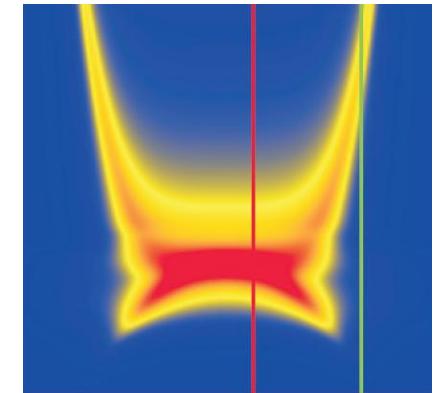
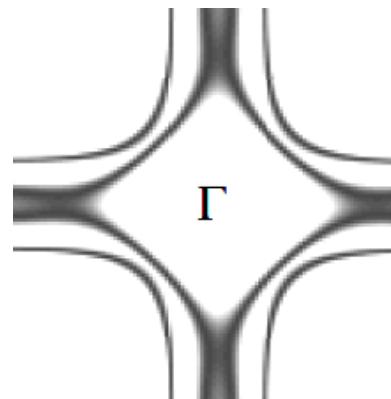
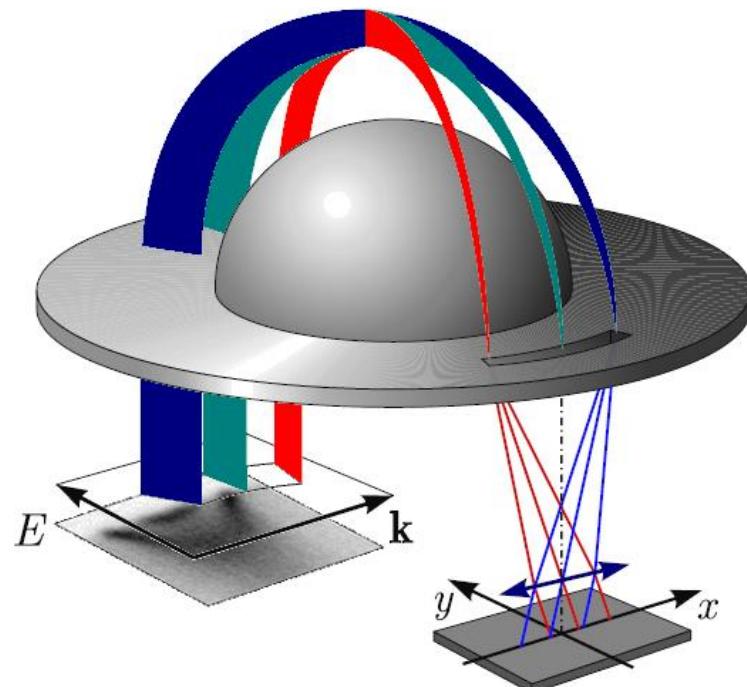
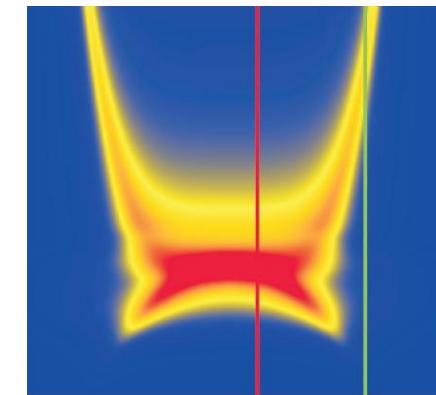
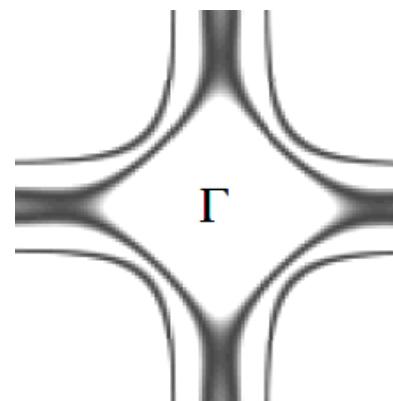
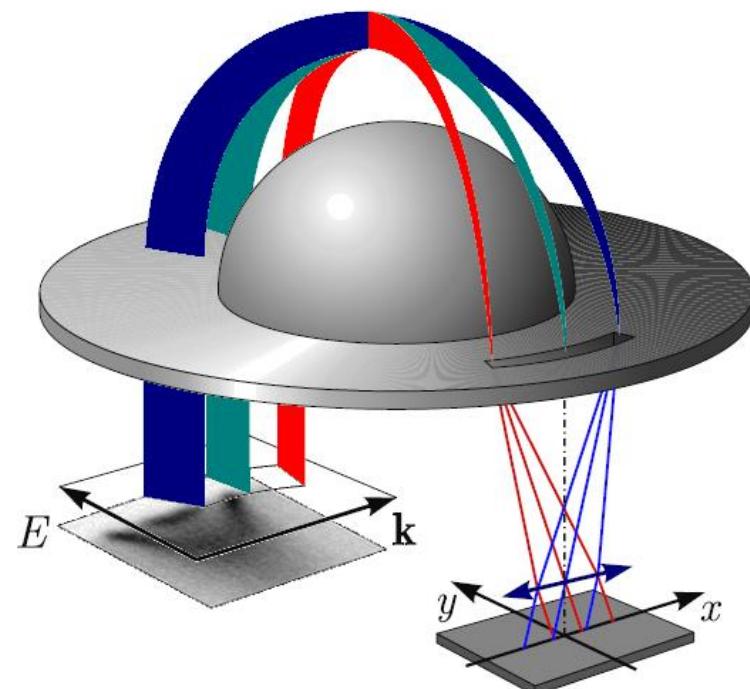


ARPES — фотоэлектронная спектроскопия квазидвумерных металлов



[А. А. Кордюк](#)
Институт металлофизики
им. Г.В. Курдюмова НАН Украины

ARPES — photoelectron spectroscopy of quasi-2D metals



[A. A. Kordyuk](#)
Institute of Metal Physics
Kyiv, Ukraine

"entities should not be multiplied beyond necessity"

Occam's razor

**Electronic band structure defines electro-magnetic properties of metals
(inc. “strongly correlated”)**

Plan

- **Electronic structure** (intro 1)
- ... and ARPES (intro 2)
- **HTSC cuprates**: ARPES on HTSC and electron-spin interaction
- **TM dichalcogenides**: electron instability and Fermi surface nesting
- **Iron-based superconductors**: Fermi surface topology
- **Topological insulators**: topologically protected surface states

Electronic structure

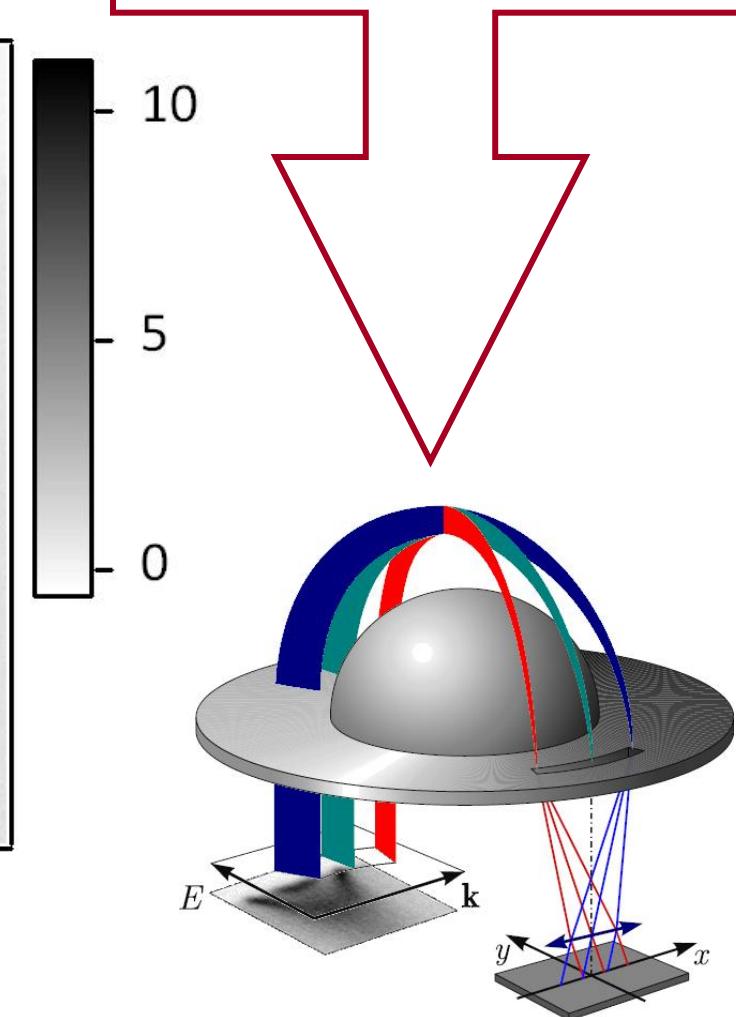
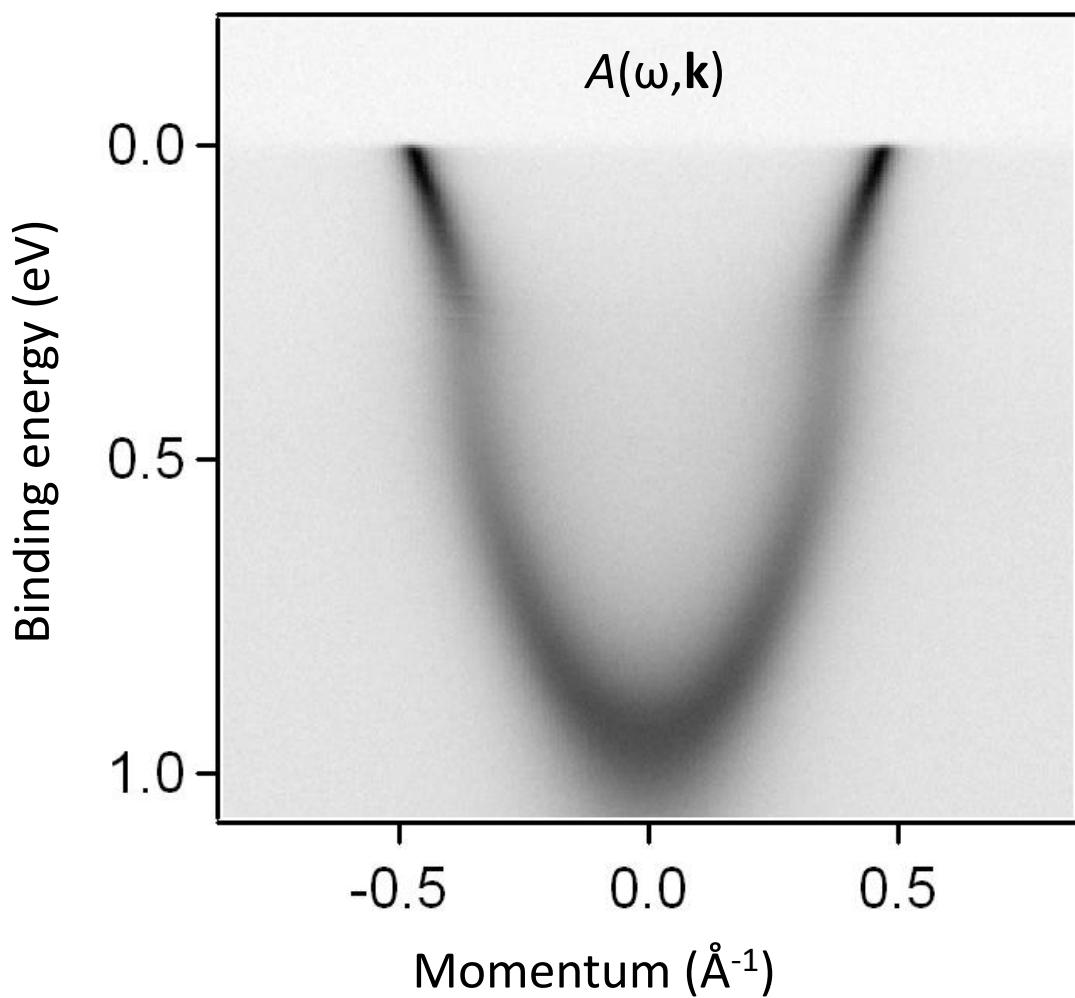
Electronic spectrum

=

Spectrum of one-electron excitations

=

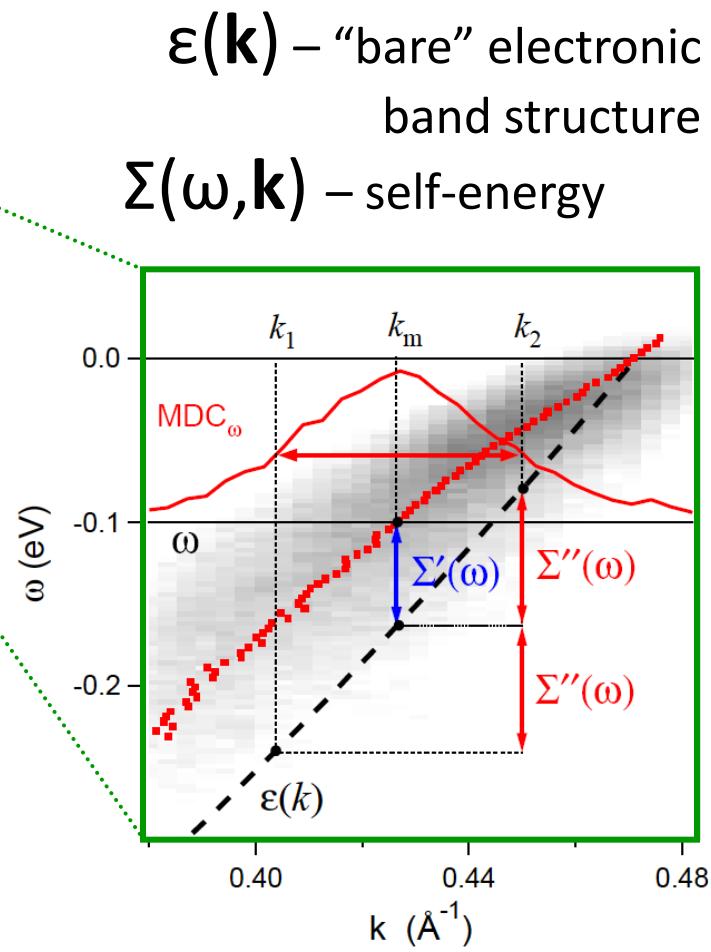
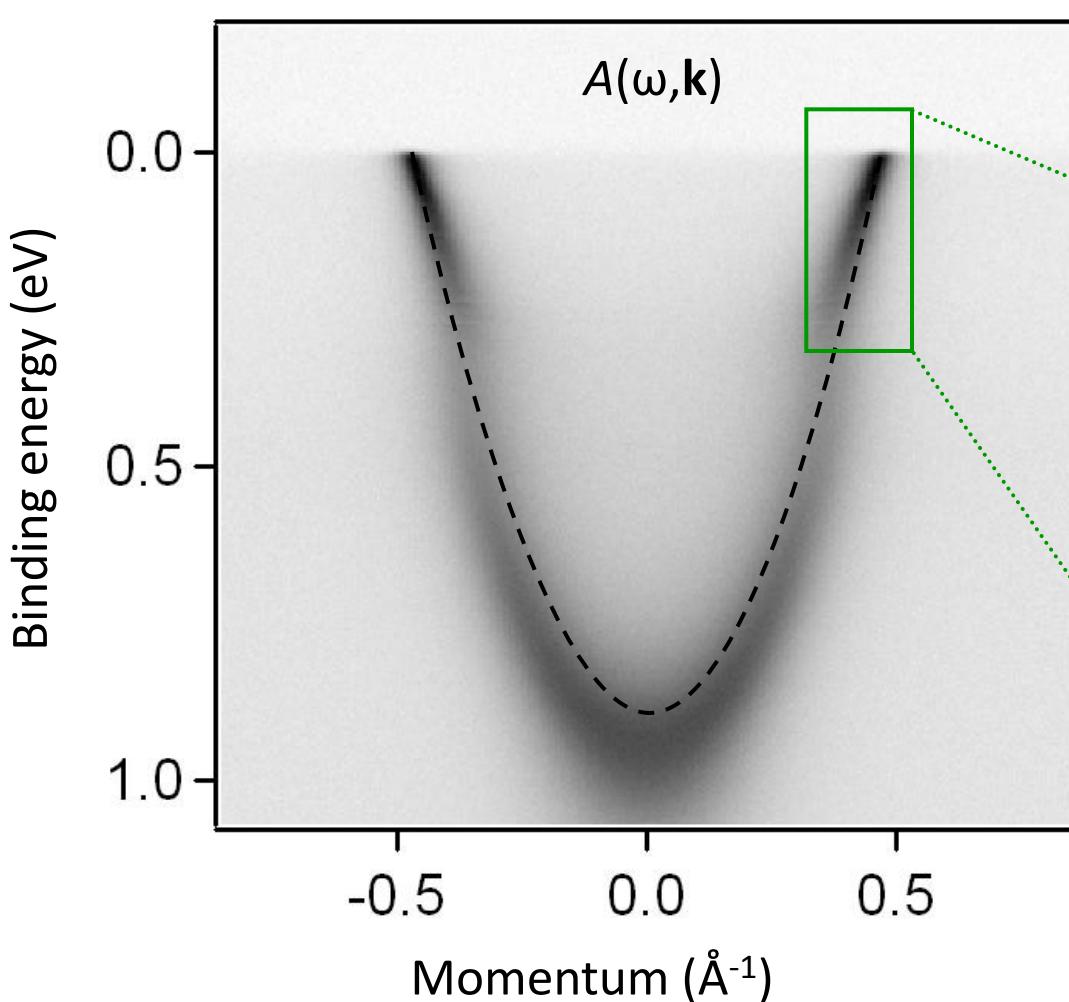
Probability to find electron with momentum \mathbf{k} and energy ω



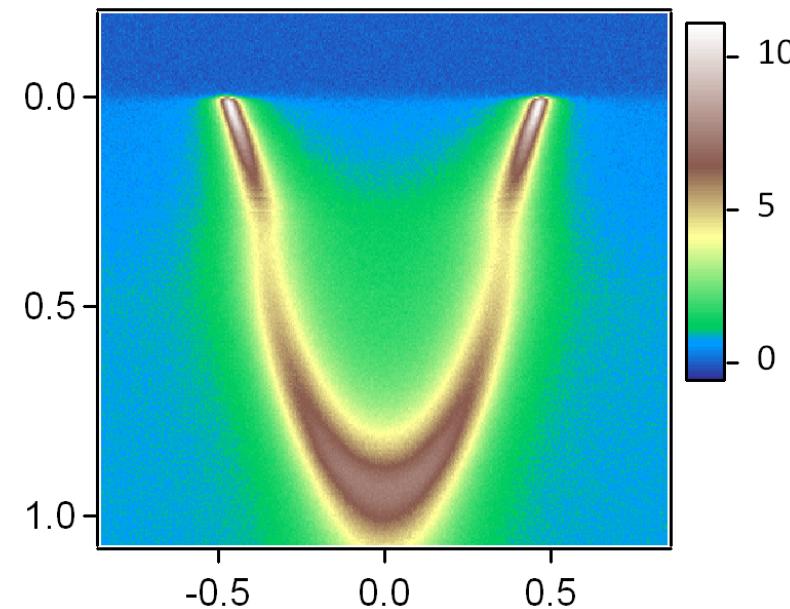
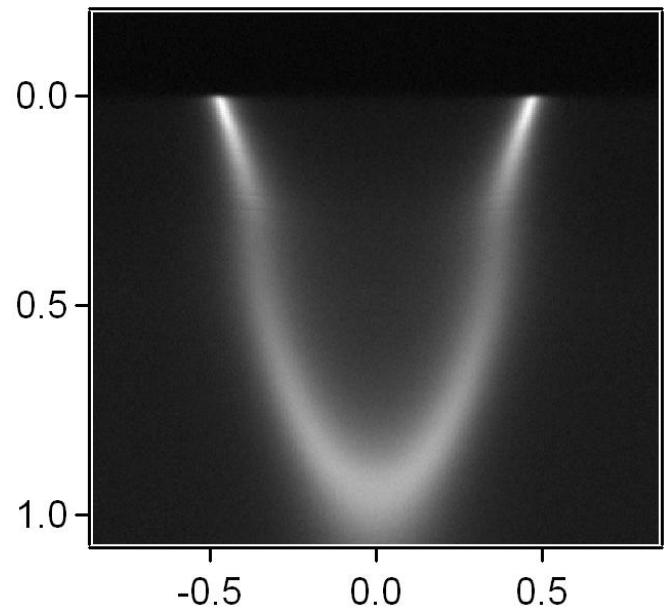
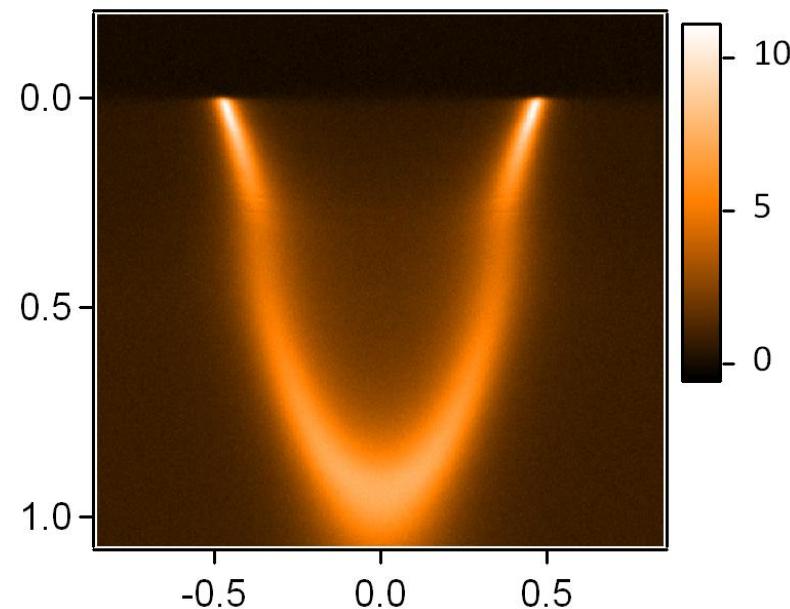
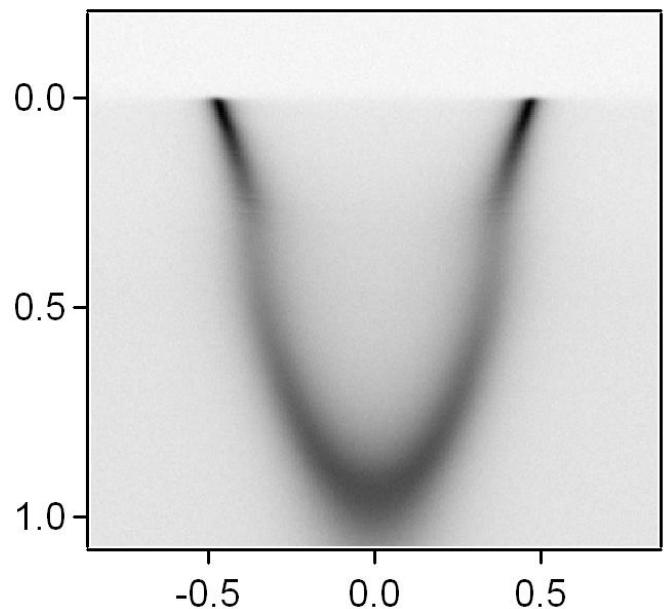
Structure of electronic spectrum

Spectral function

$$A(\omega, \mathbf{k}) = -\frac{1}{\pi} \frac{\Sigma''(\omega)}{(\omega - \varepsilon(\mathbf{k}) - \Sigma'(\omega))^2 + \Sigma''(\omega)^2}$$

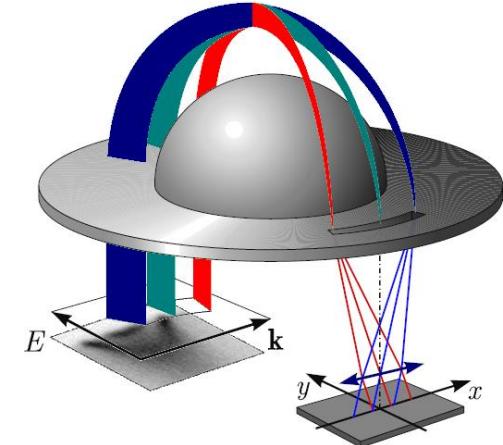
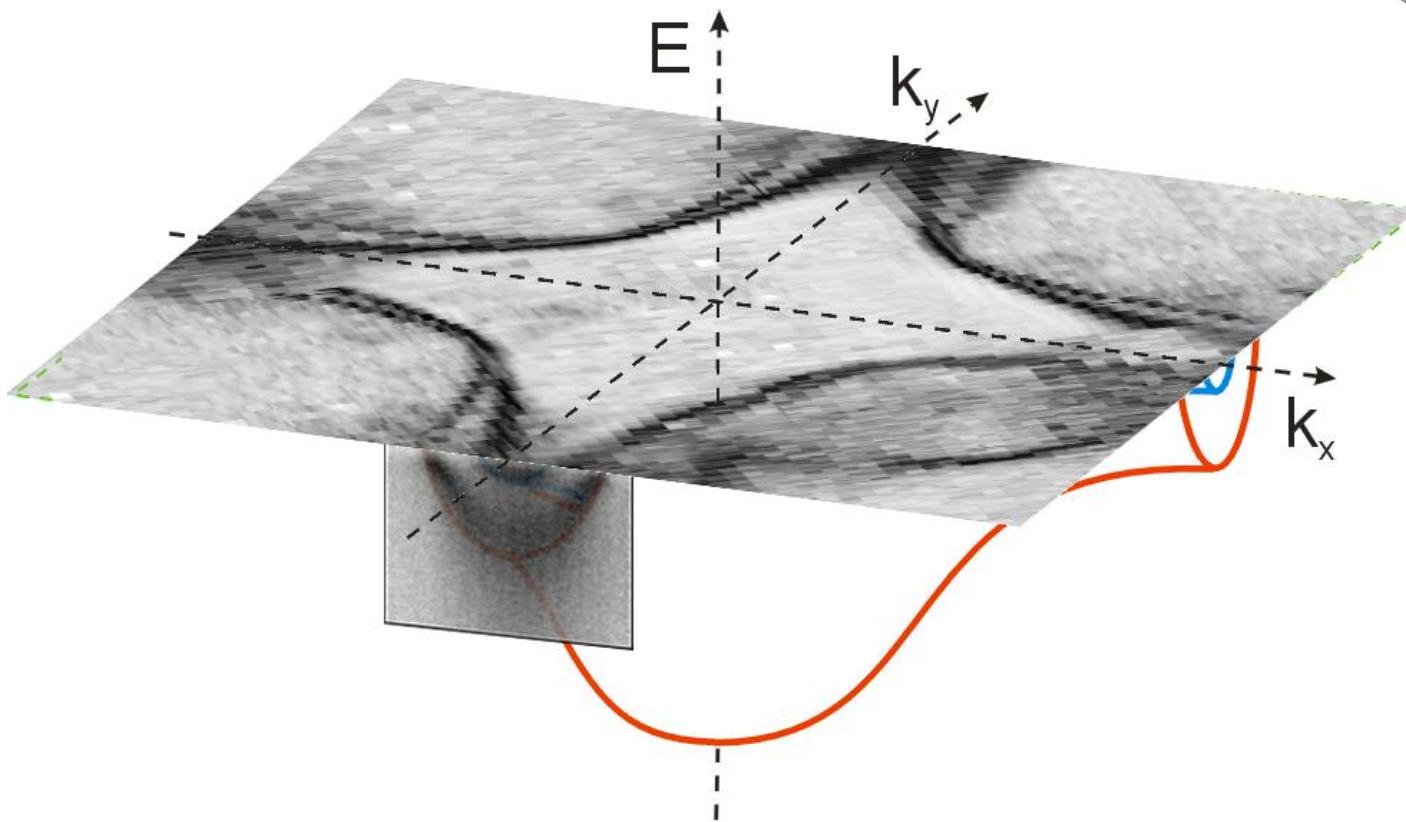


ARPES spectrum: color scales

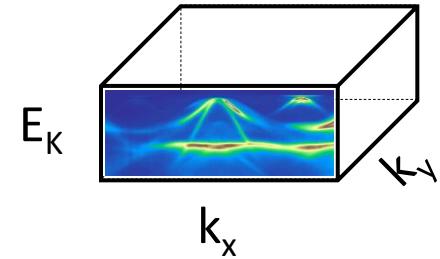


Electronic spectrum of quasi-2D crystals

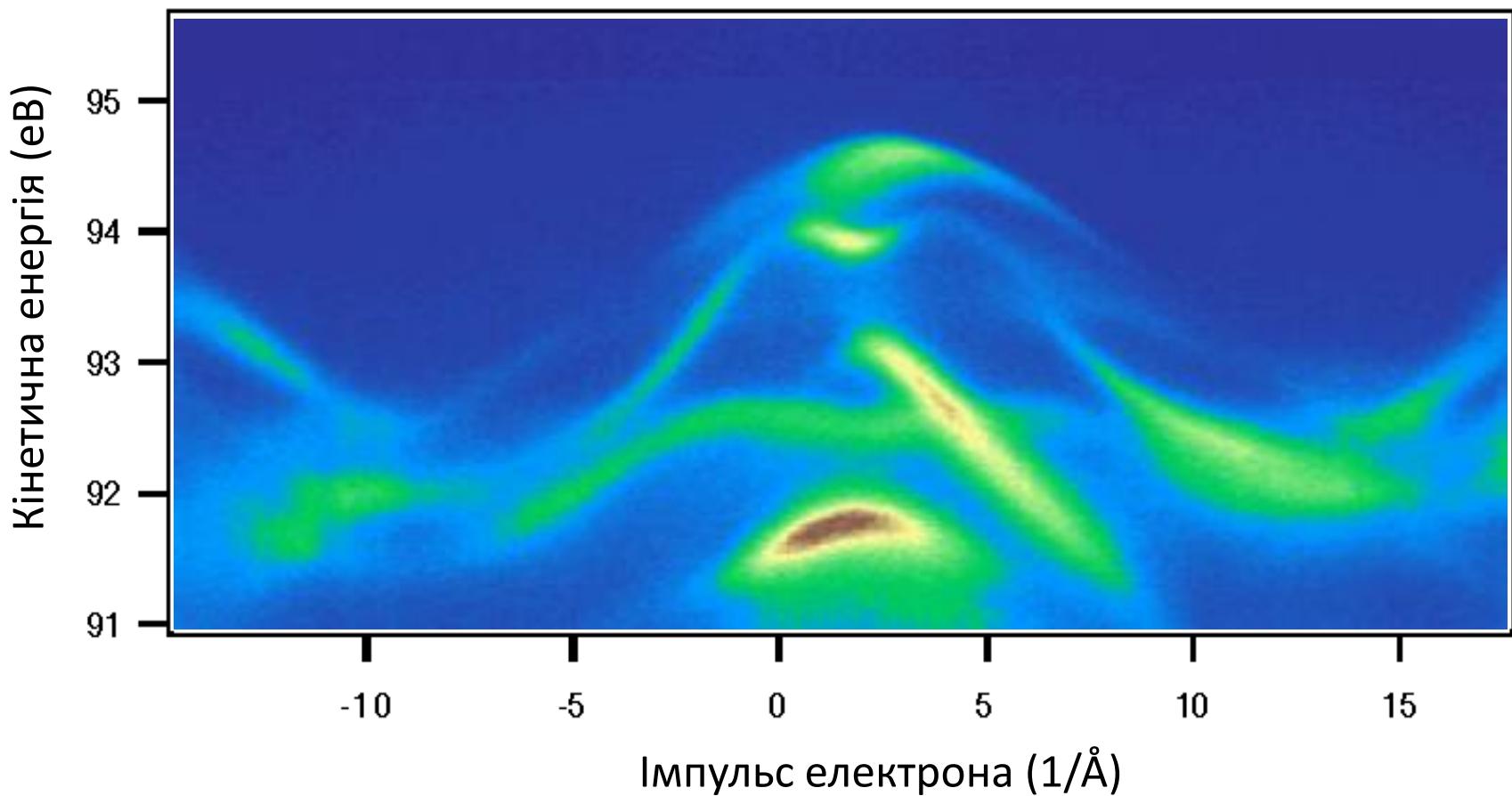
$$\varepsilon(k_x, k_y) \rightarrow A(\omega, k_x, k_y)$$



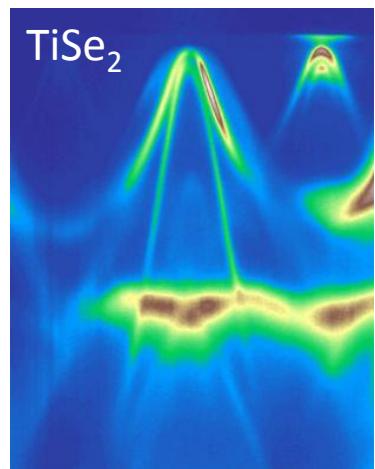
Electronic spectrum in momentum-energy 3D space



TiSe_2 - «ексітонний ізолятор»

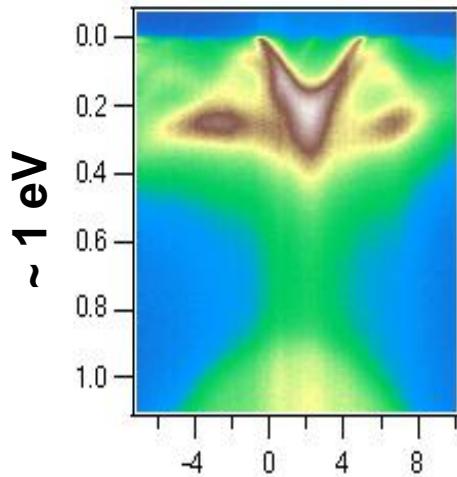


Valence band



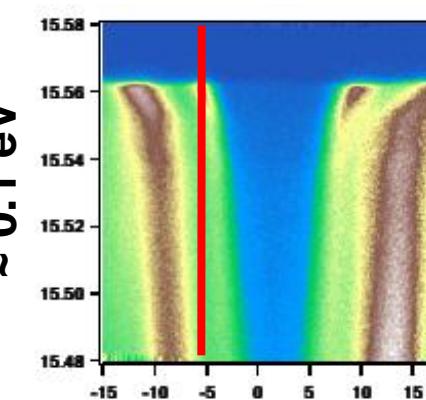
$\sim 5 \text{ eV}$

Conduction band



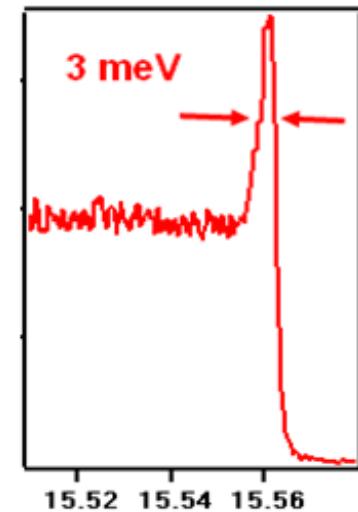
$\sim 1 \text{ eV}$

Phonon spectrum



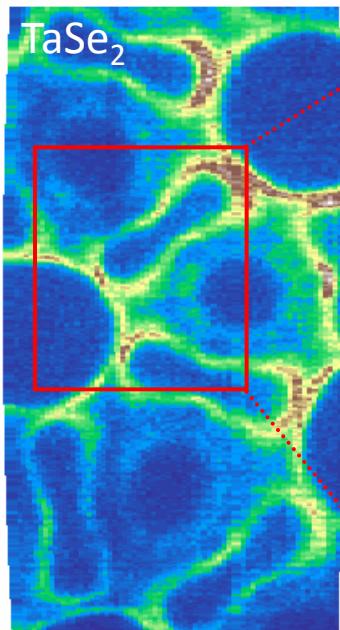
$\sim 0.1 \text{ eV}$

EDC



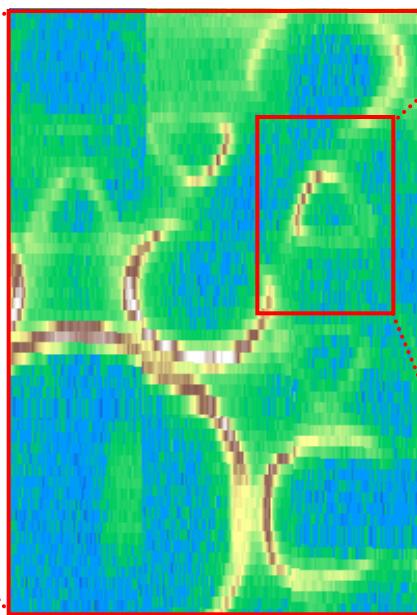
3 meV

$\sim 5 \text{ \AA}^{-1}$



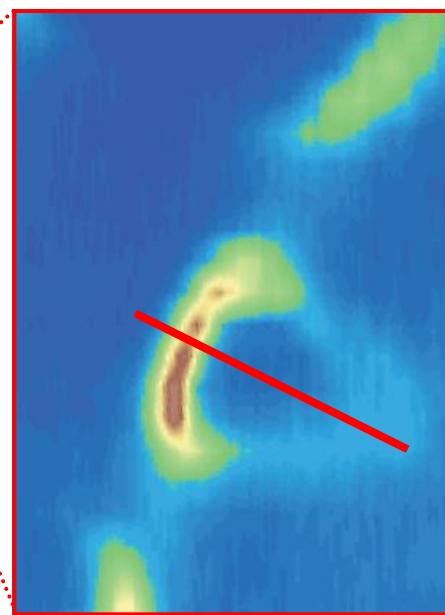
Fermi surface

$\sim 1 \text{ \AA}^{-1}$



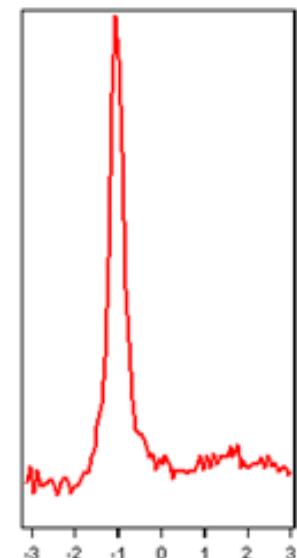
1-st Brillouin zone

$\sim 0.1 \text{ \AA}^{-1}$



A few Brillouin zones

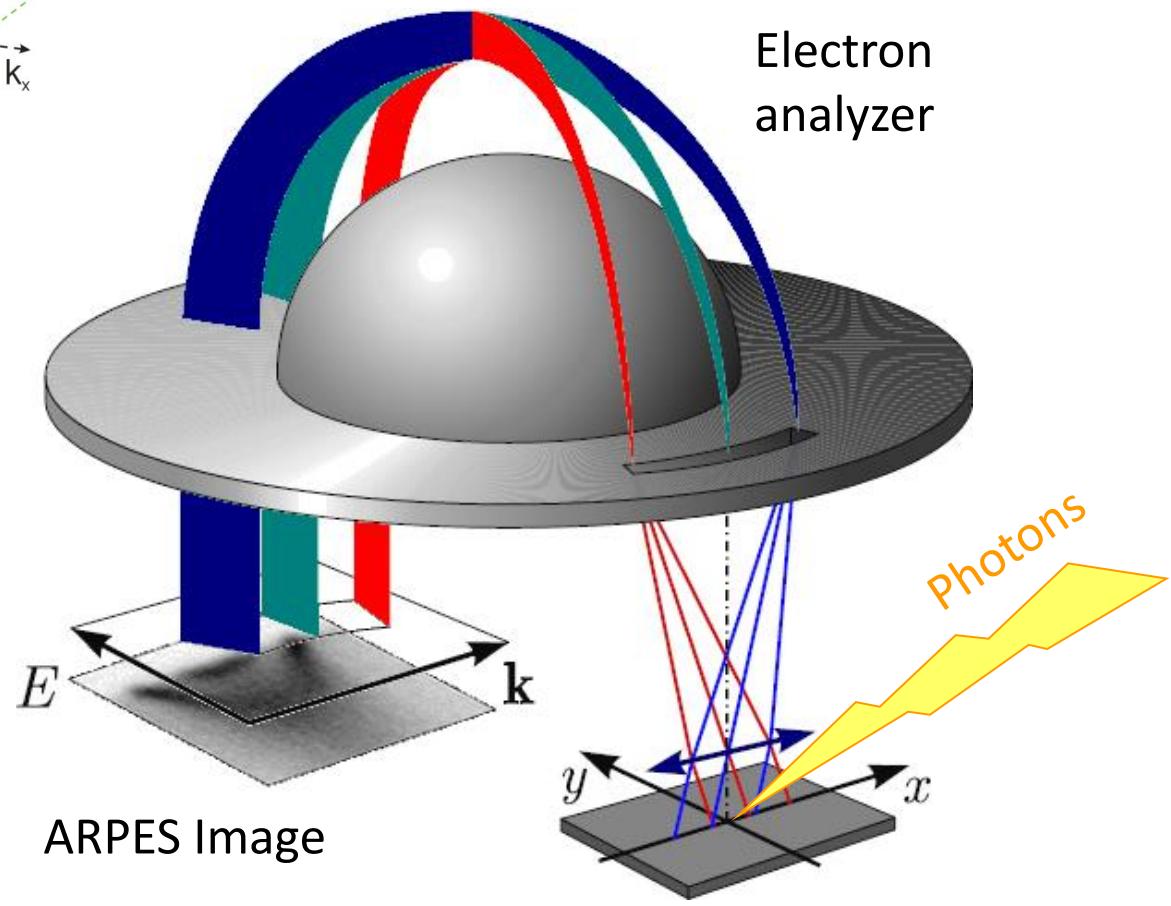
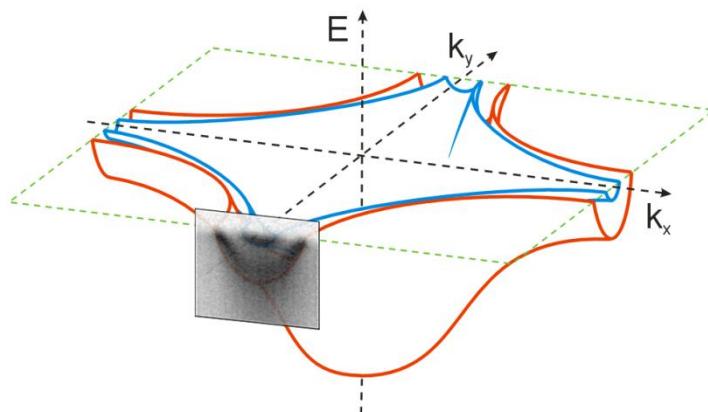
MDC



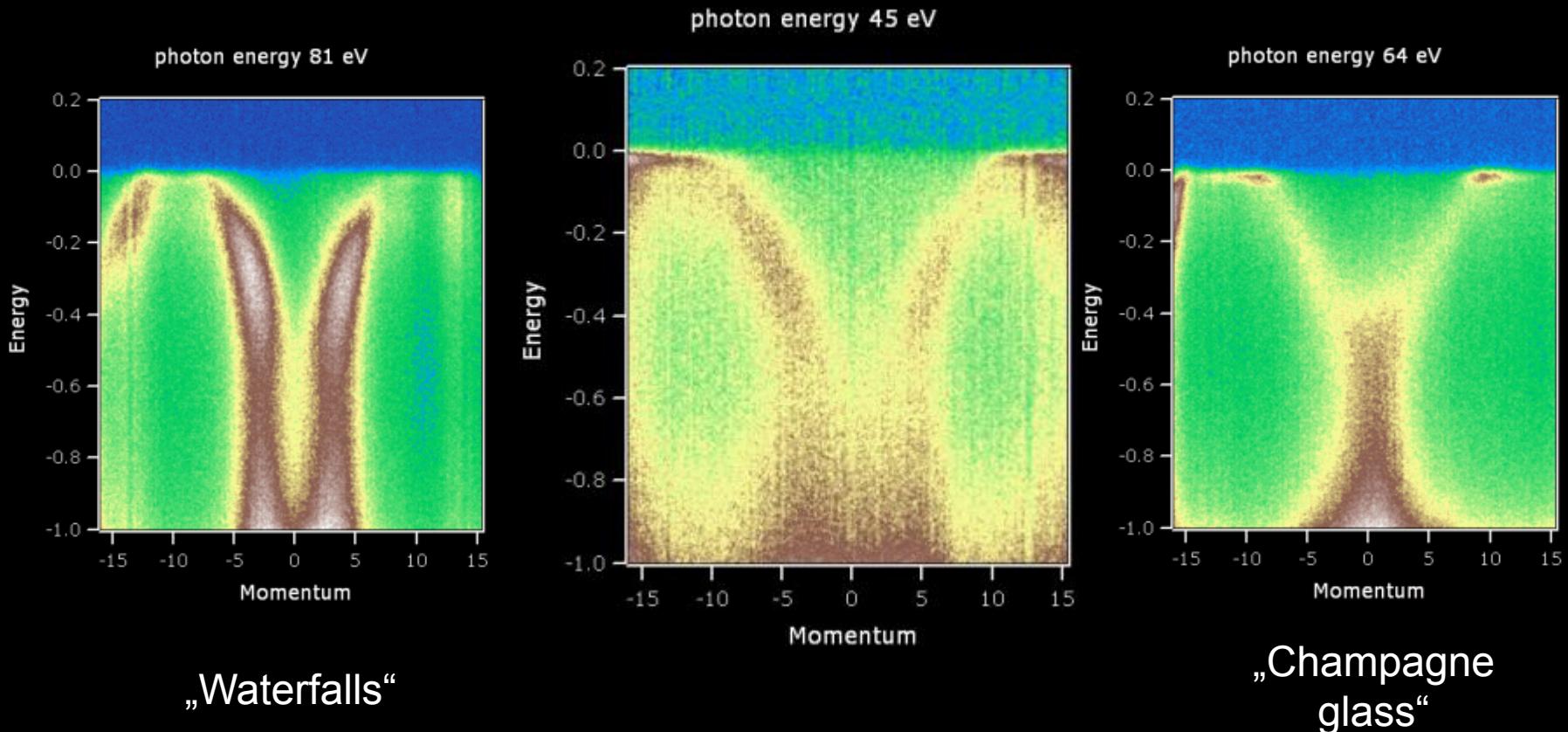
Part of Fermi surface

ARPES: Angle Resolved Photoelectron Spectroscopy

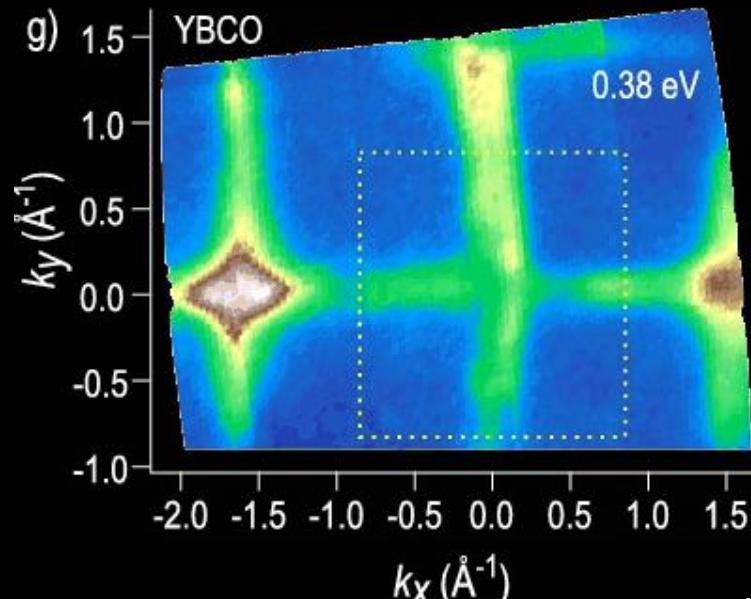
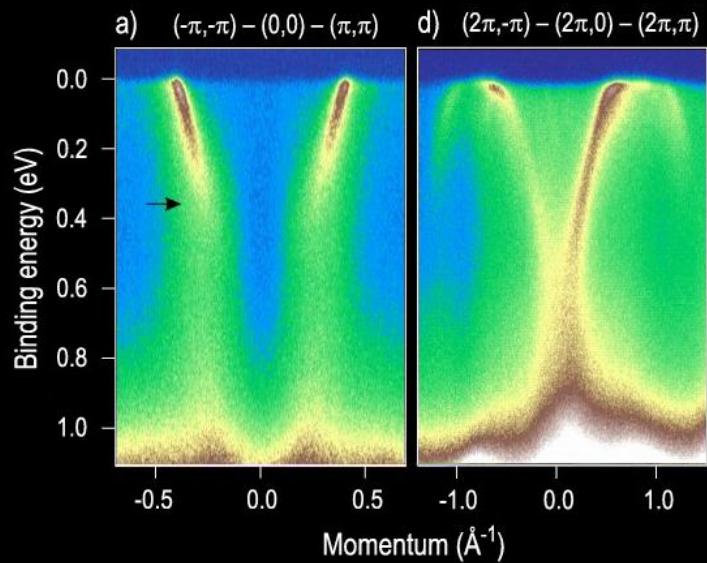
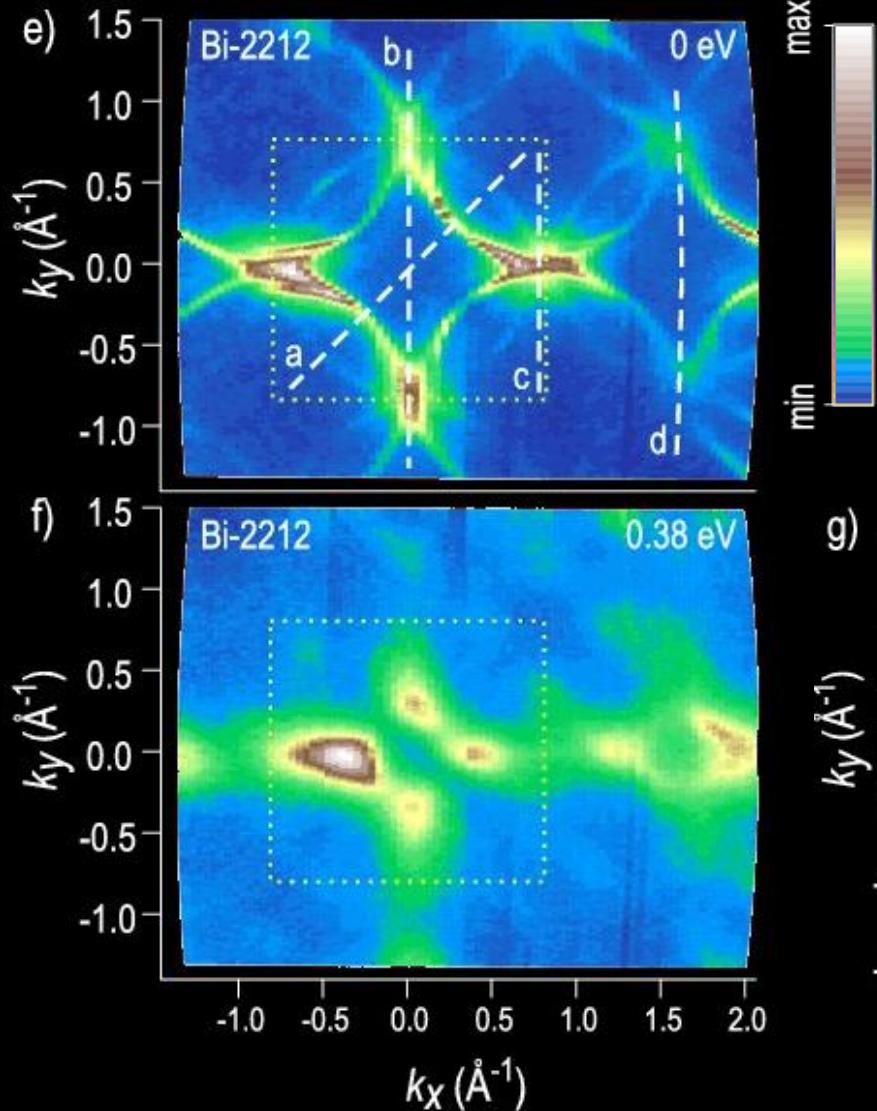
ARPES
=
photo effect
+
analyzer
+
manipulator



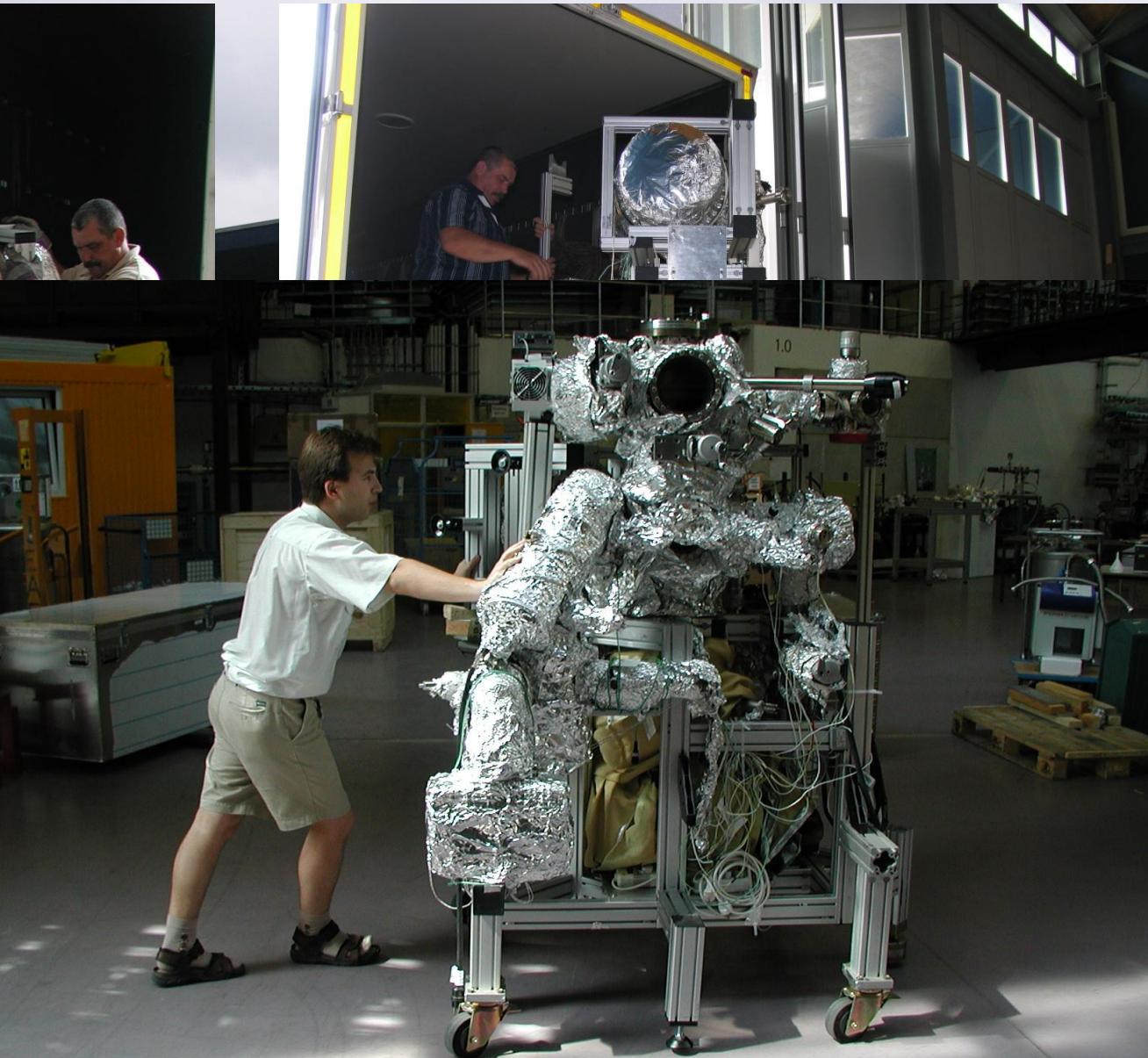
Photon energy – an important parameter



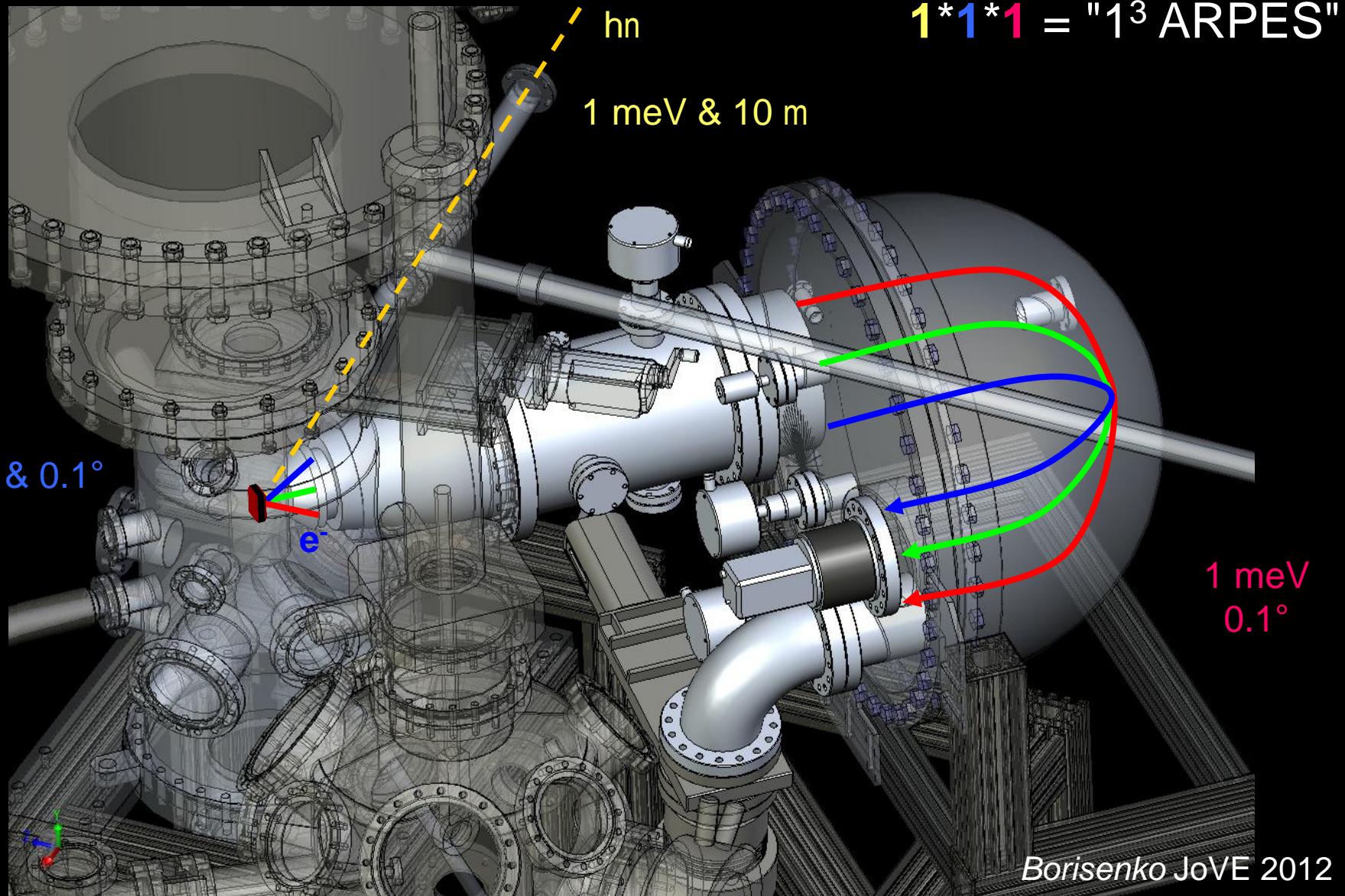
Waterfalls in cuprates



...travelling chamber

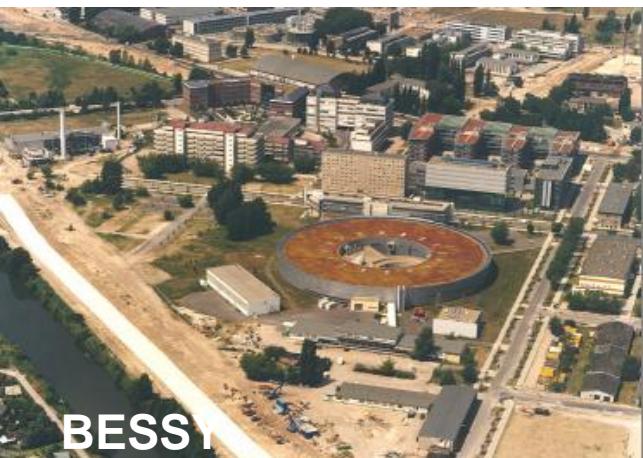


ARPES anatomy



ARPES =

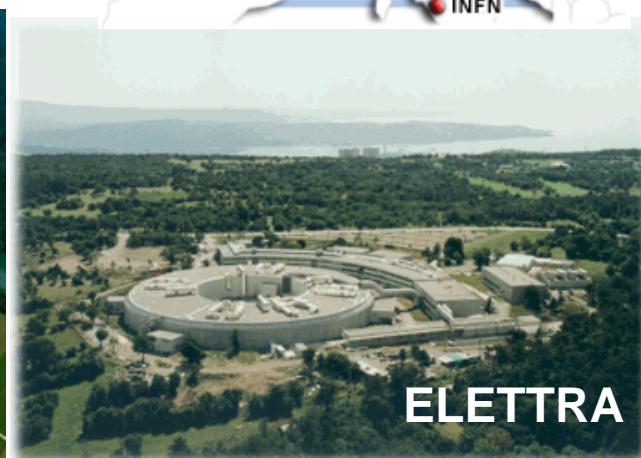
analyzer + manipulator (10^6 €)
+ synchrotron



BESSY



SLS



ELETTRA

- New direction:
time resolved ARPES,
XFEL



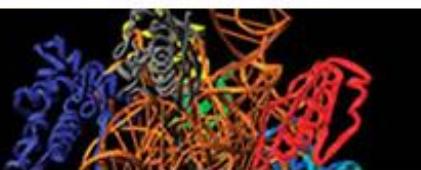
XFEL



European X-ray Free Electron Laser



TINY STRUCTURES



Examples

- Deciphering the structure of biomolecules
- Exploring the nanoworld in 3D

Experiment stations

SPB, SCS and MID

ULTRAFAST PROCESSES



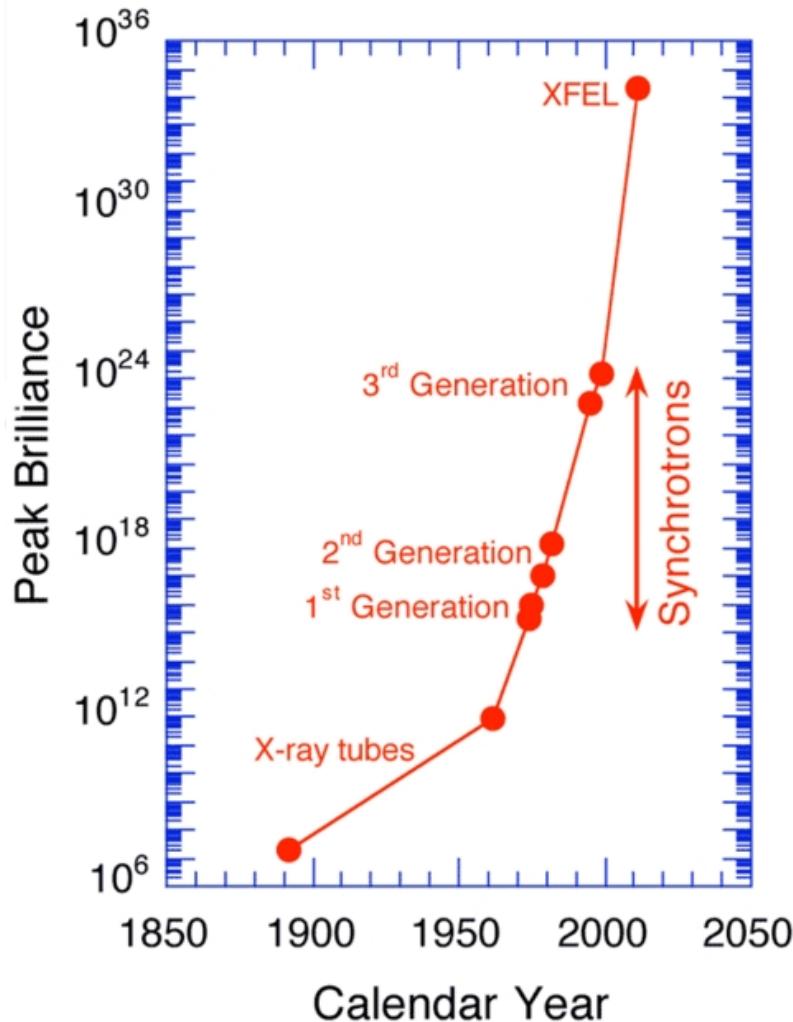
Examples

- Filming chemical reactions
- Unravelling magnetization

Experiment stations

SPB, MID, FXE, HED, SQS, SCS

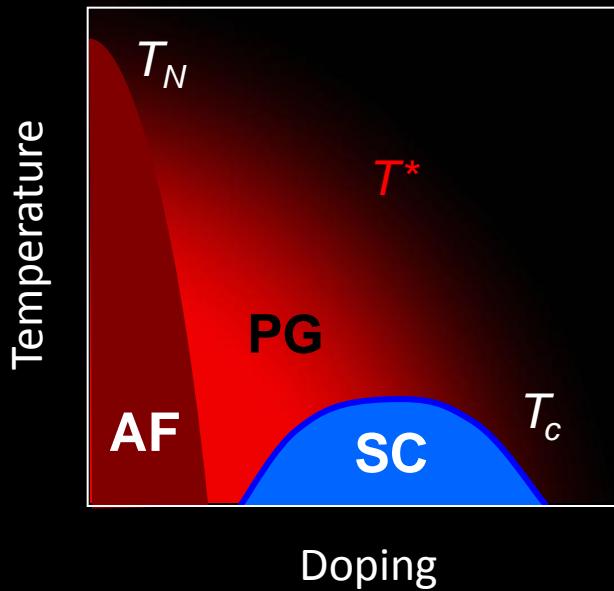
2009-2015: ~ 1 000 000 000 €



HTSC cuprates

HTSC cuprates: electron-spin interaction

1986 ...



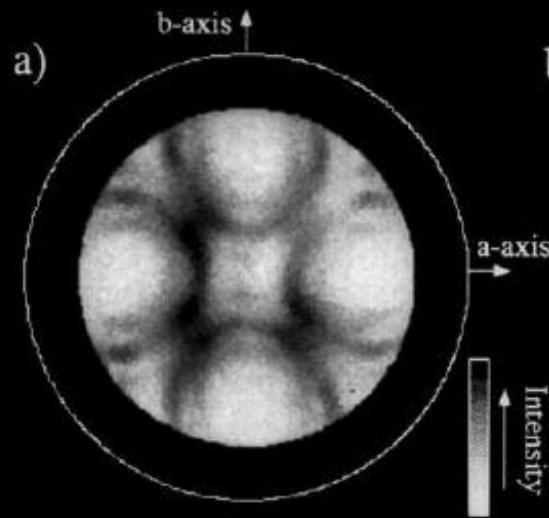
Anti-ferromagnet – metal transition?

What is “normal state”??

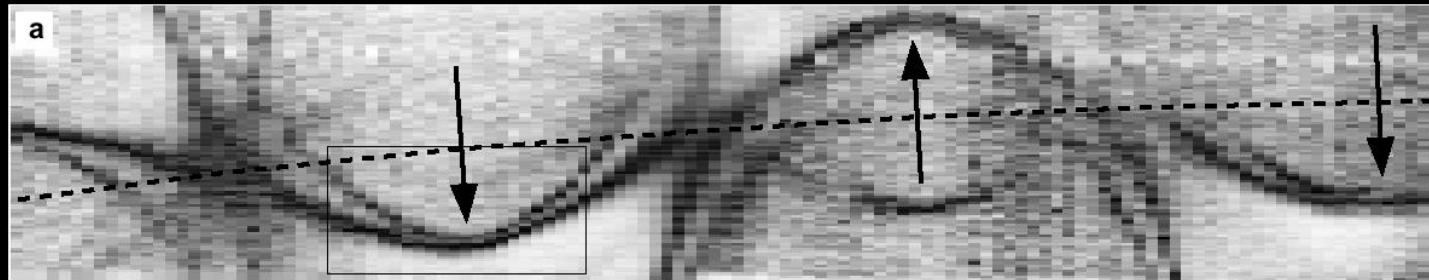
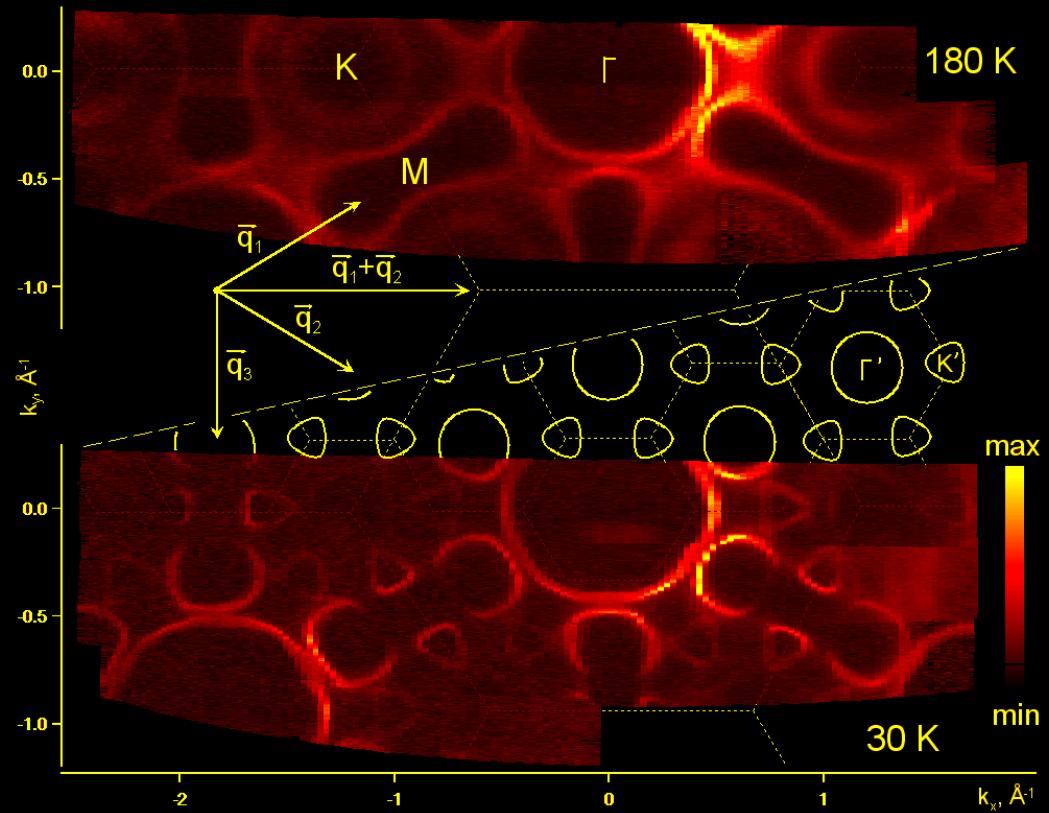
Pseudogap???

Mechanism of superconductivity????

ARPES in HTSC problem



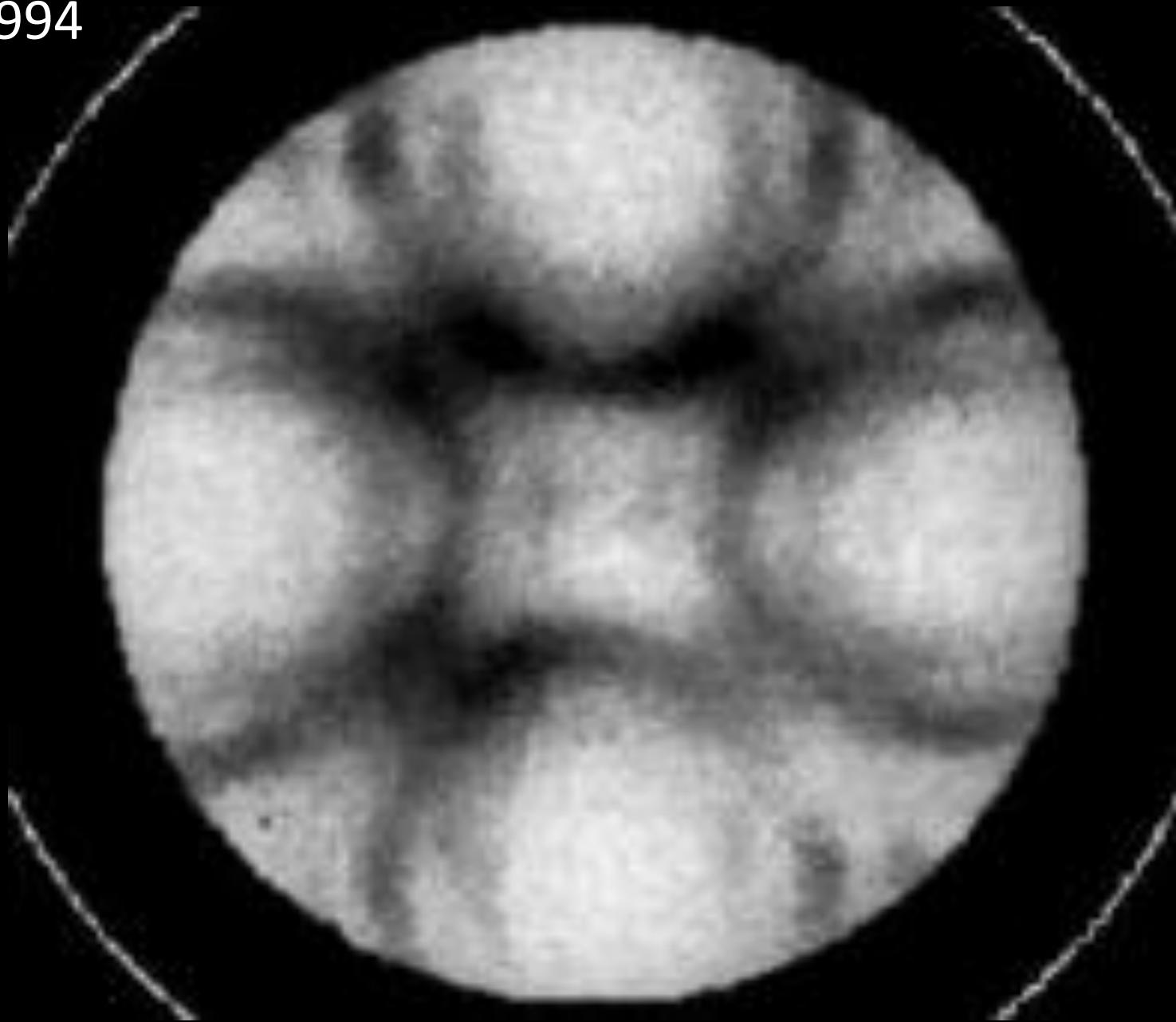
Aebi *PRL* 1994



Kordyuk *PRB* 2004

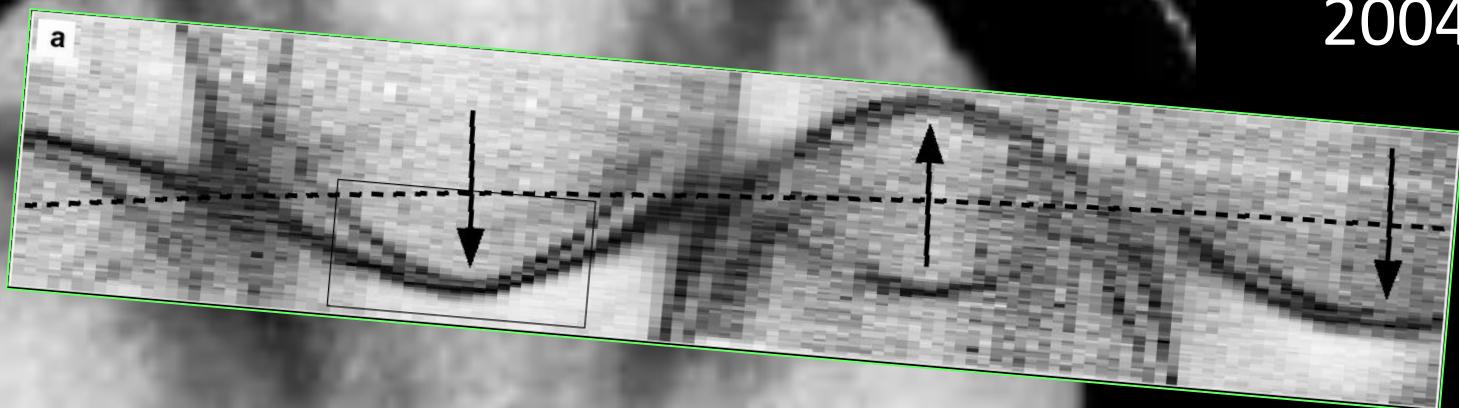
Borisenko *PRL* 2008

1994

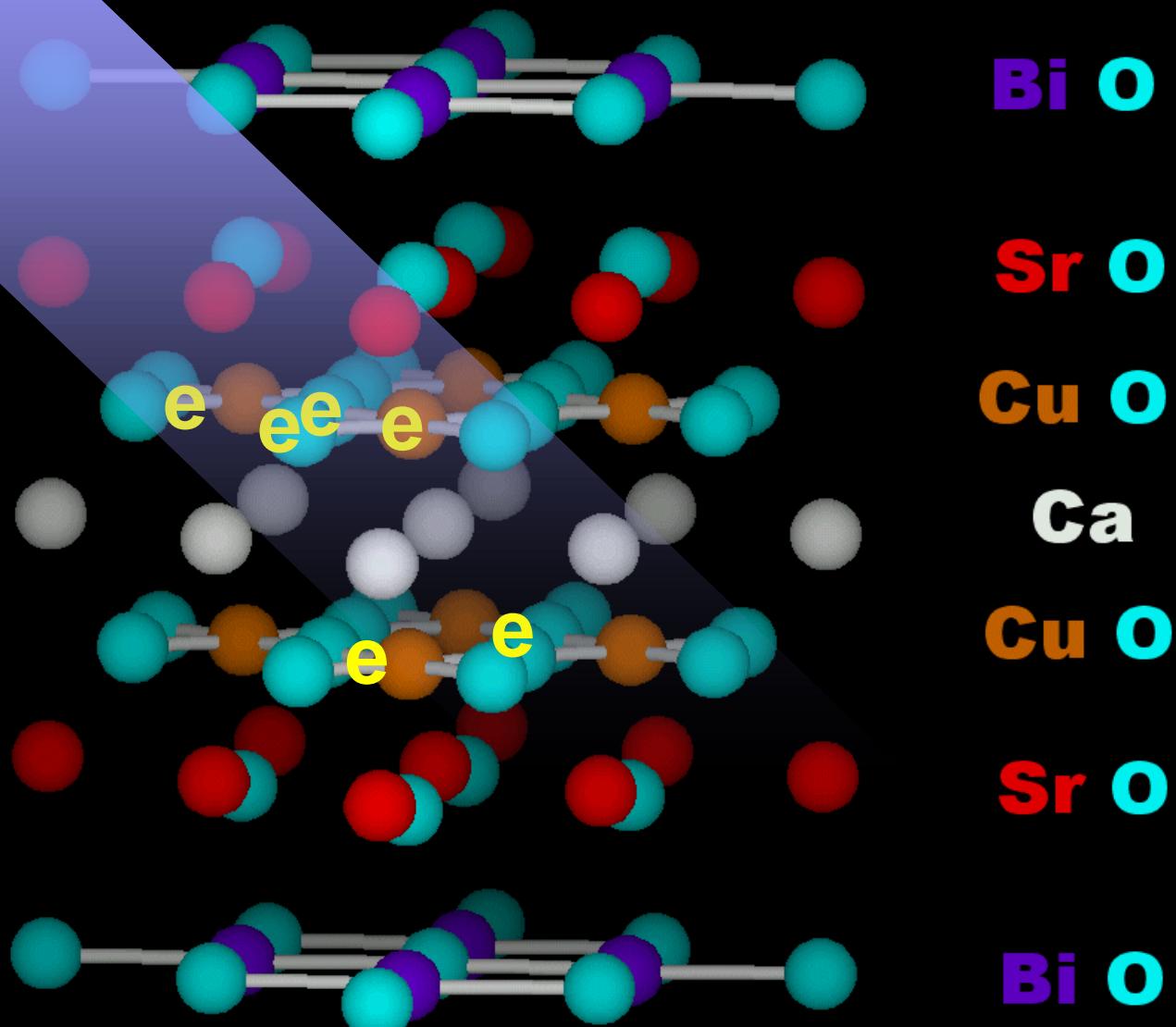


1994

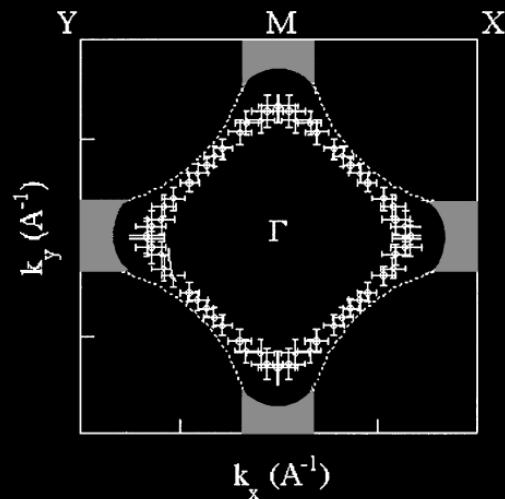
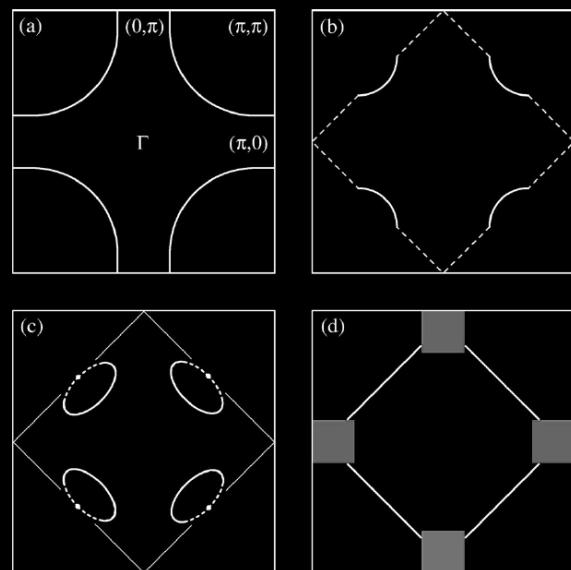
2004



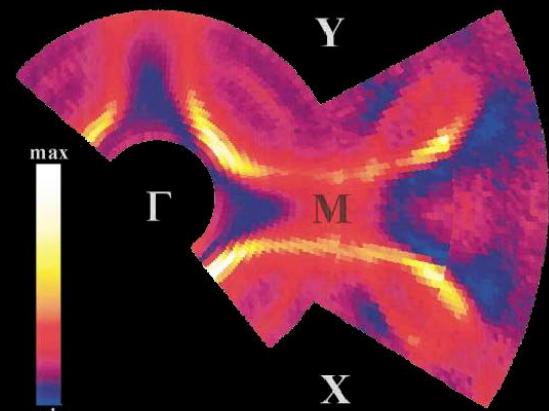
The most studied Bi-2212



Electronic structure of cuprates: FS topology

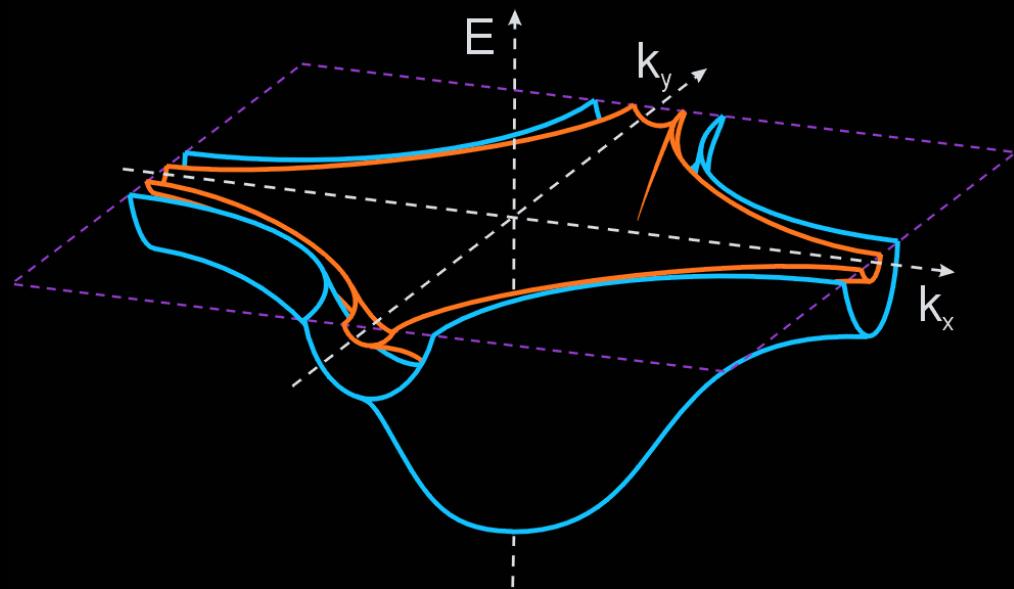


Bogdanov *PRL* 2000

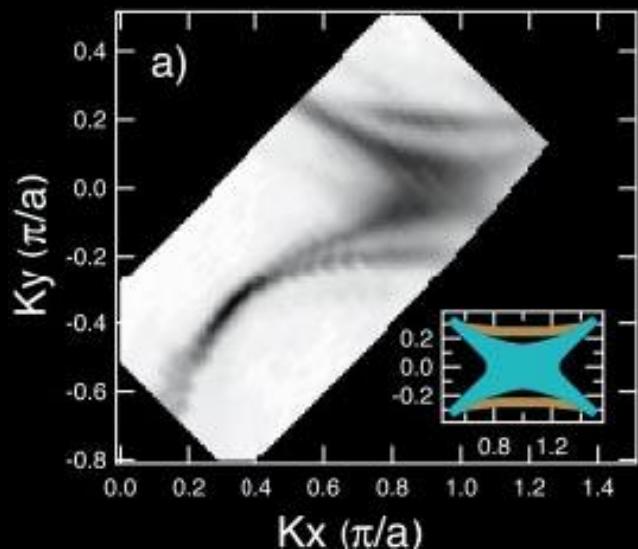
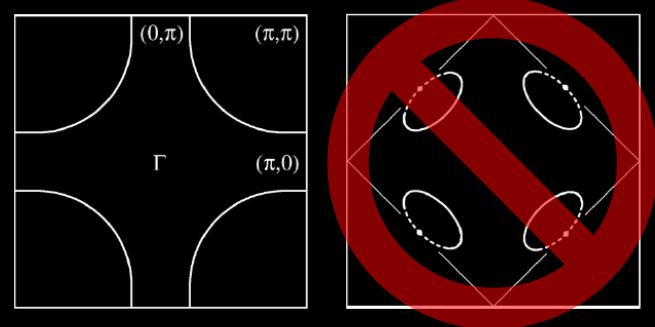
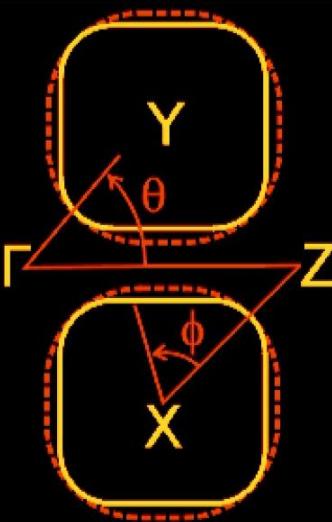
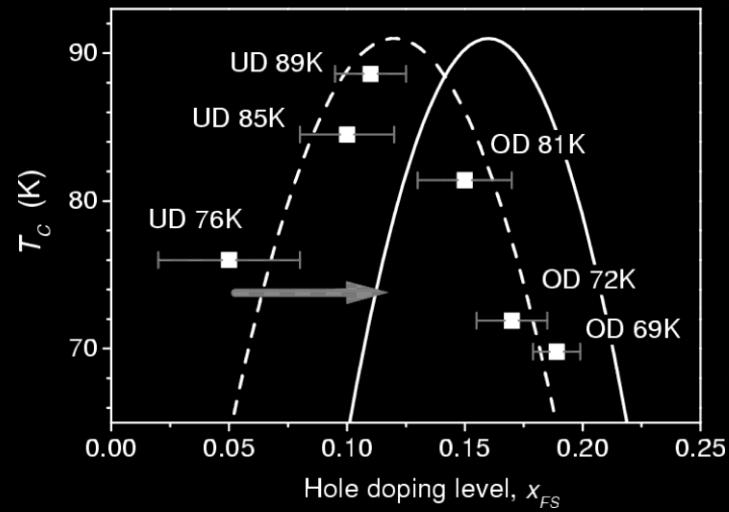
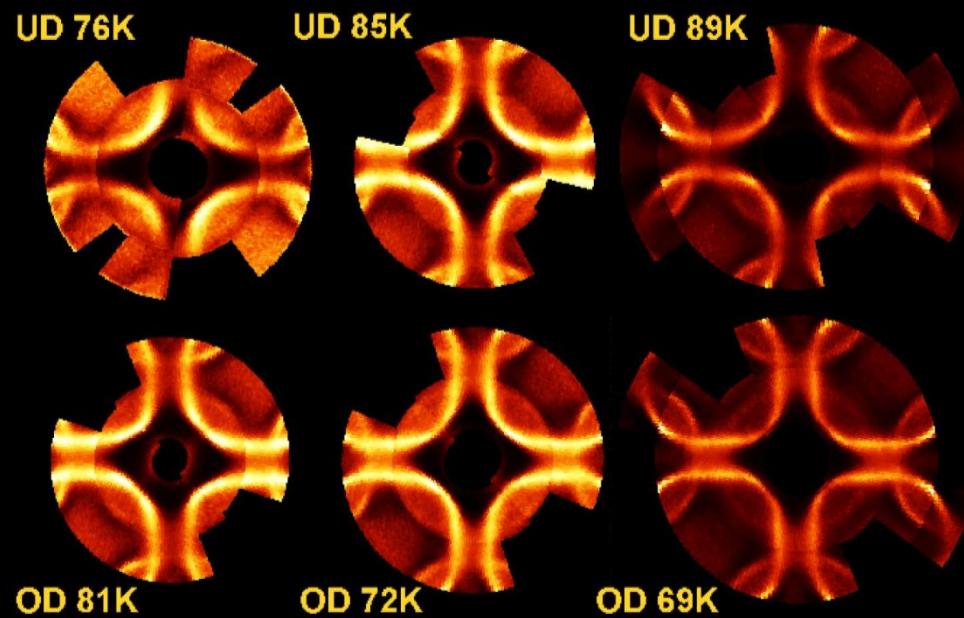


Borisenko *PRL* 2000

Damascelli *RMP* 2003



Electronic structure of cuprates: large FS and bilayer splitting

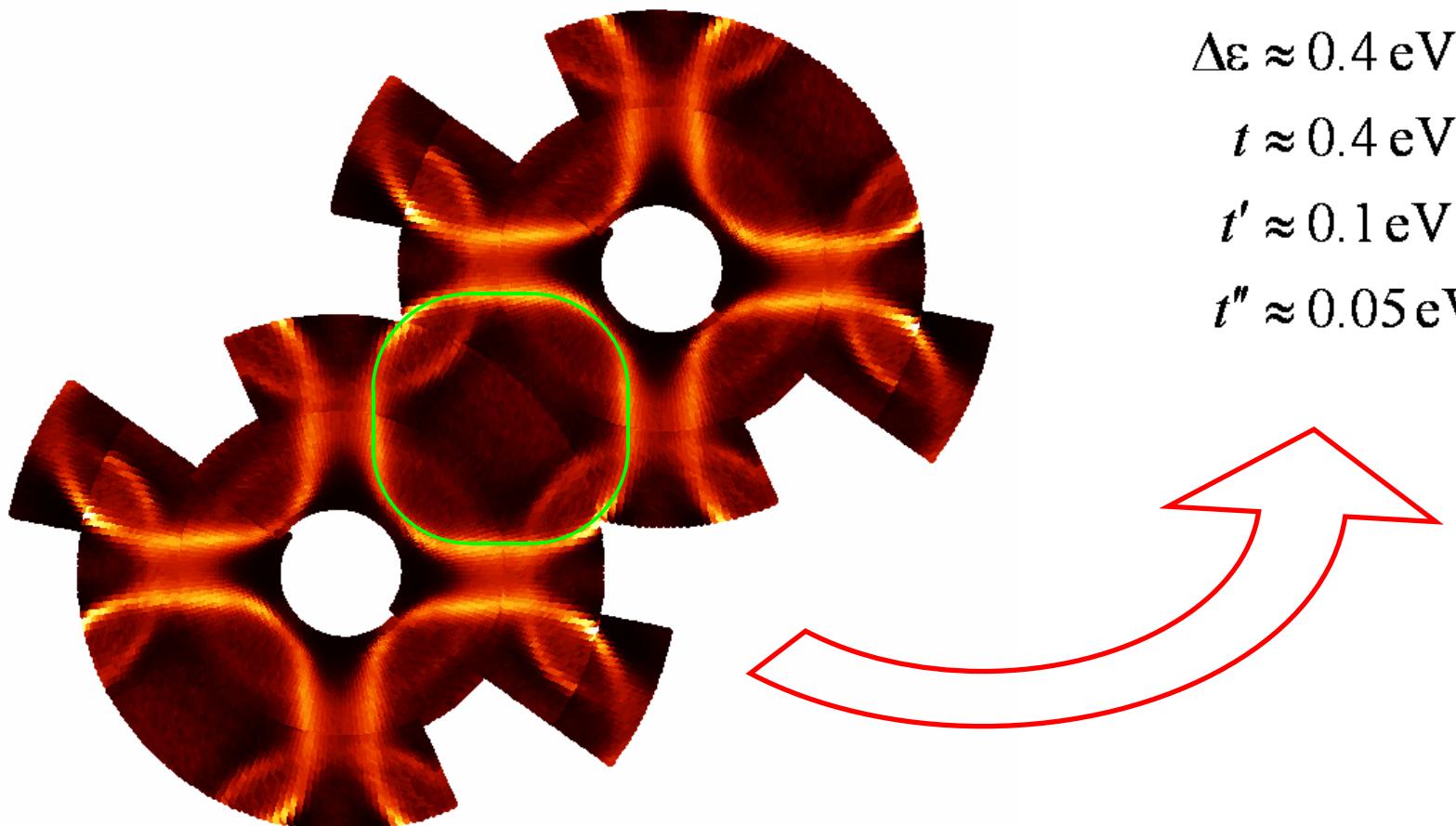


Kordyuk *PRB* 2002

Bogdanov *PRB* 2001
Feng *PRL* 2001

Band structure: TBF

$$\varepsilon(k_x, k_y) = \Delta\varepsilon - 2t(\cos k_x + \cos k_y) + 4t' \cos k_x \cos k_y - 2t''(\cos 2k_x + \cos 2k_y)$$



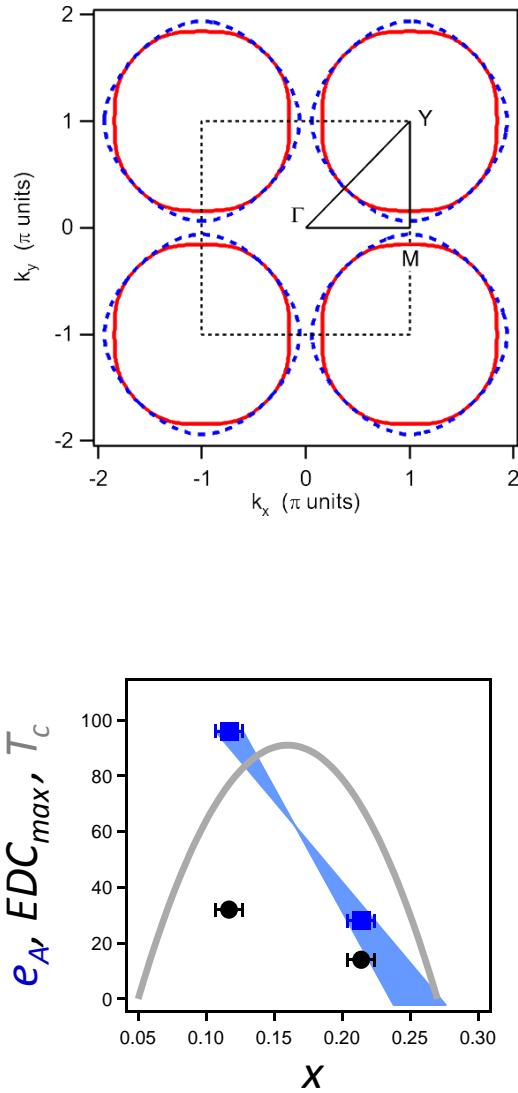
$$\Delta\varepsilon \approx 0.4 \text{ eV}$$

$$t \approx 0.4 \text{ eV}$$

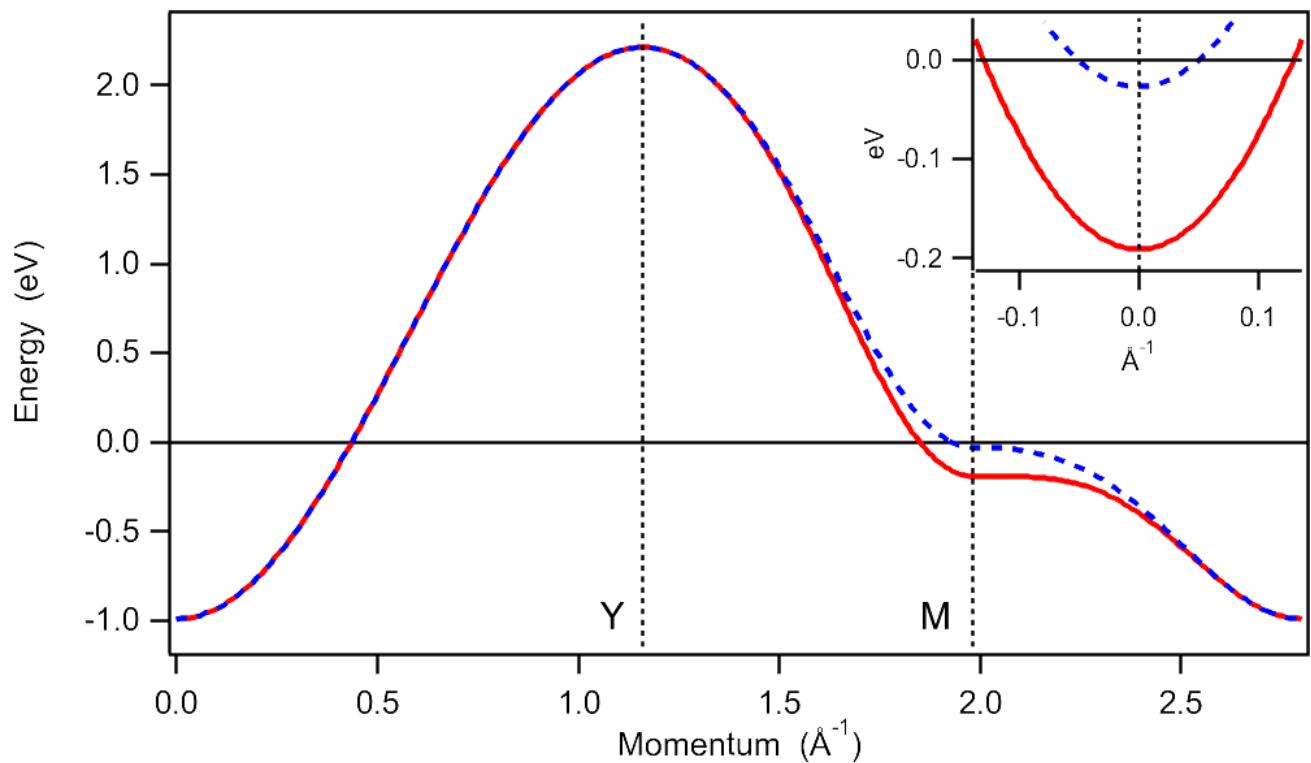
$$t' \approx 0.1 \text{ eV}$$

$$t'' \approx 0.05 \text{ eV}$$

Bare band structure



Sample	t (eV)	t' (eV)	t'' (eV)	t_\perp (eV)	$\Delta\epsilon$ (eV)
OD 69 K	0.40	0.090	0.045	0.082	0.43
UD 77 K	0.39	0.078	0.039	0.082	0.29



Bilayer splitting and peak-dip-hump (PDH)

VOLUME 79, NUMBER 18

PHYSICAL REVIEW LETTERS

3 NOVEMBER 1997

Unusual Dispersion and Line Shape of the Superconducting State Spectra of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$

M. R. Norman,¹ H. Ding,^{1,2} J. C. Campuzano,^{1,2} T. Takeuchi,^{1,3} M. Randeria,⁴ T. Yokoya,⁵ T. Takahashi,⁵ T. Mochiku,⁶ and K. Kadowaki^{6,7}

¹*Materials Sciences Division, Argonne National Laboratory, Argonne, Illinois 60439*

²*Department of Physics, University of Illinois at Chicago, Chicago, Illinois 60607*

³*Department of Crystalline Materials Science*

⁴*Tata Institute of Fundamental Research, Mumbai 400005, India*

⁵*Department of Physics, Tohoku University, Aoba, Sendai 980, Japan*

⁶*National Research Institute for Metals, Tokyo 100, Japan*

⁷*Institute of Materials Science, University of Tsukuba, Ibaraki 305, Japan*

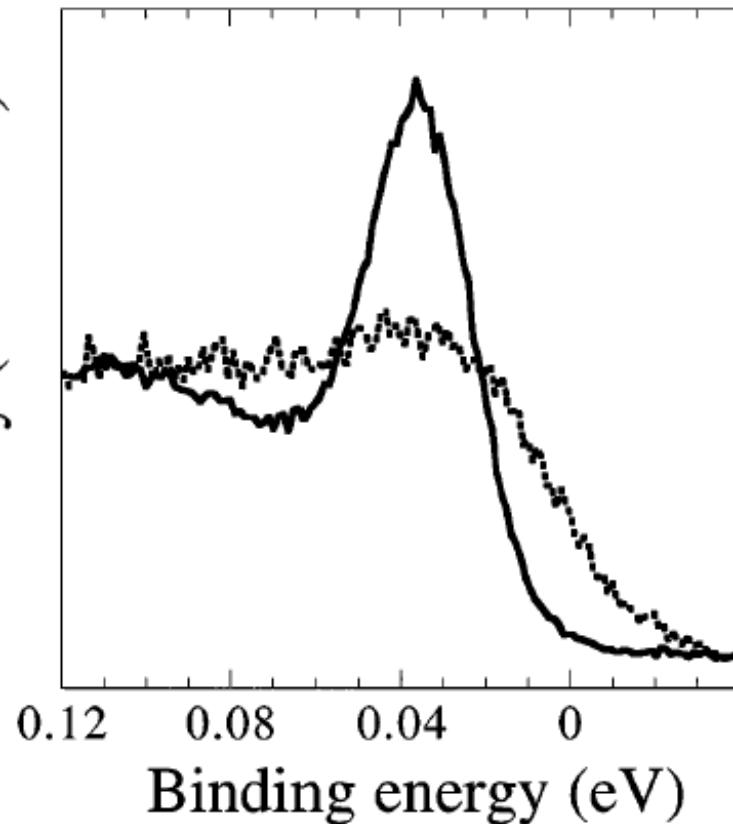
(Received 18 February 1997)

Photoemission spectra of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ below the superconducting transition temperature T_c show bilayer splitting of the zone: a sharp peak at low energy and a dip at higher energy. This bilayer splitting persists at low energy even as one moves away from T_c . The dispersion which correlates well with the bilayer splitting can be naturally explained by the interaction of the two layers. We also speculate that the latter may be related to the peak-dip-hump (PDH) feature observed in the photoemission spectra [Phys. Rev. Lett. 77, 3043 (1996); Phys. Rev. Lett. 77, 3047 (1996)].

Keywords: 74.25.Jb, 74.72.Hs, 79.60.Bm

Photoemission data on the quasi-two-dimensional electronic structure of the superconducting state of the one-electron spectral function can be obtained by analysis of the angle-resolved photoemission spectroscopy (ARPES) changes from the normal to the superconducting (SC) state, can be obtained by analysis of the angle-resolved photoemission spectroscopy (ARPES)

Intensity (arb. units)



Electronic Excitations in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$: Fermi Surface, Dispersion, and Absence of Bilayer Splitting

H. Ding,^{1,2} A. F. Bellman,^{1,3} J. C. Campuzano,^{1,2} M. Randeria,¹ M. R. Norman,¹ T. Yokoya,⁴ T. Takahashi,⁴ H. Katayama-Yoshida,⁴ T. Mochiku,⁵ K. Kadowaki,⁵ G. Jennings,¹ and G. P. Brivio³

¹Materials Sciences Division, Argonne National Laboratory, Argonne, Illinois 60439

²Department of Physics, University of Illinois at Chicago, Chicago, Illinois 60607

³Dipartimento di Fisica, Universita di Milano, 20133 Milano Italy

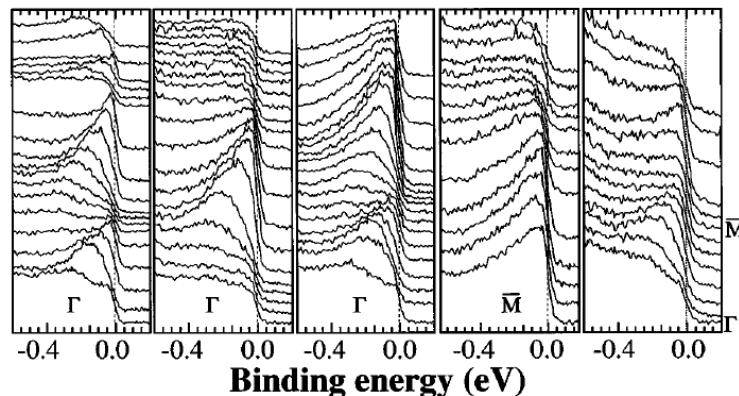
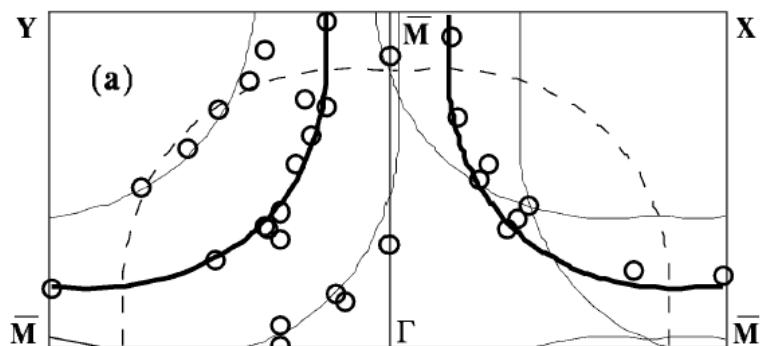
⁴Department of Physics, Tohoku University, 98

⁵National Research Institute for Metals, Senken, Tsuk

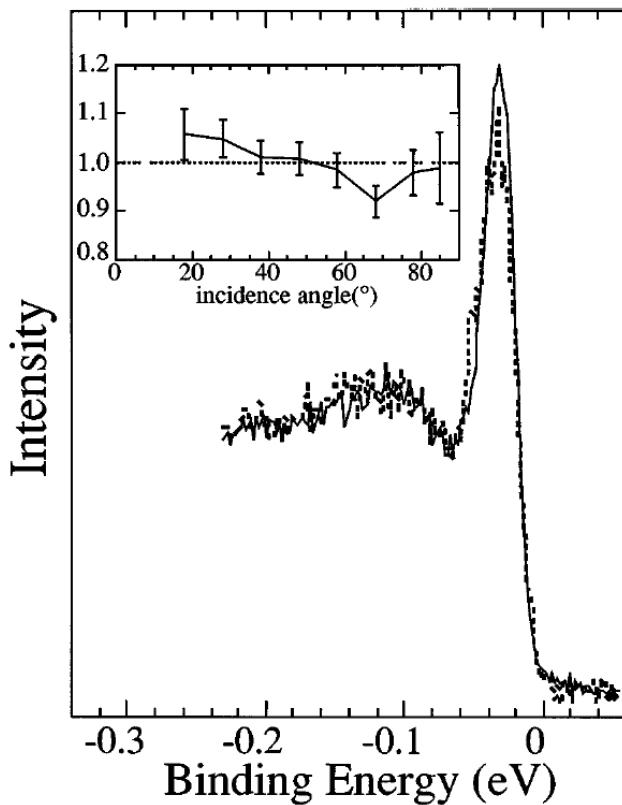
Received 5 July 1995)

arization dependence, we find only one Cu umklapps from the supe like band theory, the line argue that the "dip feature" many-body effects.

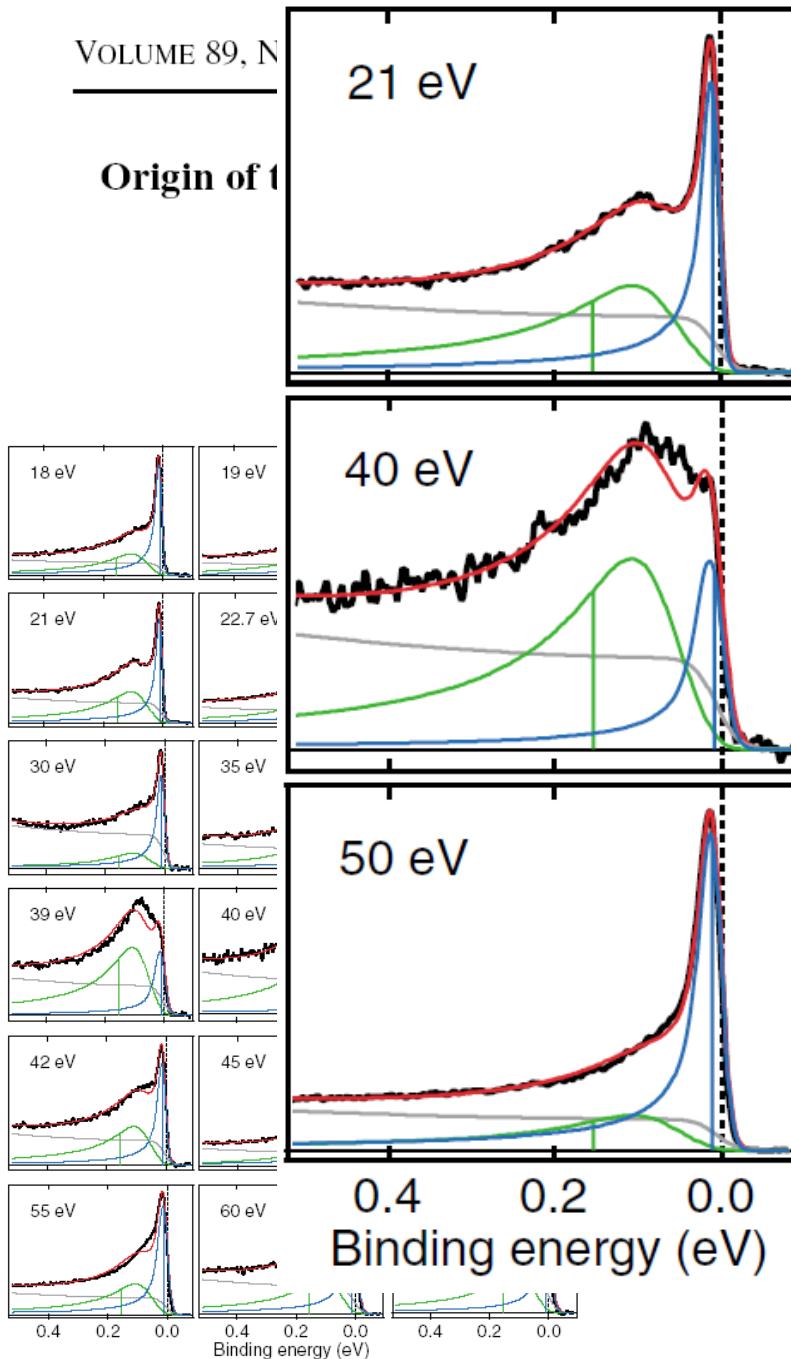
9.60.Bm



many factors contribute as microscopy detail in our aim can be explained. Finally, we data on other $\text{YBa}_2\text{Cu}_4\text{O}_8$. The results high quality used in our samples and



Origin of t



ϵ in the Superconducting-State ($\pi, 0$) Photoemission of $\text{Bi}_2\text{Sr}_2\text{Ca}\text{Cu}_2\text{O}_8$

O.¹ T. K. Kim,¹ K. A. Nenkov,¹ M. Knupfer,¹ I. V. Slobodcikov,² H. Berger,⁴ and R. Follath⁵

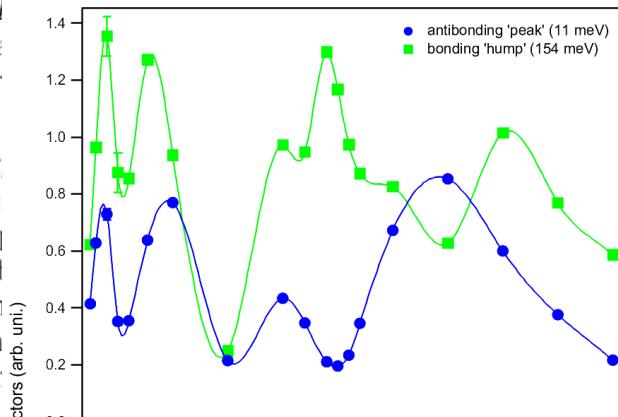
Dresden, P.O. Box 270016, D-01171 Dresden, Germany

Academy of Sciences of Ukraine, 03142 Kyiv, Ukraine

¹ University of Amsterdam, NL-1018 XJ Amsterdam, ² Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, ³ Stein-Strasse 15, 12489 Berlin, Germany, ⁴ Institut für Materialphysik, Universität Regensburg, D-9304 Regensburg, Germany, ⁵ Institute for Solid State Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria

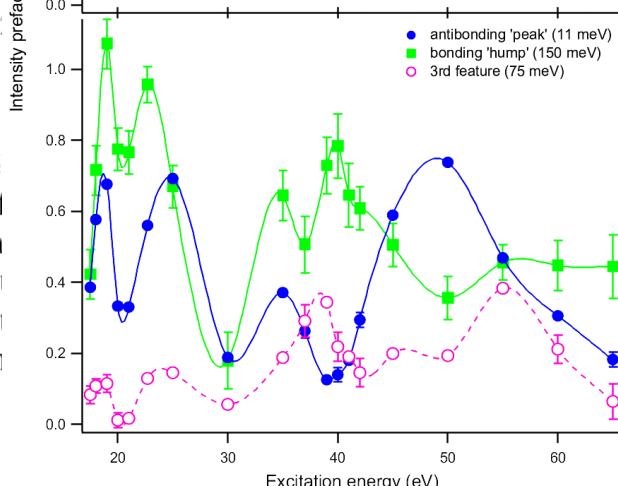
Received 17 April 2002; revised manuscript received 12 June 2002; published 30 July 2002

elements of the photon energy spectrum of the bilayer Bi high-temperature superconductor. The shape is dominated by a superconducting gap which reside at different locations of the Brillouin zone. The particle spectral functions. The superconducting gap is formed by the "peak" being the bilayer-split counterpart of the



PACS numbers: 74.70.D

near the Fermi level to a single-band spectrum. The high-energy part of the spectrum is dominated by a single-band spectrum. The single-band spectrum is characterized by a single-band gap. The single-band gap is formed by the superconducting gap being the bilayer-split counterpart of the

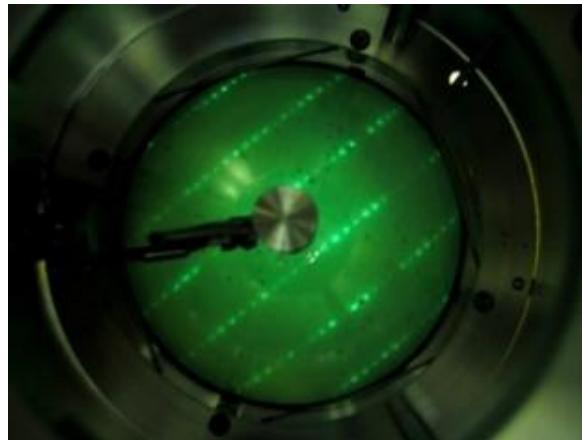


Surface superstructure

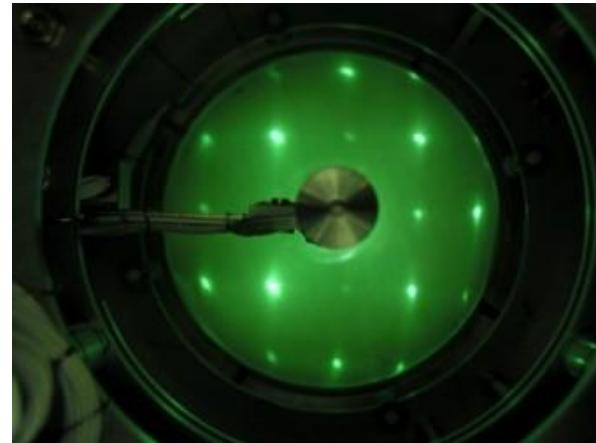
“Pb or not Pb?”
M. Golden

LEED

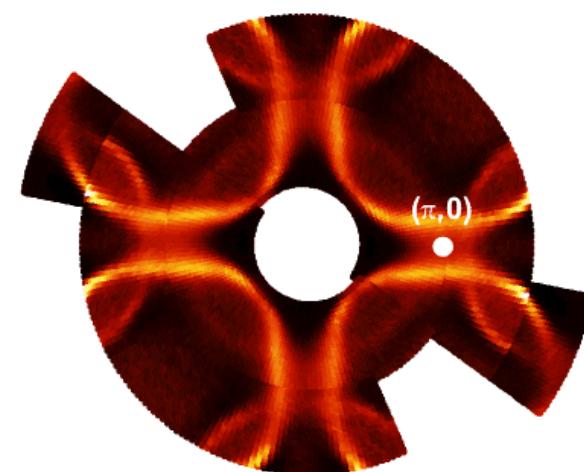
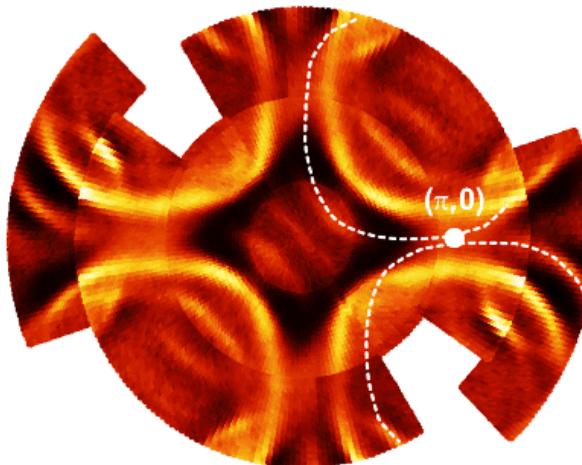
Bi-2212



Bi(Pb)-2212



ARPES



Proposal for an experiment to test a theory of high-temperature superconductors

C. M. Varma

Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974

(Received 21 October 1999)

A theory for the phenomena observed in copper-oxide based high-temperature superconducting materials derives an elusive time-reversal and rotational symmetry-breaking order parameter for the observed pseudogap phase ending at a quantum-critical point near the composition for the highest T_c . An experiment is proposed to observe such a symmetry breaking. It is shown that angle-resolved photoemission yields a current density which is different for left and right circularly polarized photons. The magnitude of the effect and its momentum dependence is estimated. Barring the presence of domains of the predicted phase, an asymmetry of about 0.1 is predicted at low temperatures in moderately underdoped samples.

I. INTRODUCTION

Despite twelve years of intensive experimental and theoretical studies of copper-oxide based superconducting compounds,¹ no consensus about the fundamental physics or even about the minimum necessary Hamiltonian to describe the phenomena has emerged. One of the few theoretical ideas which has clearly survived experimental tests is that at den-

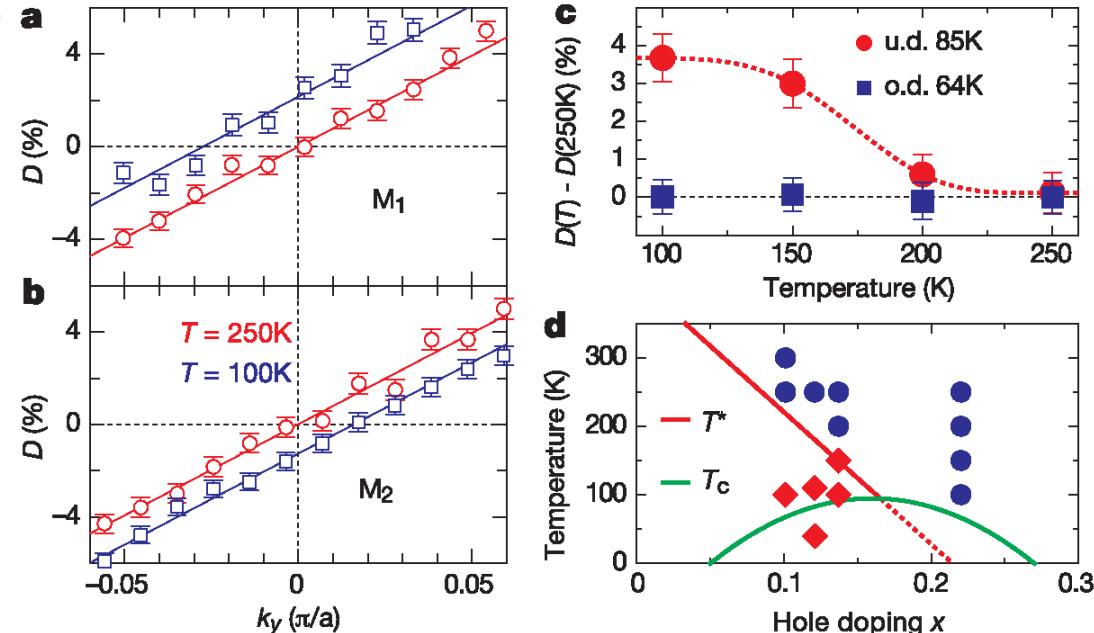
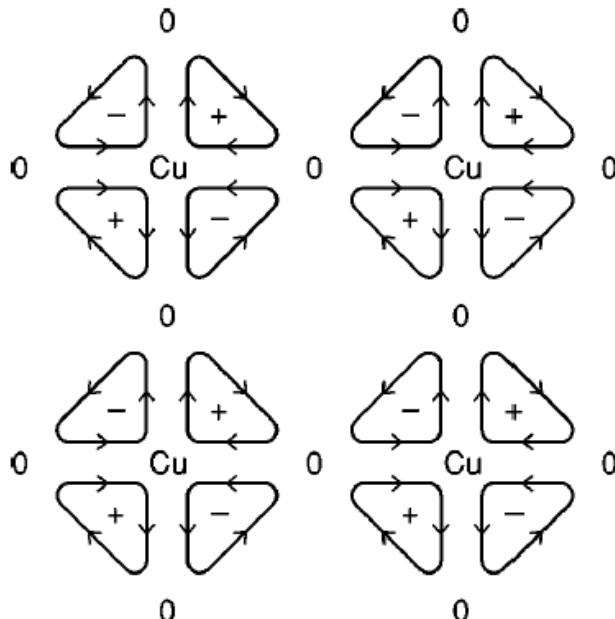
Cu-O compounds is the symmetry in region II of the so-called pseudogap phase.

A systematic theory^{5,6} starting with a general model for Cu-O compounds provides an answer to this question. Region II in Fig. 1 is derived to be a phase in which a fourfold pattern of current flows in the ground state in each unit cell as shown in Fig. 2. Time-reversal symmetry as well as rotational symmetry is broken but the product of the two is con-

phase has been called the circulating-current phase. Quantum fluctuations about this phase are

ve MFL fluctuations, characteristic of region I. fluctuations promote “d” or generalized

irrigating d



Spontaneous breaking of time-reversal symmetry in the pseudogap state of a high- T_c superconductor

A. Kaminski*, **S. Rosenkranz^{†,‡}**, **H. M. Fretwell[‡]**, **J. C. Campuzano^{*†}**,
Z. Li[§], **H. Raffy[§]**, **W. G. Cullen[†]**, **H. You[†]**, **C. G. Olson^{||}**, **C. M. Varma[¶]**
& **H. Höchst[#]**

* Department of Physics, University of Illinois at Chicago, Chicago, Illinois 60607, USA

† Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

‡ Department of Physics, University of Wales Swansea, Swansea SA2 8PP, UK

§ Laboratoire de Physique des Solides, Université Paris-Sud, 91405 Orsay, France

|| Ames Laboratory, Iowa State University, Ames, Iowa 50011, USA

¶ Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey 07974, USA

Synchrotron Radiation Center, Stoughton, Wisconsin 53589, USA

A change in ‘symmetry’ is often observed when matter undergoes a phase transition—the symmetry is said to be spontaneously

Circular Dichroism in Angle-Resolved Photoemission Spectra of Under- and Overdoped Pb-Bi2212

S. V. Borisenko,¹ A. A. Kordyuk,^{1,2} A. Koitzsch,¹ T. K. Kim,¹ K. A. Nenkov,¹ M. Knupfer,¹ J. Fink,¹ C. Grazioli,³ S. Turchini,³ and H. Berger⁴

¹Institute for Solid State Research, IFW-Dresden, P.O. Box 270116, D-01171 Dresden, Germany

²Institute of Metal Physics of National Academy of Sciences of Ukraine, 03142 Kyiv, Ukraine

³Istituto di Struttura della Materia, Consiglio Nazionale delle Ricerche, Area Science Park, I-34012 Trieste, Italy

⁴Institute of Physics of Complex Matter, EPFL, CH-1015 Lausanne, Switzerland

(Received 7 May 2003; published 19 May 2004)

We use angle-resolved photoemission with circularly polarized excitation to demonstrate that in the 5×1 superstructure-free $(\text{Pb}, \text{Bi})_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Pb-Bi2212) material there are no signatures of time-reversal symmetry breaking in the sense of the criteria developed earlier [Kaminski *et al.*, Nature (London) **416**, 610 (2002)]. The dichroic signal retains reflection antisymmetry as a function of temperature and doping and in all mirror planes, precisely defined by the experimental dispersion at low energies. The obtained results demonstrate that the signatures of time-reversal symmetry violation in pristine Bi2212, as determined by angle-resolved photoemission spectroscopy, are not a universal feature of all cuprate superconductors.

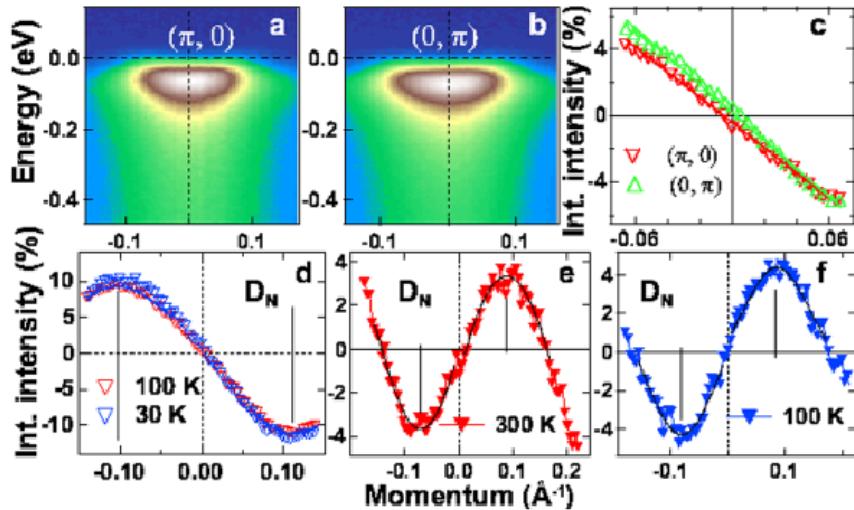
DOI: 10.1103/PhysRevLett.92.207001

PACS numbers: 74.25.Jb, 74.72.Hs, 79.60.-i

The variety of specific points, lines, and regions in the “normal state” part of the phase diagram of the high-temperature superconductors clearly demonstrates not only its complexity but also the absence of its detailed understanding [1]. It is therefore important to realize which of them are really universal boundaries of particular phases and which just designate intermediate states with properties defined by the proximity to the well established phases such as superconductivity. A recent

out on the systems with reduced interference of temperature-sensitive structural modifications together with the development of an improved experimental methodology aiming at more precise and reliable investigation of circular dichroism effects in low energy photoemission would be of special interest today.

In this Letter we present the results of the ARPES investigation of the $(\text{Pb}, \text{Bi})_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Pb-Bi2212) cuprates known to have no 5×1 superstructure. We de-



brief communications arising

Superconductors

Time-reversal symmetry breaking?

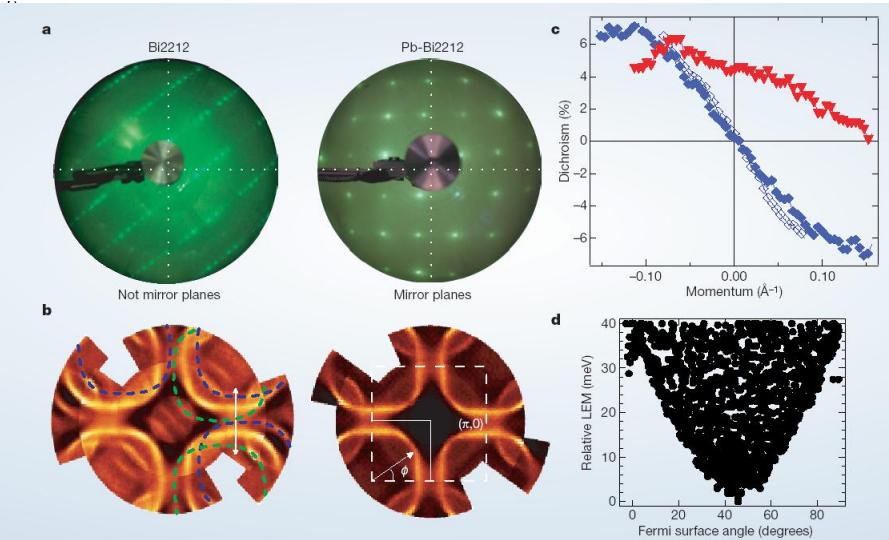
Sergey V. Borisenko*, Alexander A. Kordyuk*, Andreas Koitzsch*, Martin Knupfer*, Jörg Fink*, Helmuth Berger†, Chengtian T. Lin§

Arising from: Kaminski, A. *et al.* *Nature* **416**, 610–613 (2002)

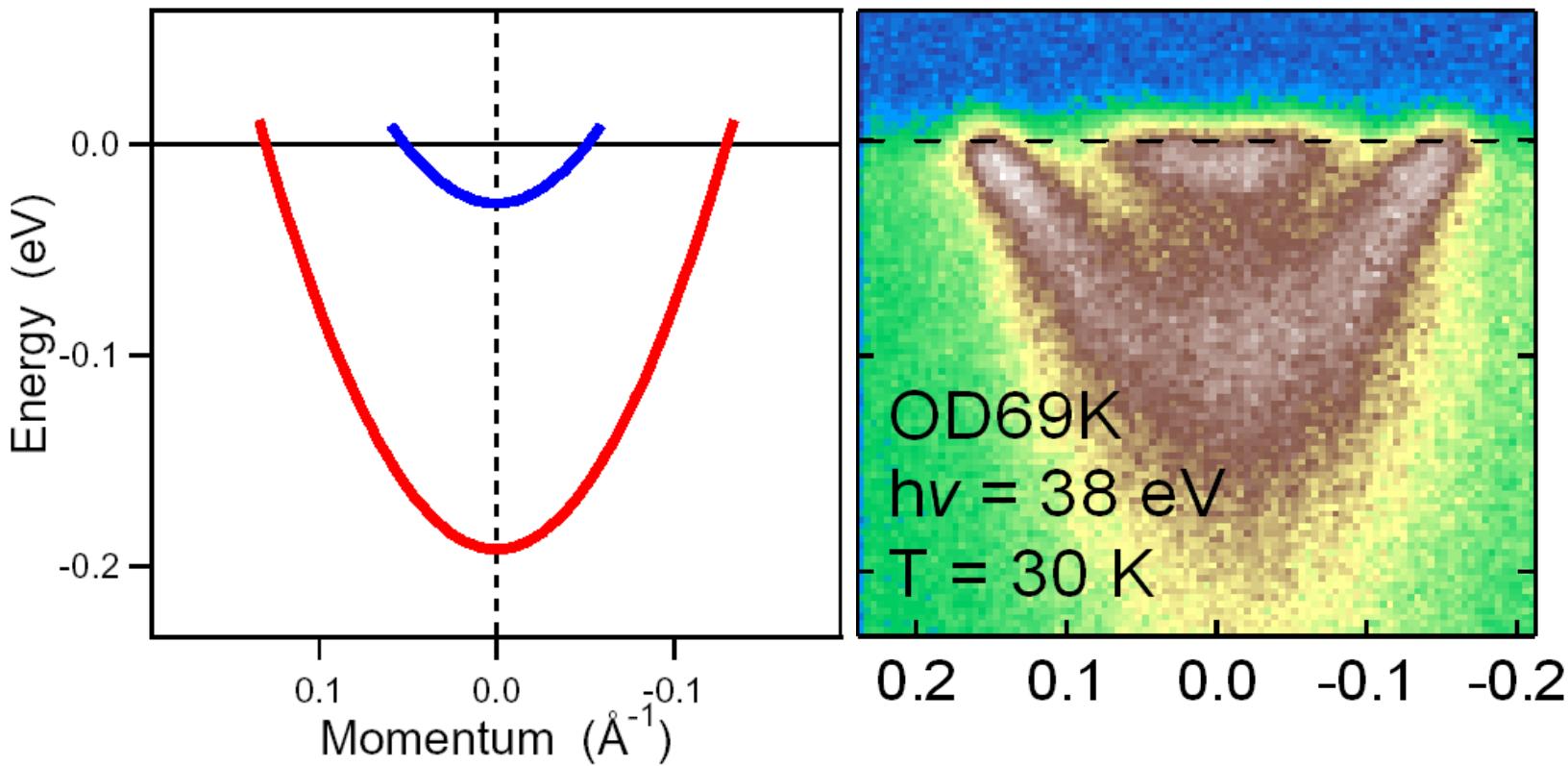
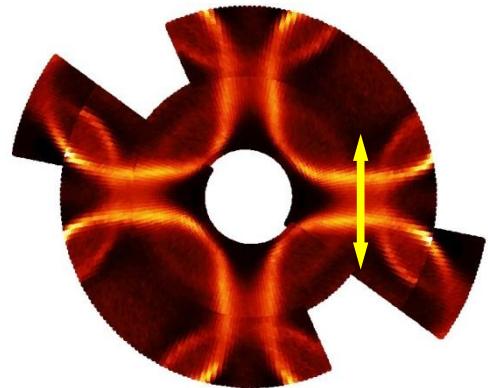
One of the mysteries of modern condensed-matter physics is the nature of the pseudogap state of the superconducting cuprates. Kaminski *et al.*¹ claim to have observed signatures of time-reversal symmetry breaking in the pseudogap regime in underdoped $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi2212). Here we argue that the observed circular dichroism is due to the 5×1 superstructure replica of the electronic bands and therefore cannot be considered

pristine Bi2212, the dichroic signal is non-zero in the $(\pi, 0)$ plane.

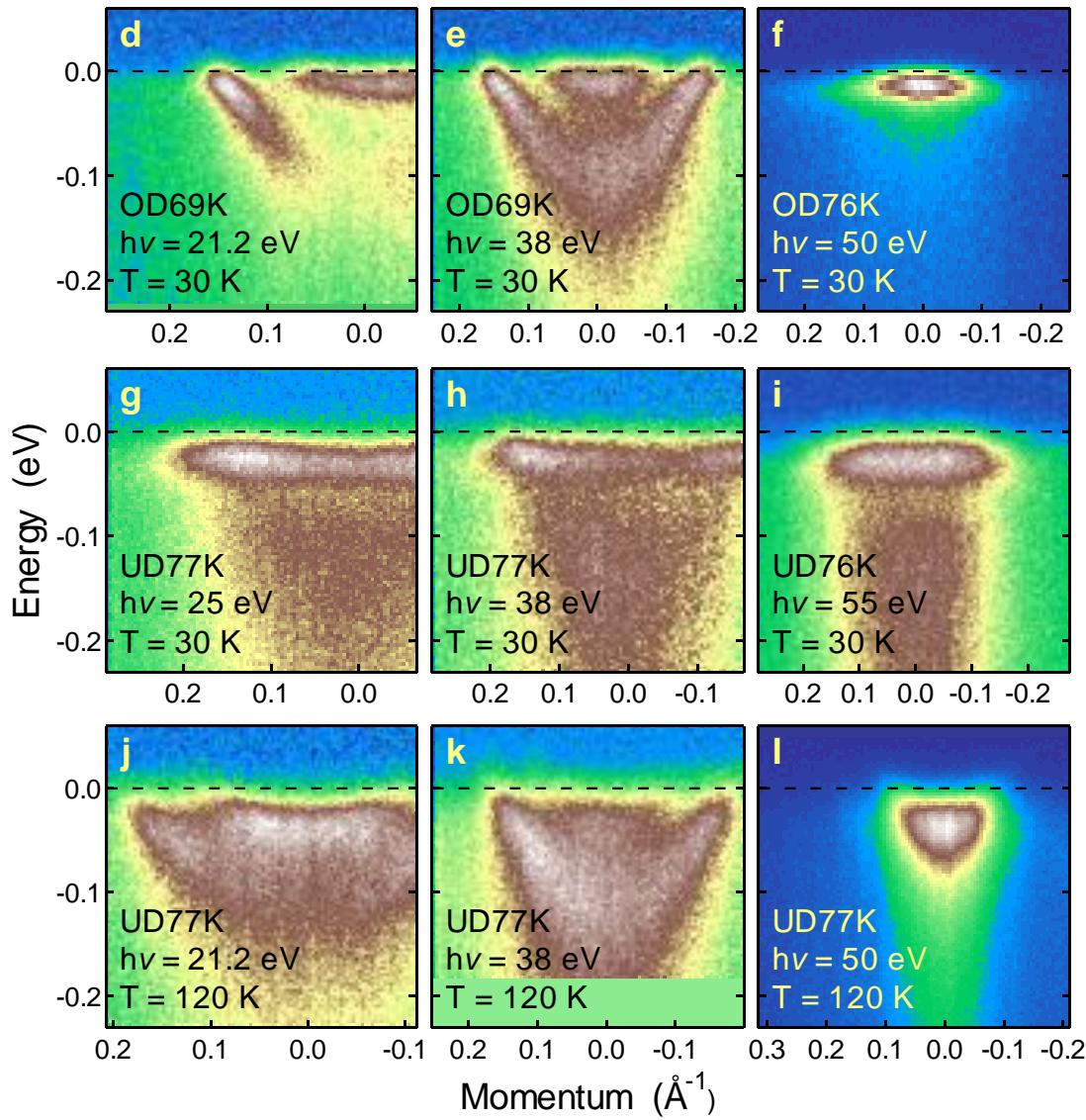
This result can readily be explained. The superstructure results in diffraction replicas of the electronic structure seen in the momentum-distribution map (Fig. 1b) as green and blue dashed curves. Because of the pronounced inequivalence of the matrix elements in the first and second Brillouin zones, the spectral weight of these replicas is always different near the $(\pi, 0)$ point.



Antinodal cut



Interaction with the mode

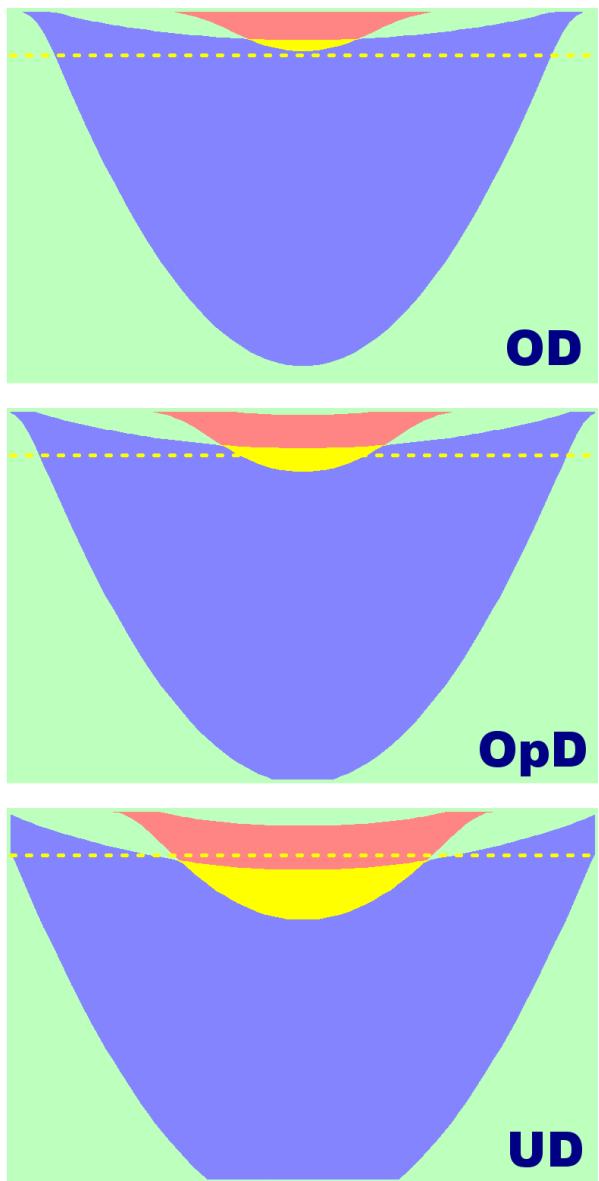
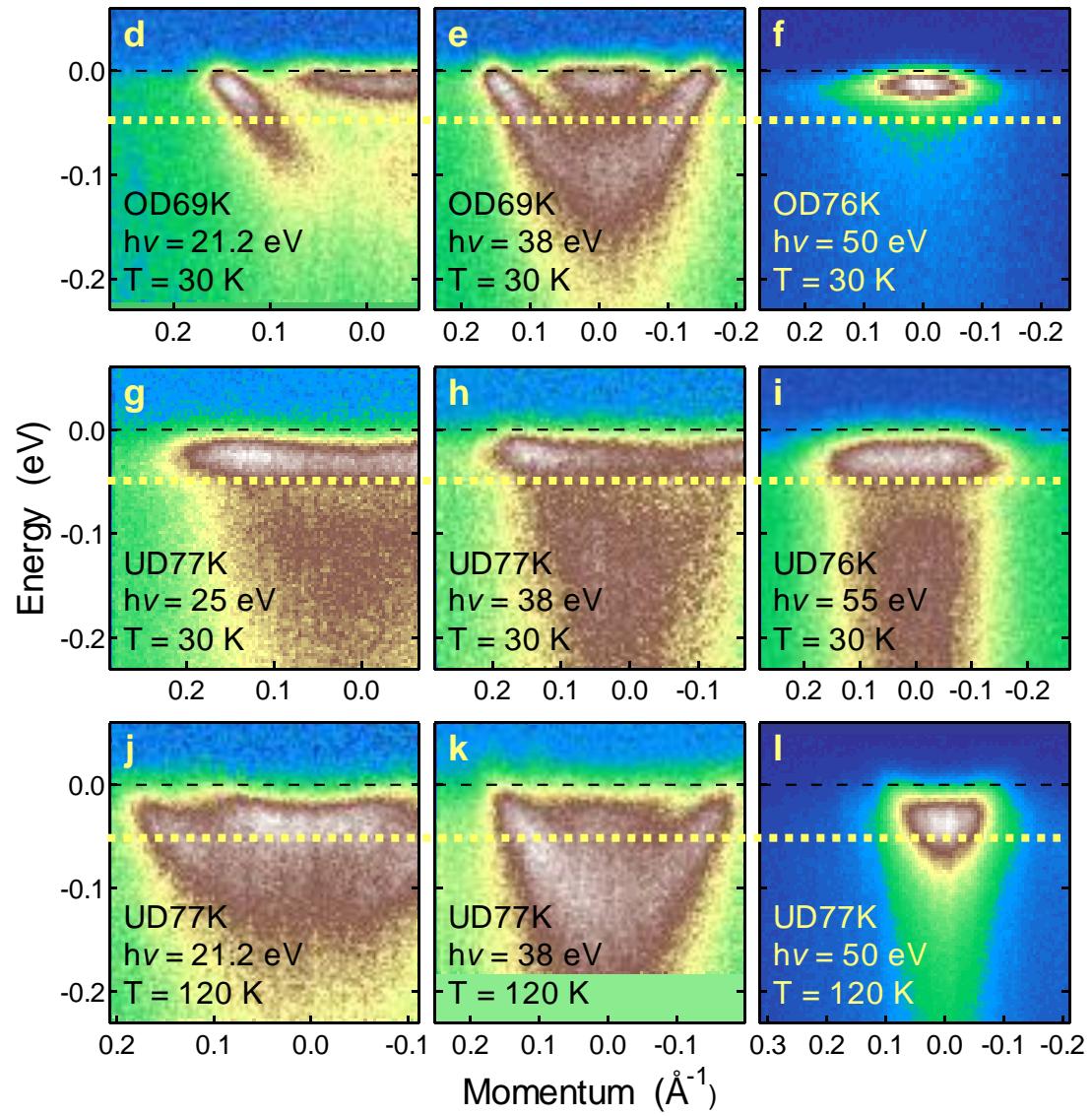


overdoped
 $T < T_c$

underdoped
 $T < T_c$

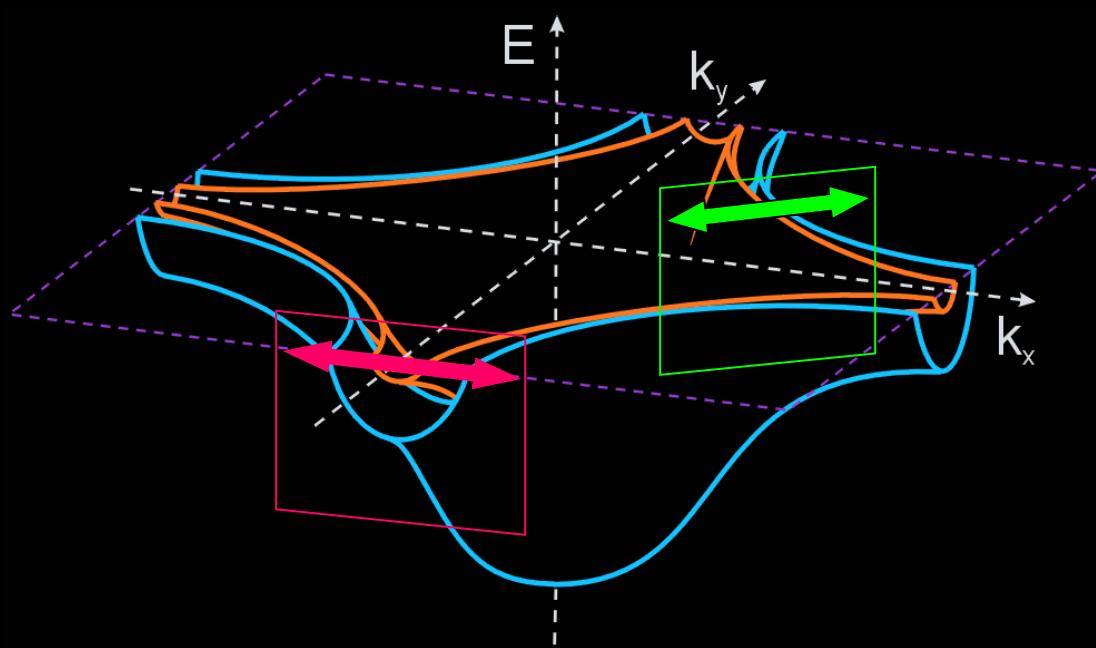
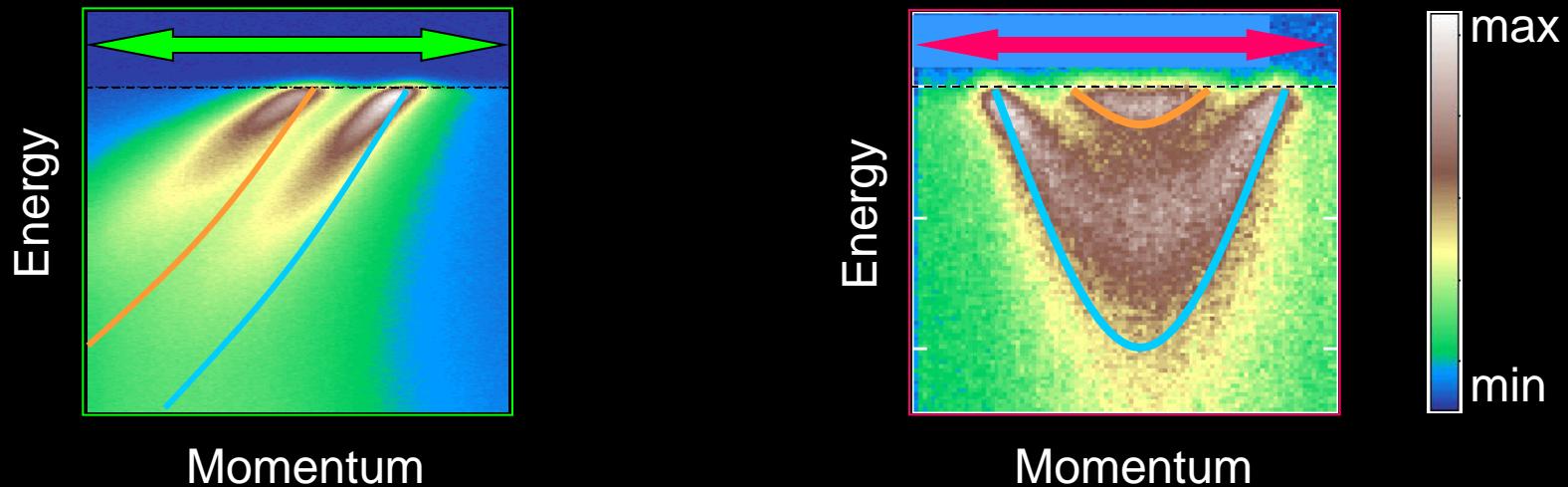
underdoped
 $T > T_c$

Interaction with the mode



Kordyuk 2002 unpublished

$$\text{HTSC} = \text{LDA} + \text{Self-energy } (\Sigma)$$



What is the main reason for the self-energy
(what scatters electrons),

phonons

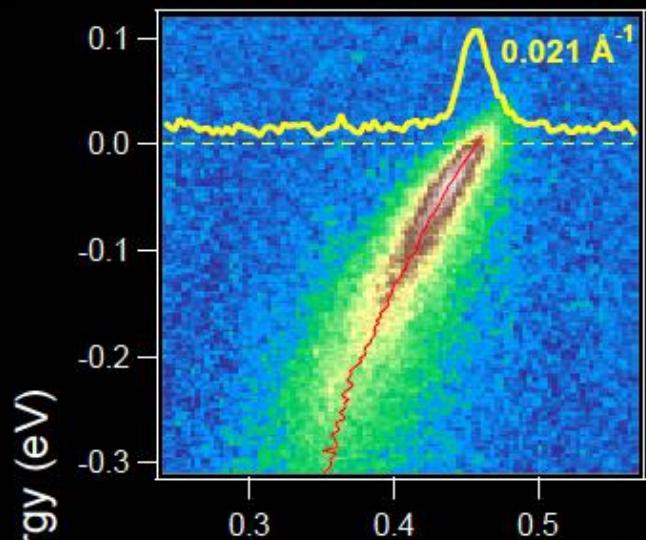
or

spin-fluctuations ?

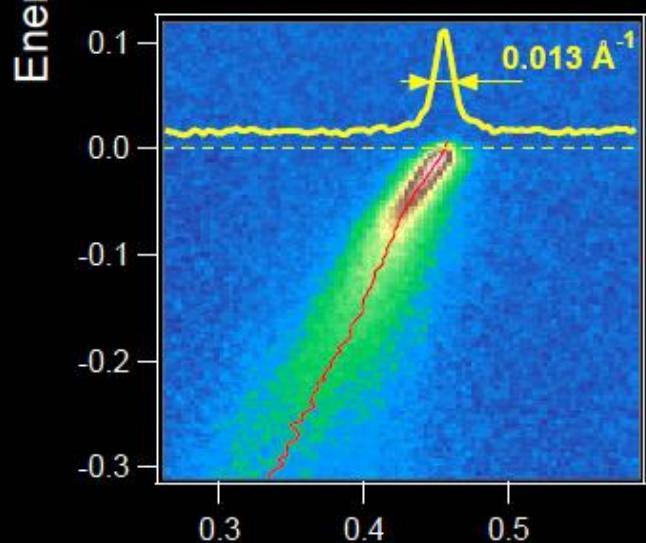
Node

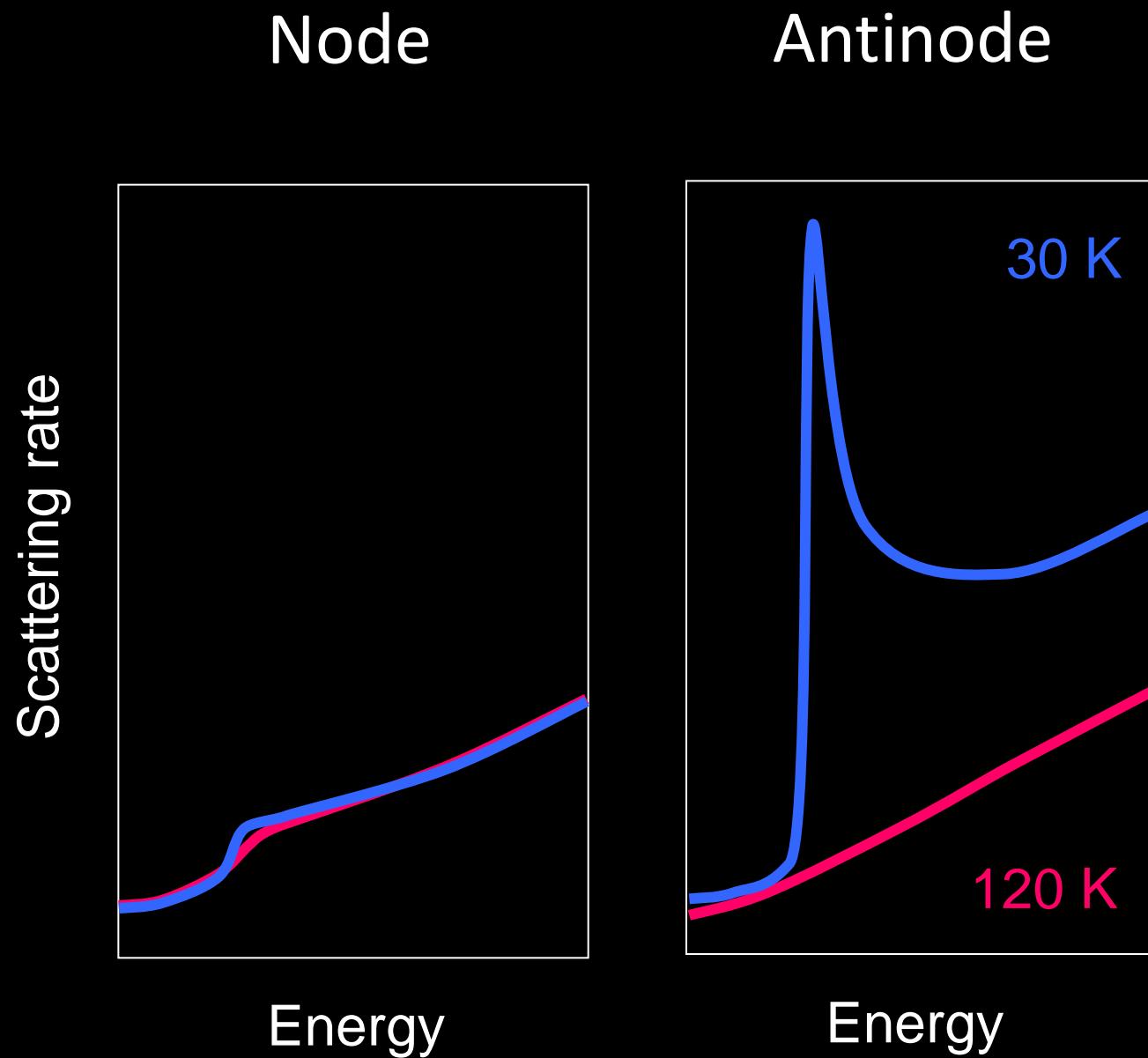
Antinode

$T > T_c$



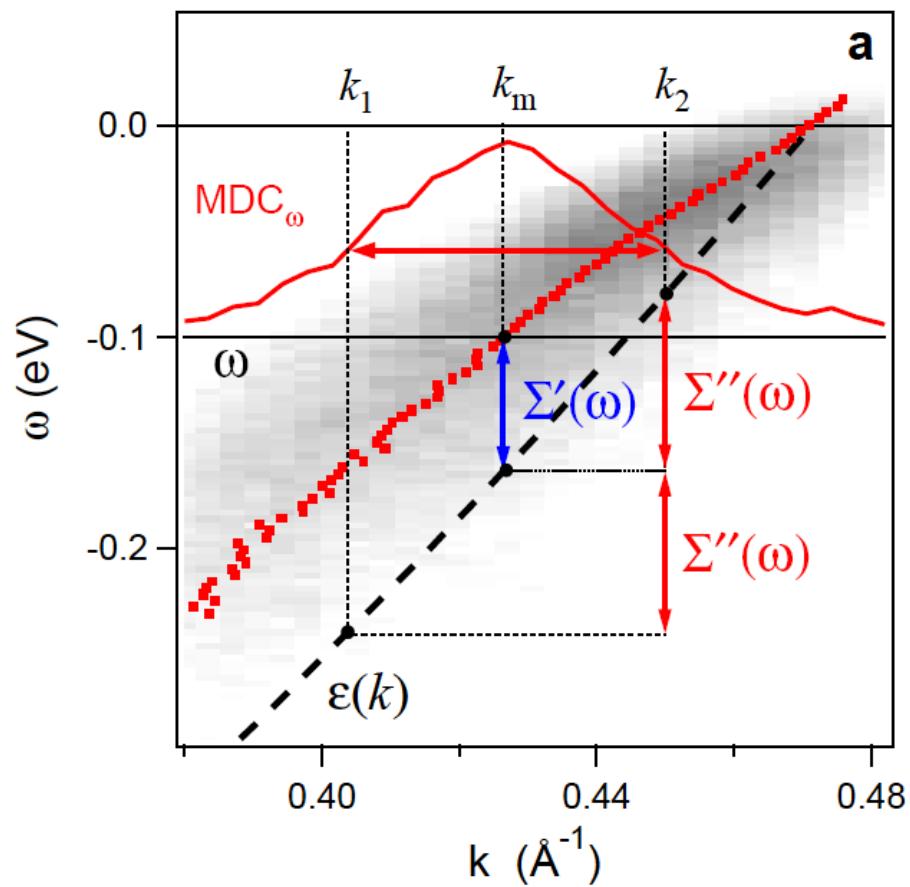
$T < T_c$





Introduction to the nodal spectra analysis

$$A(\omega, \mathbf{k}) = -\frac{1}{\pi} \frac{\Sigma''(\omega)}{(\omega - \varepsilon(\mathbf{k}) - \Sigma'(\omega))^2 + \Sigma''(\omega)^2}$$



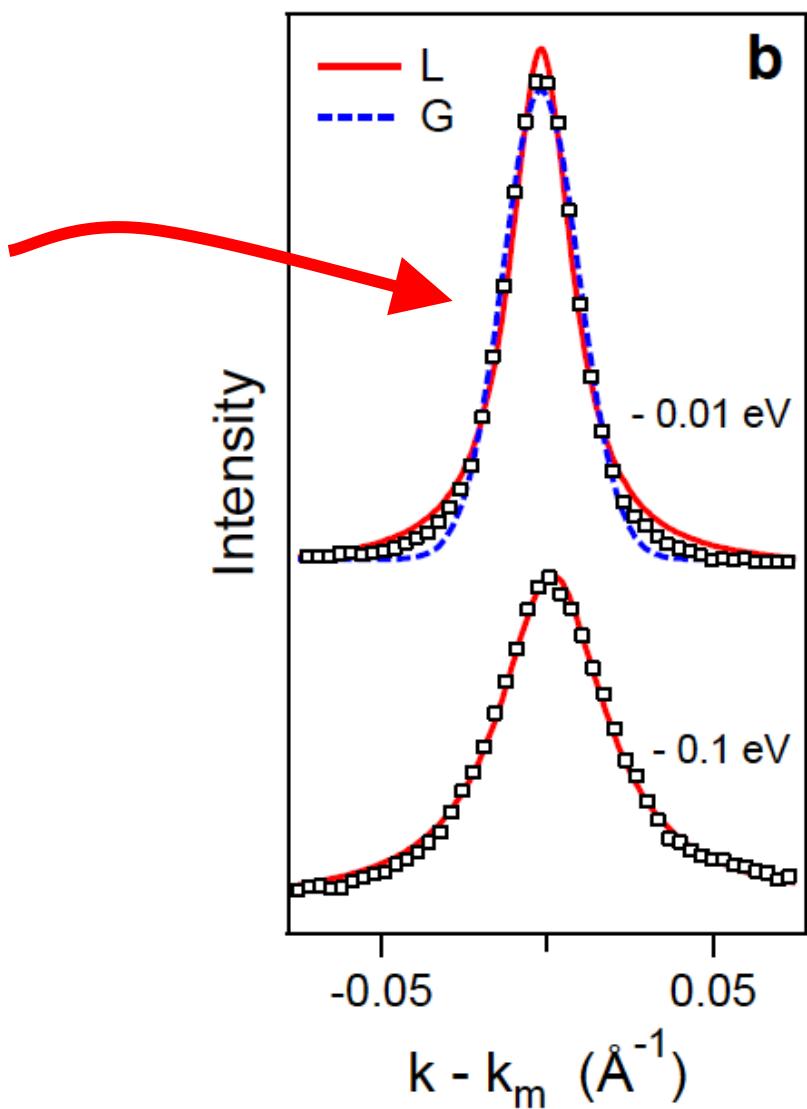
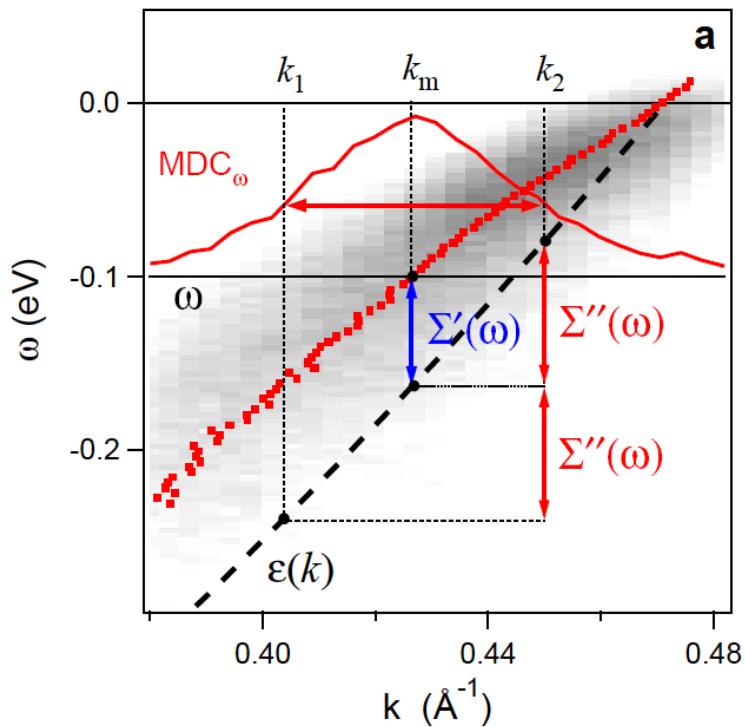
$$\Sigma'(\omega) = \omega - \varepsilon(k_m)$$

$$\Sigma''(\omega) = -v_F W(\omega)$$

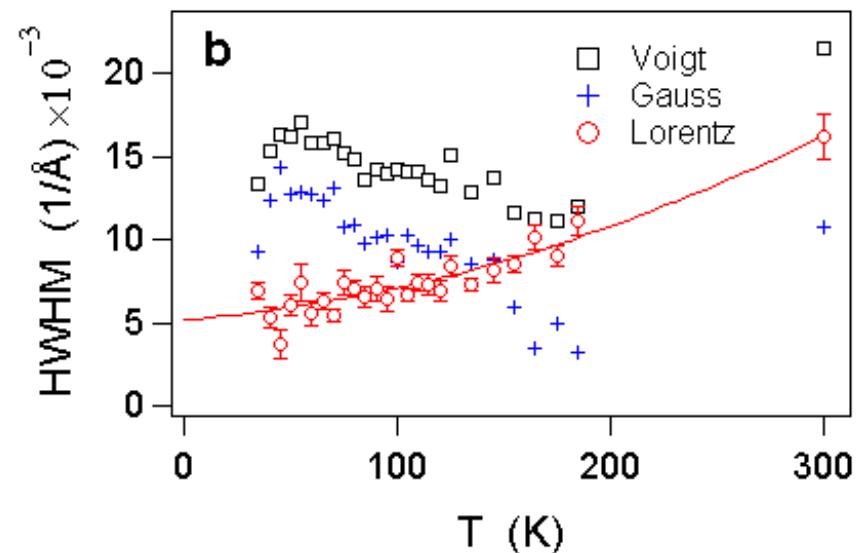
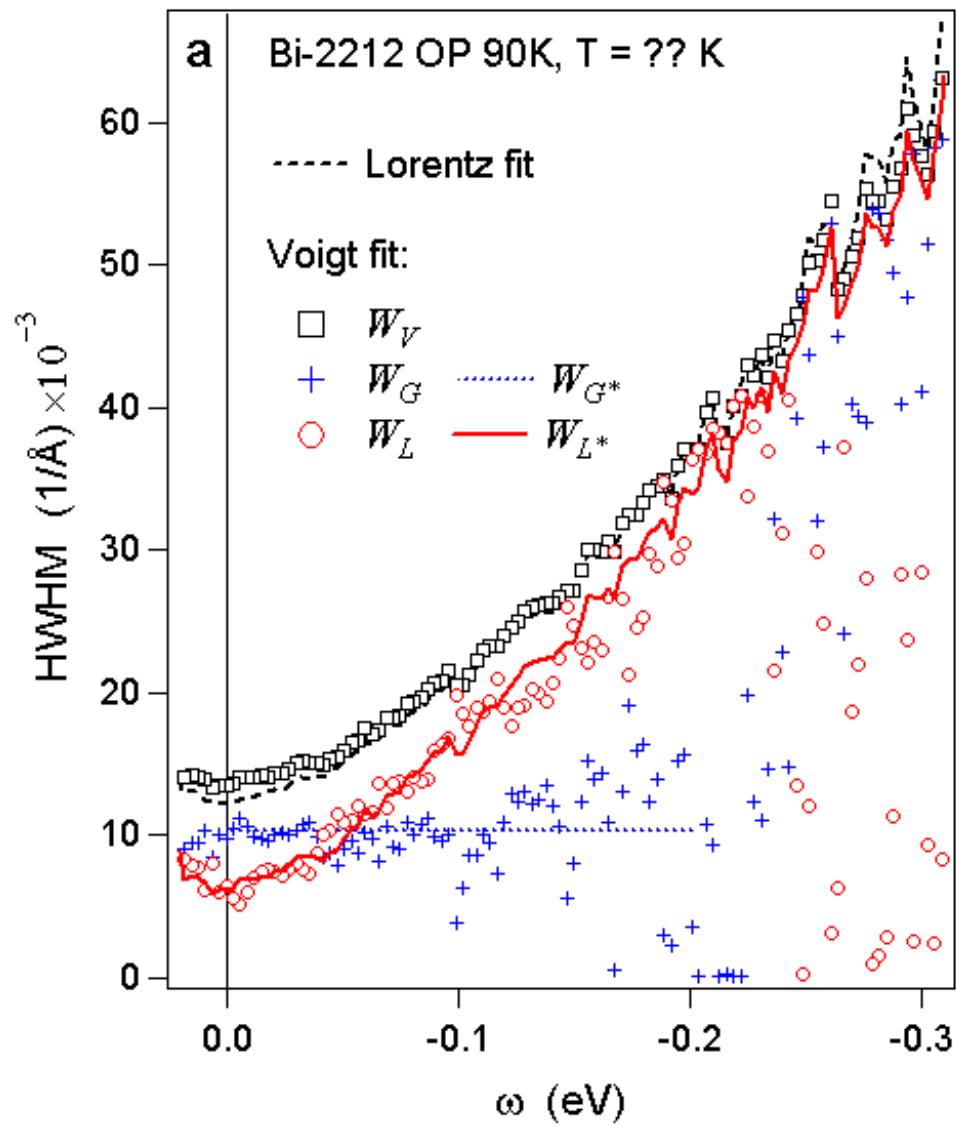
Unadulterated spectral function

Lorentzian to Gaussian

Voigt profile = Lor \otimes Gauss



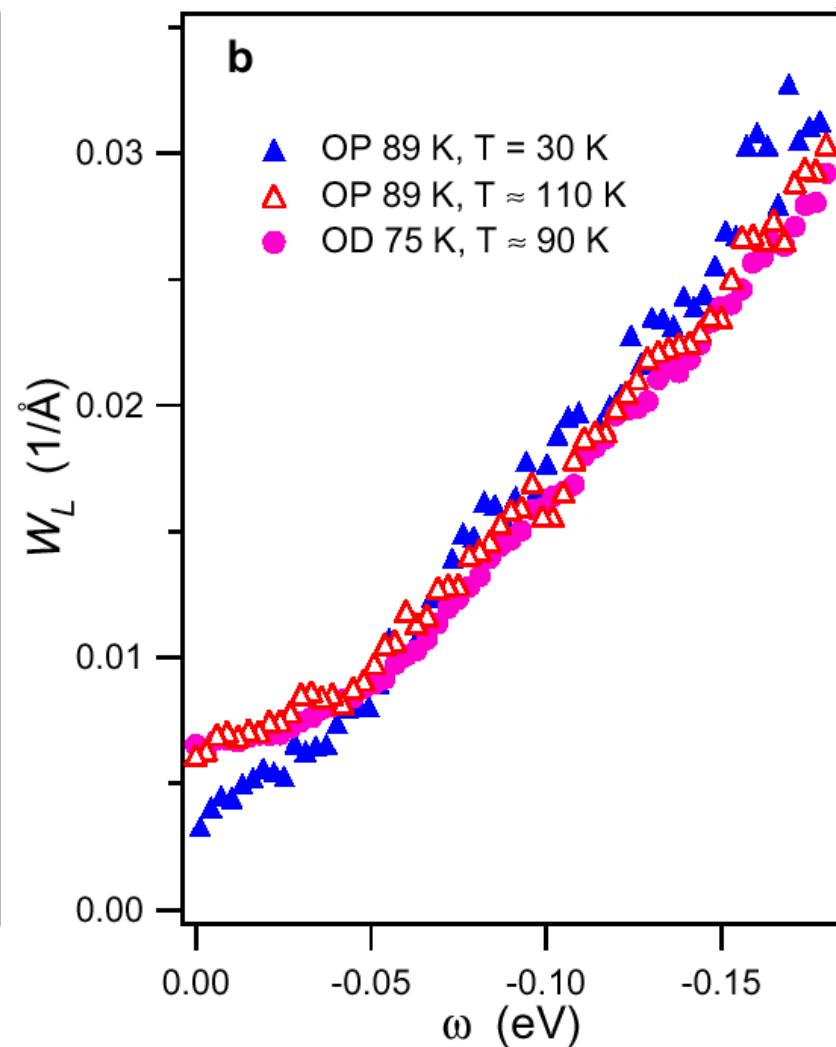
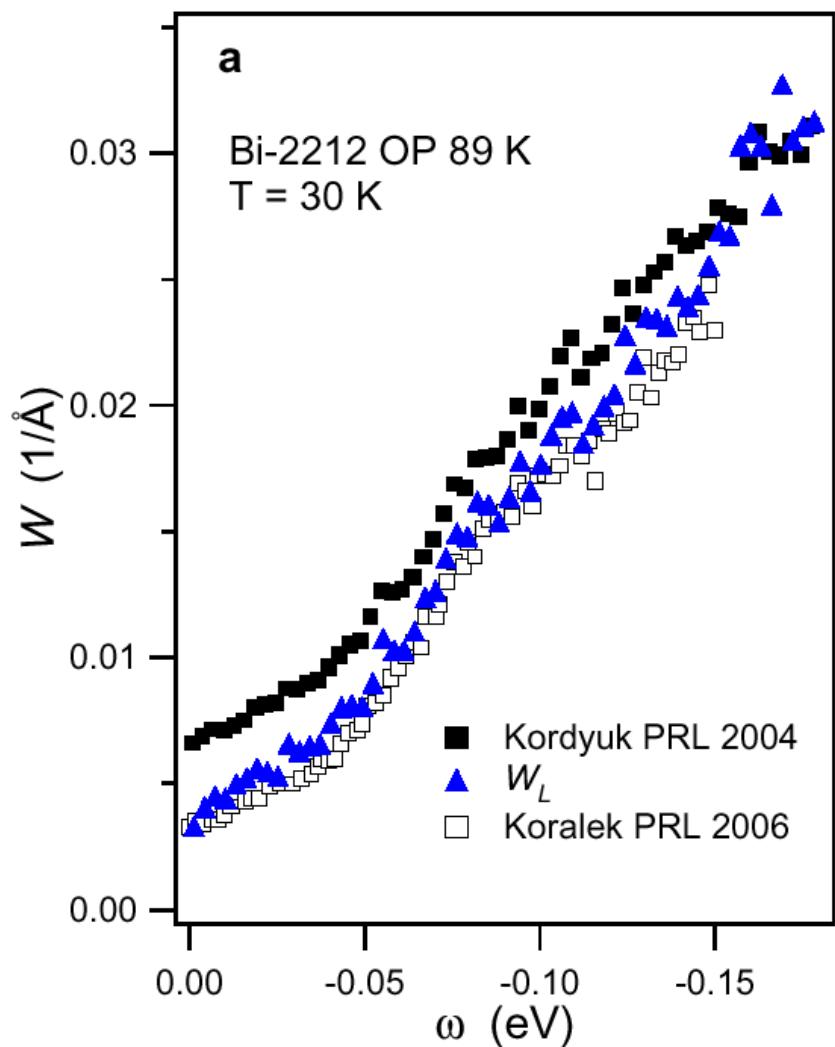
Voigt fitting procedure



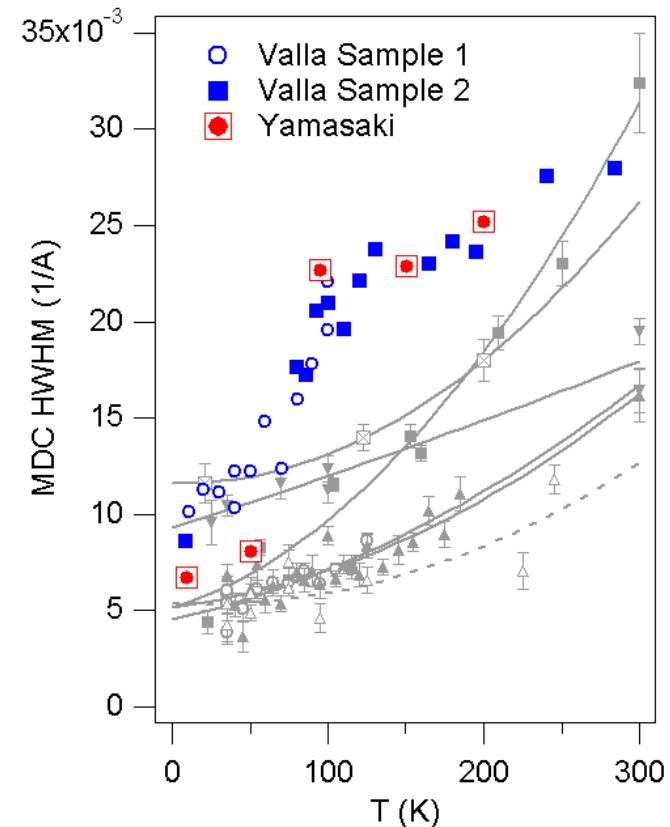
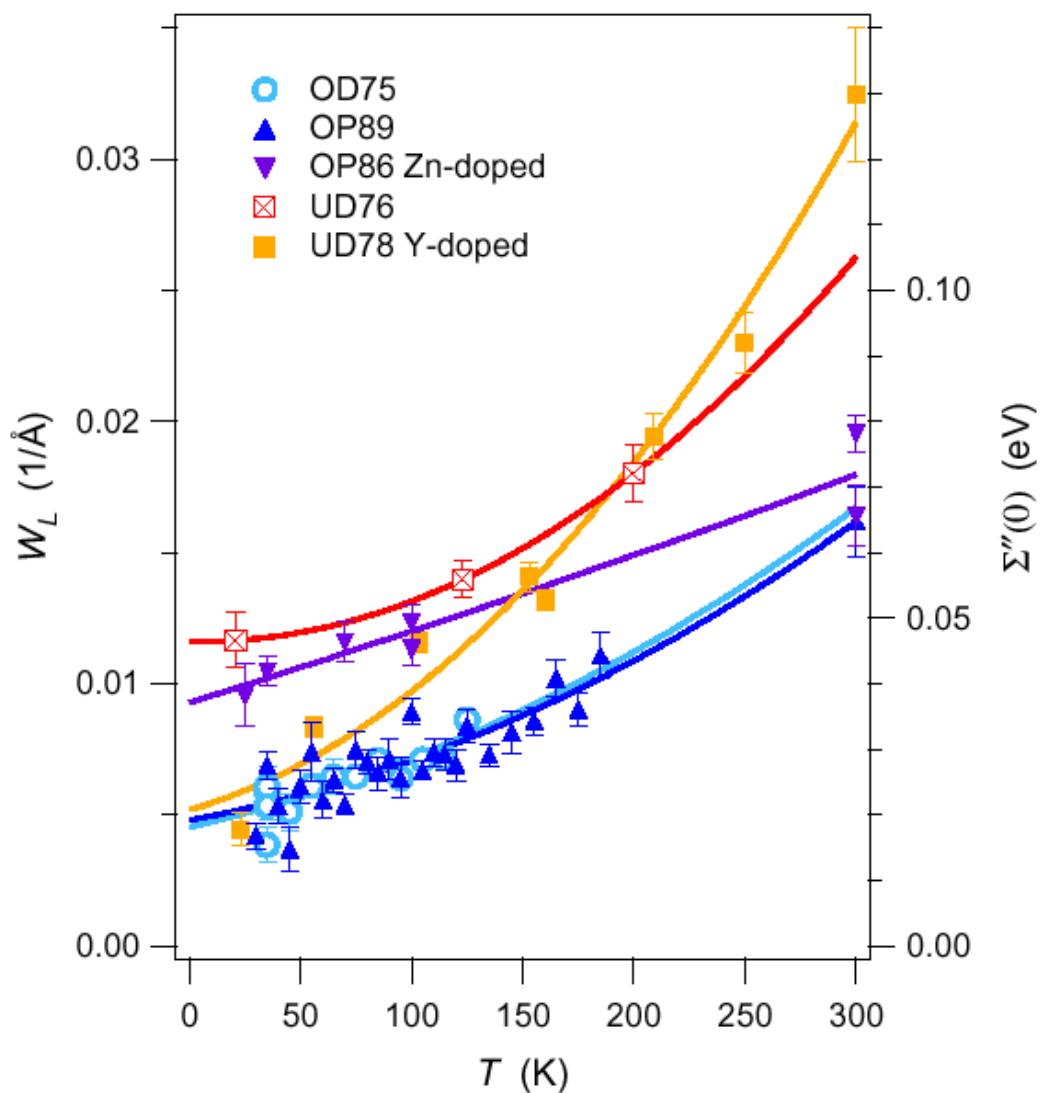
$$W_V = V(W_L, W_G)$$

$$= \frac{W_L}{2} + \sqrt{\frac{W_L^2}{4} + W_G^2}$$

Energy dependence



Temperature dependence



pseudo-gap

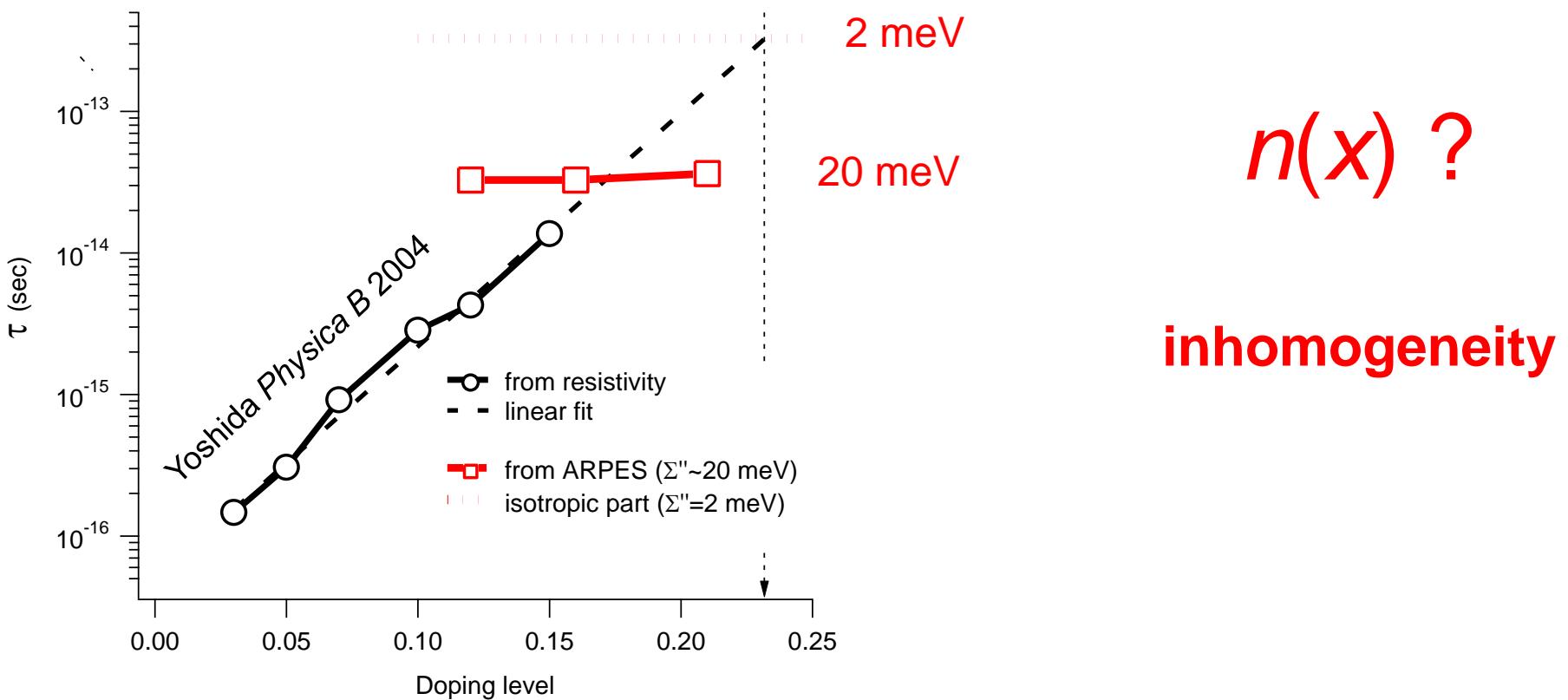
no "arcs" !

Impurity scattering

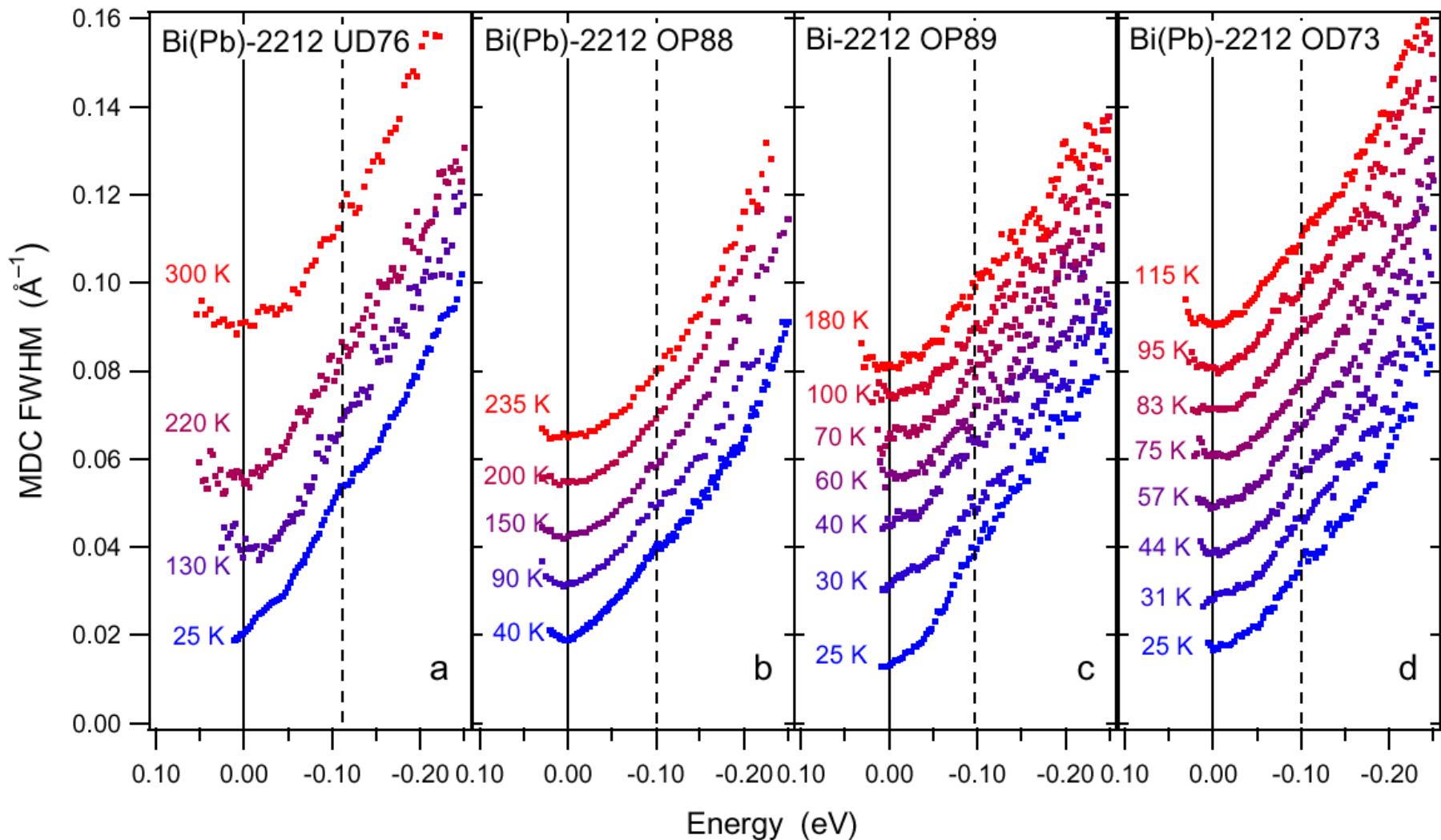
$$\rho_0 = \frac{m^*}{ne^2\tau} \approx \frac{k_F}{ne^2\hbar} \frac{\Sigma''_{im}}{v_r}$$

forward and isotropic (unitary)?

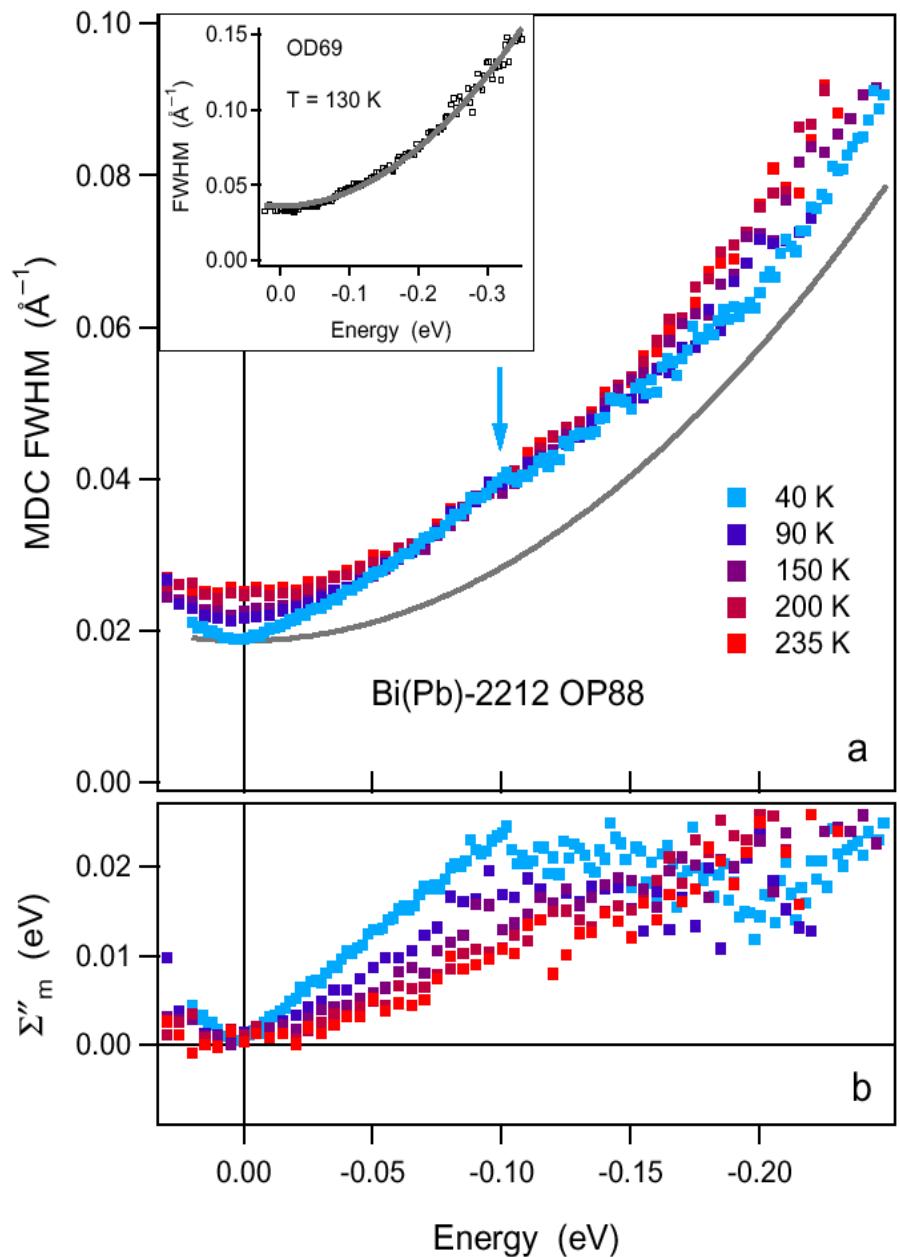
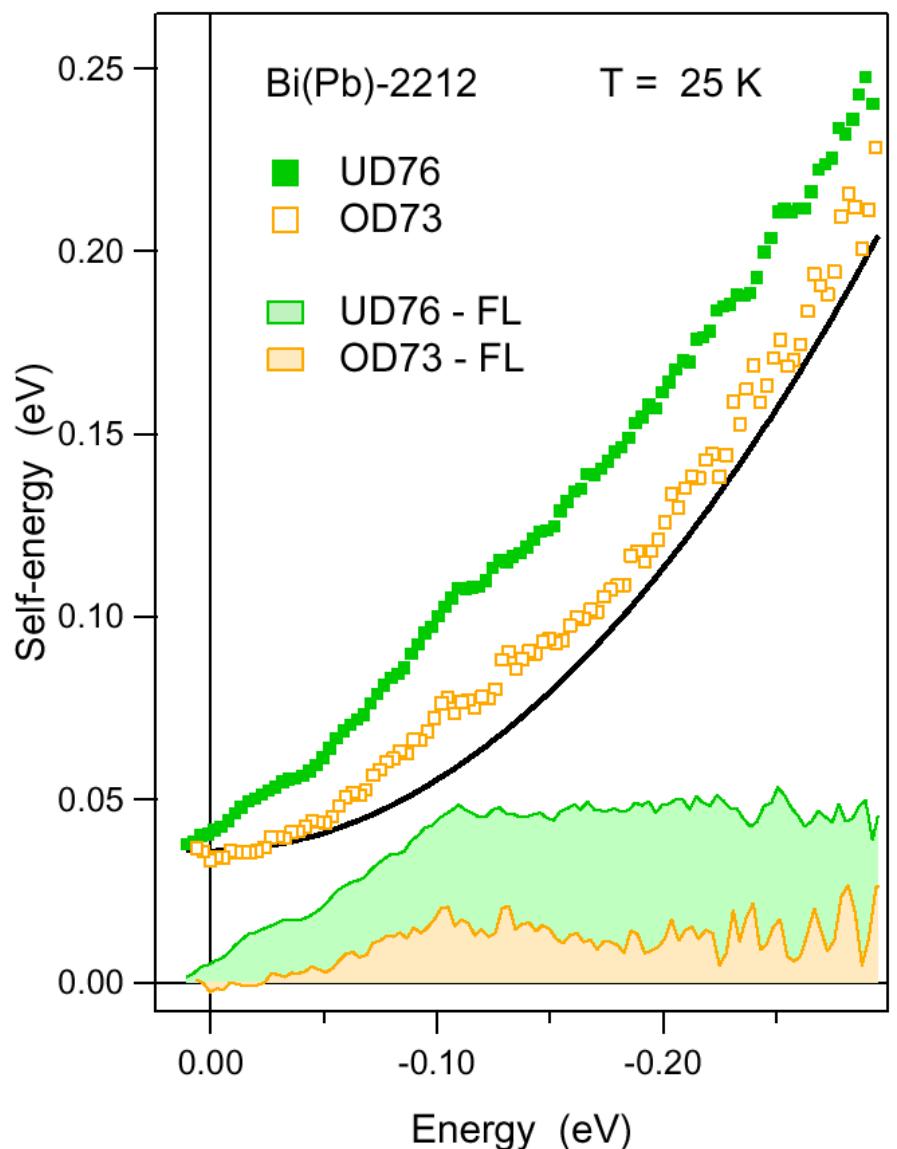
$$n \sim 1 - x$$



Nodal scattering rate



Scattering rate

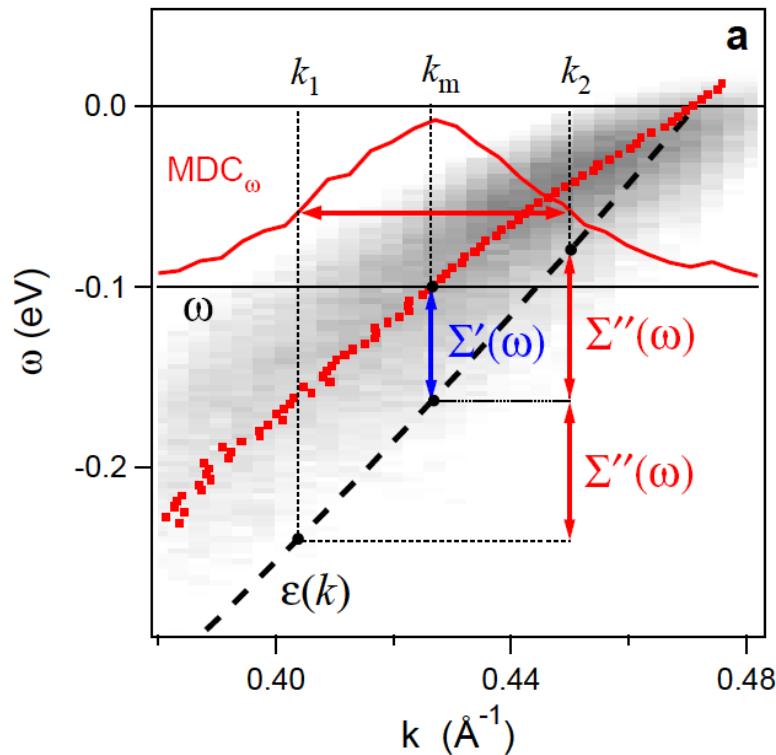


How Kramers-Kronig consistency works

Why we believe it is applicable

Bare Fermi velocity from the nodal spectrum

$$A(\omega, \mathbf{k}) = -\frac{1}{\pi} \frac{\Sigma''(\omega)}{(\omega - \varepsilon(\mathbf{k}) - \Sigma'(\omega))^2 + \Sigma''(\omega)^2}$$

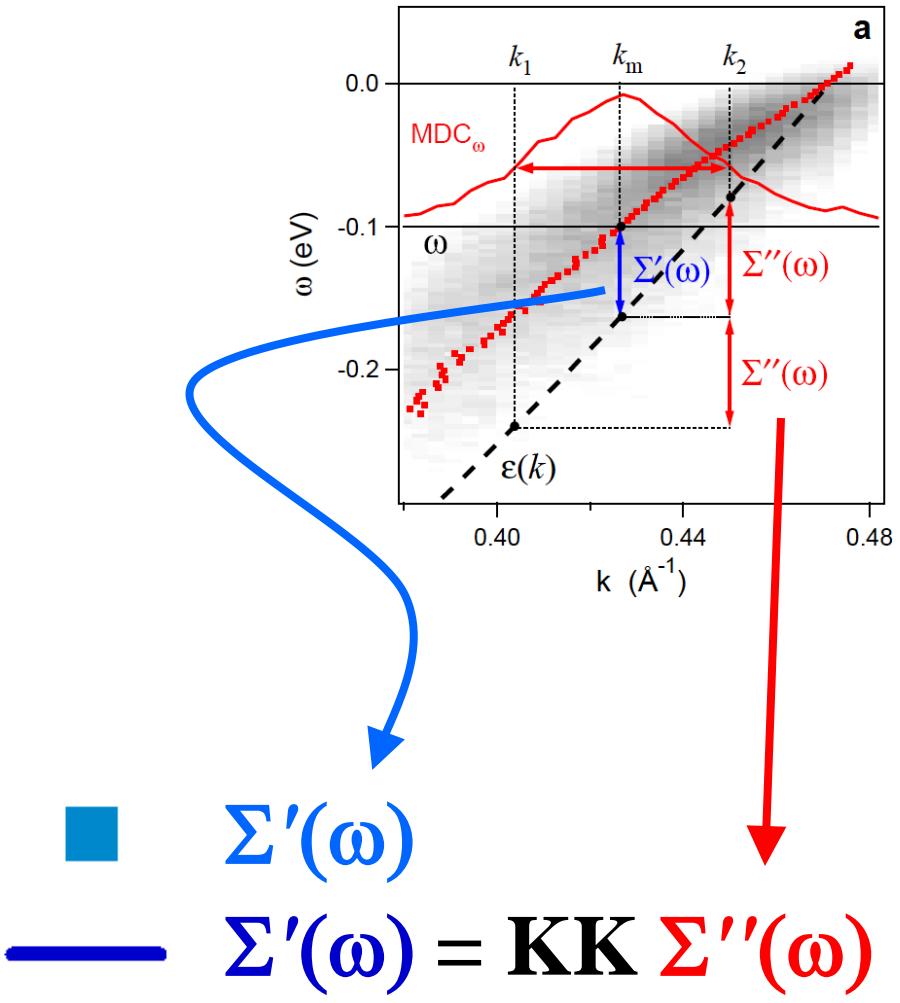
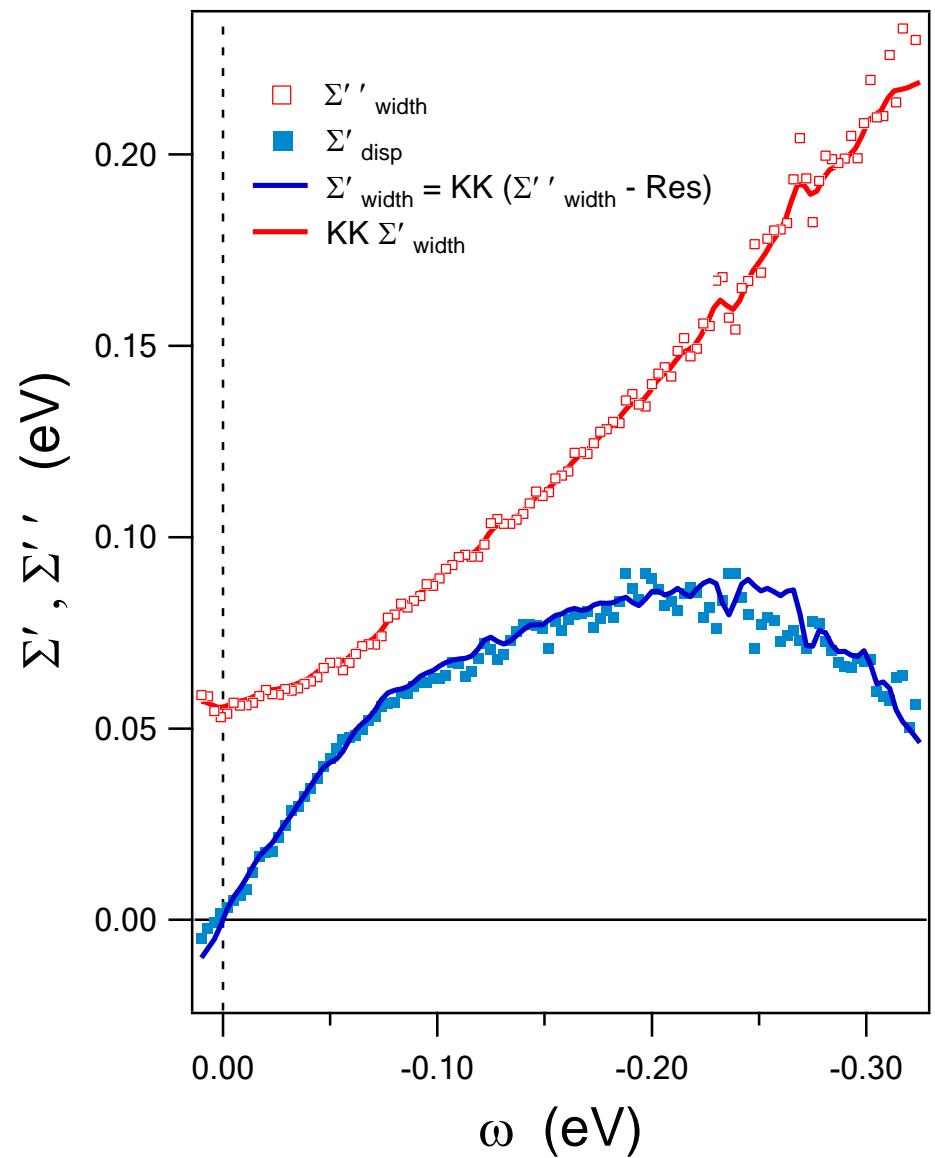


$$\Sigma'(\omega) = \omega - \varepsilon(k_m)$$

$$\Sigma''(\omega) = -v_F W(\omega)$$

$$\Sigma'(\omega) = K \Sigma''(\omega)$$

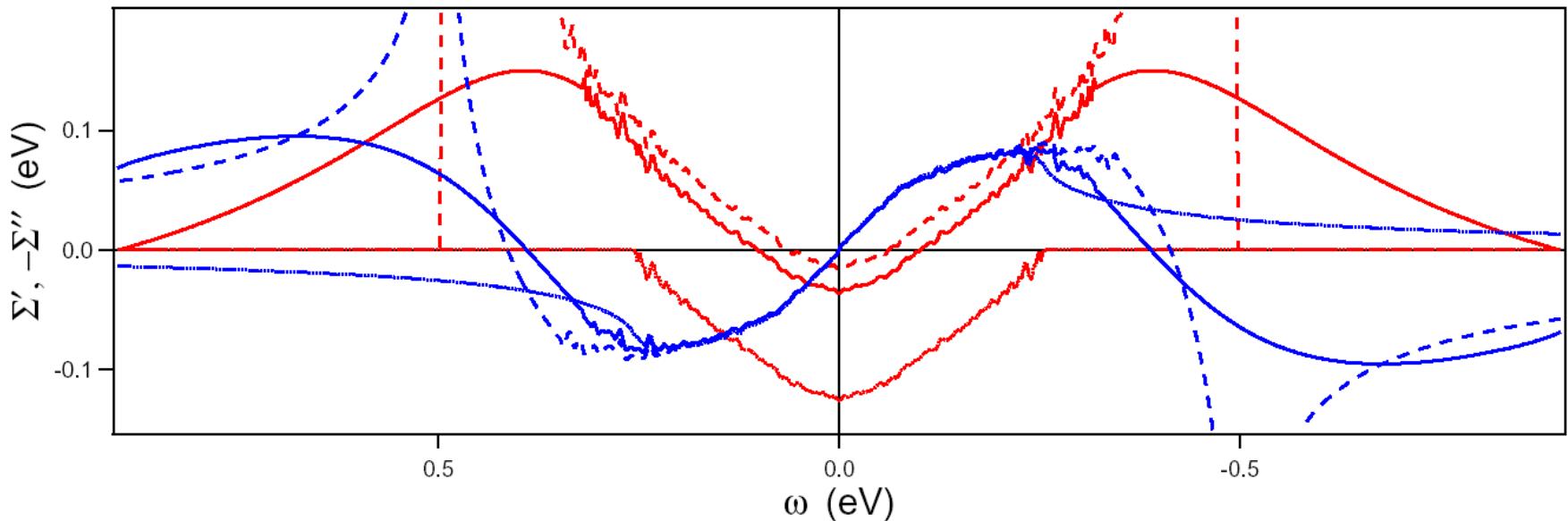
Kramers-Kronig transform



Kordyuk PRB 2005

Kramers-Kronig transform

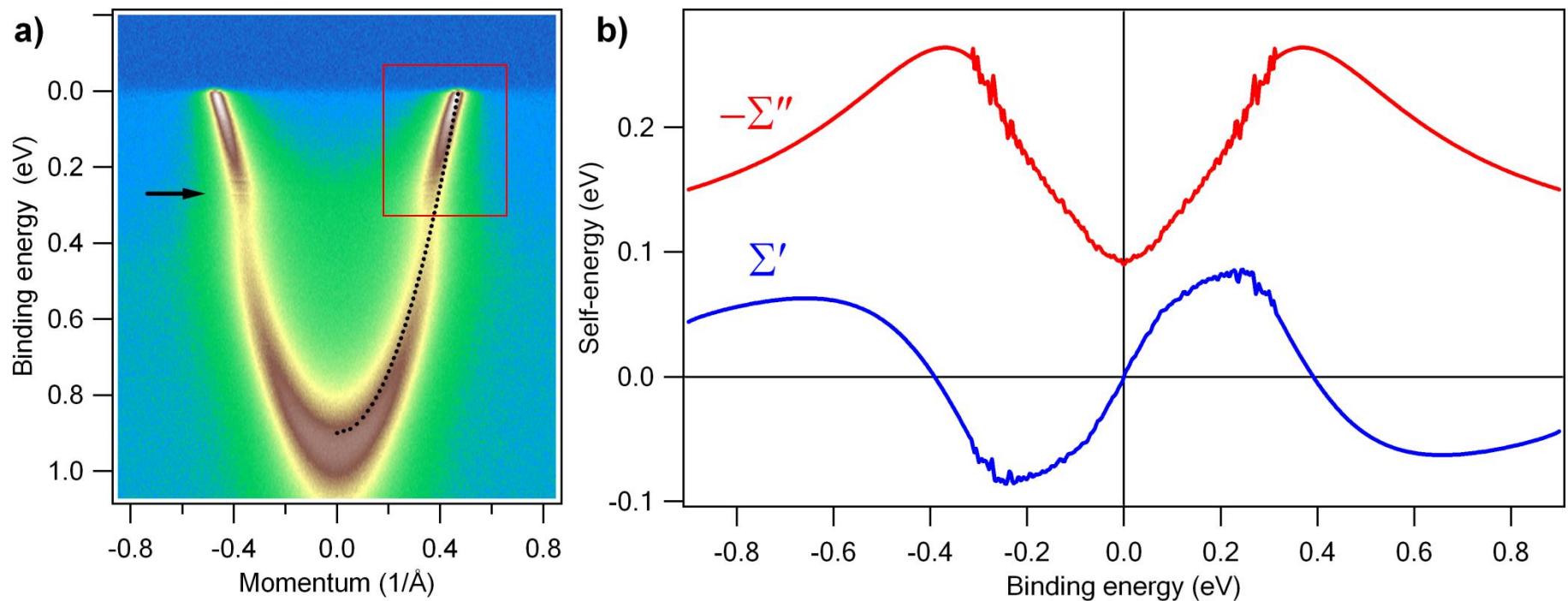
$$\Sigma'(\omega) = \text{KK } \Sigma''(\omega)$$



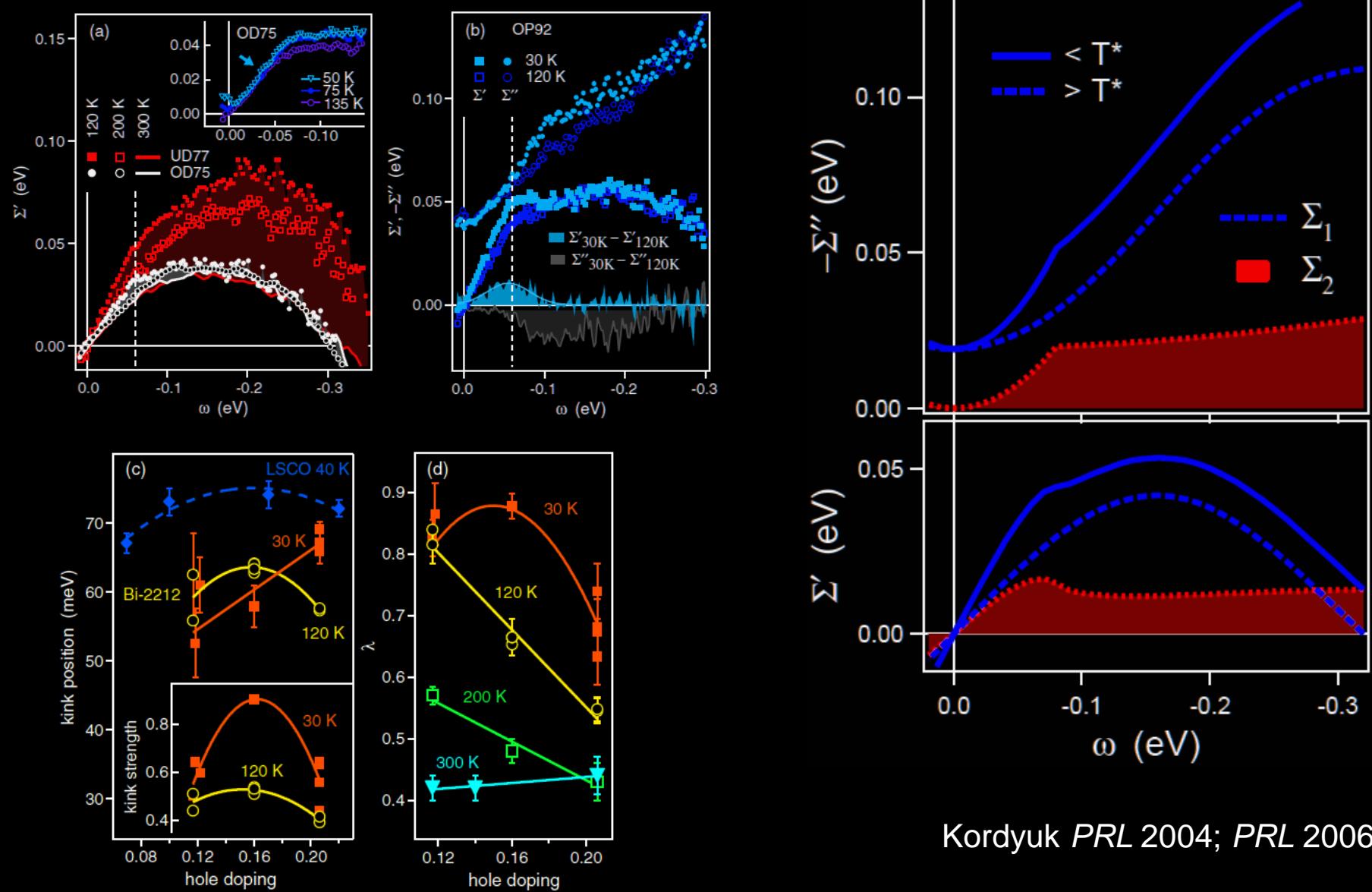
$$\Sigma''(\omega) = \begin{cases} \Sigma''_{width}(|\omega|) & \text{for } |\omega| < \omega_m, \\ \Sigma''_{mod}(\omega) & \text{for } |\omega| > \omega_m, \end{cases}$$

$$\Sigma''_{mod}(\omega) = -\frac{\alpha \omega^2 + C}{1 + \left| \frac{\omega}{\omega_c} \right|^n},$$

"High-energy scale"

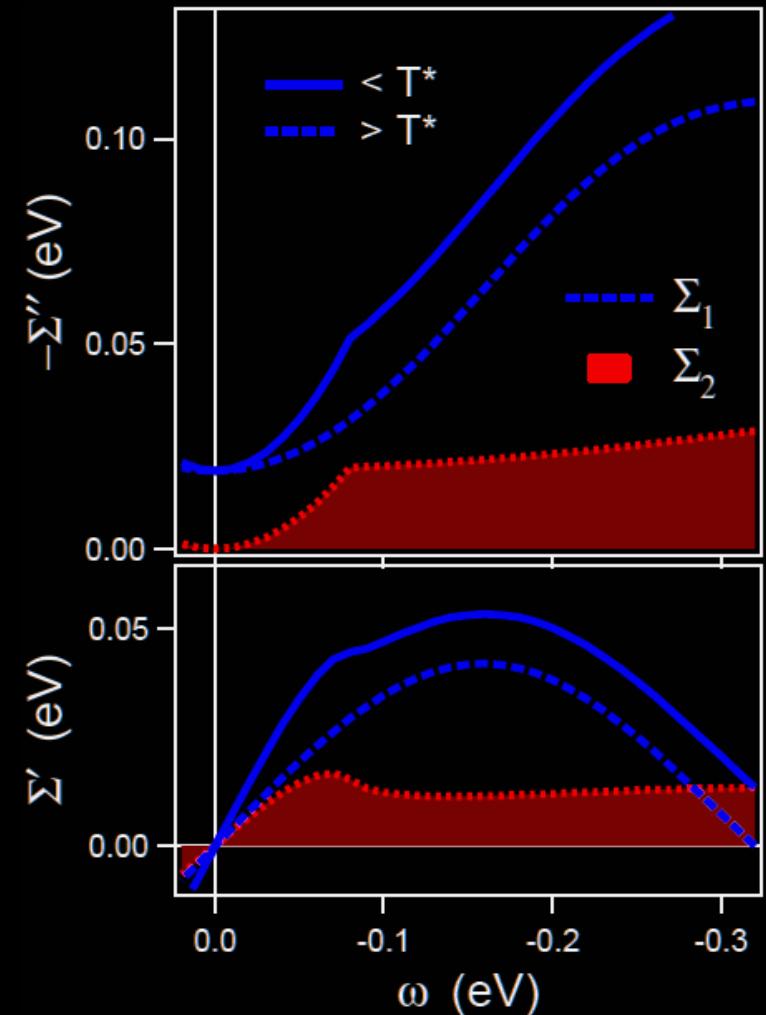
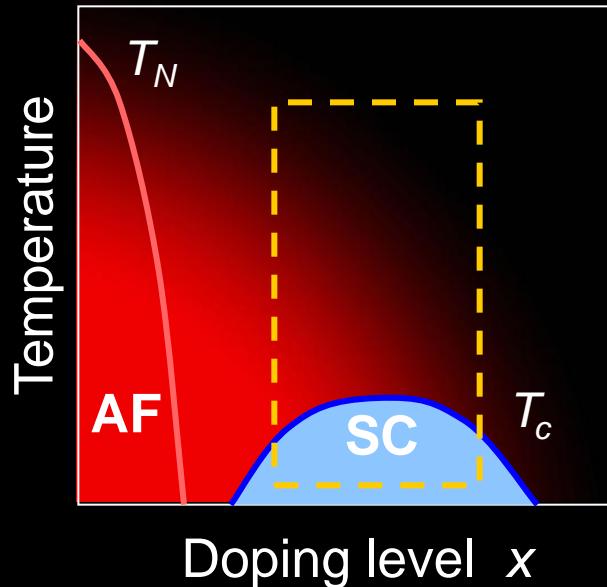


Self-energy structure: two channels



Kordyuk PRL 2004; PRL 2006

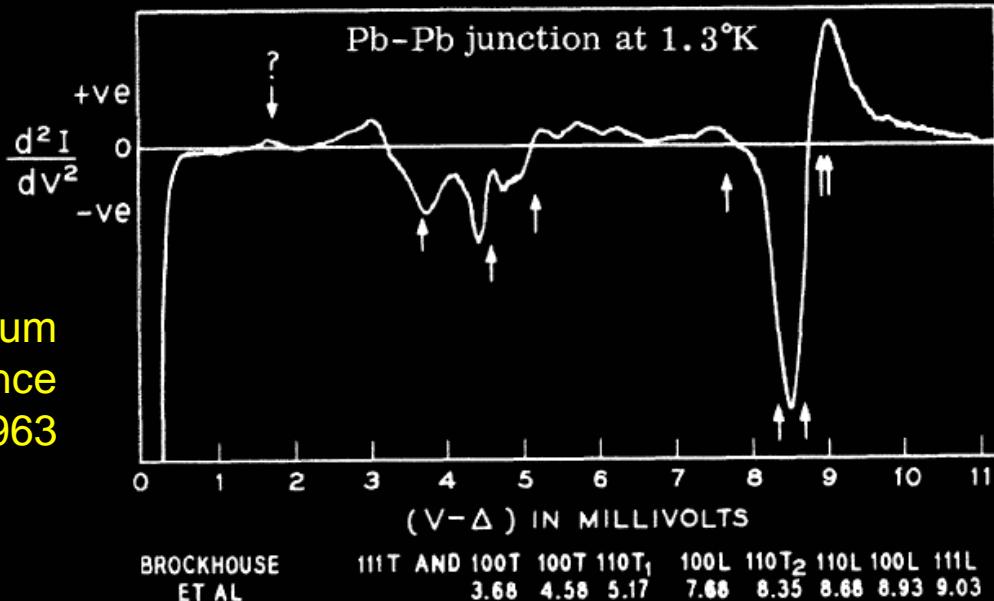
Self-energy structure: two channels



the only channel which reveals some energy scale is critically doping dependent
→ spin fluctuations

„Fingerprints“ story

“fingerprints” of the phononic spectrum
in tunneling differential conductance
by Rowell *PRL* 1963



$$\Delta(\omega) = \frac{1}{Z(\omega)} \int_0^{\omega_c} d\omega' \operatorname{Re} \left\{ \frac{\Delta(\omega')}{(\omega'^2 - \Delta^2(\omega'))^{1/2}} \right\} [K_+(\omega', \omega) - N(0)U_c]$$

$$[1 - Z(\omega)]\omega = \int_0^\infty d\omega' \operatorname{Re} \left\{ \frac{\omega'}{(\omega'^2 - \Delta^2(\omega'))^{1/2}} \right\} K_-(\omega', \omega)$$

$$K_{\pm}(\omega, \omega') = \sum_{\lambda} \int_0^\infty d\nu \alpha_{\lambda}^2(\nu) F_{\lambda}(\nu) \left[\frac{1}{\omega' + \omega + \nu + i\delta} \pm \frac{1}{\omega' - \omega + \nu - i\delta} \right]$$

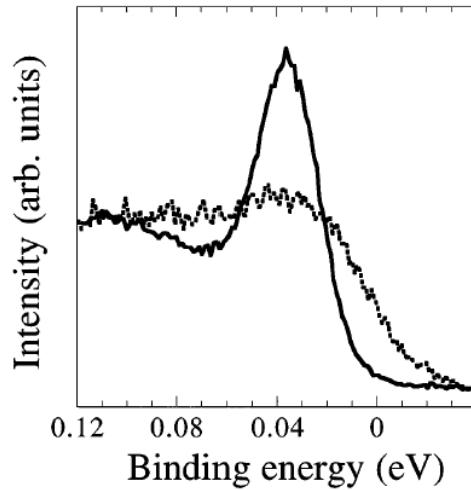
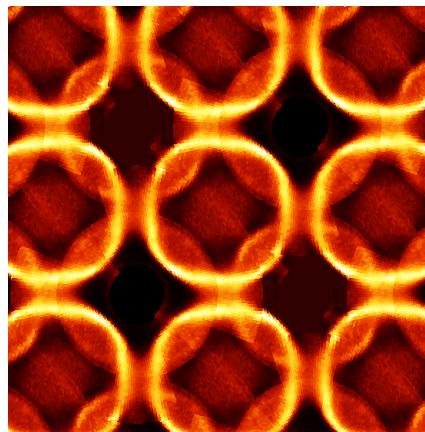
el-ph coupling constant

phonon DOS

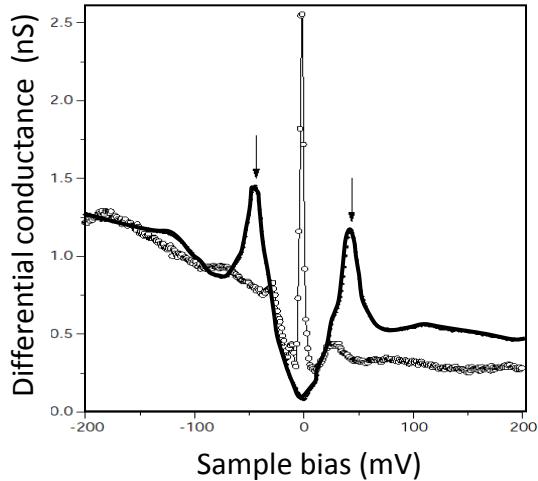
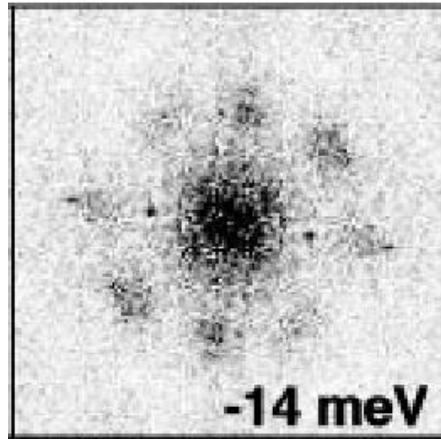
Scalapino *PR* 1966

Modern momentum resolving techniques

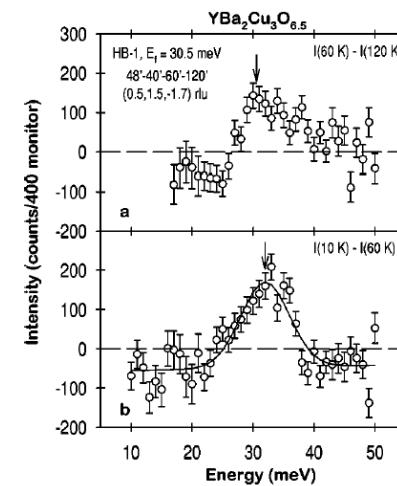
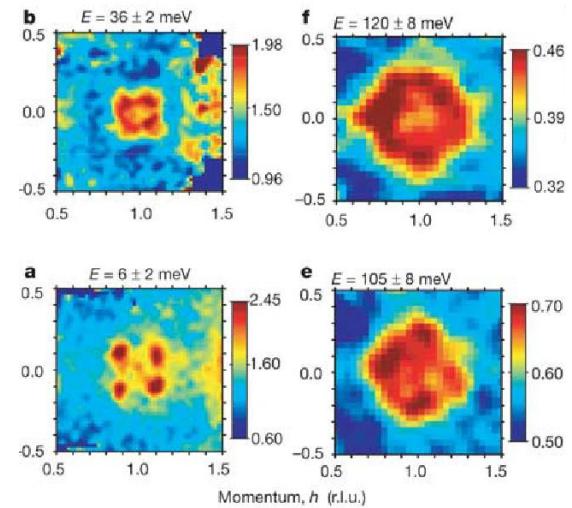
ARPES



STS

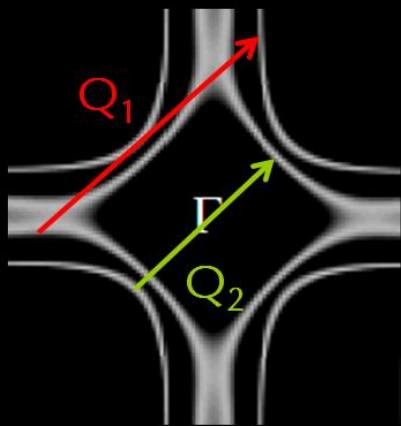


INS



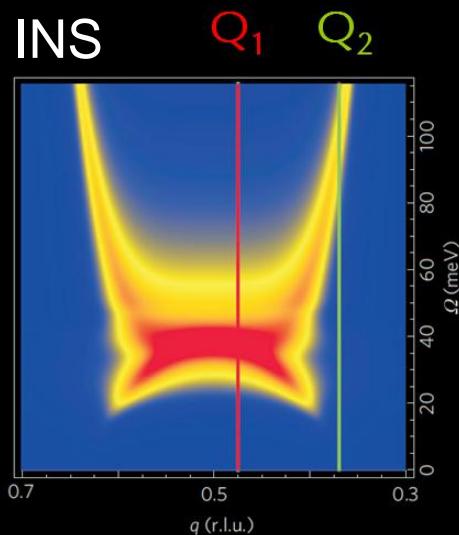
Spin-fluctuations and superconductivity

ARPES



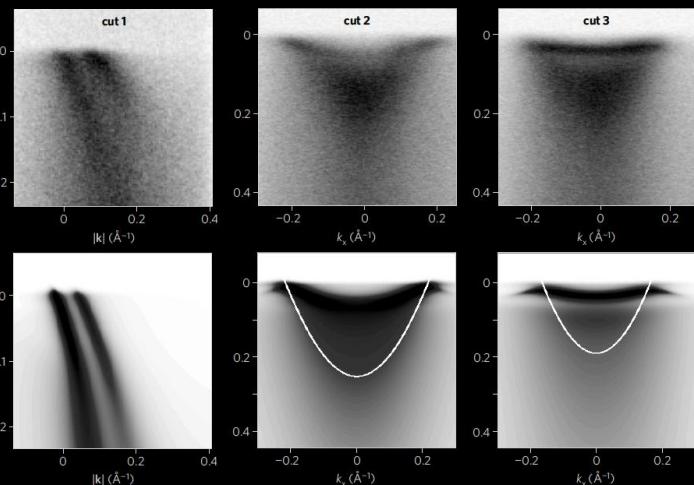
$\text{Im } G_0(\mathbf{k}, \omega)$

INS



$\text{Im } \chi(\mathbf{q}, \Omega)$

ARPES



$\text{Im } G(\mathbf{k}, \omega)$

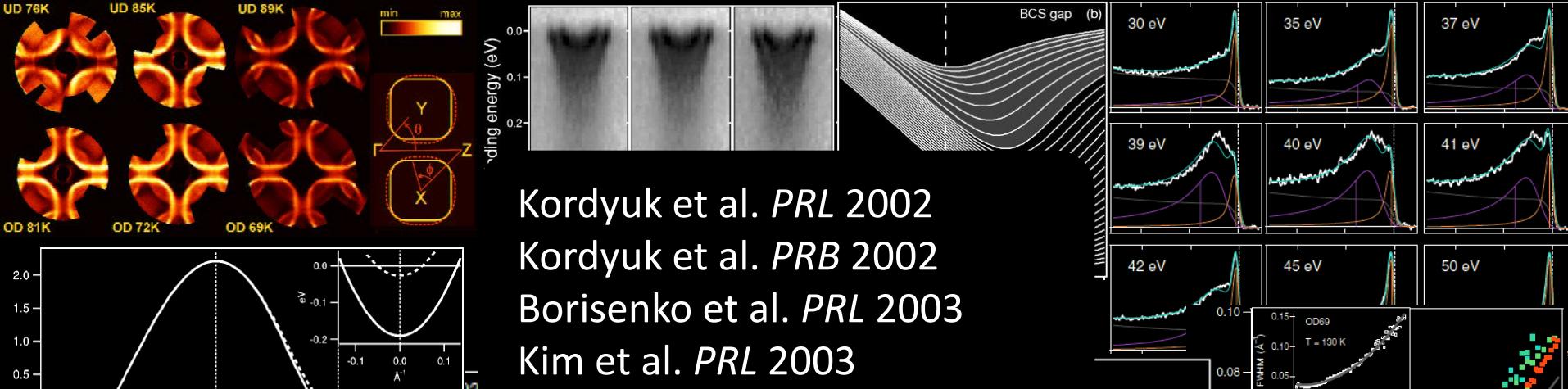
Formula of cuprates:

$$\mathbf{G}_0^{-1} + \overbrace{\alpha^2 \mathbf{G} \star \mathbf{X}}^{\Sigma} = \mathbf{G}^{-1}$$

$$\mathbf{G}_0^{-1} + \alpha^2 \mathbf{G} \star \overbrace{\mathbf{G} \star \mathbf{G}} = \mathbf{G}^{-1}$$

- 1. ARPES and INS
-> spin-fluctuations
- 2. $T_c \sim 150$ K.

D. Inosov et al., [PRB 2007](#)
 T. Dahm et al., [Nature Phys 2009](#)
 A. Kordyuk et al., [EPJ ST 2010](#)

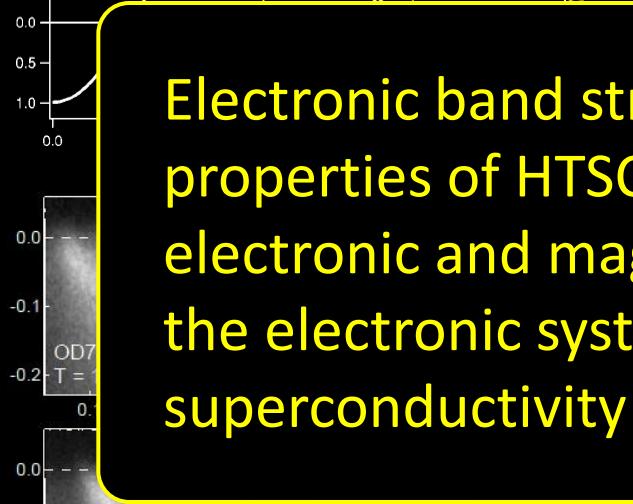


Kordyuk et al. *PRL* 2002

Kordyuk et al. *PRB* 2002

Borisenko et al. *PRL* 2003

Kim et al. *PRL* 2003



Electronic band structure plays crucial role in all electronic properties of HTSC: it determines the formation of both electronic and magnetic spectra, as well as the instabilities of the electronic system such as spin density wave and superconductivity

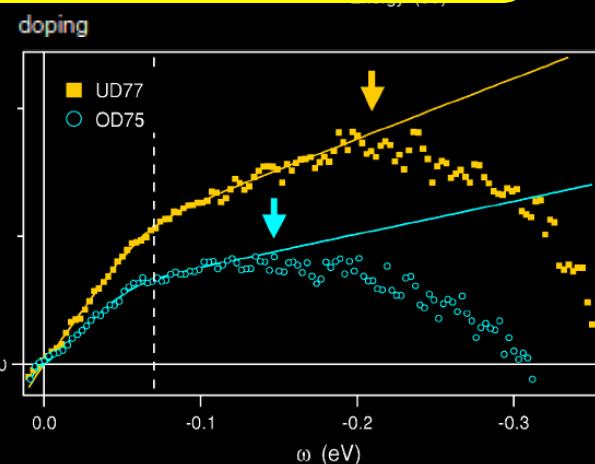
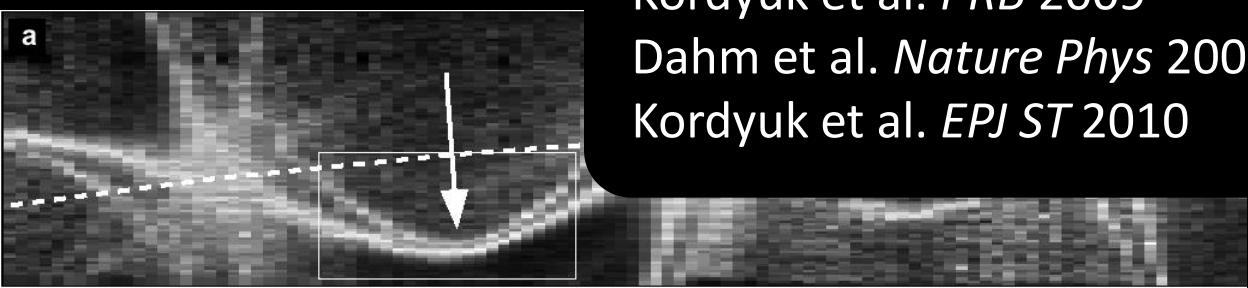
Inosov et al. *PRL* 2007

Inosov et al. *PRB* 2008

Kordyuk et al. *PRB* 2009

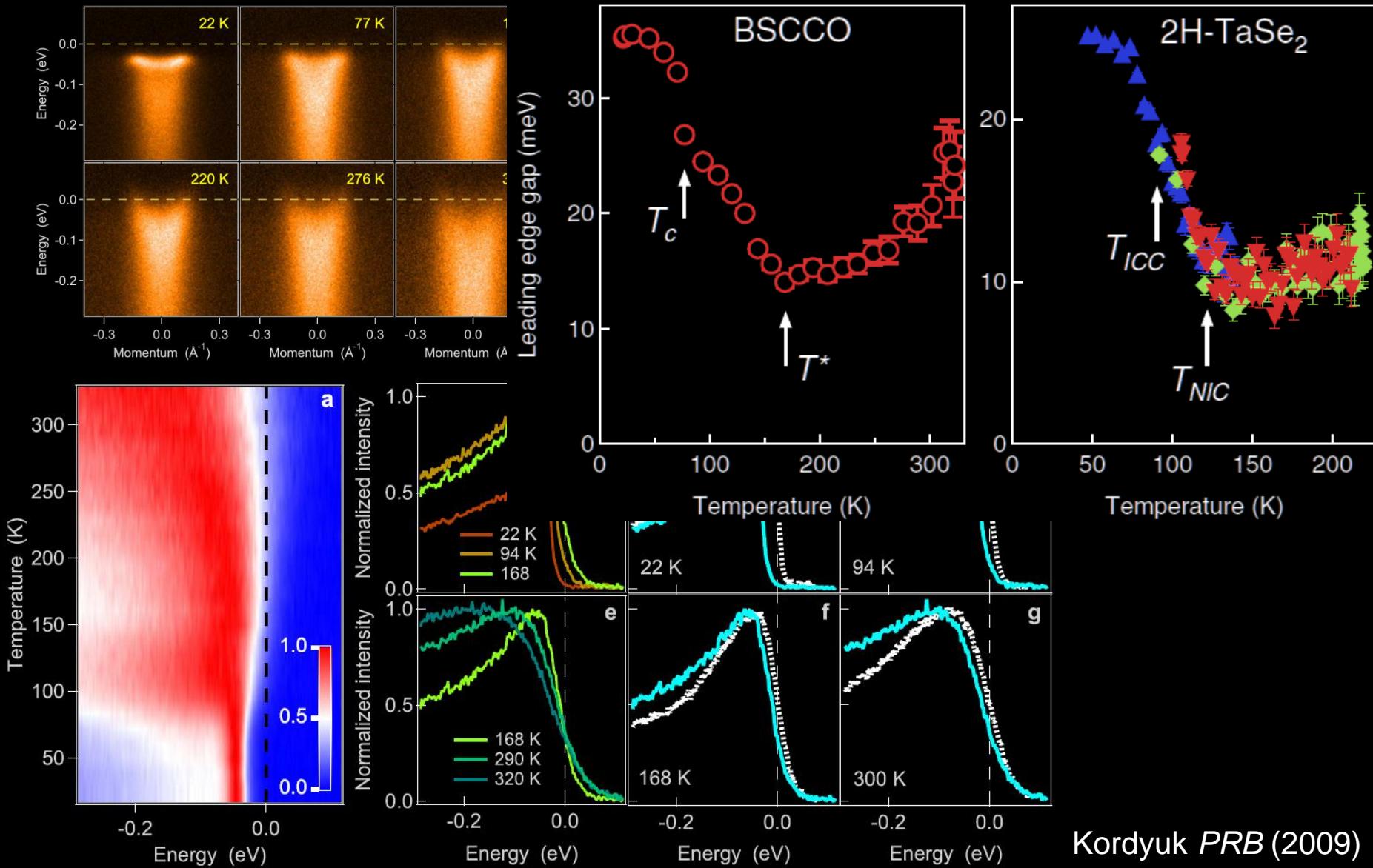
Dahm et al. *Nature Phys* 2009

Kordyuk et al. *EPJ ST* 2010

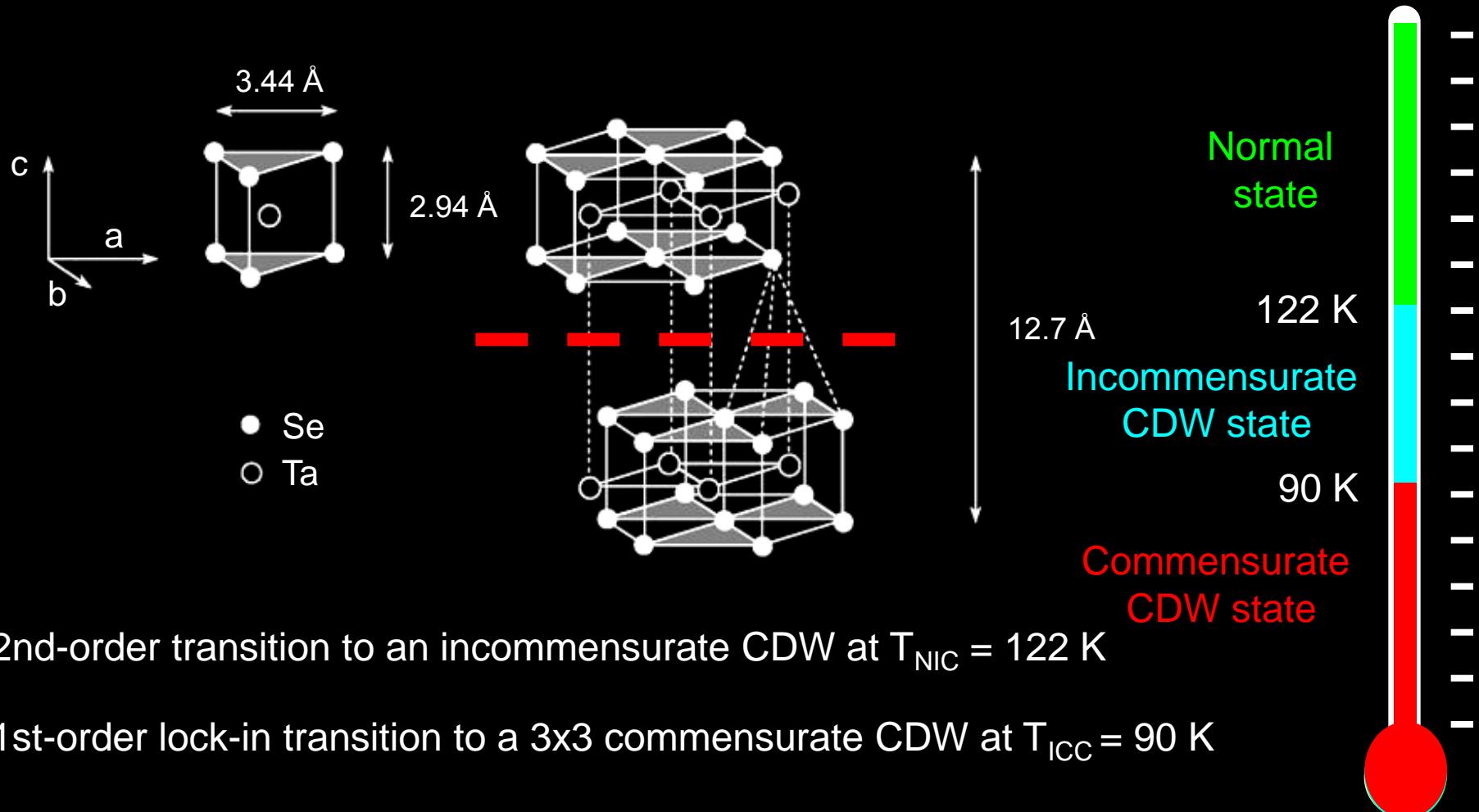


Pseudogap in HTSC cuprates
and
electron instability and Fermi surface nesting
in 2D metals in general

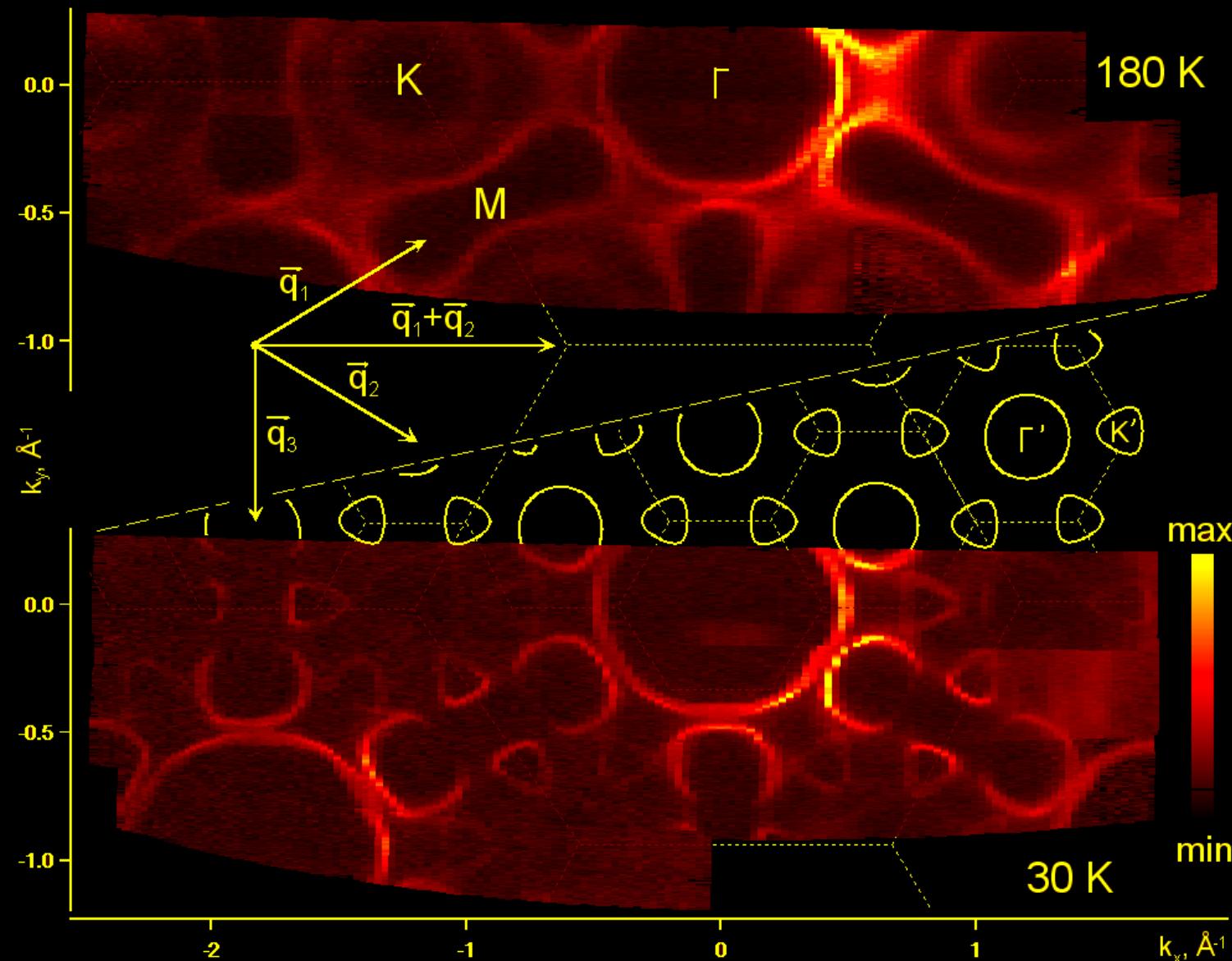
Non-monotonic pseudogap in BSCCO



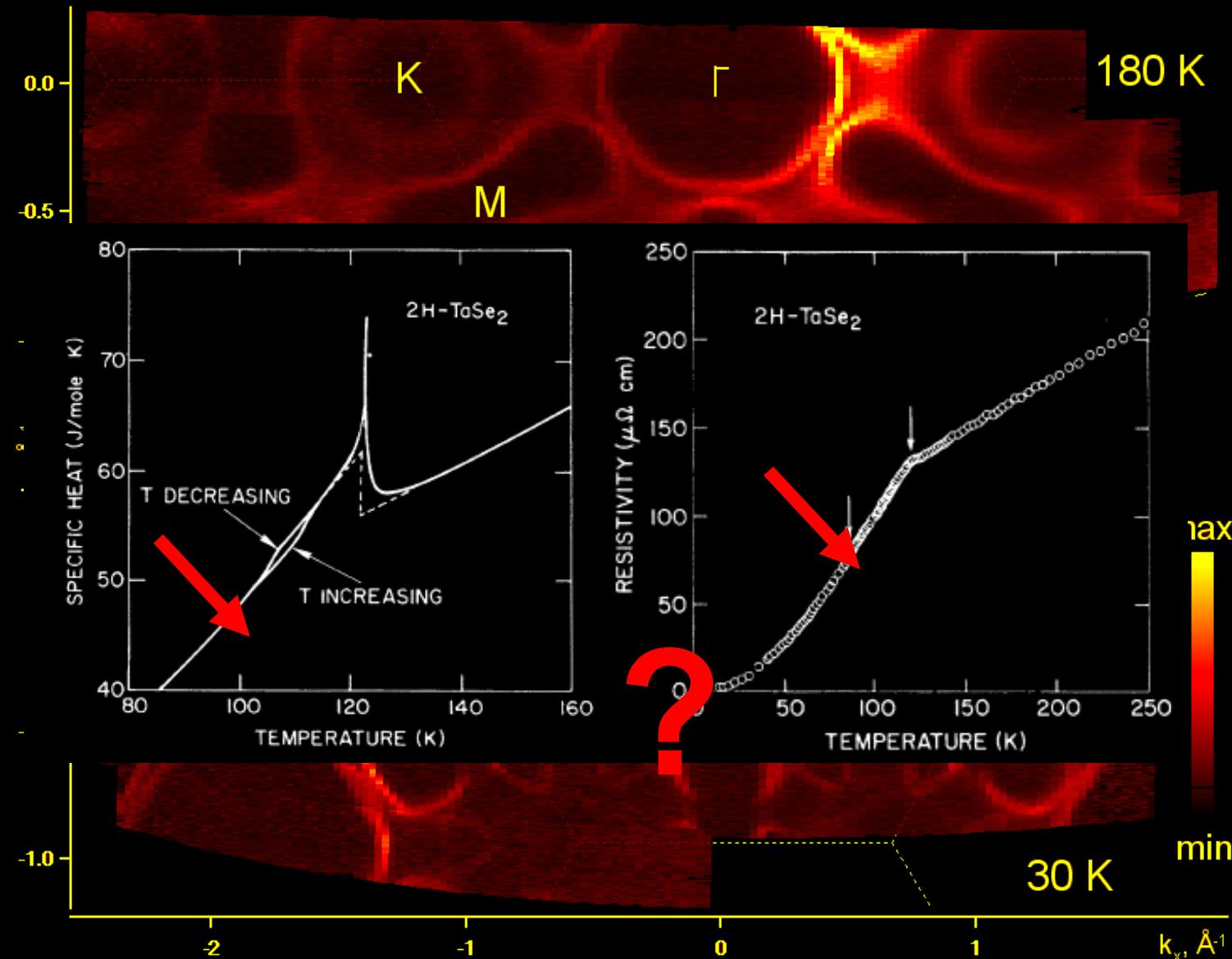
2H-TaSe₂ crystal structure, CDW transitions



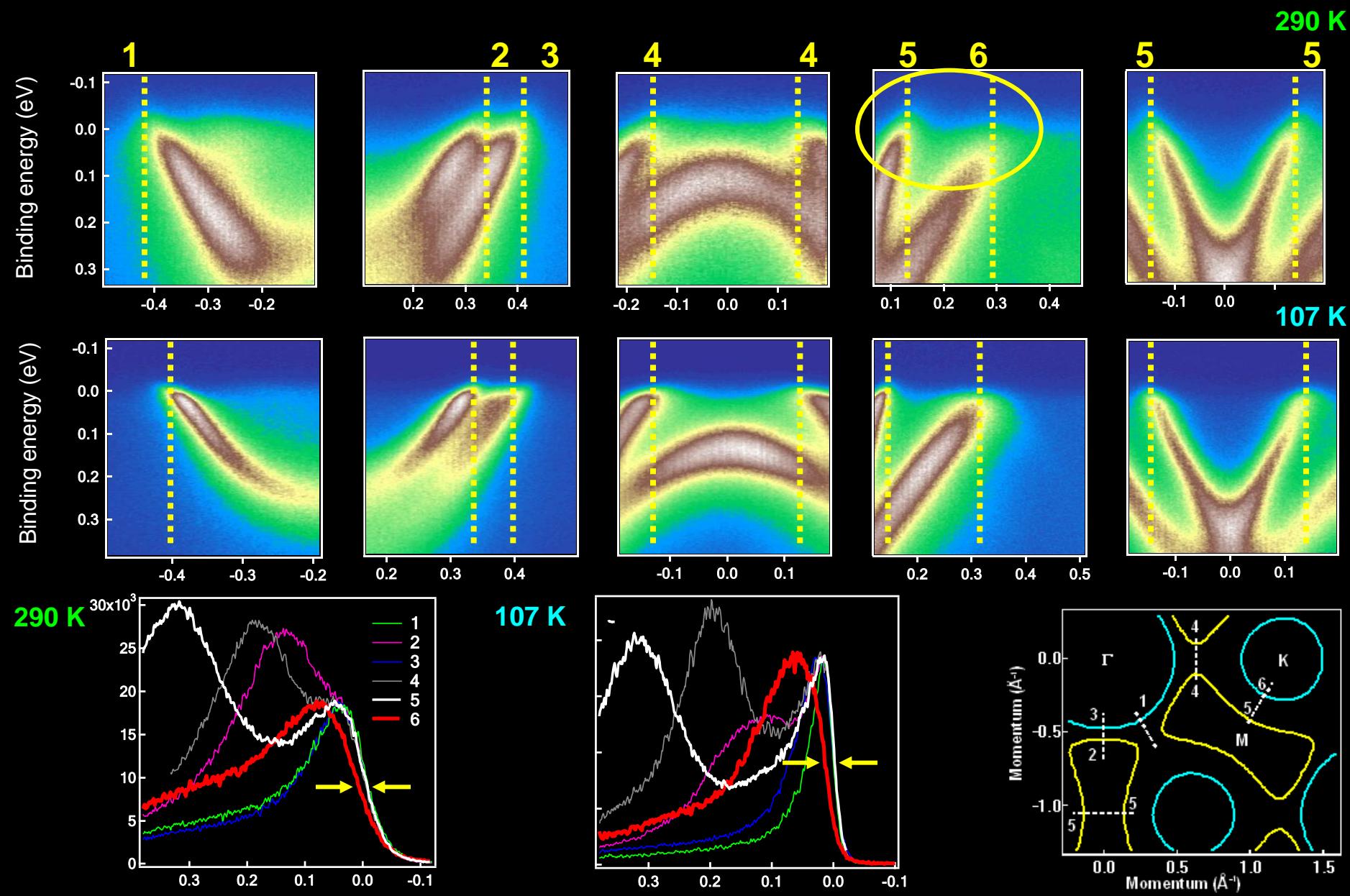
CDW γ TaSe₂: commensurate CDW state



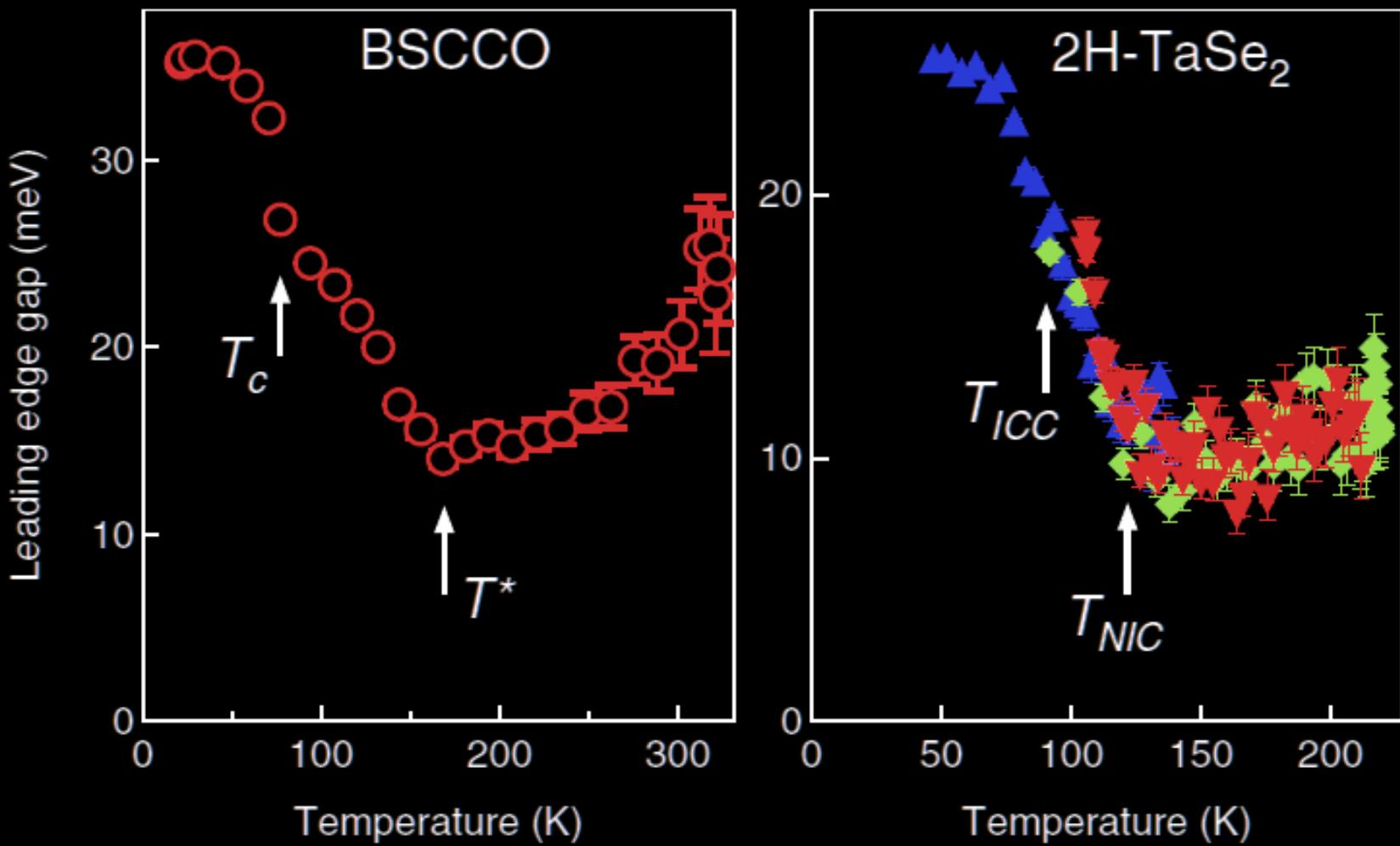
CDW γ TaSe₂: commensurate CDW state



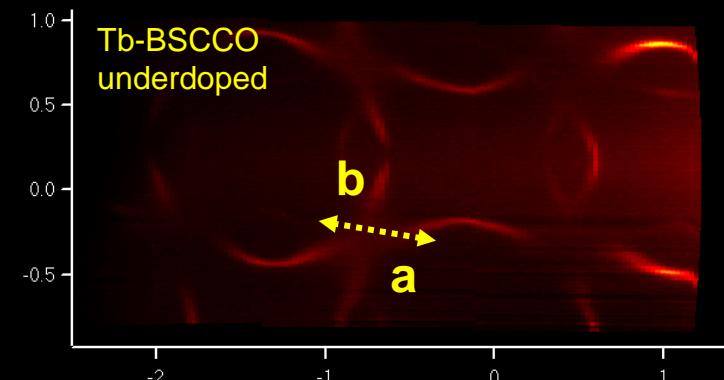
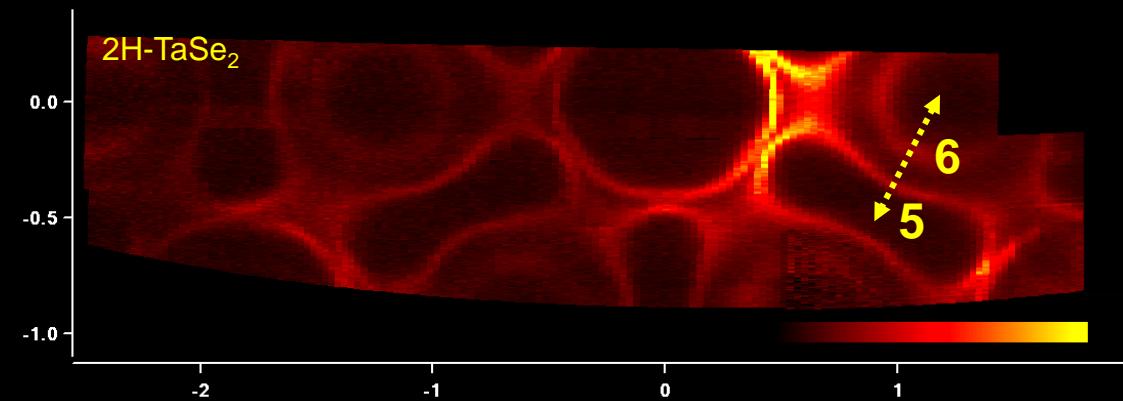
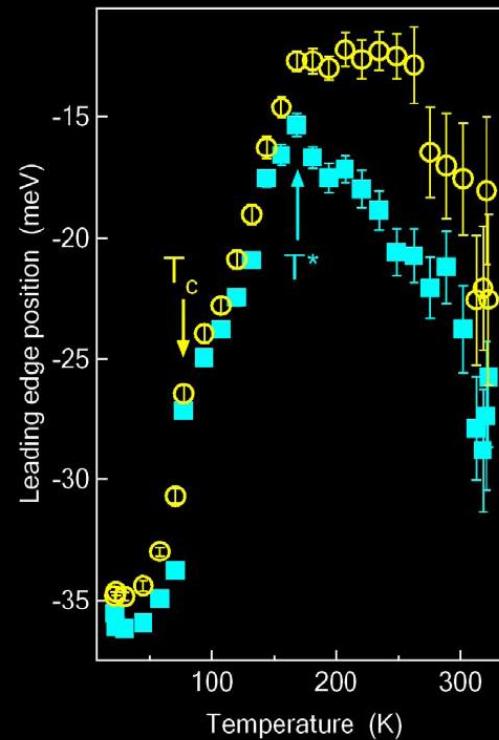
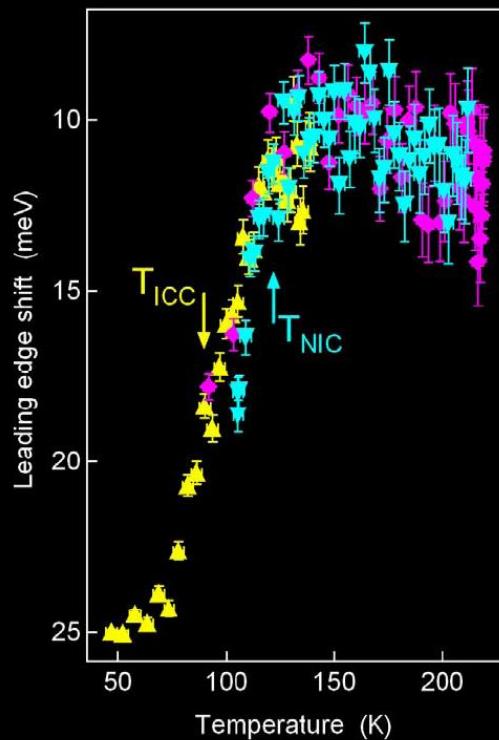
Incommensurate CDW and normal state



T-dependence of the pseudogaps

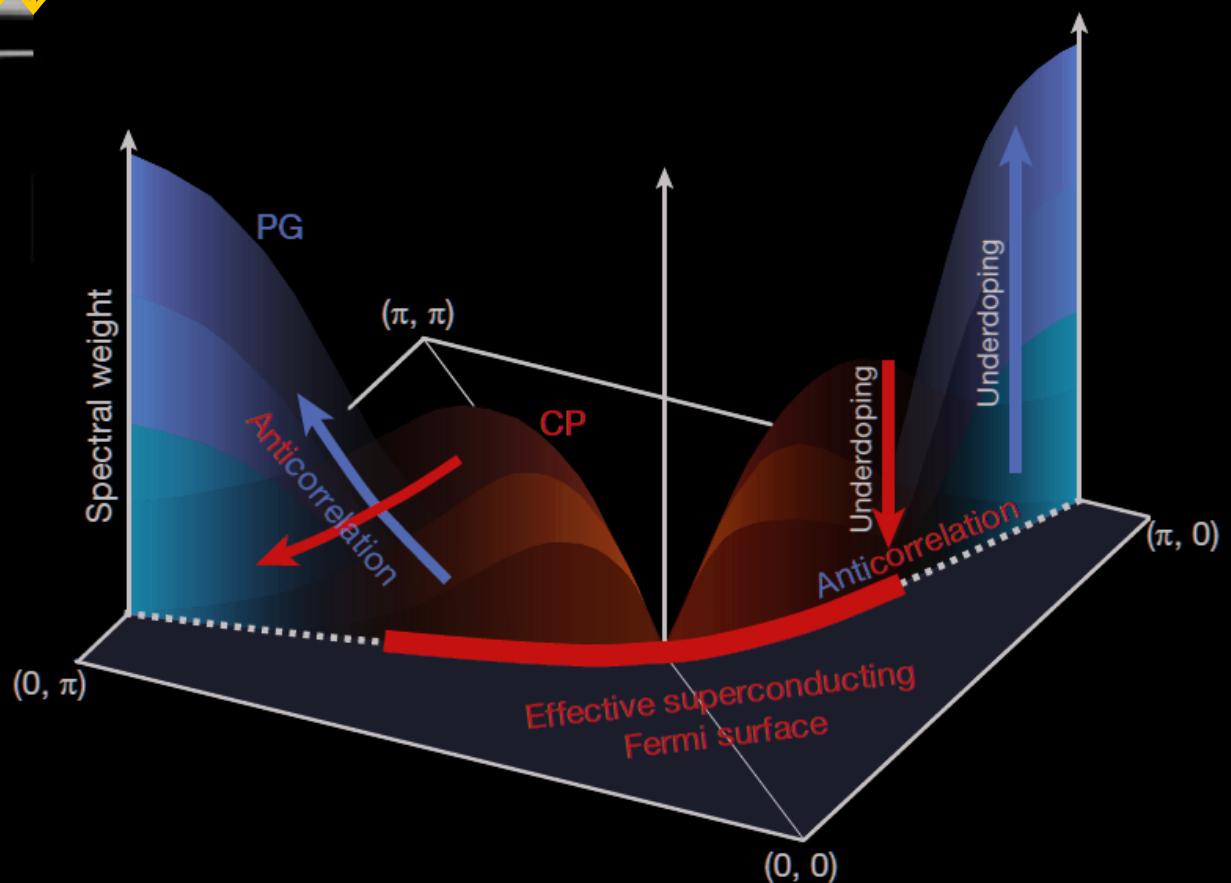
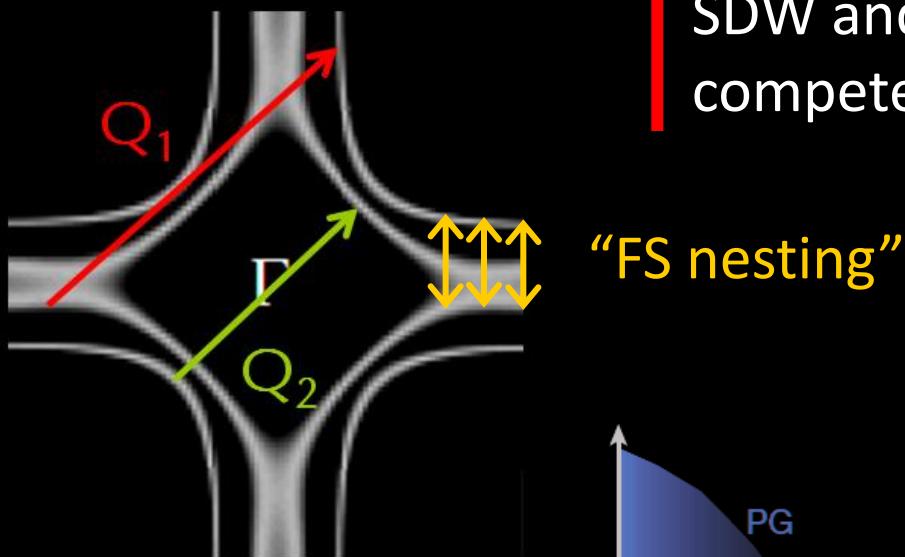


Pseudogap in 2H-TaSe₂ and Tb-BSCCO



“Two-gap scenario”

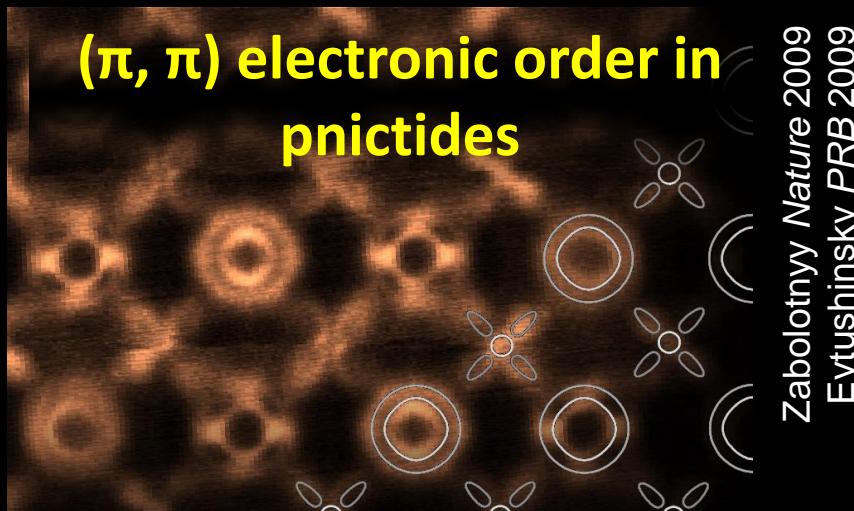
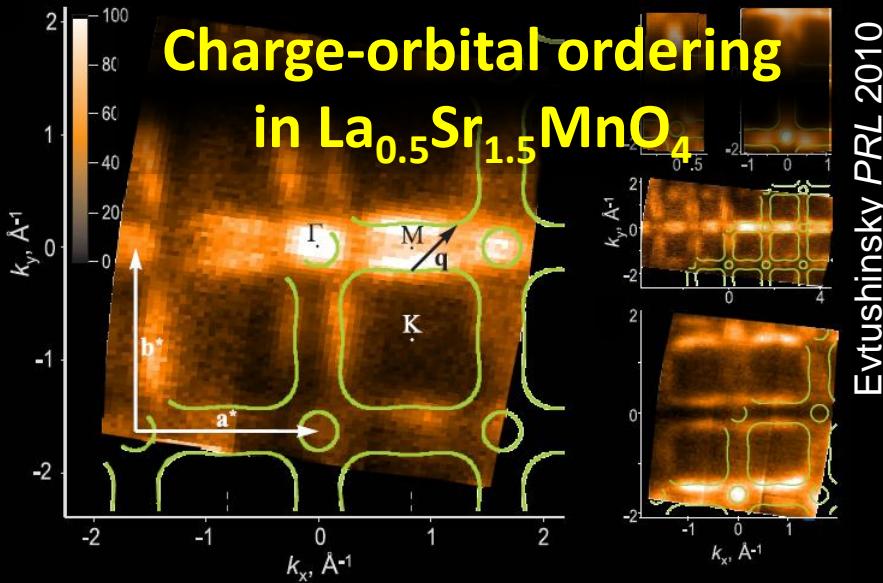
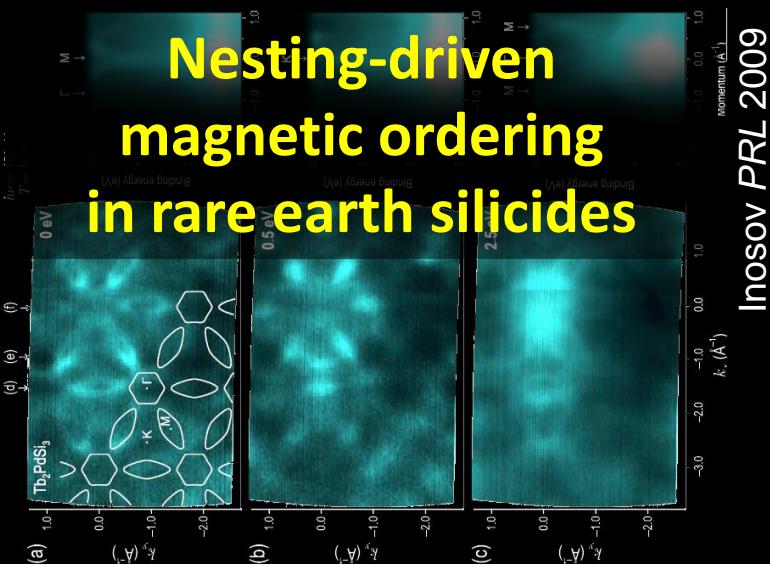
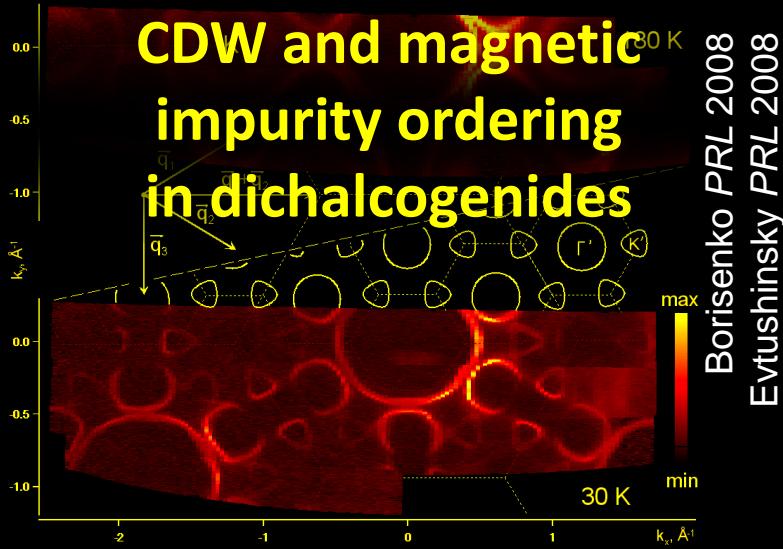
SDW and superconductivity compete for the phase space

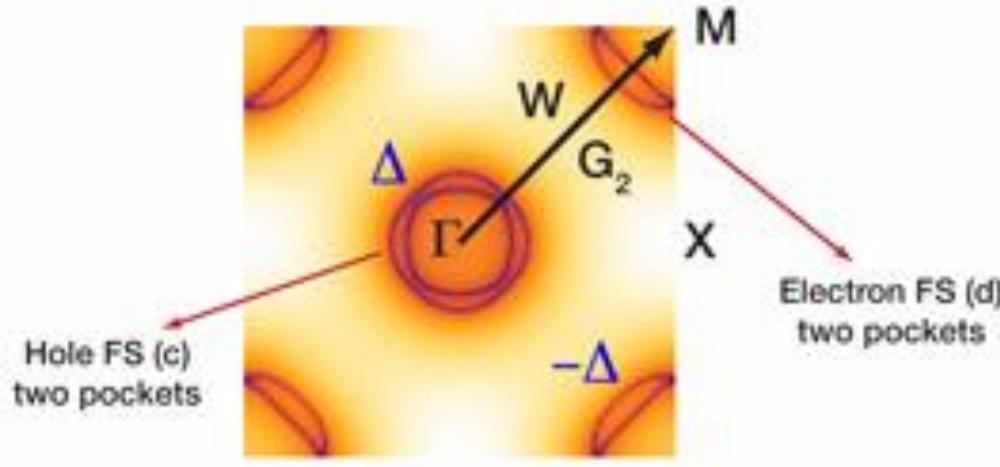


Conclusions on HTSC

1. HTSC = LDA + PG + Self-energy = QP spectrum
2. Self-energy = CHARGE + MAGNETIC
3. MAGNETIC = QP spectrum \square SF spectrum  $T_c = 150 \text{ K}$
4. PG = Electron density modulation =
= incommensurate SDW

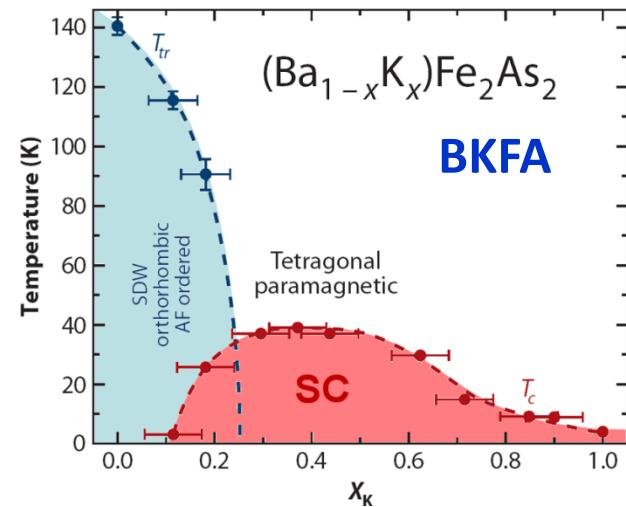
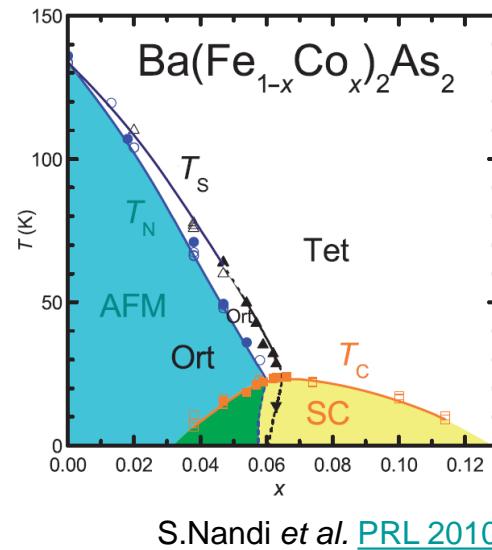
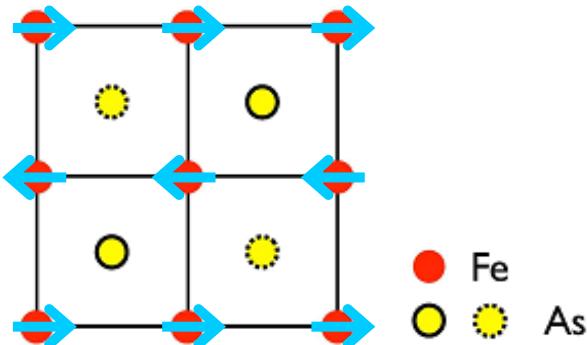
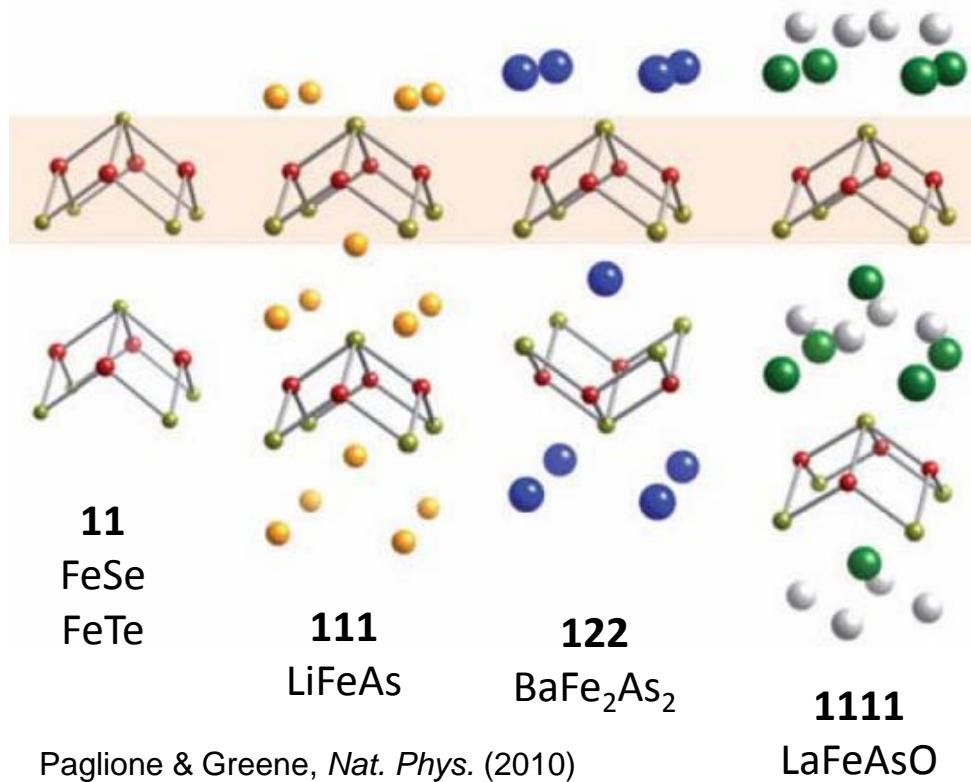
Nesting and ordering in other 2D metals





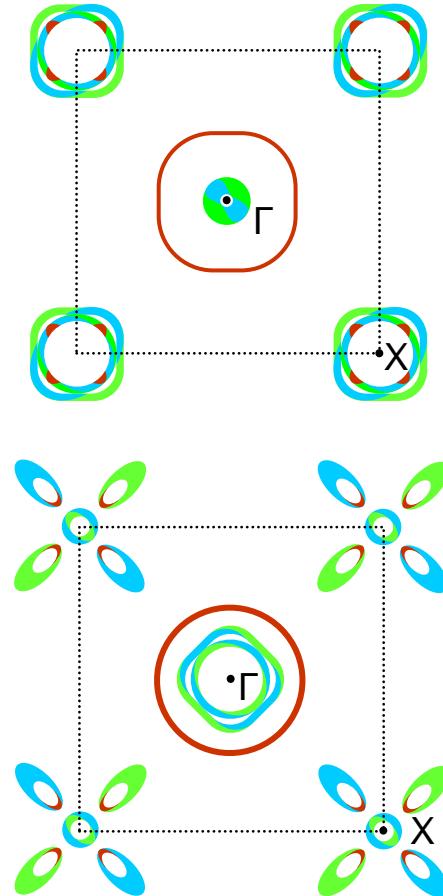
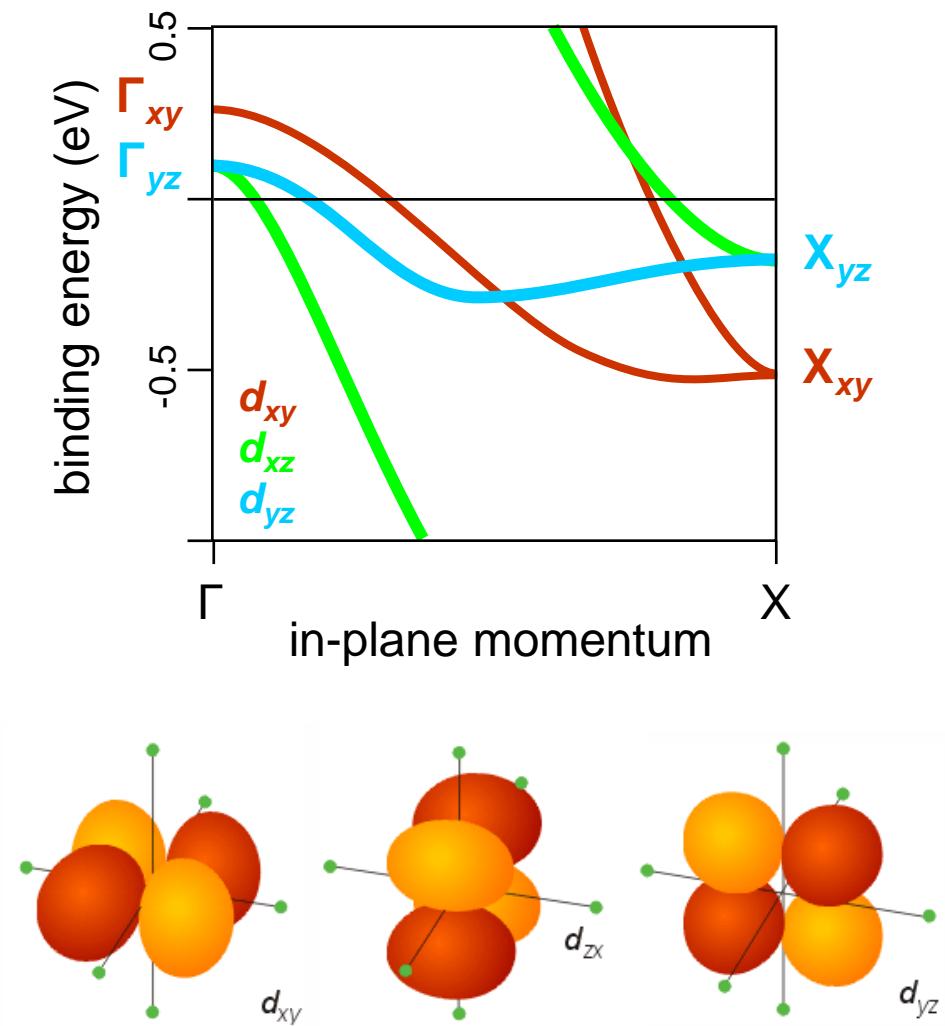
Iron-based superconductors: Fermi surface topology

Iron-based superconductors (FeSC)

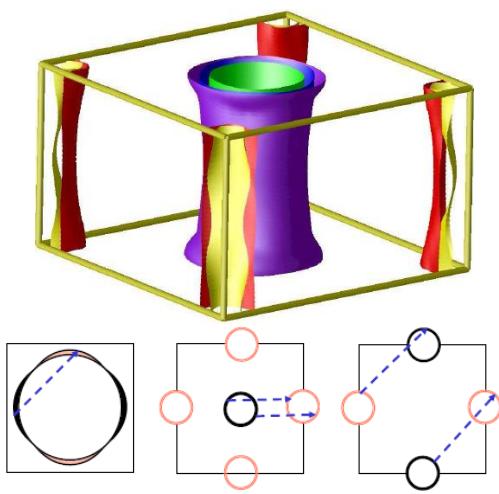


H.-H.Wen & S.Li [Annu. Rev. Cond. Mat. Phys. 2011](#)

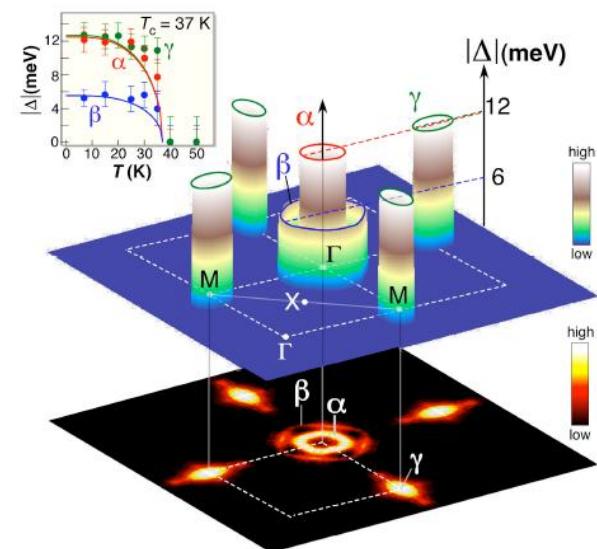
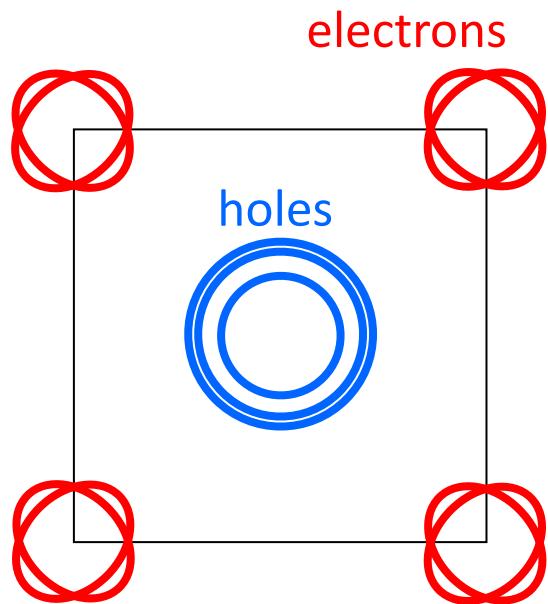
Iron-based superconductors: electronic structure



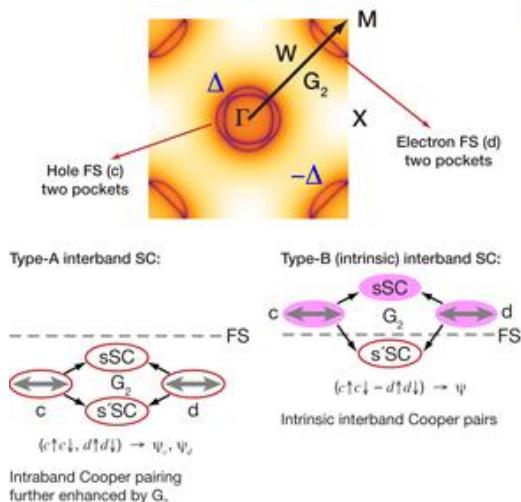
Fermi surface of BKFA



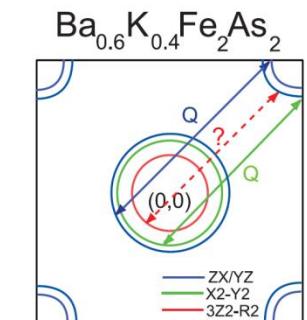
Mazin & Schmalian 2009



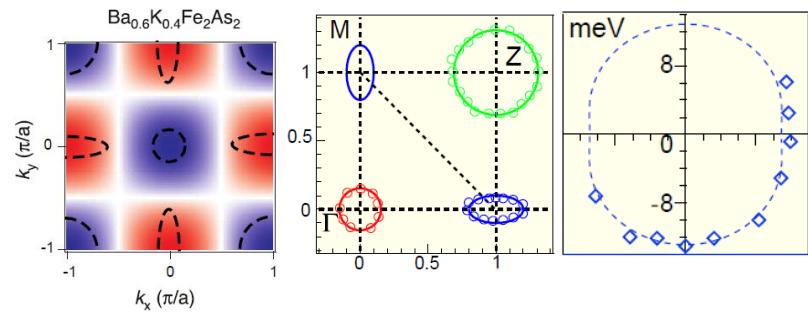
Ding EPL 2008



Tesanovic Physics 2009

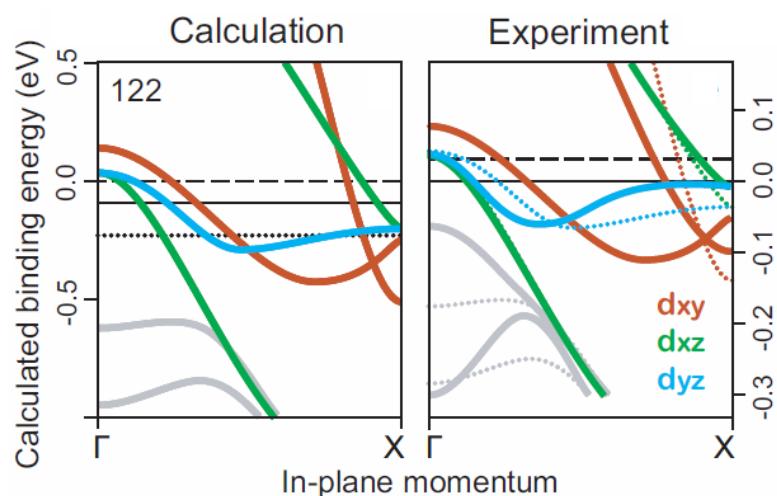
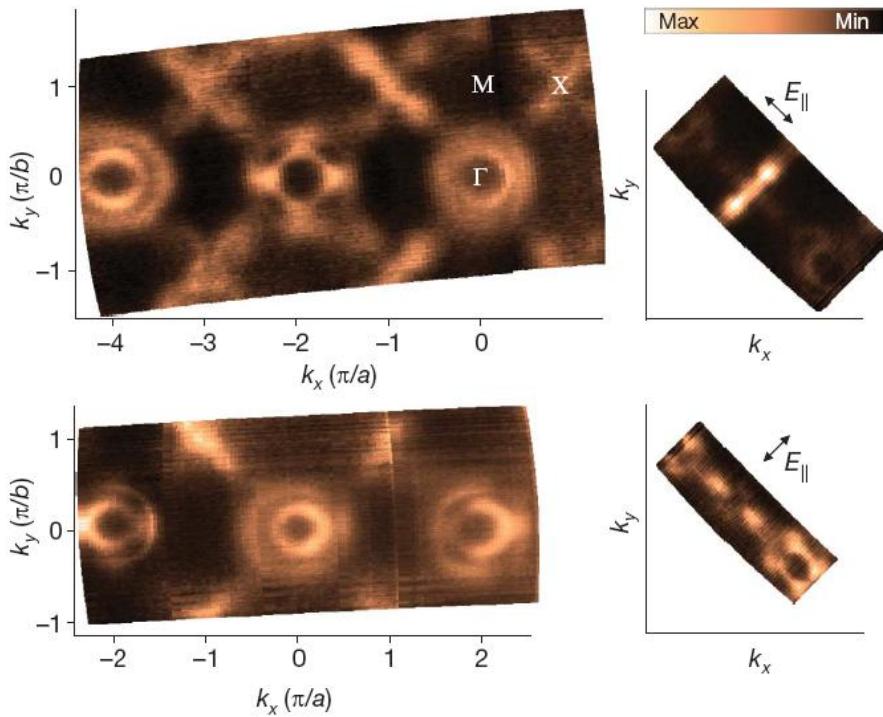
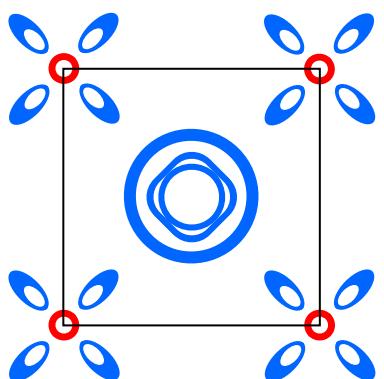
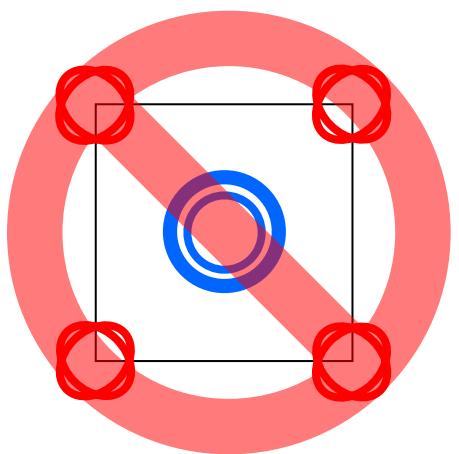


Shimojima Science 2011

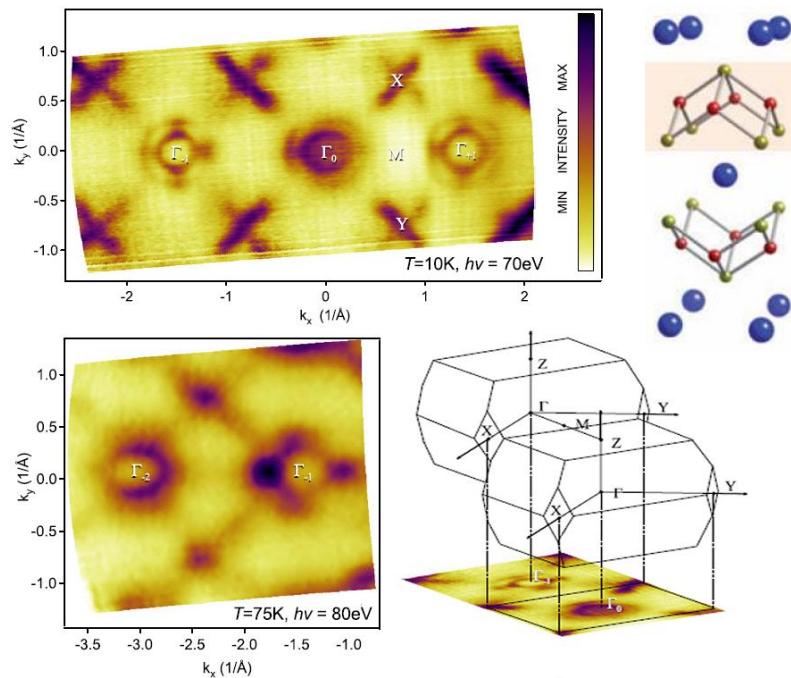


Hu & Ding arXiv:1107.1334

Fermi surface of BKFA

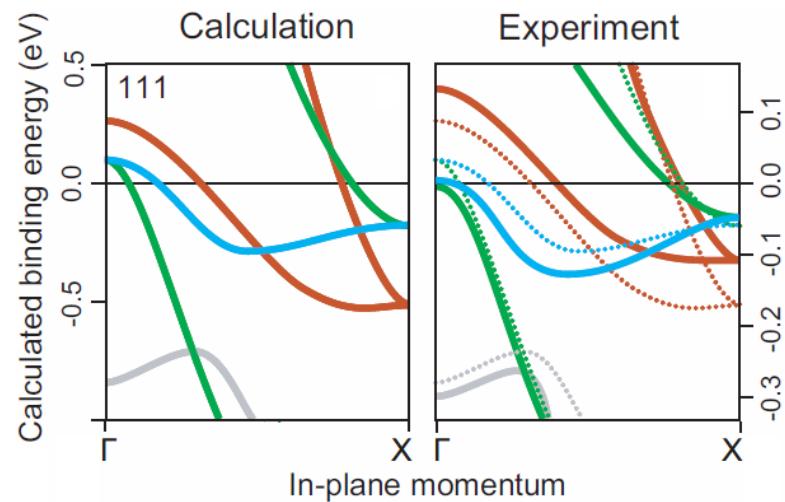
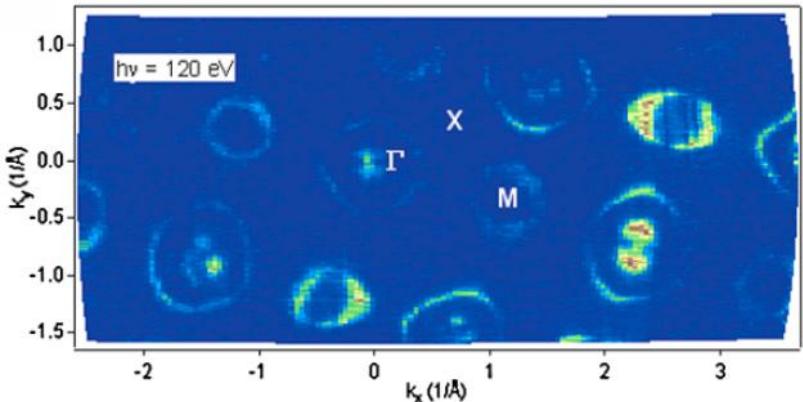
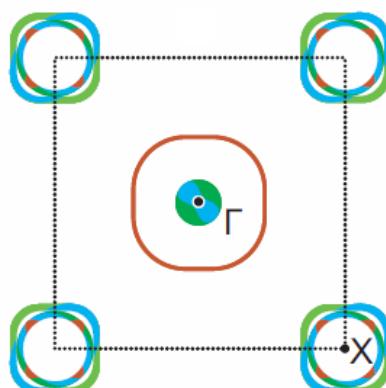
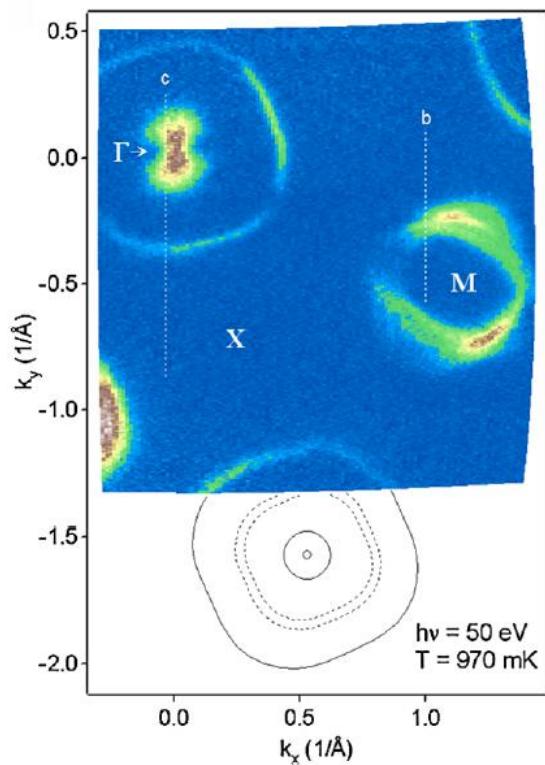


A. A. Kordyuk, *J. Supercond. Nov. Magn.* 2012



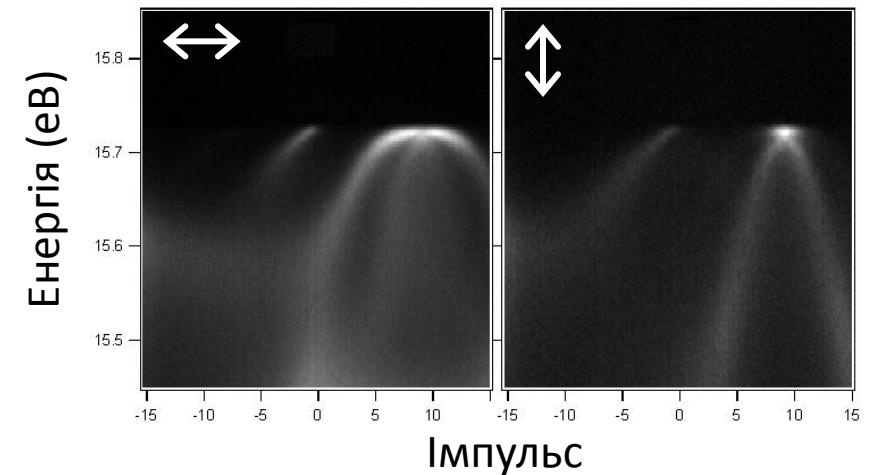
V. Zabolotnyy *Nature* 2009

Fermi surface of LiFeAs



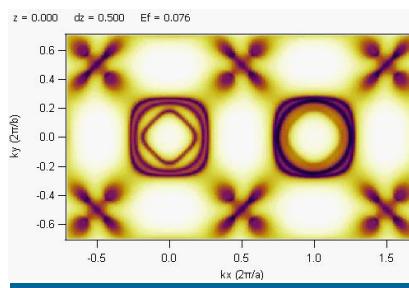
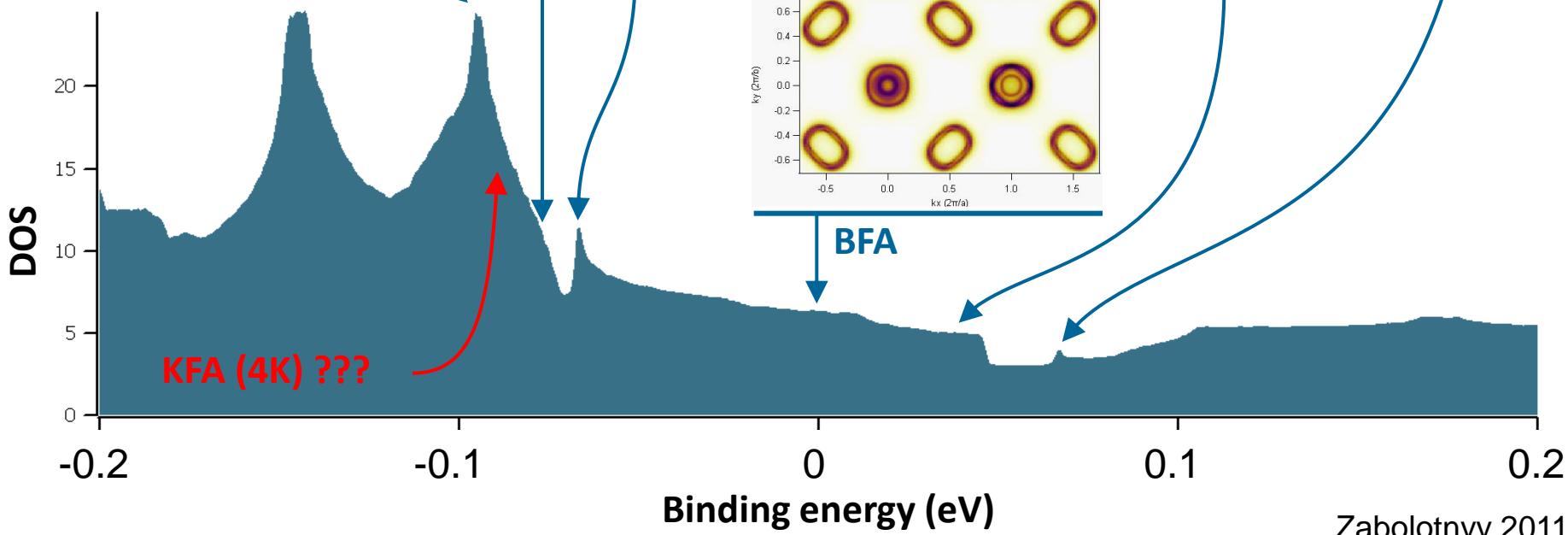
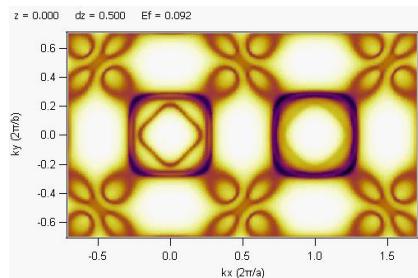
Kordyuk, J. Supercond. Nov. Magn. 2012

поляризація



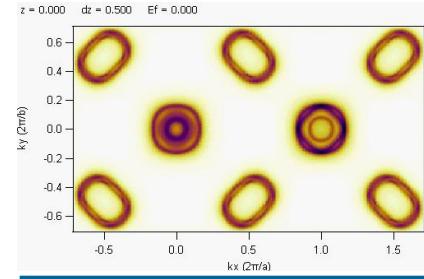
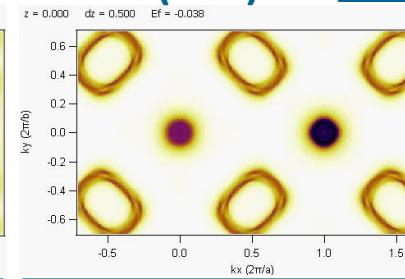
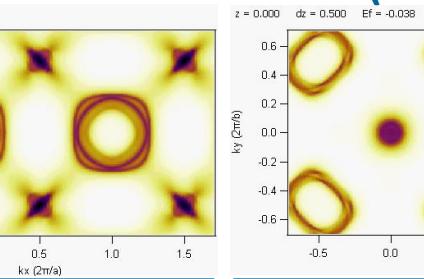
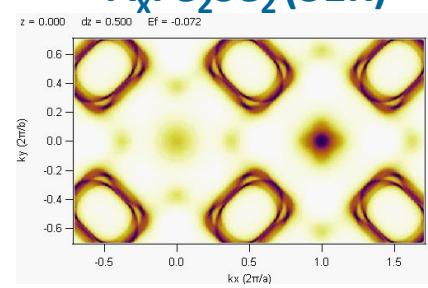
BFA: density of states

Hole doped KFA

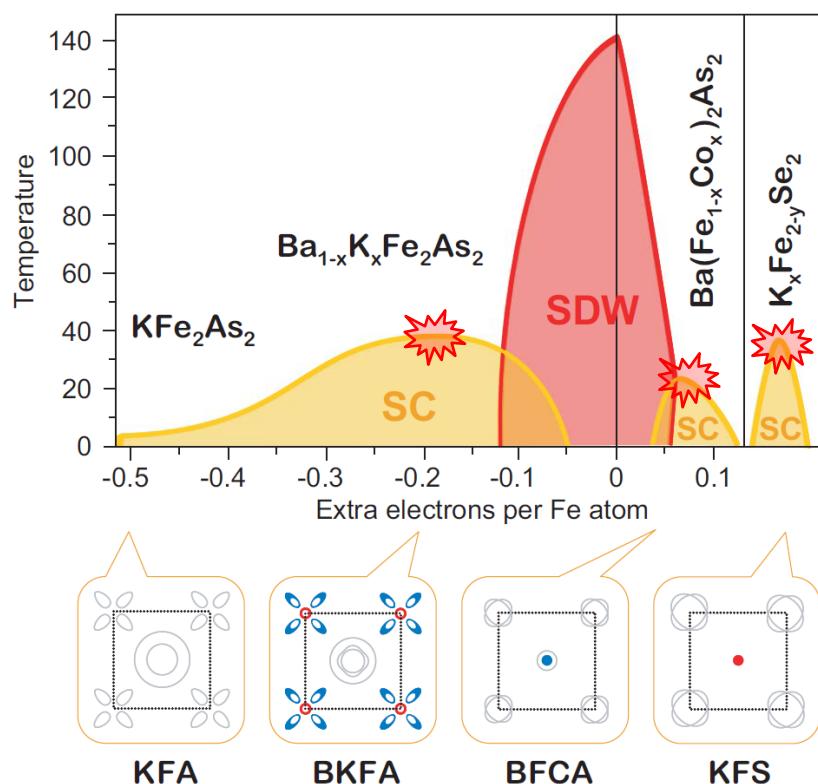
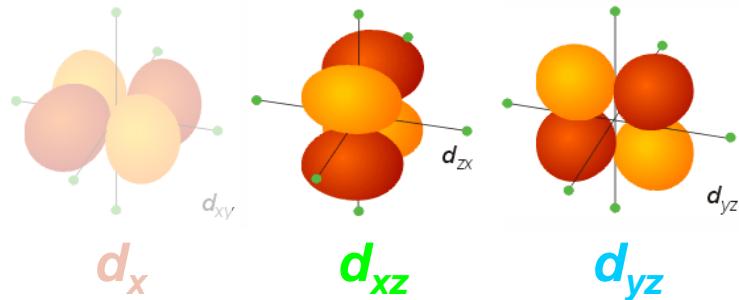
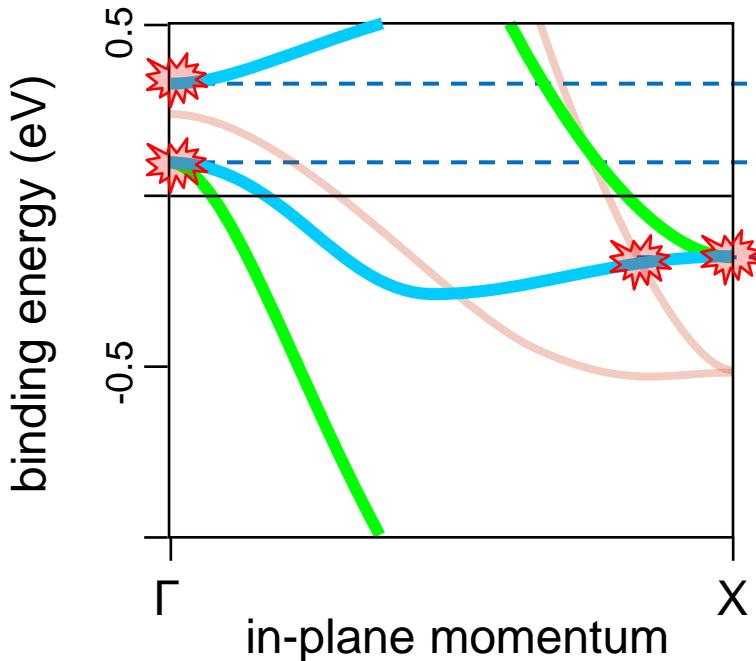


BKFA (38K)

BFCA (26K)
LiFeAs (18K)



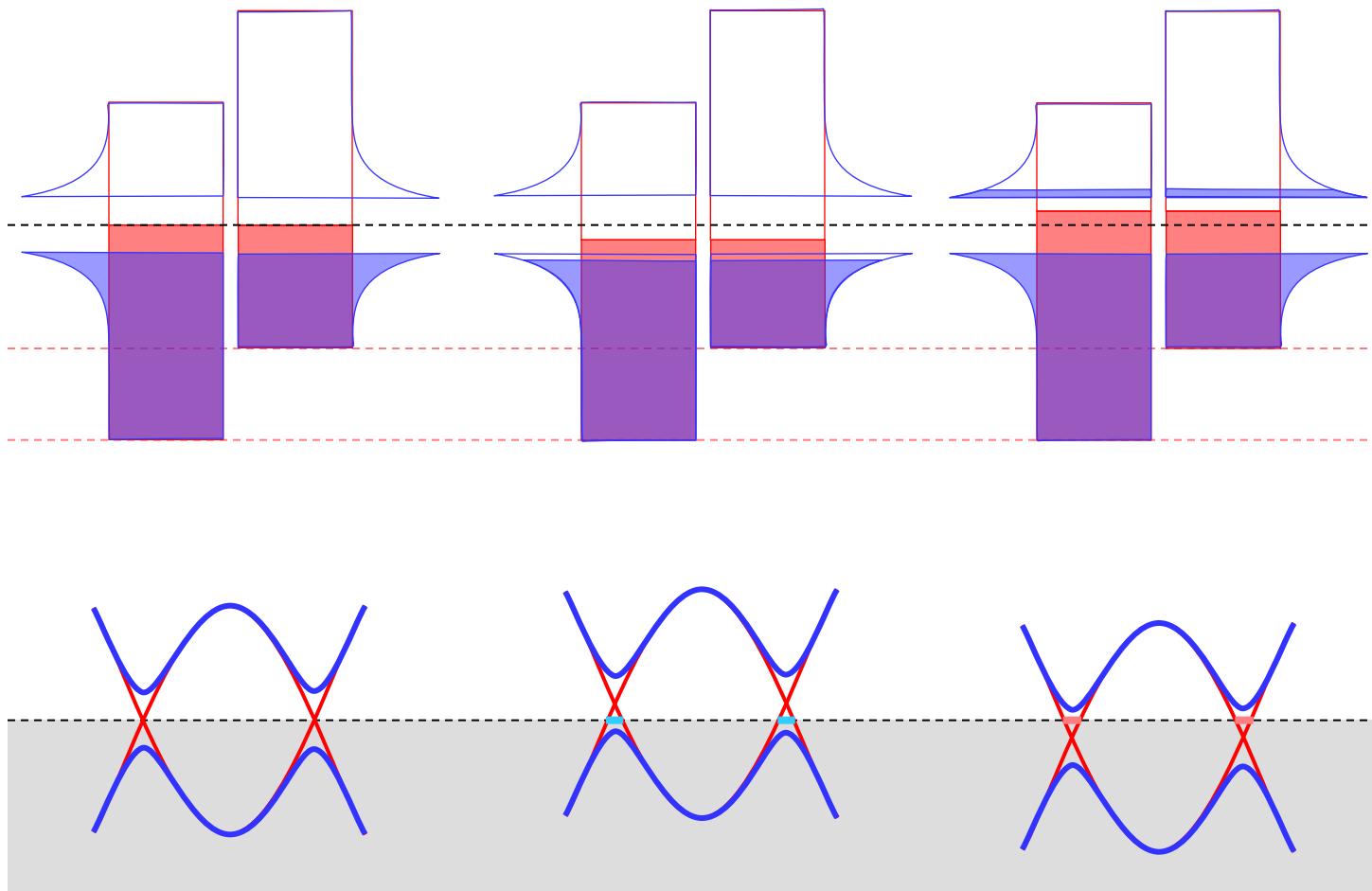
FeSC: electronic structure and superconductivity



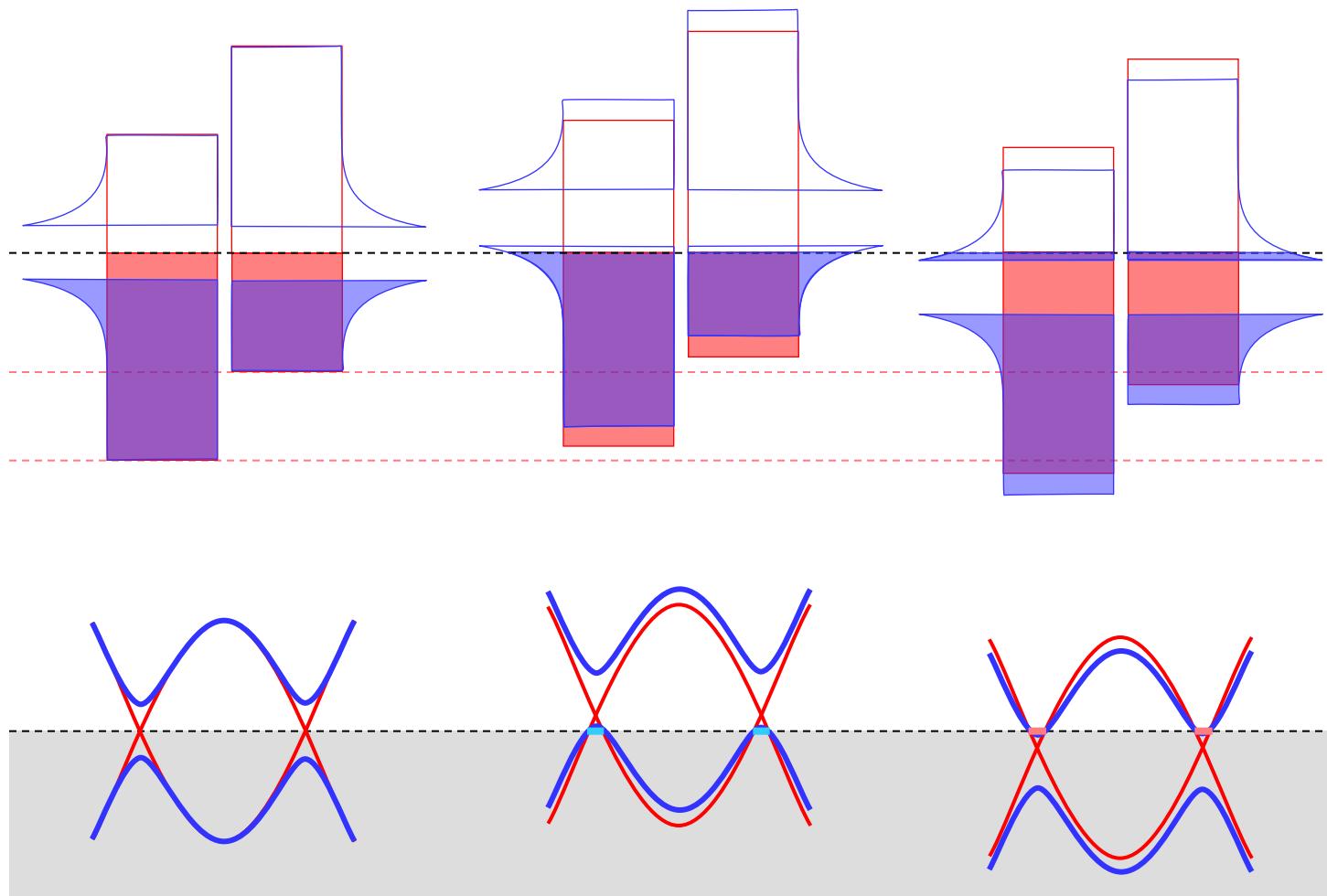
A. A. Kordyuk, *J. Supercond. Nov. Magn.* (2012)

A. A. Kordyuk et al., *Phys. Rev. B* **83**, 134513 (2011)

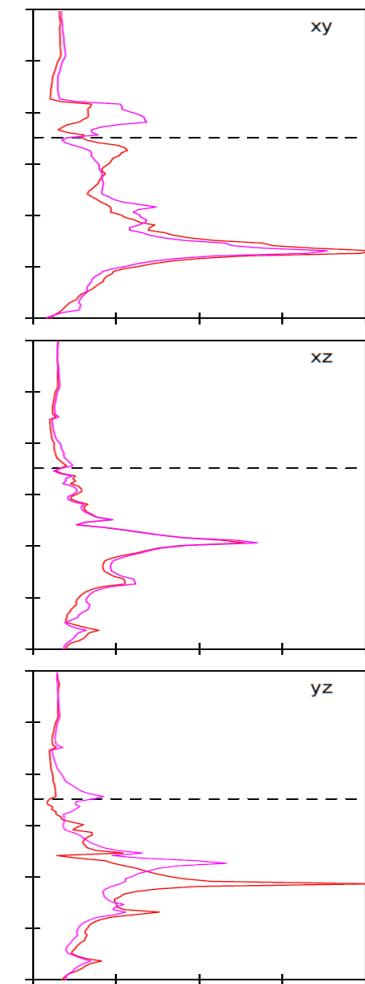
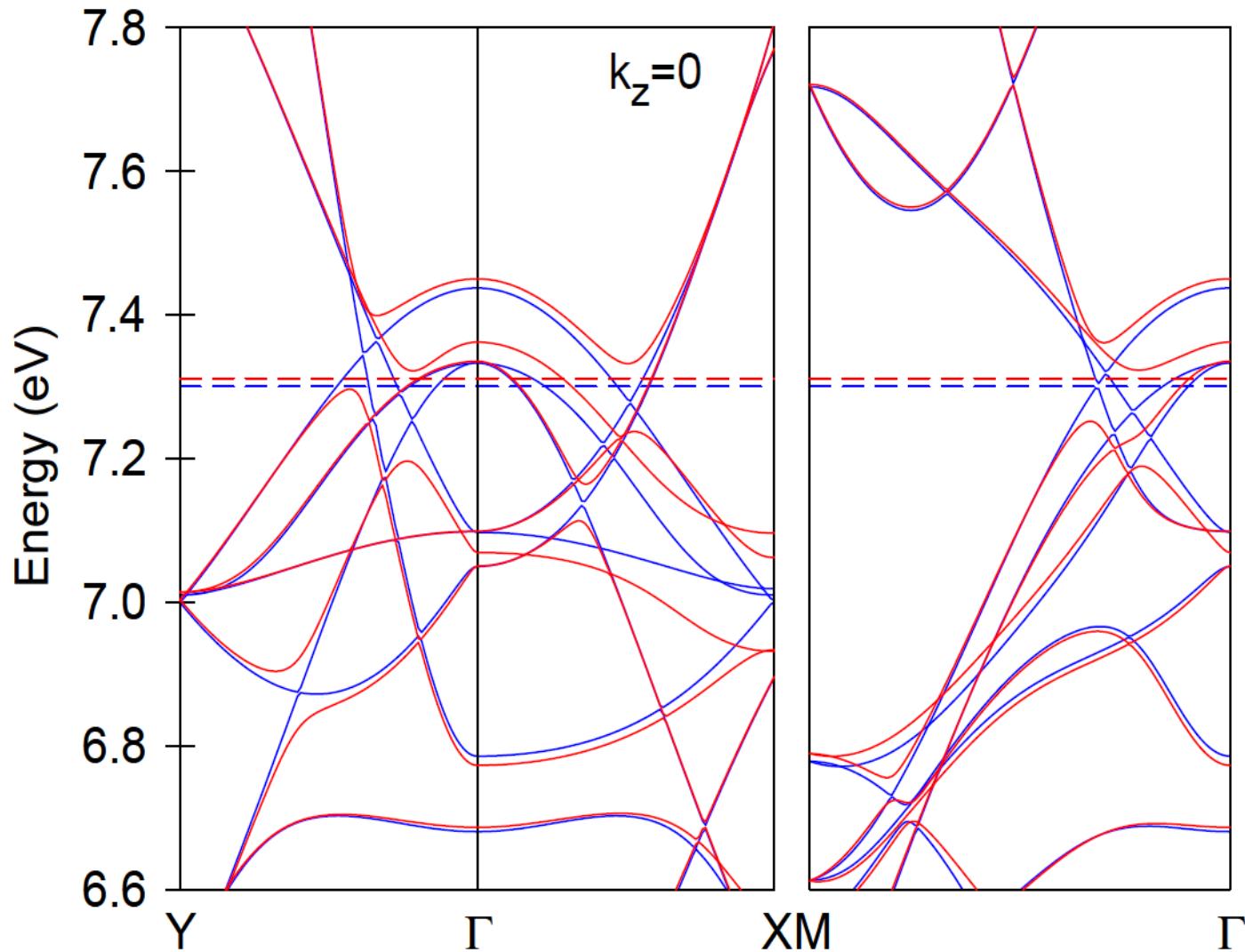
SC & SDW



SC & SDW



SC & SDW

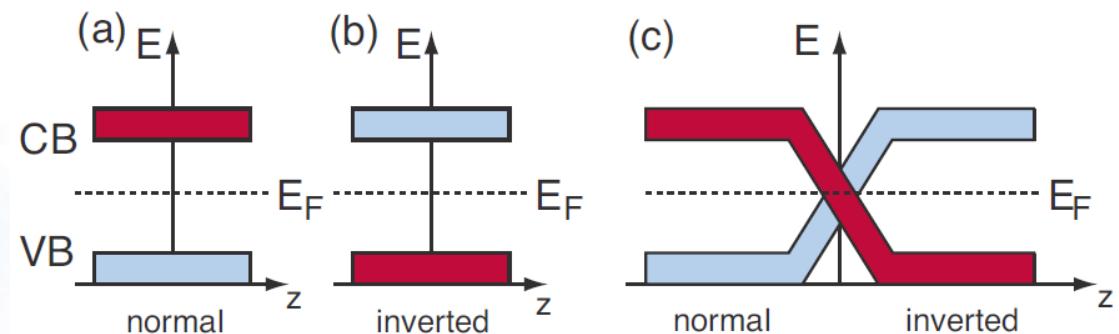


Conclusions on FeSC

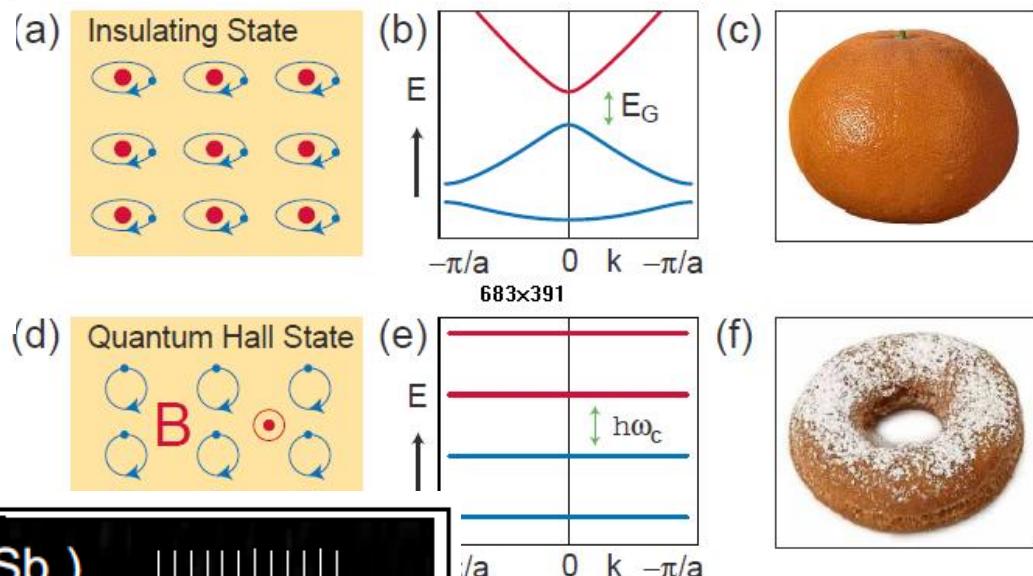
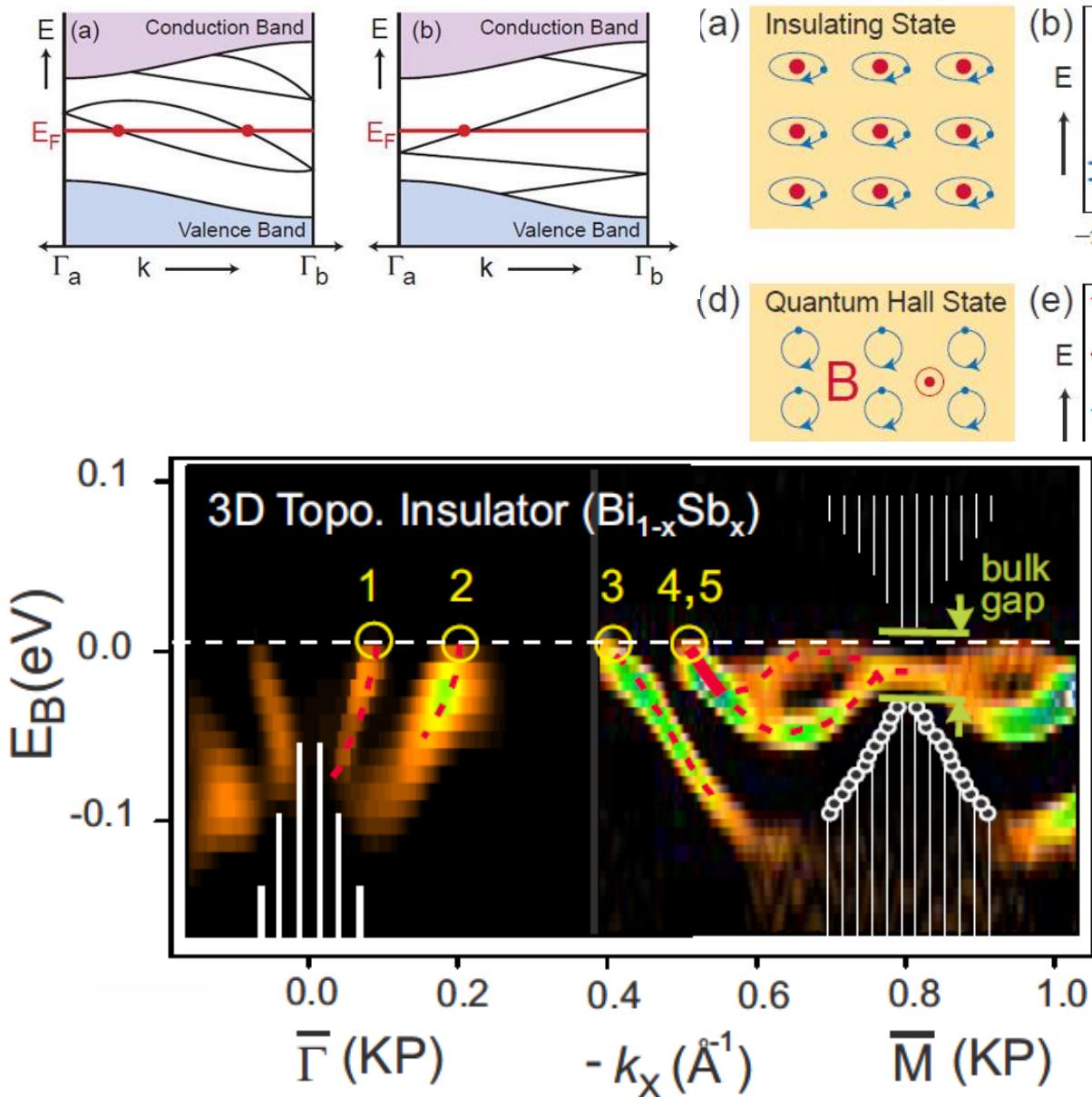
- The band structure of Fe-SC is well captured by LDA but do not take it too literally. The calculated Fermi surface is usually bad starting point for theory.
- Main contributors to SC are dxz, yz electrons and T_c for different compounds seems to correlate with the position of the Van Hove singularities (Lifshitz transitions) for the xz - and yz -bands.
- Both the renormalization and SDW do increase the DOS at the Fermi level for dxz, yz - electrons.

Topological insulators

Topological insulators

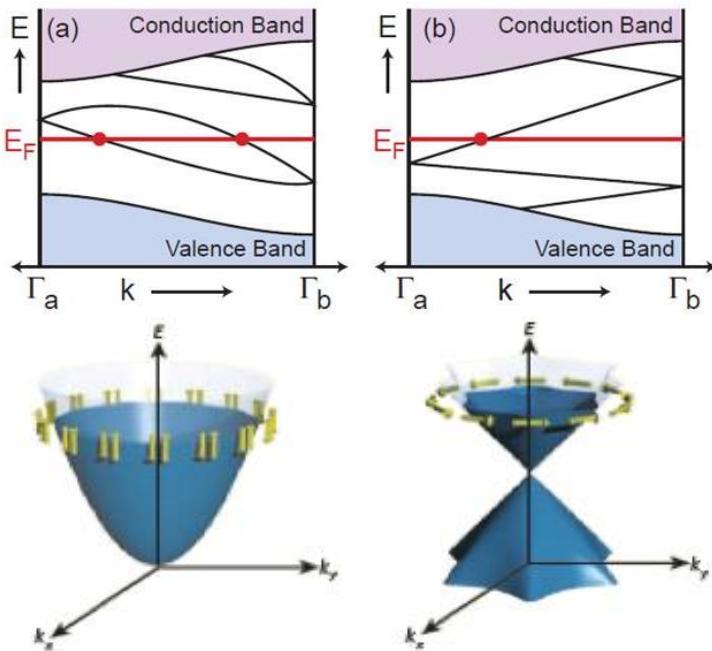


Topological insulators

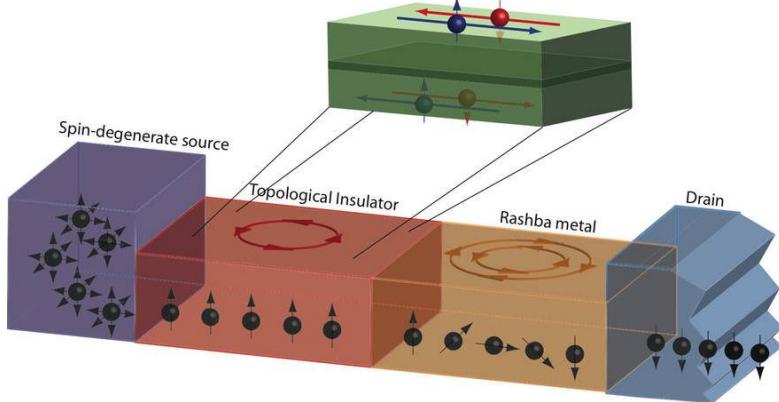


Hsieh *Nature* 2008
Hasan *RMP* 2010

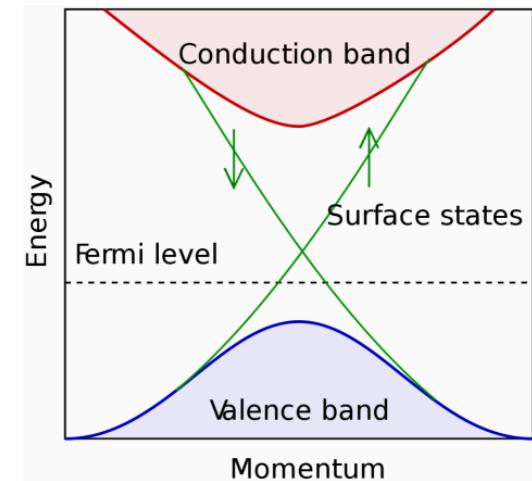
Topological insulators



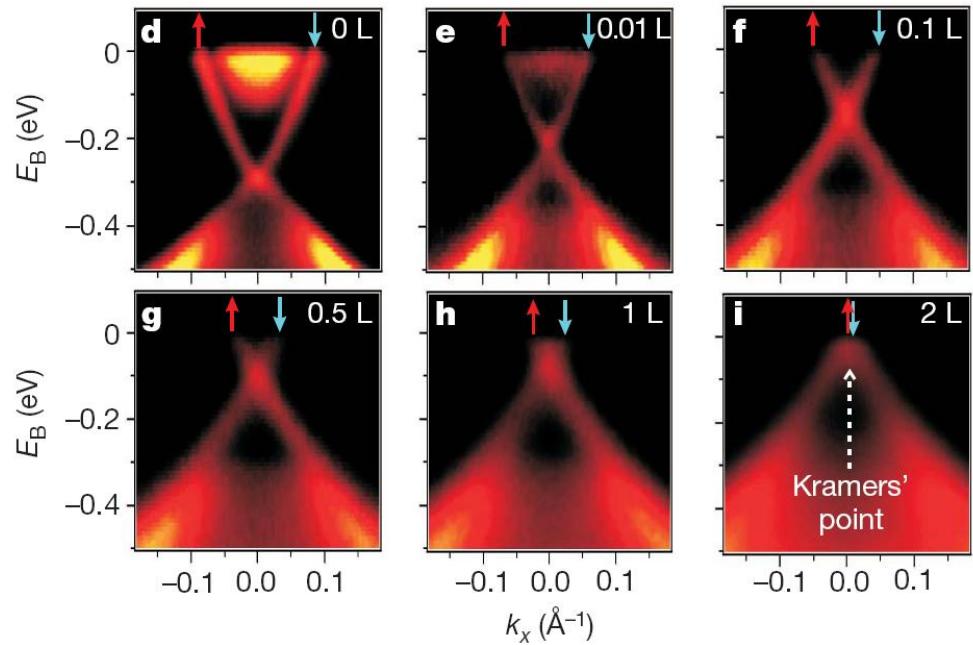
Franz *Nature* 2009



Spin injector: Hugo Dil, PSI, 2010



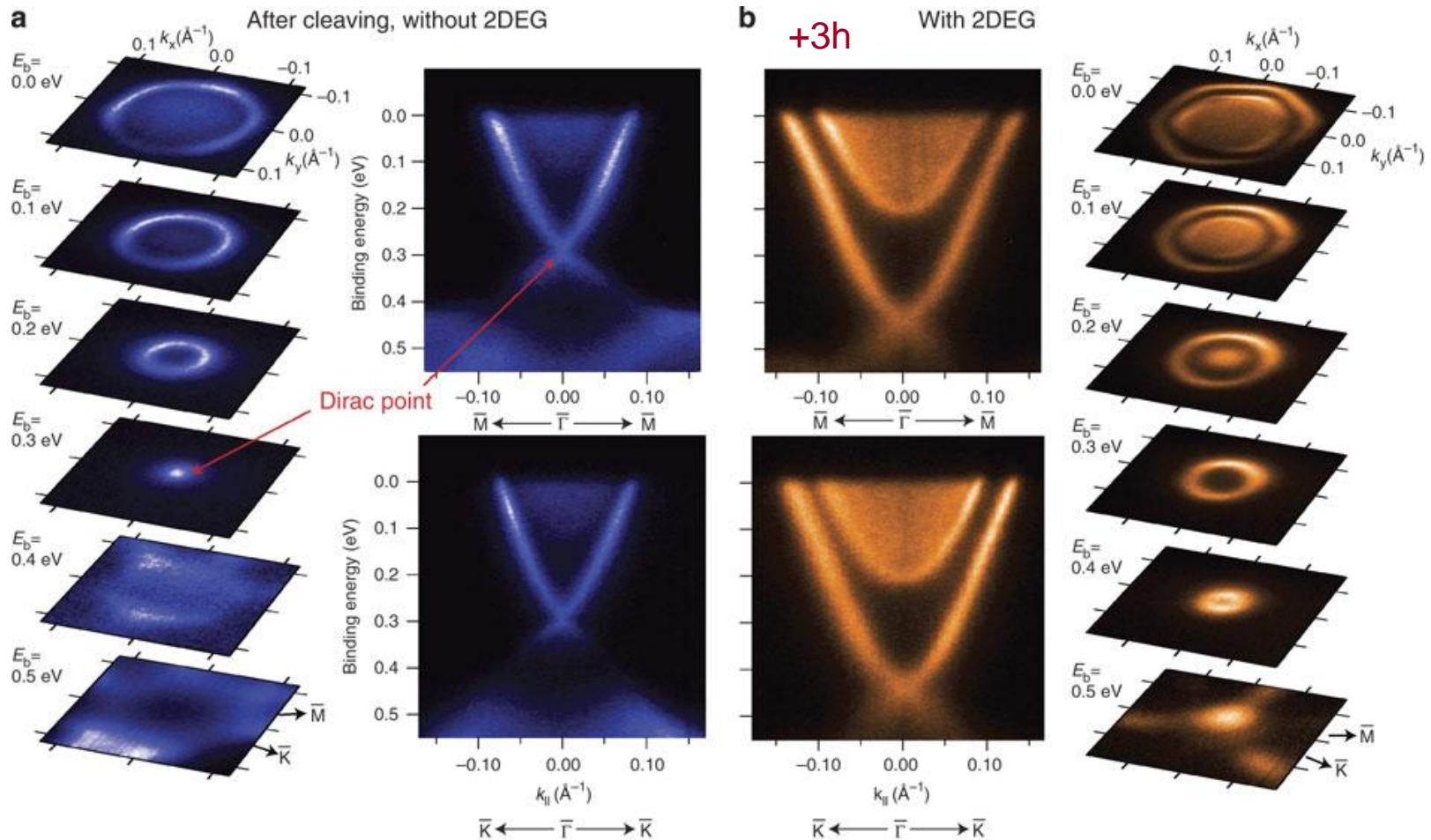
Bi_2Se_3



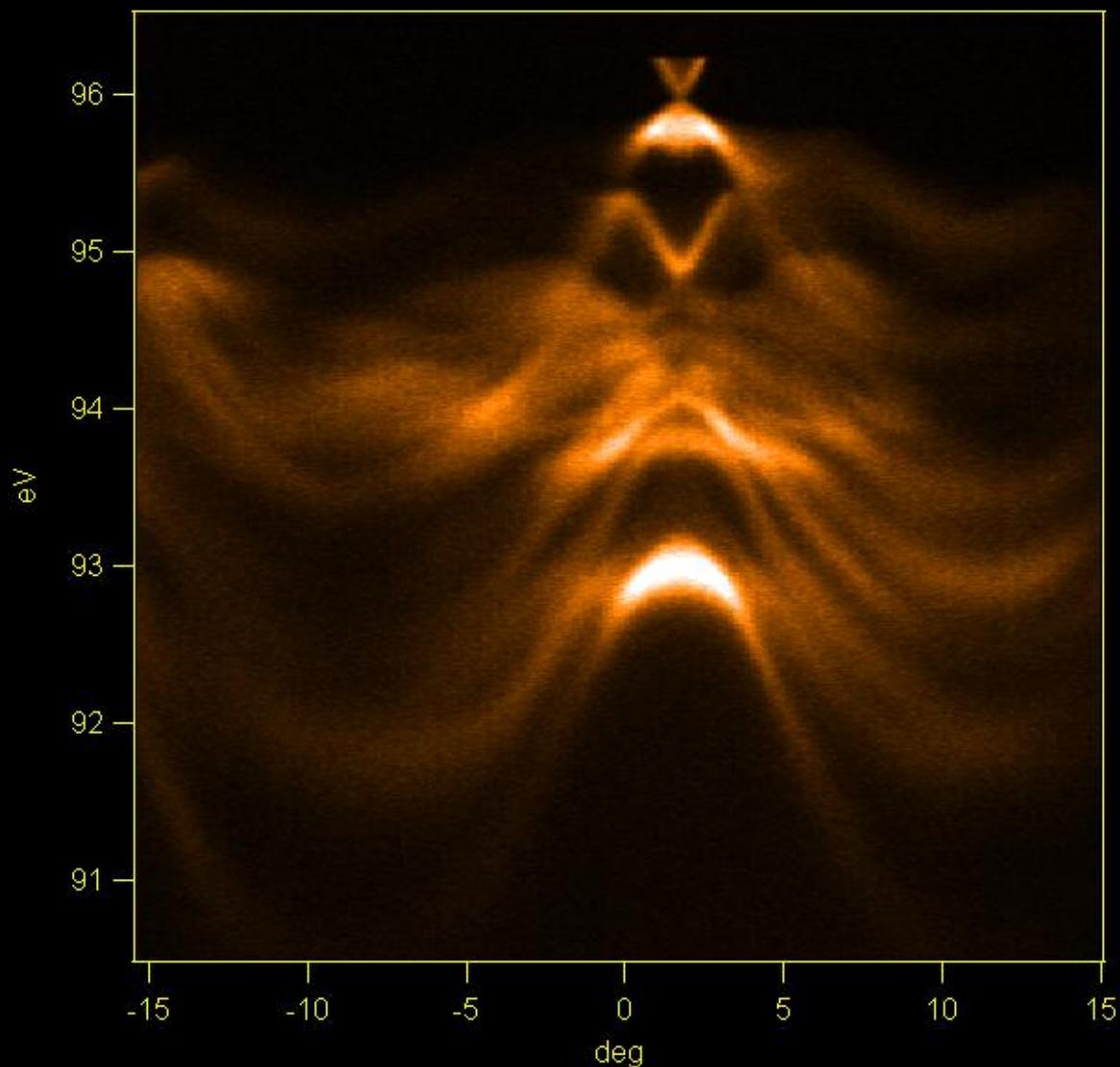
Hsieh *Nature* 2009,

Xia *Nature Physics* 2009

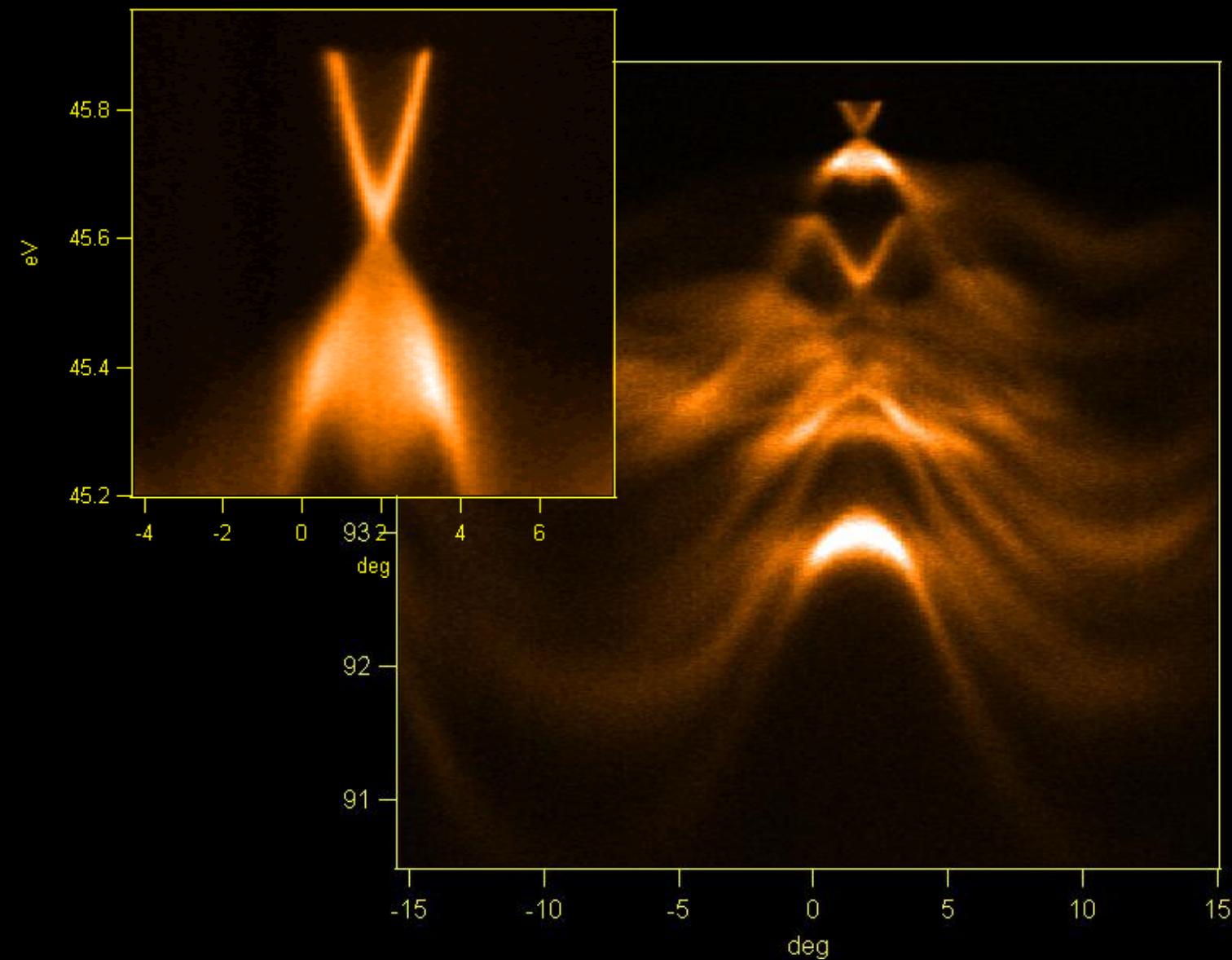
ARPES on Bi_2Se_3



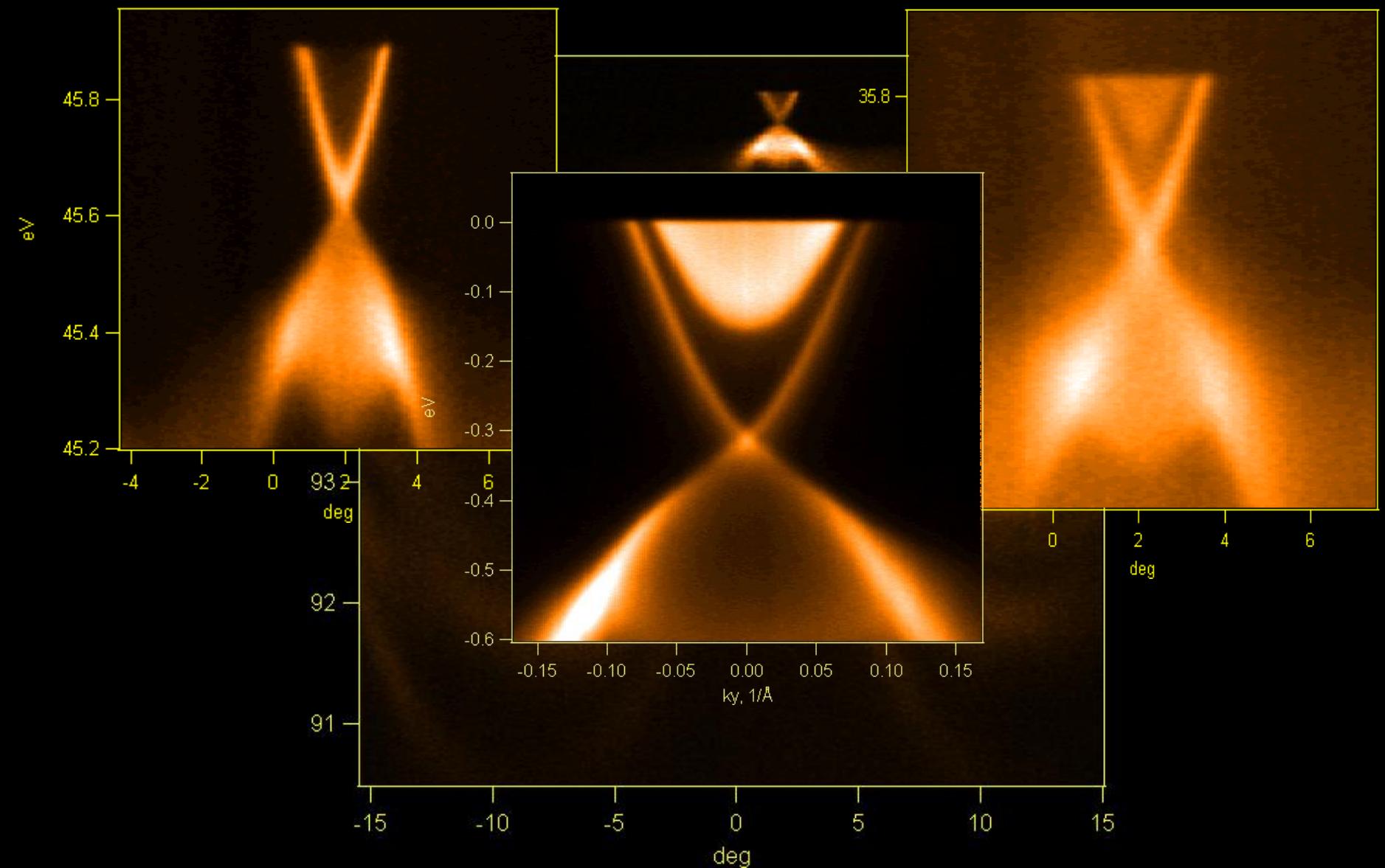
Bi₂Se₃ as seen by ARPES



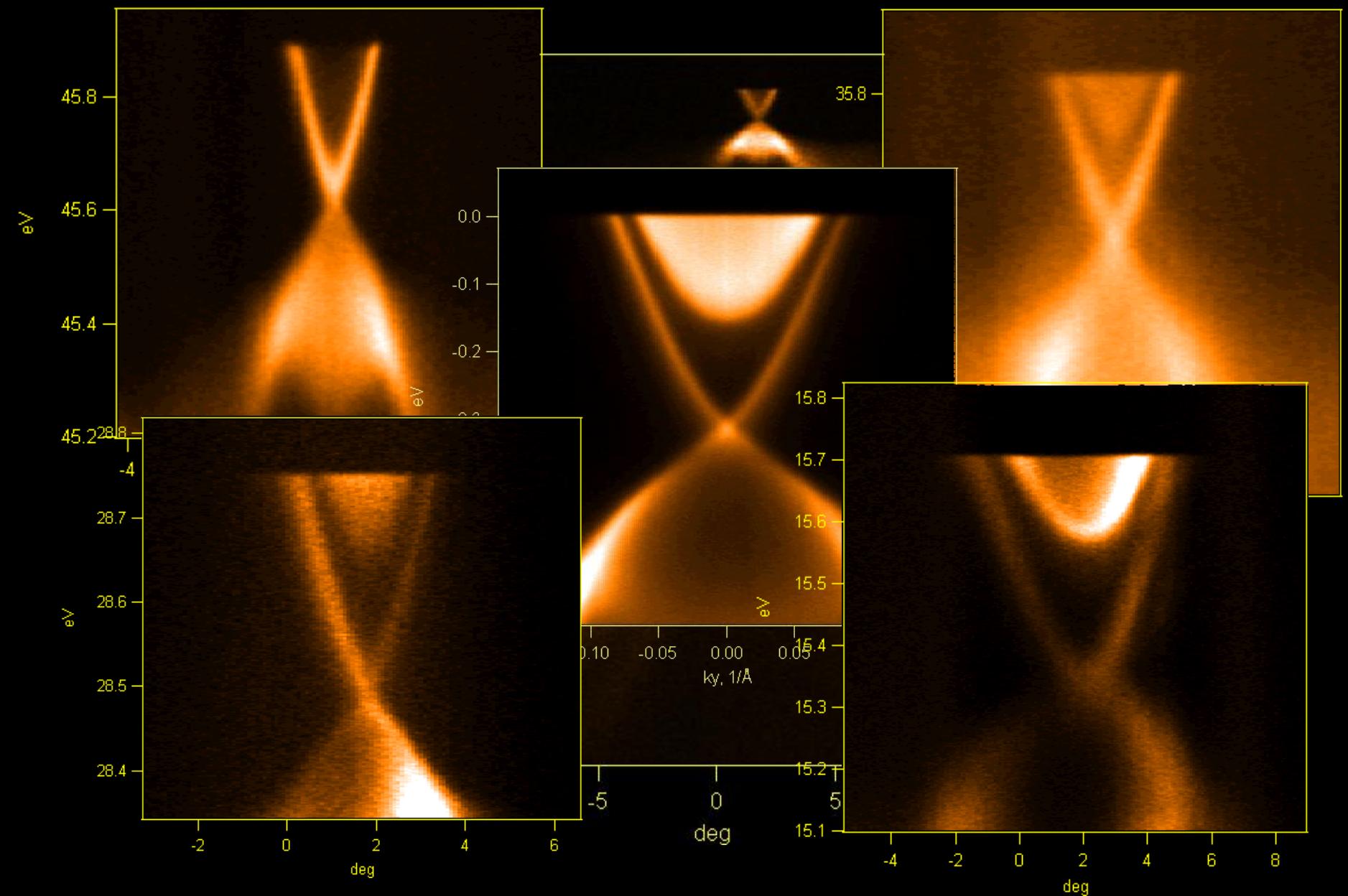
Bi_2Se_3 as seen by ARPES



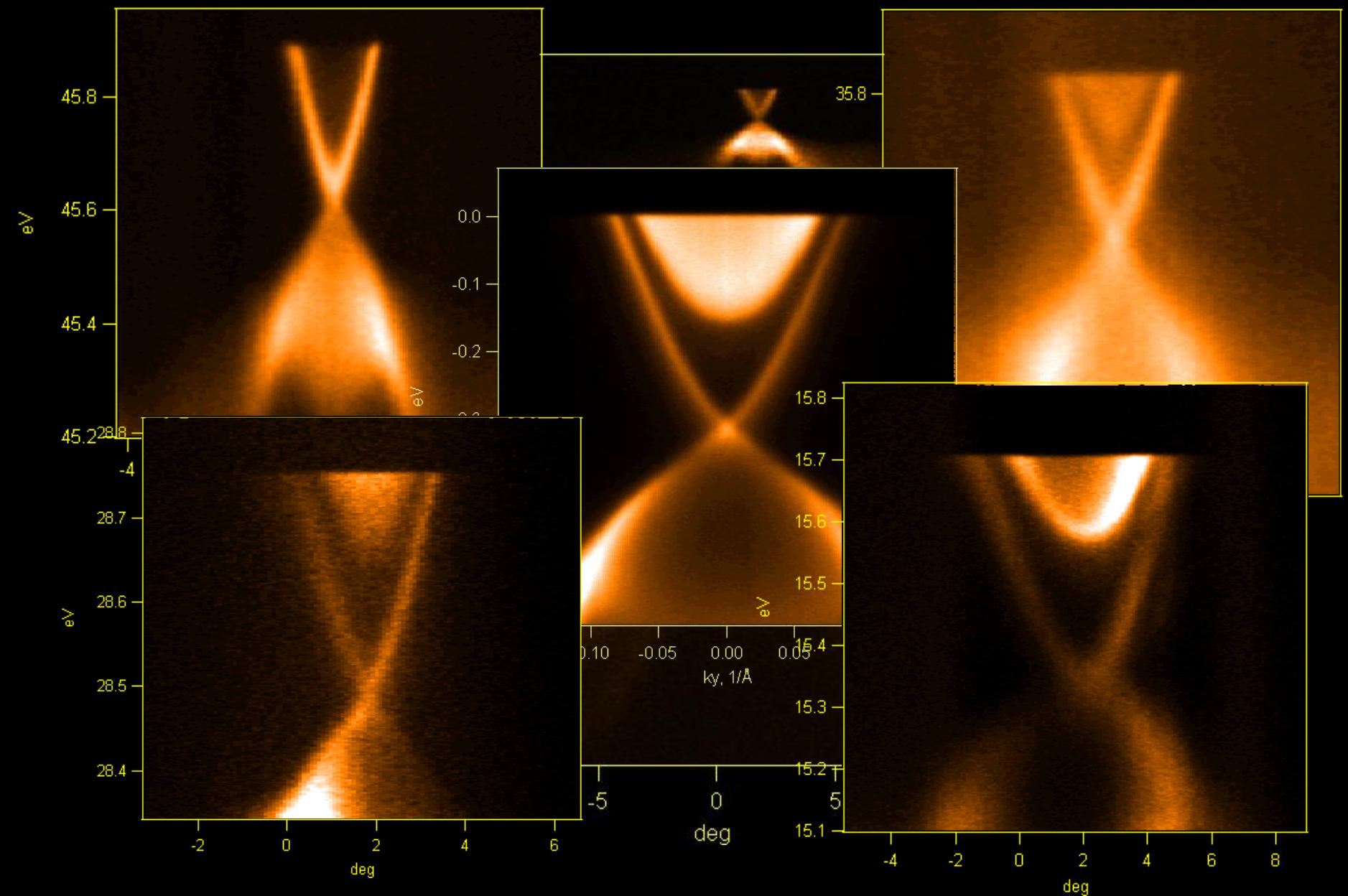
Bi_2Se_3 as seen by ARPES



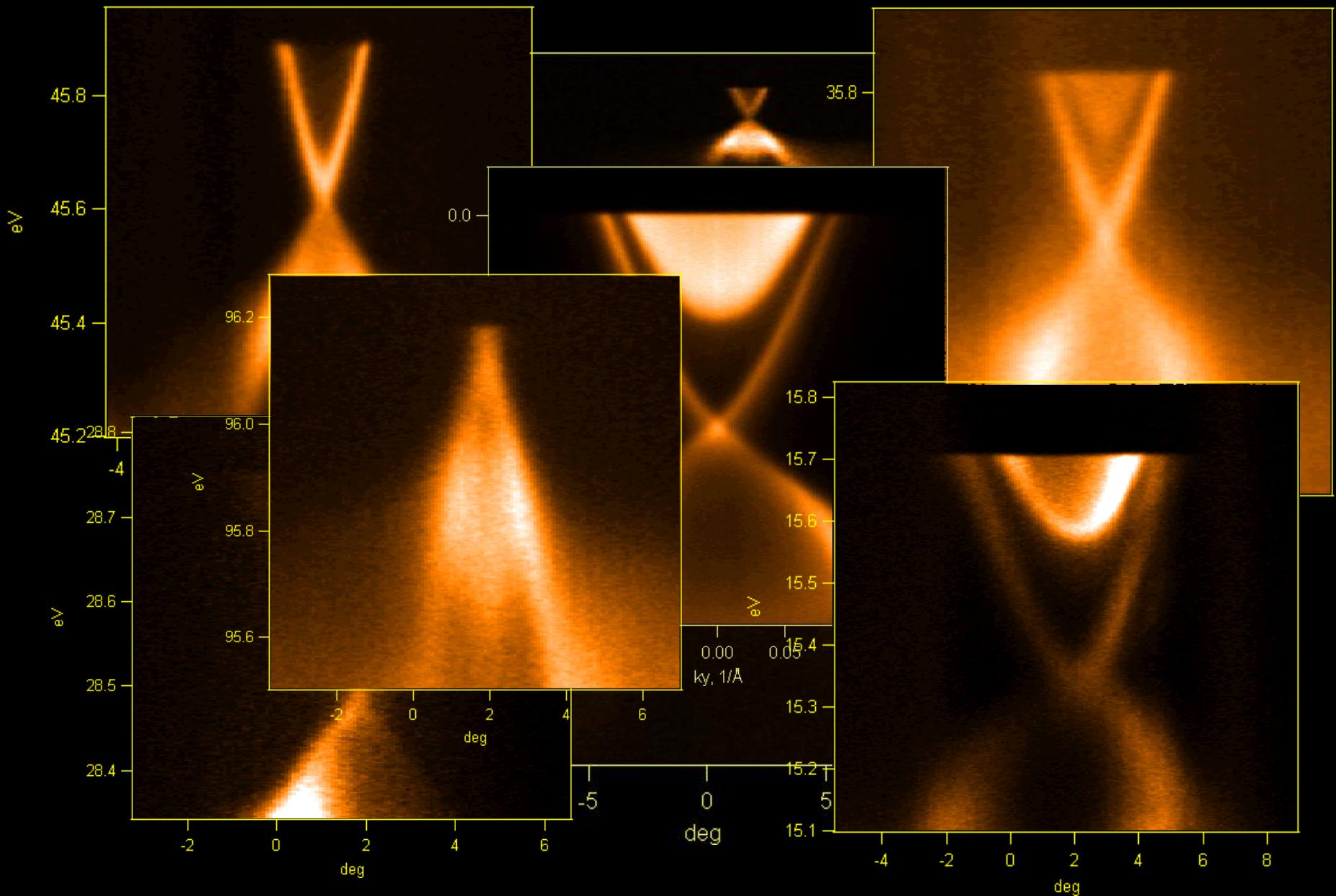
Bi_2Se_3 as seen by ARPES



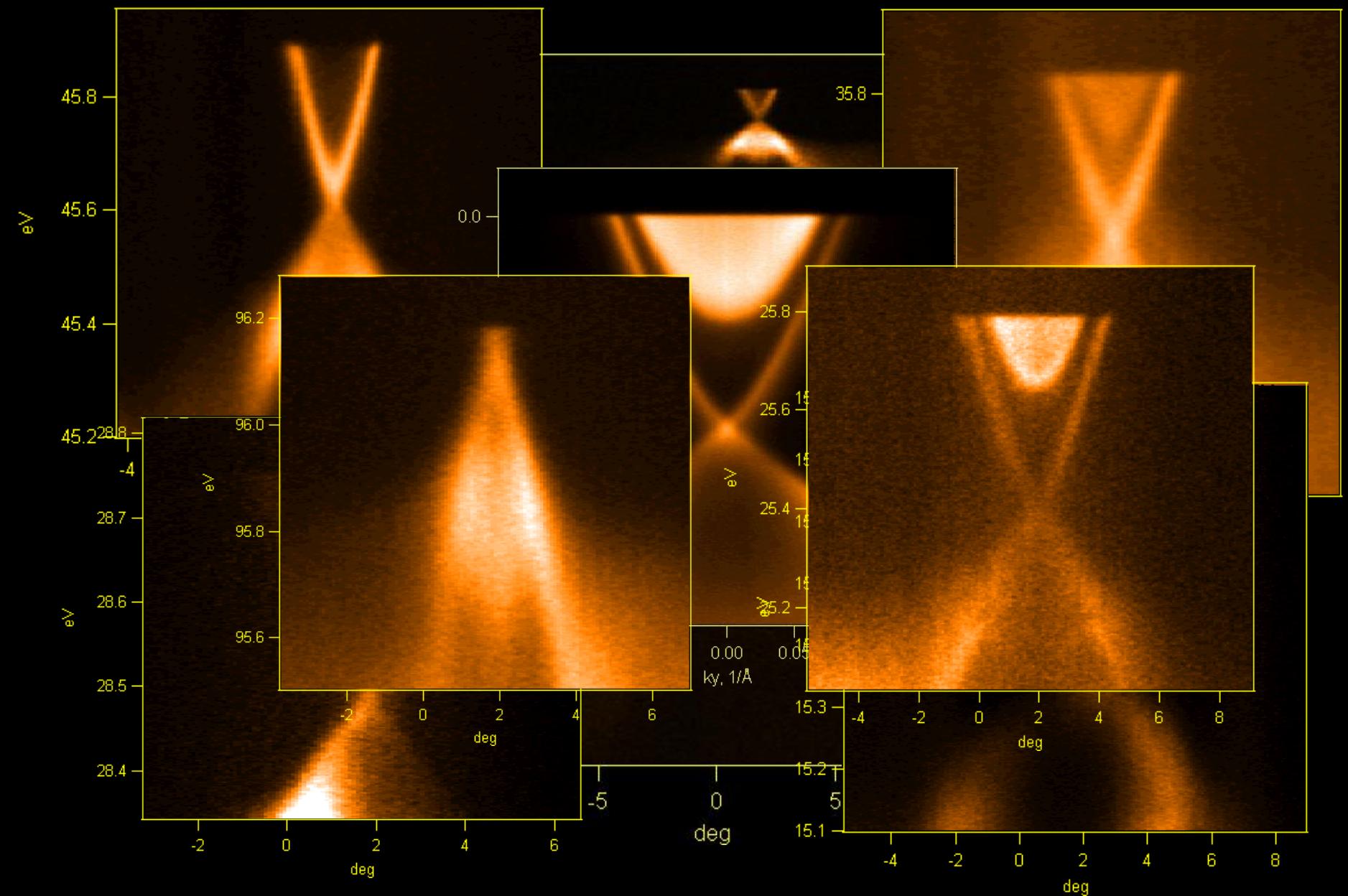
Bi_2Se_3 as seen by ARPES



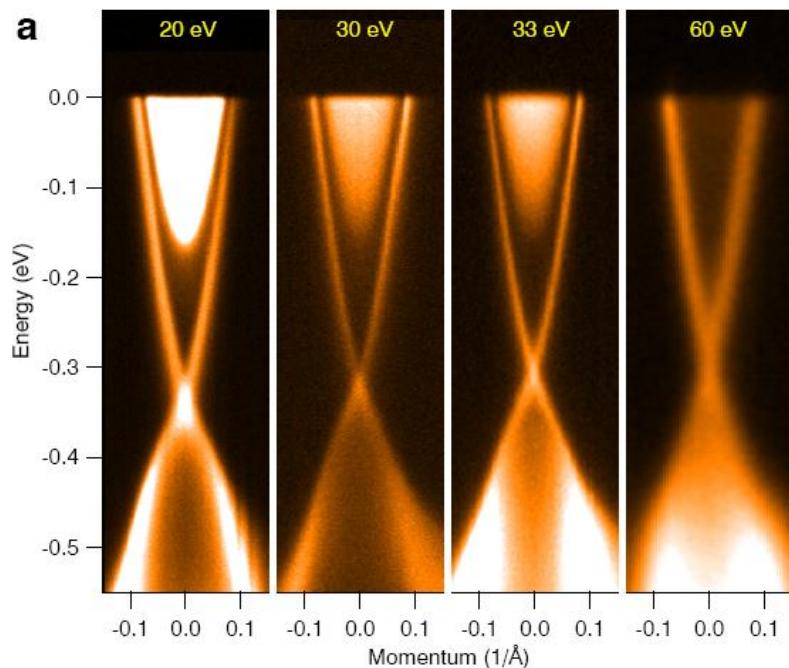
Bi_2Se_3 as seen by ARPES



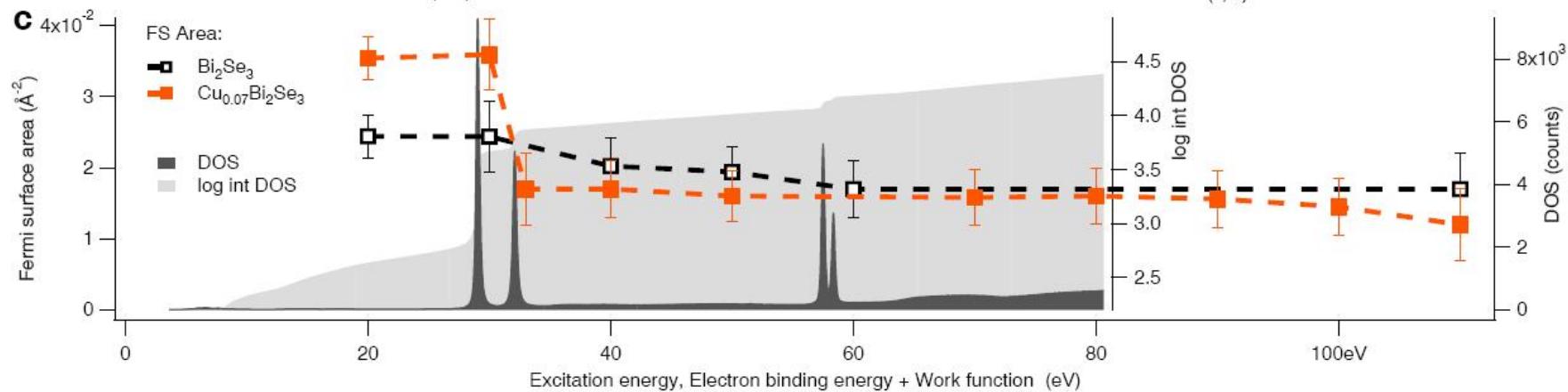
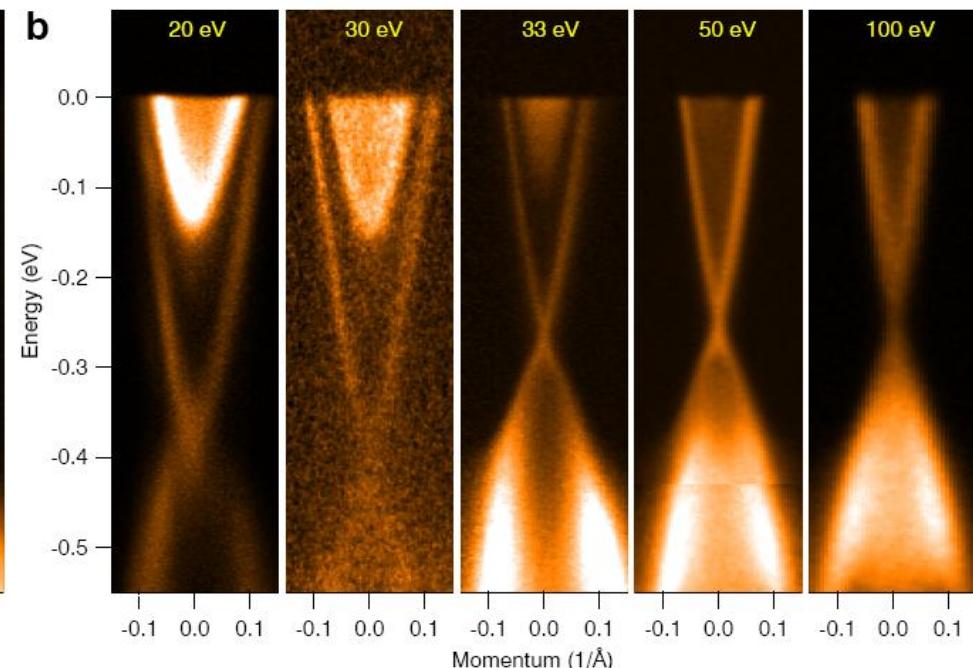
Bi_2Se_3 as seen by ARPES



Bi_2Se_3



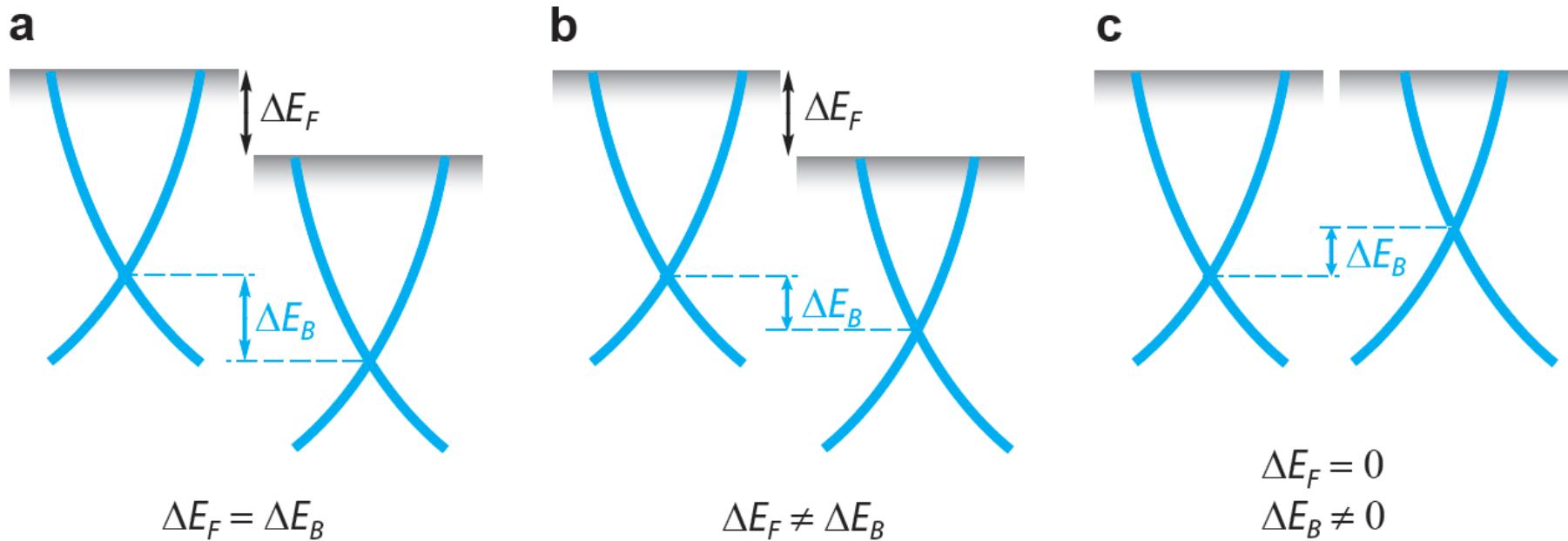
$\text{Cu}_x\text{Bi}_2\text{Se}_3$



$5d_{5/2}$ and $5d_{3/2}$

Kordyuk PRB 2011

Gating vs Charging

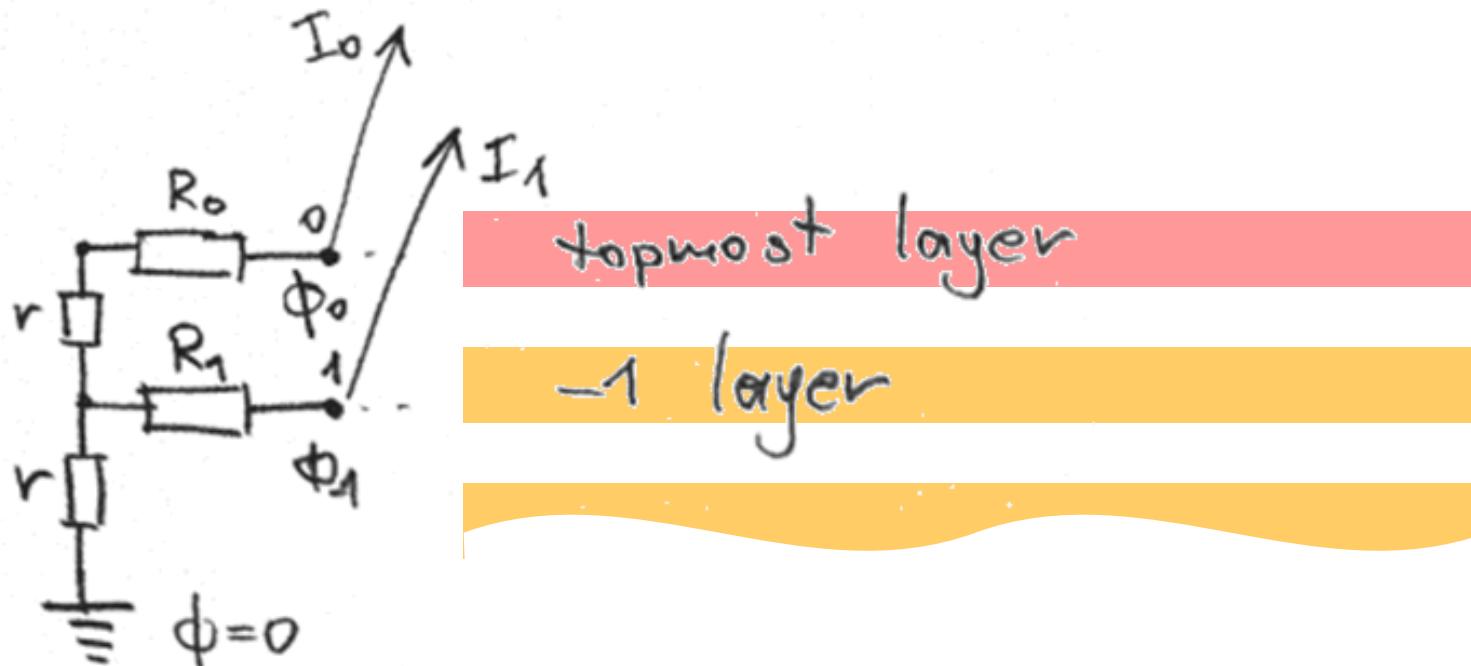


(a) “Charging” of the whole sample due to absence of a good Ohmic contact between the surface of the sample and an electron analyser appears as a shift, ΔE_F , of the Fermi level, E_F , of the sample under illumination in respect to its equilibrium position or to the E_F of the analyser.

(b) The most general case: the light induced photovoltage does both affect the surface charge region and create the charge of the sample.

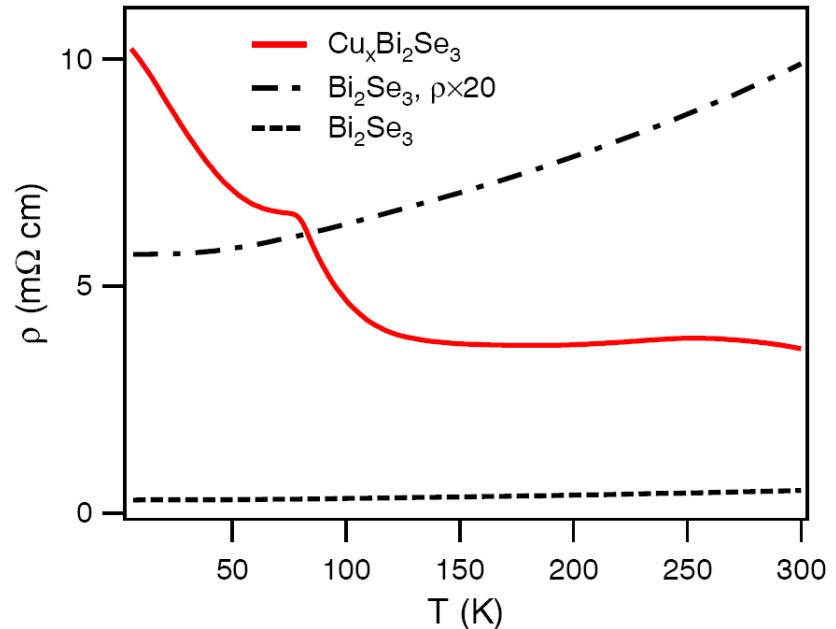
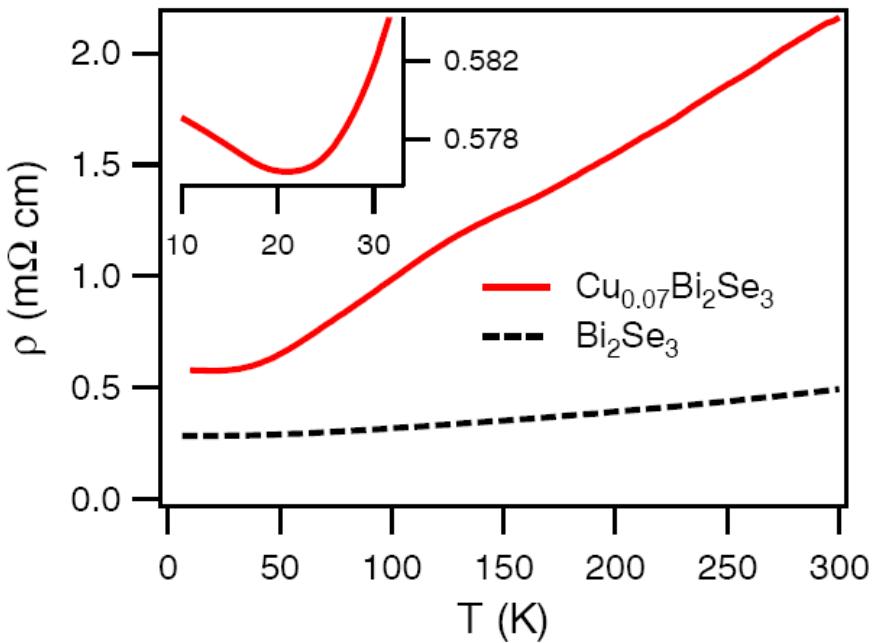
(c) “Gating”: in case of a highly conductive surface (and poorly conductive or insulating sample volume), its Fermi level remains equal to E_F of the analyser and the only observed photovoltage effect is the surface states gating.

instead of a model



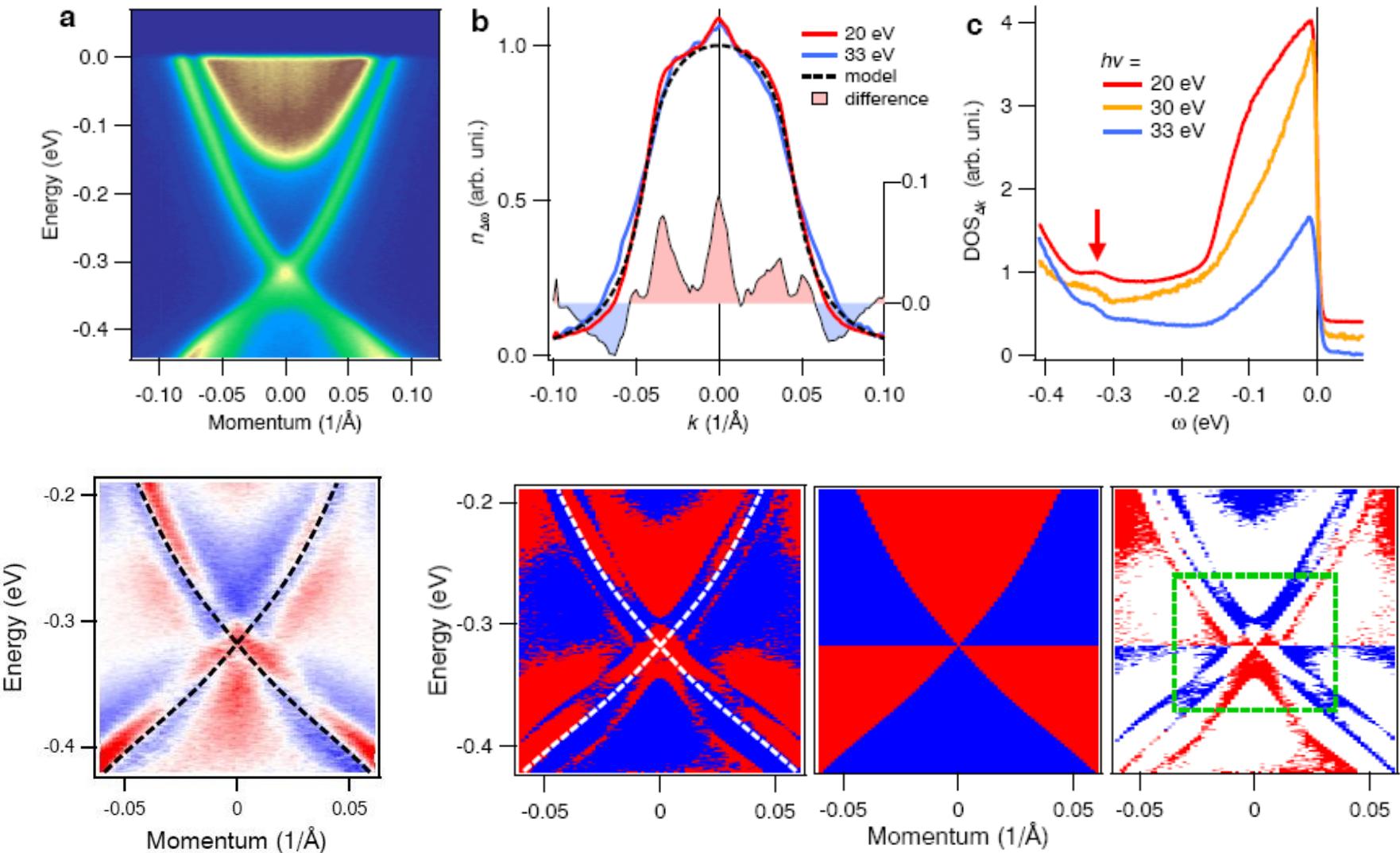
$$R_1 \gg R_0, r$$

$\text{Cu}_x\text{Bi}_2\text{Se}_3$



$r_c = 7\text{--}38 \ \Omega\text{ cm}$ at 10 K
10–18 $\text{m}\Omega\text{ cm}$ at 300 K

Anomalously enhanced photoemission from the Dirac point



Conclusions on TI

- We observe the effect of **photoemission induced gating** of the topological surface states on $\text{Cu}_x\text{Bi}_2\text{Se}_3$ that may stimulate the use of the topological insulators in electronics.
- The observed enhancement of the effect by **Cu intercalation** shows the way to control it from the material side.
- While the peculiarities caused by the presence of the topologically protected surface states have to be understood, the very fact that the photovoltage effect has been observed directly for the compound in which the surface states dispersion can be measured in details and controlled opens opportunity to study the microscopic mechanisms of the **surface photovoltage effects on semiconducting surfaces and interfaces**.
- Detailed dependences of the effect on temperature, doping, and flux intencity are needed to make a model.

Collaboration

IMP

Daniil Evtushinsky
Alexander Plyushchay
Roman Viznichenko

ARPES, IFW Dresden

Sergey Borisenko
Volodymyr Zabolotny
Timur Kim
Dmytro Inosov
Andreas Koitzsch
Roland Hübel
Jörg Fink

ARPES Worldwide

Mark Golden (UvA)
Toni Valla (BNL)
...



Neutron Scattering

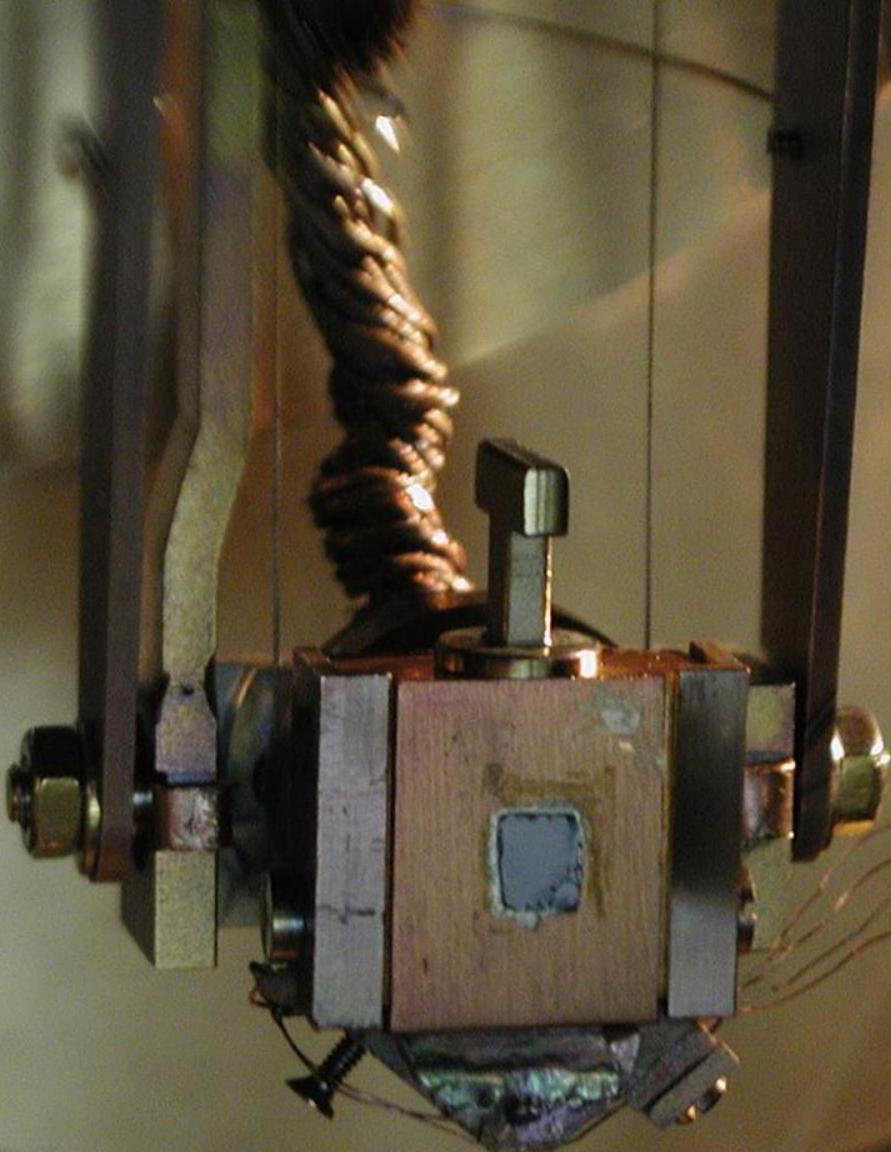
Vladimir Hinkov
Bernhard Keimer
Dmytro Inosov

STM & Transport

Cristian Hess
Bernd Buehner
Alexey Pan
Vladimir Karbovskii

Theory

Alexander Yaresko
Eugene Krasovskii
Thomas Dahm
Doug Scalapino
Andrey Chubukov
Ilya Eremin



Single Crystals

Cuprates

Helmut Berger (EPFL Lausanne)

Chengtian Lin (MPI Stuttgart)

S. Ono, Yoichi Ando (CRIEPI Tokyo)

Iron based superconductors

Igor Morozov (MSU)

Chengtian Lin

S. Aswartham (IFW)

S. Wurmhel (IFW)

G. Behr (IFW)

Hai-Hu Wen (IoP Beijing)

Topological insulators

Helmut Berger

S. Wurmhel

Synchrotron Light

BESSY (Berlin)

Emile Rienks
Rolf Follath
Andrei Varykhalov
Serguei Molodtsov

SLS (PSI Villigen)

Ming Shi
Vladimir Strocov
Luc Patthey
Joel Mesot

ELETTRA (Trieste)

Alexei Barinov
Pavel Dudin
Stefano Turchini



The background image shows a large stadium or arena at night. The seating tiers are illuminated from within, creating a series of bright, horizontal bands of light against the dark sky. The stadium is set against a backdrop of dark hills or mountains under a hazy, orange-tinted sky.

Thank you!

Доклад поддержан программой Фонда Дмитрия Зимина «Династия»
«Краткосрочные визиты иностранных ученых в Россию»