



**Training &
Experience Hub
Berlin**

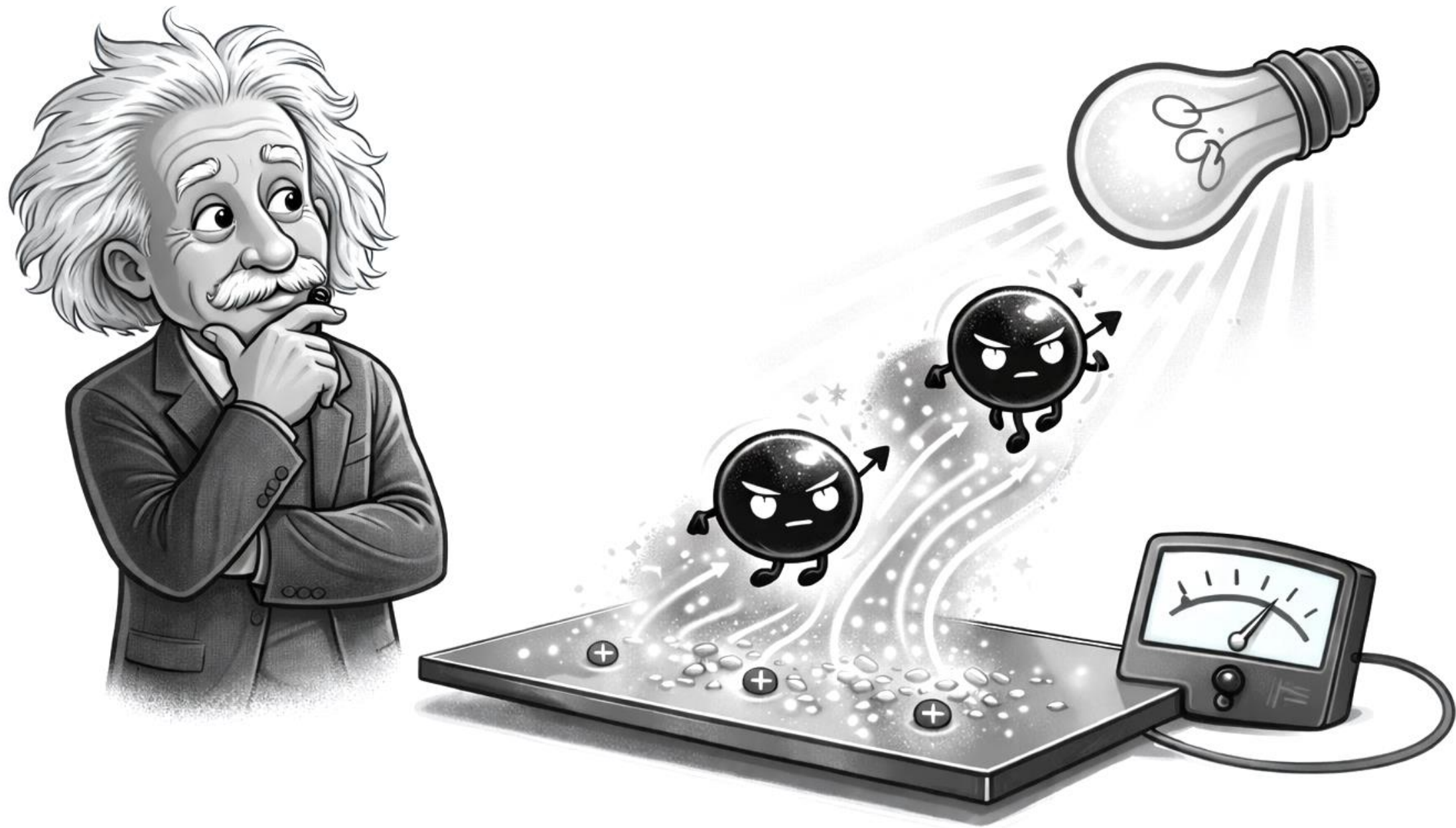
Quantum Materials: from ARPES to trARPES



16/09/2026
online

Fundamentals of ARPES: mapping the electronic band structure of solids

Alexander Kordyuk
Kyiv Academic University



Photoelectric Effect

Hertz 1887

- Photo-electric current from polished metals
- Threshold: only for $\nu > \nu_0$, that depends on metal, surface...
- Photocurrent $\sim$ light intensity
- Energy of photoelectron does not depend on intensity

Einstein 1905

- Light comes in “quanta”: $E = h\nu$
- Prediction: $E_K = \frac{1}{2}mv^2 = h\nu - \phi$

Millikan 1915

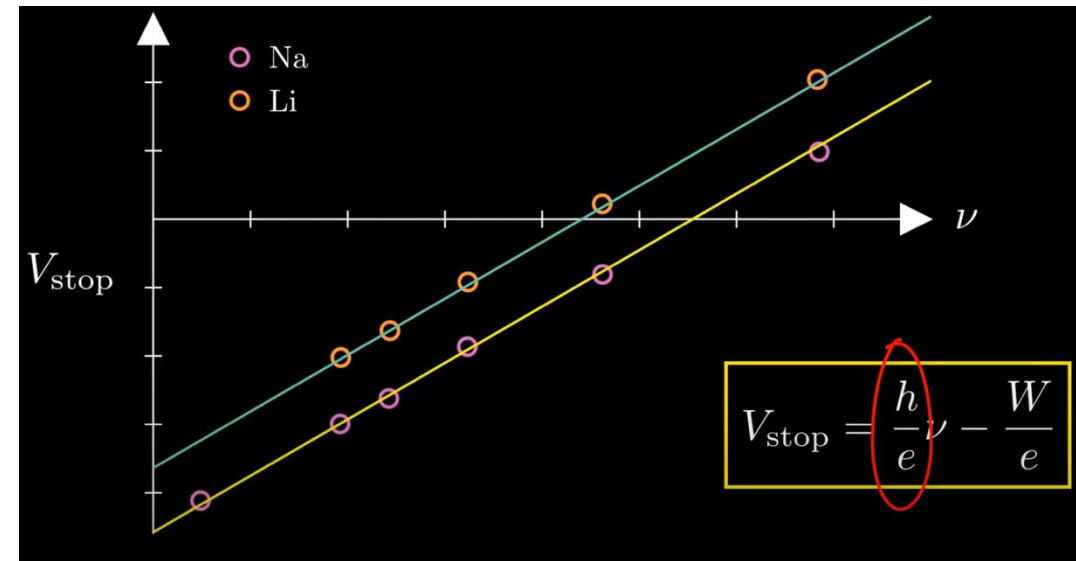
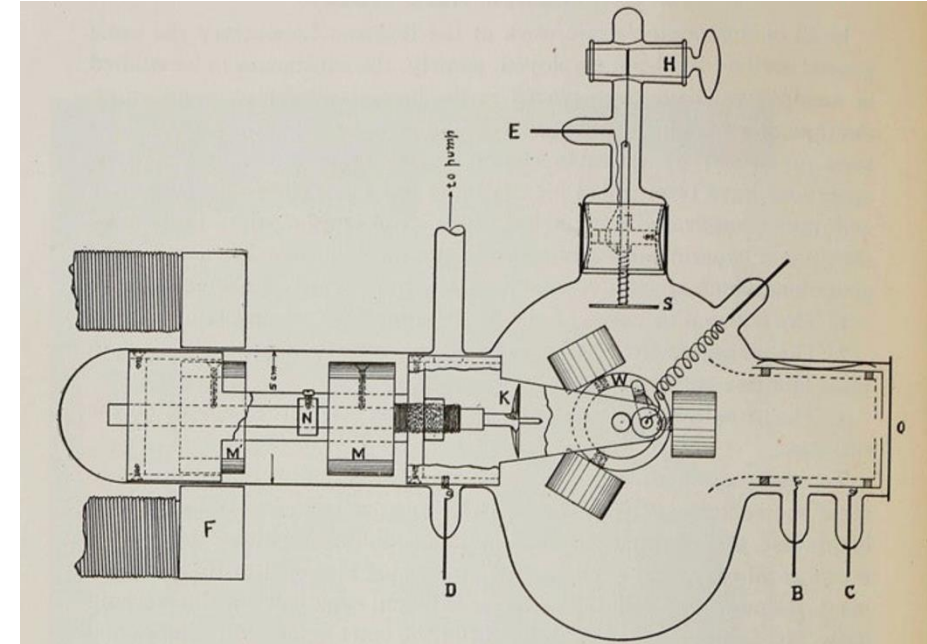
- Confirmed and measured h with 1% accuracy.

MIT OpenCourseWare: The photoelectric effect

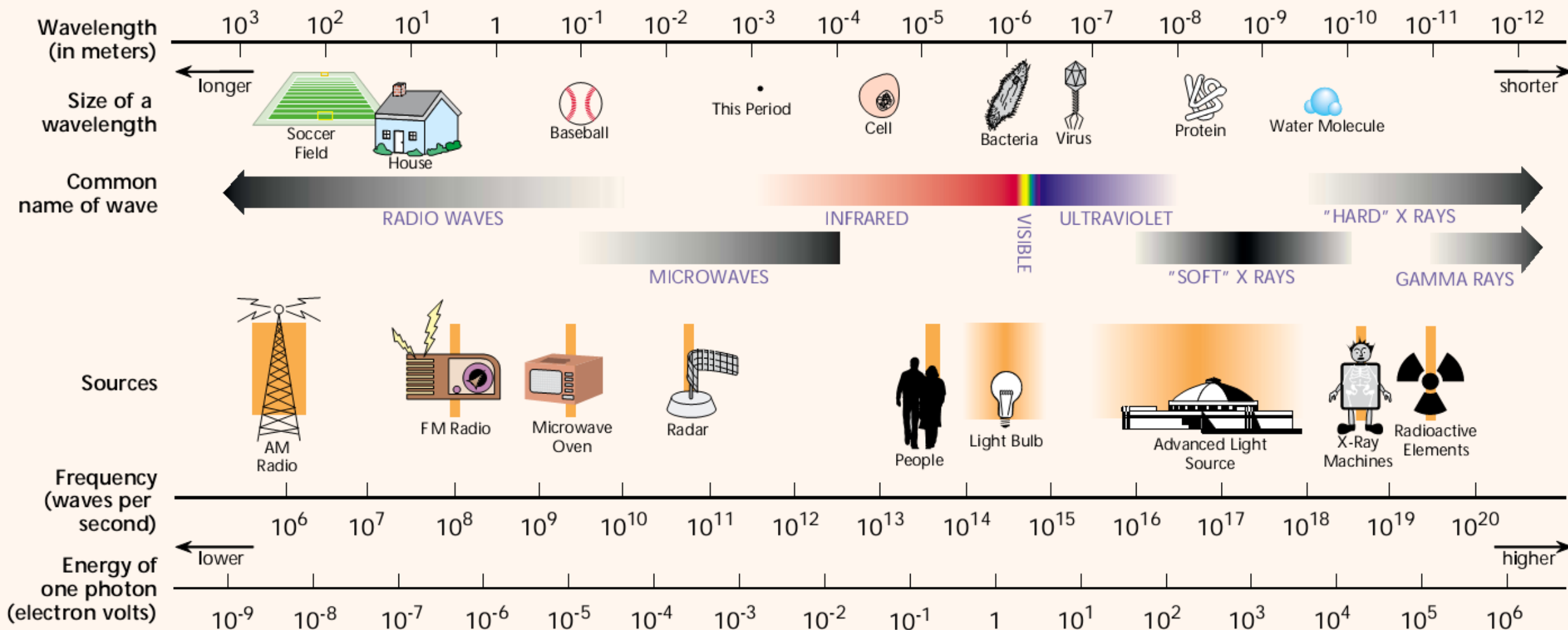
<https://youtu.be/byEaU9ILHmw>

Dr. Jorge S. Diaz: Millikan tests Einstein's Light Theory

<https://youtu.be/fQzirkXOxk>



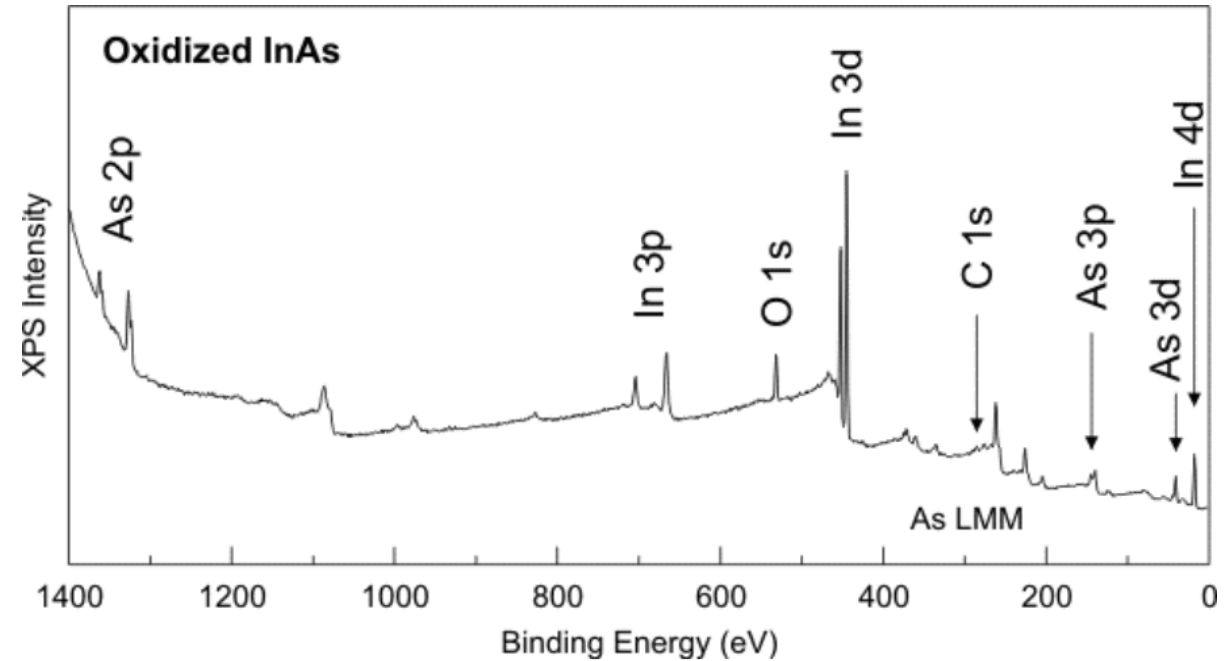
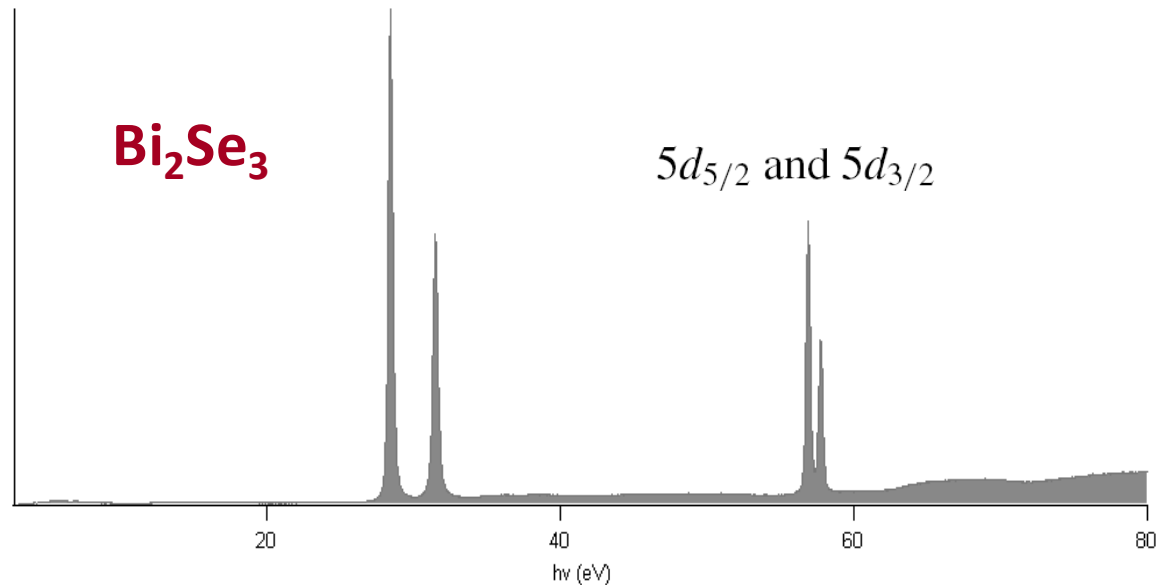
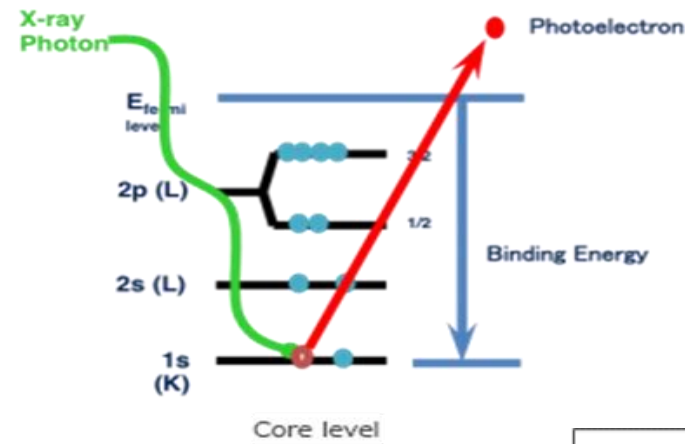
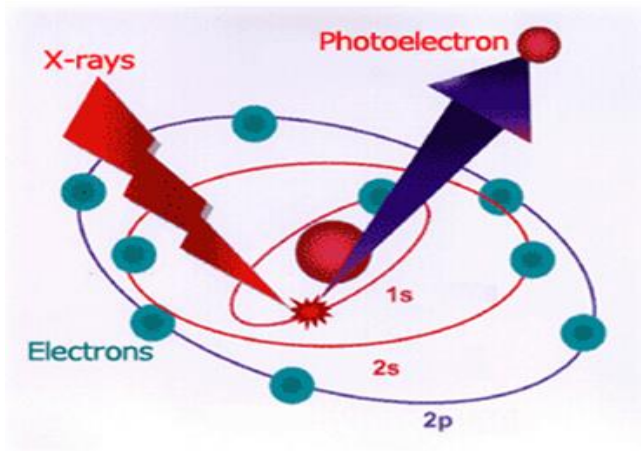
THE ELECTROMAGNETIC SPECTRUM



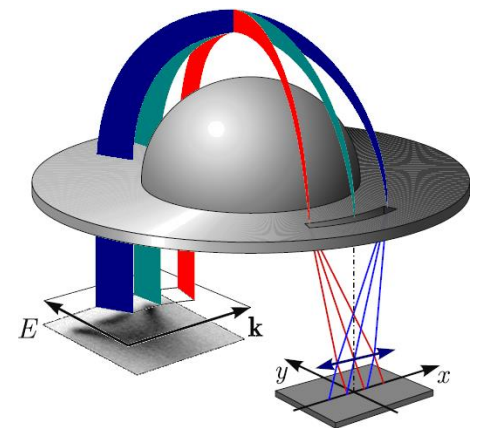
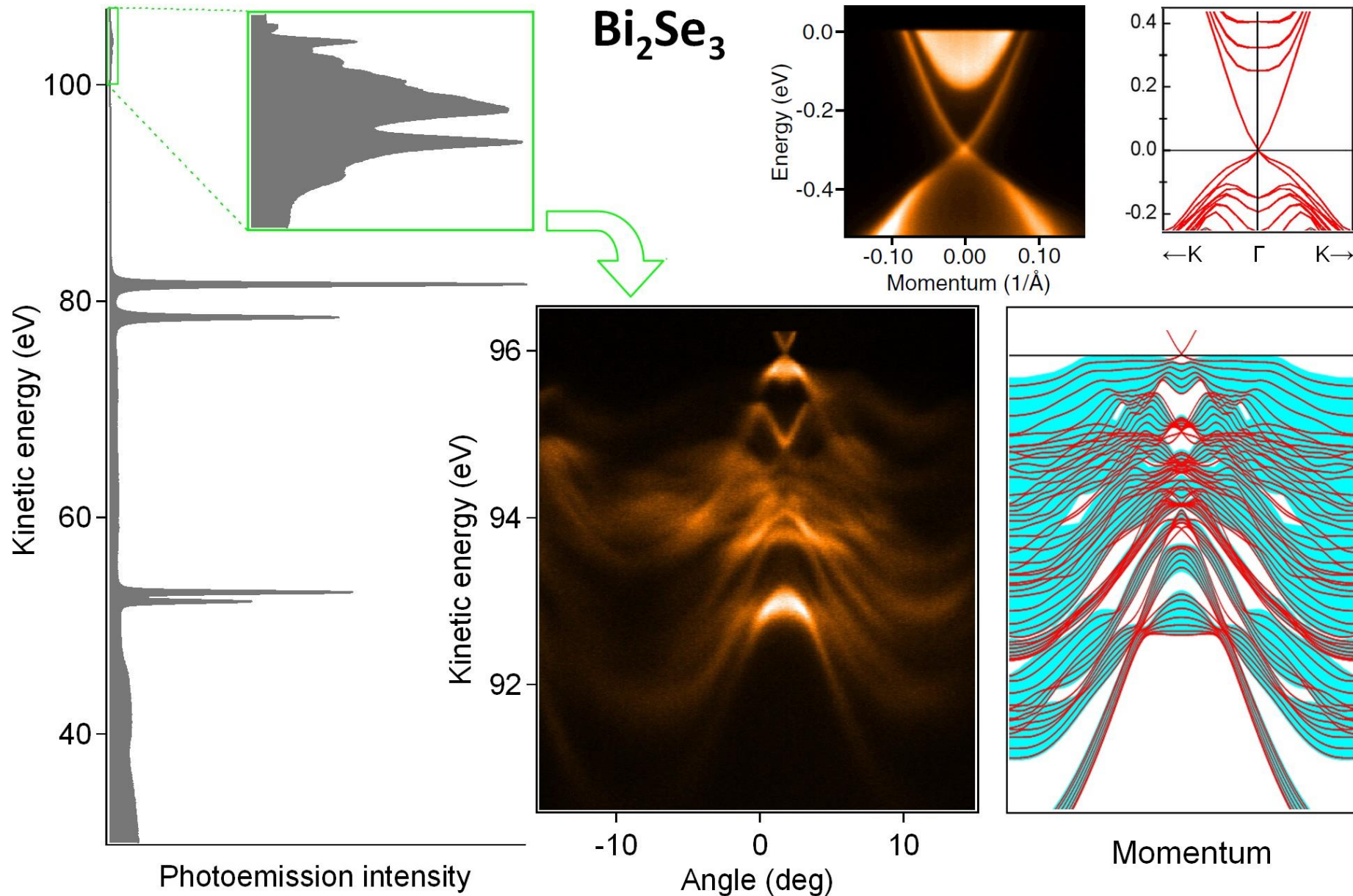
© 1996, Regents, University of California • Prepared by the Advanced Light Source, Lawrence Berkeley National Laboratory • For more information, contact Jane Cross (510) 486-4362 • ALS Web page: <http://www-als.lbl.gov/>

Source: Lawrence Berkeley National Laboratory <https://electromagneticworld.blogspot.com/2017/04/electromagnetic-spectrum.html>

XPS: X-ray Photoelectron Spectroscopy – Density of States (DOS)



ARPES – natural extension of the Photoelectric Effect



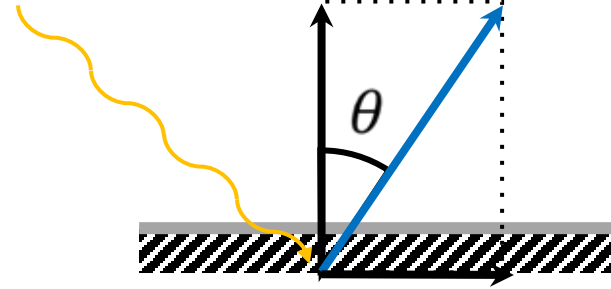
ARPES: Angle Resolved Photoemission Spectroscopy

$$h\nu = \phi + E_B + E_K$$

$$E_K = \frac{p^2}{2m}$$

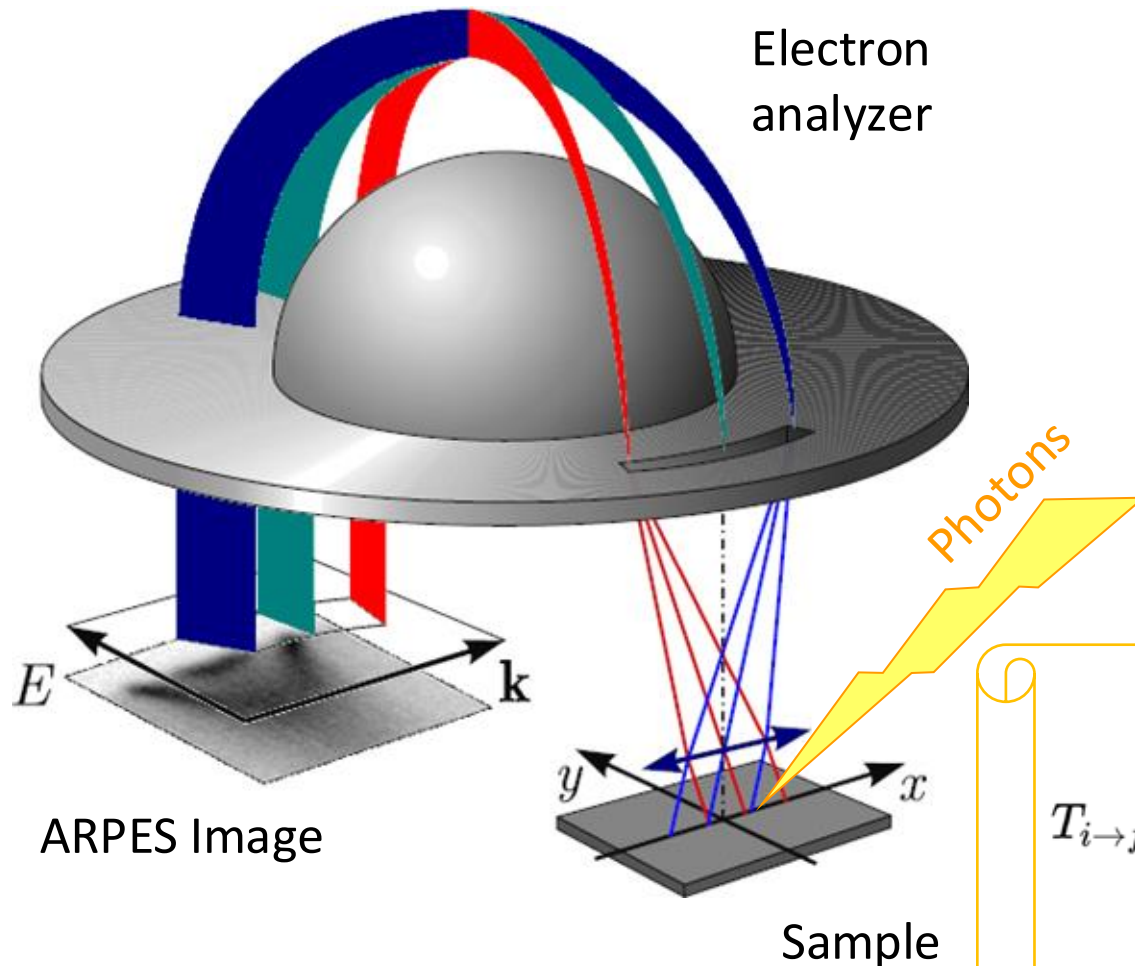
$$p = \sqrt{2mE_K}$$

Electron
analyzer



$$p_{||} = p \sin \theta$$

$$\mathbf{p}_{||} = \hbar \mathbf{k}_{||} + \hbar \mathbf{G}$$



ARPES Image

Sample

Fermi's golden rule

$$T_{i \rightarrow f} = \frac{2\pi}{\hbar} |\langle i | \hat{V} | f \rangle|^2 \delta(E_f - E_i \pm \hbar\omega)$$

Three step model

Fermi's golden rule

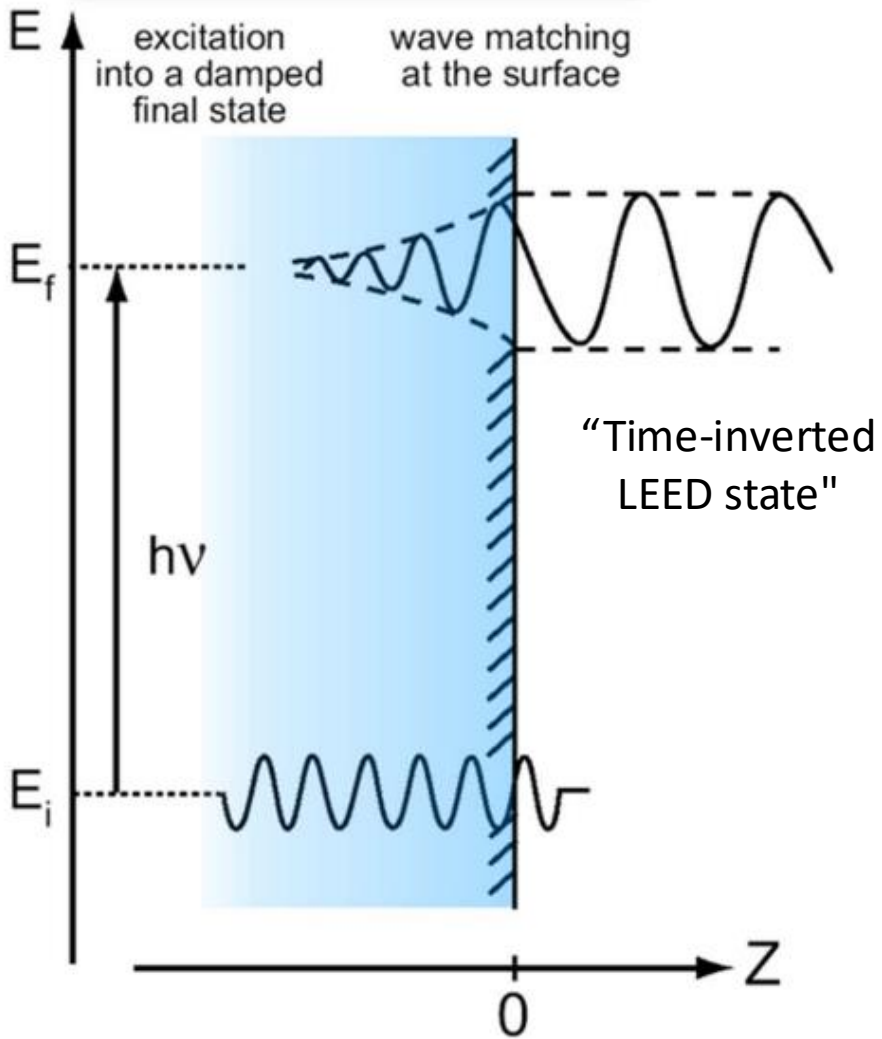
perturbation

$$\Gamma_{i \rightarrow f} = \frac{2\pi}{\hbar} |\langle f | H' | i \rangle|^2 \rho(E_f)$$

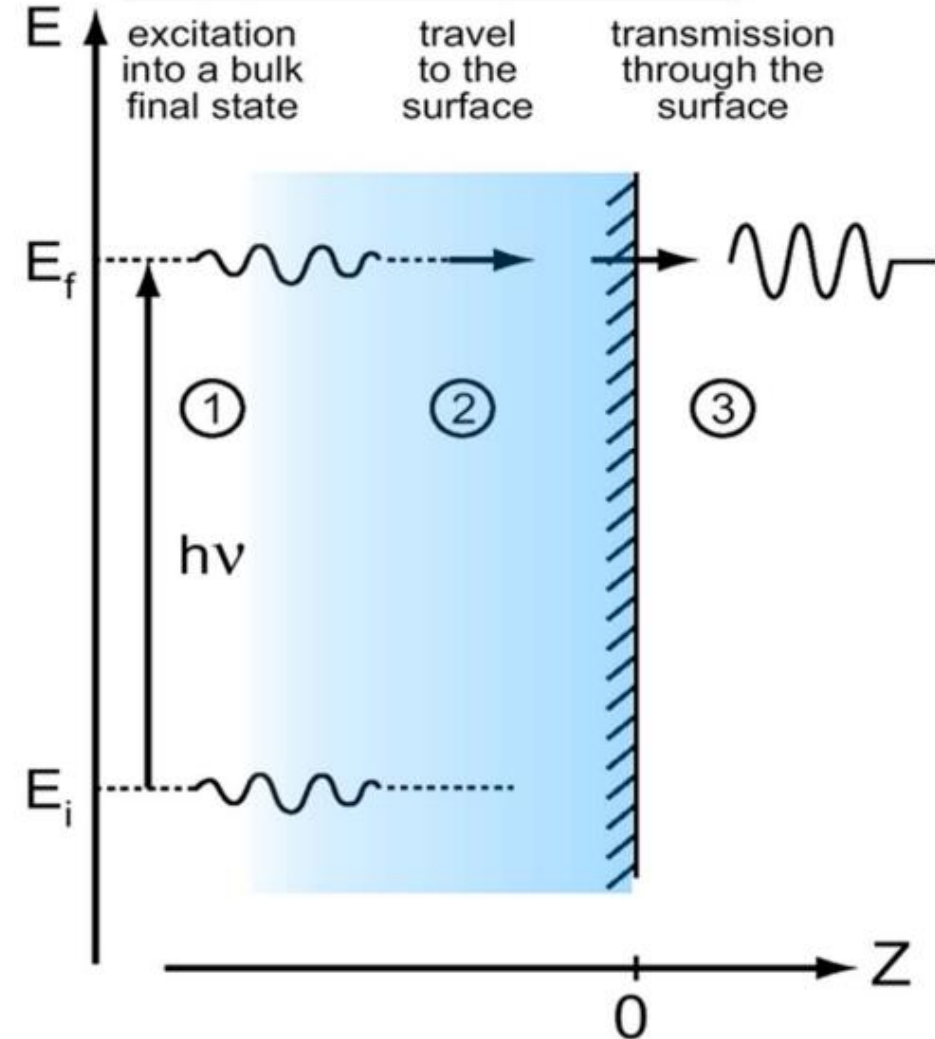
matrix element

density of states

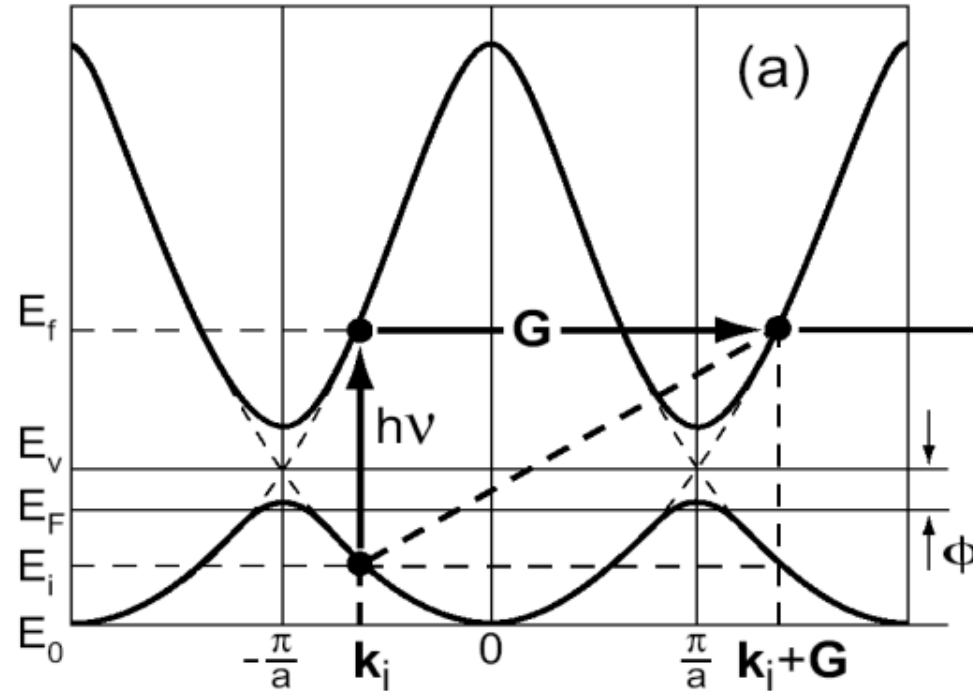
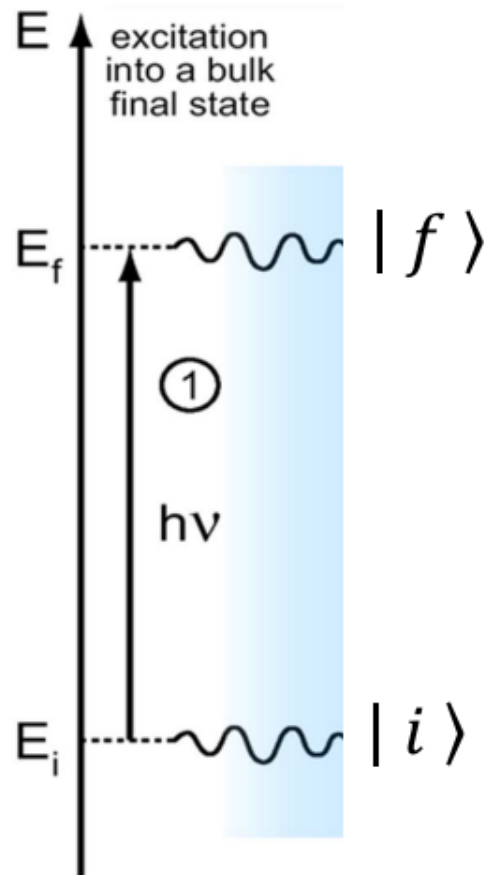
One-step model



Three-step model



$$w_{i \rightarrow f} = \frac{2\pi}{\hbar} |\langle f | \vec{A} \cdot \hat{\vec{p}} | i \rangle|^2 \delta(E_f - E_i - \hbar\omega)$$



momentum conservation:

$$\vec{k}_f = \vec{k}_i + \vec{G} + \vec{k}_{\text{photon}}$$

only "vertical"
transitions

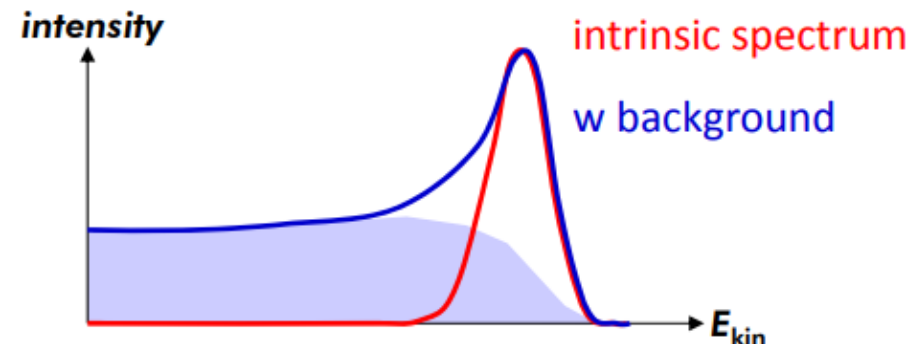
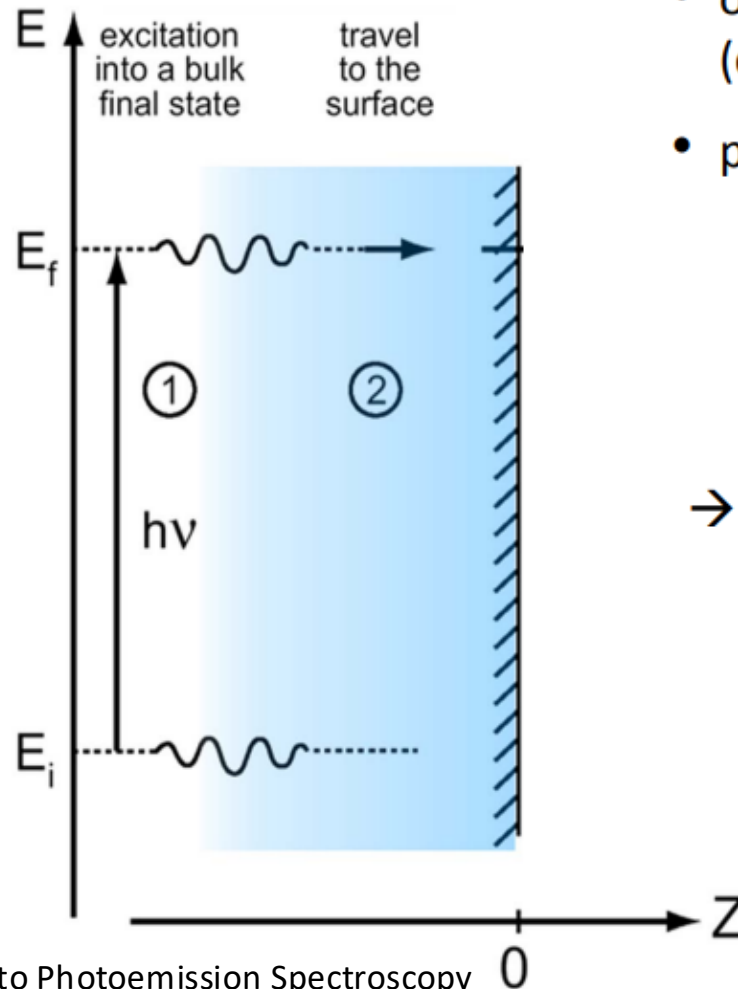
for VUV excitation

inelastic scattering of the photoelectron with

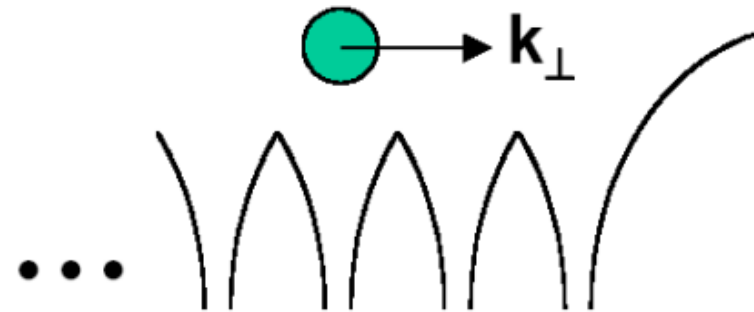
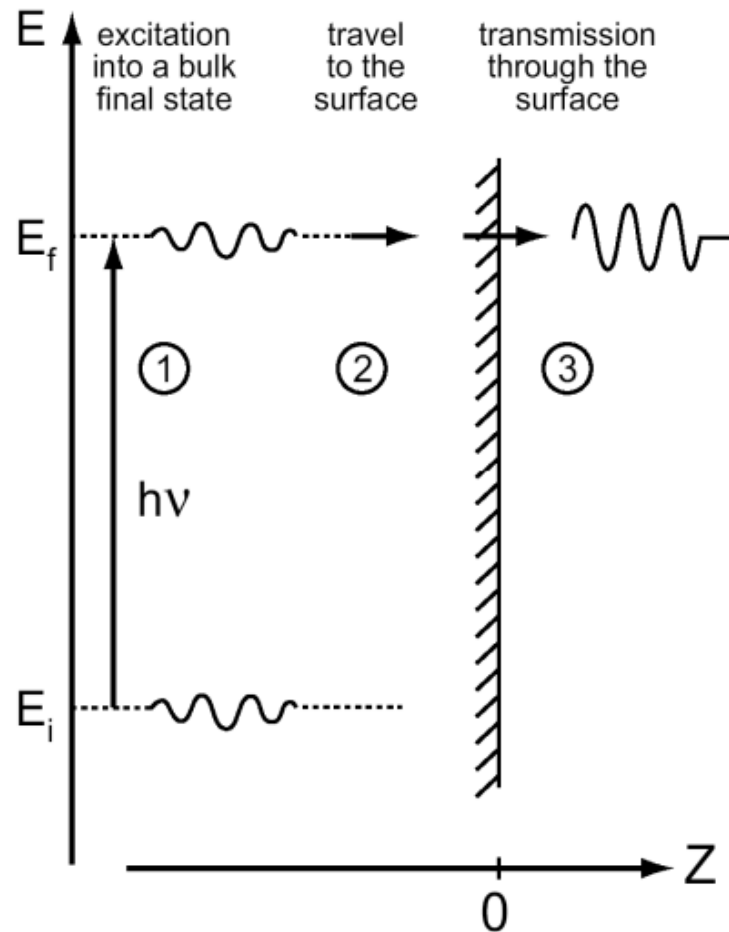
- other electrons
(excitation of e-h-pairs, plasmons)
- phonons



→ generation of secondary electrons
"inelastic background"

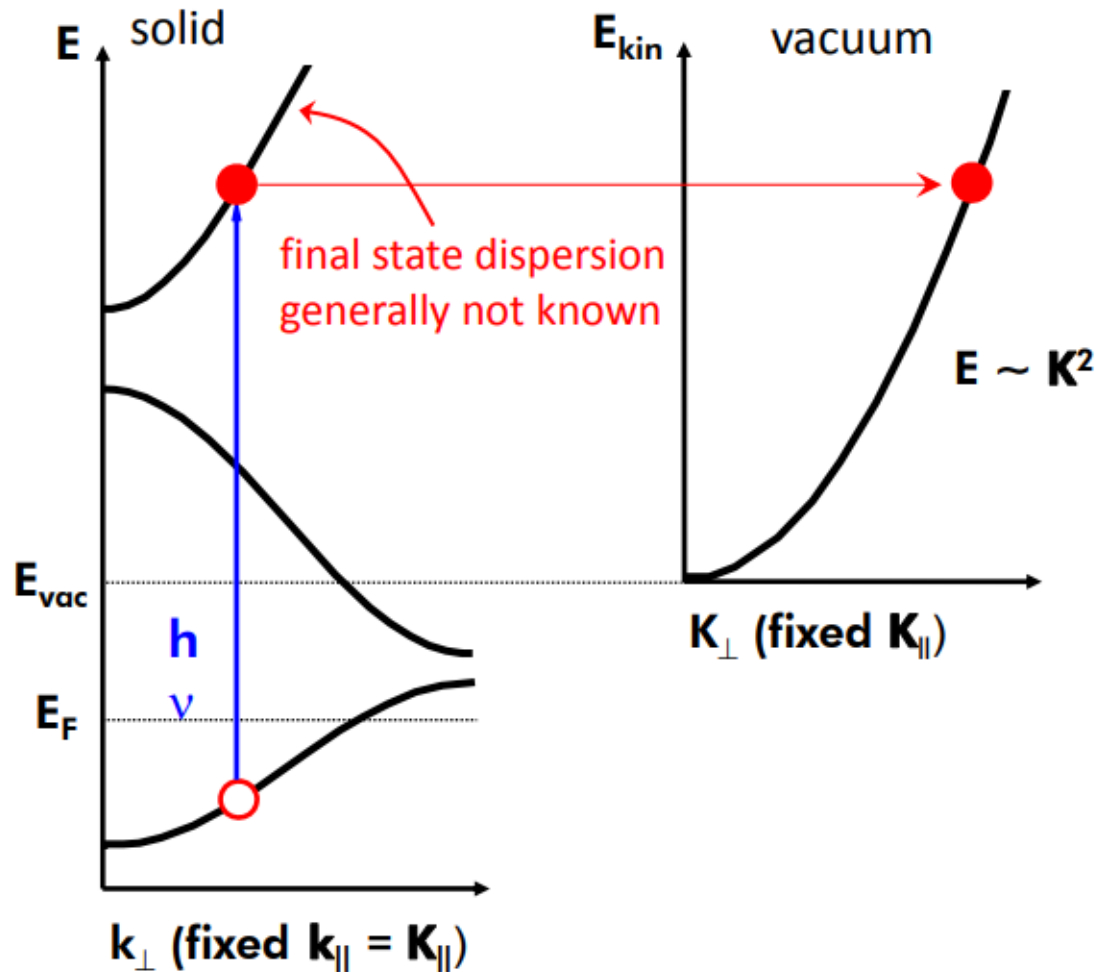


- conservation of wavevector component parallel to surface, $\vec{k}_{\parallel}$
- **But:** change of $k_{\perp}$ changes due to **electron diffraction at surface barrier**

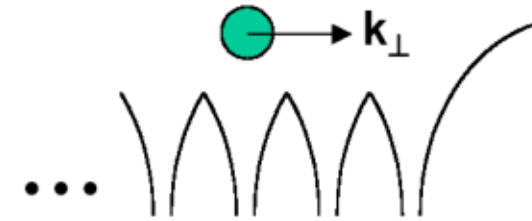


source: E. Rotenberg

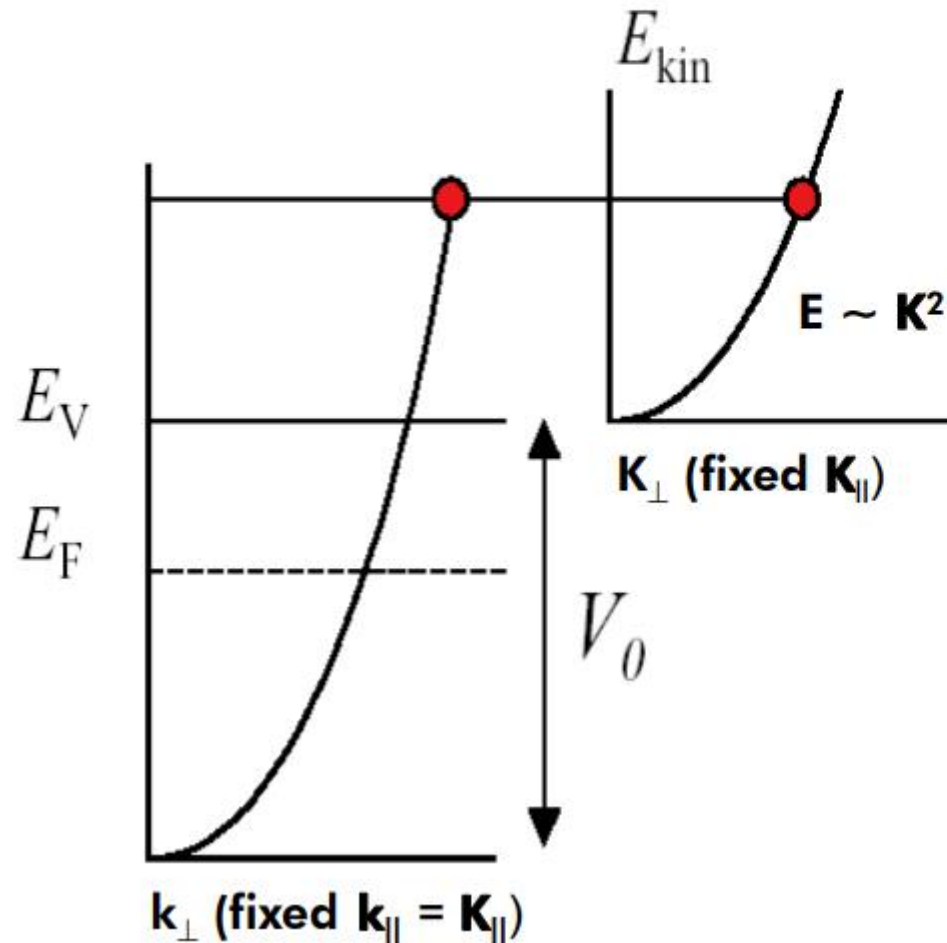
electron wave matching at the surface



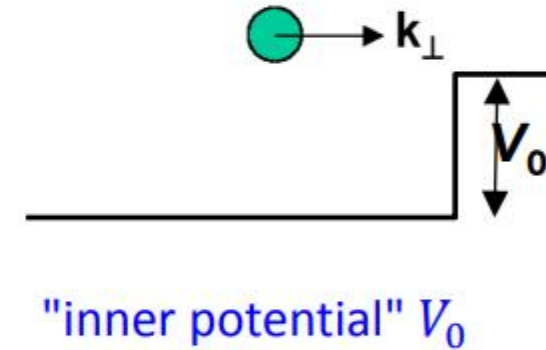
surface potential step



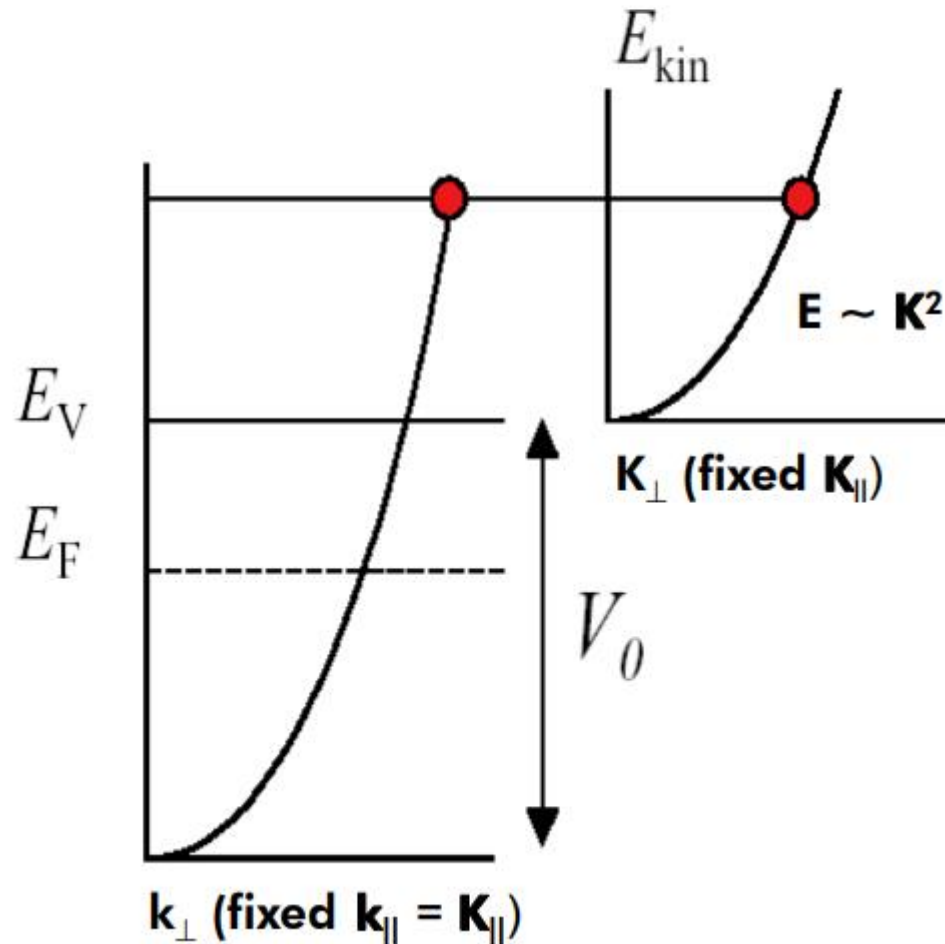
pragmatic solution: free-electron final state model



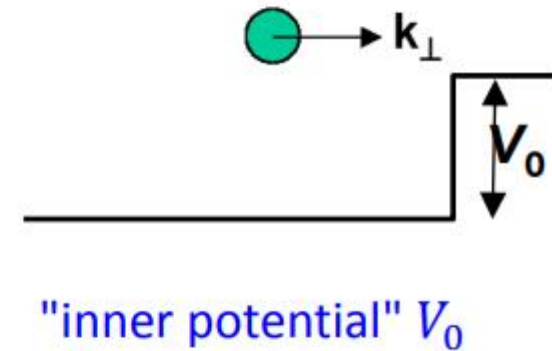
surface potential step



pragmatic solution: free-electron final state model

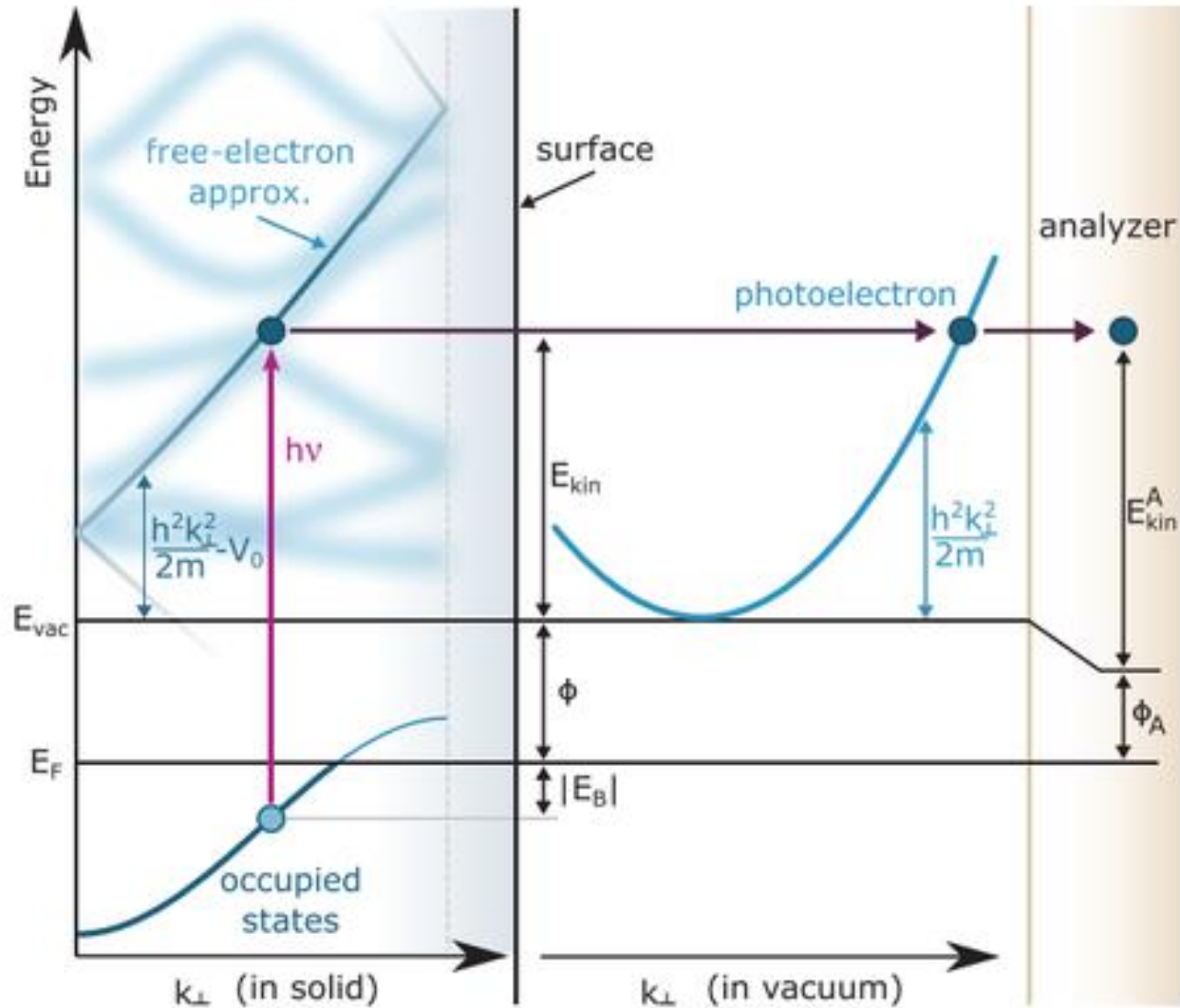


surface potential step

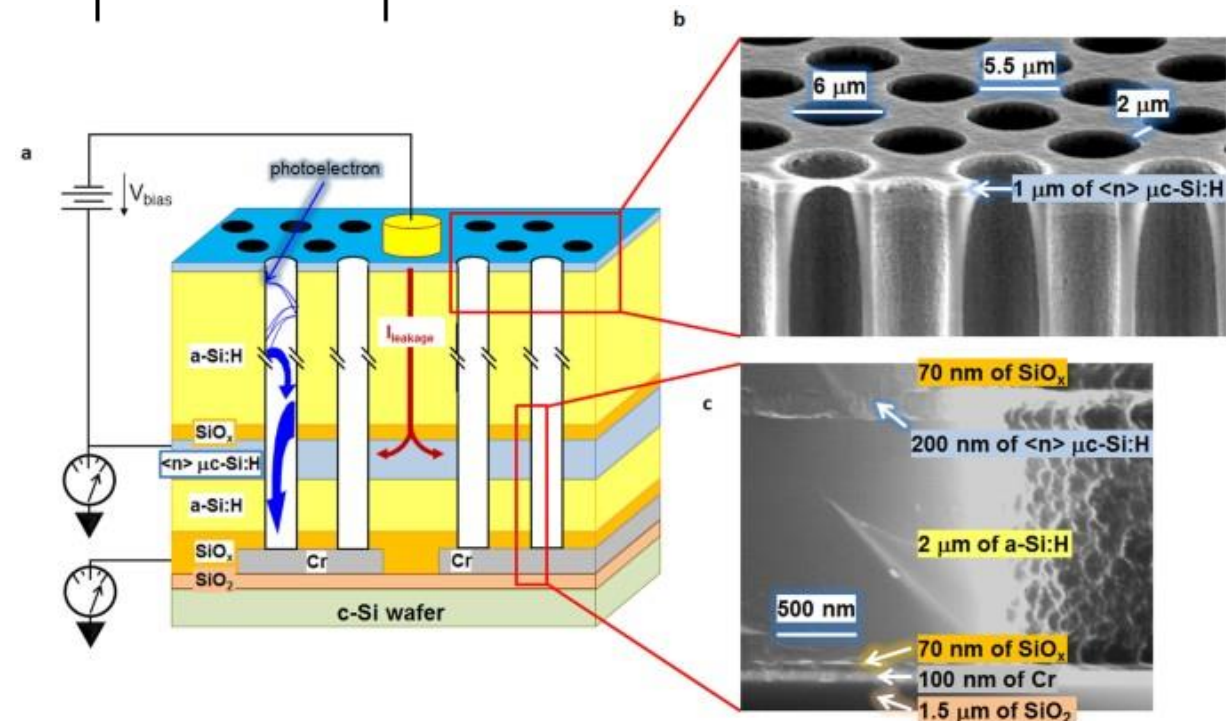
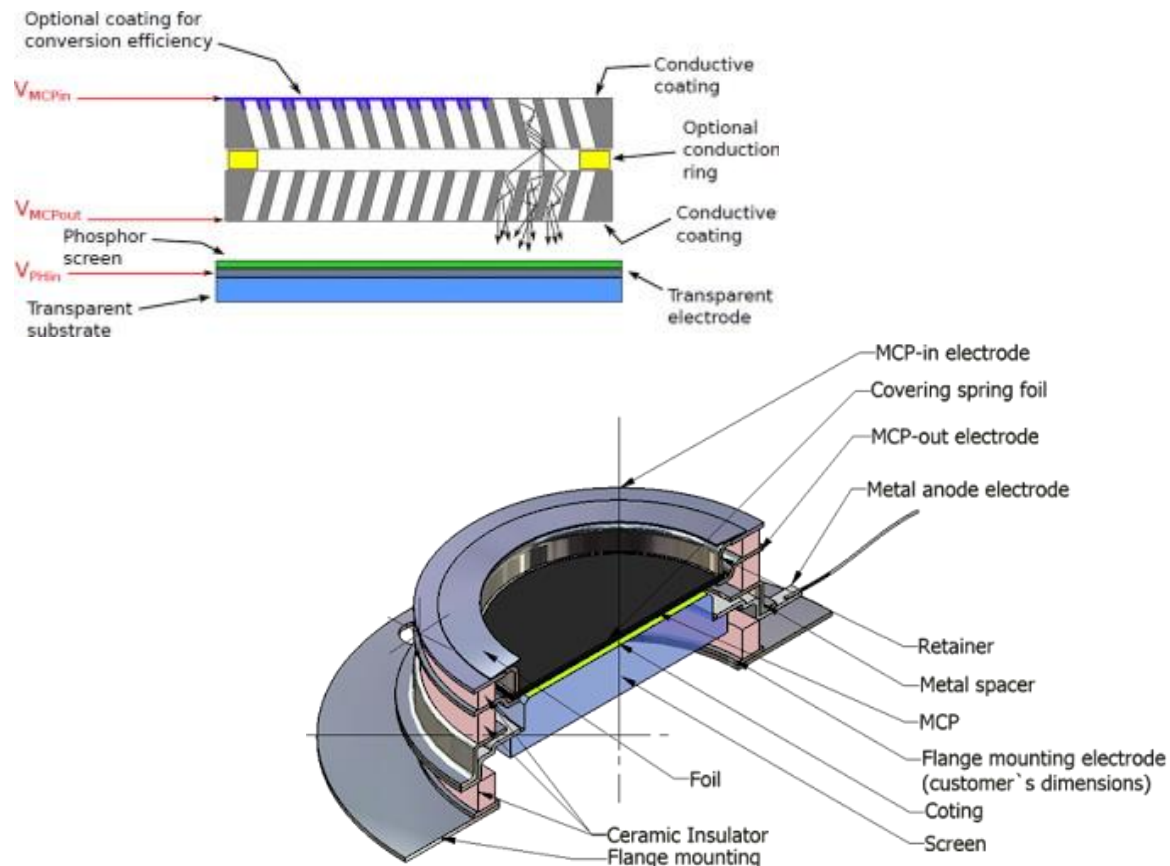
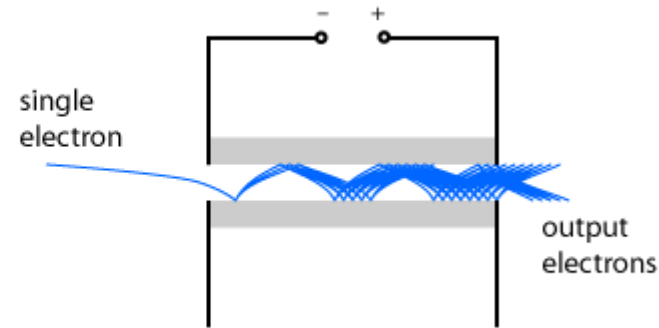
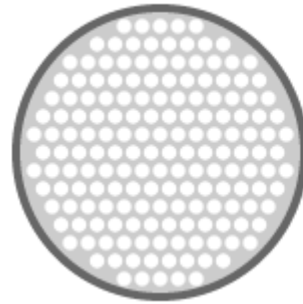
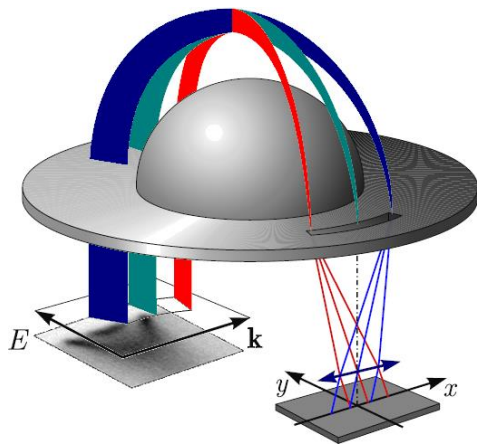


Kinematics of the photoemission process

Stanford | Shen Laboratory



ARPES: Microchannel plate detector



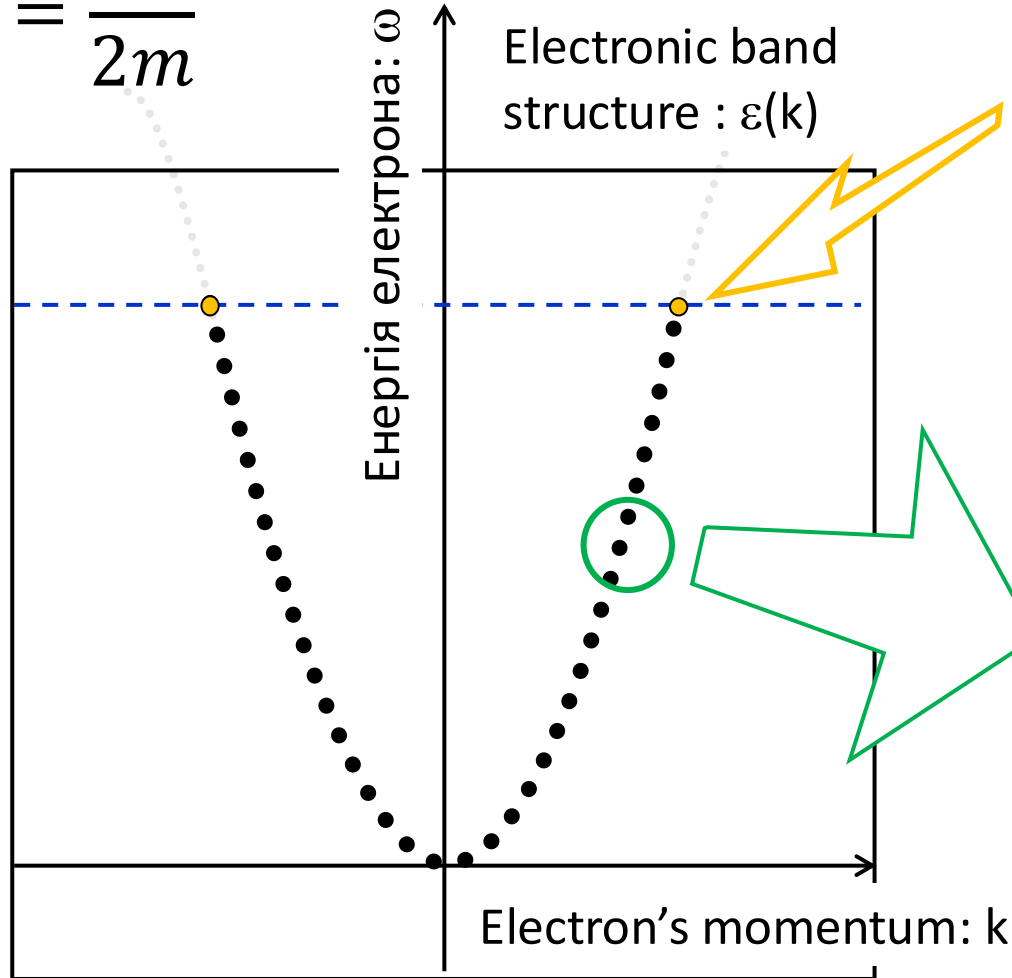
Monolithically integrated microchannel plates based on amorphous silicon
Sci Rep 4, 4597 (2014) <https://doi.org/10.1038/srep04597>

Electronic structure under the ARPES microscope:
electron states are quantized

(Heisenberg and Pauli)

$$E_k = \frac{mv^2}{2} = \frac{p^2}{2m}$$

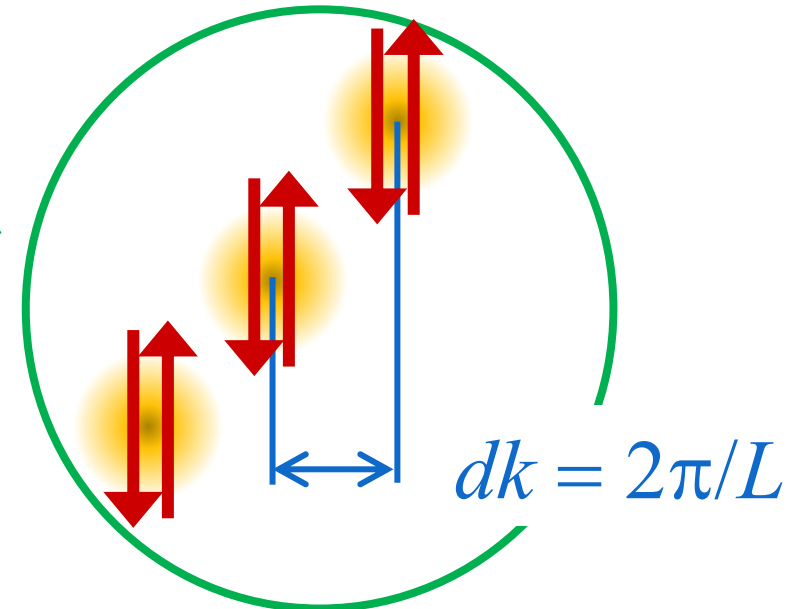
$$p = \hbar k$$



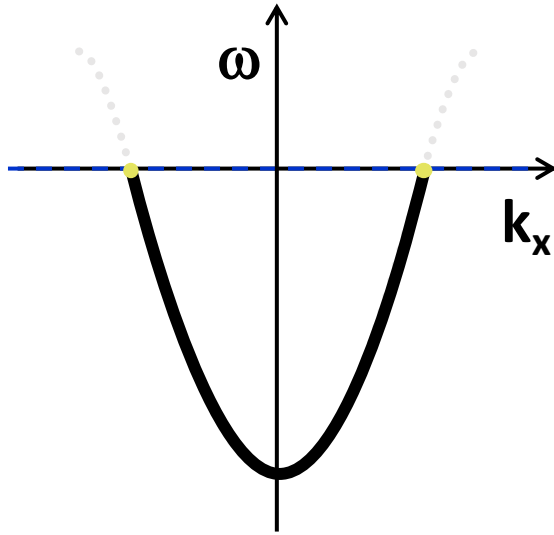
Fermi surface

$$\overbrace{\hspace{10em}}^{\hspace{10em}} L$$

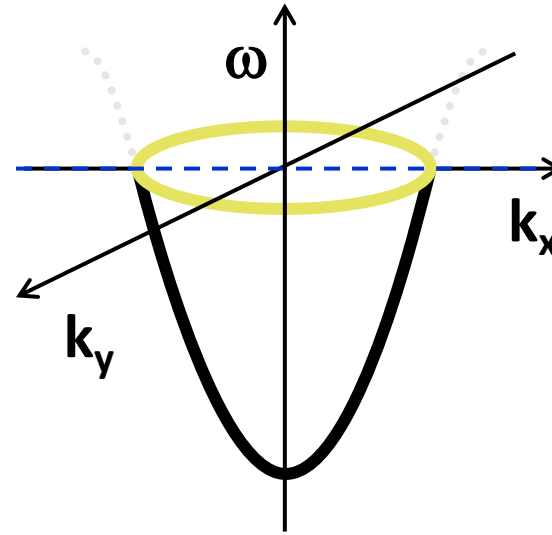
$$\Delta x \Delta p \geq \frac{\hbar}{2}$$



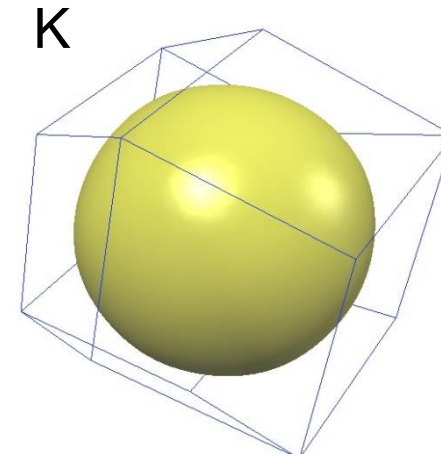
Fermi surface in 1D, 2D, and 3D



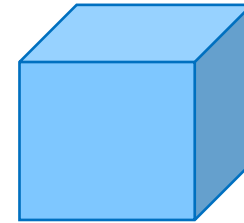
1D



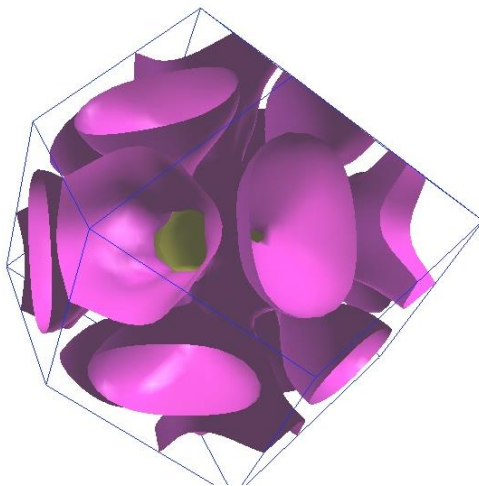
2D



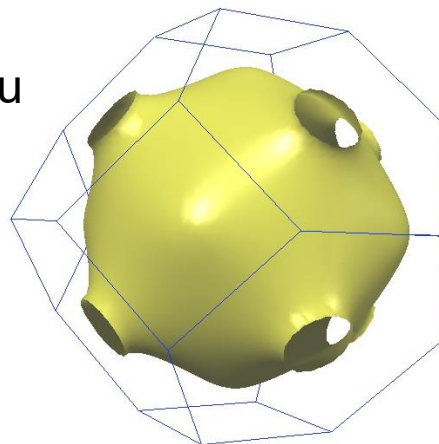
3D



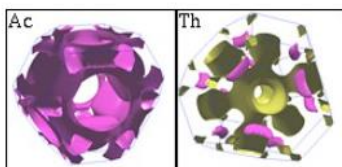
Nb



Cu



Li	Be													B	C
Na	Mg													Al	Si
K	Ca	Sc	Ti	V	Cr	Mn	Fe _{up}	Coup	Ni _{up}	Cu	Zn	Ga	Ge		
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn		
Cs	Ba	Lu	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb		

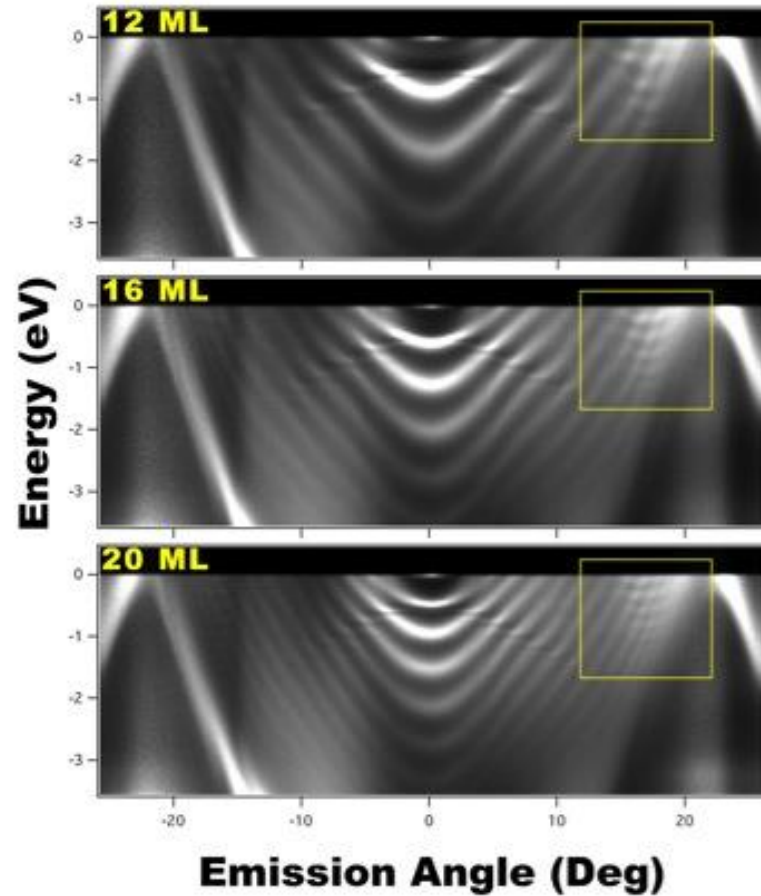


The Fermi Surface Database

(click **icons**)

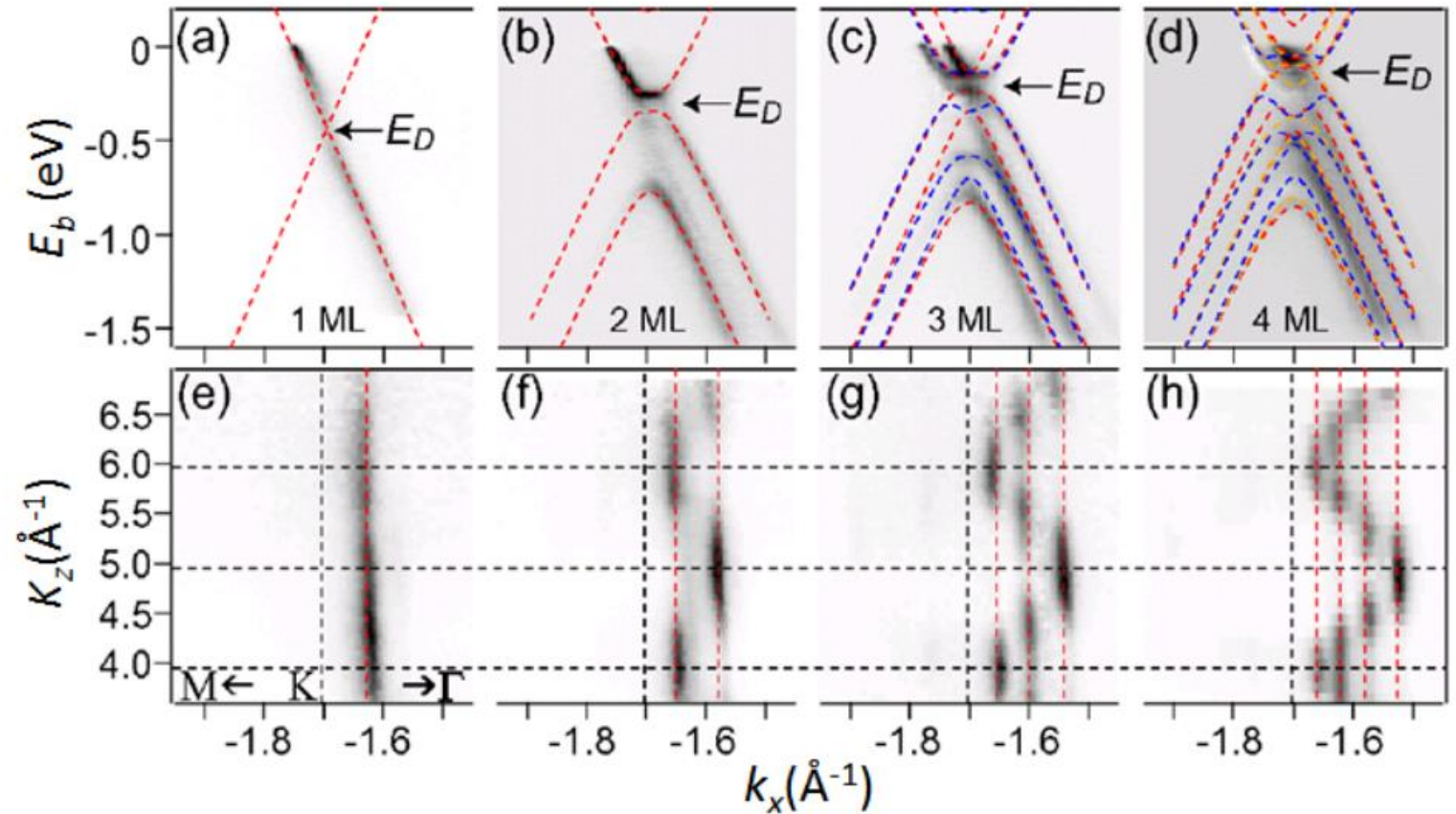
<http://www.phys.ufl.edu/fermisurface/>

Quantum confinement



ARPES data for atomically-uniform Ag films of 12, 16 and 20 monolayers (ML) grown on Si(111)-(7x7) substrates

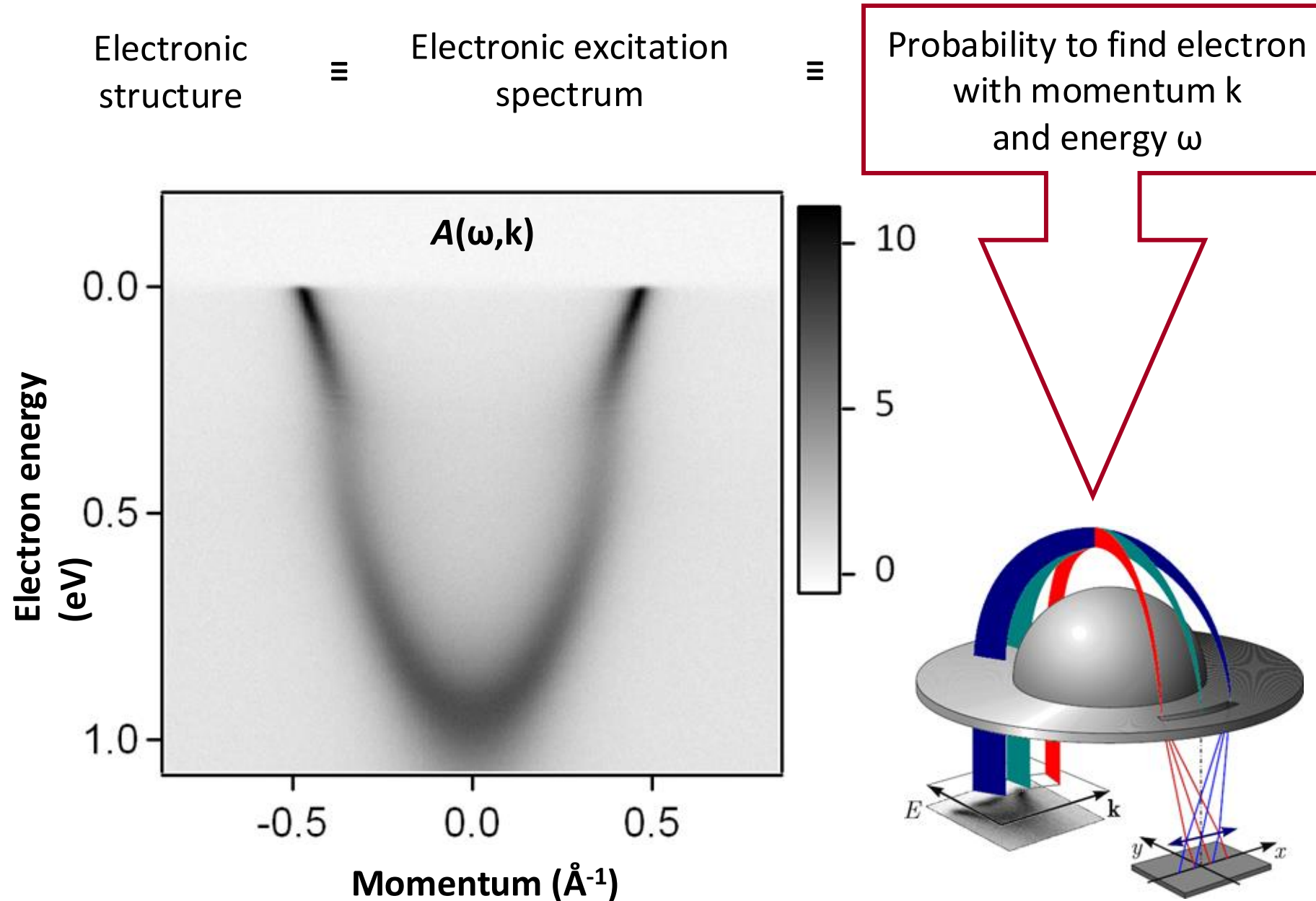
<http://groups.mrl.uiuc.edu/chiang/Speer/Nathan%20J%20Speer/Umklaapp-Mediated%20Quantized%20States.html>



ARPES data on graphene multilayers

V. N. Strocov <https://arxiv.org/abs/1801.07505>

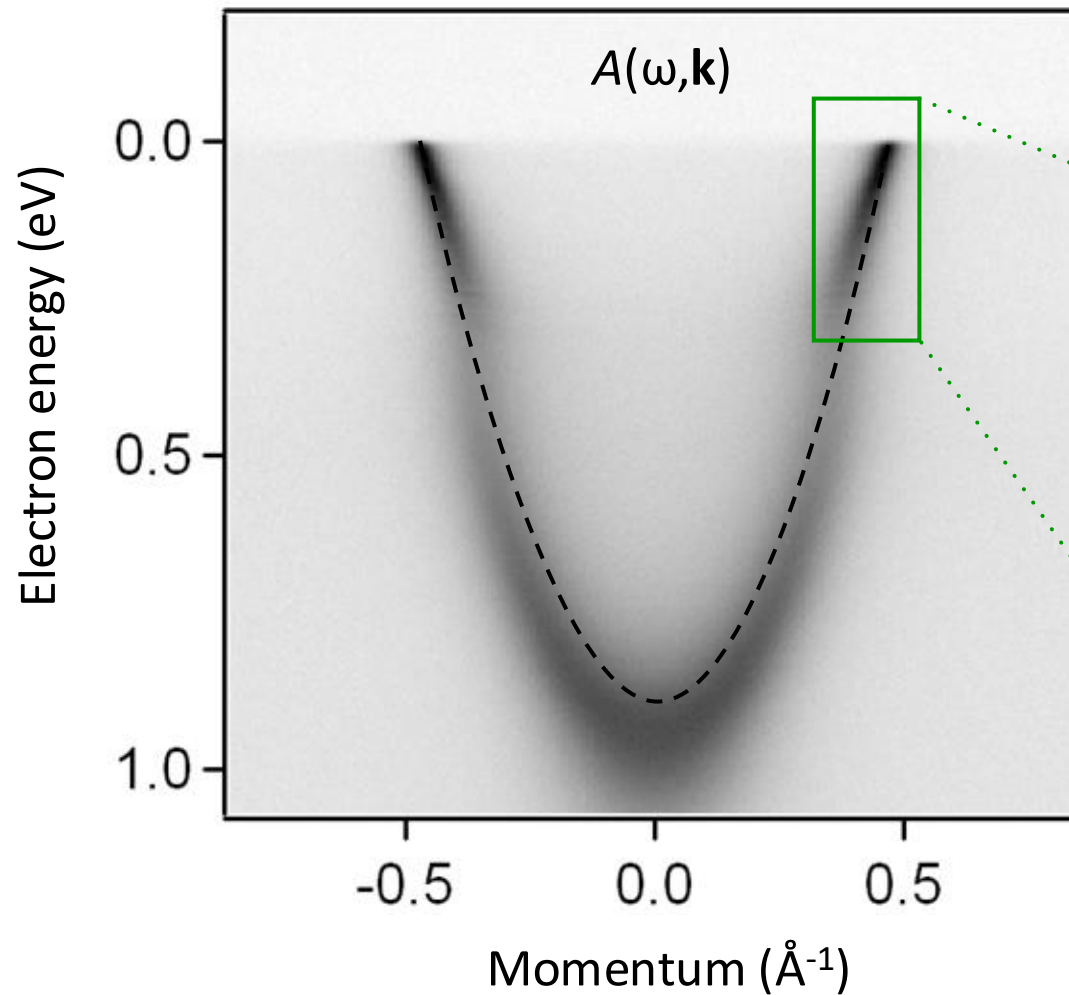
Photoemission spectrum



Structure of electronic spectrum

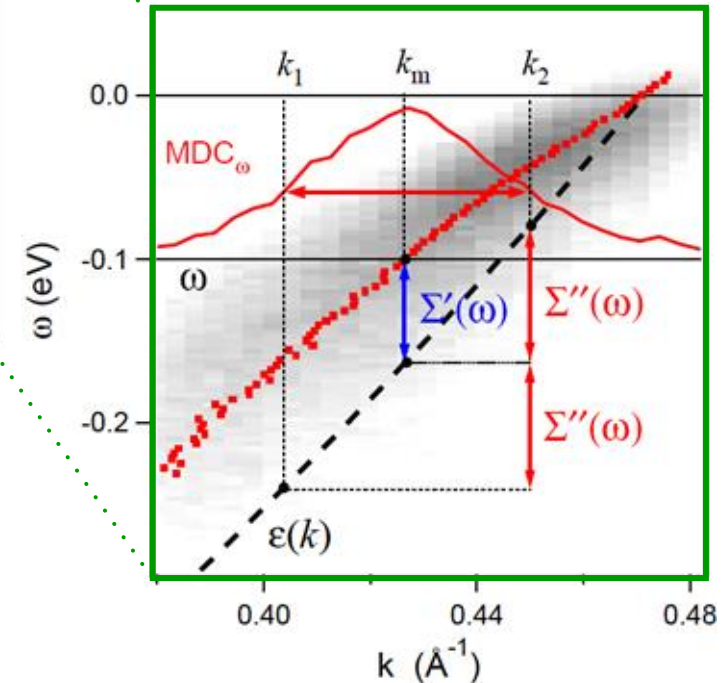
Spectral
function

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



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

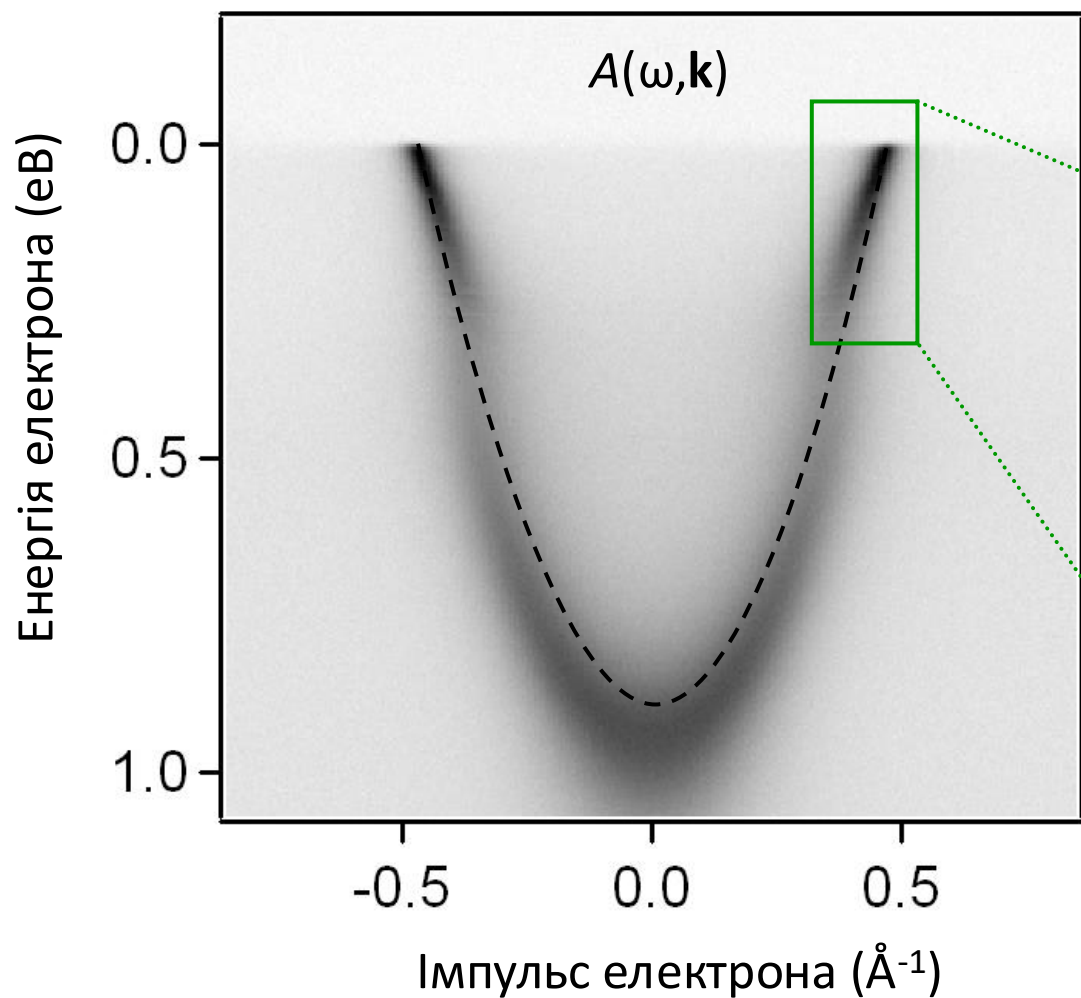
$\Sigma(\omega, \mathbf{k})$ – self-energy



Structure of electronic spectrum

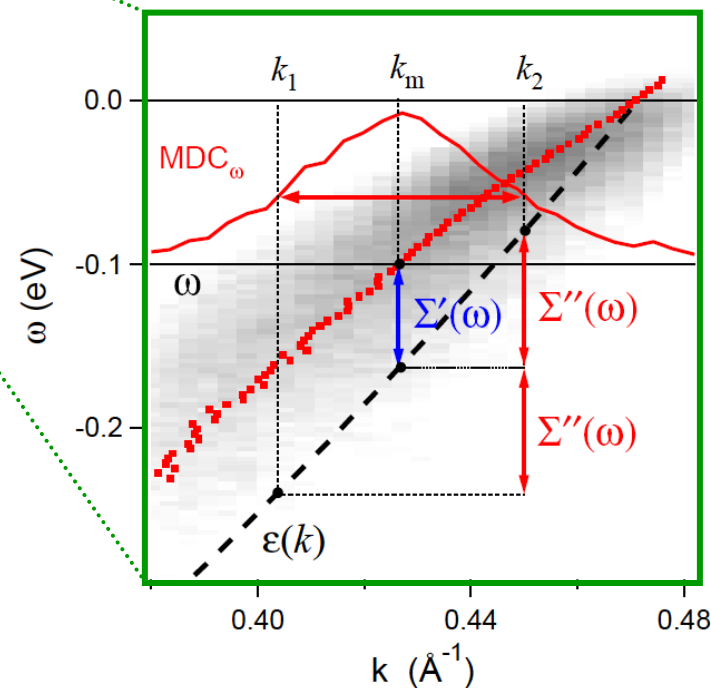
$$M(\mathbf{k}, n, h\nu) A(\omega, \mathbf{k}) f(\omega)$$

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



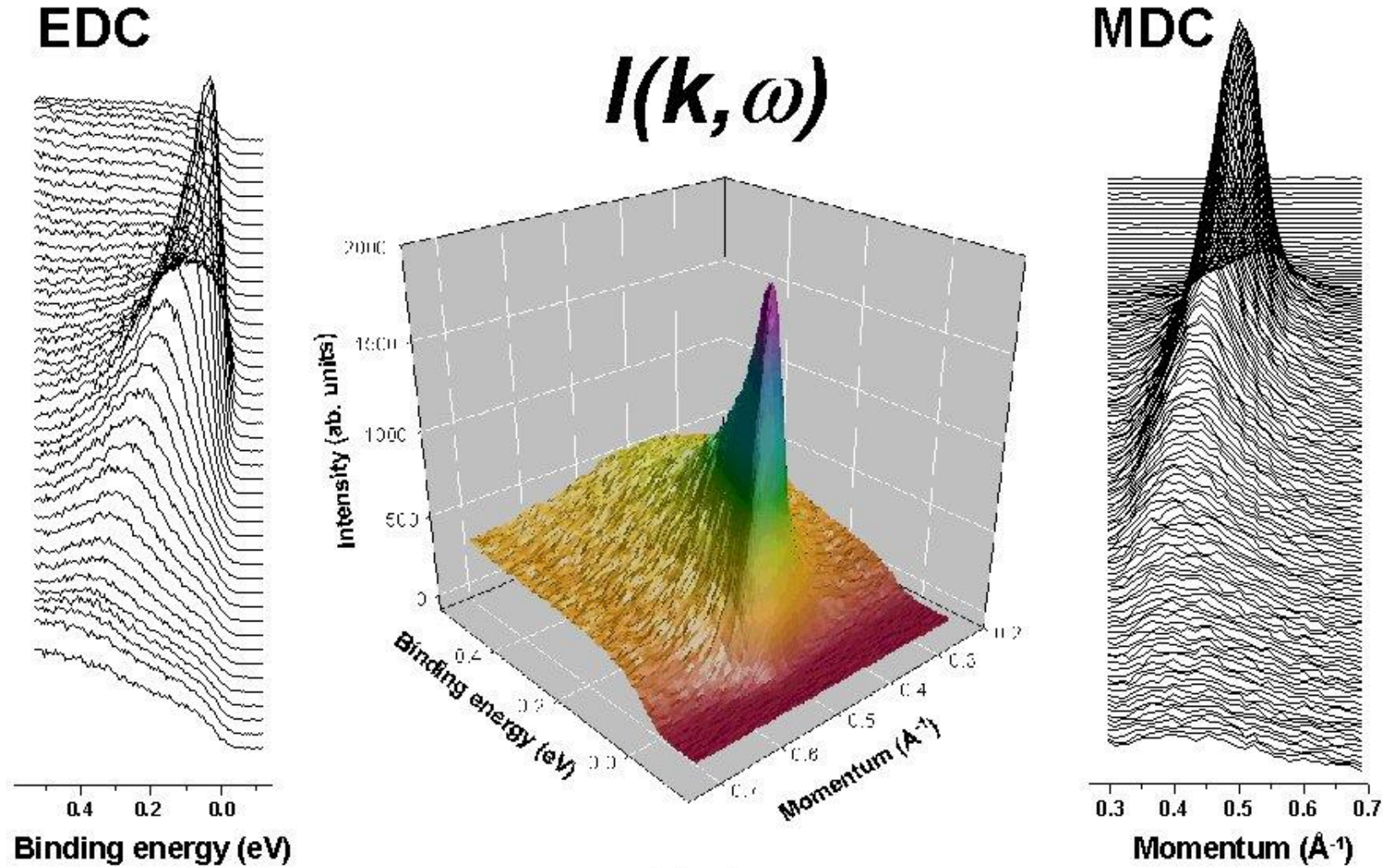
$\varepsilon(\mathbf{k})$ – "гола" електронна зонна структура

$\Sigma(\omega, \mathbf{k})$ – власна енергія

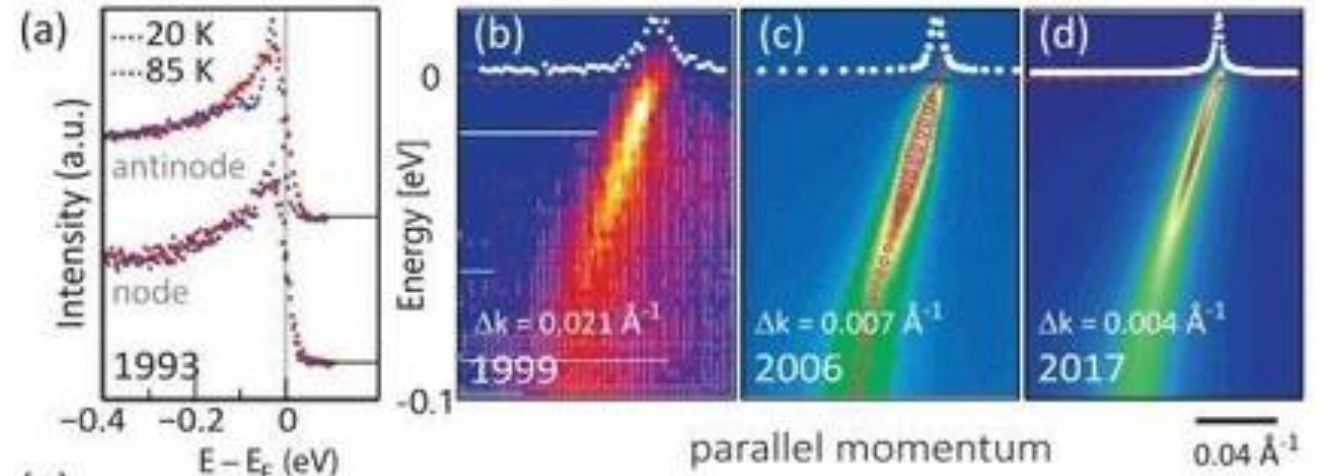
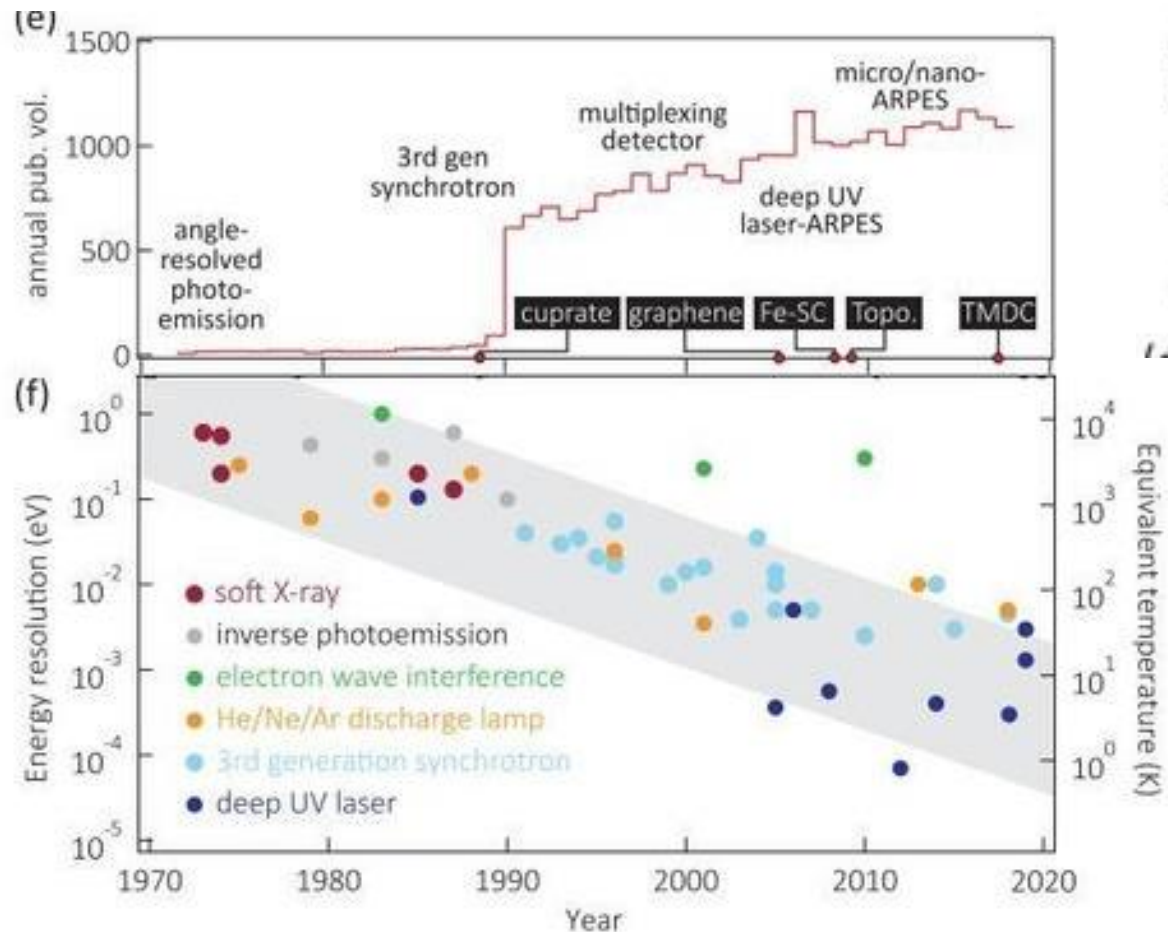


$$\Sigma''(0) = \hbar/\tau$$

Spectral function: EDC and MDC



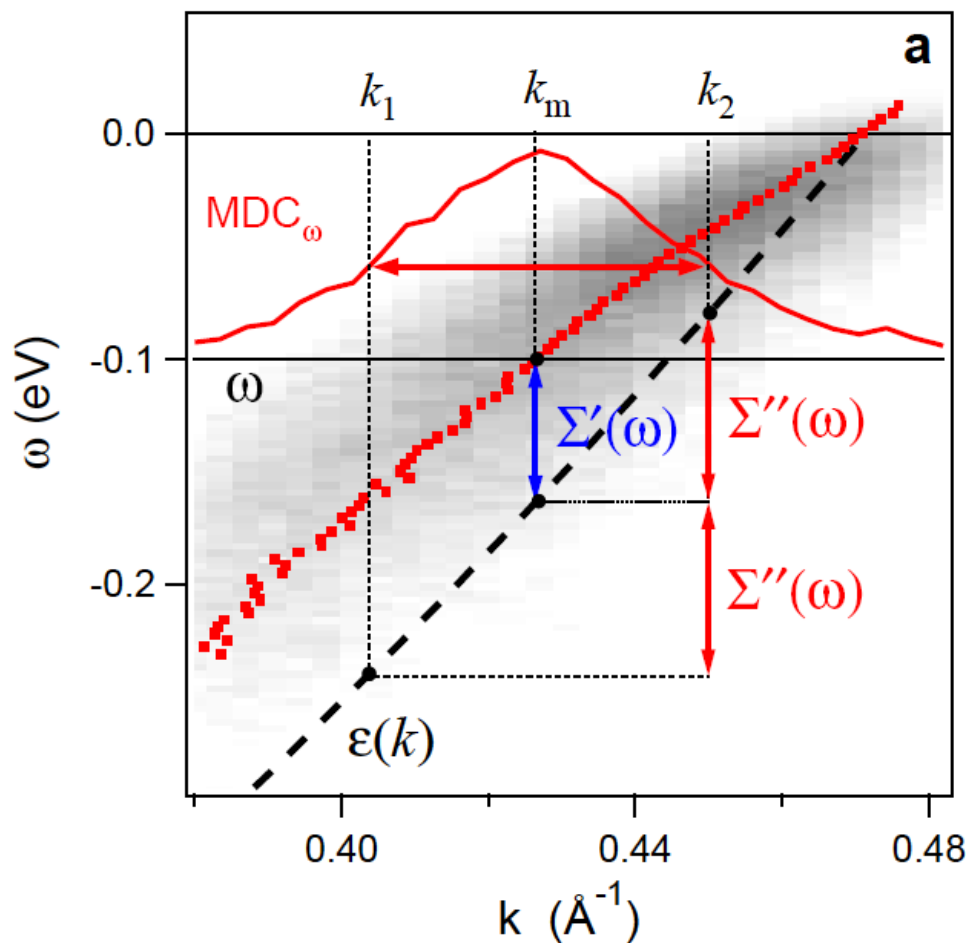
Progress in ARPES resolution



“MDC” was coined by Tony Valla

Spectral function

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

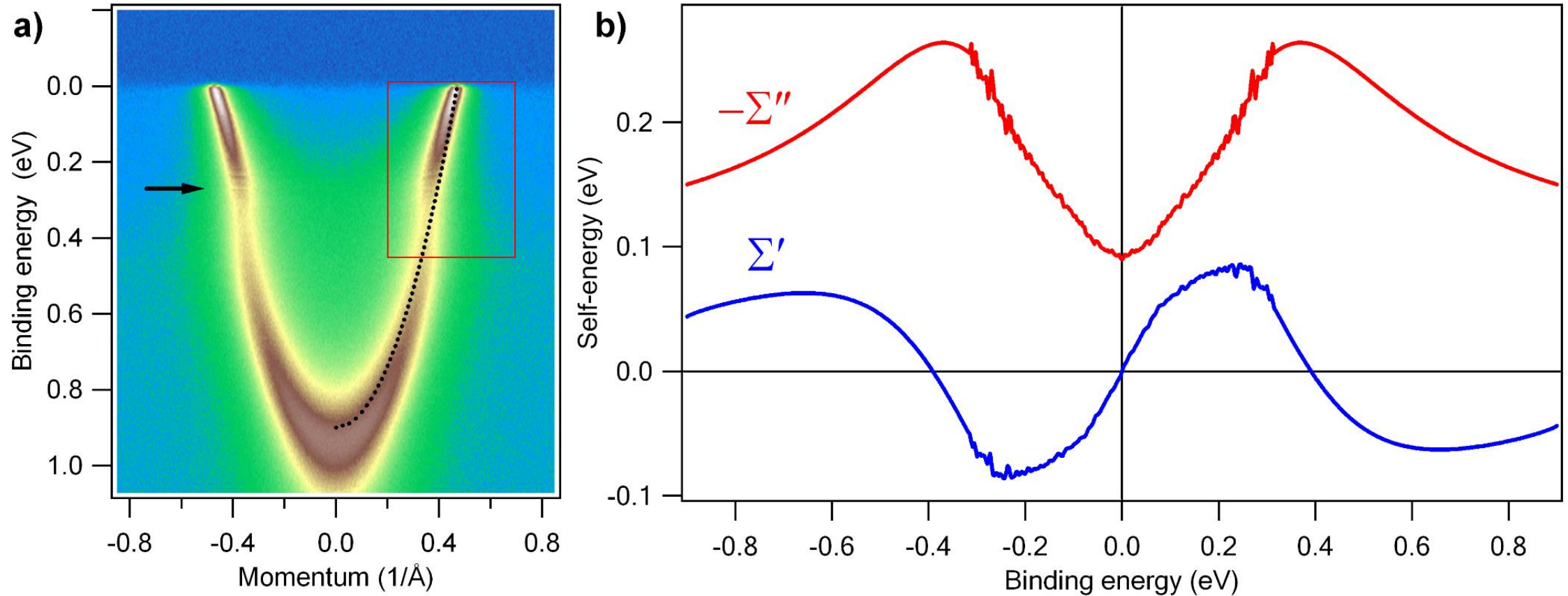


KK

$$\Sigma'(\omega) = \frac{1}{\pi} \text{PV} \int_{-\infty}^{\infty} \frac{\Sigma''(x)}{x - \omega} dx,$$

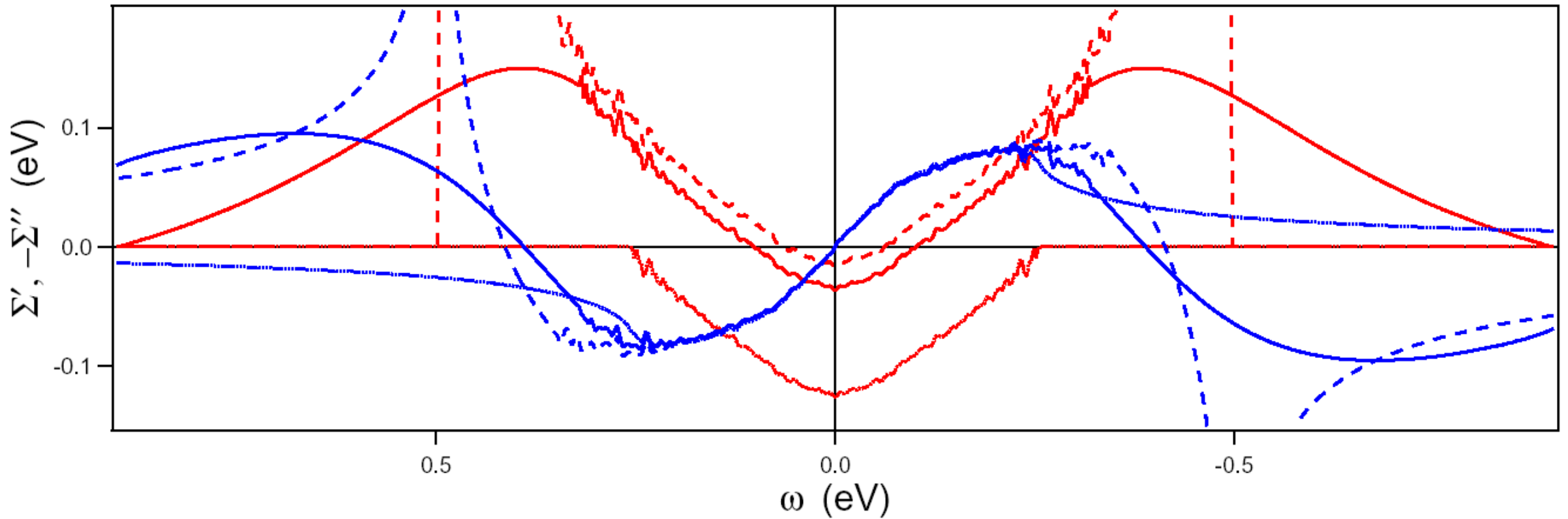
$$\Sigma''(\omega) = -\frac{1}{\pi} \text{PV} \int_{-\infty}^{\infty} \frac{\Sigma'(x)}{x - \omega} dx$$

Kramers-Kronig (KK) transformation



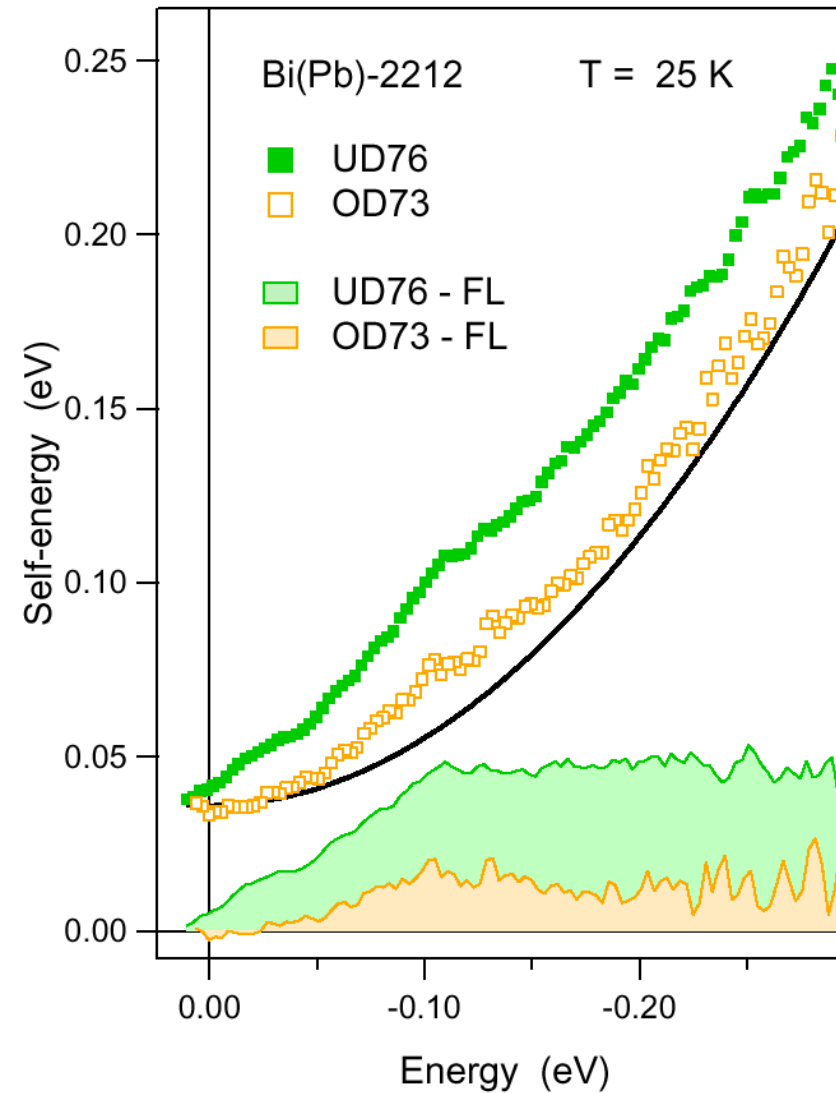
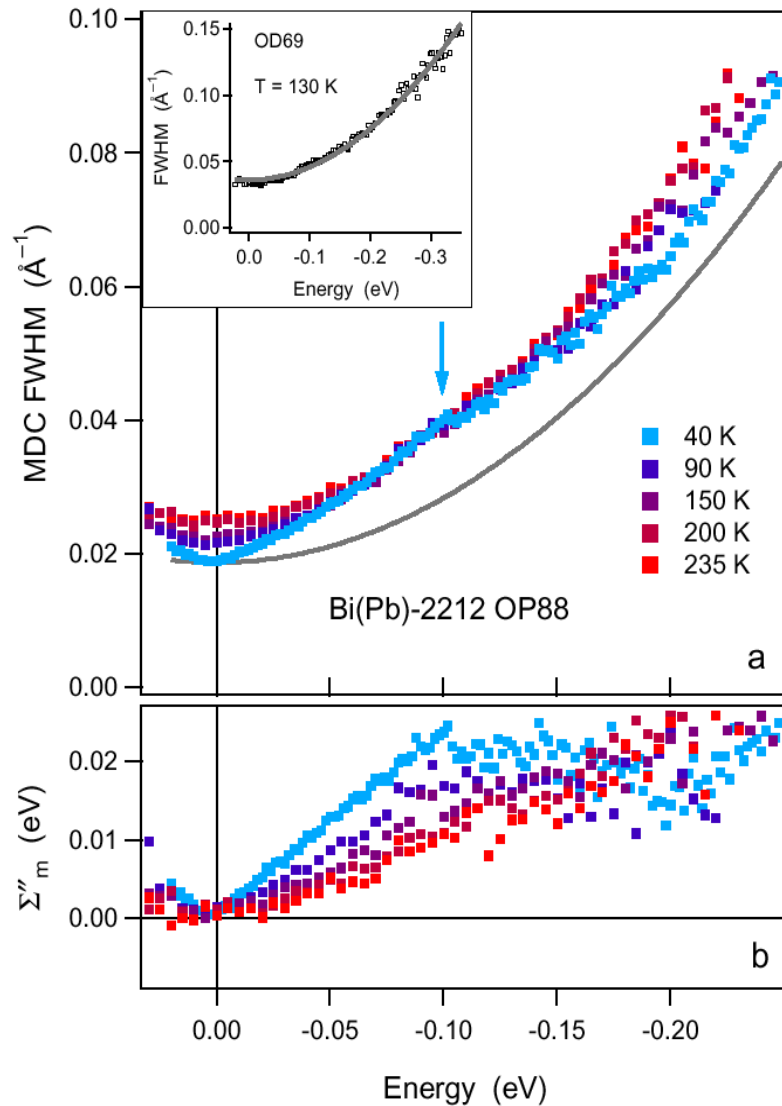
Kramers-Kronig transform

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



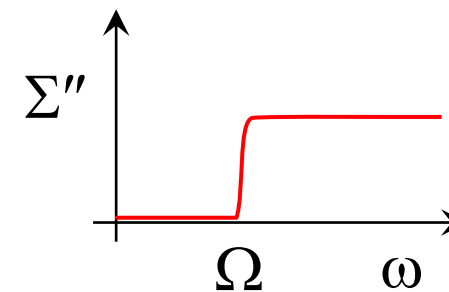
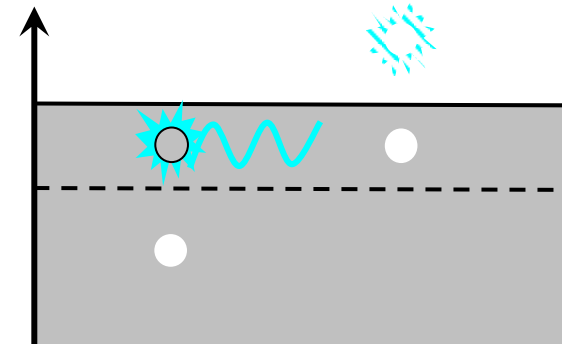
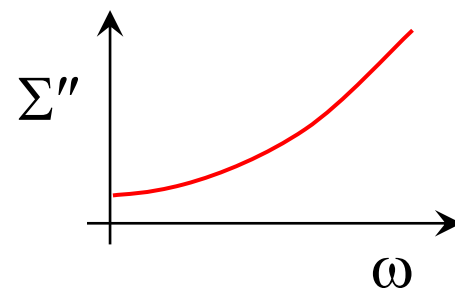
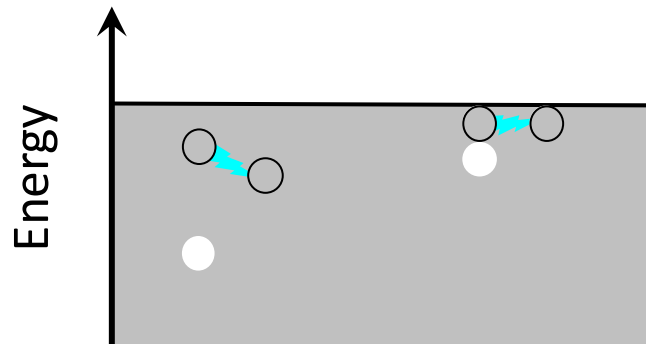
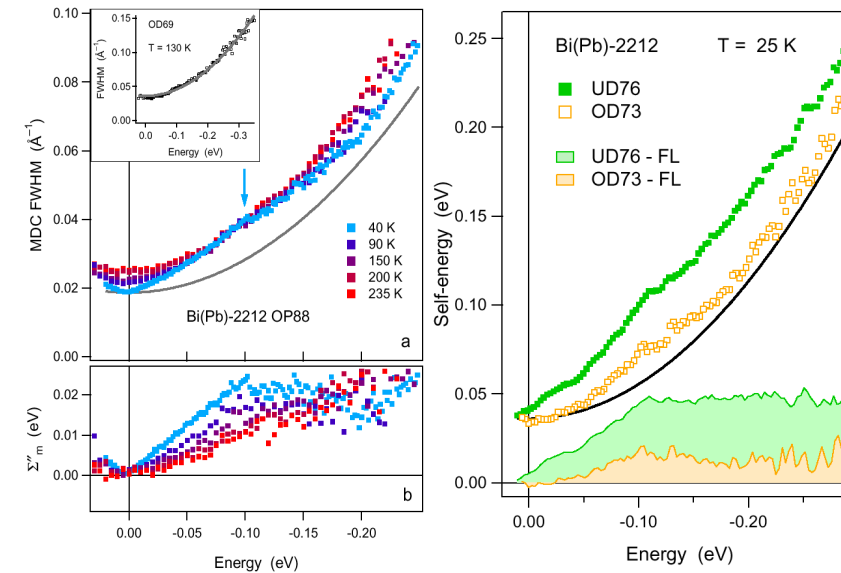
$$\Sigma''(\omega) = \begin{cases} \Sigma''_{width}(|\omega|) & \text{for } |\omega| < \omega_m, \\ \Sigma''_{mod}(\omega) & \text{for } |\omega| > \omega_m, \end{cases} \quad \Sigma''_{mod}(\omega) = -\frac{\alpha \omega^2 + C}{1 + \left| \frac{\omega}{\omega_c} \right|^n},$$

Scattering rate: T - and x - dependence

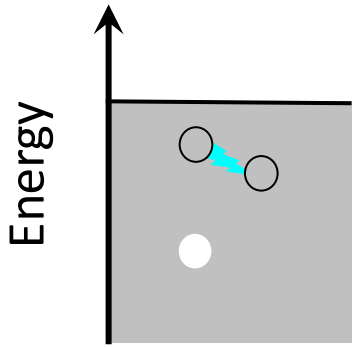


Scattering rate: Two channels

There are two channels:
1st electron-electron scattering and
2nd electron-boson scattering



Scattering probability

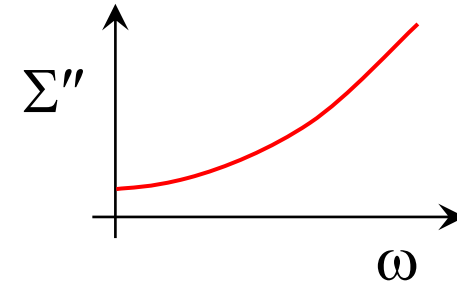
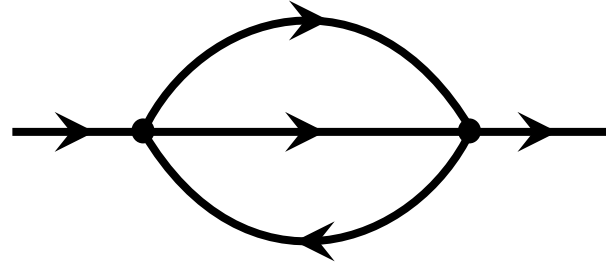
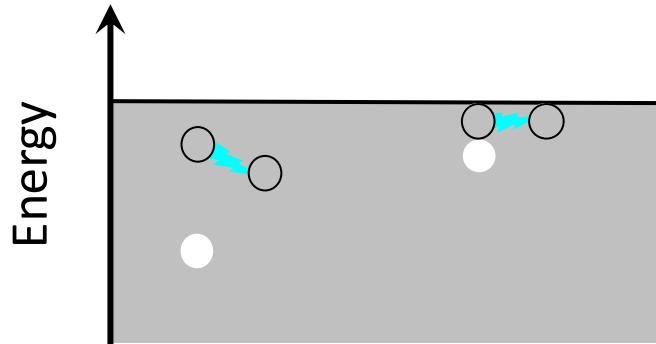


Energy conservation law: $\omega_1 + \omega_2 = \omega + \omega_3$

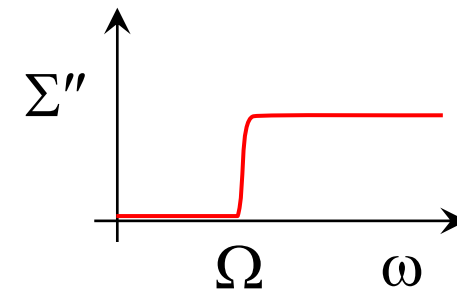
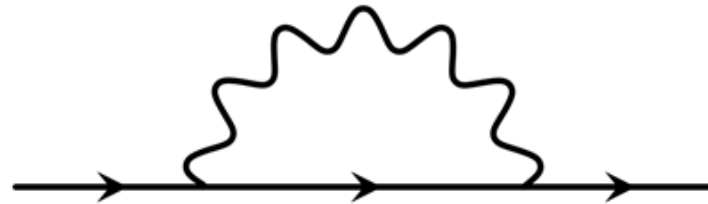
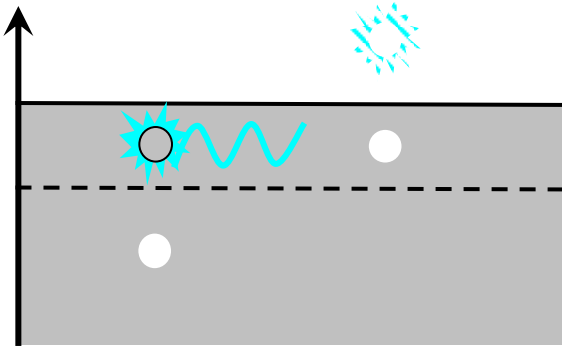
$$\Sigma''(\omega) \sim P_e(\omega_1)P_e(\omega_2)P_e(\omega_1 + \omega_2 - \omega)$$

$$\Sigma''(\omega) \sim \int_{\omega}^0 DOS(\omega_1) \int_{\omega - \omega_1}^0 DOS(\omega_2) d\omega_2 d\omega_1 = \frac{1}{2} \omega^2$$

Scattering probability



$$\Sigma''(\omega) \sim \int_{\omega}^0 DOS(\omega_1) \int_{\omega - \omega_1}^0 DOS(\omega_2) d\omega_2 d\omega_1 = \frac{1}{2} \omega^2$$



$$\Sigma''(\omega) \sim \int_{\omega}^0 DOS(\omega_1) \delta(\omega - \omega_1 - \Omega) d\omega_1 = DOS(\omega + \Omega) \theta(-\omega - \Omega)$$

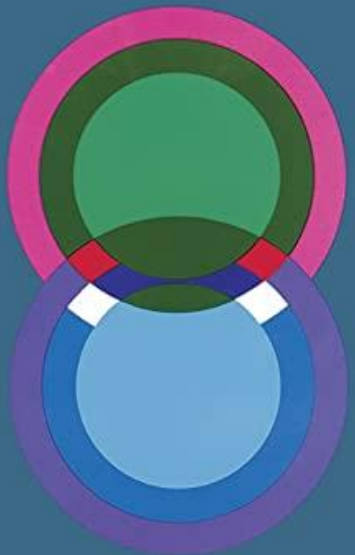
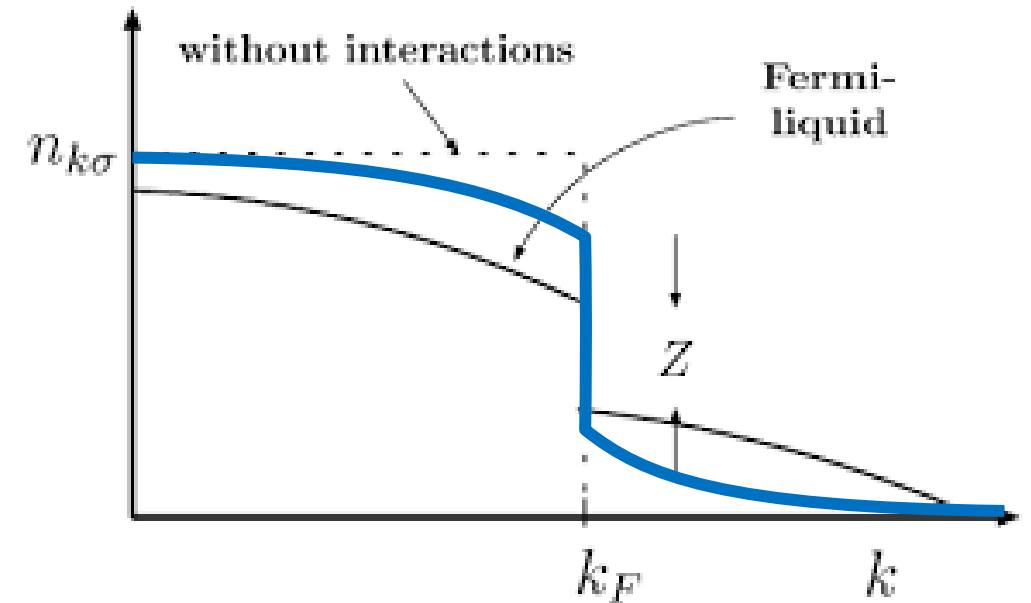
Landau Fermi liquid

$$G(\mathbf{k}, \omega) = G_{coh}(\mathbf{k}, \omega) + G_{incoh}(\mathbf{k}, \omega)$$

$$G_{coh}(\mathbf{k}, \omega) = \frac{Z_{\mathbf{k}}}{\omega - \tilde{\epsilon}_{\mathbf{k}} + i/\tau_{\mathbf{k}}}$$

$$Z_{\mathbf{k}} = \left(1 - \frac{\partial \Sigma}{\partial \omega} \right)^{-1}_{\omega=0, k=k_F}$$

$$\frac{\Sigma''(\omega)}{\omega} \rightarrow 0 \quad \Sigma'(\omega) \approx -\lambda\omega \quad Z = \frac{1}{1 + \lambda}$$



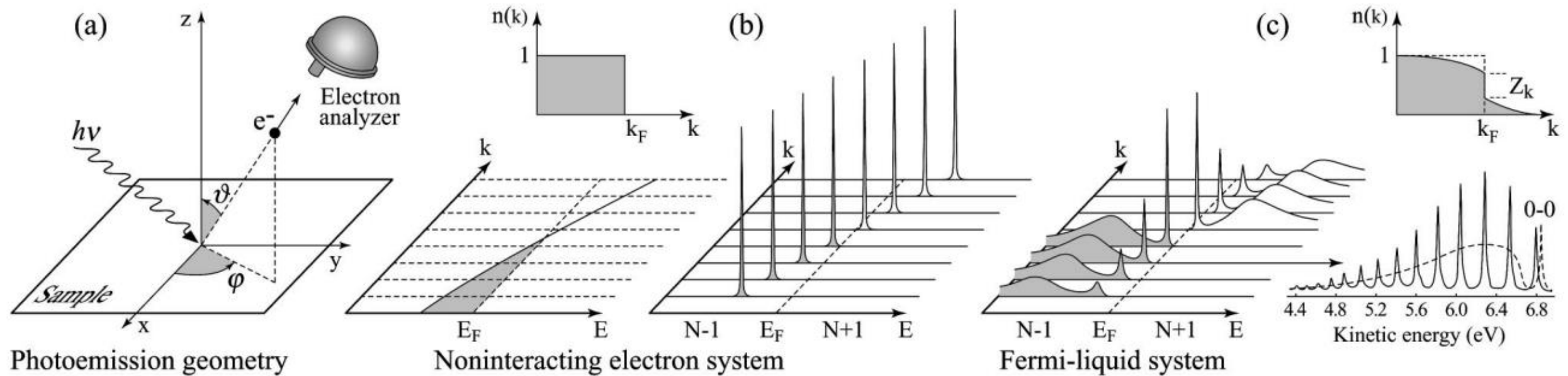
**METHODS OF
QUANTUM FIELD THEORY
IN STATISTICAL PHYSICS**

A. A. Abrikosov, L. P. Gorkov, & I. E. Dzyaloshinski
Revised English Edition Translated and Edited by Richard A. Silverman

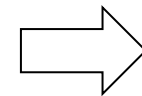
<https://arxiv.org/pdf/cond-mat/0103393.pdf>

Landau, L. D. The theory of a Fermi liquid. *J. Exp. Theor. Phys.* **30**, 1058–1064 (1956).

Landau Fermi liquid



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



$$A(\mathbf{k}, \omega) = Z_{\mathbf{k}} \frac{\Gamma_{\mathbf{k}} / \pi}{(\omega - \epsilon_{\mathbf{k}})^2 + \Gamma_{\mathbf{k}}^2} + A_{inch}$$

$$\epsilon_{\mathbf{k}} = Z_{\mathbf{k}}(\epsilon_{\mathbf{k}} + \Sigma')$$

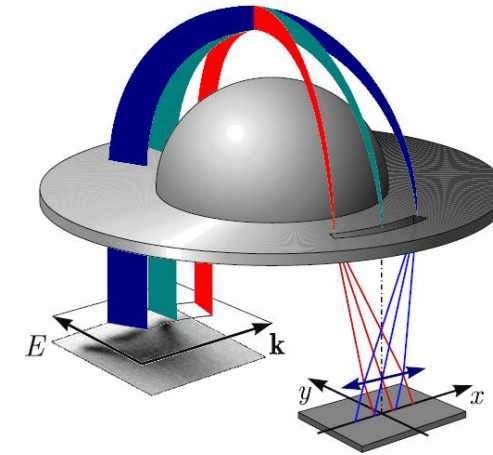
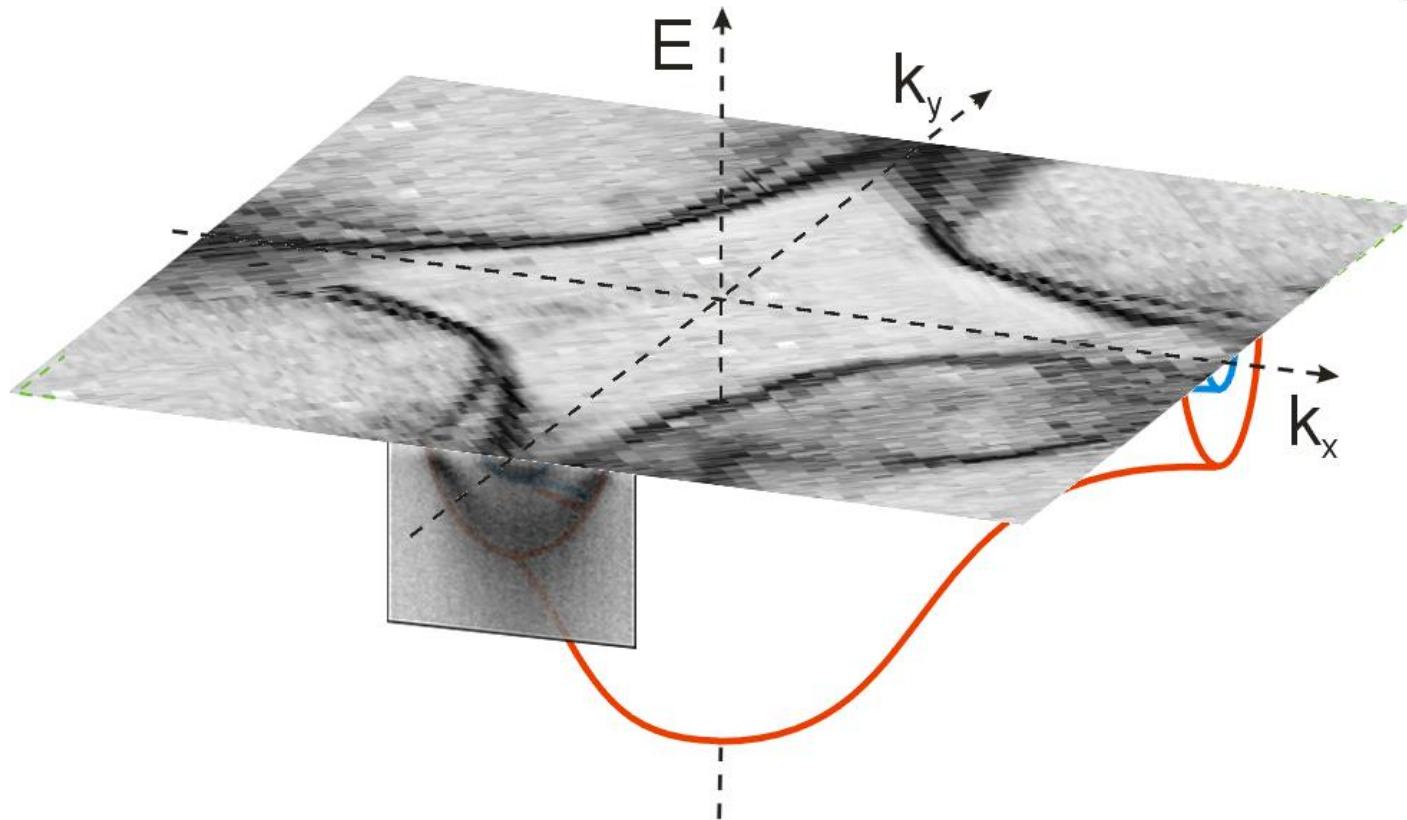
$$\Gamma_{\mathbf{k}} = Z_{\mathbf{k}}|\Sigma''|$$

Rev. Mod. Phys. 75, 473 (2003)

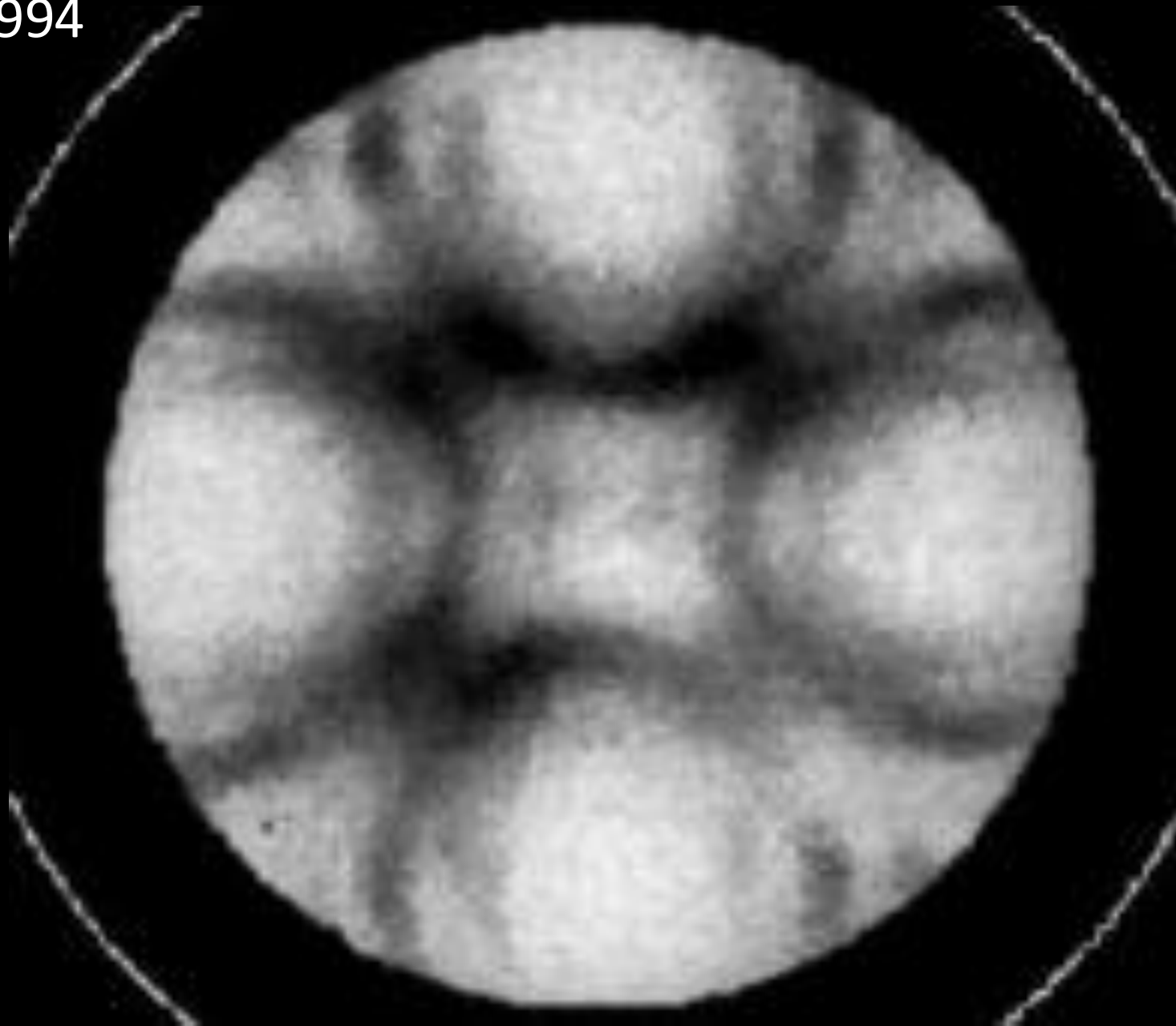
<https://doi.org/10.1103/RevModPhys.75.473>

Electronic spectrum of quasi-2D crystals

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



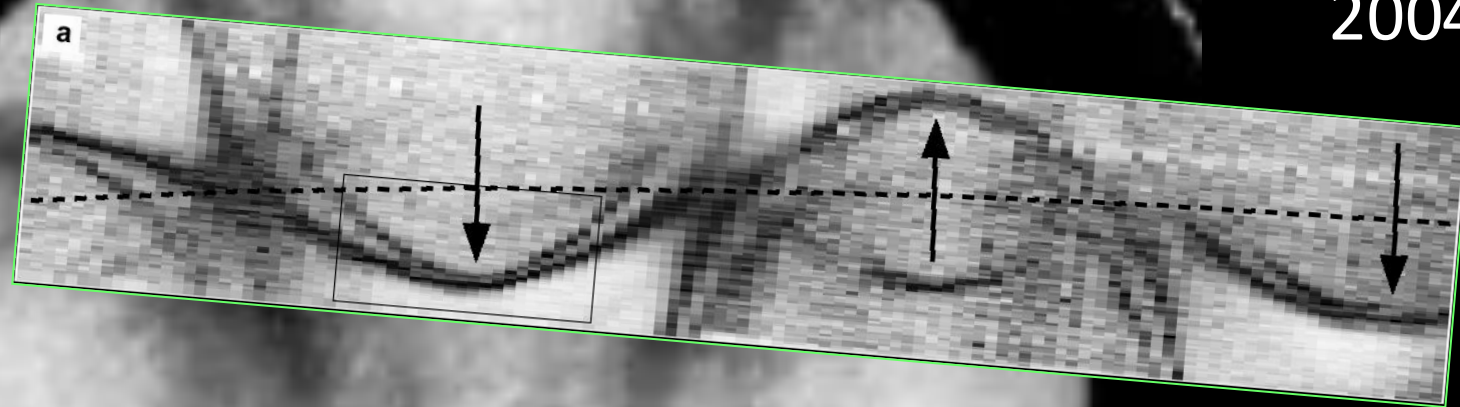
1994



Aebi *PRL* 1994

1994

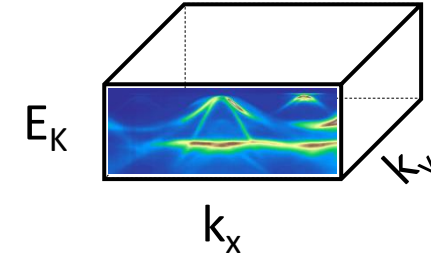
2004



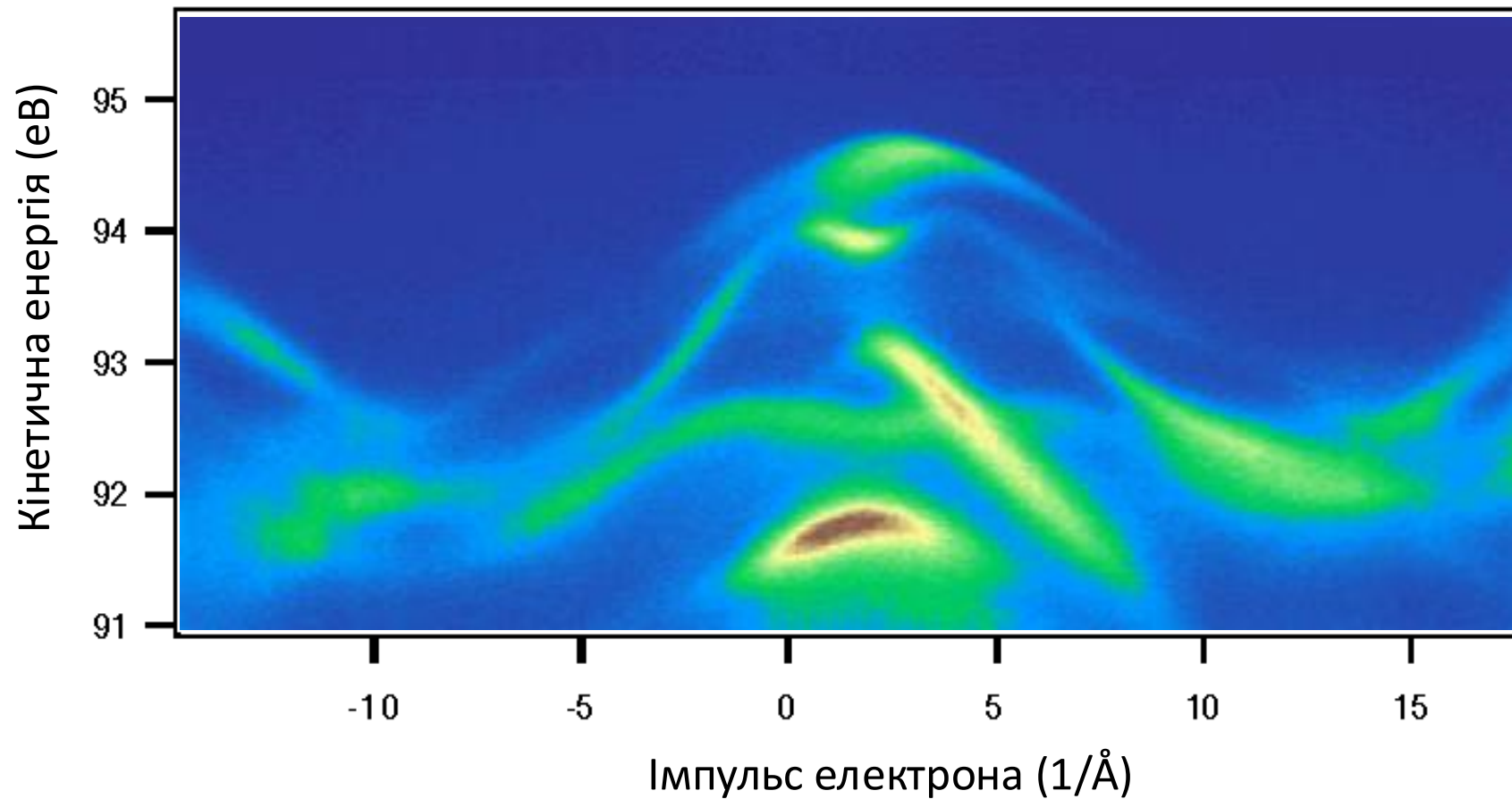
PRB 2004

Aebi *PRL* 1994

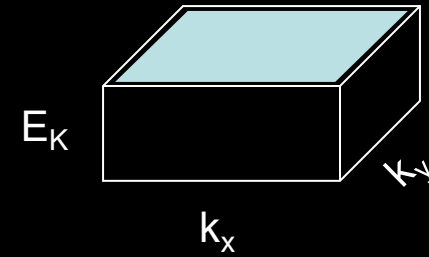
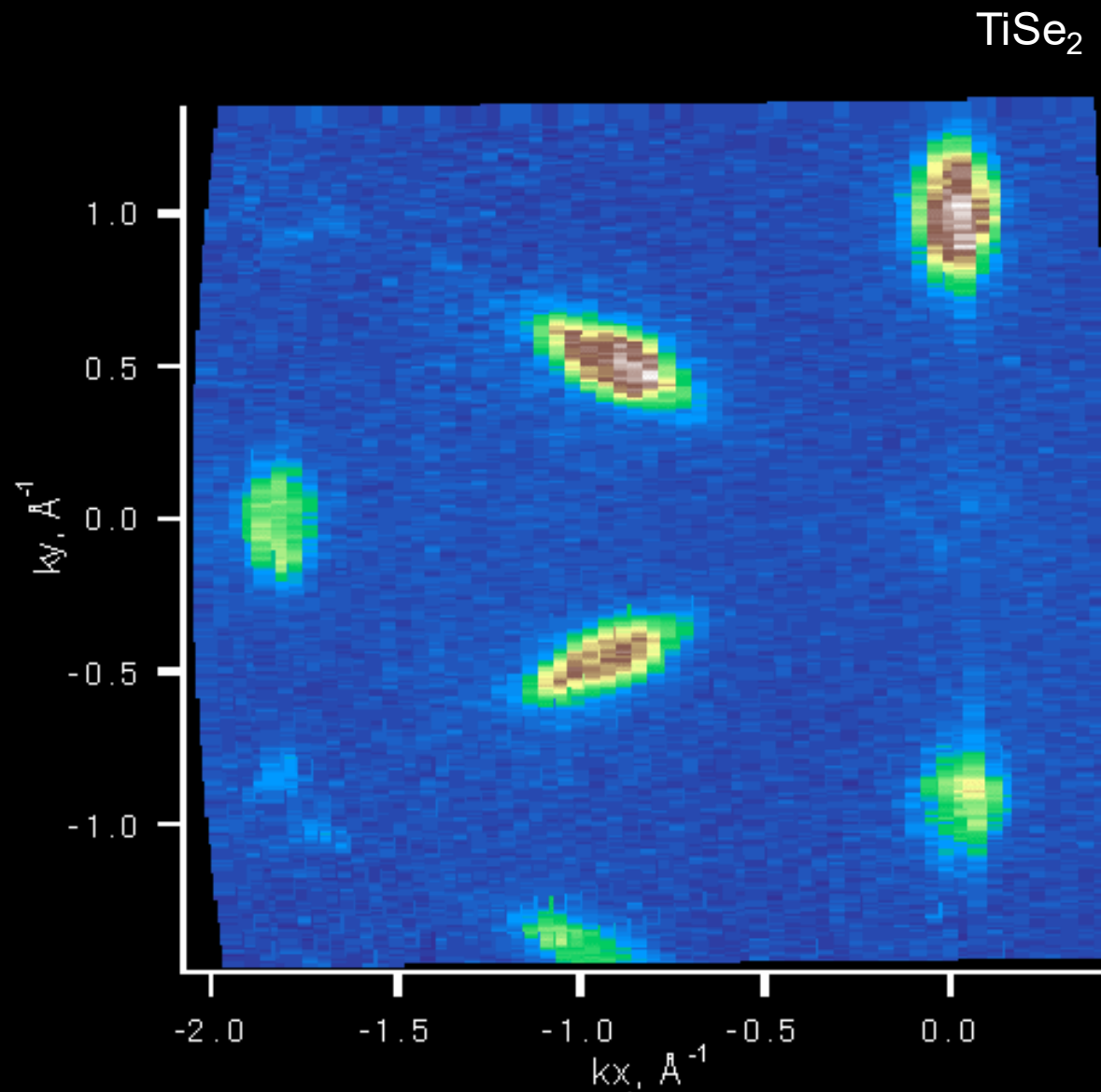
Electronic spectrum in momentum-energy 3D space



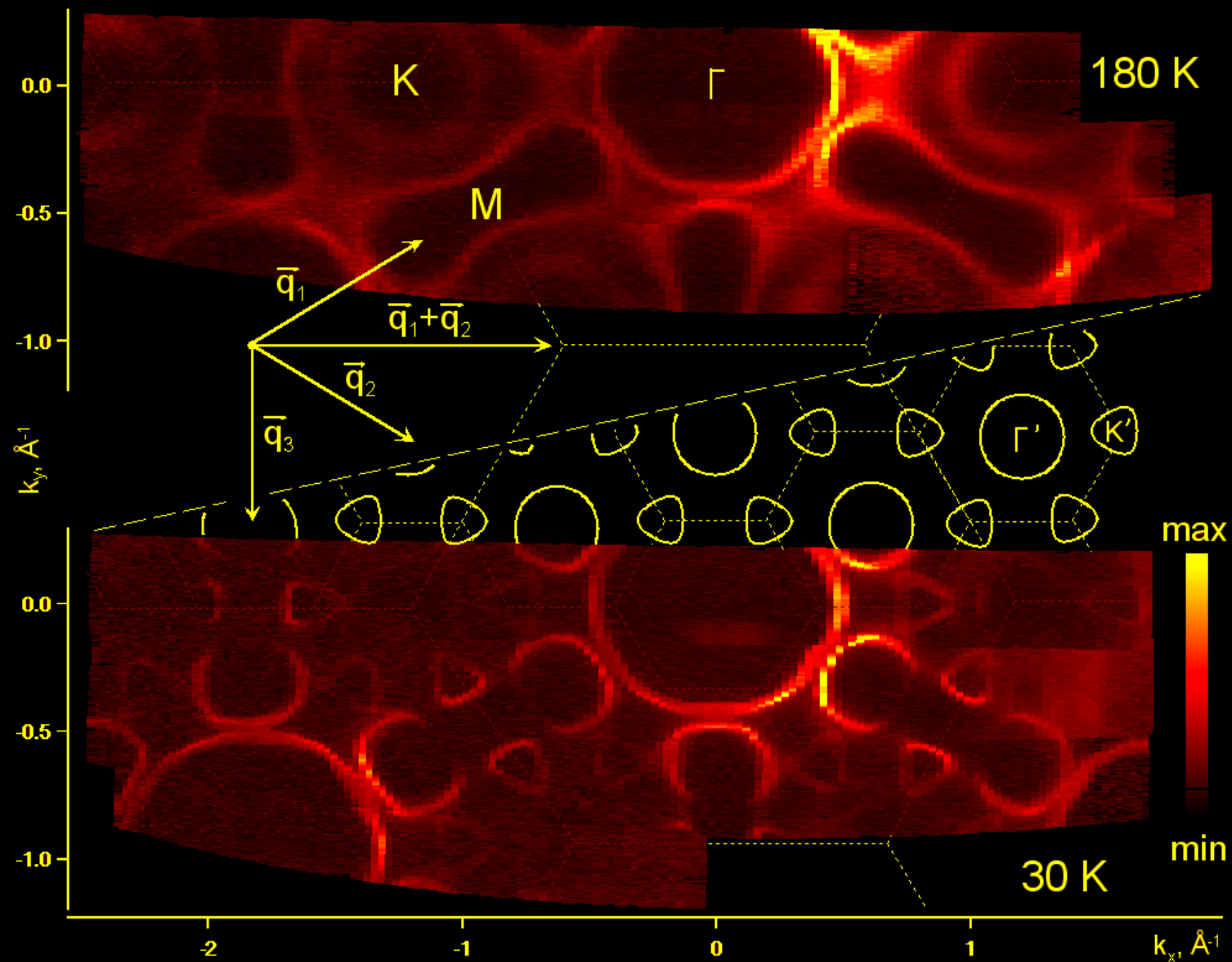
TiSe₂ - «excitonic insulator»

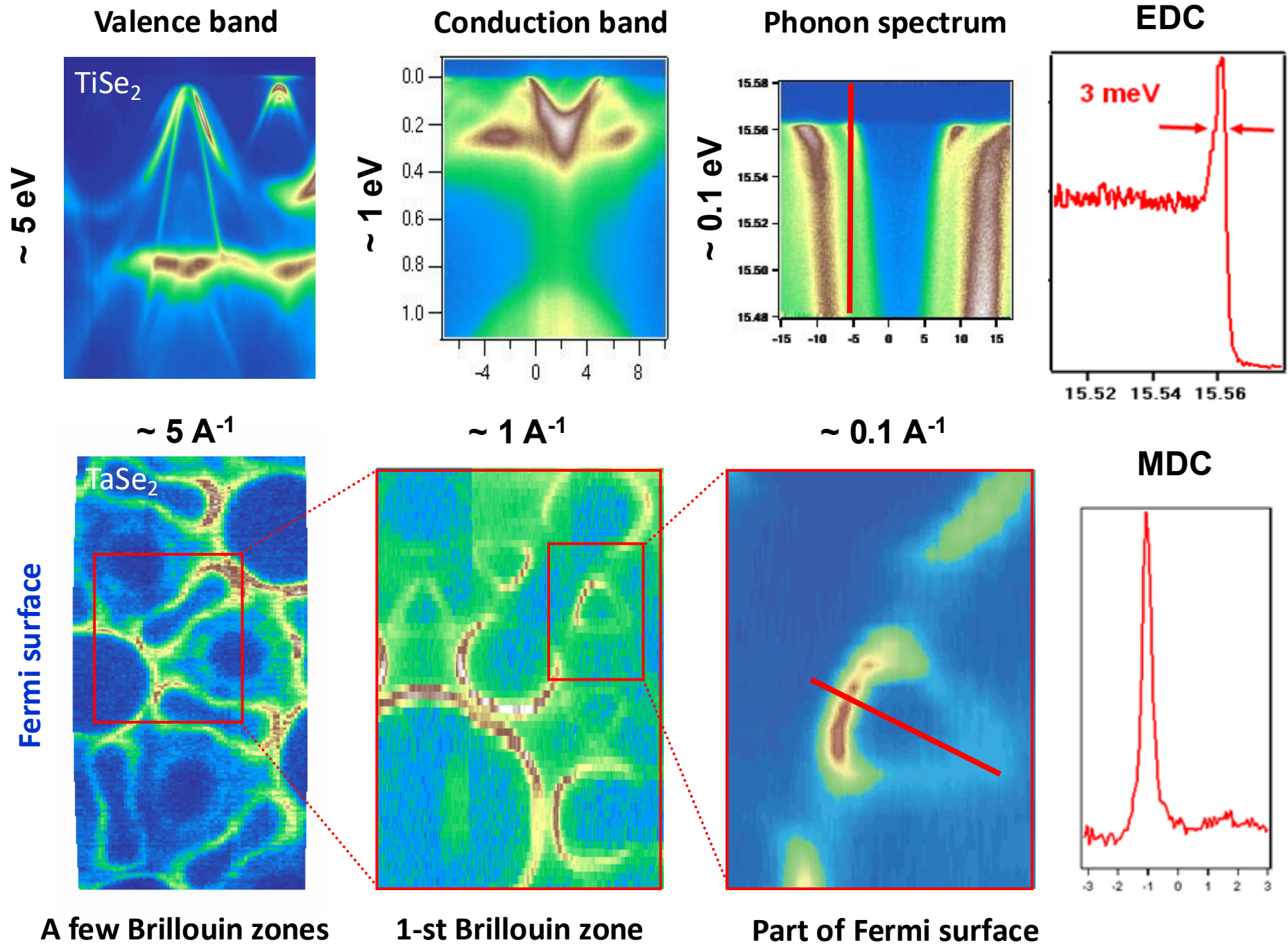


Fermi surface (energy distribution) map

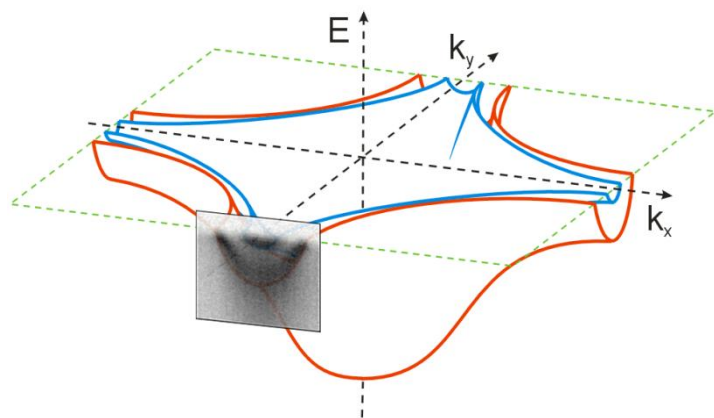


CDW y TaSe₂: commensurate CDW state

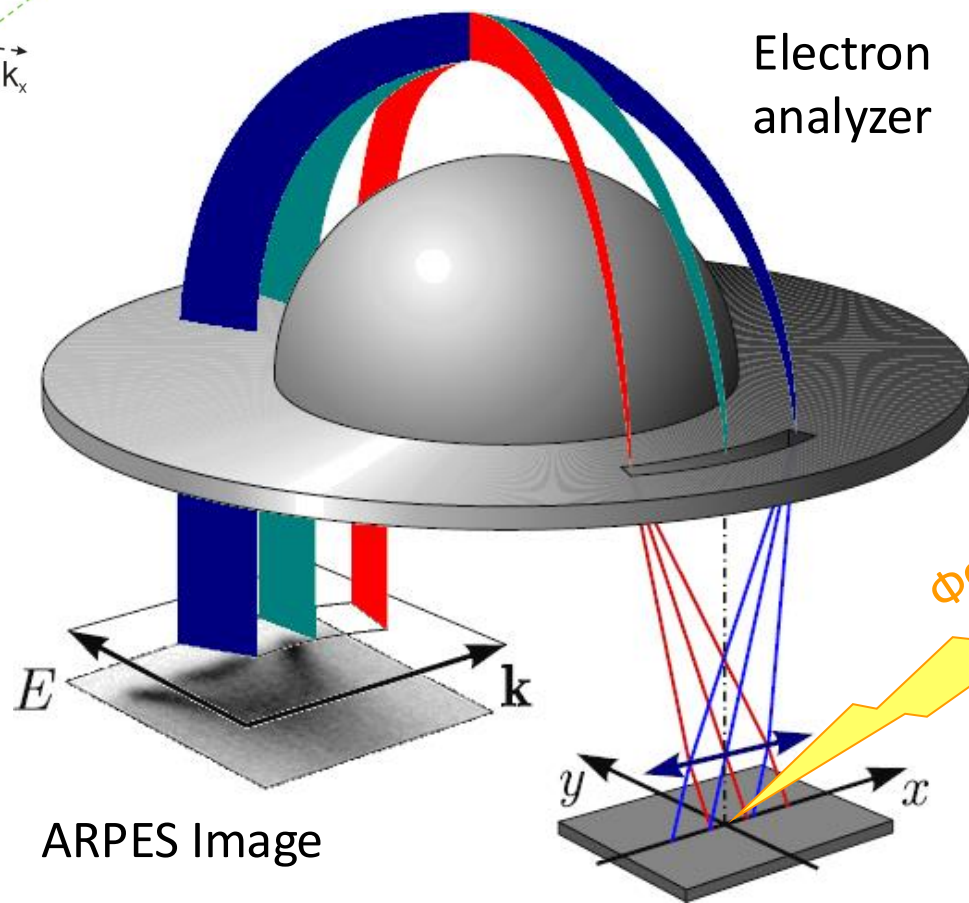




ARPES: Angle Resolved Photoelectron Spectroscopy



ARPES
=
photo effect
+
analyzer
+
manipulator



Electron
analyzer

ARPES Image

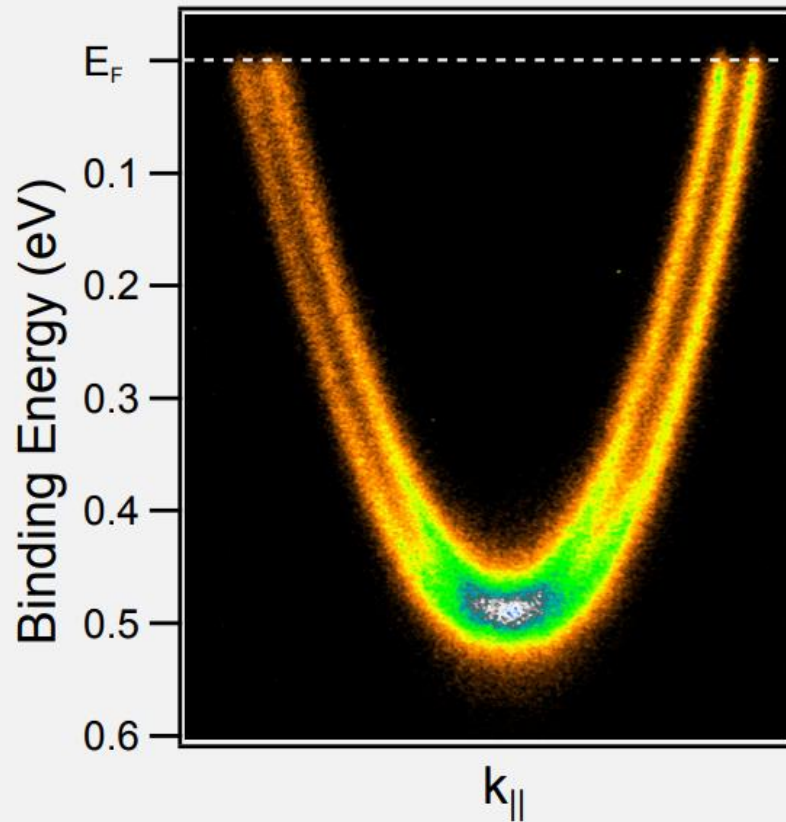
Sample

Discharge Light Source with Quartz Capillary

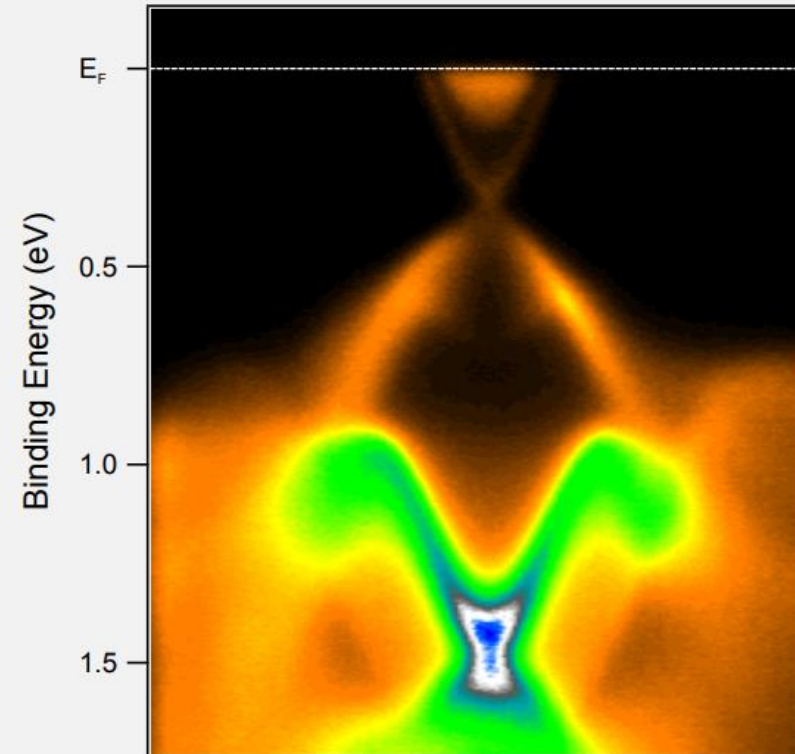


Light Sources

1. Discharge light sources (UV lamps)
2. Accelerator based light sources: Synchrotron, FEL
3. Lasers



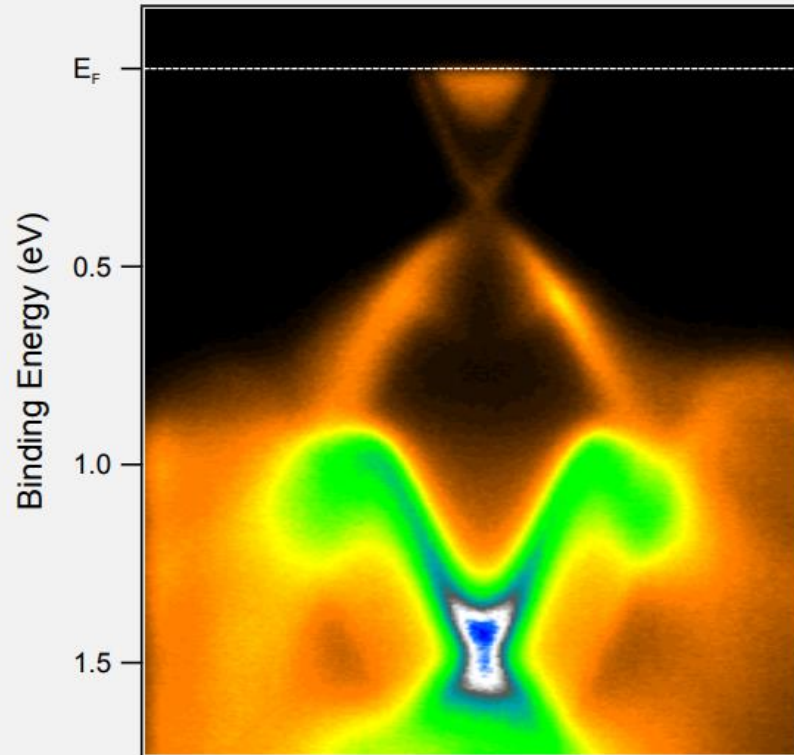
Au(111) surface state measured with a UVLS and TMM 304 at T=23 K



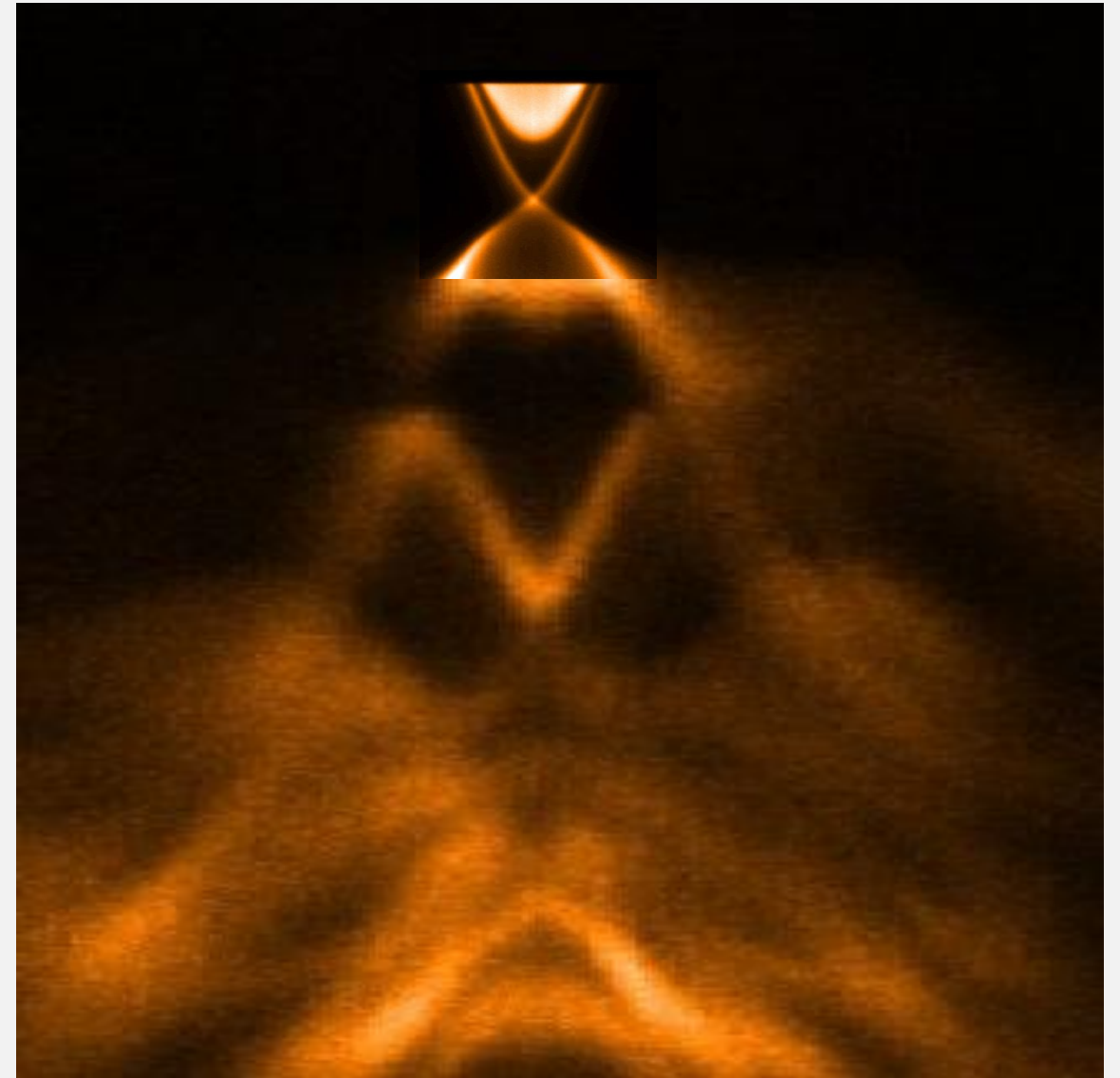
Γ point of Bi_2Te_3 , A topological insulator. Raw data from PHOIBOS 225 2D-CCD with UVLS and TMM 304 at T=70K.

Discharge Light Source with Quartz Capillary

1³ at BESSY

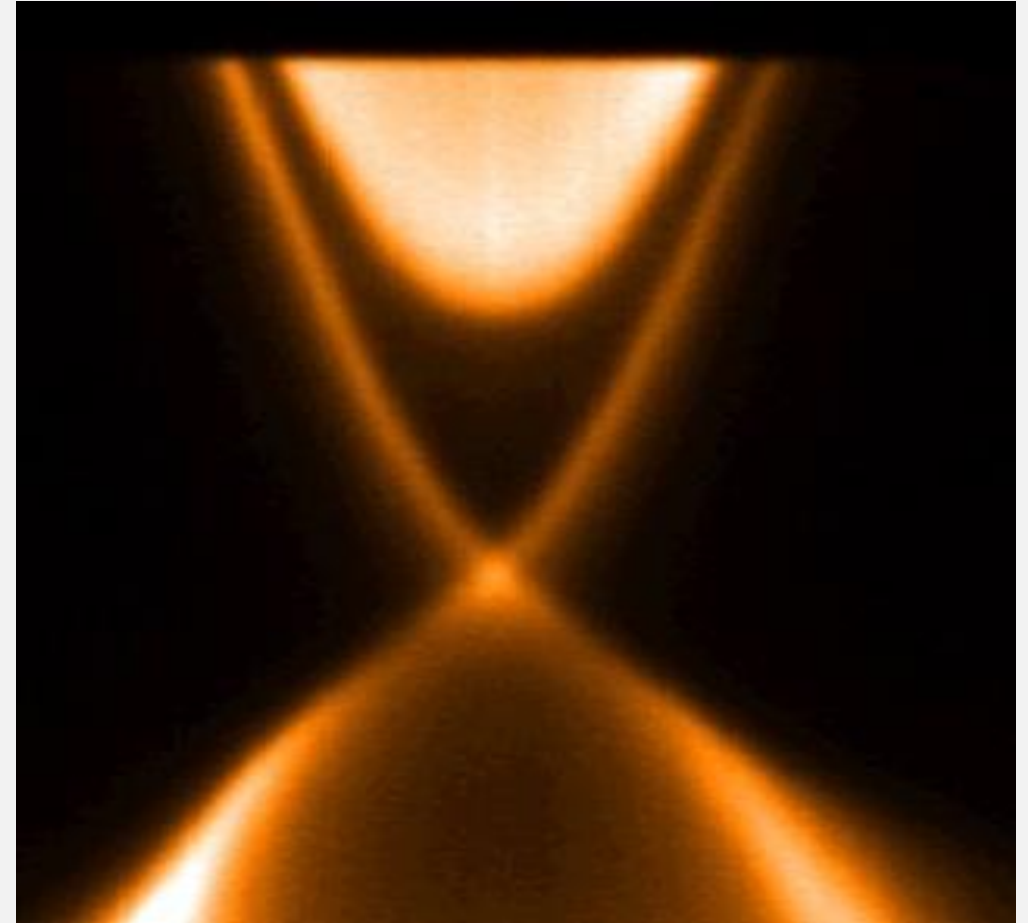
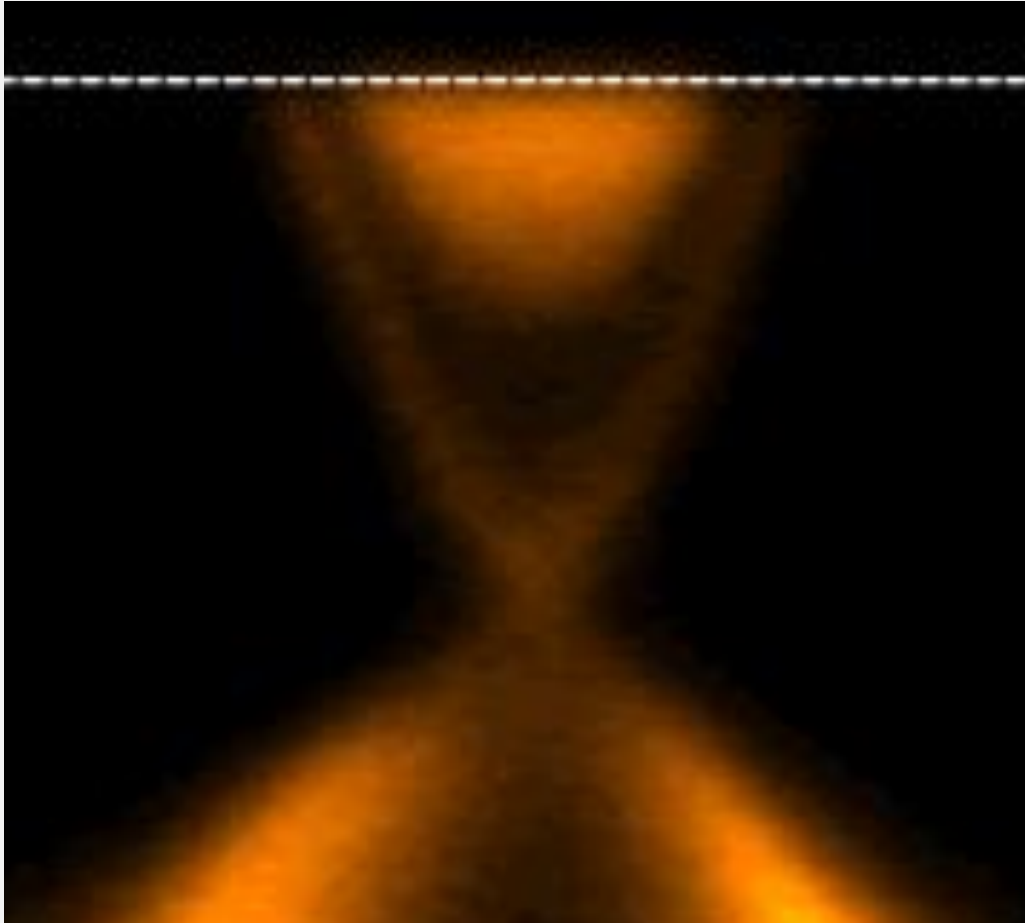


Γ point of Bi₂Te₃, A topological insulator. Raw data from PHOIBOS 225 2D-CCD with UVLS and TMM 304 at T=70K.

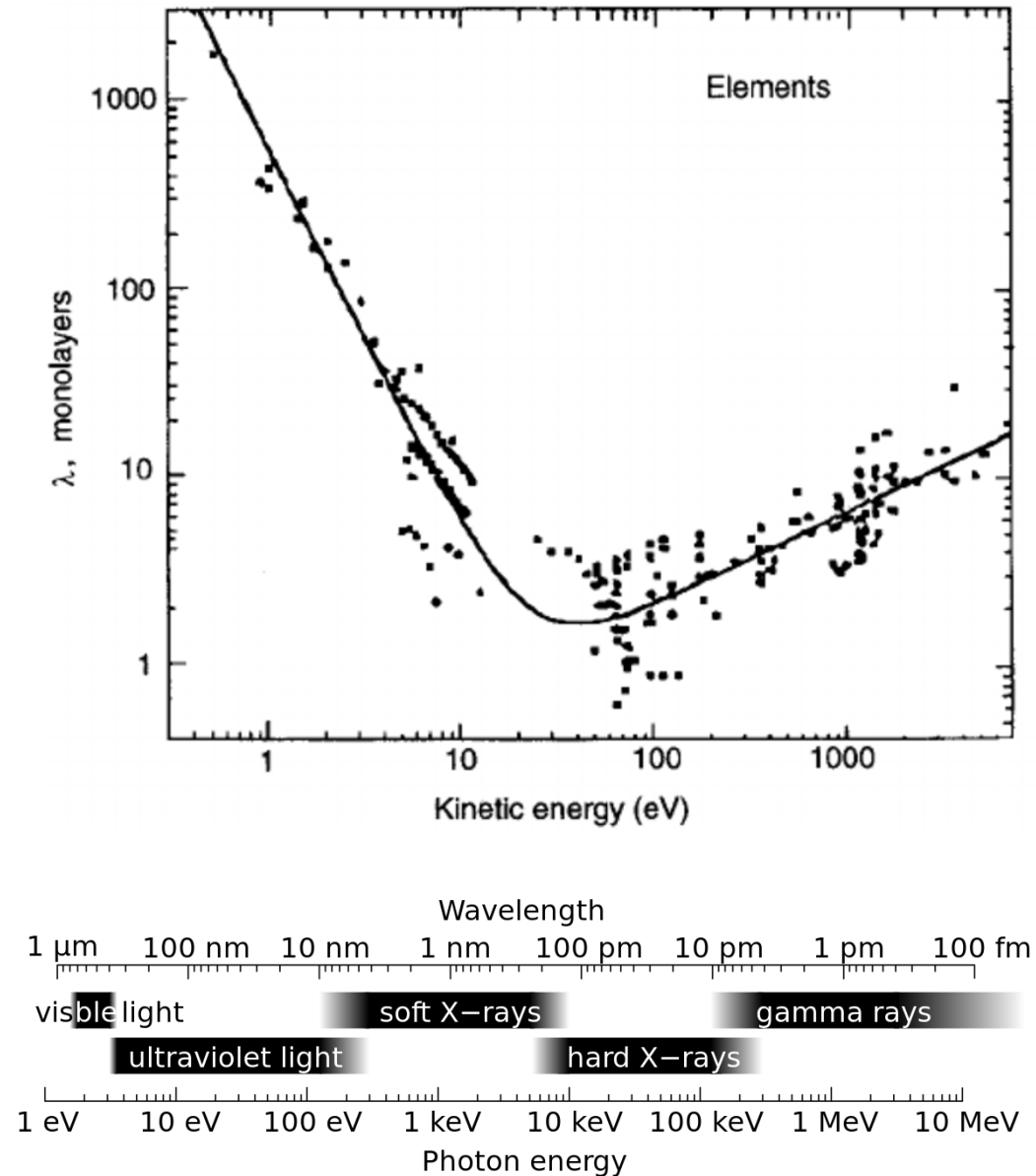


Discharge Light Source with Quartz Capillary

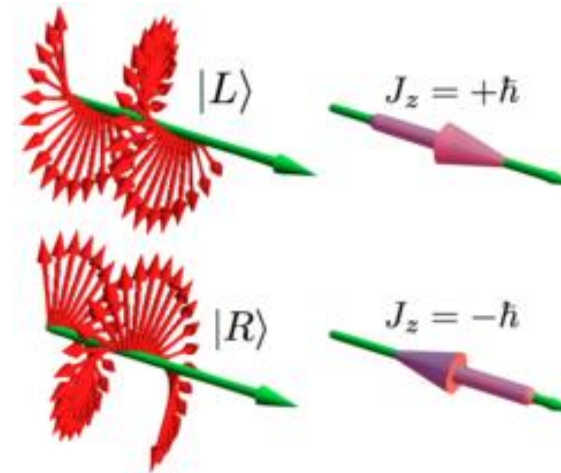
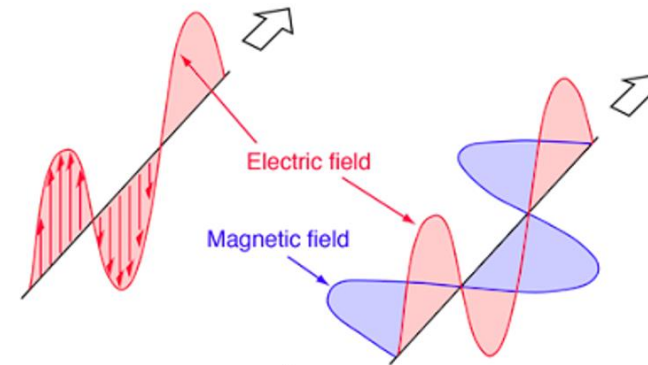
1³ at BESSY



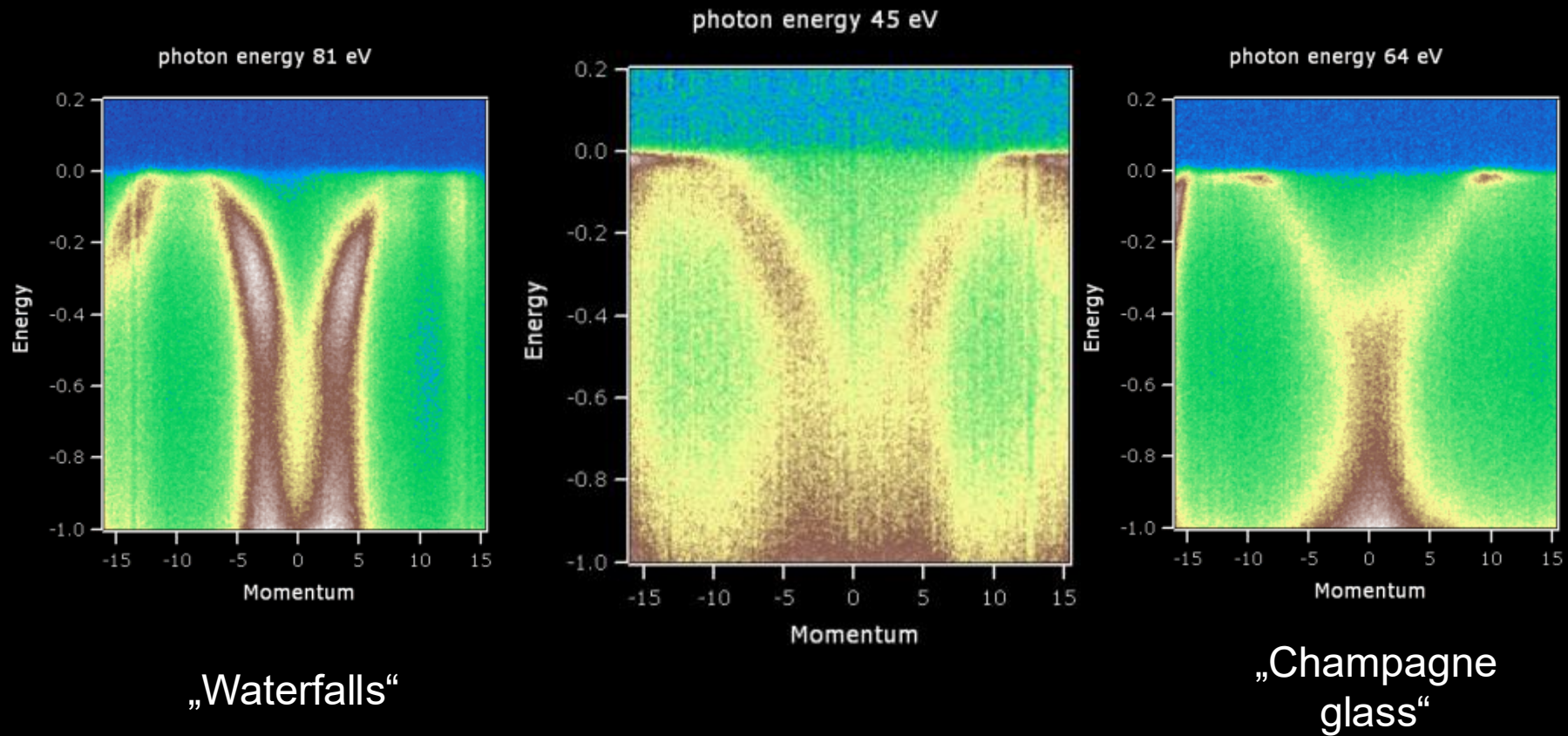
$h\nu \rightarrow$ Photoelectron escape depth + Matrix elements



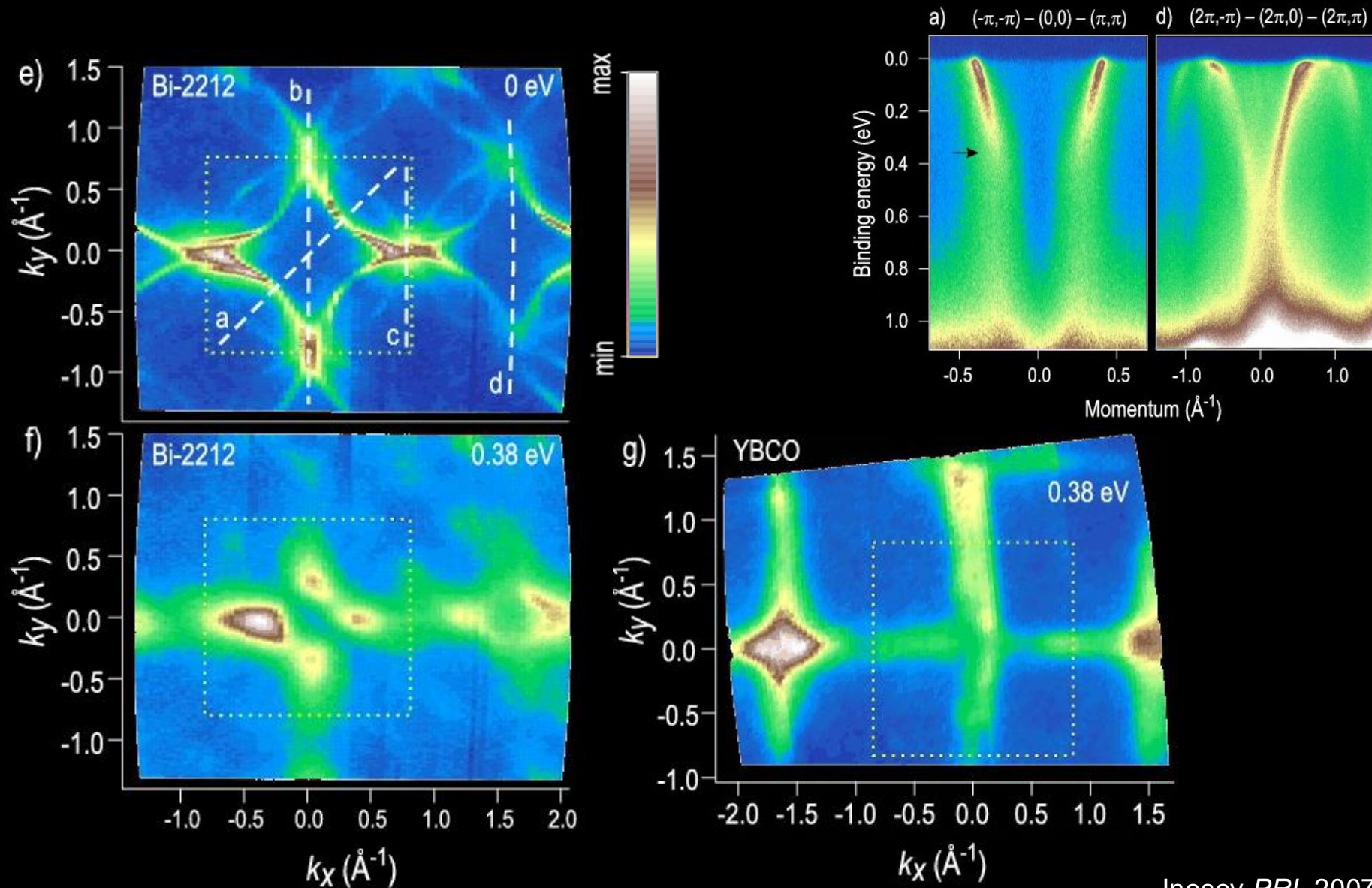
& Polarization



Photon energy – an important parameter



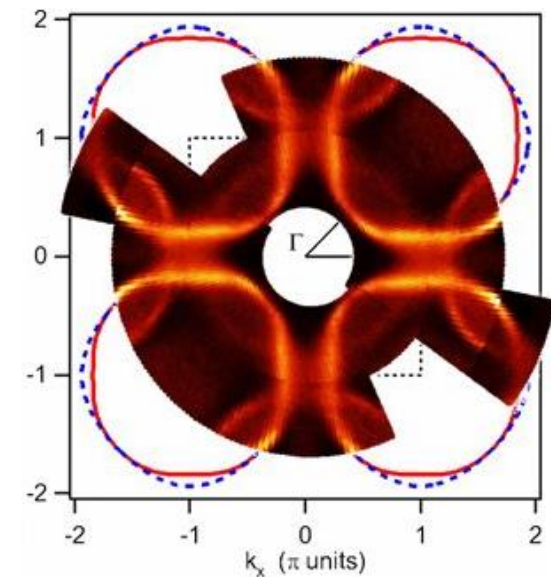
Waterfalls in cuprates



...travelling chamber







26.05 - 01.05.2025
1st beamtime at
SOLARIS at URANOS
Beamline of
KAU-IFW team

ARPES =

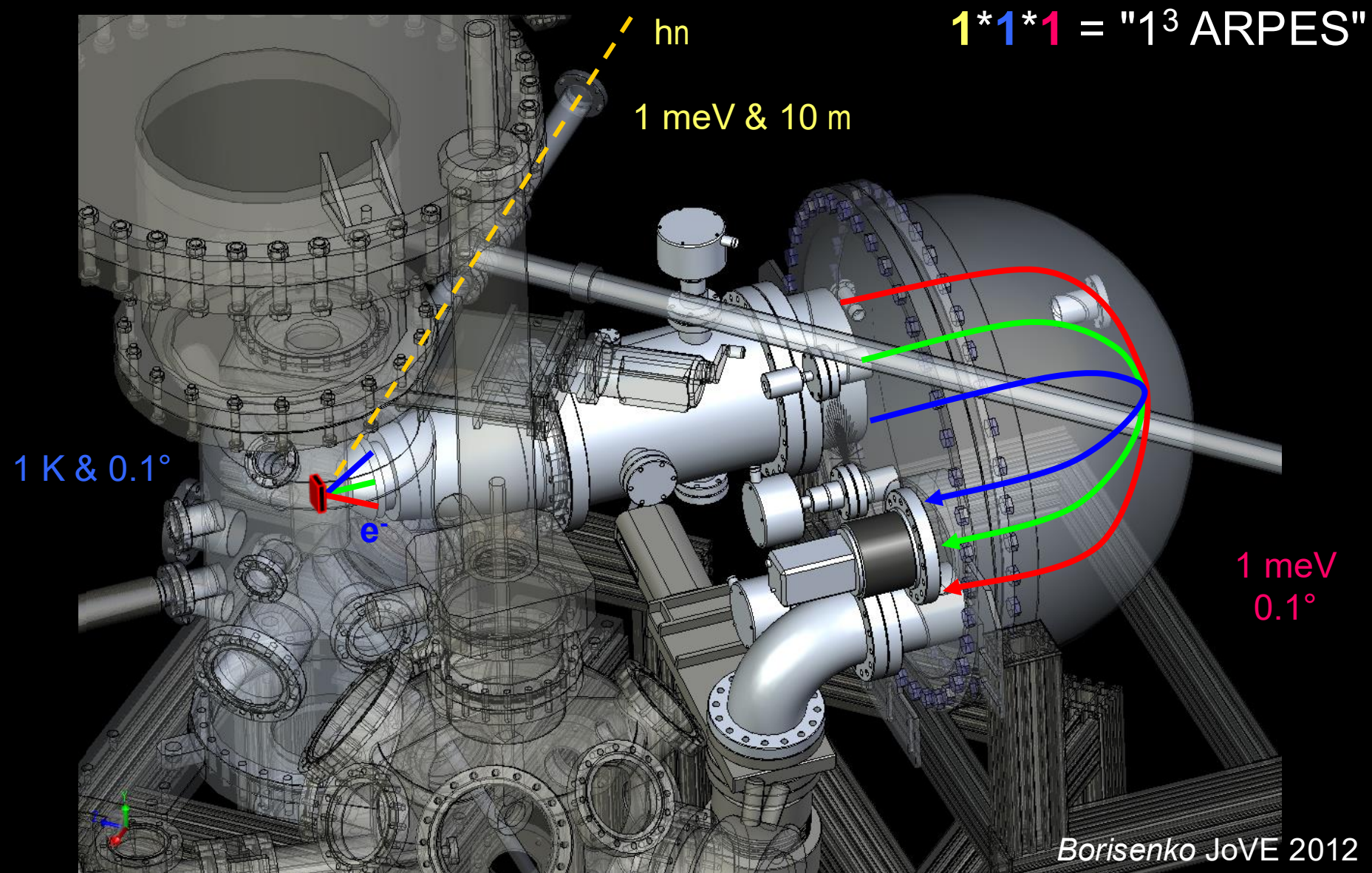
analyzer + manipulator (10^6 €)
+ synchrotron



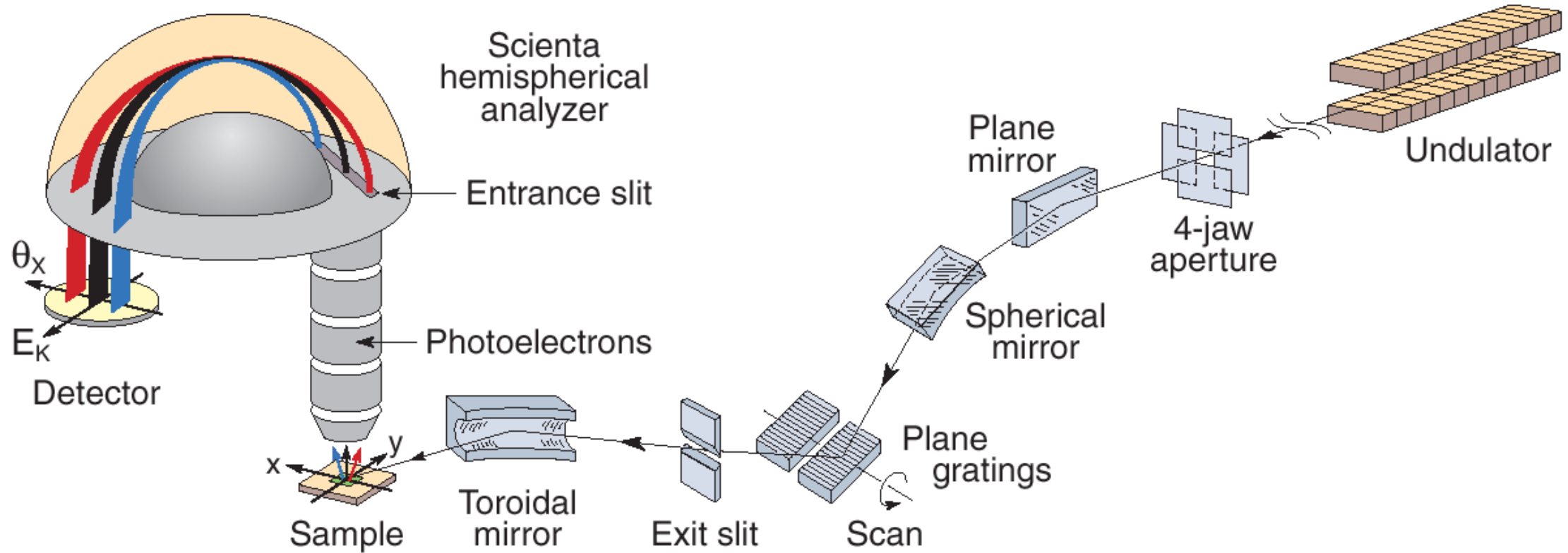
- New direction:
time resolved ARPES,
XFEL



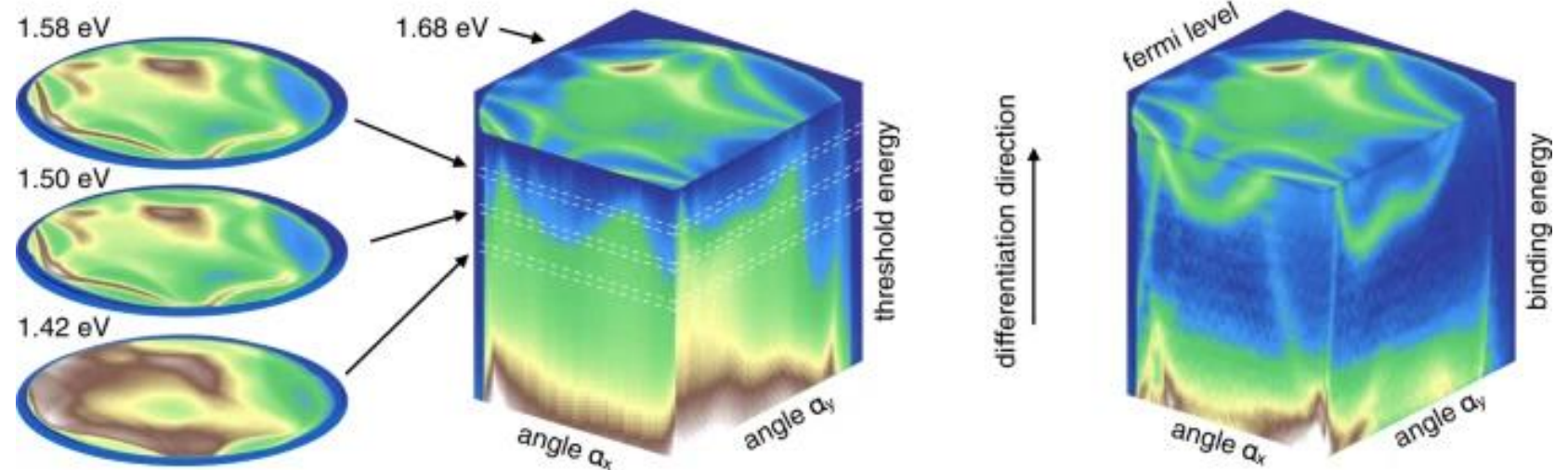
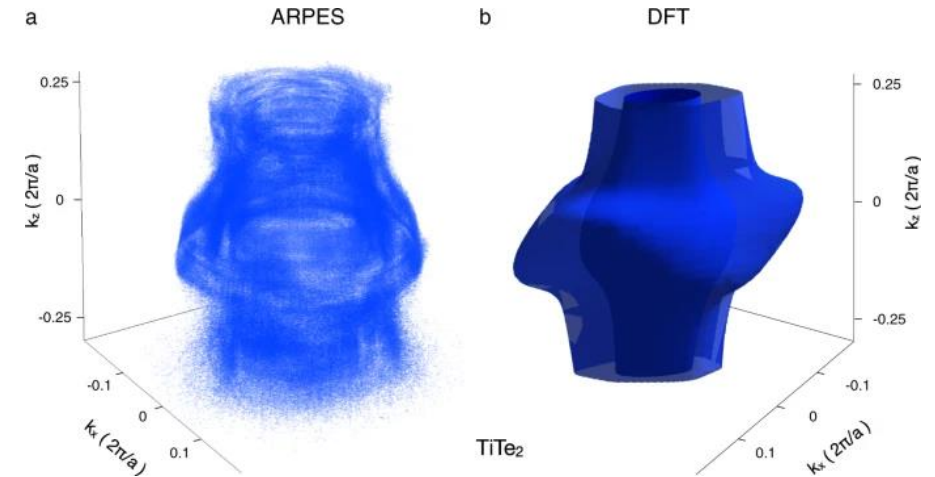
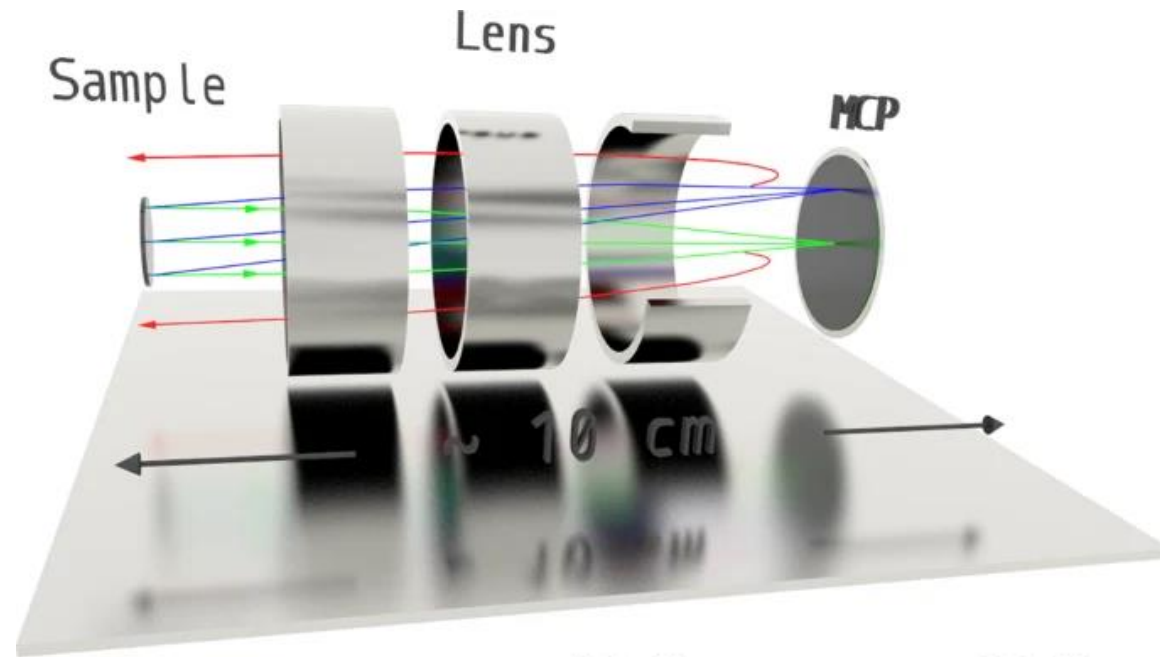
ARPES anatomy



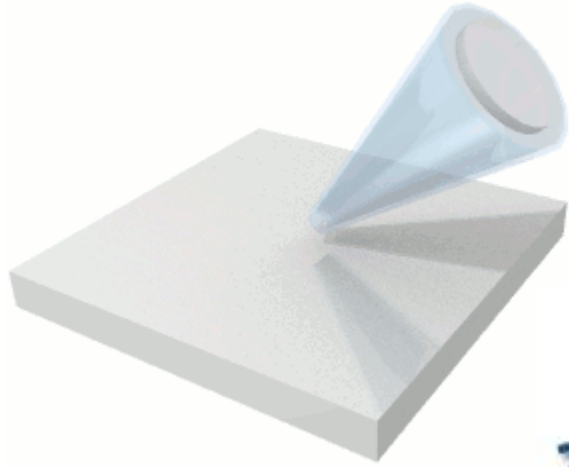
ARPES with Synchrotron Light



FeSuMa: Fermi surface tomography

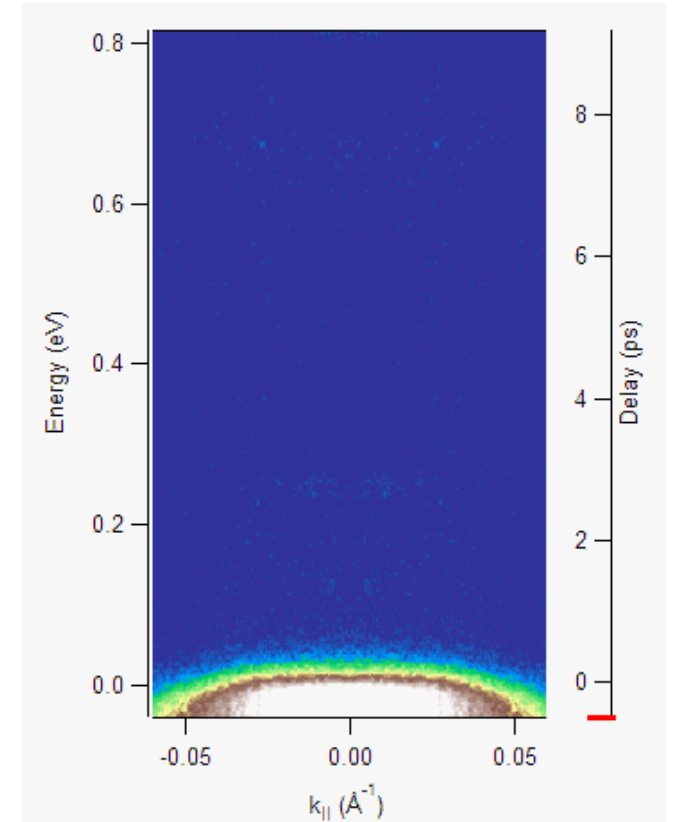
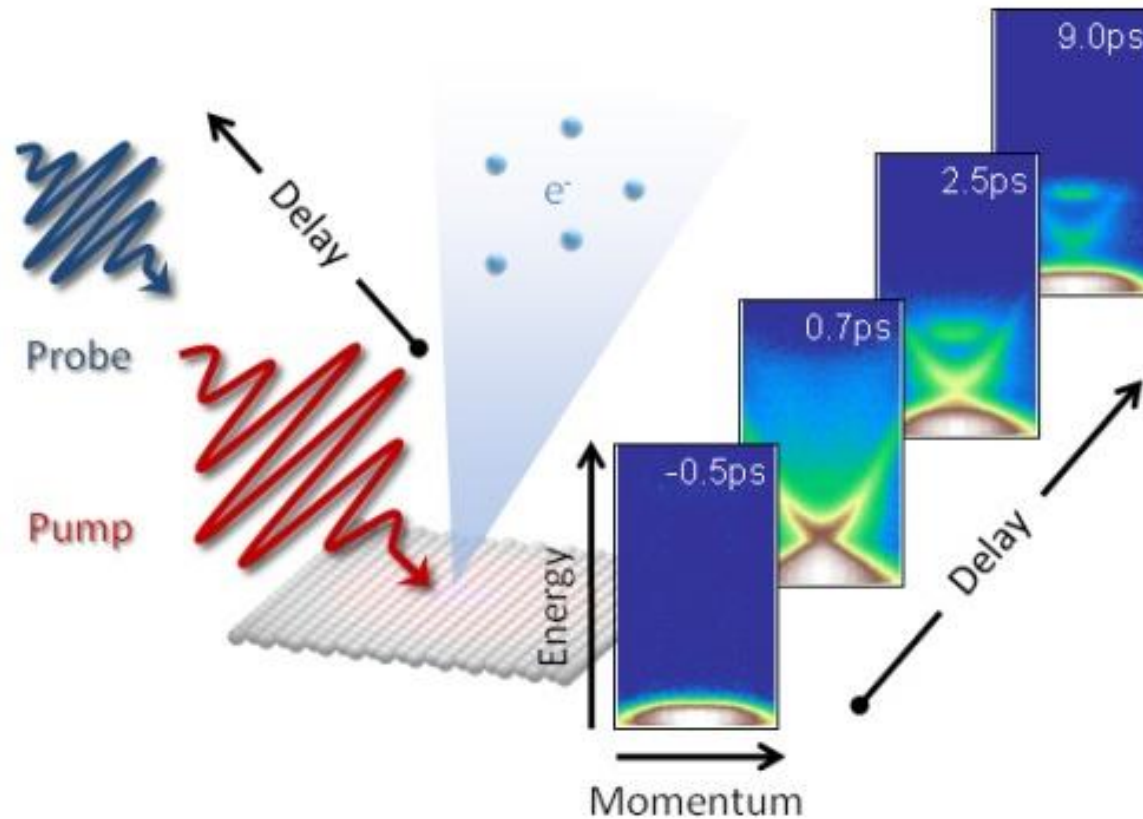


Time resolved ASRPES



$\lambda = 800 \text{ nm}$ (1.5 eV)
@ 76 MHz repetition rate

25 nJ in 50 fs pulse

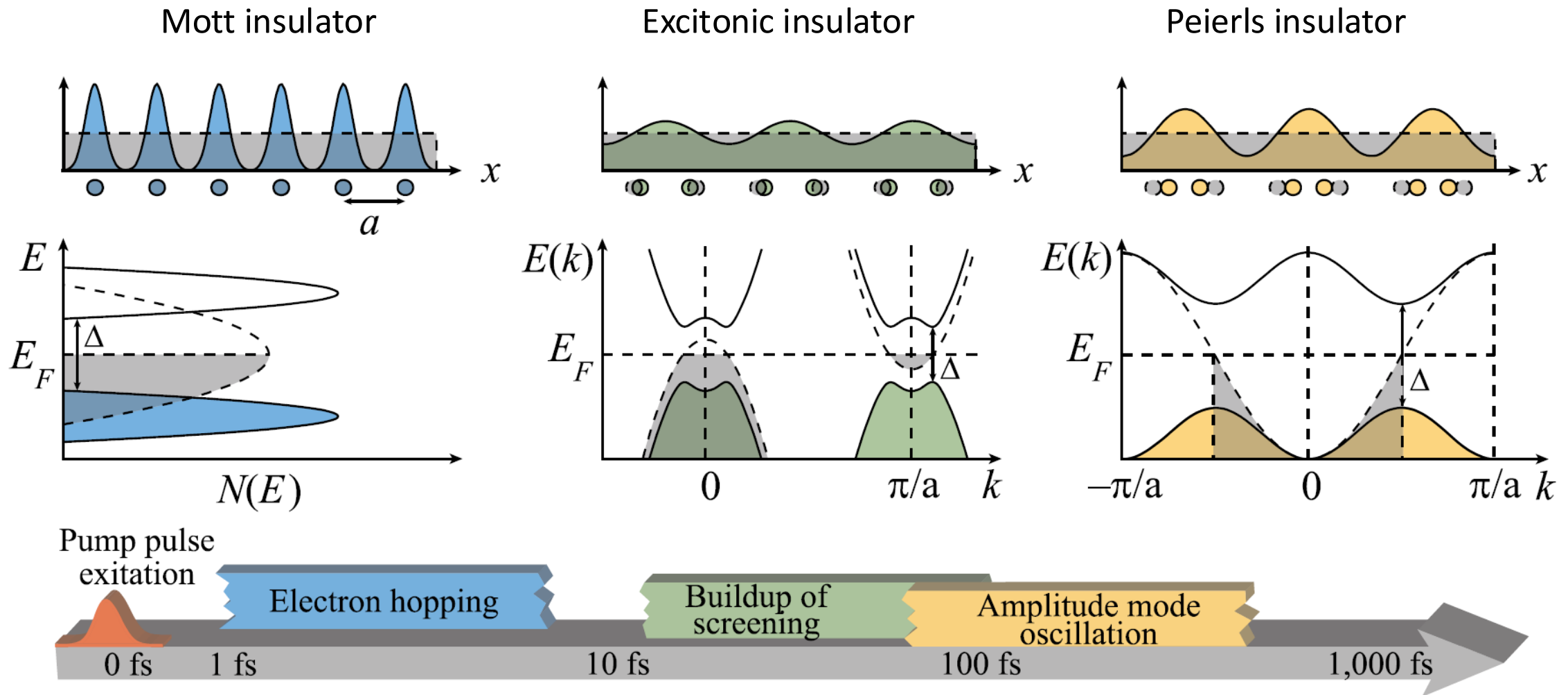


Phys. Rev. Lett. **108**, 117403 (2012)

Shen Laboratory: Time-resolved ARPES

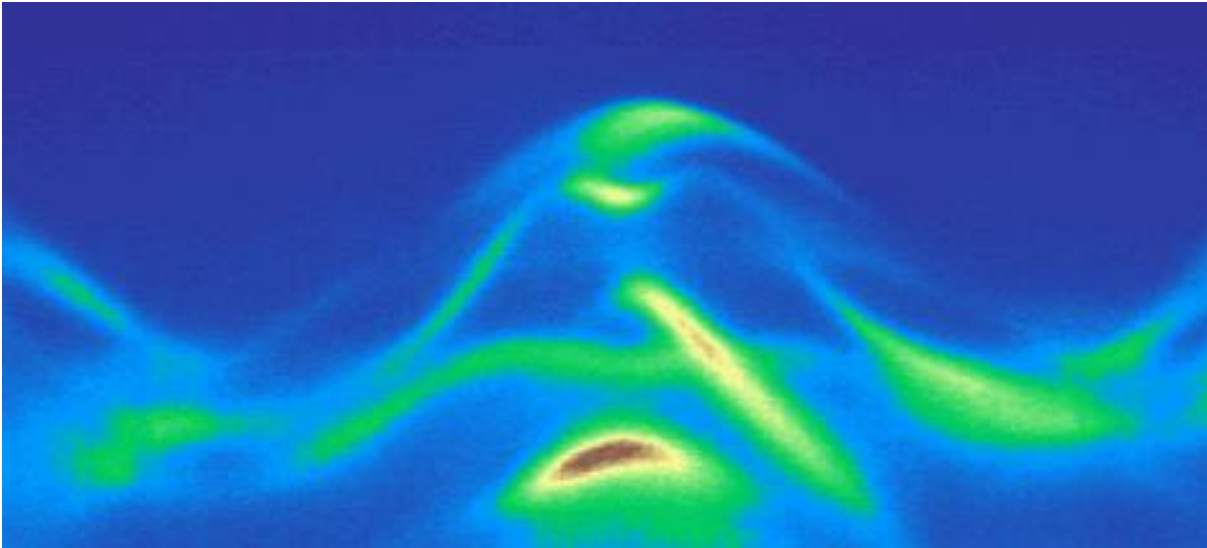
<https://arpes.stanford.edu/research/tool-development/time-resolved-arpes>

Time-domain classification of CDW insulators

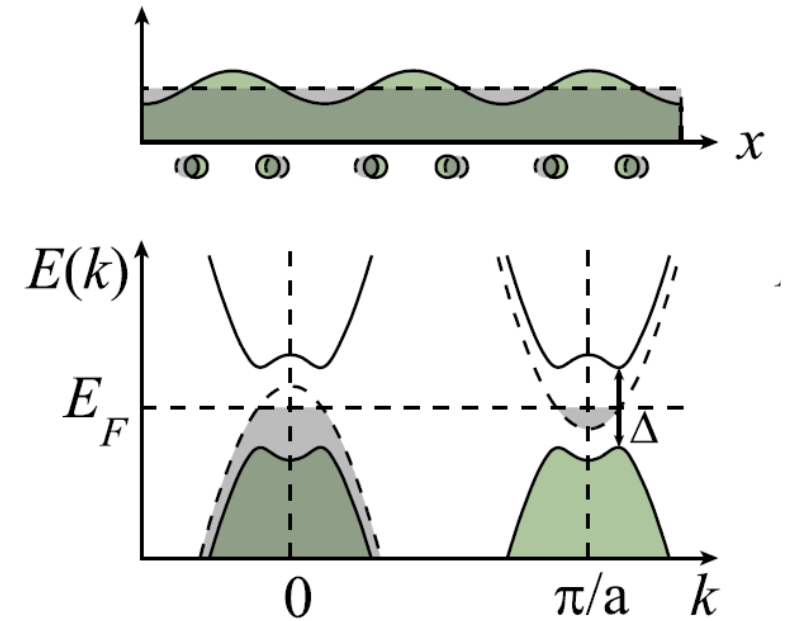


Time-domain classification of CDW insulators

1T-TiSe₂ - «excitonic insulator»

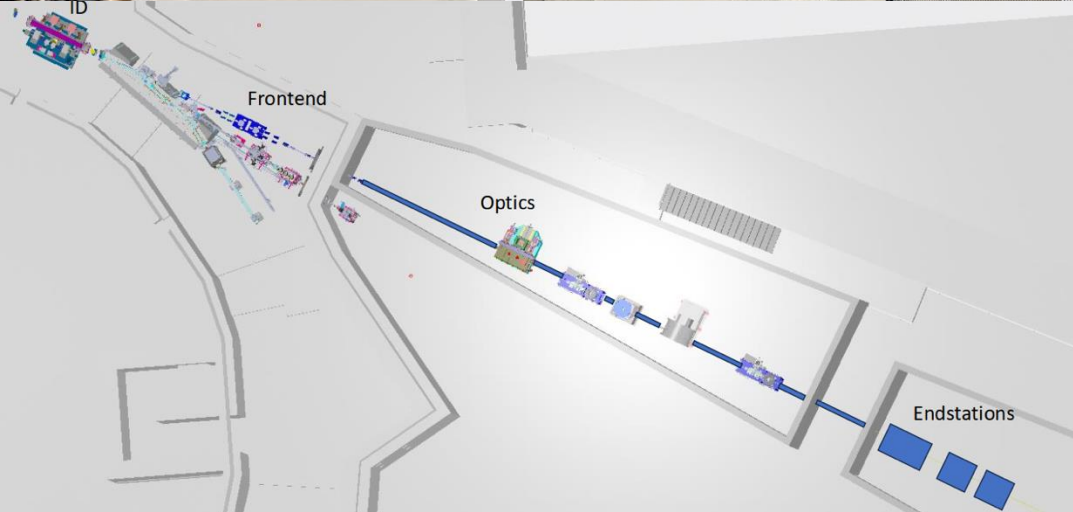


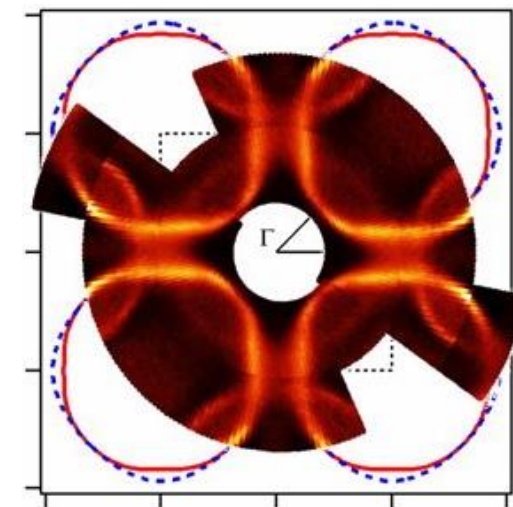
Excitonic insulator



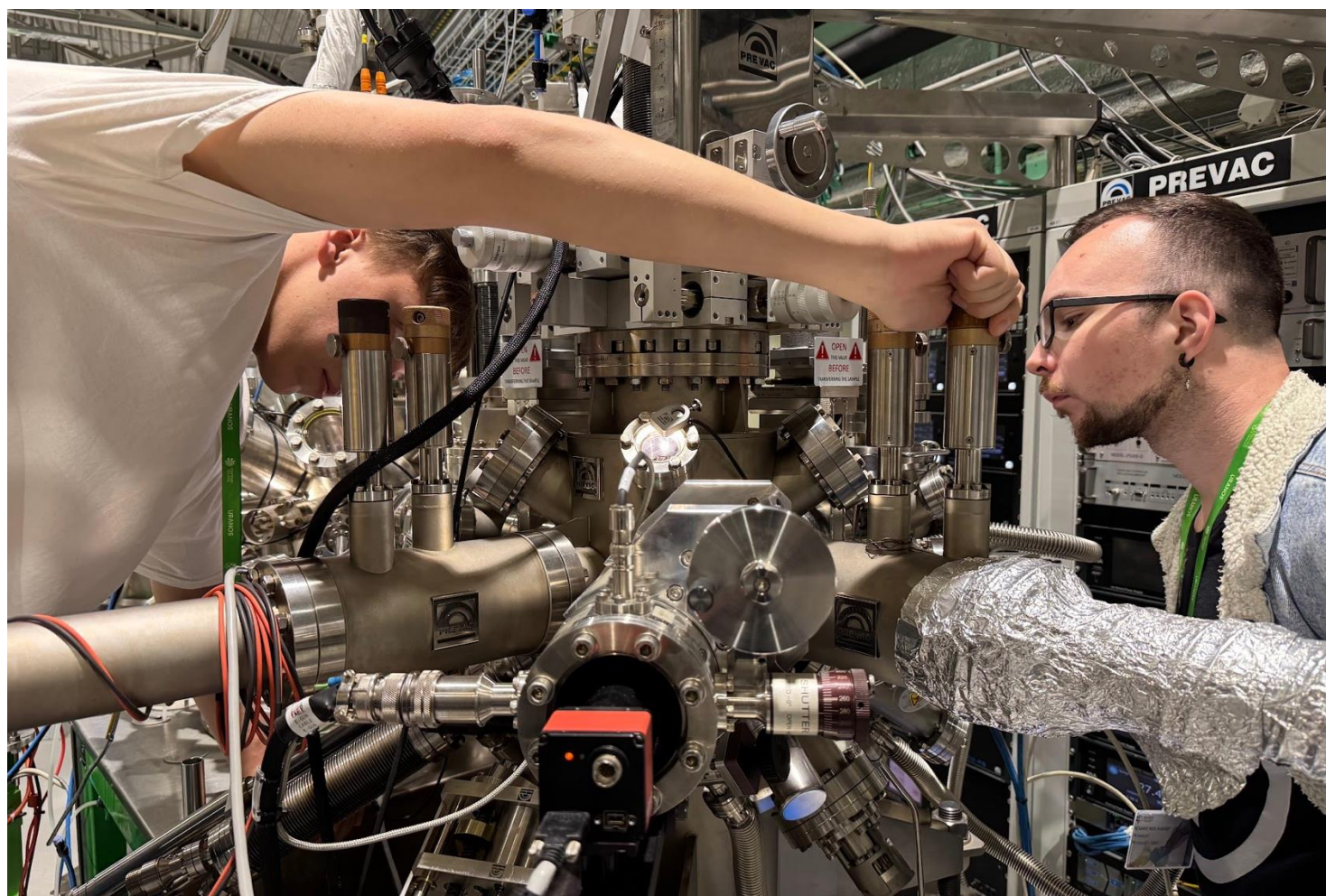
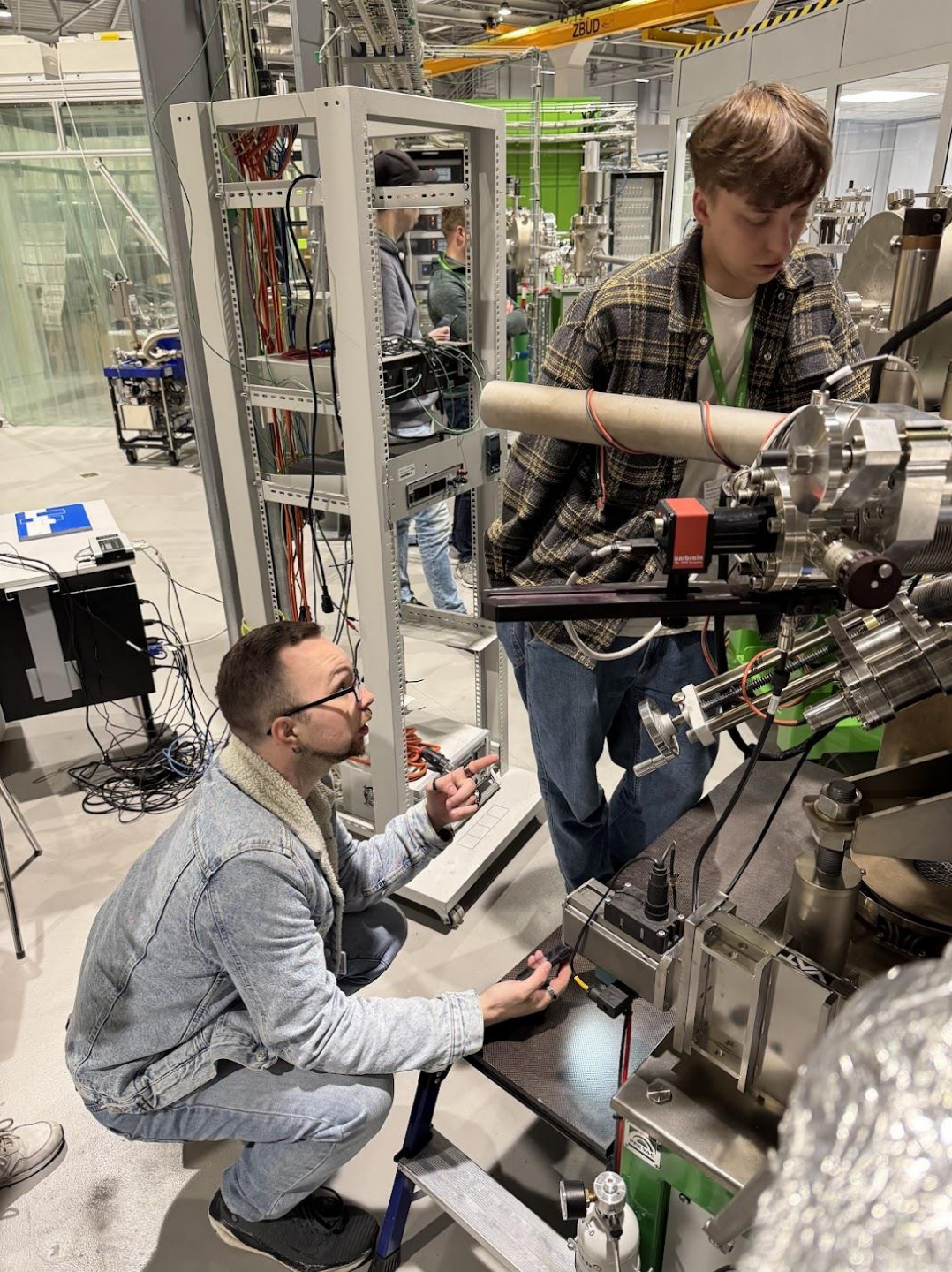
L4U Workshop at SOLARIS

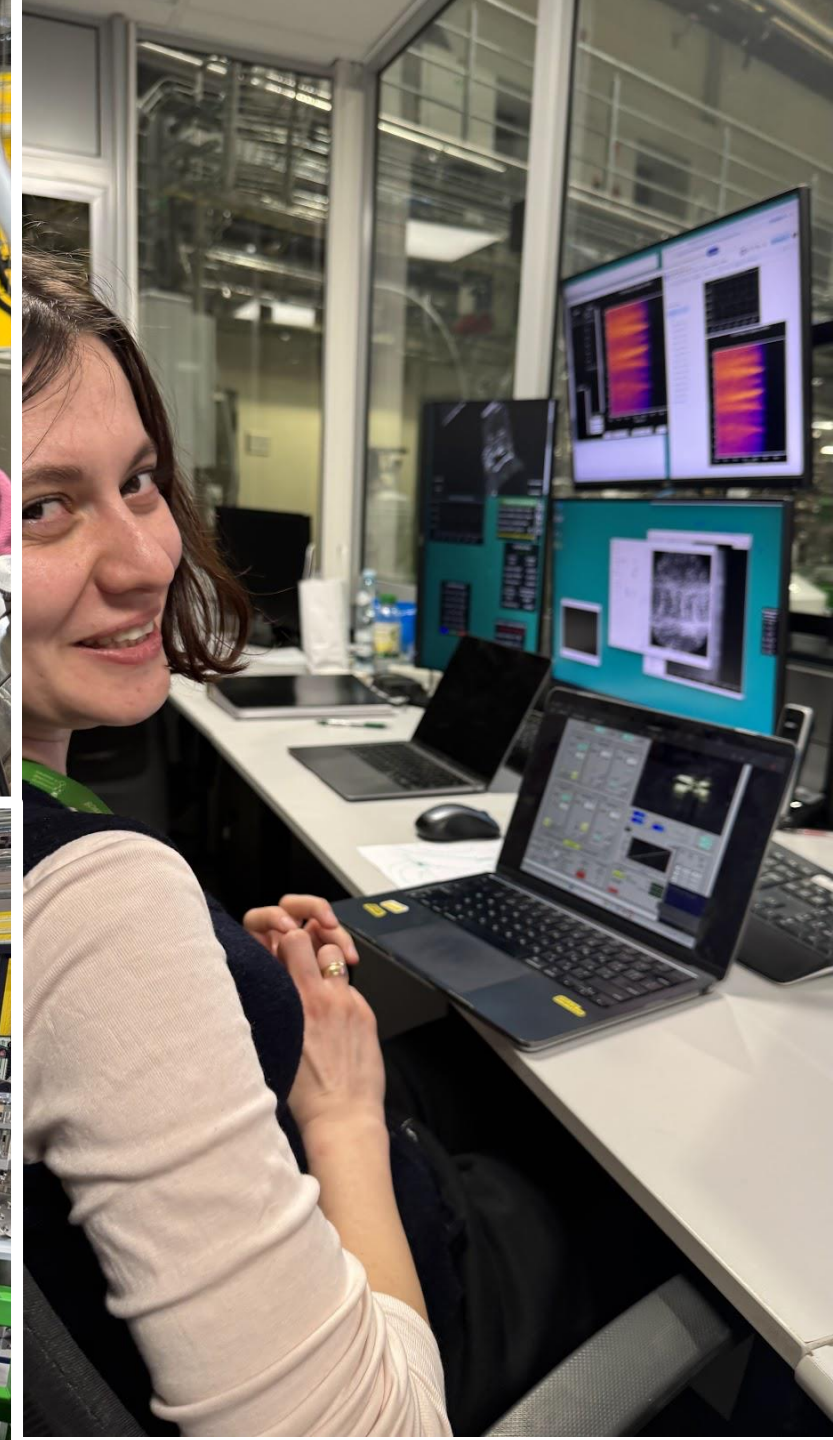
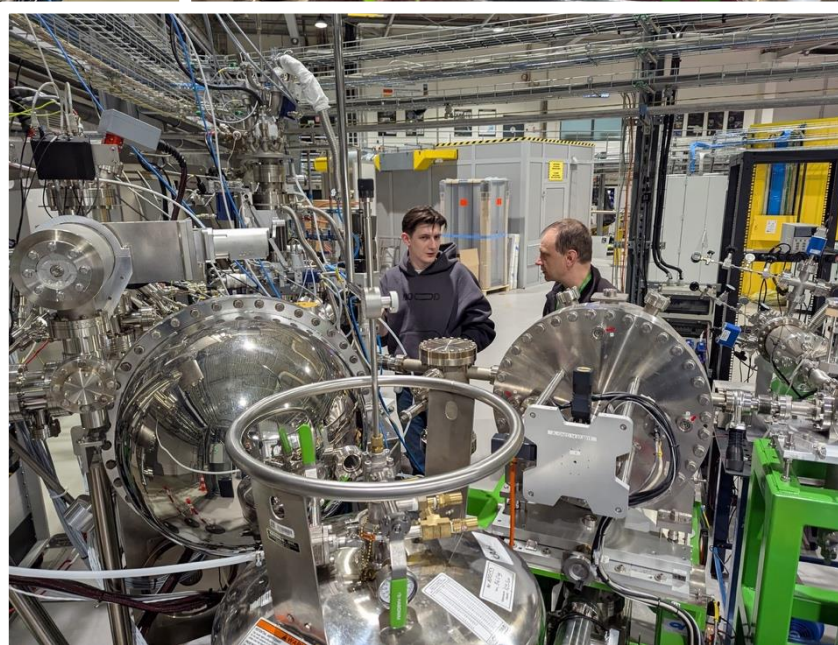
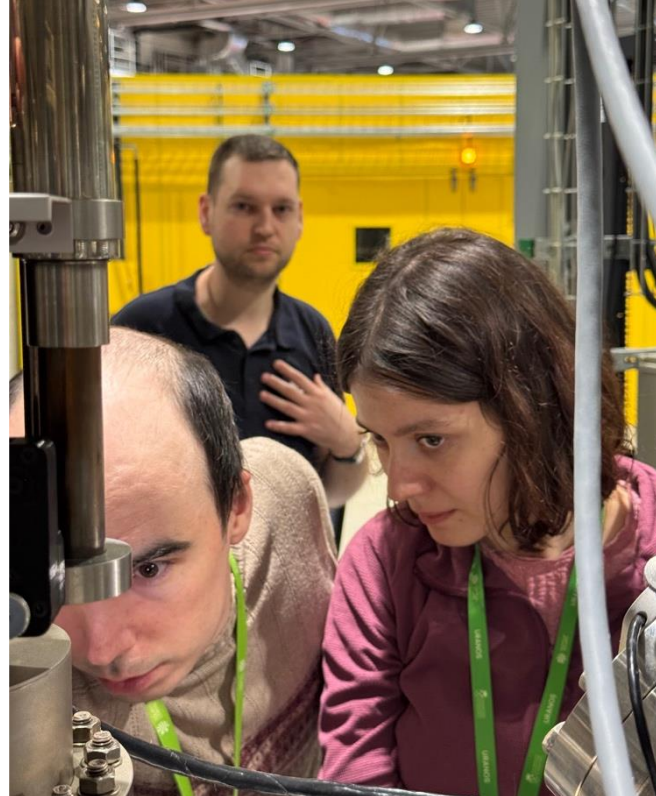
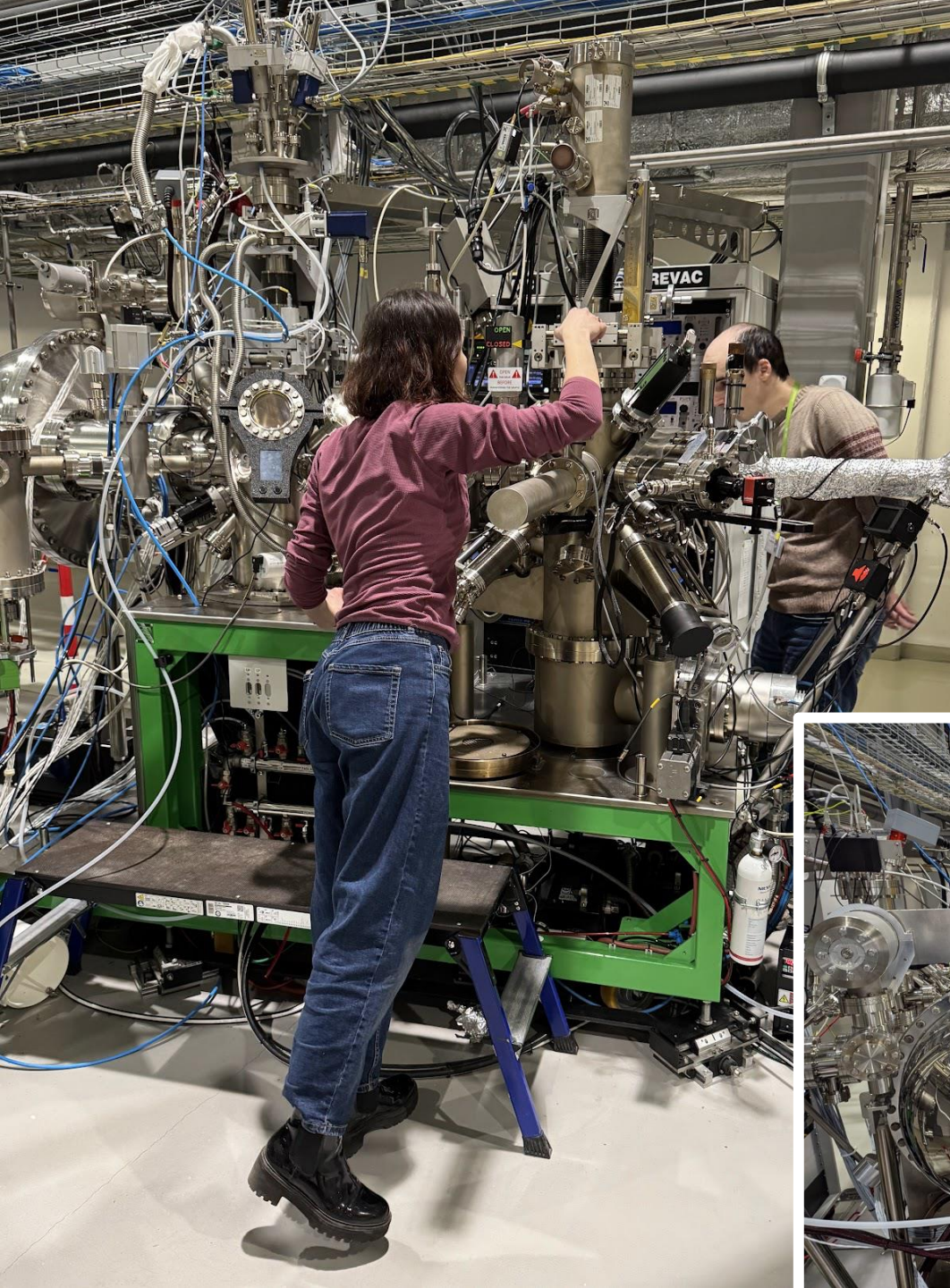
1-2 June 2025





26.05 - 01.05.2025
1st beamtime at SOLARIS
at URANOS Beamline of
KAU-IFW team





Last year statistics of Ukrainians participation

thanks to Piotr Piwowarczyk

1st edition of the **Early-Stage Researcher** programme: **2** young researchers from Ukrainian received internships (at SOLARIS and HZDR).

2nd edition: **5** Ukrainian researchers applied.

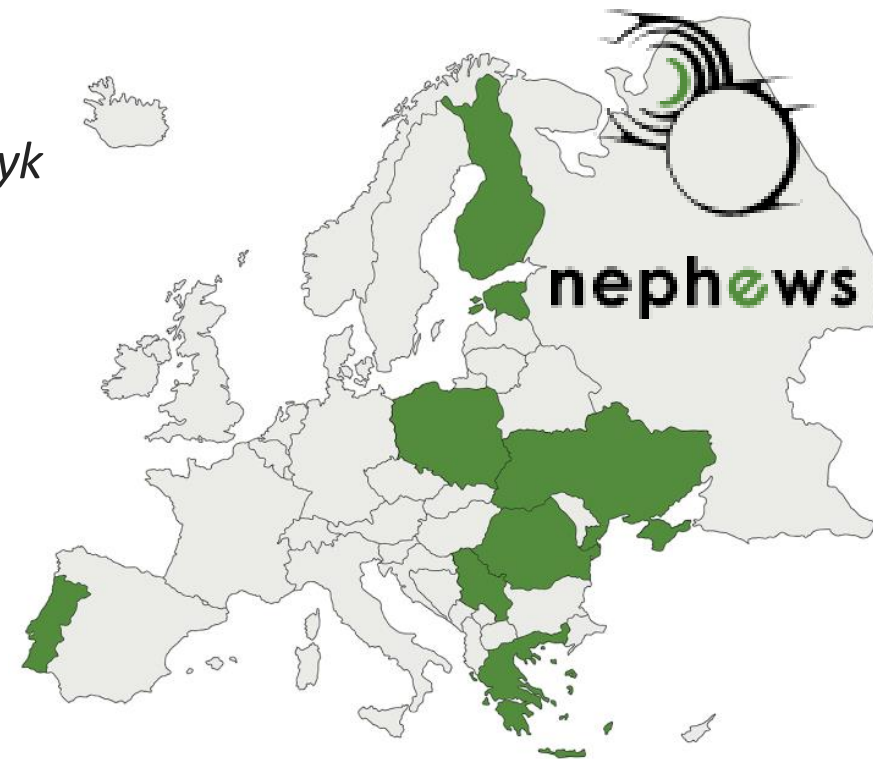
<https://beamtime.eu/programmes-support/esrs/>

Twinning programme: **13** researchers of Ukrainian nationality are registered. Some have already completed visits to research infrastructures (at SOLARIS, DESY, and ILL), while others are finalising the details of their visits.

<https://beamtime.eu/programmes-support/twinning/>

TNA: **31** researchers (SOLARIS, HZDR, HZB, DESY, and SOLEIL).

<https://beamtime.eu/programmes-support/tna/>



 SOLARIS

Join **USyNC!**

