High temperature superconductivity - insights from Angle Resolved Photoemission Spectroscopy

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IOWA STATE UNIVERSITY

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Funding:

Ames Laboratory - US Department of Energy

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Outline:

- condensed matter physics - is there anything left to understand?

- properties of conventional and “high temperature” superconductors

- introduction to Angle Resolved Photoemission Spectroscopy

- electronic properties of high temperature superconductors

- new results

condensed matter physics - is there anything left to understand?

all physics covered by electrodynamics + quantum mechanics

... but complexity and new phenomena arise from large numbers of interacting particles

US penny: 3.1 grams of copper, 2.9×10^{22} electrons

a DVD has 4×10^{10} bits

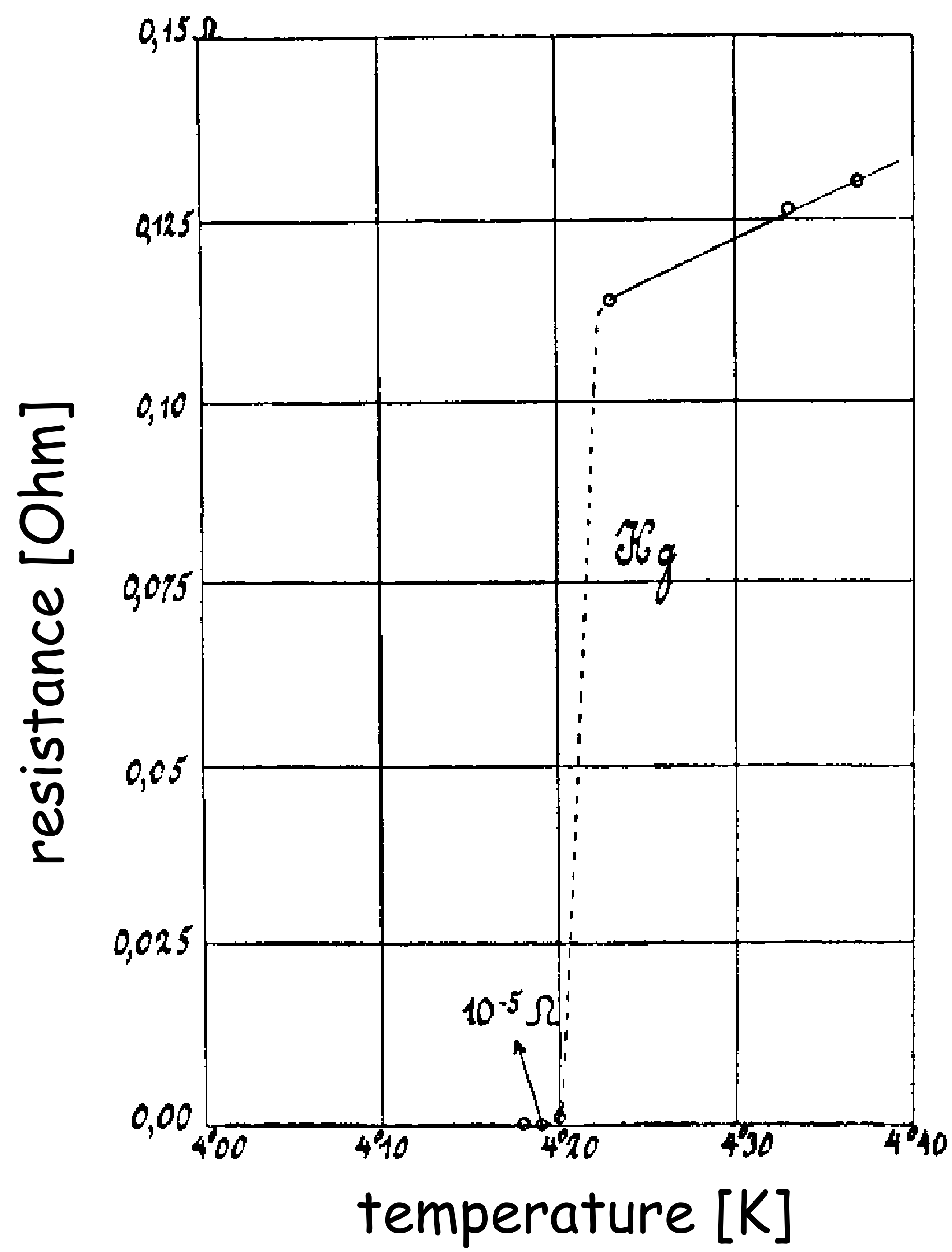
so to store information only about spin for each electron we need: 7.25×10^{11} DVD's, but this is clearly not enough to do any meaningful calculations

fortunately electrons in copper are weakly interacting and can be described by Landau Fermi Liquid model (1:1 correspondence with free electron gas), but in many systems the interactions are strong and current state of the art calculations can deal with ... 7x7 lattice

Superconductivity

Discovered in 1911 by Kamerlinght Onnes first in mercury, then many other metals and alloys

Complete theory (BCS) due to Bardeen, Cooper and Schrieffer in 1957



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Superconductivity

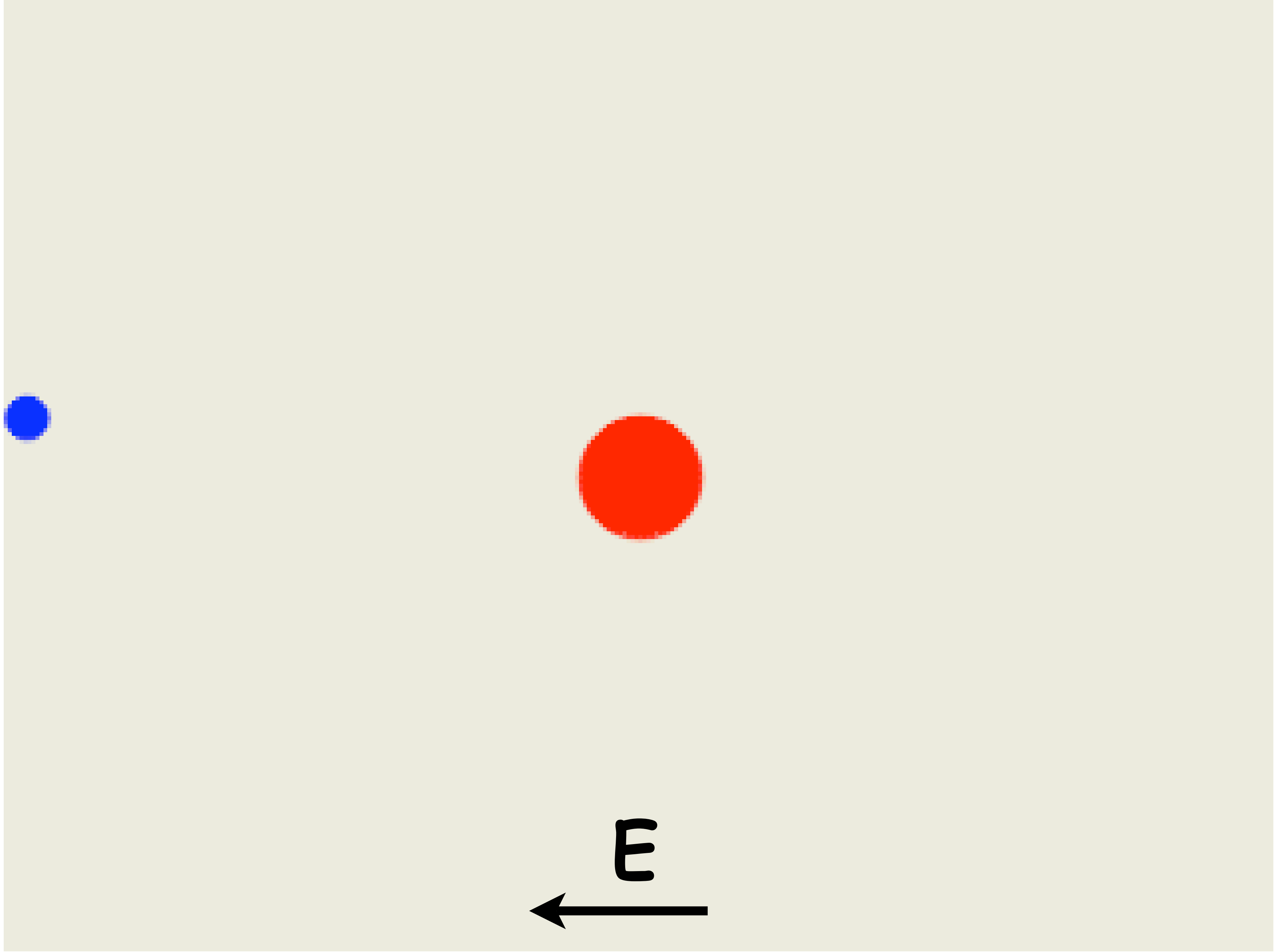
↕

pairing + condensation

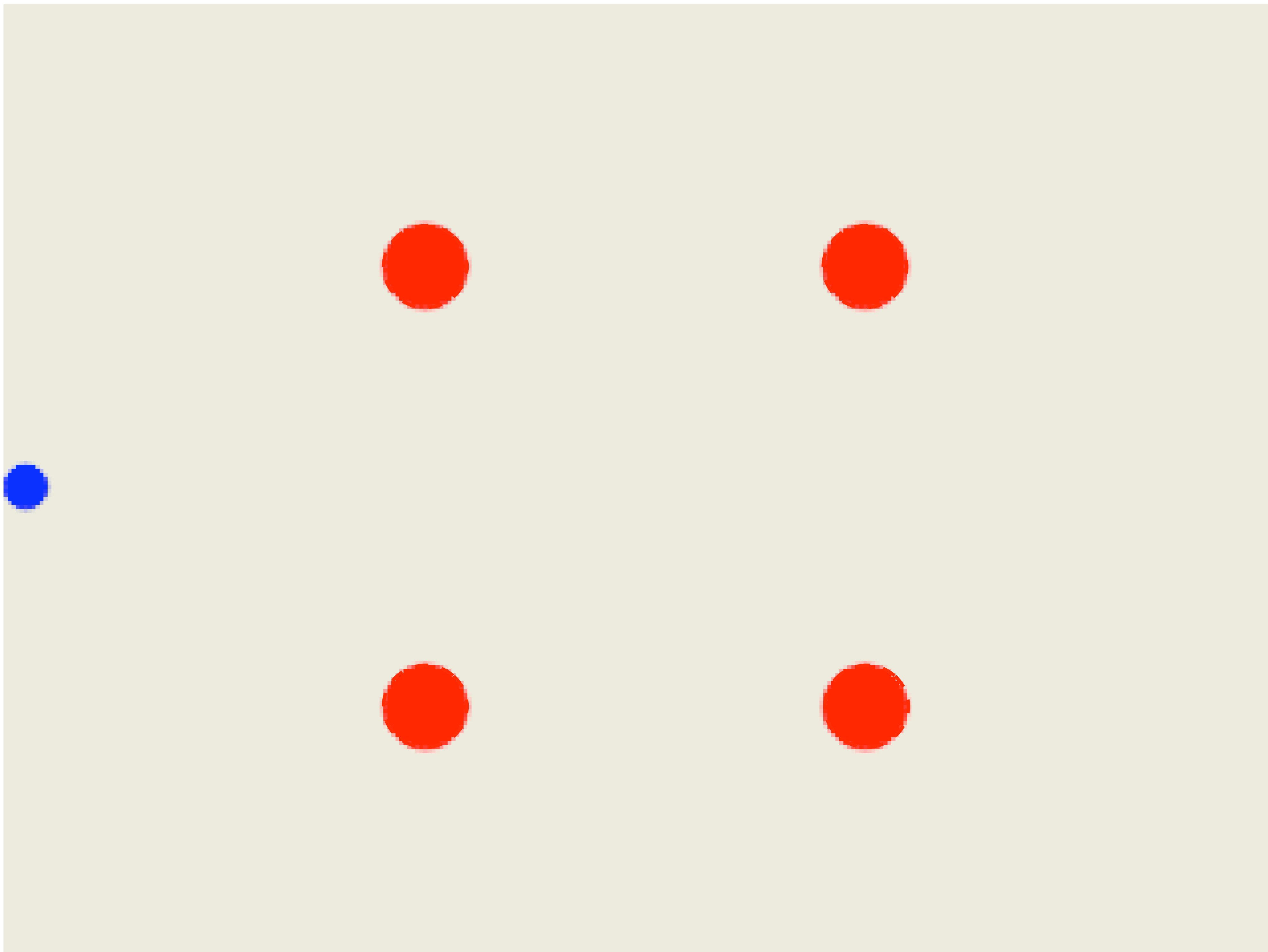
pair of two electron is a boson

bosons can condense creating superfluid

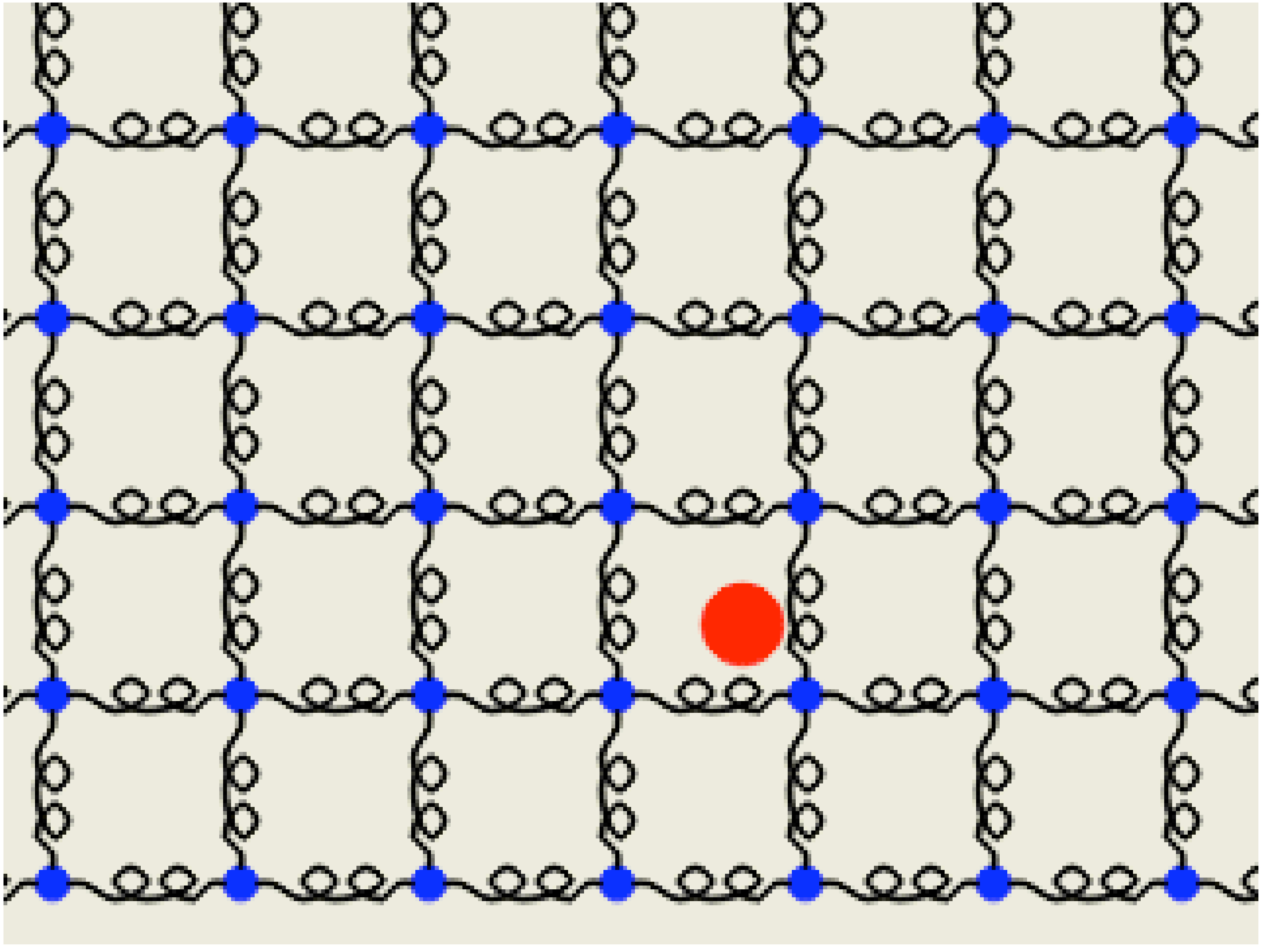
In the metals electrical resitance arises due to scattering of the conduction electrons from defects



In BCS the attractive pairing interaction between electrons arises from interaction with the lattice vibrations (phonons)



In the superconducting state current is being carried by superfluid - condensate of very large number of electron pairs



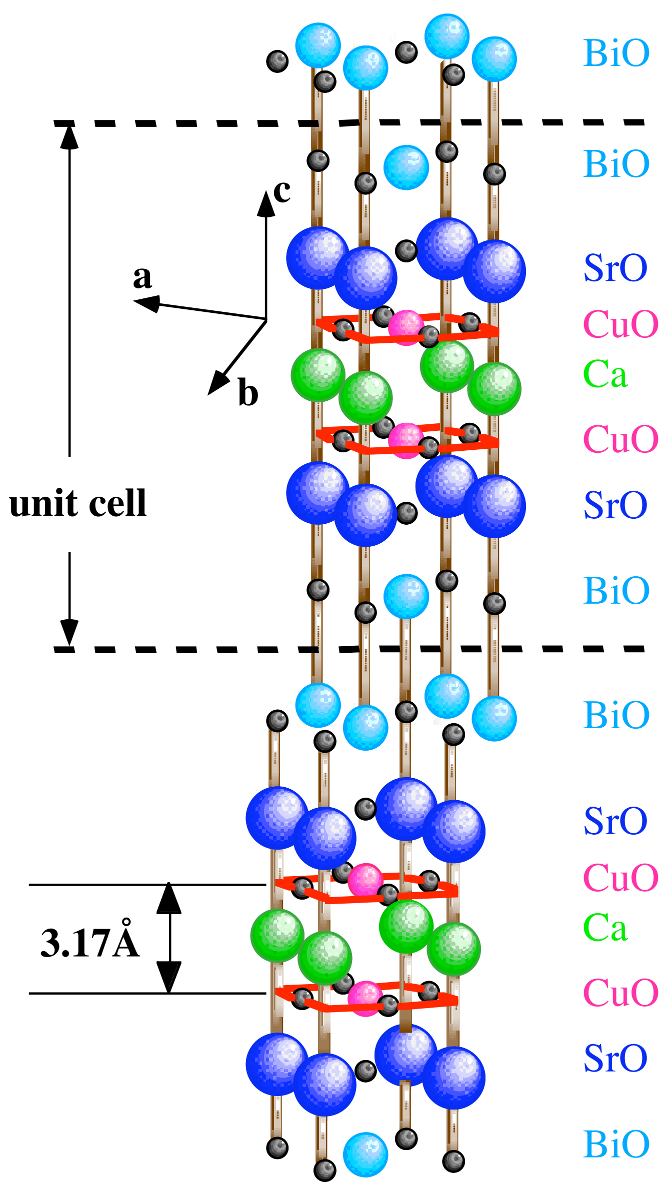
High temperature superconductors

Discovered in 1986 by Bednorz and Müller.

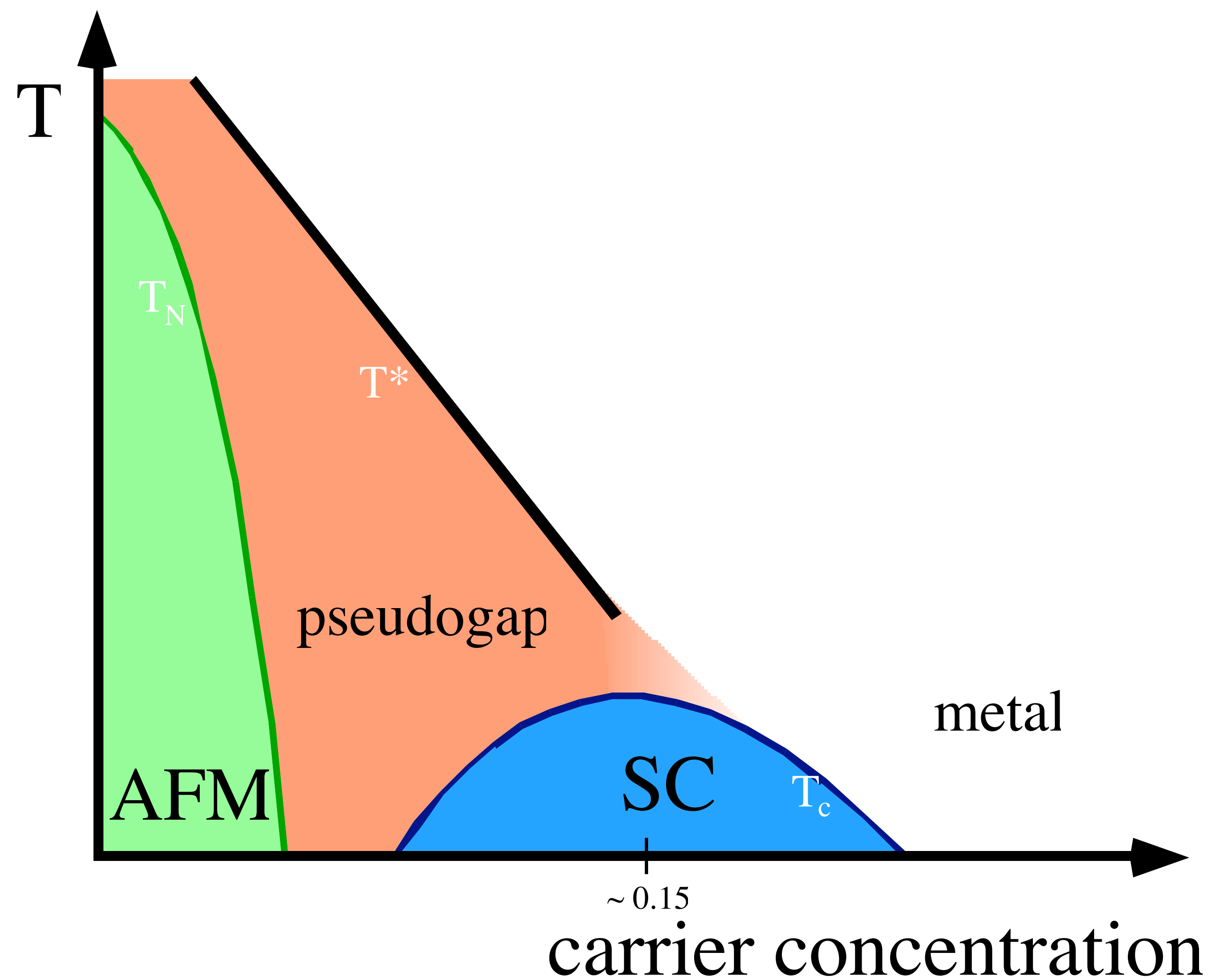
Observed so far only in materials that contain copper oxide.

Superconducting transition temperature (Tc) up to 130K.

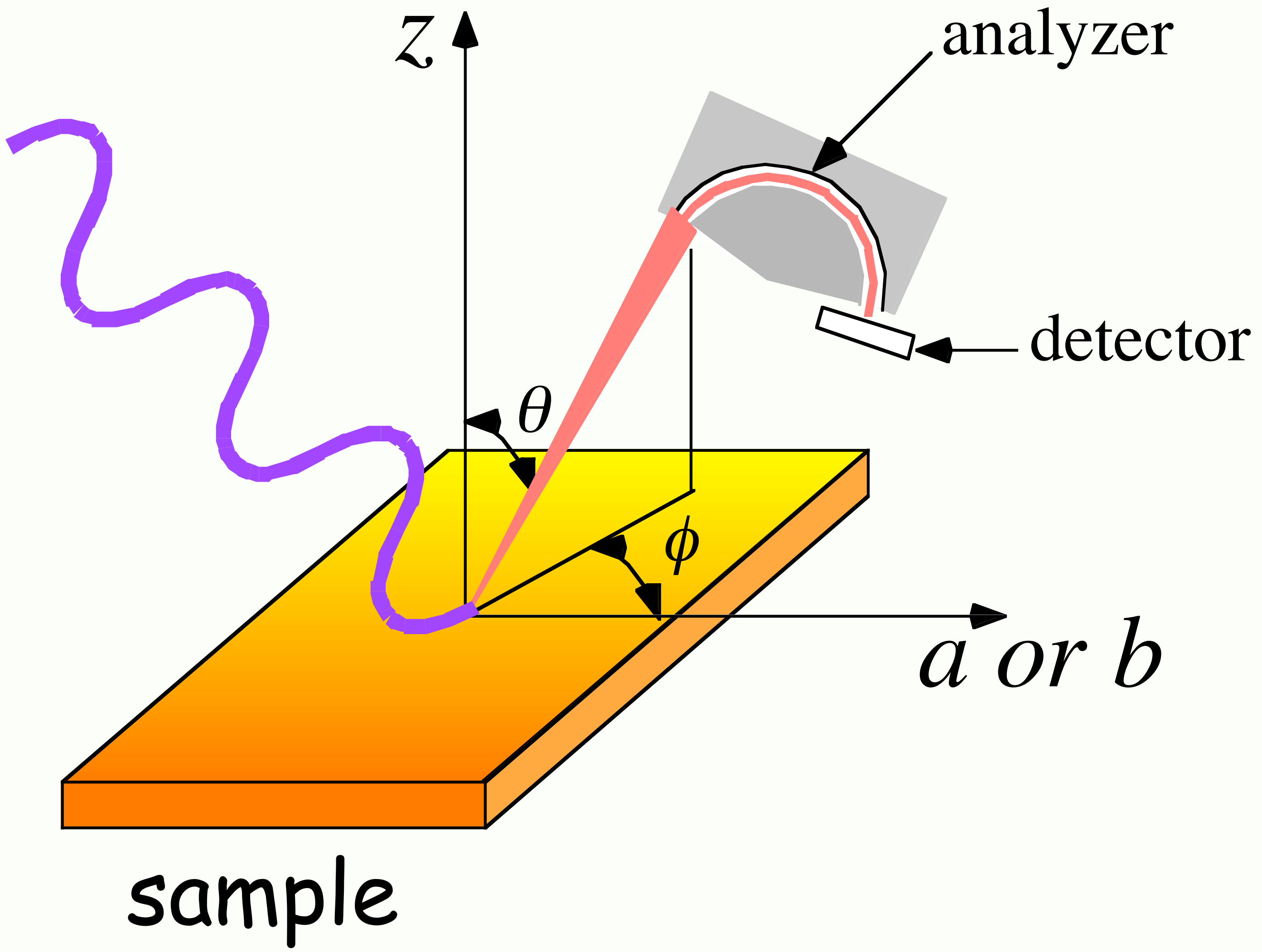
Pairing mechanism - unknown



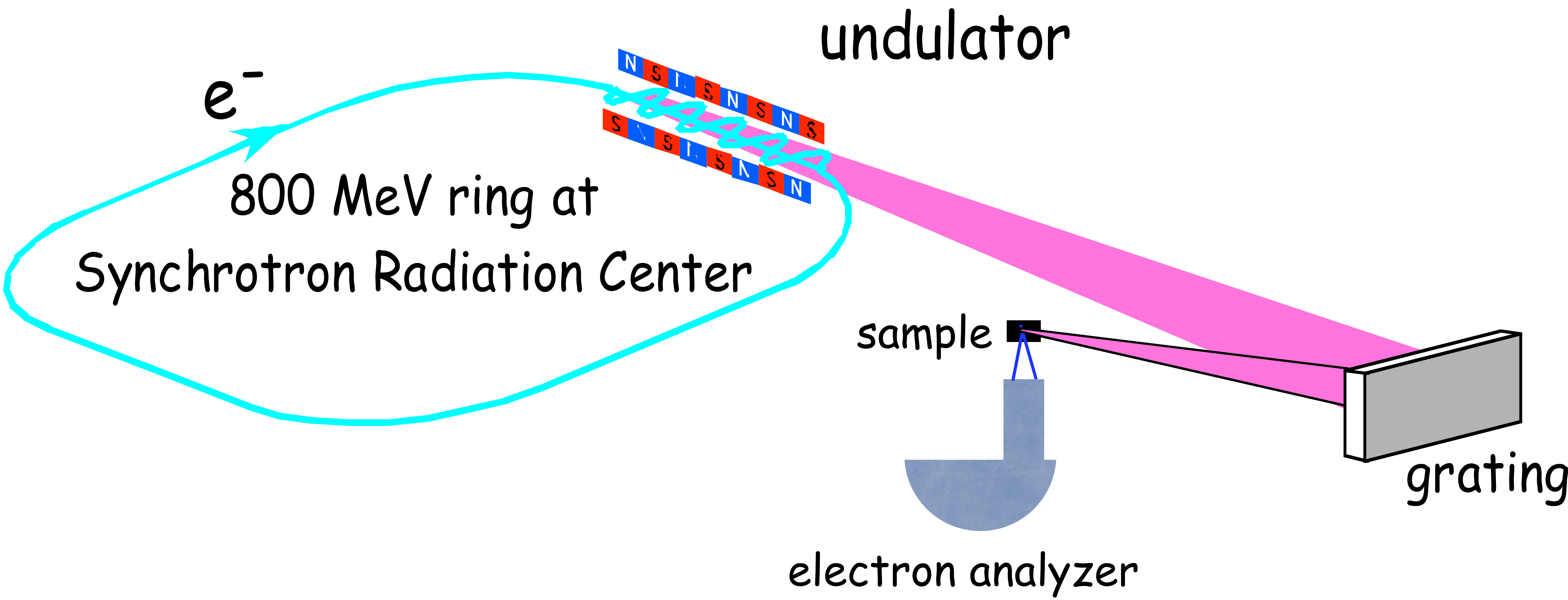
$Bi_2Sr_2CaCu_2O_{8+x}$



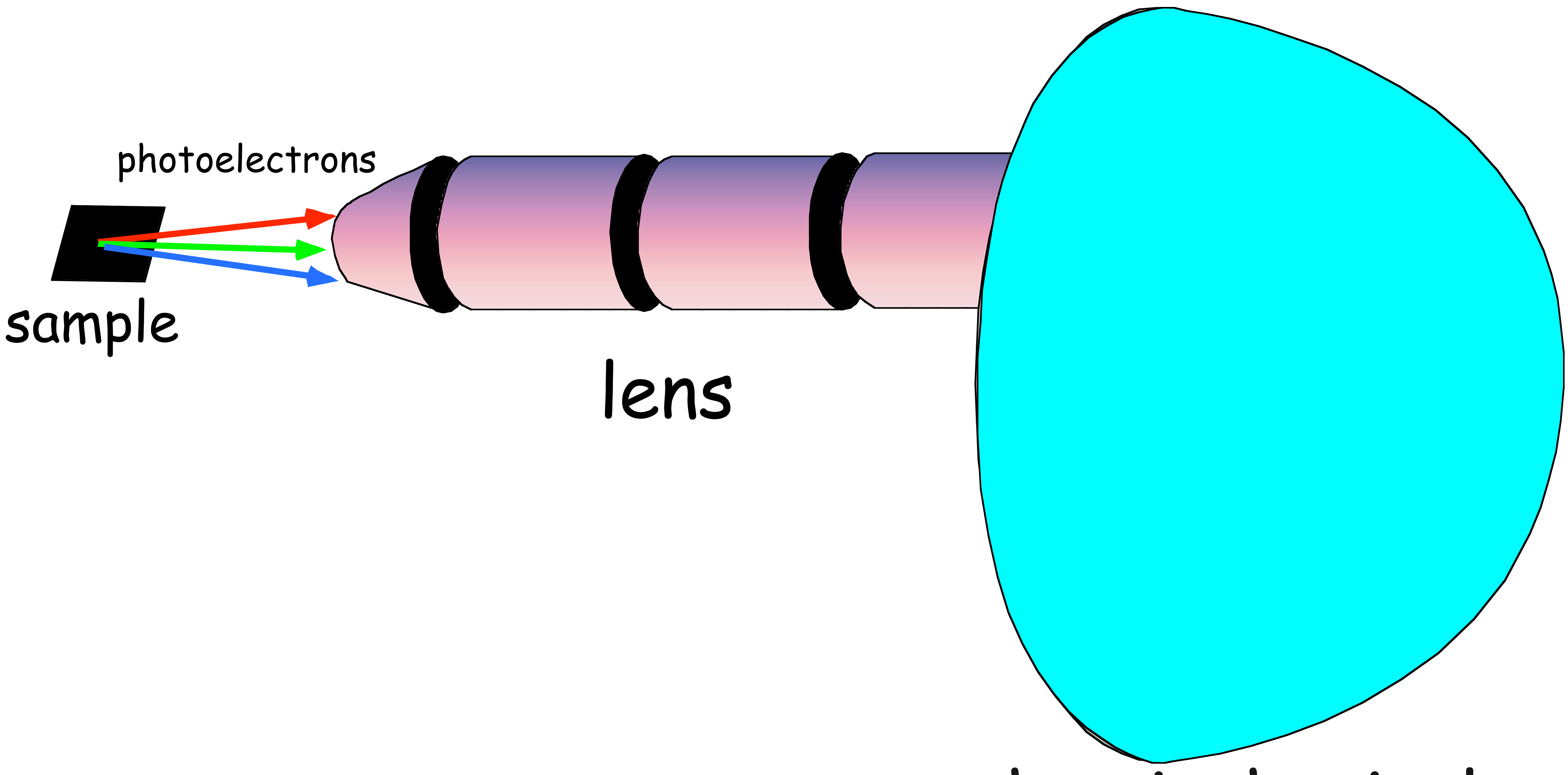
ARPES experiment



High resolution UV beamline at Synchrotron Radiation Center, Wisconsin



Electron analyzer

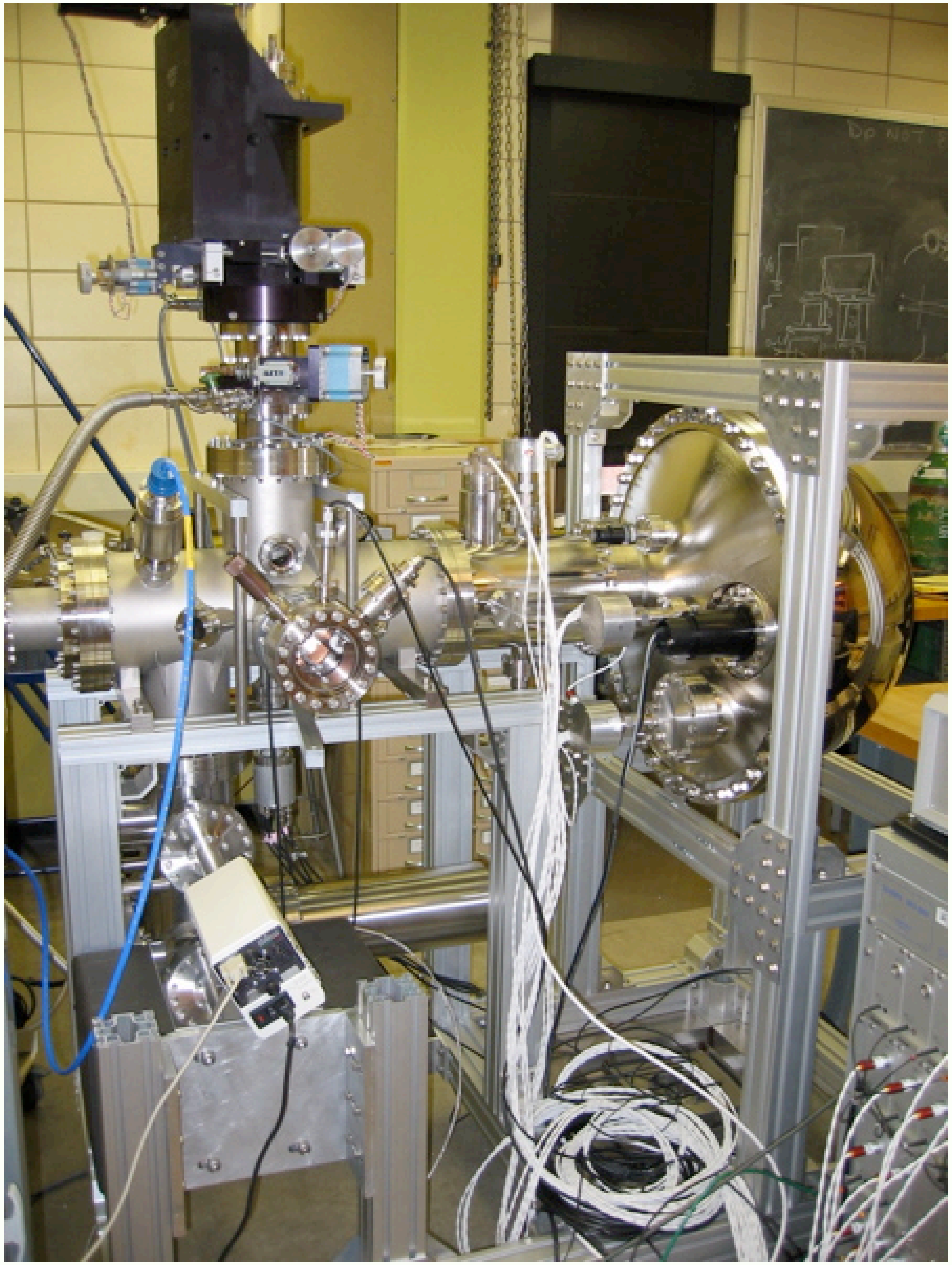


… high precision lab-based ARPES system

Energy resolution:
~1.2 meV

Angular resolution:
0.1 deg.

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



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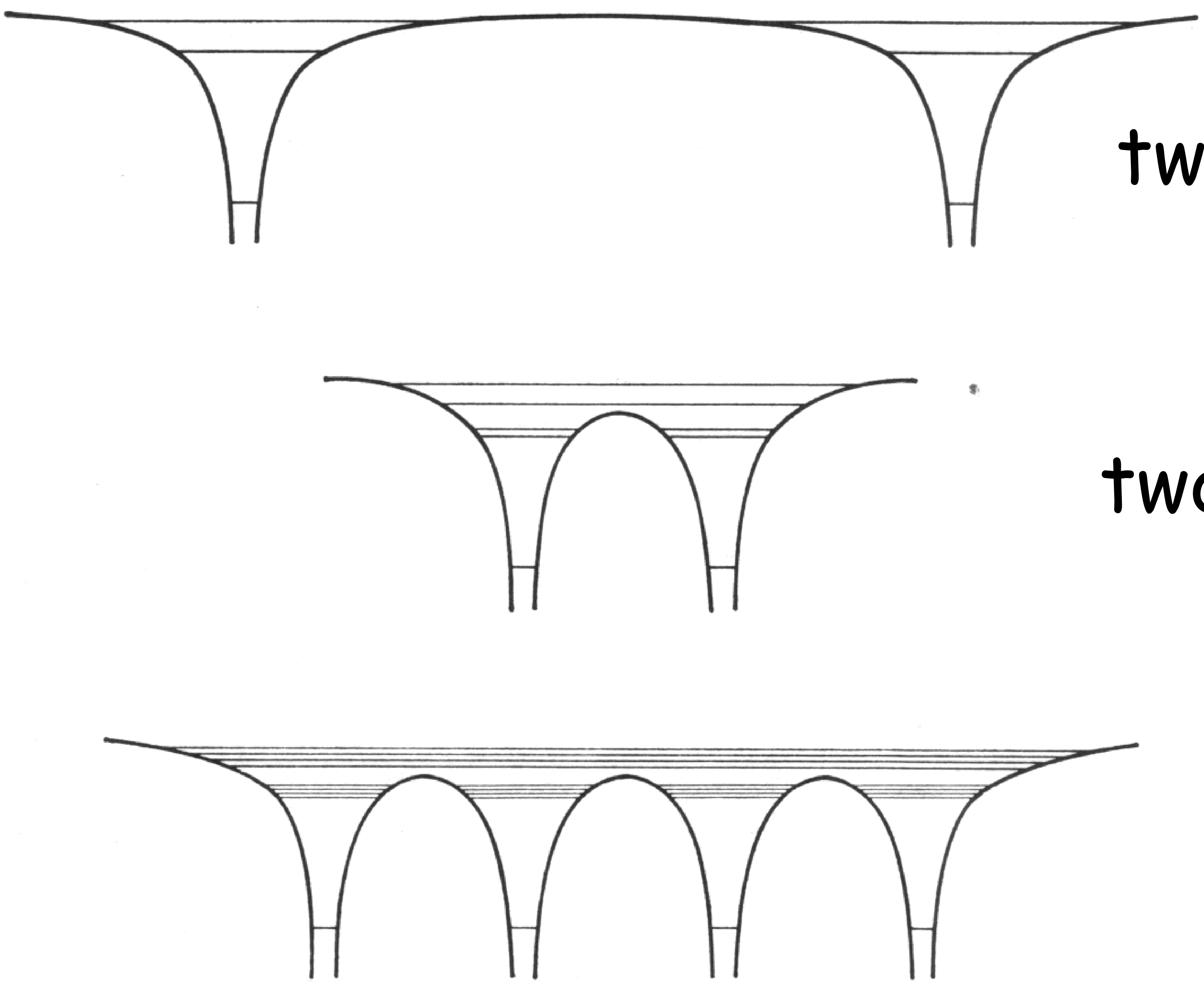
From atoms to solids:



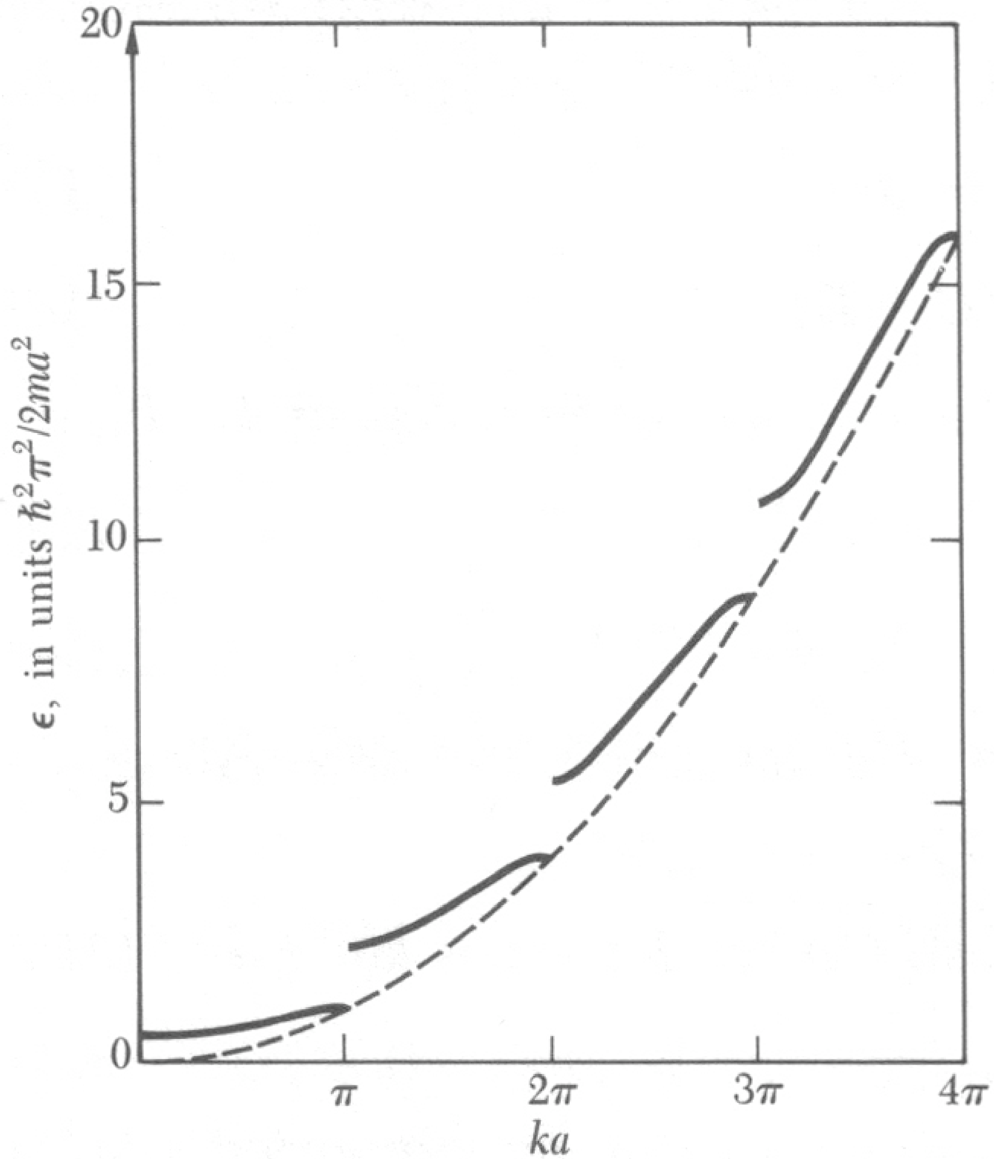
two isolated atoms

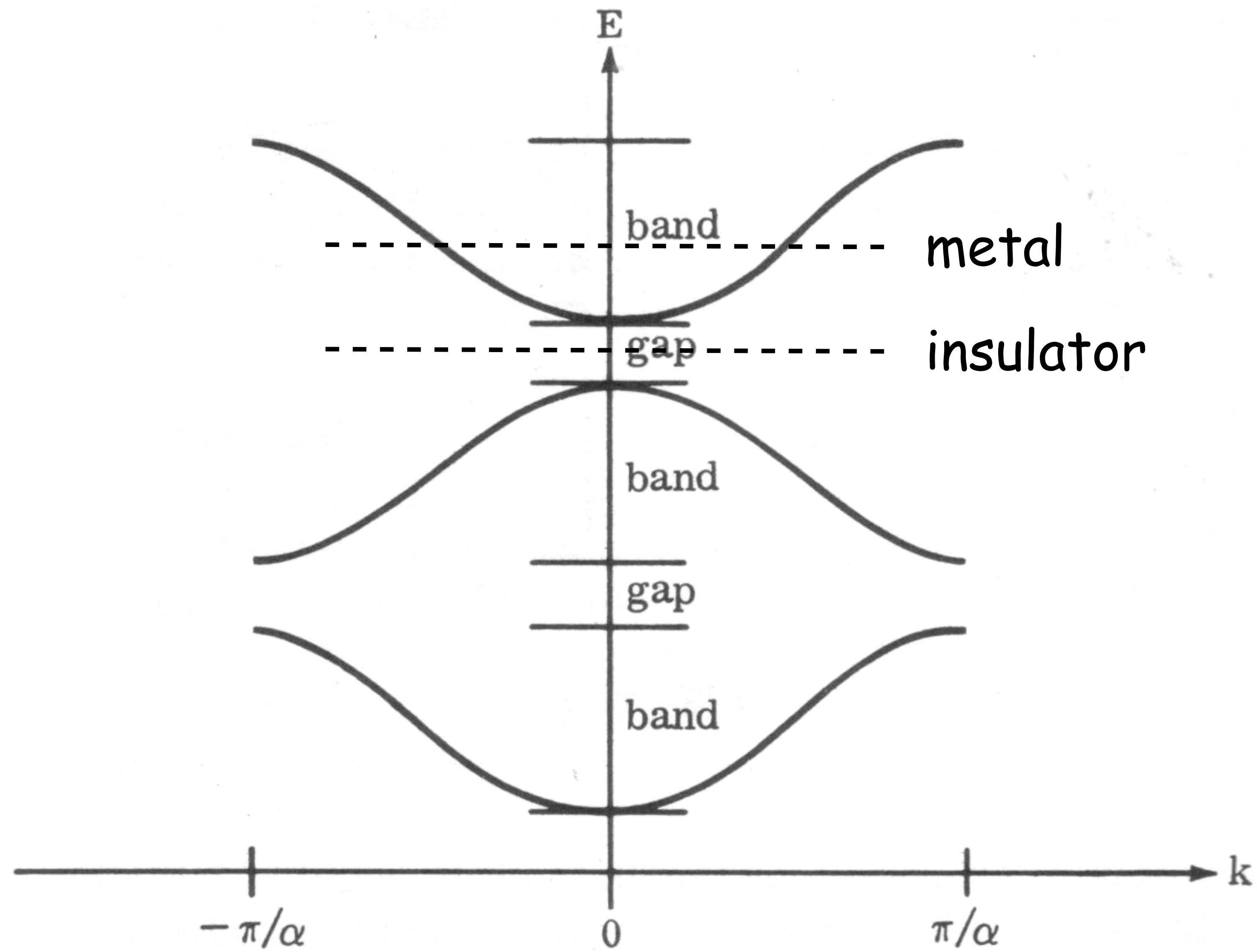
two atom molecule

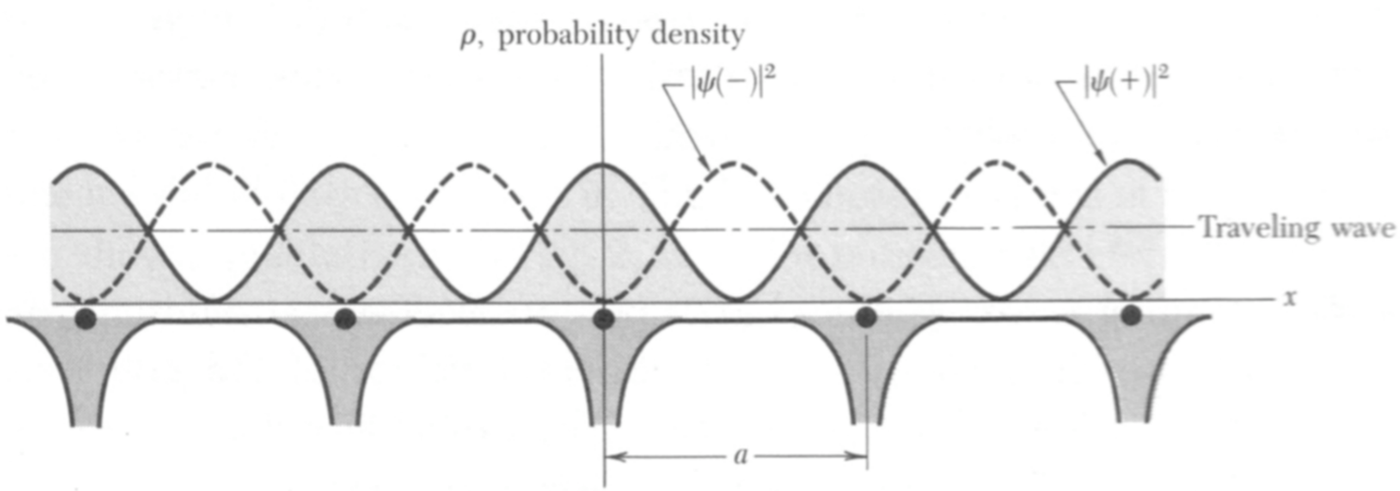
solid

Kittel - "Solid state physics"

Dispersion relation - energy bands







Kittel - “Solid state physics”

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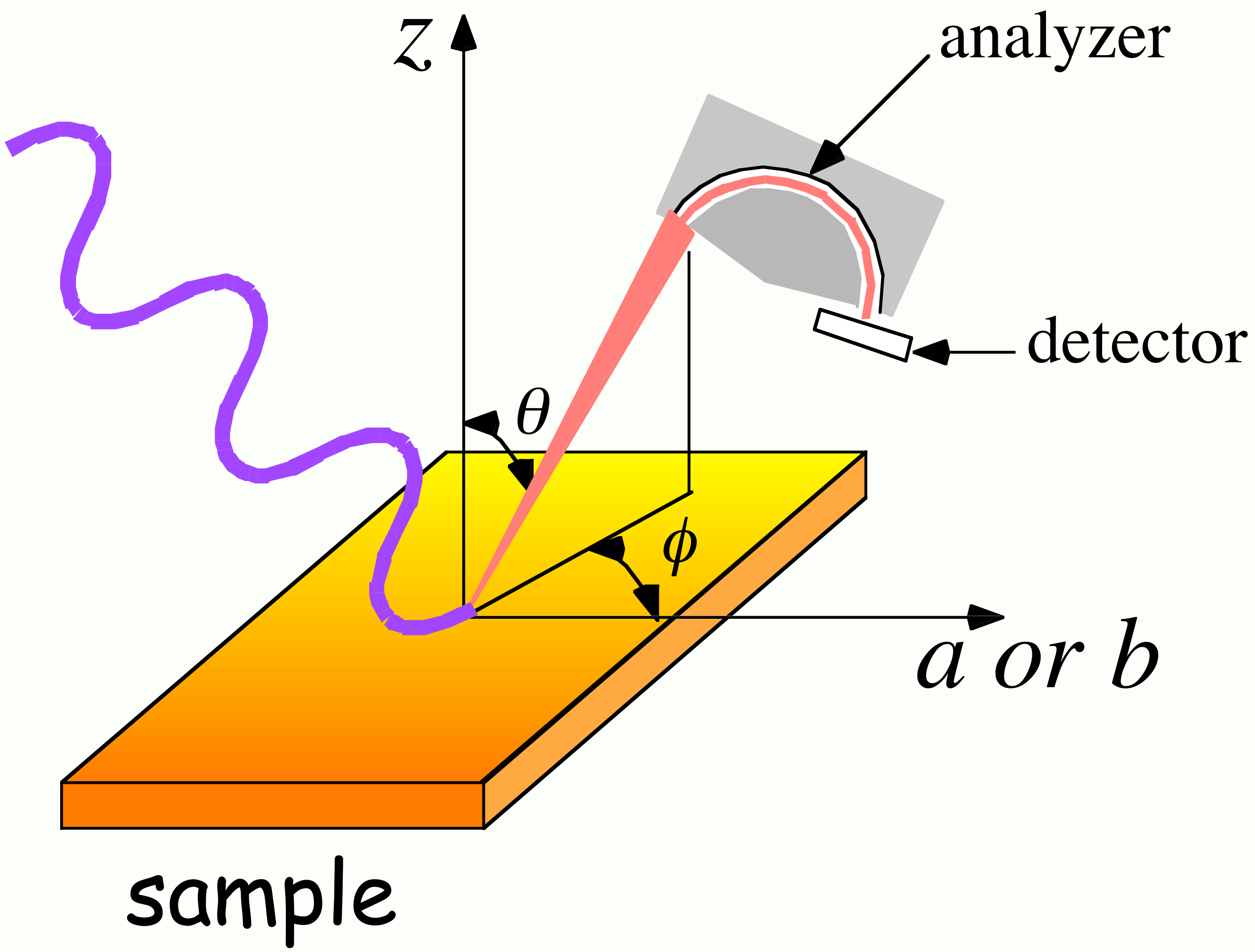
ARPES experiment



We need:

binding energy - E_b

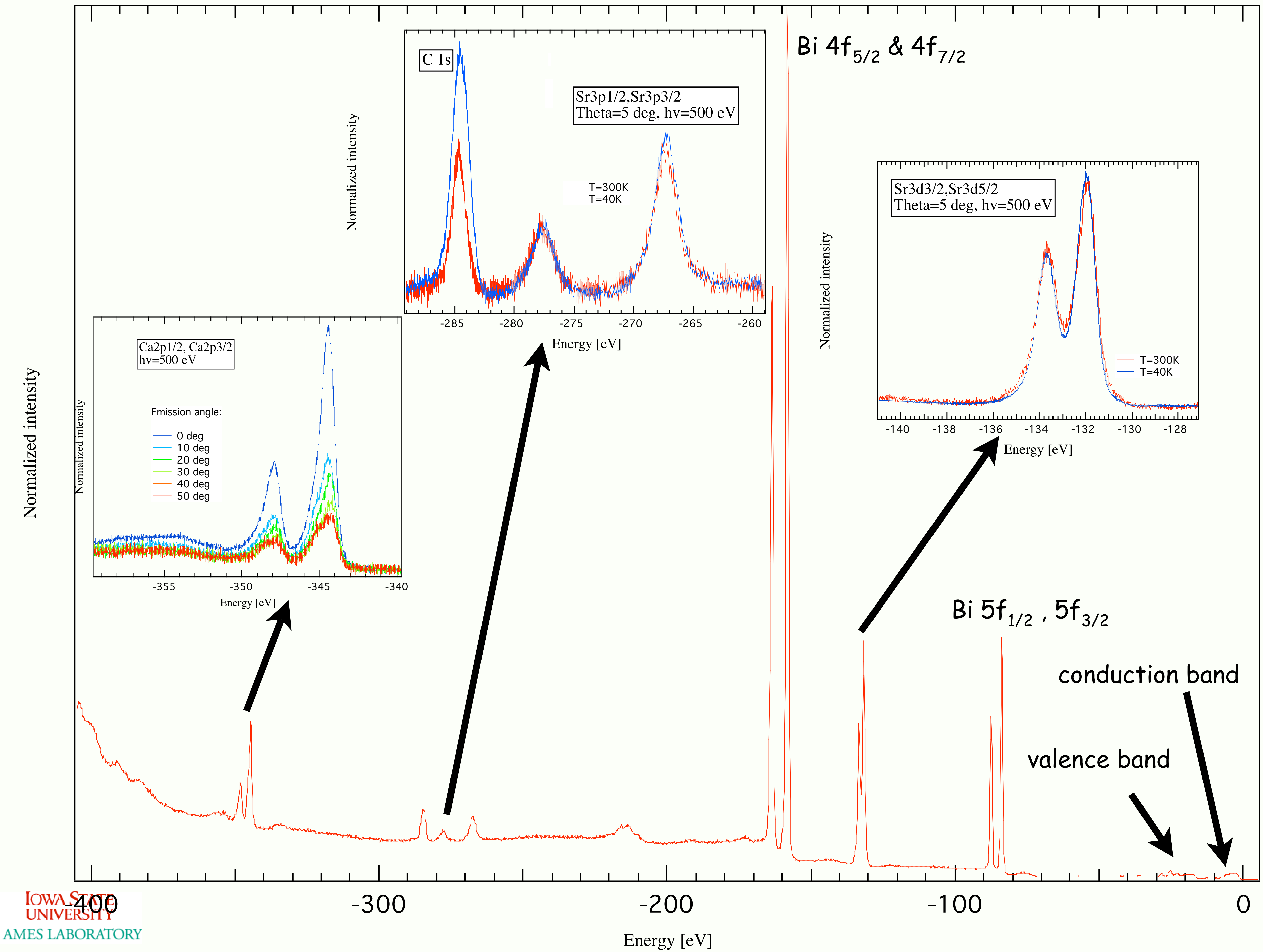
initial momentum - k^i

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

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

$k^i_{\perp} = 0$ for quasi 2D samples

typical photoemission spectrum from Bi2212



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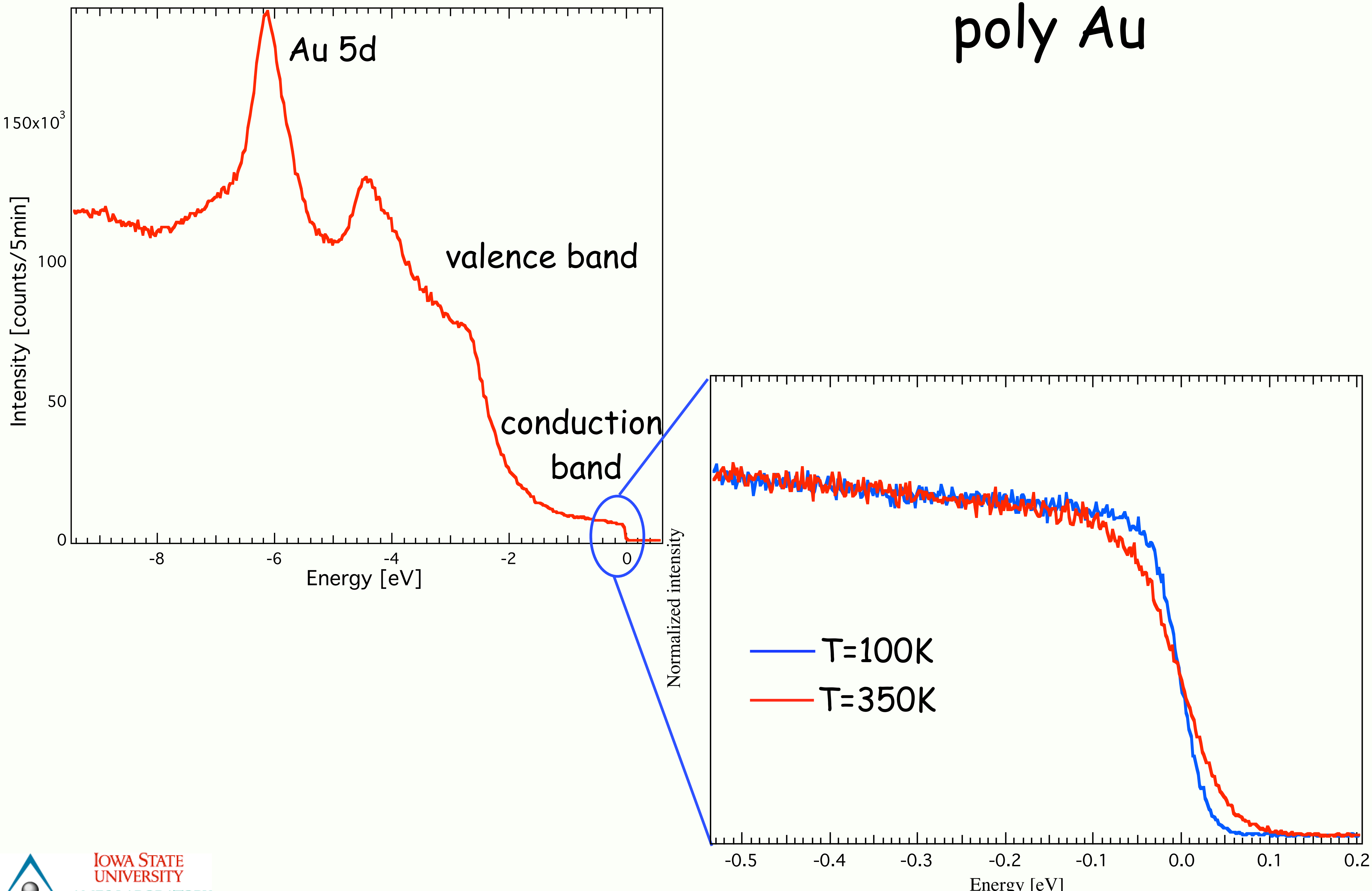
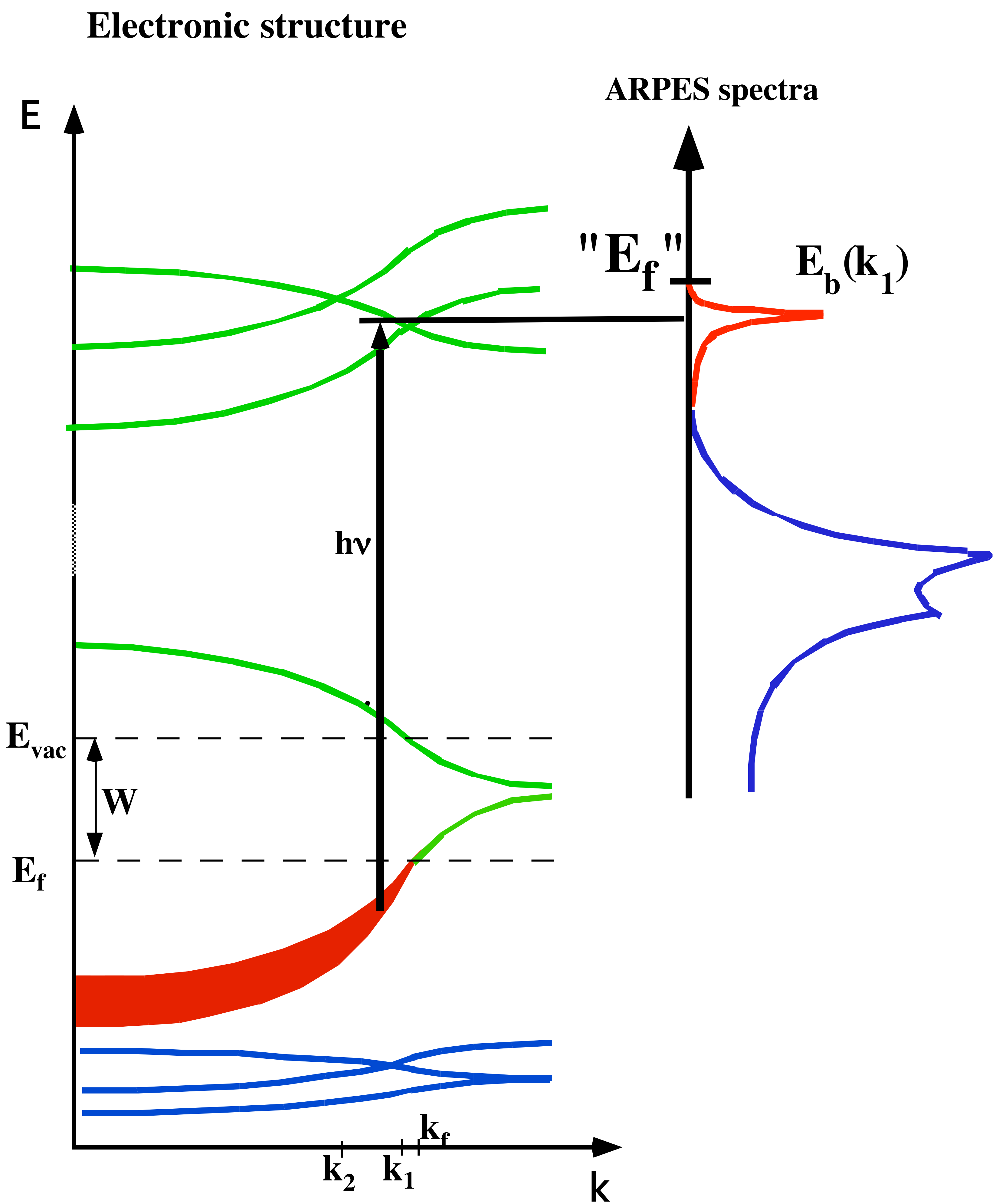
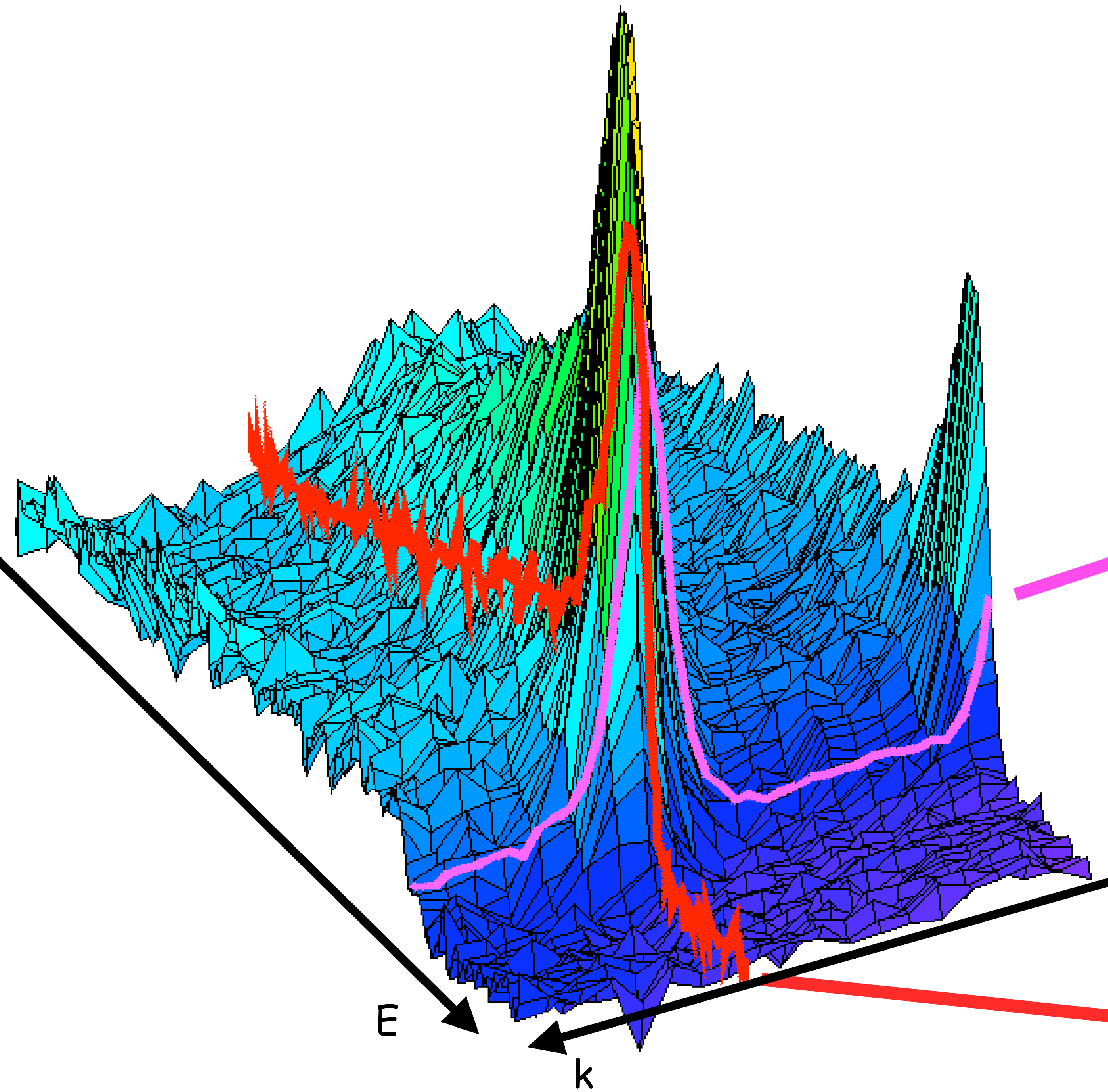
Valence and conduction bands - simplest example: poly Au





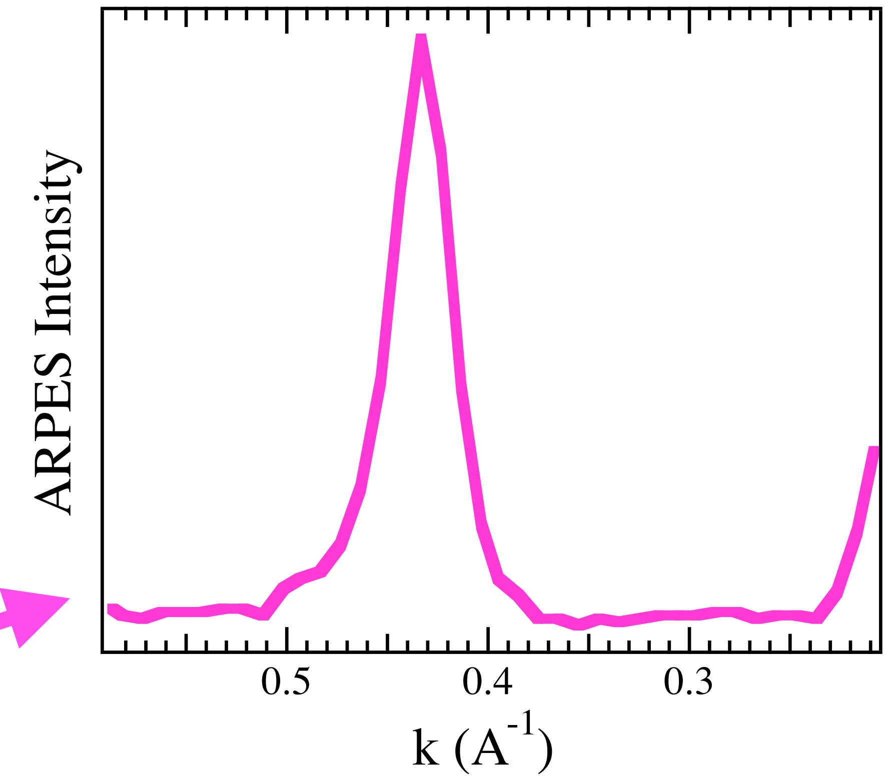
Electronic structure
ARPES spectra
E
"E_f"
E_b(k_1)
hν
E_vac
W
E_f
k_f
k_2
k_1
k

Typical "modern" ARPES data:



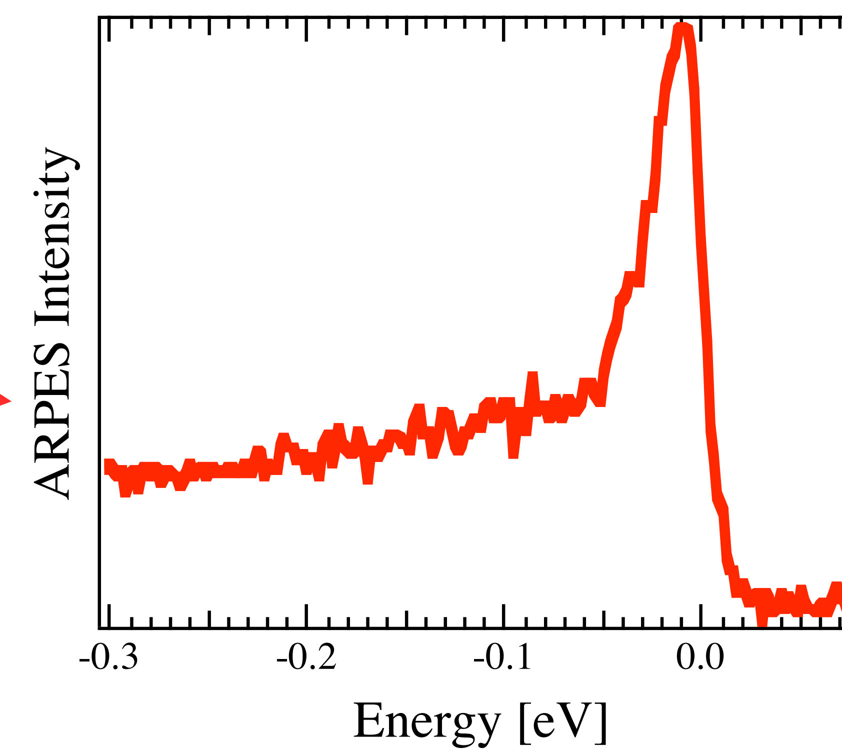
E=const

Momentum Distribution Curve (MDC)



k=const

Energy Distribution Curve (EDC)



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

symmetry of Ψ

electronic structure and interactions

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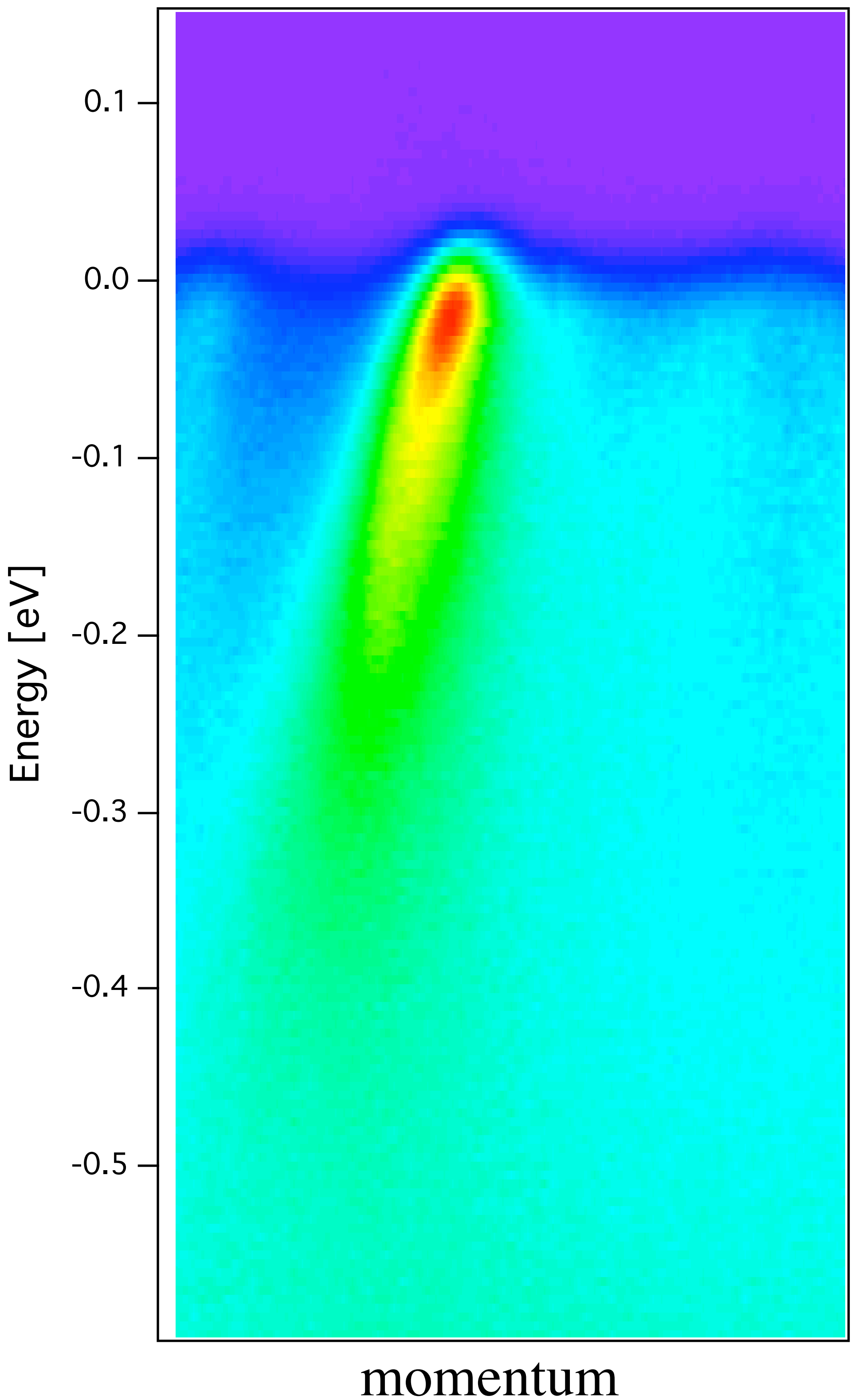
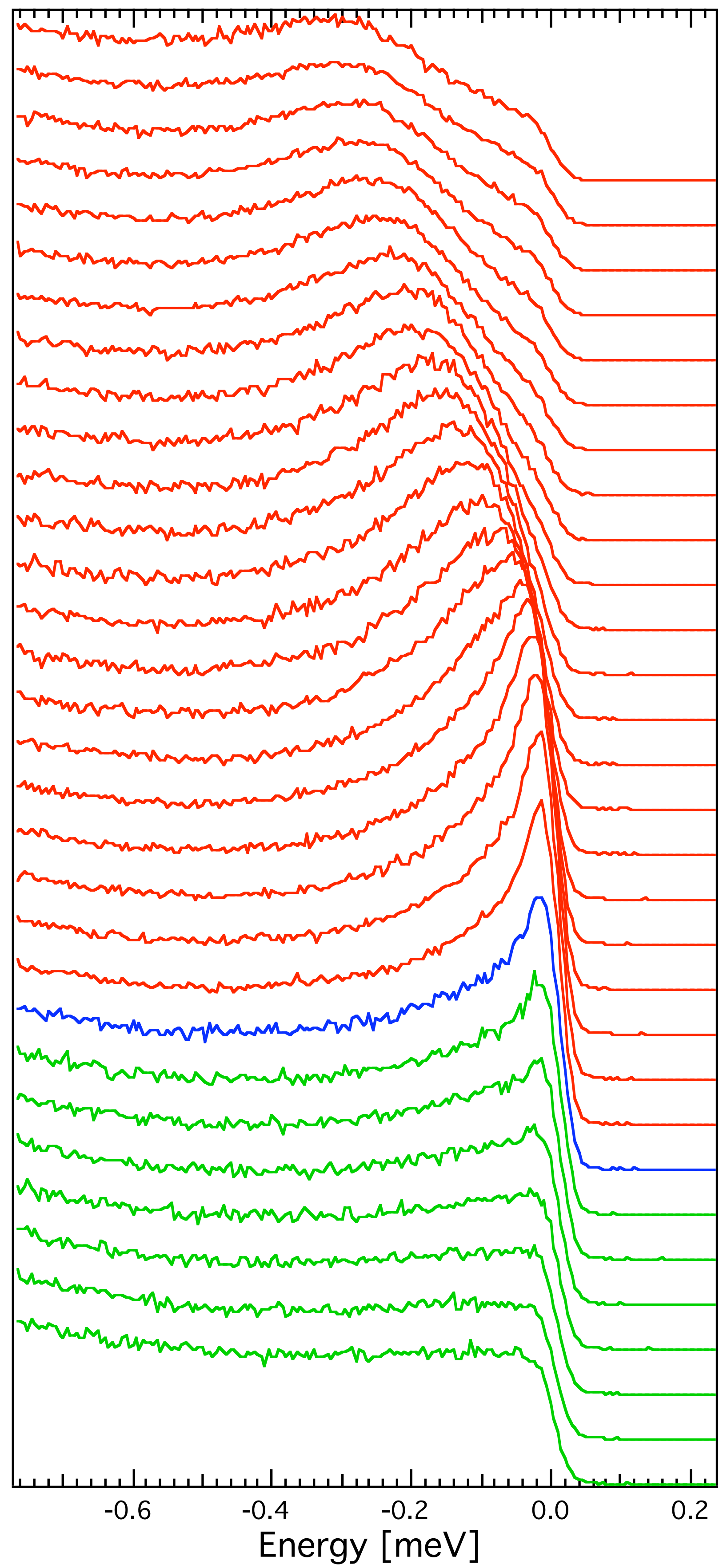
A. Kaminski et al., *Phys. Rev. Lett.* **86**, 1070 (2001)

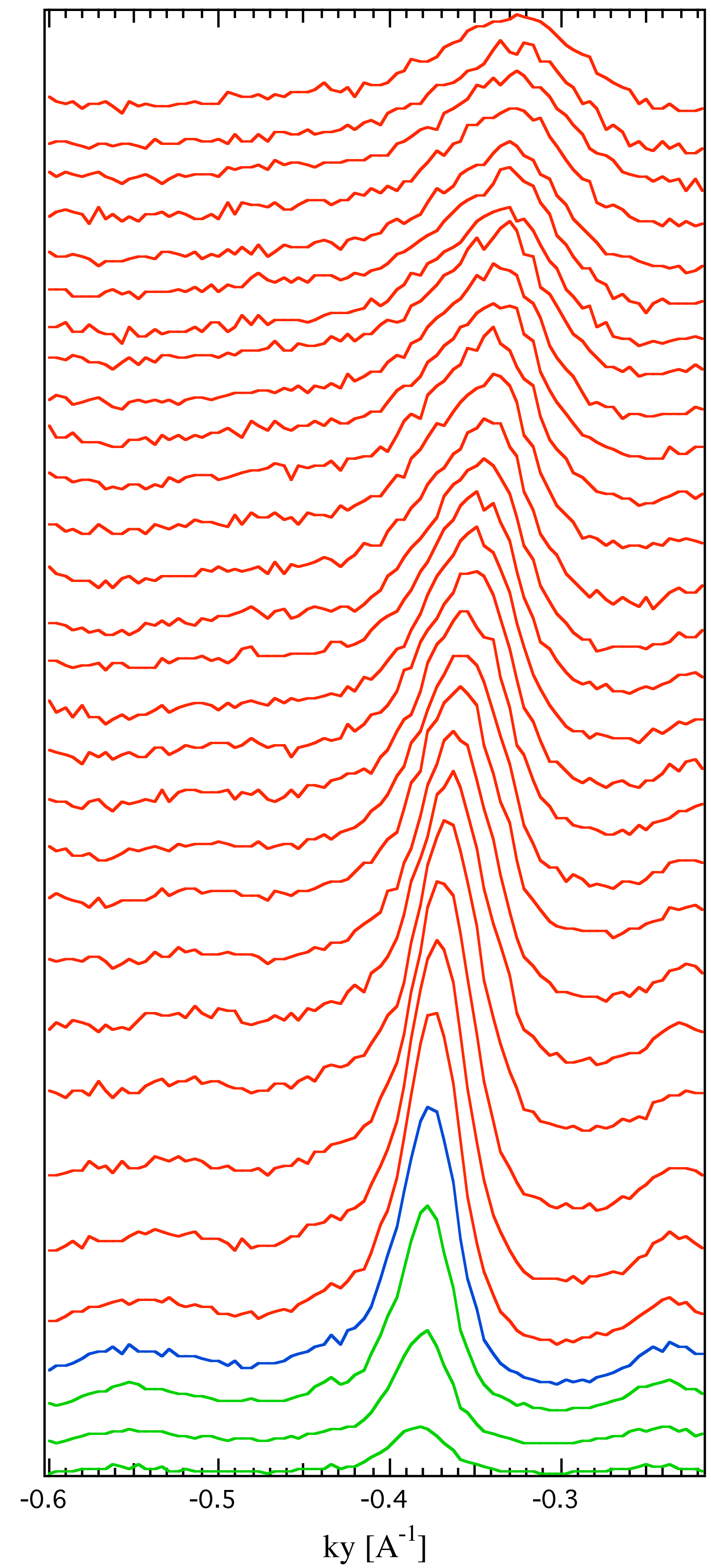
Intensity plot

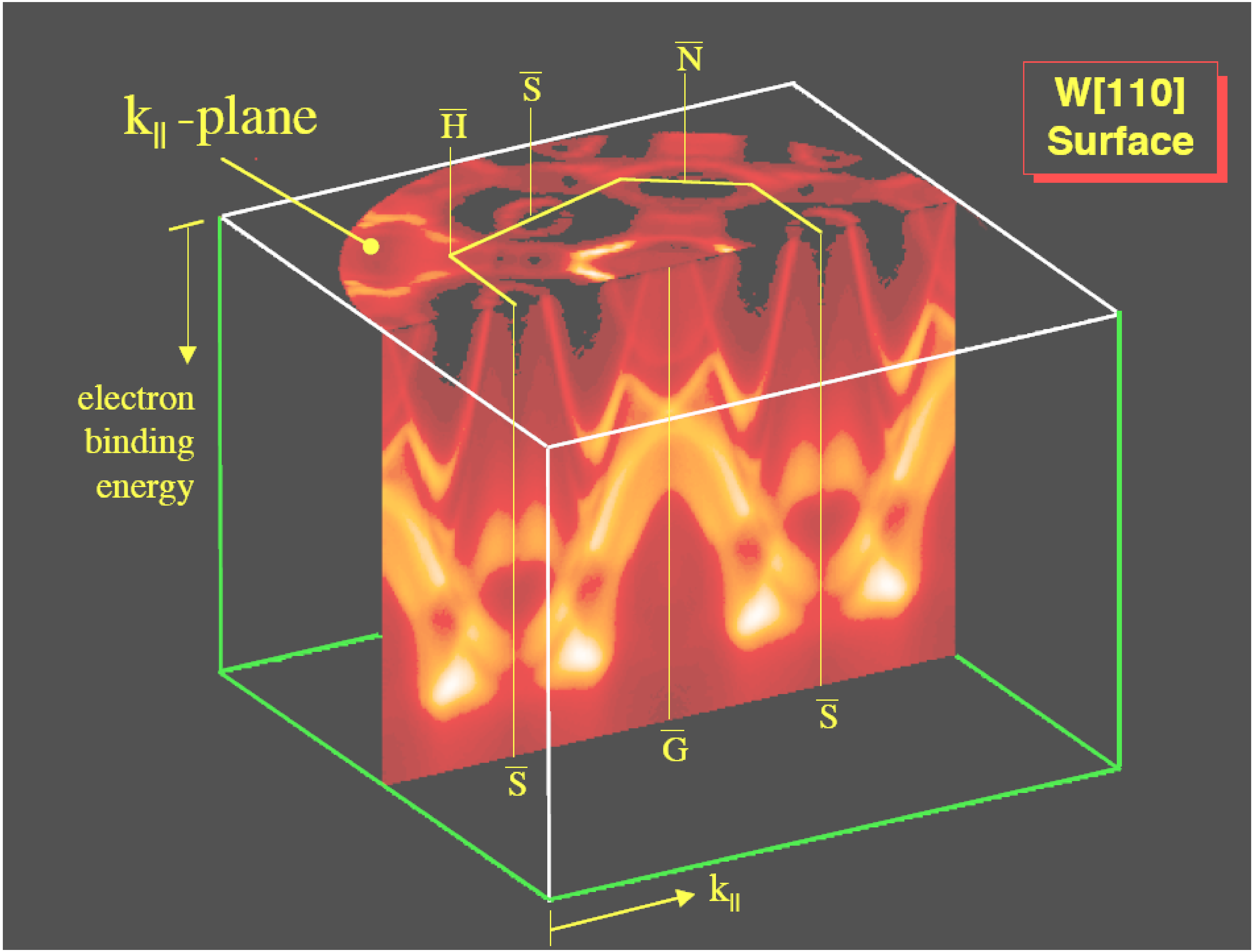


EDC



MDC





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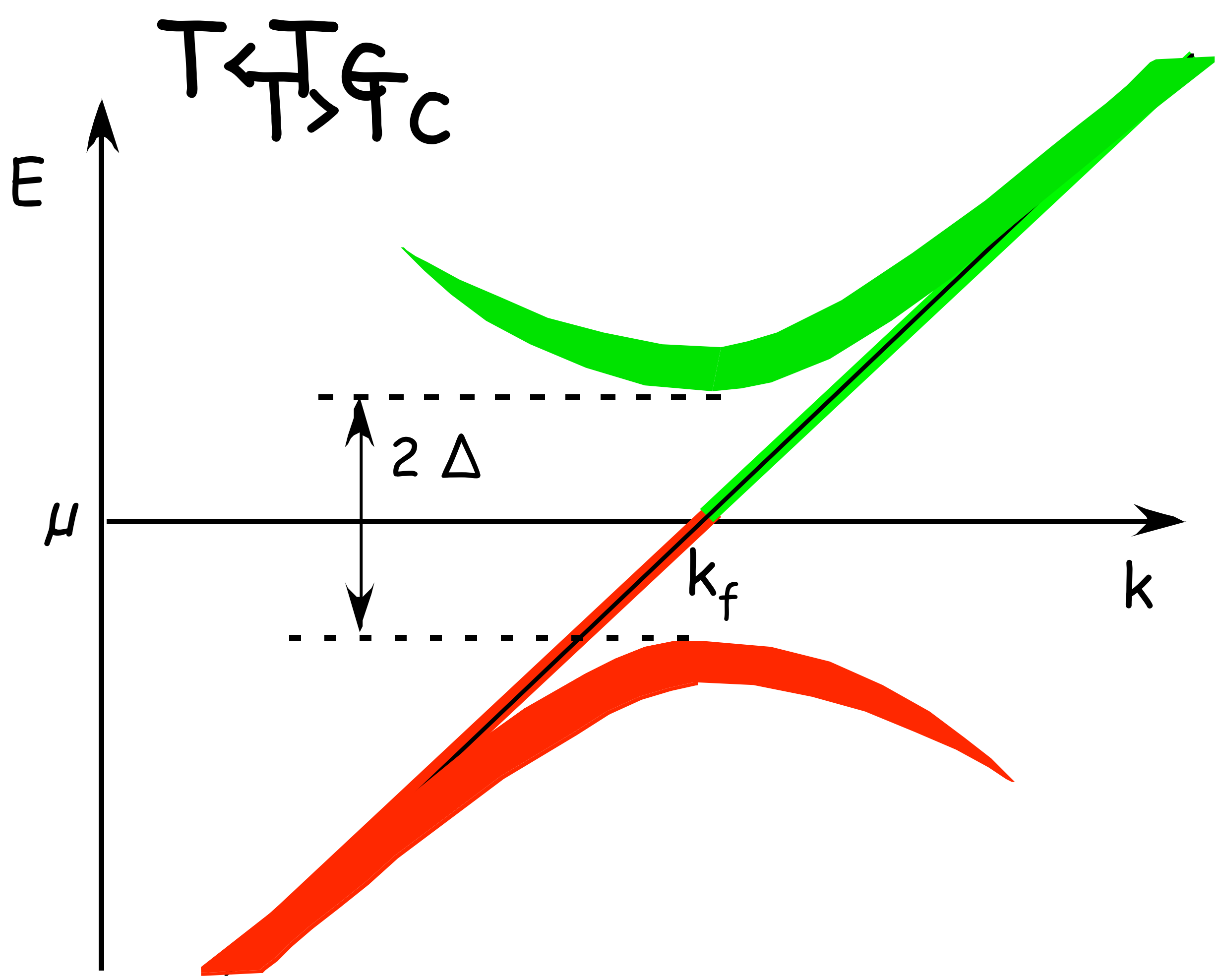
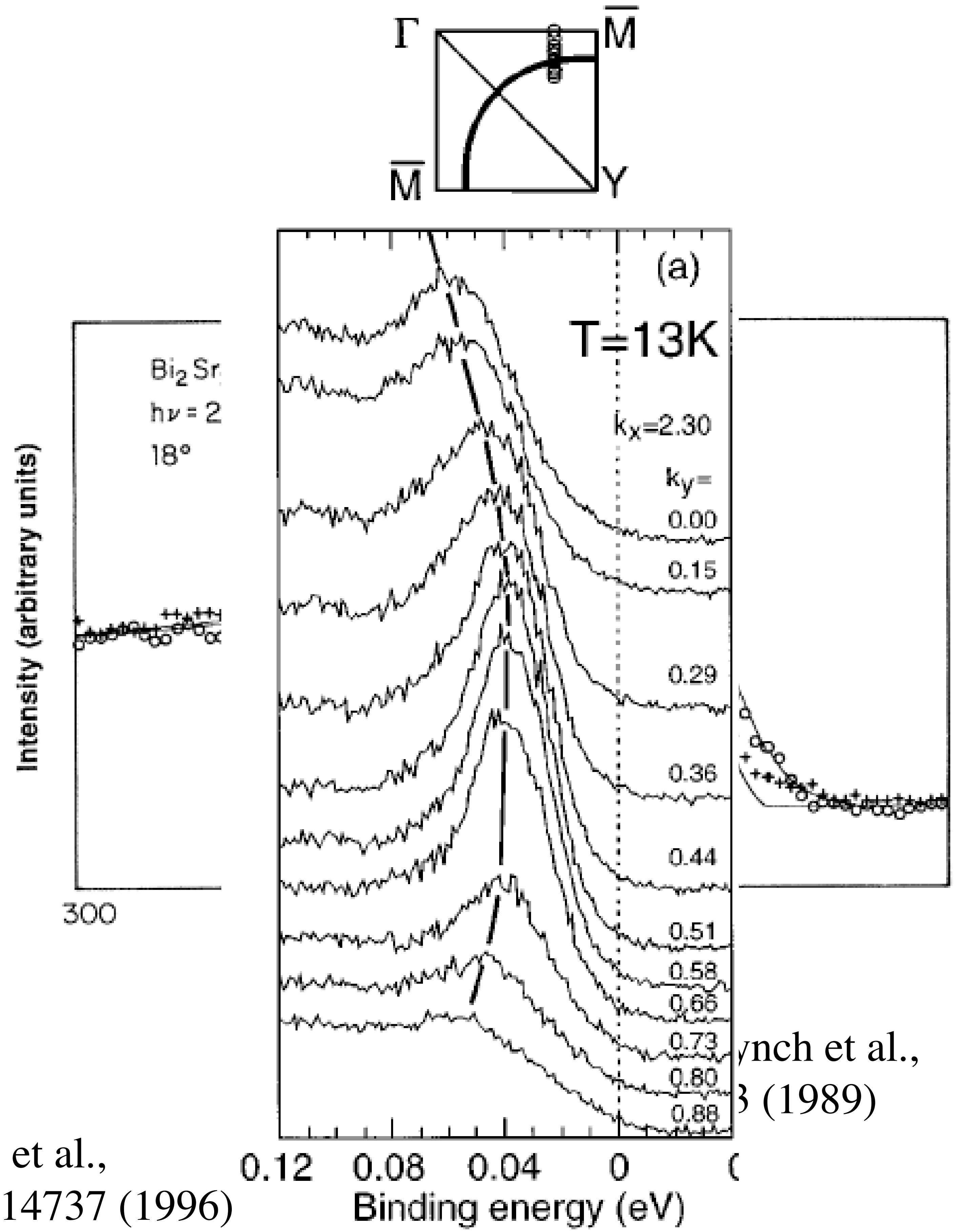
Eli Rotenberg, Advanced Light Source

Superconducting gap

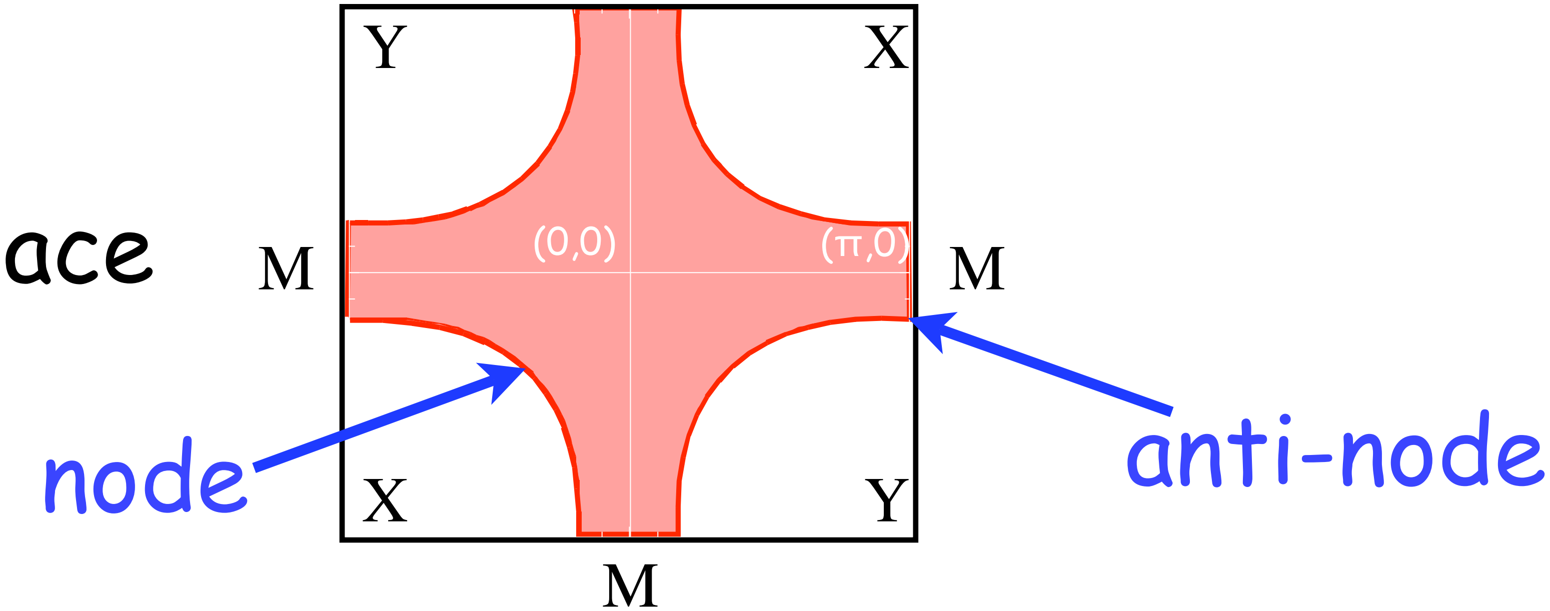




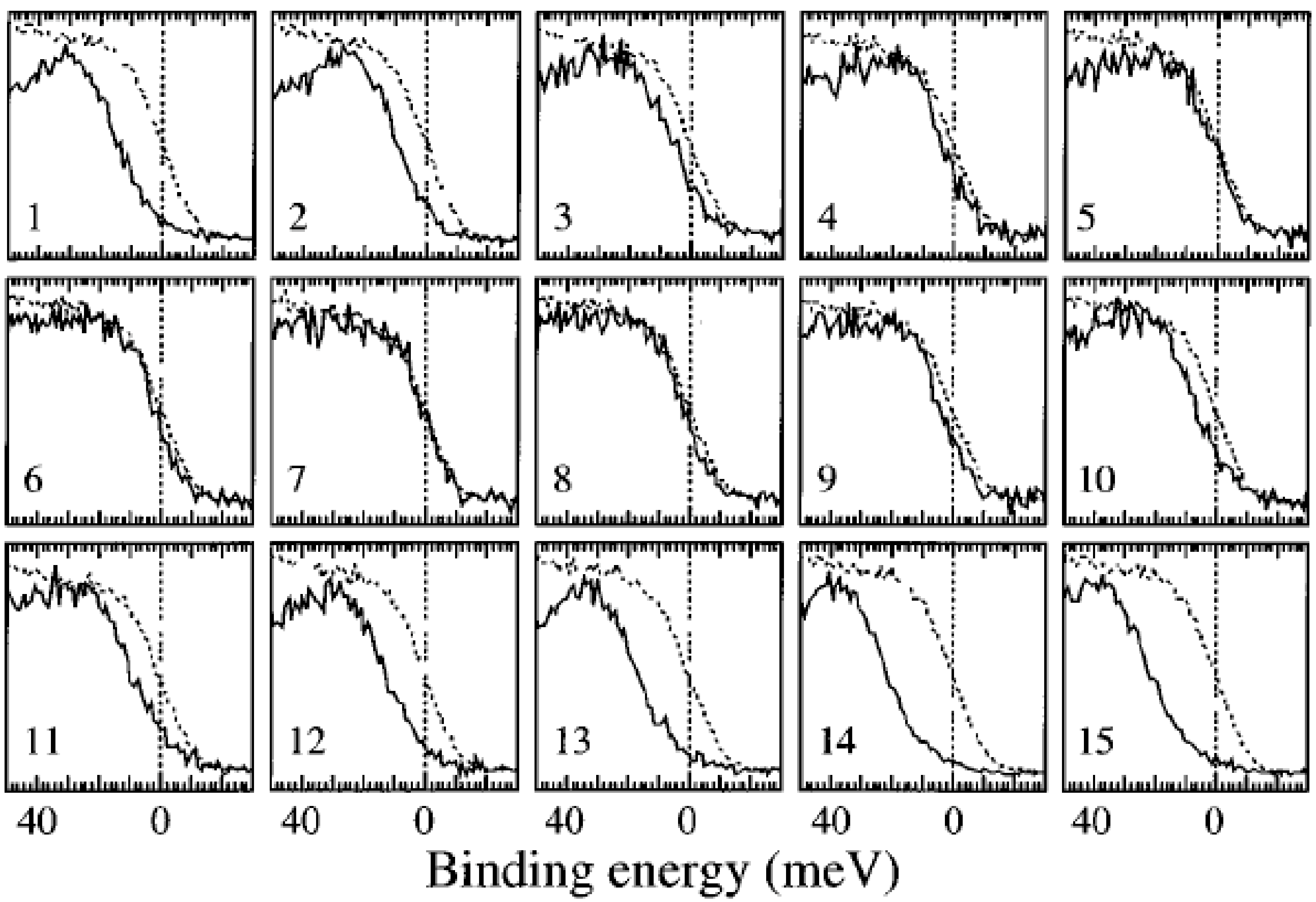
ynch et al.,
3 (1989)

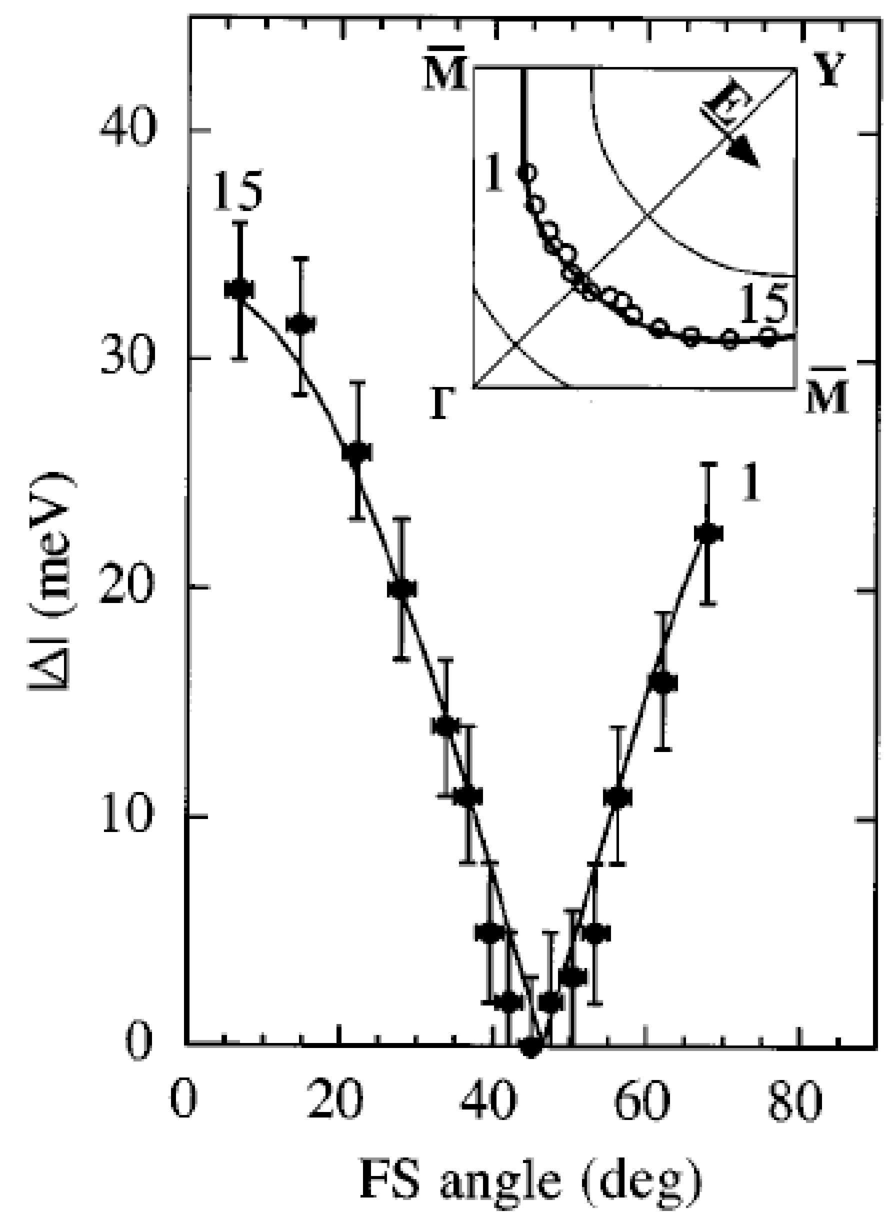
J. C. Campuzano et al.,
Phys. Rev. B **53**, 14737 (1996)

Fermi surface



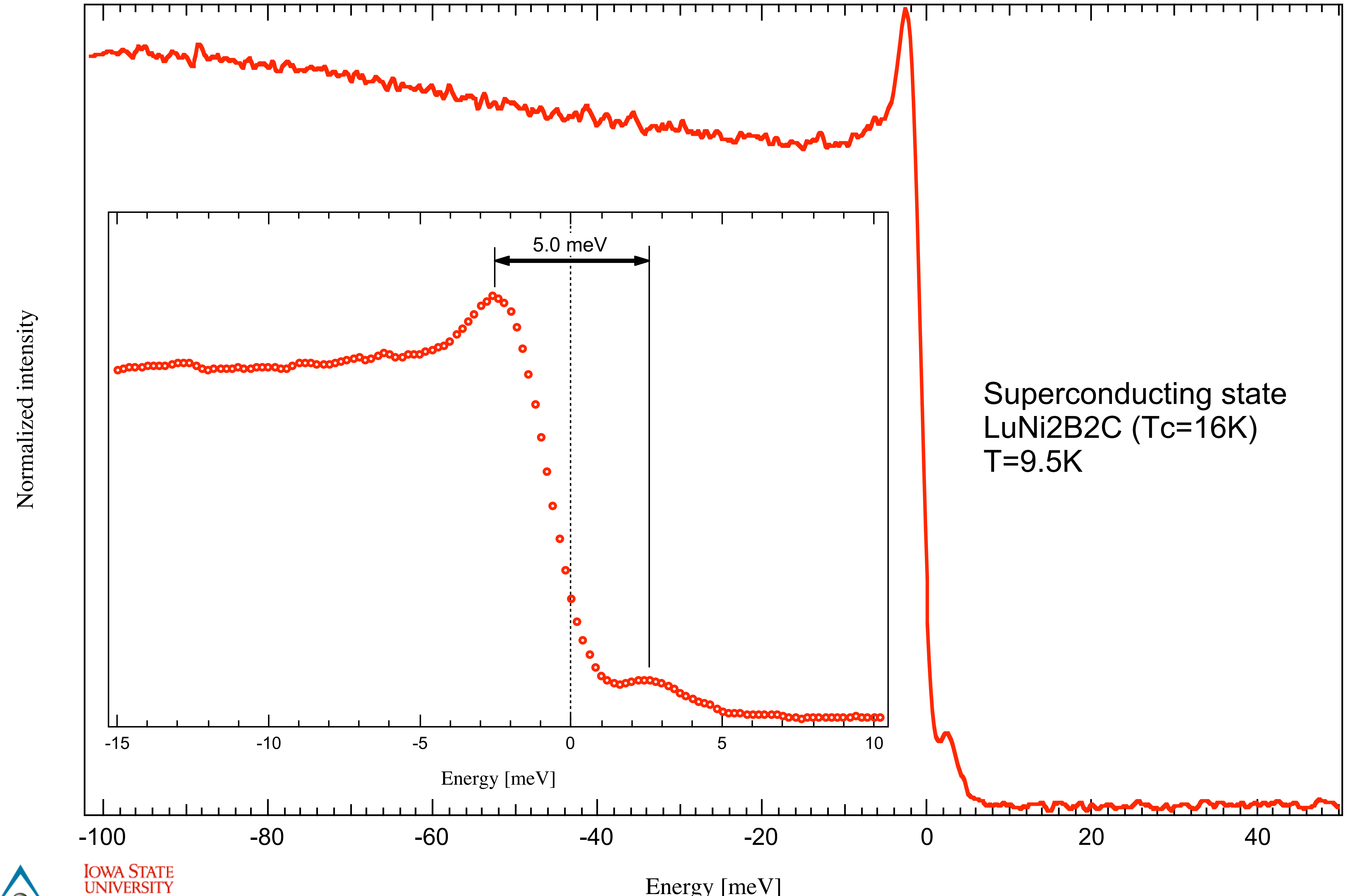
d-wave order parameter





H. Ding et al., *Phys. Rev. B* **54**, 9678 (1996)

Laboratory system: Scienta analyzer and He Lamp



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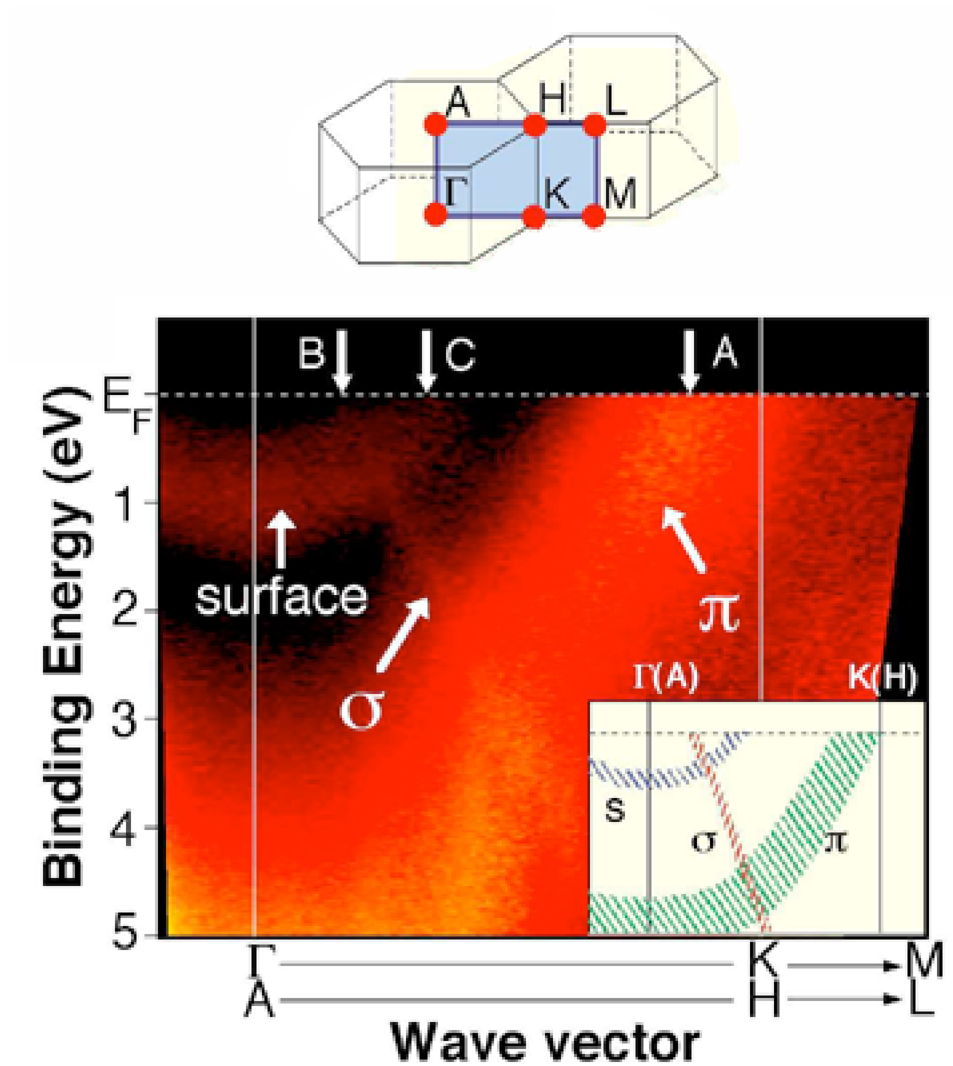

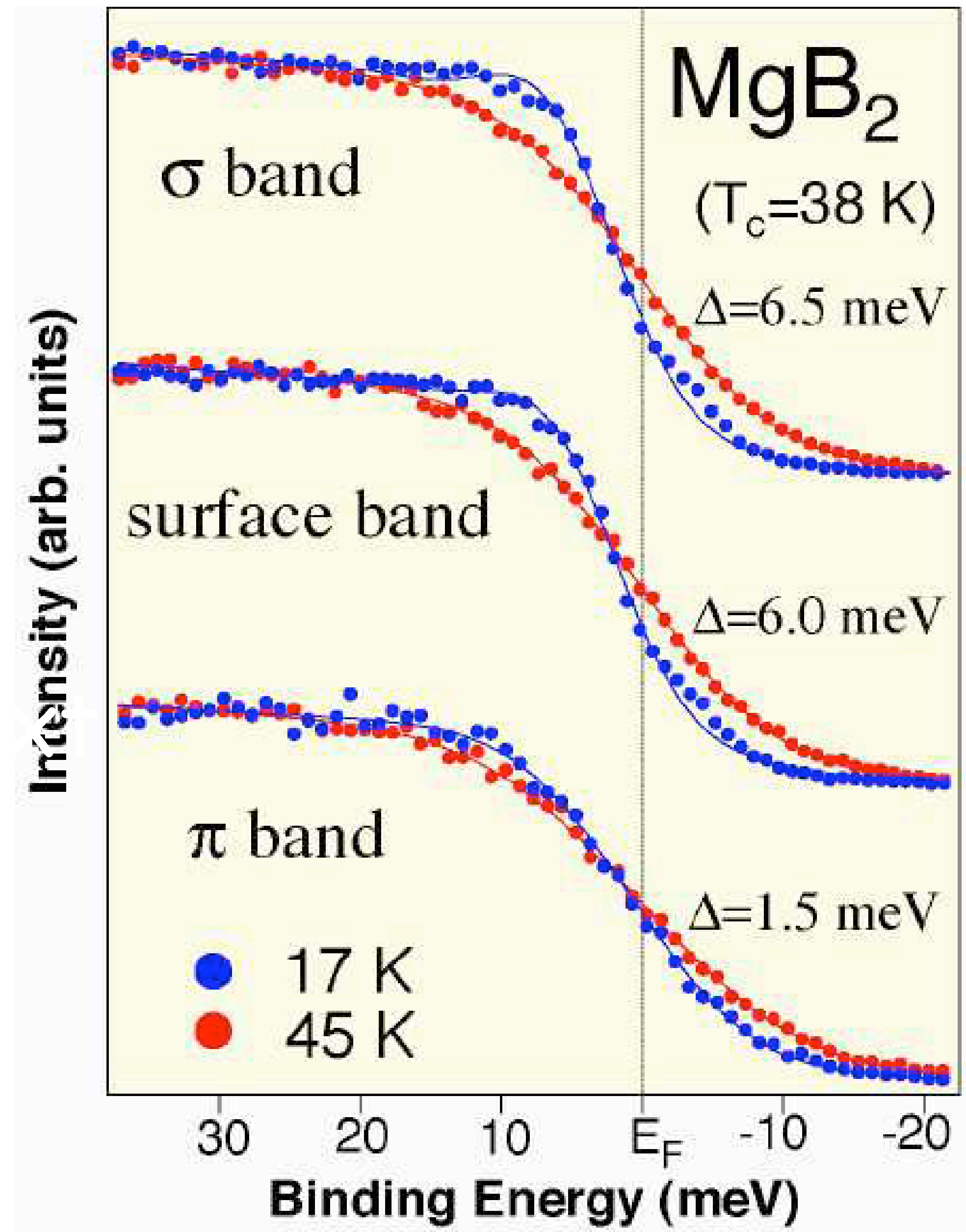

S. Souma et al., *Nature*, **423**, 65 (2003)

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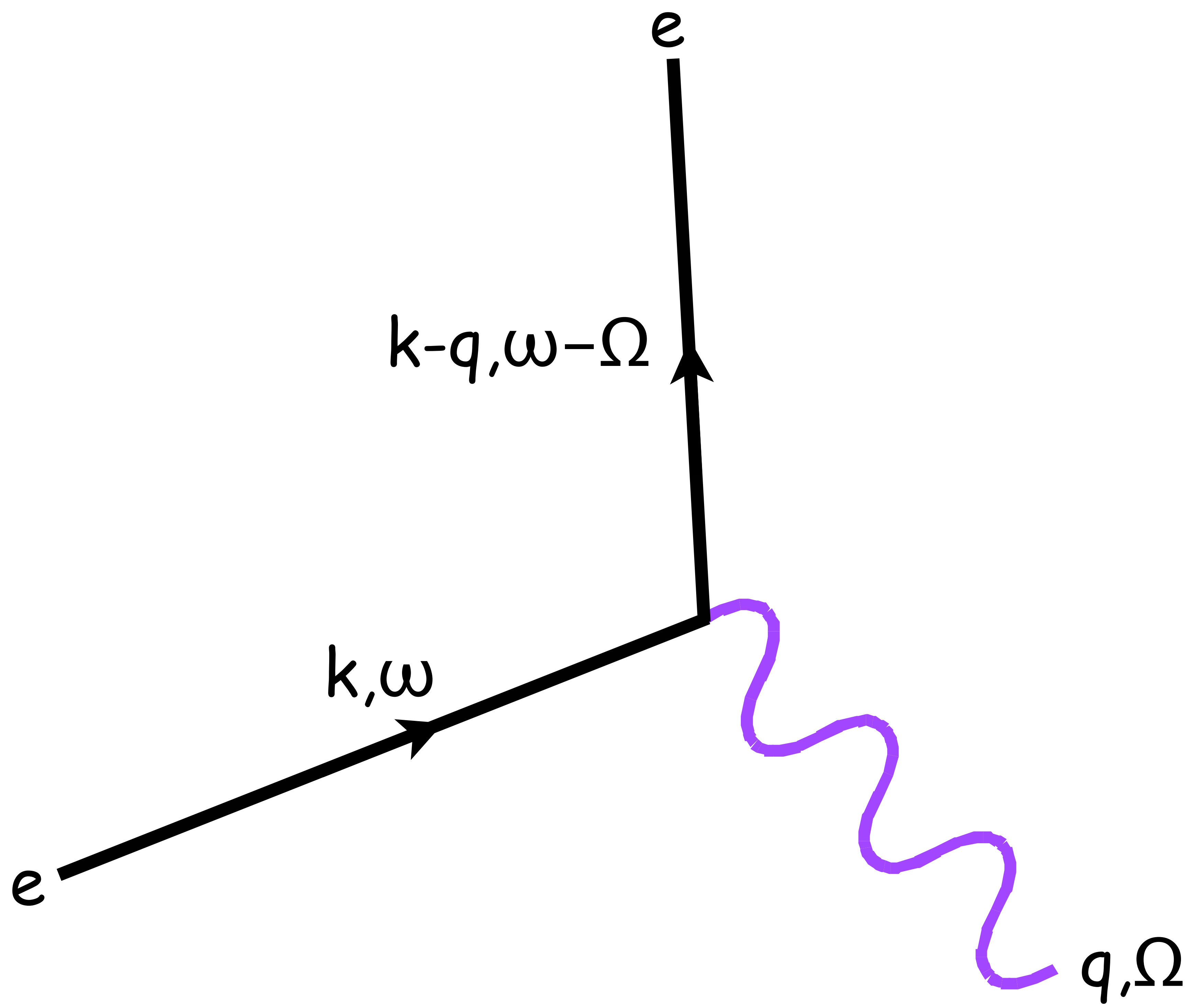
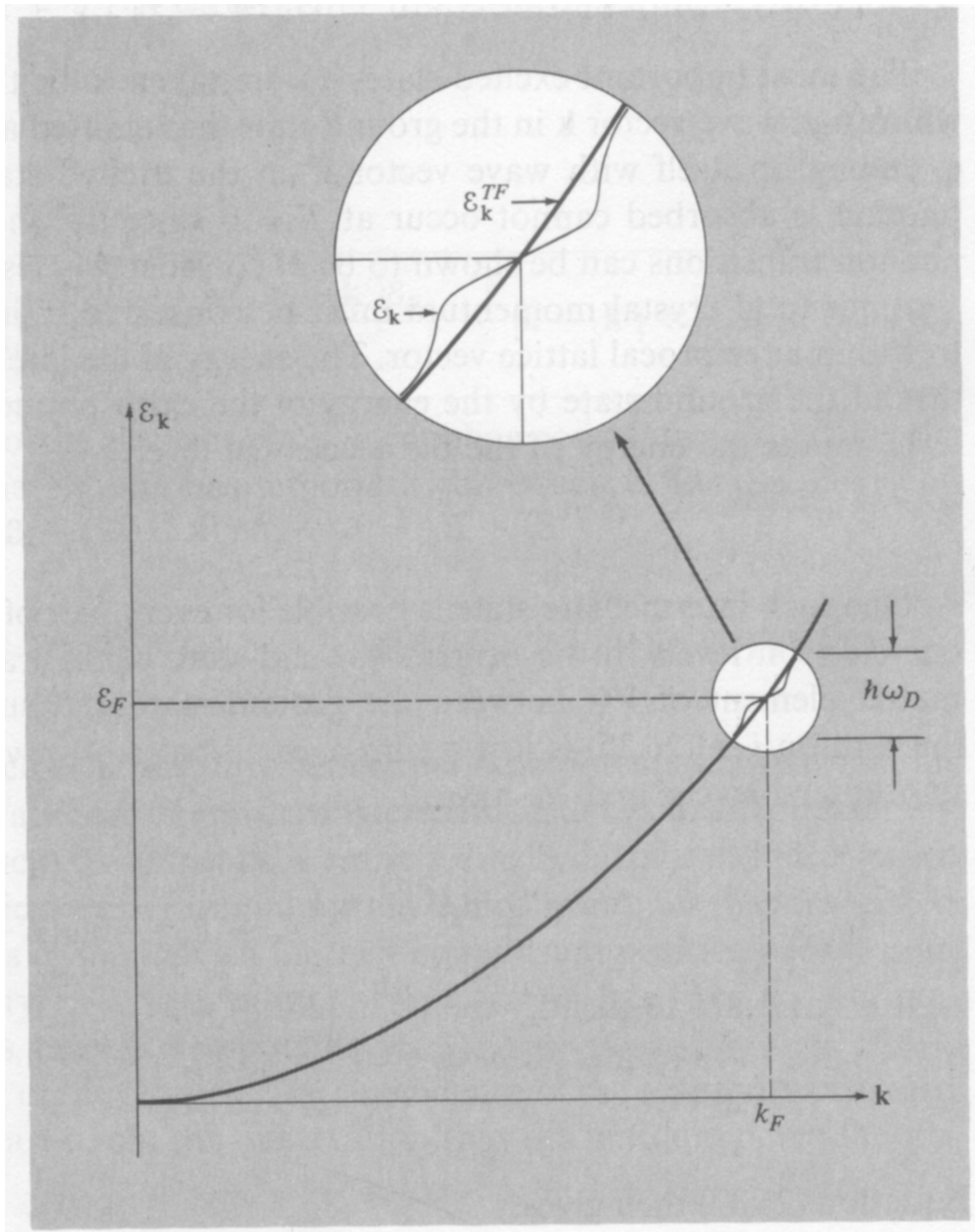
Collective modes

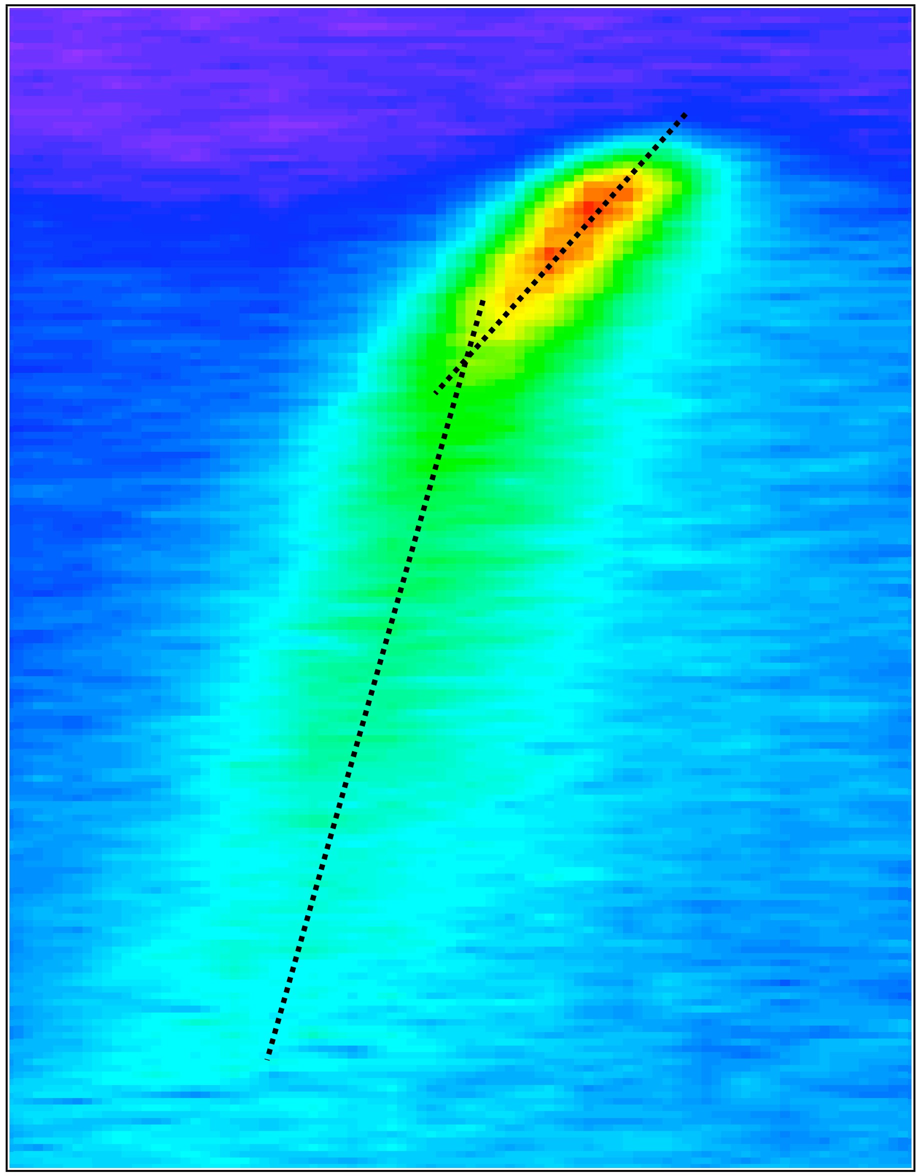


Interaction of electrons with a phonon:



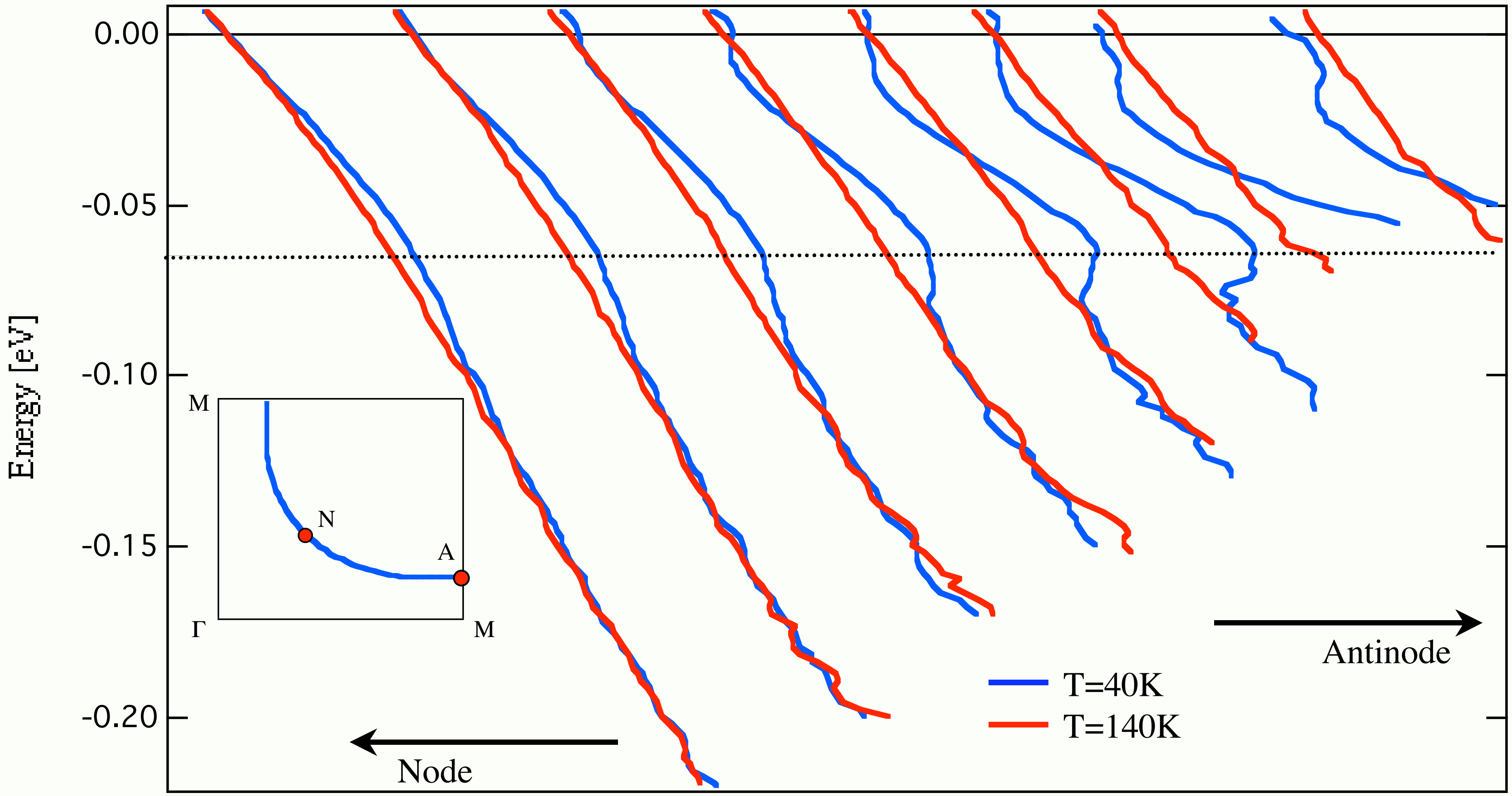
Ashcroft and Mermin
"*Solid State Physics*"

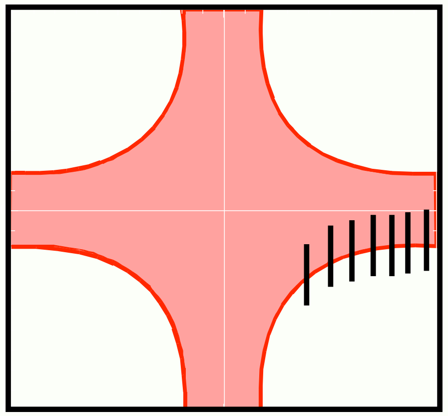
Renormalization effects along nodal direction

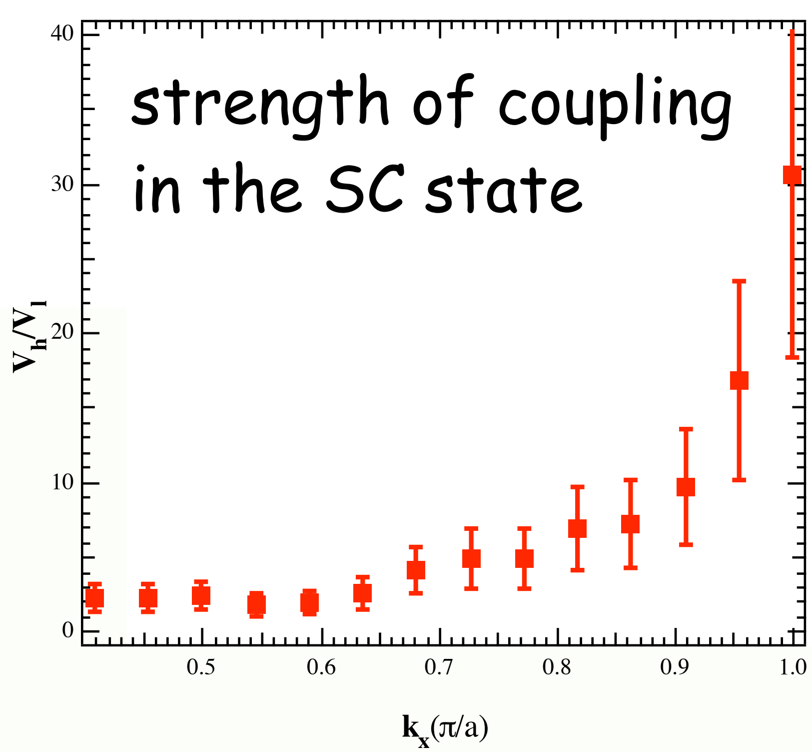


T. Valla et al., *Science* **24**, 2110 (1999)
P.V. Bogdanov et al., *Phys. Rev. Lett.* **85**, 2581 (2001)
A. Kaminski et al., *Phys. Rev. Lett.* **86**, 1070 (2001)

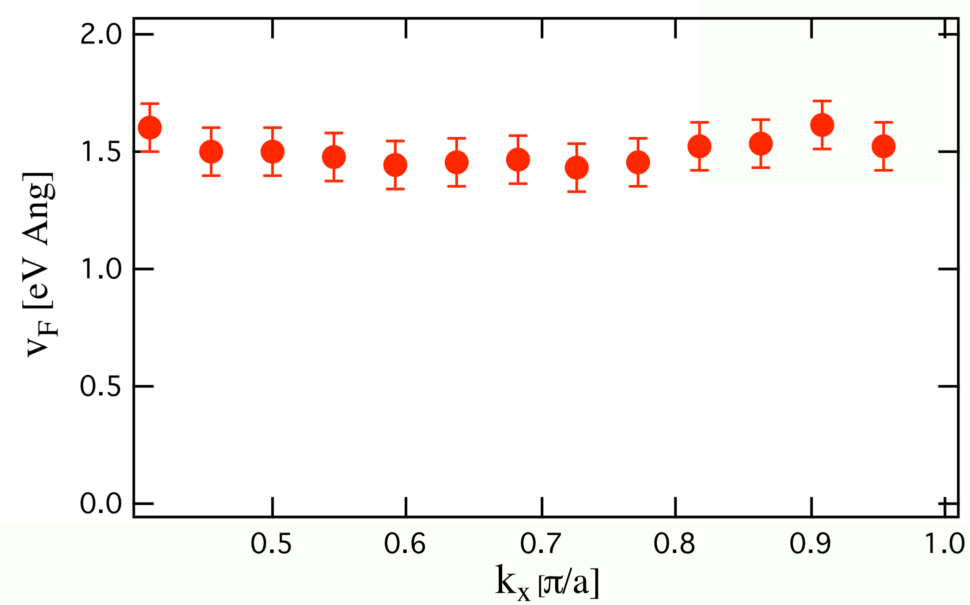
dispersion in normal and superconducting state







Fermi velocity in the normal state



A. Kaminski et al.,
Phys. Rev. Lett. **86**, 1070 (2001)

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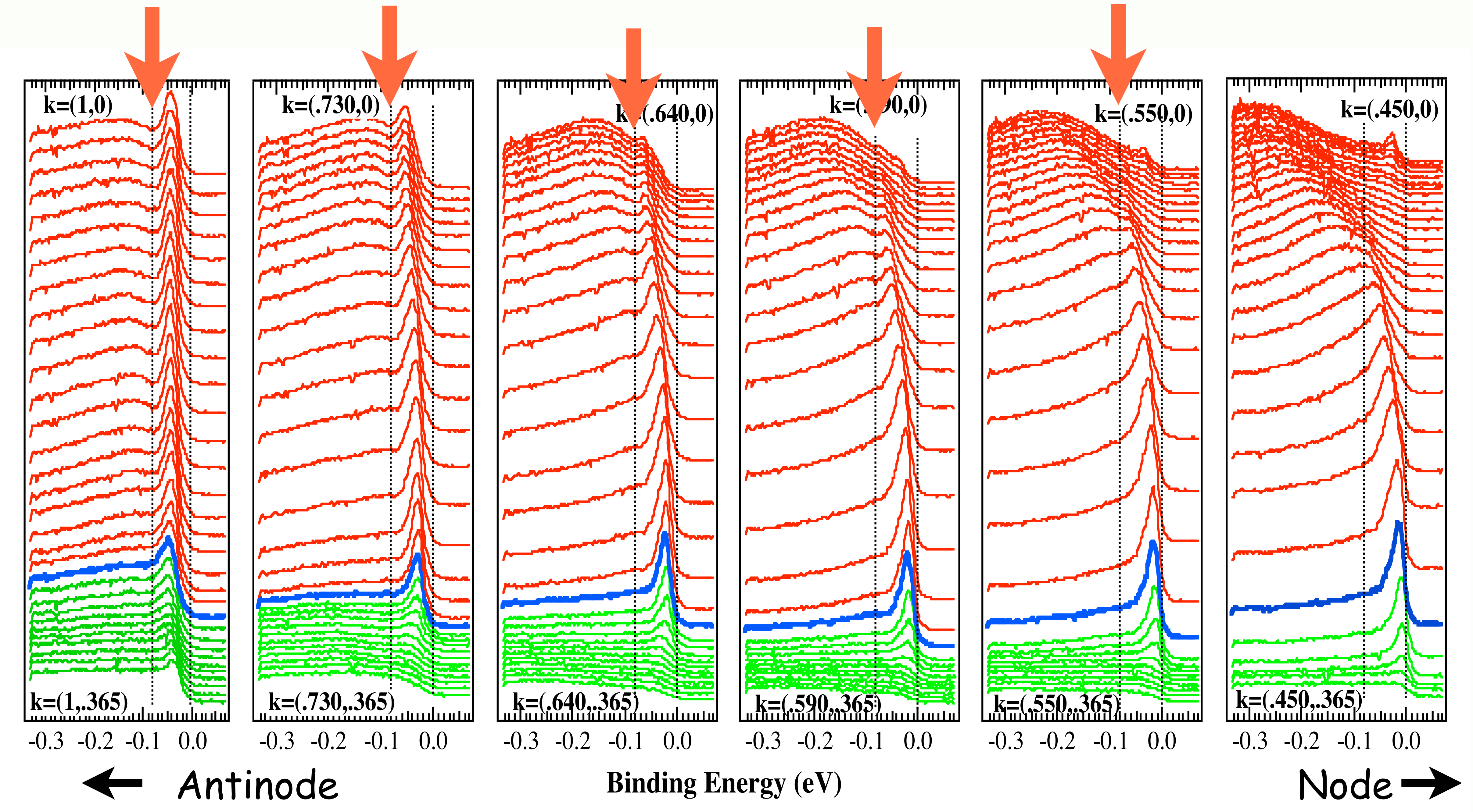
EDC's in the superconducting state



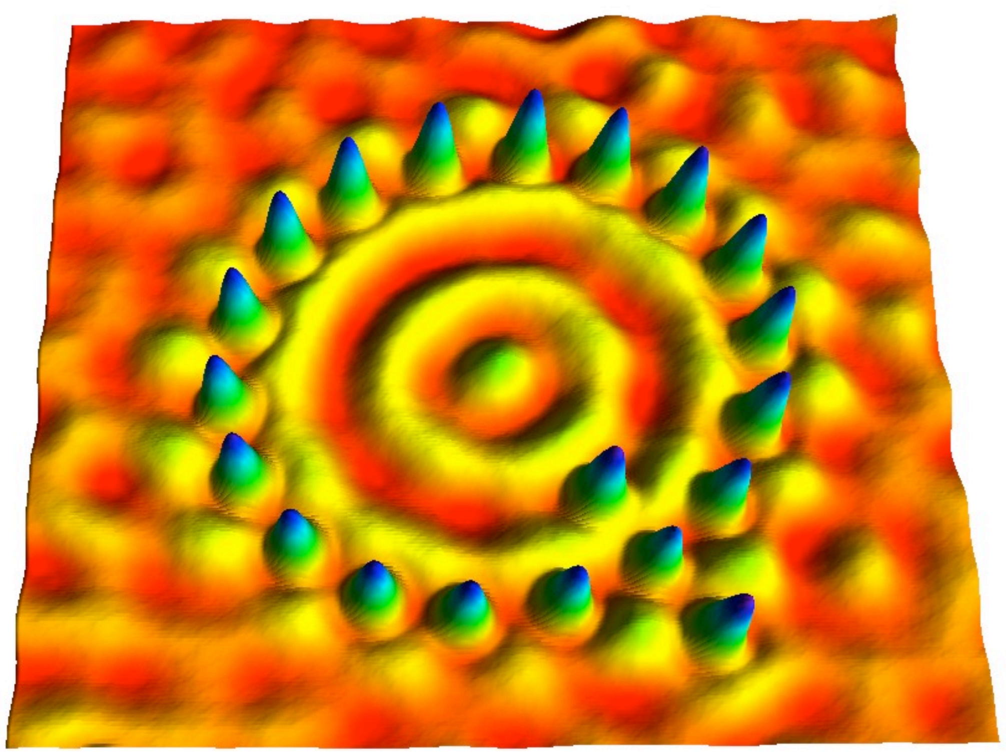
A. Kaminski et al., *Phys. Rev. Lett.* **86**, 1070 (2001)

Collective mode "score" card

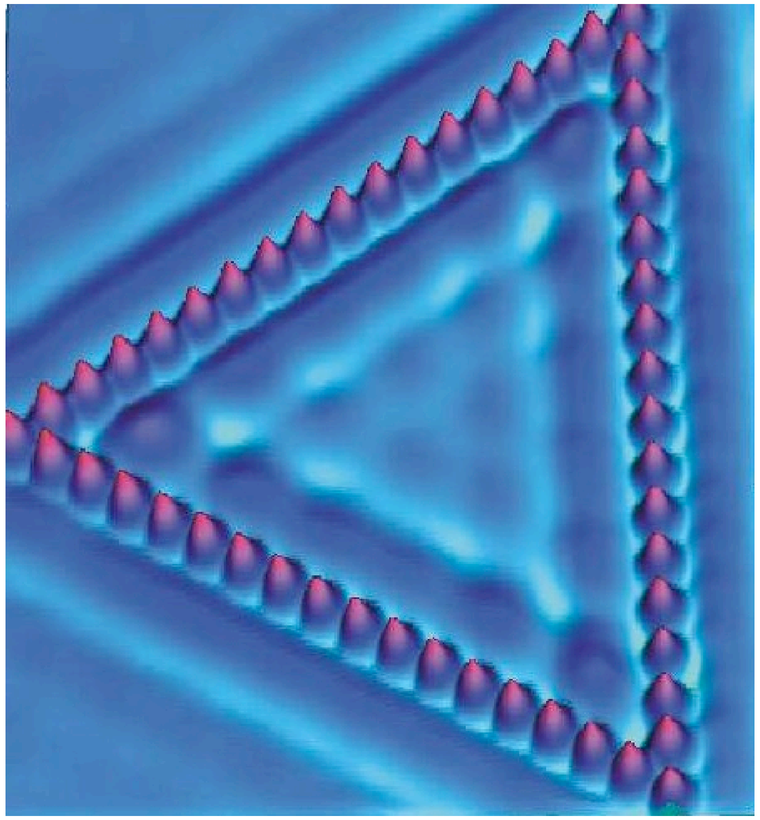
Properties of the bosonic mode	compatibility magnetic	compatibility phonons
1) isotropic energy $\Delta+\Omega$	yes	yes
2) momentum anisotropy	yes	yes, recently
3) temperature dependence	yes	not obvious
4) doping dependence	yes	not obvious

Autocorrelated (AC) ARPES - new tool in studies of scattering processes

Scattering in traditional STM



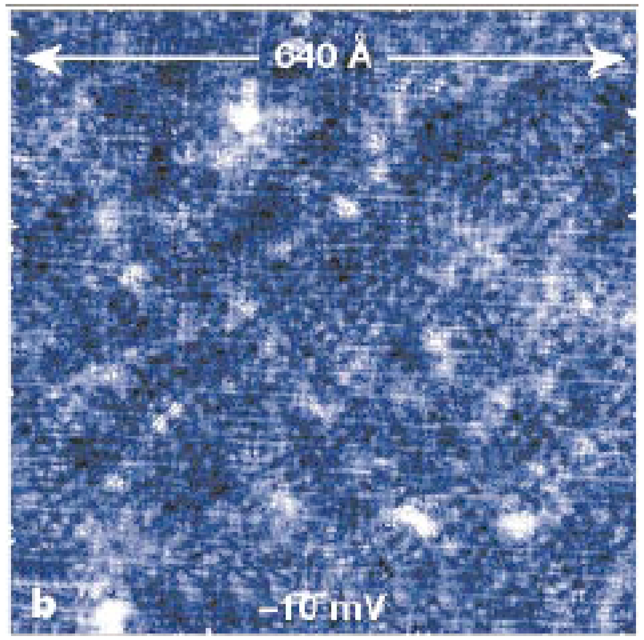
Cu on Cu(111)



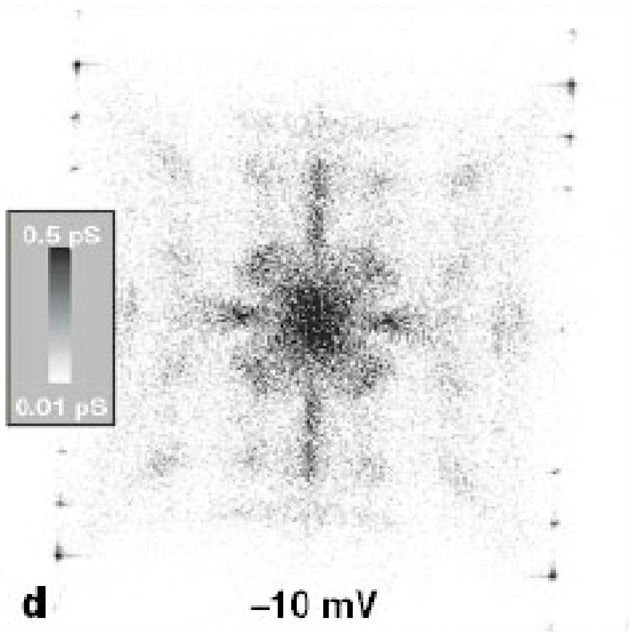
Ag on Ag(111)

SPECS website

FT STM



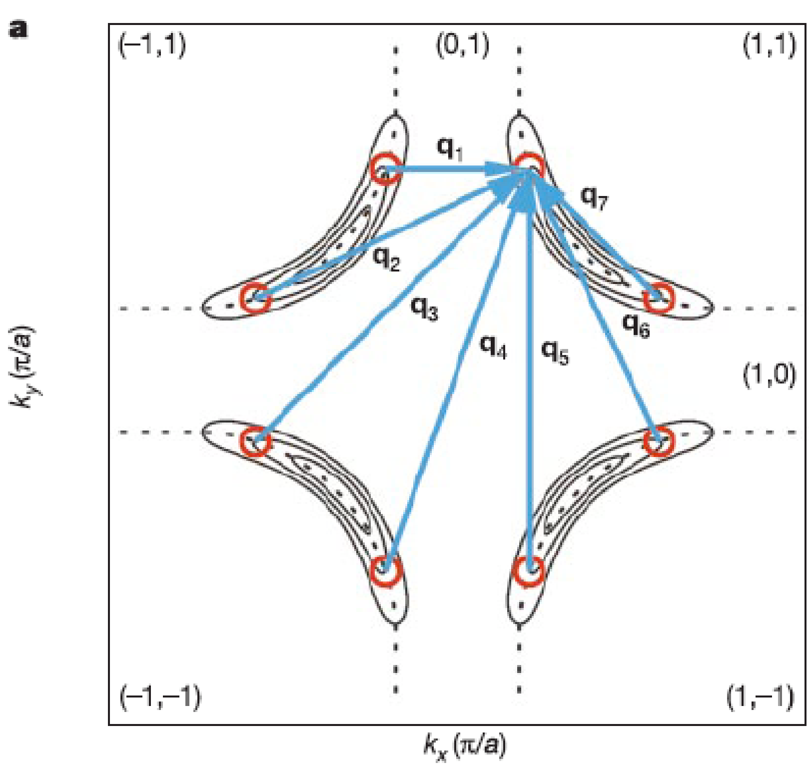
Fourier transform



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)

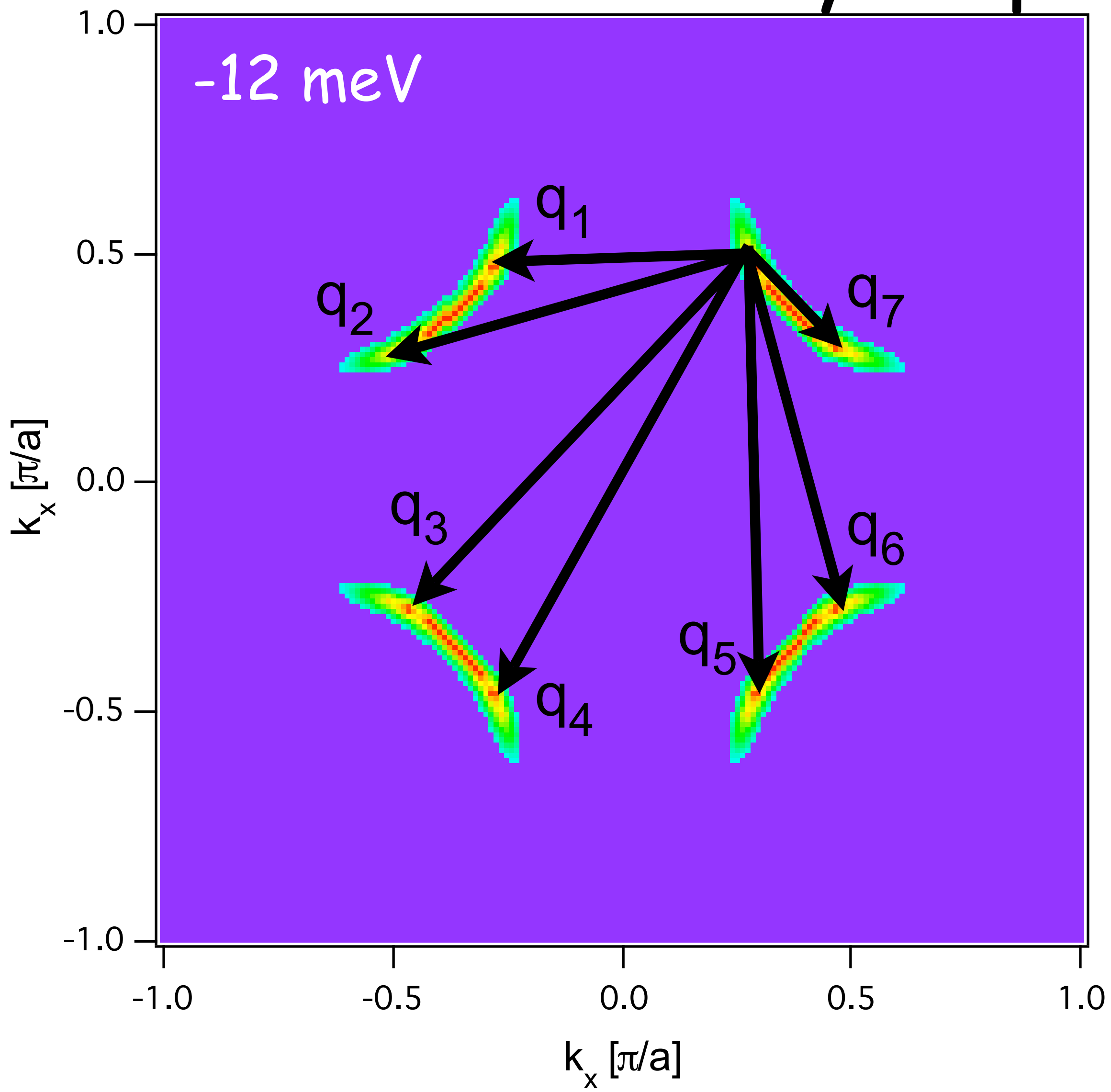


L. Capriotti et al,
PRB **68**, 014508 (2003)

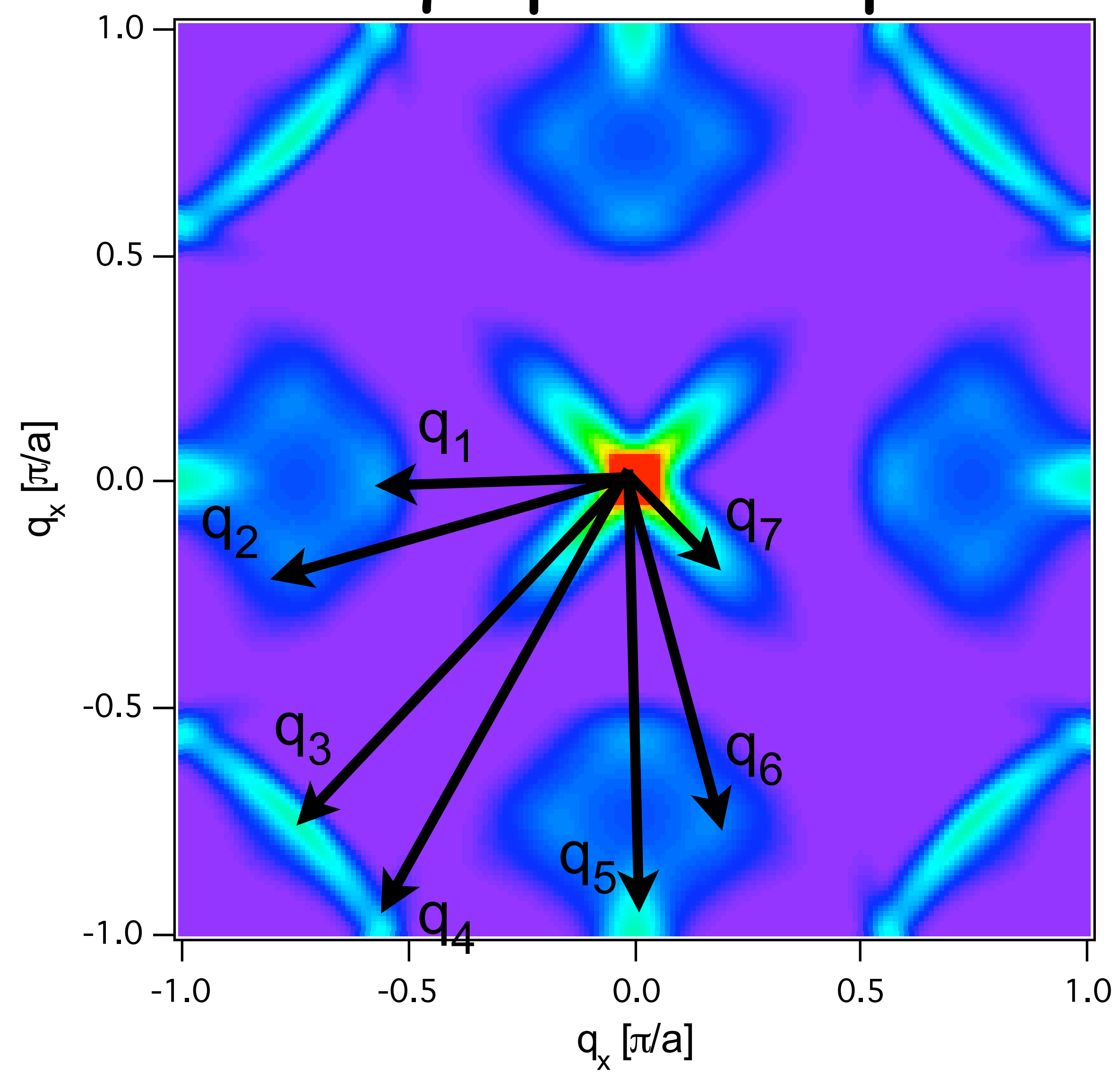
R. S. Markiewicz et al,
PRB **69**, 214517 (2004)

AutoCorrelated (AC) ARPES - ARPES data and q-space

ARPES intensity map

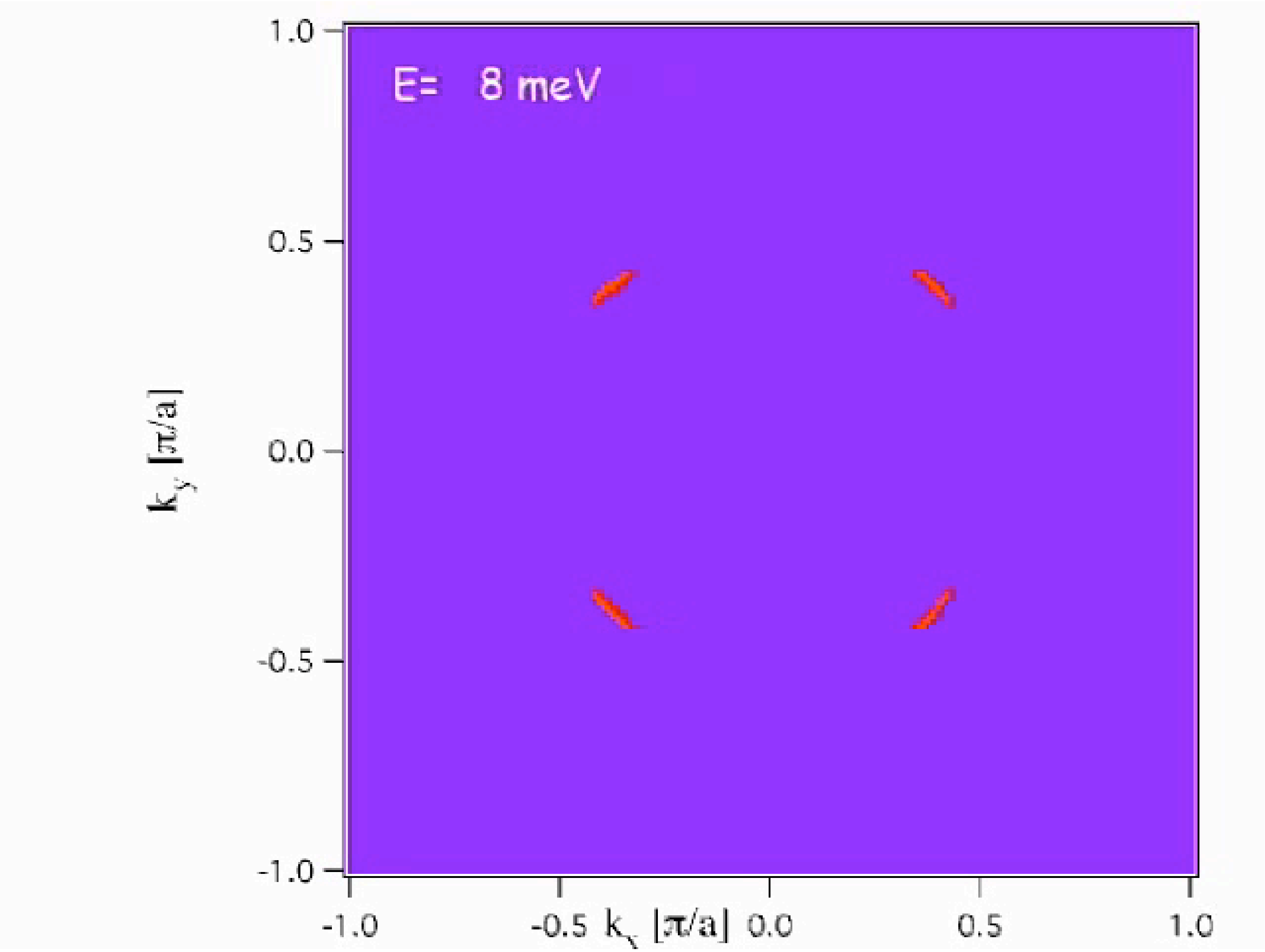


q-space map

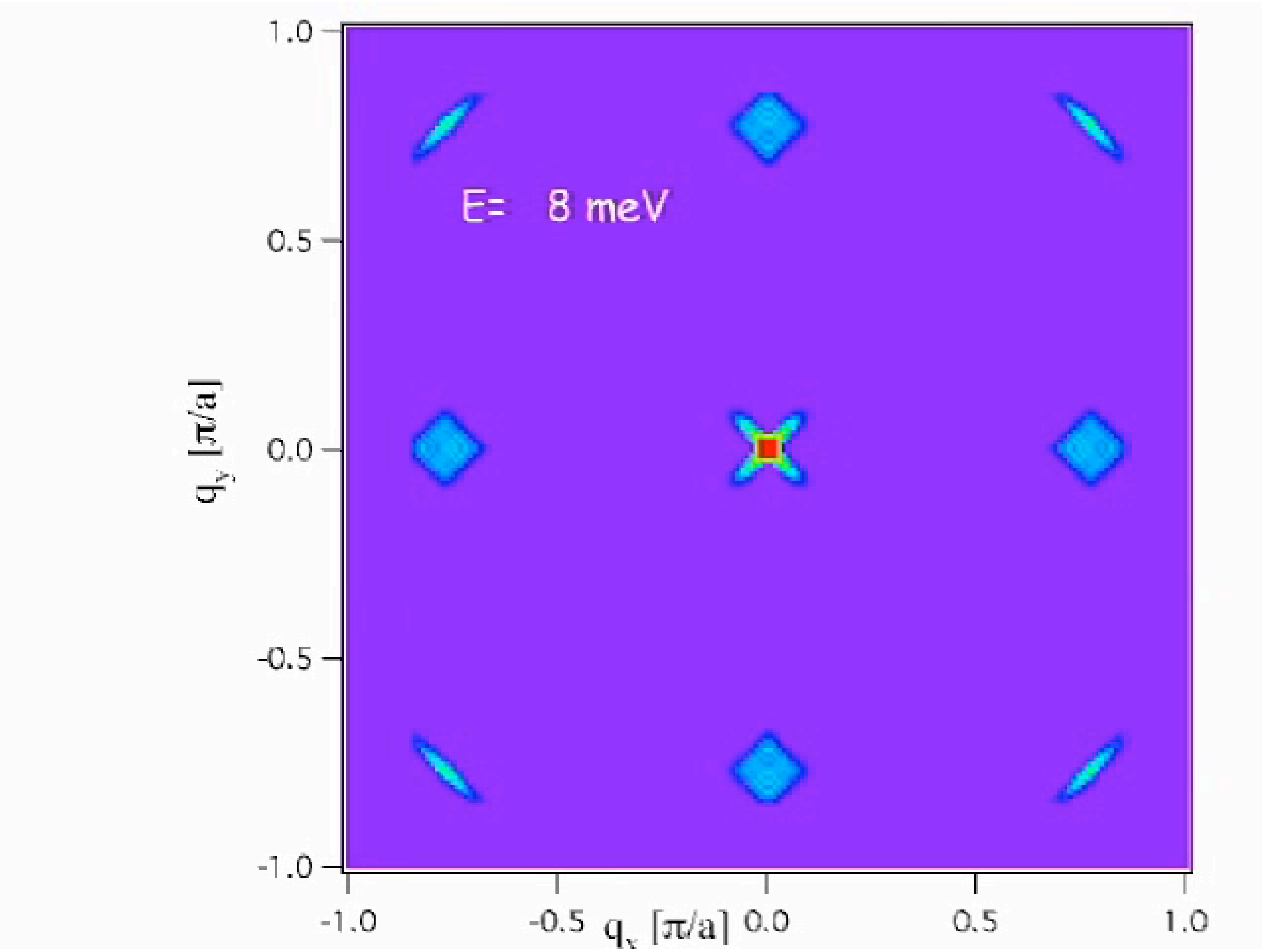


$$S(q, \omega = \omega_0) = \sum_{k_x, k_y} I(k, \omega)\, I(k + q, \omega)$$

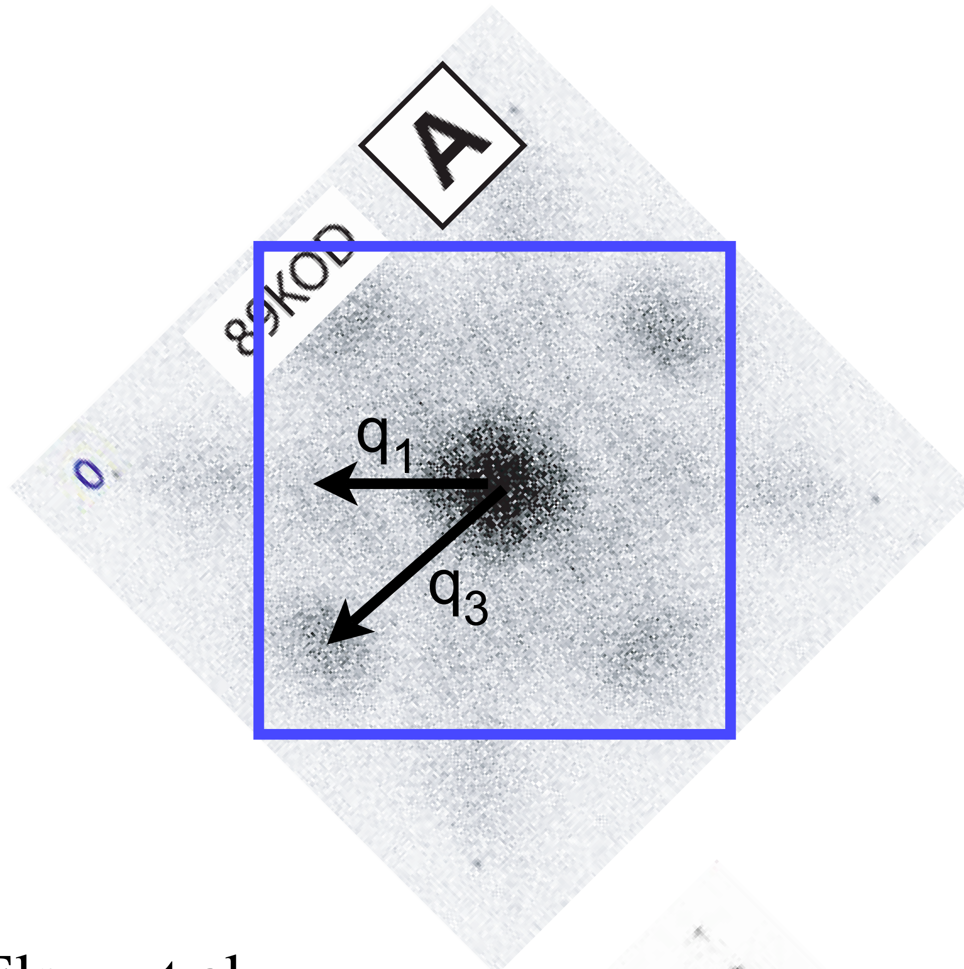
ARPES intensity maps

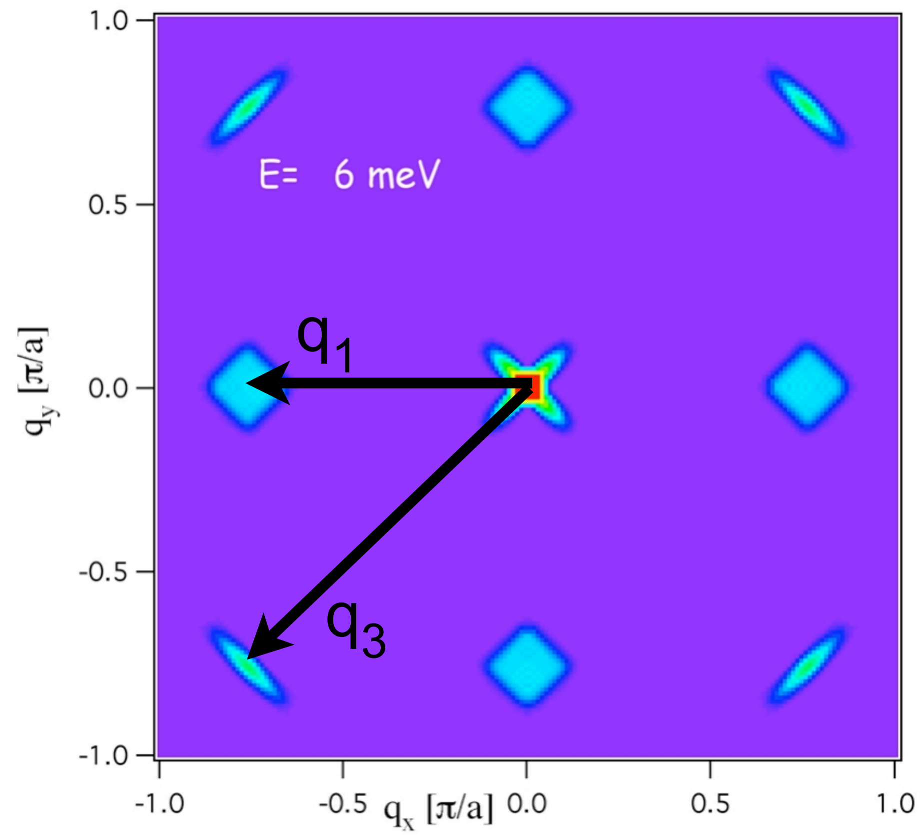


q-space



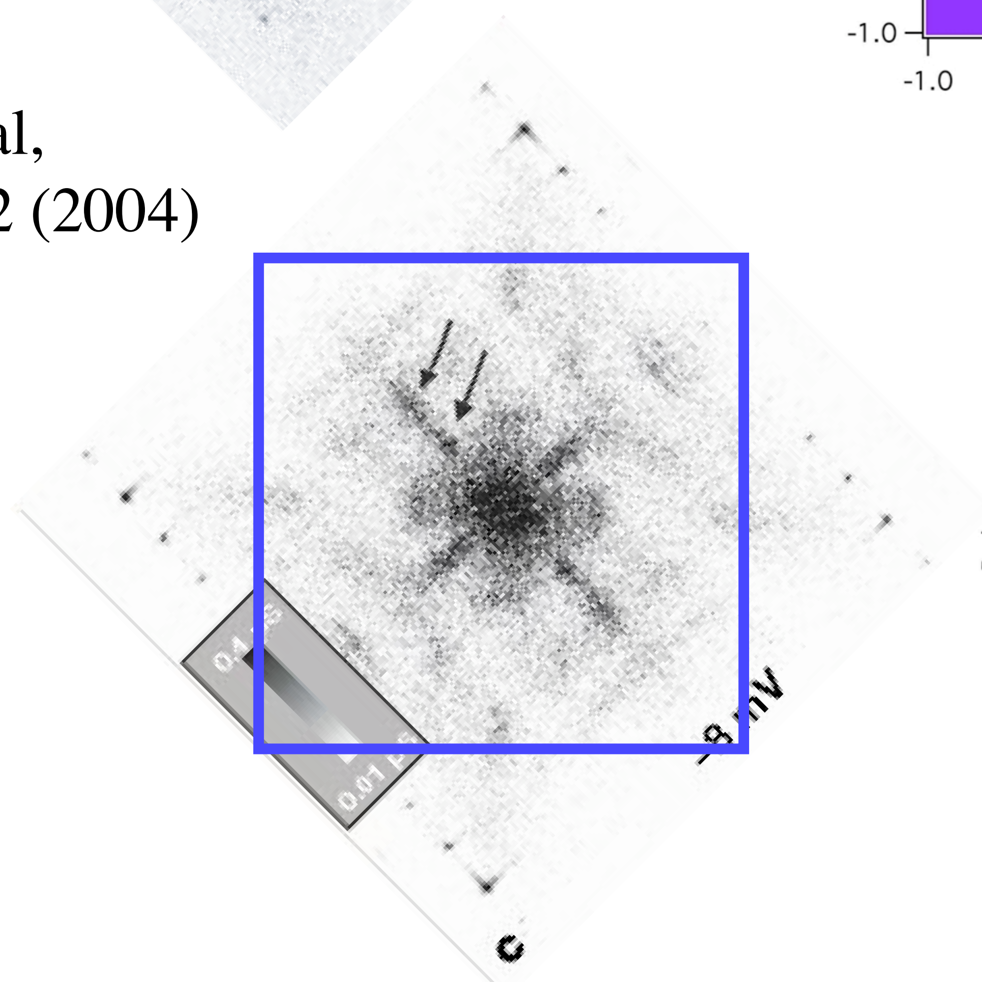
Comparison of FT STM and AC ARPES

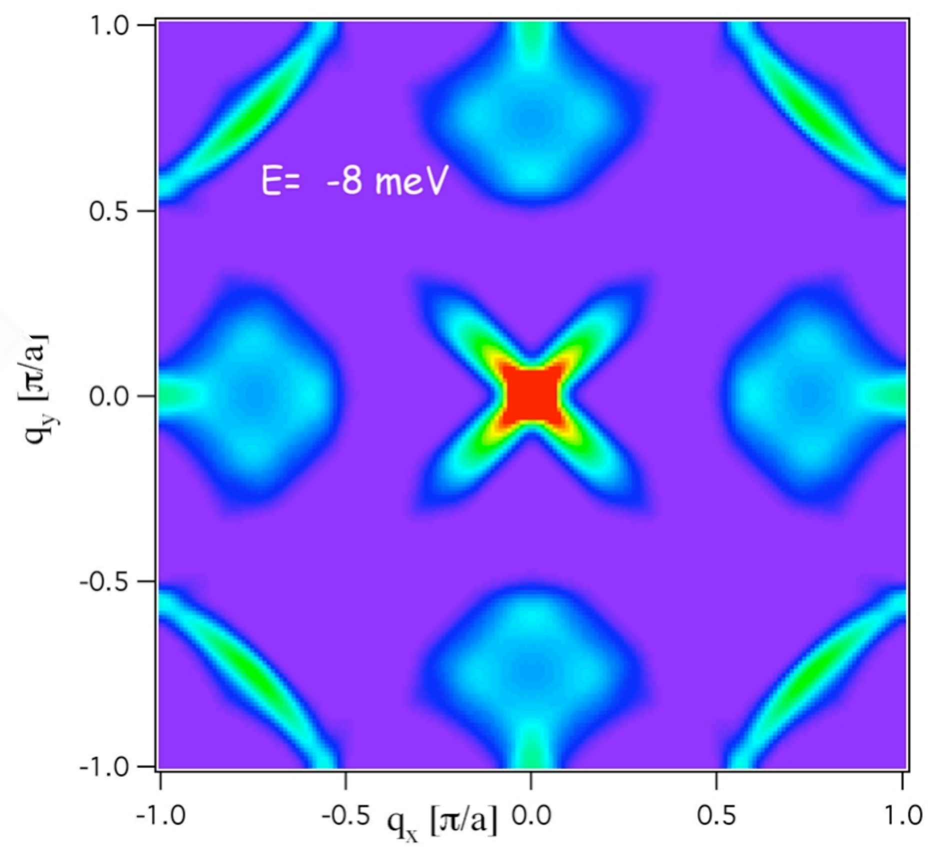




U. Chatterjee et al, *Phys. Rev. Lett.* *(submitted)*

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





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Conclusions:

- ARPES is an excellent probe to study electronic properties of strongly correlated systems such as heavy fermion systems and high temperature superconductors

- the only relevant feature in electronic structure for high temperature superconductivity is a hole pocket Fermi surface centered at $k_x=k_y=1$
- bridging the results from ARPES and FT STM will lead to better understanding of low energy excitations and possibly high temperature superconductivity