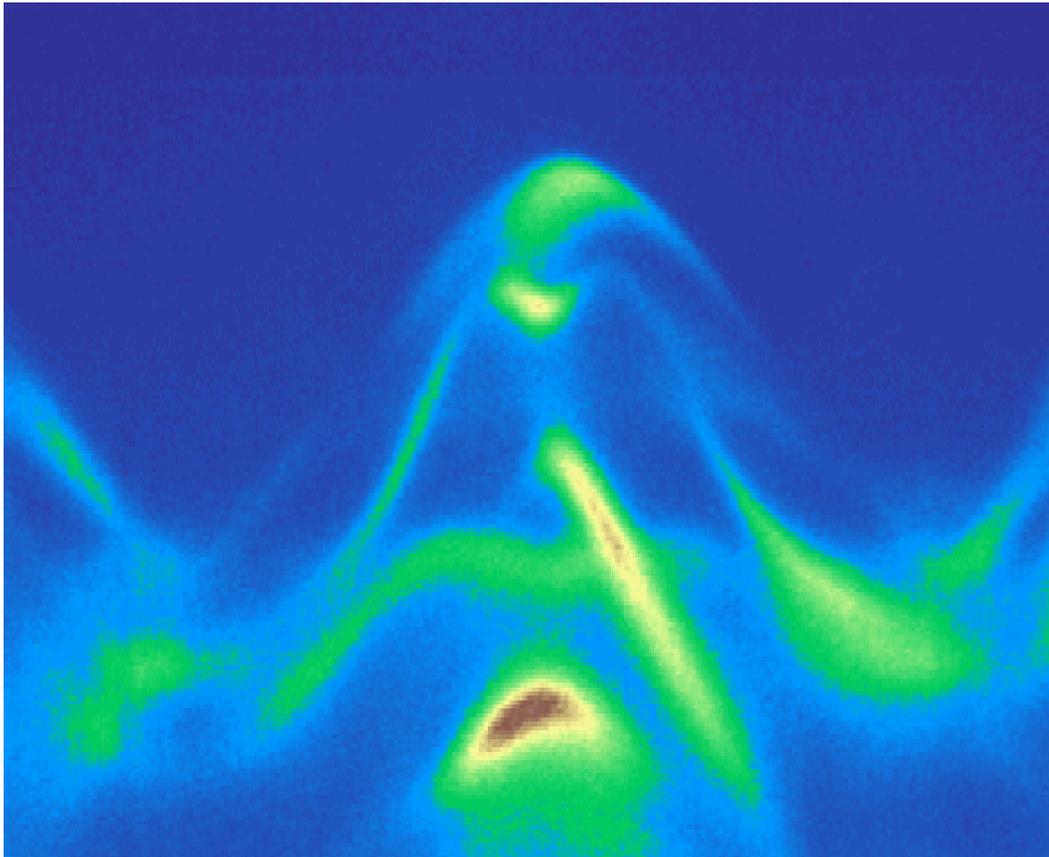


ARPES — state-of-the-art photoelectron spectroscopy

'13
ES&ES
May 20-23, Kyiv



Alexander Kordyuk
Institute of Metal Physics

Фотоелектронна спектроскопія в Україні



Петро
Григорович
Борзяк

**Володимир
Володимирович
Немошкаленко**

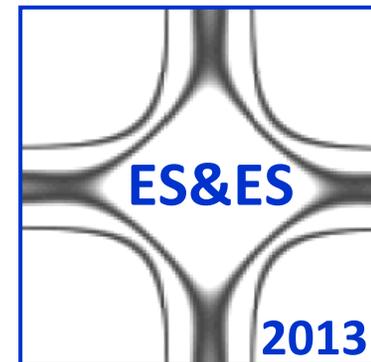
Ще у 50-х роках заклав
основи досліджень
фотоелектронної емісії
з напівпровідників



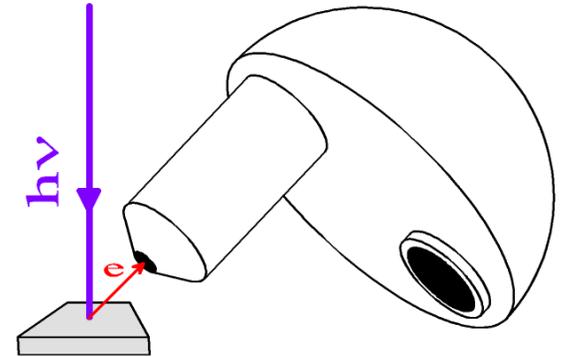
Рентгенівська та фотоелектронна спектроскопії
та методи зонних розрахунків

**Електронна Структура та
Електронна Спектроскопія**

**до 80-річчя від дня народження
академіка В. В. Немошкаленка**

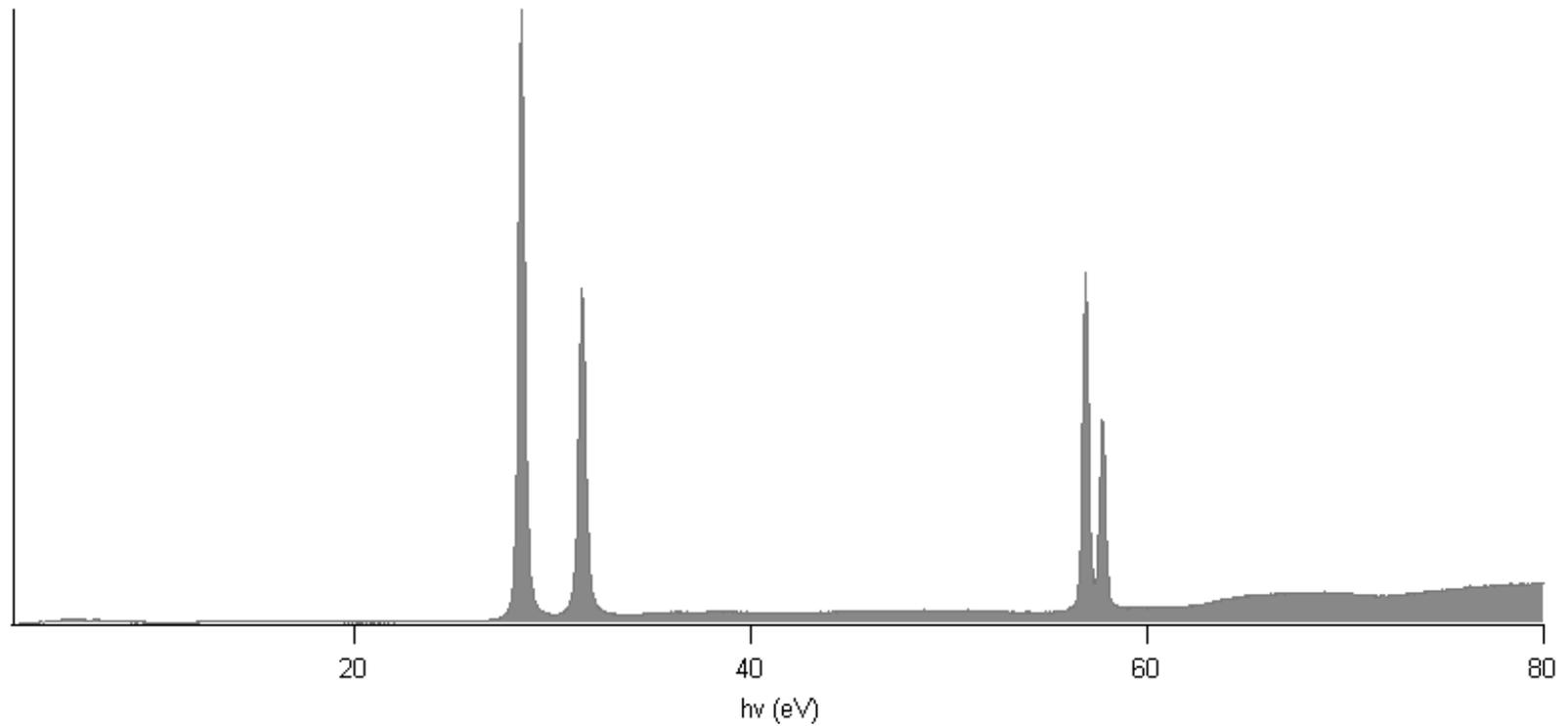


Photoelectron spectroscopy – Electronic band structure ?

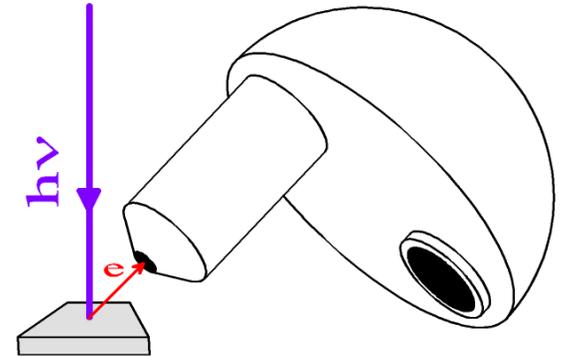


Bi₂Se₃

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

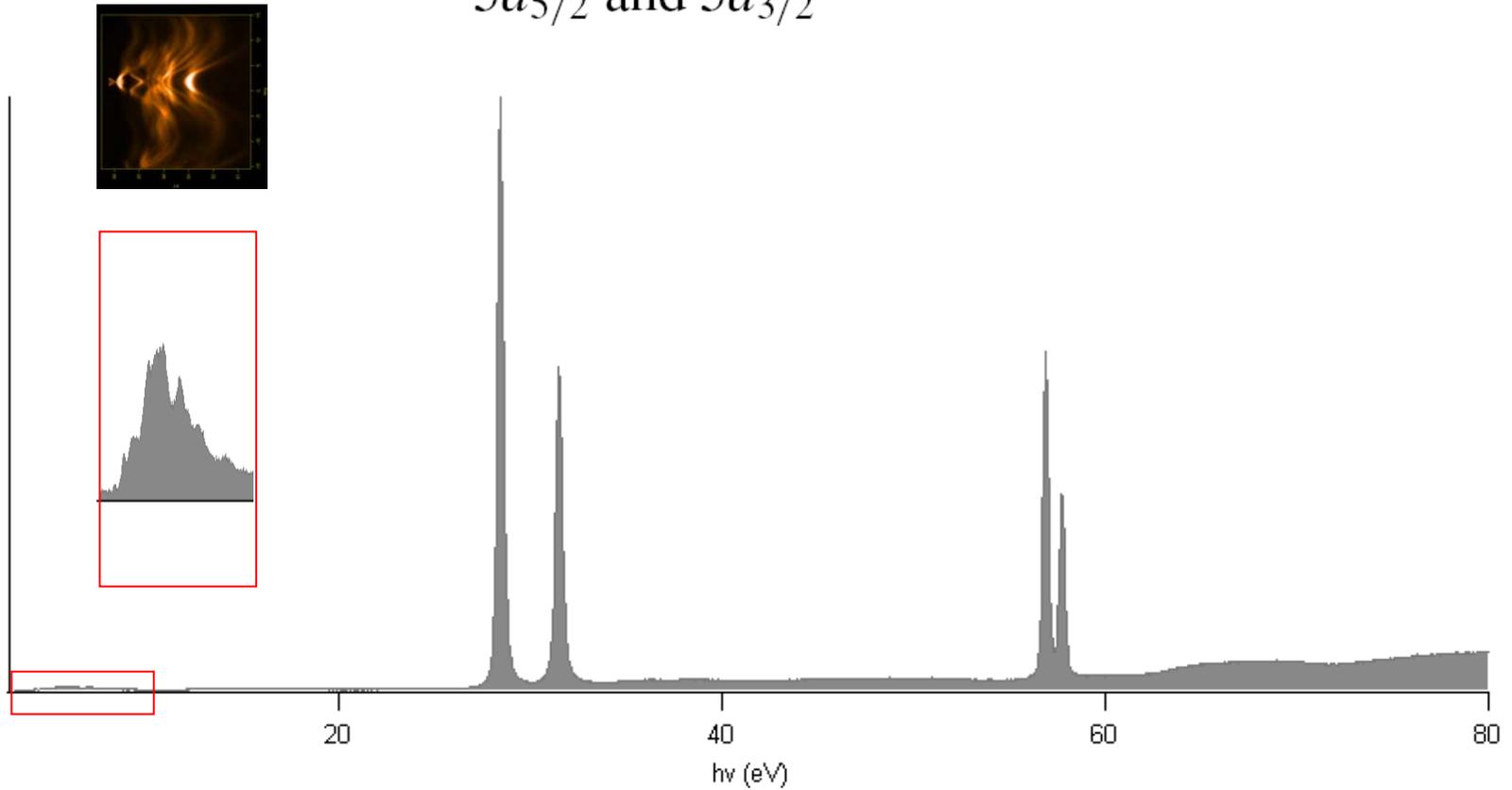


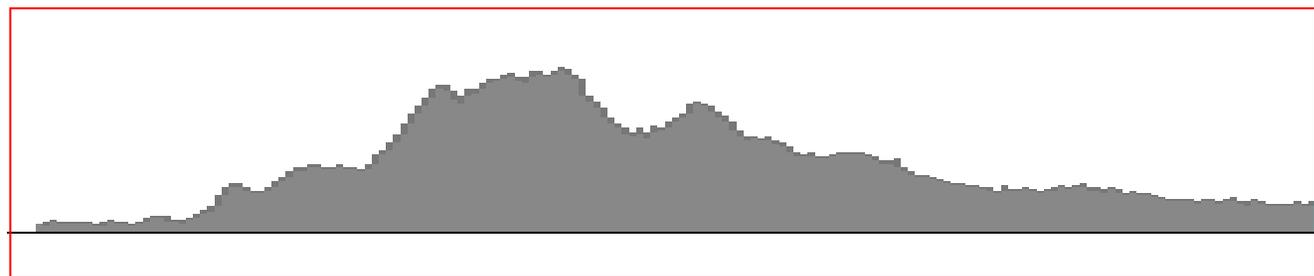
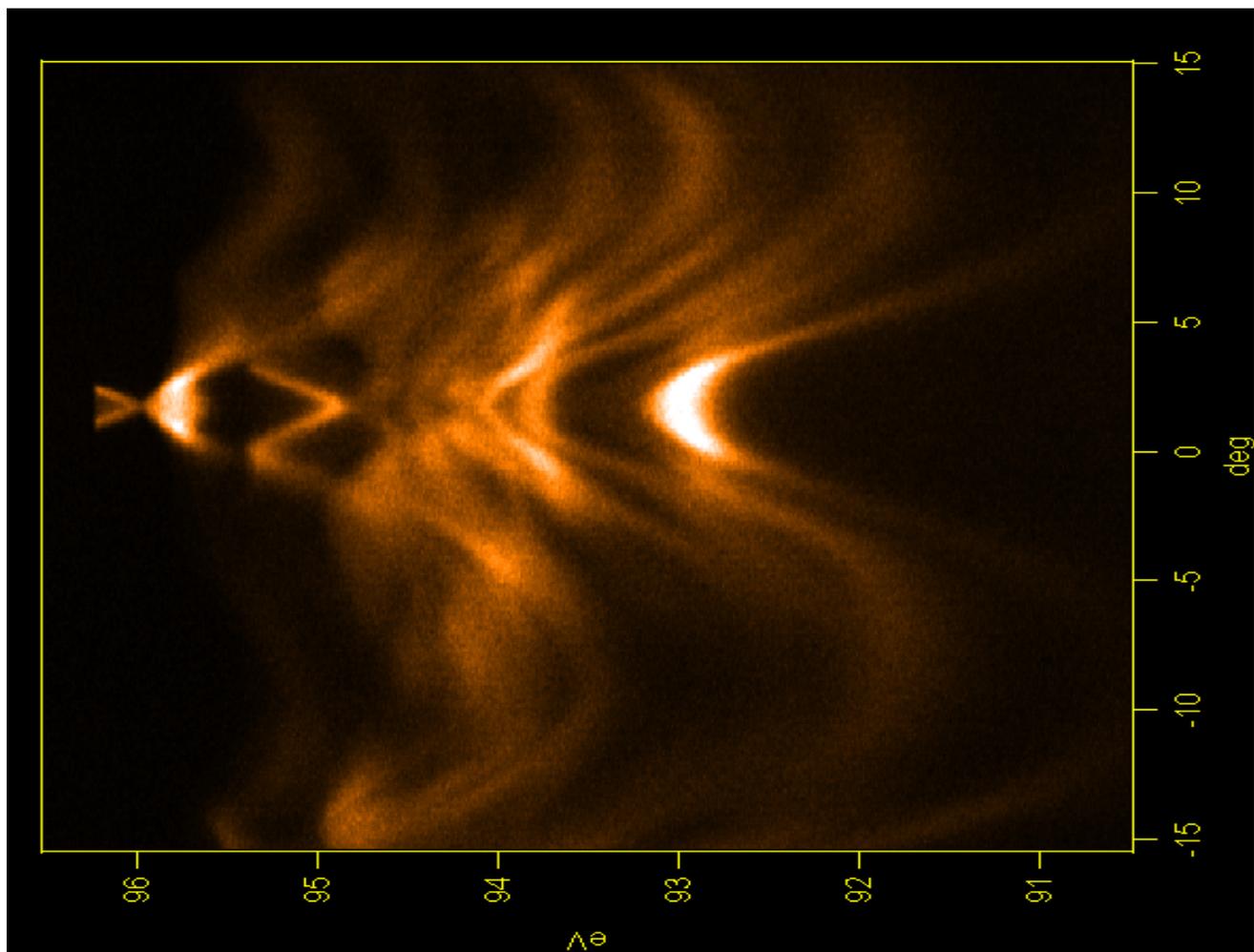
Photoelectron spectroscopy – Electronic band structure ?



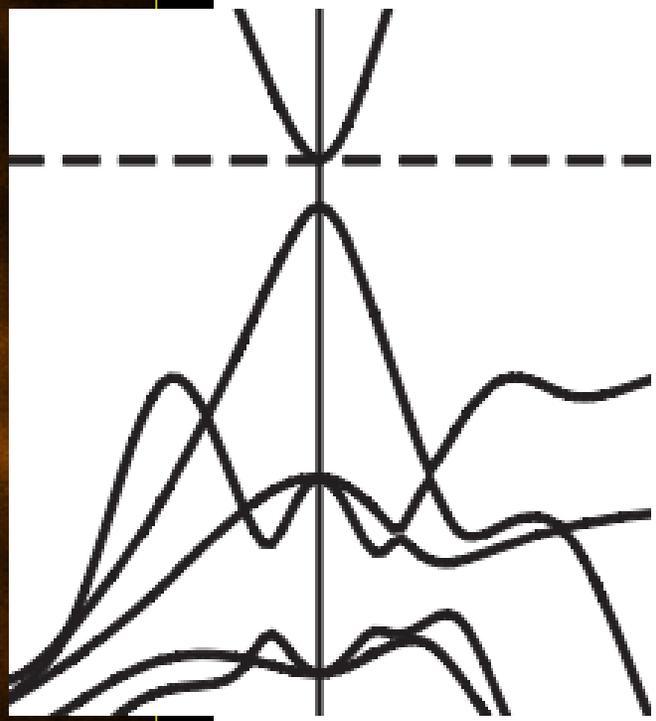
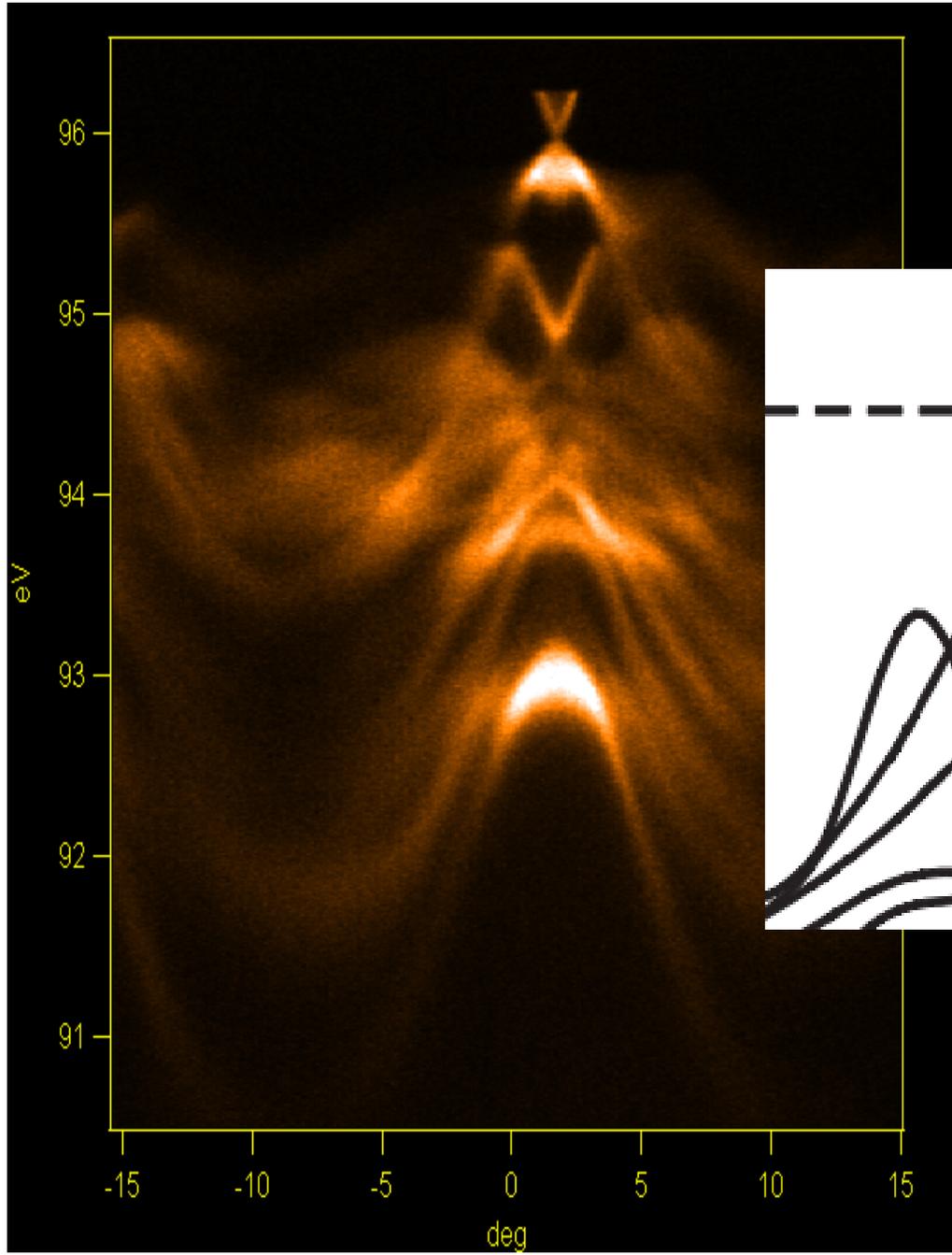
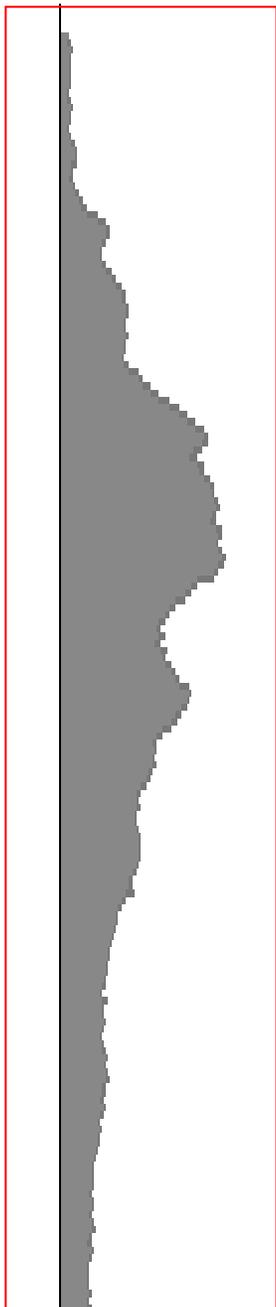
Bi₂Se₃

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

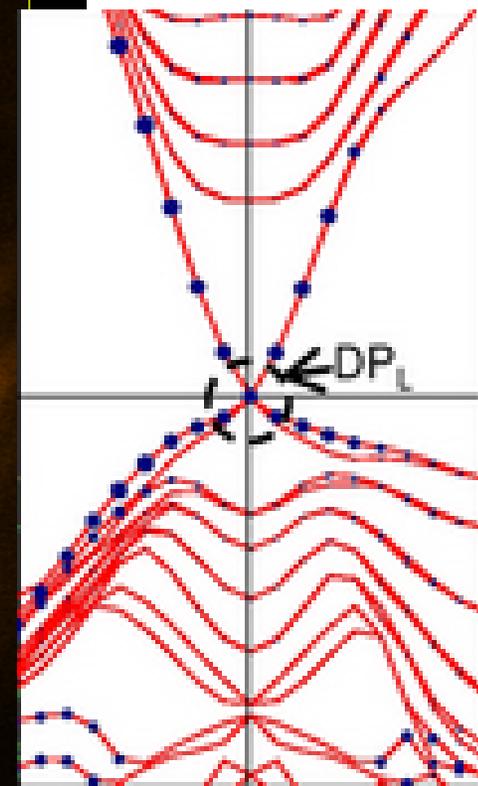
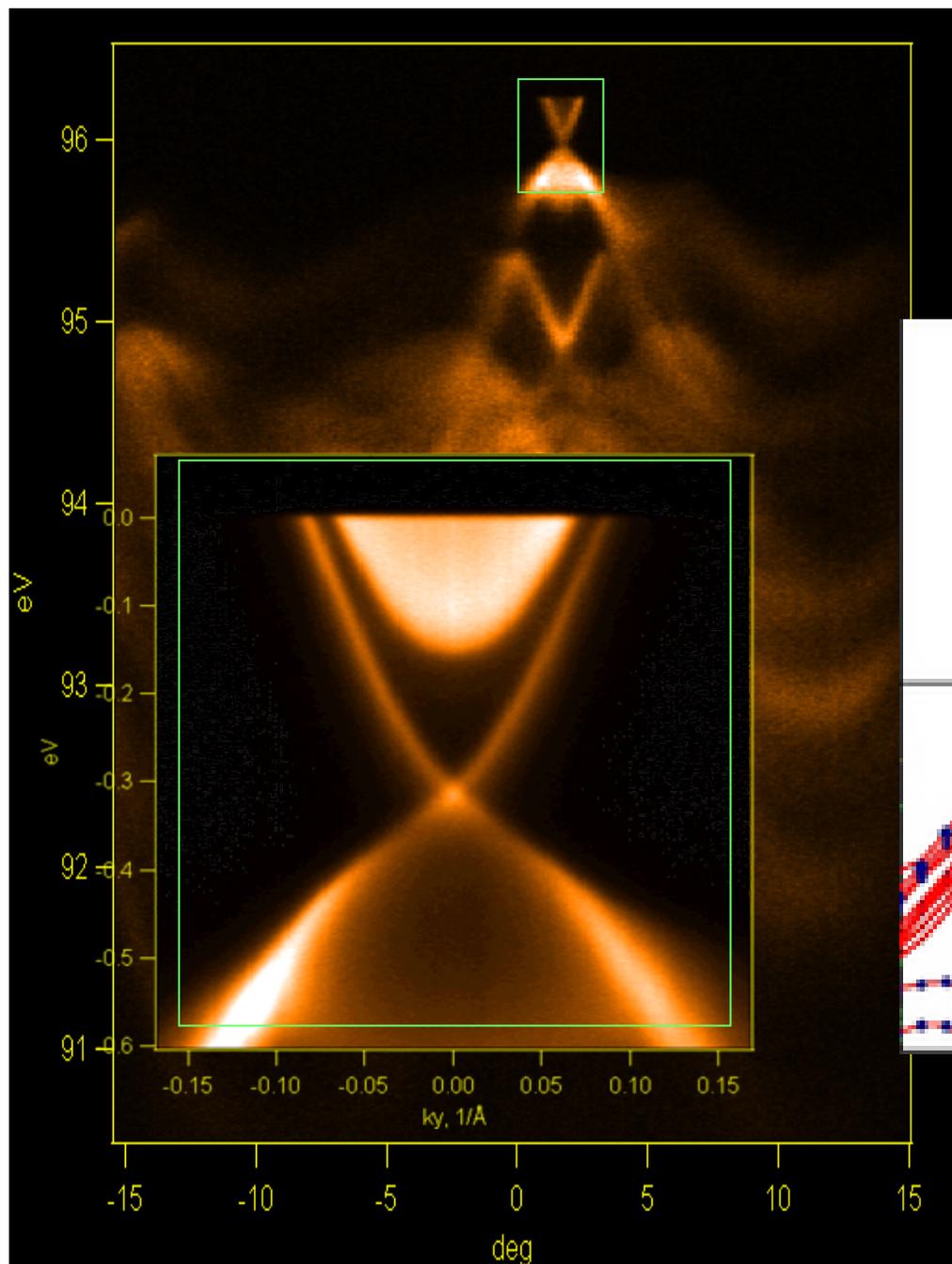
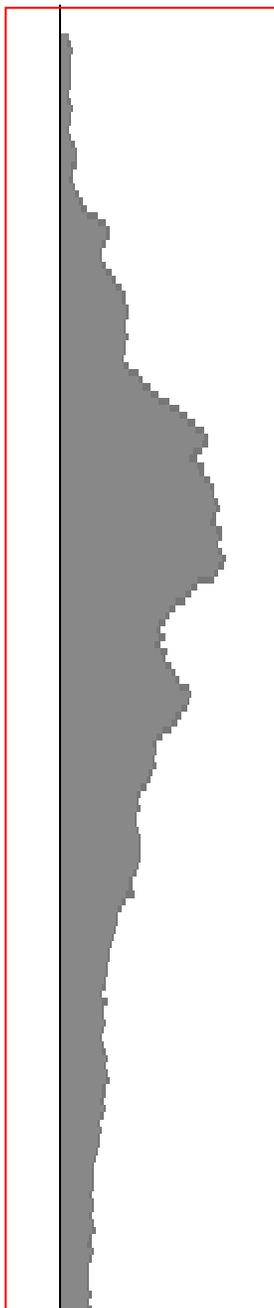




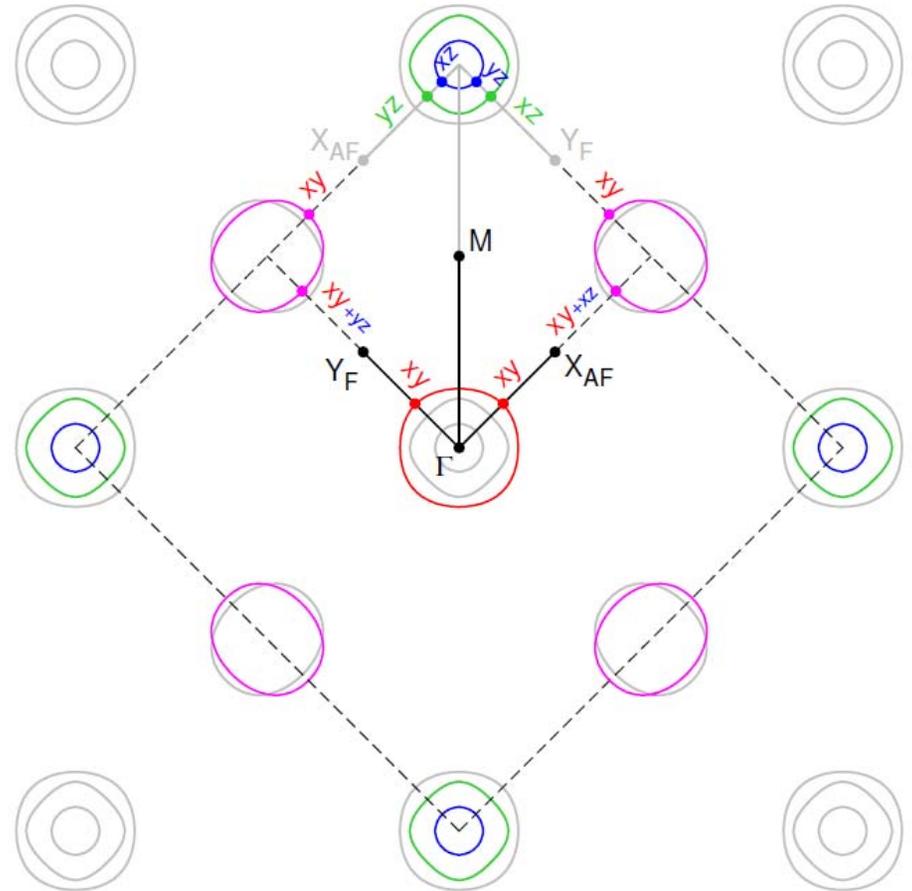
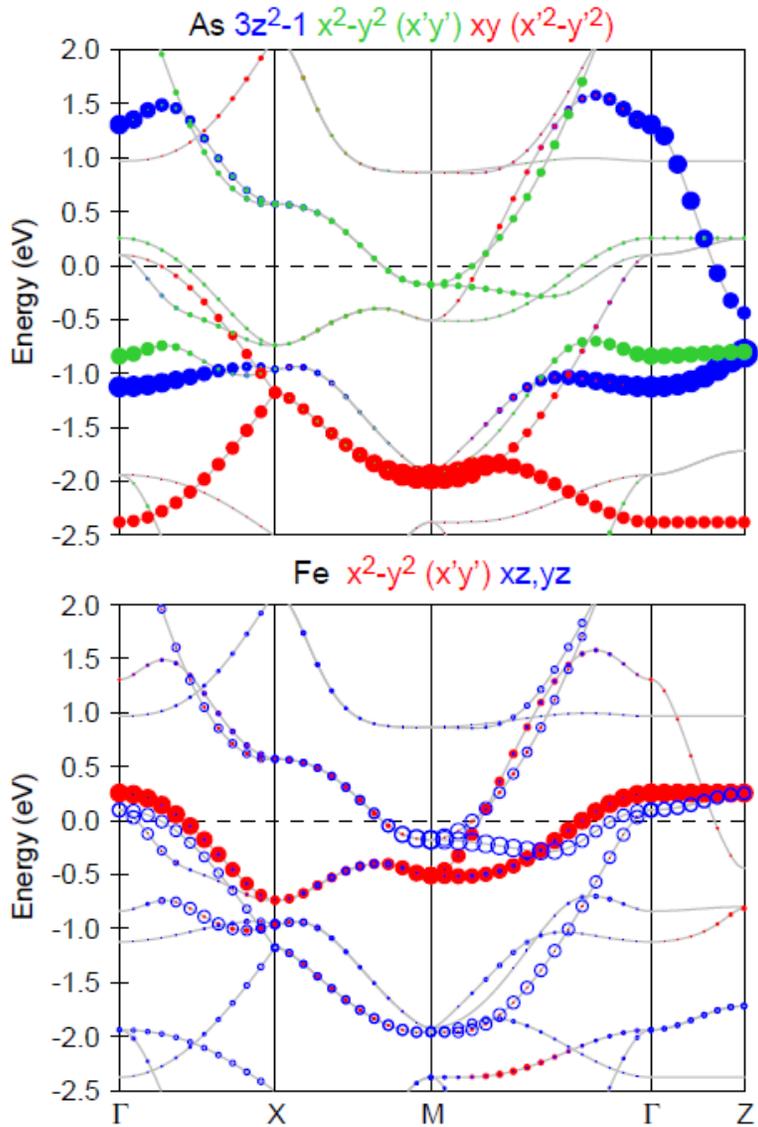
Bi₂Se₃



Bi_2Se_3



FeSC electronic band structure



**Electronic structure
&
ARPES**

Electronic structure

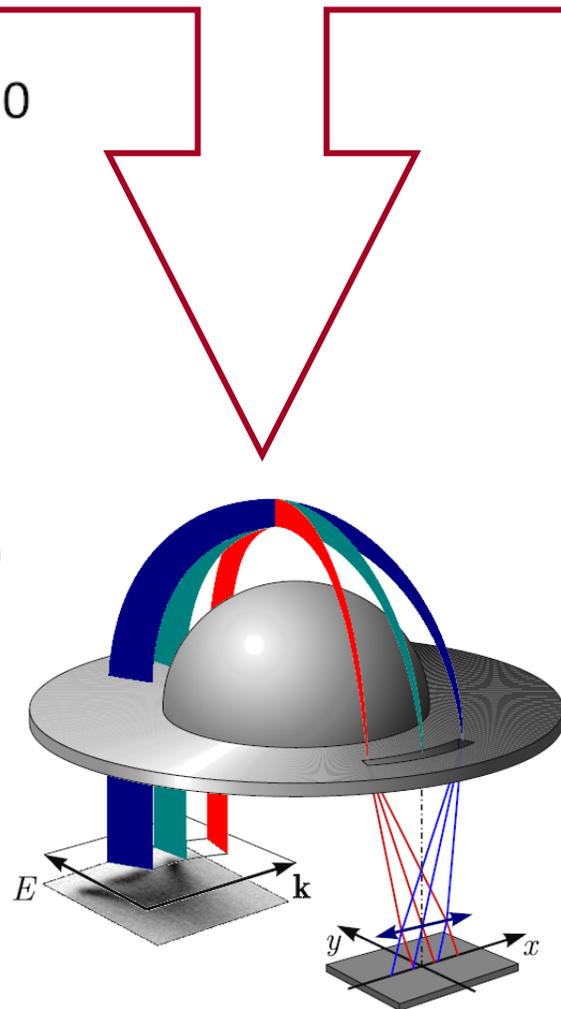
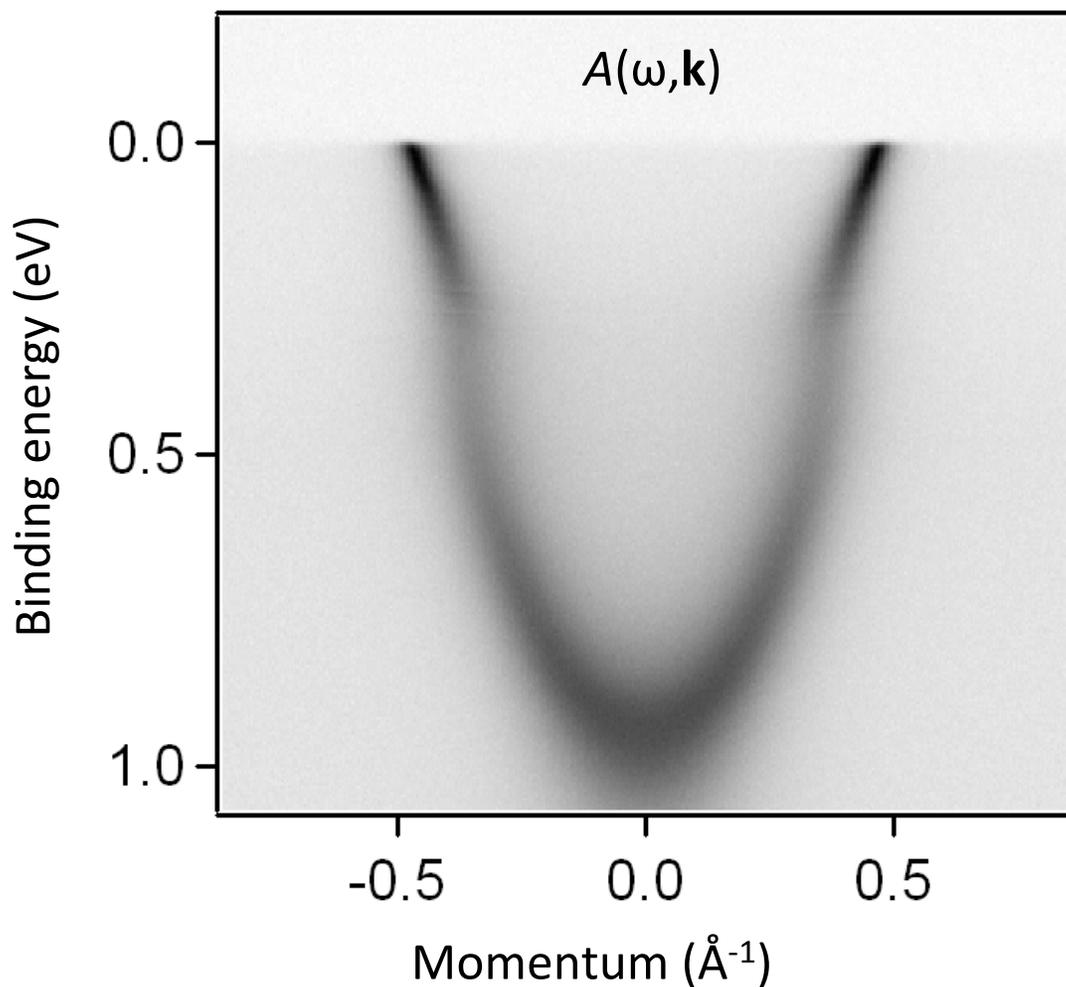
Electronic spectrum

≡

Spectrum of one-electron excitations

≡

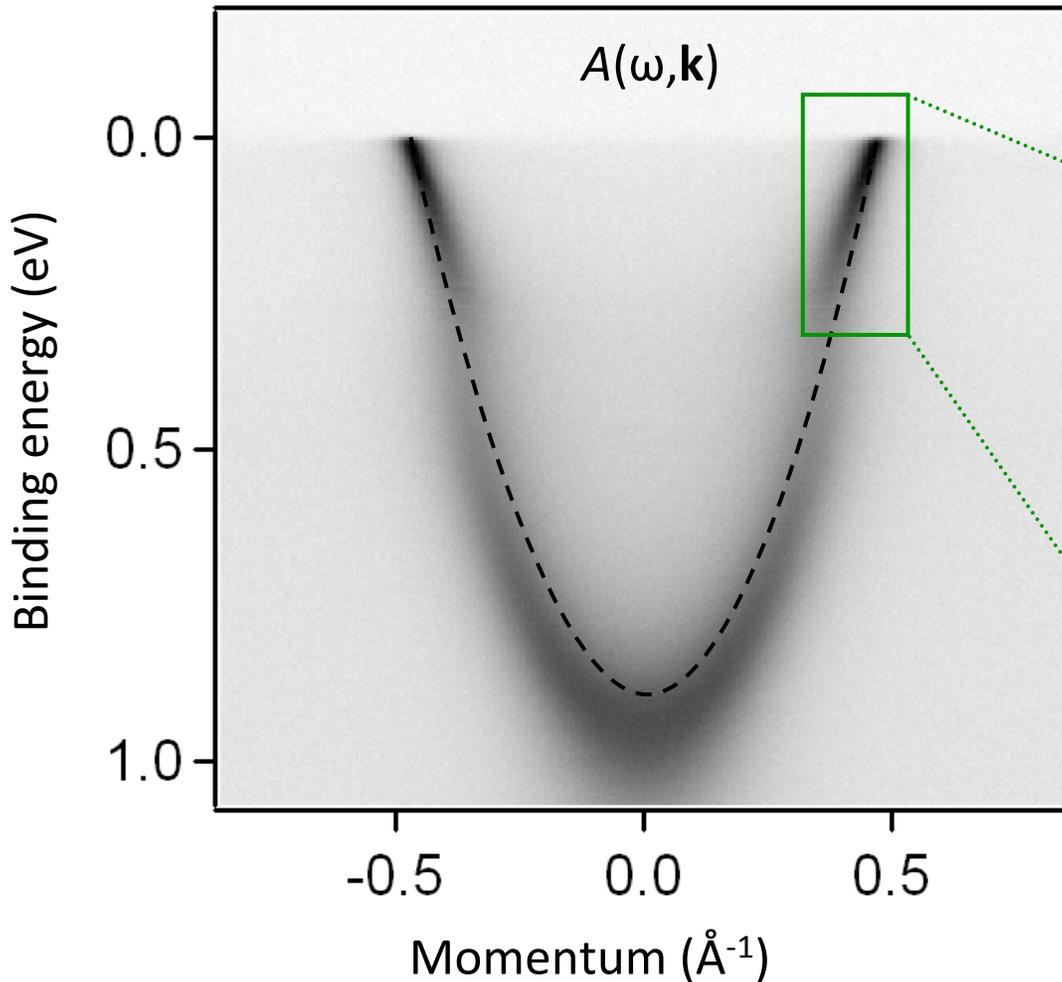
Probability to find electron with momentum \mathbf{k} and energy ω



Structure of electronic spectrum

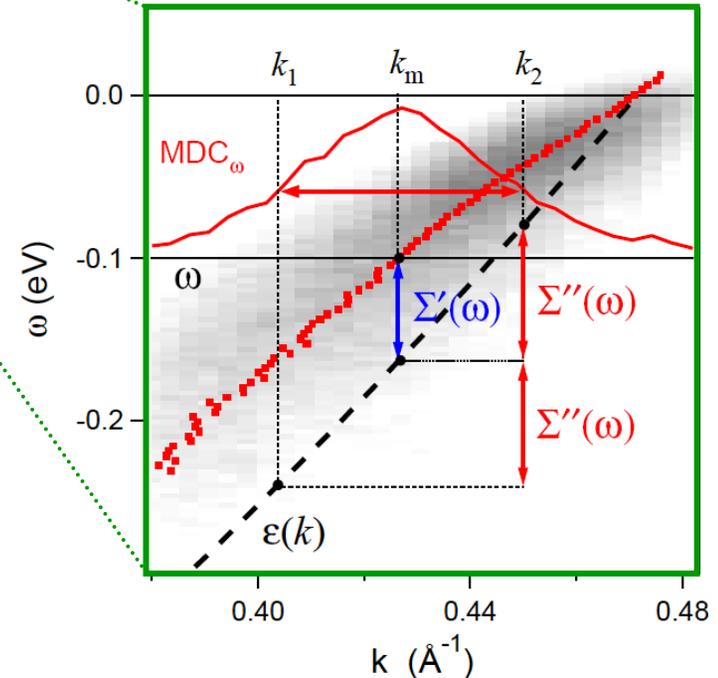
Spectral
function

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



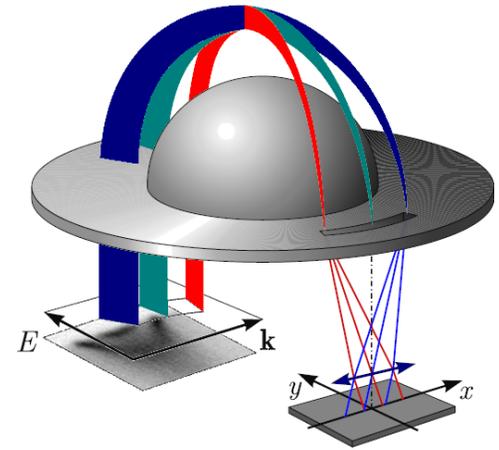
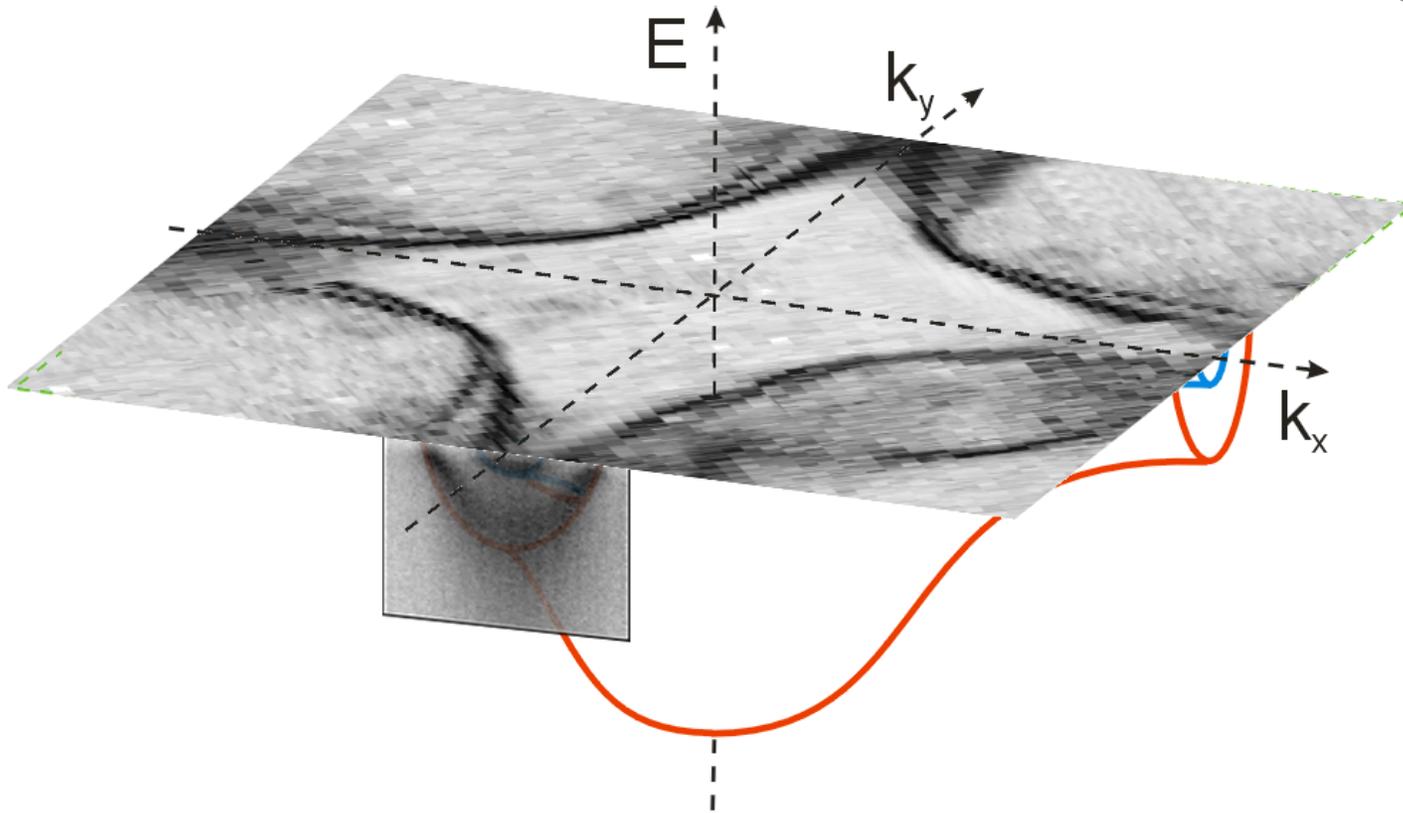
$\varepsilon(\mathbf{k})$ – “bare” electronic
band structure

$\Sigma(\omega, \mathbf{k})$ – self-energy

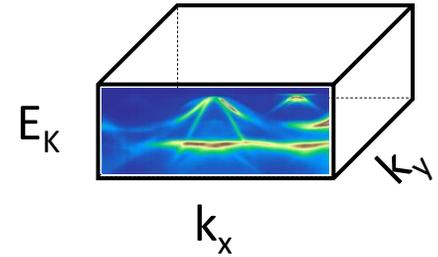


Electronic spectrum of quasi-2D crystals

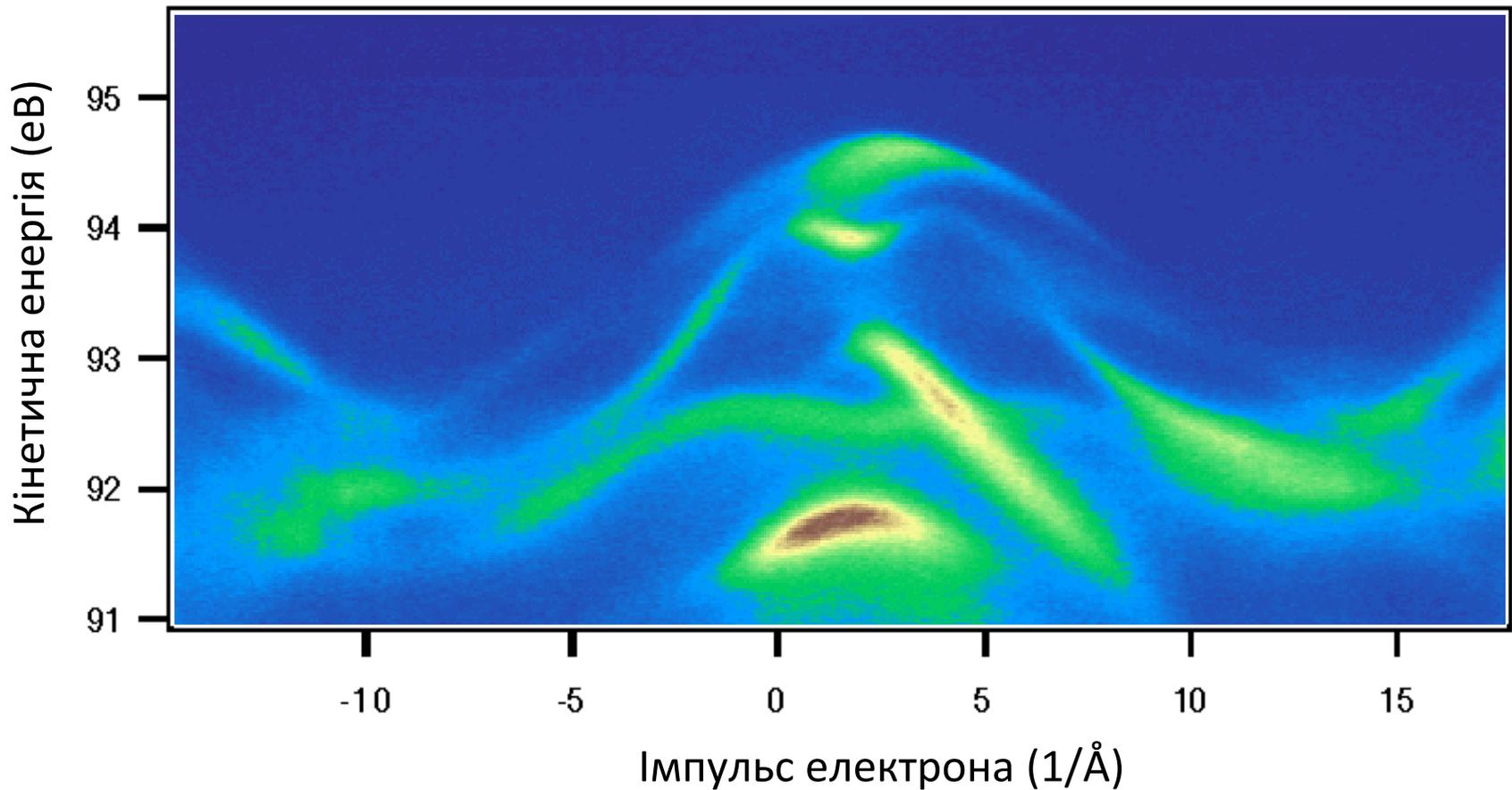
$$\varepsilon(k_x, k_y) \Rightarrow A(\omega, k_x, k_y)$$



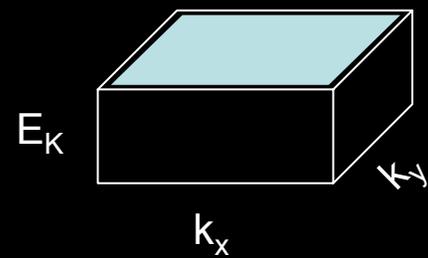
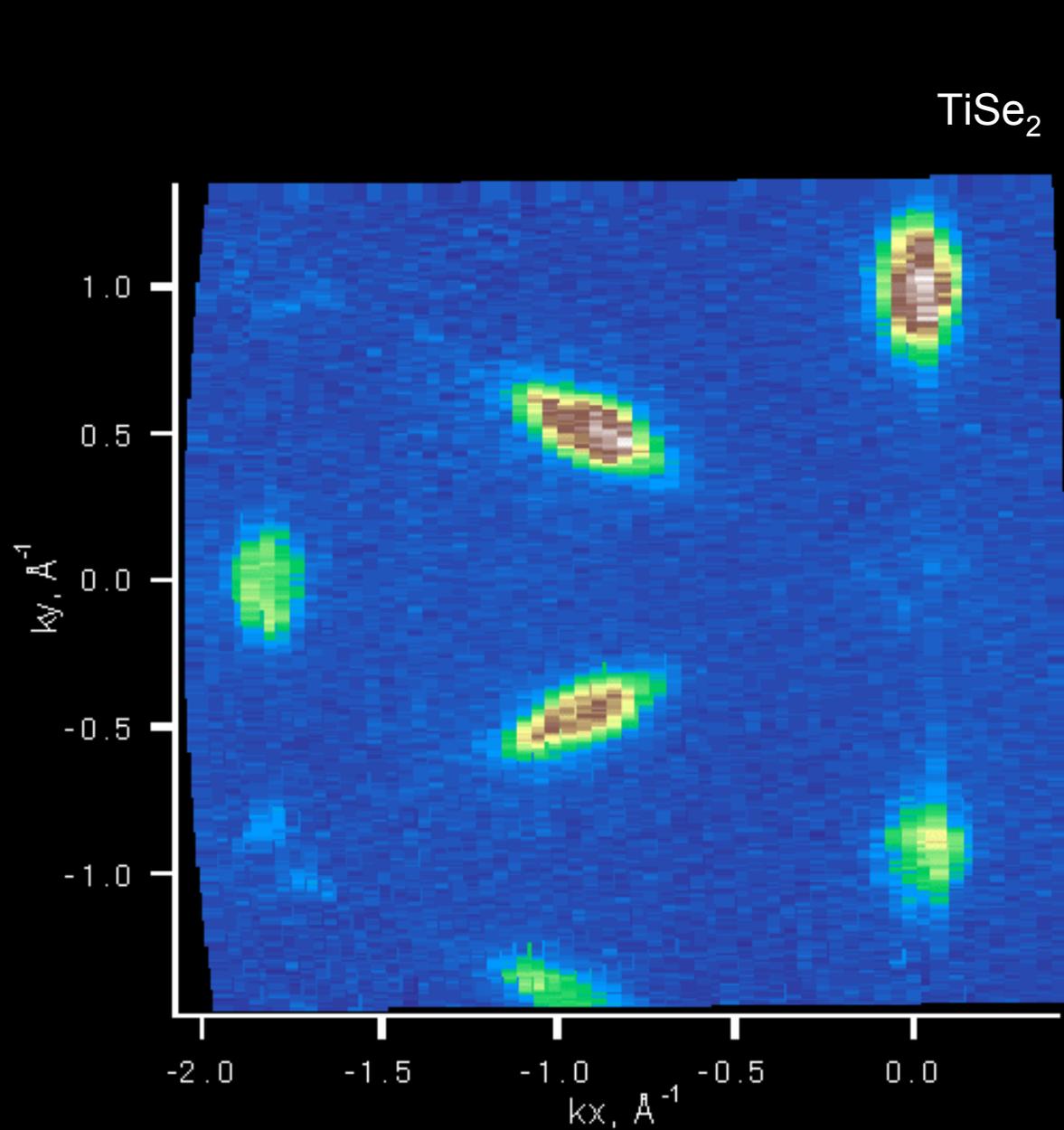
Electronic spectrum in momentum-energy 3D space



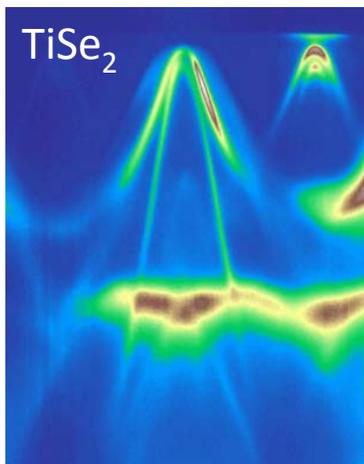
TiSe₂ - «ексітонний ізолятор»



Fermi surface (energy distribution) map

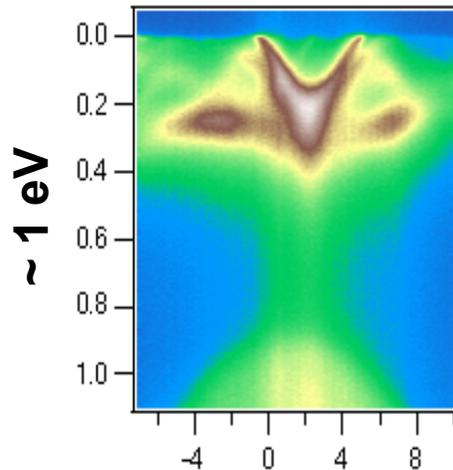


Valence band



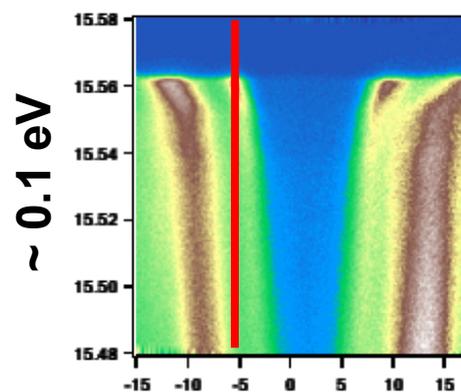
~ 5 eV

Conduction band



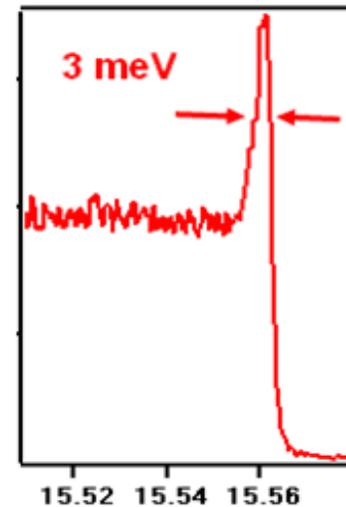
~ 1 eV

Phonon spectrum

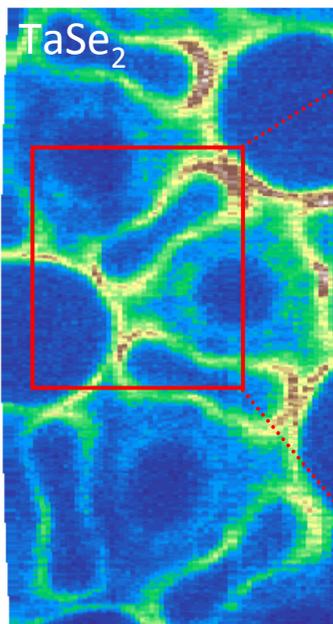


~ 0.1 eV

EDC

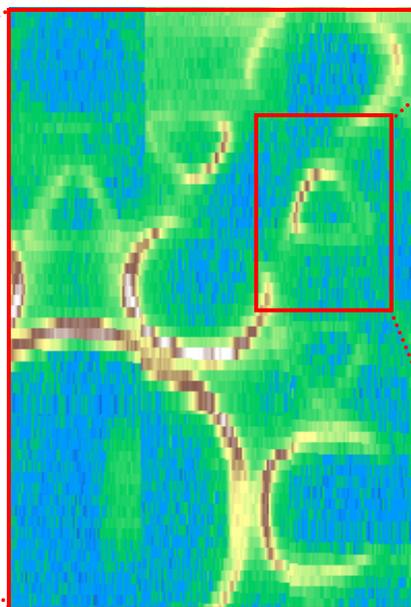


~ 5 Å⁻¹

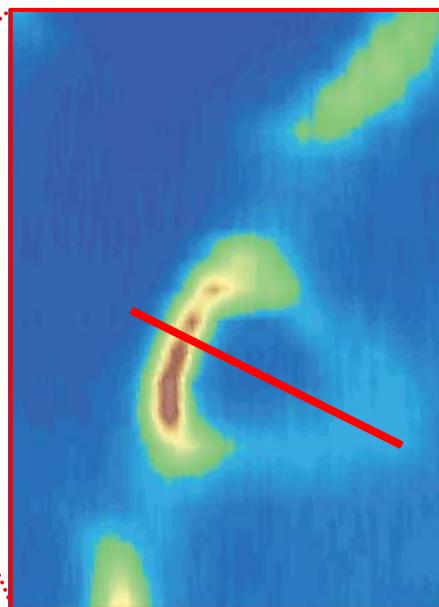


Fermi surface

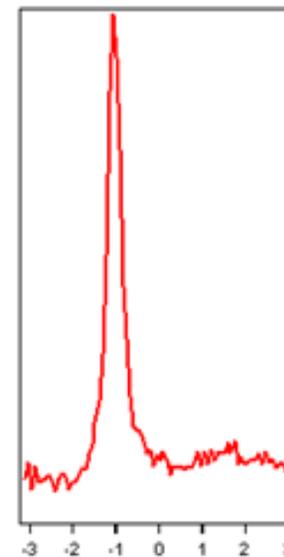
~ 1 Å⁻¹



~ 0.1 Å⁻¹



MDC

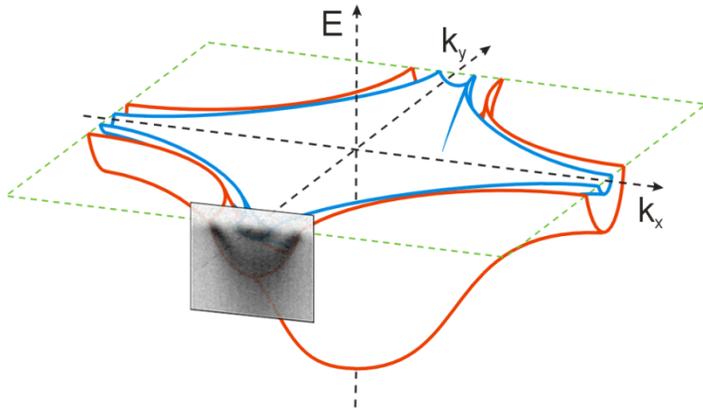


A few Brillouin zones

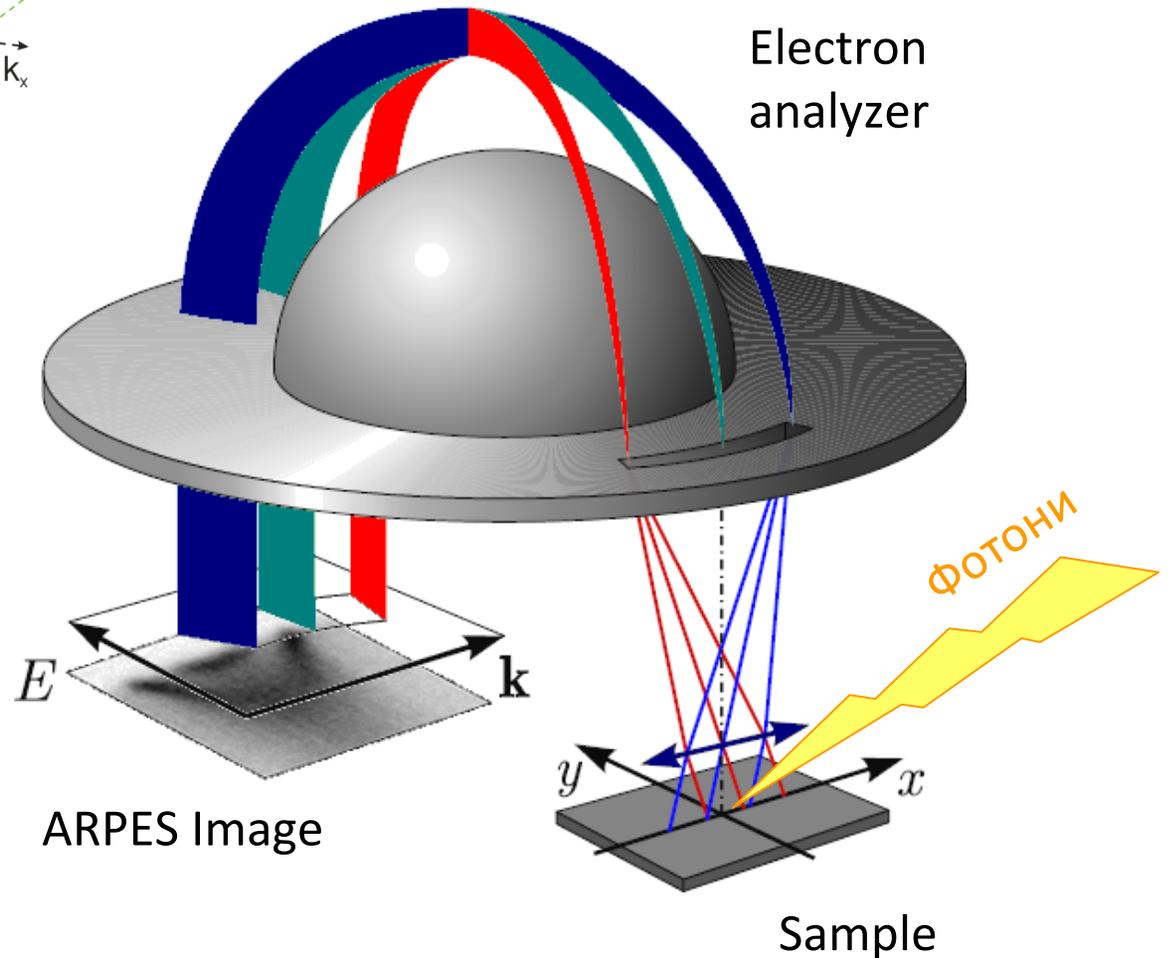
1-st Brillouin zone

Part of Fermi surface

ARPES: Angle Resolved Photoelectron Spectroscopy

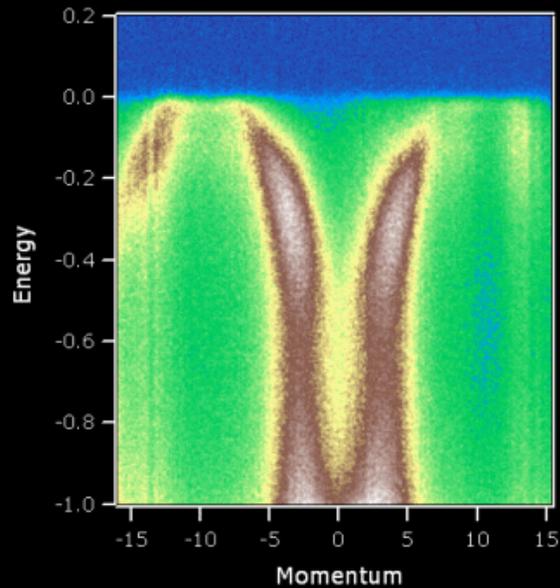


ARPES
=
photo effect
+
analyzer
+
manipulator



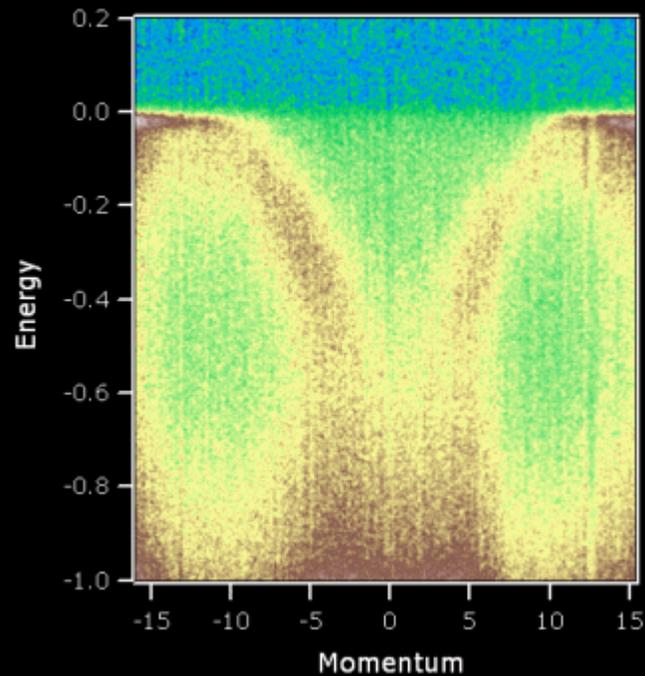
Photon energy – an important parameter

photon energy 81 eV

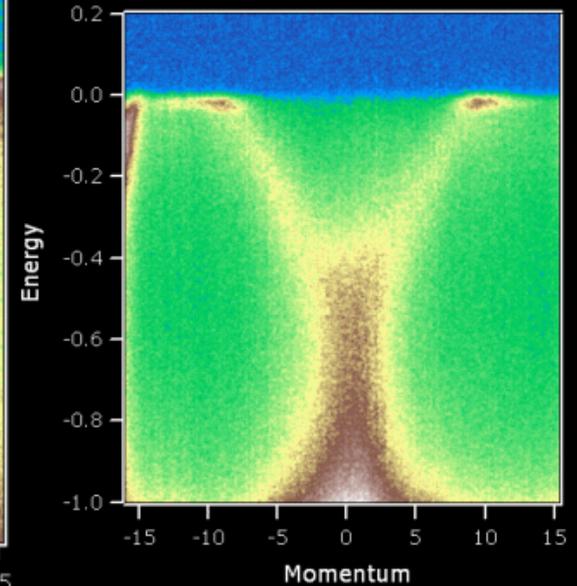


„Waterfalls“

photon energy 45 eV

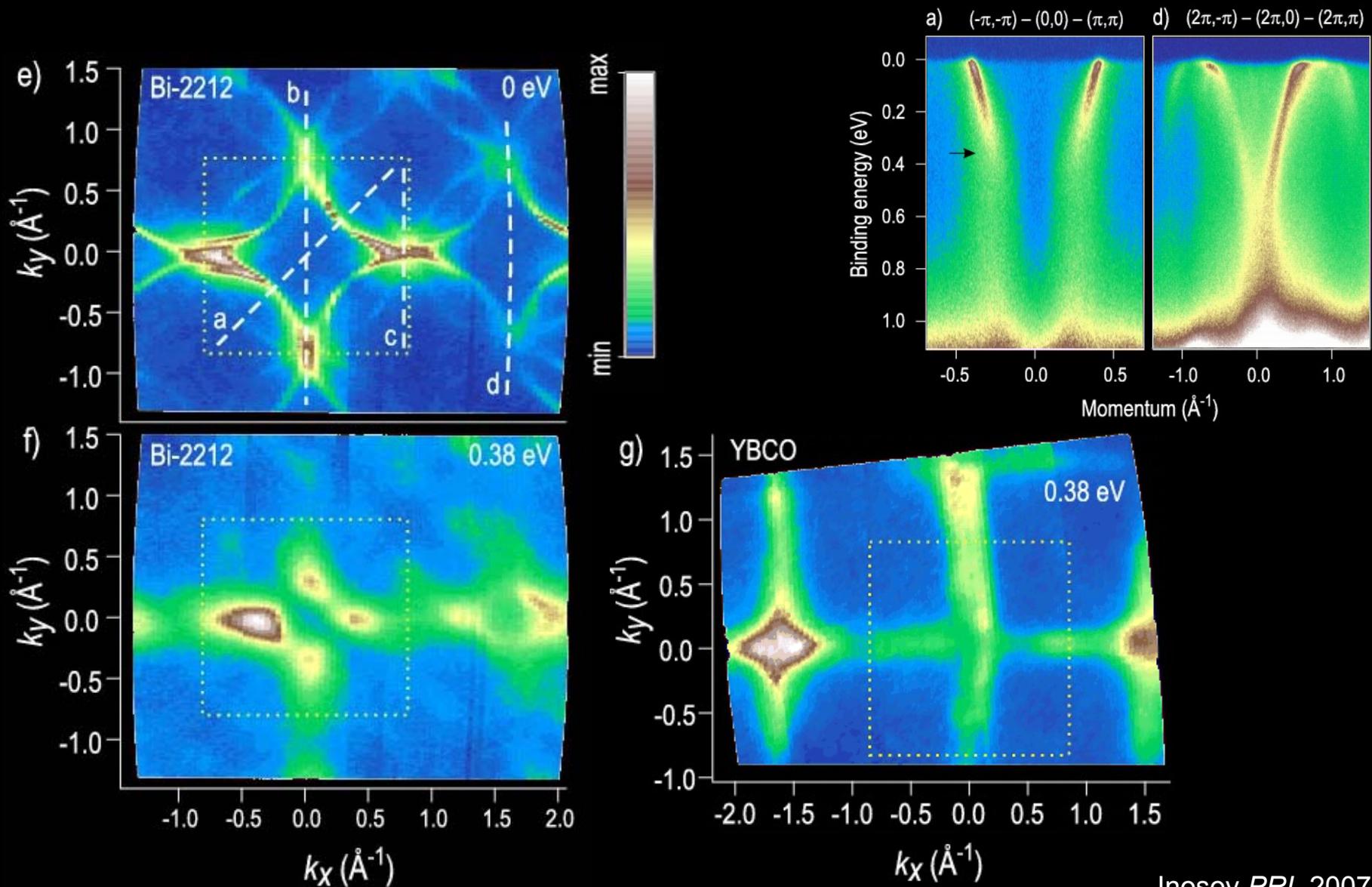


photon energy 64 eV



„Champagne glass“

Waterfalls in cuprates



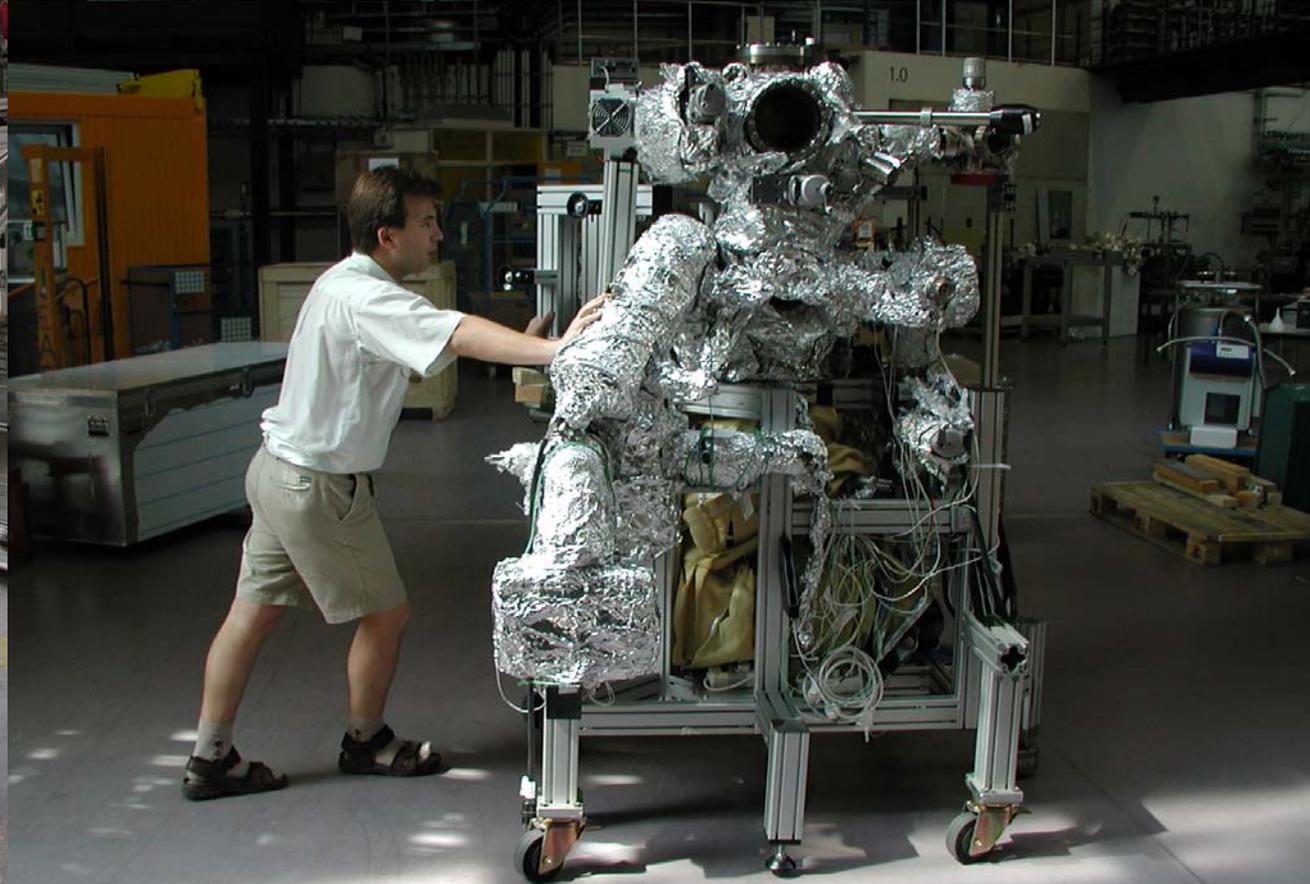
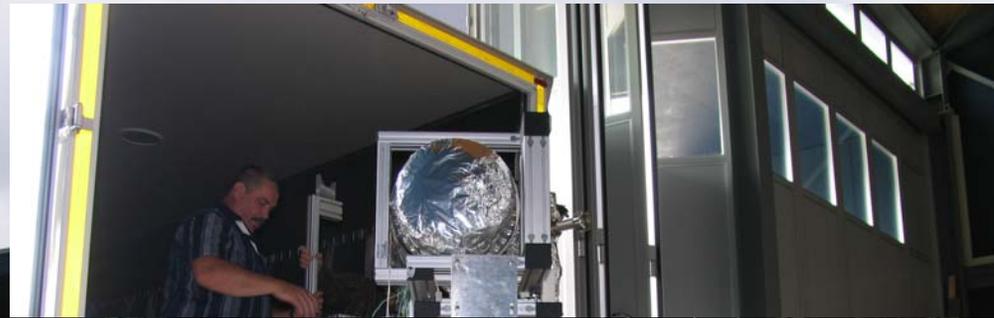
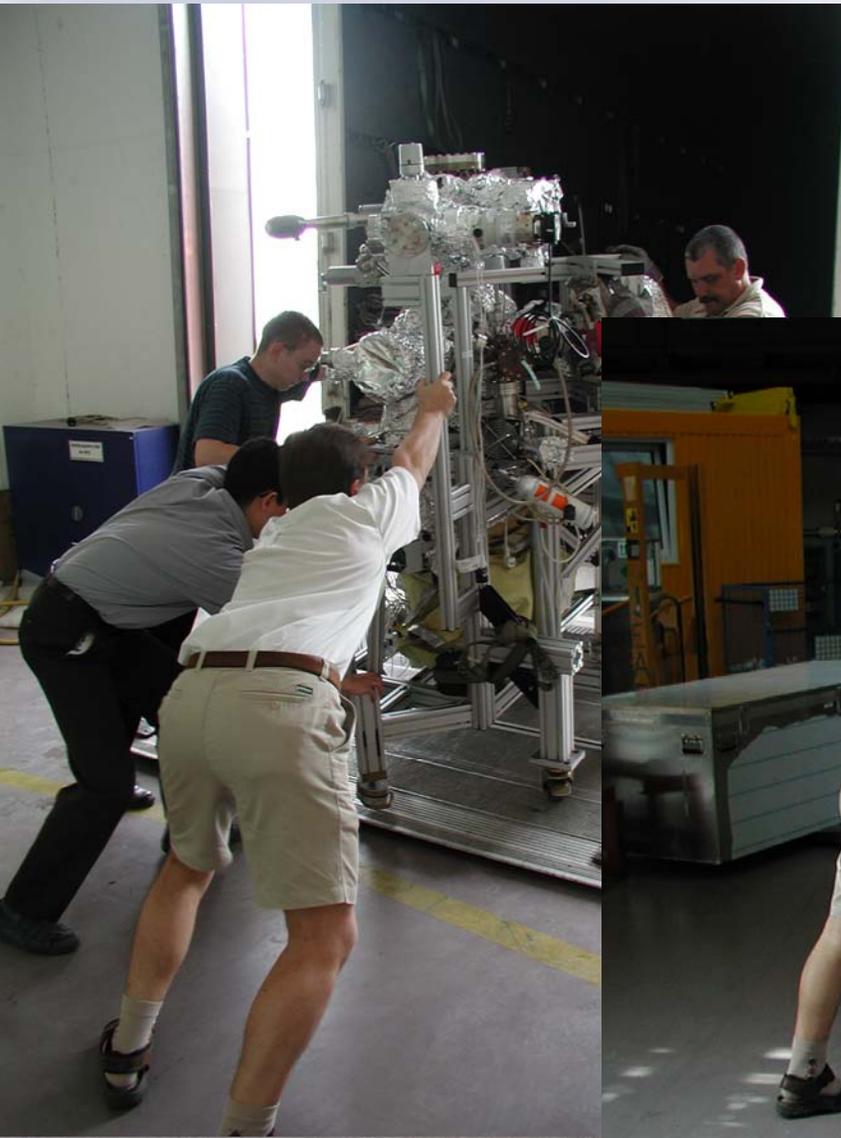
...travelling chamber



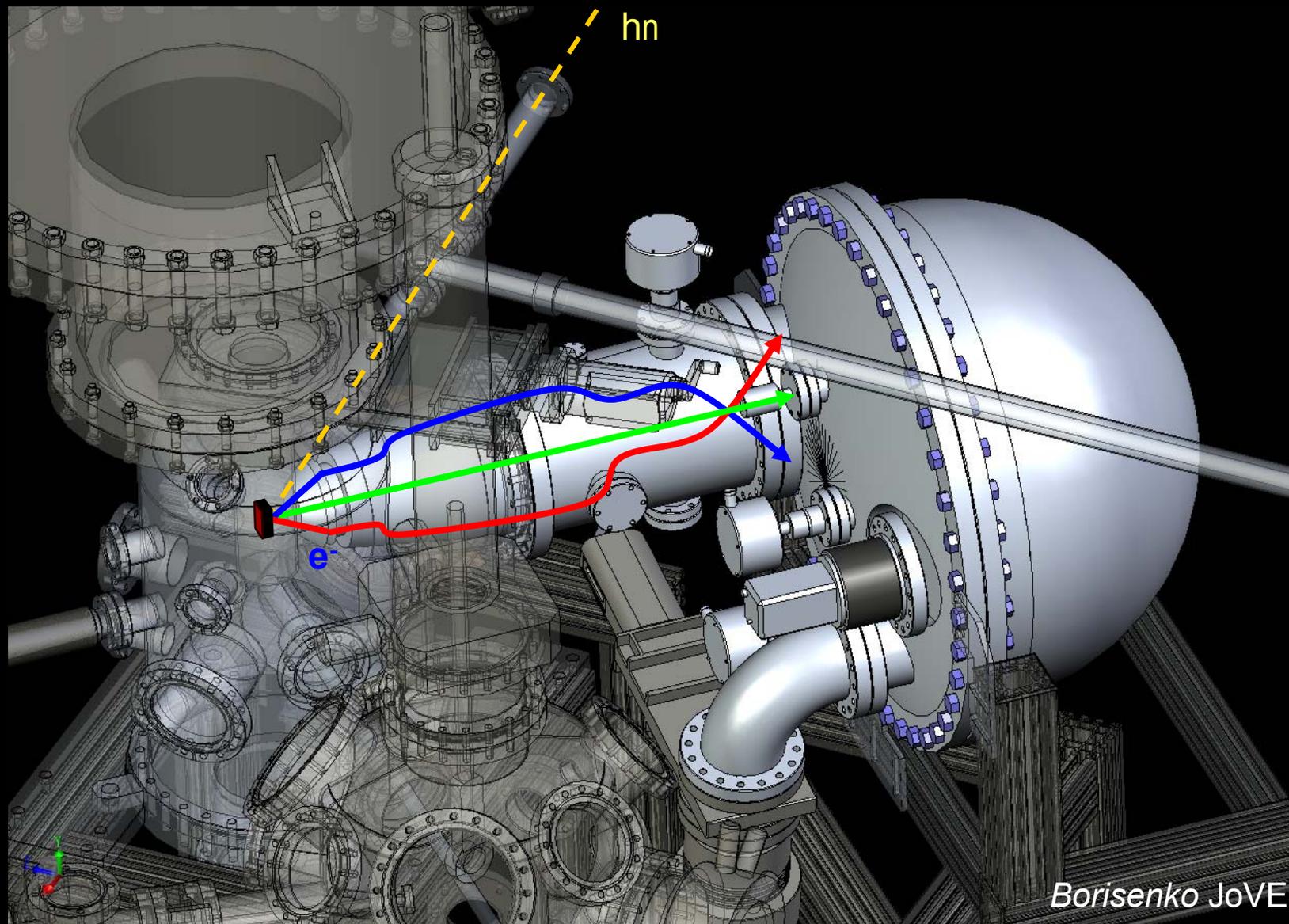
...travelling chamber



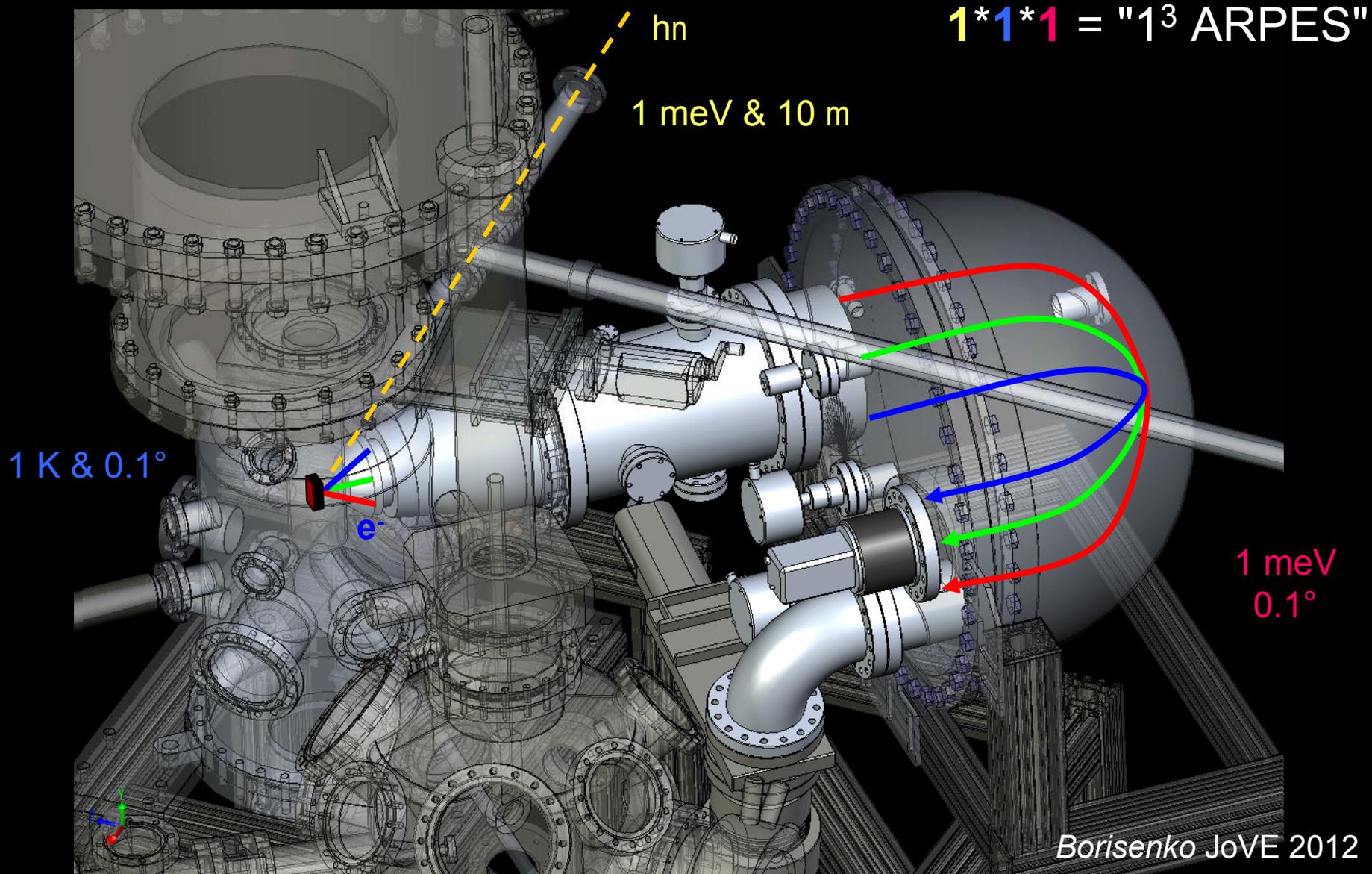
...travelling chamber



ARPES anatomy

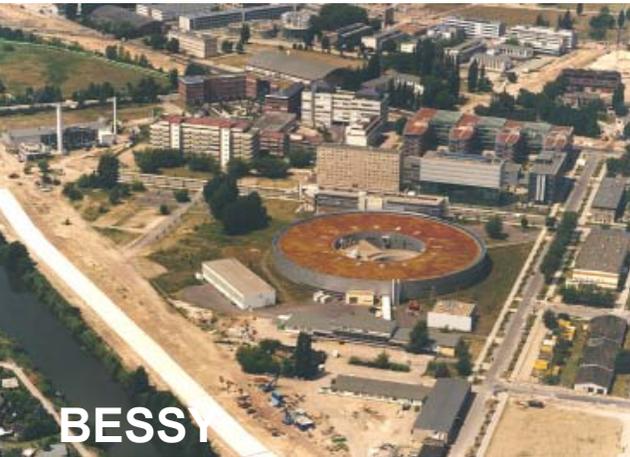


ARPES anatomy



ARPES =

**analyzer + manipulator (10^6 €)
+ synchrotron**



- New direction:
time resolved ARPES,
XFEL

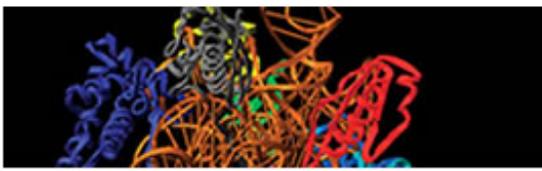




**European
X-ray
Free Electron
Laser**



TINY STRUCTURES



Examples

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

Experiment stations

SPB, SCS and MID

ULTRAFAST PROCESSES

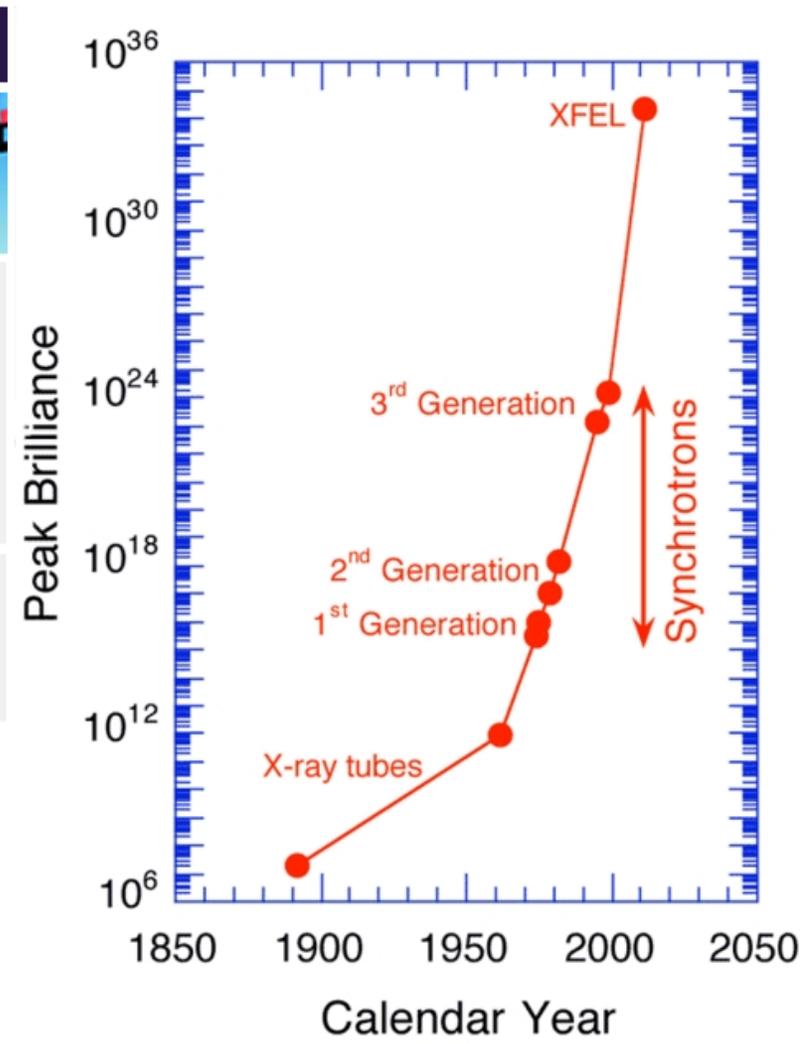


Examples

- Filming chemical reactions
- Unravelling magnetization

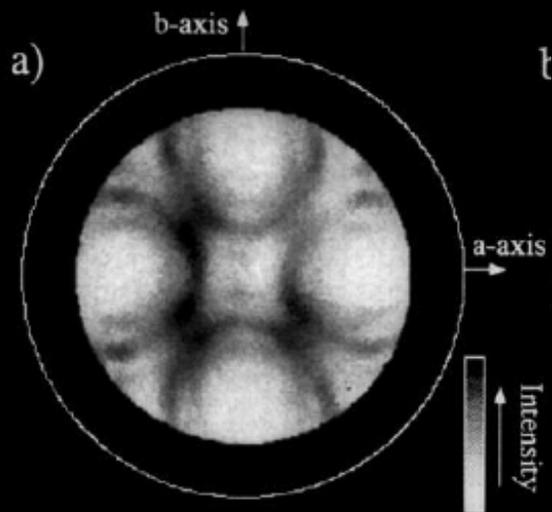
Experiment stations

SPB, MID, FXE, HED, SQS, SCS

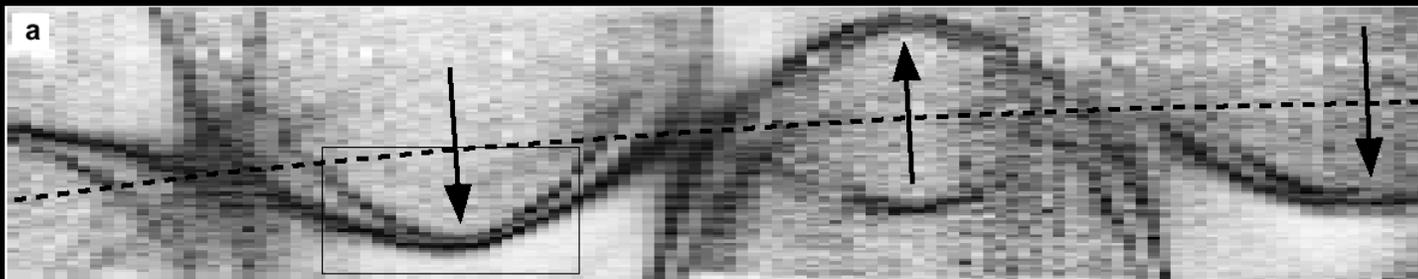
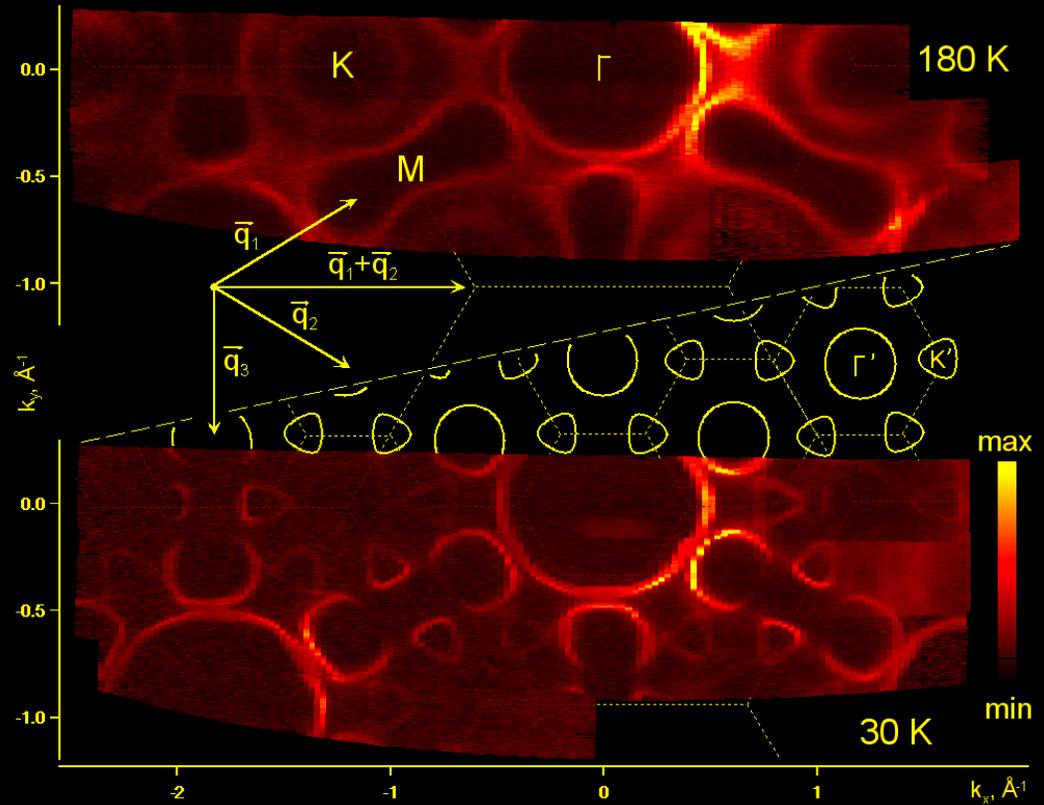


2009-2015: ~ 1 000 000 000 €

ARPES in HTSC problem



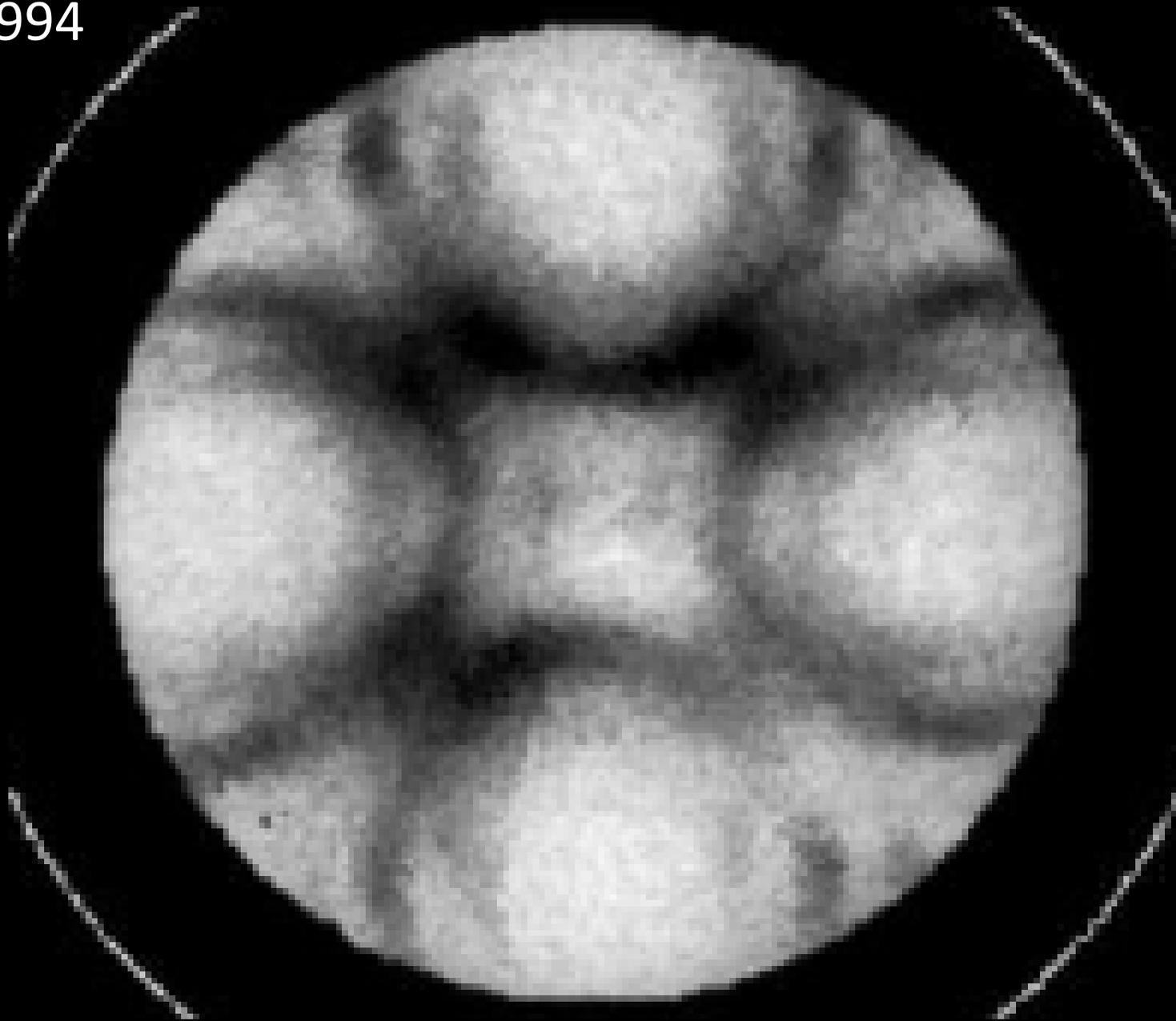
Aebi *PRL* 1994



Kordyuk *PRB* 2004

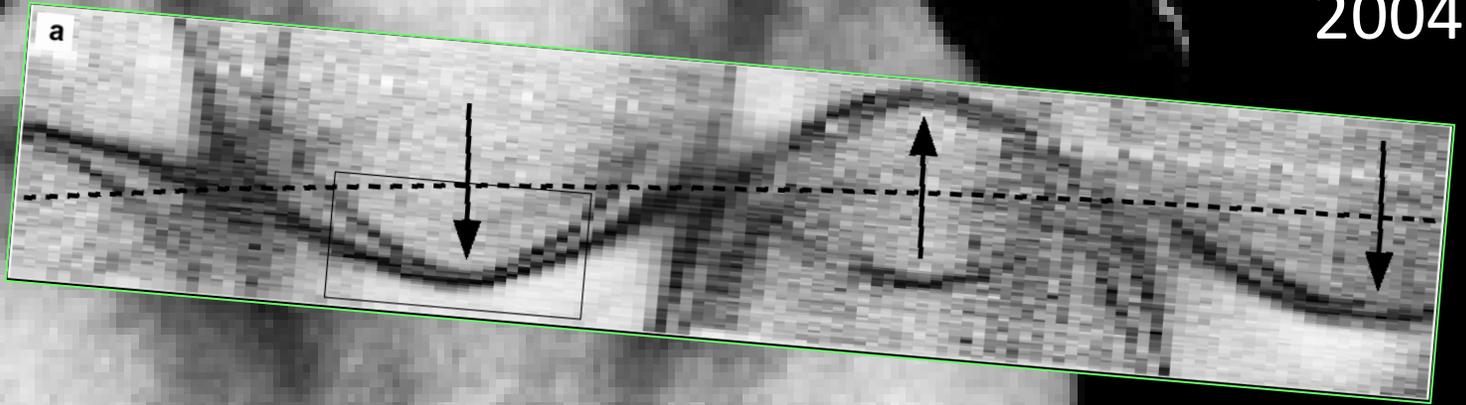
Borisenko *PRL* 2008

1994



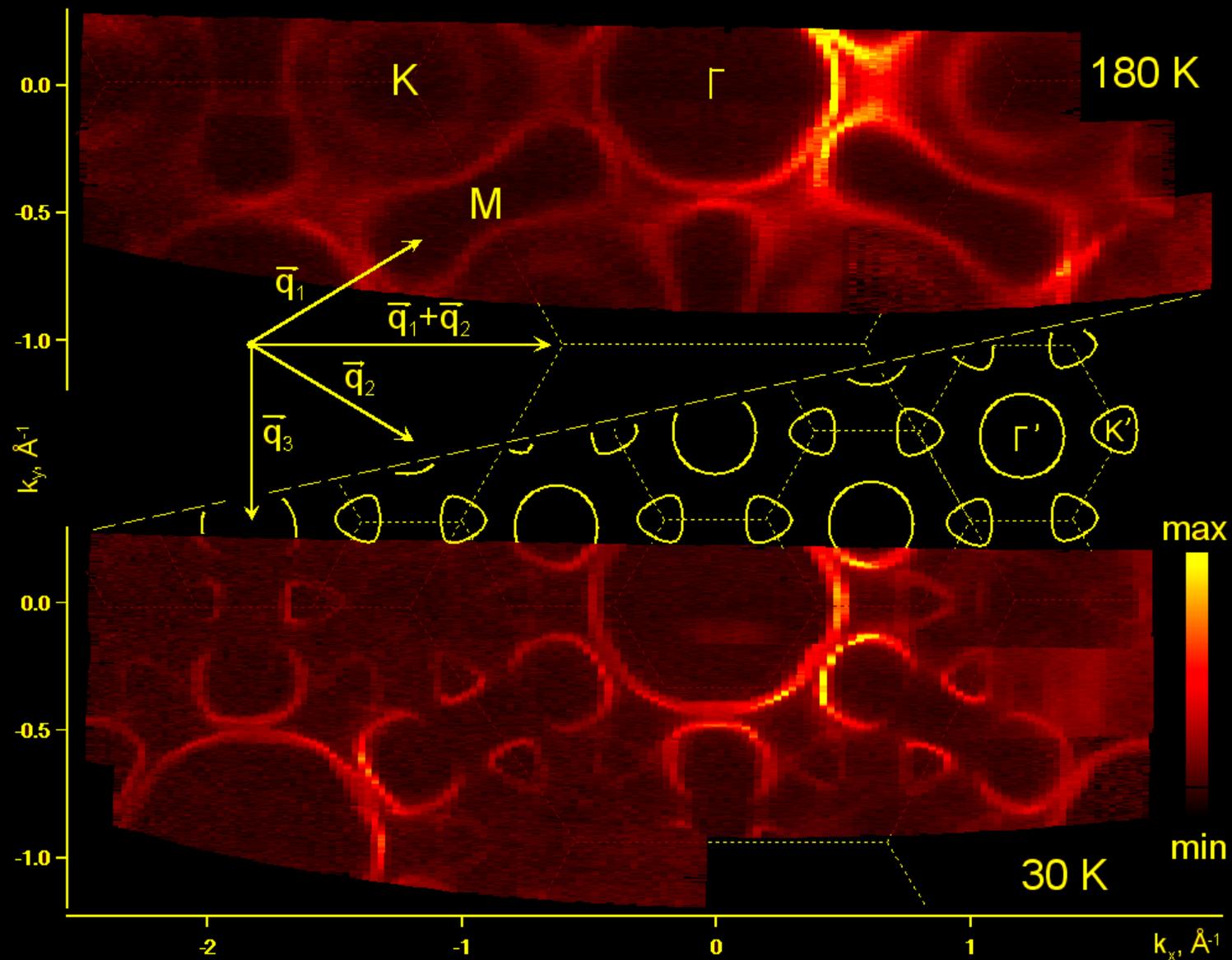
1994

2004

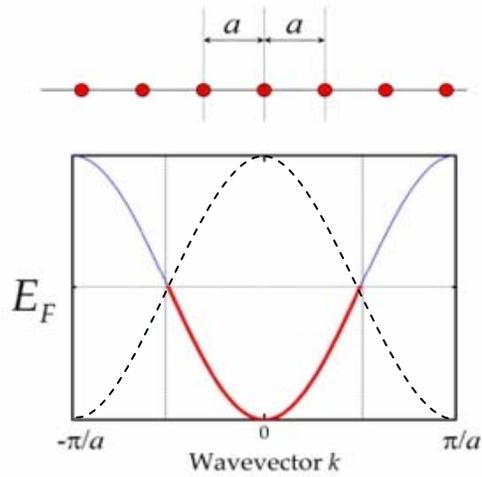


Transition metal dichalcogenides

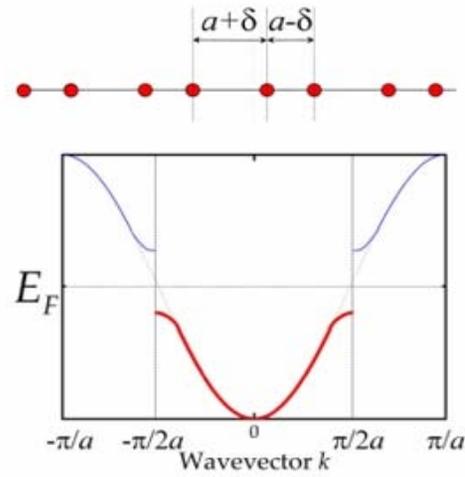
CDW y TaSe₂: commensurate CDW state



Peierls transition and Fermi surface nesting



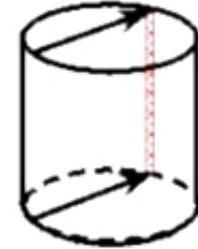
(a)



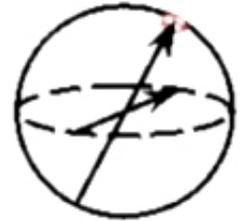
(b)



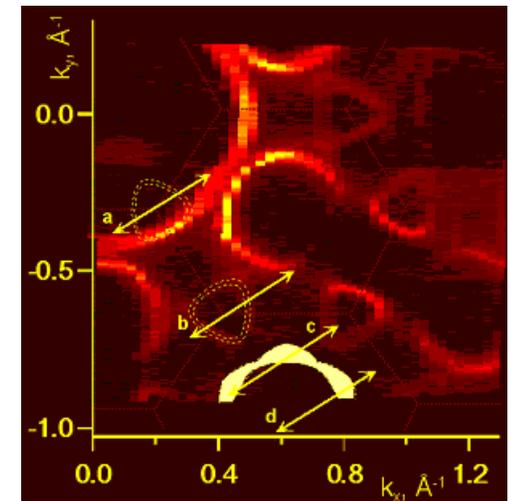
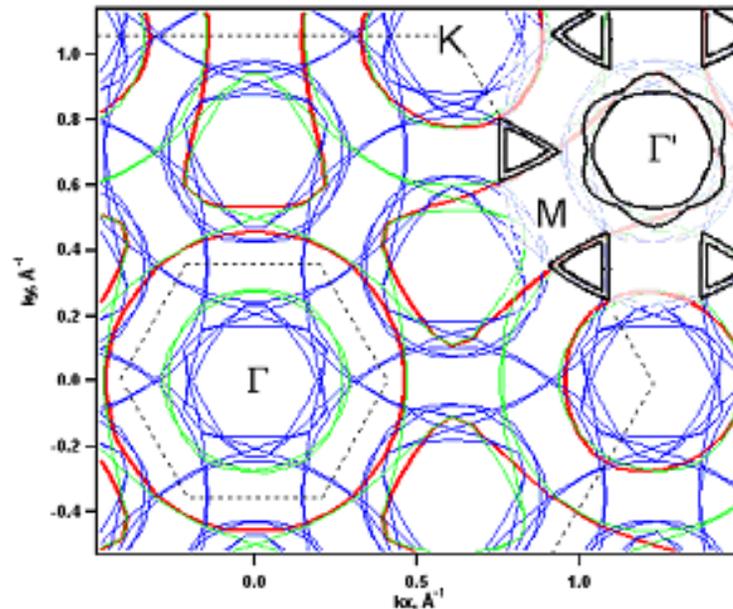
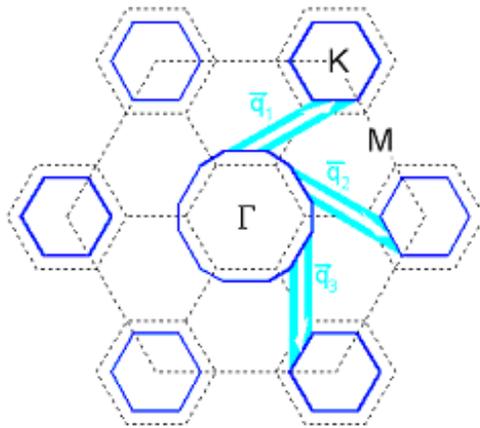
1D



2D

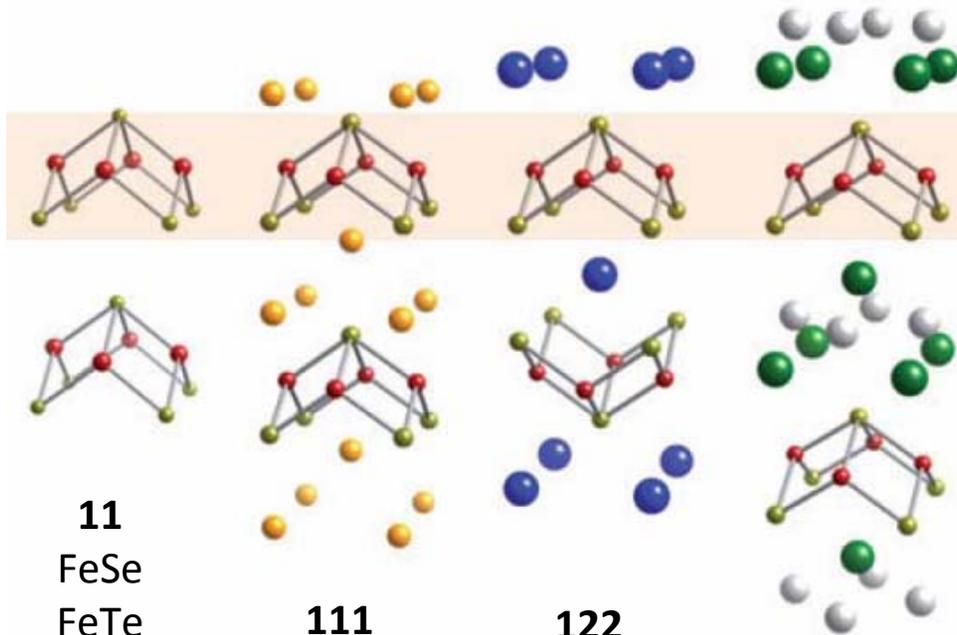


3D

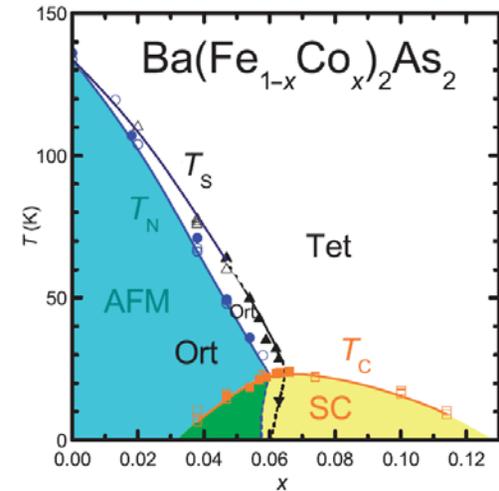
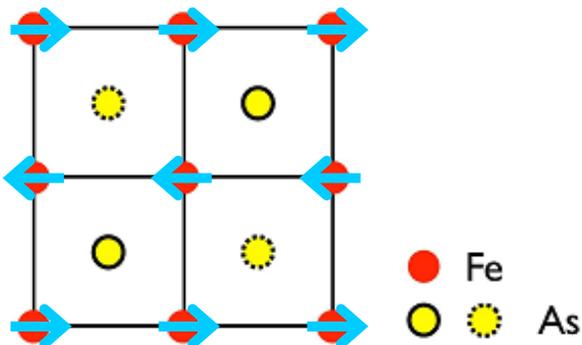


Iron-based superconductors

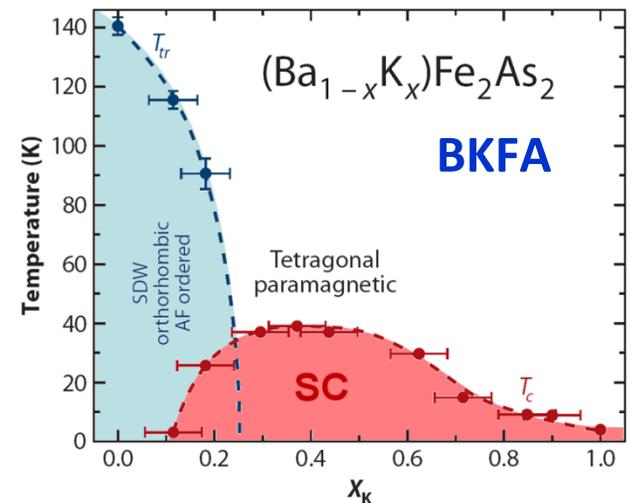
Iron-based superconductors (FeSC)



Paglione & Greene, *Nat. Phys.* (2010)

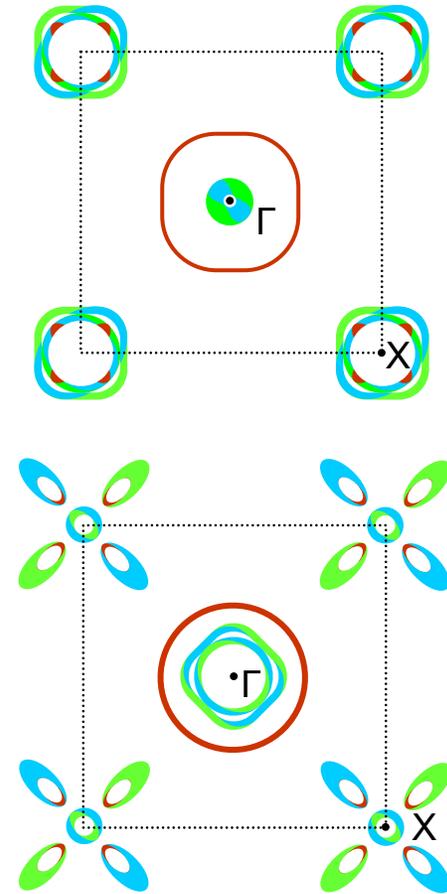
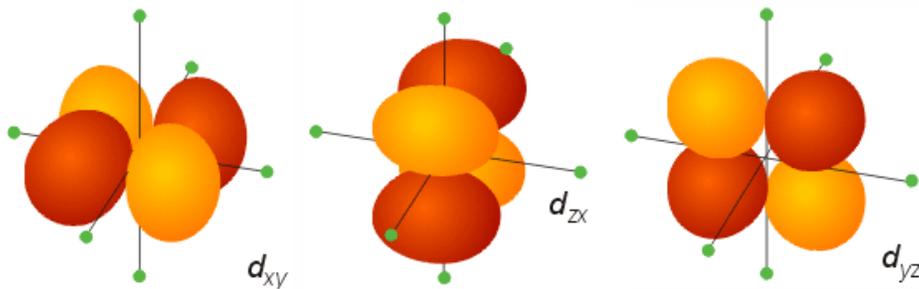
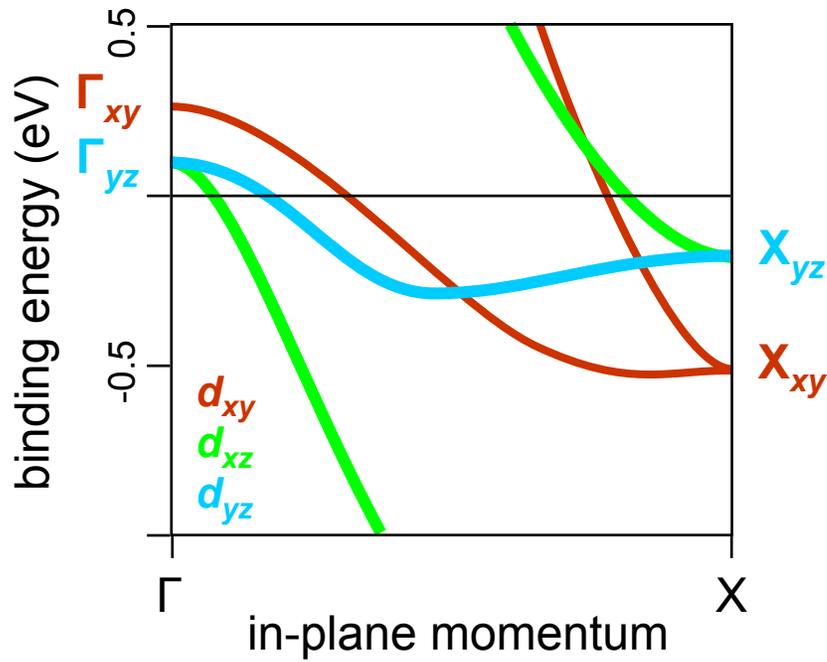


S.Nandi et al. [PRL 2010](#)

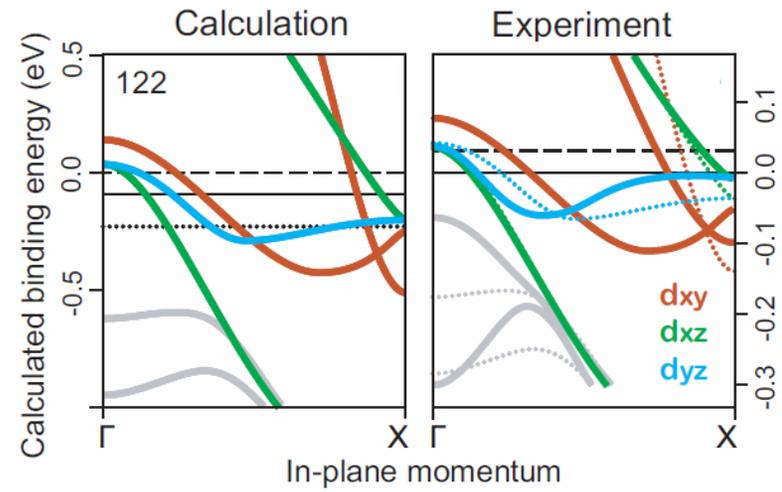
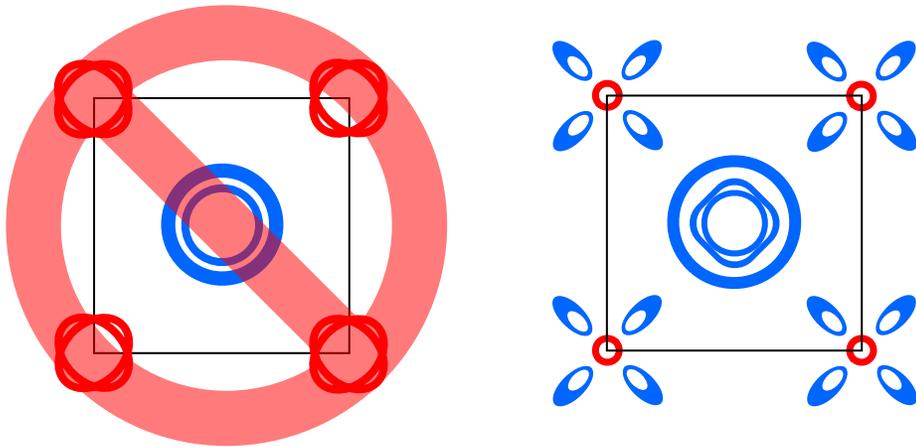


H.-H.Wen & S.Li [Annu. Rev. Cond. Mat. Phys. 2011](#)

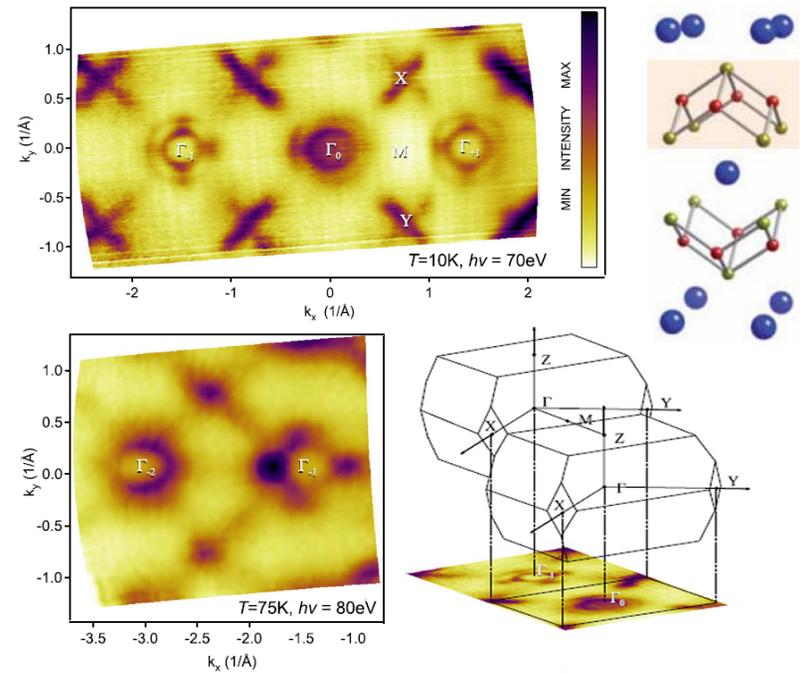
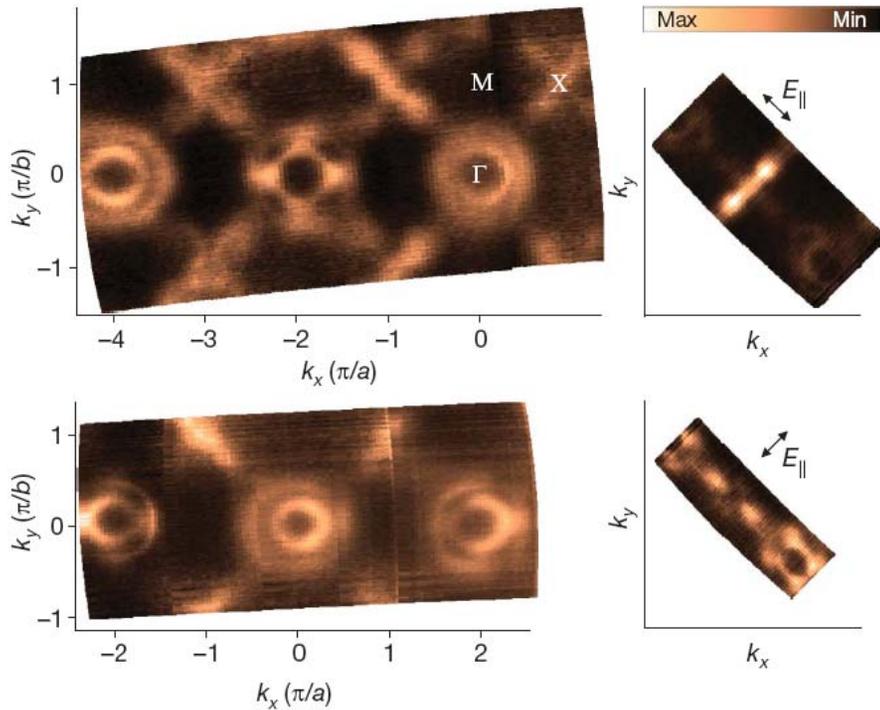
Iron-based superconductors: electronic structure



Fermi surface of BKFA

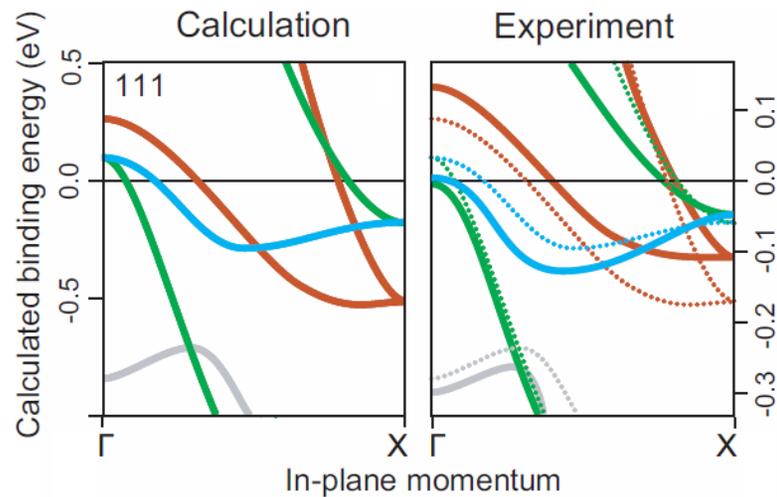
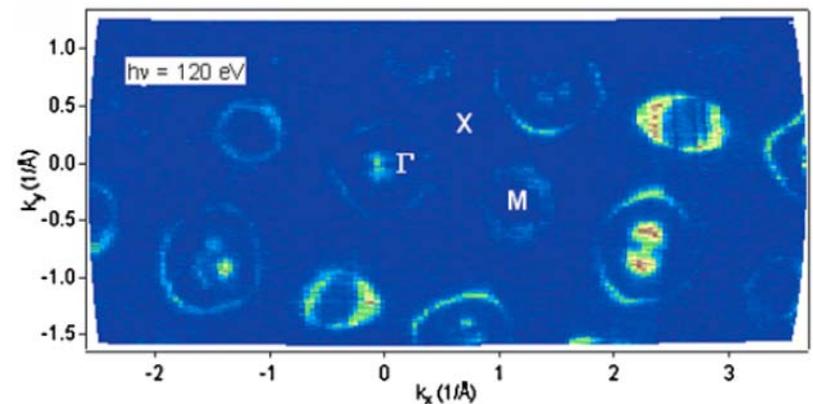
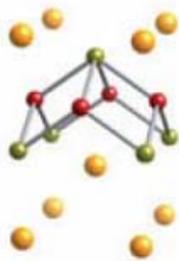
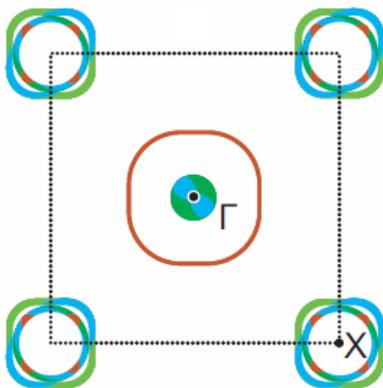
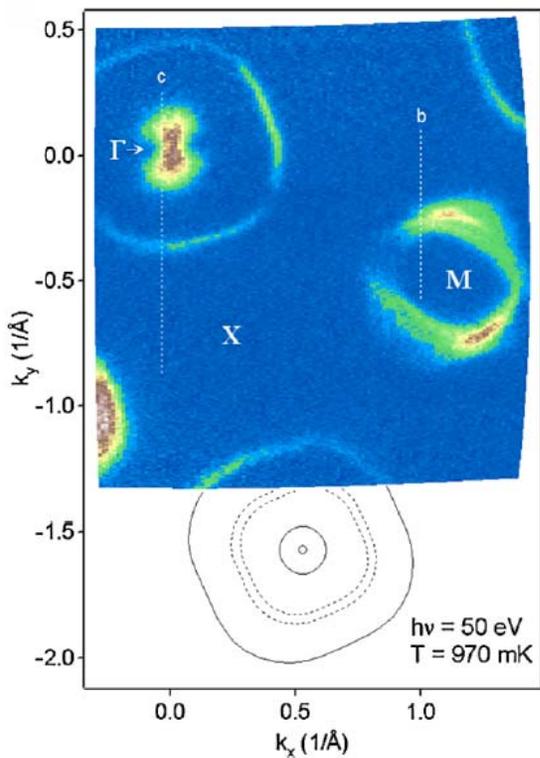


A. A. Kordyuk, *J. Supercond. Nov. Magn.* 2012



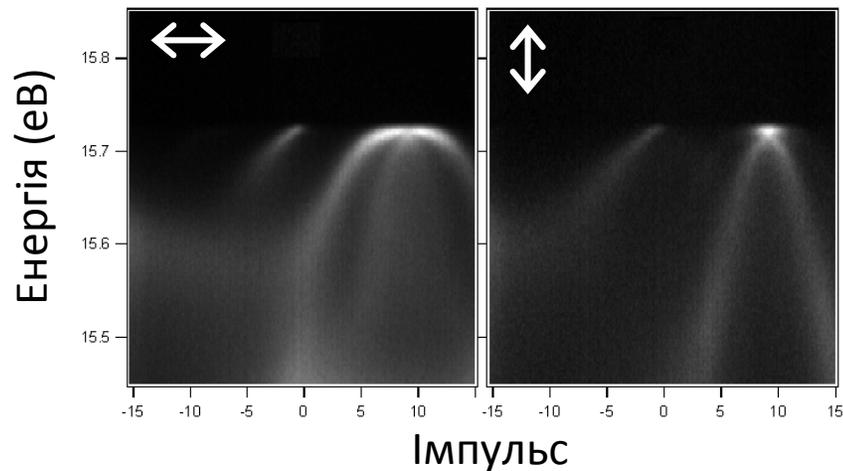
V. Zabolotnyy *Nature* 2009

Fermi surface of LiFeAs



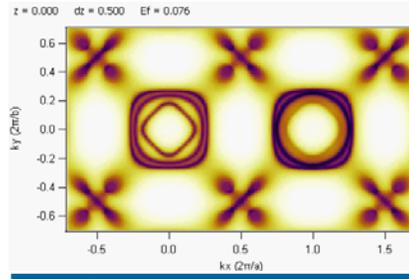
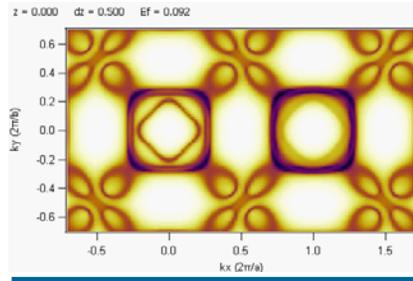
J. Supercond. Nov. Magn. 2012
Low Temp. Phys. 2012

поляризація

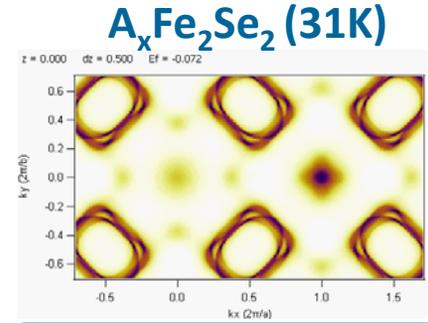


BFA: density of states

Hole doped KFA



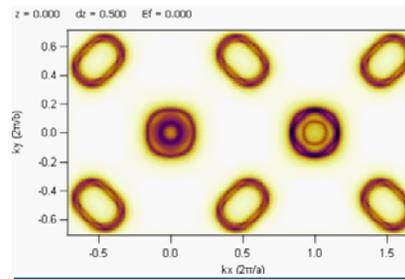
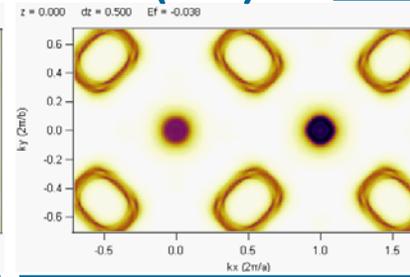
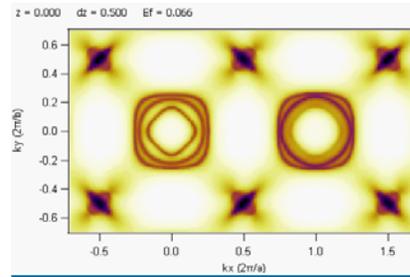
BKFA (38K)



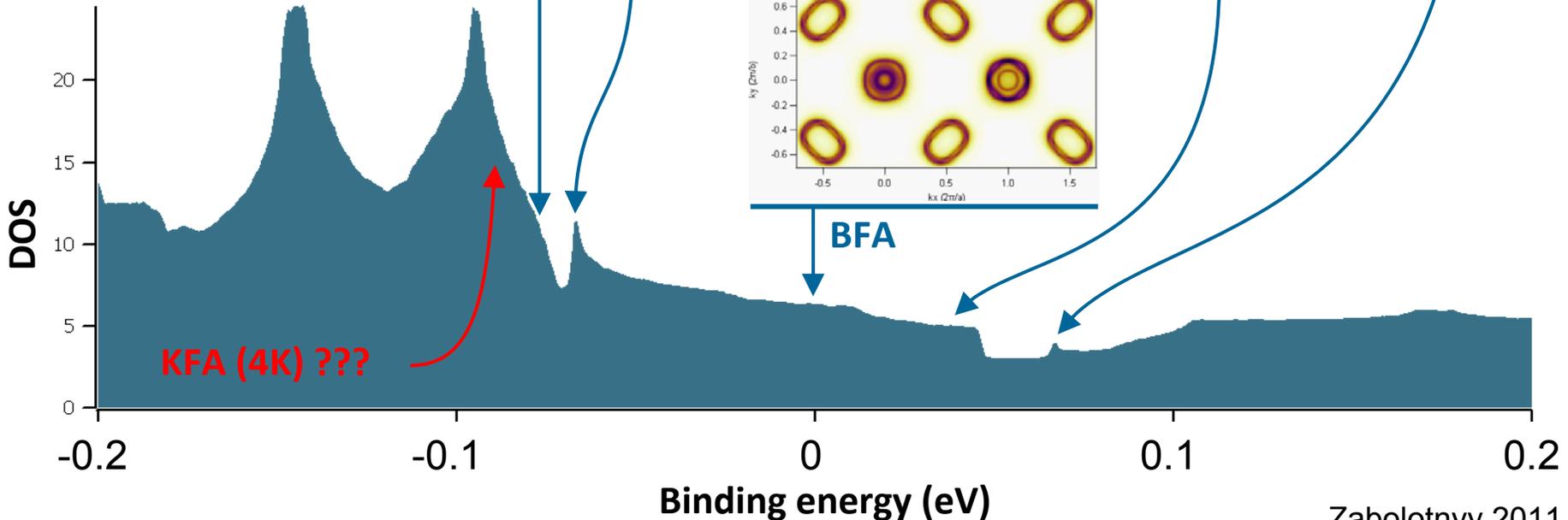
$A_xFe_2Se_2$ (31K)

BFCA (26K)

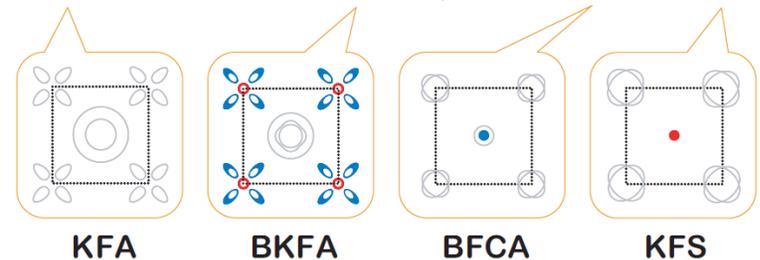
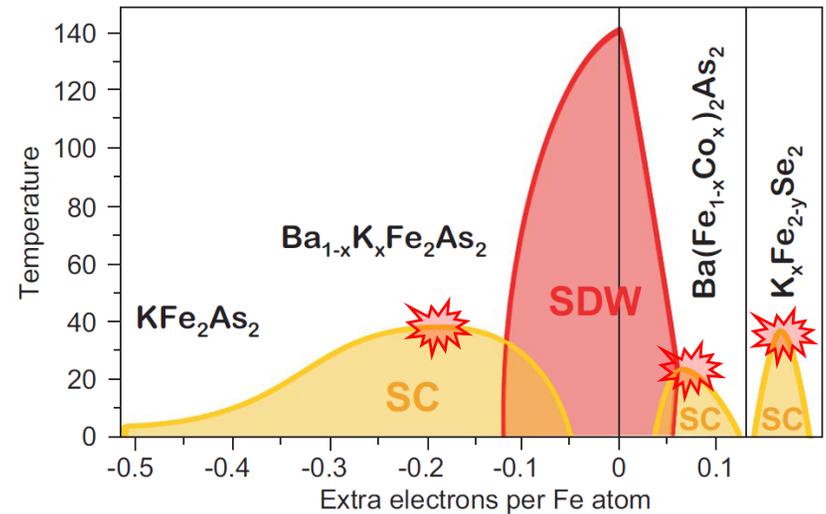
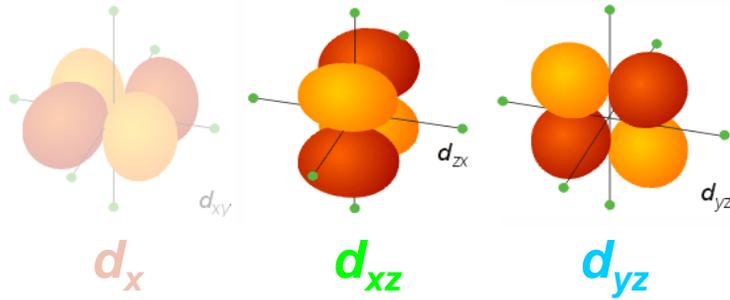
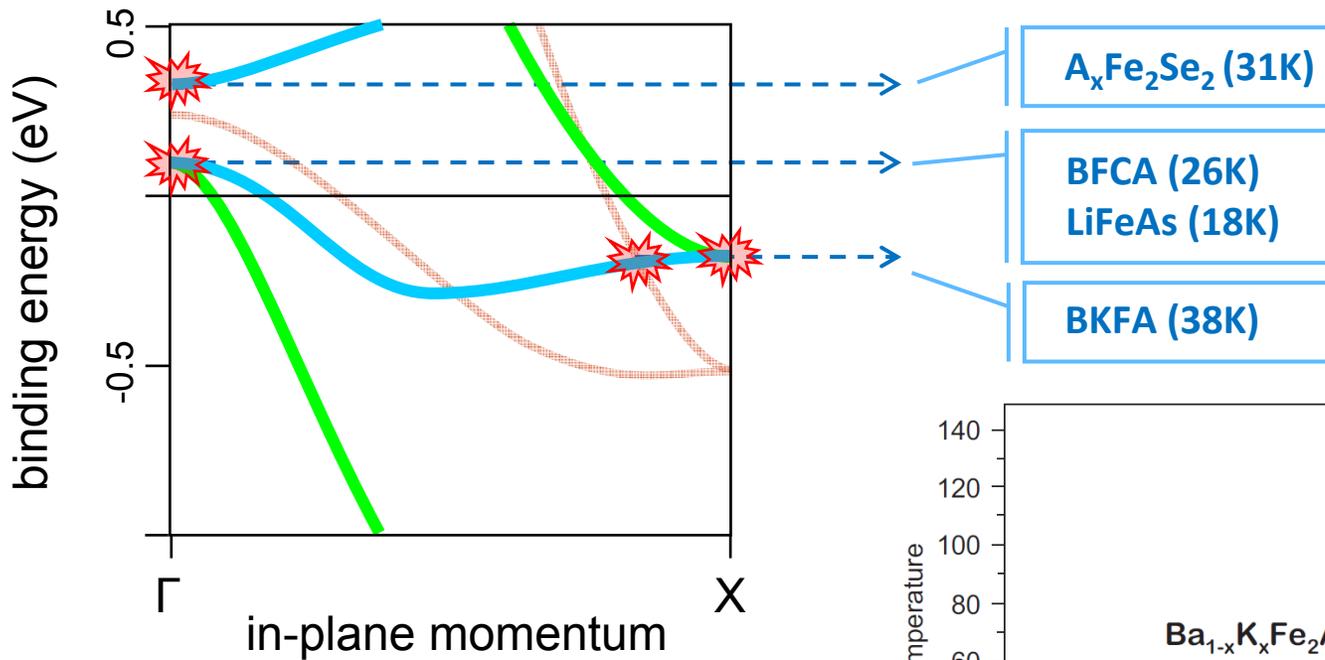
LiFeAs (18K)



BFA



FeSC: electronic structure and superconductivity

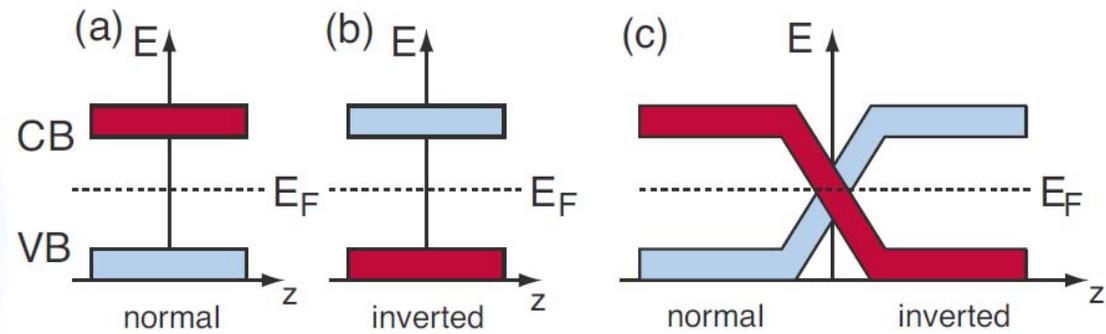


A. A. Kordyuk, *J. Supercond. Nov. Magn.* (2012)

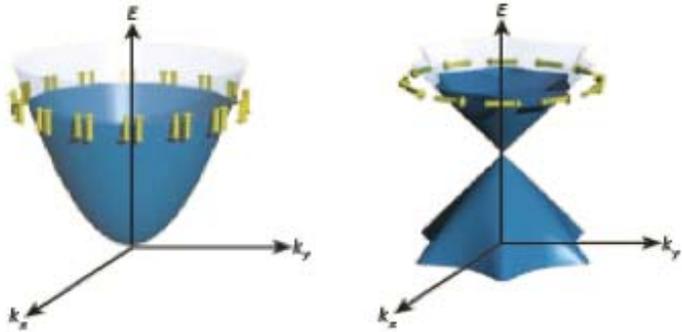
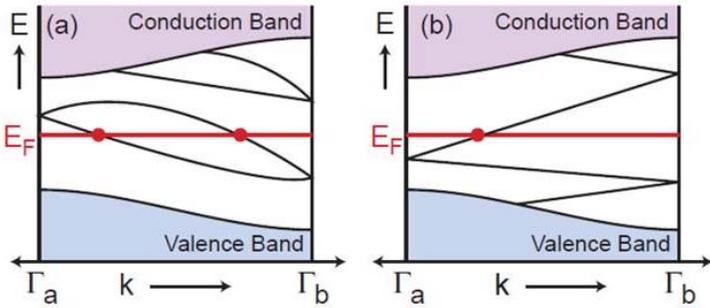
A. A. Kordyuk et al., *Phys. Rev. B* **83**, 134513 (2011)

Topological insulators

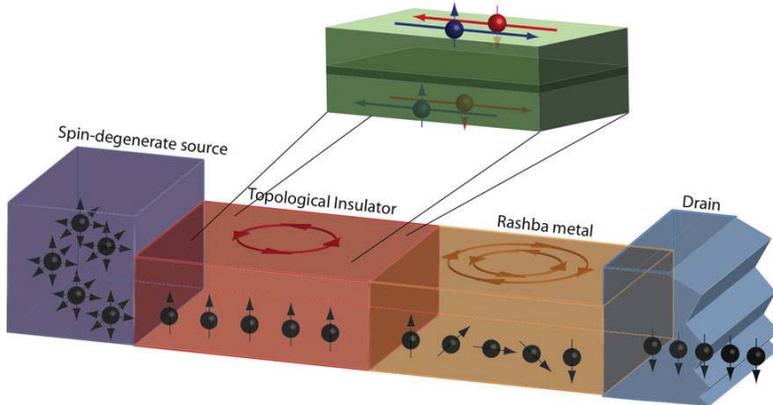
Topological insulators



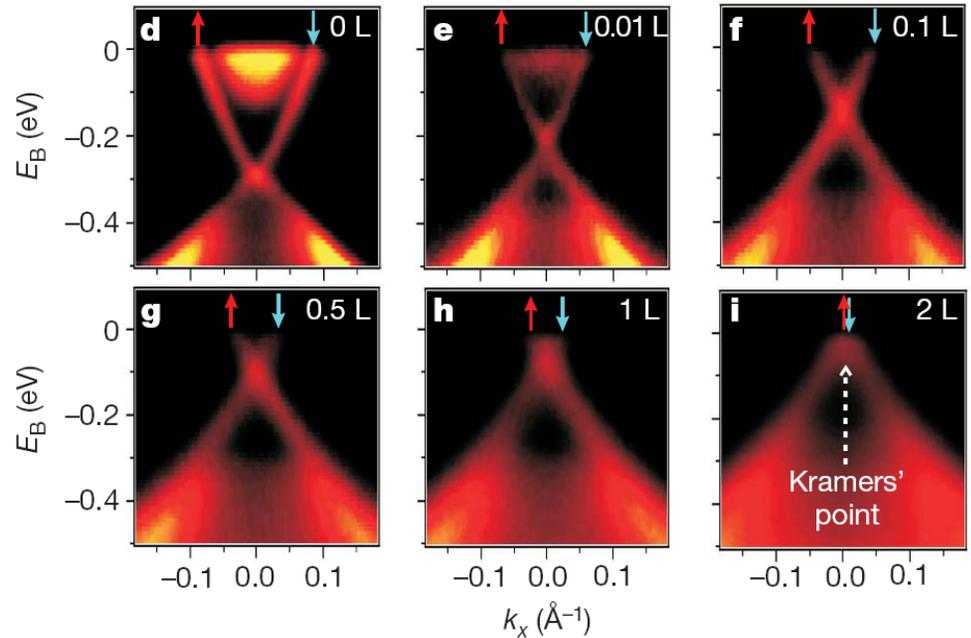
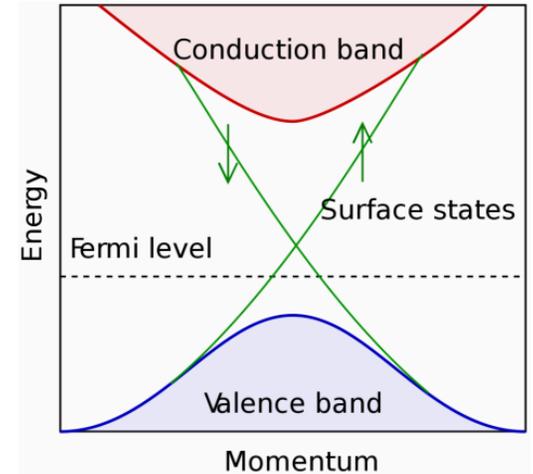
Topological insulators



Franz *Nature* 2009

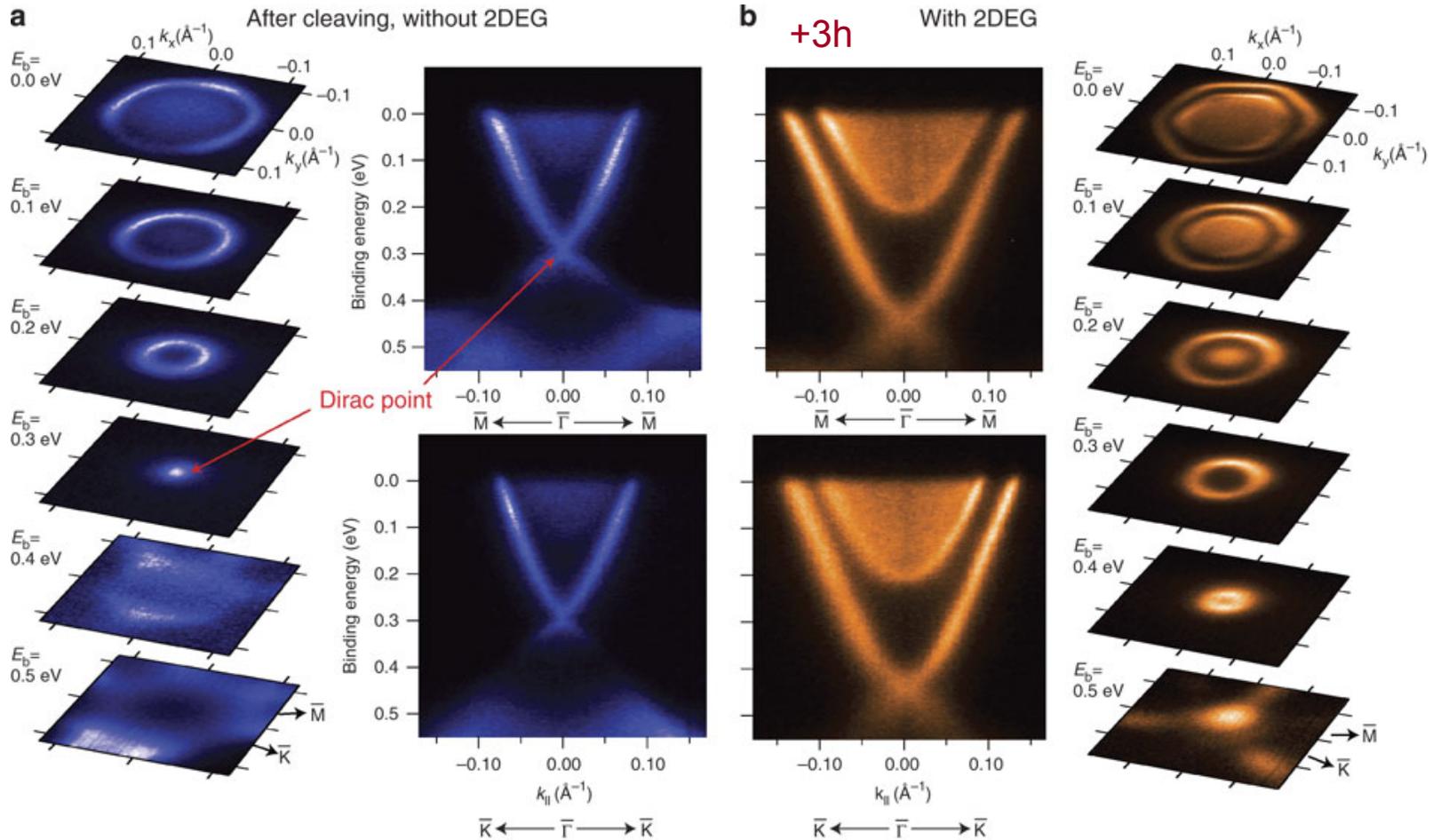


Spin injector: Hugo Dil, PSI, 2010

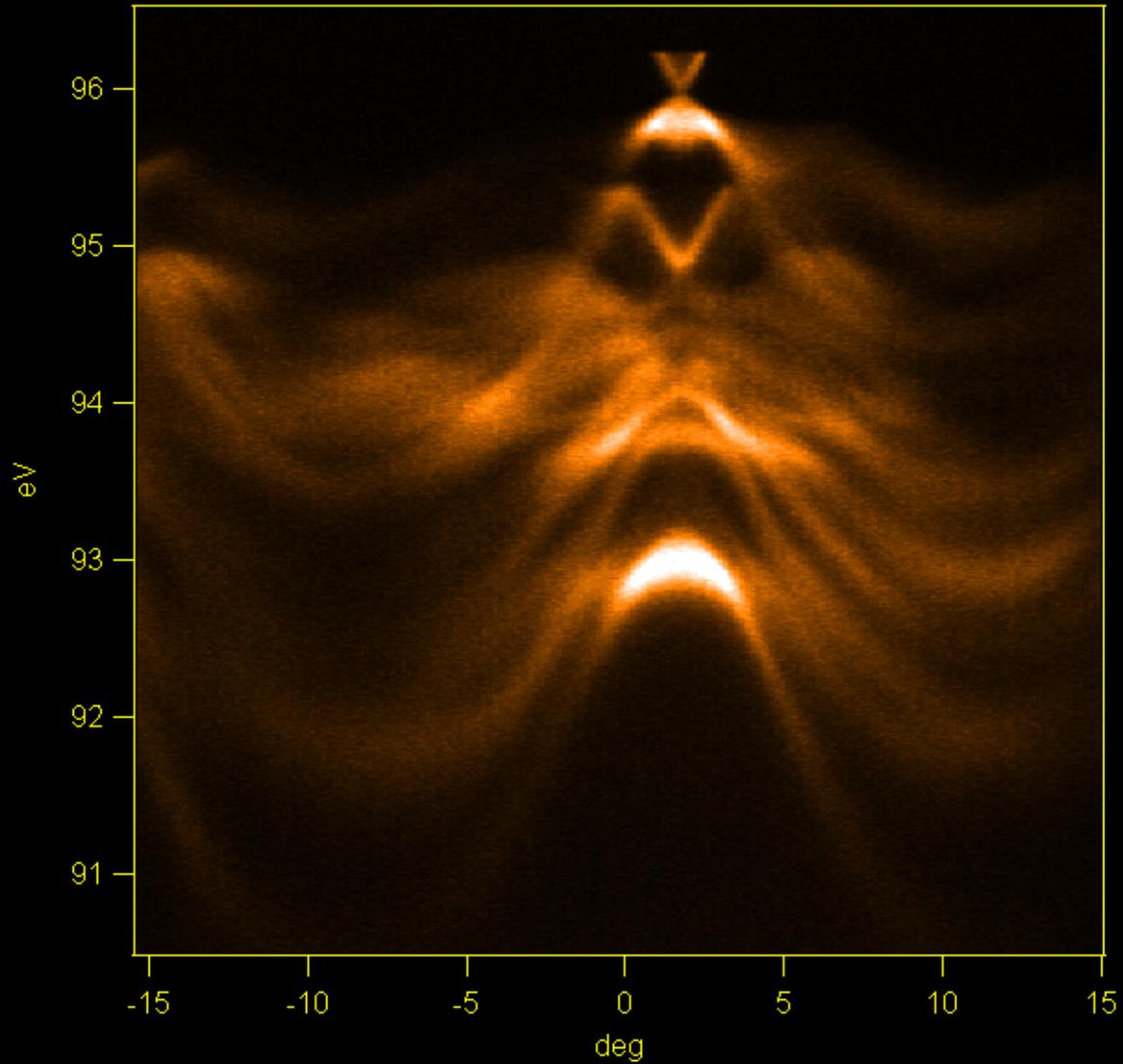


Hsieh *Nature* 2009, Xia *Nature Physics* 2009

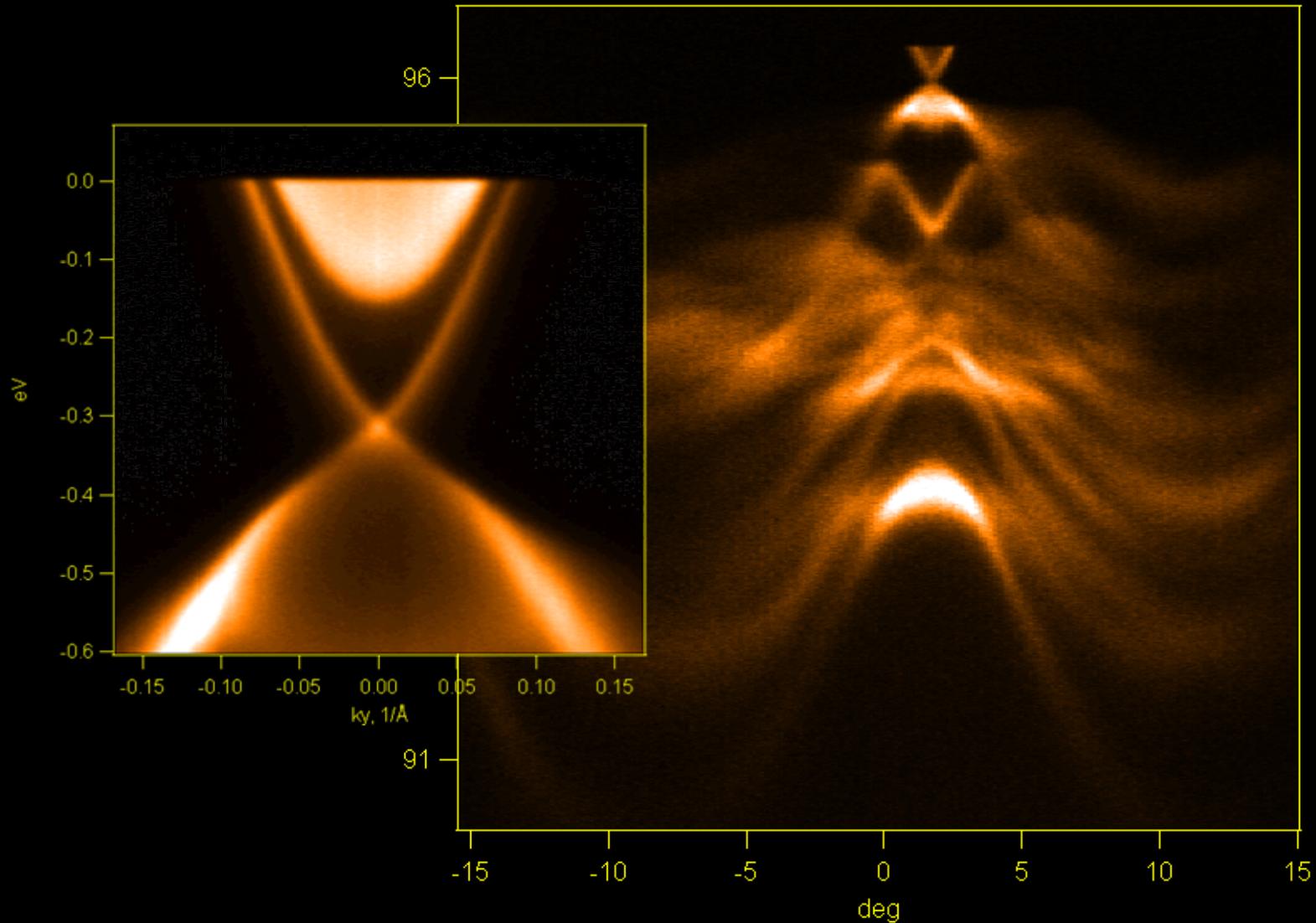
ARPES on Bi_2Se_3



Bi_2Se_3 as seen by ARPES



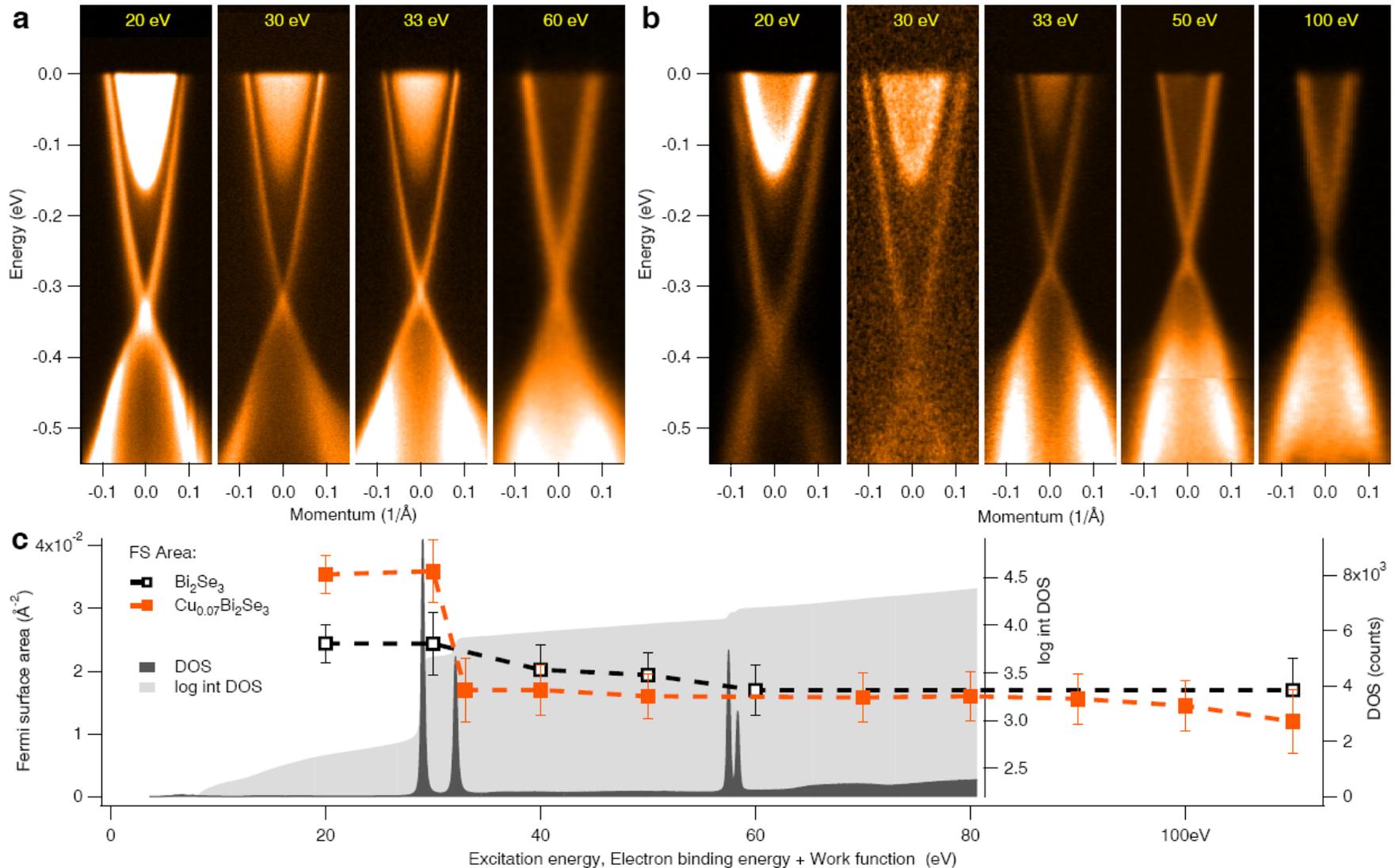
Bi_2Se_3 as seen by ARPES



Photoemission-induced gating of topological insulators

Bi₂Se₃

Cu_xBi₂Se₃



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

Kordyuk *PRB* 2011

Collaboration



IMP

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Alexander Plyushchay
Roman Viznichenko

ARPES, IFW Dresden

Sergey Borisenko
Volodymyr Zabolotny
Daniil Evtushinsky

Timur Kim

Dmytro Inosov

Andreas Koitzsch

Jörg Fink ...

ARPES Worldwide

Mark Golden (UvA)

Toni Valla (BNL)

...

Neutron Scattering

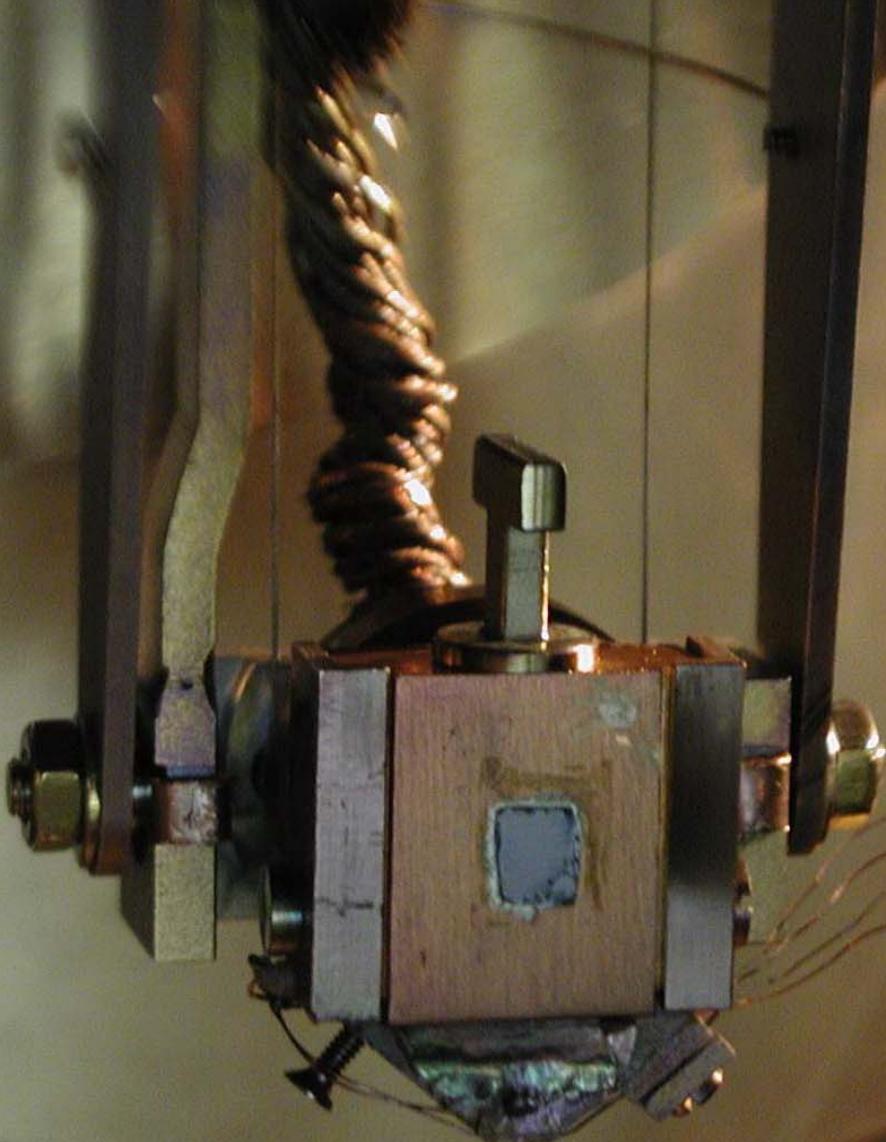
Vladimir Hinkov
Bernhard Keimer
Dmytro Inosov

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)

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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



Thanks!

