From Real- to Momentum-Space

NanoESCA - An introduction to the next generation photoemission microscope

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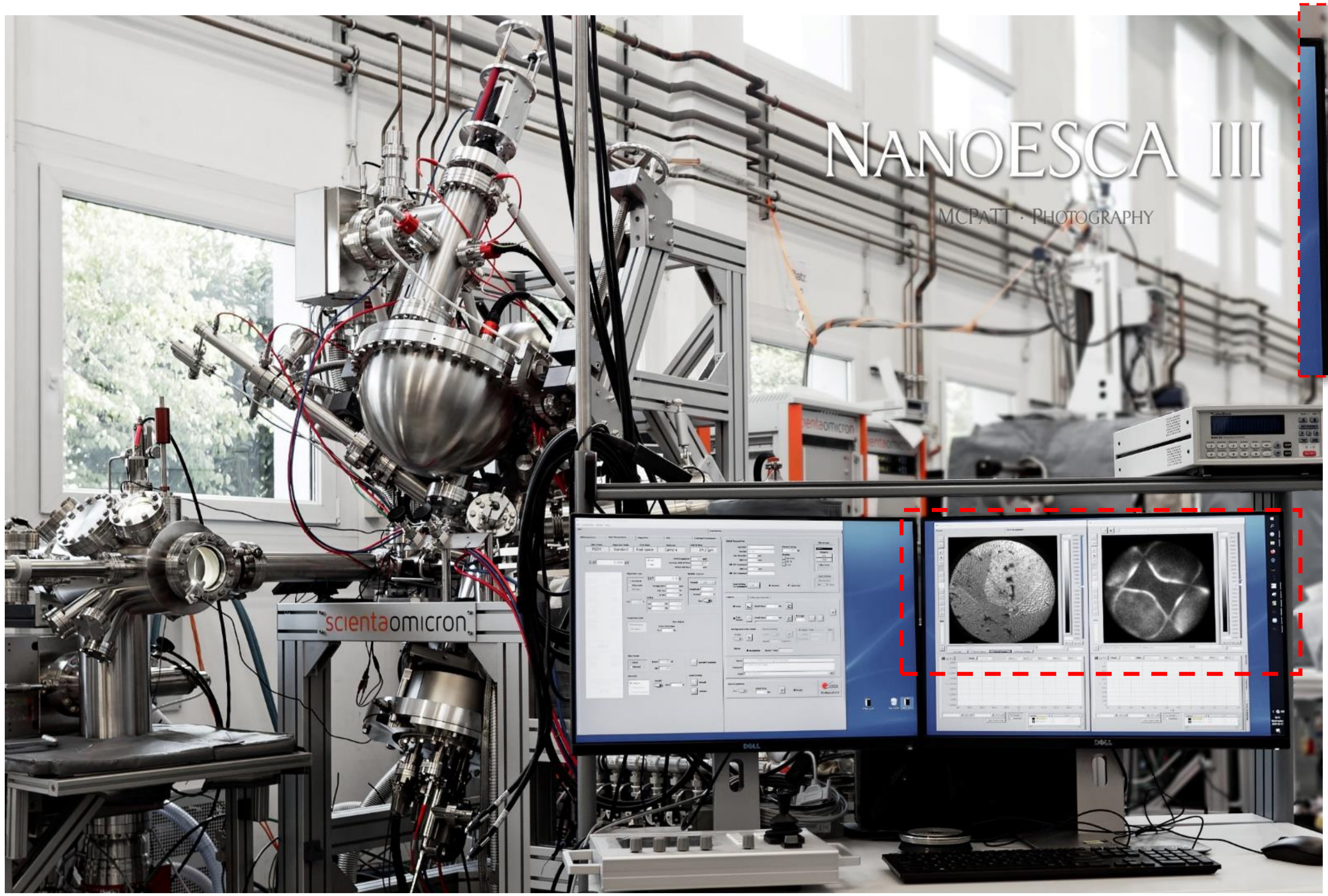
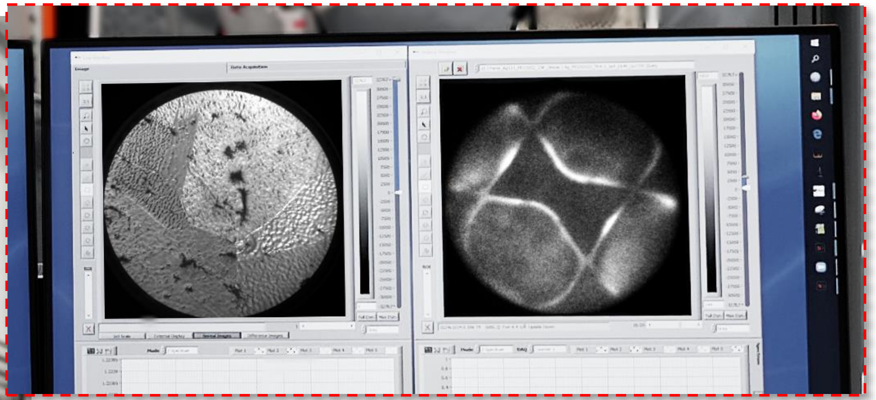
Next generation photoemission microscopy

Photography by M. Patt





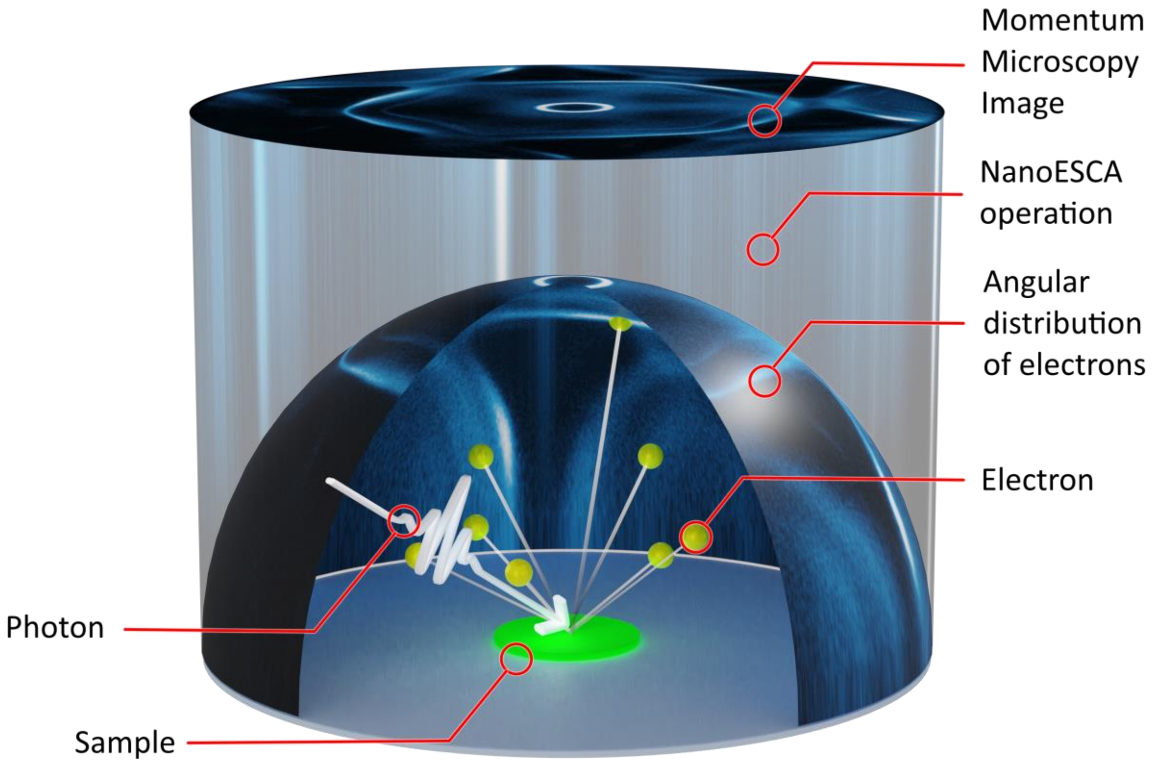
Outline

- Introduction to Momentum microscopy
- Technique and workflow
- Imaging Spin-Filter

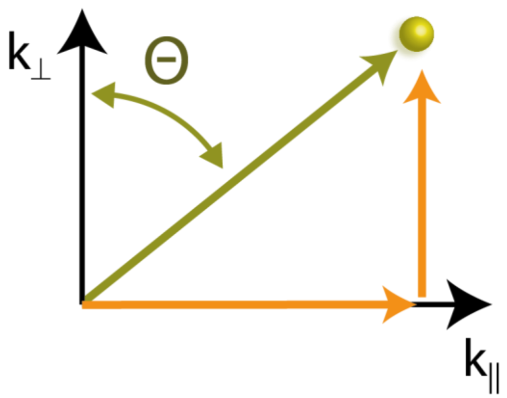
Momentum Microscopy approach

Momentum projection of angular distribution

(Energy-filtered, e.g. Au(111) Fermi-level)



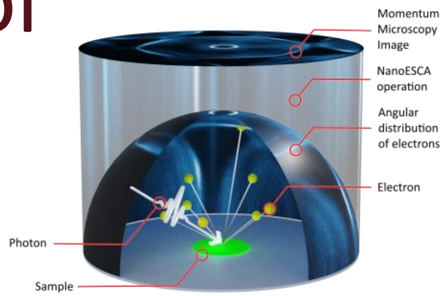
Band structure mapping

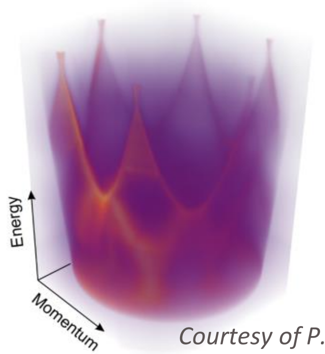


$$|k_{||}| = \sqrt{\frac{2m_e}{\hbar^2}}\sqrt{E_{kin}} \cdot \sin\Theta$$

- The electronic band structure of a material is mapped by measuring the electron momentum parallel to the sample surface, versus their kinetic energy
- Momentum microscopy can map the complete angular distribution of the half sphere (or zoom into details)
- no sample scanning necessary
- The momentum is measured directly (not the angle)
- The momentum maps are energy-filtered, the energy is scanned over the range of interest

NanoESCA: A universal tool for photoemission

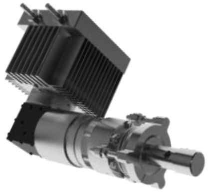




Courtesy of P. Rosenzweig, MPI Stuttgart

- band structure mapping
- micro ARPES
- orbital tomography

Mercury lamp



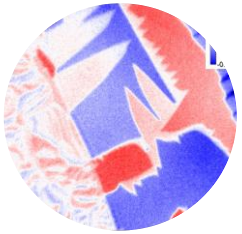
HIS 14 mono

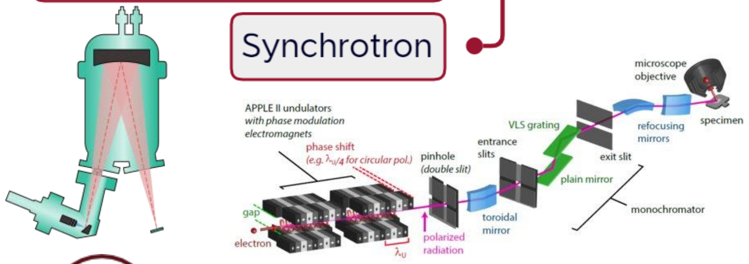
- UV source
- VUV source
- Laser
- Laboratory x-Ray source
- Synchrotron

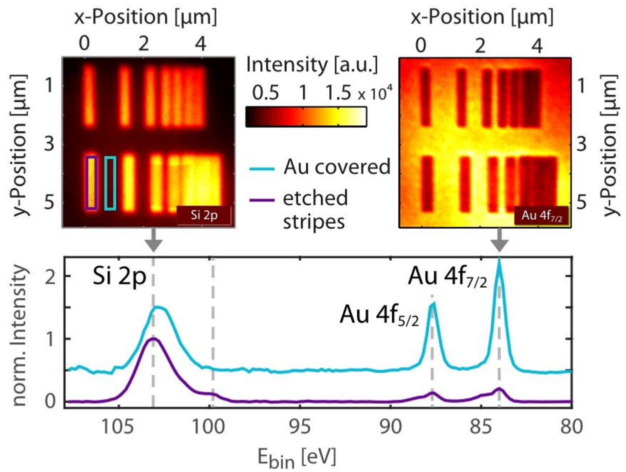
→ Photo excitation

NanoESCA Analyzer

Imaging Mode → Momentum Space / Real Space → Energy Filter → Imaging Spin-Filter



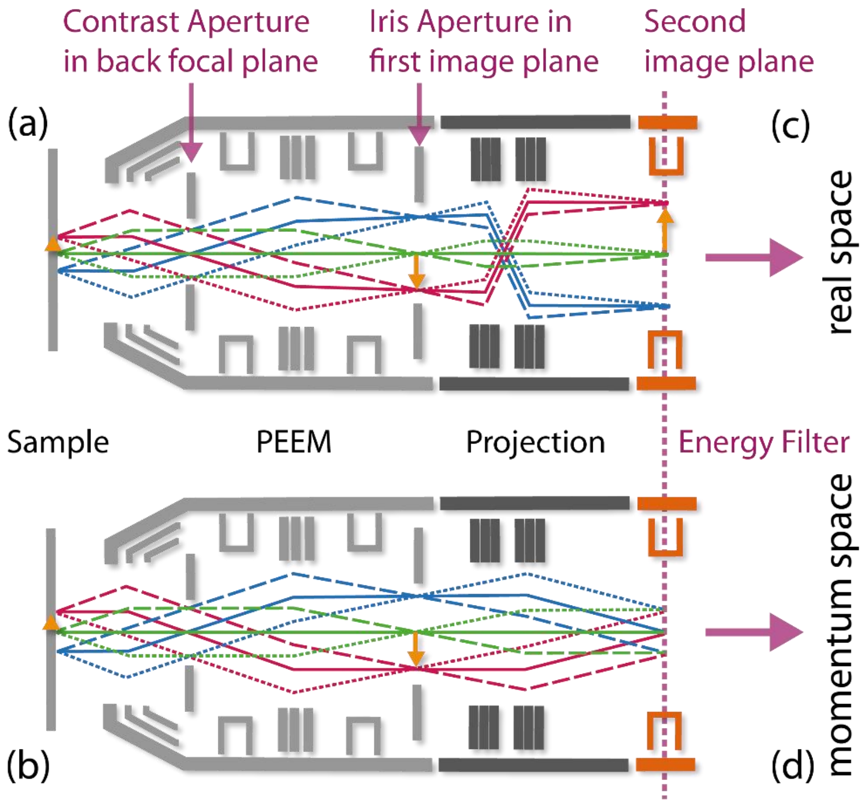




- chemical imaging
- work function mapping
- sample navigation

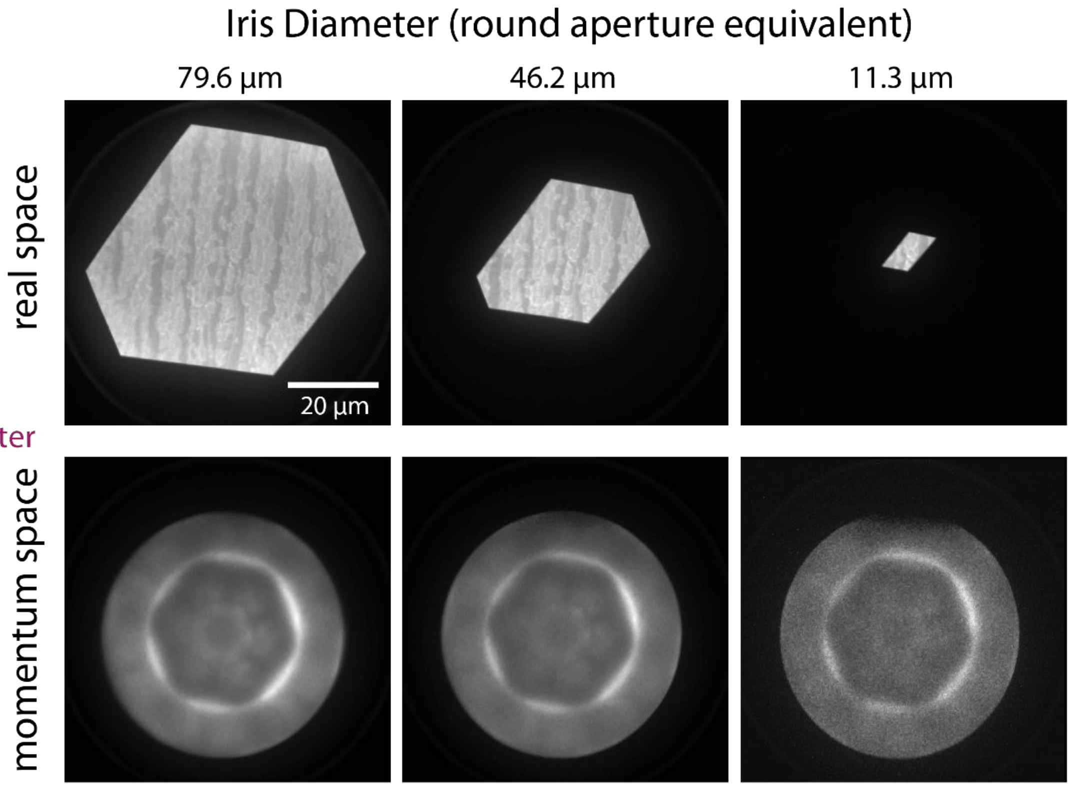
Switch between real and momentum space

Electron trajectories in PEEM



Graphic from M. Patt, PhD thesis, http://hdl.handle.net/2128/10192

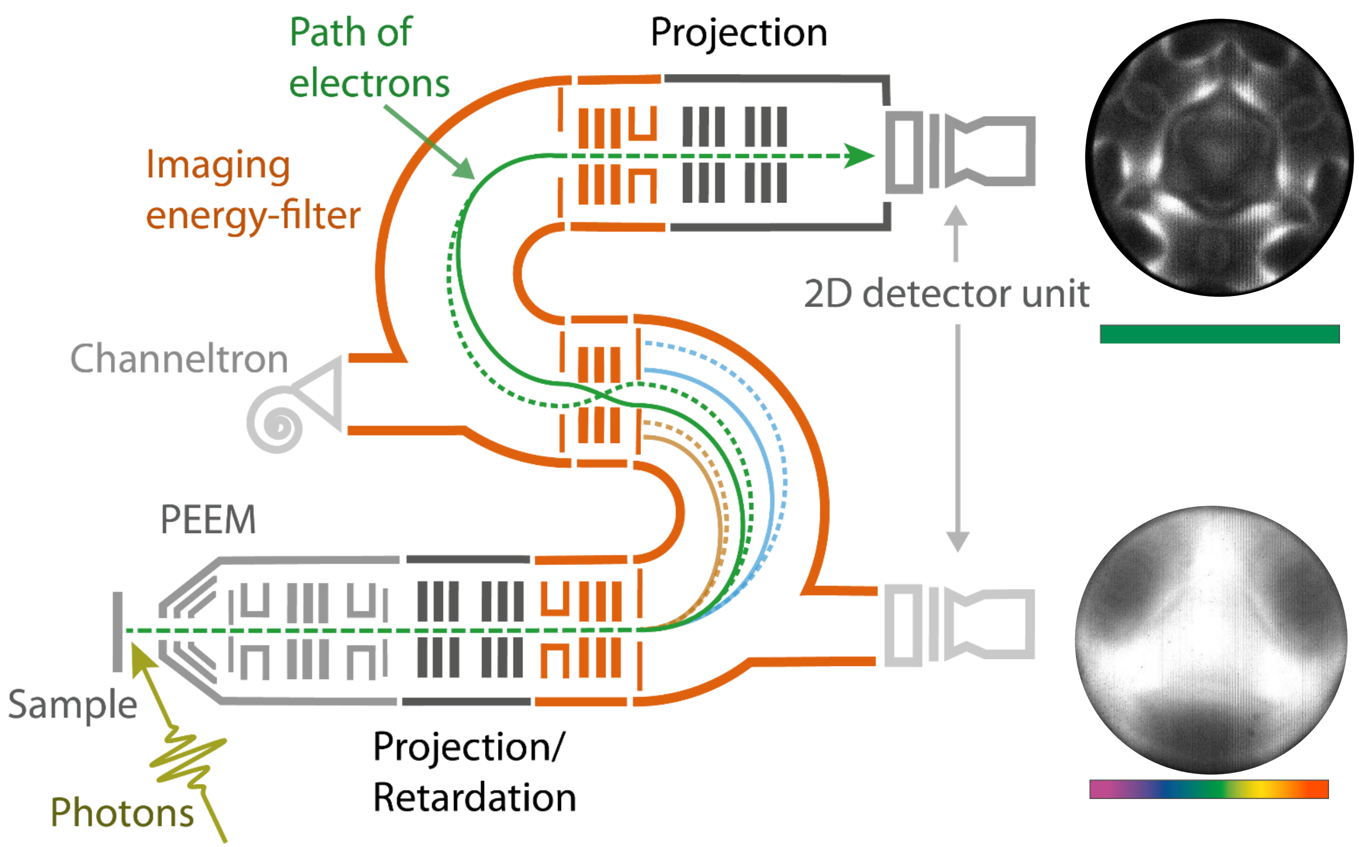
Energy-filtered measurements



The lateral resolution for ARPES is defined by the Iris aperture, not by the spot diameter of the light source (unless you use super focused sources at synchrotrons)

Measured with:
NanoESCA, MPI Stuttgart
HIS 14 VUV-Source, He I
10 s exposure time for each image

Analyzer concept

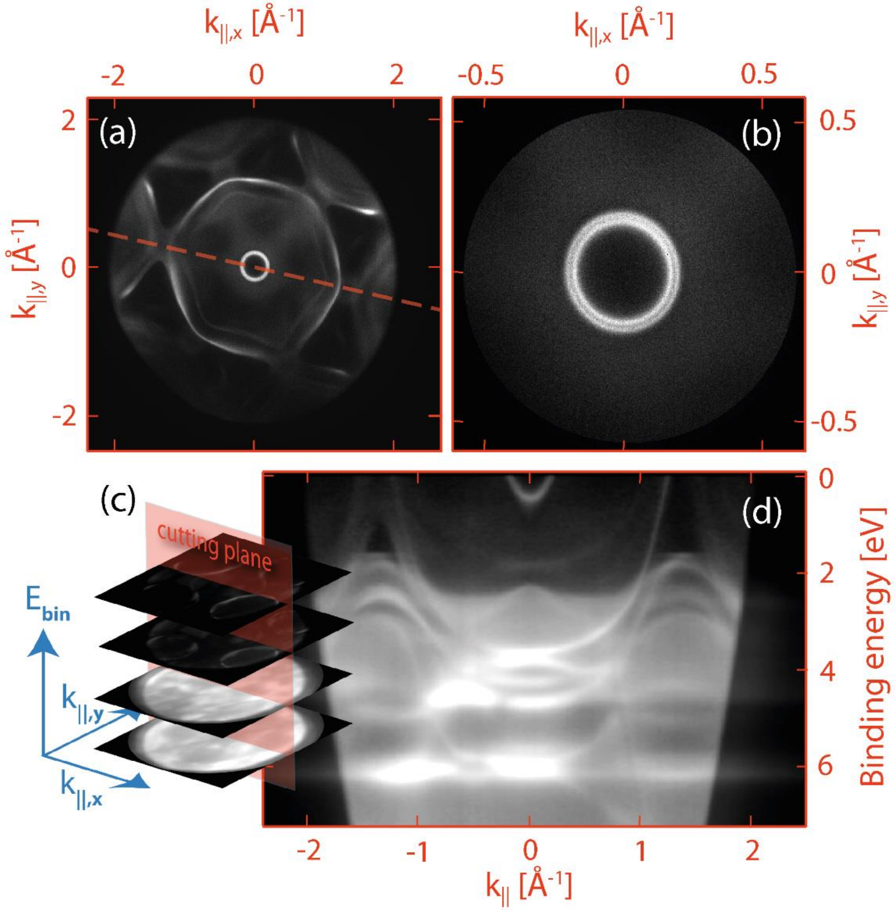


Graphic from M. Patt, PhD thesis,
http://hdl.handle.net/2128/10192

- **The PEEM makes the image**
  - Real-space projection
  - Momentum-space projection
- **Electrons are retarded to the pass energy of the analyzer**
- **This Image is energy-filtered by the double-hemispherical analyzer**
  - Energy selection by slit after dispersion of first hemisphere
  - Image correction in second hemisphere
- **Final projection onto 2D detector (including a wide range of zooming)**

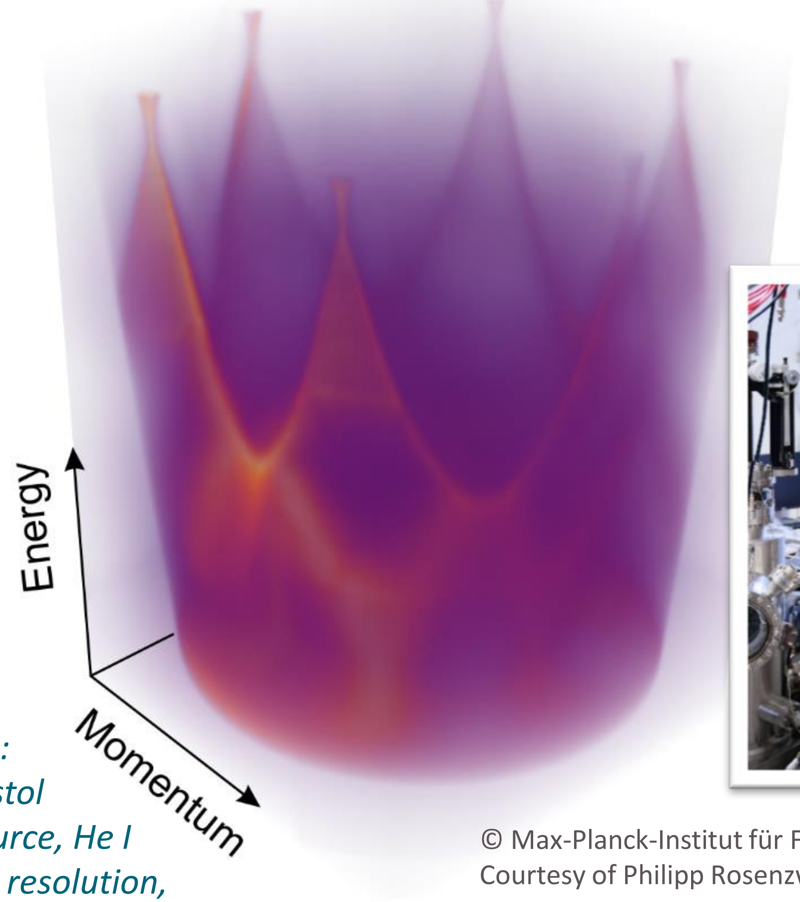
Momentum microscopy measurement

Au (111) single crystal



Measured with:
NanoESCA, Bristol
HIS 14 VUV-Source, He I
50 meV energy resolution,
T= 30 K

Monolayer Graphene on SiC



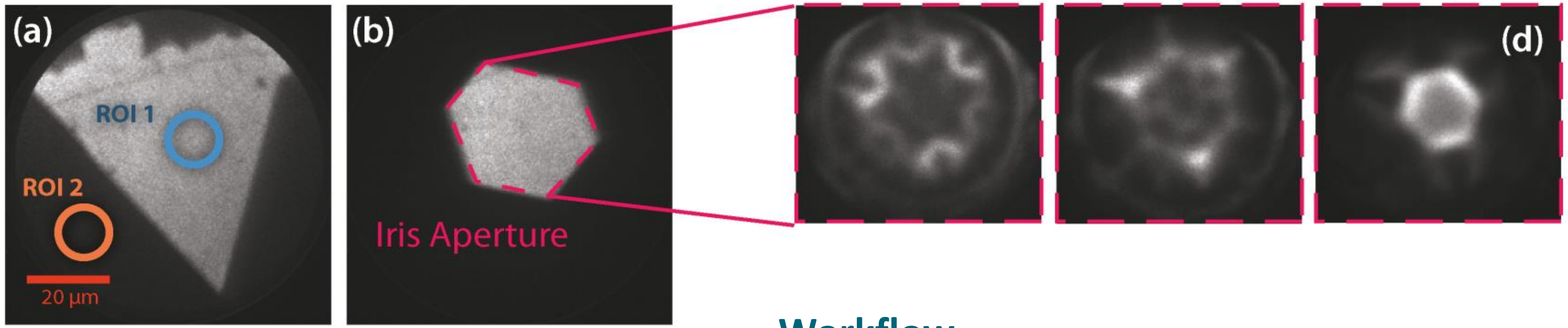
Measured with:
NanoESCA, MPI Stuttgart
HIS 14 VUV-Source, He I
30 µm lateral FoV
100 meV energy resolution,
room temperature
From Fermi level to 6 eV below Fermi level

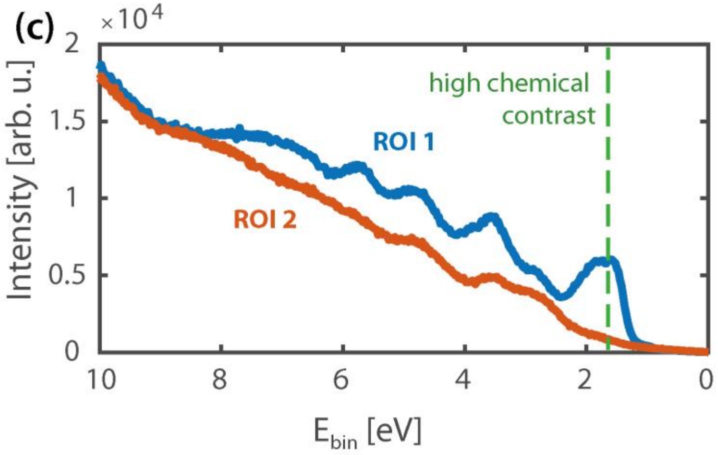
Micro ARPES workflow

WSe2 on highly orientated pyroytic graphite (HOPG)

Chemical imaging (real space)

Momentum imaging (different E_{bin})





Demo-Measurement with:
NanoESCA, Bristol
HIS 14 Mono VUV-Source, He I
100 meV energy resolution,
Room temperature
Extractor Voltage reduced to 2 kV

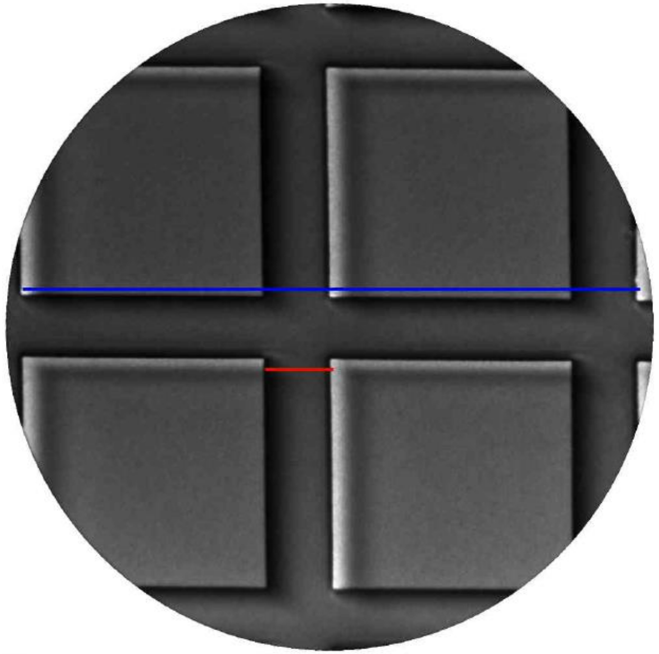
Workflow

- Localize a feature in real space (a)
- Use energy-filter for high chemical contrast (c)
- Close iris aperture to isolate region of interest (b)
- Switch to momentum space
- Acquire momentum images for a range of binding energy (d)

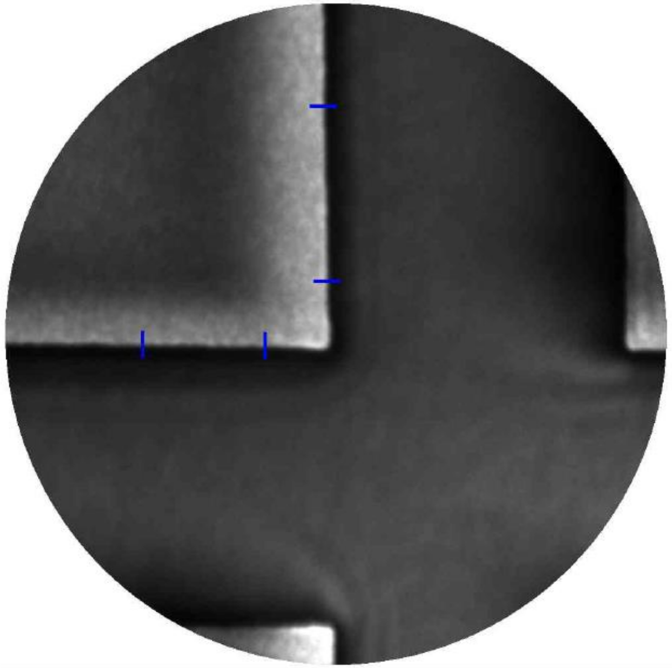
- Real-space resolution < 35 nm
- Easy sample navigation
- Strong chemical contrast
- Precise region definition for micro ARPES

Lateral resolution

Real space images

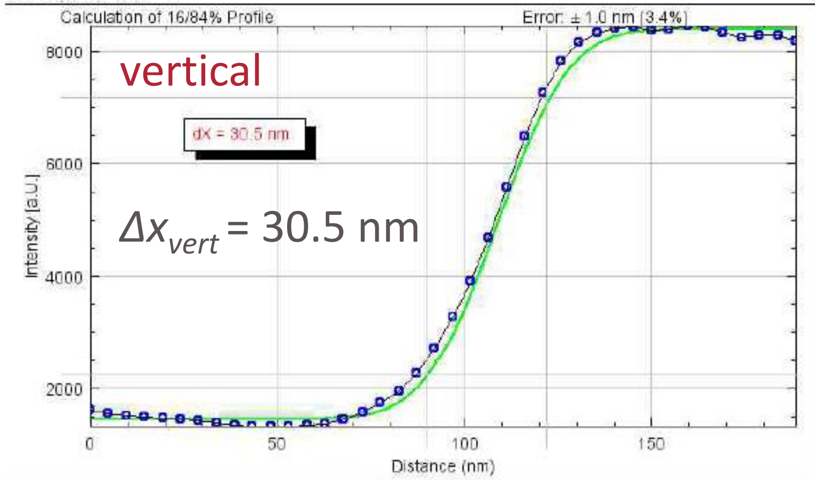


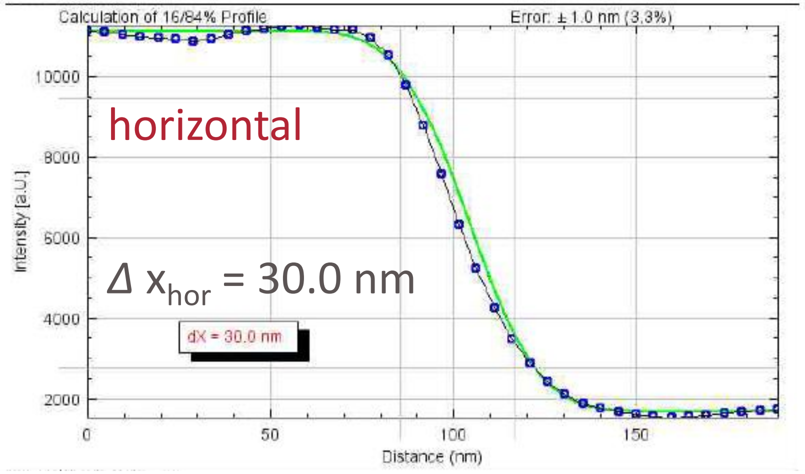
FoV 20.9 µm



FoV 4.8 µm

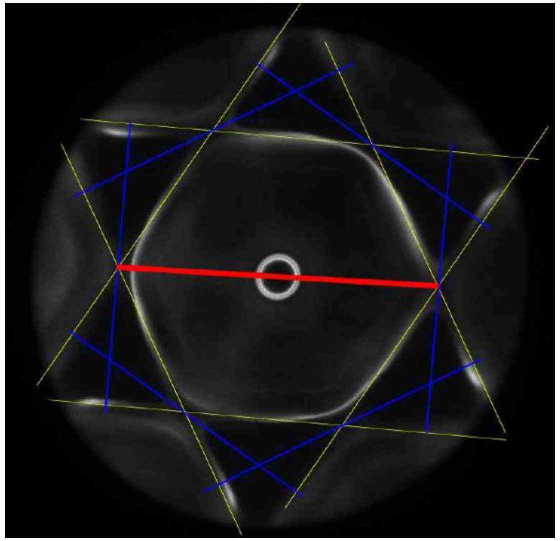
Real-space resolution

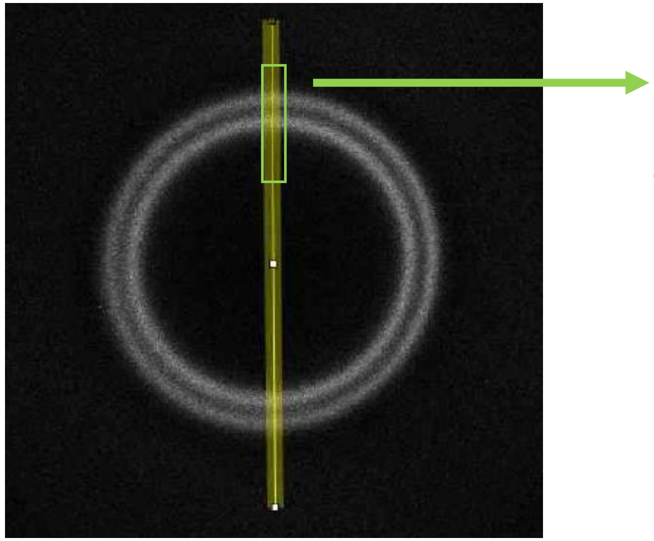




Resolving Au (111) surface state

Momentum image



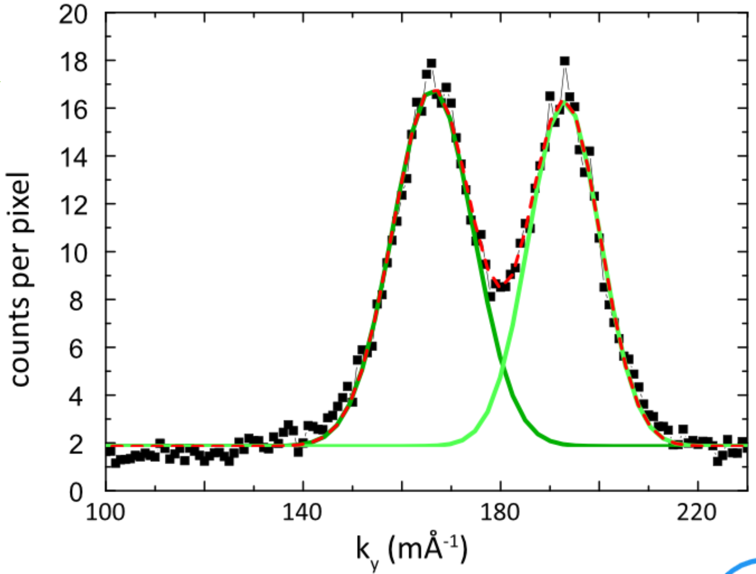


Momentum scale calibration at Brillouin zone

Brillouin zone = 2.516 Å^{-1}
Lattice constant = 4.078 Å

Zoom into surface state feature

Line profile Fit (Gauss)



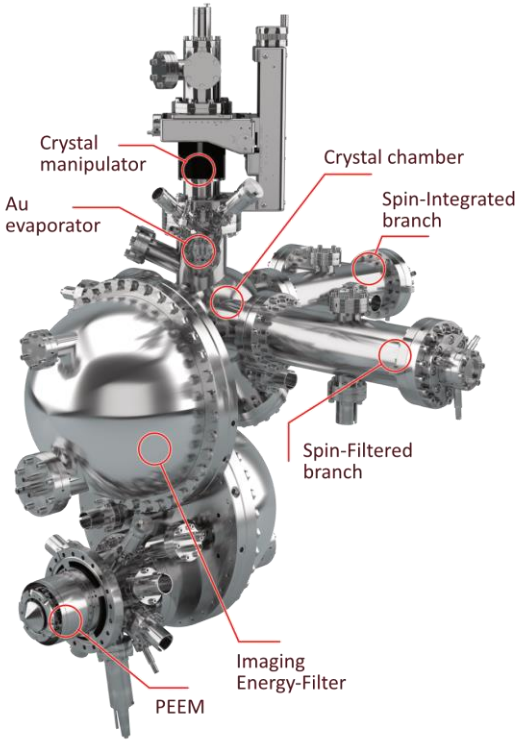
Fit Results

FWHM$_1$ = 19.23 mÅ^{-1}
FWHM$_2$ = 17.07 mÅ^{-1}

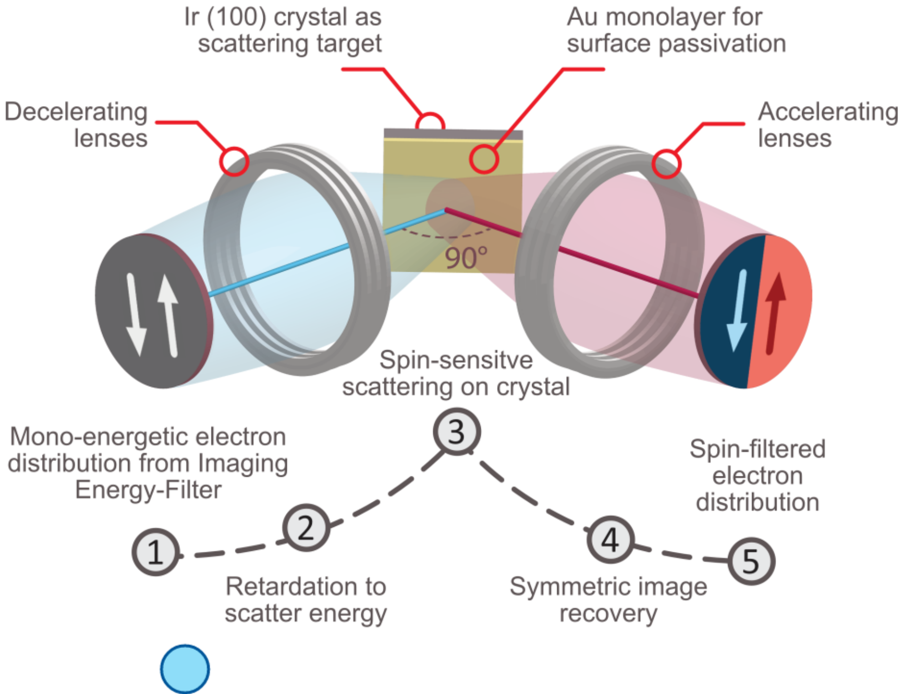
Momentum-space resolution < 0.015 1/Å

Imaging Energy resolution < 25 meV

Imaging Spin-Filter

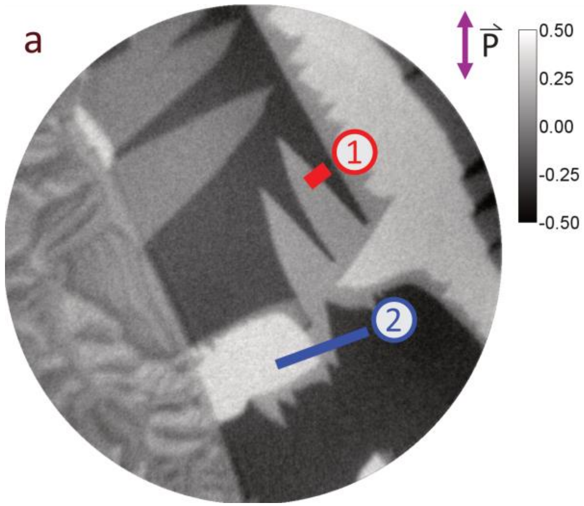


Working principal

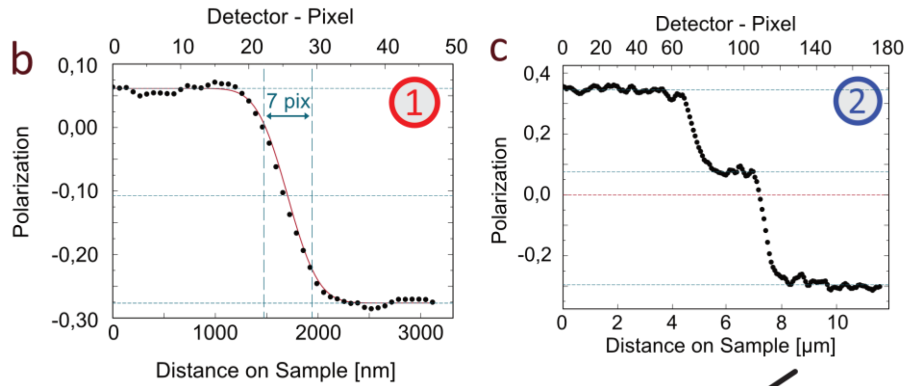


- Stable scattering conditions for weeks
- Sherman function > 60%
- Reflectivity > 1%
- > 10'000 parallel detection channels

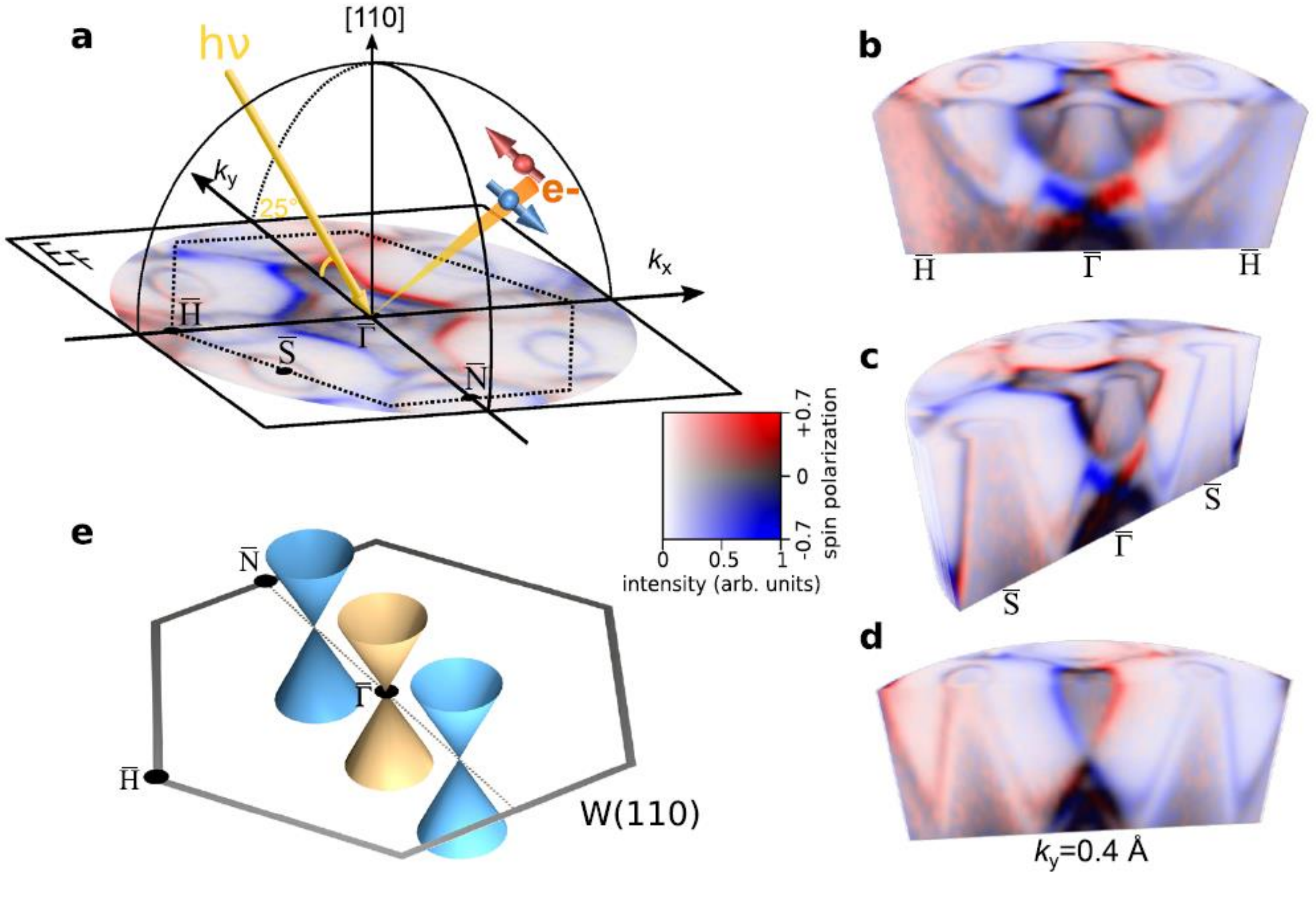
Magnetic domains on poly-Fe sample



Measured with:
NanoESCA, ELI-ALPS
Hg-discharge lamp
100 meV instrumental energy resolution,
Room temperature
200 s exposure time
66 µm lateral FoV



Spin-filtered band structure mapping



Ying-Jiun Chen, Christian Tusche et al., Comm. Phys. (2021) 4:179 (CC-by 4.0 License)

Dirac fermions in W(110)

- Experimental geometry for spin- and momentum-resolved PES (a)
- Full 3D spin resolved momentum map, photon energy hv = 50 eV, different cuts along high symmetry points (b-d)
- Schematic of the tree observed Dirac states (e)
- Still using W (100) as scattering target for Imaging Spin-filtering

Measured with: NanoESCA, Elettra (Trieste, Italy)
Synchrotron radiation, hv=50 eV, p-polarized
T=130 K

Summary

- **Momentum Microscopy** is a fast and comprehensive technique for **band structure mapping**
- **NanoESCA** technique provides a **fast and reliable workflow**
- Combining **Real-Space** and **Momentum Microscopy** is of high importance, especially for **inhomogeneous samples & devices**
- **2D Imaging Spin Filter** makes the Spin-properties of the electron band-structure accessible with **high efficiency**

Thank you for your attention!

Live-Videos from the FOCUS PEEM workshop 2021

Please visit our workshop homepage:
https://www.focus-gmbh.com/workshop-2021/

*With 1,5 hours **Live-Demo** Videos about **PEEM** and **NanoESCA** measurement workflows*

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  - TOF-PEEM
  - NanoESCA
- Spin-Filter
  - Ferrum
  - Imaging Spin-Filter
- Lightsources
  - HIS VUV sources
  - UV sources

Surface Science Toolbox

- Evaporators
  - EFM 3
  - EFM 3T
  - EFM 4
  - EFM-H
- Ion-Sources
  - FDG 15
  - FDG 150