Курс:
Фізичні методи дослідження матеріалів

Тема:
Спектроскопічні методи

Лектор: О. А. Кордюк

1. Температура

2. Тиск *+ вимірювання*
+ навантаження

3. Поле

dc

Магнітне

Електричне

ac

Спектроскопії

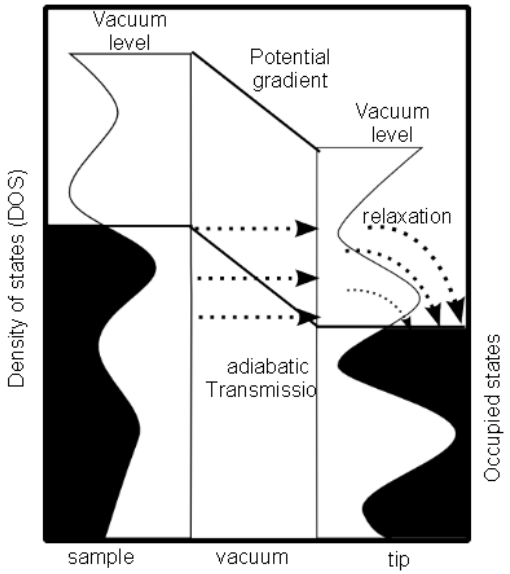
Spectroscopic Techniques

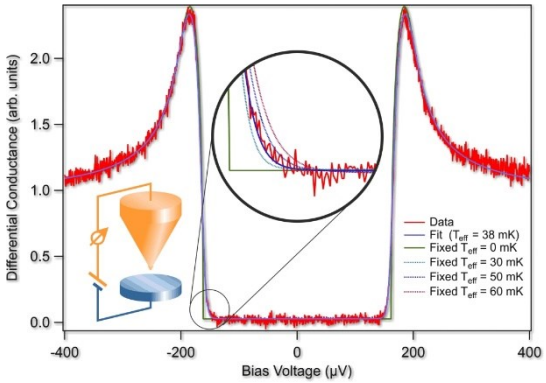
In \ Out	*hv*	*electrons*	*A*
hv	**XD, IR, Raman**	**ARPES, XPD**	**LA**
e	**IPS, EDX (SEM)**	**SEM, LEED, EELS**	**ESD**
A	**BLE**	**IAES**	**RBS, SIMS**
T			**TDS**
E		**STM/STS, FEM**	**FIM**

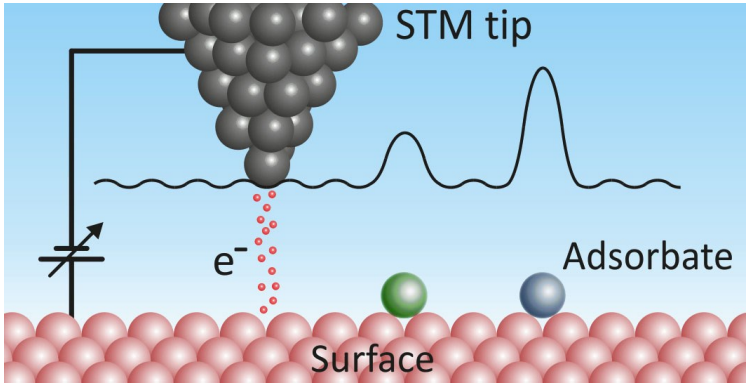
n-n: **ND, INS**

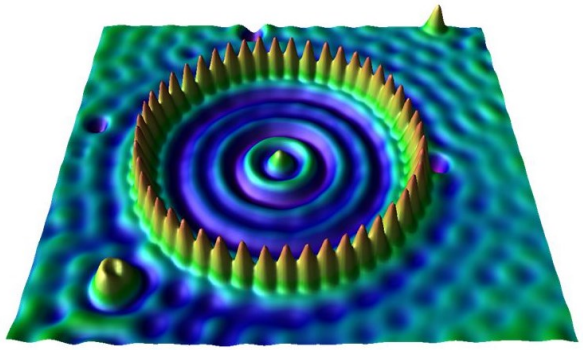
μ-e^+: **µSR**

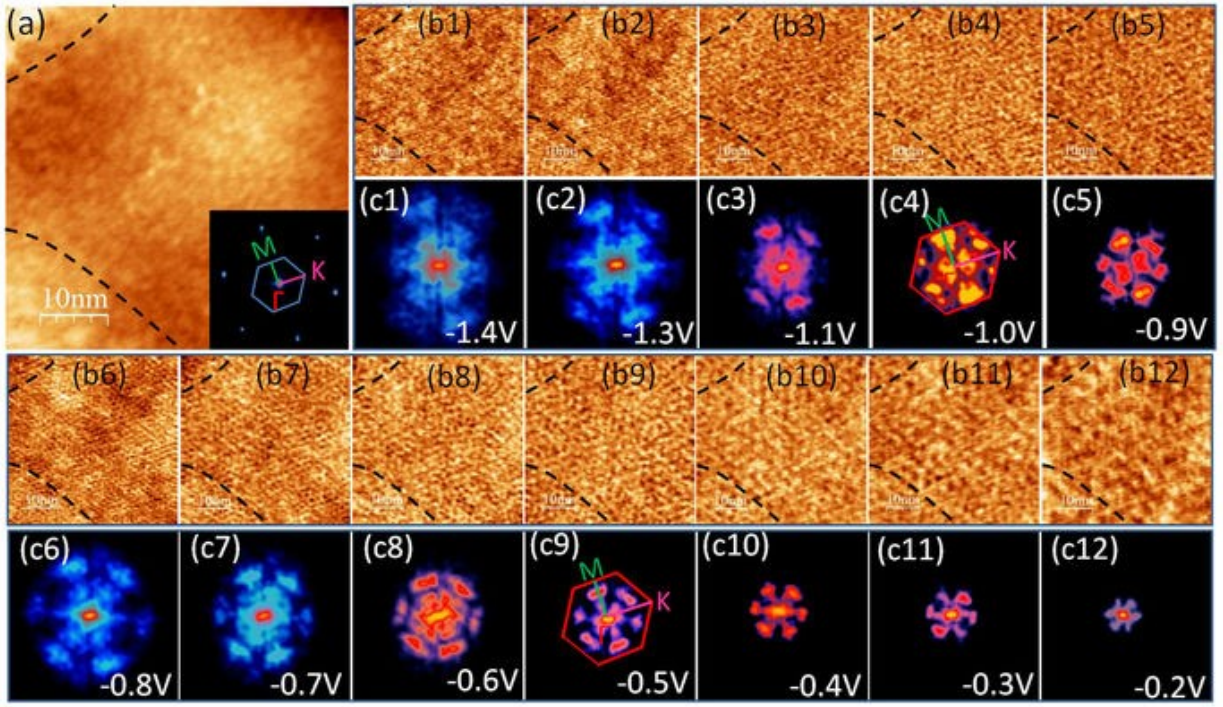
Scanning tunneling spectroscopy (STS)











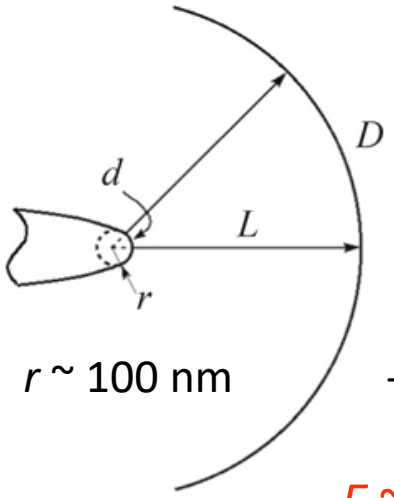
Spectroscopic Techniques

In \ Out	*hv*	*electrons*	*A*
hv	**XD, IR, Raman**	**ARPES, XPD**	**LA**
e	**IPS, EDX (SEM)**	**SEM, LEED, EELS**	**ESD**
A	**BLE**	**IAES**	**RBS, SIMS**
T			**TDS**
E		**STM/STS, FEM**	**FIM**

n-n: **ND, INS**

μ-e^+: **µSR**

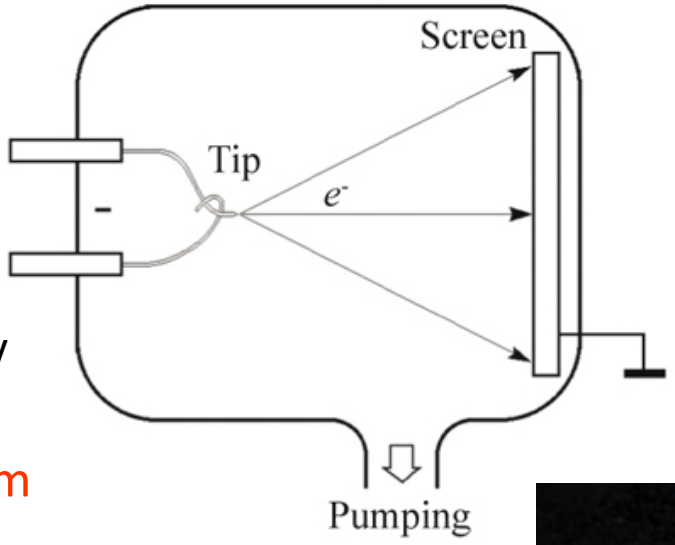
Field-emission microscopy (FEM)



r ~ 100 nm

High voltage

-(1–10) kV



$E \sim 10^{10}$ V/m

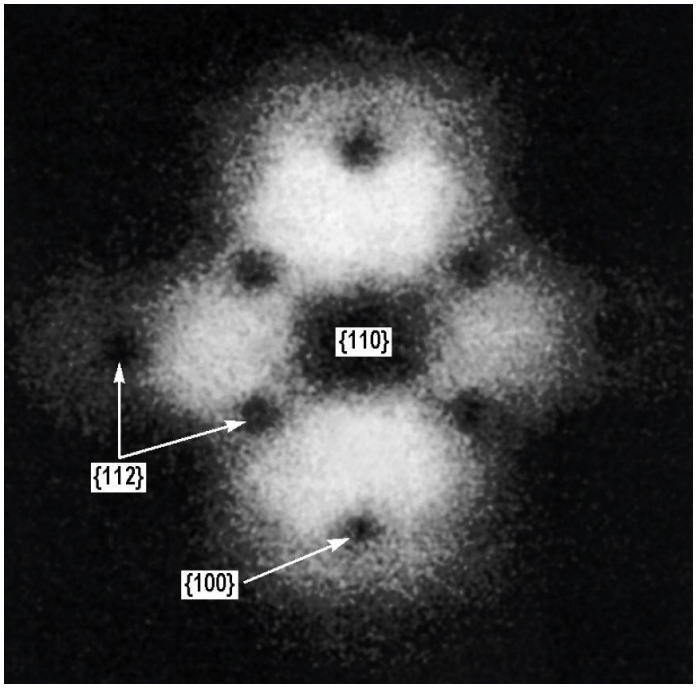
1936, Erwin Müller

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

*	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
**	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Refractory metals

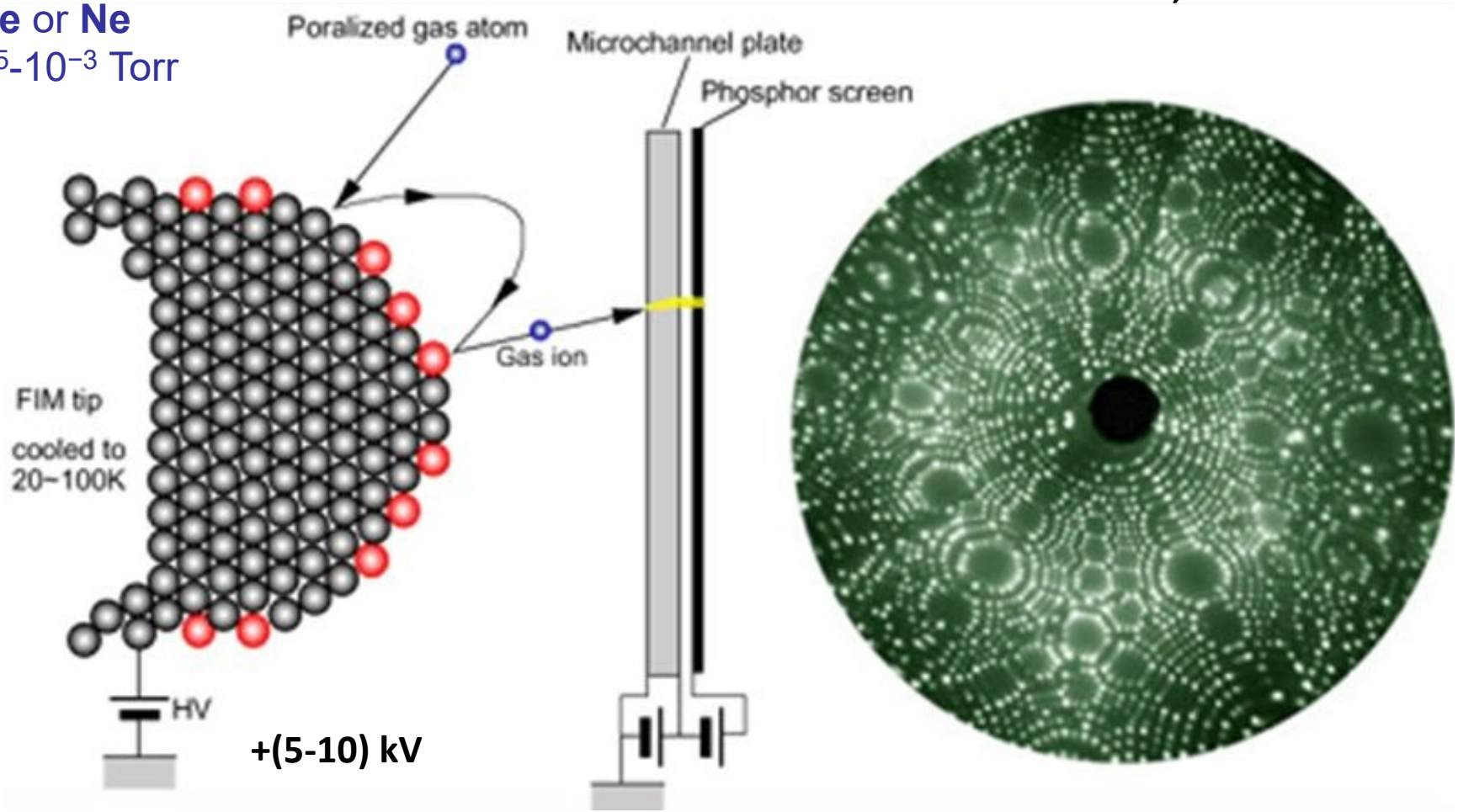
Wider definition of refractory metals[1]



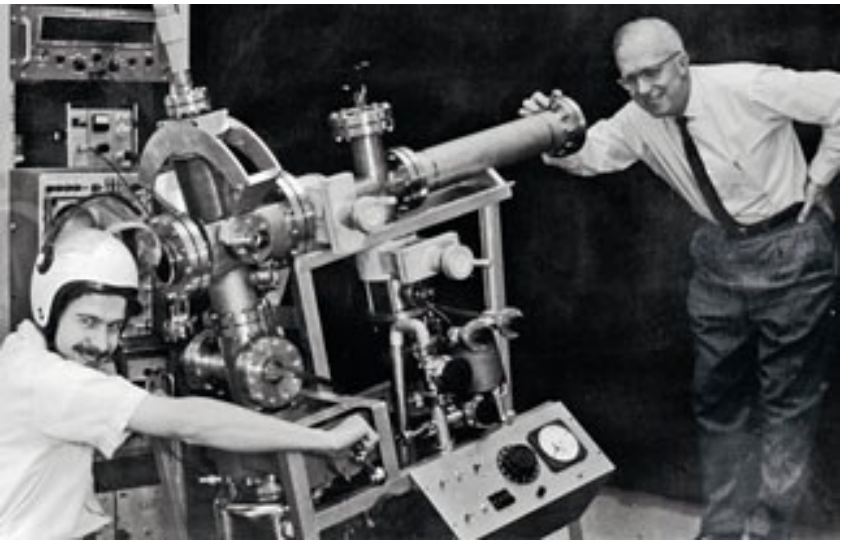
Field ion microscope (FIM)

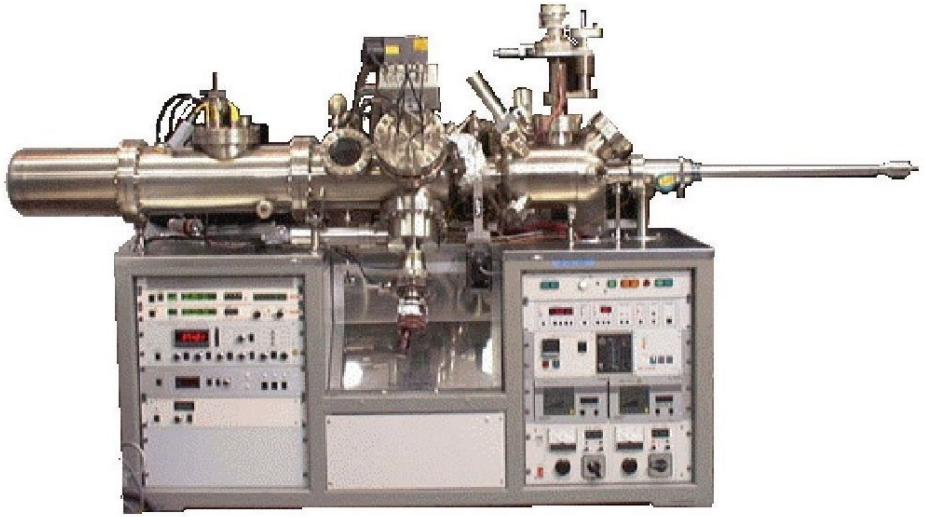
1955, Erwin Müller

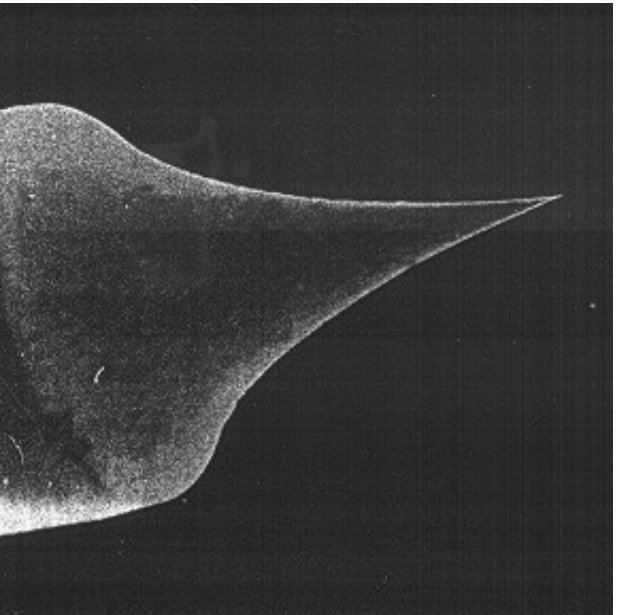
He or **Ne**
10^{-5}-10^{-3} Torr

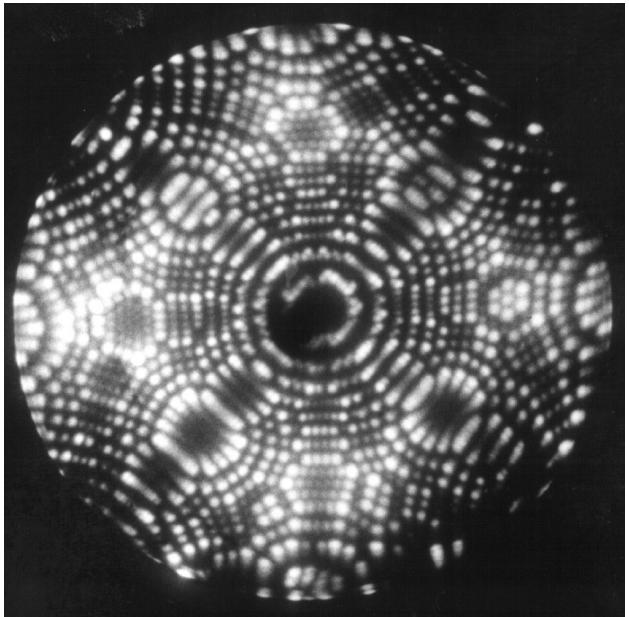


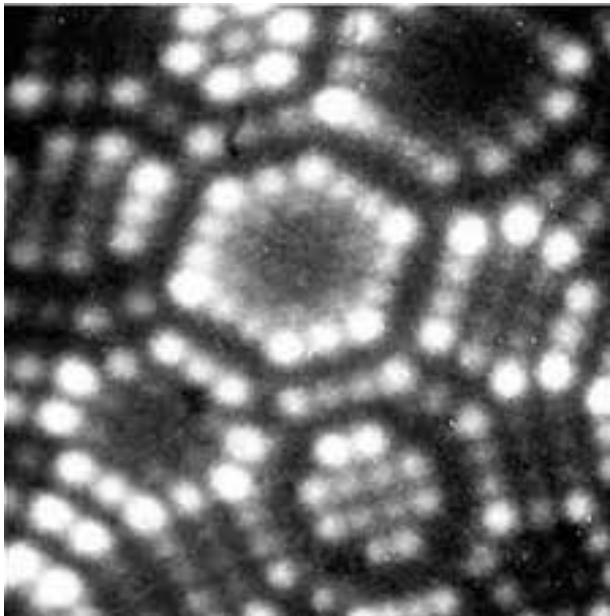
Field ion microscope (FIM)



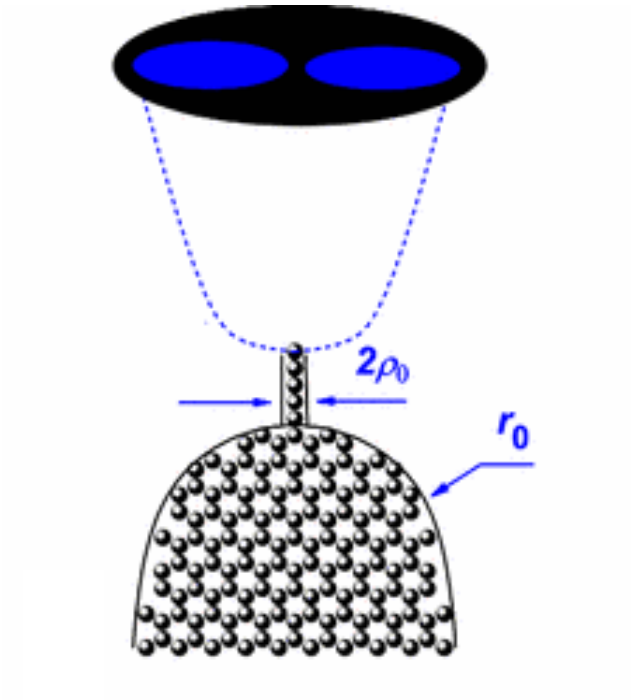


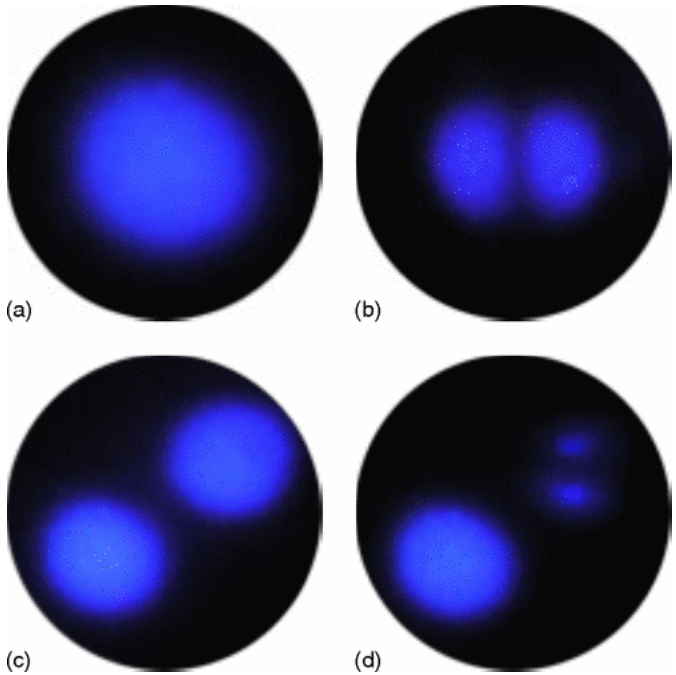




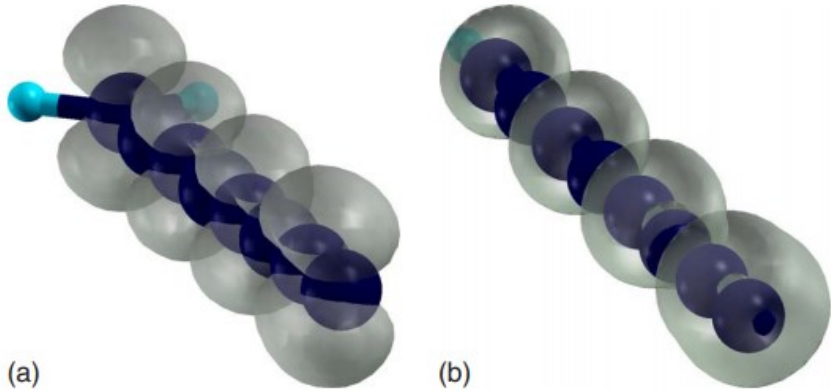


Ultrahigh resolution field-emission electron microscopy

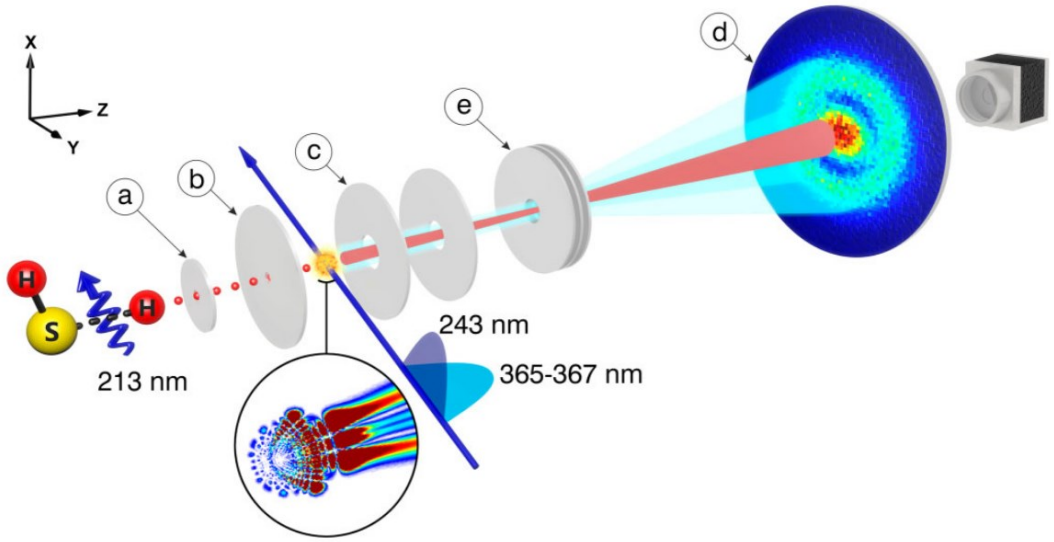


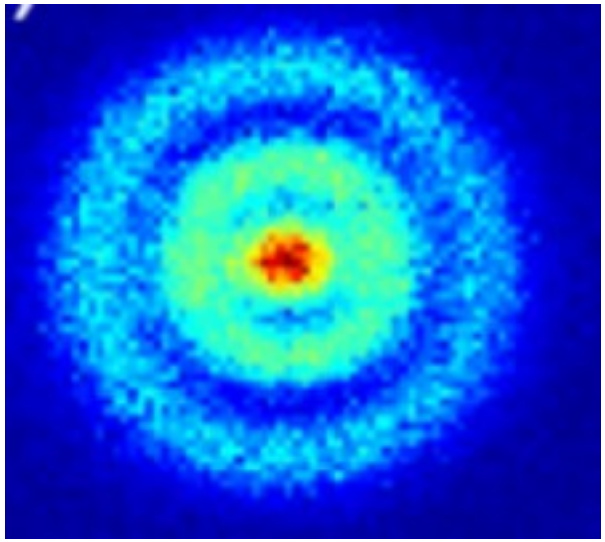


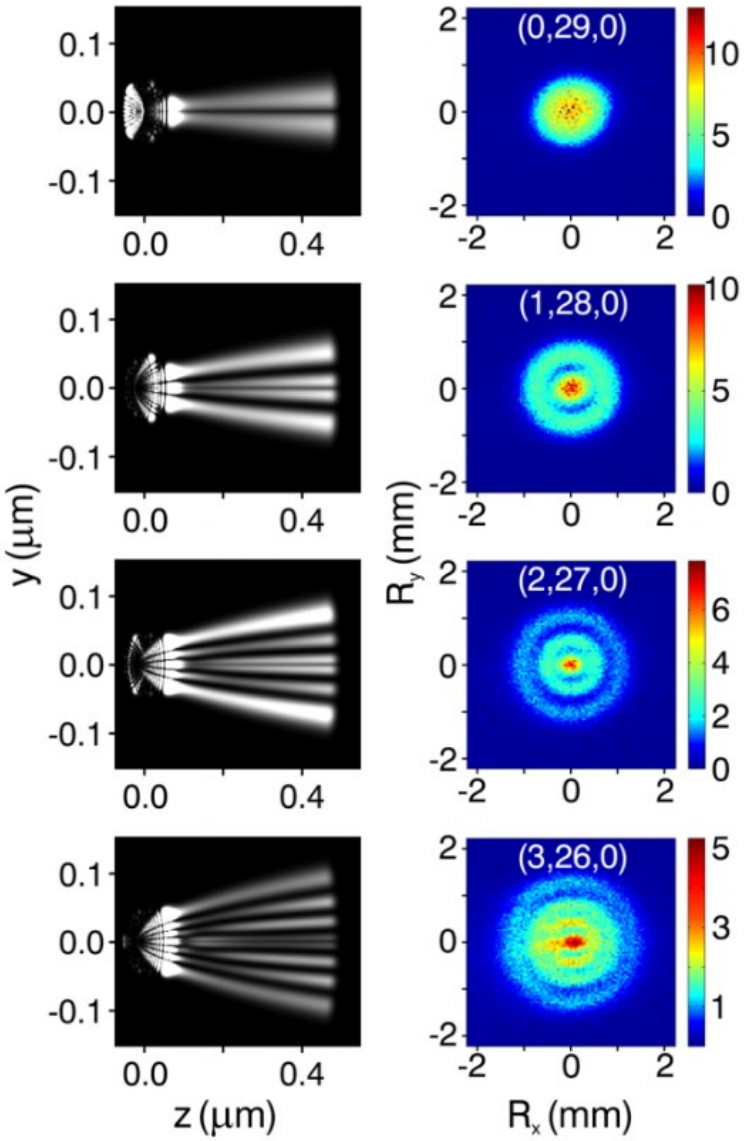
Mikhailovskij *PRB* 2009
see also Comment and Answer



Velocity map imaging spectrometer (VMI)







Stodolna *PRL* 2013

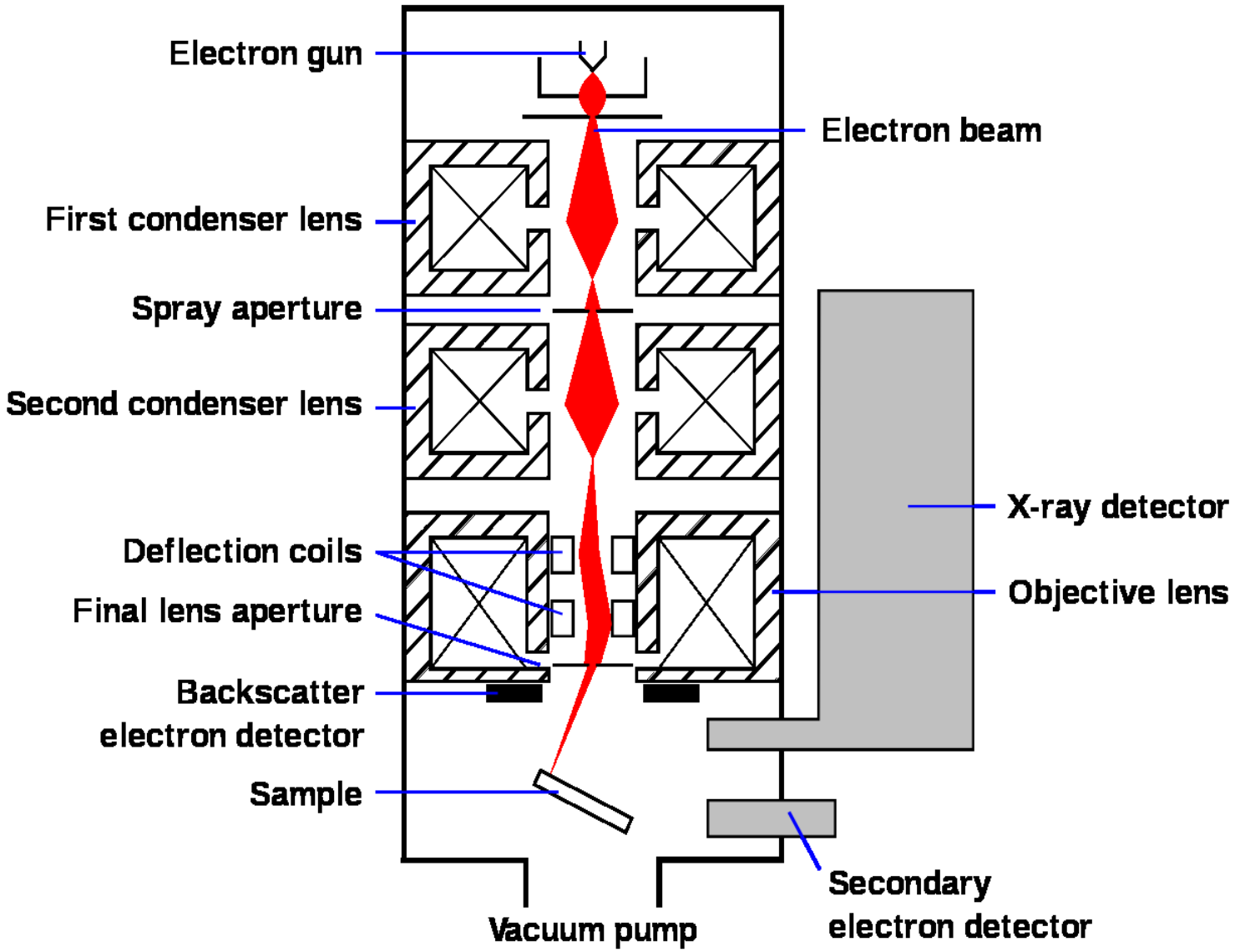
Spectroscopic Techniques

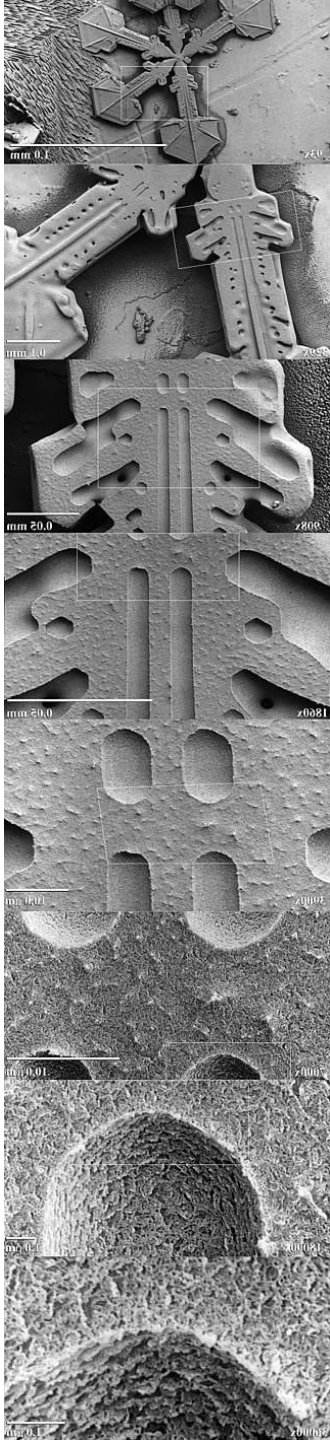
In \ Out	*hv*	*electrons*	*A*
hv	**XD, IR, Raman**	**ARPES, XPD**	**LA**
e	**IPS, EDX (SEM)**	**SEM, LEED, EELS**	**ESD**
A	**BLE**	**IAES**	**RBS, SIMS**
T			**TDS**
E		**STM/STS, FEM**	**FIM**

n-n: **ND, INS**

μ-e^+: **μSR**

Scanning electron microscope (SEM)





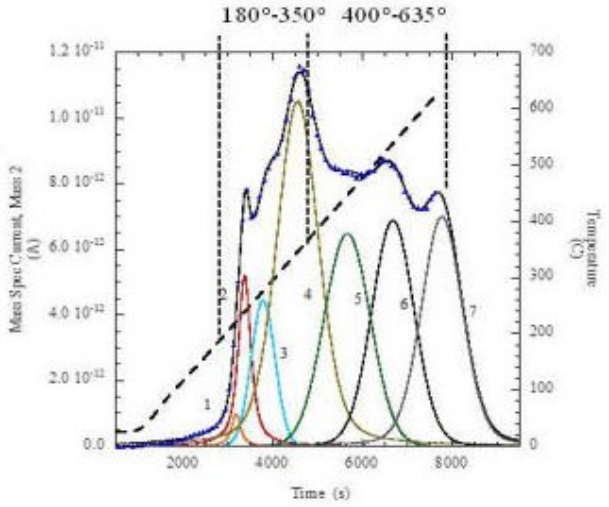
Spectroscopic Techniques

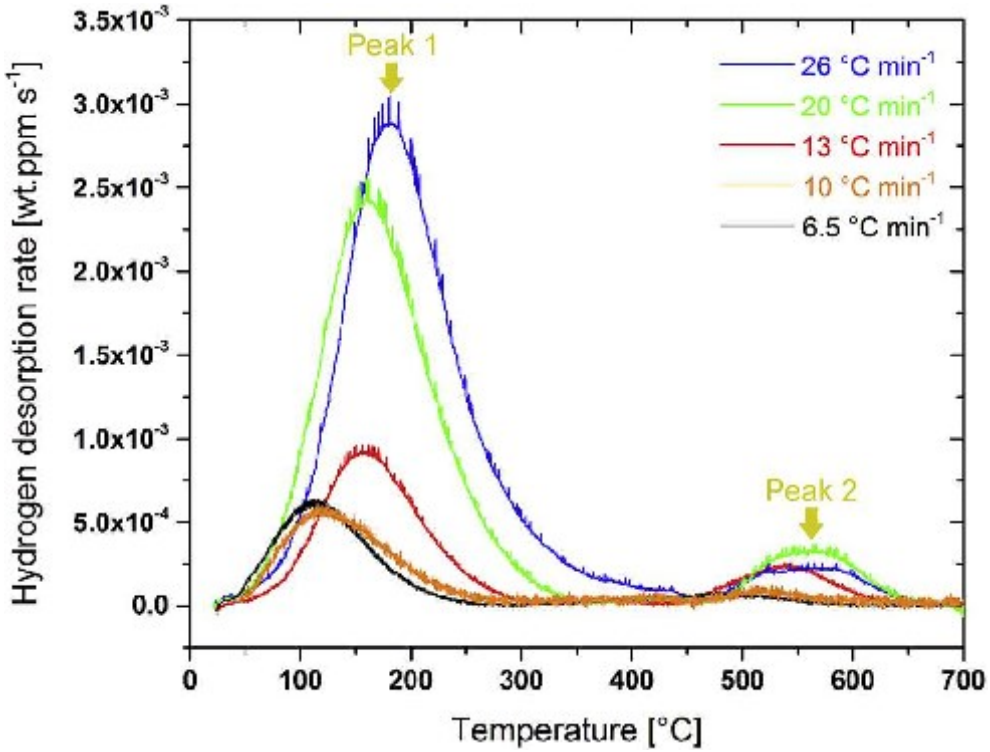
In \ Out	*hv*	*electrons*	*A*
hv	**XD, IR, Raman**	**ARPES, XPD**	**LA**
e	**IPS, EDX (SEM)**	**SEM, LEED, EELS**	**ESD**
A	**BLE**	**IAES**	**RBS, SIMS**
T			**TDS**
E		**STM/STS, FEM**	**FIM**

n-n: **ND, INS**

μ-e^+: **μSR**

Thermal desorption spectroscopy (TDS) or Temperature programmed desorption (TPD)





Arrhenius equation

$$r(\sigma) = -\frac{\mathrm{d}\sigma}{\mathrm{d}t} = v(\sigma)\sigma^n e^{-E_{\mathrm{act}}(\sigma)/RT}$$

$r(\sigma)$ the desorption rate [mol/(cm^2 s)] as a function of σ,

n order of desorption,

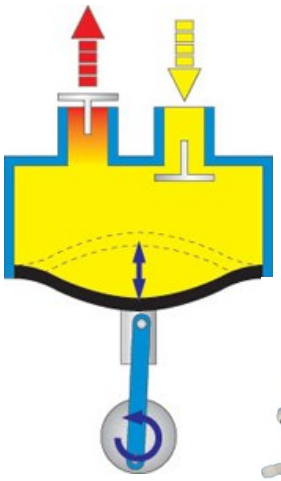
σ surface coverage,

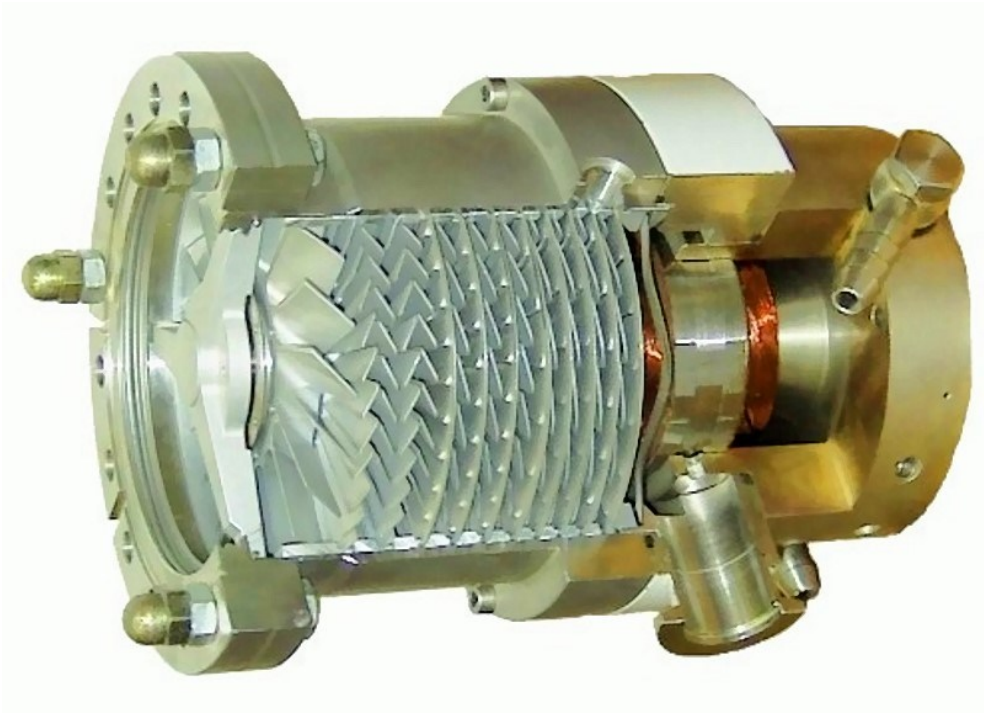
$v(\sigma)$ pre-exponential factor [Hz] as a function of σ,

$E_{\mathrm{act}}(\sigma)$ activation energy of desorption [kJ/mol] as a function of σ

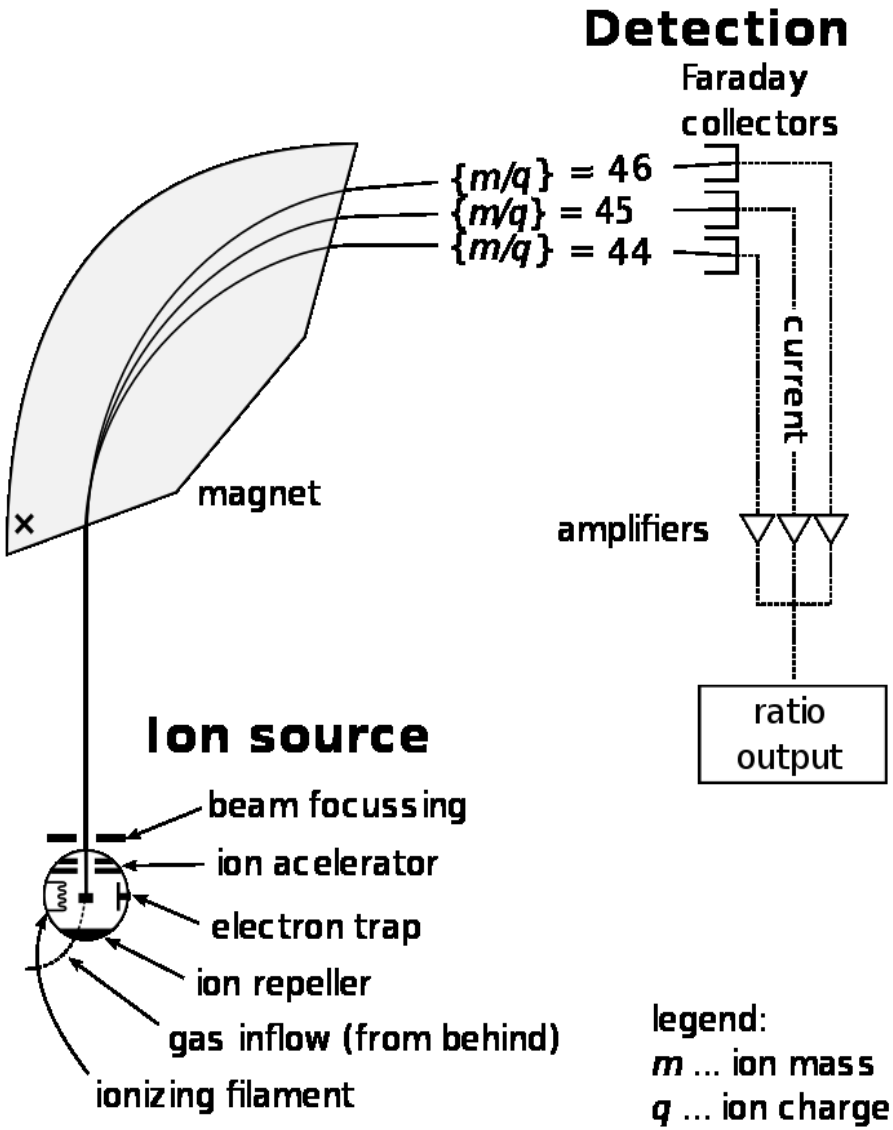
Ступені вакууму

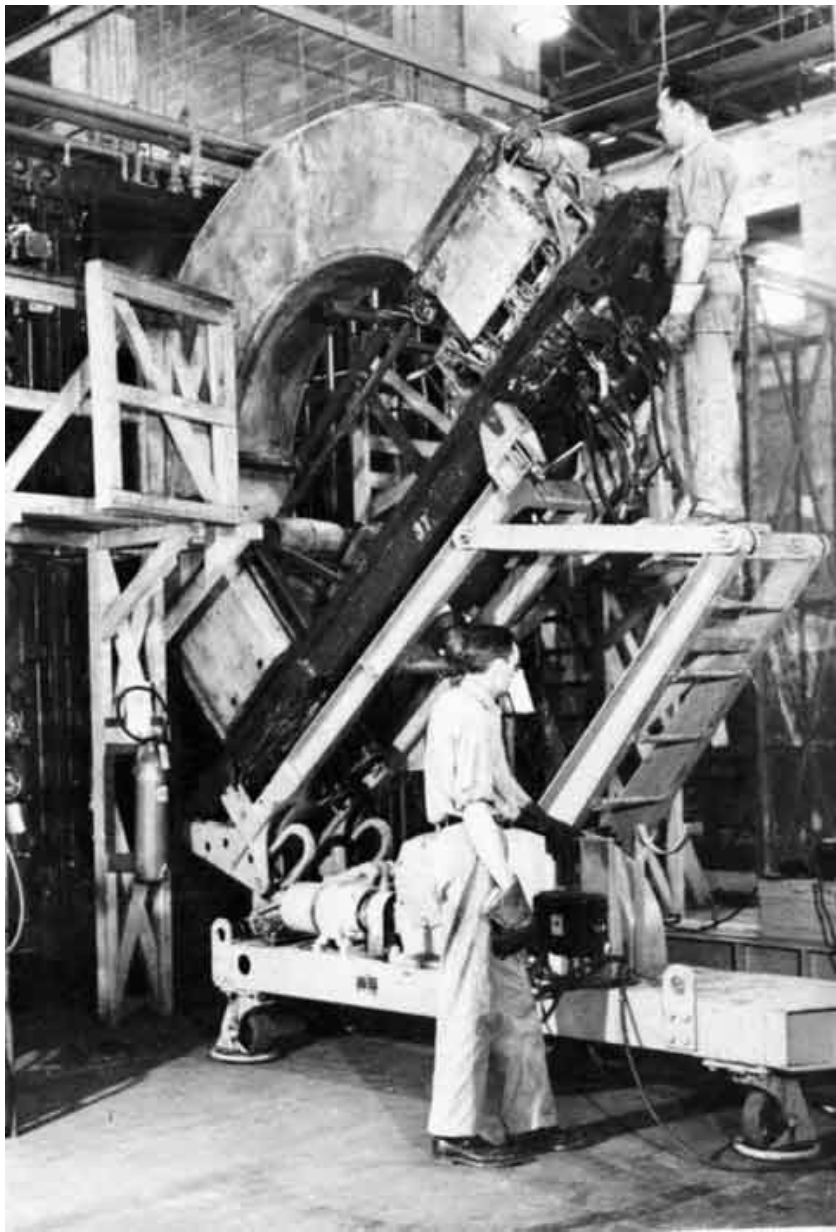
Ступінь вакууму	Тиск, P (Торр)	Густина газу, n ($м^{-3}$)	Середня довжина пробігу, λ (м)	Час утворення моношару, τ (с)
Атмосфера	760	2×10^{25}	7×10^{-8}	10^{-9}
Низький	1	3×10^{22}	5×10^{-5}	10^{-6}
Середній	10^{-3}	3×10^{19}	5×10^{-2}	10^{-3}
Високий	10^{-6}	3×10^{16}	50	1
Ультра-високий	10^{-10}	3×10^{12}	5×10^{5}	10^{4}



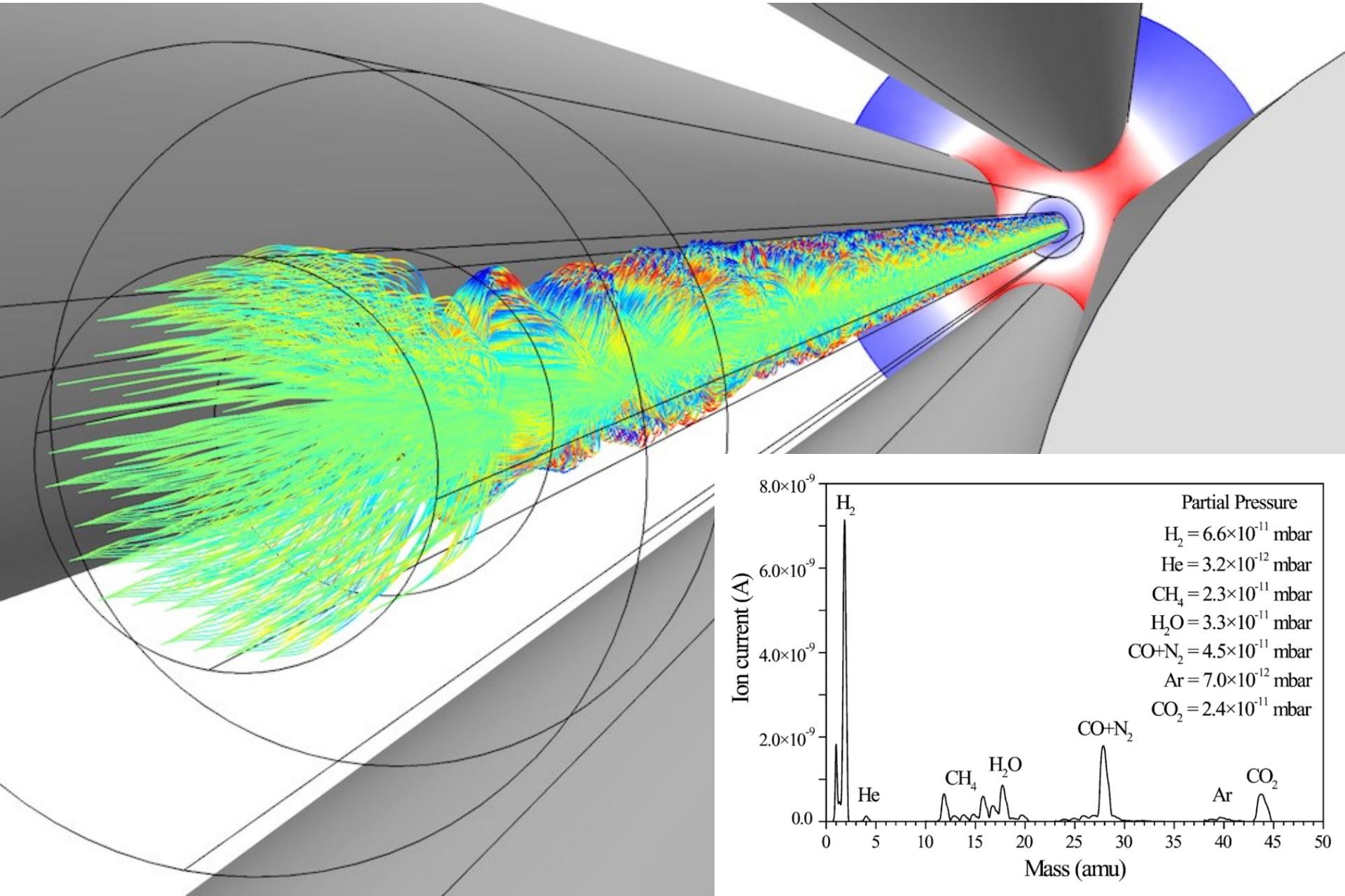


Mass spectrometry

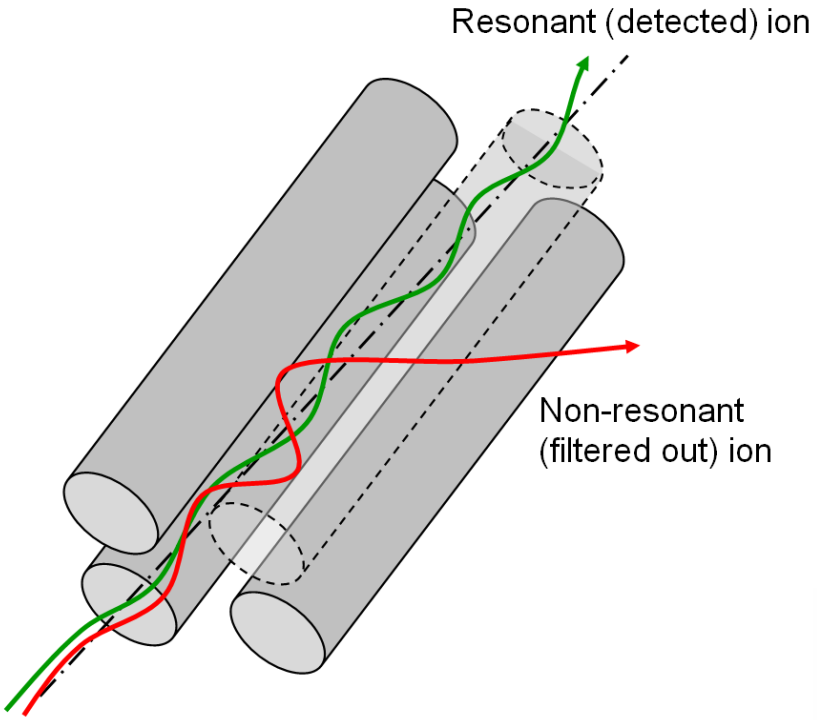


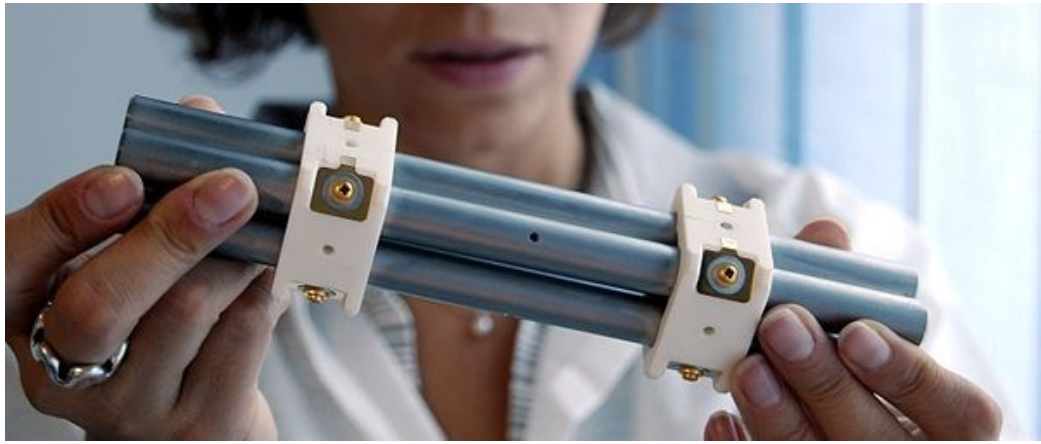


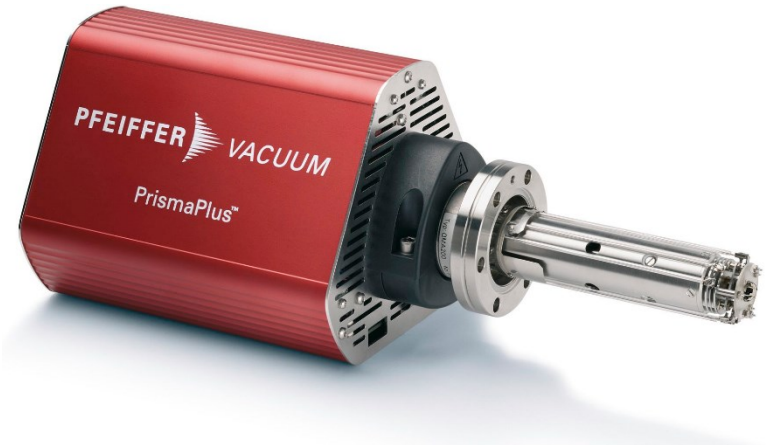
Quadrupole mass analyzer

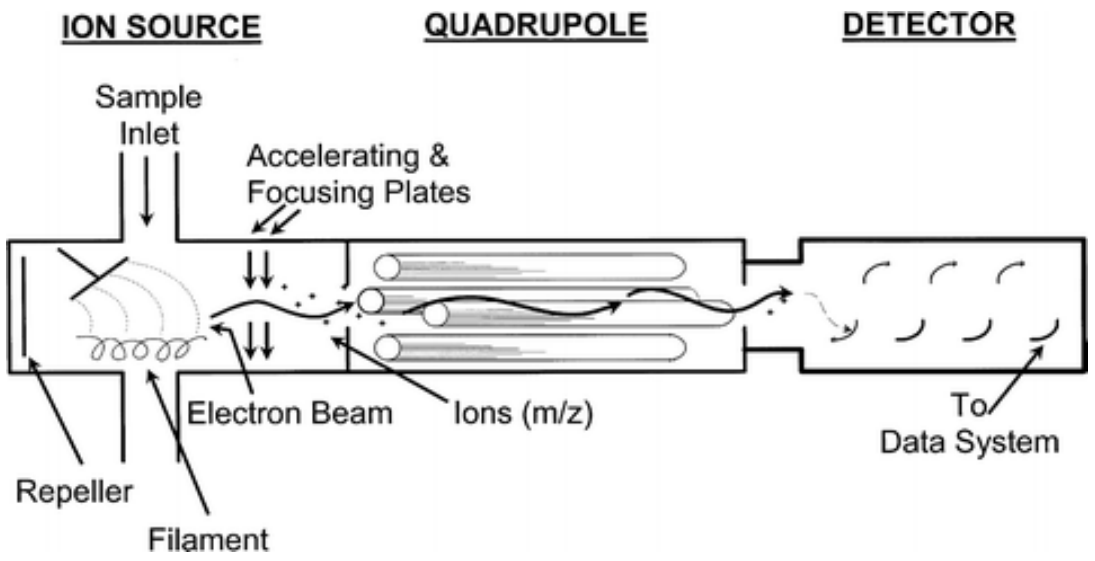


Quadrupole mass spectrometer (QMS)









Spectroscopic Techniques

In \ Out	*hv*	*electrons*	*A*
hv	**XD, IR, Raman**	**ARPES, XPD**	**LA**
e	**IPS, EDX (SEM)**	**SEM, LEED, EELS**	**ESD**
A	**BLE**	**IAES**	**RBS, SIMS**
T			**TDS**
E		**STM/STS, FEM**	**FIM**

n-n: **ND, INS**

μ-e^+: **μSR**

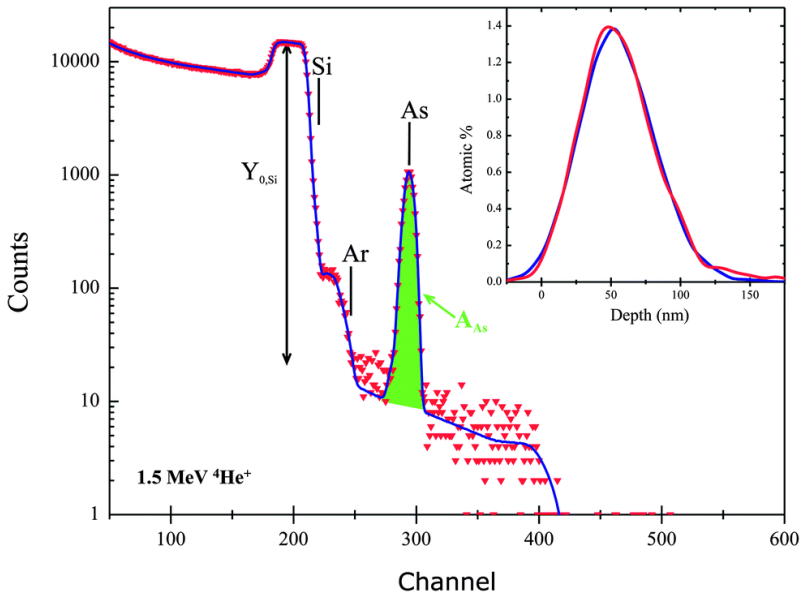
Rutherford backscattering spectrometry (RBS)

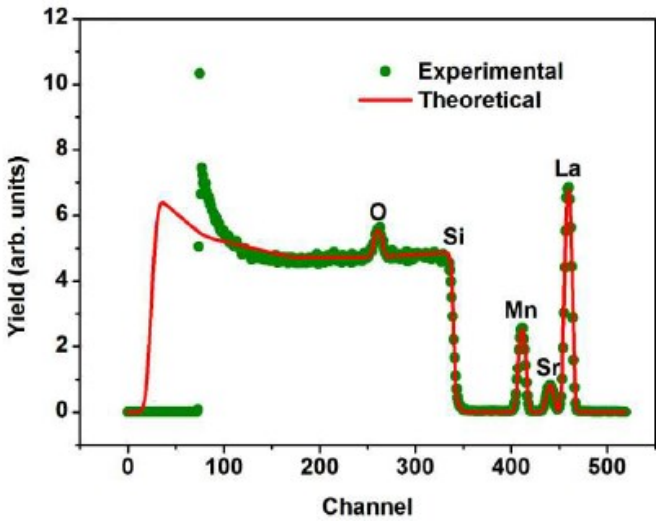
$$\frac{E_1}{E_0} = \left(\frac{m_1 \cos\theta_1 \pm \sqrt{m_2^2 - m_1^2 (\sin\theta_1)^2}}{m_1 + m_2} \right)^2$$

differential cross-section of the backscattering event:

$$\frac{d\omega}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{4E_0} \right)^2 \frac{1}{(\sin\theta/2)^4}$$

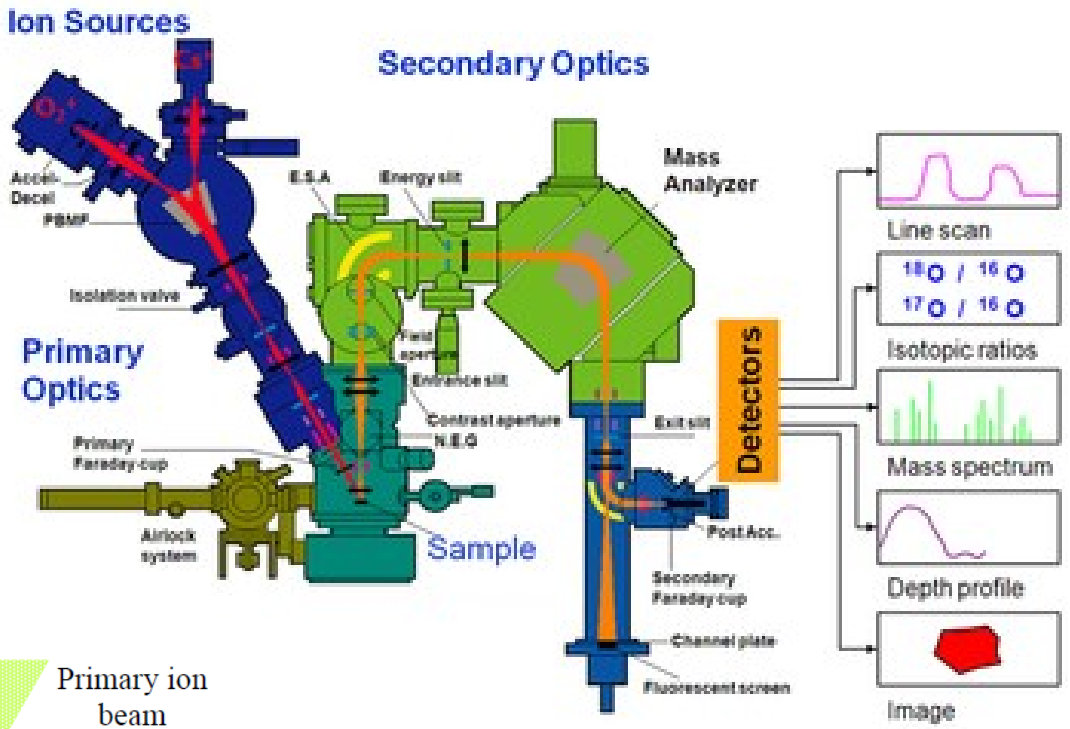
As and Ar implants into silicon

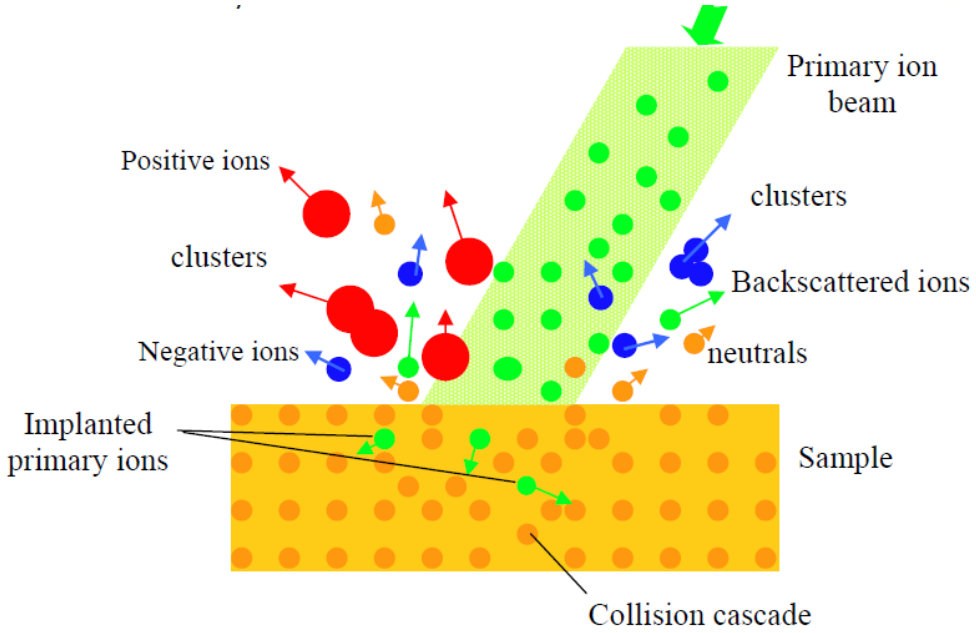




LSMO thin films

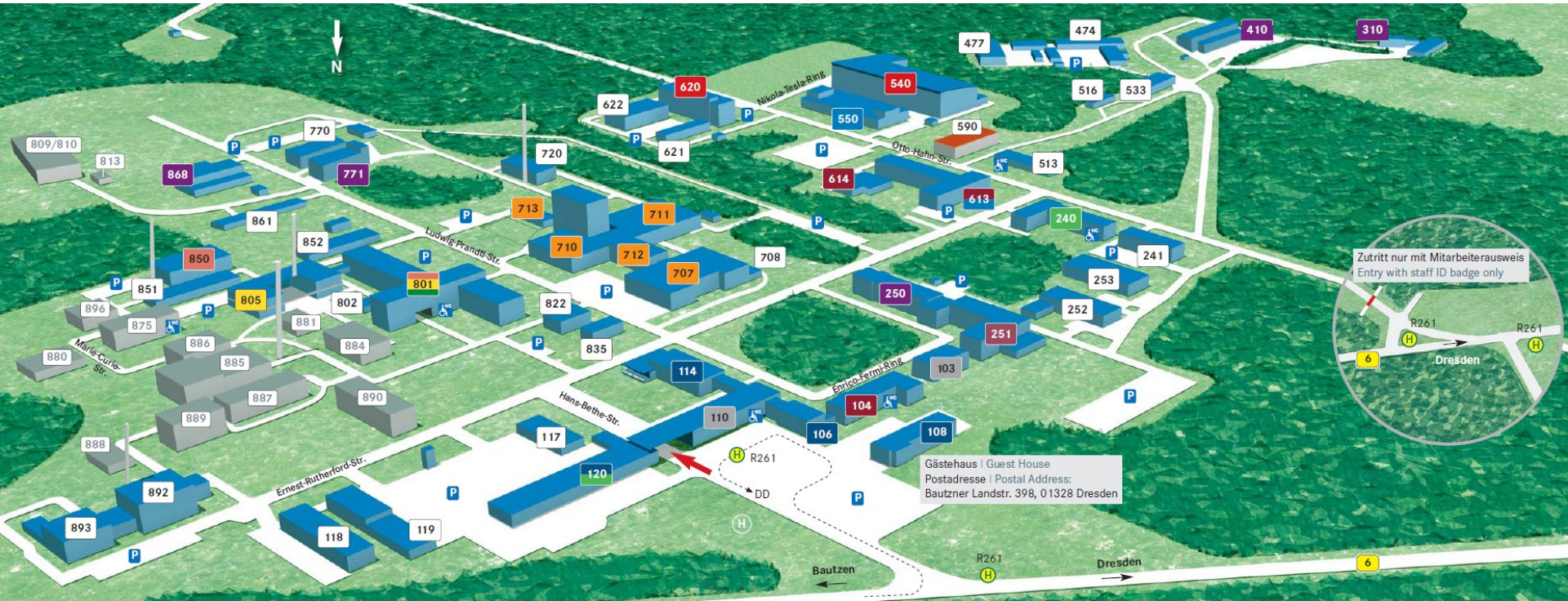
Secondary-ion mass spectrometry (SIMS)





HZDR

HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF



HZDR

The scientific branch of the **Helmholtz-Zentrum Dresden-Rossendorf** is comprised of **eight institutes** as well as two departments: Research Technology and Information Services and Computing

Dresden High Magnetic Field Laboratory

HLD.

This laboratory focuses on modern materials research in high magnetic fields. In particular, electronic properties of metallic, semiconducting, superconducting, and magnetic materials are investigated. This way the High Magnetic Field Laboratory serves as a research facility for both in-house and user projects.

Director: Prof. Joachim Wosnitza

More ▸

IBC.

ELBE.

Institute of Ion Beam Physics and Materials Research

This institute conducts materials research for future applications, e. g. in information technology and for energy conversion. To this end use is made of the various possibilities offered by the Ion Beam Center (IBC) for synthesis, modification, and analysis of thin films and nanostructures.

Directors: Prof. Manfred Helm, Prof. Jürgen Fassbender

More ▸

Institute of Radiation Physics

Basic research in accelerator, nuclear, hadron and laser physics is this institute's top-priority. The Institute of Radiation Physics is also engaged in new ways of producing radiation and particle beams, and new detectors and measurement techniques for application to cancer research, nuclear safety and advanced materials.

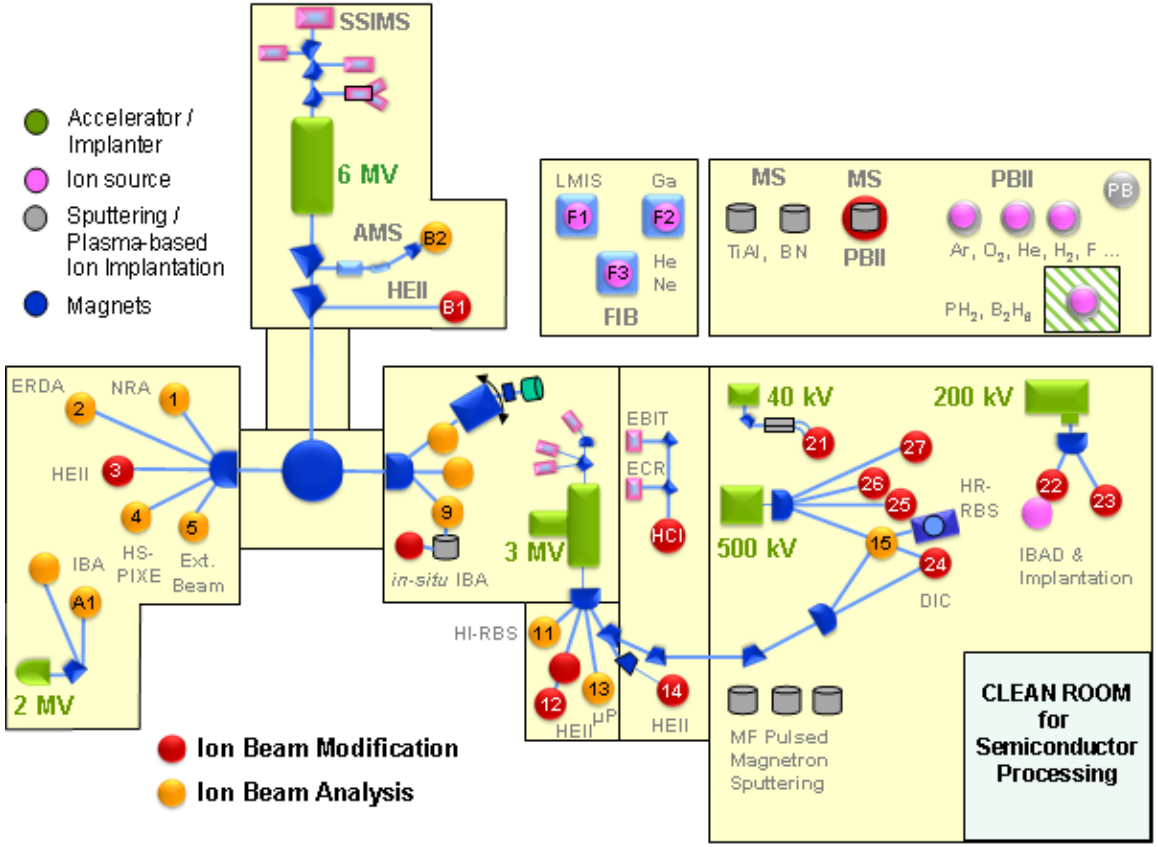
Directors: Prof. Thomas E. Cowan, Prof. Ulrich Schramm

More ▸

Institute of Ion Beam Physics and Materials Research

IBC. Institute of Ion Beam Physics and Materials Research

IBC. Institute of Ion Beam Physics and Materials Research



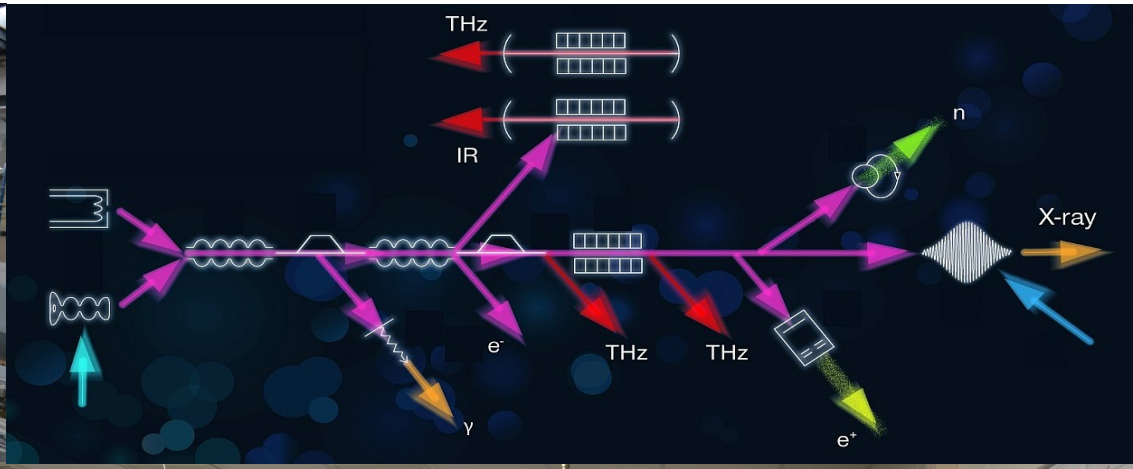
Ion Beam Center (IBC)

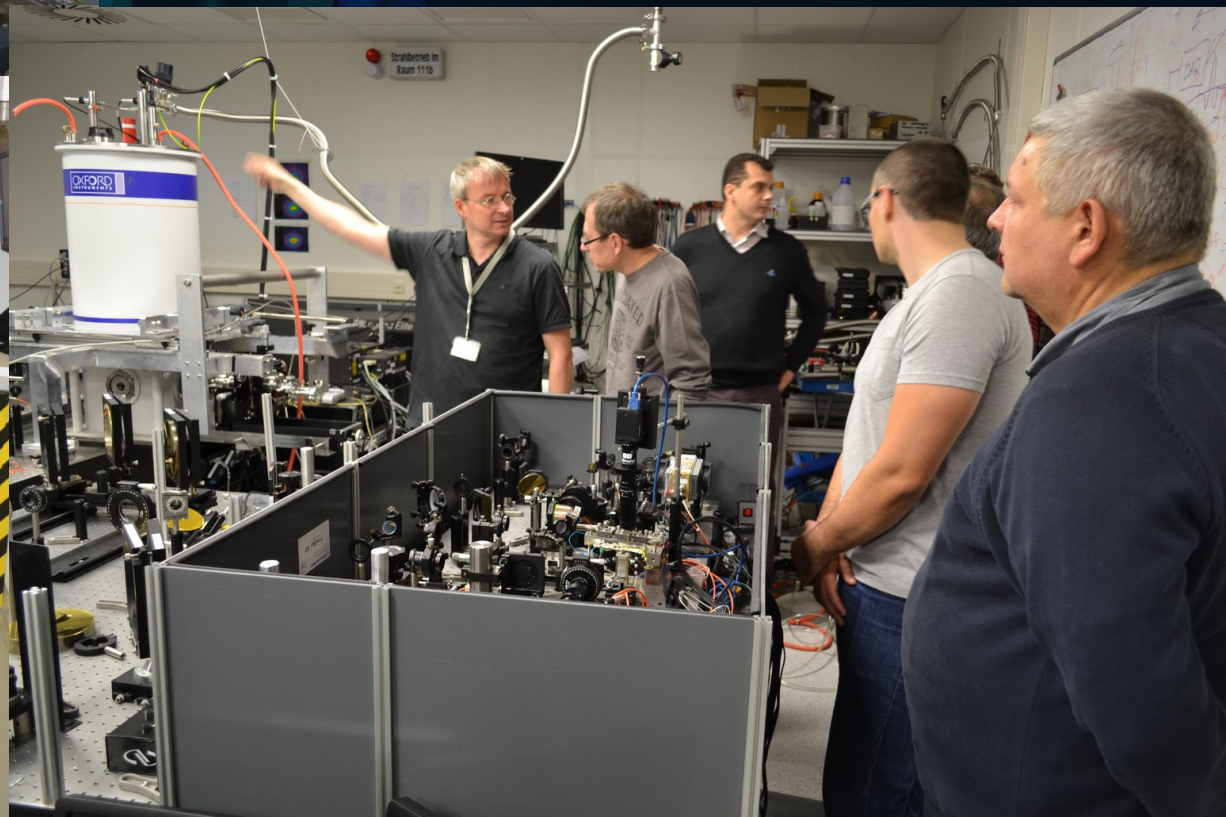
for ion beam modification and ion beam analysis of materials

electrostatic accelerators,
ion implanters,
other ion- and plasma-based equipment

Energy range: 10 eV - 100 MeV
Depth in solids: 0.1 nm - 10 μm

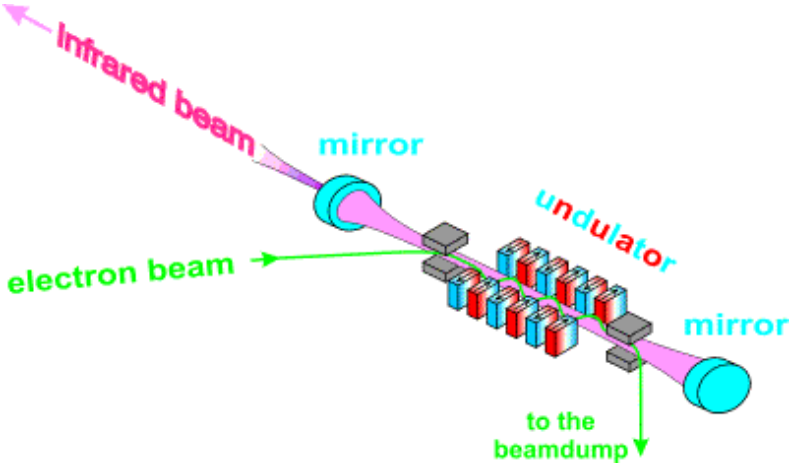
ELBE. Institute of Radiation Physics





ELBE. Institute of Radiation Physics

ELBE (**E**lectron **L**inac for beams with high **B**rilliance and low **E**mittance)



Radiation

Undulator	U27	U100
Wavelength [µm]	4 - 22	18 - 250
Average output power [W]	0.1 - 40	0.1 - 40
Pulse energy [µJ]	0.01 - 3	0.01 -3

Electron beam

Kinetic energy [MeV]	12 - 34
Bunch charge [pC]	77
Bunch repetition rate [MHz]	13
Average beam current [mA]	1
Long. beam emittance [keV*ps]	50
Transverse beam emittance [mm*mrad]	13

Undulators

Undulator	U27	U100
Undulator period [mm]	27.3	100
Number of periods	2*34	38
Undulator parameter	0.3 - 0.7	0.5 - 2.7

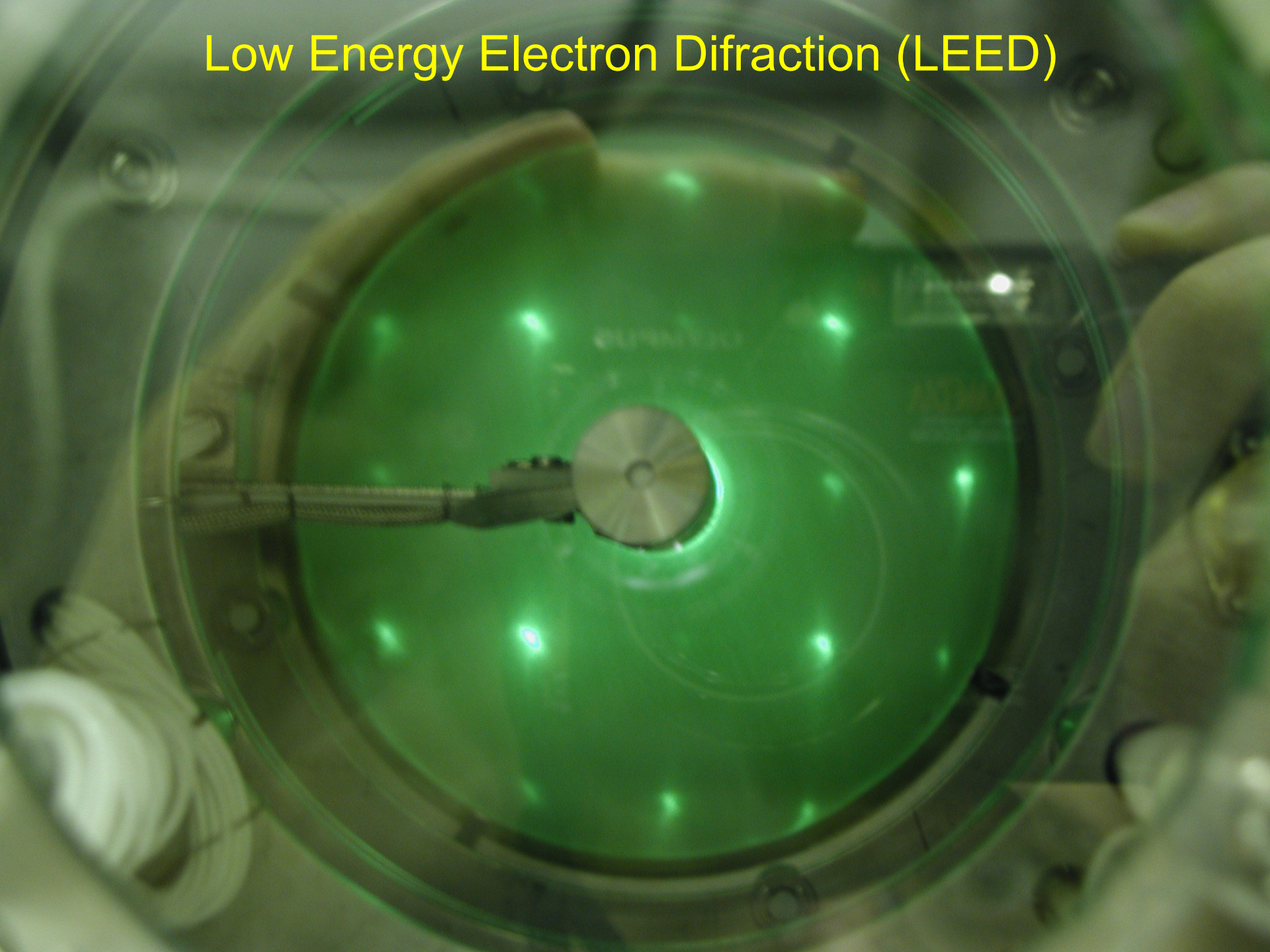
Spectroscopic Techniques

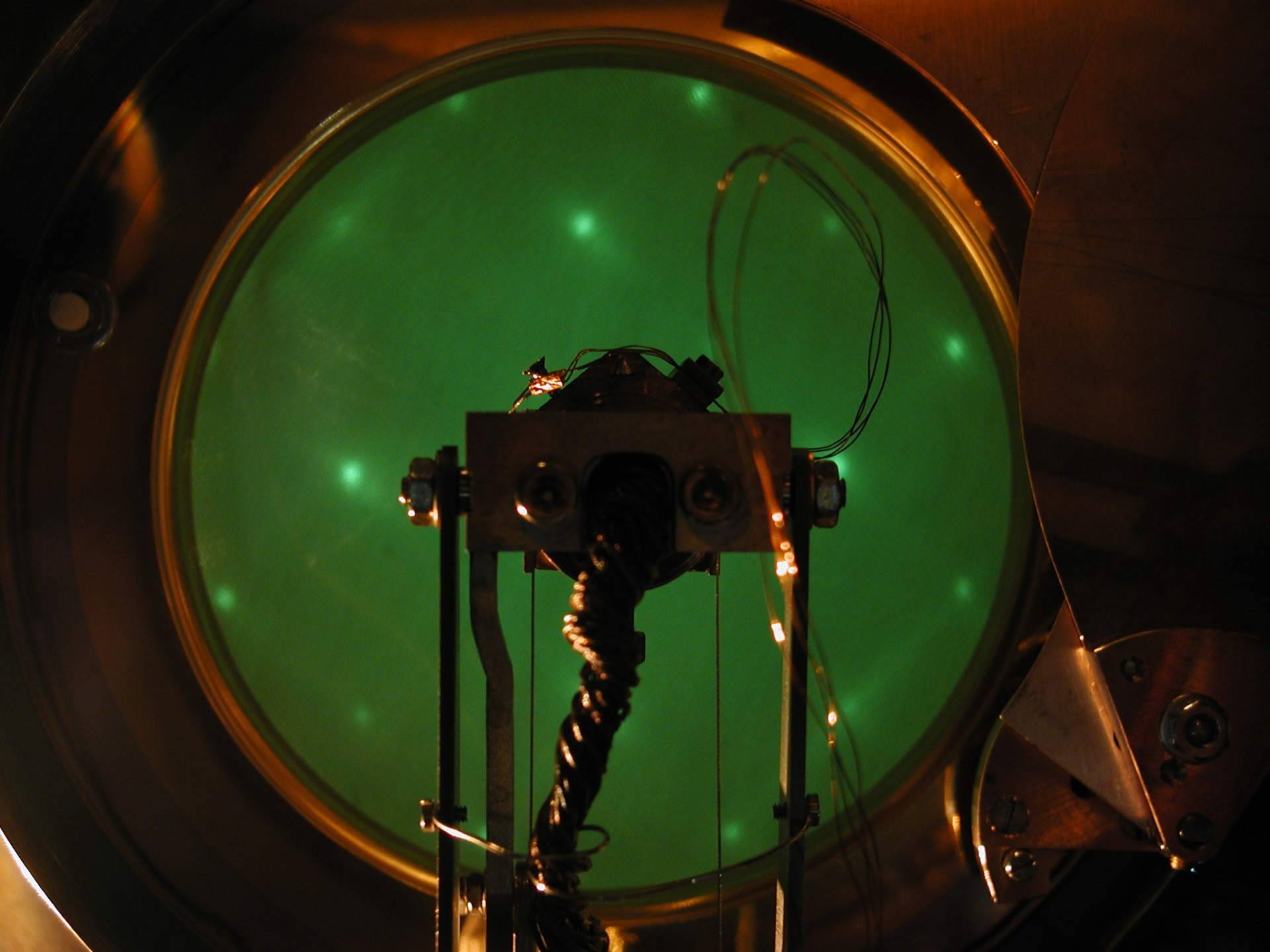
In \ Out	*hv*	*electrons*	*A*
hv	**XD, IR, Raman**	**ARPES, XPD**	**LA**
e	**IPS, EDX (SEM)**	**SEM, LEED, EELS**	**ESD**
A	**BLE**	**IAES**	**RBS, SIMS**
T			**TDS**
E		**STM/STS, FEM**	**FIM**

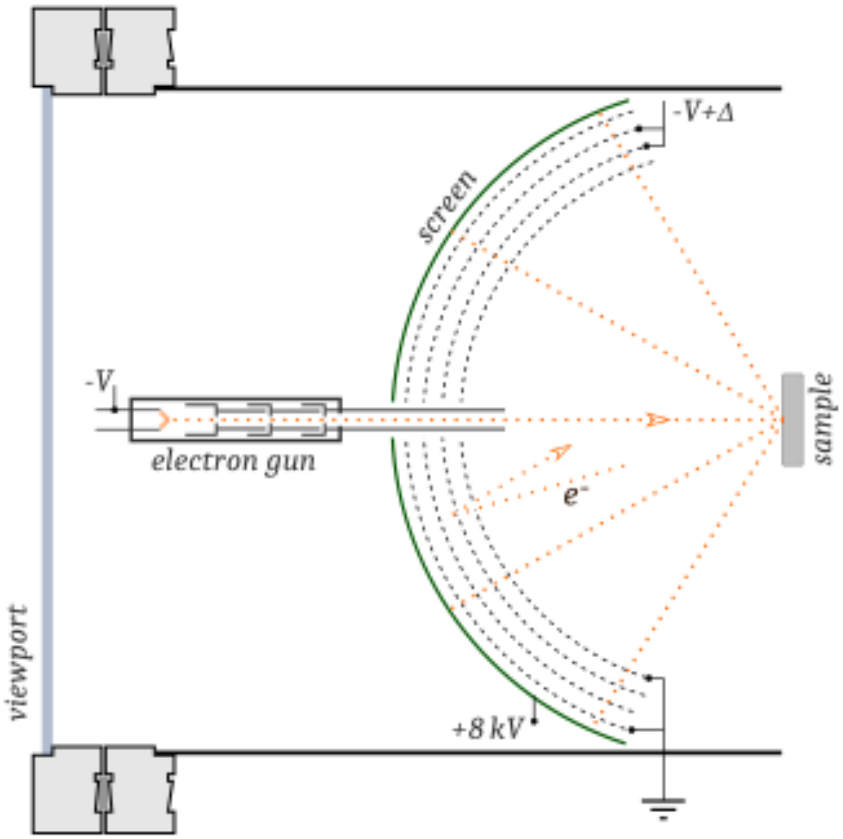
n-n: **ND, INS**

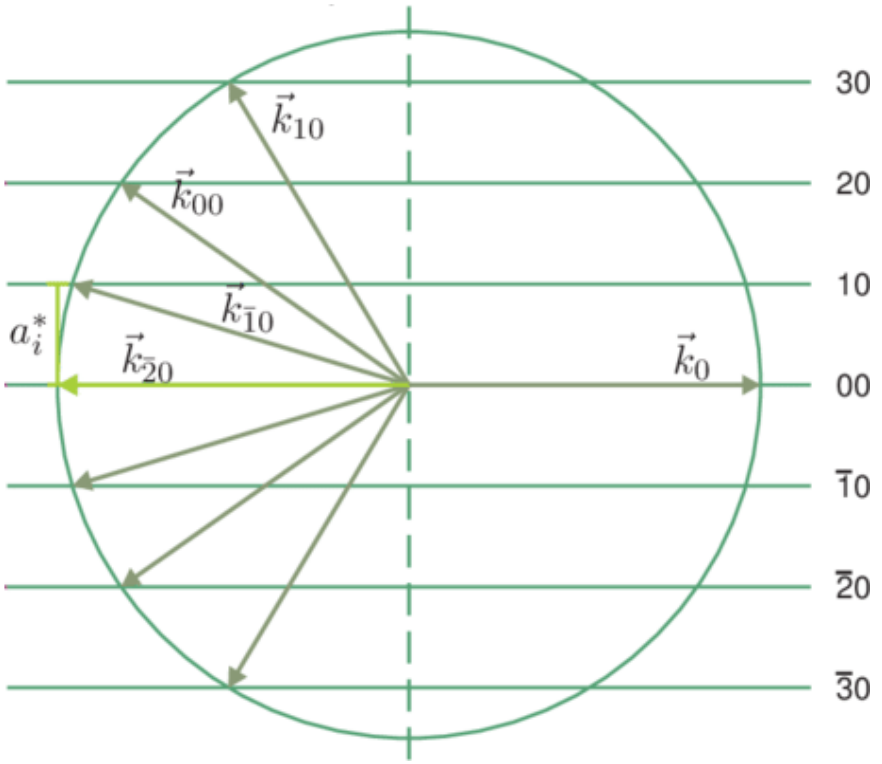
μ-e^+: **μSR**

Low Energy Electron Difraction (LEED)

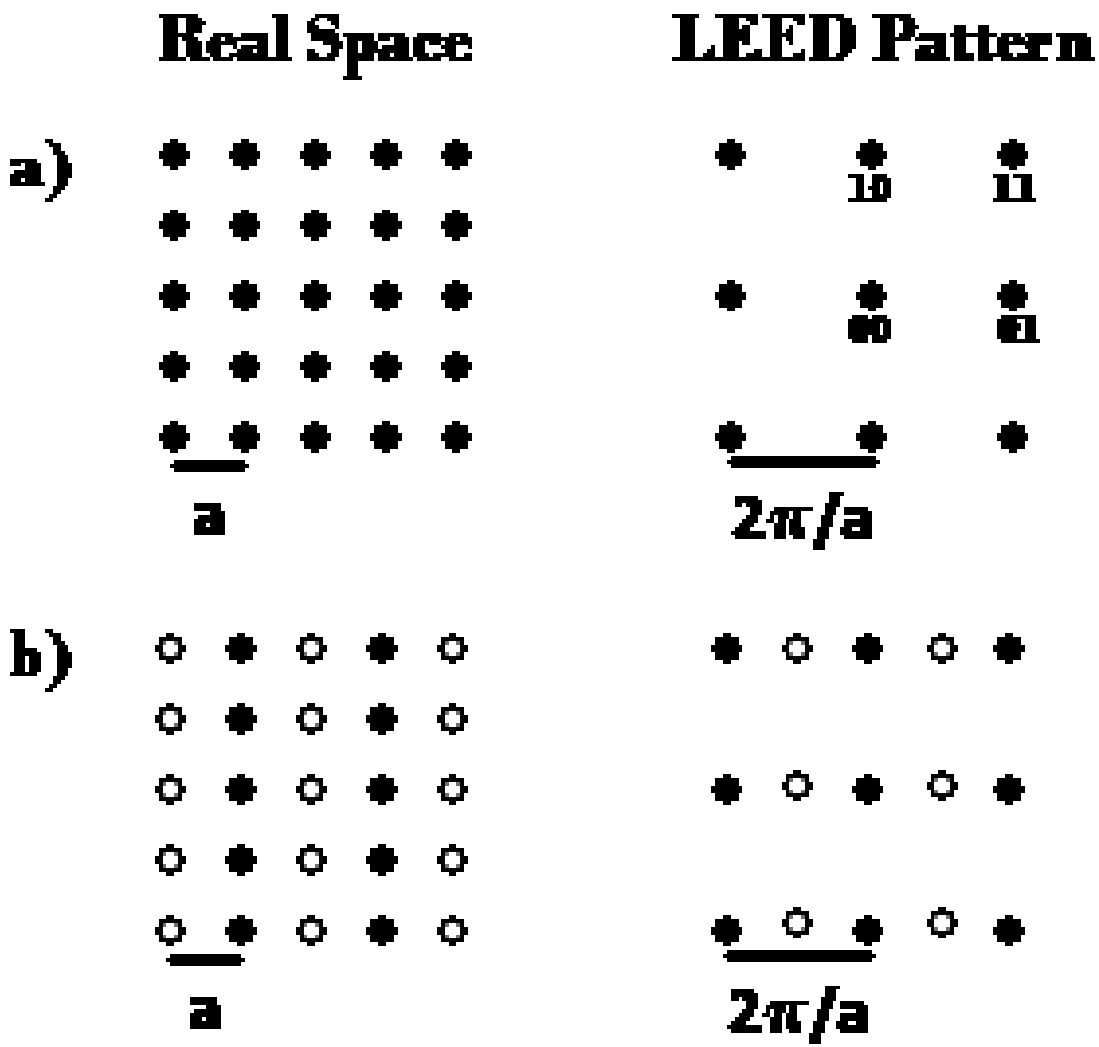


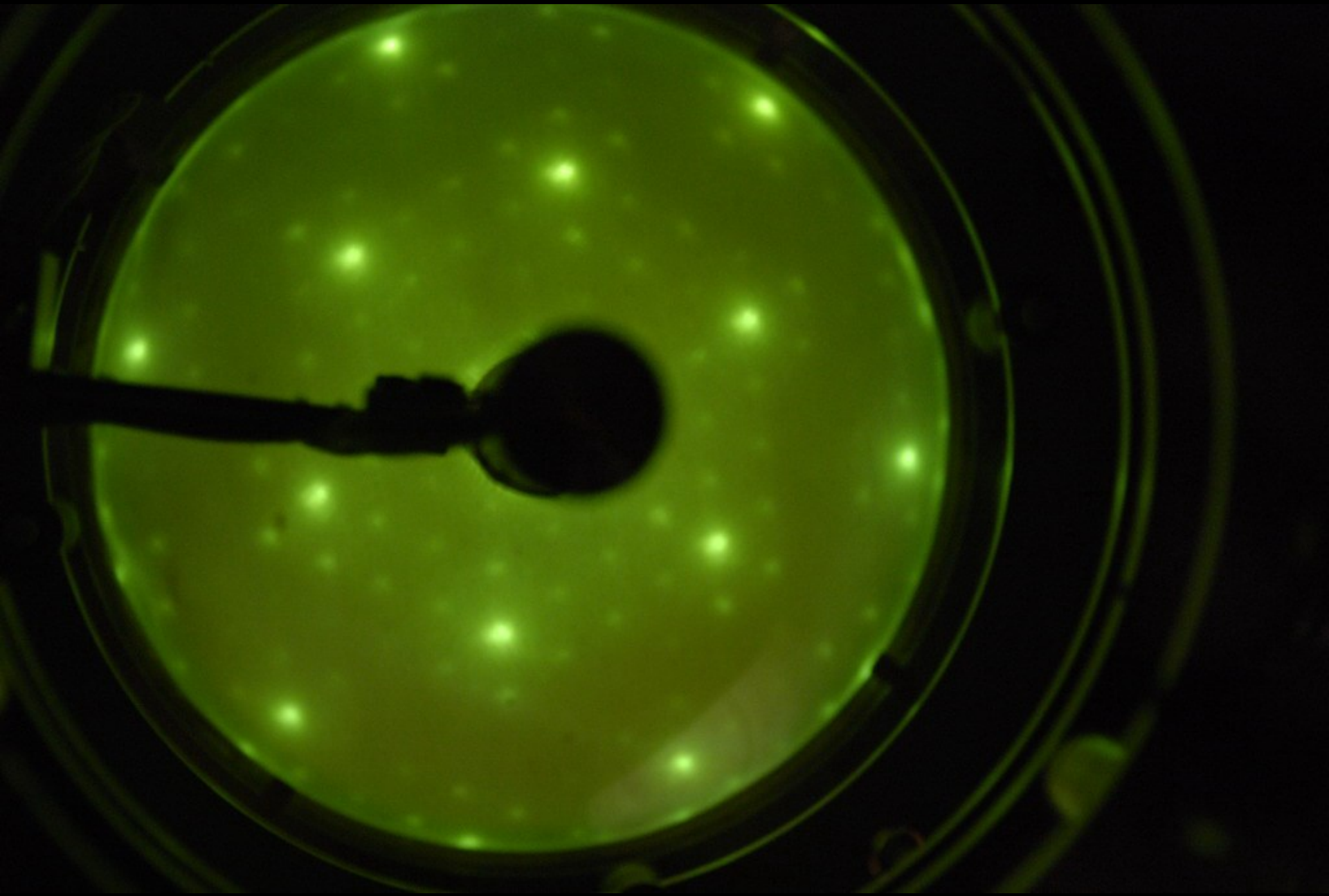




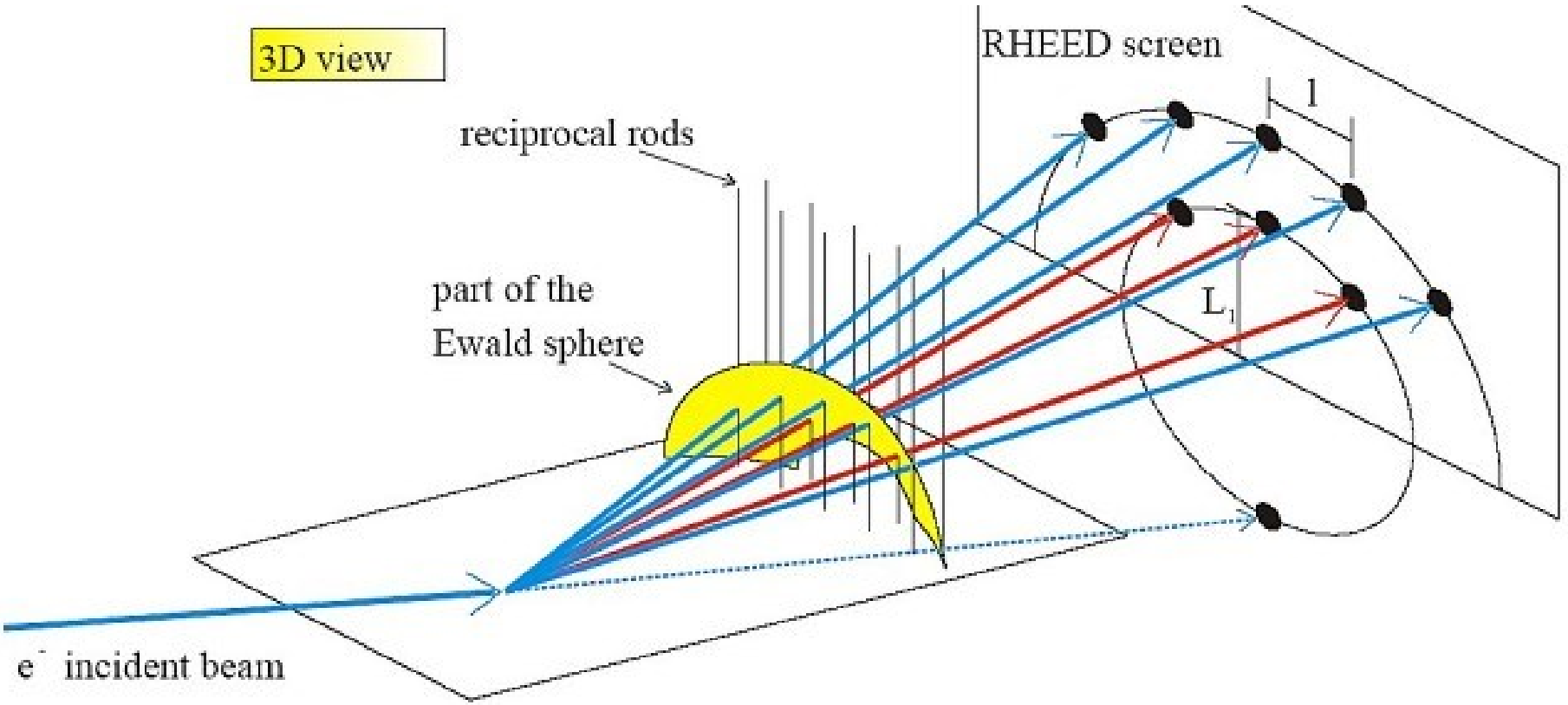


Ewald's sphere construction for the case of normal incidence of the primary electron beam. The diffracted beams are indexed according to the values of h and l.


Real Space
LEED Pattern
a)
10
11
00
01
a
2π/a
b)
a
2π/a

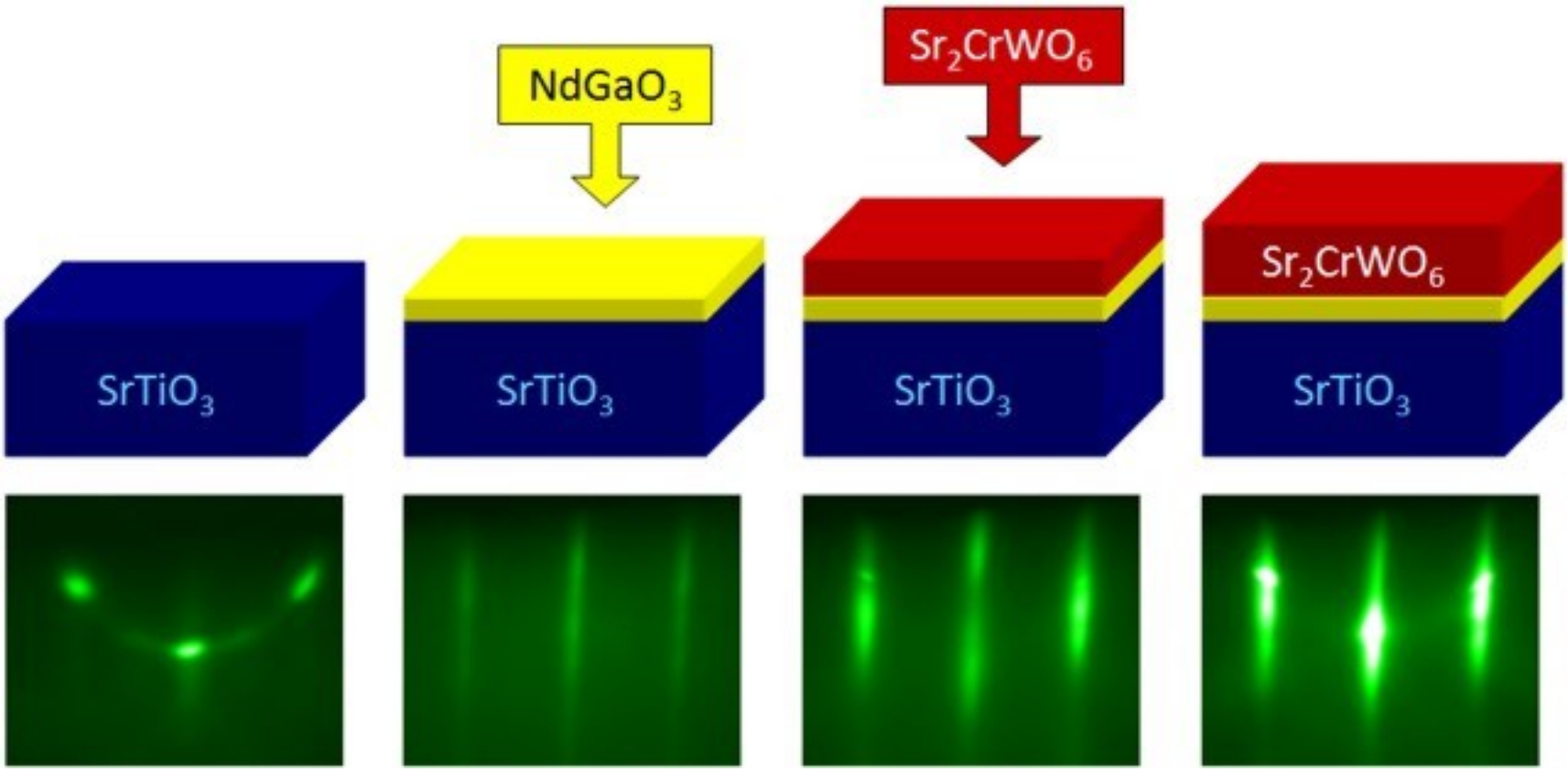


Reflection High Energy Electron Diffraction (**RHEED**)



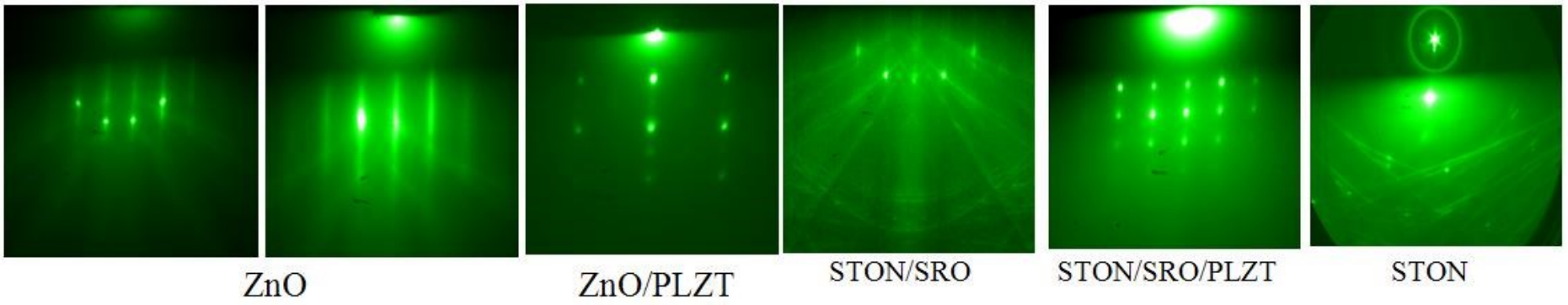
Jürgen Klein, Epitaktische Heterostrukturen aus dotierten Manganaten,
PhD Thesis, University of Cologne (2001)
http://www.wmi.badw.de/methods/leed_rheed.htm

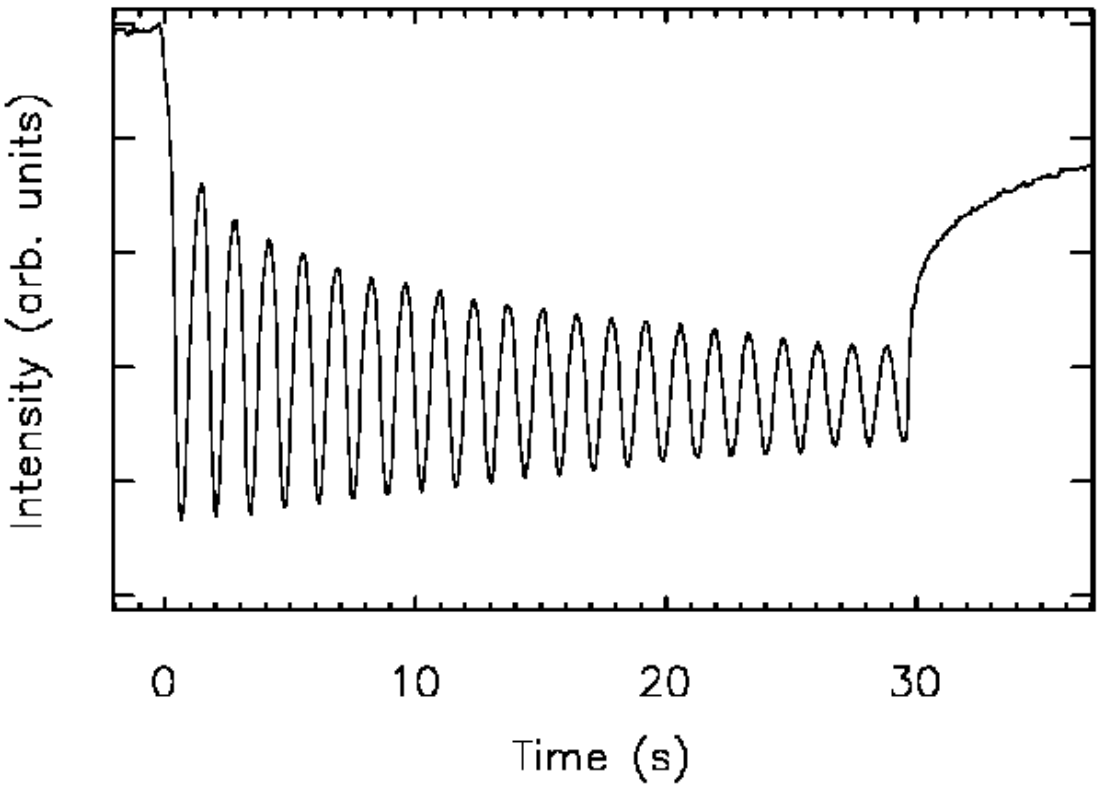
Reflection High Energy Electron Diffraction (**RHEED**)



Jürgen Klein, Epitaktische Heterostrukturen aus dotierten Manganaten,
PhD Thesis, University of Cologne (2001)
http://www.wmi.badw.de/methods/leed_rheed.htm

Reflection High Energy Electron Diffraction (**RHEED**)





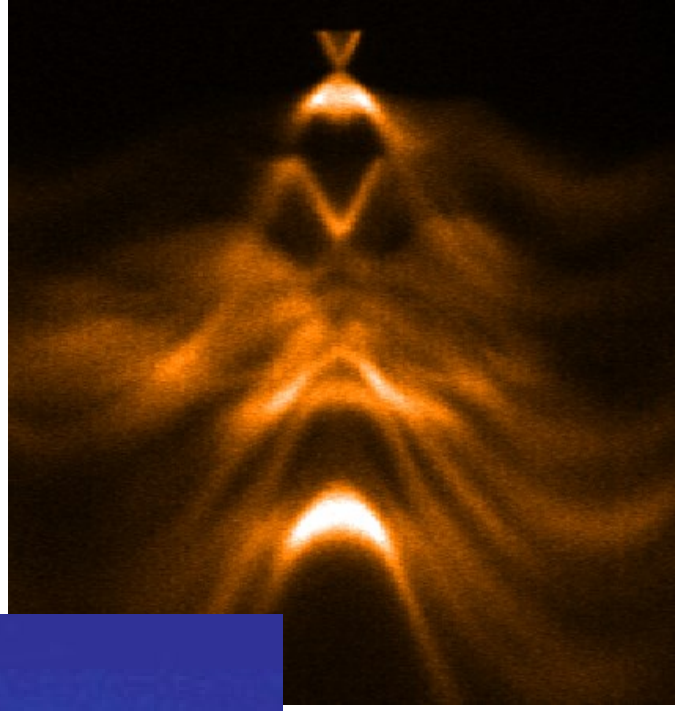
Spectroscopic Techniques

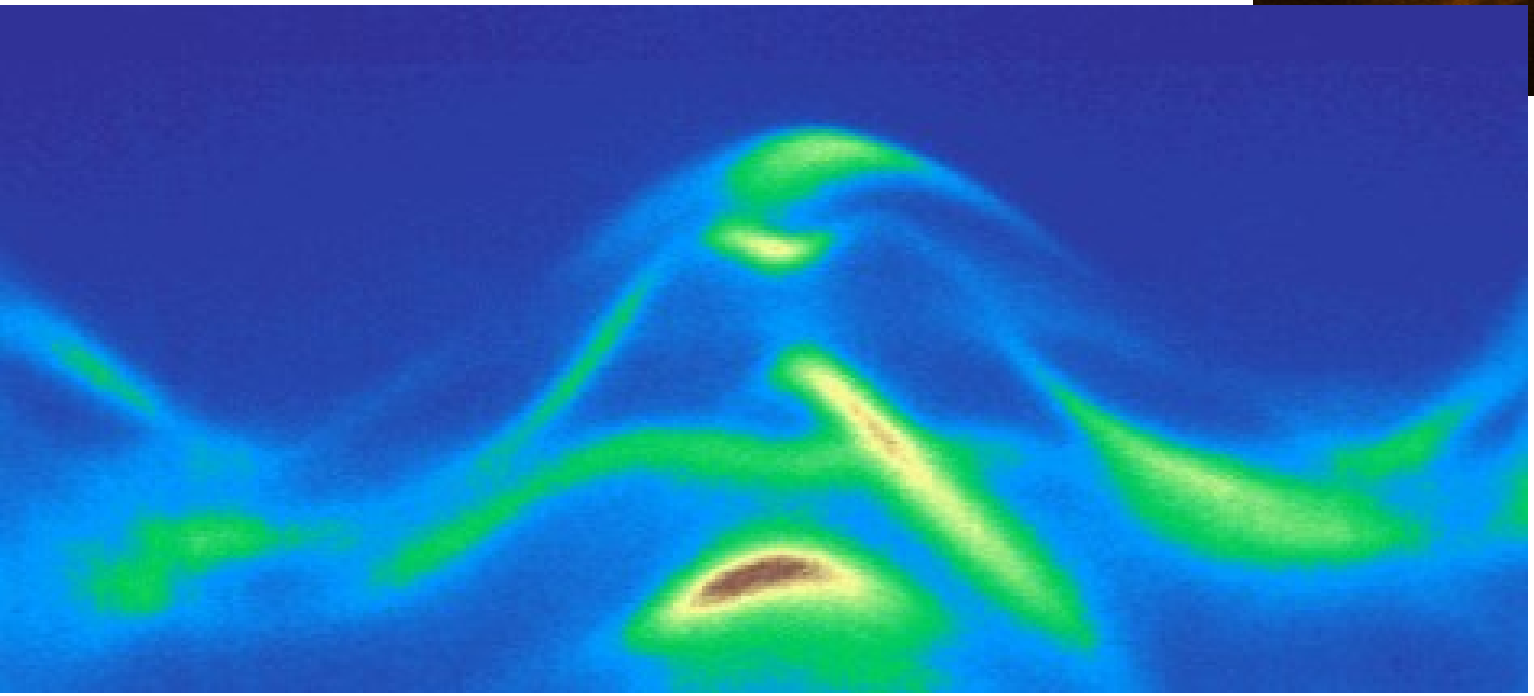
In \ Out	*hv*	*electrons*	*A*
hv	**XD, IR, Raman**	**ARPES, XPD**	**LA**
e	**IPS, EDX (SEM)**	**SEM, LEED, EELS**	**ESD**
A	**BLE**	**IAES**	**RBS, SIMS**
T			**TDS**
E		**STM/STS, FEM**	**FIM**

n-n: **ND, INS**

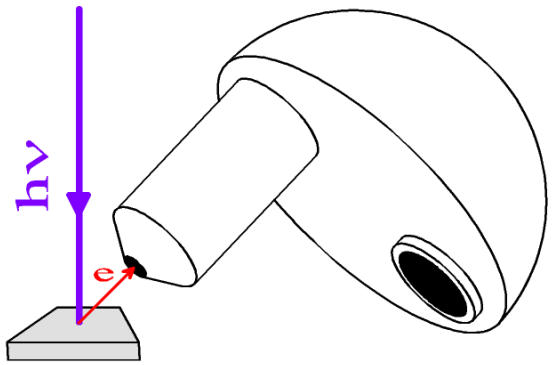
μ-e^+: **μSR**

Electrons in momentum-energy space



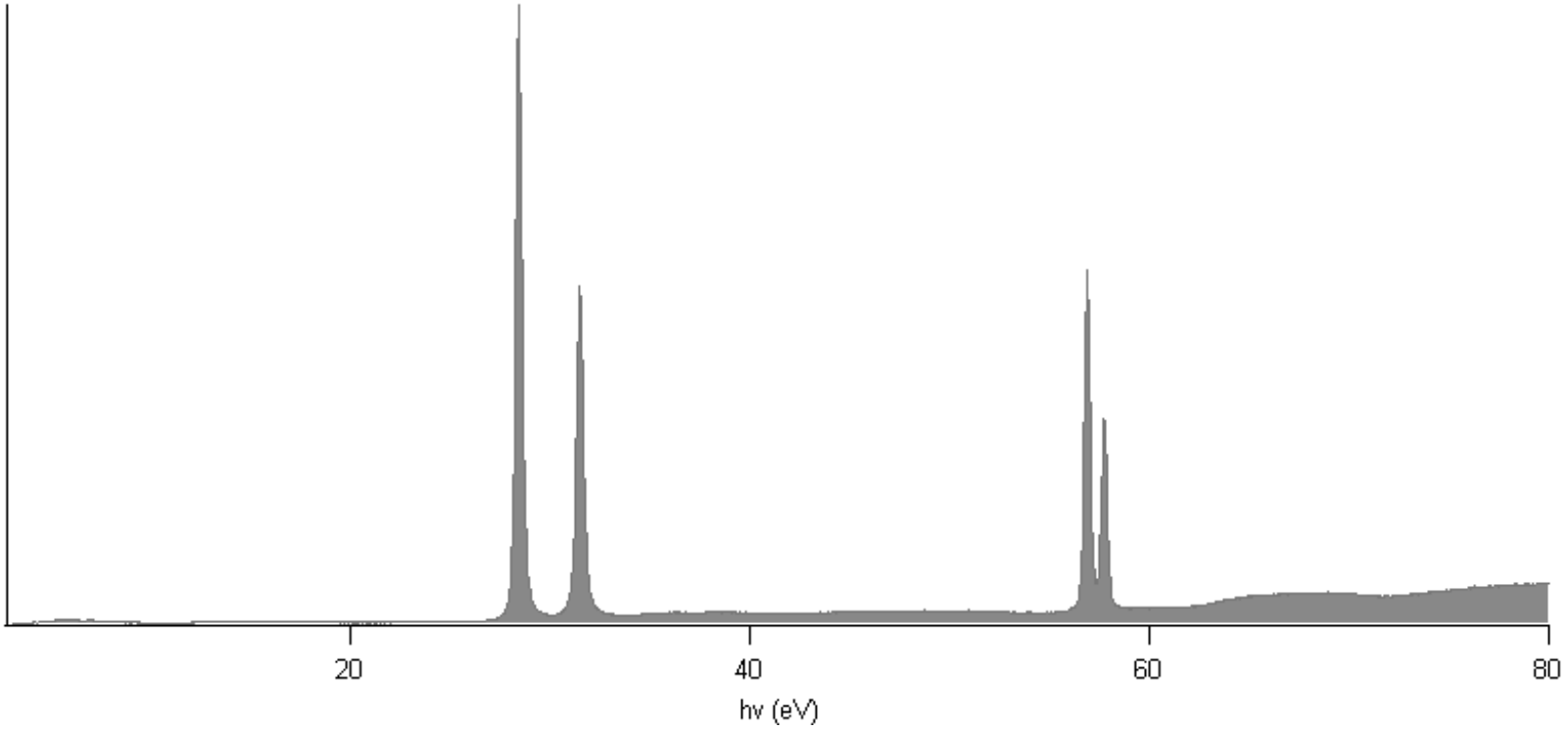


Photoelectron spectroscopy – Electronic band structure ?

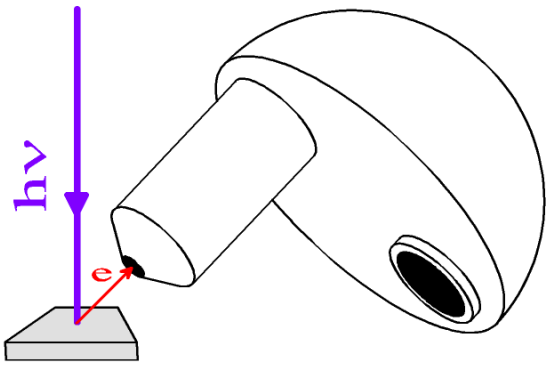


Bi_2Se_3

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

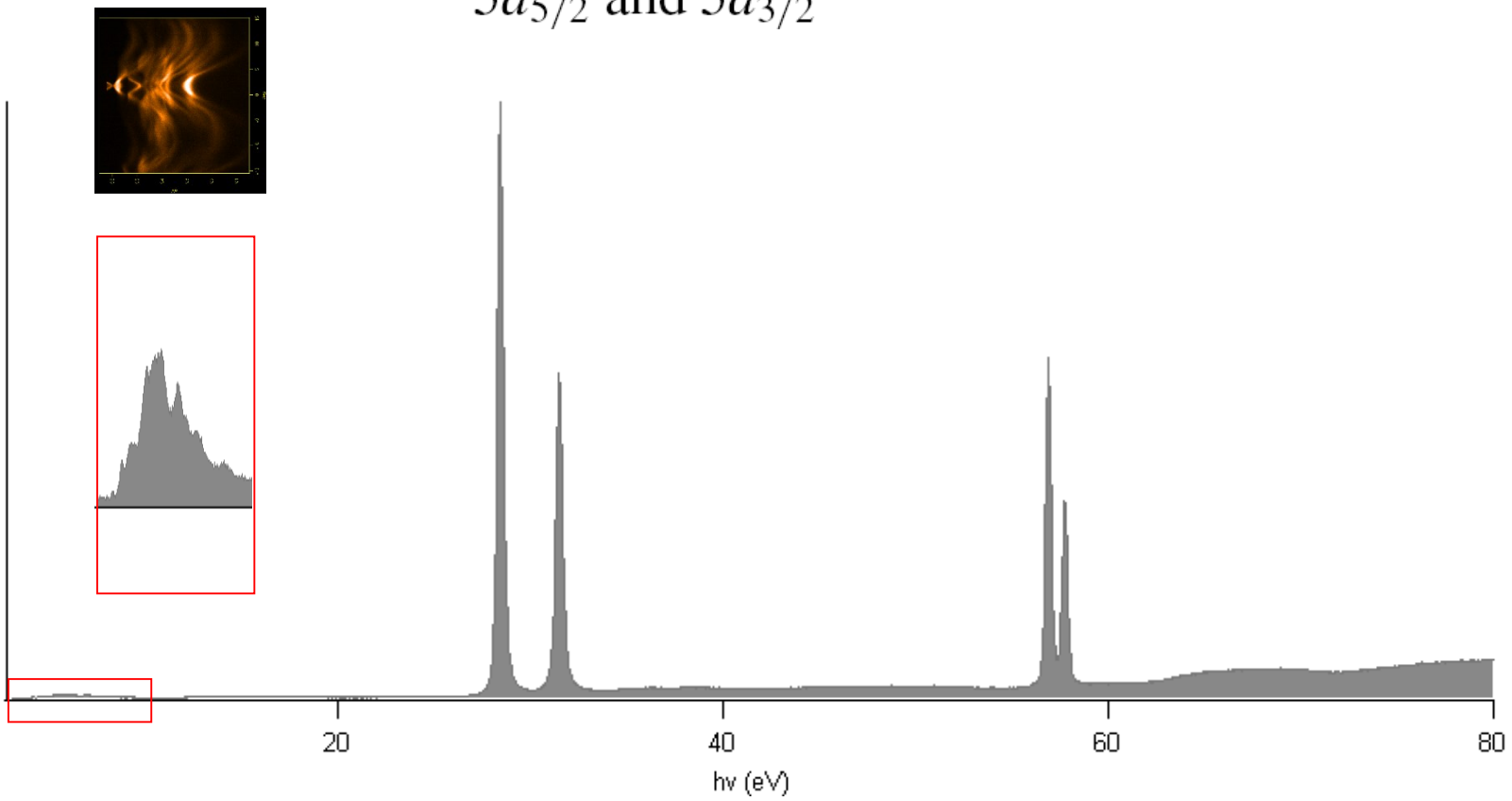


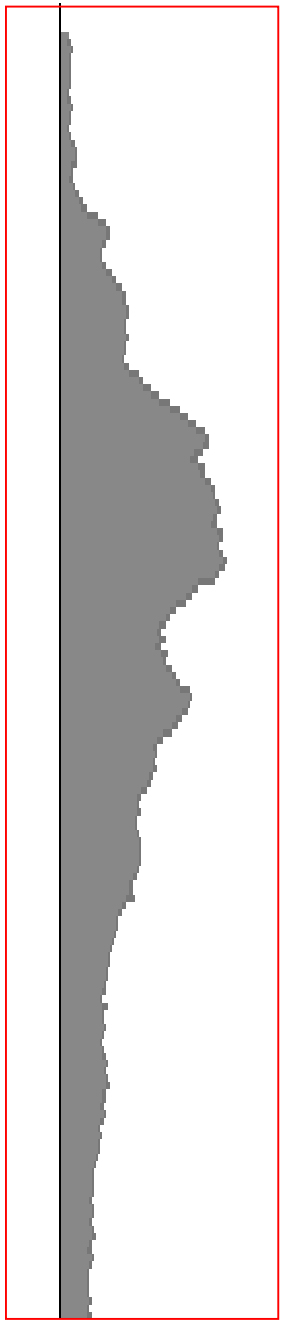
Photoelectron spectroscopy – Electronic band structure ?

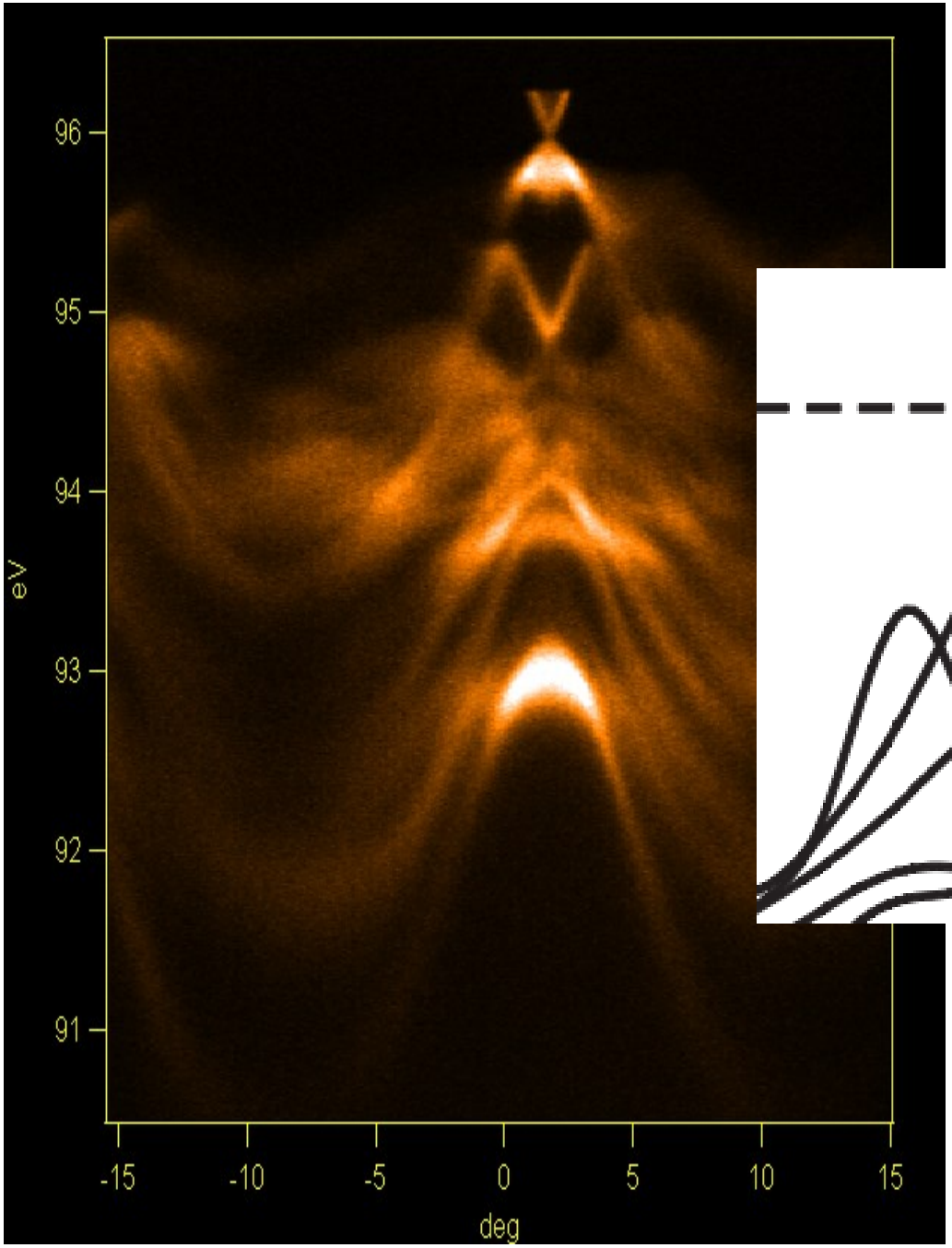


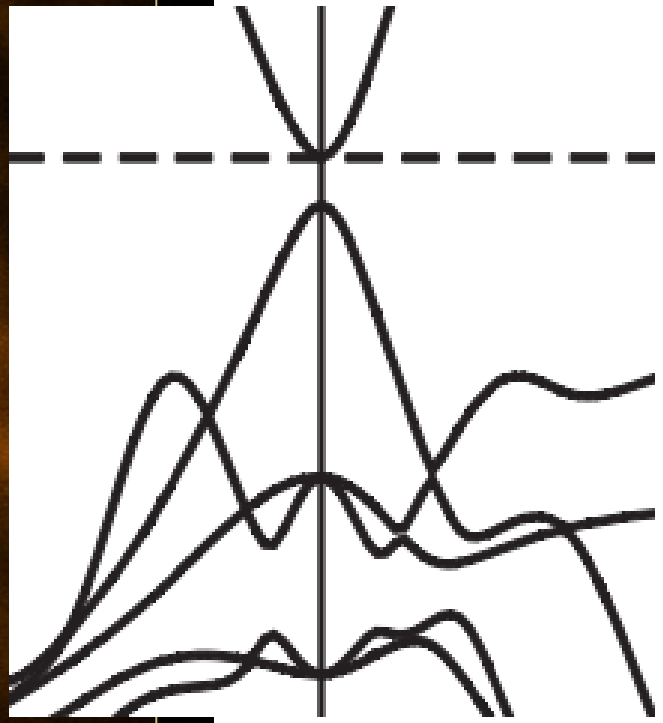
Bi_2Se_3

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

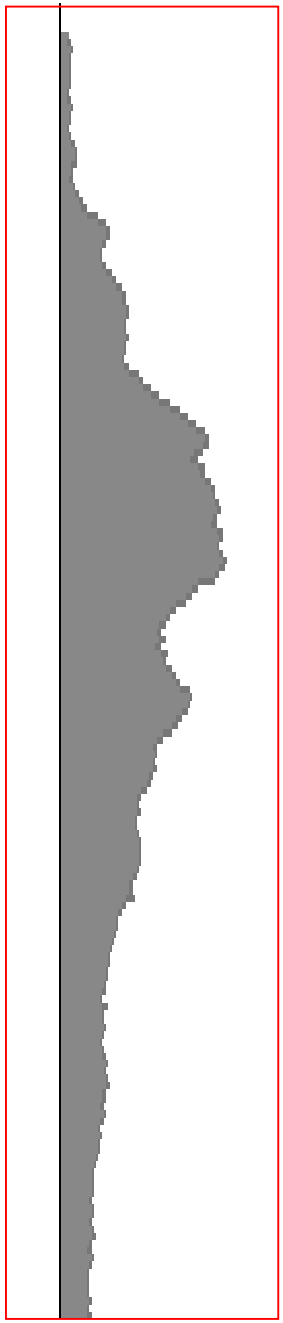


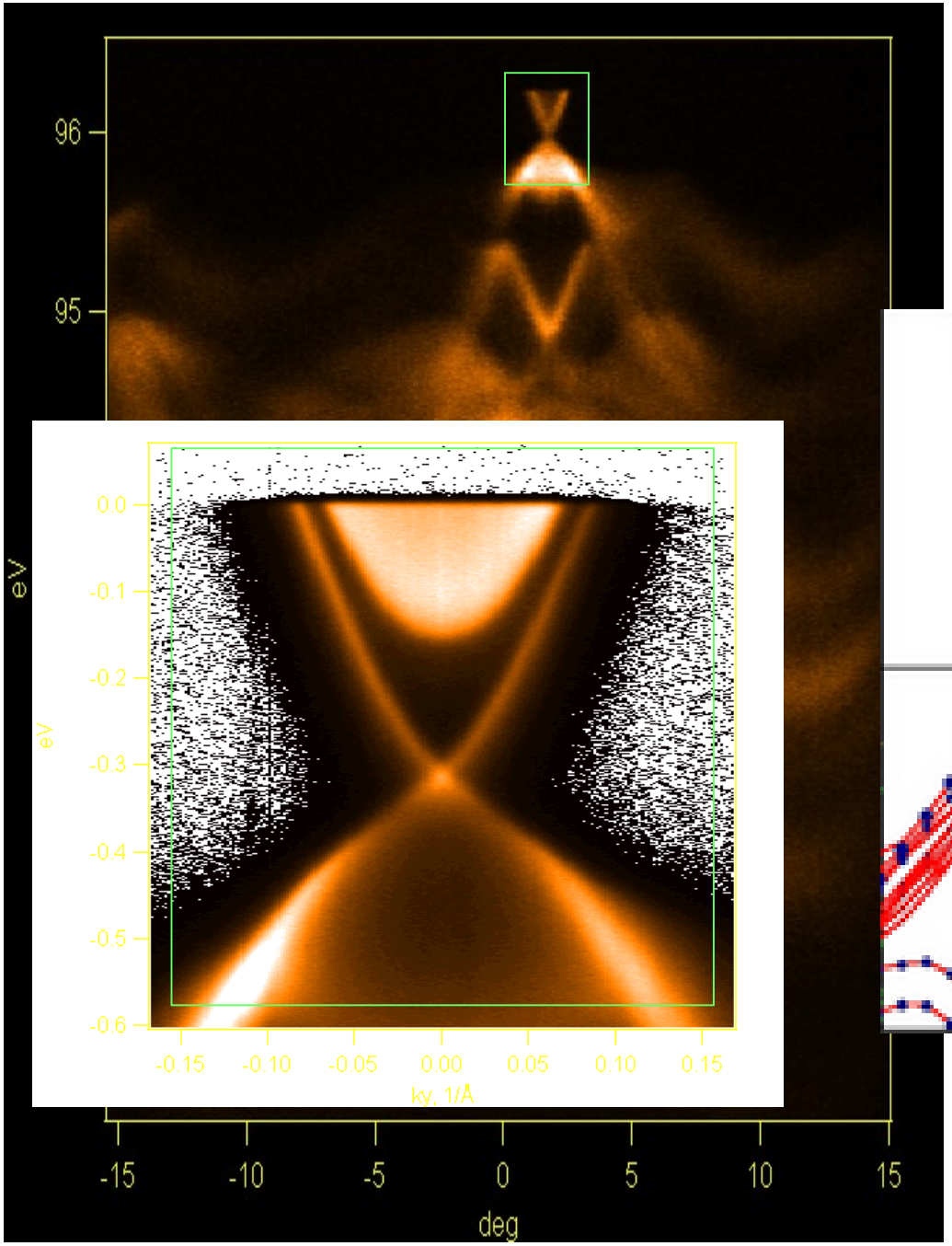


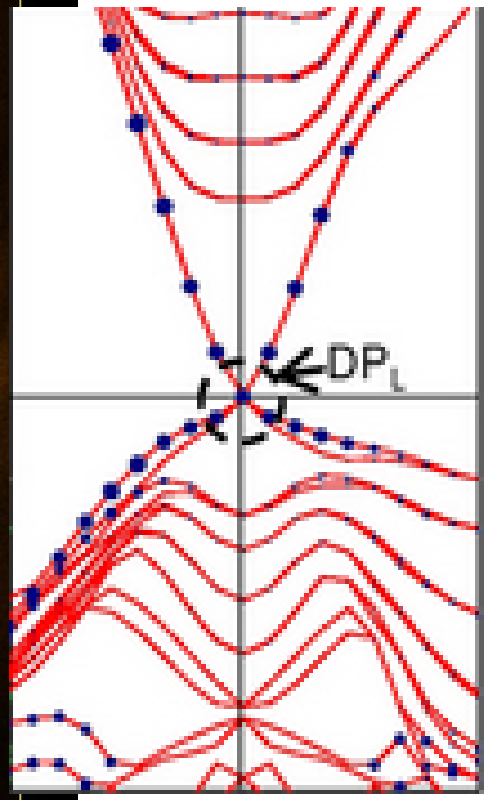




Bi_2Se_3

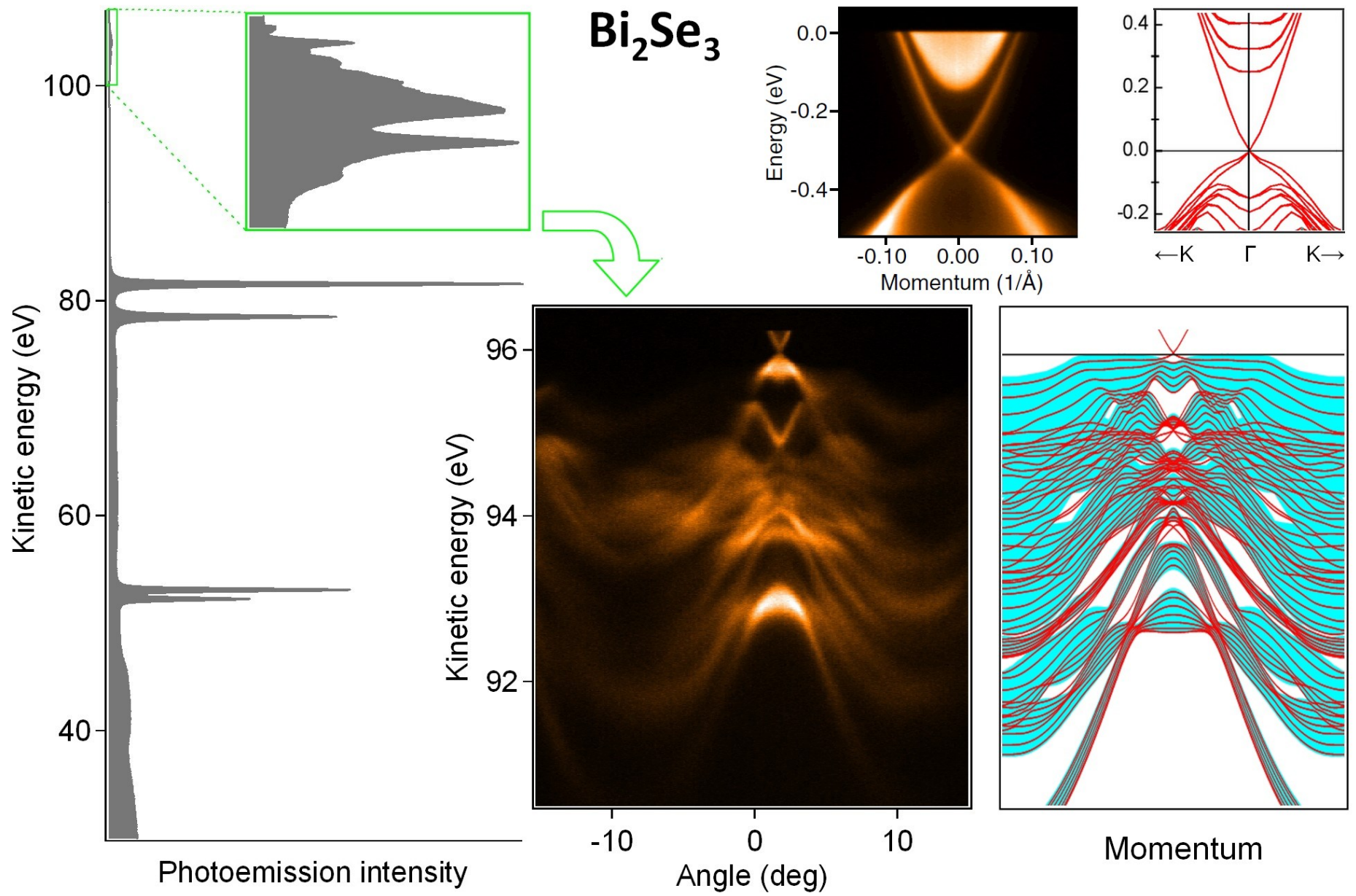



96
95
eV
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.15
-0.10
-0.05
0.00
0.05
0.10
0.15
ky, 1/A
-15
-10
-5
0
5
10
15
deg

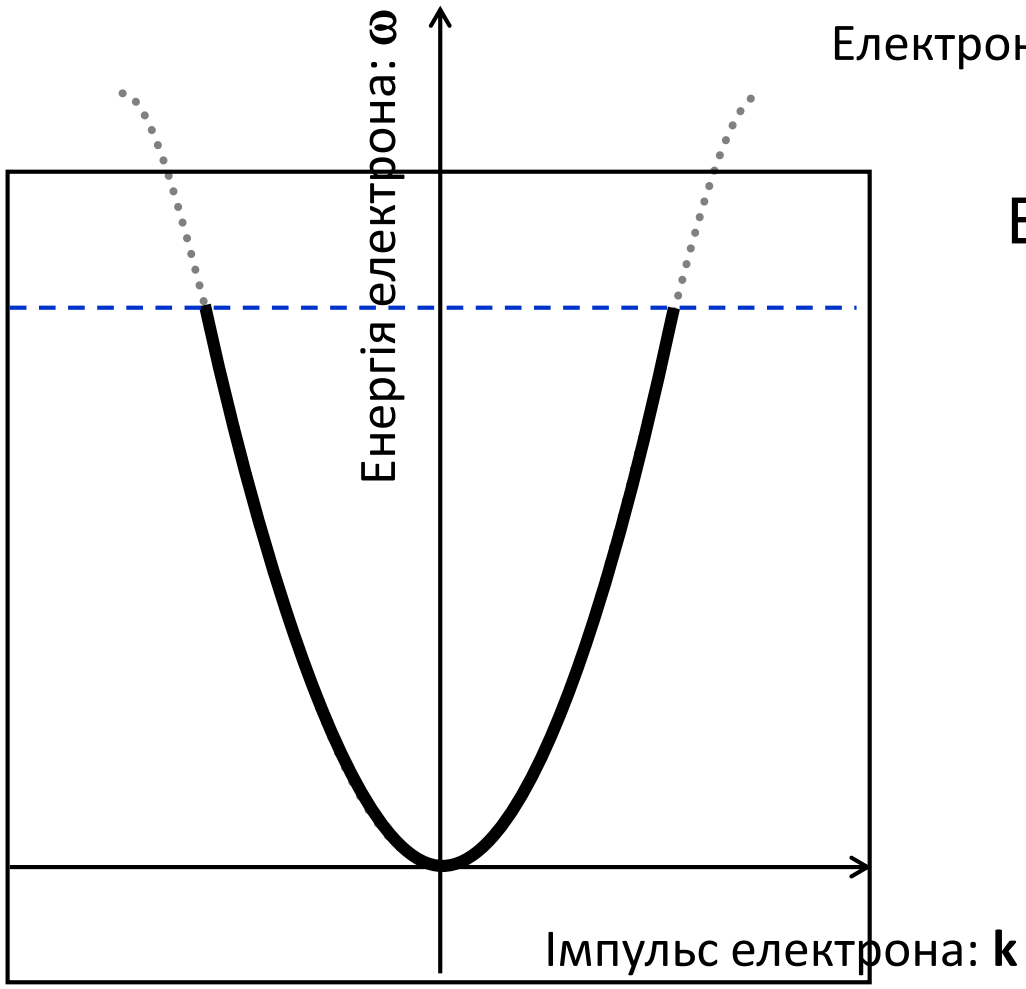

DP$_L$

Bi_2Se_3

ARPES: **A**ngle **R**esolved **P**hoto**e**mission **S**pectroscopy



Electronic structure

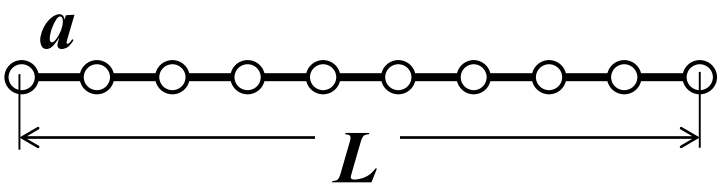


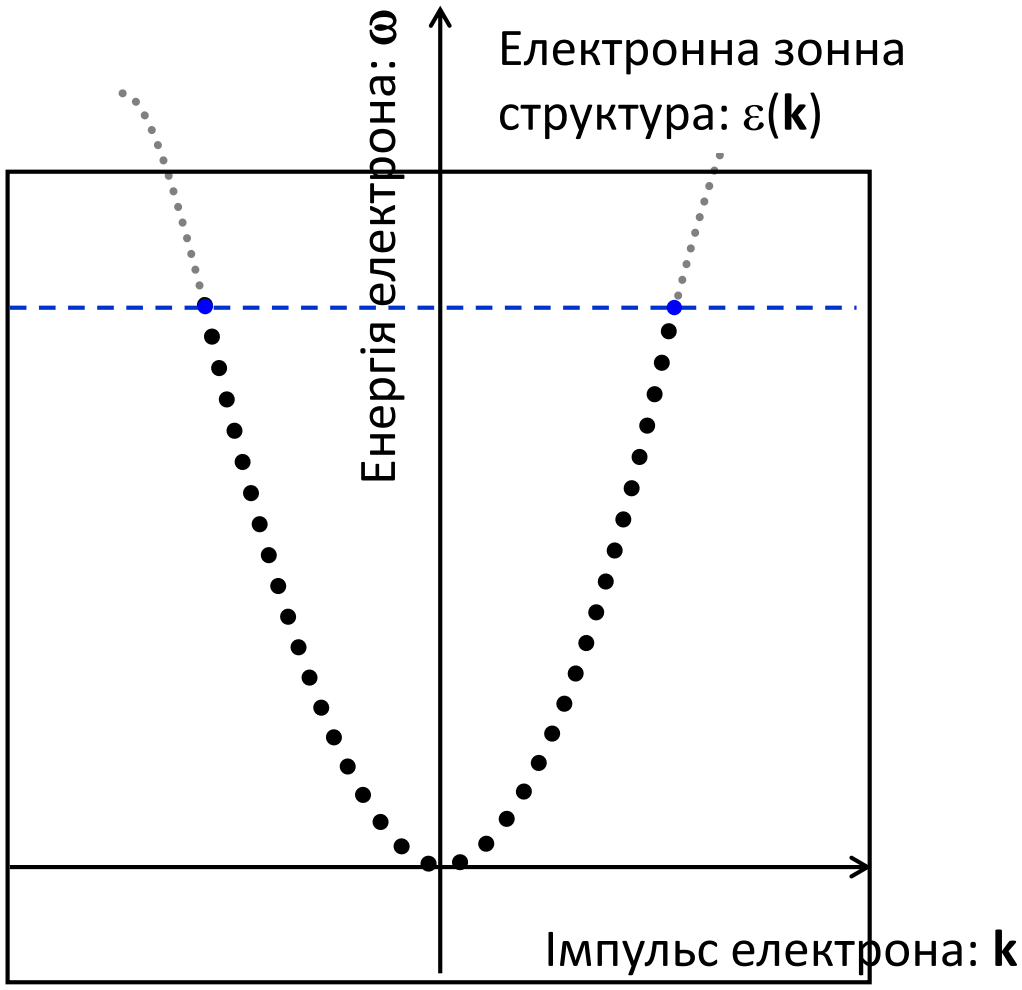
Електронна зонна структура: $\varepsilon(\mathbf{k})$

$$E = mv^2/2 = p^2/2m$$

$$p = \hbar k$$

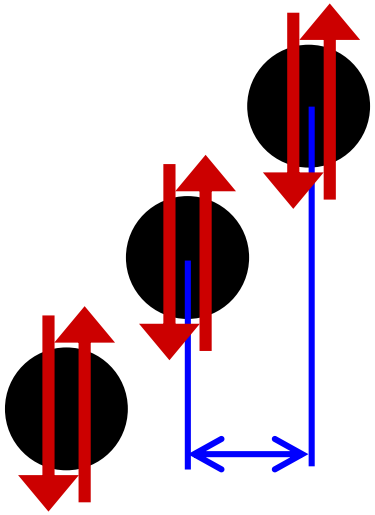
Electronic structure





Електронна зонна структура: $\varepsilon(\mathbf{k})$

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

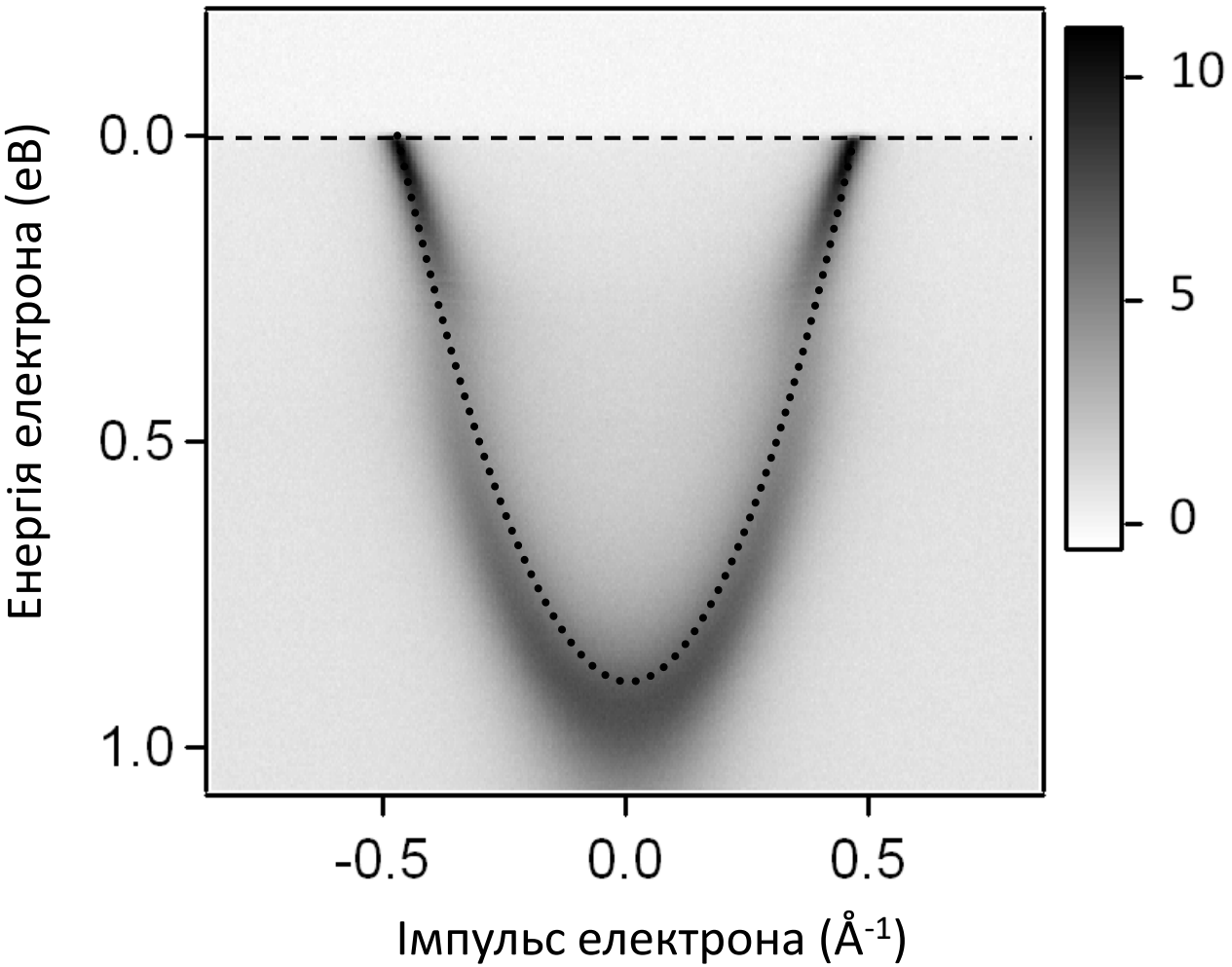


$$dk = 2\pi/L$$

Electronic structure

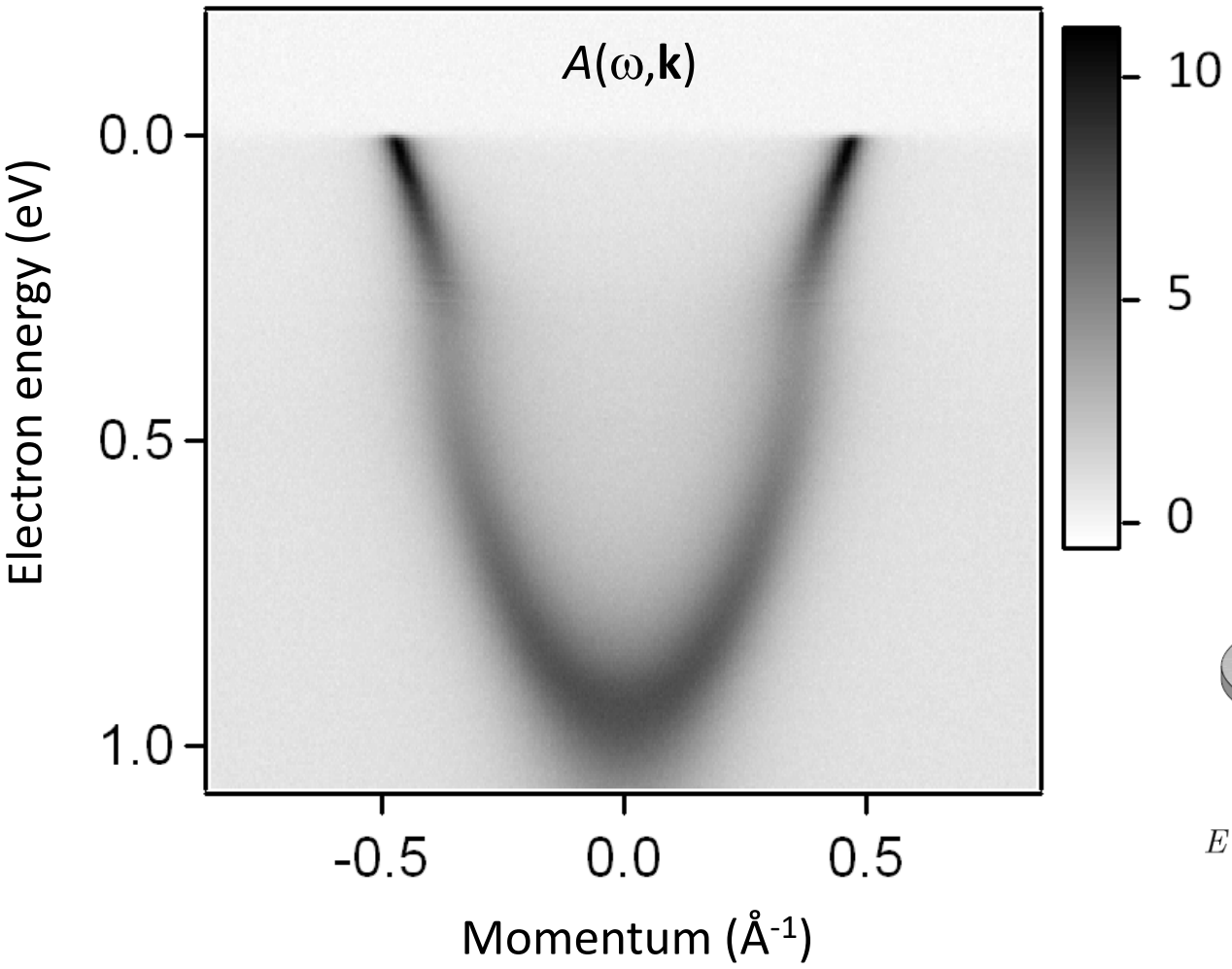
Електронна зонна структура: $\varepsilon(\mathbf{k})$

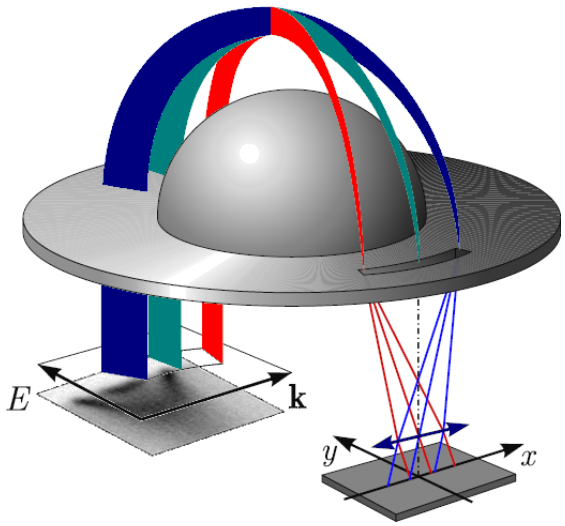
Електронна структура: $A(\omega,\mathbf{k})$



Electronic structure

Electronic structure ≡ Electronic excitation spectrum ≡ Probability to find electron with momentum **k** and energy ω





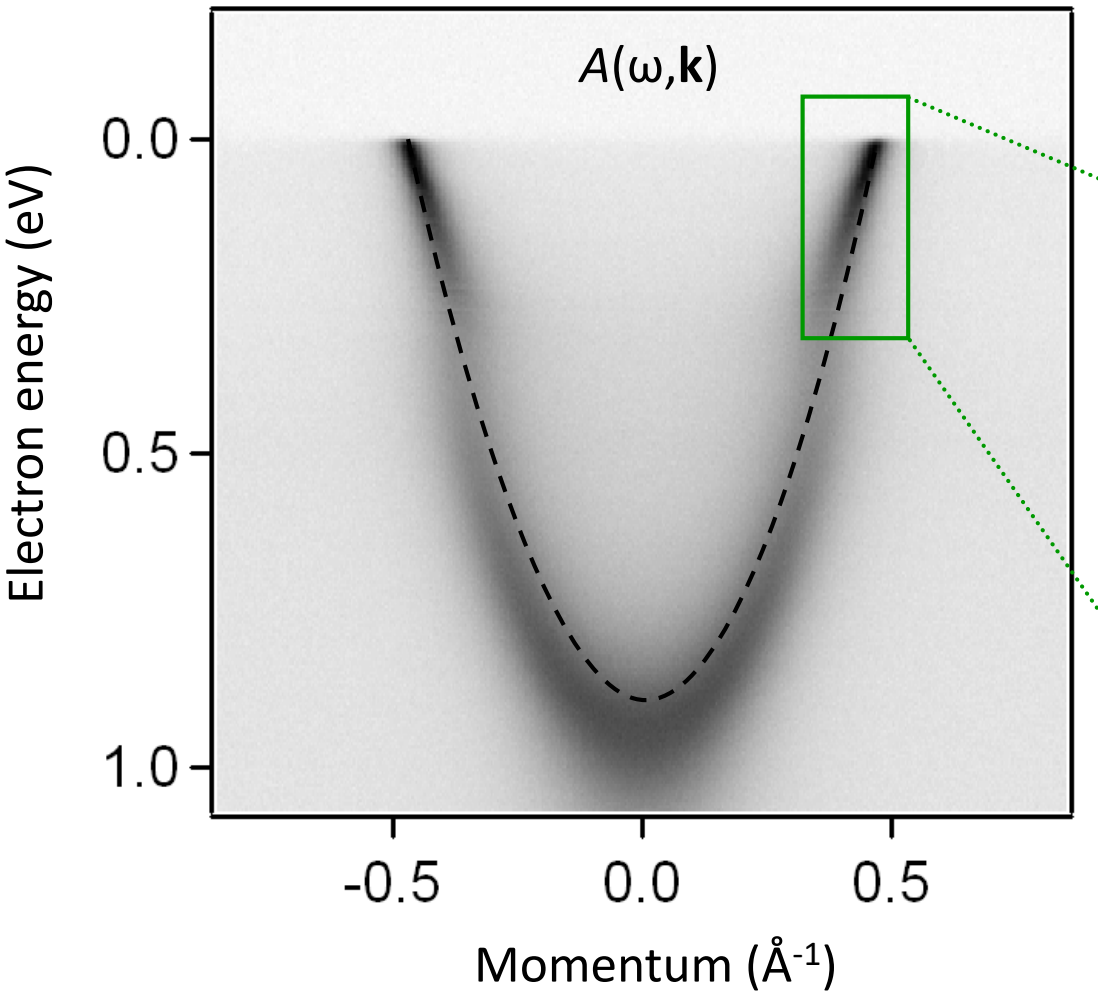
Structure of electronic spectrum

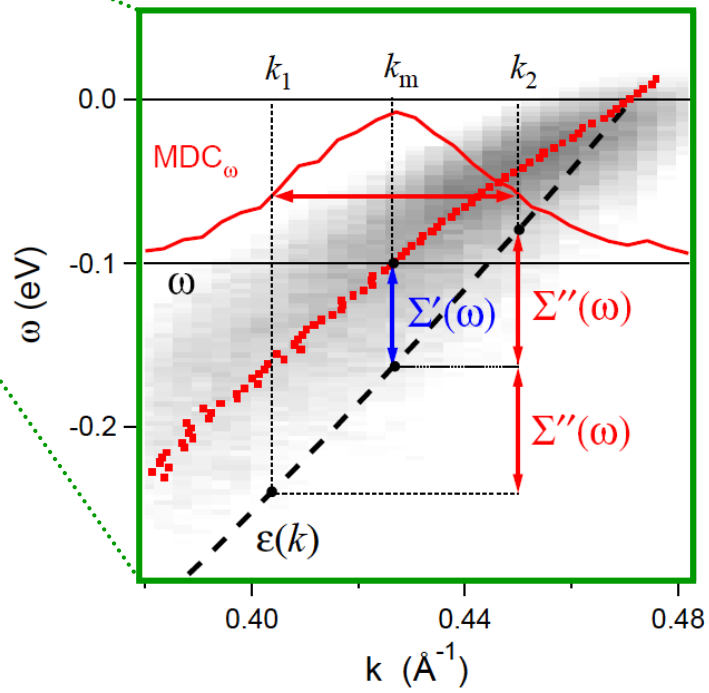
Spectral function

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

ε(k) – "bare" electronic band structure

Σ(ω,k) – self-energy

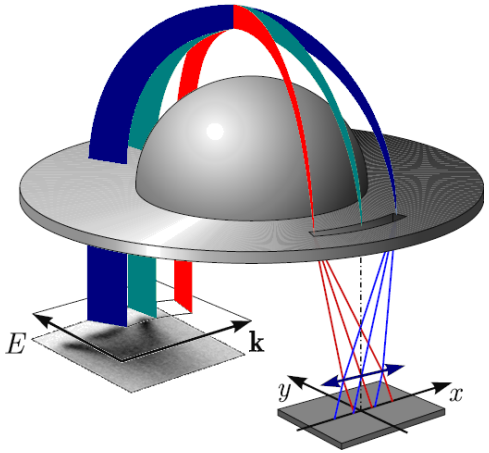


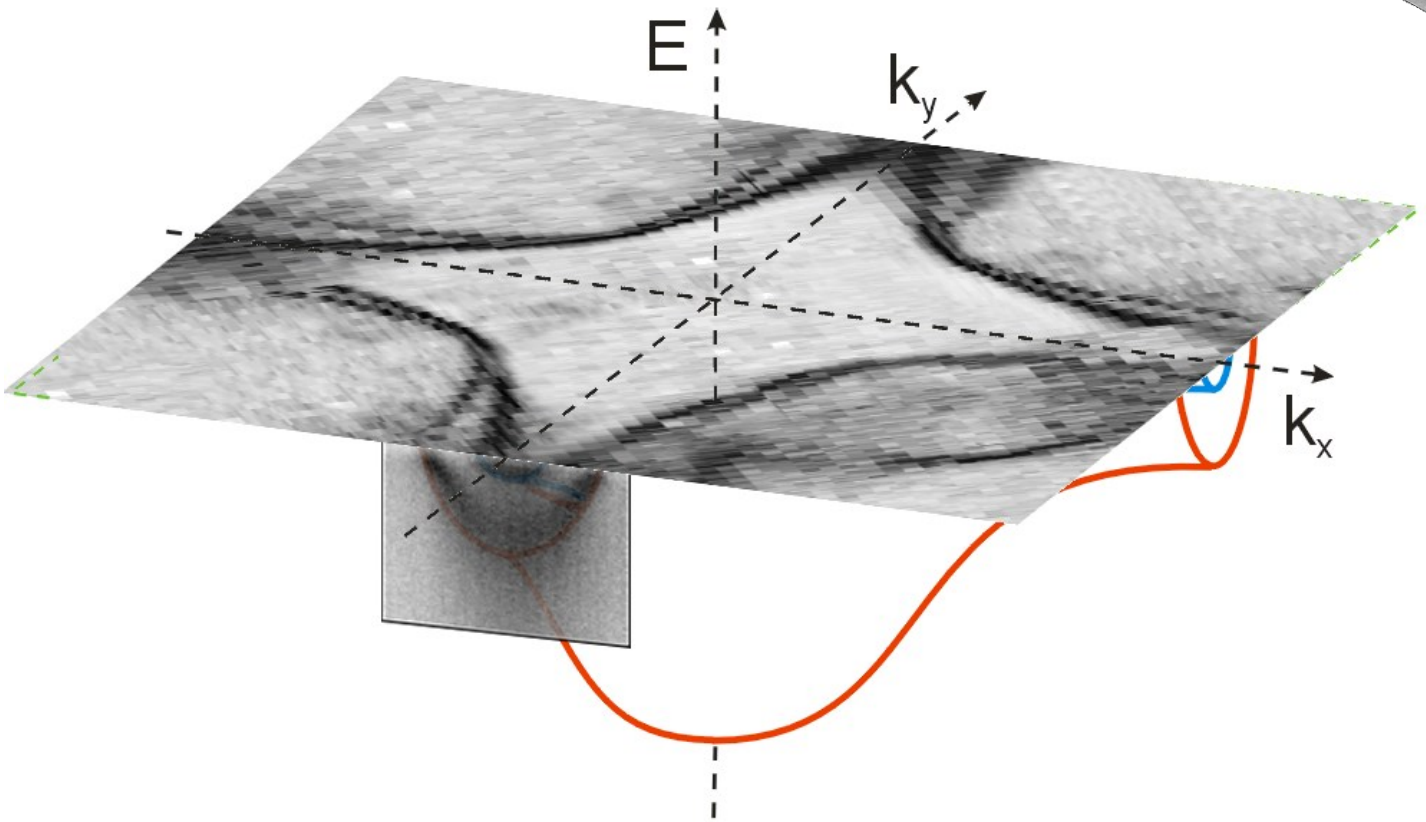


Kordyuk *PRB* 2005

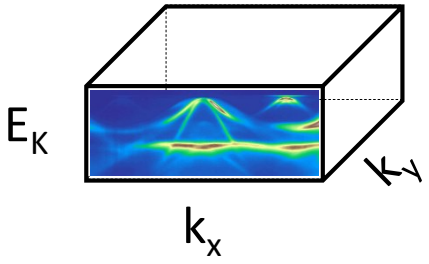
Electronic spectrum of quasi-2D crystals

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

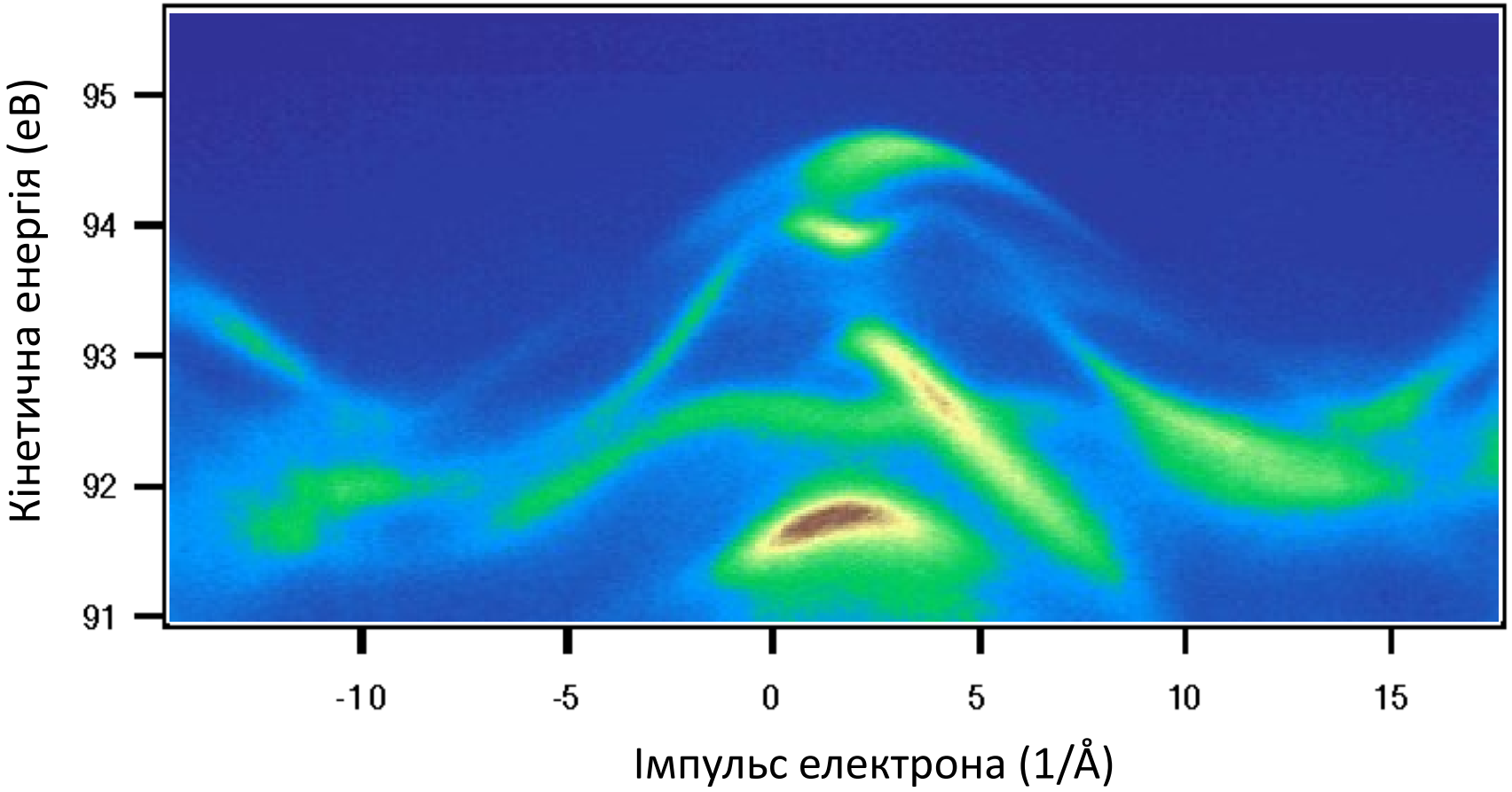




Electronic spectrum in momentum-energy 3D space

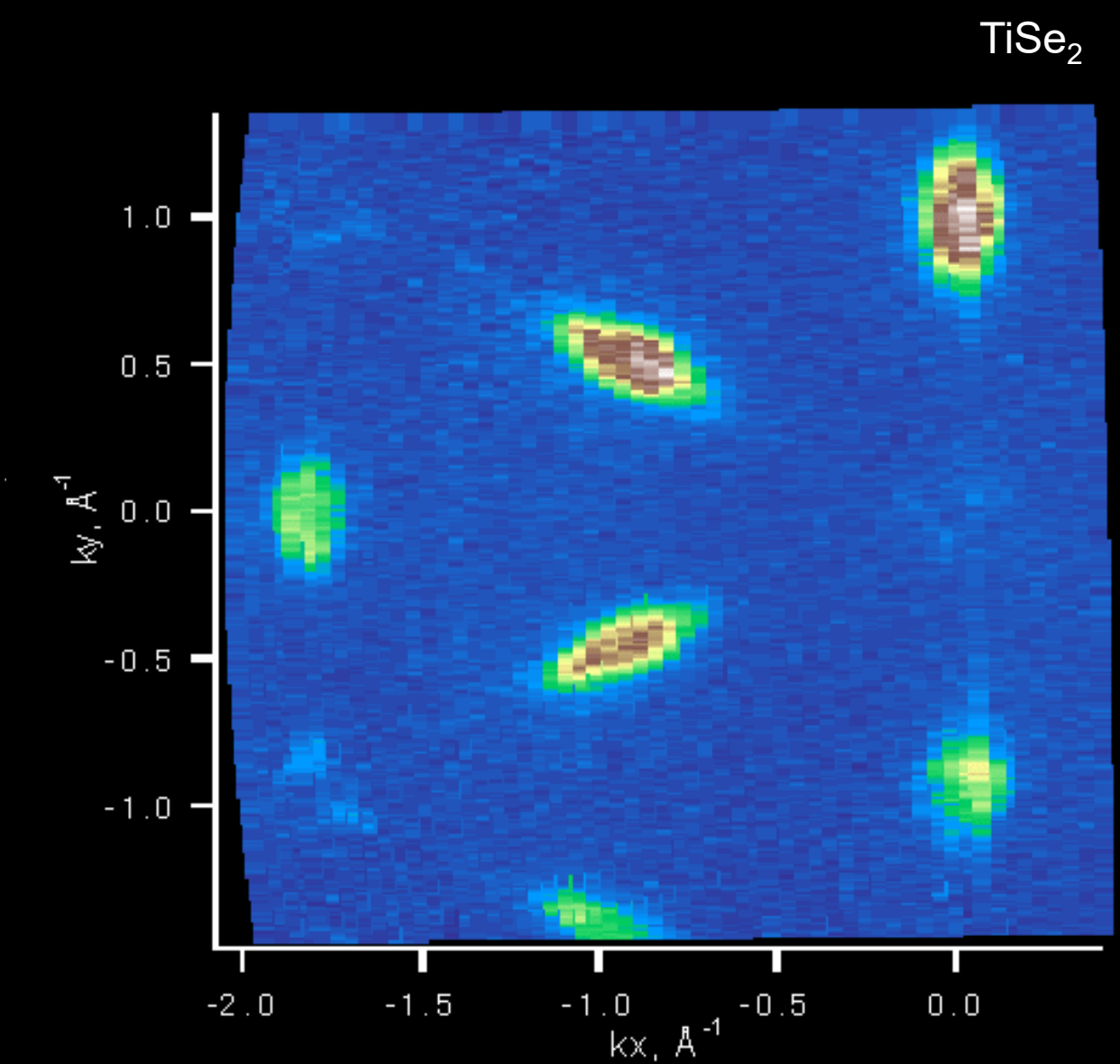


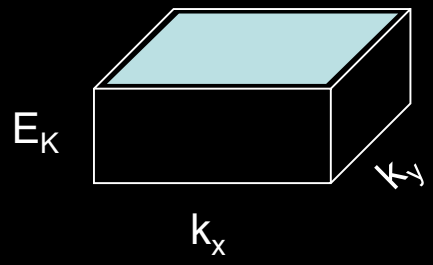
$TiSe_2$ - «excitonic insulator»



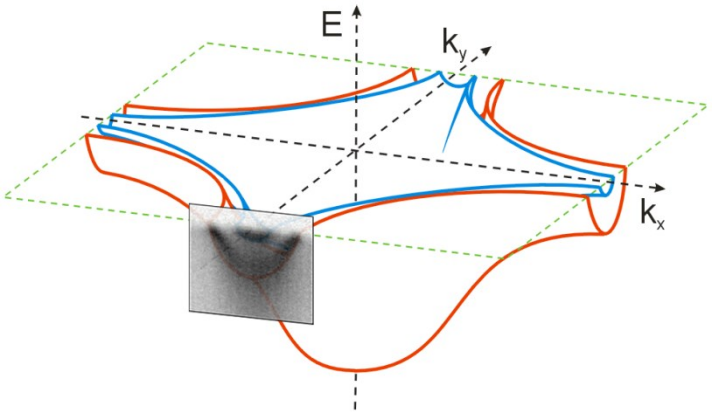
Borisenko JoVE 2012

Fermi surface (energy distribution) map





ARPES: Angle Resolved Photoelectron Spectroscopy



ARPES

=

photo effect

+

analyzer

+

manipulator