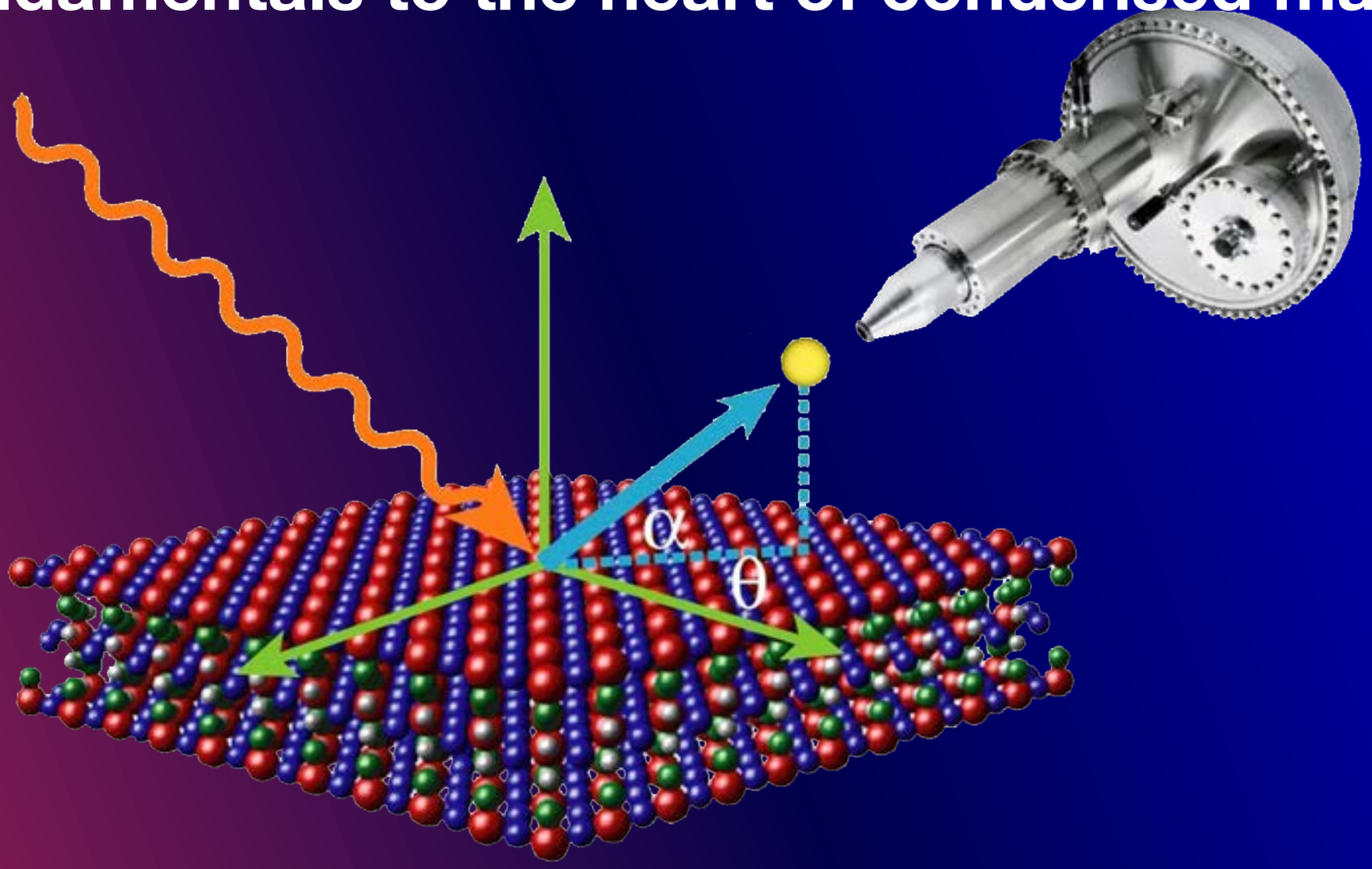
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

SEVERO OCHOA SCHOOL

ICMAB
INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA
EXCELENCIA SEVERO OCHOA

Angle Resolved Photoemission Spectroscopy

From fundamentals to the heart of condensed matter



6-7 FEBRERO, 2023

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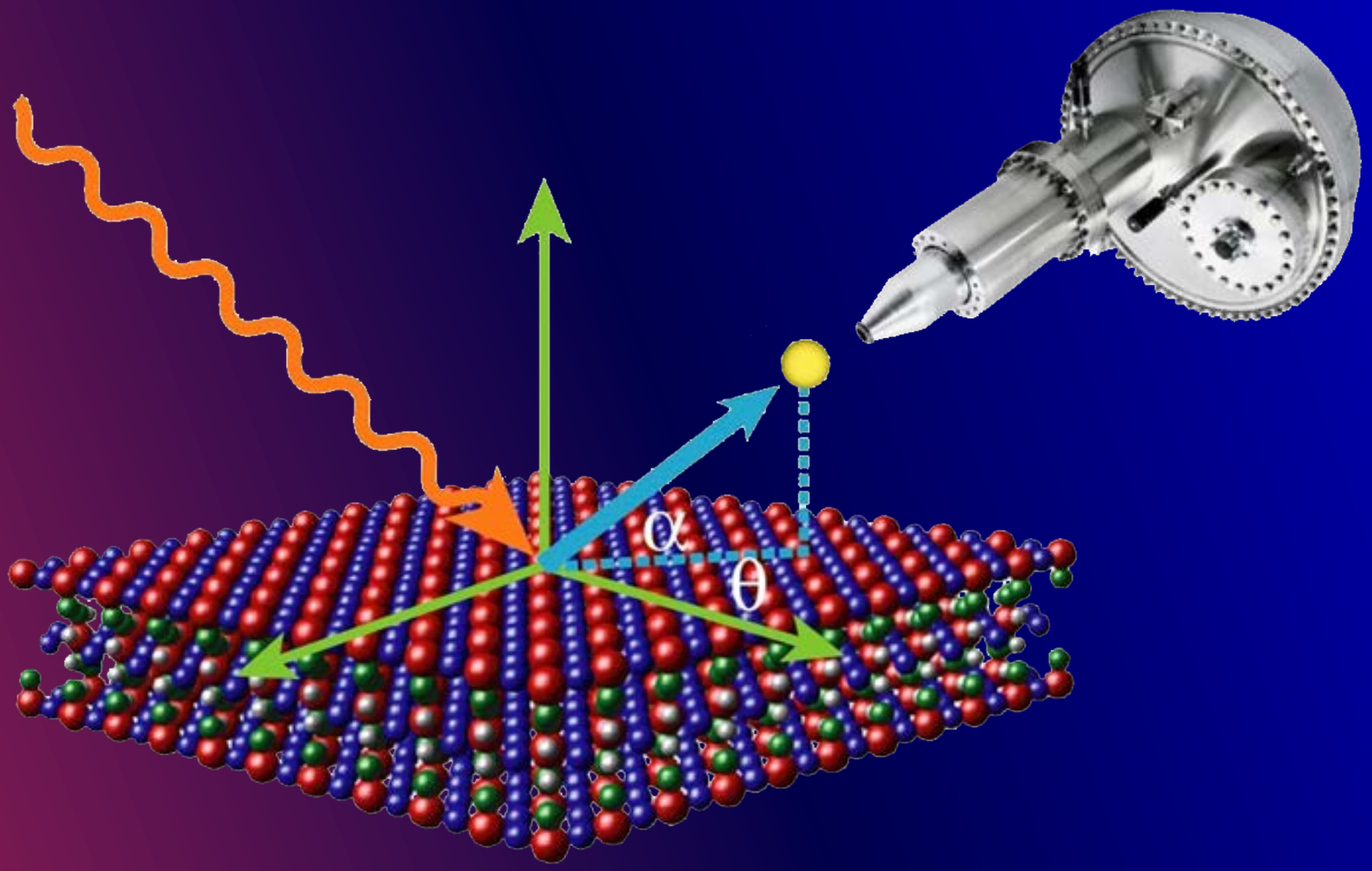
Lecture #4 : Frontiers in ARPES
Time, Space, and Spin



Thanks to Luca Moreschini & Shuolong Yang

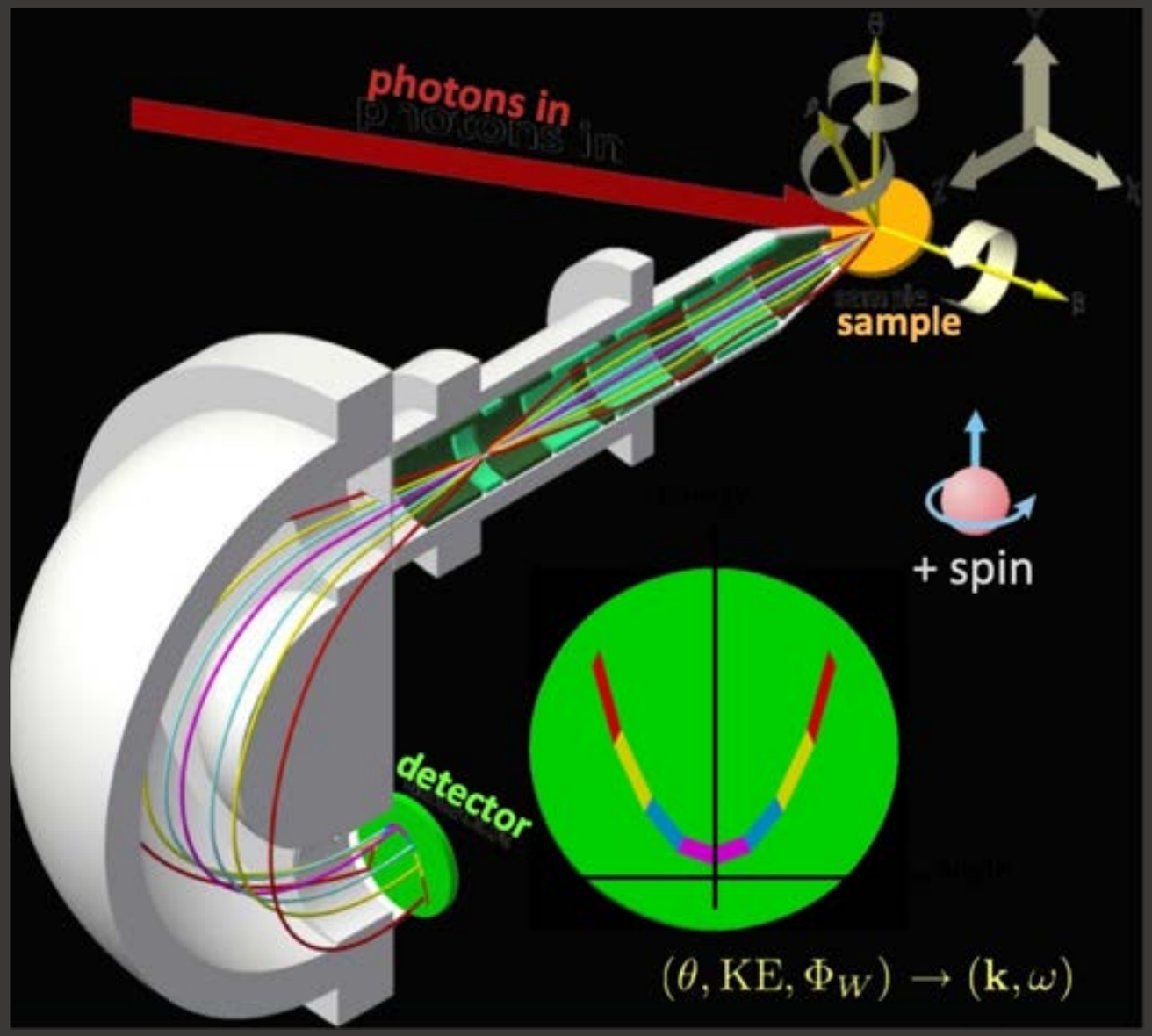
6-7 FEBRERO, 2023

ARPES + something else!

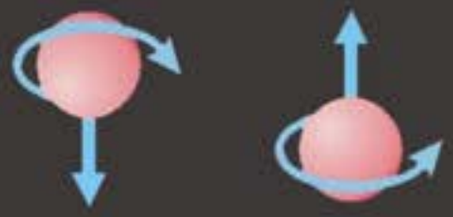
1. Spin detection

2. Time-resolution

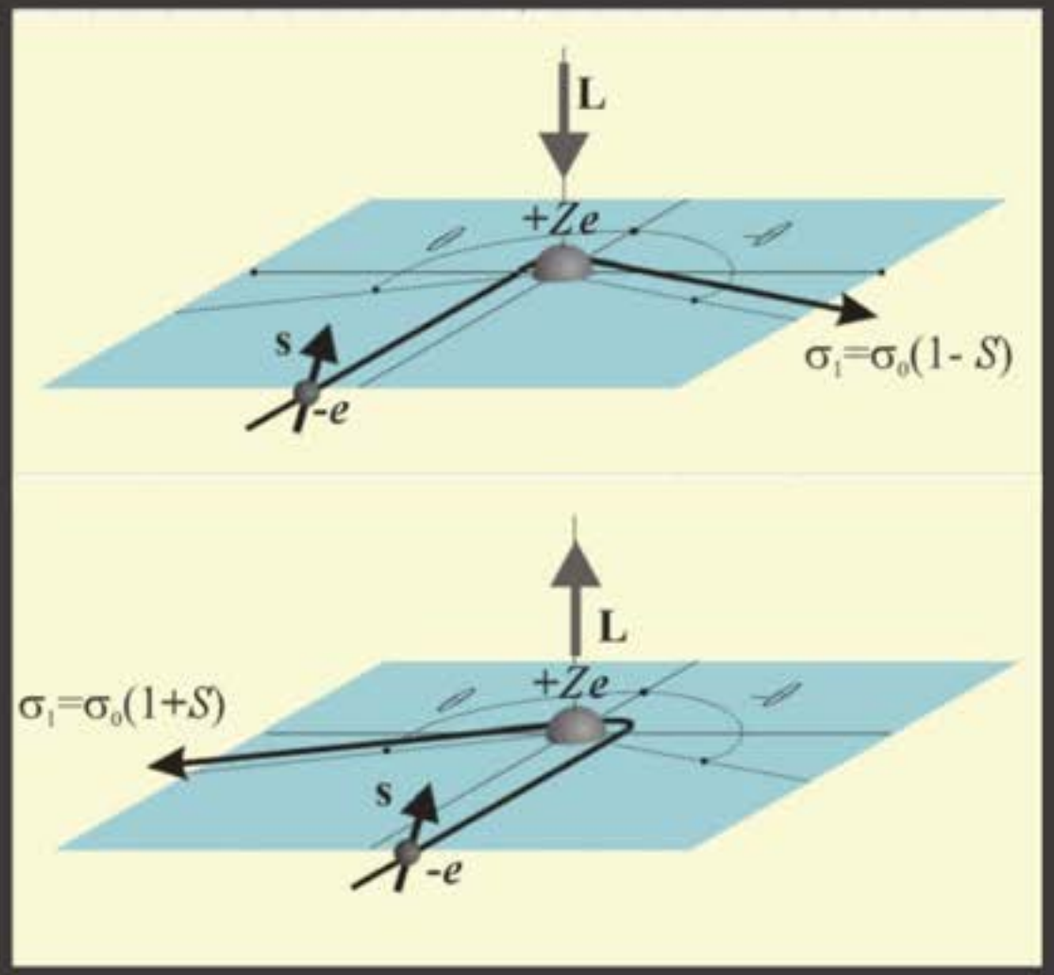
3. Spatial resolution



Spin polarimetry



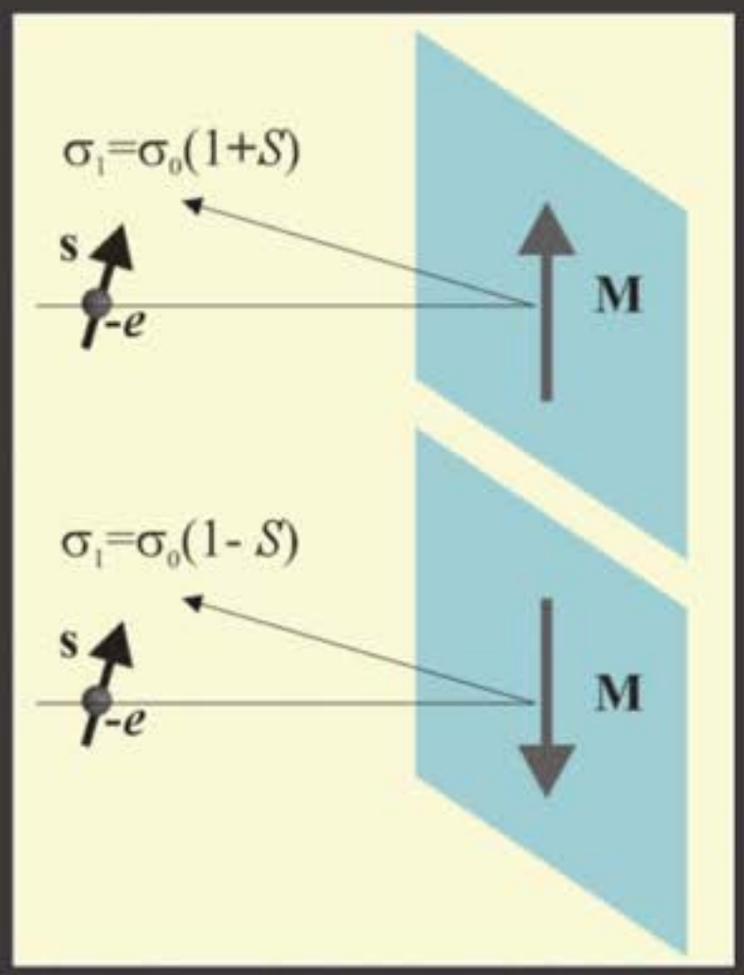
Mott scattering
+ stability, - efficiency



coupling between the atomic orbital momentum and the spin of the electron

different cross section for two different scattering directions

exchange scattering (VLEED)
- stability, + efficiency

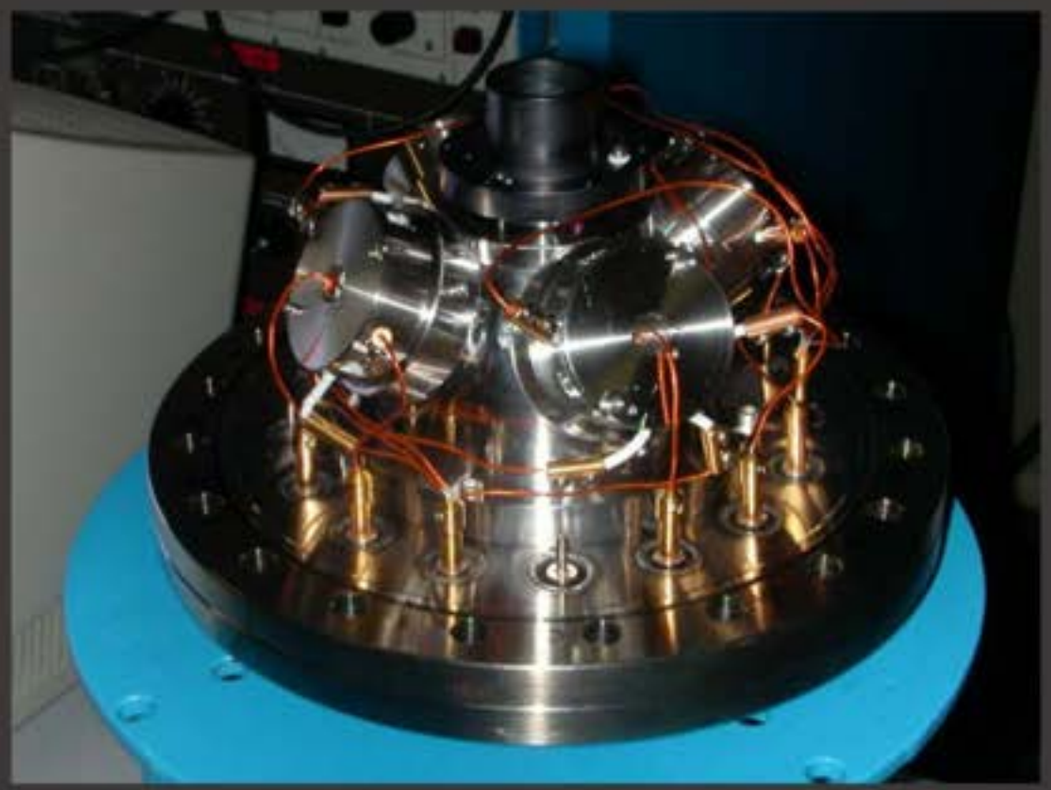


coupling between the ferromagnet magnetic moment and the spin of the electron

different reflectivity for two opposite magnetization directions

Spin polarimetry

Mott scattering
+ stability, - efficiency



different cross section
for two different scattering directions

L. Moreschini *et al.*, *Rev. Sci. Instrum.* ***79***, *033905 (2008)*

exchange scattering (VLEED)
- stability, + efficiency

different reflectivity
for two opposite magnetization directions

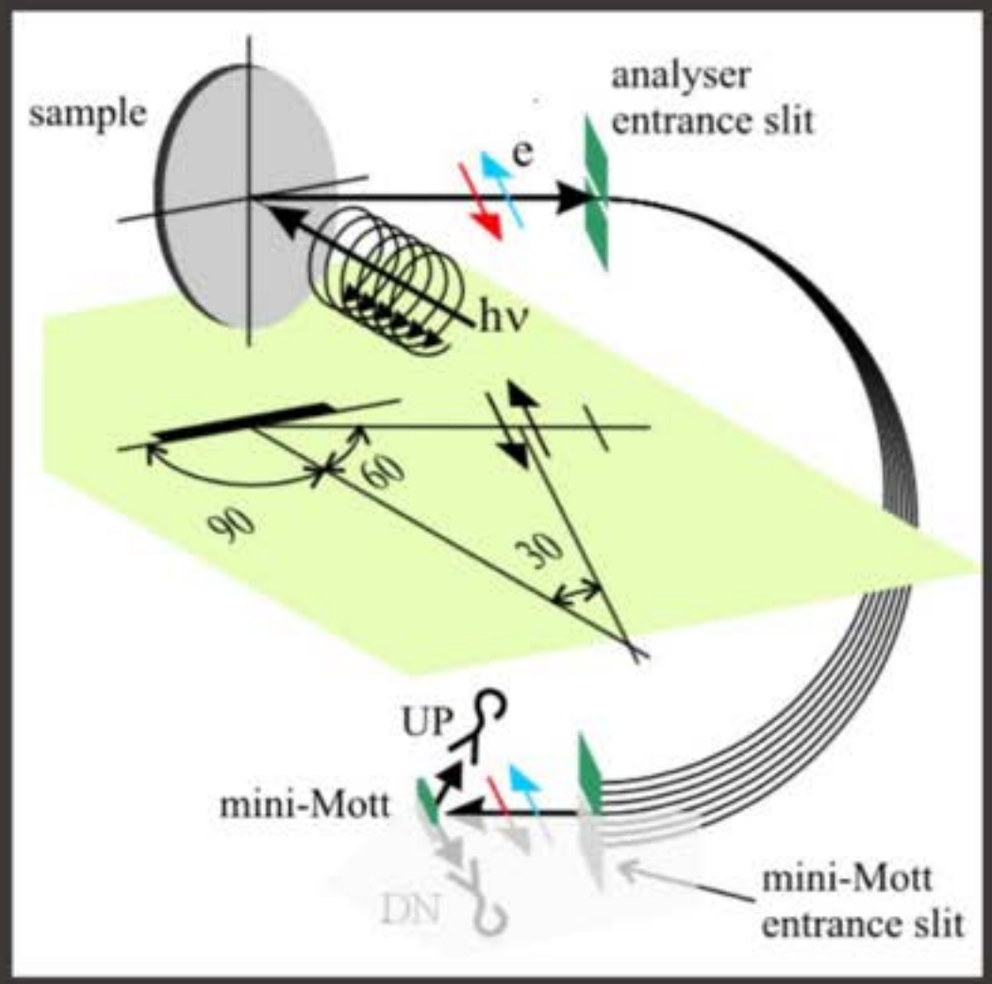
C. Jozwiak *et al.*, *Rev. Sci. Instrum.* ***81***, *053904 (2010)*

Electron analyzers for spin polarimetry

From hemispherical analyzers to time-of-flight analyzers

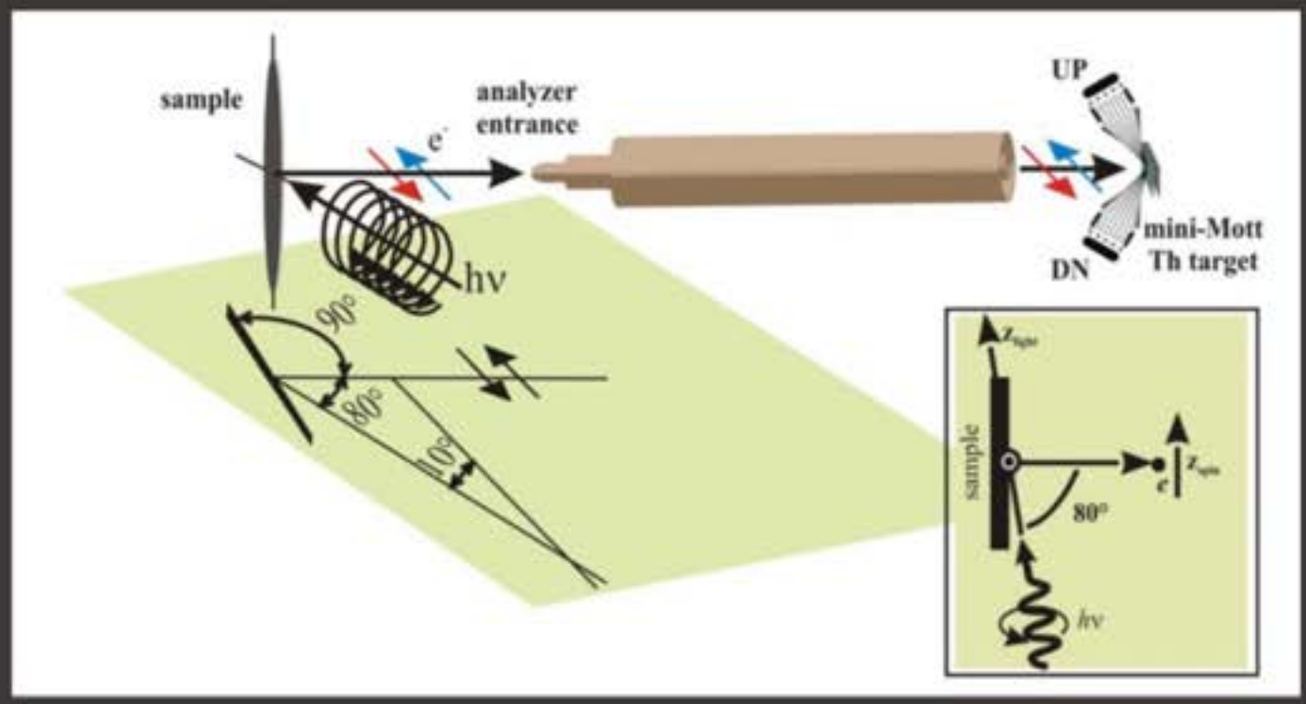
Hemispherical EA-Mott

+ resolution/stability vs hν
- efficiency (serial acquisition)



TOF-Mott

resolution/stability vs hν
+ efficiency (parallel acquisition)

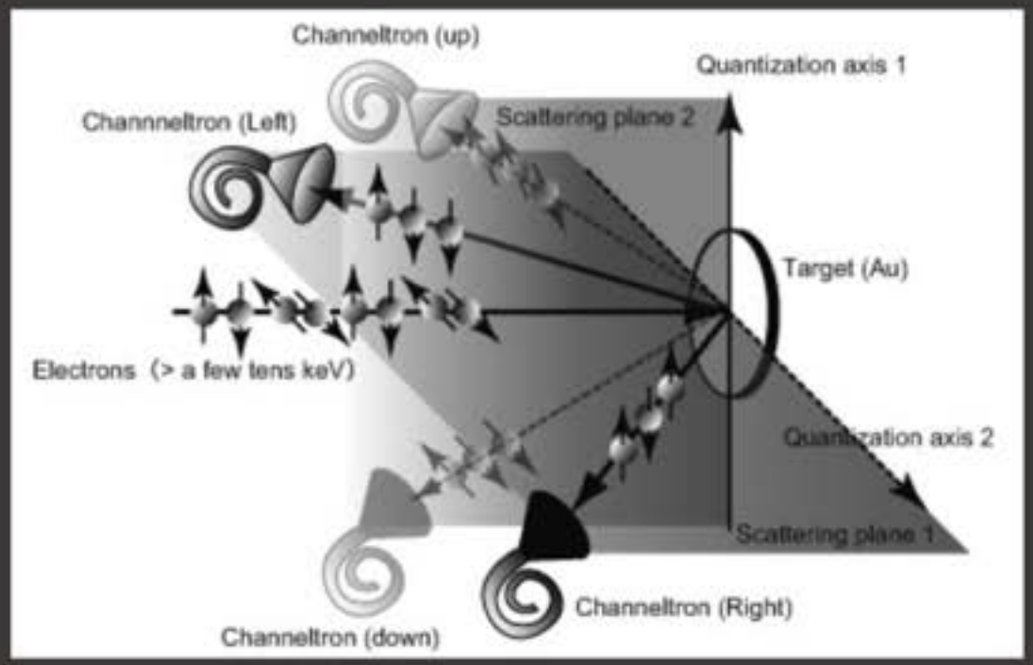


G. Ghiringhelli *et al., Rev. Sci. Instrum.* **70**, 4225 (1999)

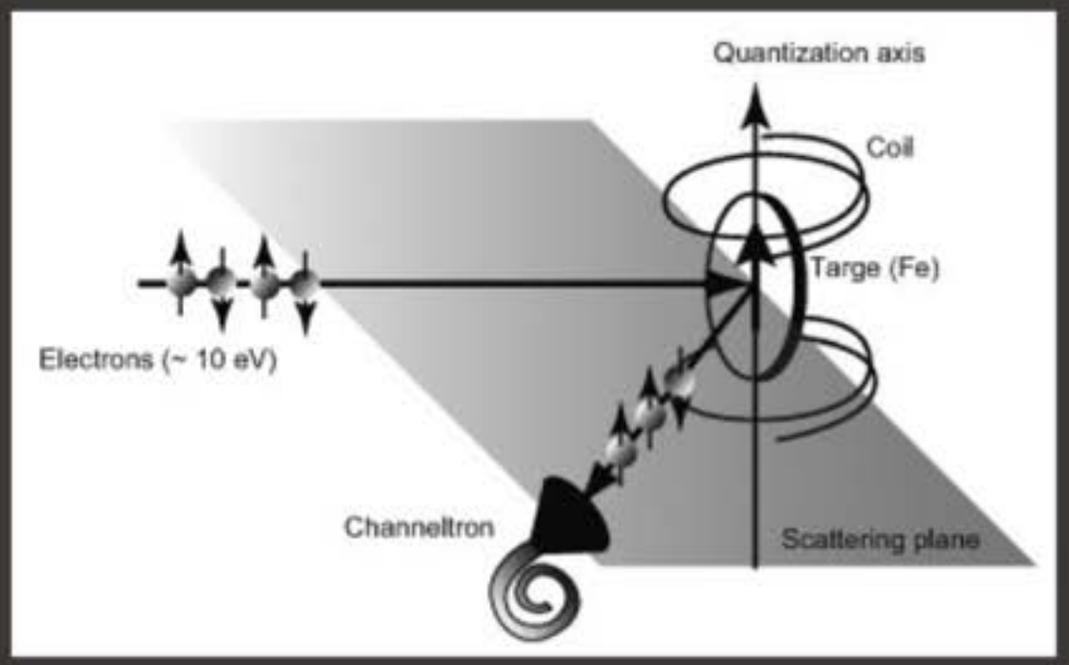
L. Moreschini *et al., Rev. Sci. Instrum.* **79**, 033905 (2008)

Coupling spin detection and ARPES

Mott polarimetrs
two axes in parallel

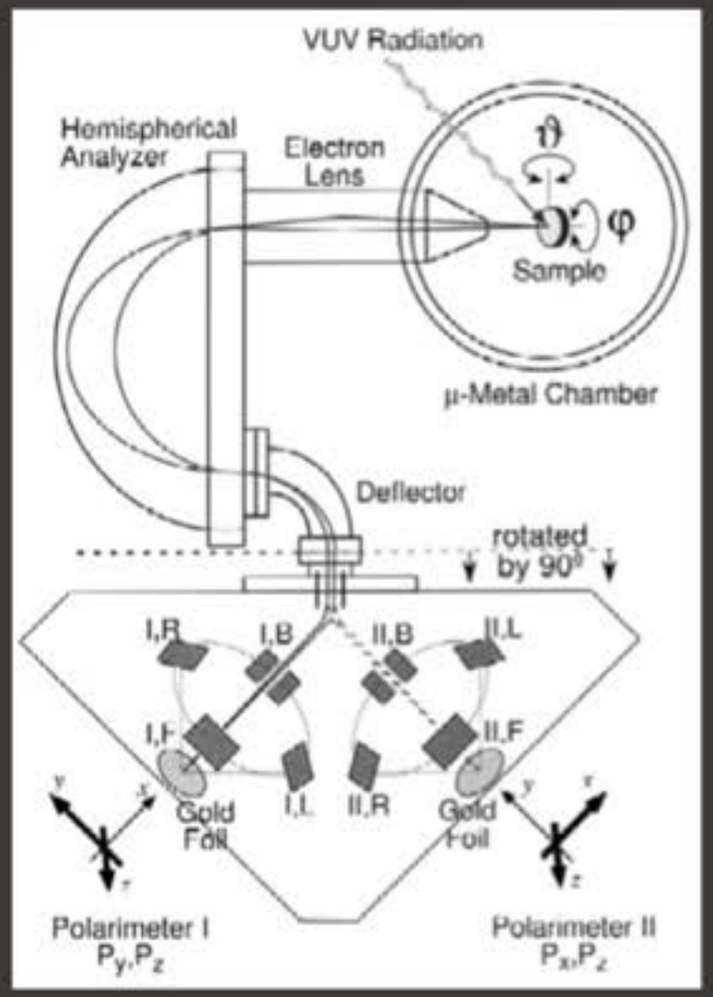


VLEED polarimeters
one axis at a time



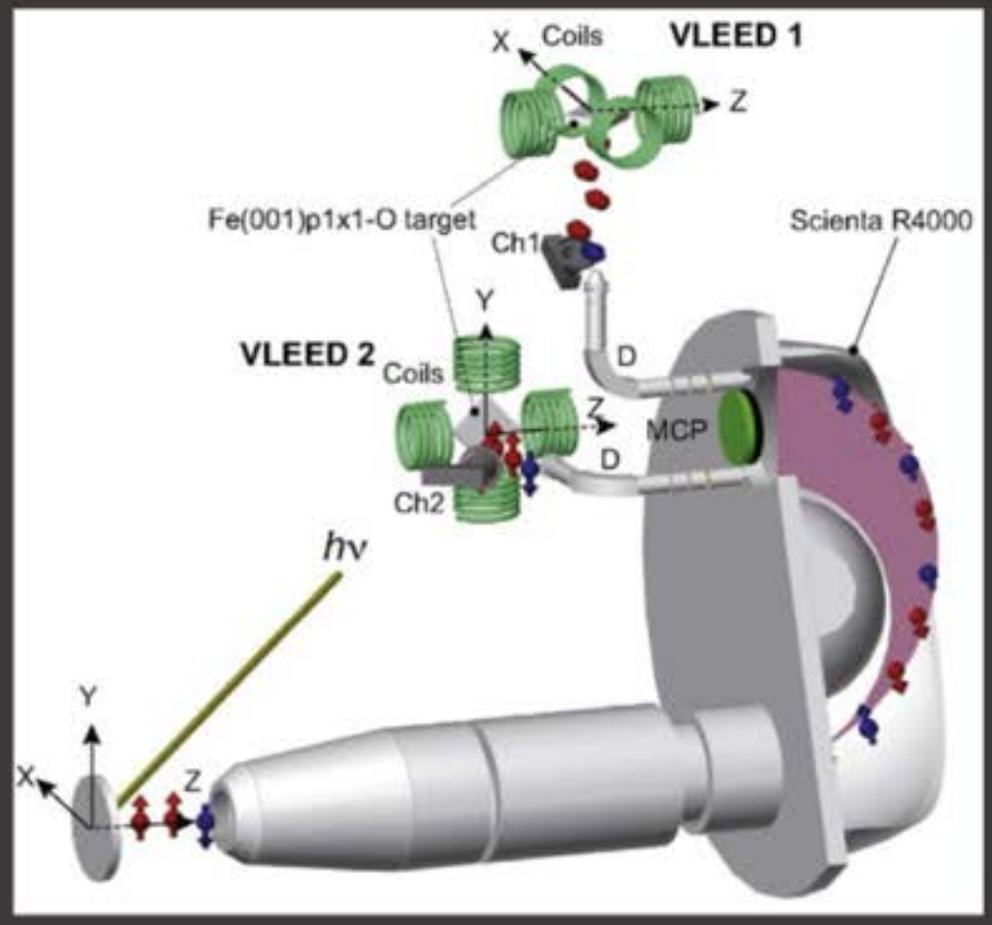
T. Okuda *et al.*, *Rev. Sci. Instrum.* **201**, 23 (2015)

Coupling spin detection and ARPES - a few examples



Hemispherical EA + Mott

M. Hoesch *et al.*, *JESRP* **124**, 263 (2002)

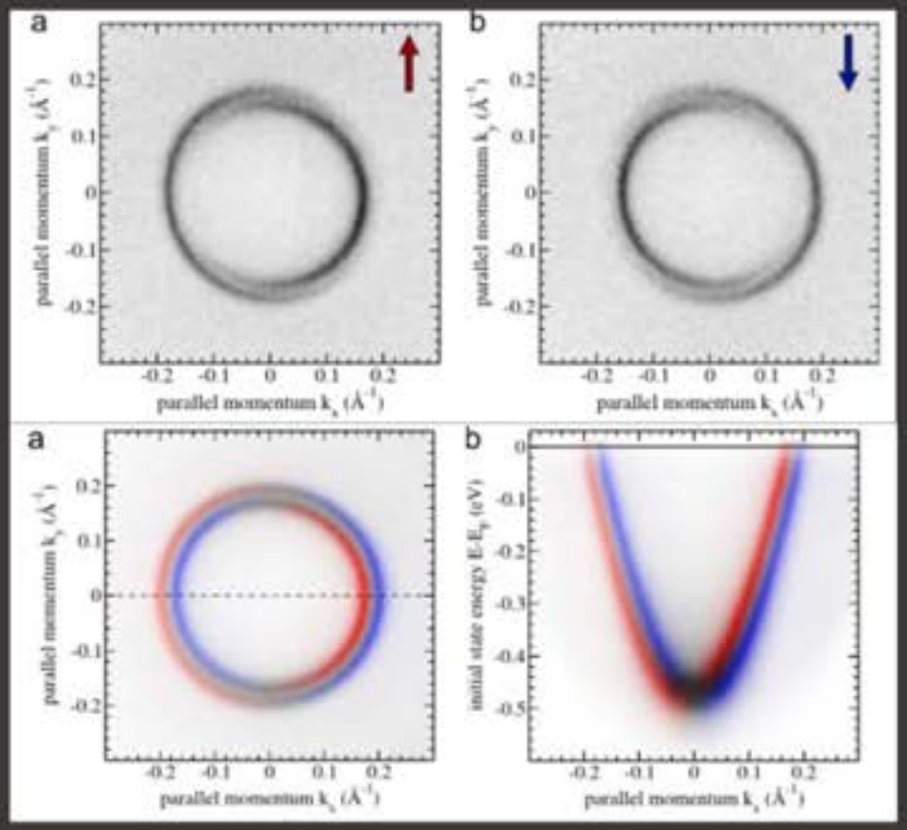


Hemispherical EA + VLEED

T. Okuda *et al.*, *Rev. Sci. Instrum.* **82**, 103302 (2011)
T. Okuda *et al.*, *Rev. Sci. Instrum.* **201**, 23 (2015)

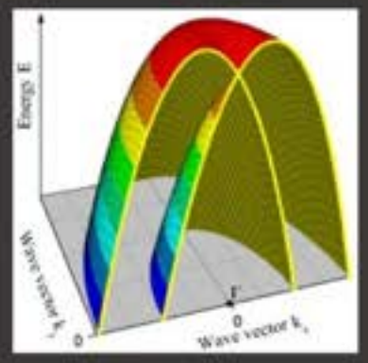
Rashba systems - examples

Au(111)

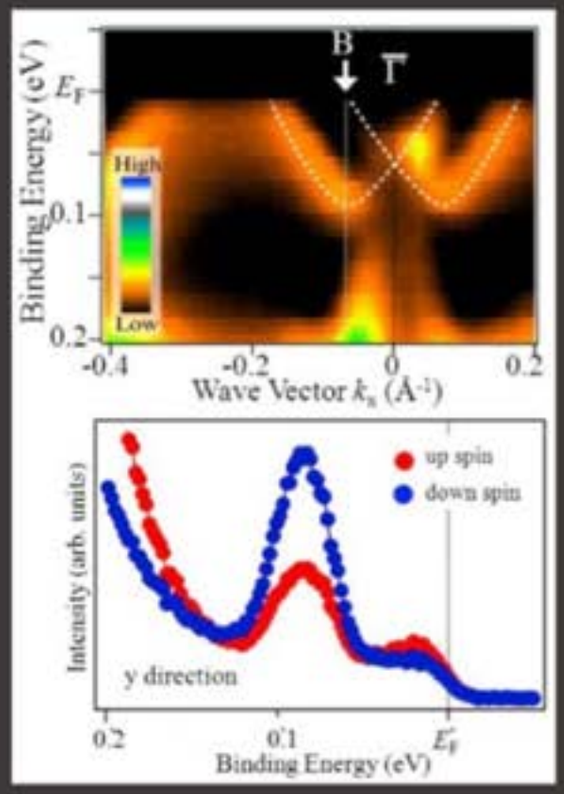


Shockley states in noble metals

C. Tusche *et al.*, Ultramicroscopy, **159**, 520 (2015)



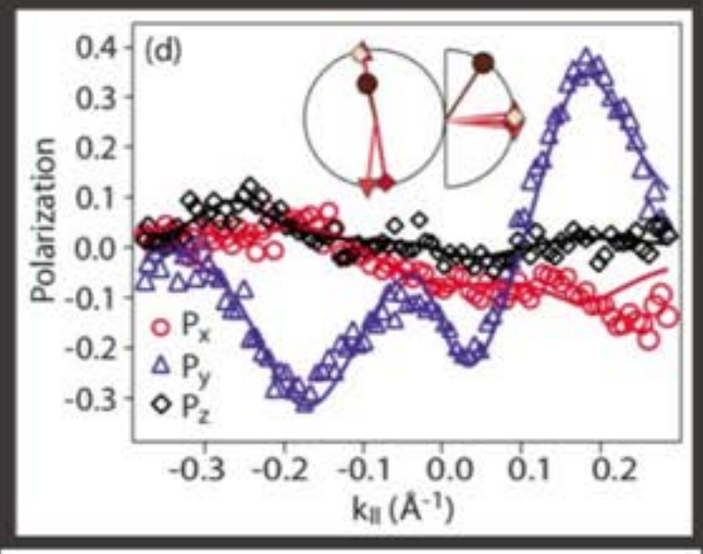
Bi (111)

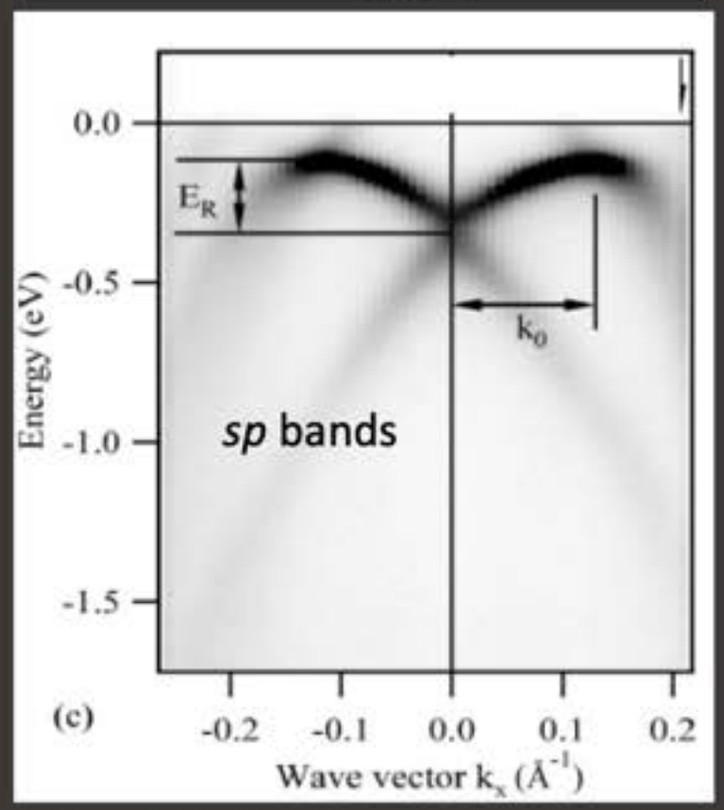


surface states in heavy metals

A Takayama *et al.*,
New J. Phys. **16** 055004 (2014)

Bi/Ag(111)

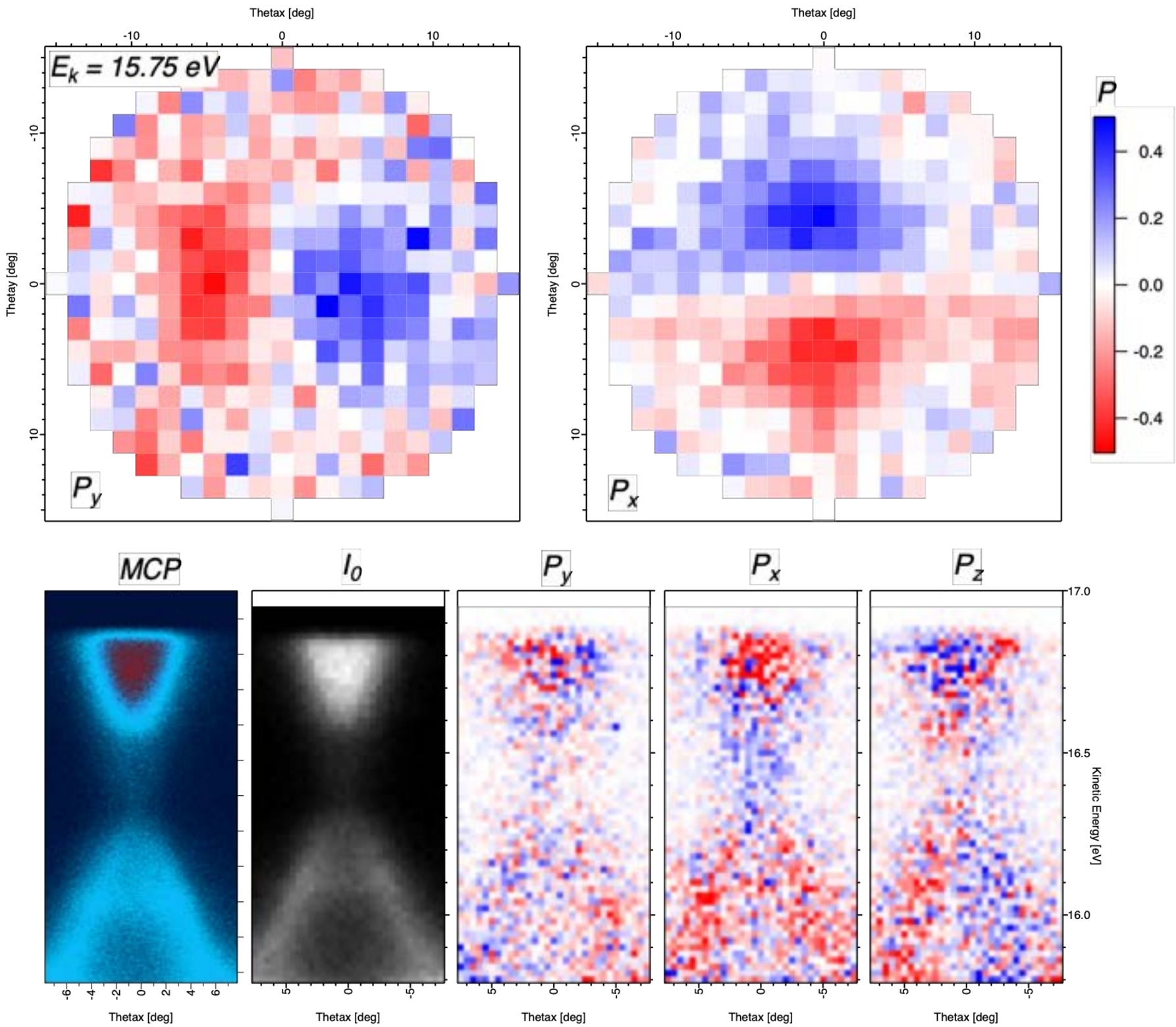




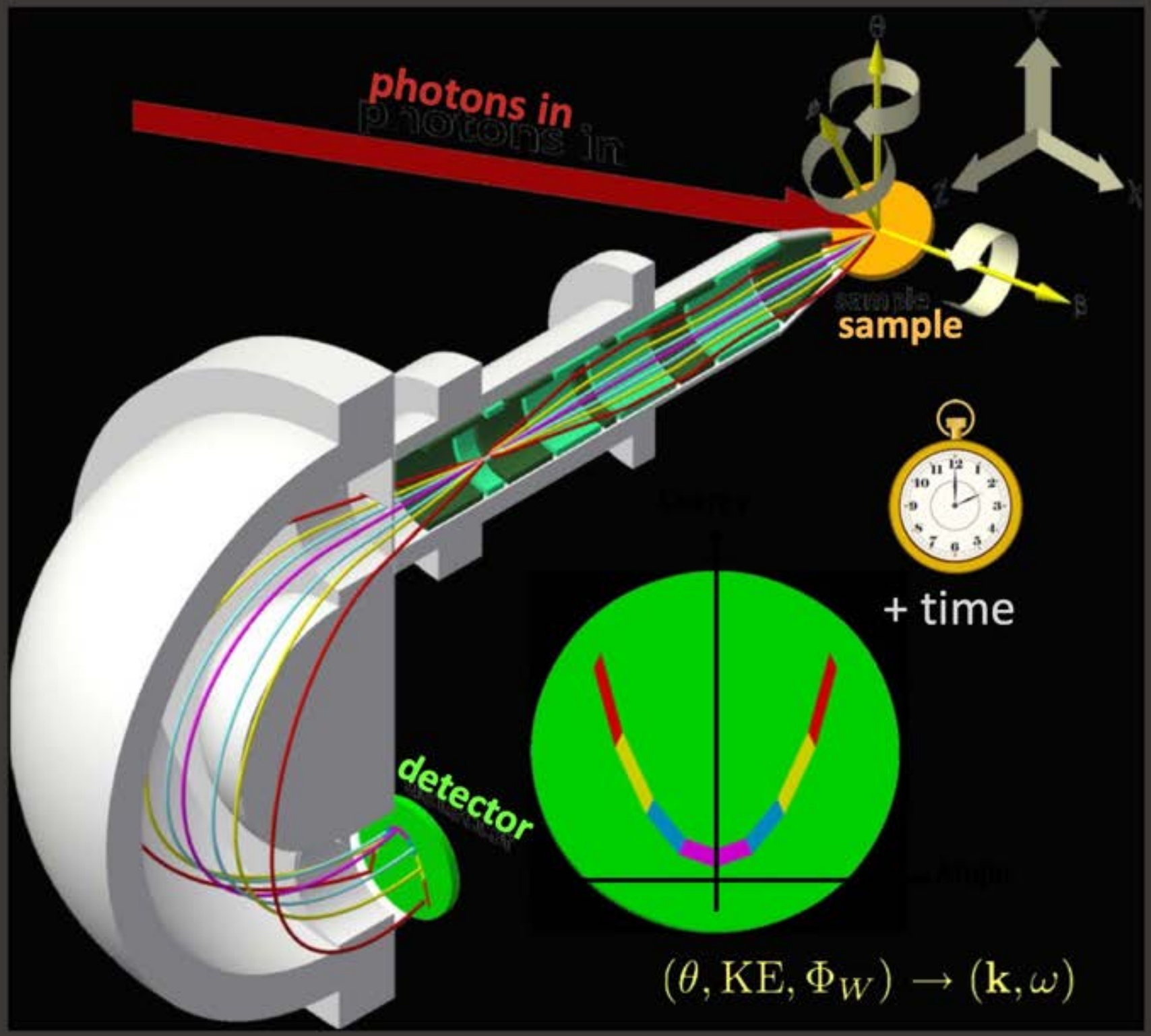
interface states in surface alloys

F. Meier *et al.*, Phys. Rev. B **77**, 165431 (2008)

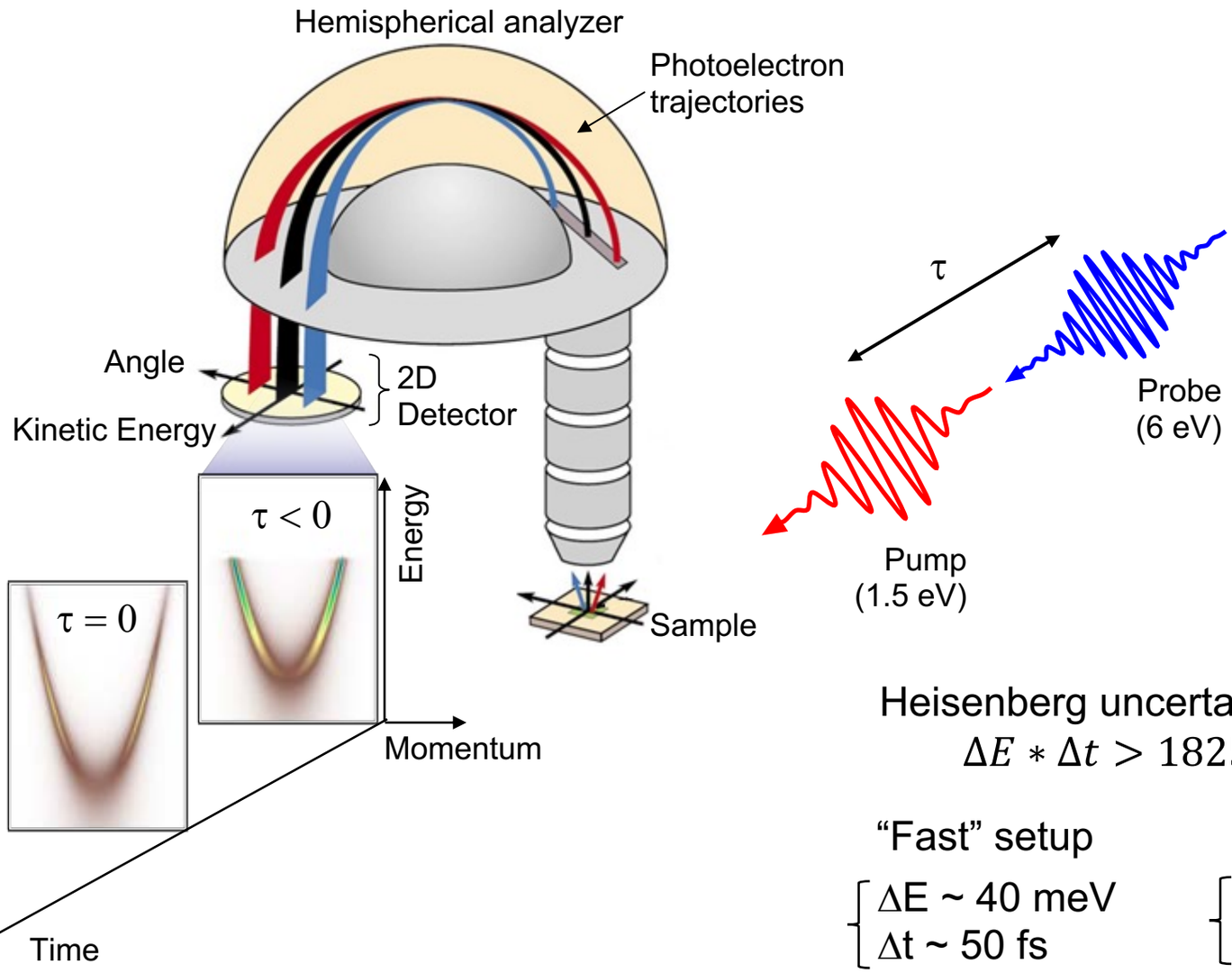
Spin-Resolved ARPES using VLEED detection



Angle-resolved photoelectron spectroscopy
+ something else

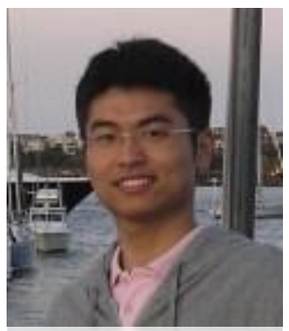


Time-Resolved ARPES : Visualizing Electron Dynamics



Heisenberg uncertainty principle:
$\Delta E * \Delta t > 1825$ meV.fs

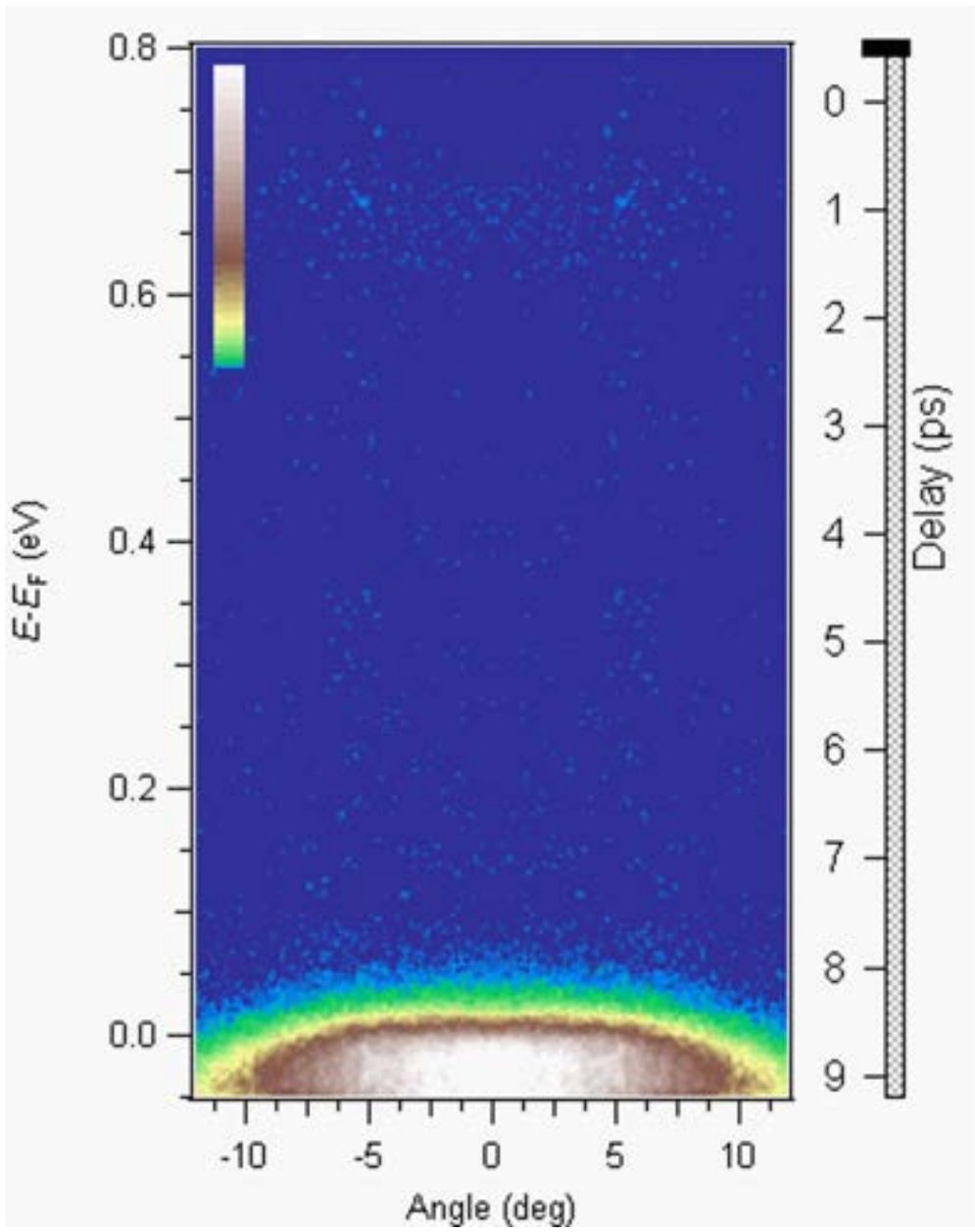
"Fast" setup	"Slow" setup
ΔE ~ 40 meV	ΔE ~ 20 meV
Δt ~ 50 fs	Δt ~ 100 fs



Slides courtesy of Shuolong Yang (U. Chicago)

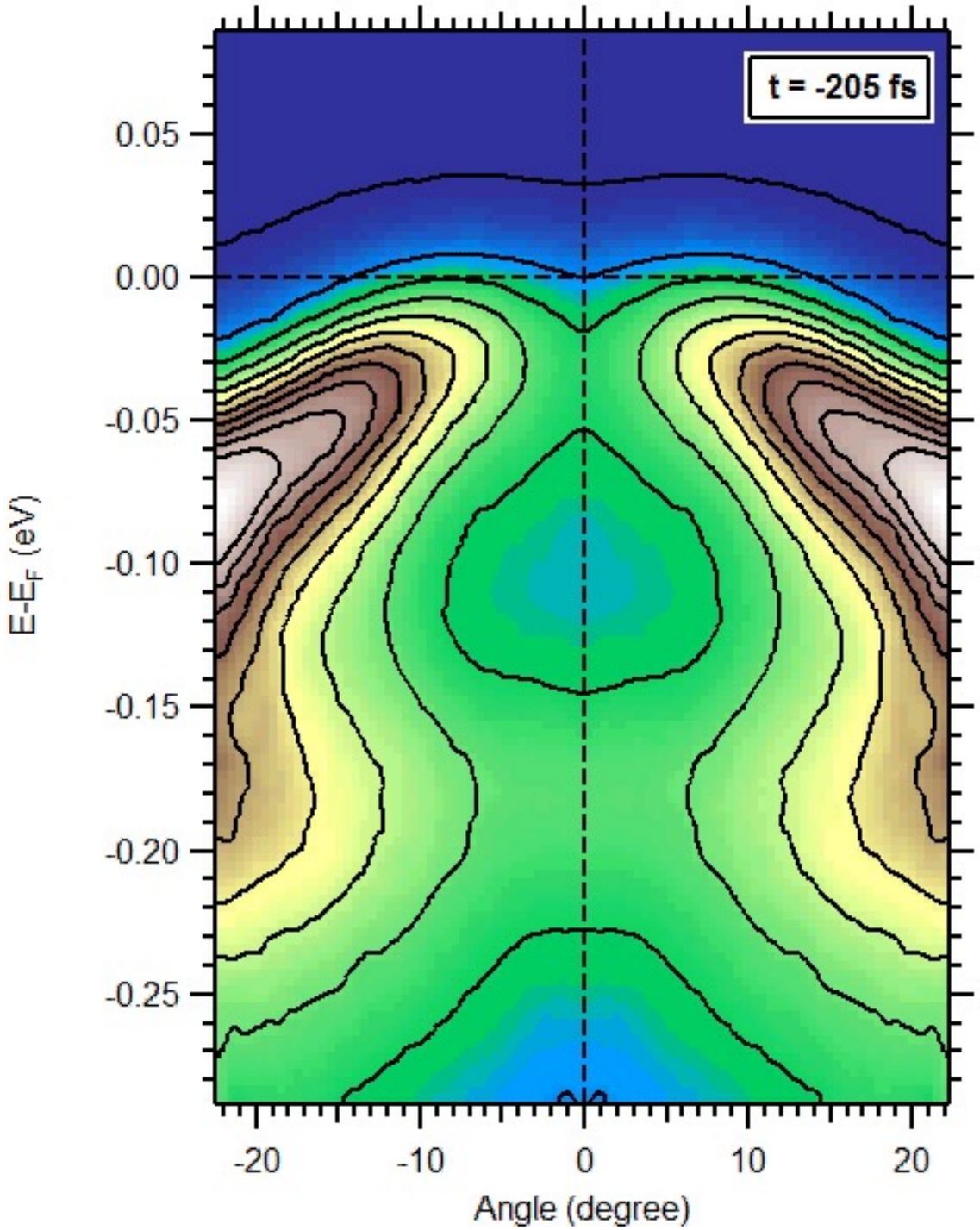
Surface states in topological insulators

Topological insulator Bi_2Se_3

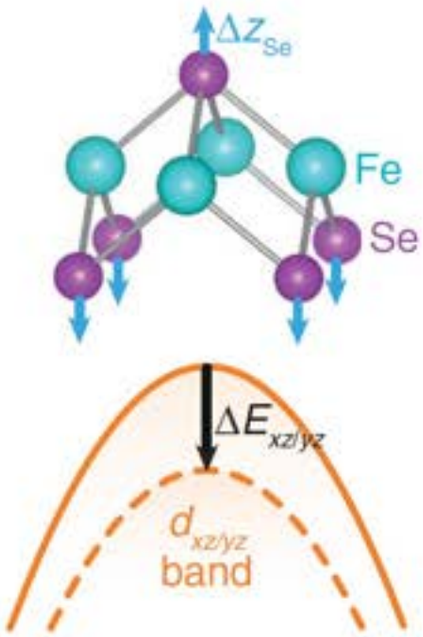


Sobota and Yang et al., PRL 108, 117403 (2012)

Coherent vibration of FeSe electronic bands



Perturbation launches coherent modes



Gerber* and Yang* *et al. Science* **357,** 71 (2017)

What is Time-Resolved ARPES good for?

trARPES tool set

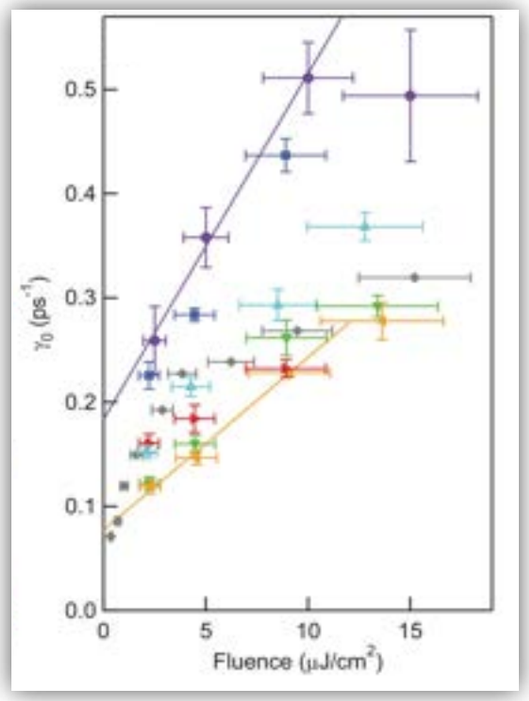
Resolving lifetimes

Launching collective excitations

Promoting electrons above E_F

Transiently modifying emergent properties

Cuprates [1]



Material physics problems

Complex scattering processes

Collective modes

Unoccupied band structure

Material control

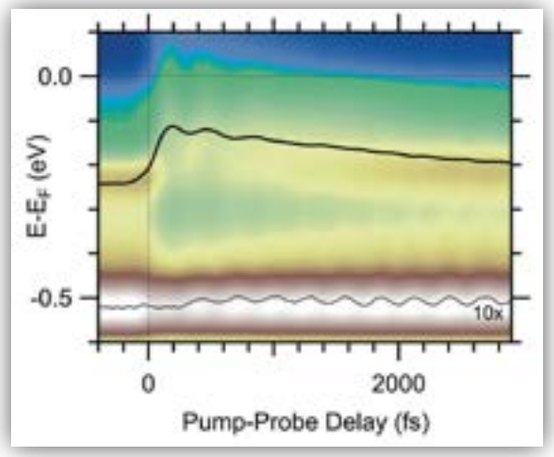
[1] Smallwood *et al. Science* **336**, 1137 (2012) [2] Schmitt *et al. Science* **321,** 1649 (2008)
[3] Sobota *et al. Phys. Rev. Lett.* **111**, 136802 (2013) [4] Mahmood *et al. Nat. Phys.* Advance Online Publication (2016)

What is Time-Resolved ARPES good for?

trARPES tool set

- Resolving lifetimes
- Launching collective excitations
- Promoting electrons above E_F
- Transiently modifying emergent properties
- ⋮

$TbTe_3$ [2]



Material physics problems

- Complex scattering processes
- Collective modes
- Unoccupied band structure
- Material control
- ⋮

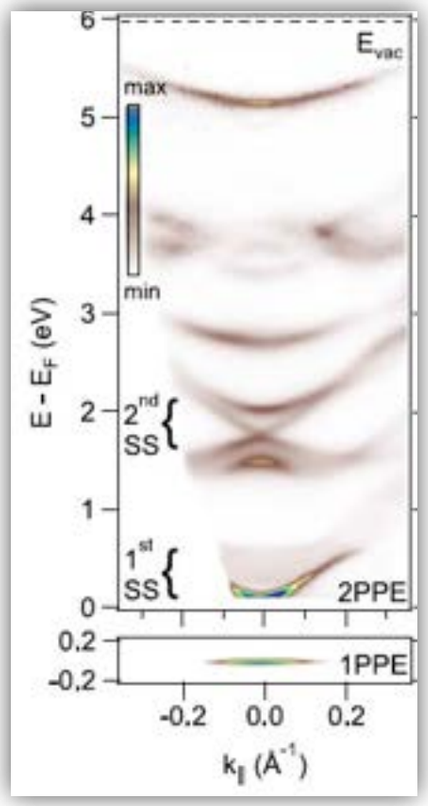
[1] Smallwood *et al. Science* **336**, 1137 (2012) [2] Schmitt *et al. Science* **321,** 1649 (2008)
[3] Sobota *et al. Phys. Rev. Lett.* **111**, 136802 (2013) [4] Mahmood *et al. Nat. Phys.* Advance Online Publication (2016)

What is Time-Resolved ARPES good for?

trARPES tool set

- Resolving lifetimes
- Launching collective excitations
- Promoting electrons above E_F
- Transiently modifying emergent properties
- ⋮

Bi_2Se_3 [3]



Material physics problems

- Complex scattering processes
- Collective modes
- Unoccupied band structure
- Material control
- ⋮

[1] Smallwood *et al. Science* **336**, 1137 (2012) [2] Schmitt *et al. Science* **321,** 1649 (2008)
[3] Sobota *et al. Phys. Rev. Lett.* **111**, 136802 (2013) [4] Mahmood *et al. Nat. Phys.* Advance Online Publication (2016)

What is Time-Resolved ARPES good for?

trARPES tool set

- Resolving lifetimes
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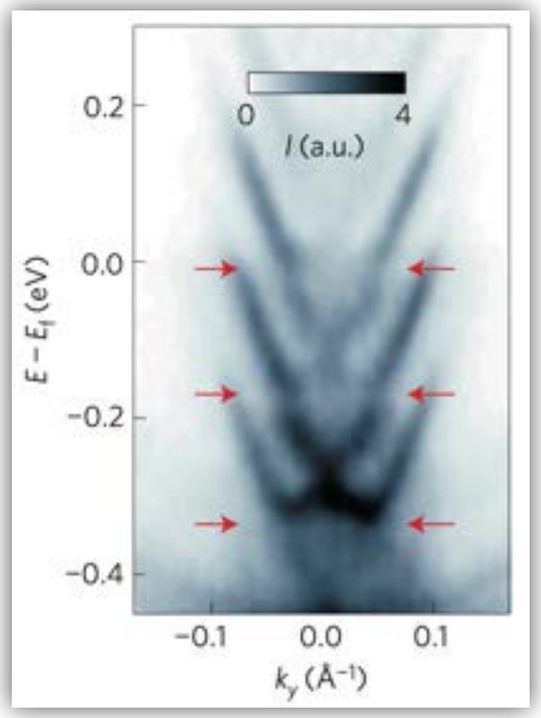
- ⋮

Bi_2Se_3 [4]



Material physics problems

- Complex scattering processes
- Collective modes
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- ⋮

[1] Smallwood *et al. Science* **336**, 1137 (2012) [2] Schmitt *et al. Science* **321,** 1649 (2008)
[3] Sobota *et al. Phys. Rev. Lett.* **111**, 136802 (2013) [4] Mahmood *et al. Nat. Phys.* Advance Online Publication (2016)

TR-ARPES
some useful reviews

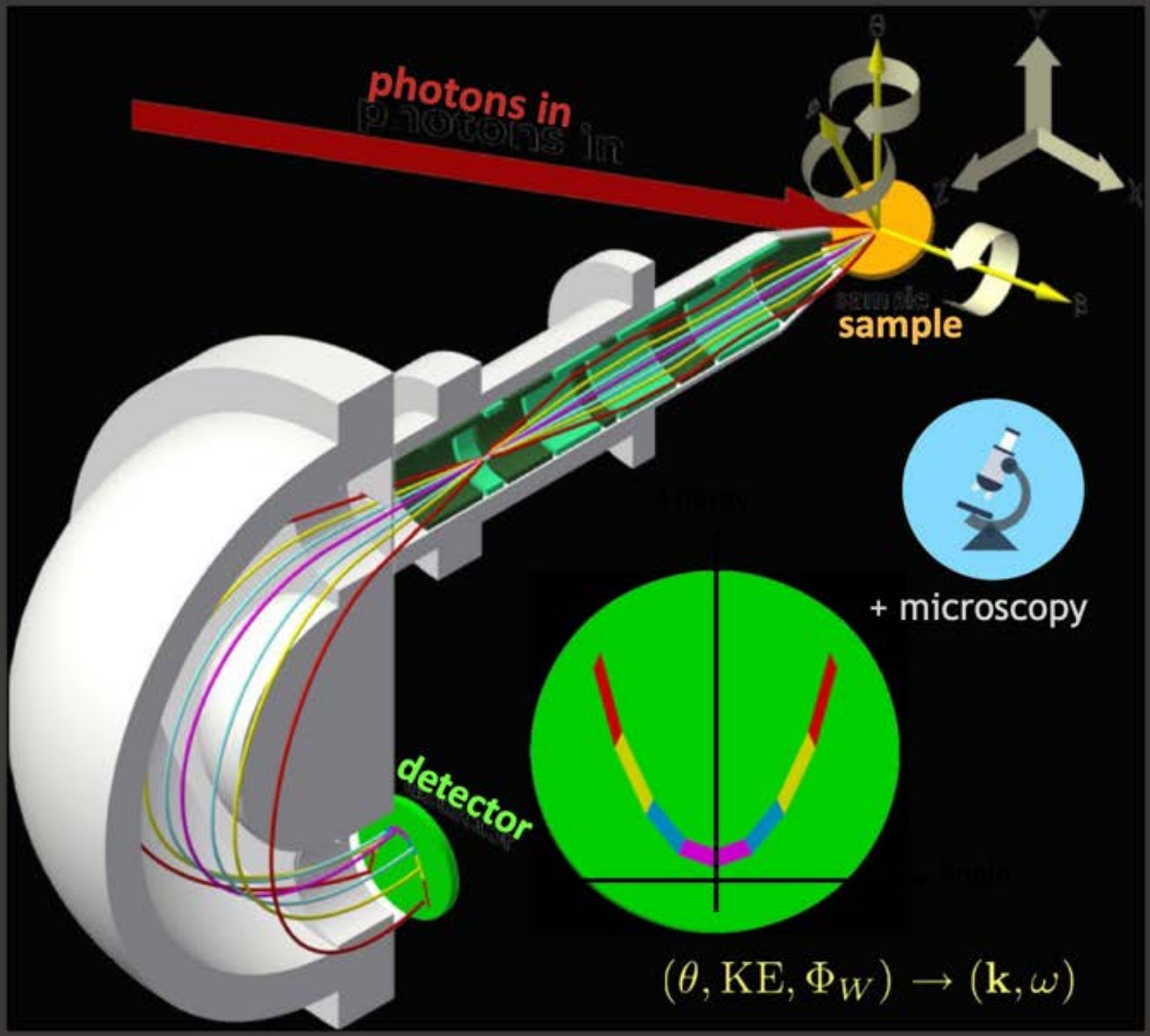
experiment

S. Mathias *et al.*, J. of Phys.: Conf. Ser. **148**, 012042 (2009)
U. Bovensiepen and P. S. Kirchmann, Laser Photonics Rev. **6**, 589 (2012)
C. Giannetti *et al.*, Adv. in Phys. **65**, 58 (2016)
C. L. Smallwood *et al.*, Europhys. Lett. **115**, 27001 (2016)

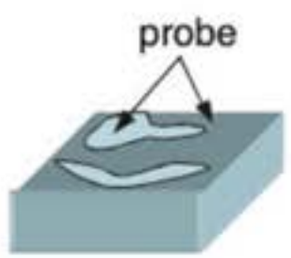
theory

H. Aoki *et al.*, Rev. Mod. Phys. **86**, 779 (2014)
A. F. Kemper *et al.*, Ann. Phys. 1600235 (2017)

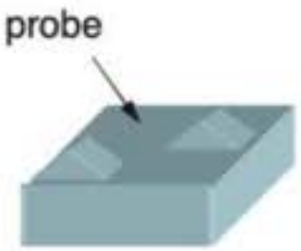
Angle-resolved photoelectron spectroscopy
+ something else



The case for going smaller

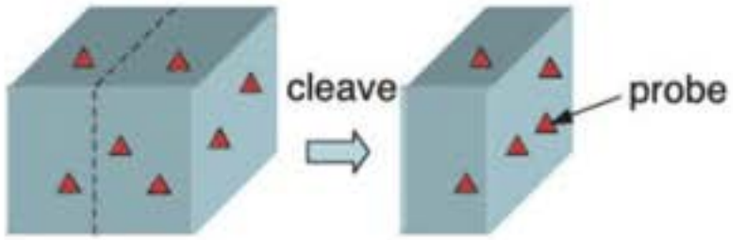


(a) phase separation
- doped Mott insulators
- magnetism

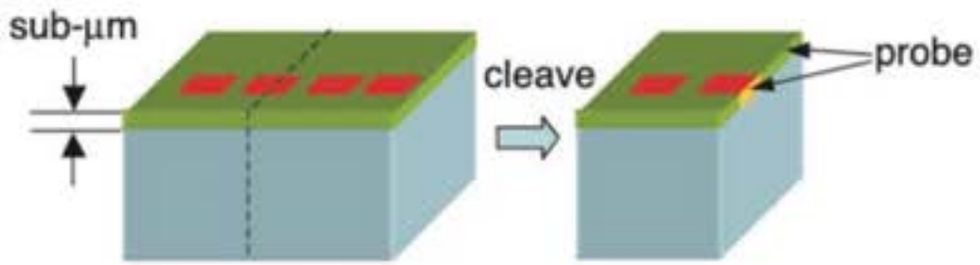


(b) isolating flat regions of irregular cleaves

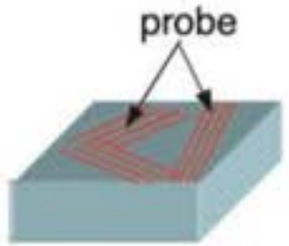
(c) 2-d plane of needle-like samples, e.g. $NbSe_3$, quasicrystals, etc



(d) microcrystallites embedded in a host material for cleavage



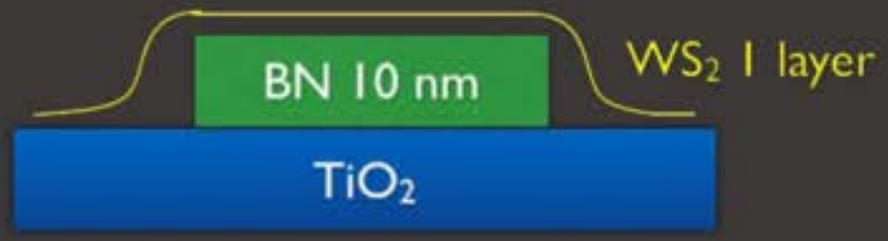
(e) thin films grown ex situ; also quantum dots, other nano-engineered devices

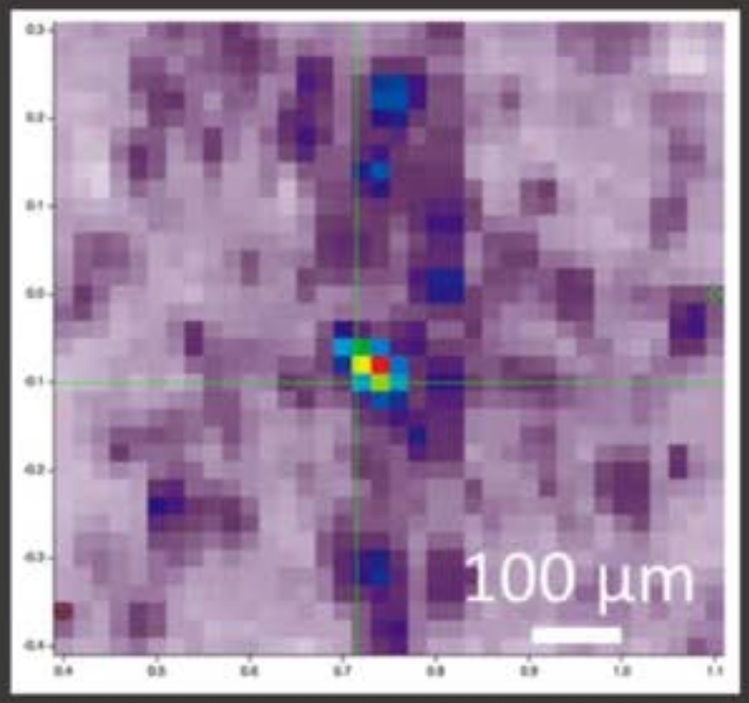


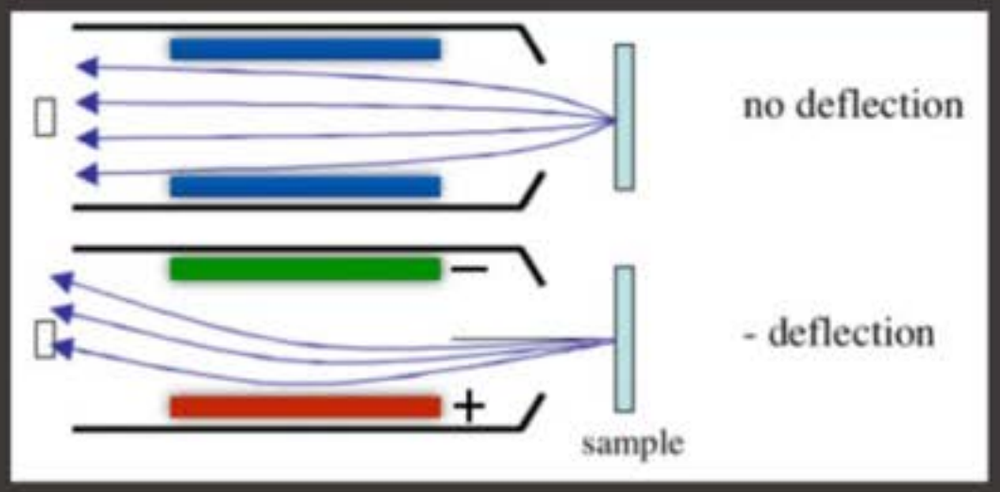
(f) isolating mixed phases on epitaxial film surfaces

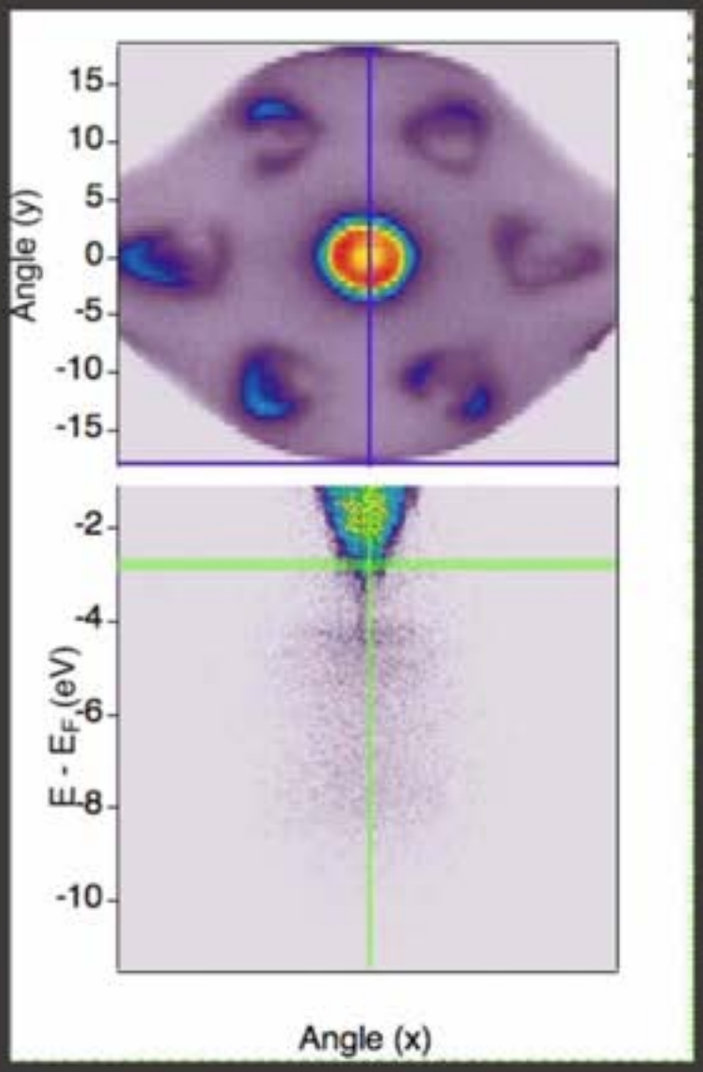
ackn. E. Rotenberg

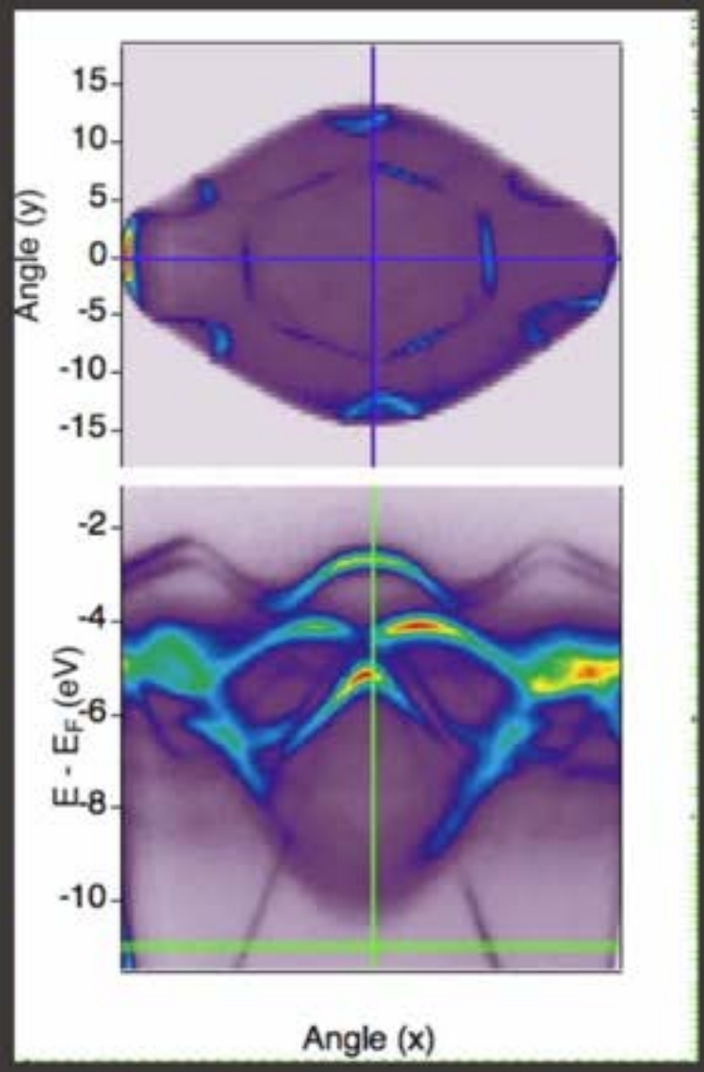
Take 1 – μARPES with deflectors







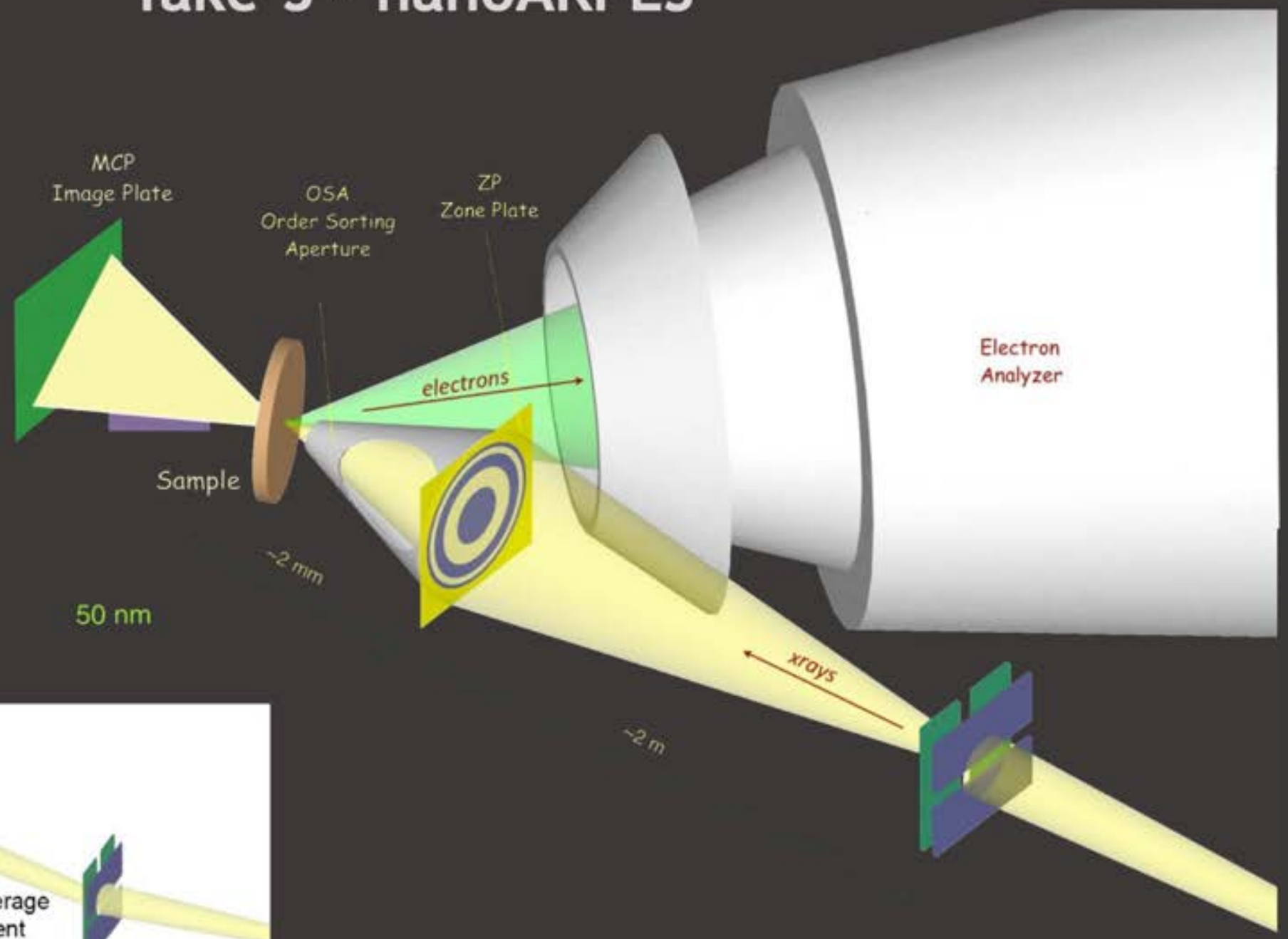


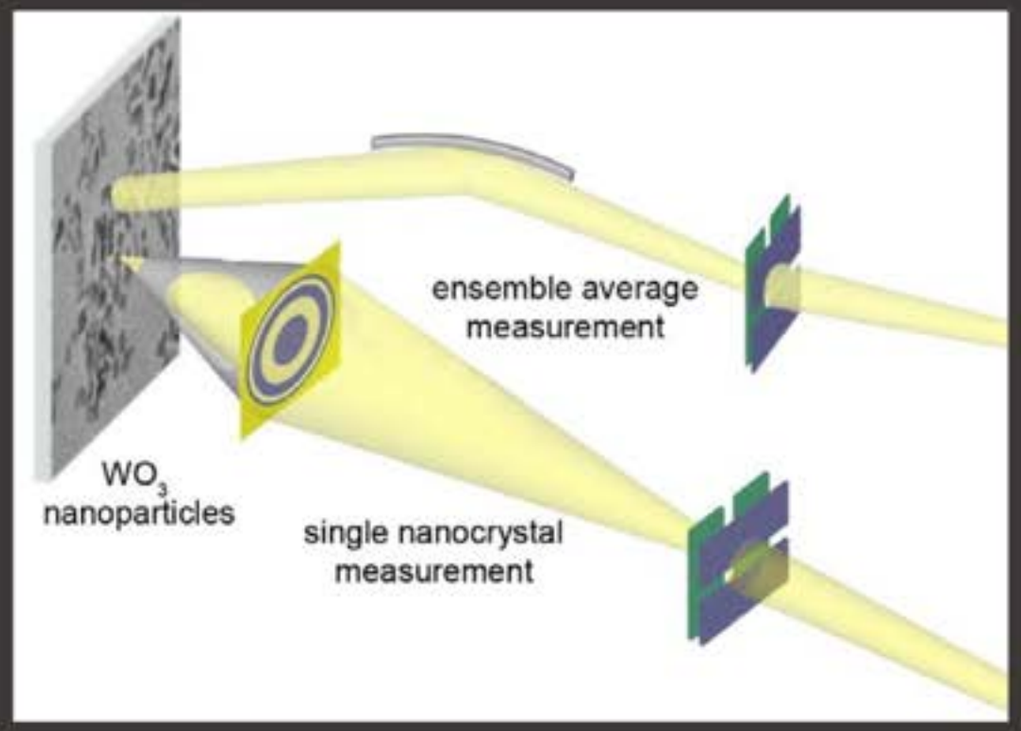


data: J. Katoch and S. Ulstrup

ackn. E. Rotenberg, A. Bostwick, R. Koch

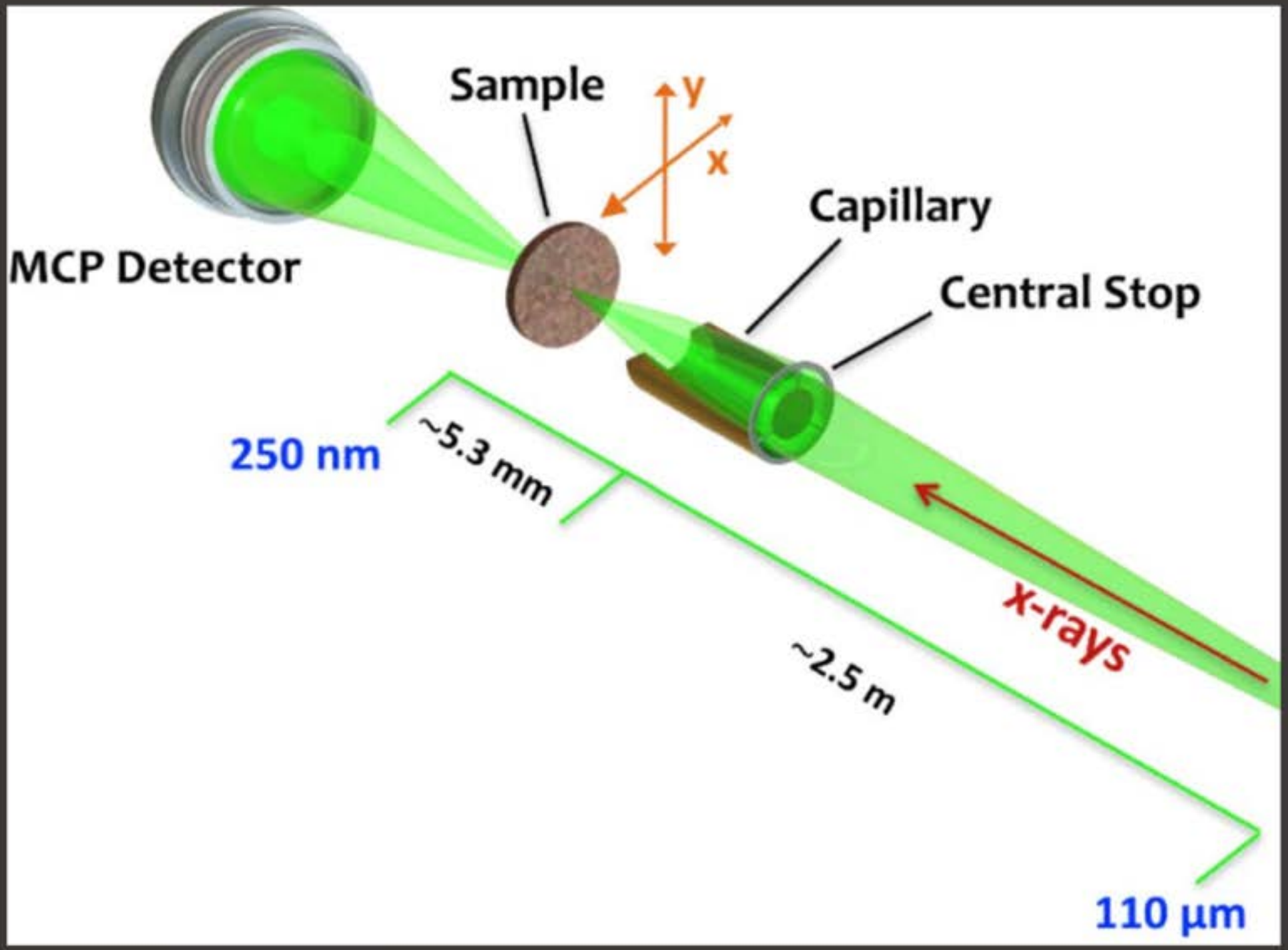
Take 3 - nanoARPES





<120 nm spatial resolution
100 times slower than μARPES

(almost) nanoARPES with KB optics



In collaboration with SIGRAY

R. J. Koch *et al.*, Synchrotron Radiation News **31**, 50 (2018)

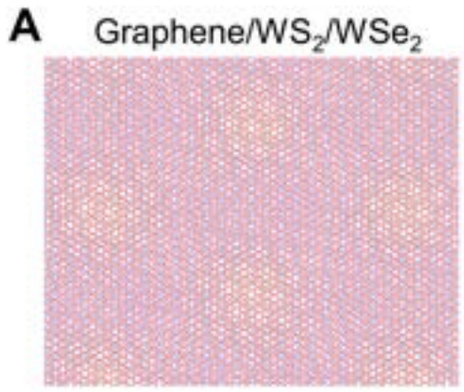
Spatially Resolved ARPES : on micro-structures

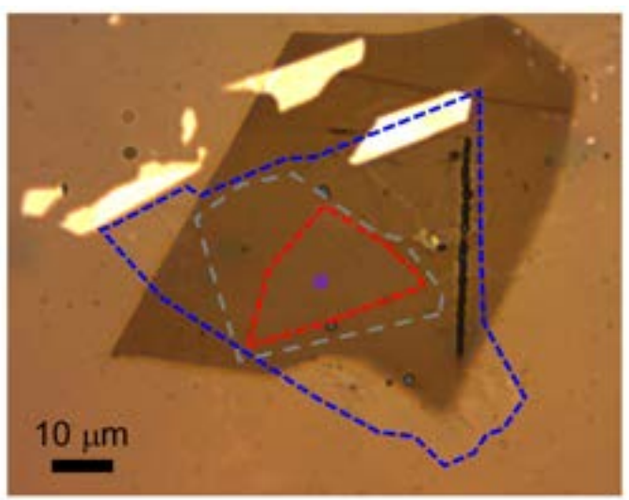
SCIENCE ADVANCES | RESEARCH ARTICLE

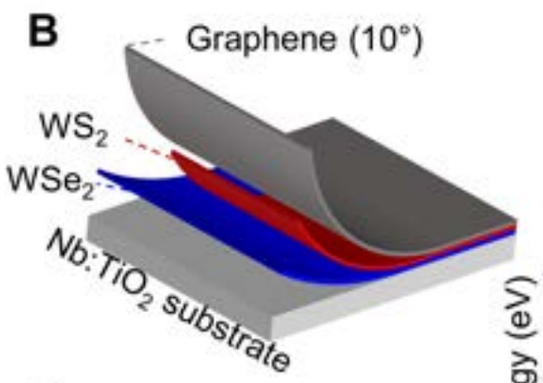
PHYSICAL SCIENCES

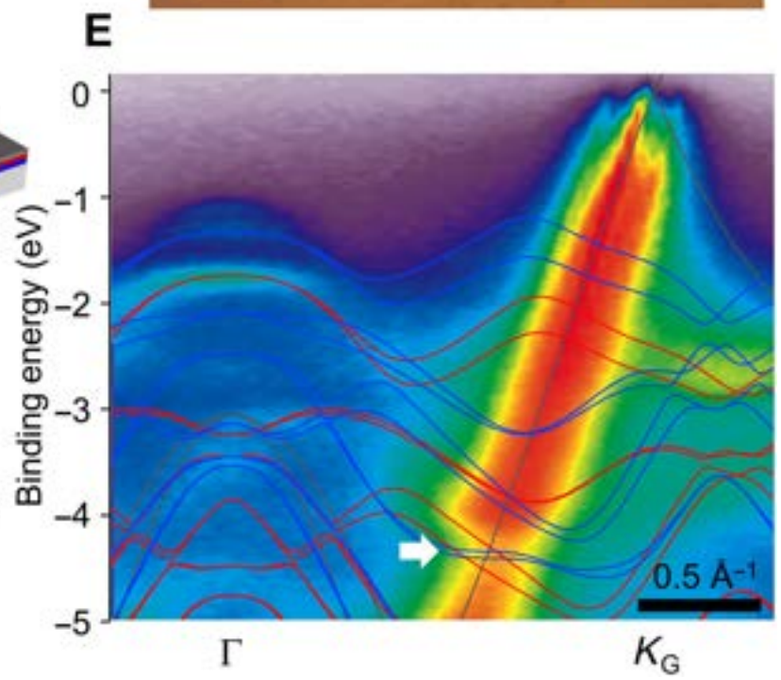
Strong interlayer interactions in bilayer and trilayer moiré superlattices

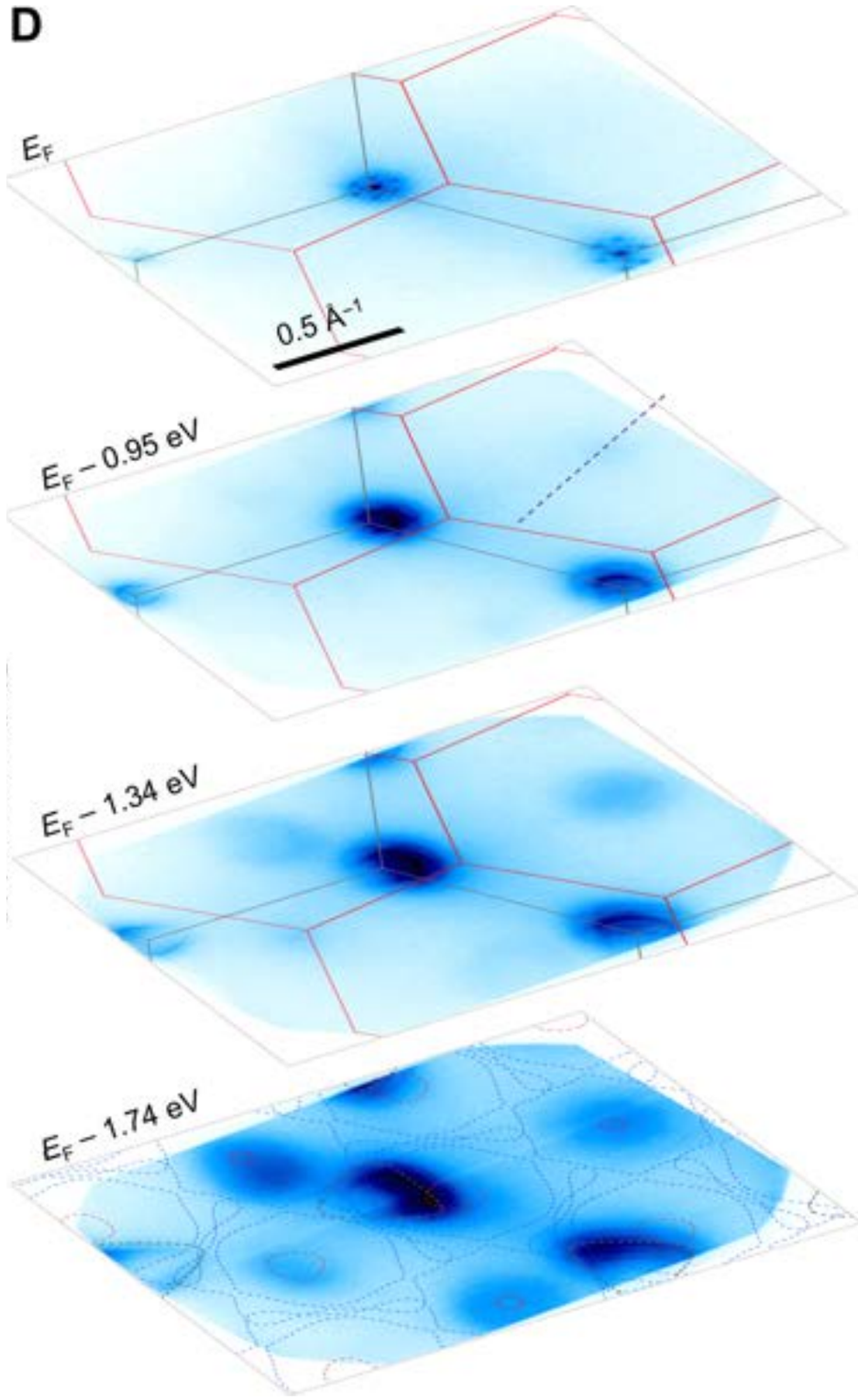
Saien Xie[1,2,3]*, Brendan D. Faeth[1], Yanhao Tang[4], Lizhong Li[4], Eli Gerber[4], Christopher T. Parzyck[1], Debanjan Chowdhury[1], Ya-Hui Zhang[5], Christopher Jozwiak[6], Aaron Bostwick[6], Eli Rotenberg[6], Eun-Ah Kim[1], Jie Shan[1,3,4], Kin Fai Mak[1,3,4], Kyle M. Shen[1,3]*











Spatially Resolved ARPES : on micro-structures