X-ray Photoemission Spectroscopy

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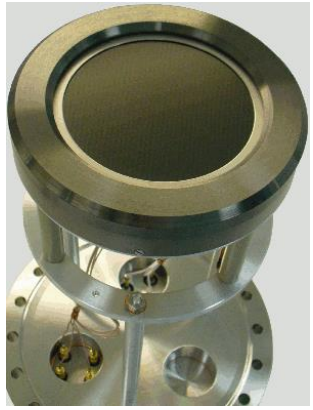
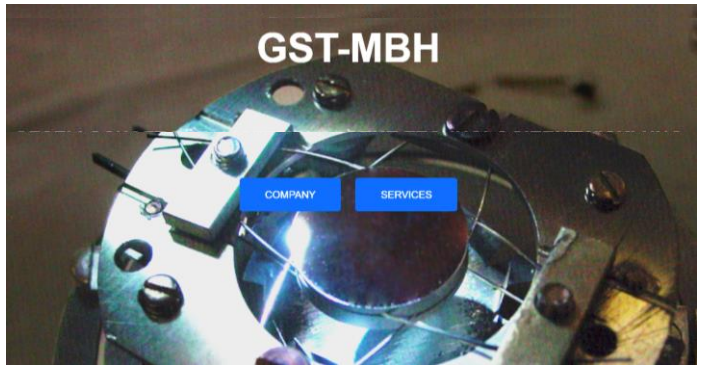
https://www.komet334.physik.uni-mainz.de/

SURFACE CONCEPT



https://www.surface-concept.com



http://gst-mbh.com

Outline:

Method: Time-of-flight momentum microscopy (ToF-MM)

3D (E_B,k_x,k_y) recording

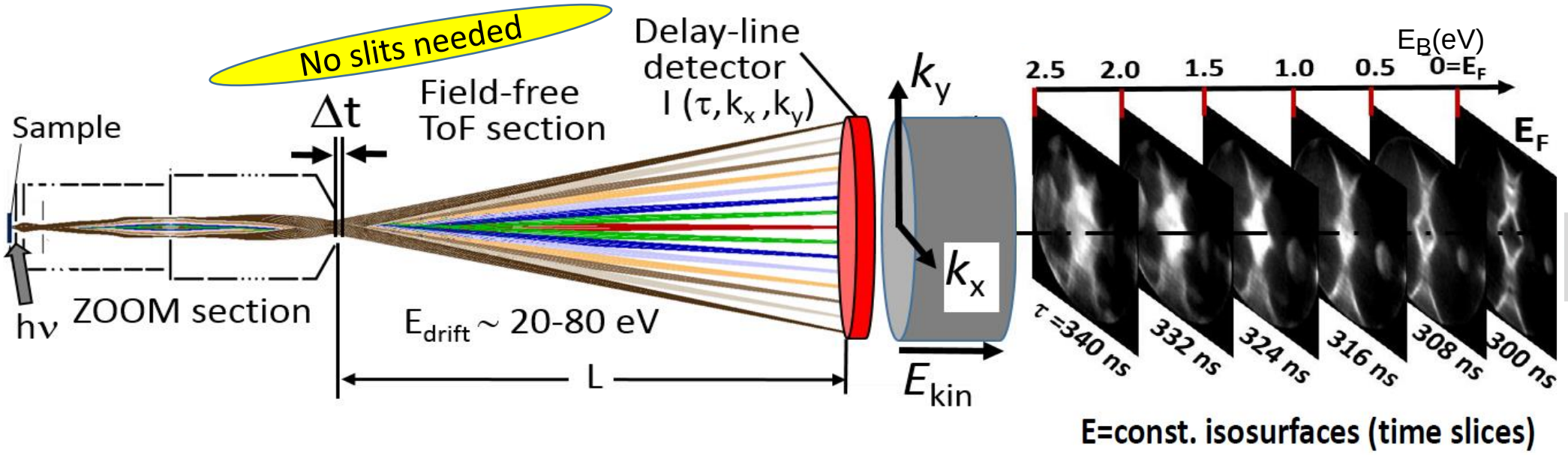
Modes of operation in soft and hard X-ray ranges:

- ***k*-space tomography** 4D **(E_B,k)**
- **XPD** photoelectron diffraction probes geometrical structure
- **SPIN** mapping
- **PEEM** (real space imaging)
- **XPS** (chemical analysis in ToF survey mode)

Why @ FREIA ?

Specifications

3D Recording Method: k_x-k_y imaging + ToF energy recording



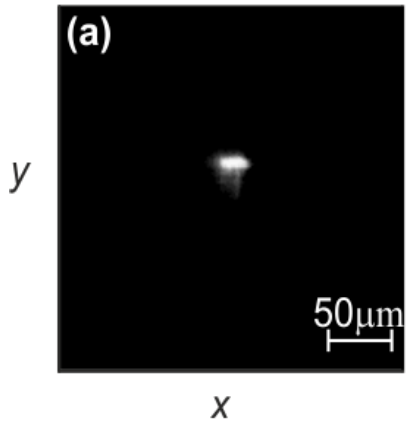
10^5 (k_x, k_y) x 100 E_B
~ 10^7 voxels

E=const. isosurfaces (time slices)

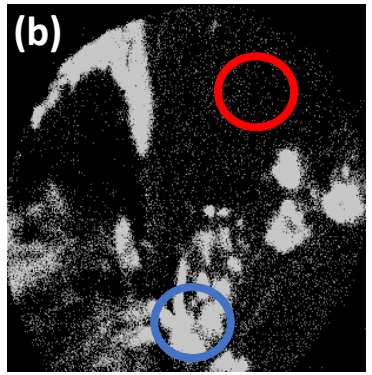
K. Medjanik et al., *Nat. Materials* **16**, 615 (2017)

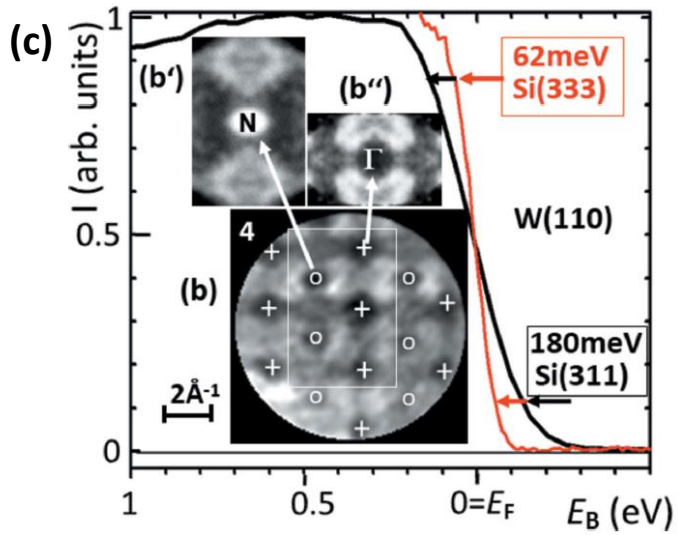
Real-Space (PEEM) images:

photon footprint



Freshly cleaved SmB_6





Resolution measurements:

Si(111) : 450 meV FWHM
Si(311): 180 meV FWHM
Si(333): 62 meV FWHM

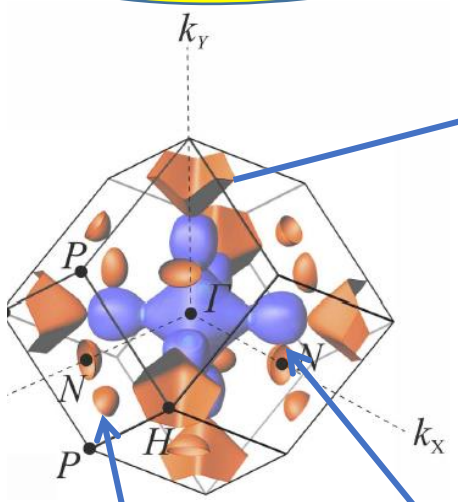
ToF resolution @ 5977 eV 40 meV
@ 6 eV < 20meV

K. Medjanik et al.,
J. Synchrotron Radiation **26,** 1996 (2019)

4D-mapping: $I(E_B, k_x, k_y, k_z)$ „k-space tomography“

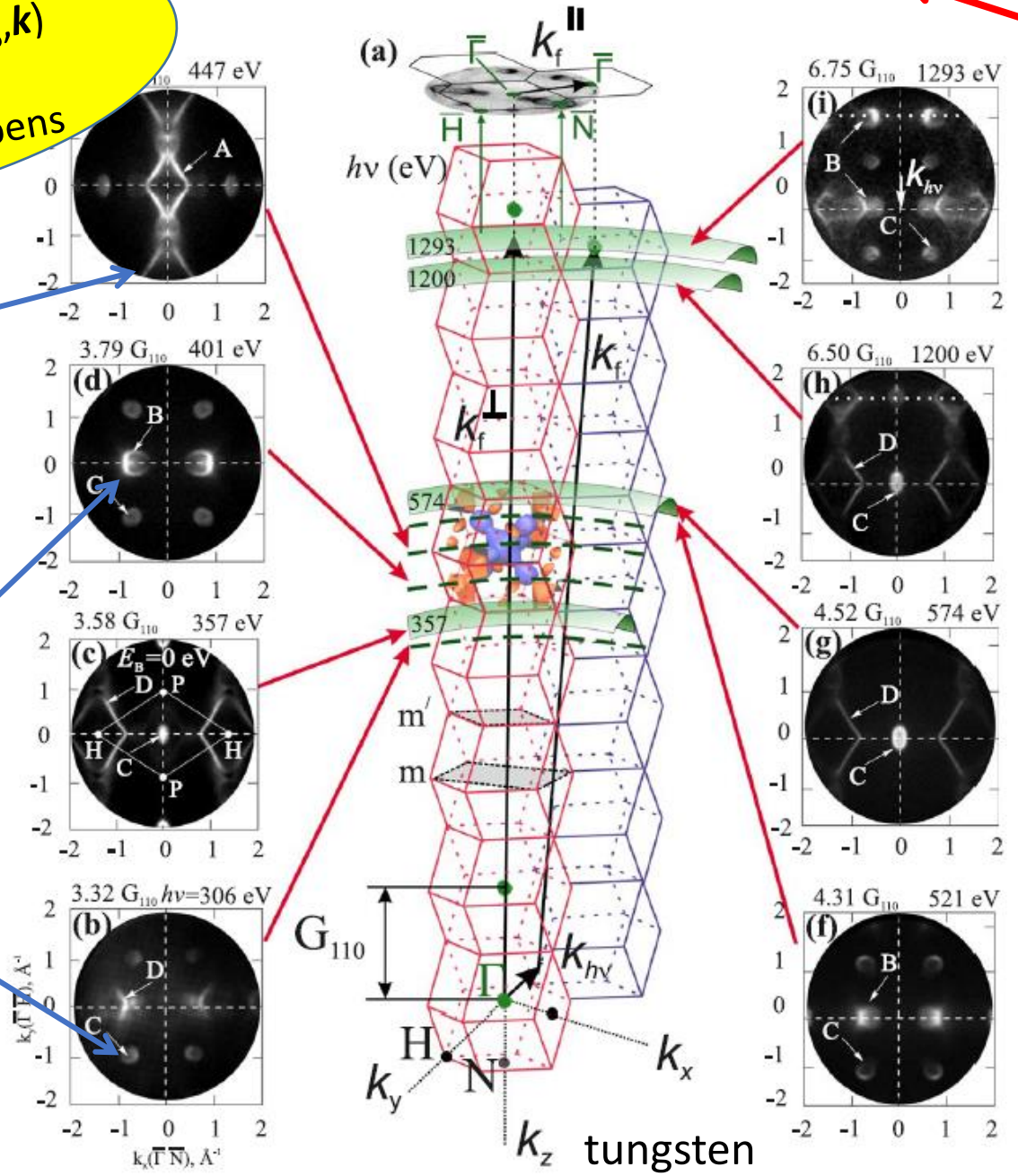
Not necessary to know in advance where in 4D (E_B,$\boldsymbol{k}$) parameter-space the interesting physics happens

via photon-energy scan



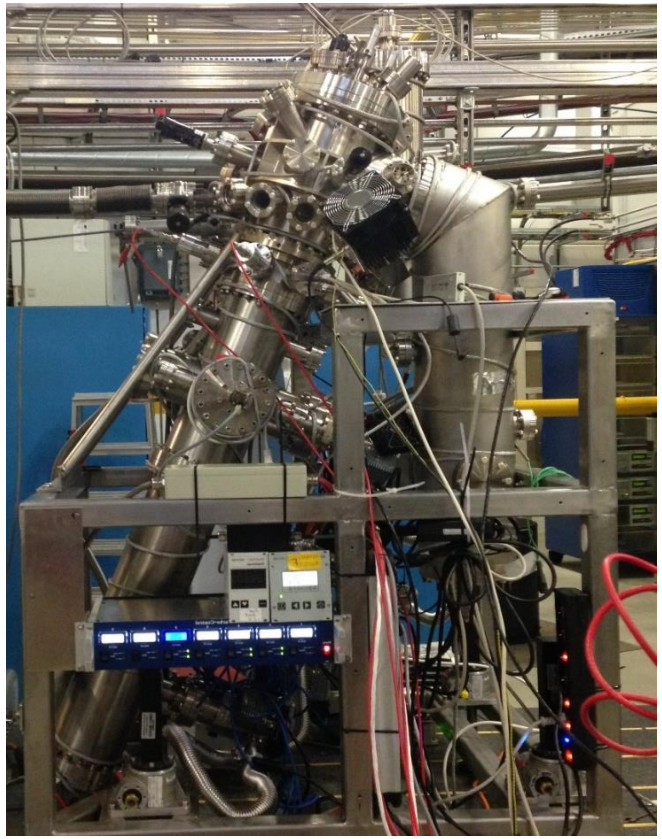
electron balls at the central octahedron

ellipsoidal hole pockets



tungsten

k-ToF @ P04 (Petra III)



O. Fedchenko et al., *New Journal of Physics* **21**, (2019)

4D-mapping: $I(E_B, k_x, k_y, k_z)$ „k-space tomography“

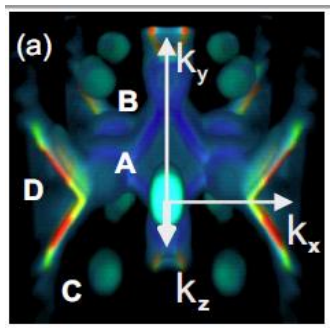
via photon-energy scan

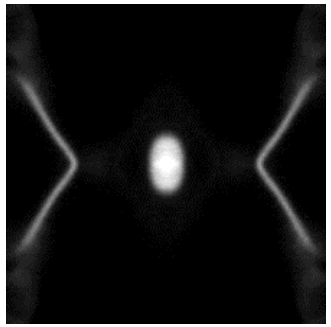
Measured Fermi surfaces incl. $\mathbf{v}_F(\boldsymbol{k})$

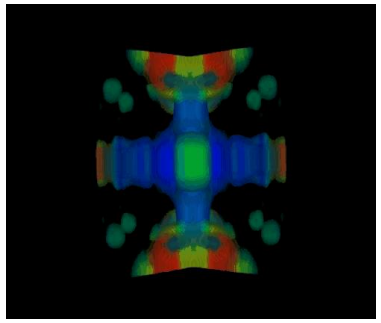
$$\boldsymbol{v}_F = \frac{1}{\hbar}\boldsymbol{\nabla}_k E(k)|_{E=E_F}$$

k_z scan:
20 3D-stacks concatenated

W

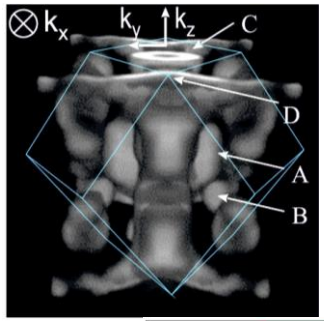




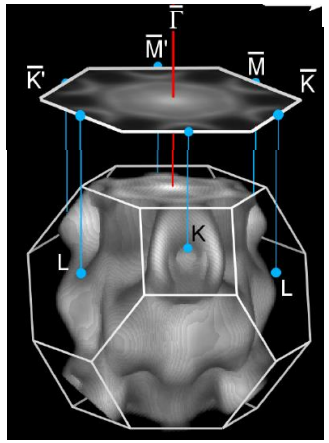


Nat. Materials **16**, 615 (2017)

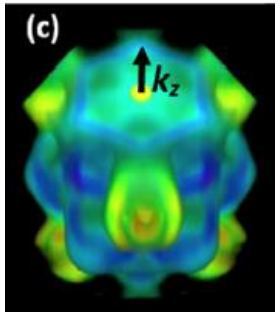
Mo

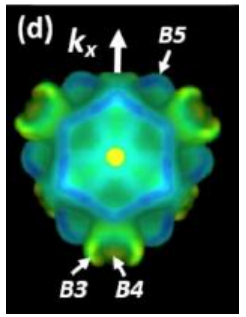


Comms.Phys. **2**, 107 (2019)



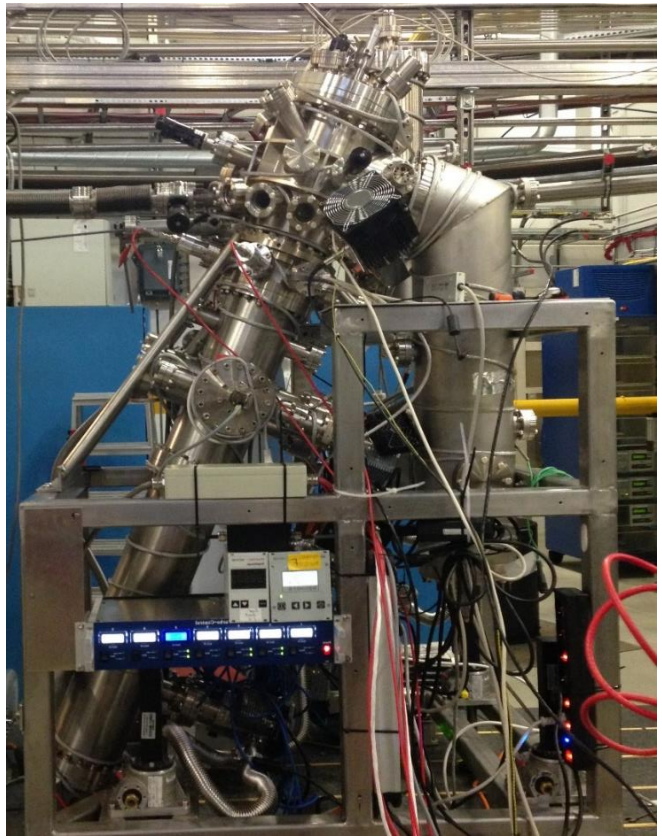
Ir



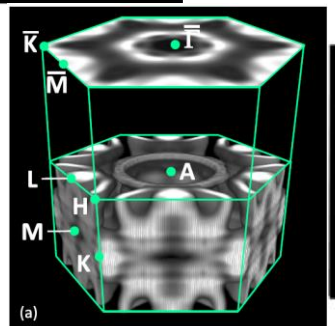


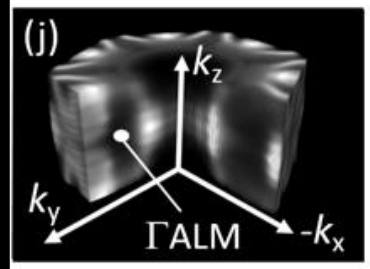
Ultramicroscopy **183**, 19 (2017)

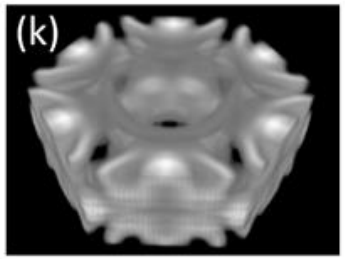
k-ToF @ P04 (Petra III)

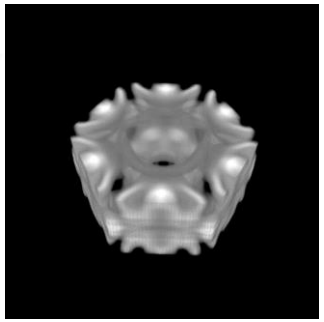


Re



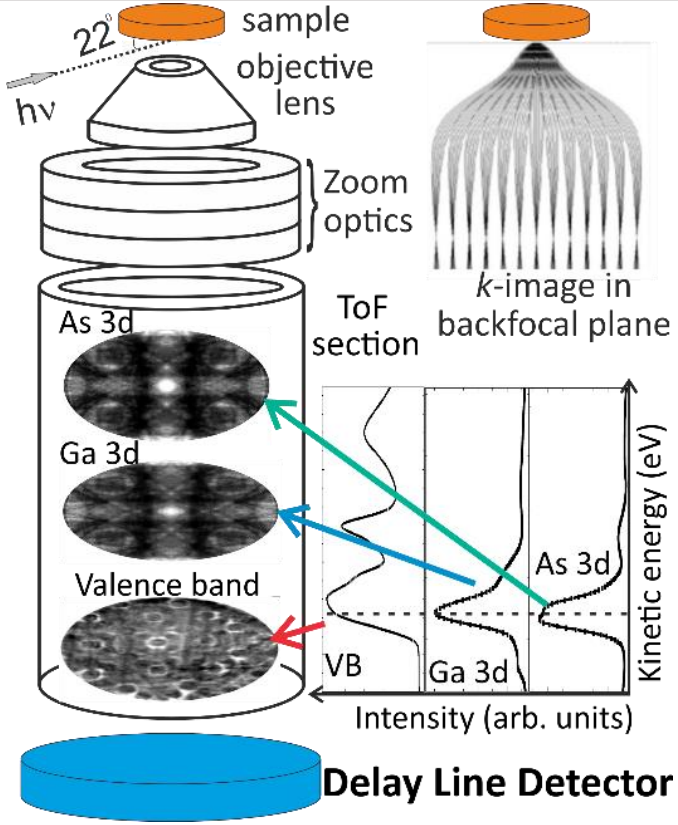


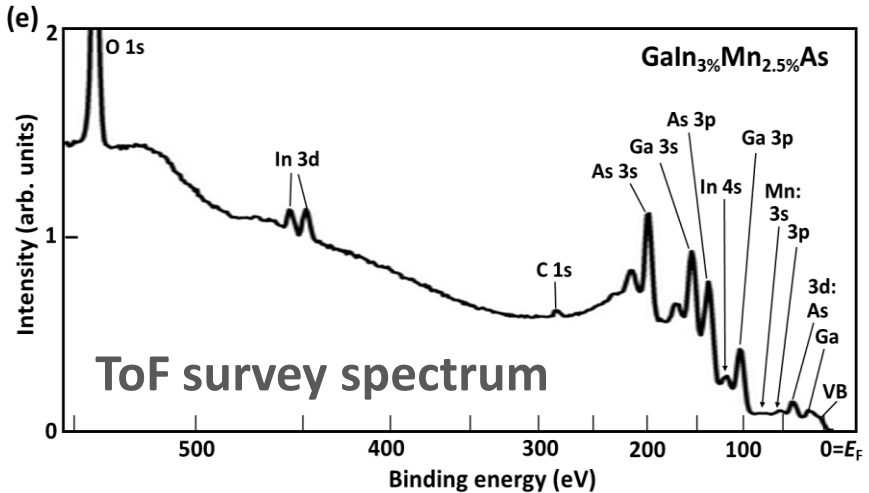




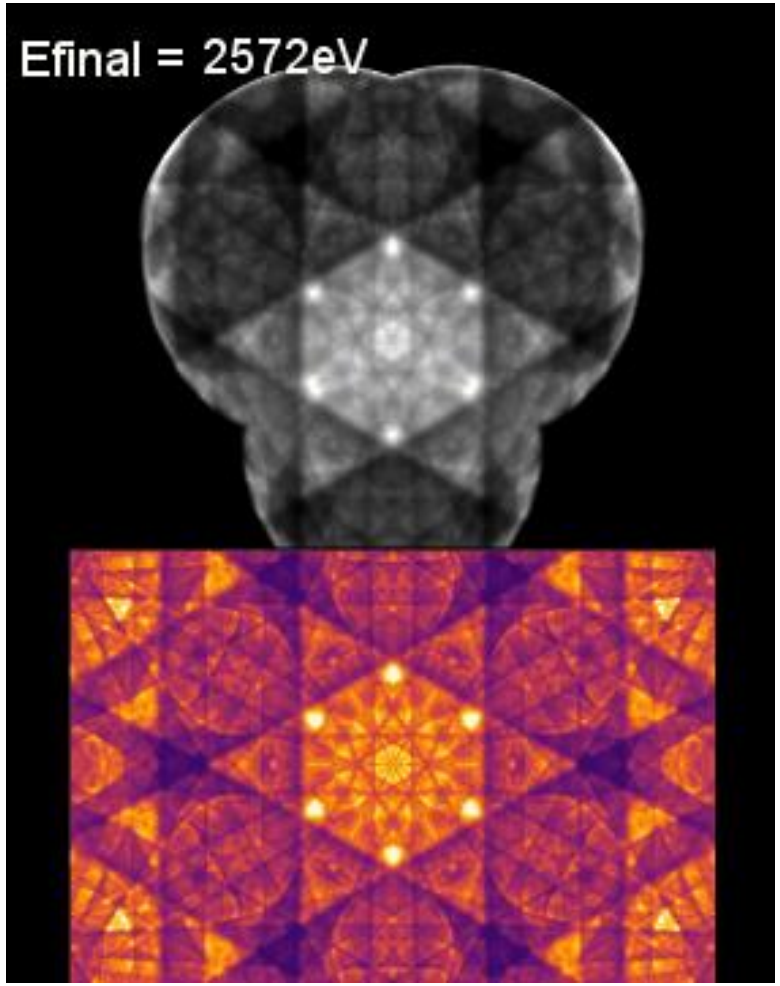
Phys. Rev. Research **2**, 013296 (2020)

hXPD: How does it work?





1st experiment: graphite

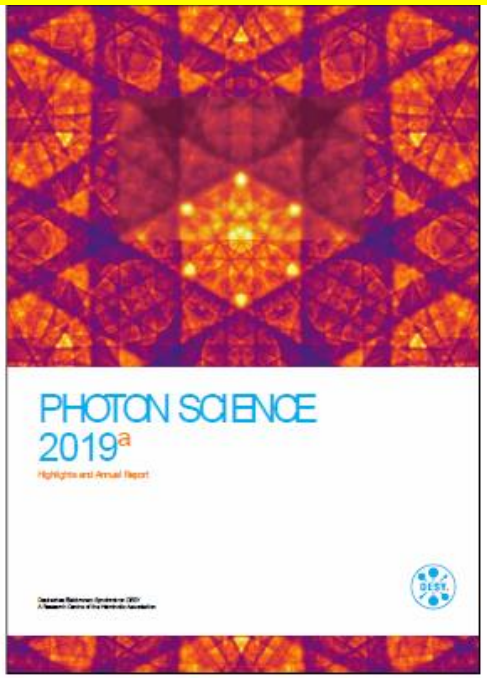


Bloch wave calculation

O. Fedchenko et al., *New J. of Phys.* **21**, 113031 (2019)

O. Fedchenko et al., *New J. of Phys.* **22**, 103002 (2020)

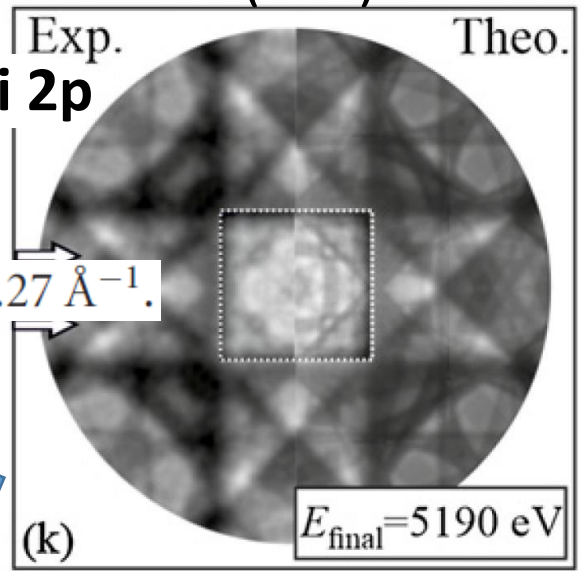
DESY Highlights 2019



Si (100)

Si 2p

$G_{220} = 3.27\ \text{Å}^{-1}$.



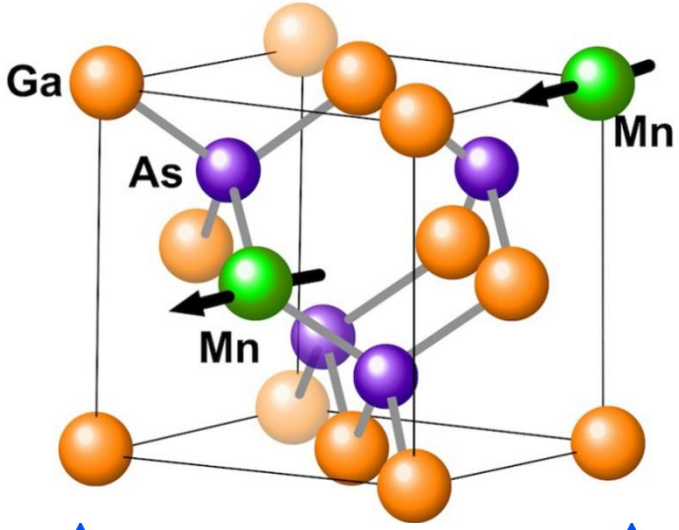
Hard X-ray photoelectron diffraction hXPD

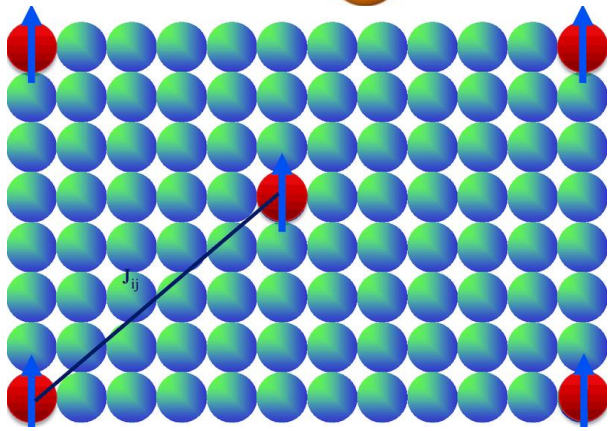
GaAs (3% In, 2.5 or 5.6% Mn) high-quality MBE film

Dilute Ferromagnetic Semiconductors:

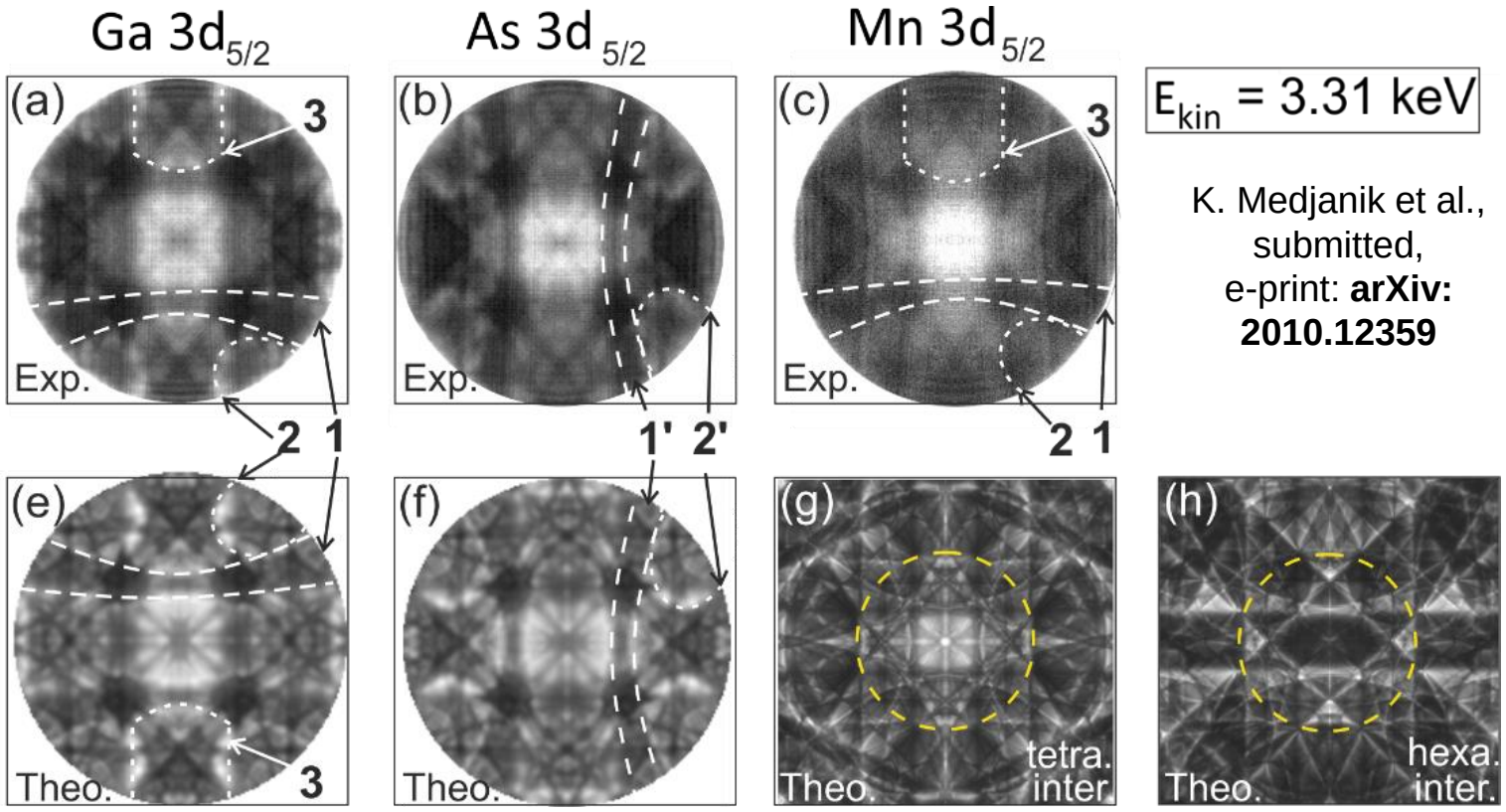
What is the origin of ferromagnetism?

Mn sites in hyper-doped regime?



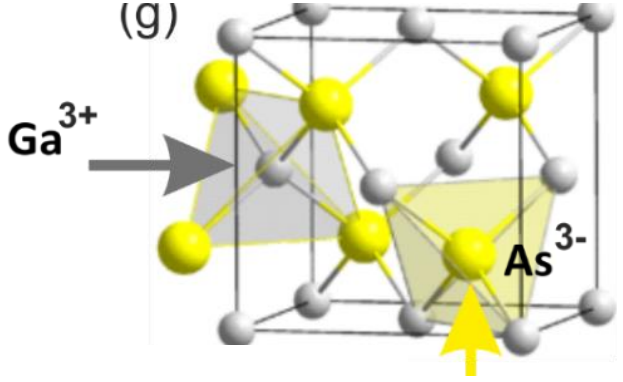


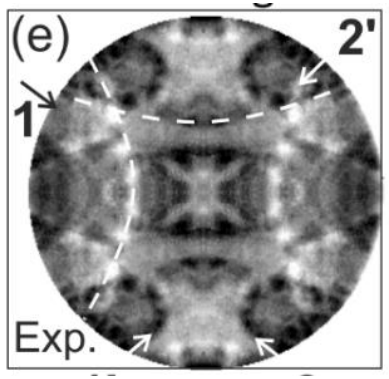
p-d Zener model vs impurity model



E_{kin} = 3.31 keV

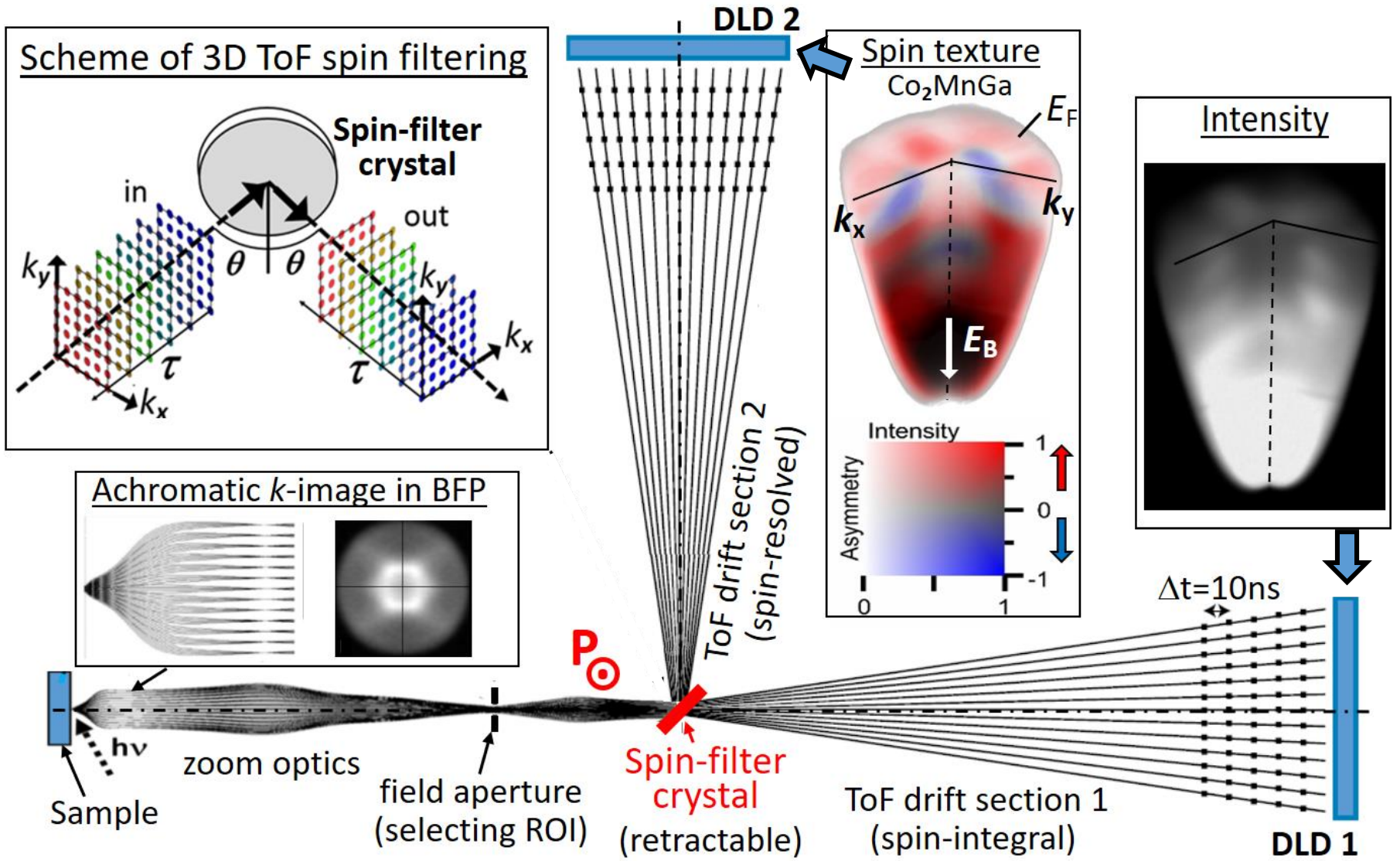
K. Medjanik et al., submitted, e-print: **arXiv: 2010.12359**



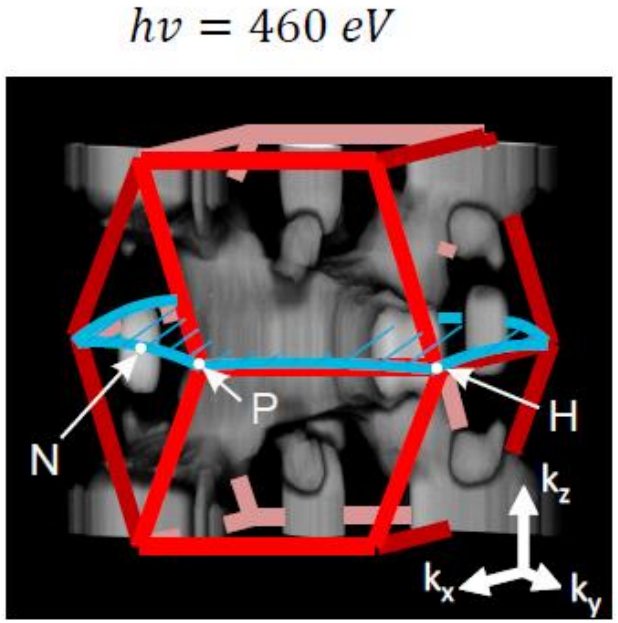


As 3d/Ga 3d ratio image

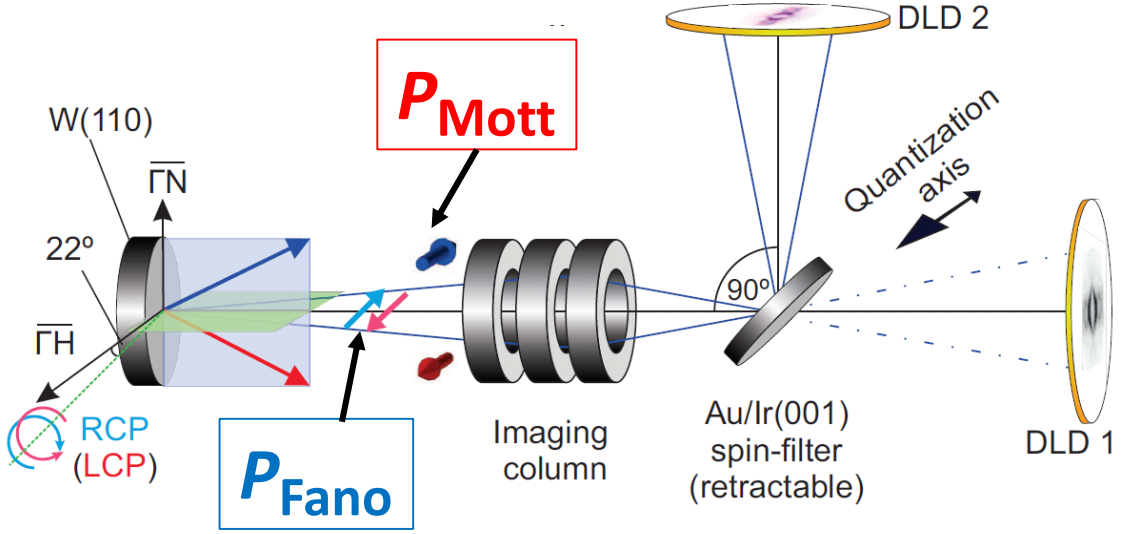
Imaging Spin Filter: How does it work?



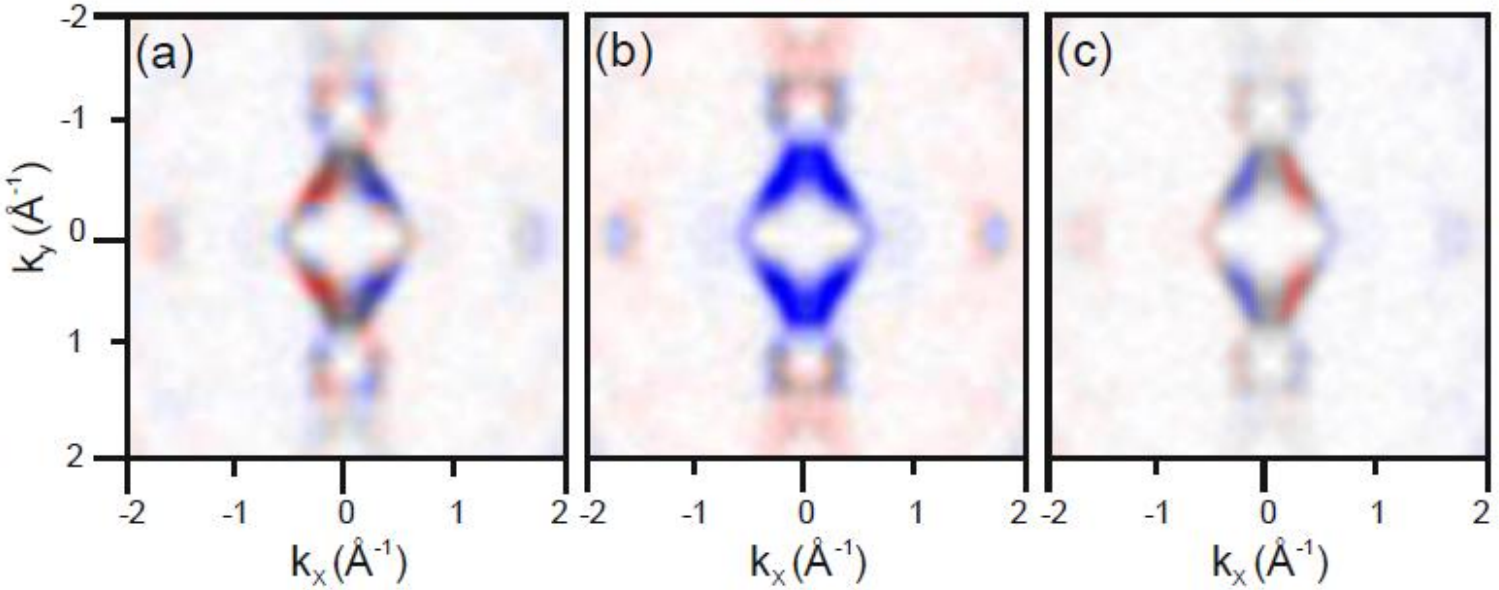
Spin-texture mapping in soft X-ray range

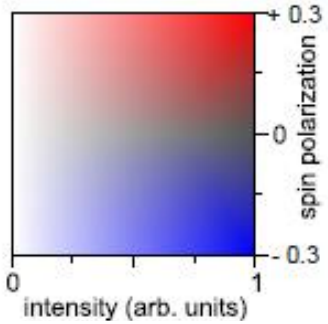


tungsten



Mott **Fano** **CDAD**

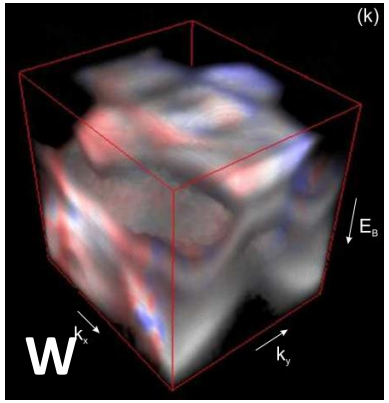


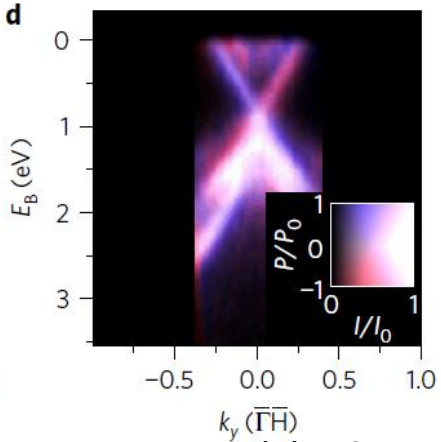


D.Vasilyev et al.,
J. Phys. Cond. Matter
32, 135501 (2020)

Spin texture mapping in various spectral ranges

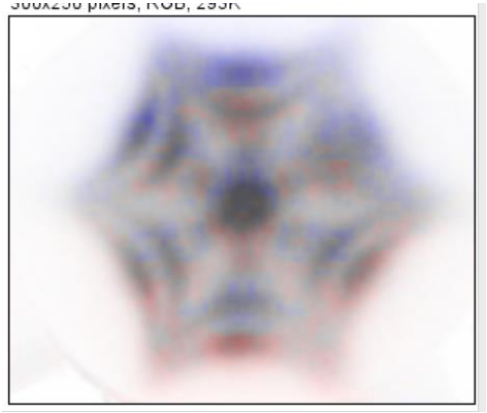
W(110): spin texture Dirac-type spin texture

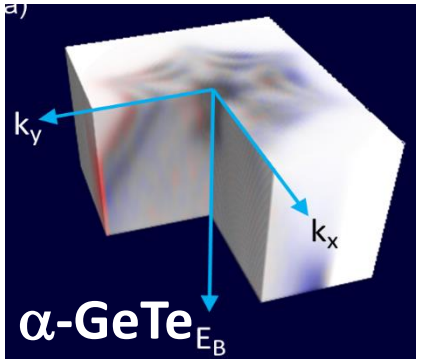




Nat. Materials **16**, 615 (2017)

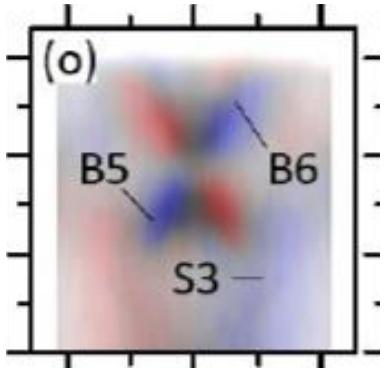
α-GeTe(111): bulk Rashba ferroelectric semiconductor





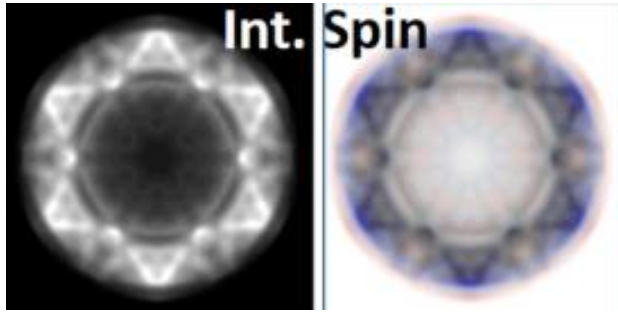
*Phys.Rev.*B **94,** 201403 (2016)

Ir(111): spinres. E-$k_{||}$



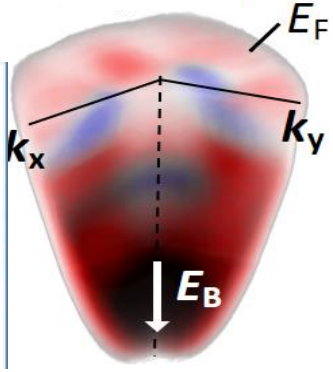
Ultramicroscopy **183**, 19 (2017)

$DyAg_2$/Ag(111): ferro-magnetic surface alloy

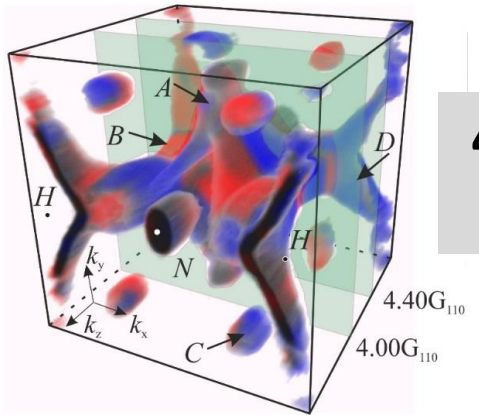


Under review (PRL)

Co_2MnGa: full Heusler



Under review (PRB)



4D movie CDAD

New J.Phys. **21,** 013017(2019

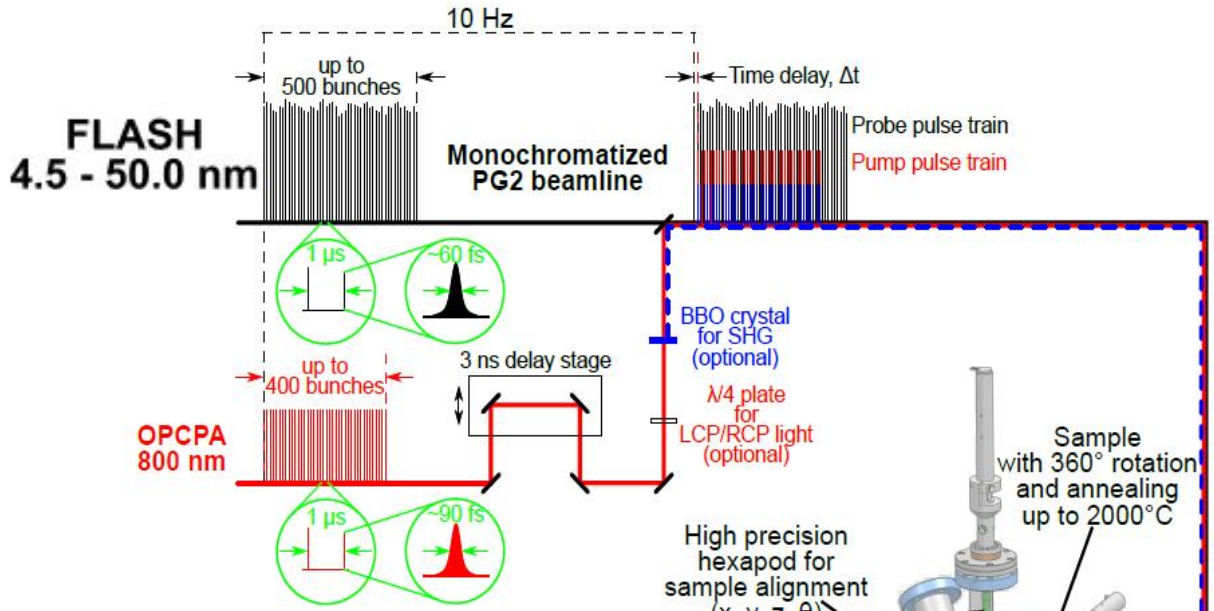
fs-photoemission: *Multidimensional recording: I (E_B, $k_{x,y,z}$, $\sigma_{x,y,z}$, τ)*

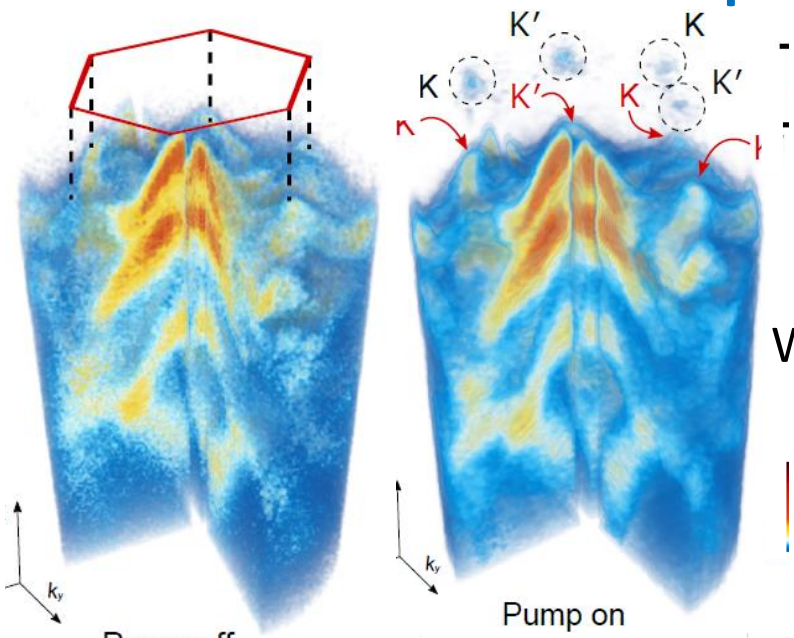
Spin

Pump-probe delay

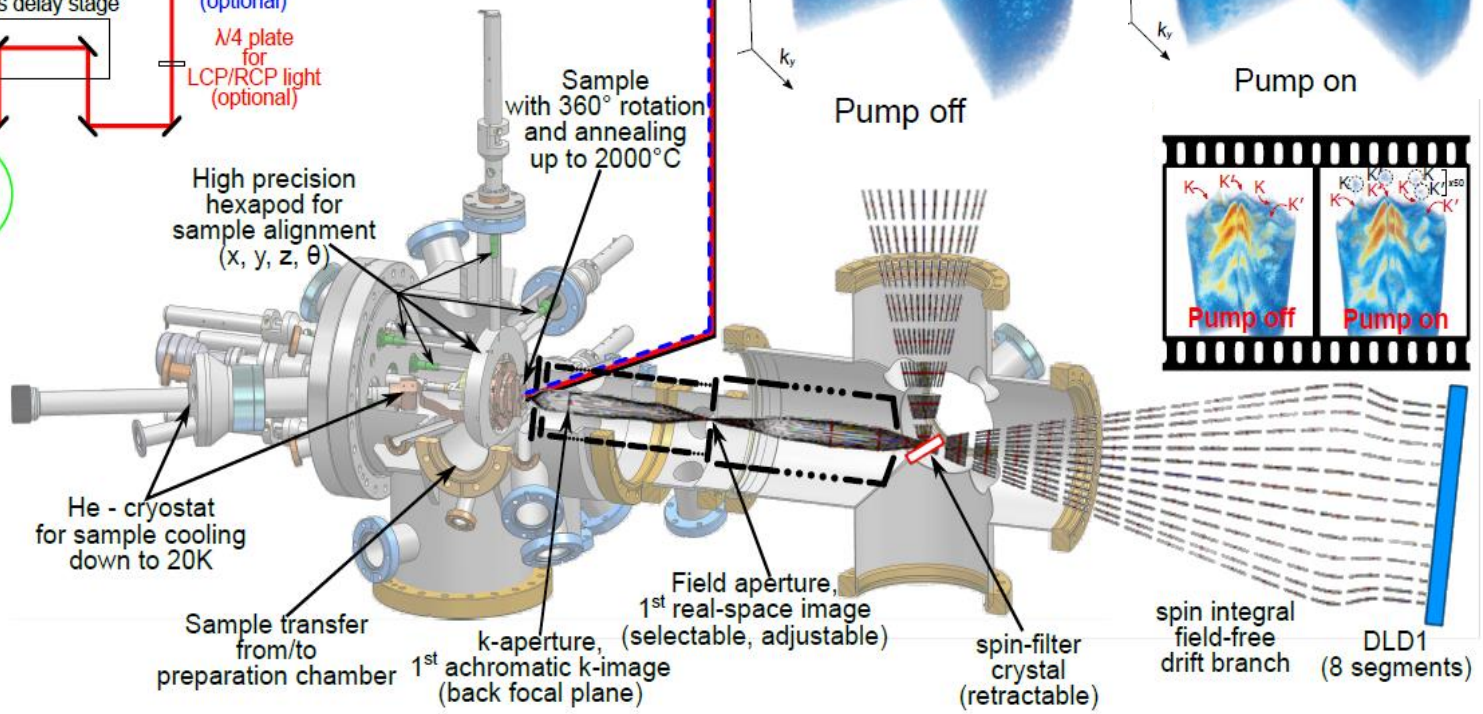
Time-resolved pump-and-probe experiment:

We sort counting events into a **5D histogram** $I(E_B, k_x, k_y, \tau, I_{pump})$





WSe_2



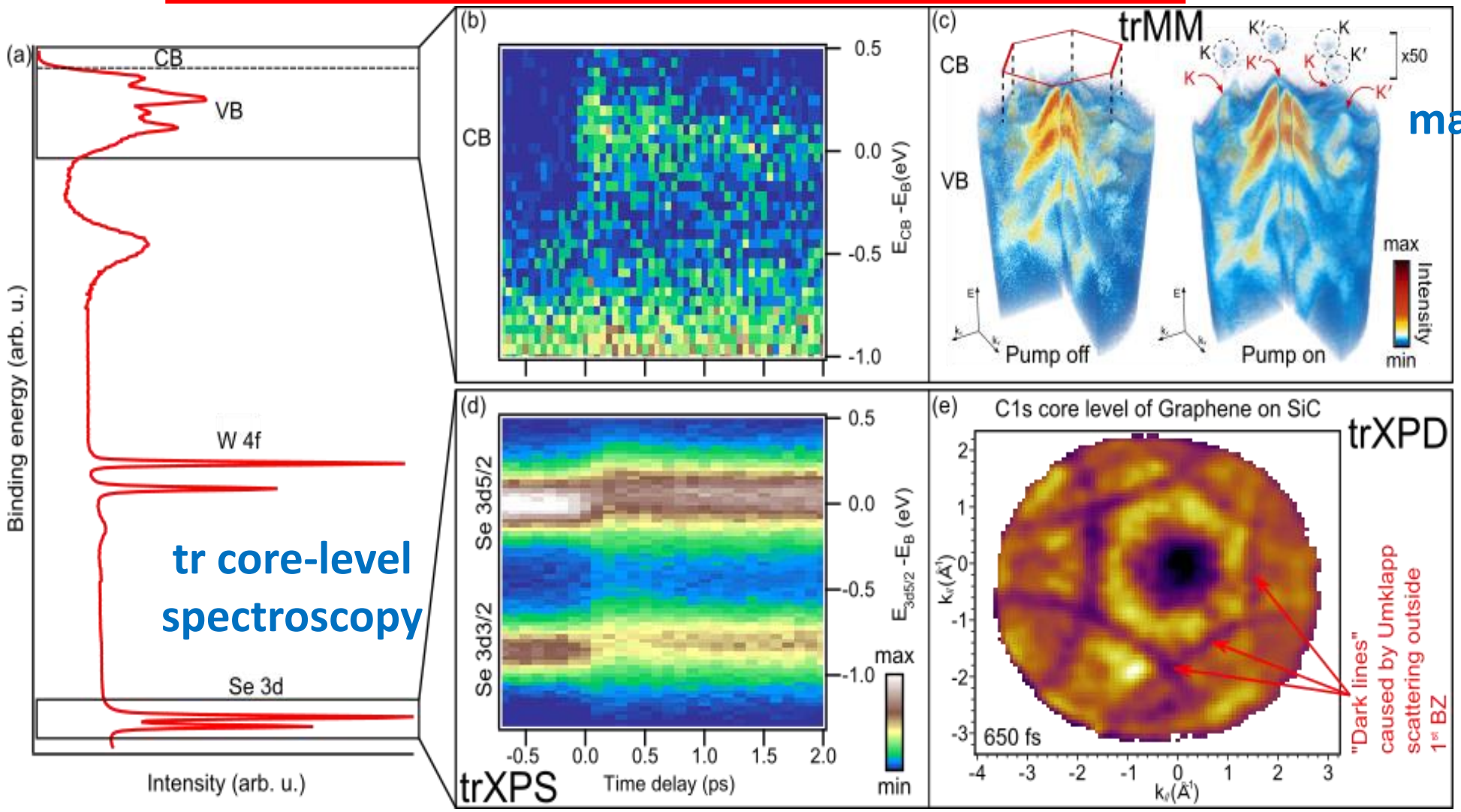
D. Kutnyakhov et al.,
Rev. Sci. Instrum.
91, *013109 (2020)*

@ FREIA: *Multidimensional recording: $I(E_B, k_{x,y,z}, \sigma_{x,y,z}, \tau)$*

Spin

Pump-probe delay

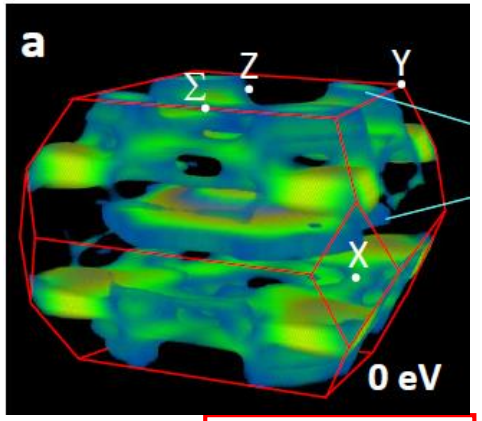
Combining three time-resolved photoemission techniques in a single instrument



tr core-level spectroscopy

tr Valence-band mapping (R. Ernstorfer)

tr „Fermiology“



$YbRh_2Si_2$

tr photoelectron diffraction (D. Curcio, P. Hofmann)

time-resolved *5D-mapping:* $I(E_B, k_x, k_y, k_z, \tau)$

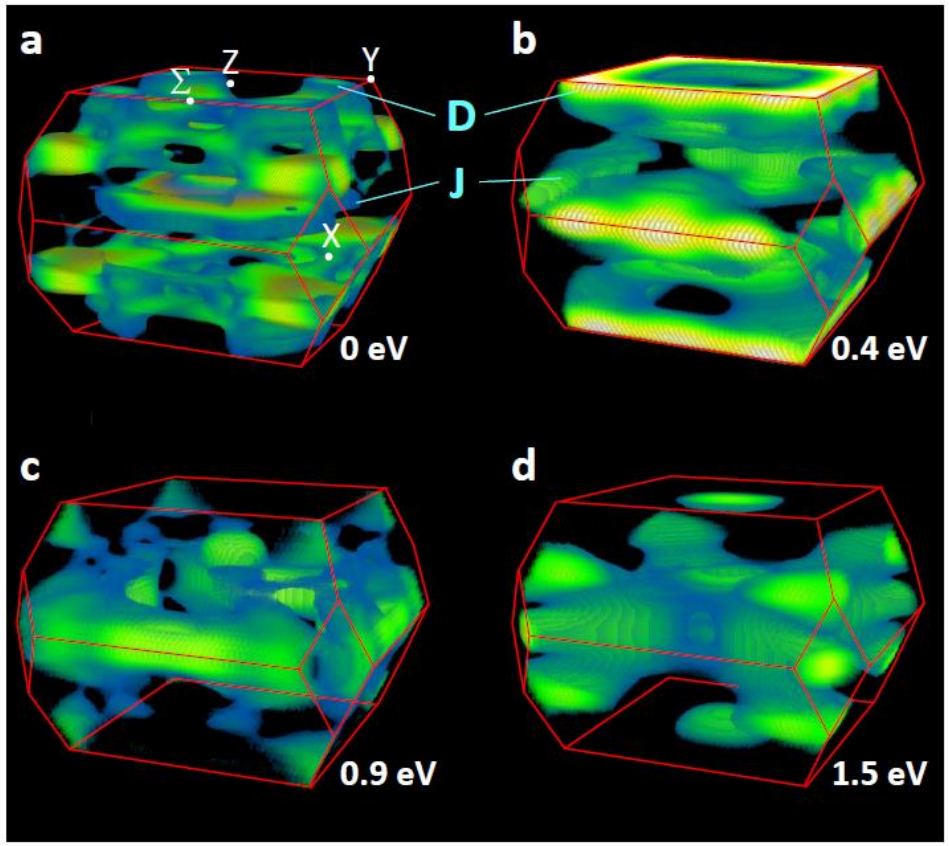
Particularly interesting example: „Temperature dependent Fermi Surface of Kondo Lattice System“

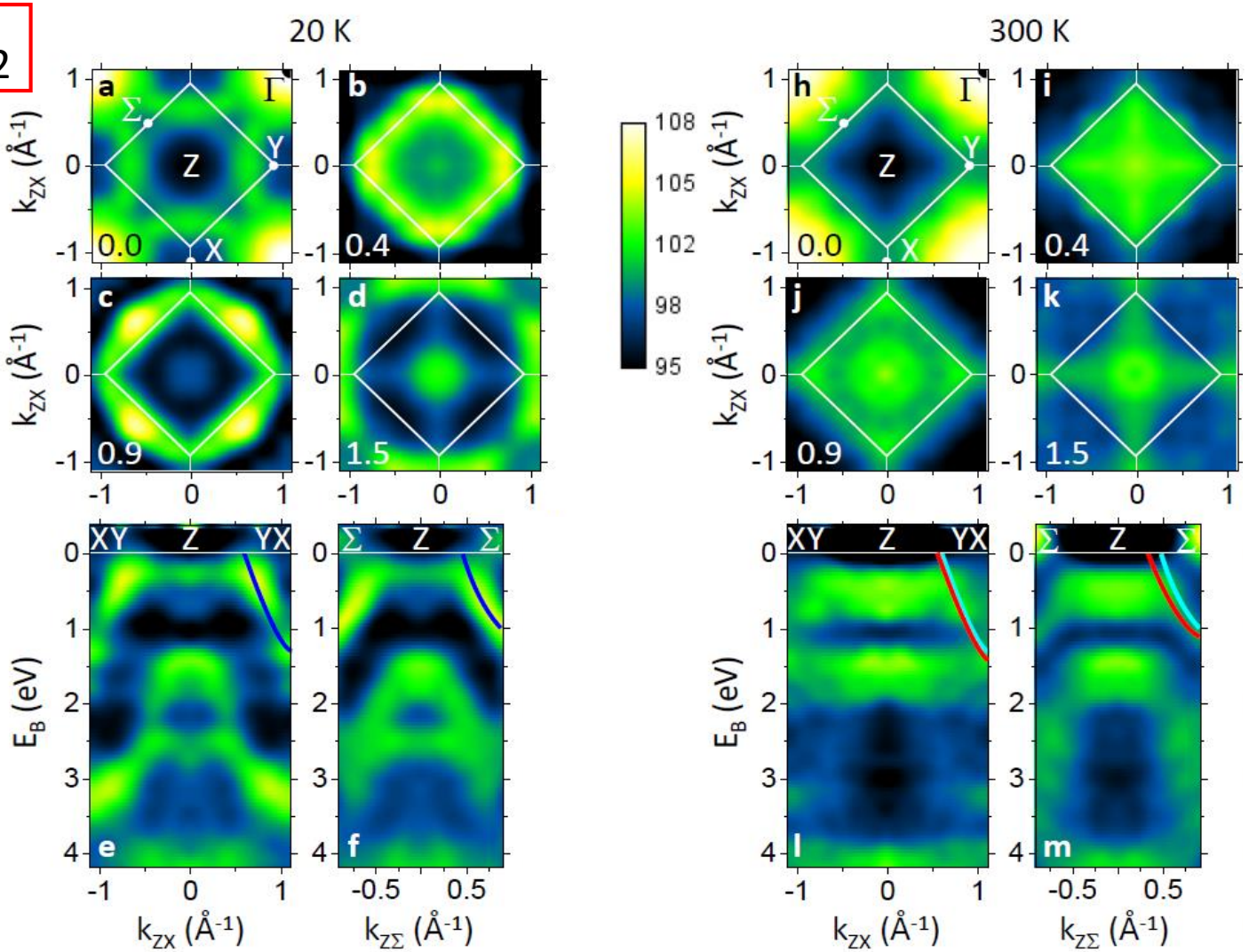
via photon energy

Pump-probe delay

tr „Fermiology“

$YbRh_2Si_2$





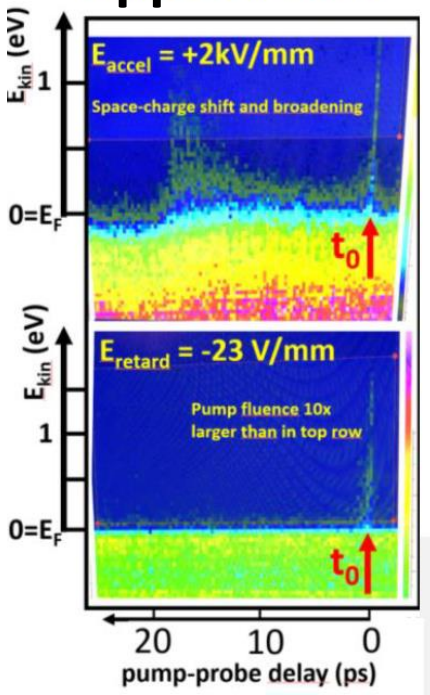
S. Agustsson et al., *submitted* (2020)

Why Momentum Microscope ?

- **Ultra-efficient 3D detection:**
  (k_x, k_y) imaging + E_{kin} ToF measurement
- **Large tunable *k*-field of view:** <2…>20 Å^{-1}
- **High *k* resolution:** ~10^{-2} Å^{-1}
  angular resolution: **0.03°**
- **Large energy window:**
  5-10 eV (high res.); >100 eV (low res.)
- **High energy resolution:**
  ~15 meV (low-energy ARPES)
  ~30 meV (soft x-ray ARPES)
  40 meV ToF-resolution @ 5977 eV

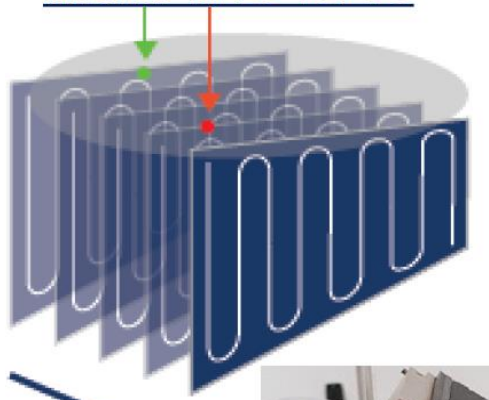
Present developments

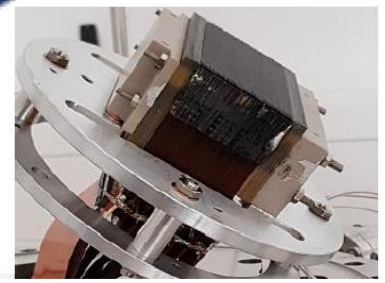
Space-charge suppression



Multi-hit recording

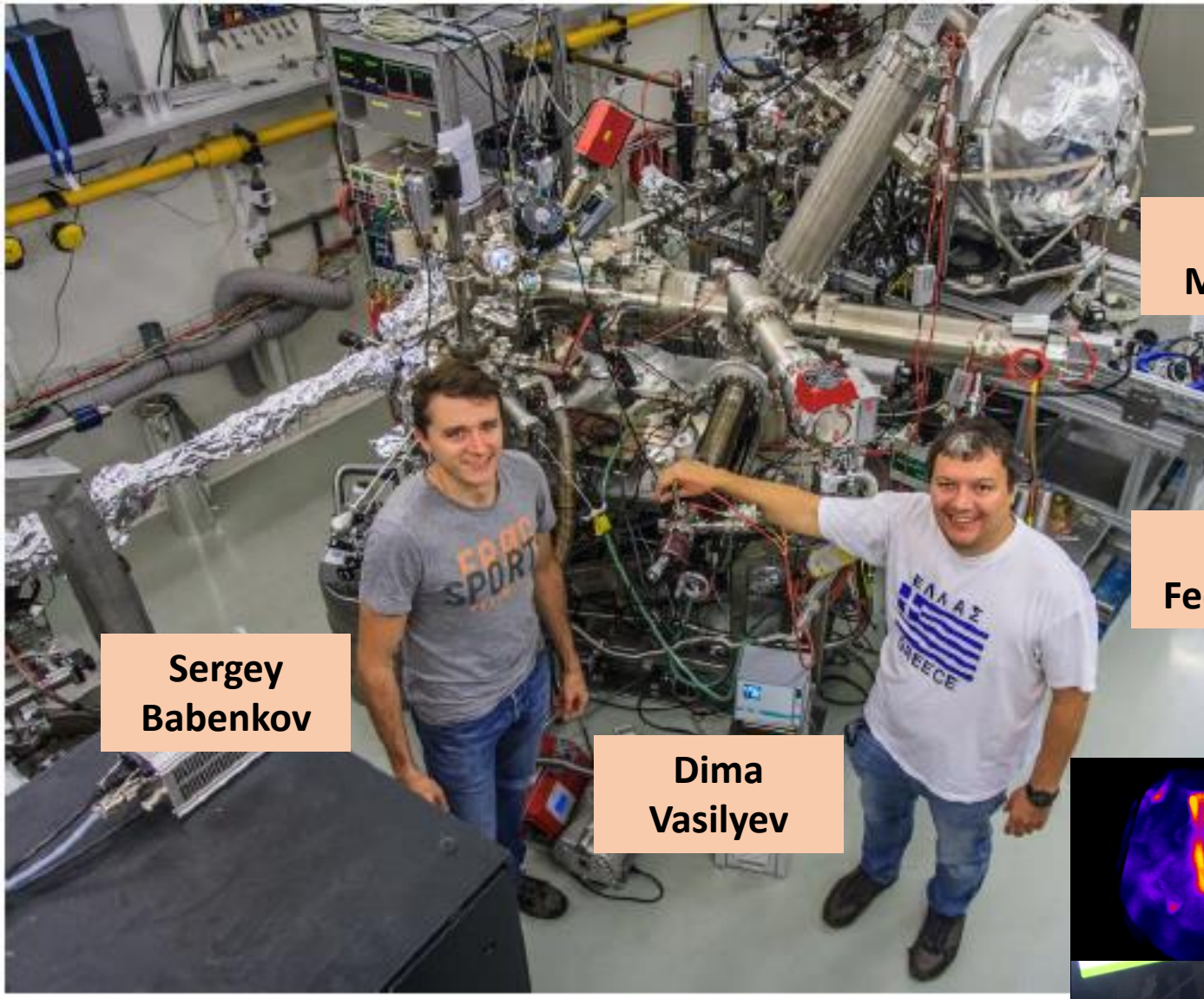
Multi-line DLD





ToF & bandpass filter

Rev. Sci. Instrum. in print (e-print on arXiv2007.16095)



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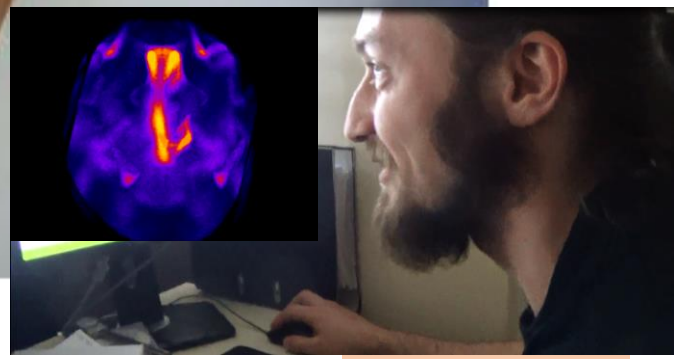

Sergey Chernov

THANKS FOR LISTENING, STAY SAFE !