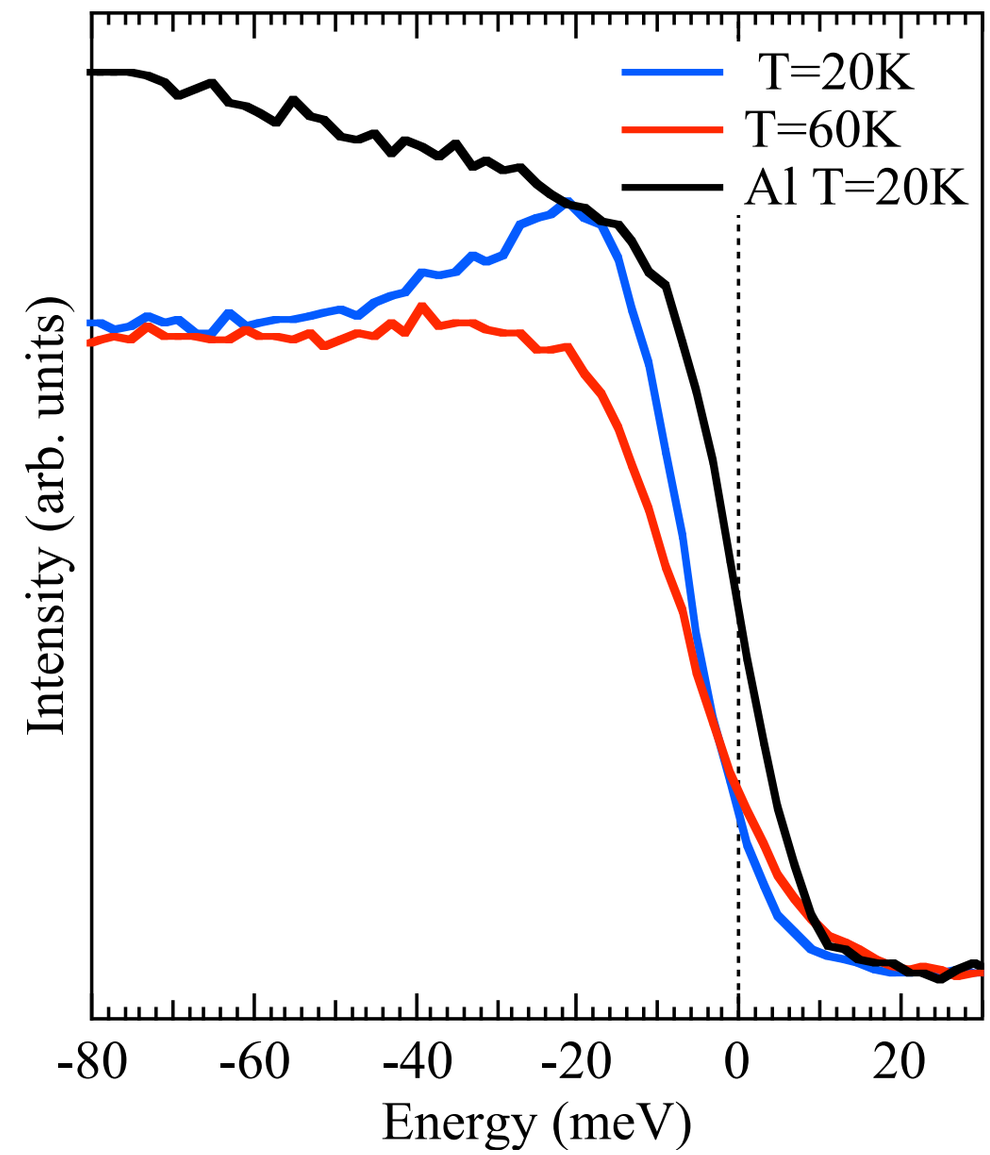


S. Souma et al., *Nature*, **423**, 65 (2003)

Superconducting gap

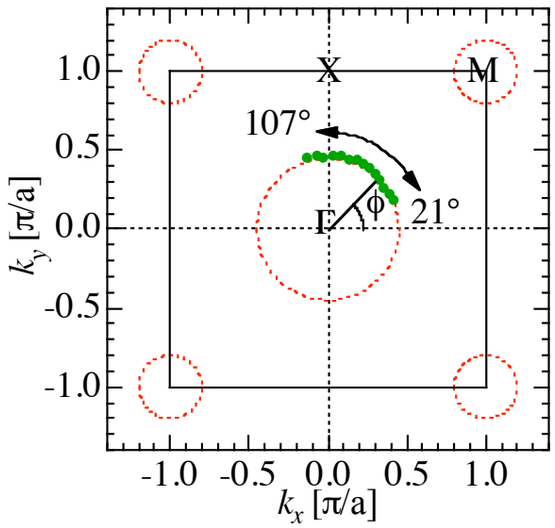


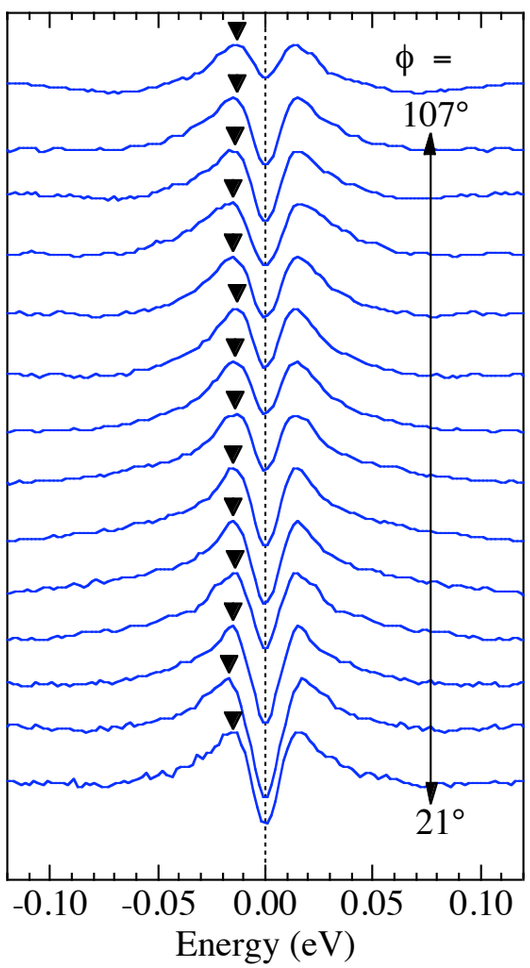




C. Liu *et al*., submitted

Momentum dependence of the superconducting gap





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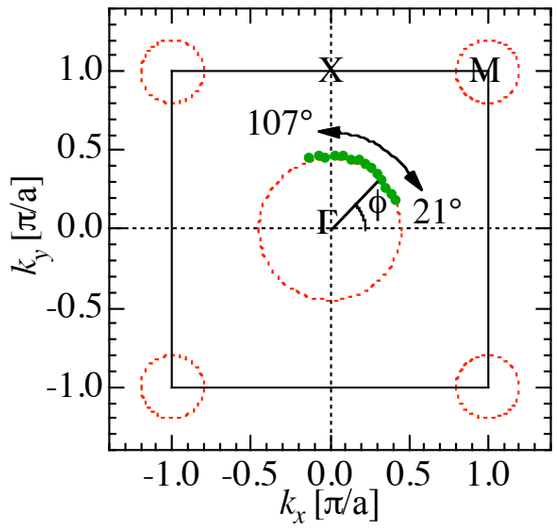
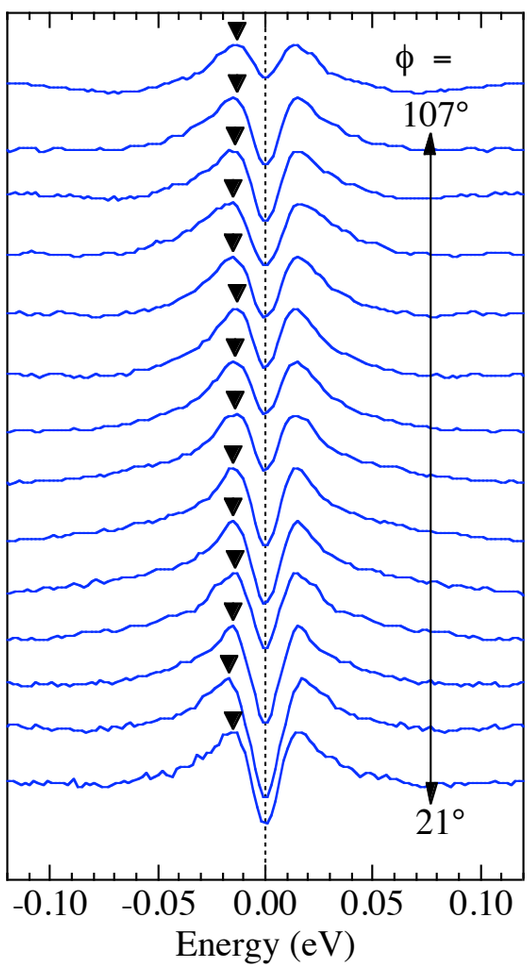
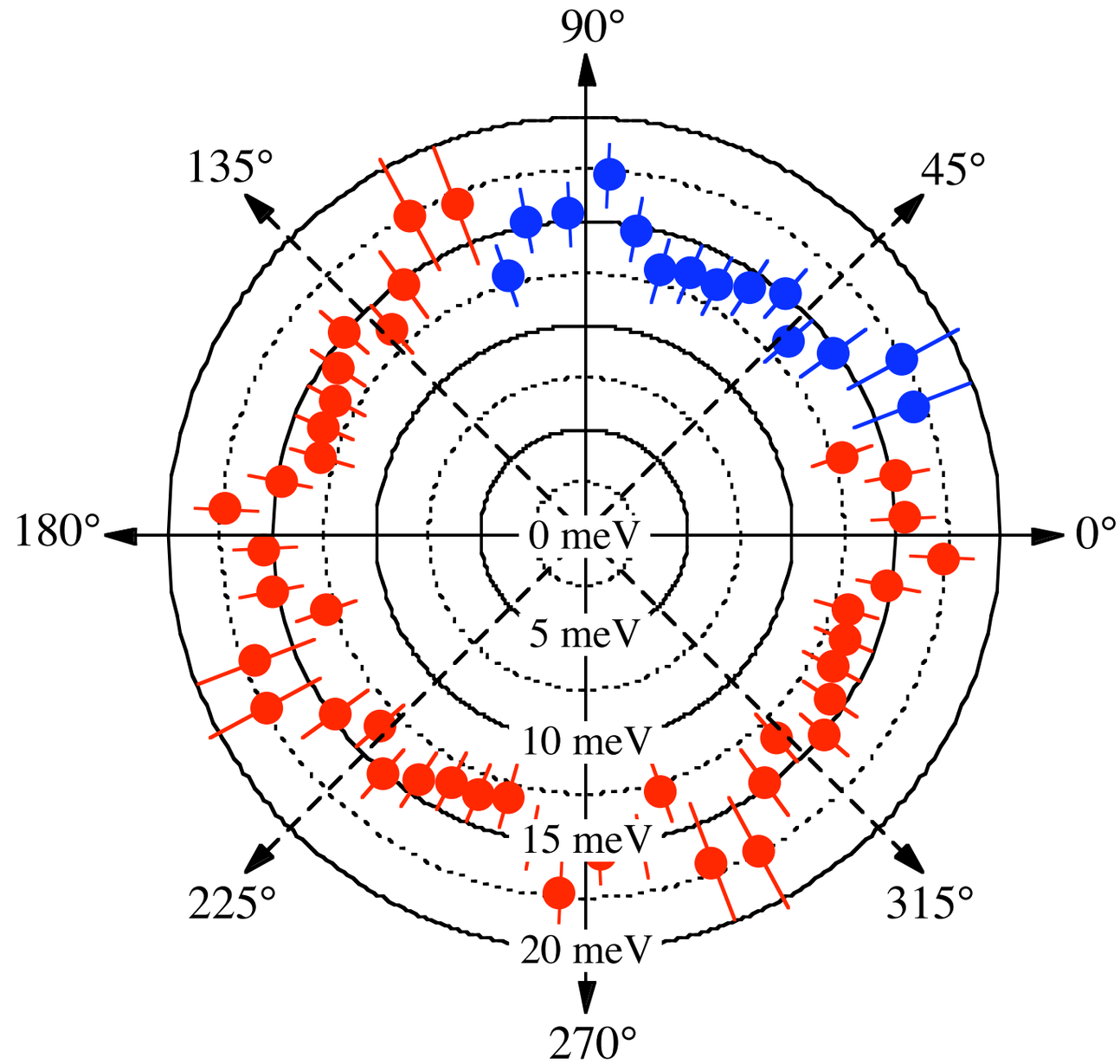
T. Kondo *et al*., Phys. Rev. Lett. - accepted

Momentum dependence of the superconducting gap



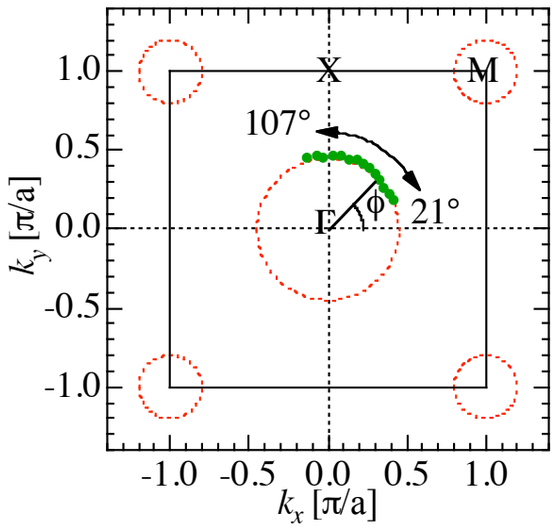


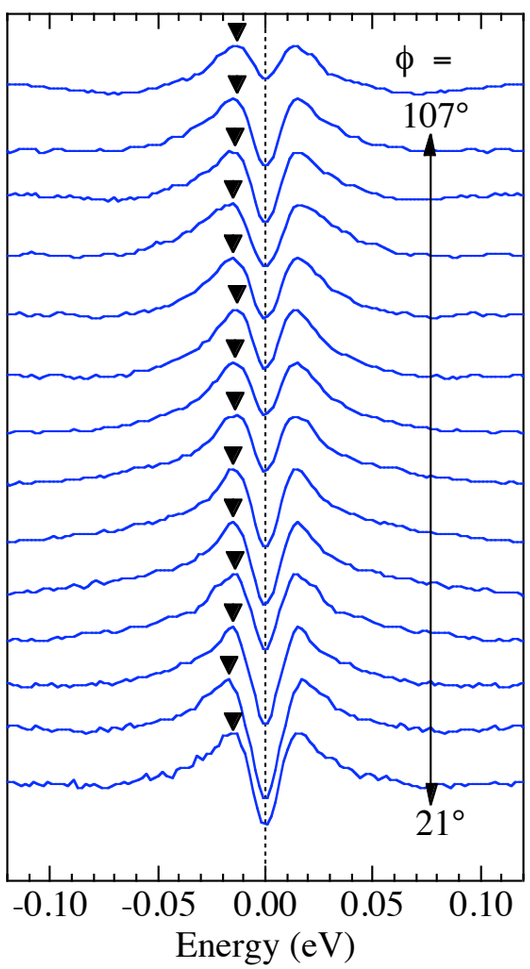


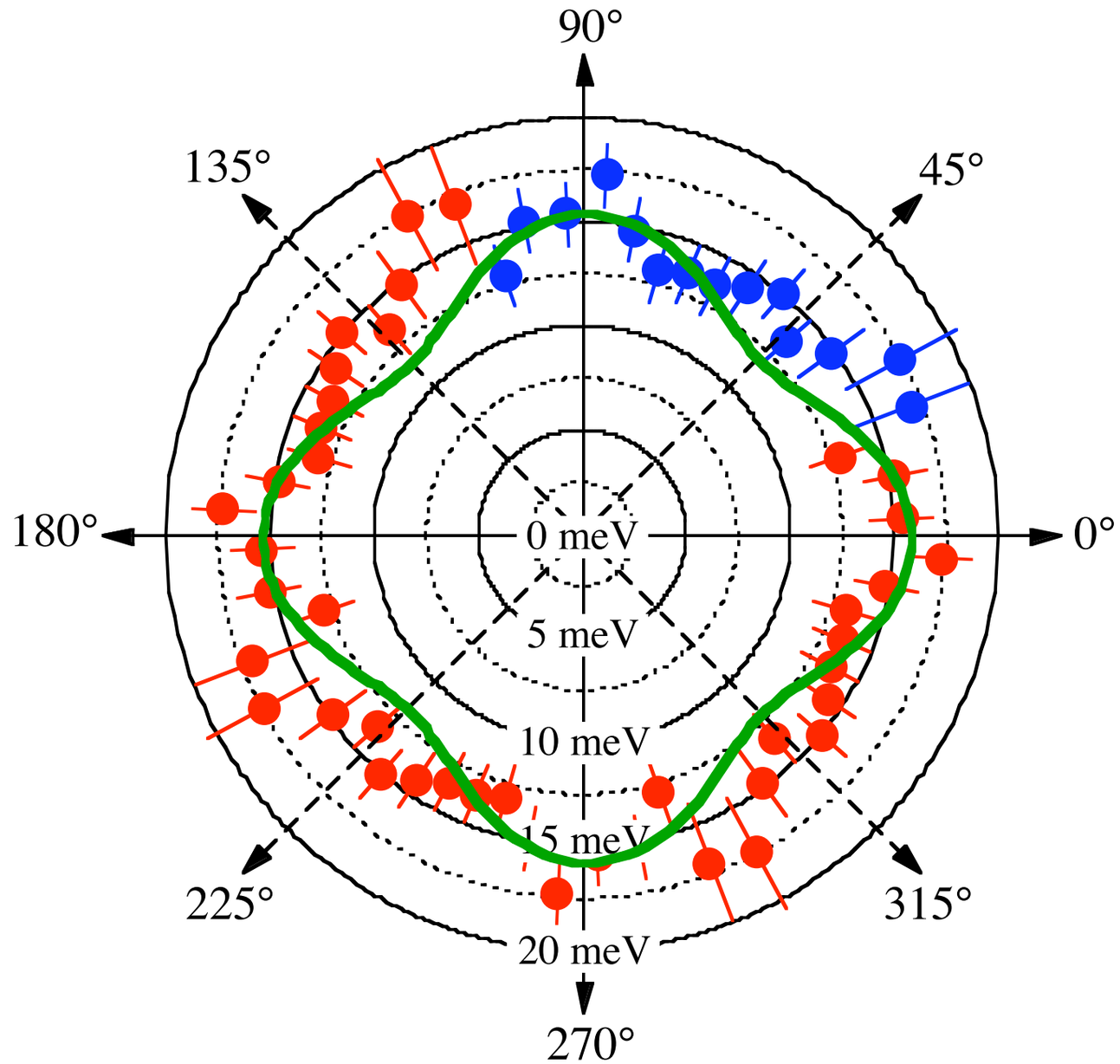
We can exclude d-wave symmetry of the order parameter

T. Kondo *et al*., Phys. Rev. Lett. - accepted

Momentum dependence of the superconducting gap







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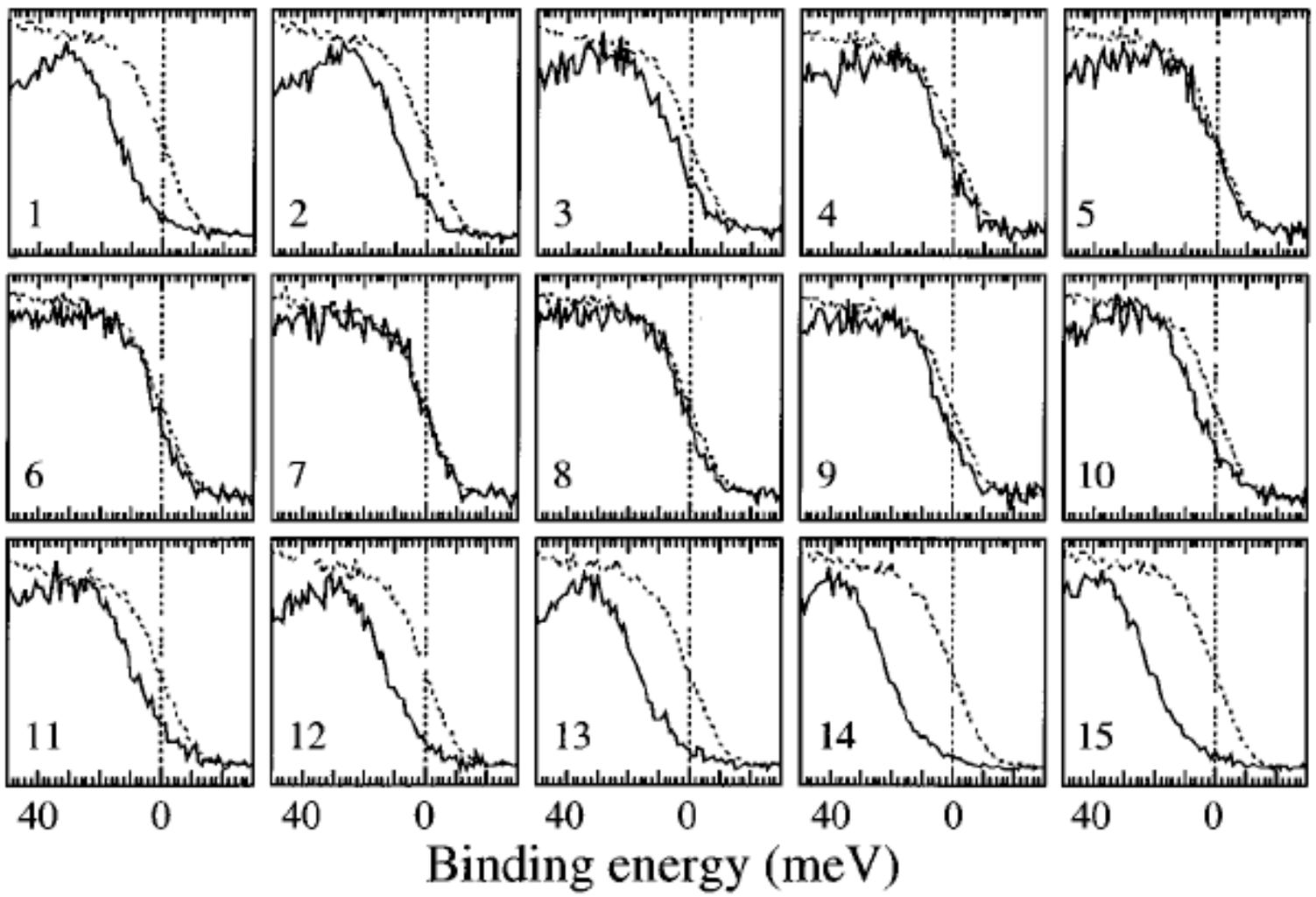
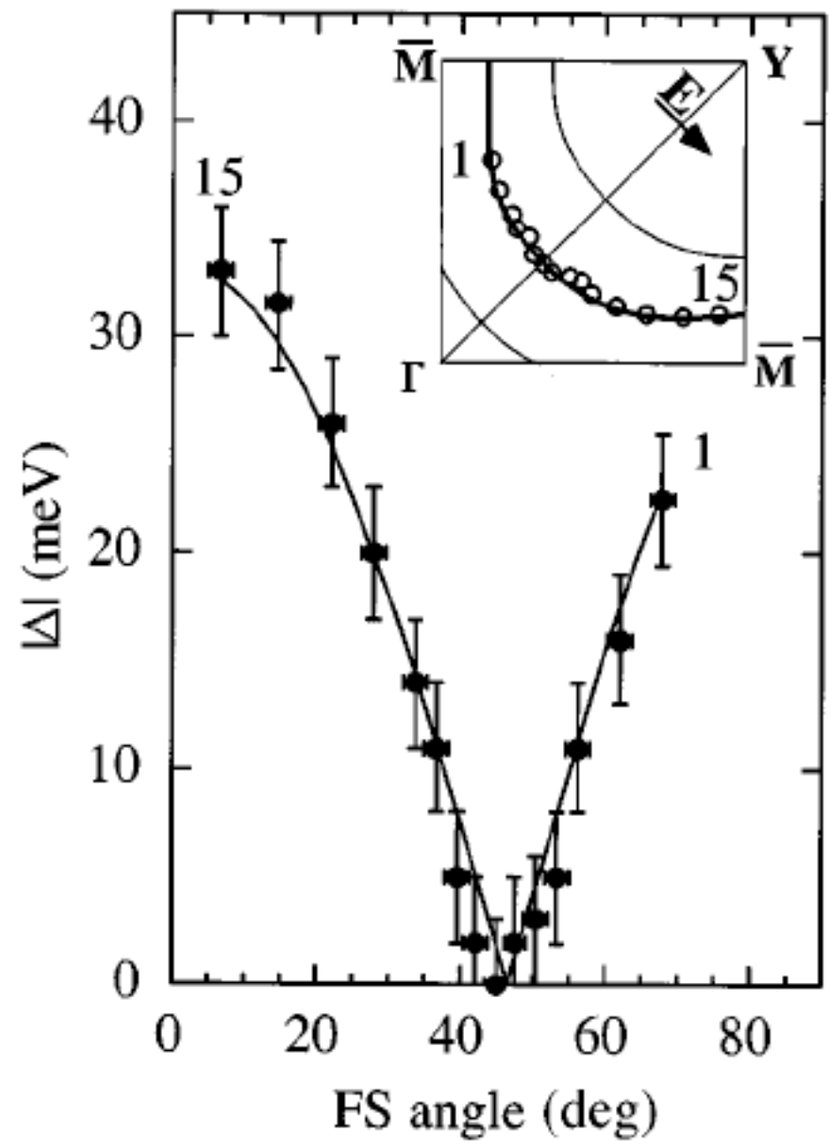
T. Kondo *et al.*, Phys. Rev. Lett. - accepted

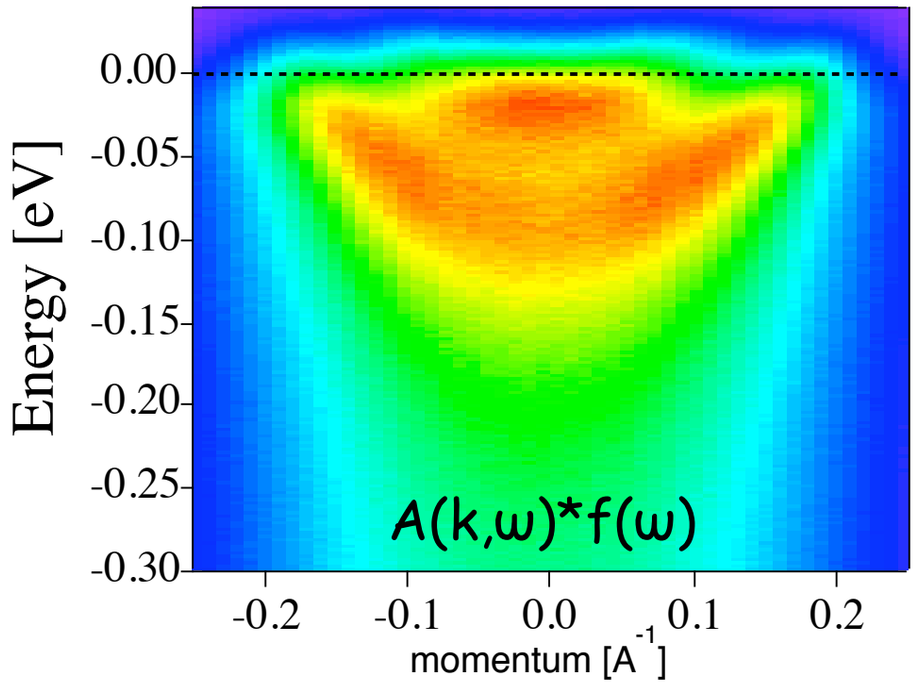
superconducting gap => order parameter

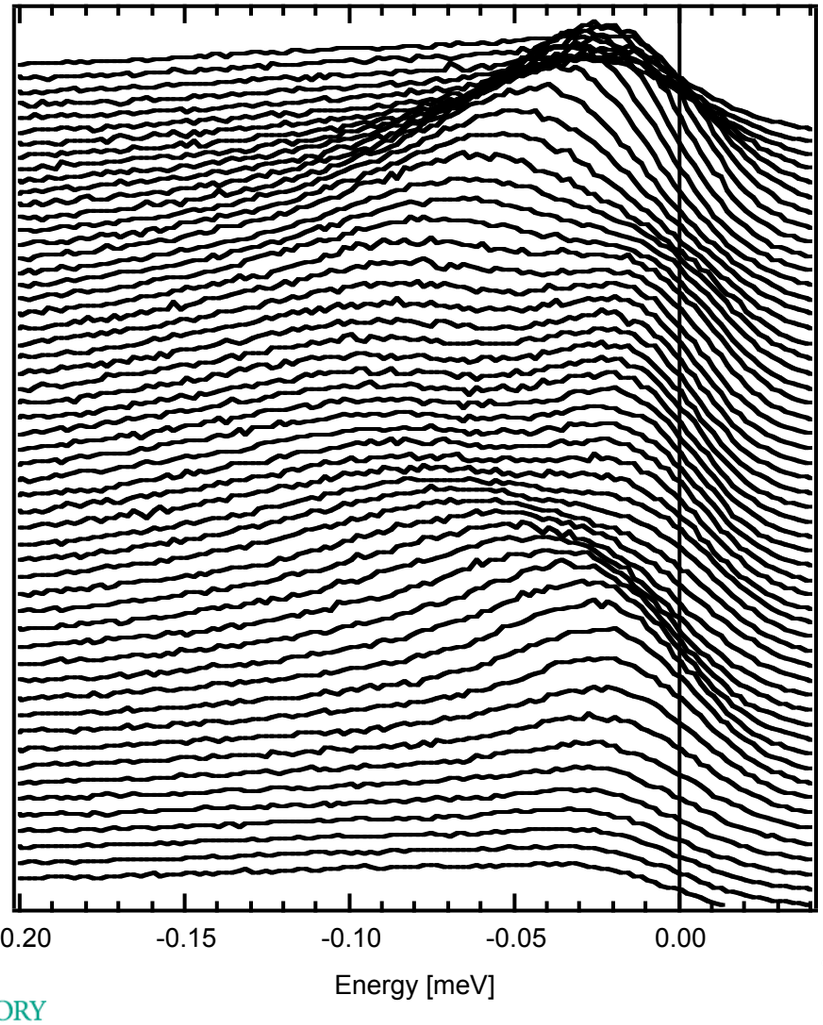




$$I = \langle \Psi_i | \mathbf{A} \cdot \mathbf{p} | \Psi_f \rangle^2 A(k,\omega)\, f(\omega)$$

ARPES intensity





$A(k,\omega)*f(\omega)/f(\omega)= A(k,\omega)$

T=100K

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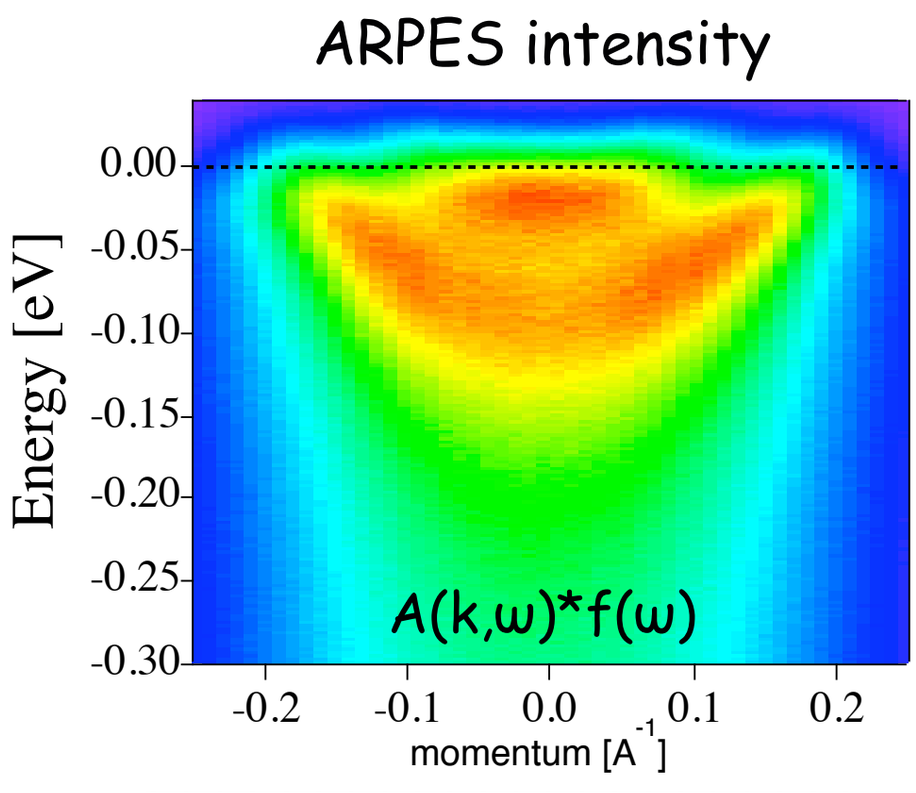

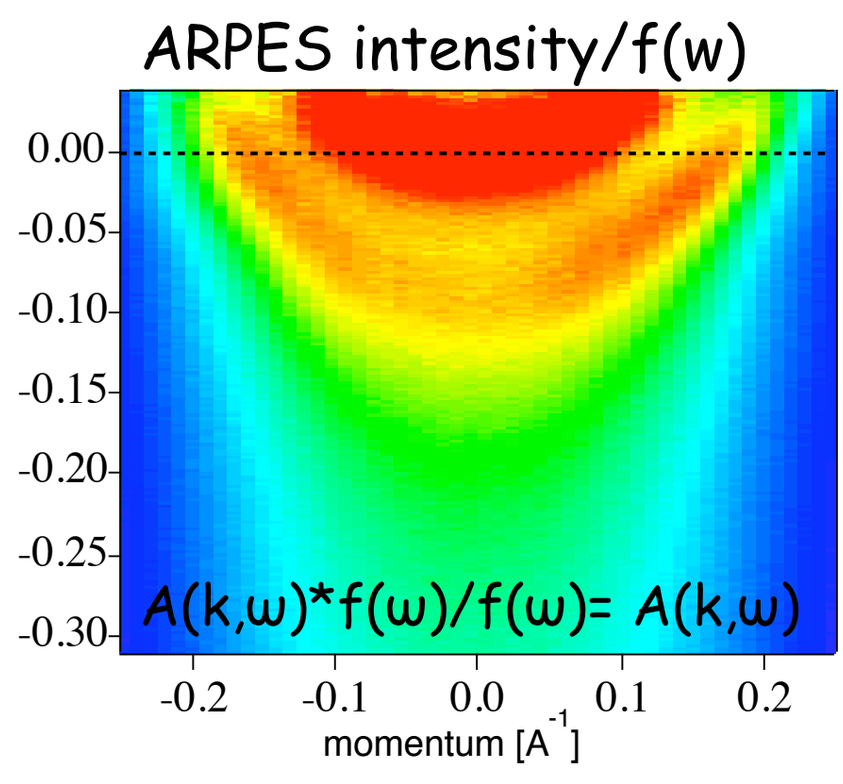

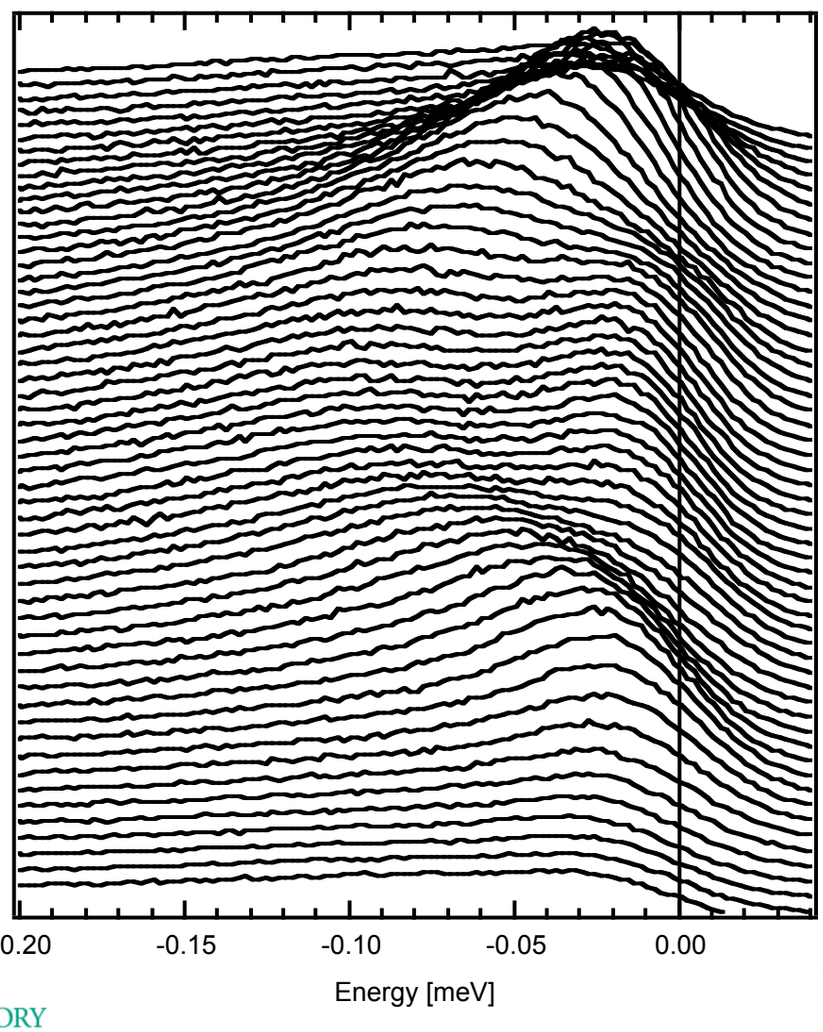

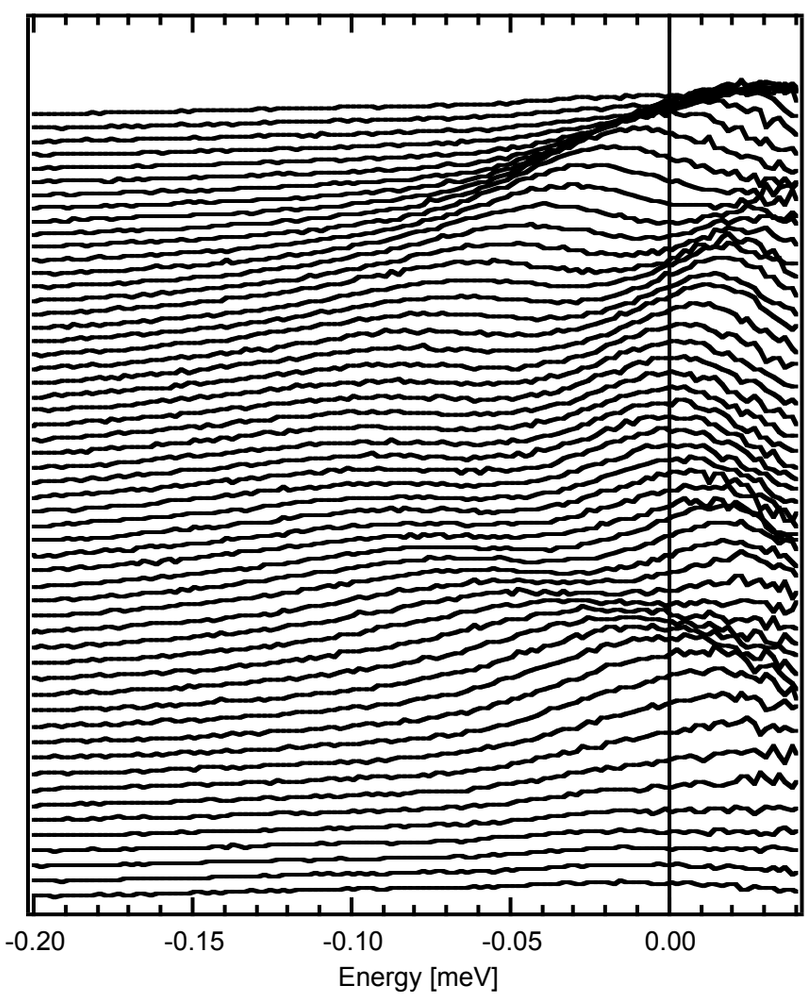

T=100K

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Useful tool for analyzing gaps in ARPES spectra: symmetrization method.

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

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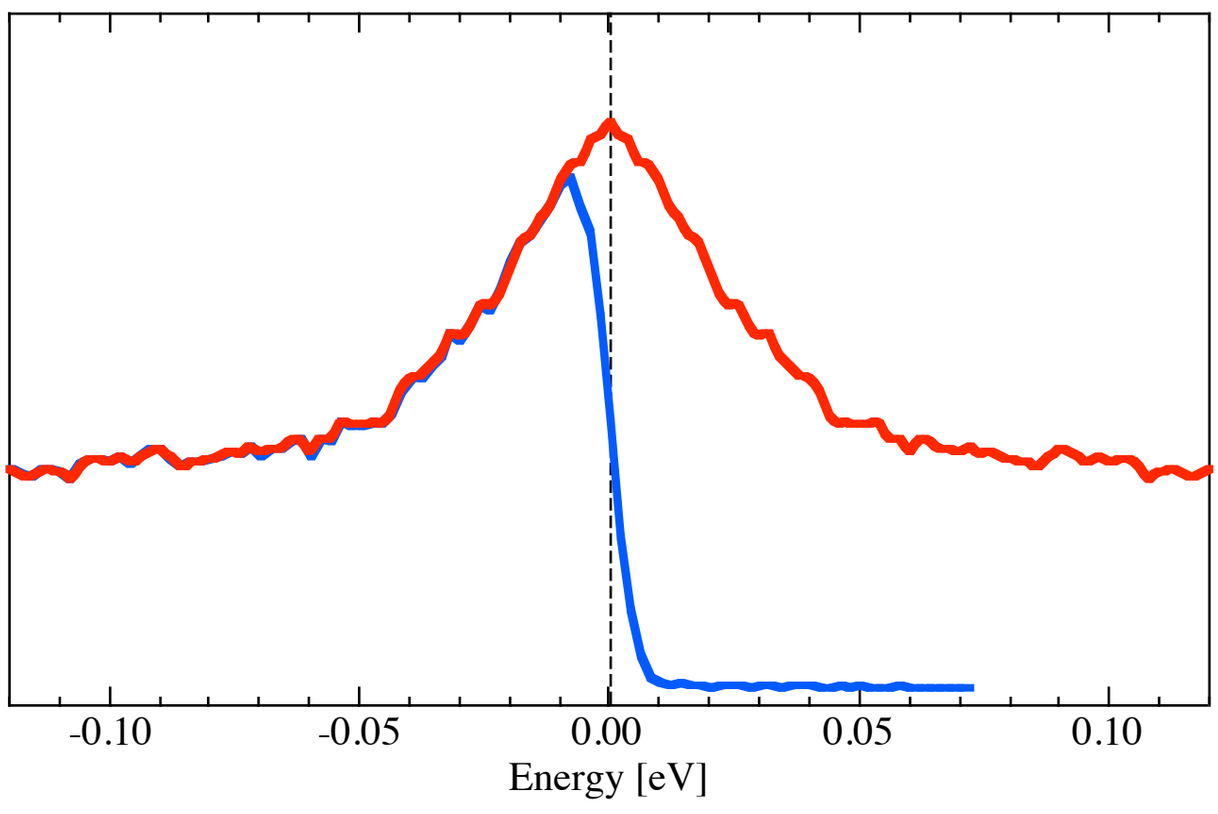

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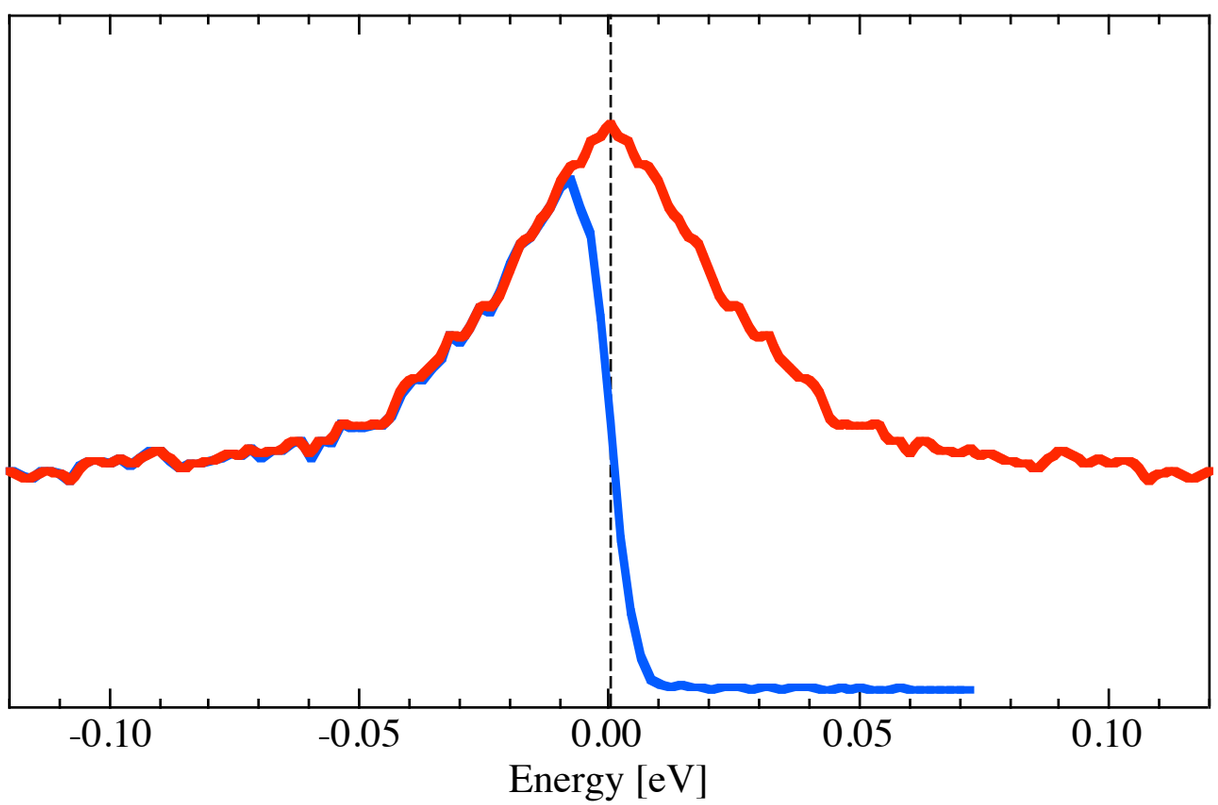

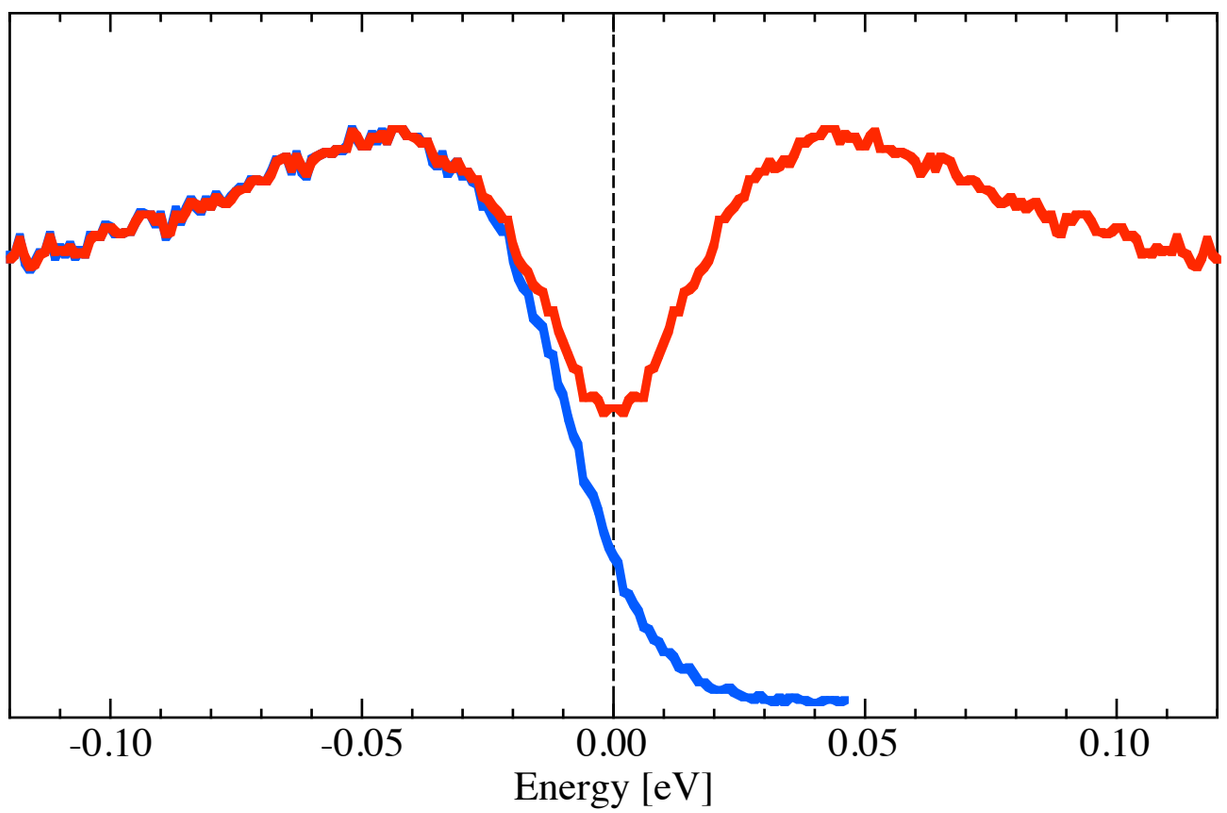

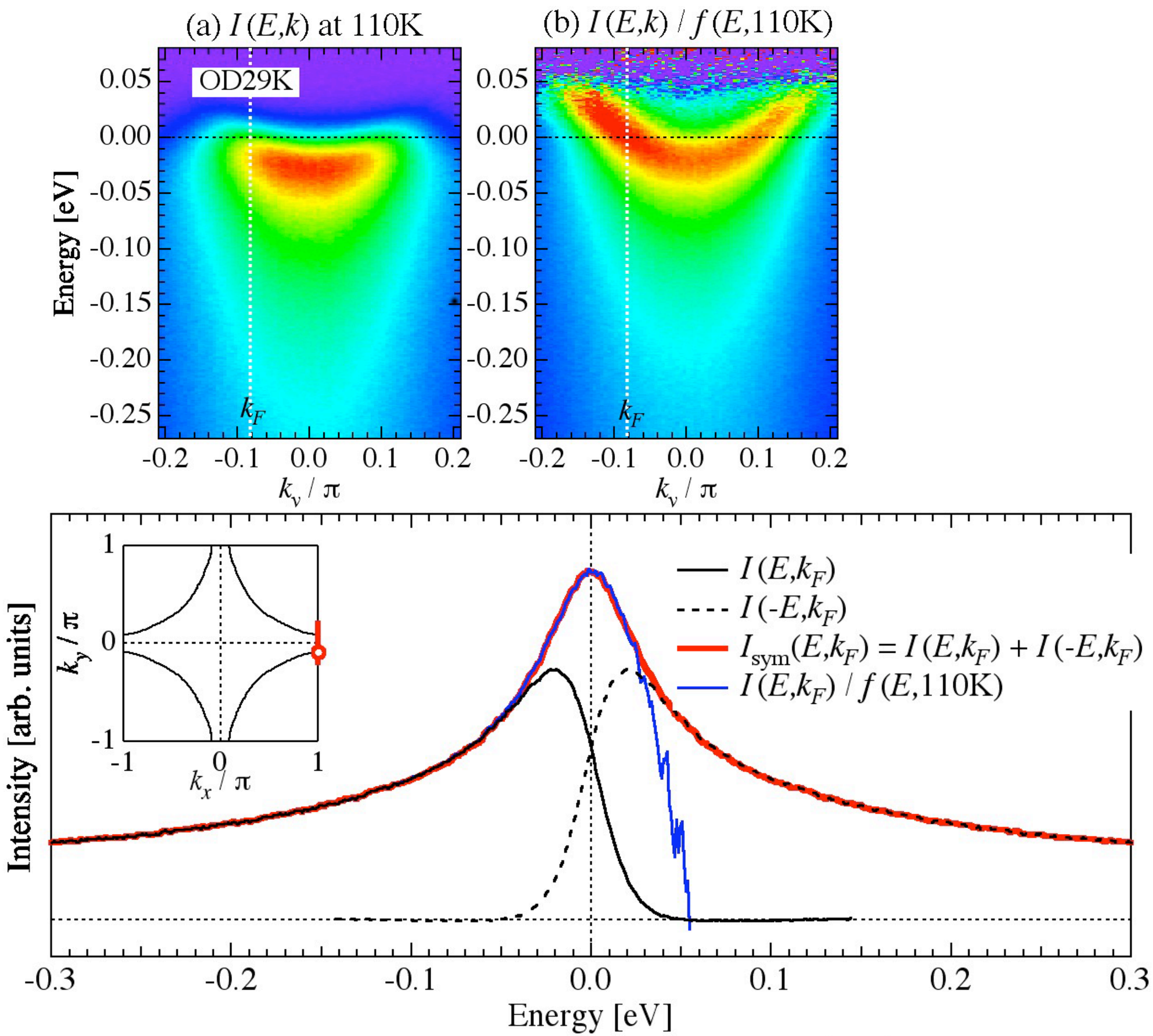

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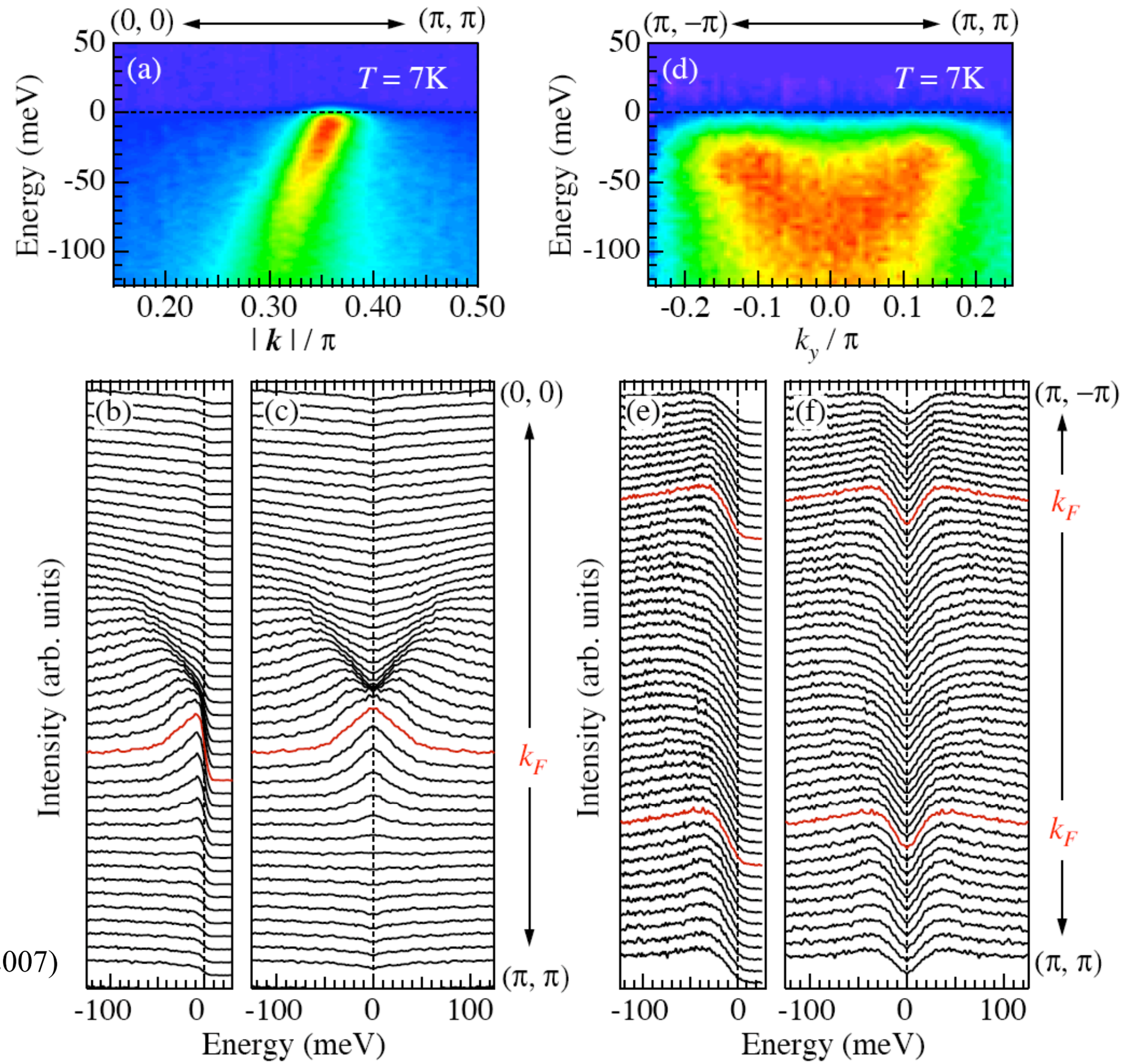

T. Kondo et al.,
Phys. Rev. Lett. **98**, 267004 (2007)

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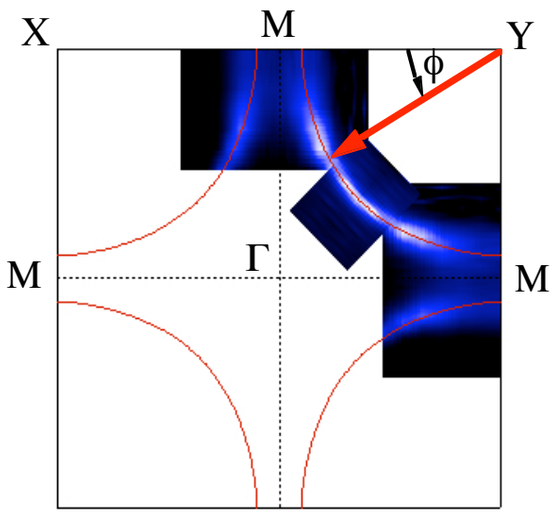

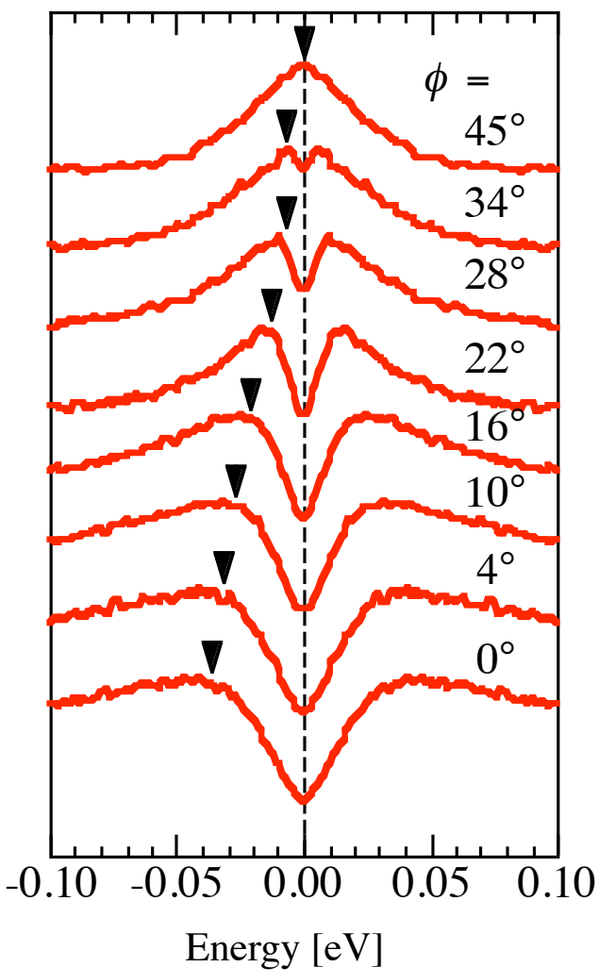

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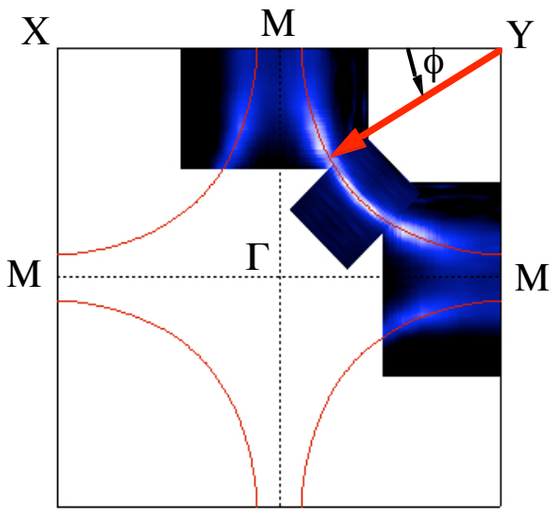

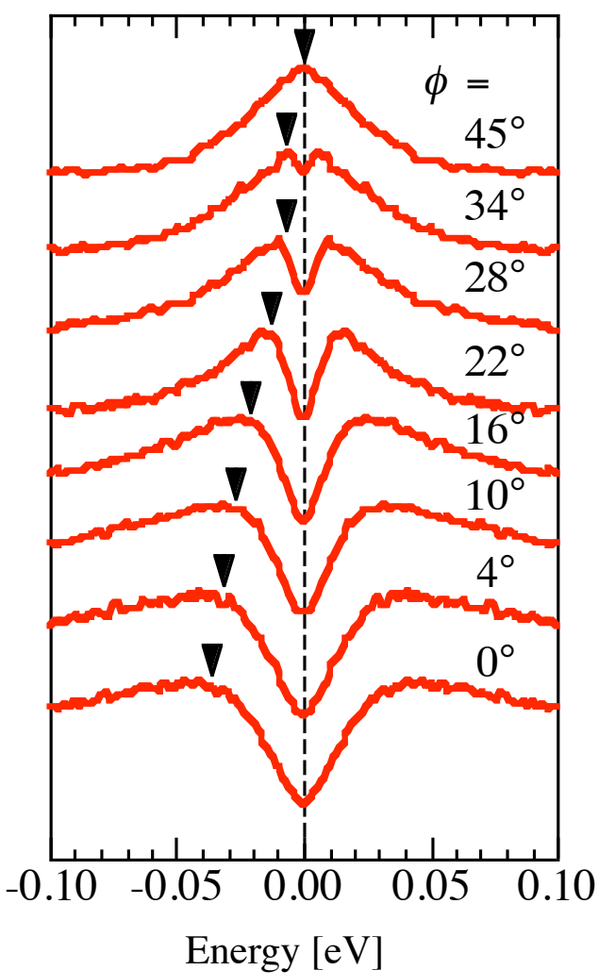

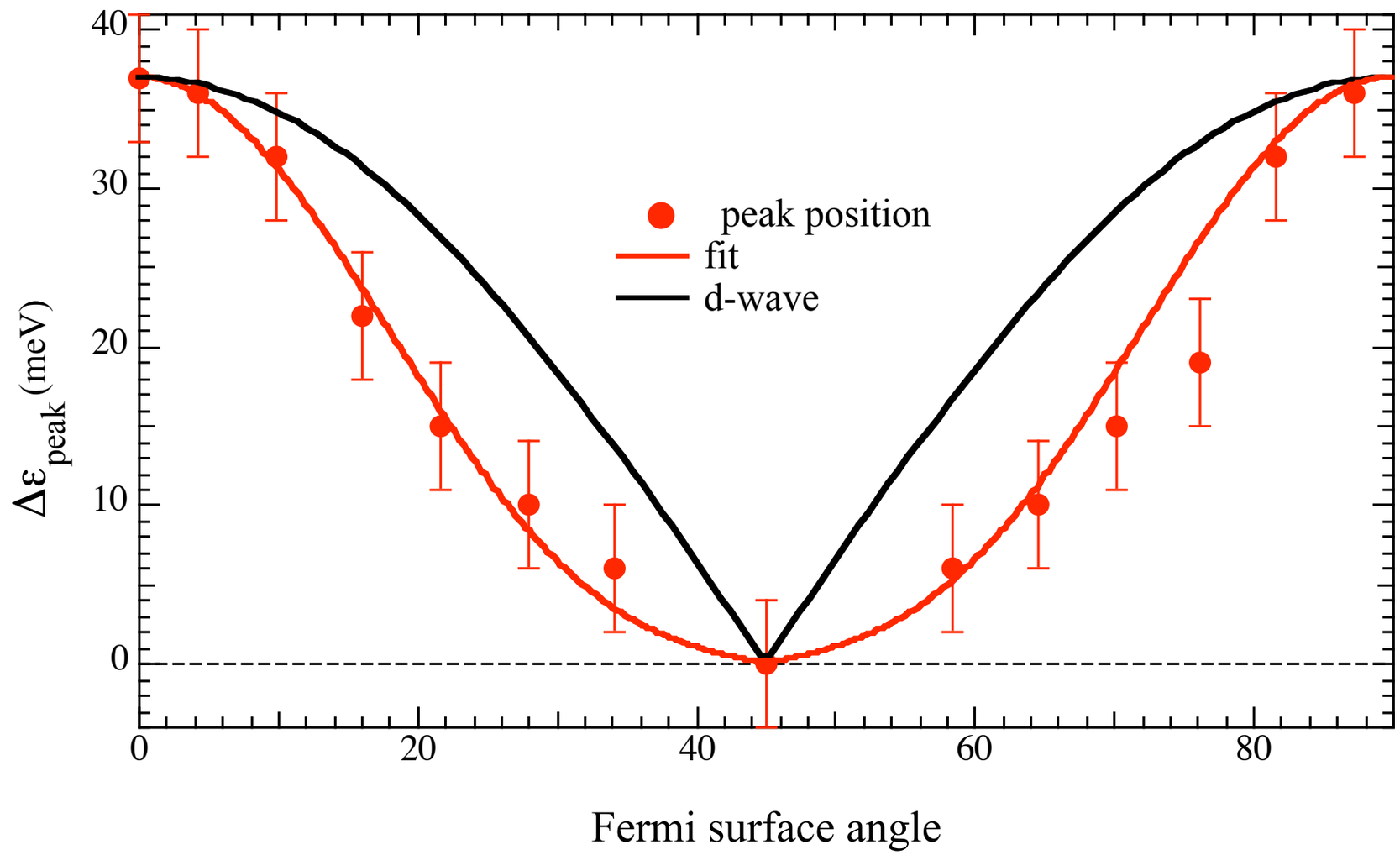

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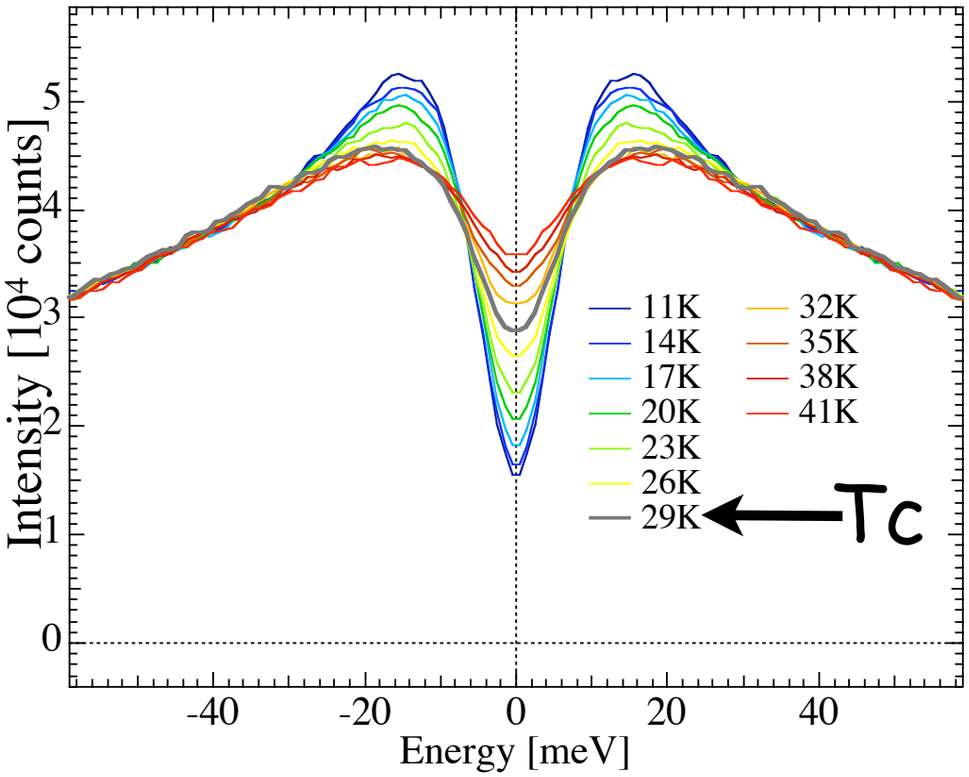
Spectral changes across Tc and T* at antinode



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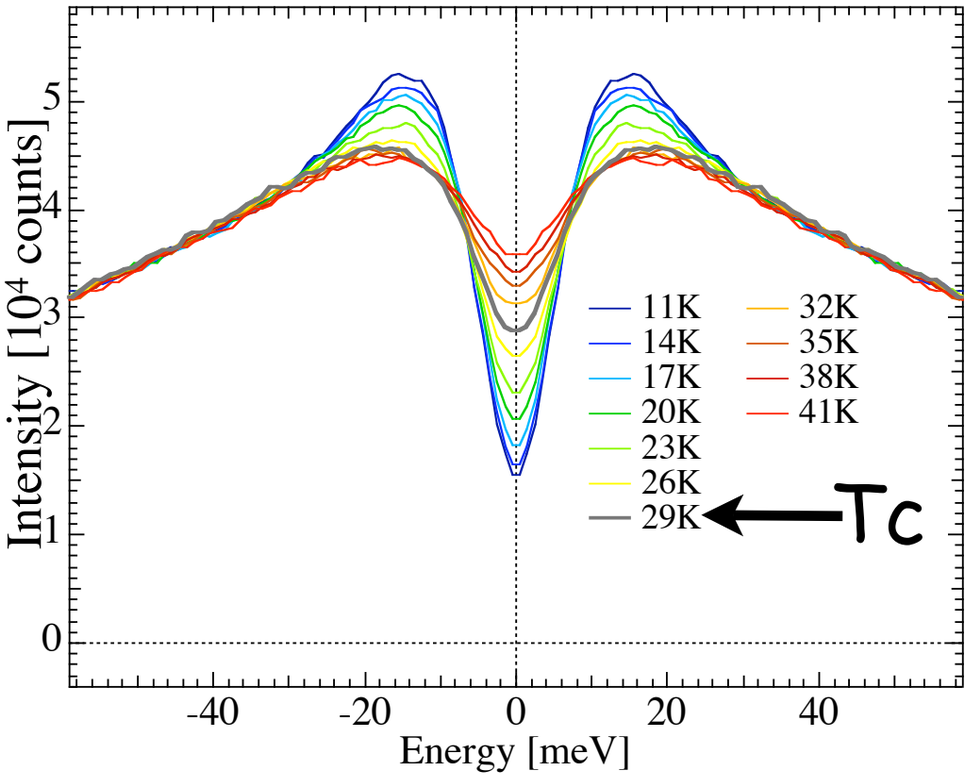

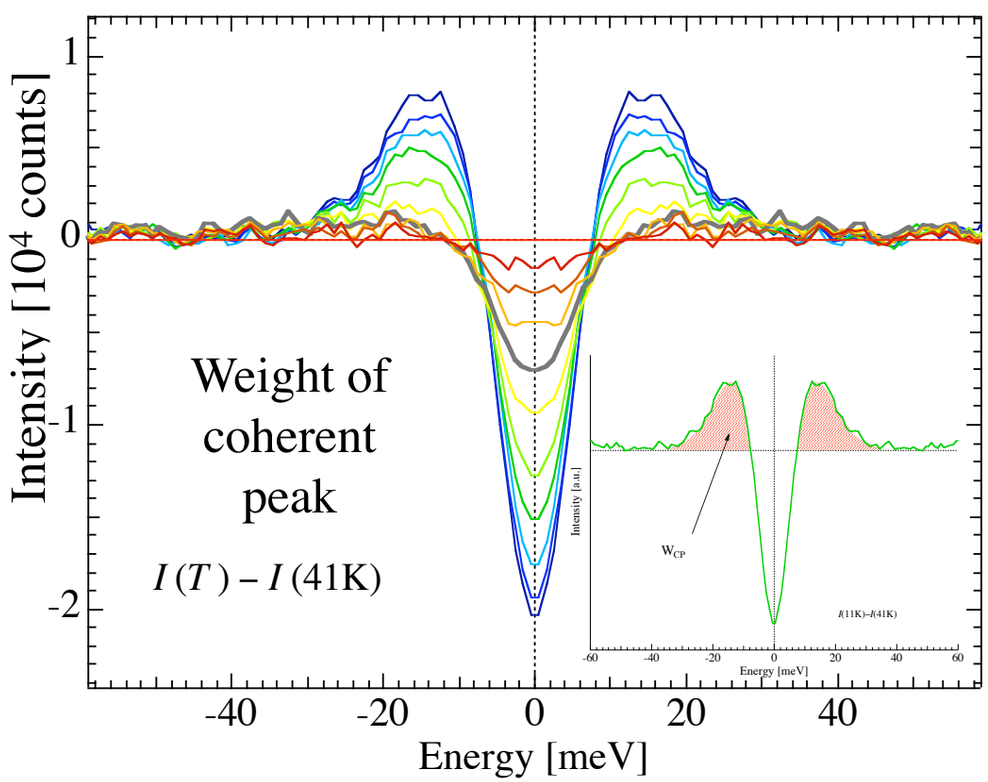

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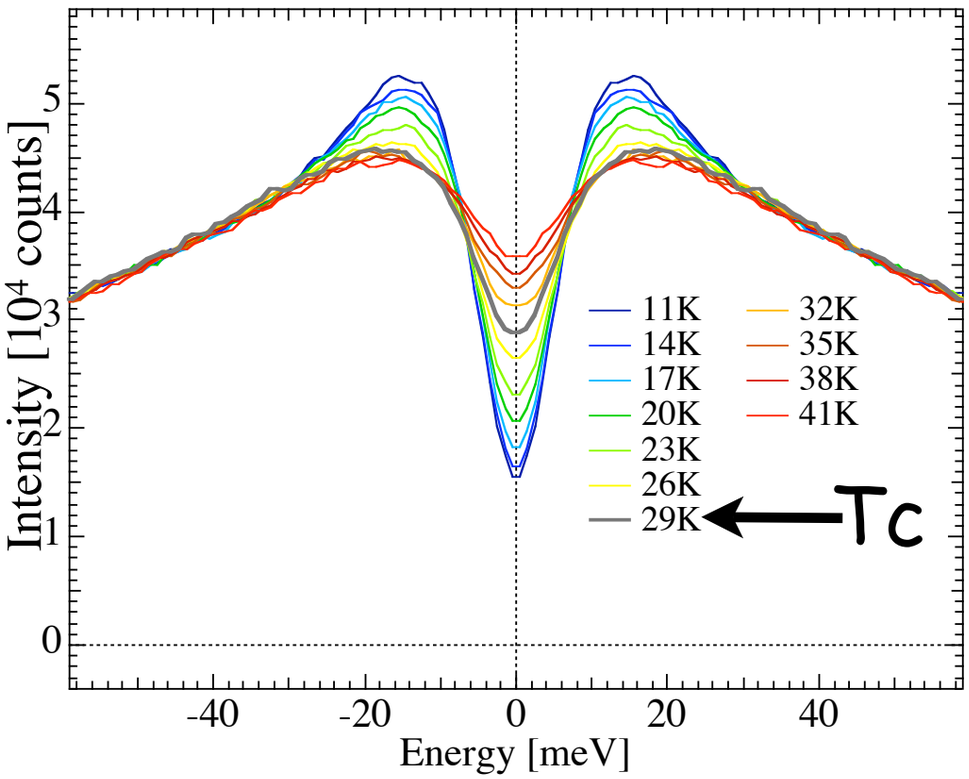

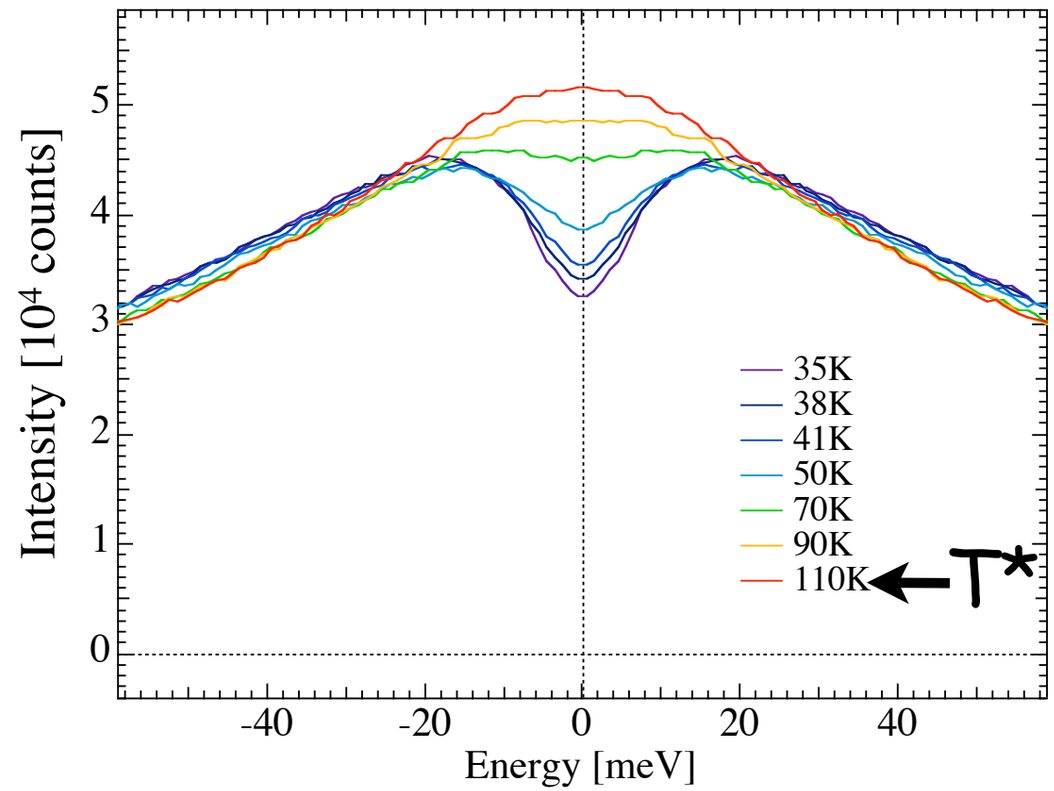

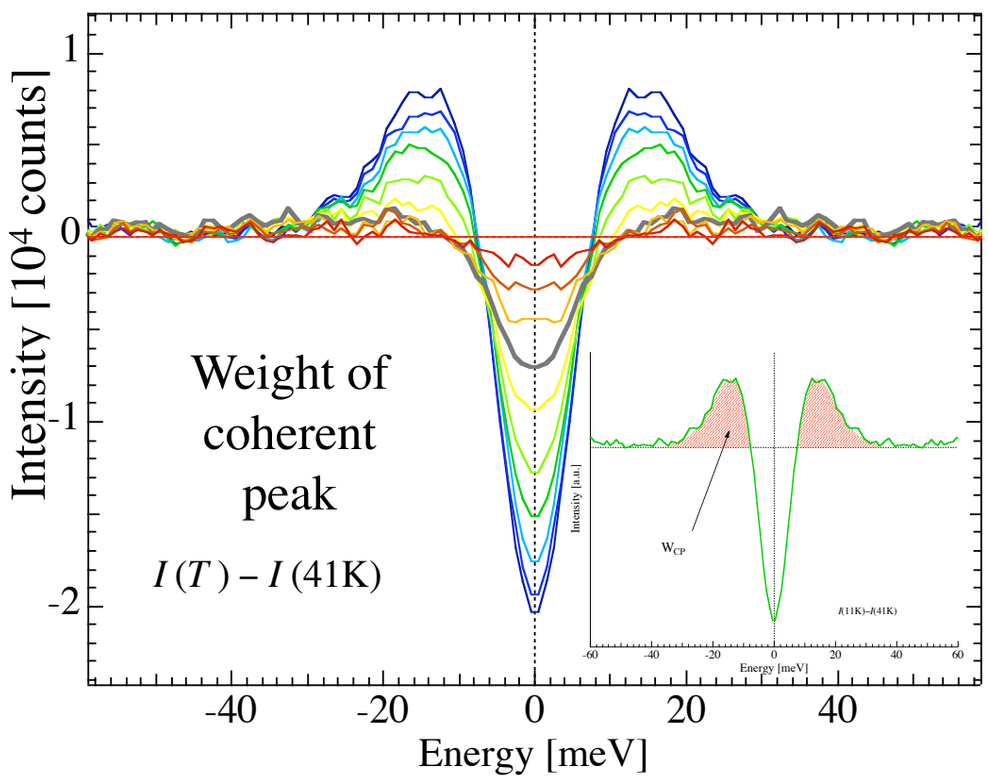

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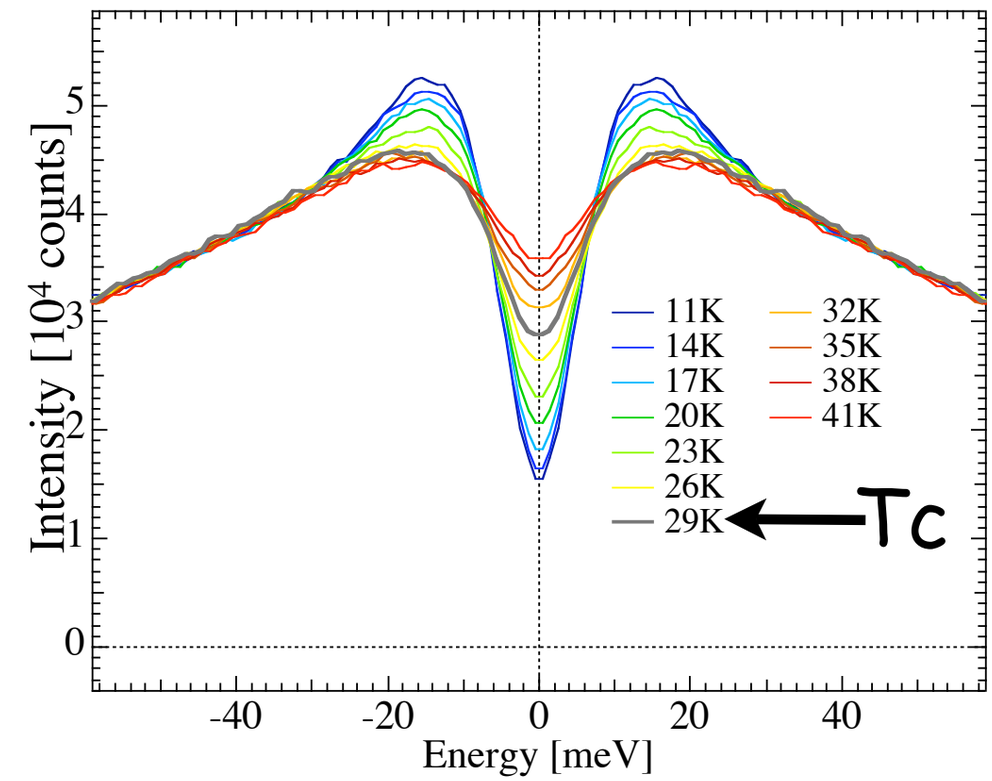
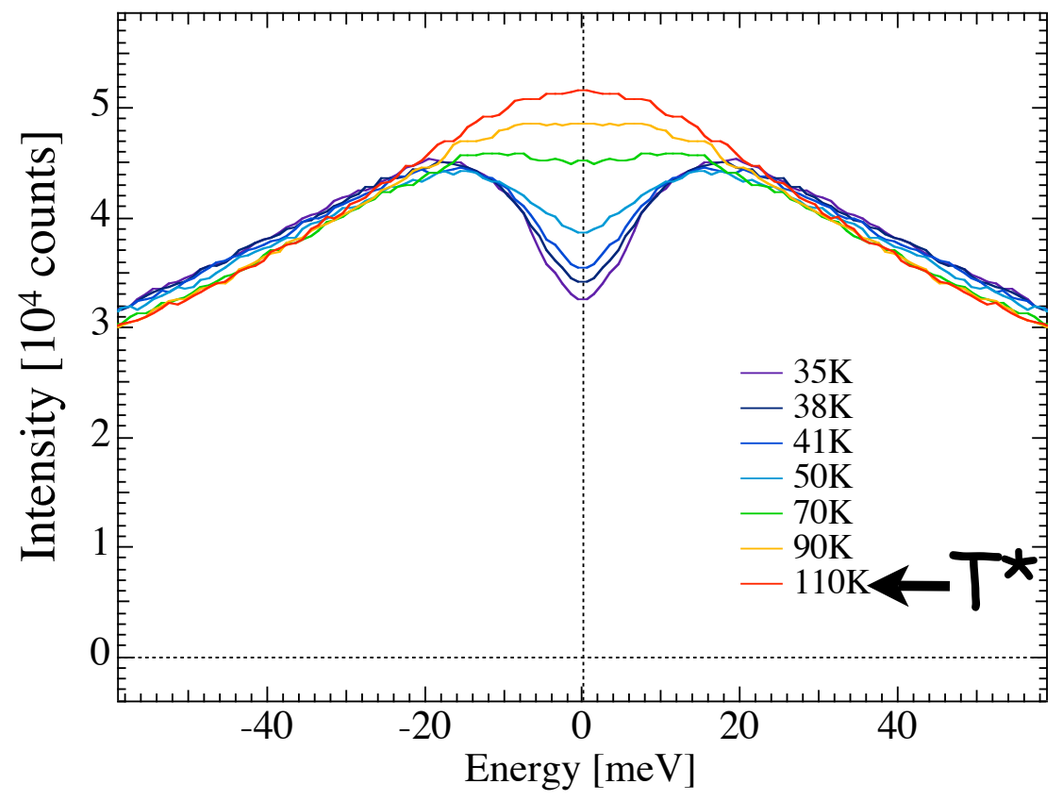
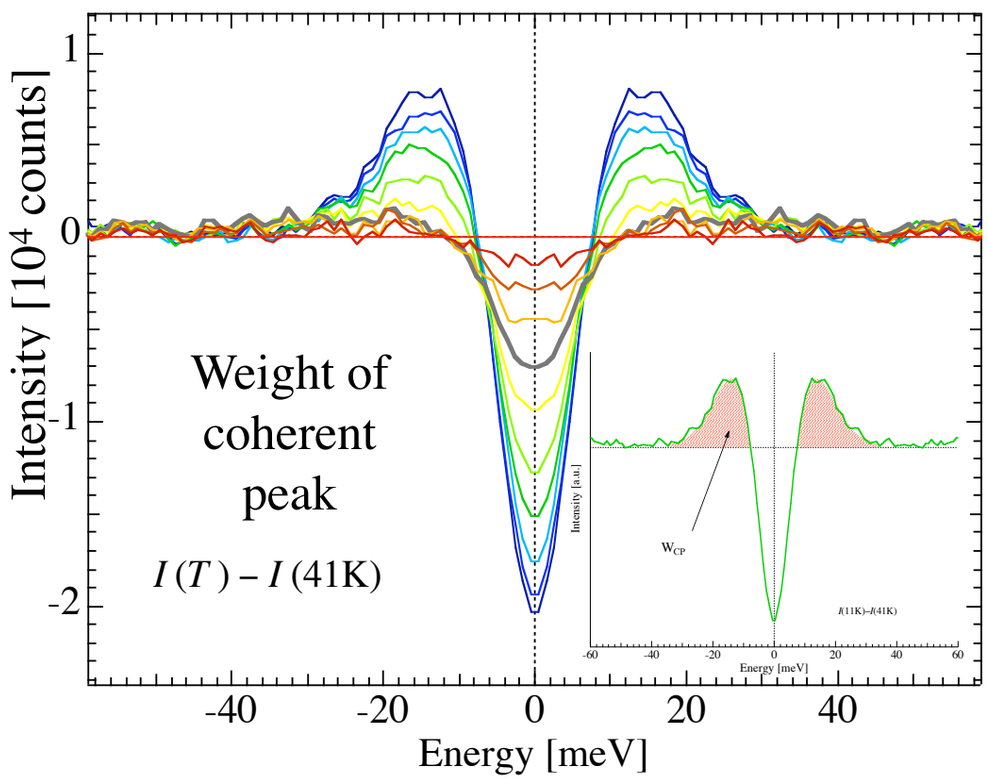
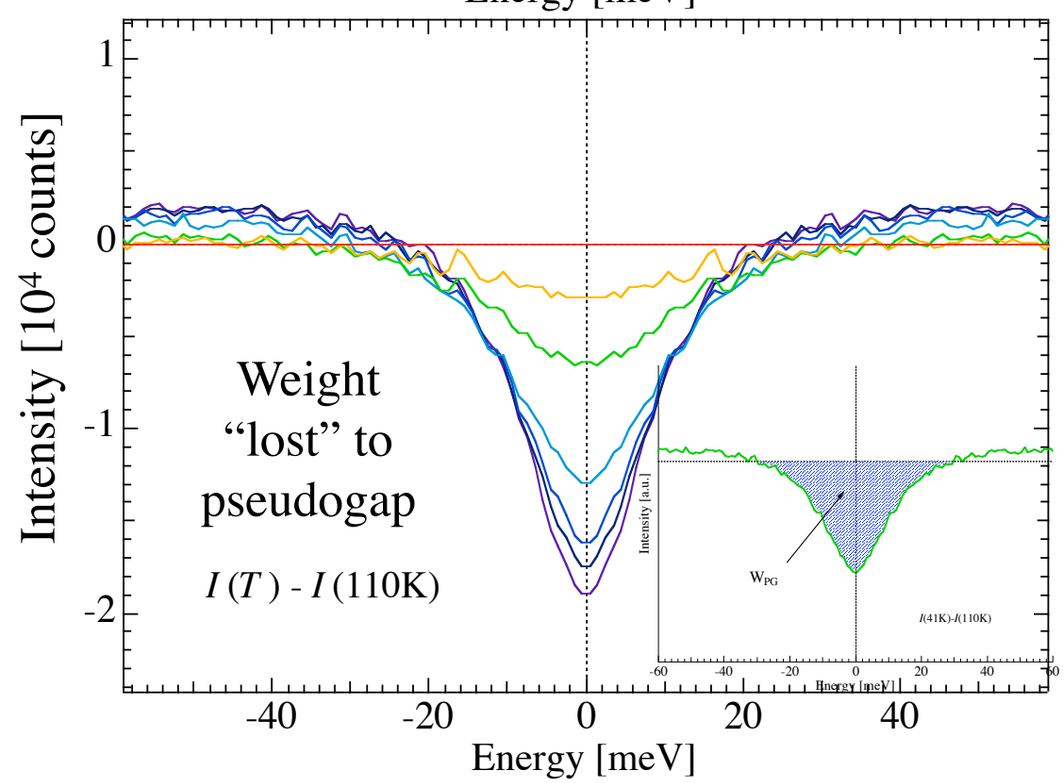
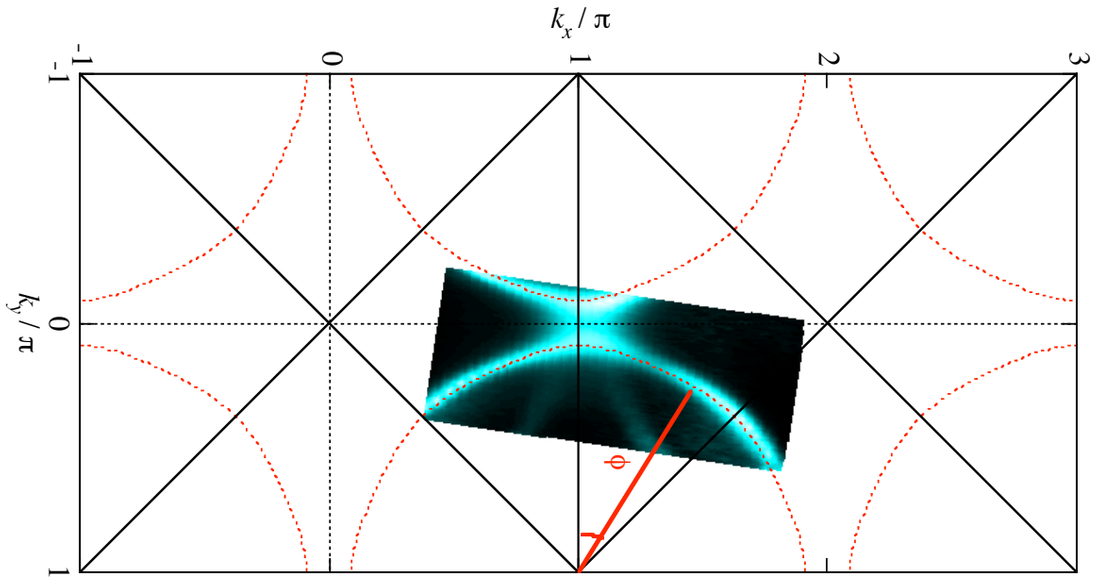


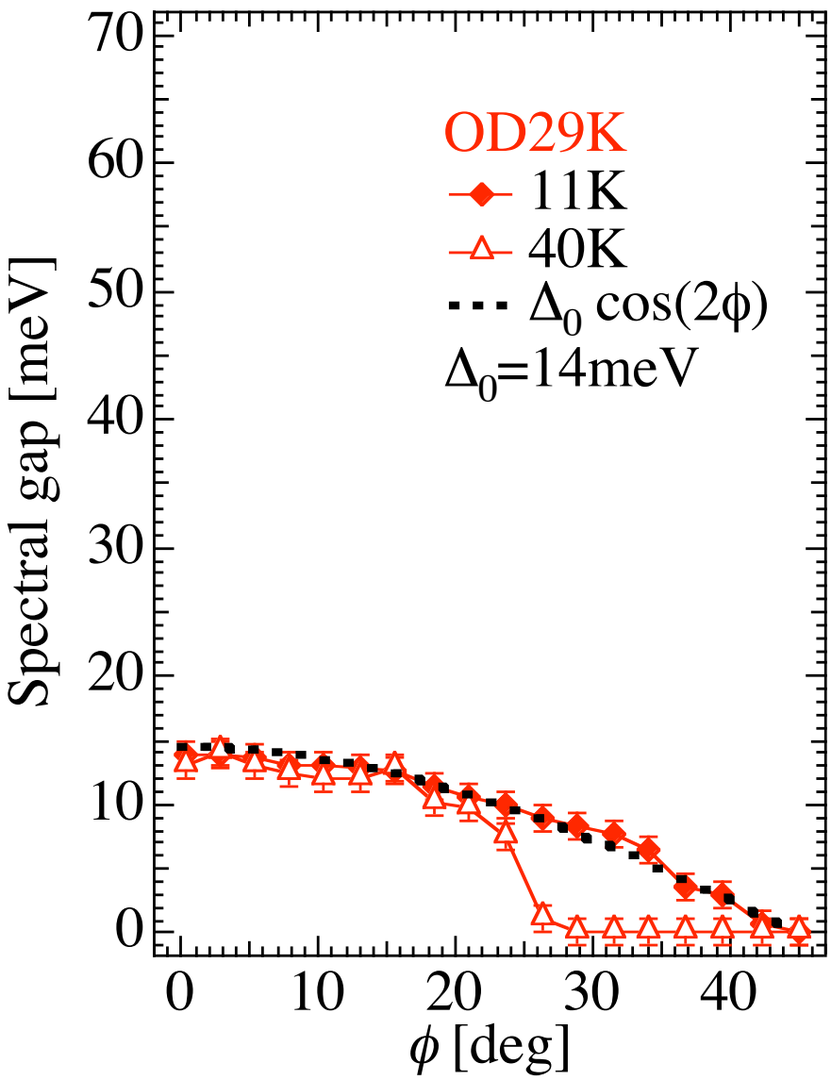


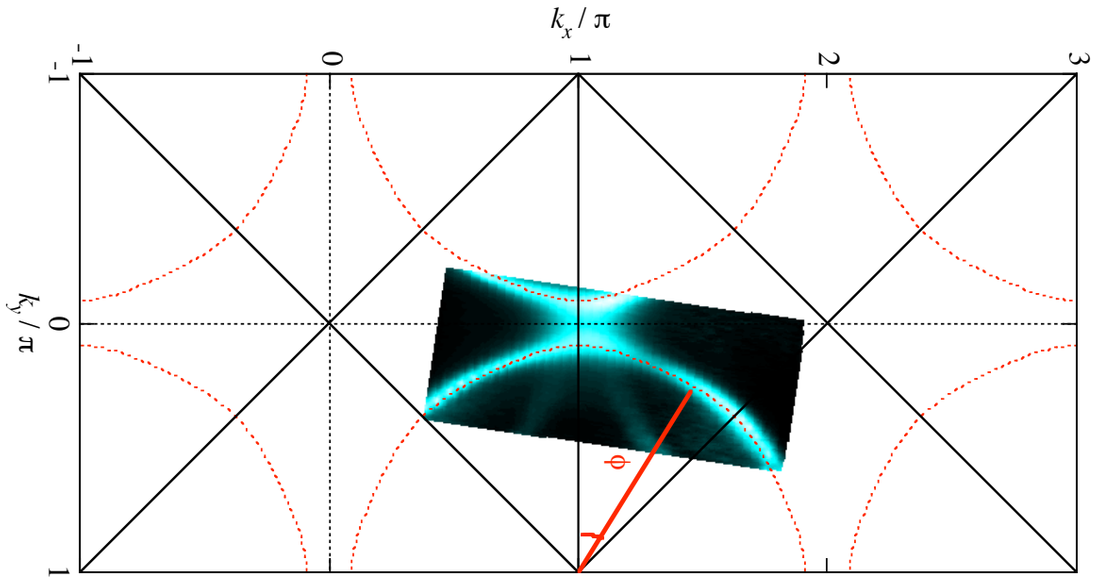




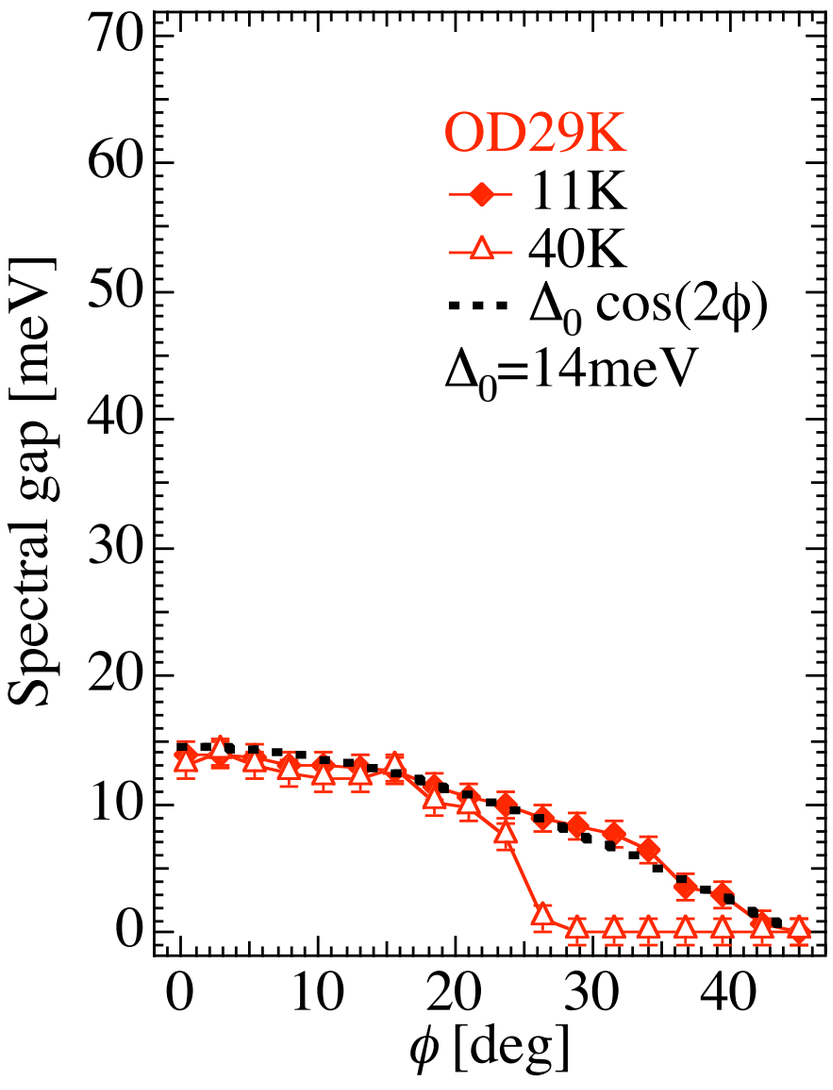


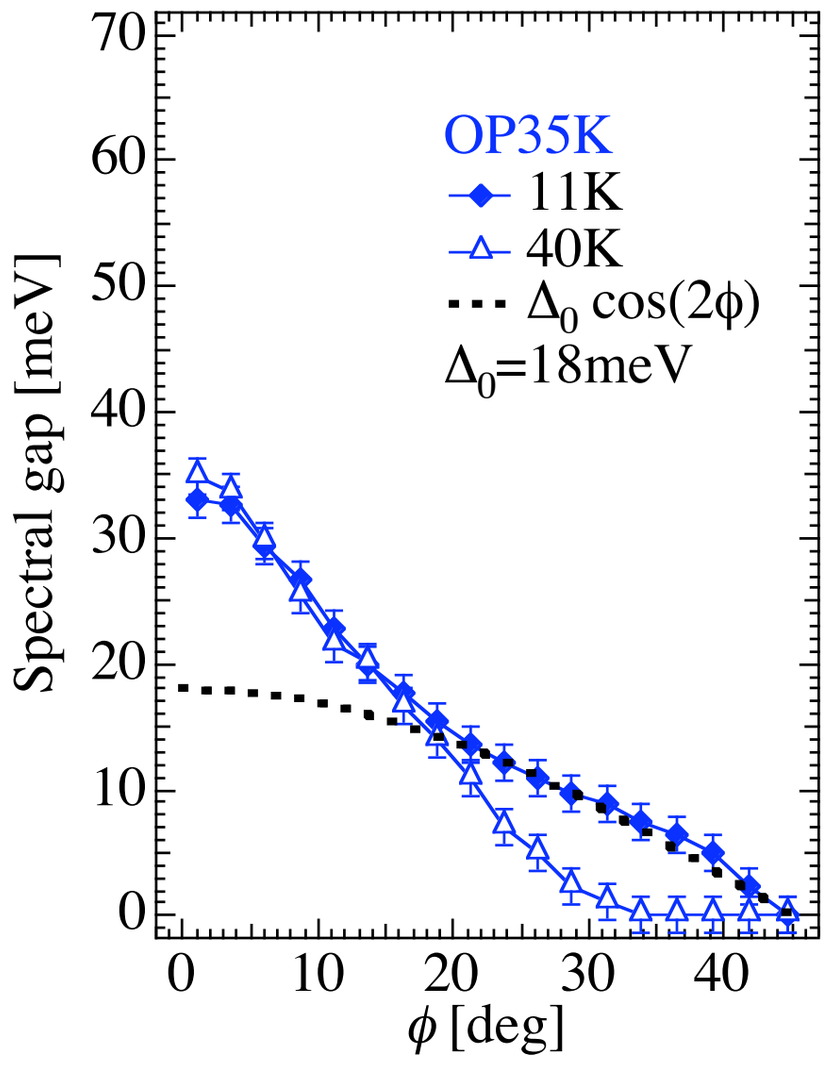
Spectral gap

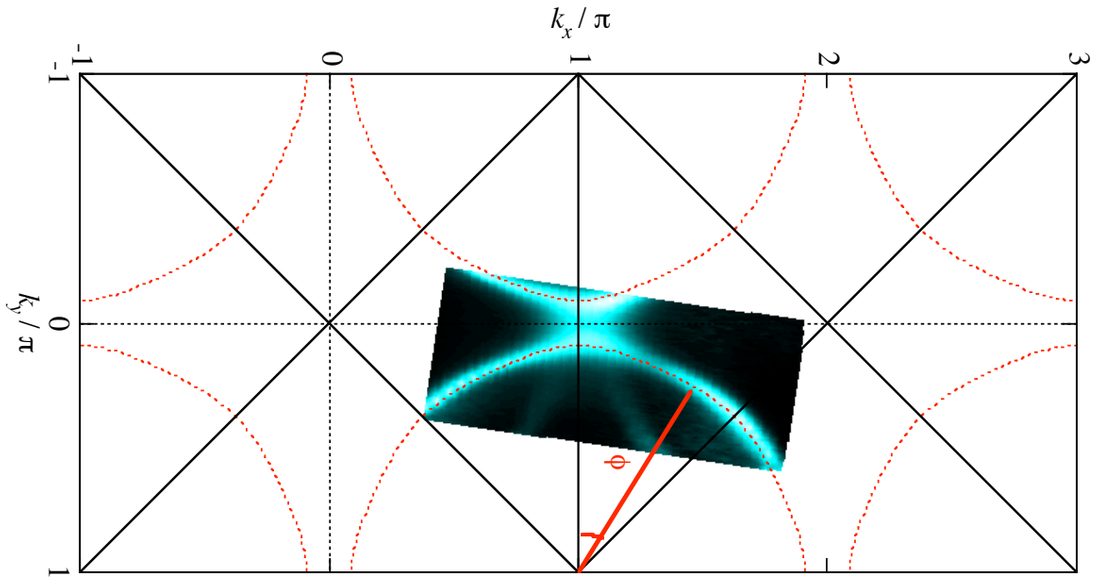




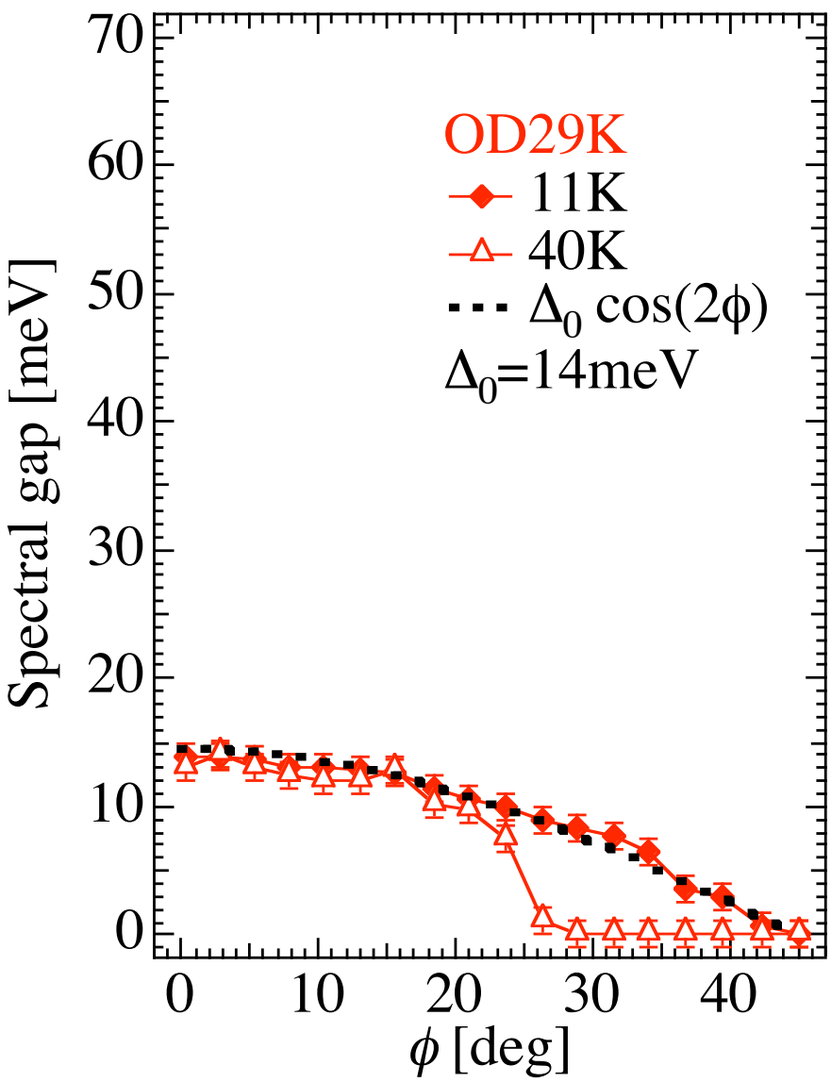
Spectral gap

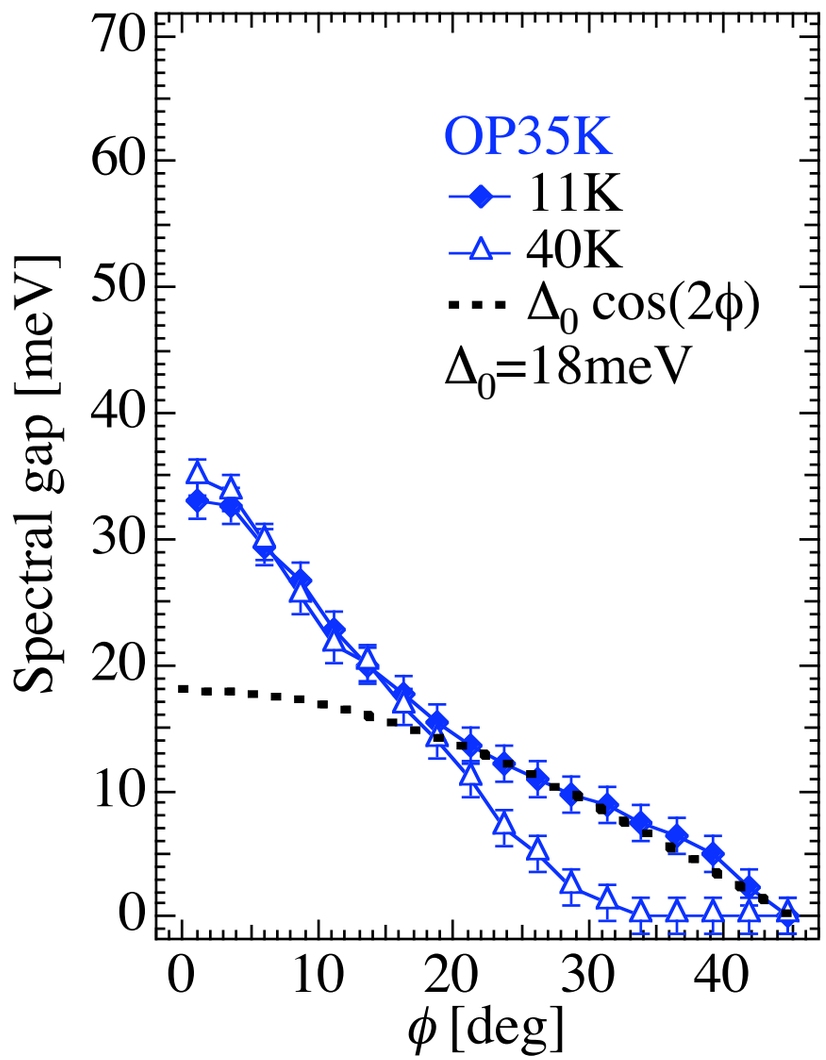


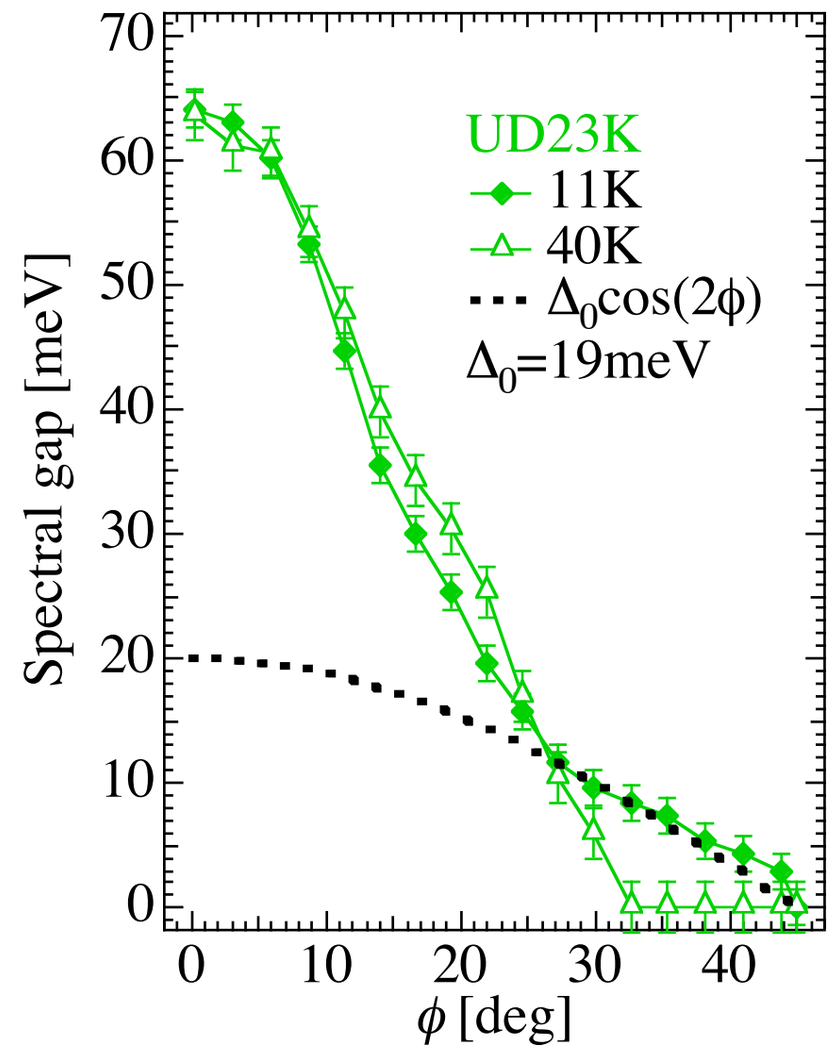




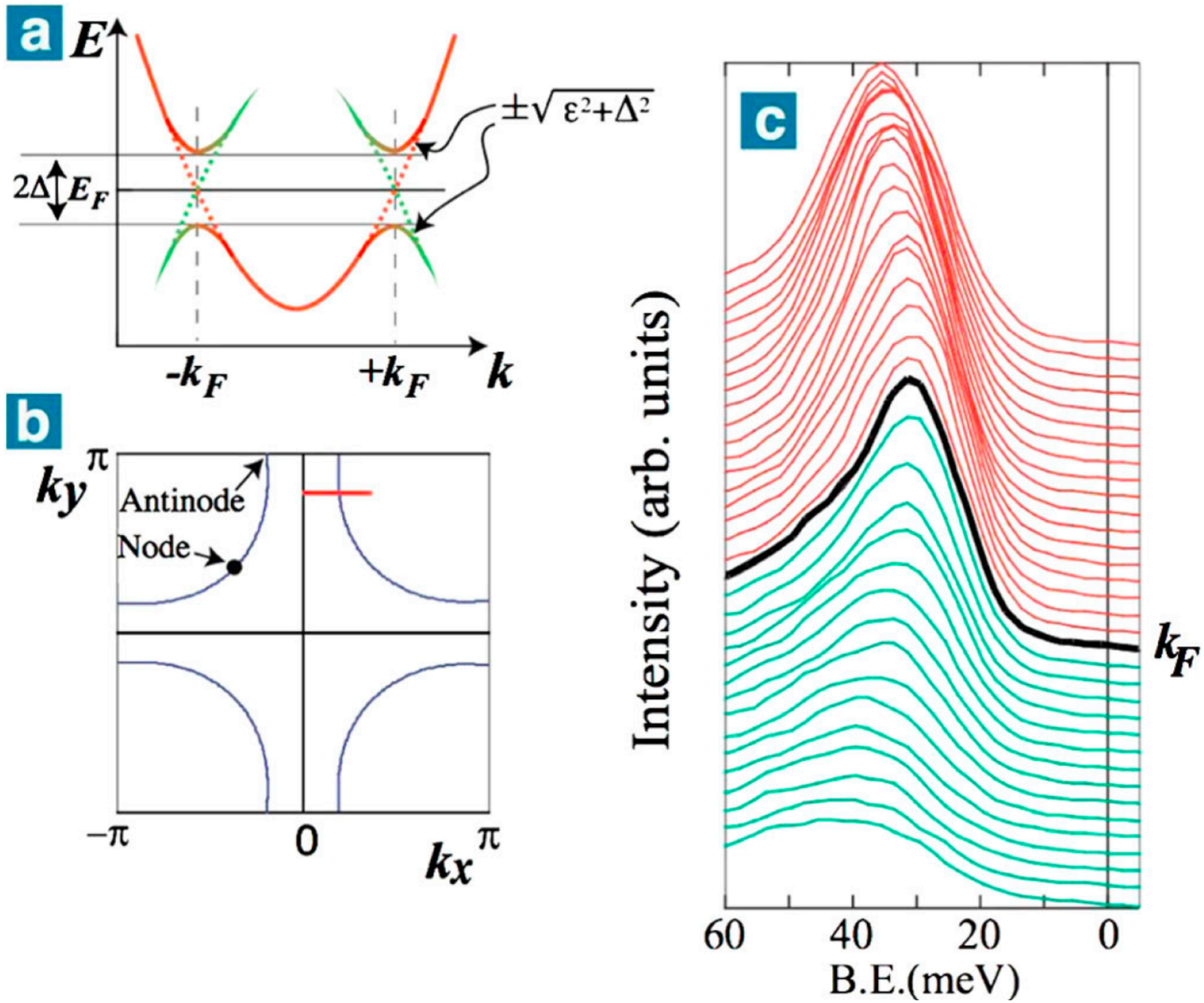
Spectral gap





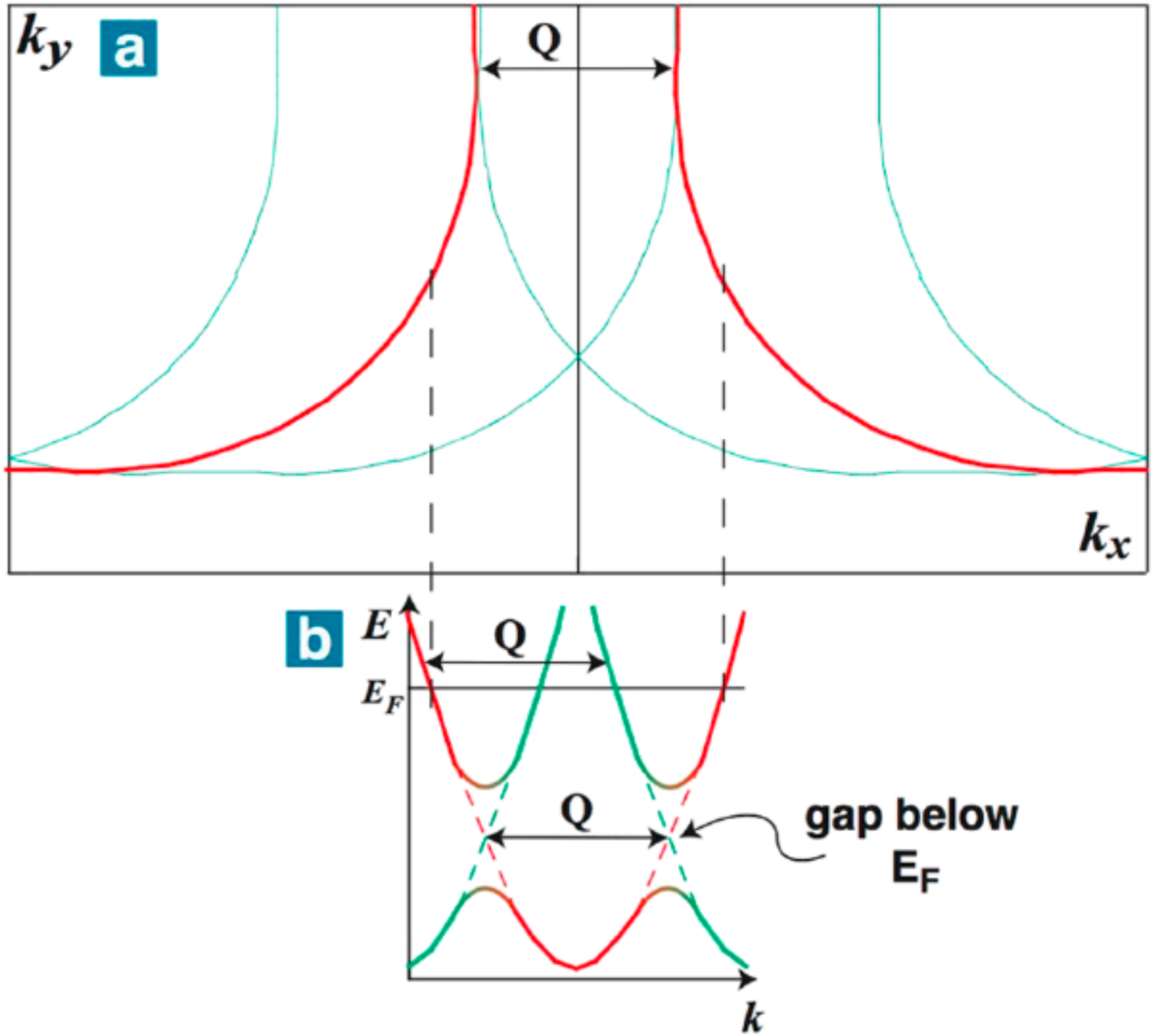


Superconducting (pairing) gap



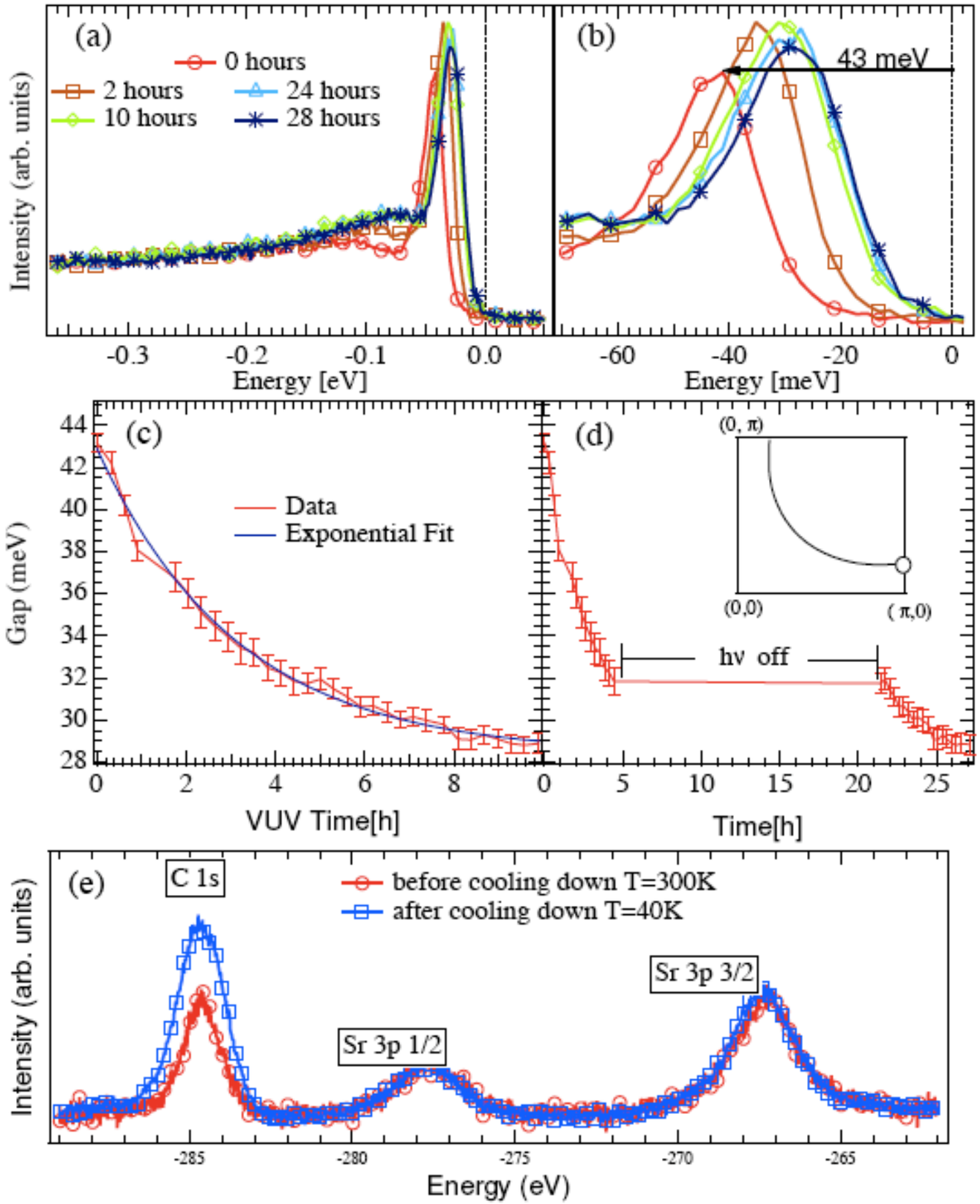
A. Kanigel et al., Phys. Rev. Lett 101, 137002 (2008)

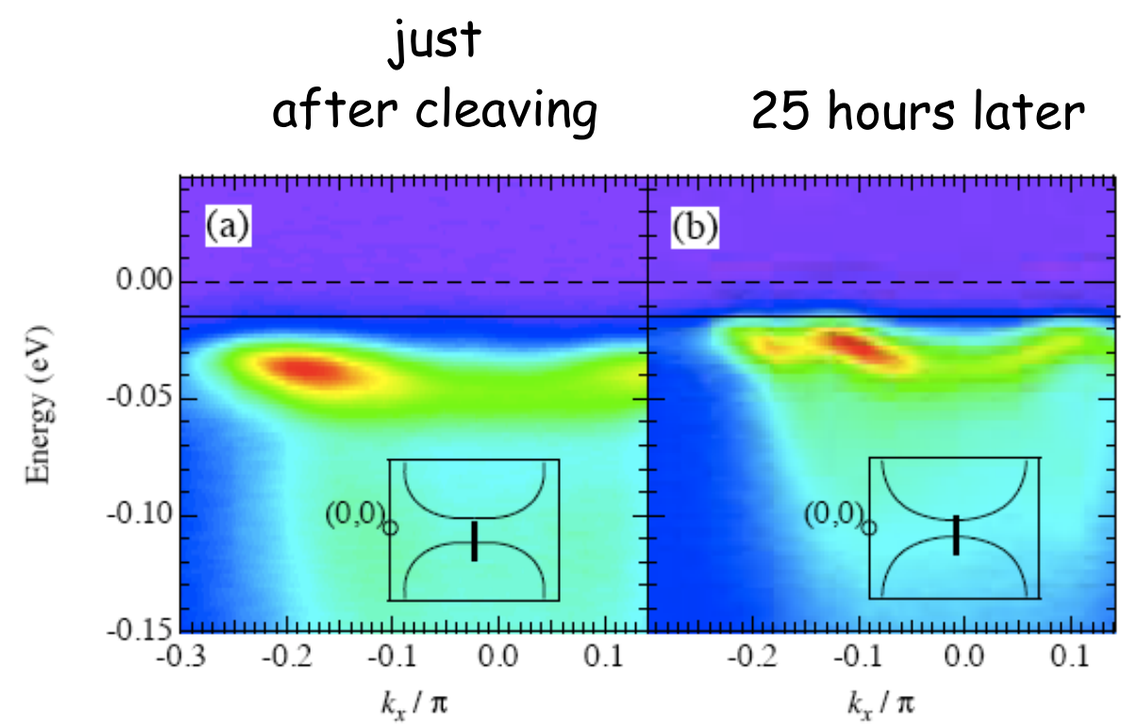
Charge Density Wave (CDW) gap



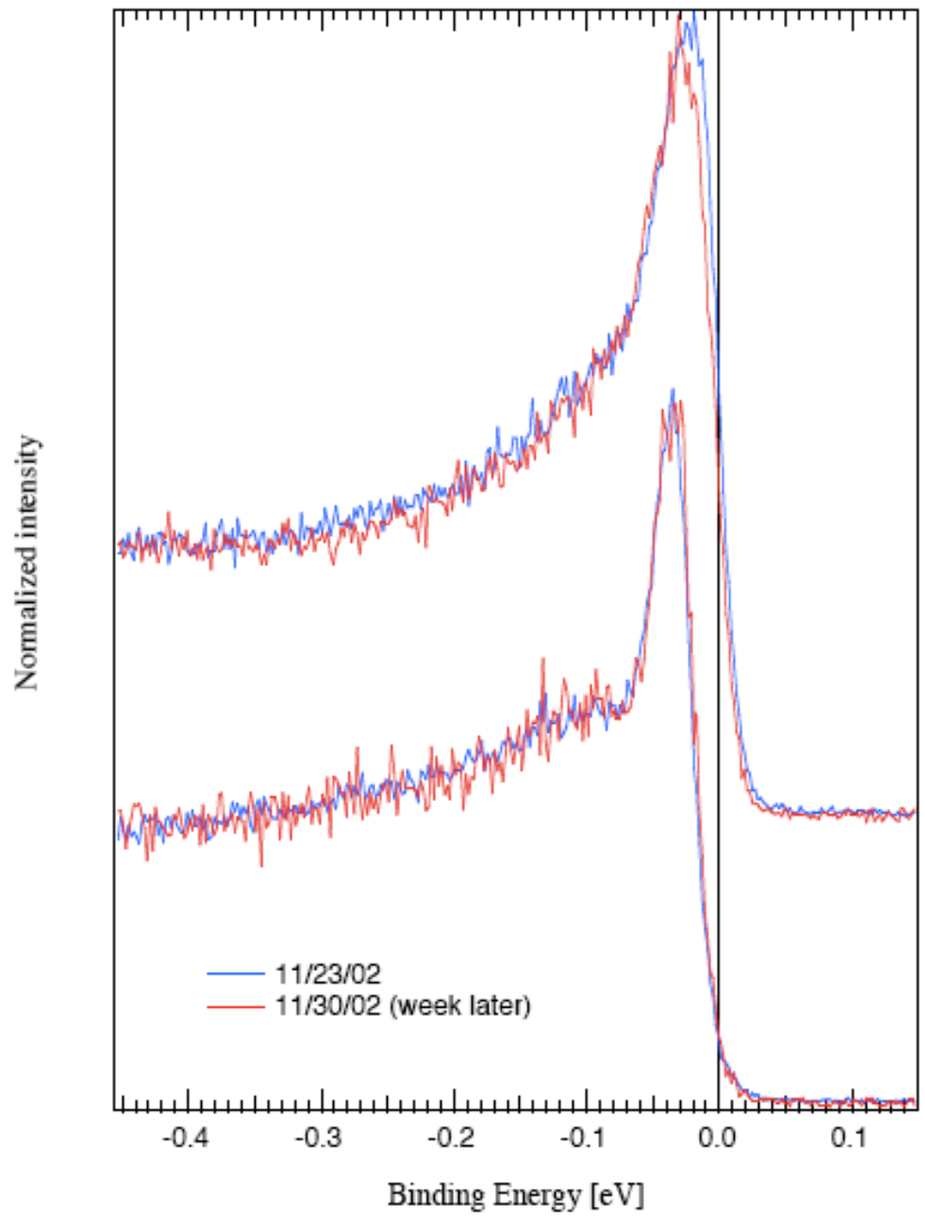
A. Kanigel et al., Phys. Rev. Lett 101, 137002 (2008)

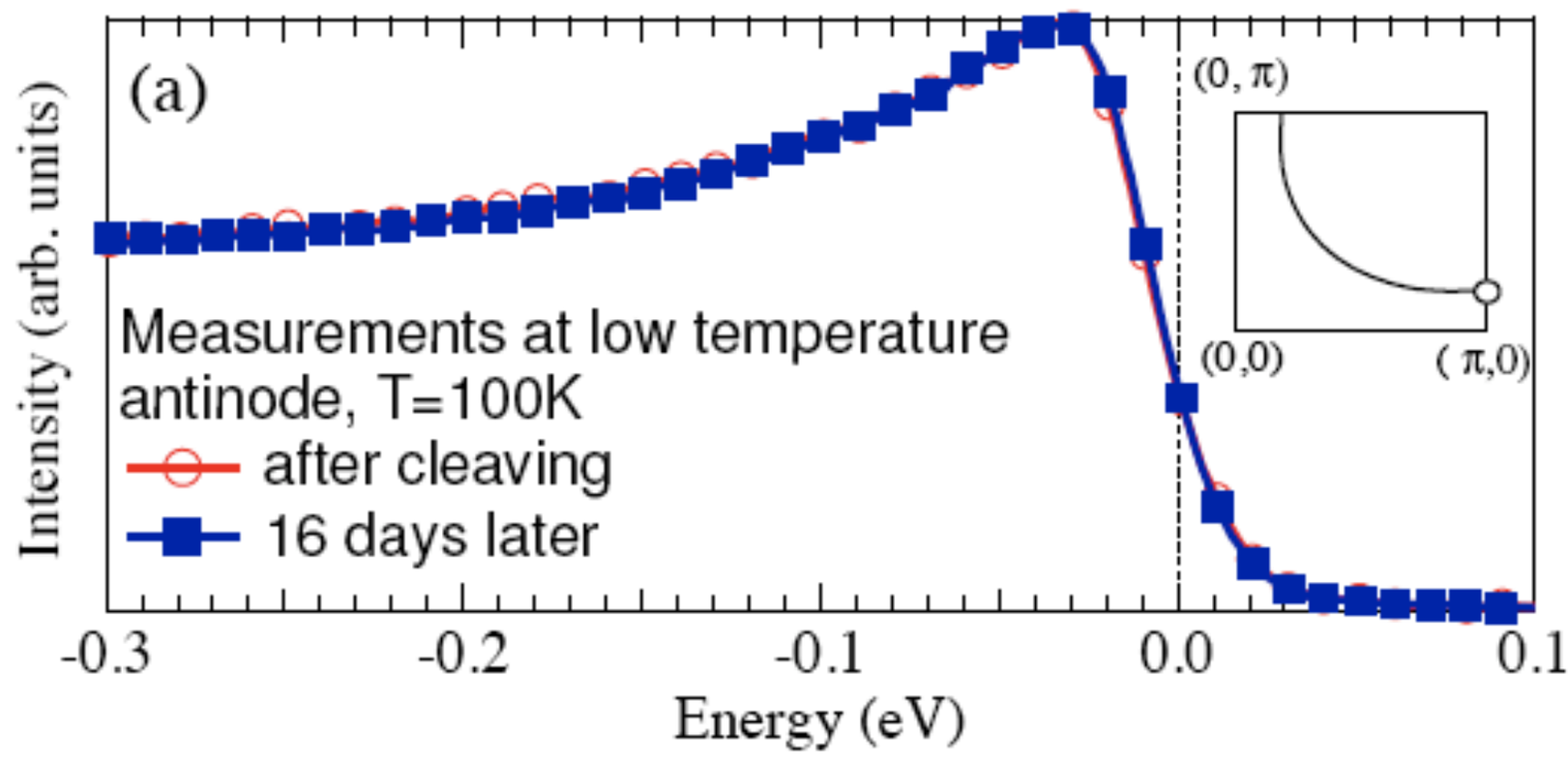
side note - less than perfect vacuum conditions



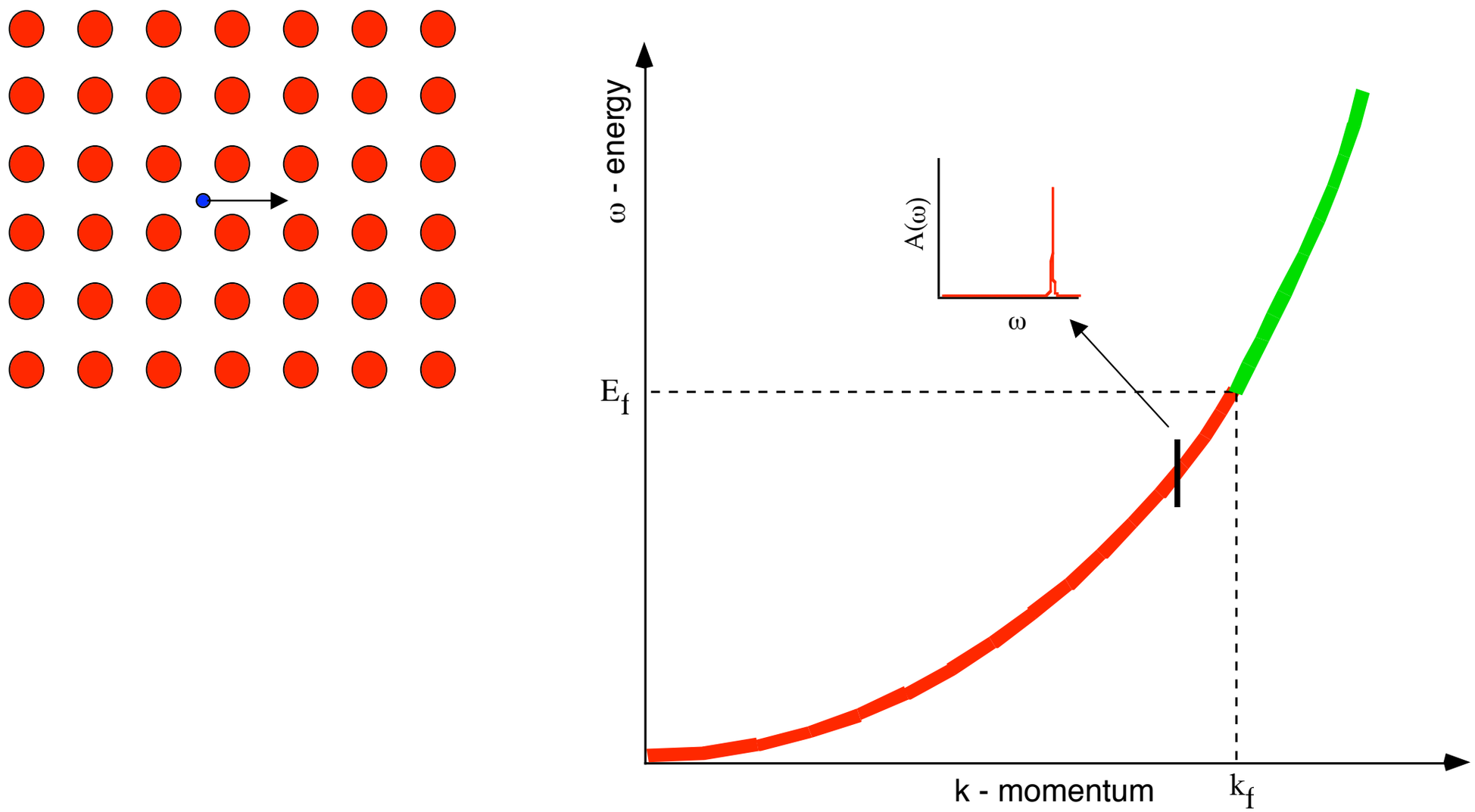


side note - decent vacuum conditions

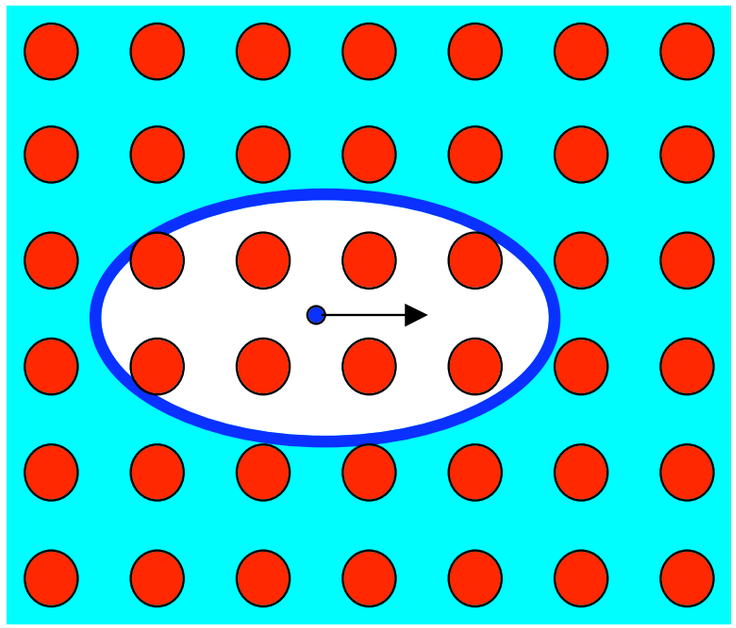




non-interacting electrons - free electron model



weakly interacting electrons - Fermi liquid model

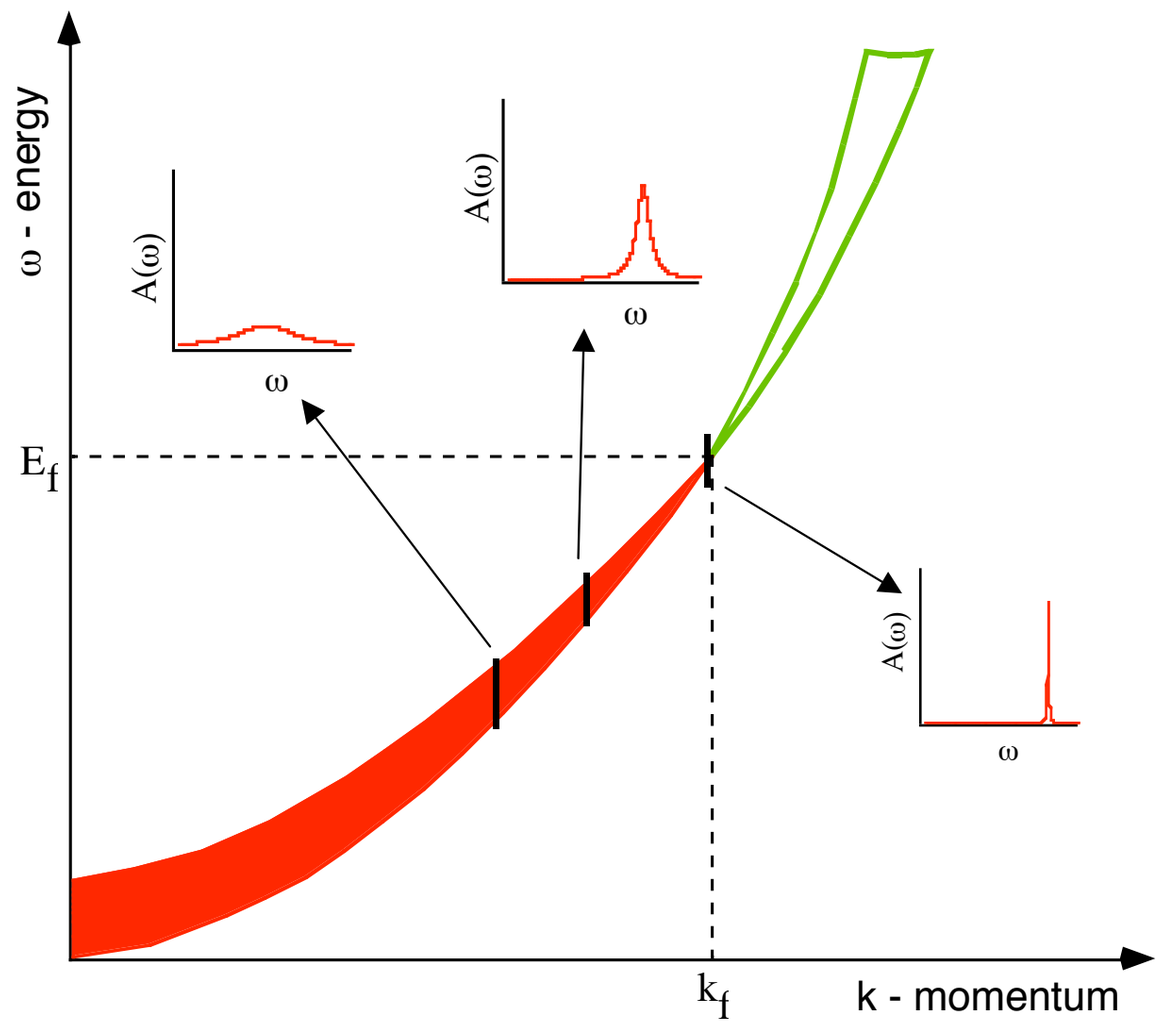


Quasiparticle="renormalized electron"

m^* , τ

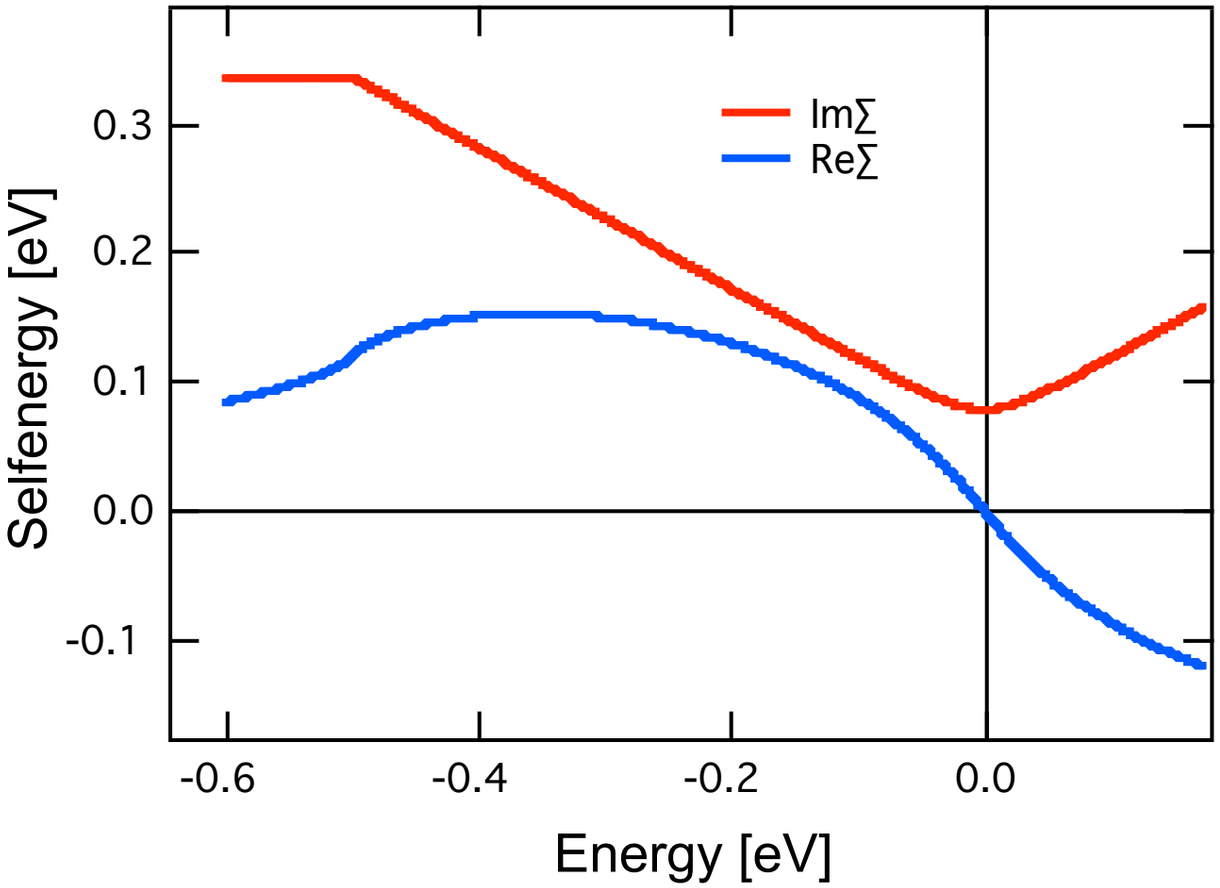
Σ – self energy

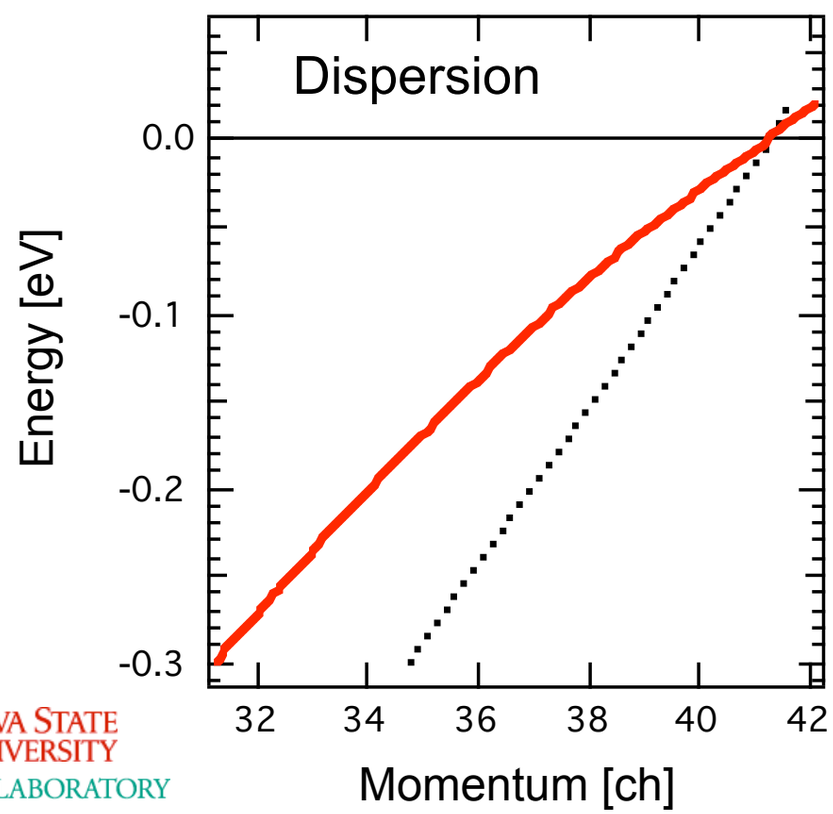
$$\Sigma(k,\omega)=\alpha\omega+i(\beta\omega^2+\gamma T^2)$$

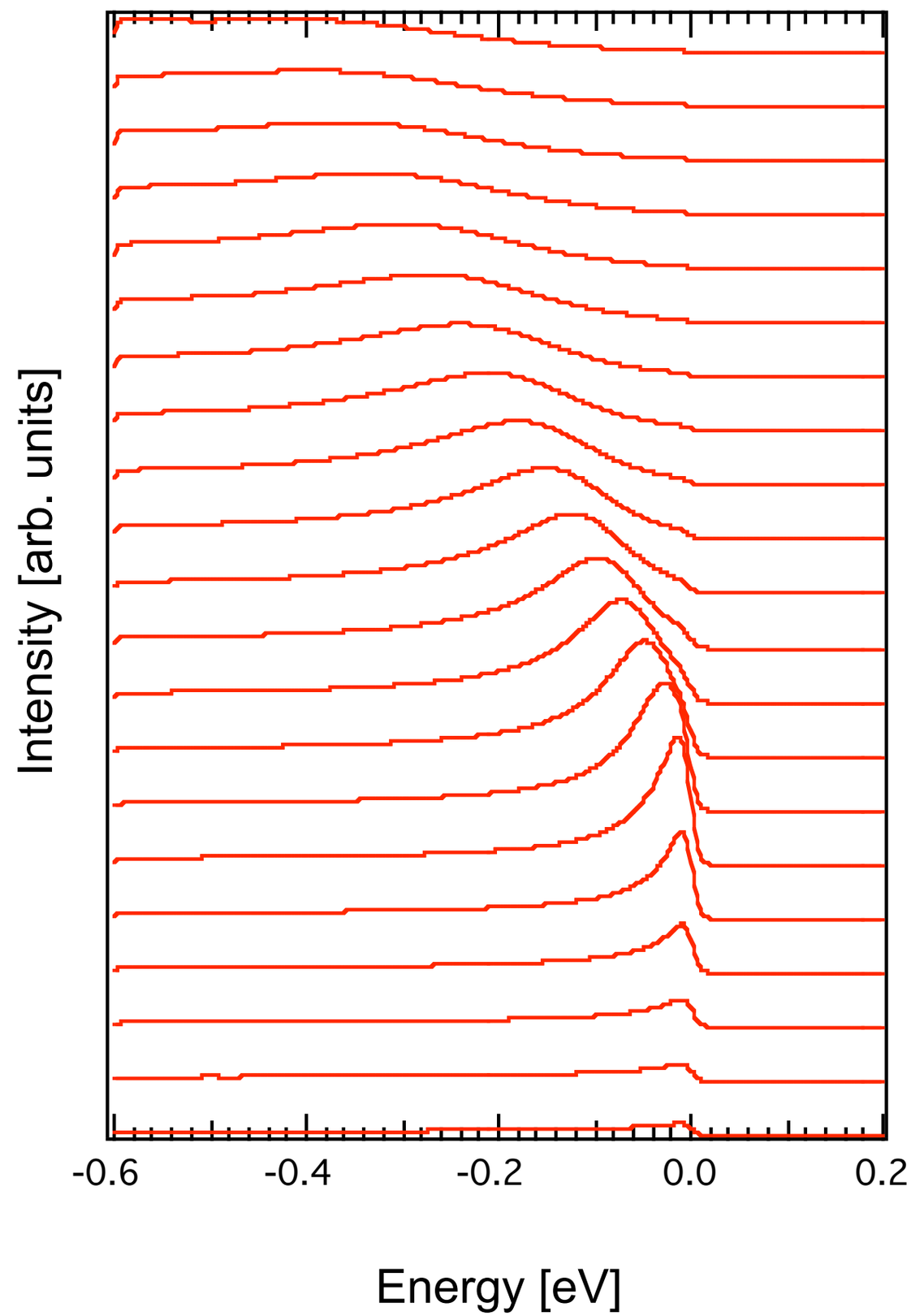


Scattering rates

$$A(k,\omega) = Im(G(k,\omega)) = \frac{\Sigma''(k,\omega)}{(\omega - \epsilon(k) - \Sigma'(k,\omega))^2 - (\Sigma''(k,\omega))^2}$$







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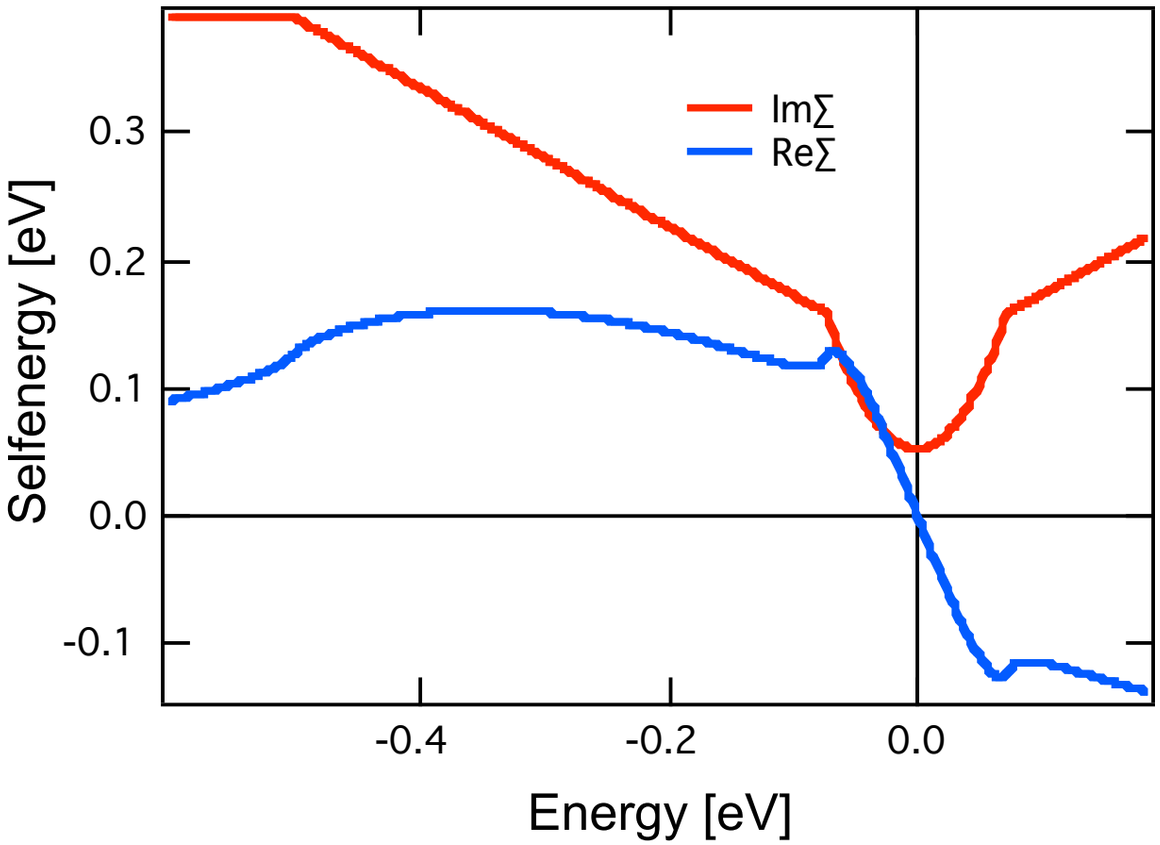
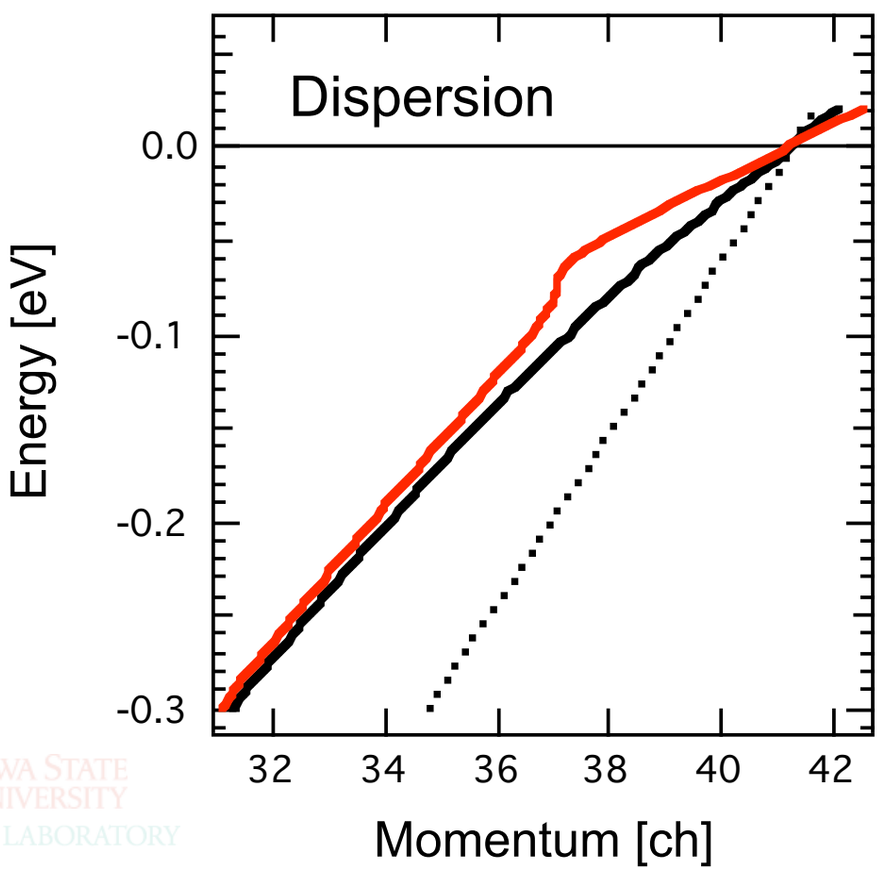
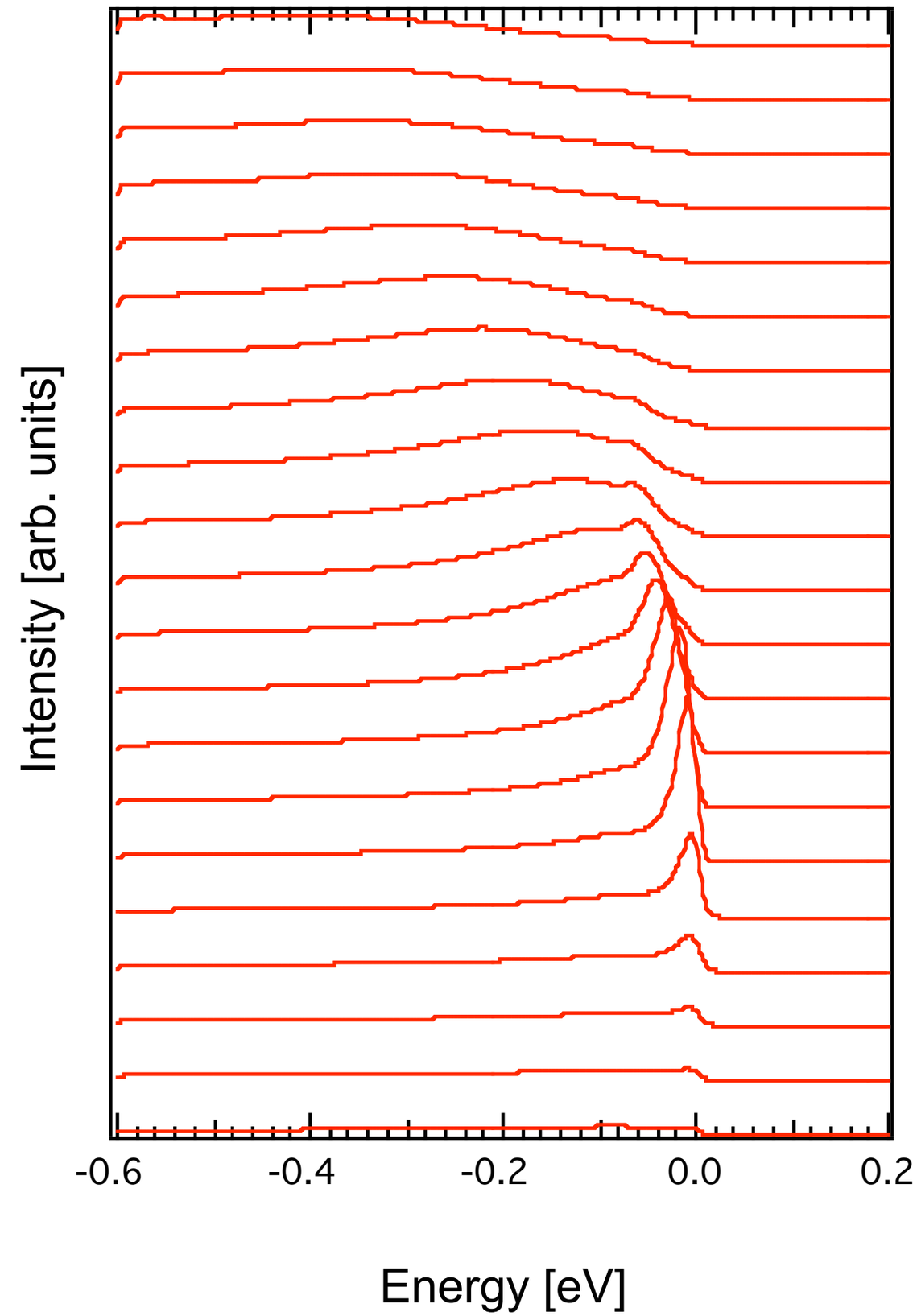
Simulation - weak interaction with collective mode







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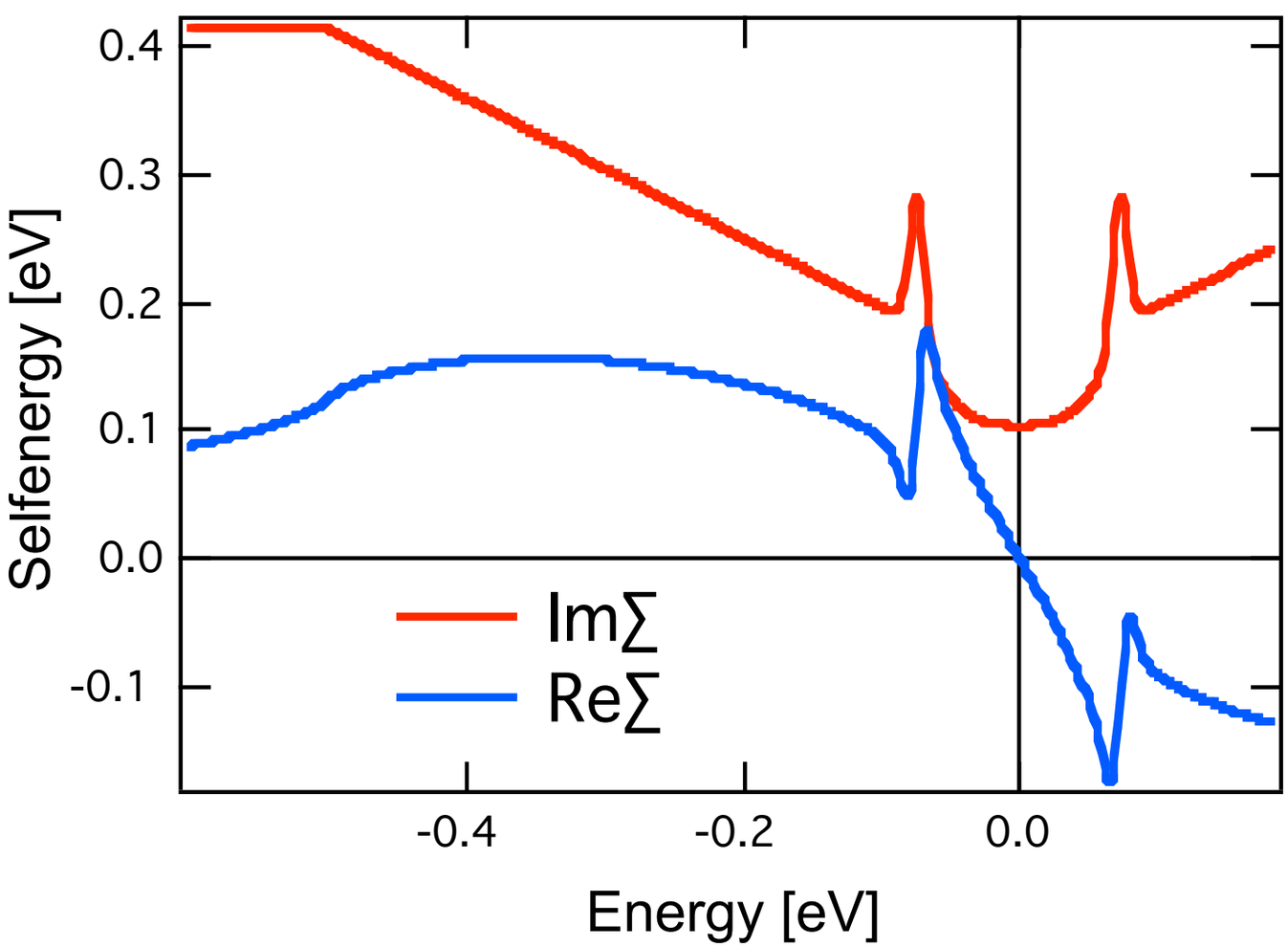
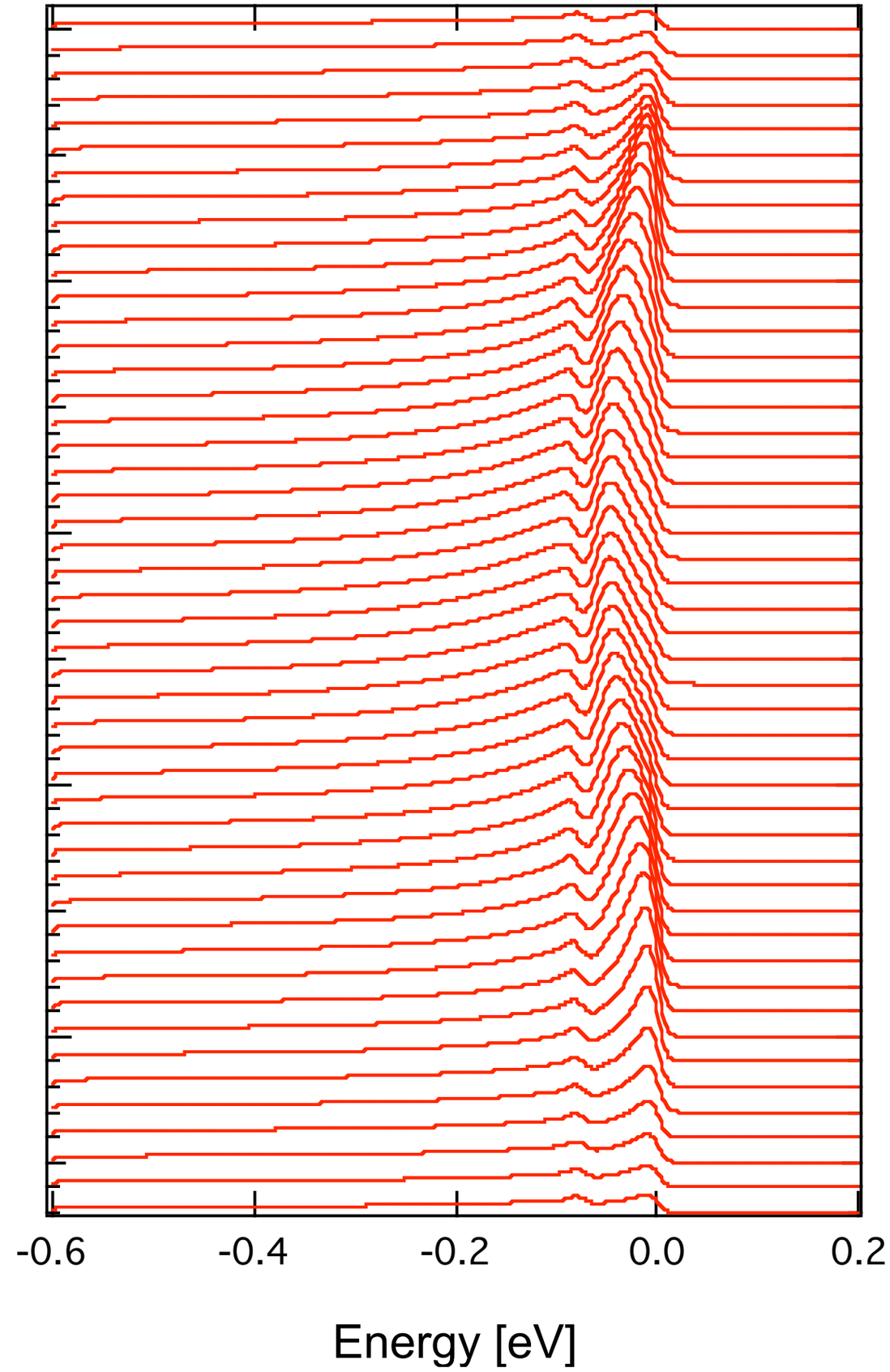
Simulation - strong interaction with collective mode





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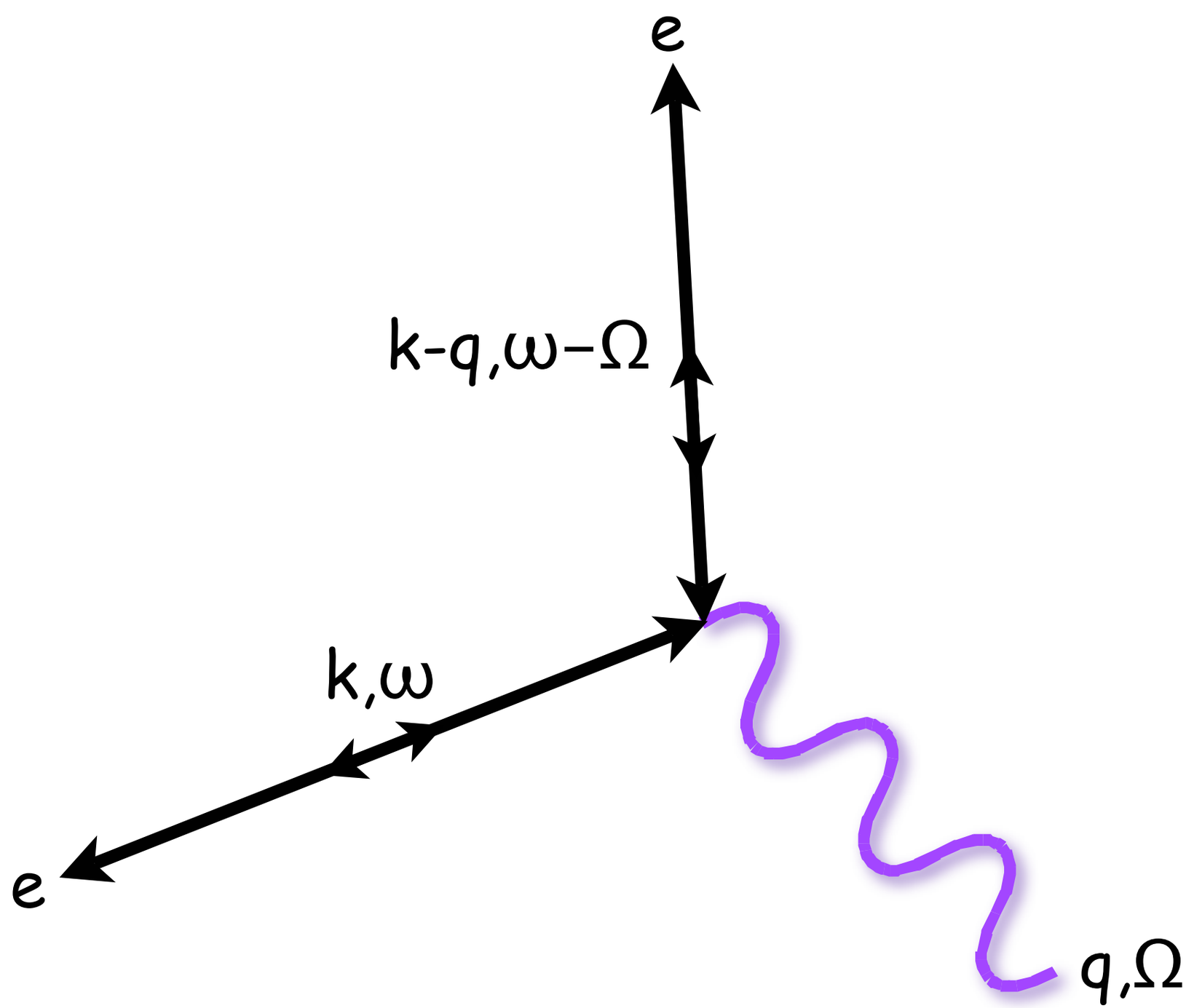
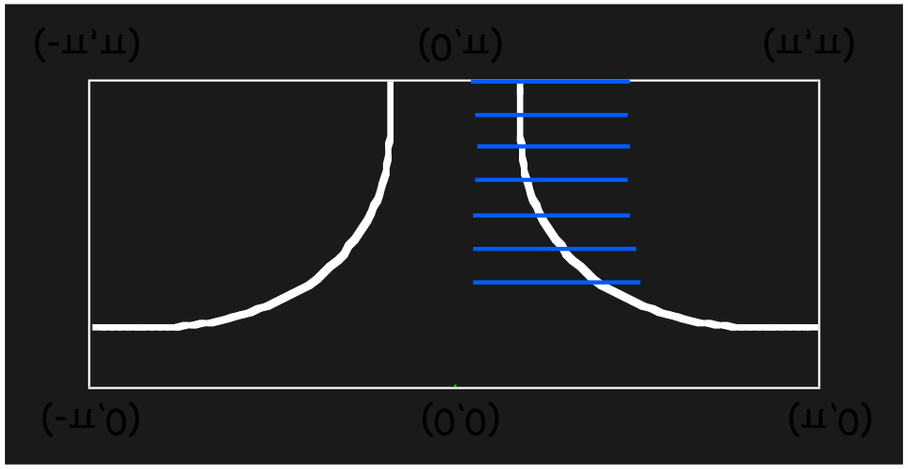
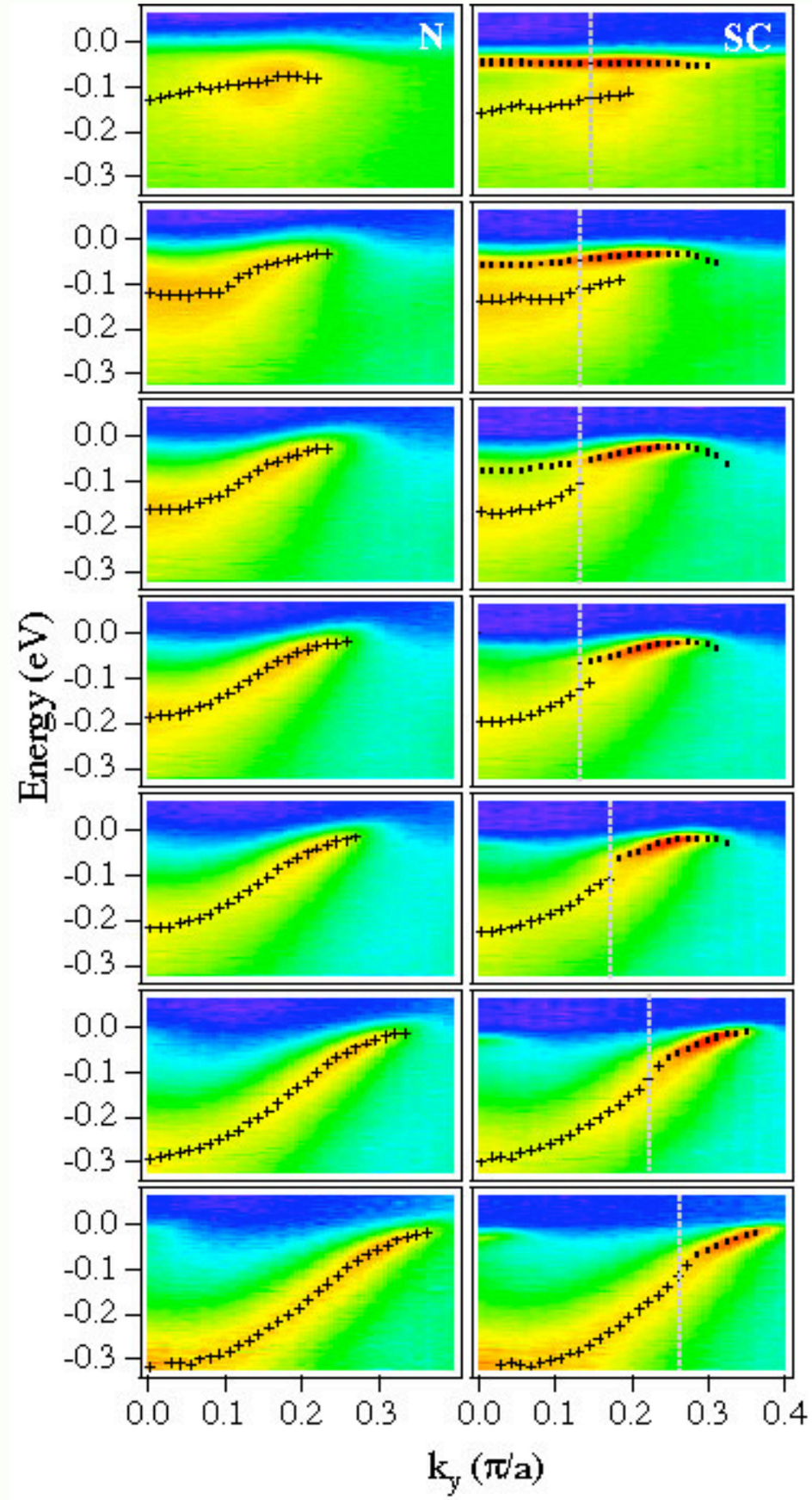
Ames Laboratory

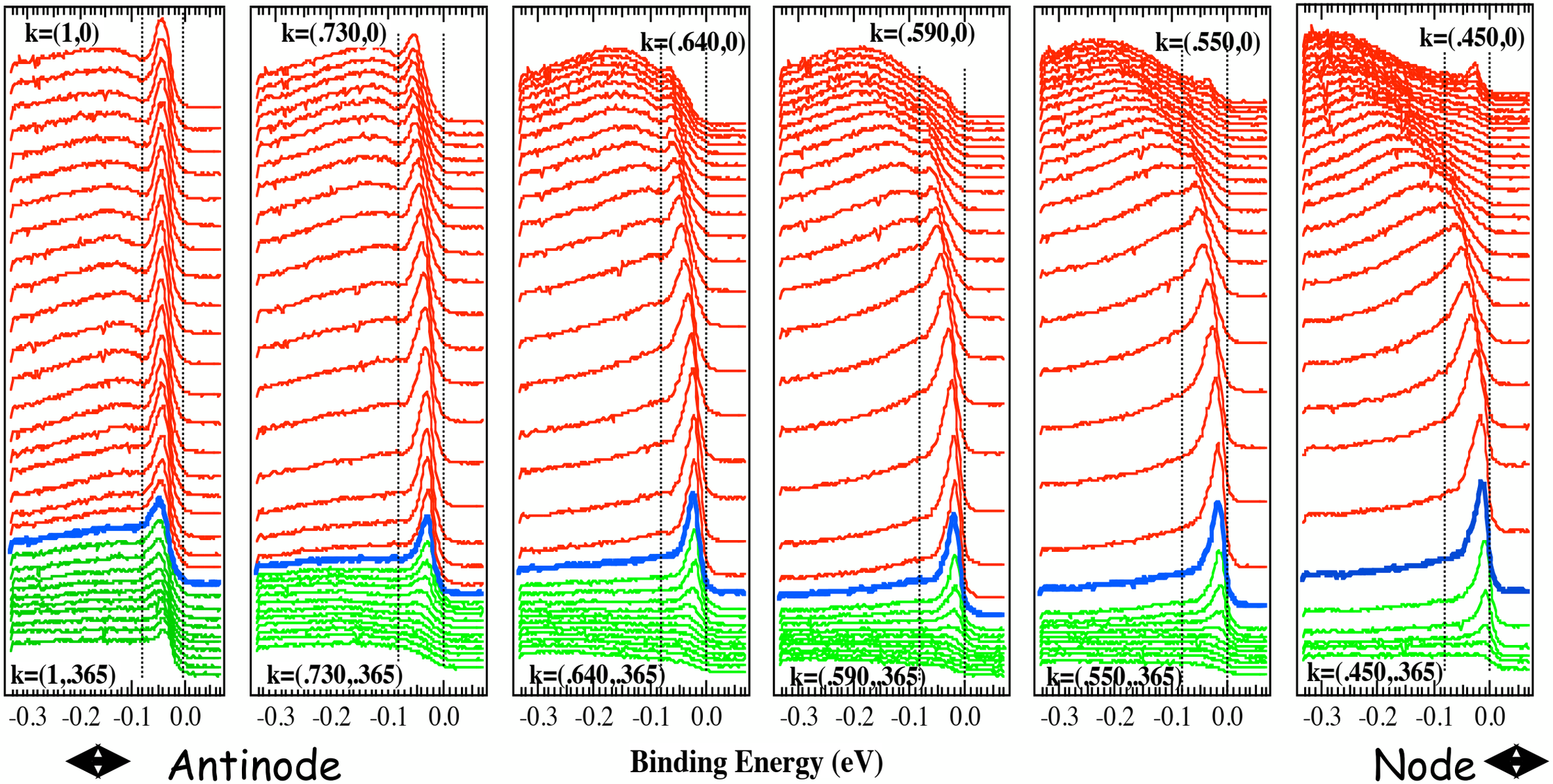
Collective modes



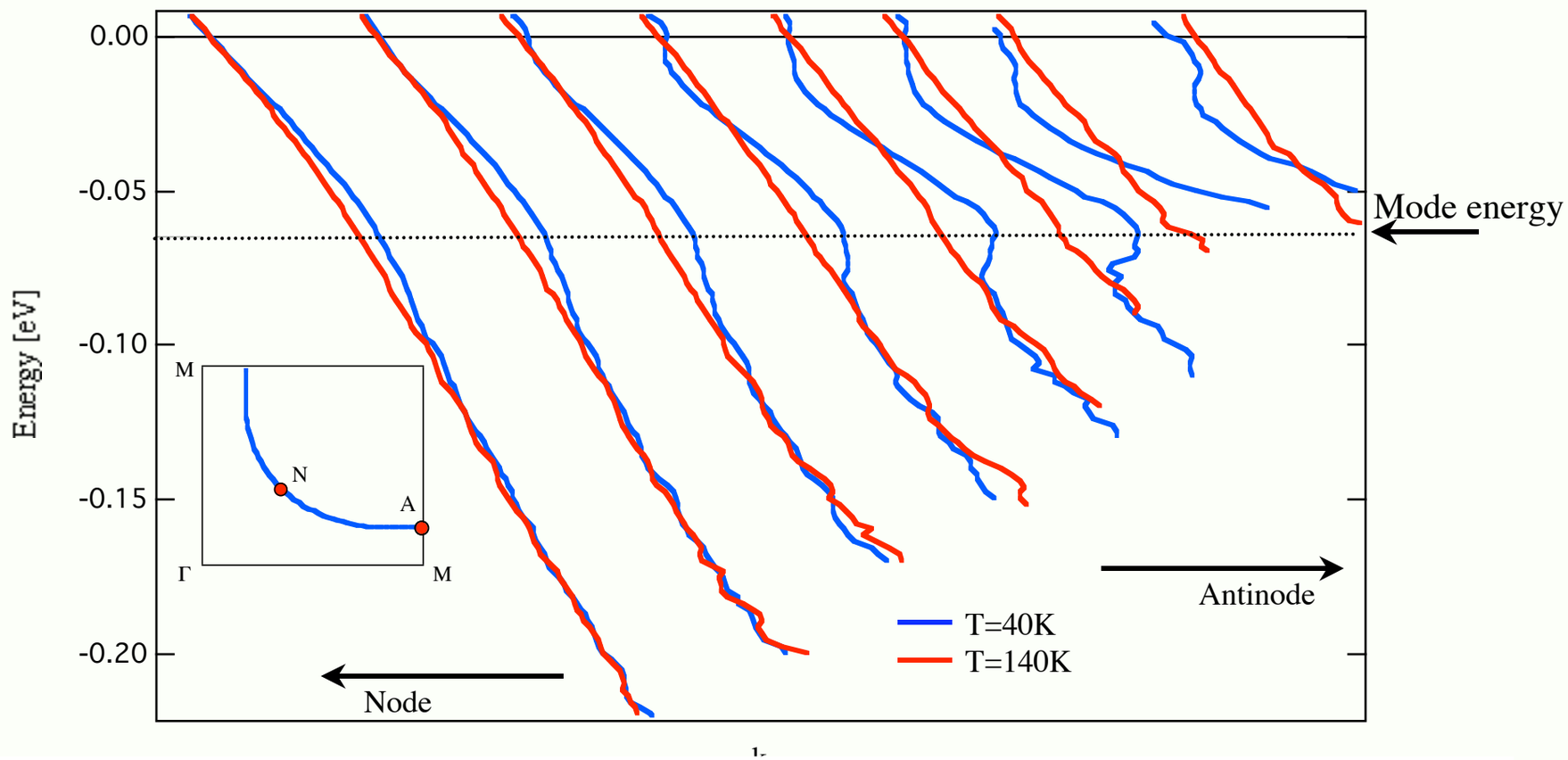

(-π,π)
(0,π)
(π,π)
(-π,0)
(0,0)
(π,0)


N
SC
Energy (eV)
0.0
-0.1
-0.2
-0.3
0.0 0.1 0.2 0.3 0.0 0.1 0.2 0.3 0.4
k_y (π/a)

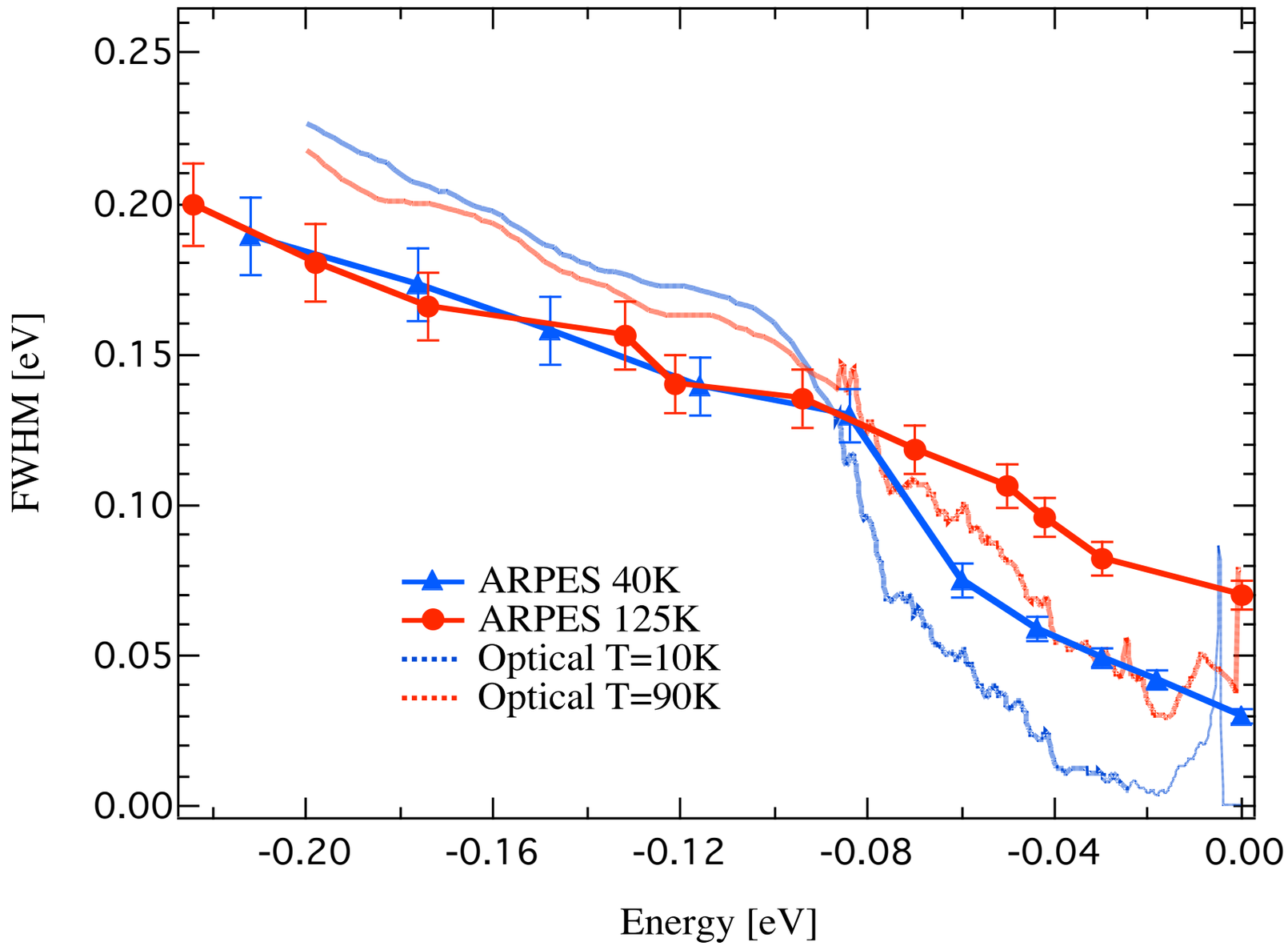
EDC's in the superconducting state



Interaction of the electrons with a collective mode



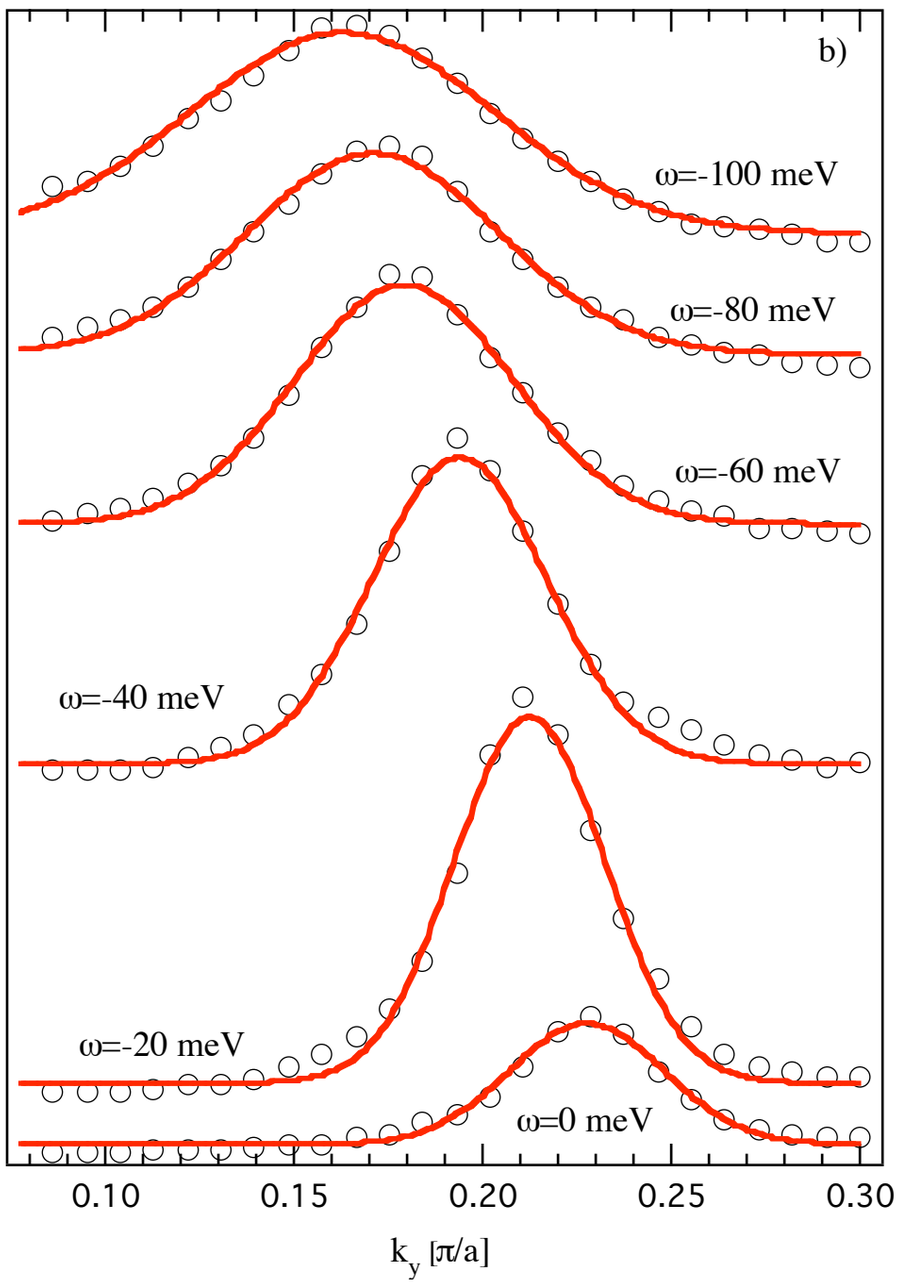
Self energy (=> scattering rate)



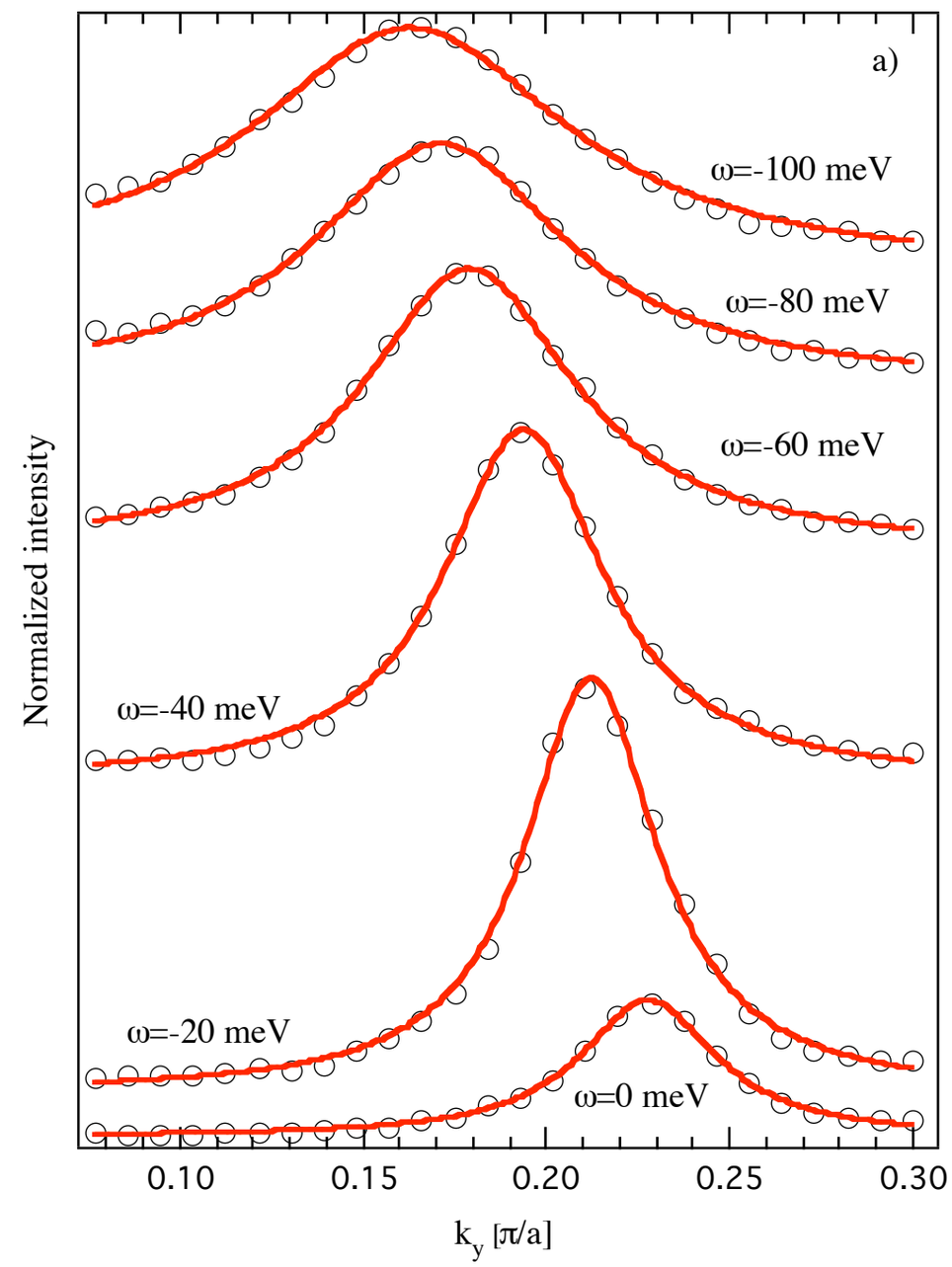
ARPES estimate of of scattering rate compares well to the one obtained from optical reflectivity data
A.V. Puchkov, D.N. Basov, and T. Timusk, J. Phys. Condens. Matter **8**, 10 049 (1996).

Fits to the MDCs':

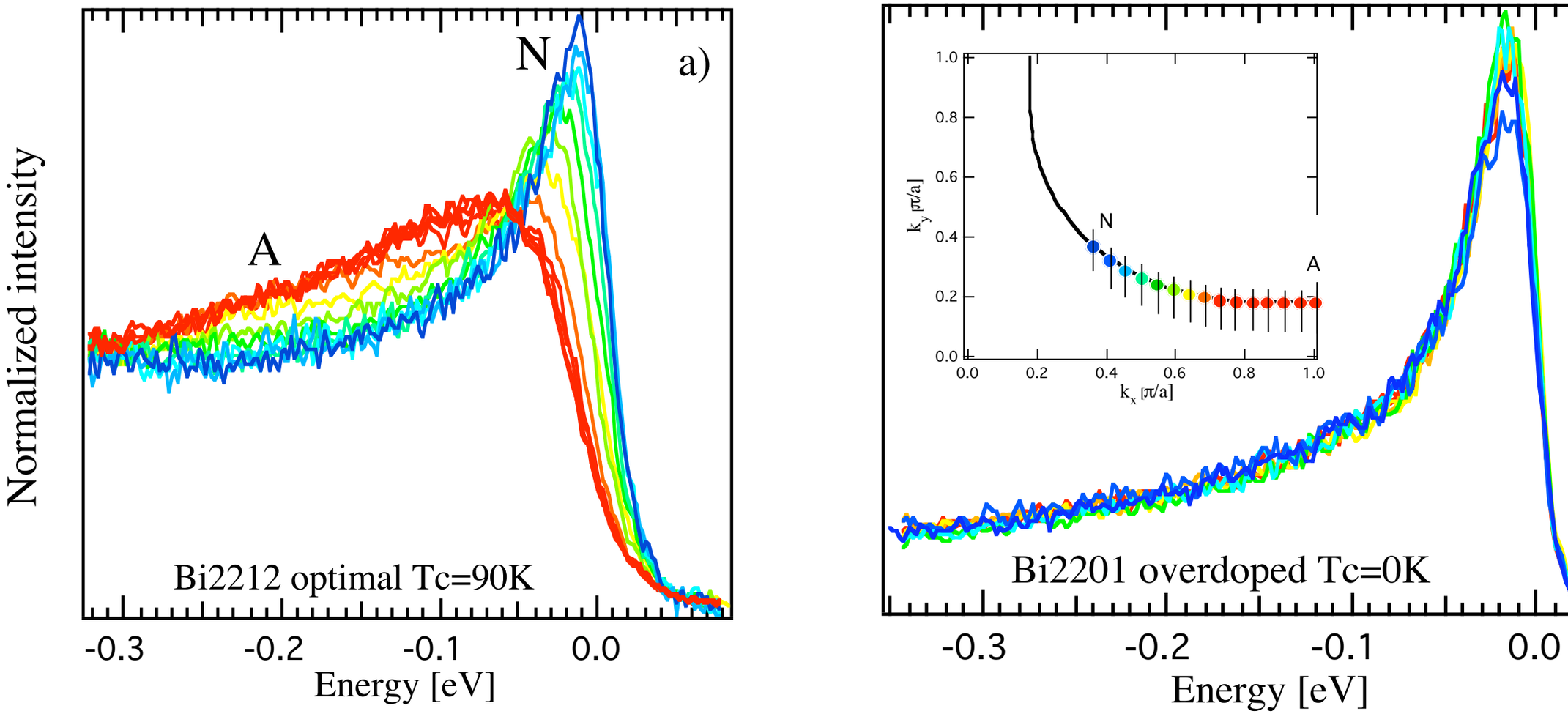
gaussian

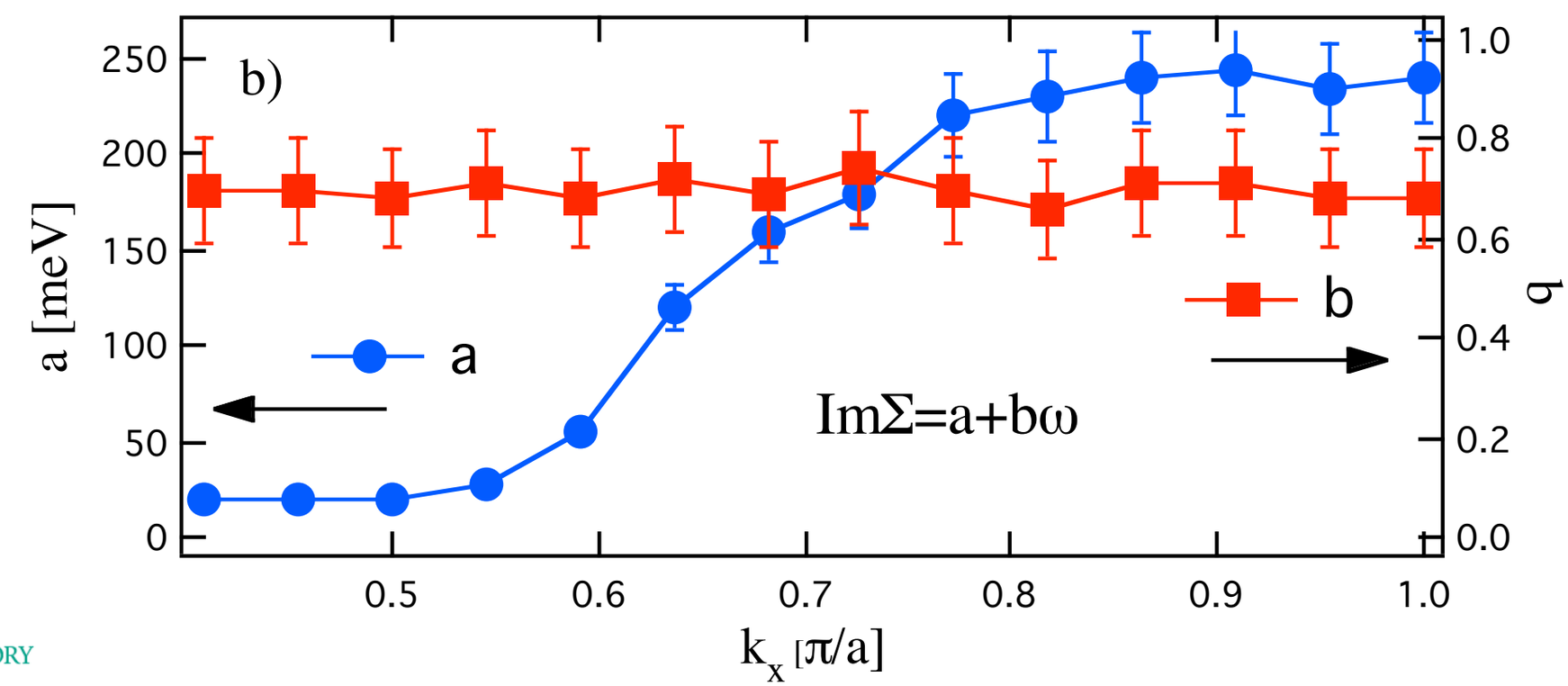


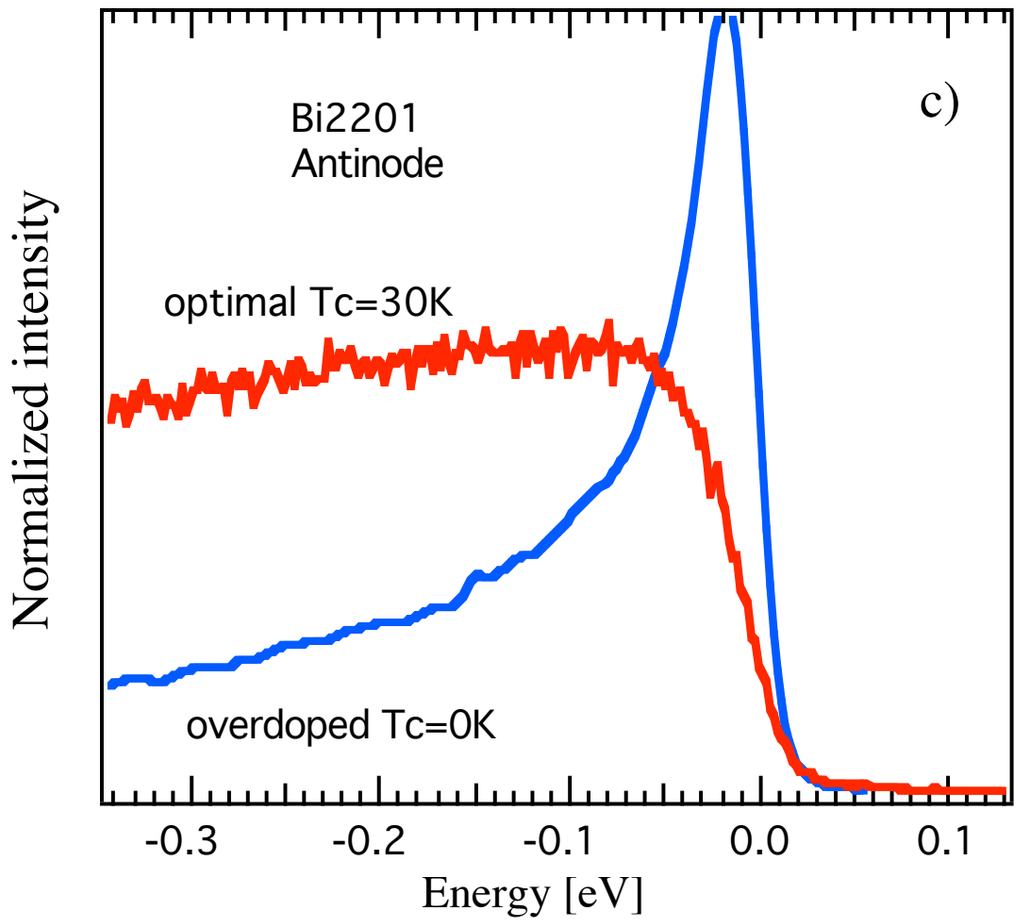
lorentzian

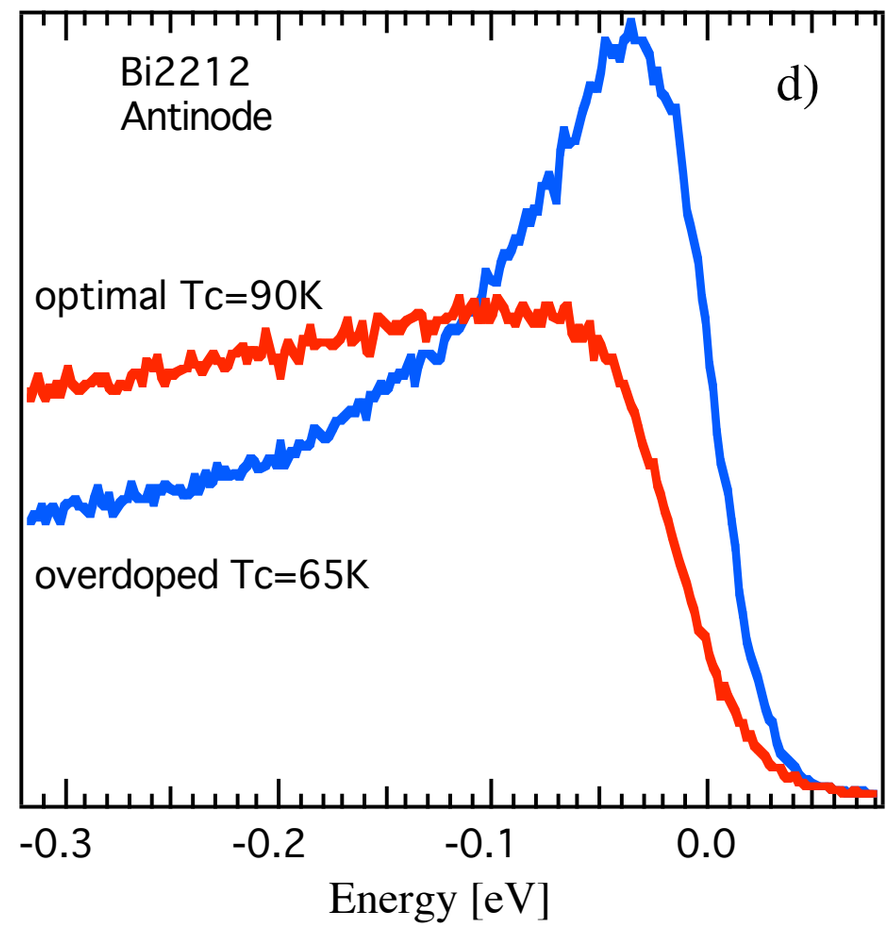


Momentum anisotropy of the scattering rate

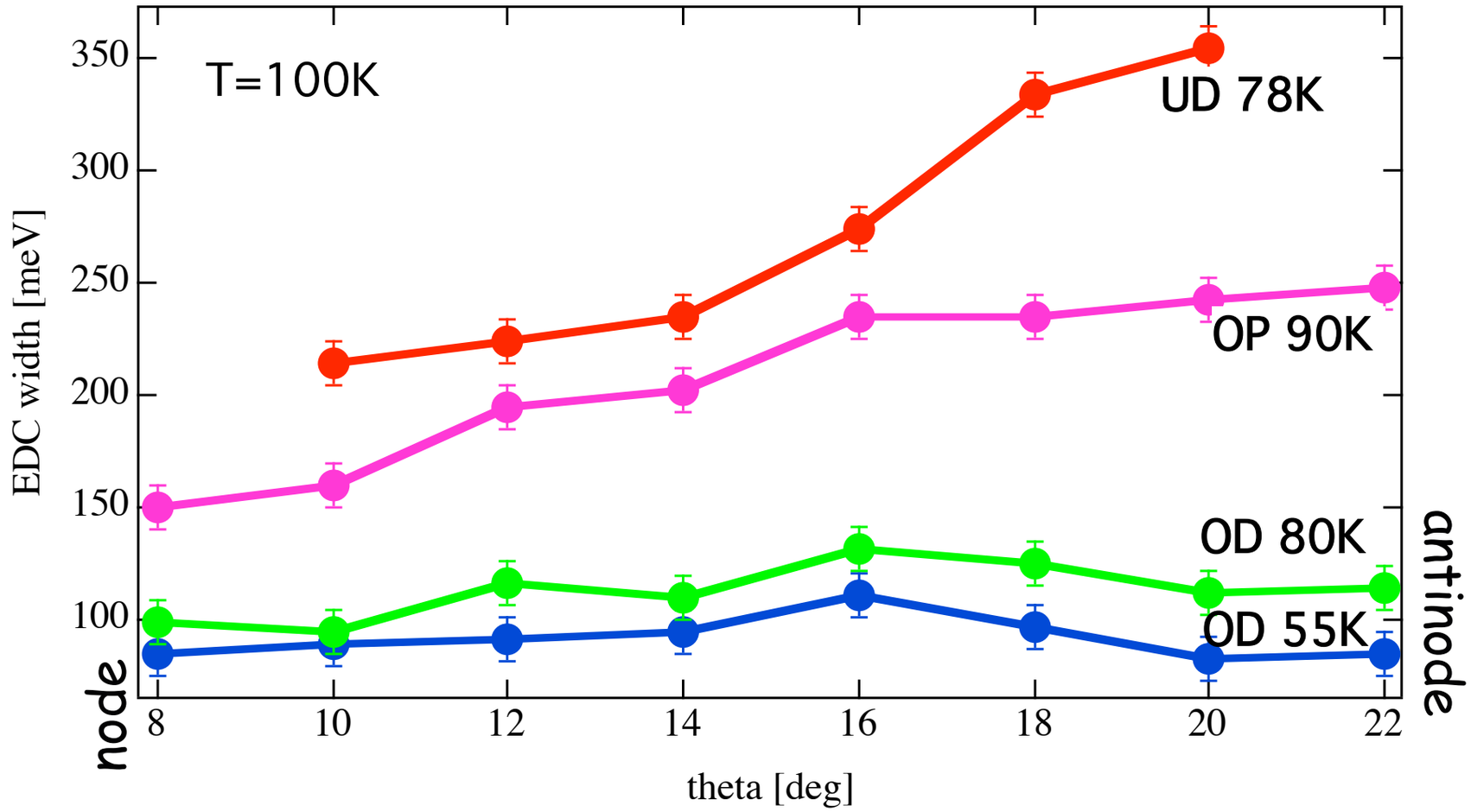




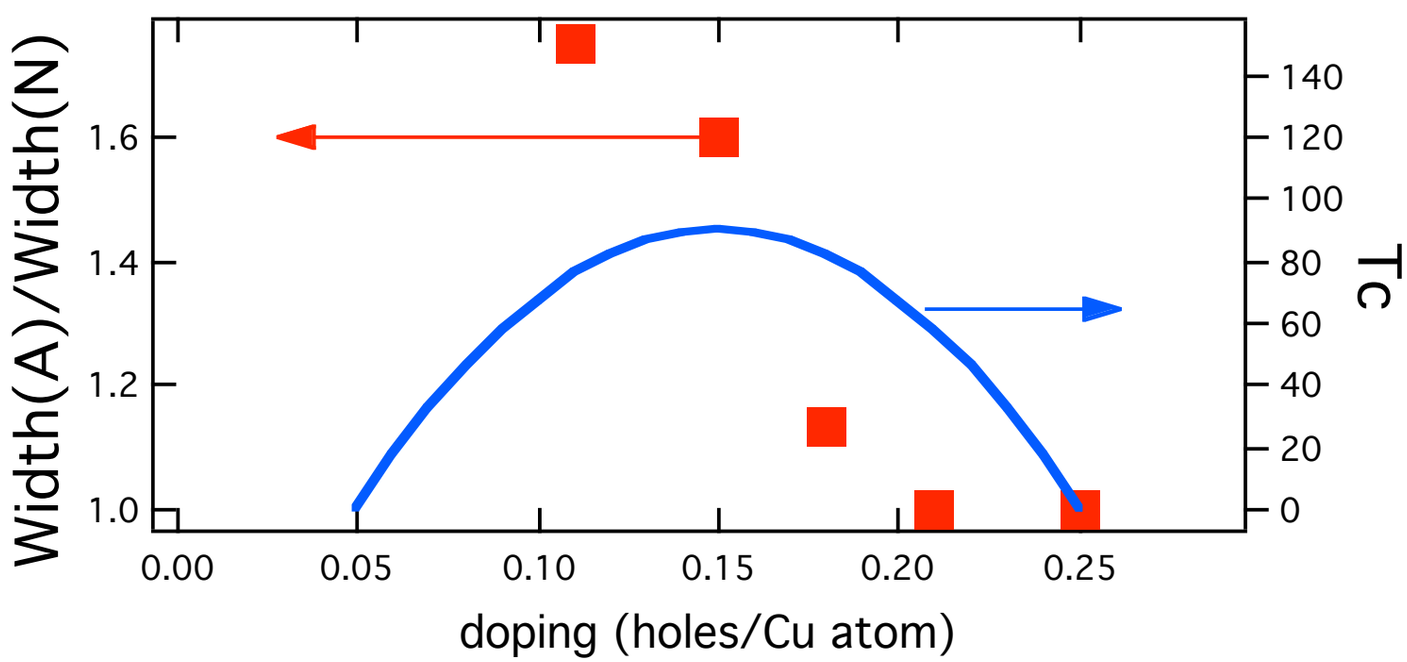

Bi2201
Antinode
c)
optimal Tc=30K
overdoped Tc=0K
Normalized intensity
-0.3
-0.2
-0.1
0.0
0.1
Energy [eV]


Bi2212
Antinode
d)
optimal Tc=90K
overdoped Tc=65K
-0.3
-0.2
-0.1
0.0
Energy [eV]

EDC width around the Fermi surface



doping dependence of the anisotropy



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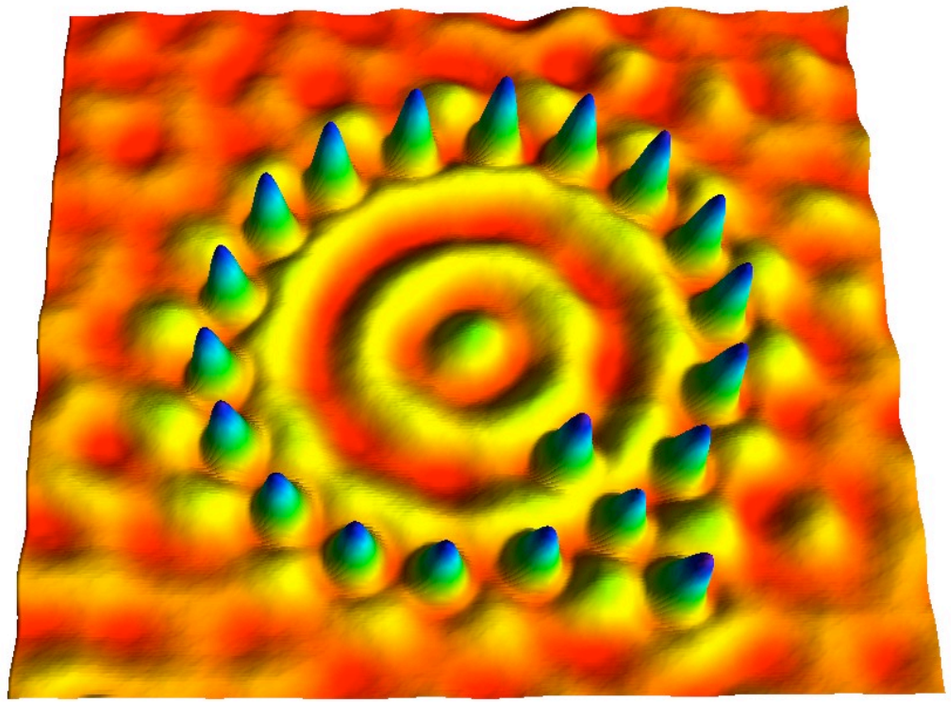
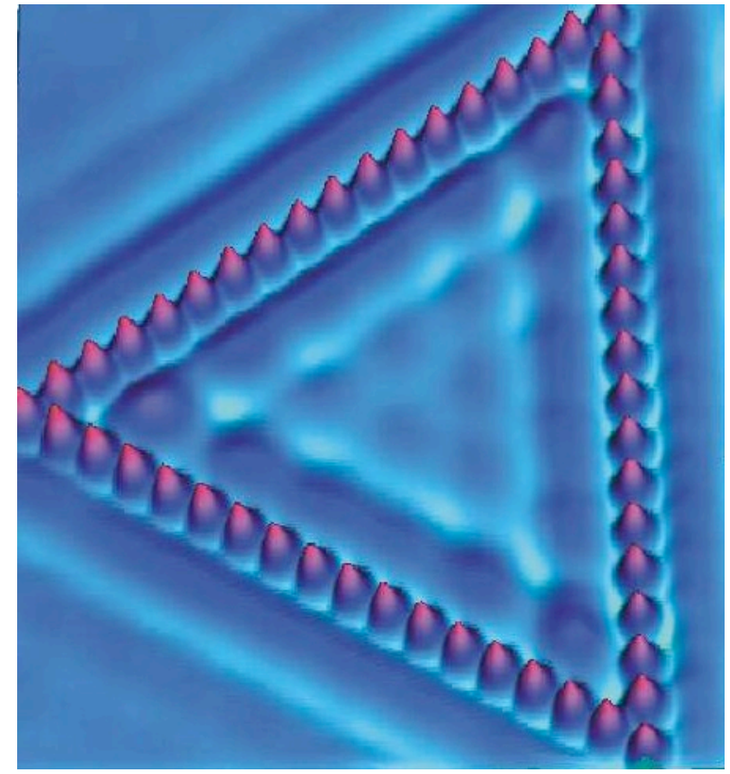
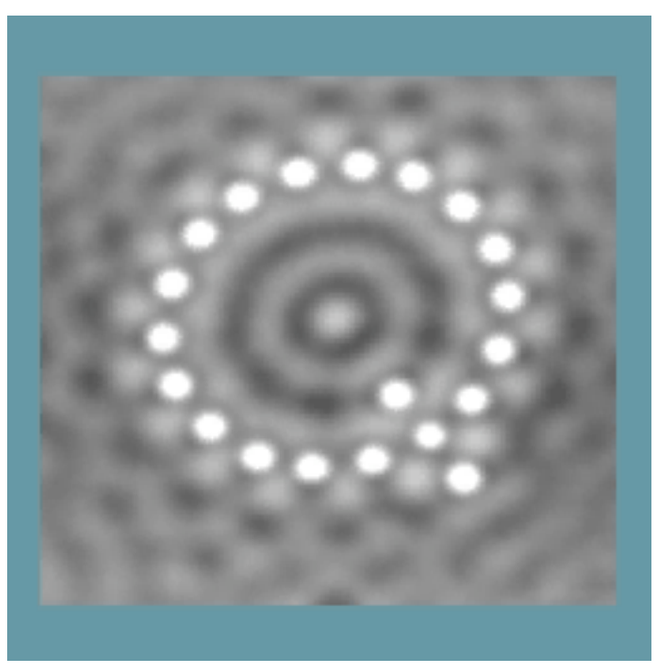
Scattering in traditional STM



Cu on Cu(111)



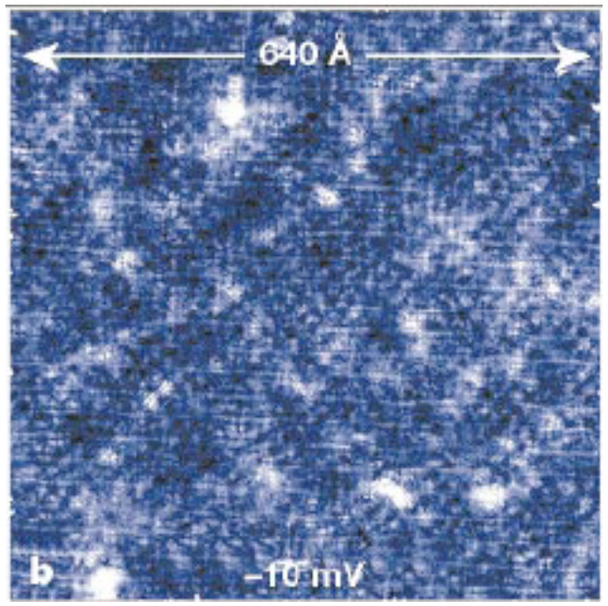
Ag on Ag(111)



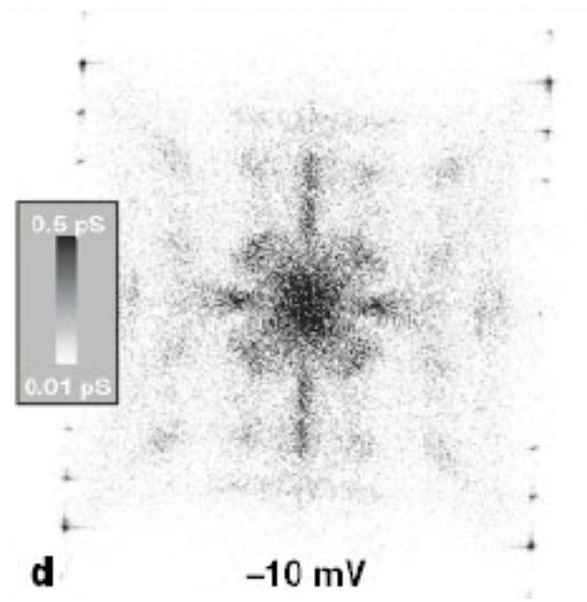
9K => 12K

Fourier Transform STM

(FT STM)



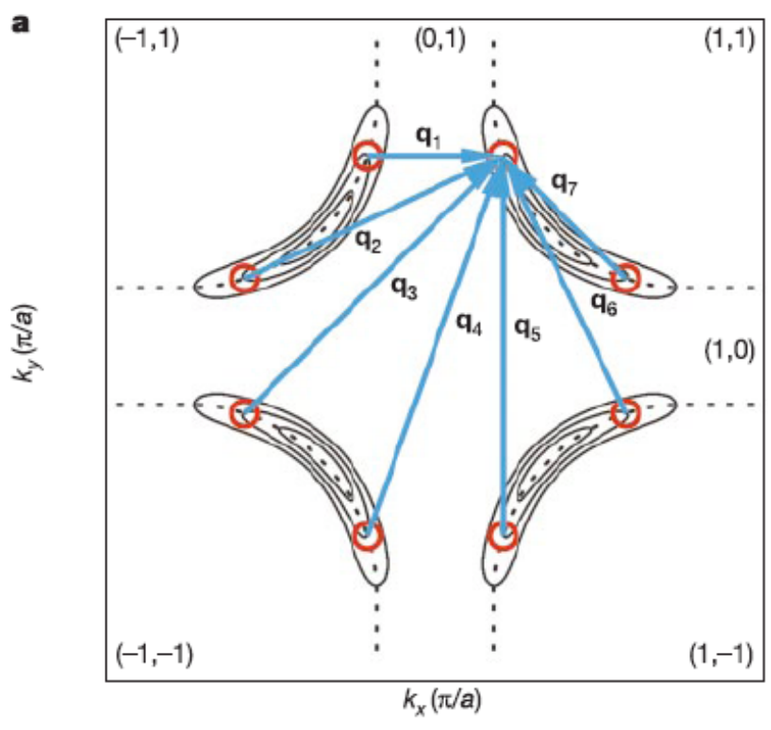
Fourier transform



J. E. Hoffman et al,
Science **295**, 466 (2002)

J. E. Hoffman et al,
Science **297**, 1148 (2002)

K. McElroy et al,
Nature **422**, 592 (2004)

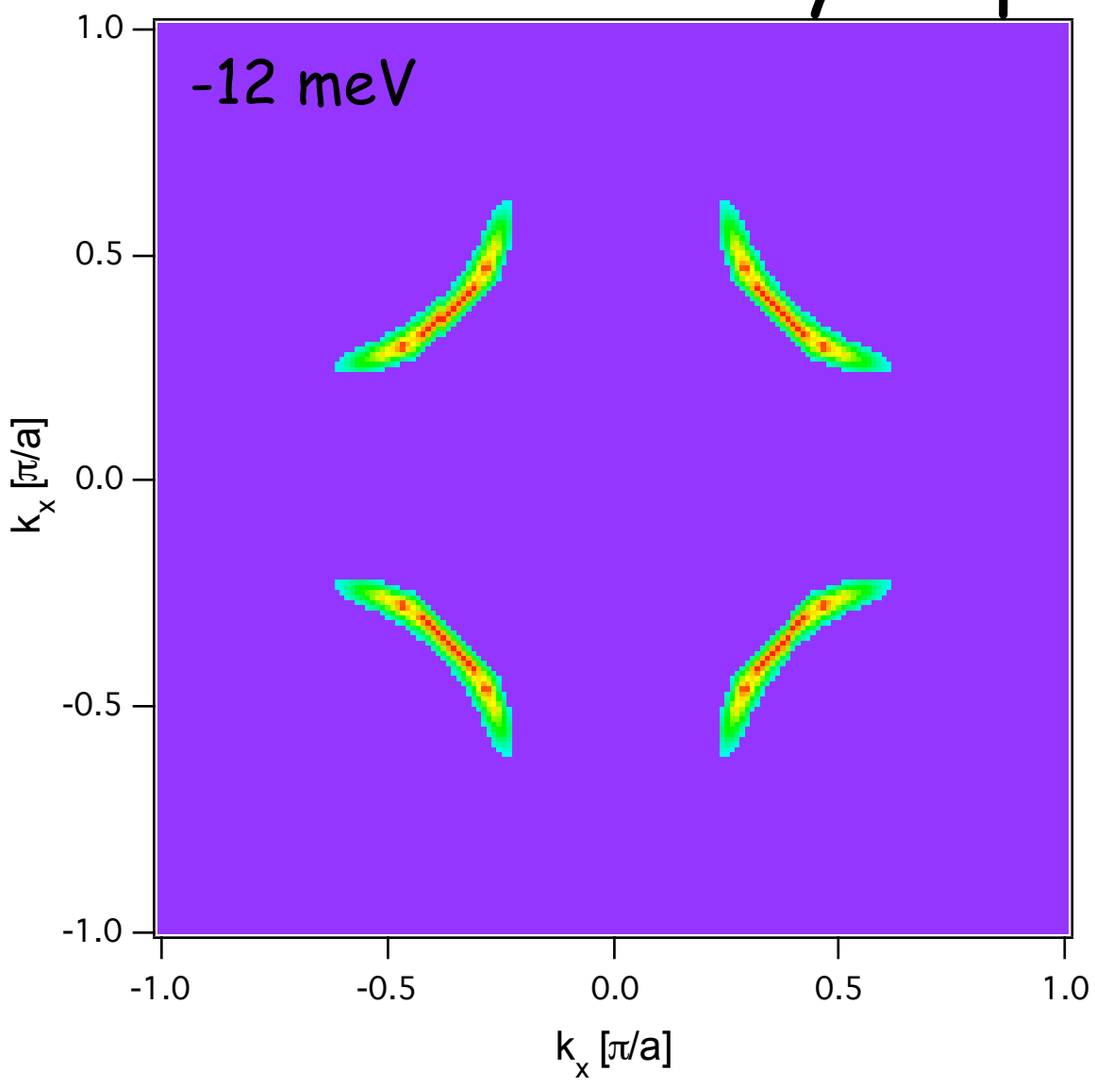


L. Capriotti et al,
PRB **68**, 014508 (2003)

R. S. Markiewicz et al,
PRB **69**, 214517 (2004)

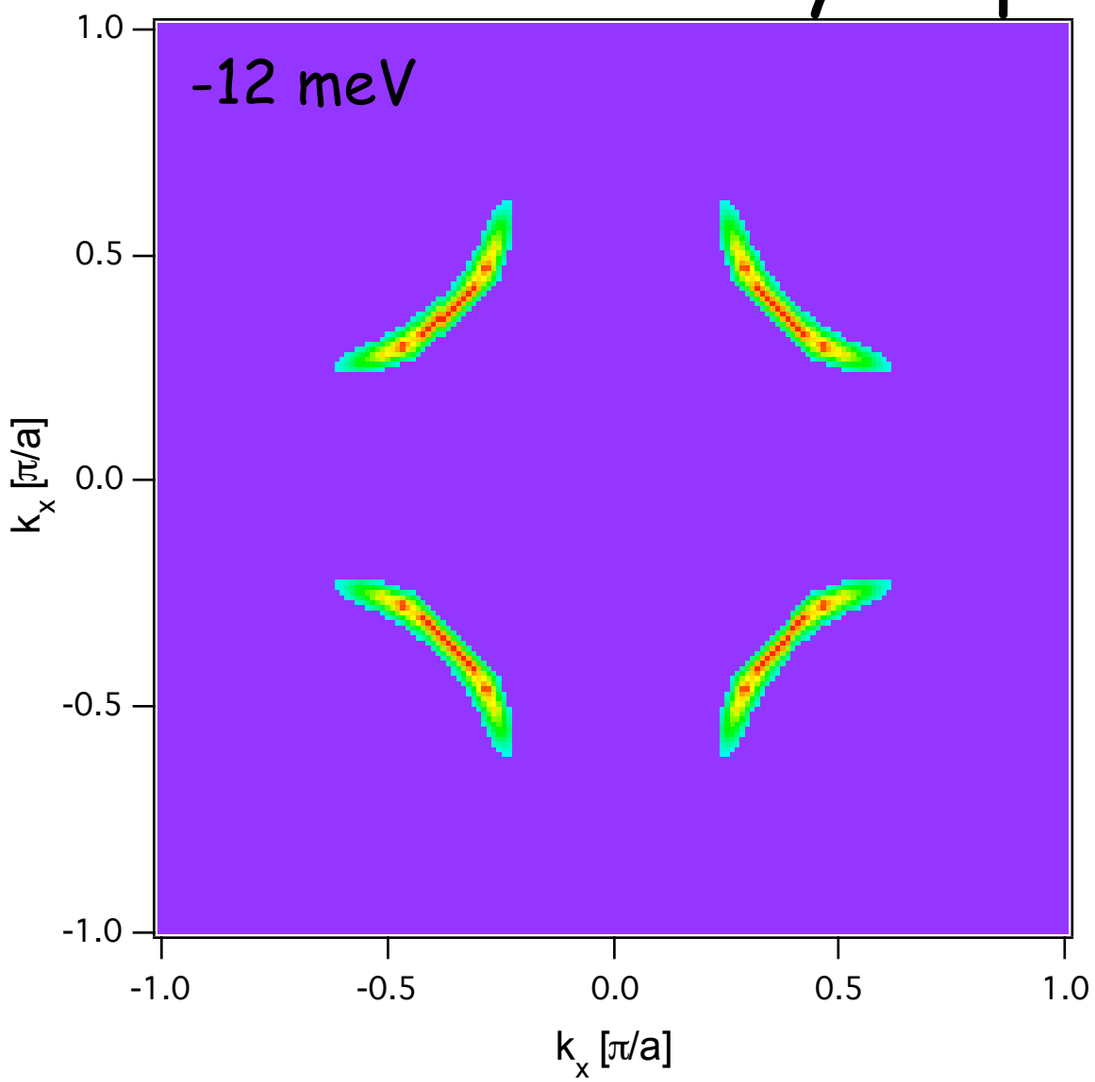
Probe of scattering processes: AutoCorrelated (AC) ARPES

ARPES intensity map



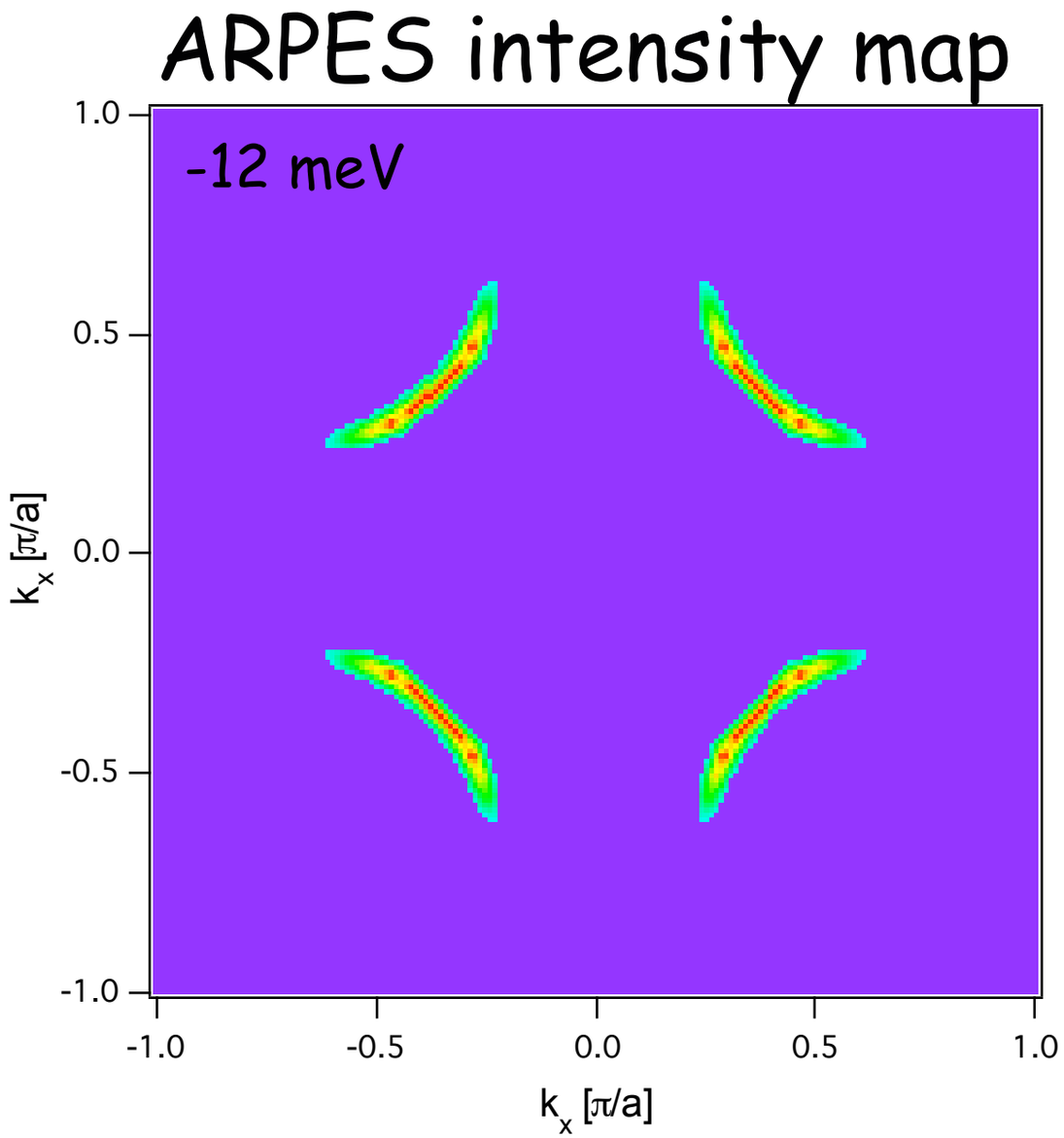
Probe of scattering processes: AutoCorrelated (AC) ARPES

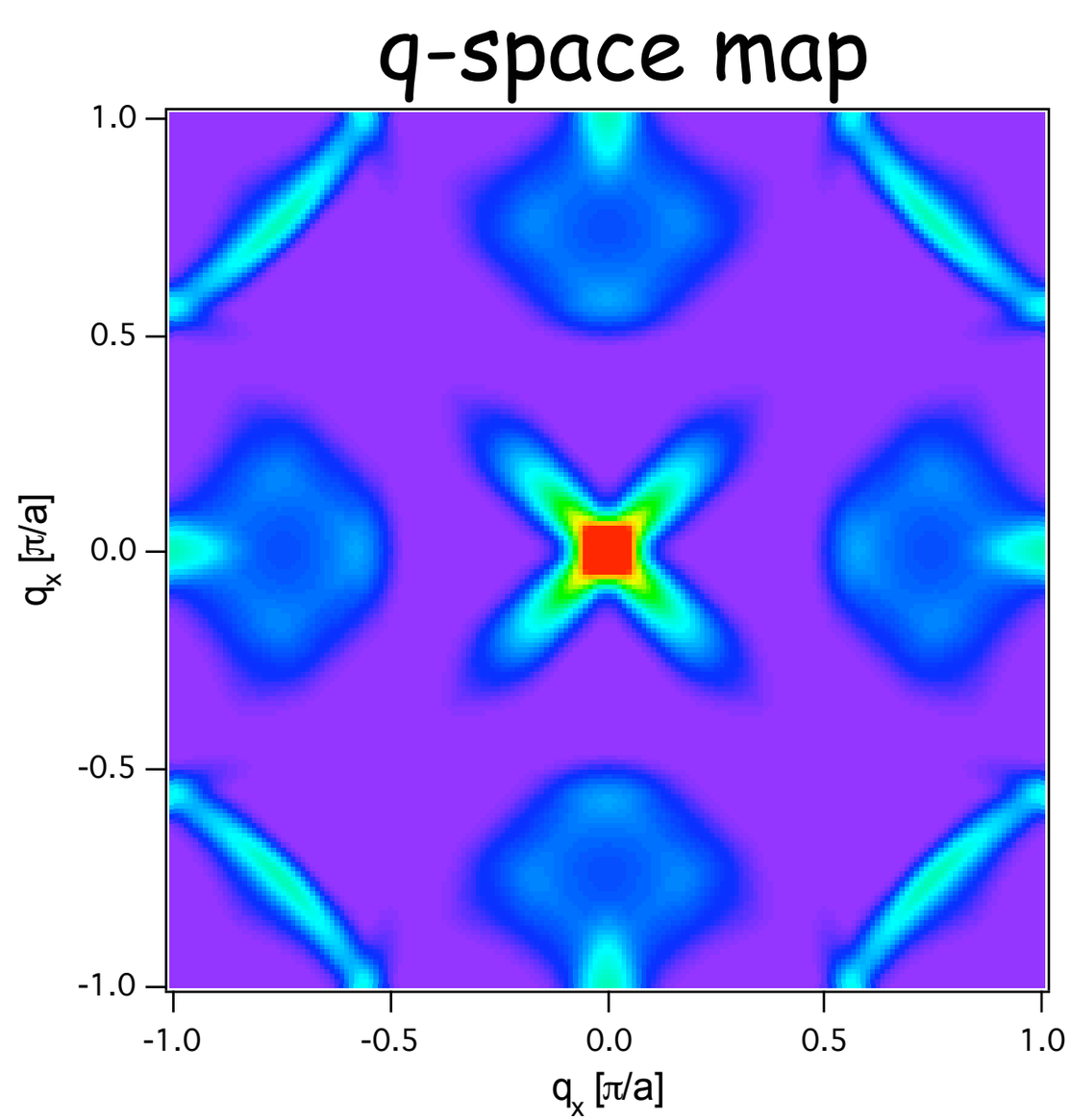
ARPES intensity map



$$S(q,\omega=\omega_0)=\sum_{k_x,k_y} I(k,\omega)\, I(k+q,\omega)$$

Probe of scattering processes: AutoCorrelated (AC) ARPES

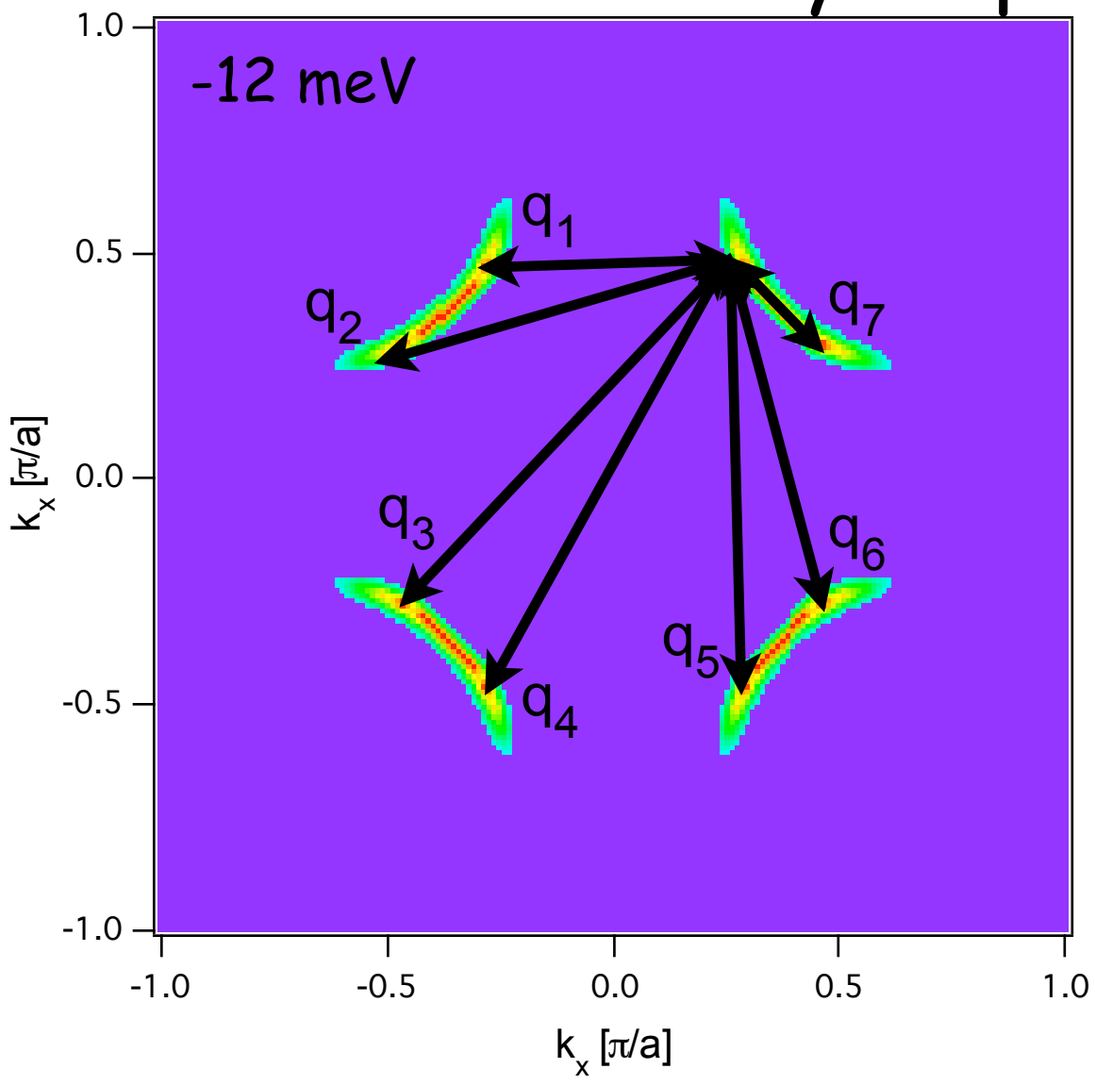




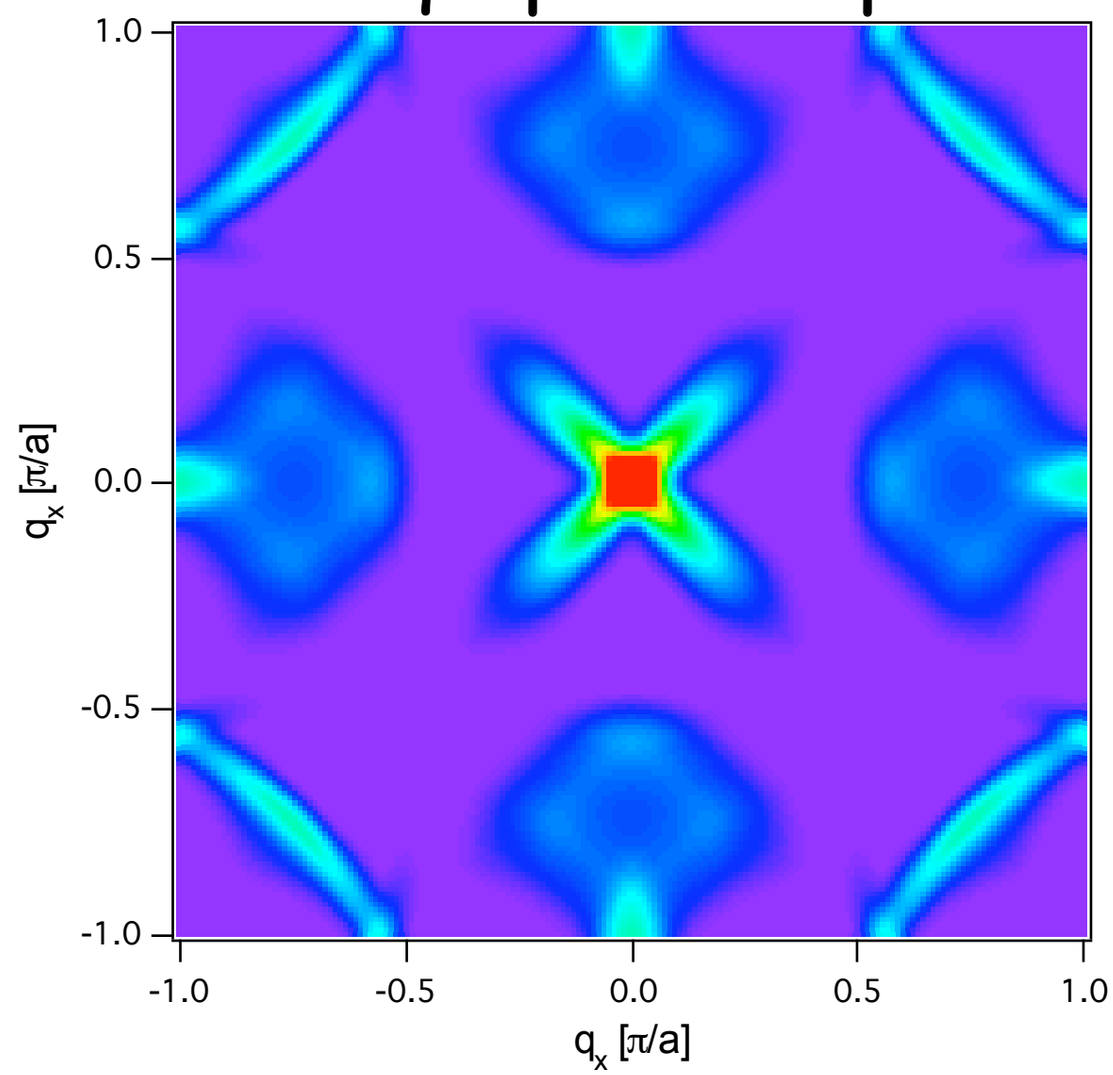
$$S(q,\omega=\omega_0)=\sum_{k_x,k_y} I(k,\omega)\, I(k+q,\omega)$$

Probe of scattering processes: AutoCorrelated (AC) ARPES

ARPES intensity map

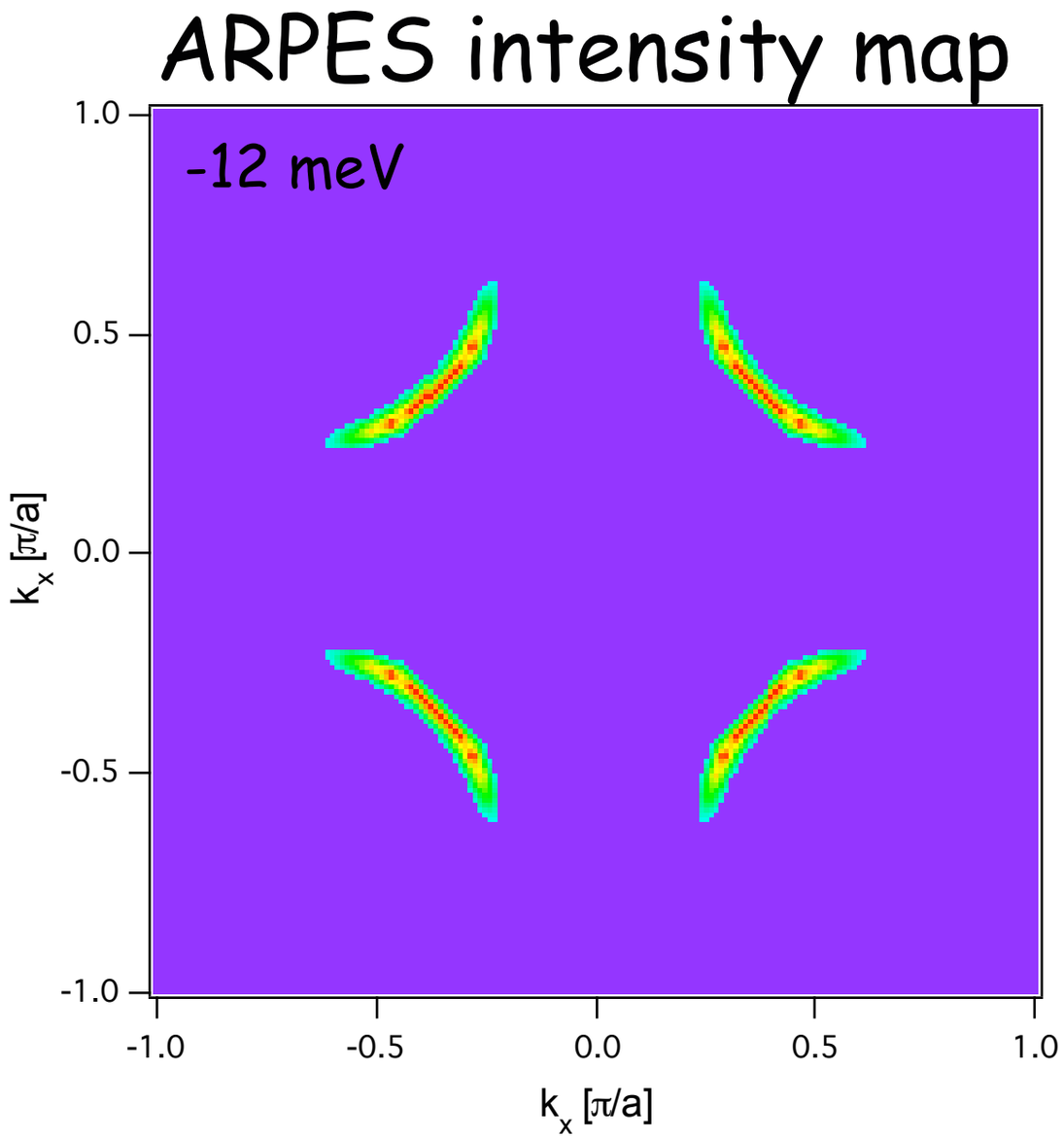


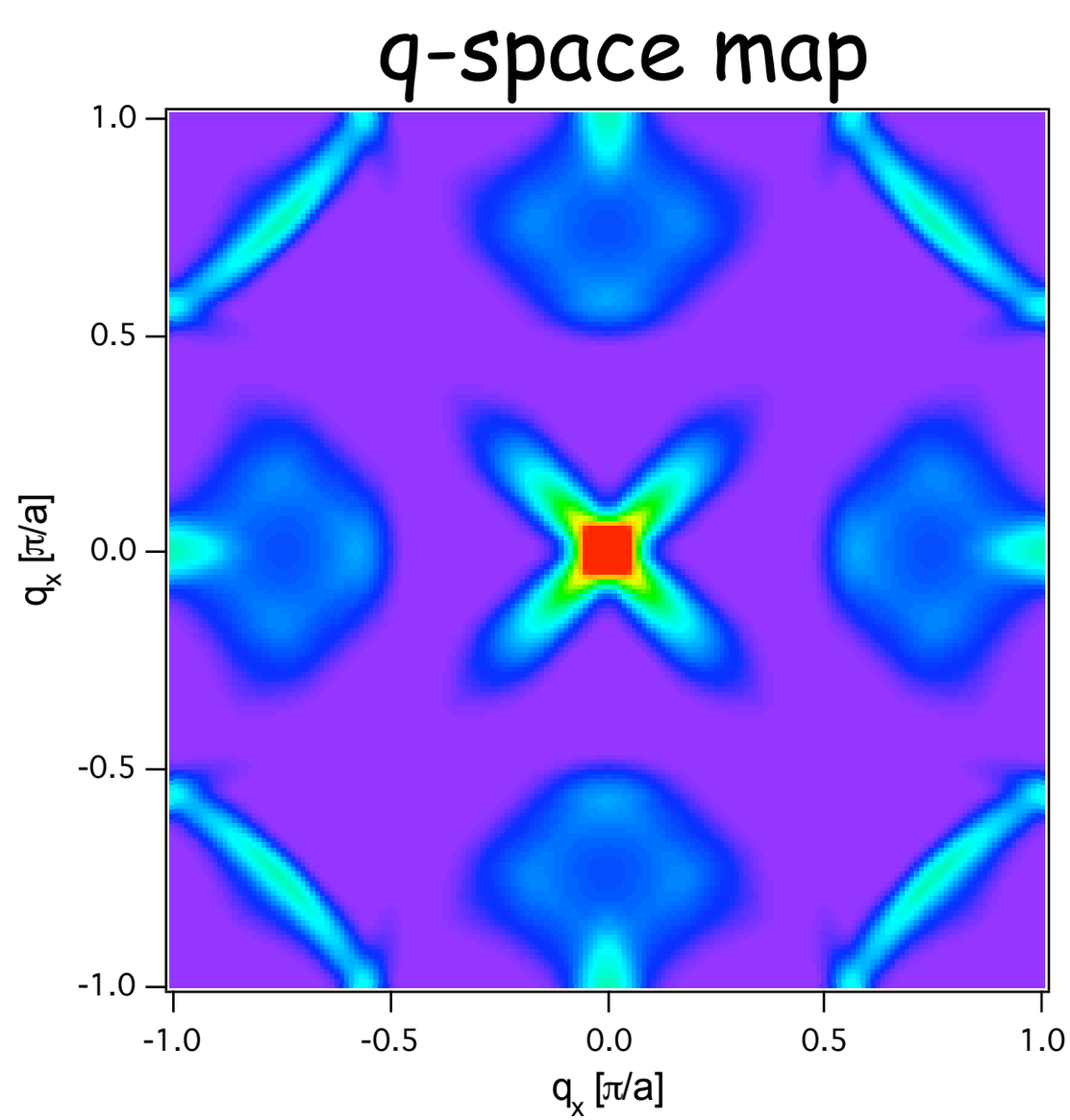
q-space map



$$S(q,\omega=\omega_0)=\sum_{k_x,k_y} I(k,\omega)\, I(k+q,\omega)$$

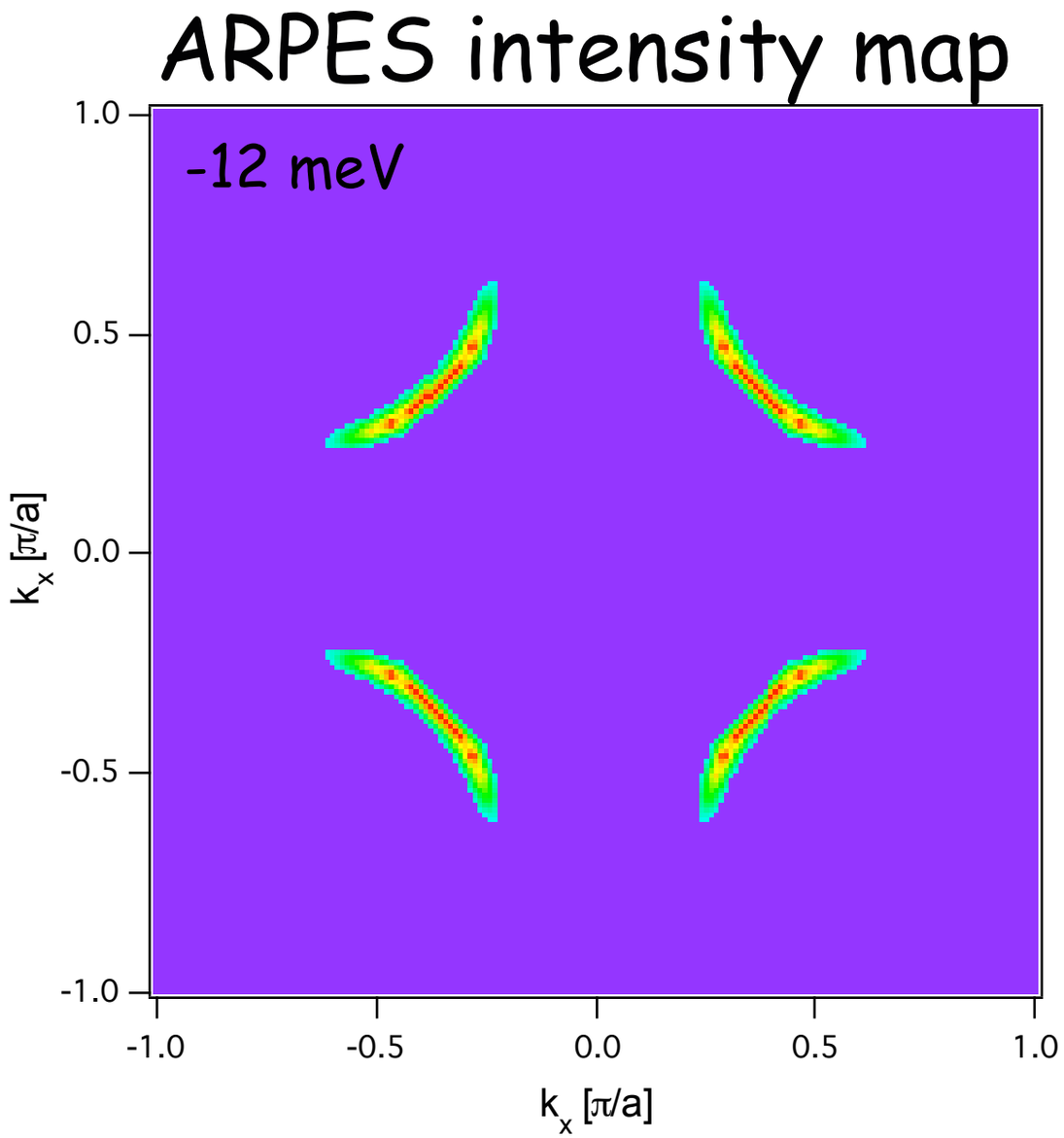
Probe of scattering processes: AutoCorrelated (AC) ARPES

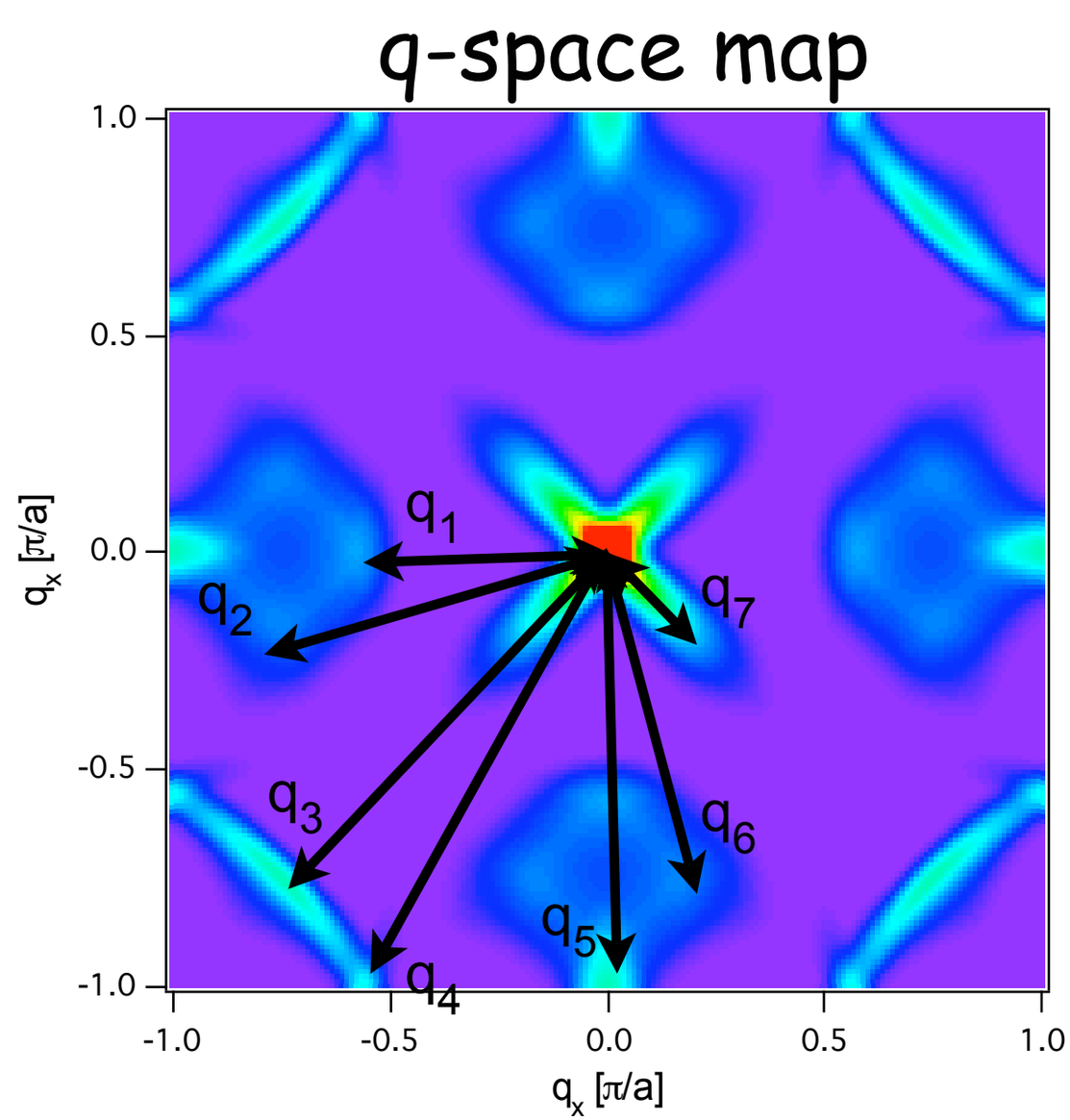




$$S(q,\omega=\omega_0)=\sum_{k_x,k_y} I(k,\omega)\, I(k+q,\omega)$$

Probe of scattering processes: AutoCorrelated (AC) ARPES





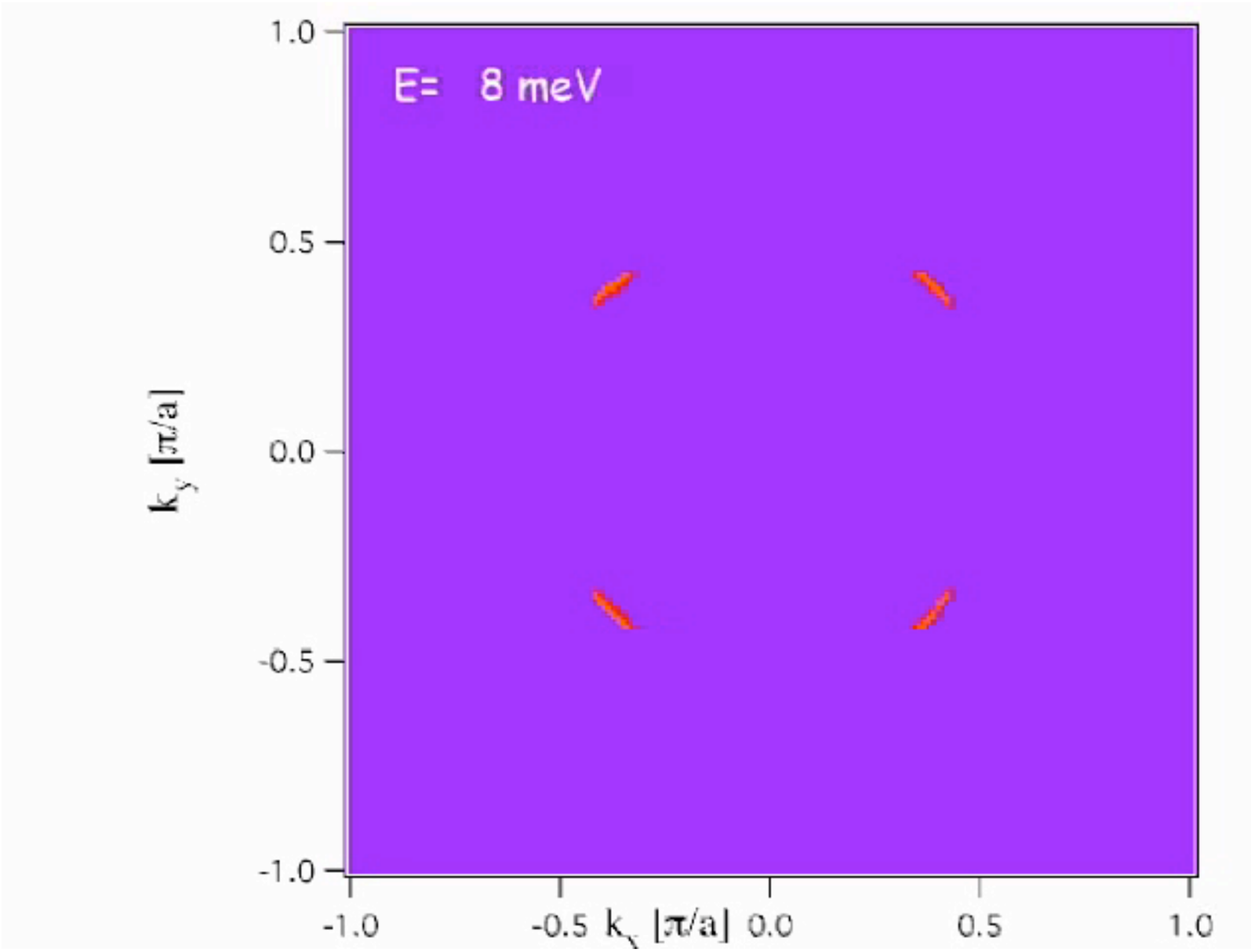
$$S(q,\omega=\omega_0)=\sum_{k_x,k_y} I(k,\omega)\, I(k+q,\omega)$$

Scattering maps

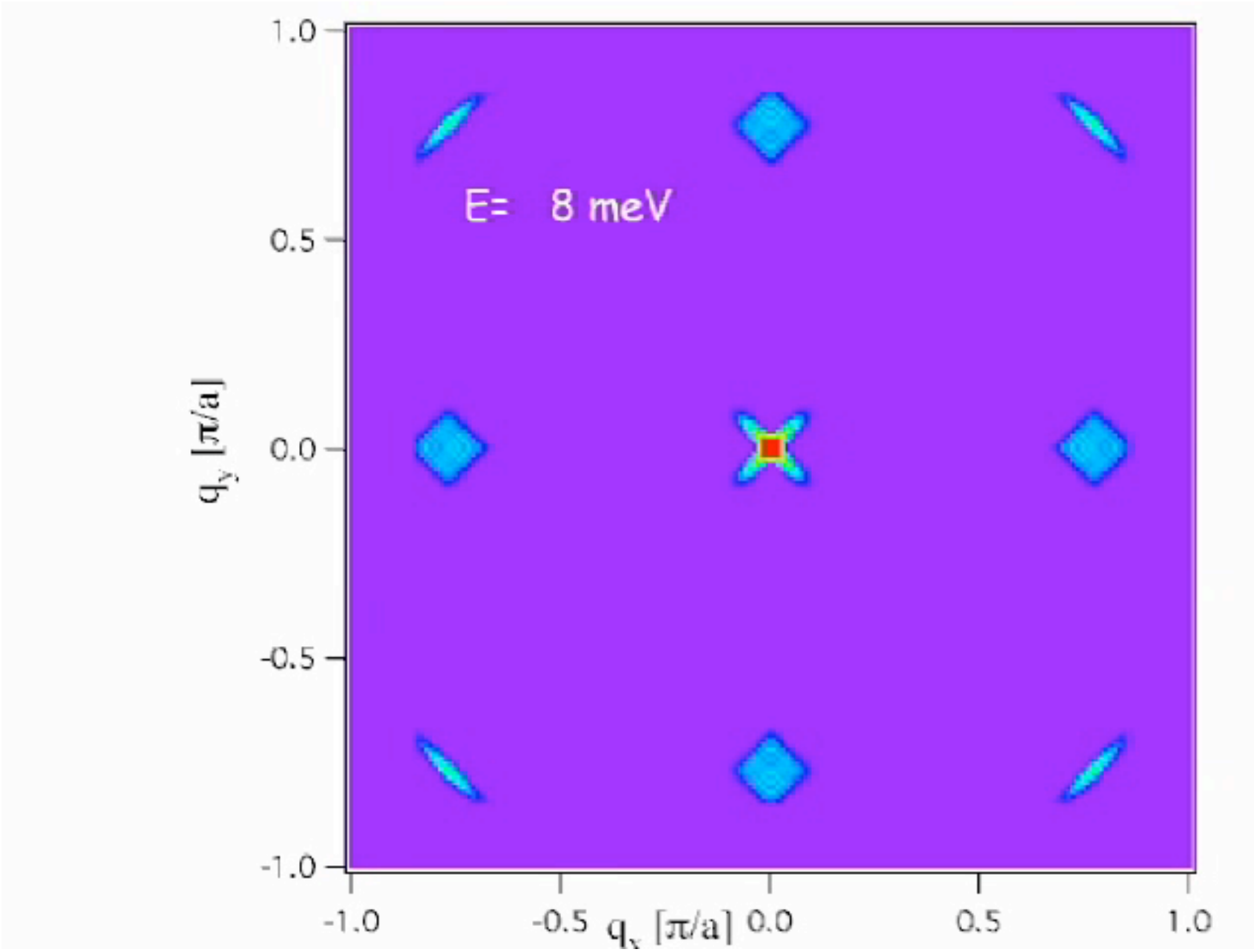
- elastic ($\Omega=0$) - analogous to FT STM

- inelastic ($\Omega\neq0$) - analogous to INS

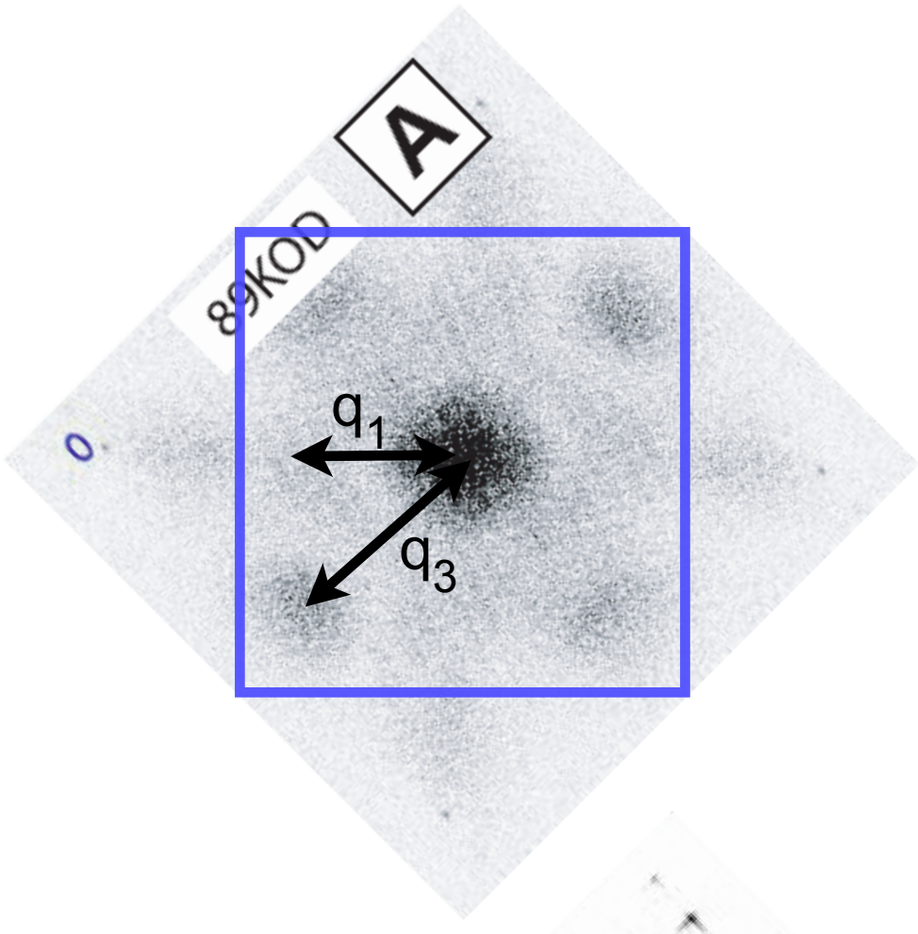
ARPES intensity maps

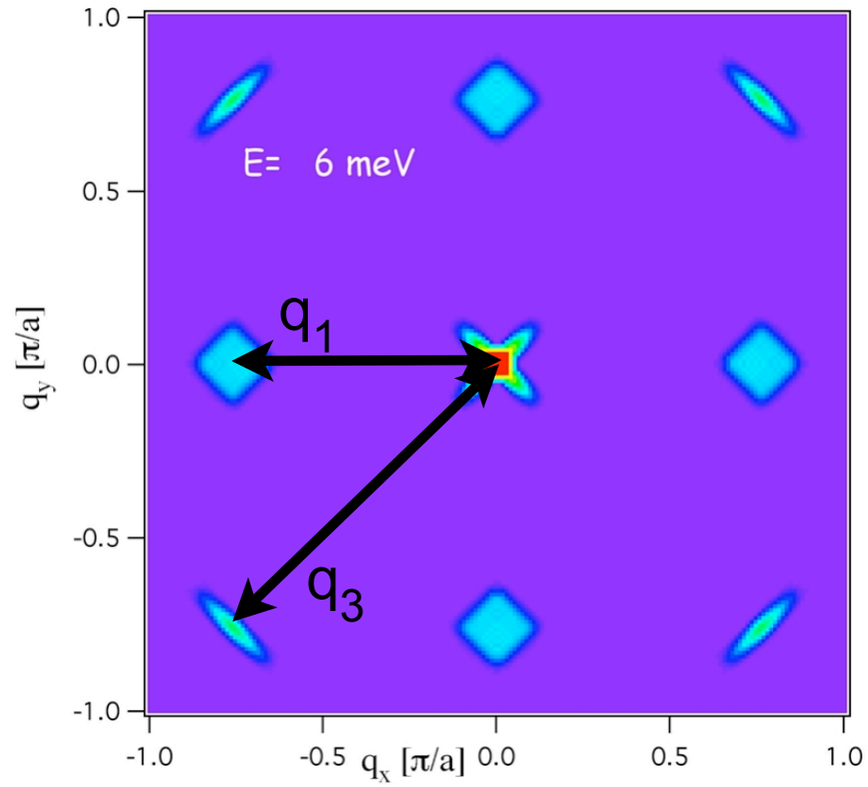


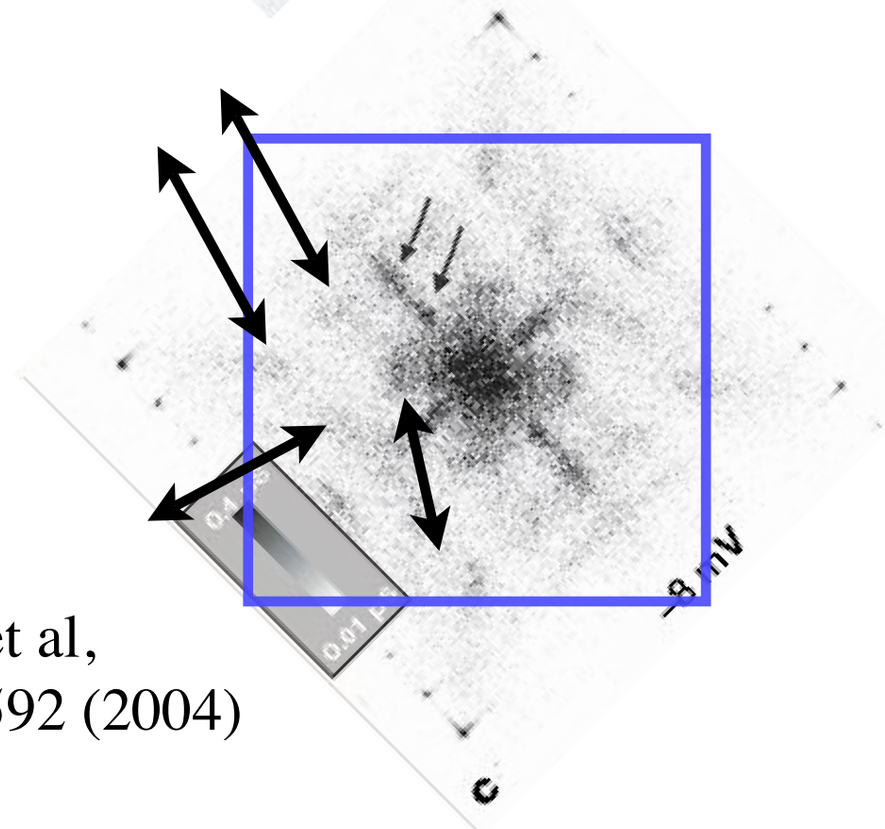
q-space

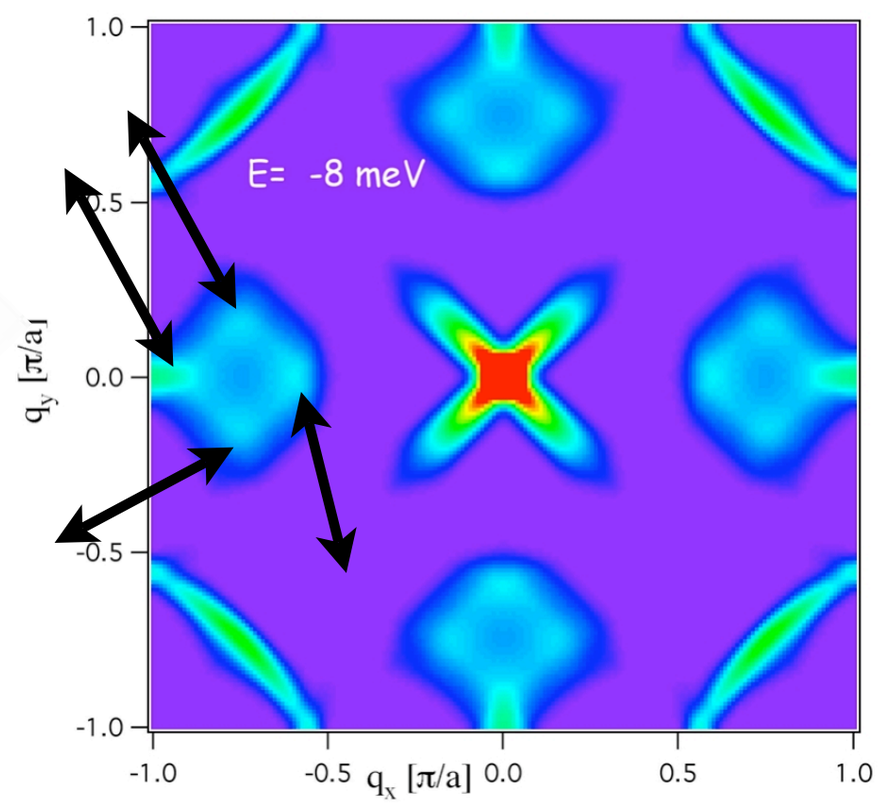


Comparison of FT STM and AC ARPES









K. McElroy et al,
Nature **422**, 592 (2004)