ES&ES 2013

Probing spin textures of topological insulators by spin- and angle-resolved photoemission

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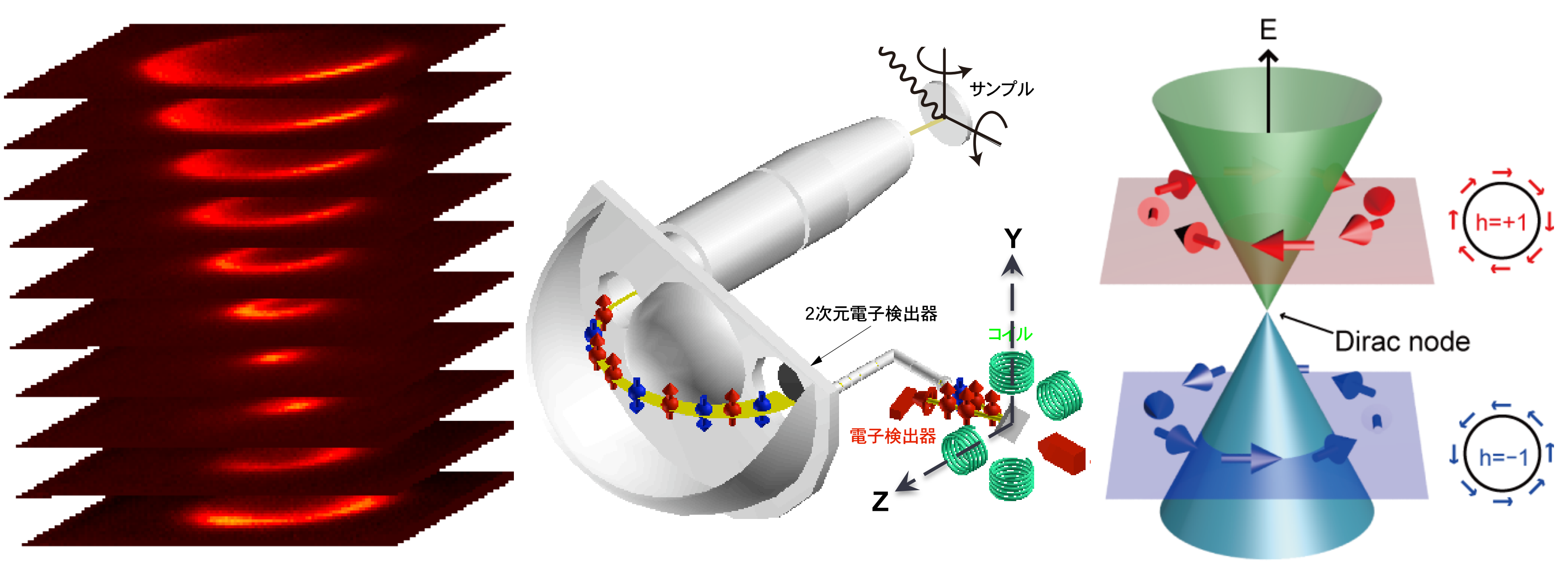

May. 22nd, 2013 @ Institute of Metal Physics

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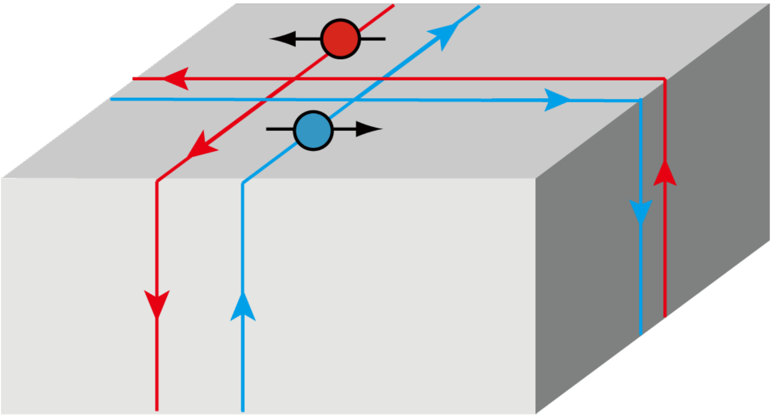
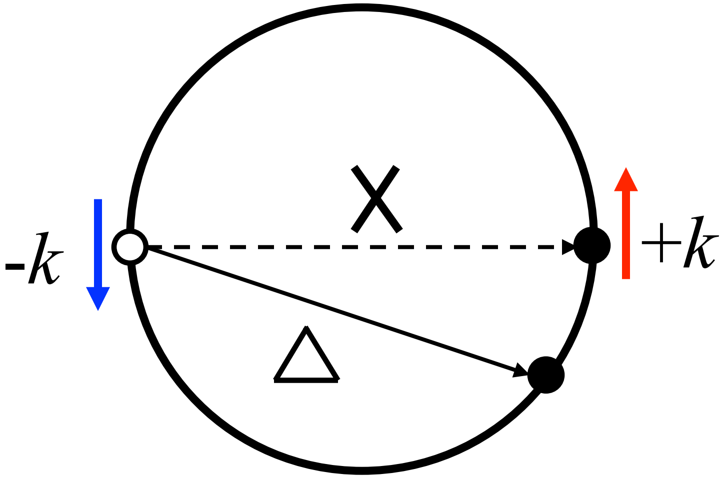
3D Topological Insulator

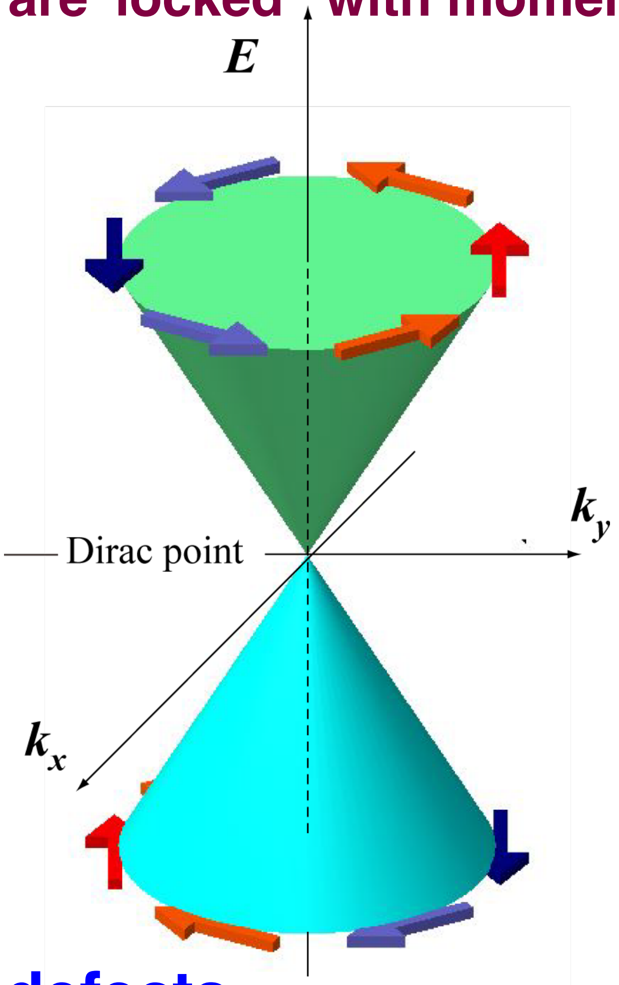


Suppressed backscattering



Massless Dirac Fermion

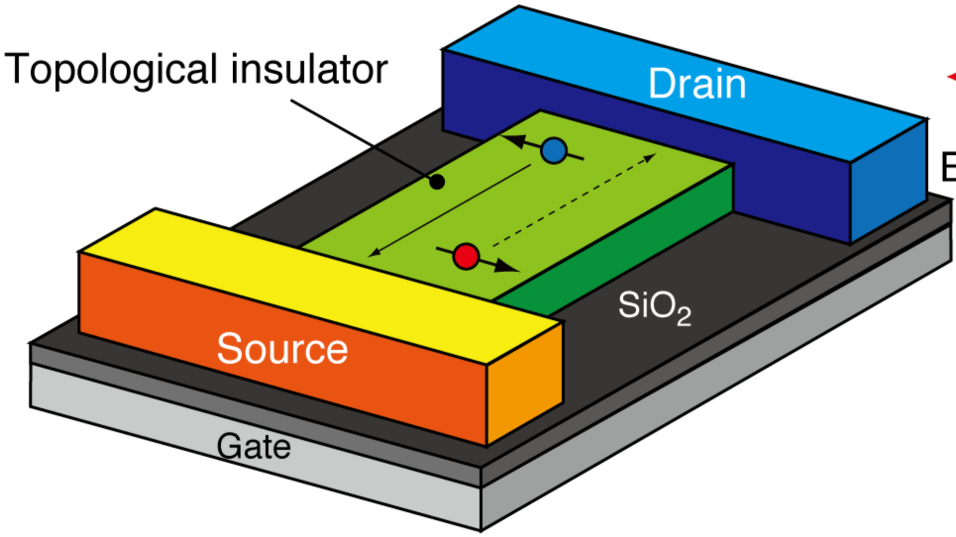
Spins are 'locked' with momenta.

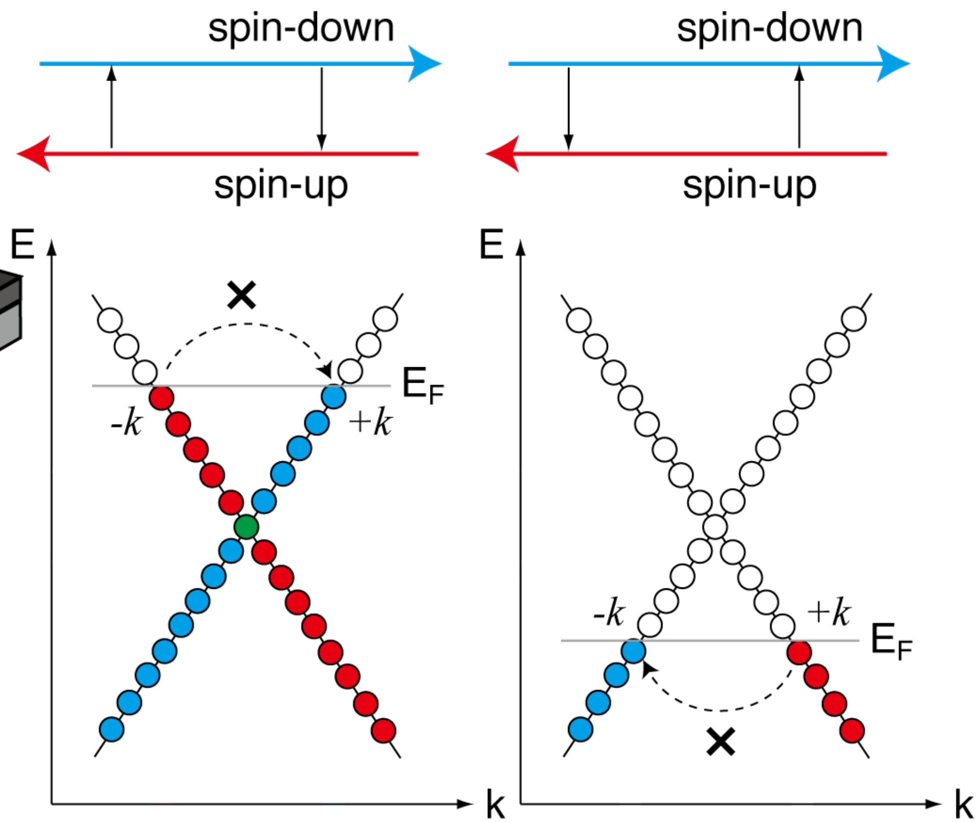


Robust to nonmagnetic impurities and defects.

Dissipationless spin transport

Topological field effect transistor





$V_G > 0$ $V_G < 0$

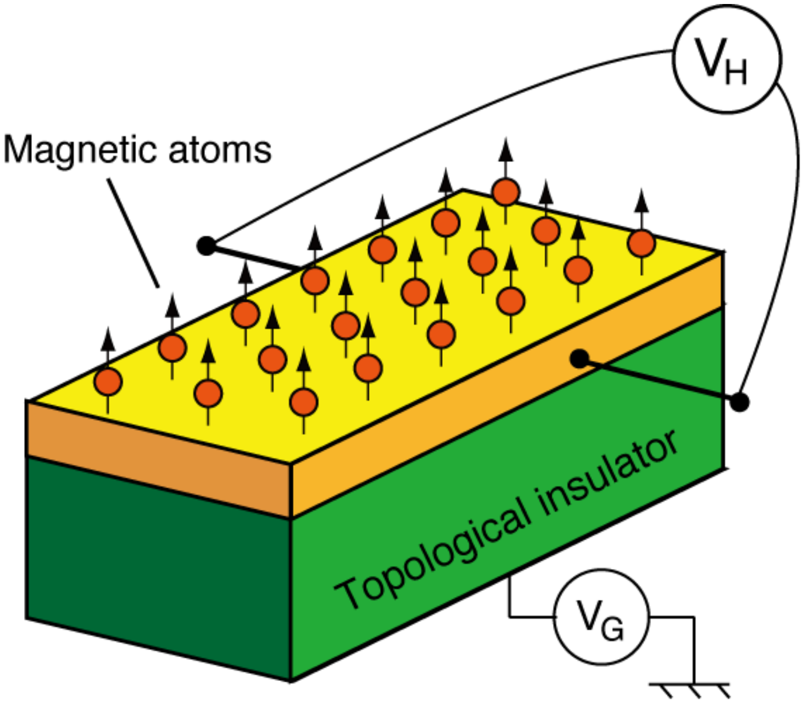
Topological channel

- **Fast operation**
- **Extremely large mobility**
- **Very low consuming power**

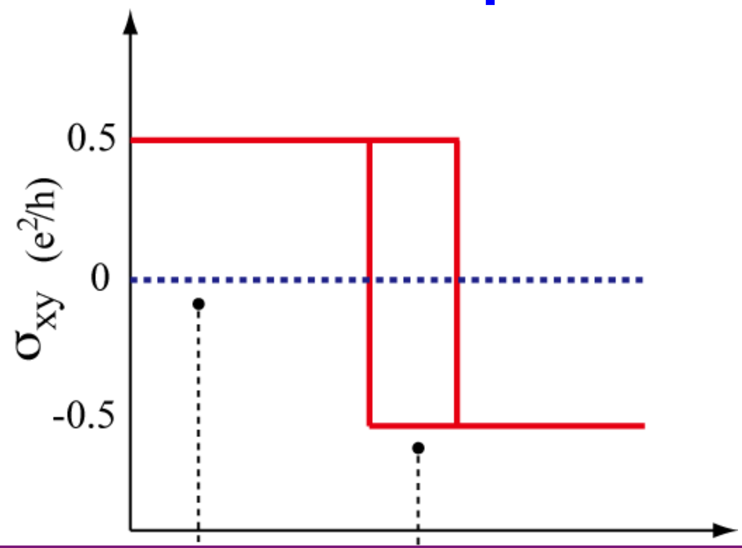
Consuming power can be much reduced with topological channel

Topological MRAM ?

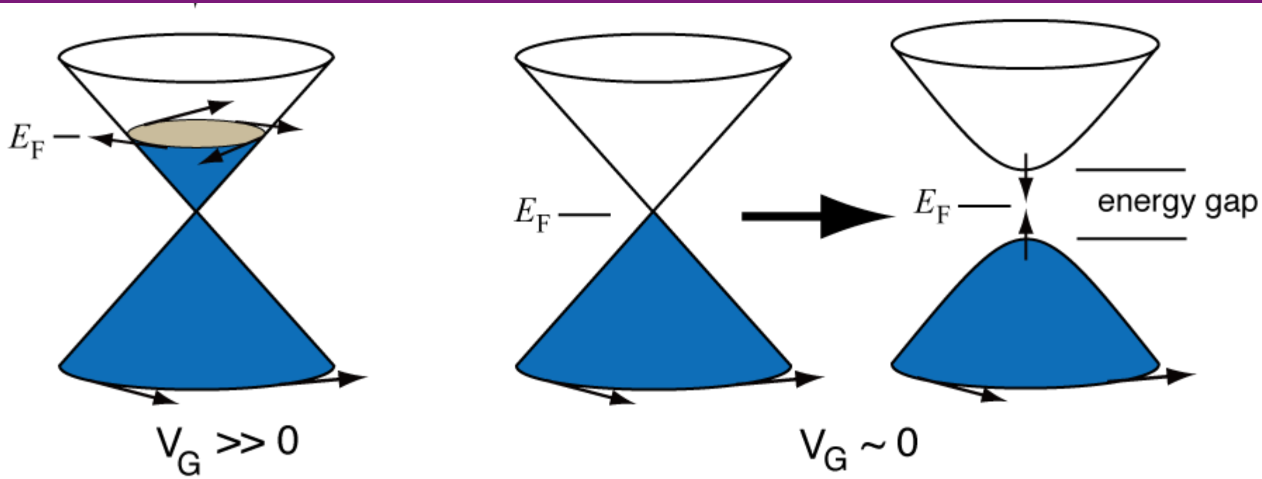
T. Fujita et al., APEX **4** (2011) 094201.



Anomalous Hall effect is half quantized

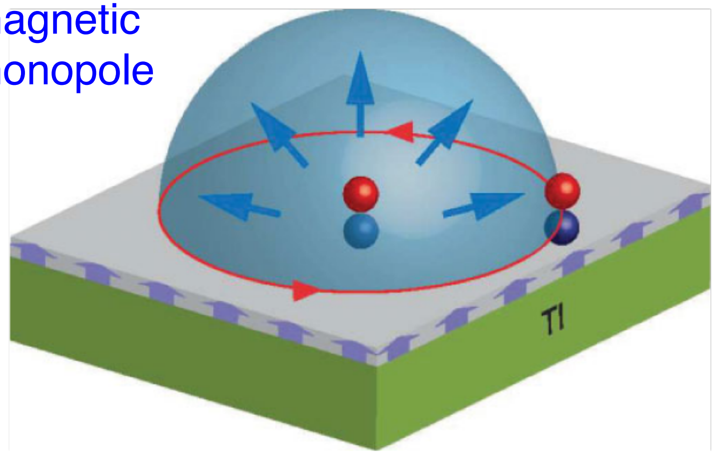


Readout: robust to crystal imperfections e.g. defects, disorders



3D TOPOLOGICAL INSULATORS

Image magnetic monopole



- Suppressed backscattering
- Half integer surface QHE
- Topological magnetoelectric effect
- Emergence of Majorana fermion

- Topological FET
- Topological MRAM
- Fault tolerant quantum computing

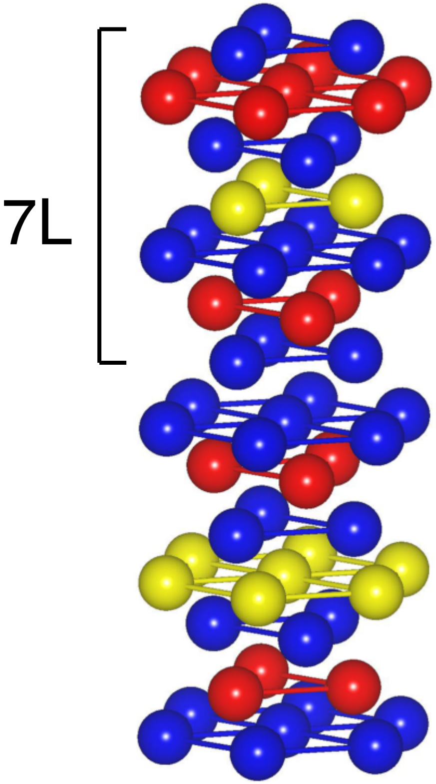
✓ Need to find ideal materials with an ideal Dirac cone SS.

✓ New material design with the first principles cal..

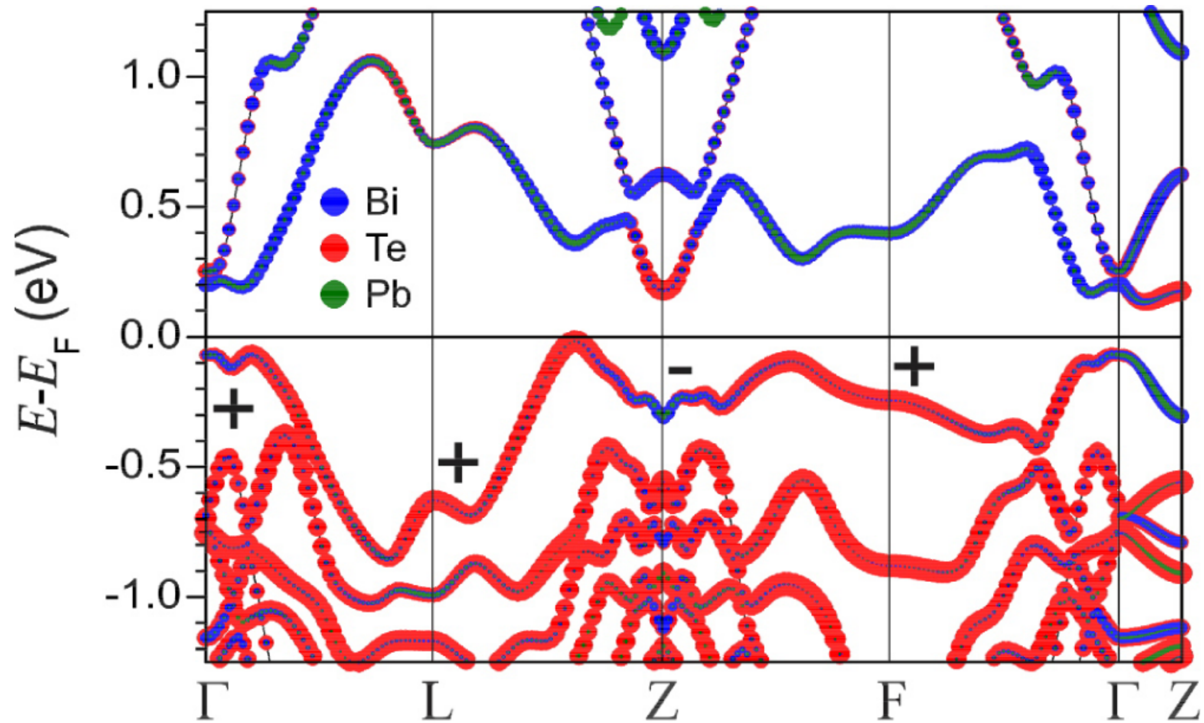
⬇

Angle resolved photoemission spectroscopy with spin resolution

Theoretical prediction for $PbBi_2Te_4$



cf. T. V. Menshchikova *et al.*, JETP Lett. (2011).



Z_2 topological invariants for 3D - Fu-Kene-Mele, PRL (2007)

$$(-1)^{\nu_0} = \prod_{i=1}^{8} \prod_{m=1}^{N} \xi_{2m}(\Gamma_i)$$

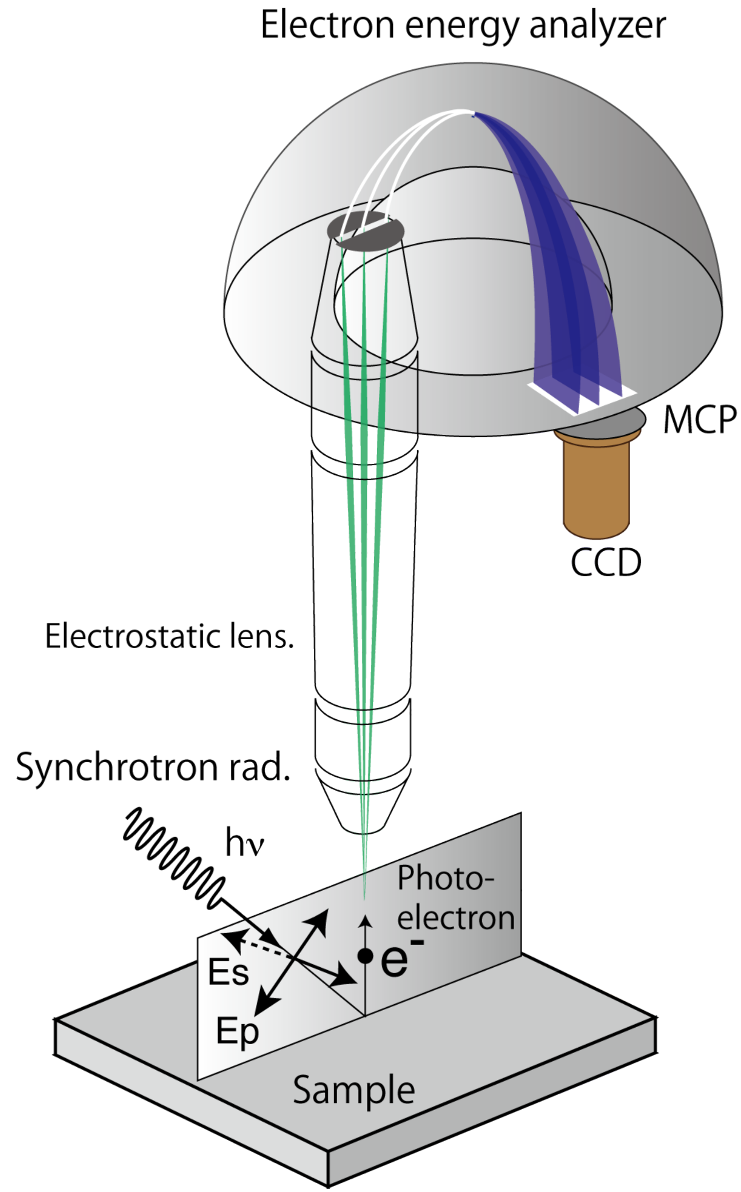
$$(-1)^{\nu_k} = \prod_{i=(n_1 n_2 n_3),\, n_k=1}^{8} \prod_{m=1}^{N} \xi_{2m}(\Gamma_i)$$

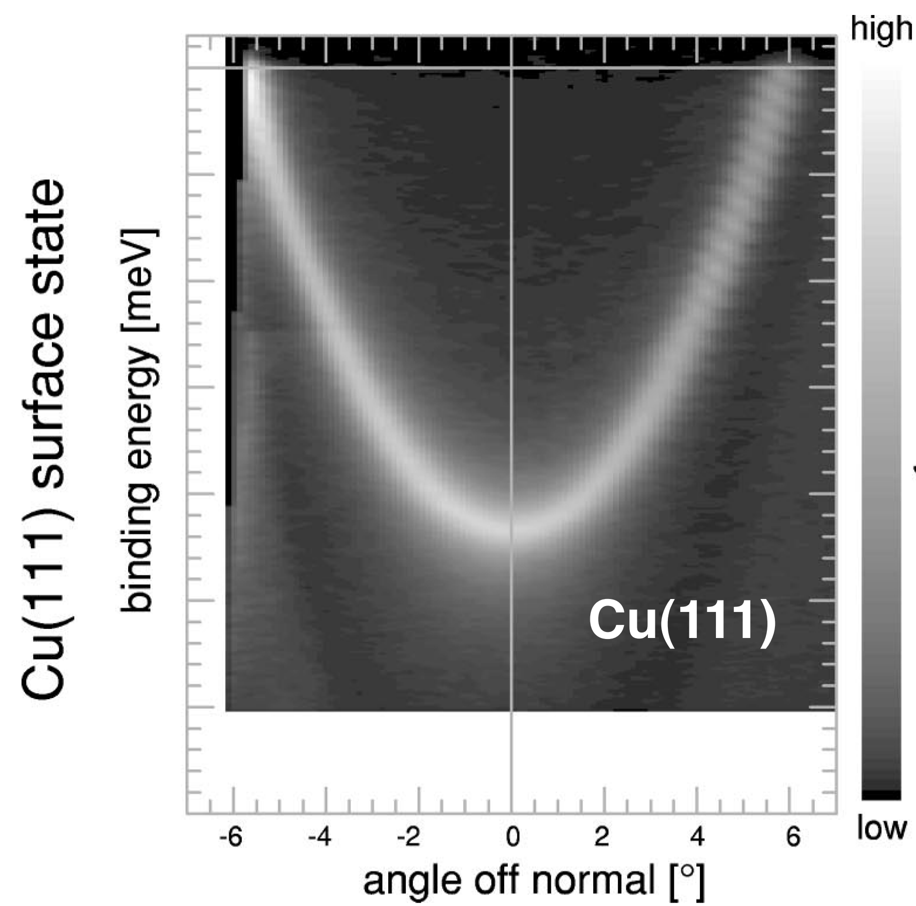
Parity inversion takes place at Z point.

ν_0; $(\nu_1 \nu_2 \nu_3)$=1; (111)

cf. ν_0; $(\nu_1 \nu_2 \nu_3)$=1; (000) for Bi_2Se_3

Angle-resolved photoelectron spectroscopy

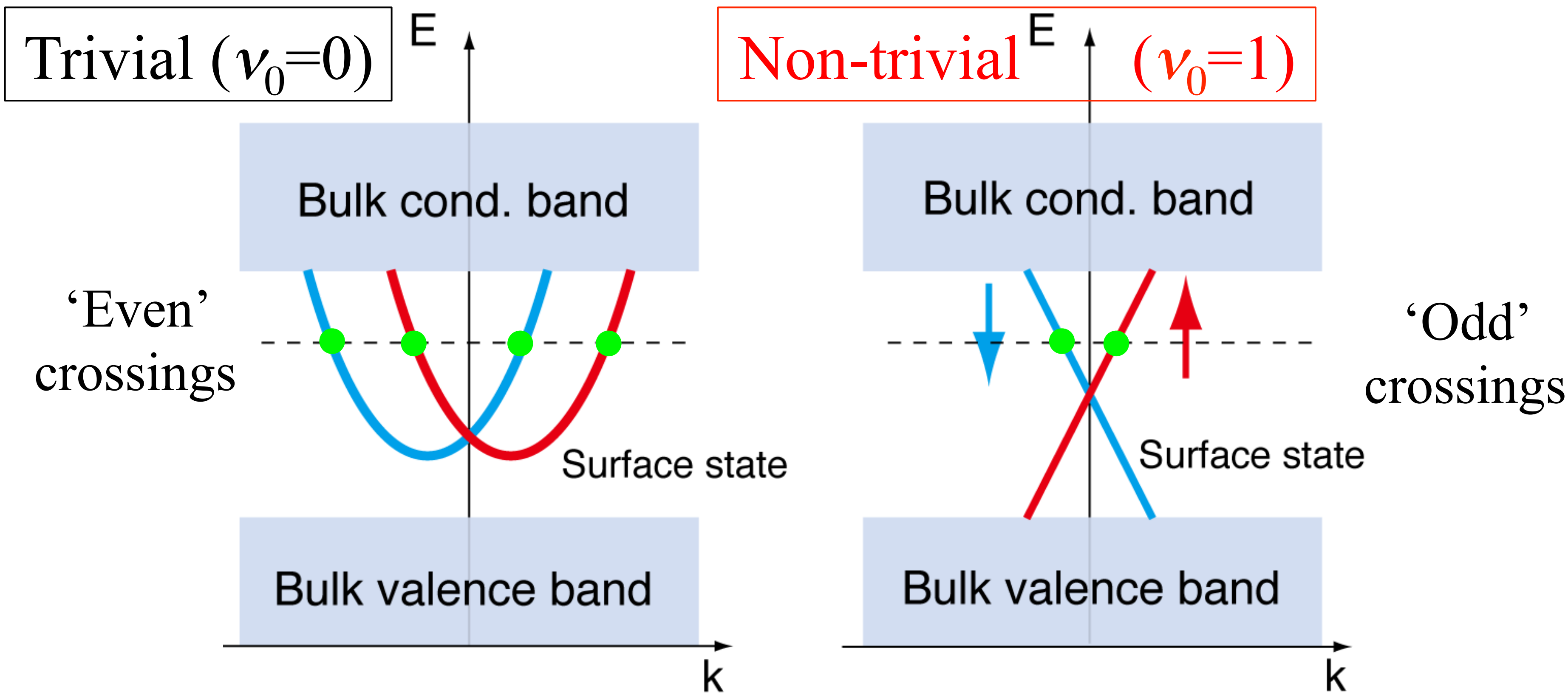




F. Reinert et al.

- **Multi-channel detection**
- **High energy and angular resolution**

Role of ARPES for 3D topological insulators



- Probing odd number of surface states between two TRIMs.
- Spin resolution is indispensable.
- Probing *k*-space location of SS and bulk continuum state.
- Coupling parameters like el.-ph. interaction.

High resolution & Spin resolved ARPES + Synchrotron radiation.

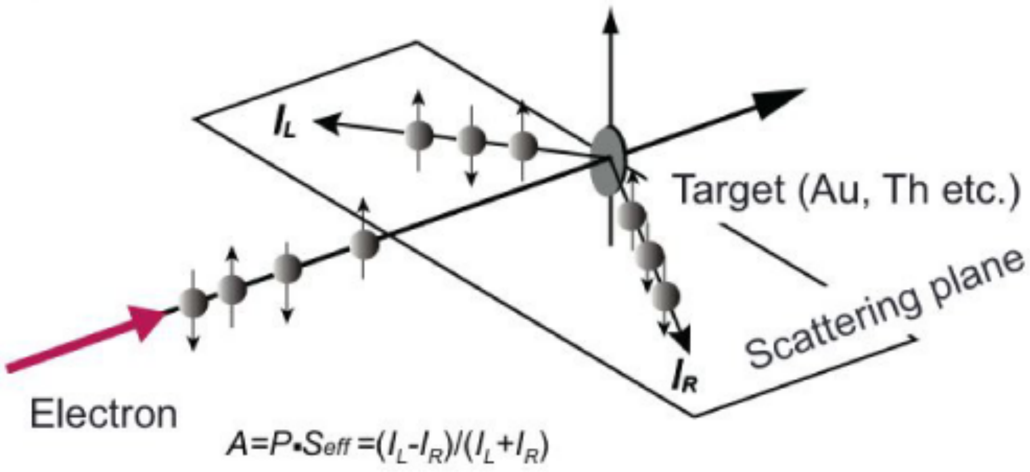
Hiroshima Synchrotron Radiation Center

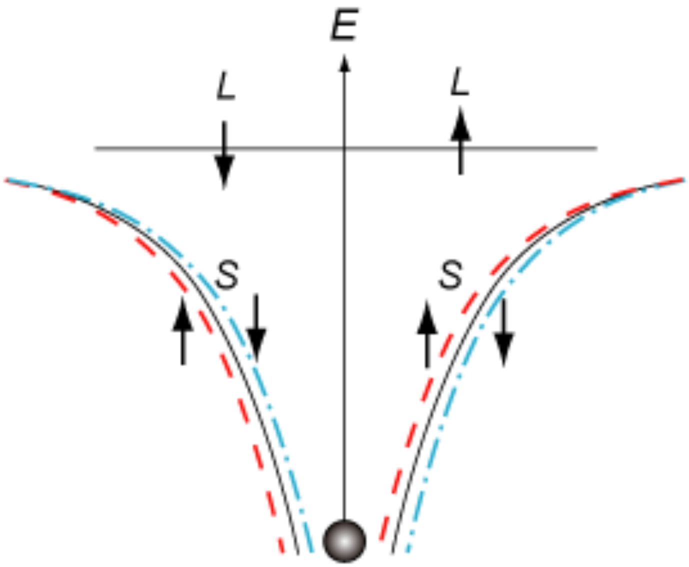
HiSOR

For ARPES on electronic structure study of solids

How to measure the spin polarizations?

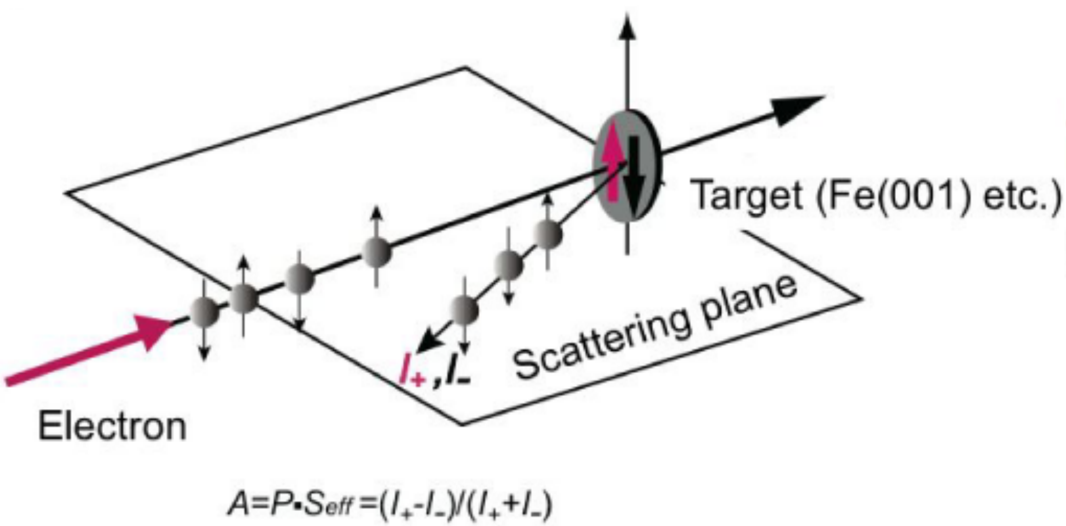
Mott scattering

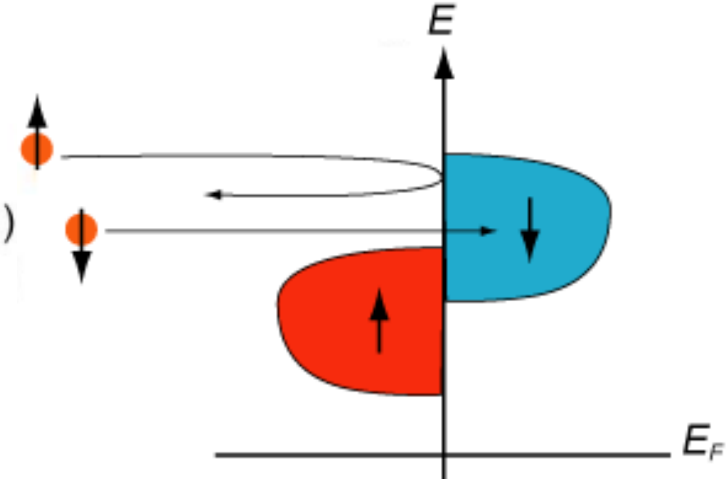




Au target

Exchange scattering

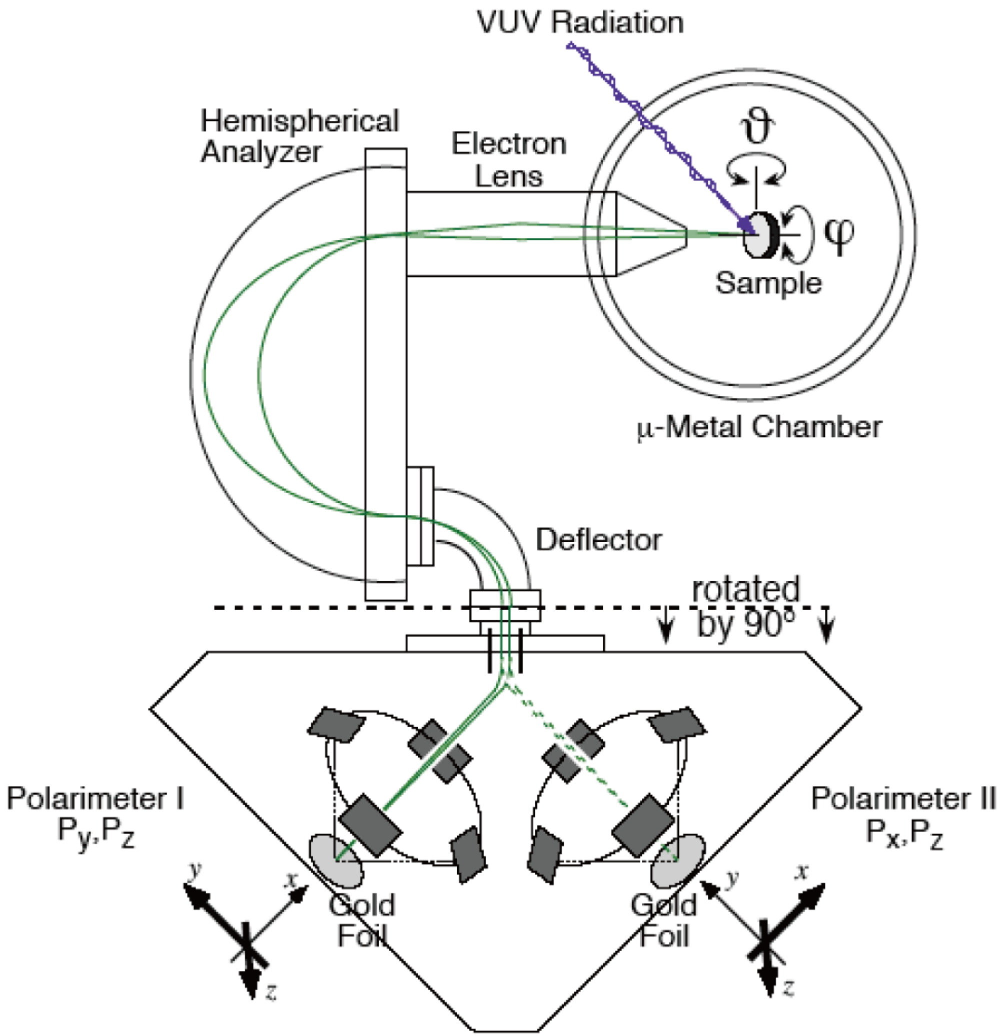


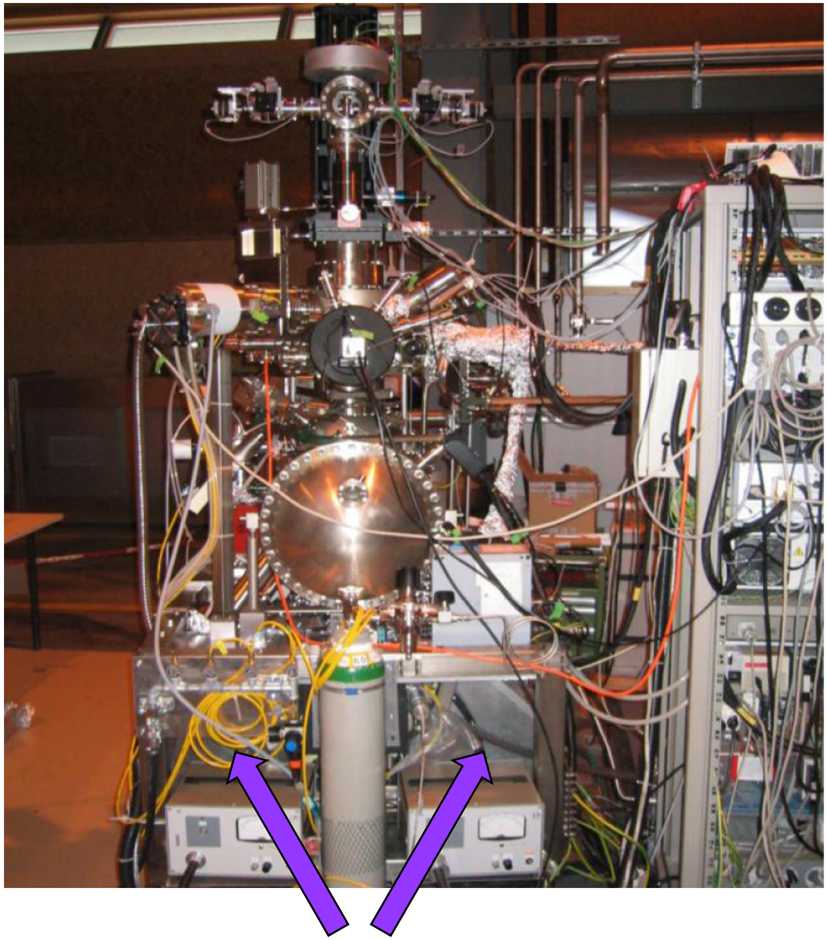


Fe(001) target

3D spin analysis at Swiss Light Source (SLS)

COPHEE (COmplete PHotoEmission Experiment) machine

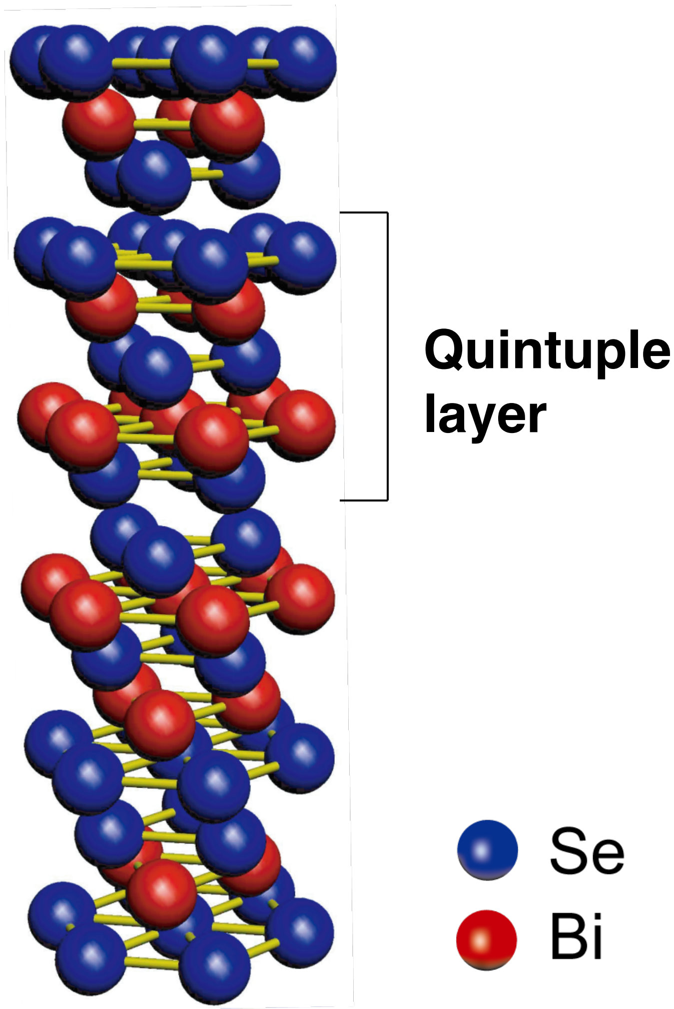


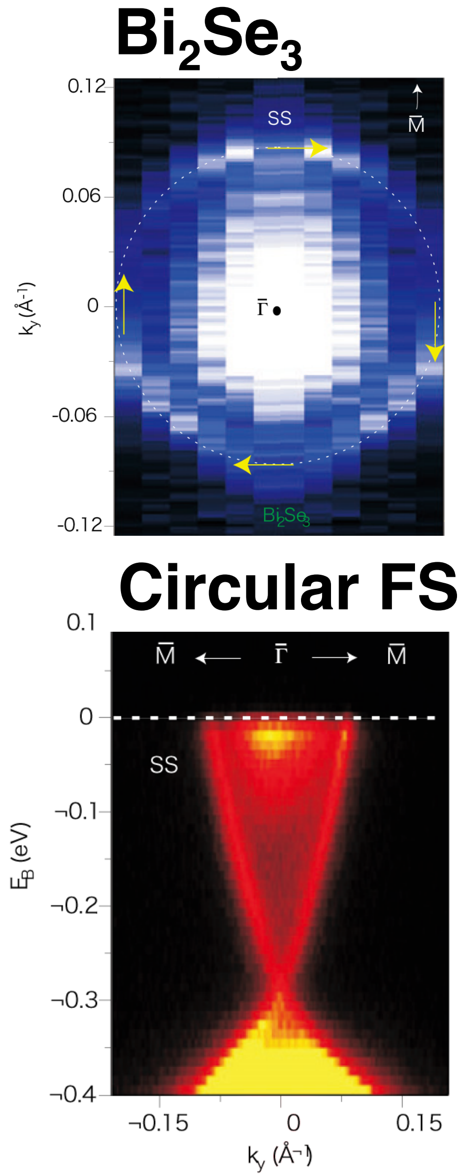


Two Mott detectors

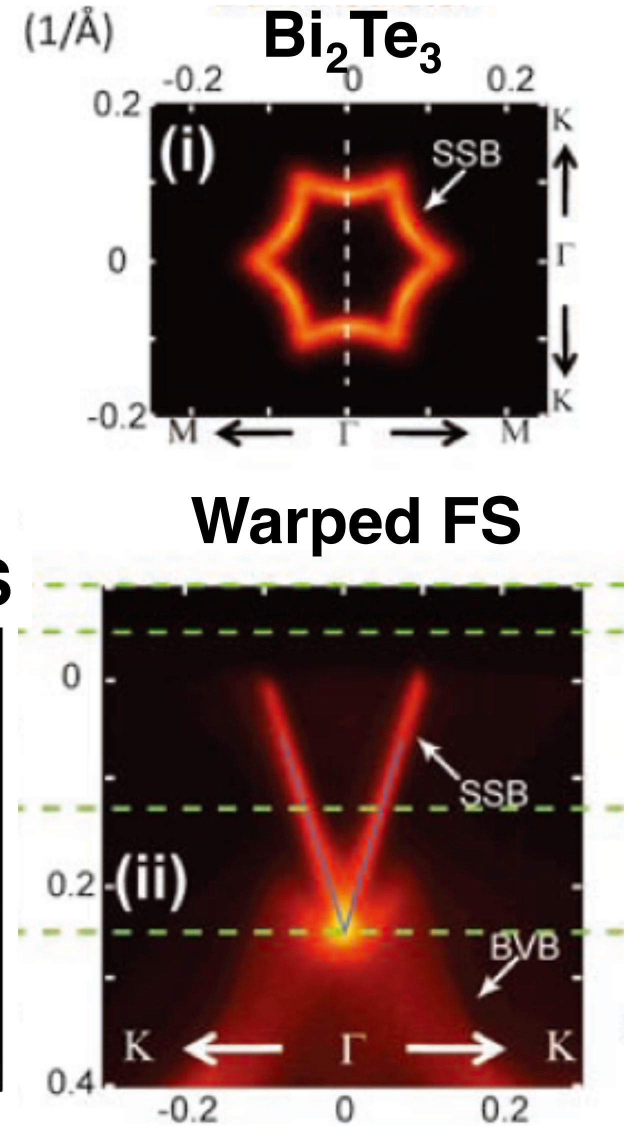
M. Hoesch et al. J. Electron Spectrosc. Relat. Phenom.**124**,263 (2002).

Surface Dirac cones of Bi_2Y_3





Y. Xia et al., Nature Phys. **5**, 398 (2009).

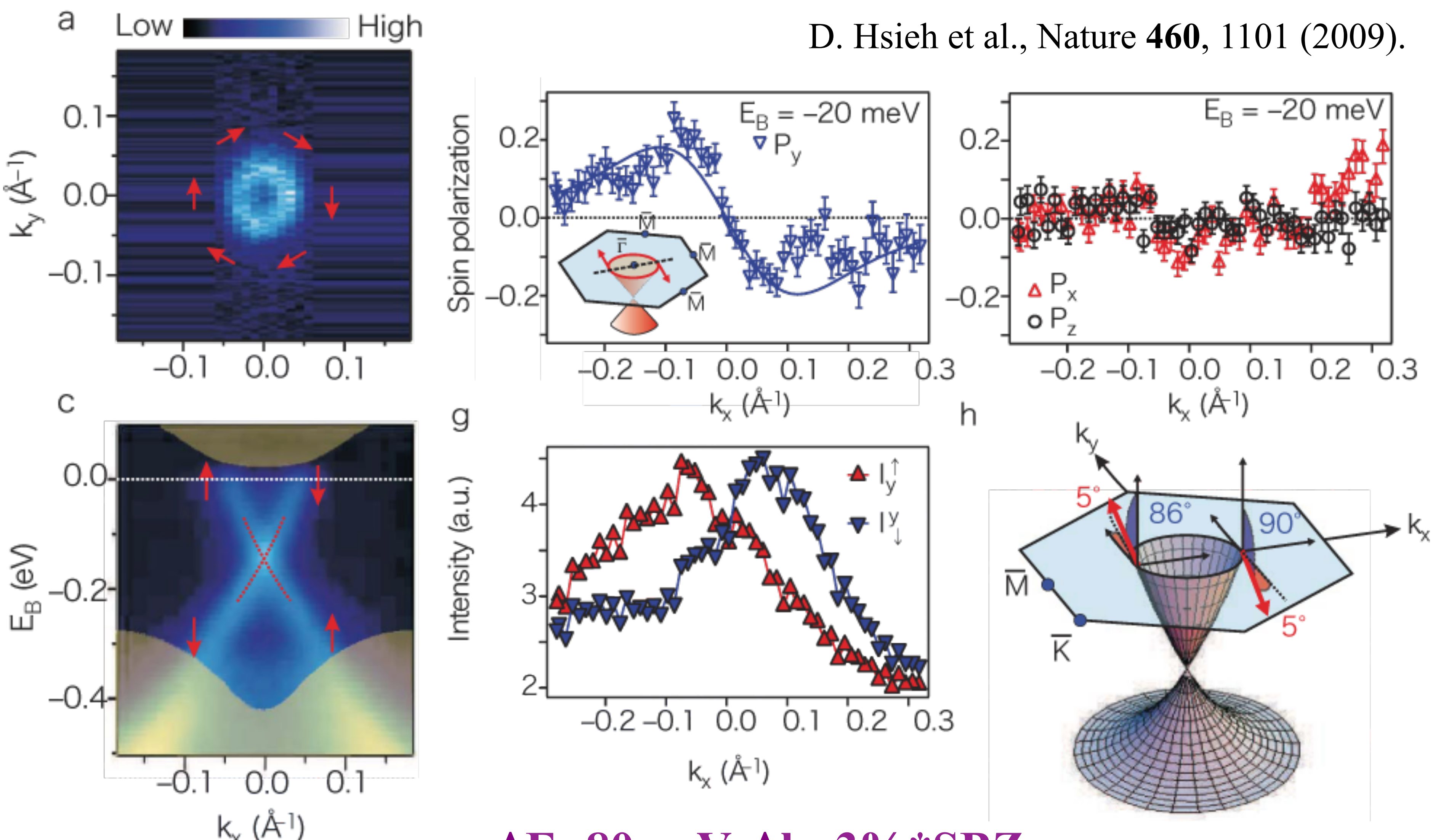


Y. L. Chen et al., Science **325**, 178 (2009).

$$\nu_0; (\nu_1 \nu_2 \nu_3)=1; (000)$$

Pioneering work of spin ARPES (Bi_2Se_3)

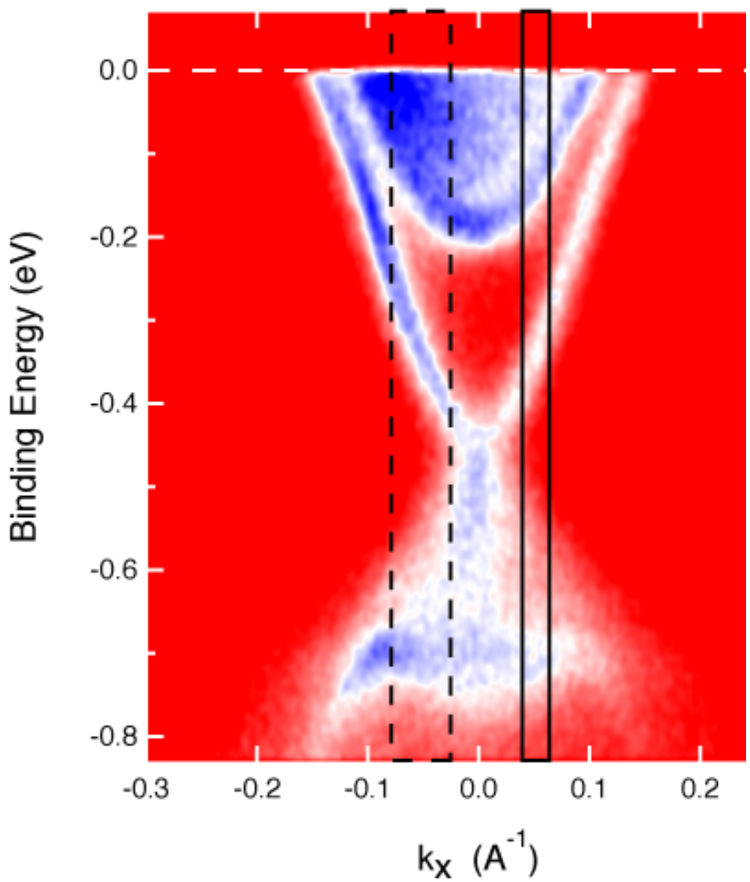
D. Hsieh et al., Nature **460**, 1101 (2009).



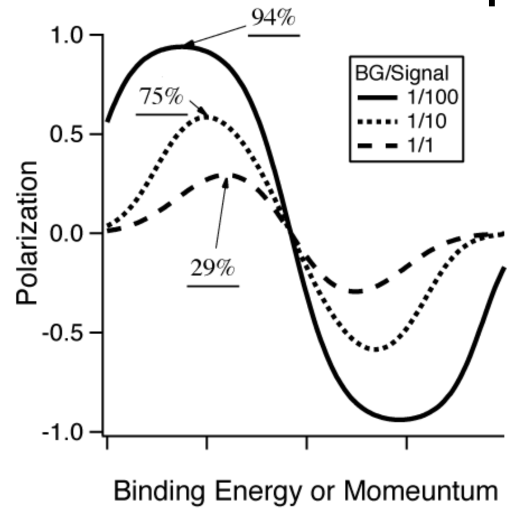
ΔE=80meV, Δk=3%*SBZ.

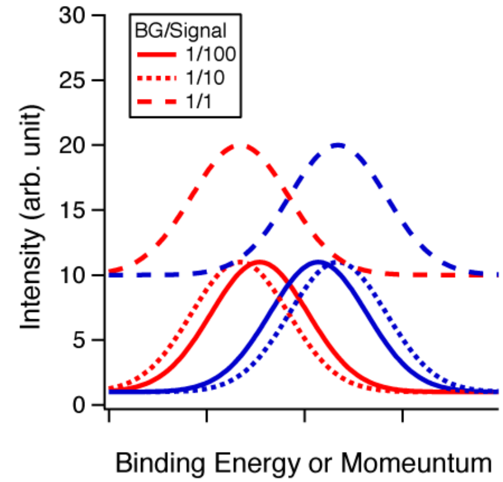
The observed spin pol. is as small as 20% (<<100%)

Simulated spin polarizations spectra

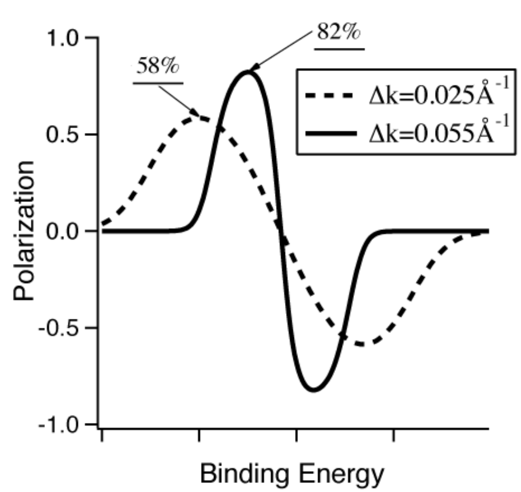


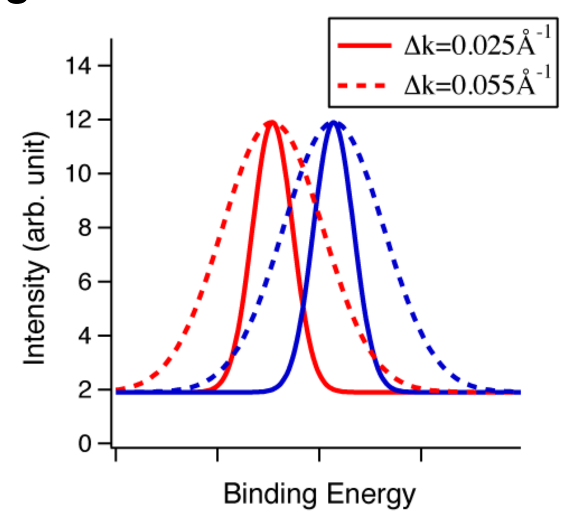
Effect of non-pol. background.





Effect of angular resolution.

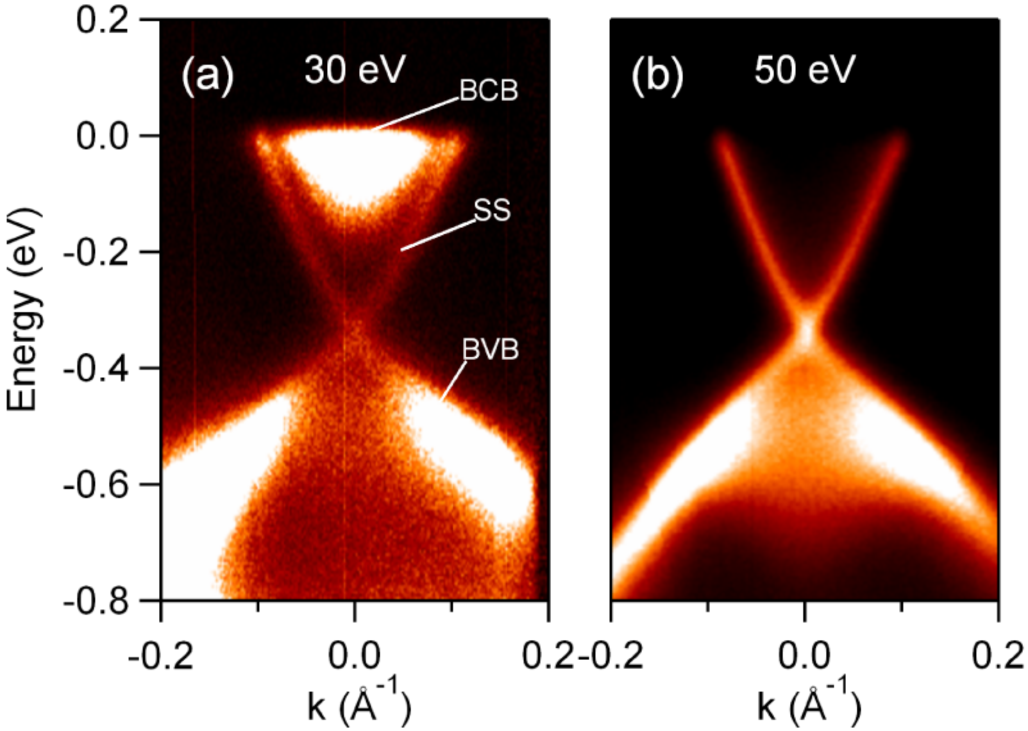


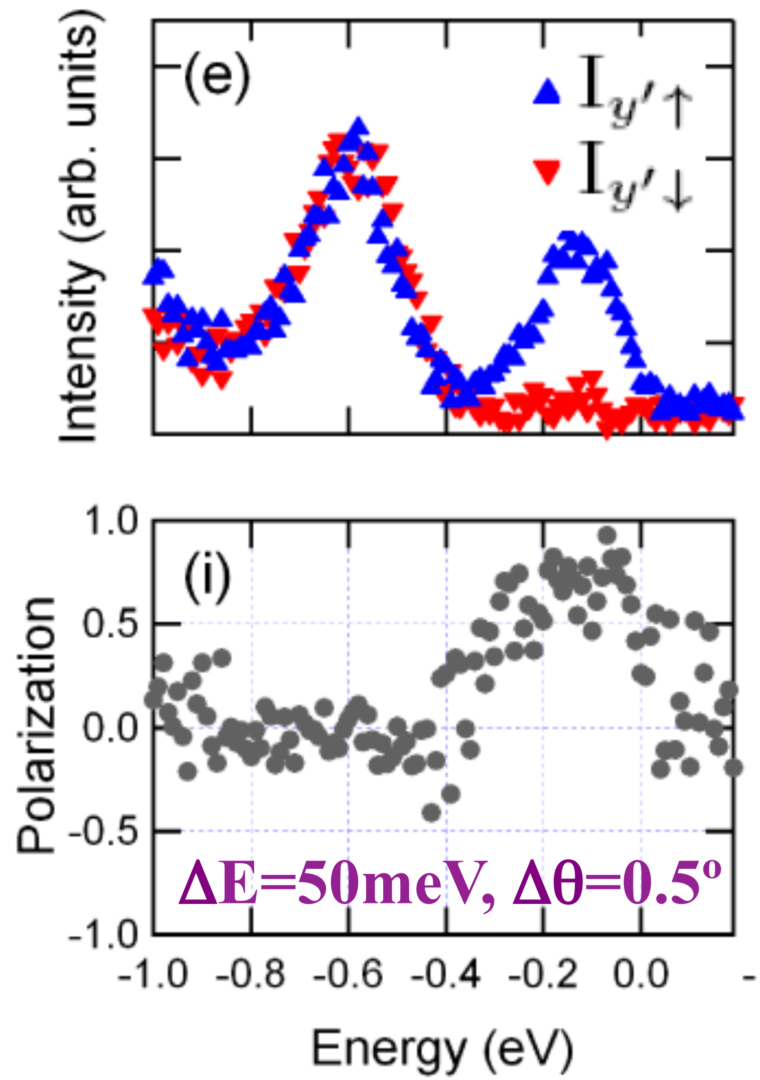


High angular (momentum) resolution is necessary.

Following spin ARPES study of Bi_2Se_3

H. Pan et al. PRL **106**, 257004 (2011).





U5UA @ NSLS

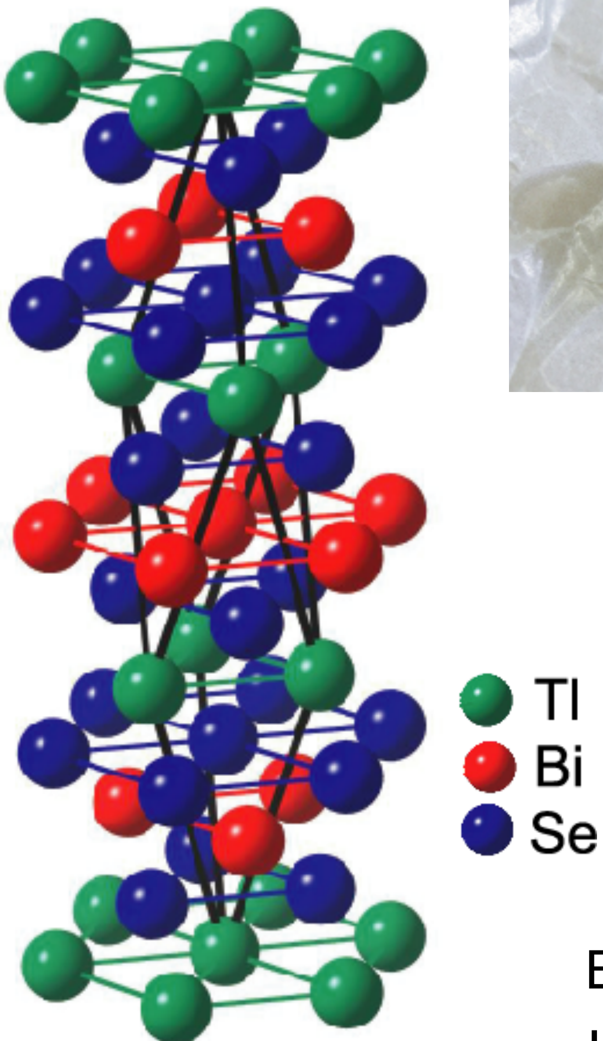
ΔE=50meV, $\Delta\theta$=0.5°

Well suppressed bulk conduction band at hν=50eV (near Z point of BZ).

A high-degree of spin pol. (~75%) above the Dirac point, while noting below.

Ternary Chalcogenides: Tl-V-VI$_2$

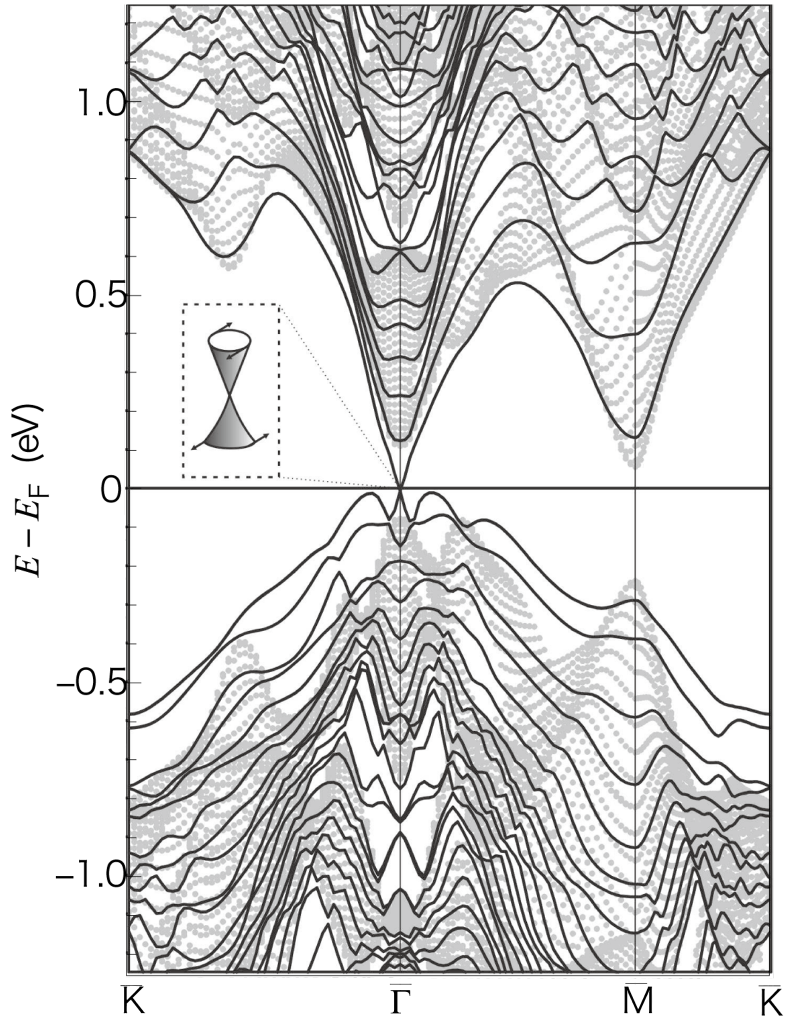
TlBiSe$_2$



High-quality single crystal

3D character

No vdW gap

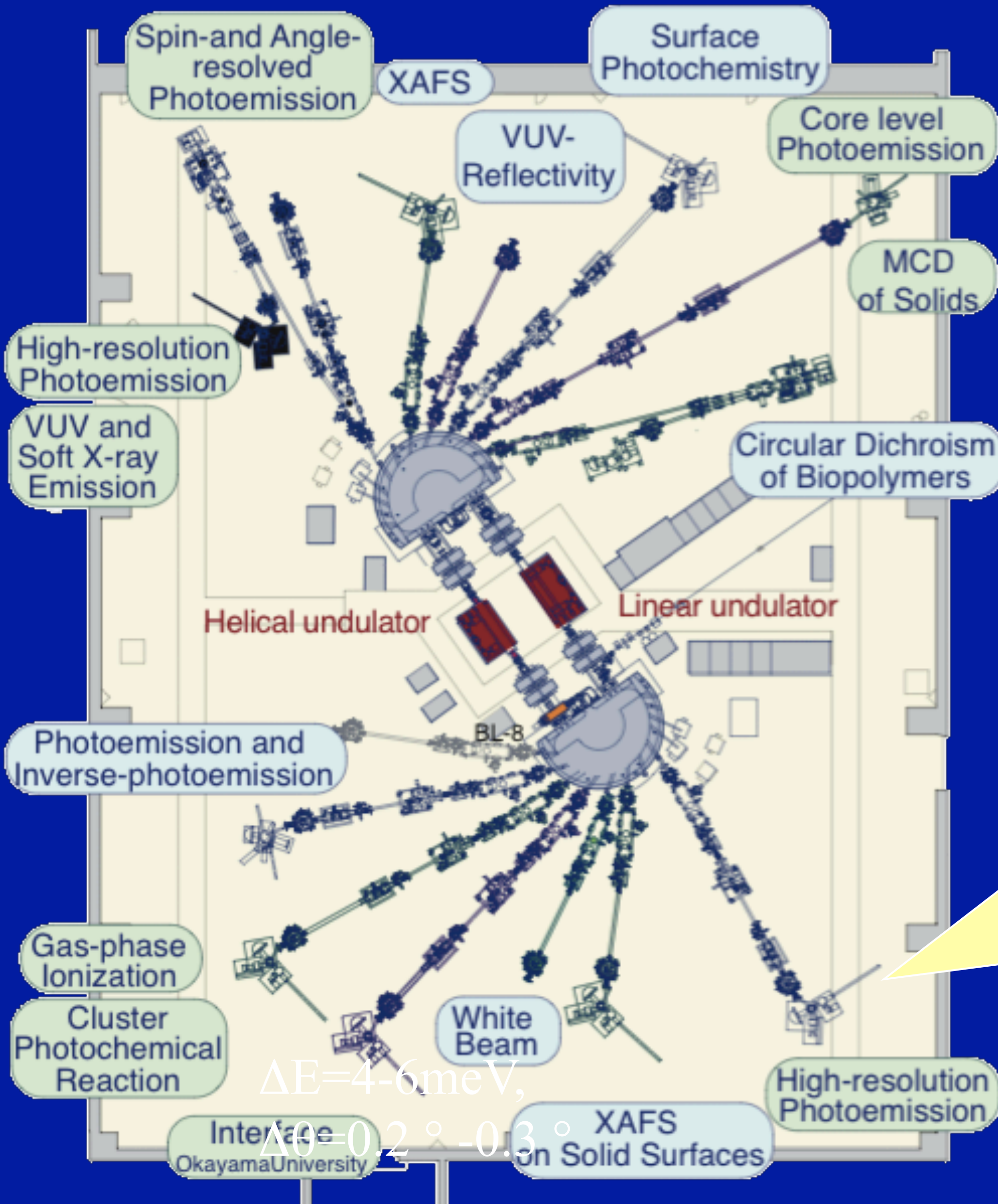


B. Yan et al., Europhys. Lett. (2010).

H. Lin et al., Phys. Rev. Lett. (2010).

S. Eremeev et al., JETP Lett. 91, 594 (2010).

HiSOR Beamlines



BL-1

ΔE=4-6meV,
$\Delta\theta$=0.2 ° -0.3 °

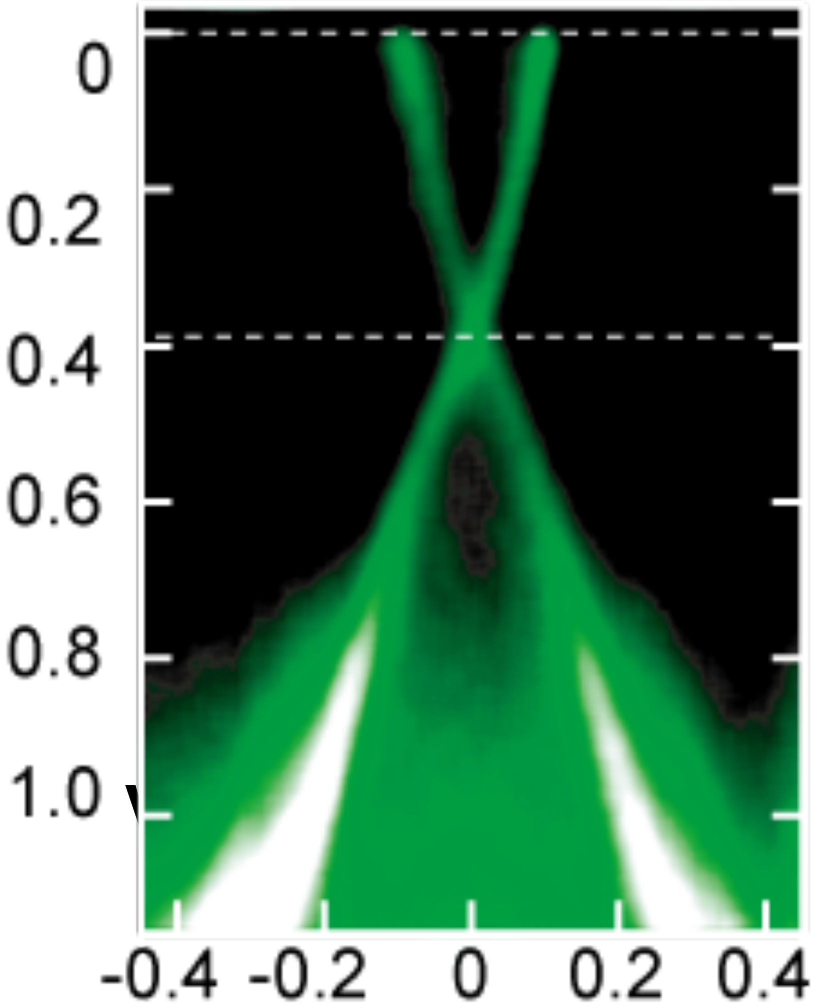
ΔE=4-6meV,
$\Delta\theta$=0.2 ° -0.3 °

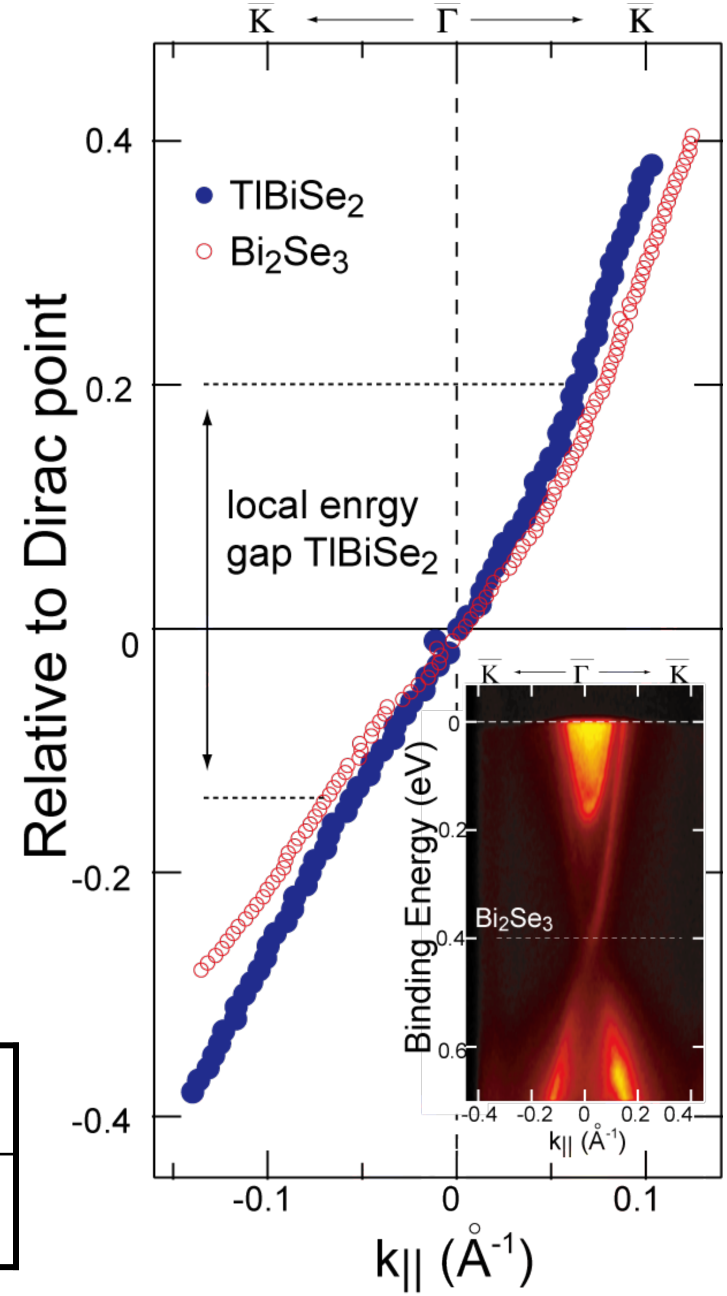
BL-1

- Linear undulator
- $h\nu$ = 26-300eV
- VG-Scienta R4000
- s- and p- polarizations

A more ideal Dirac cone of $TlBiSe_2$

BL-1



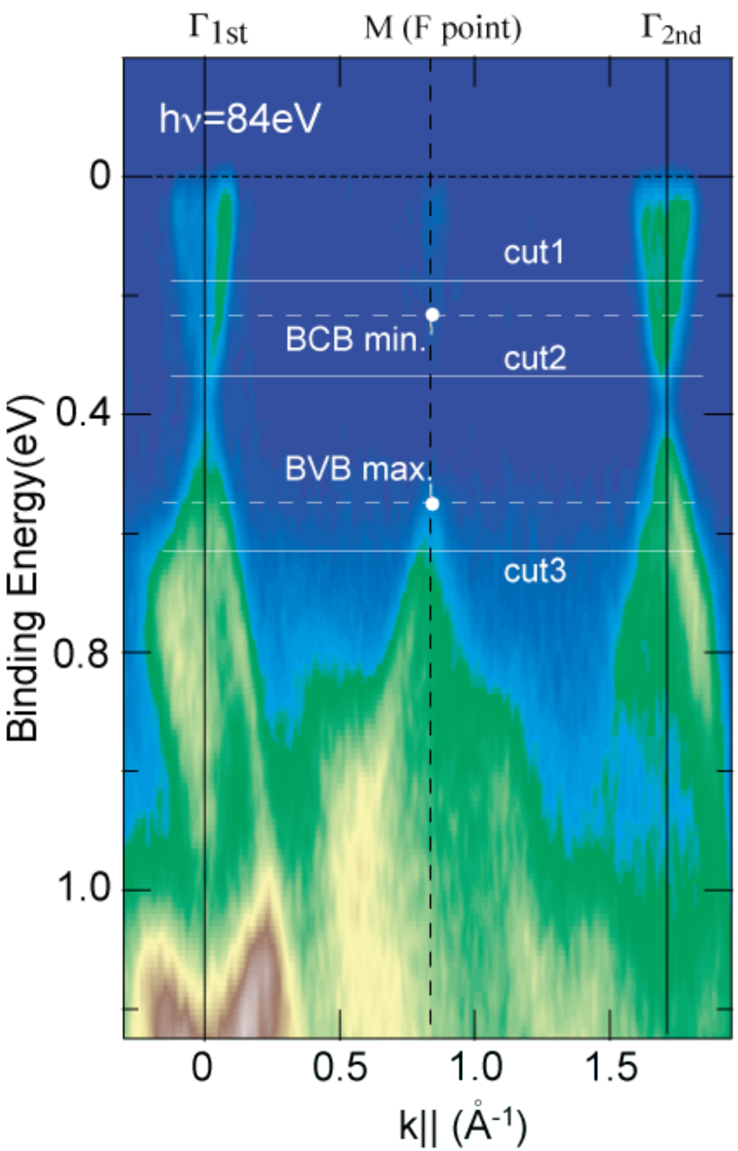


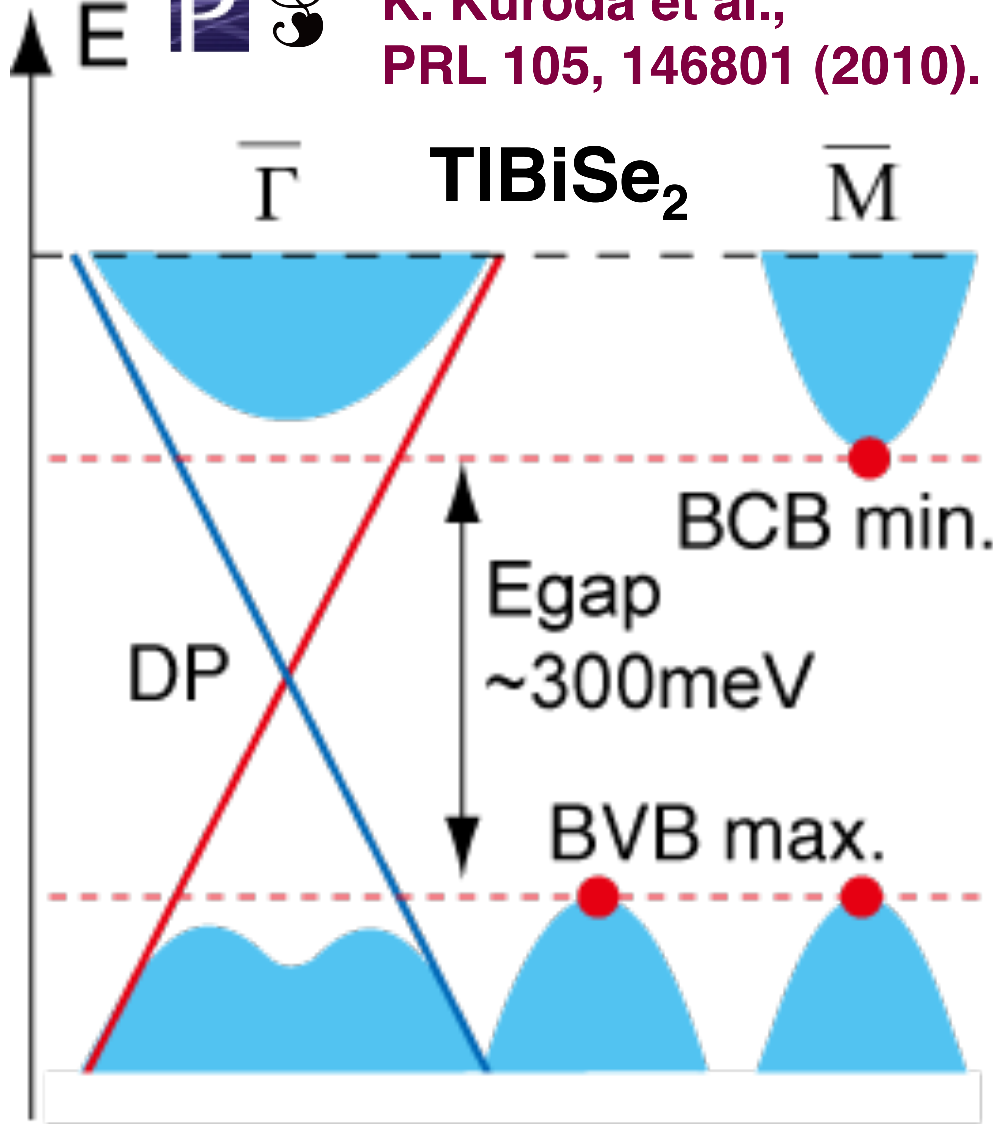
Bi_2Se_3	**$TlBiSe_2$**
2.9×10^5 m/s	**3.9×10^5 m/s**

Photon energy dependence

BL-1

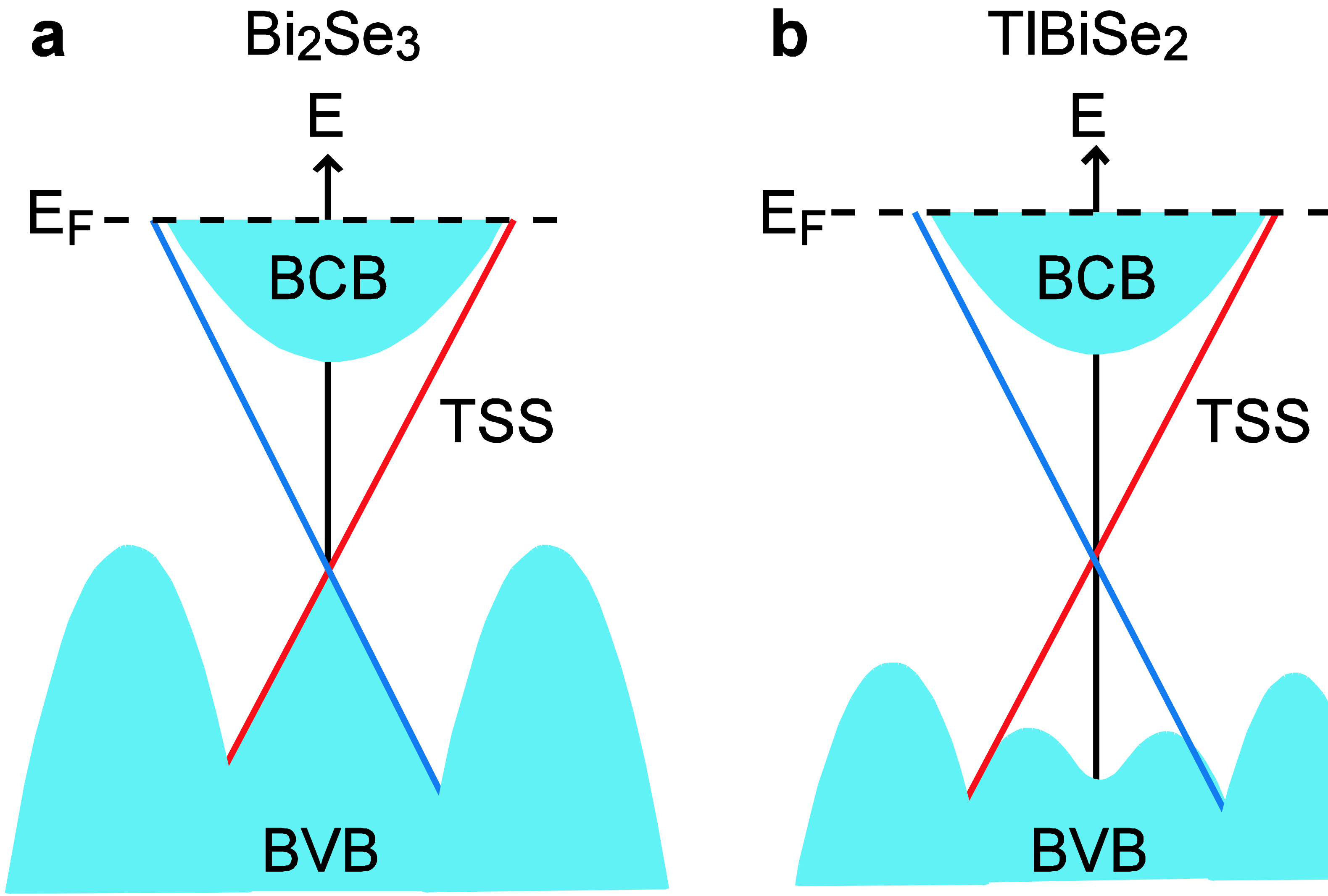
K. Kuroda et al., PRL 105, 146801 (2010).





Both lower and upper cones are within the bulk gap.

Bi_2Se_3 v. s. $TlBiSe_2$

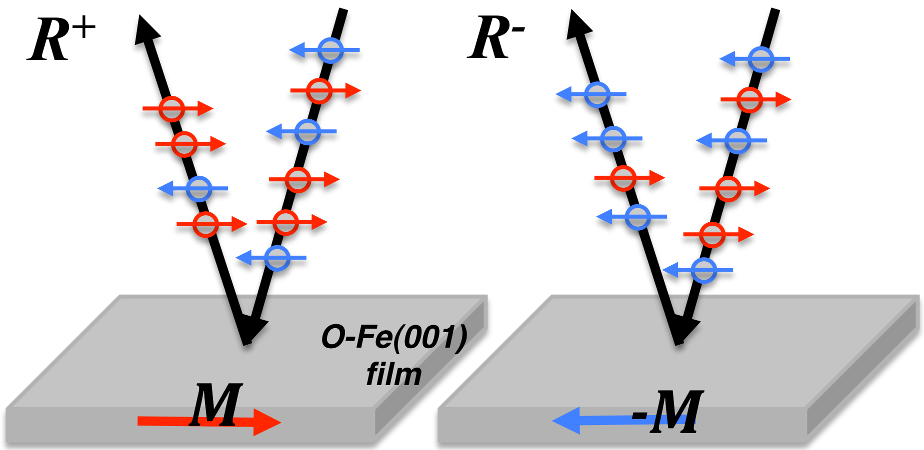


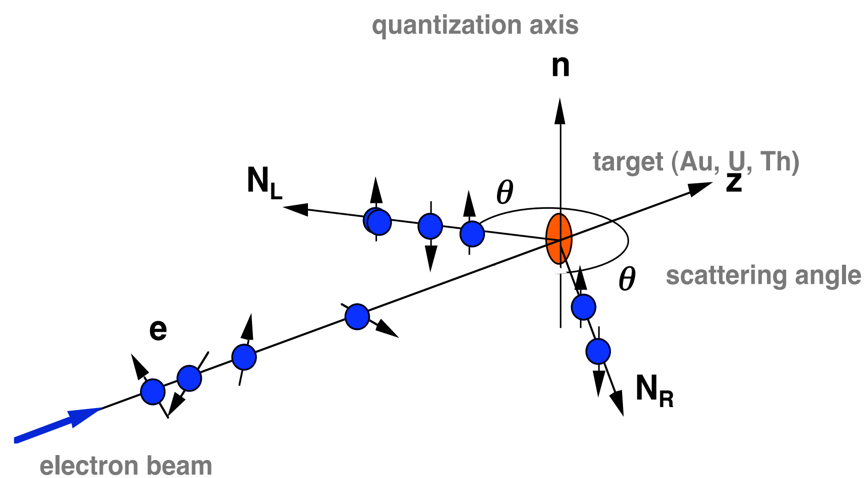
Both lower and upper cones are in the bulk gap for $TlBiSe_2$.

Spin detector

Very low energy electron diffraction（VLEED）type

VLEED (Hiroshima) v.s. Mott (COPHEE@Swiss)



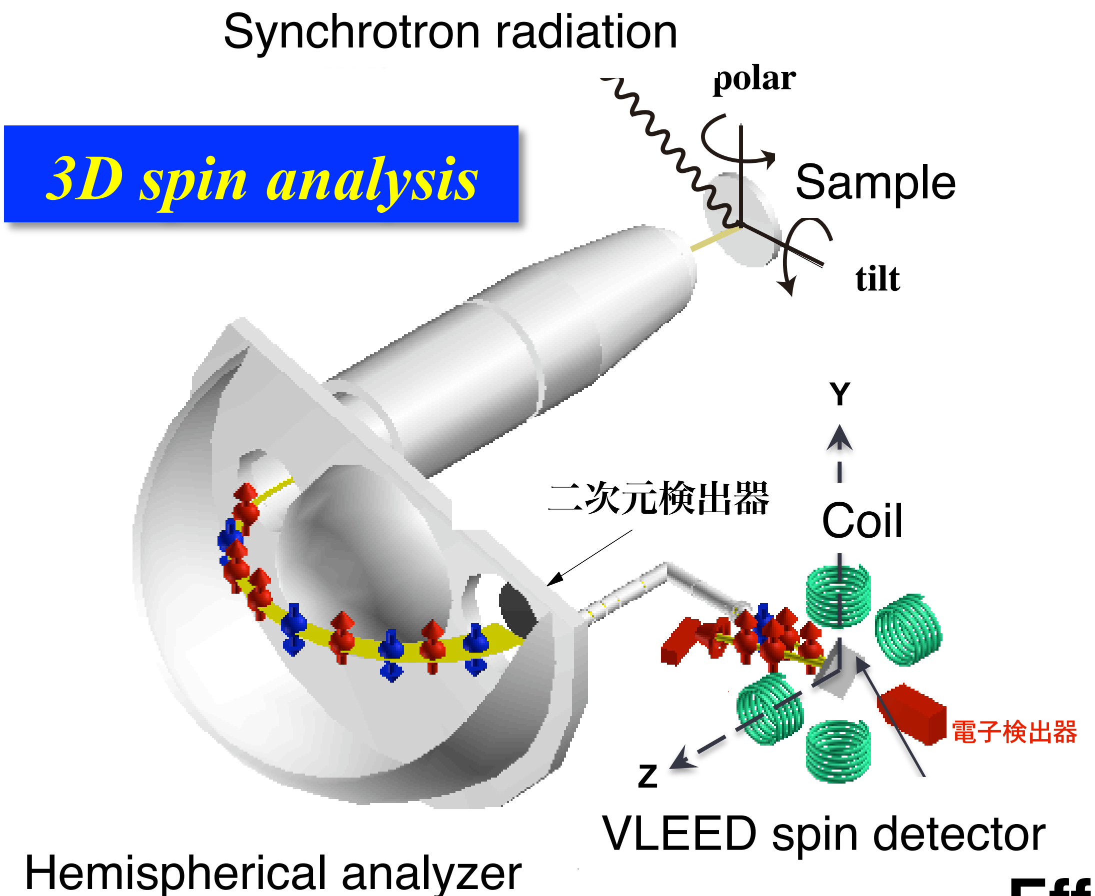


	Basic Interaction	Operating Voltage	S_{eff}	Reflectivity I/I_0	Efficiency (FOM) ε
Mott	Spin-Orbit	25-50 kV	0.14	9.7×10^{-3}	1.9×10^{-4}
VLEED	Exchange	10 V	0.44	0.1	2×10^{-2}

- ☐ **100 higher efficiency than Mott** → Improved Δk
- ☐ **Minimized instrumental asymmetry** → Suitable for TI study

ESPRESSO - Efficient SPin-REsolved SpectroScOpy

3D spin analysis



Efficiency $\varepsilon = \dfrac{I}{I_0} \cdot S_{eff}^2 \approx 10^{-2}$

100 times higher than Mott

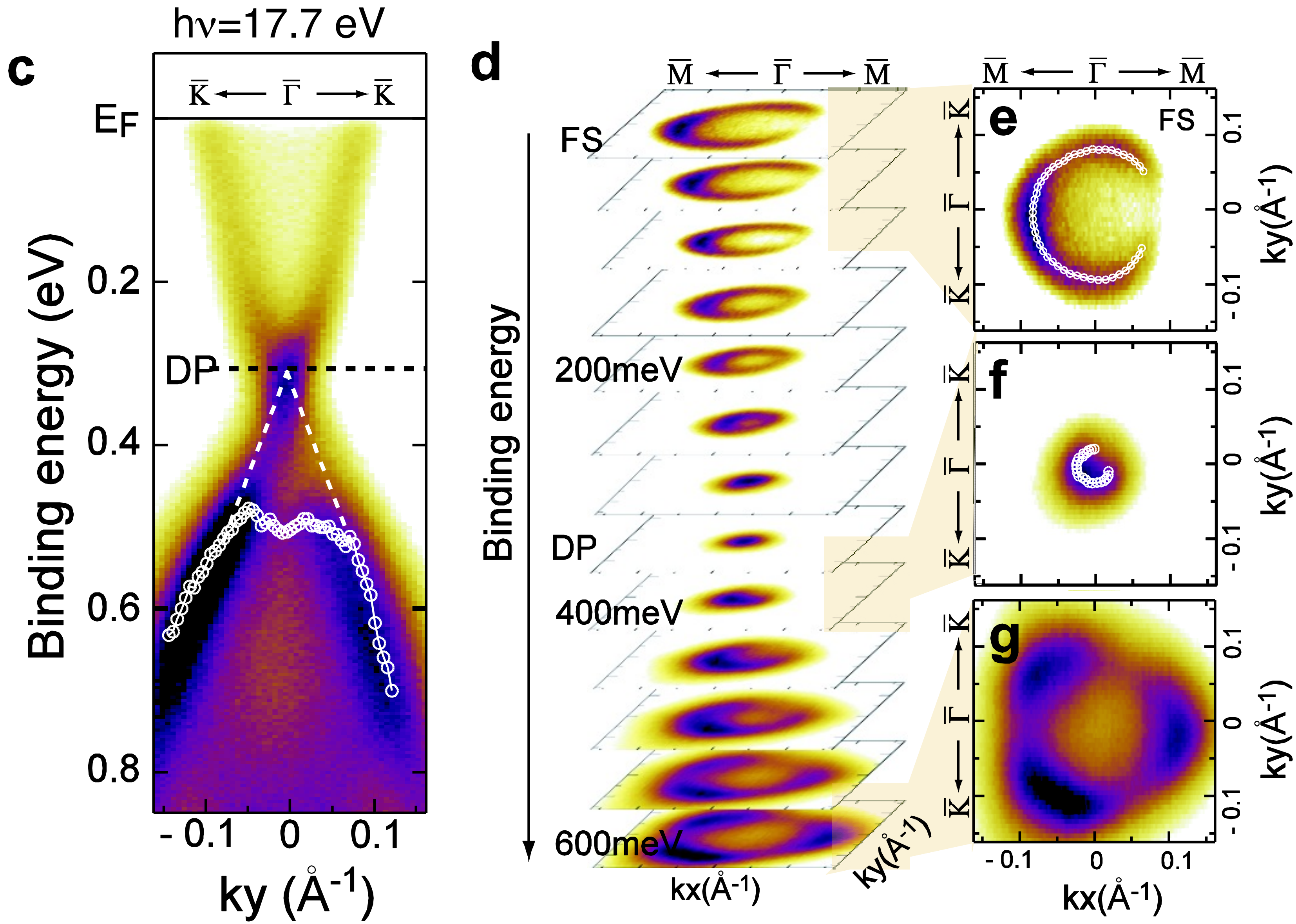
$\Delta E \sim 7.5$ **meV** $\Delta\theta \sim \pm 0.18^{\mathrm{o}}$

広島大学

広島大学放射光科学研究センター
Hiroshima Synchrotron Radiation Center Hiroshima University

Constant energy contour of $TlBiSe_2$

BL-9B



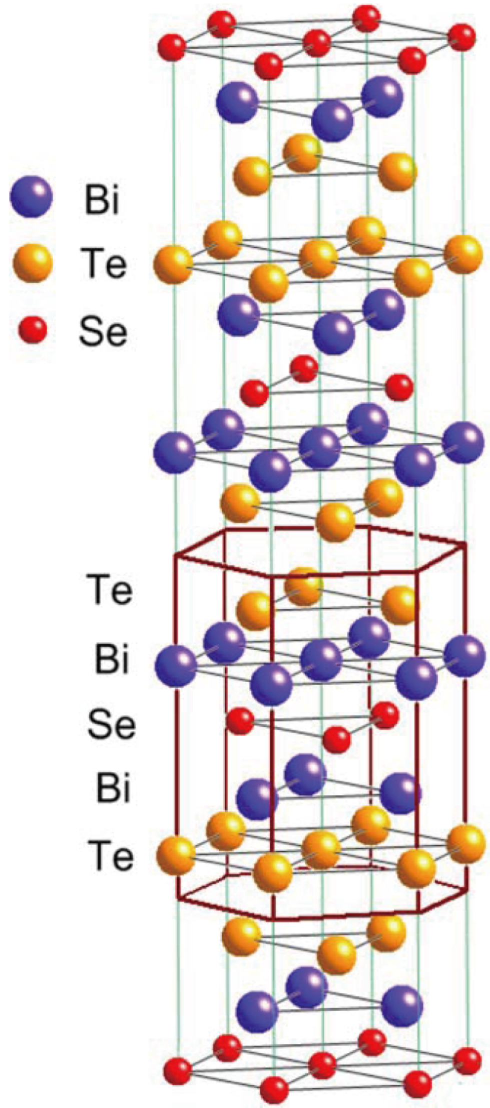
Isotropic constant energy surfaces for $TlBiSe_2$

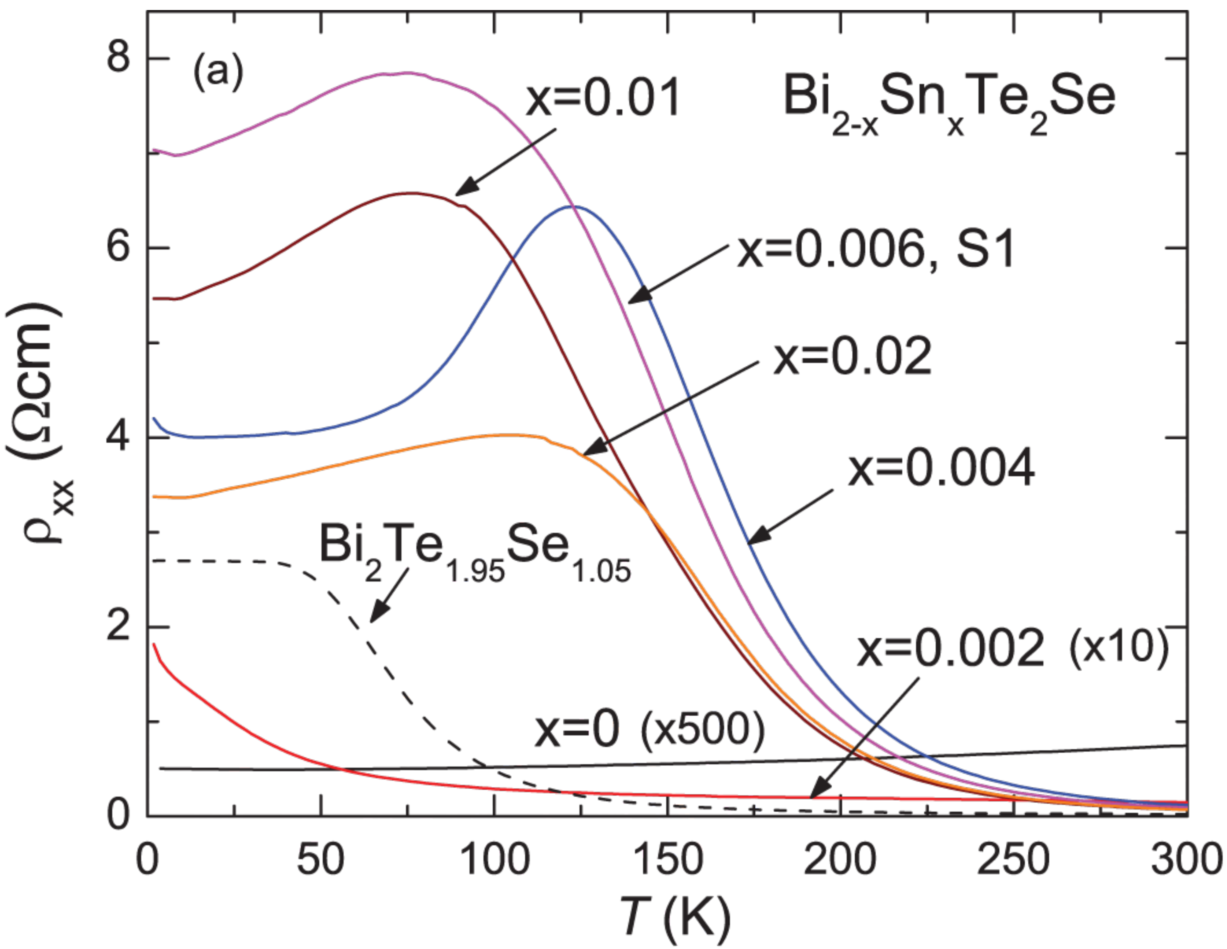
New TI with high bulk resistivity: Bi_2Te_2Se

Z. Ren, Y. Ando et al., PRB **82**, 241306(R) (2010).

J. Xiong, N. P. Ong et al., Physica E **44**, 917 (2012).

Z. Ren, Y. Ando et al., PRB **85**, 155301 (2012).



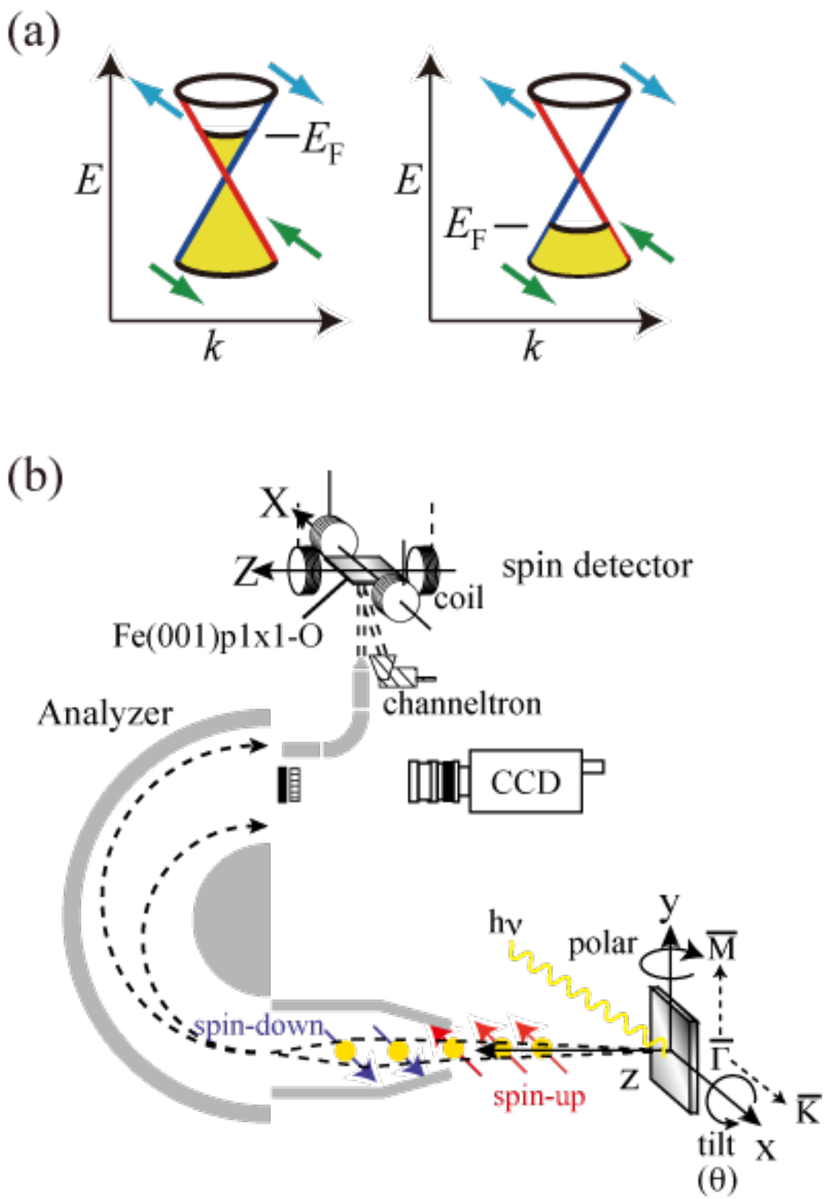


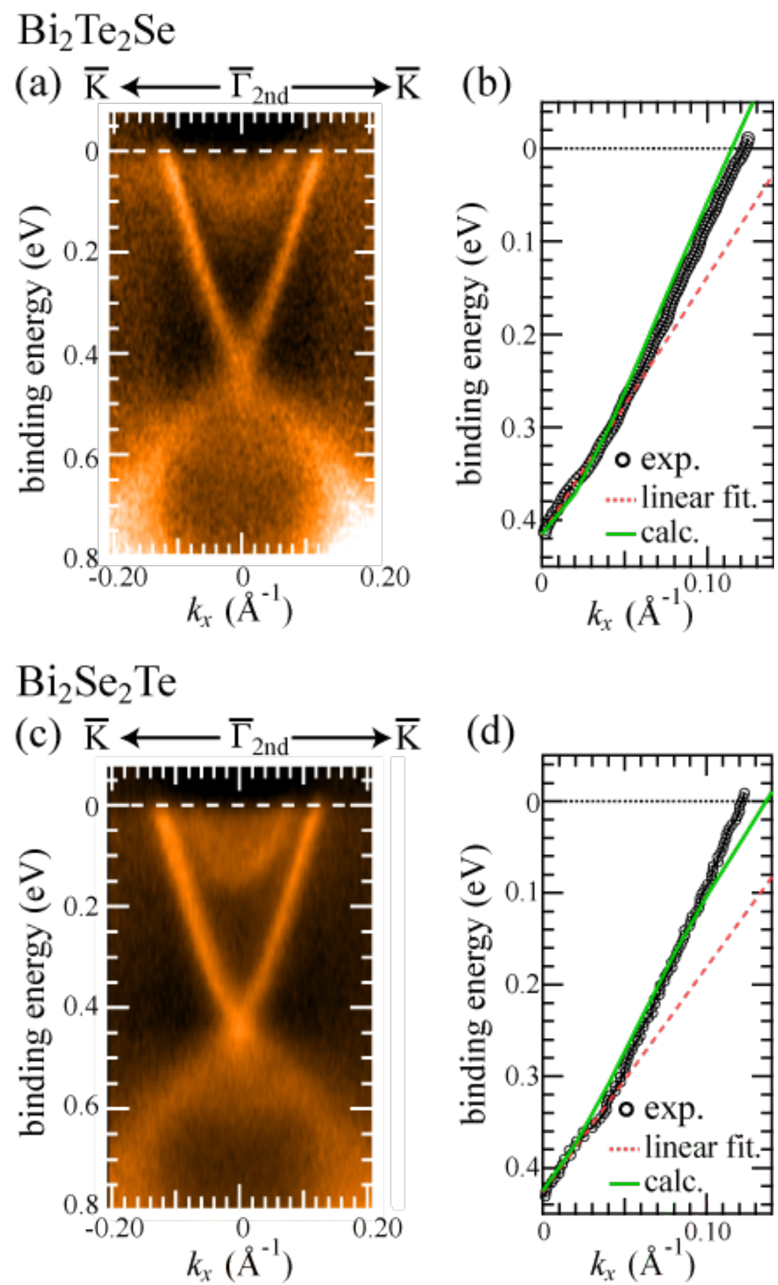
Suppressed Se vacancies

Suppressed Bi-Te anti-site defects

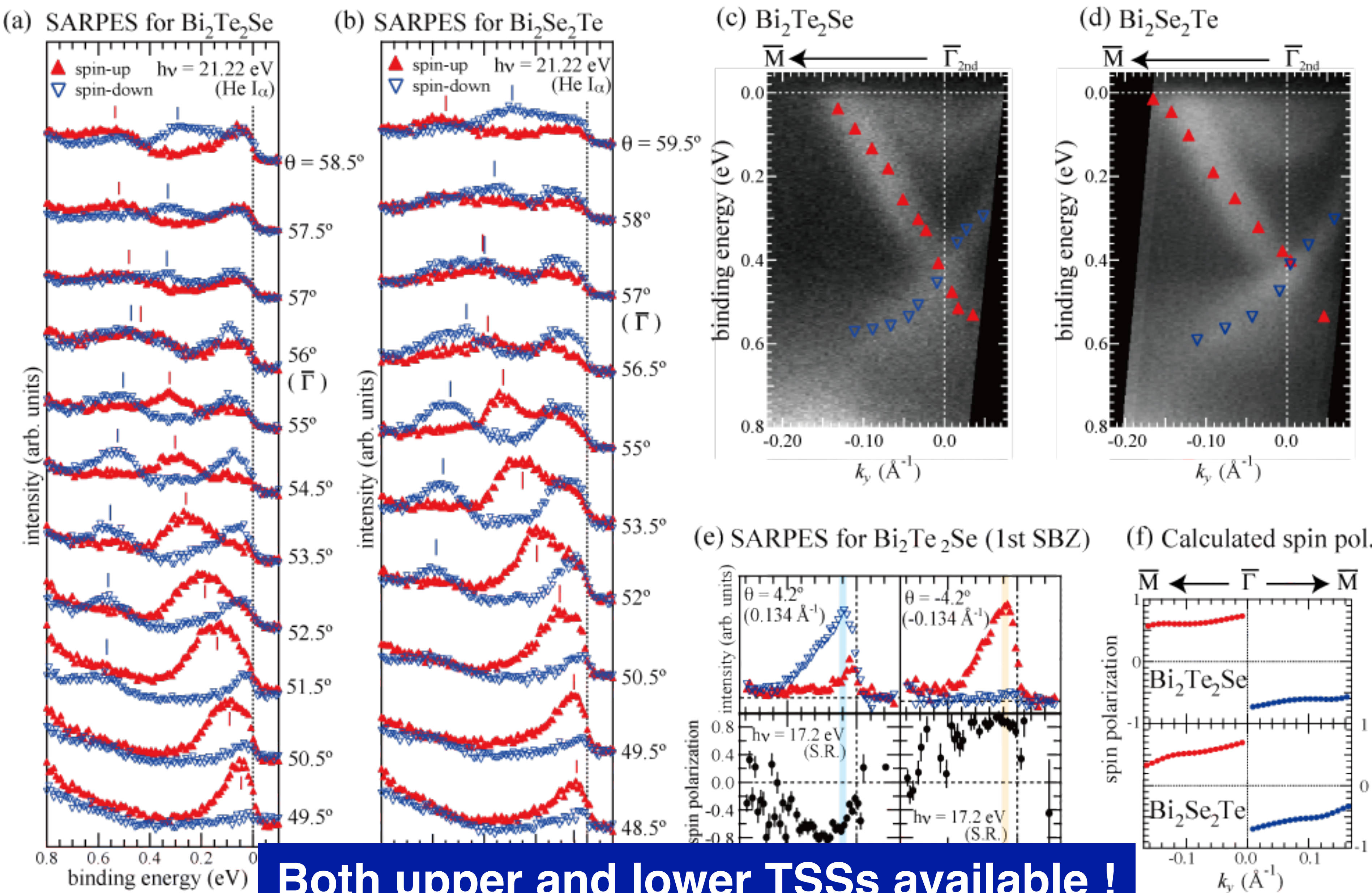
Spin resolved ARPES of Bi_2Te_2Se & Bi_2Se_2Te

Koji Miyamoto (Hiroshima)





Spin resolved ARPES of Bi_2Te_2Se & Bi_2Se_2Te

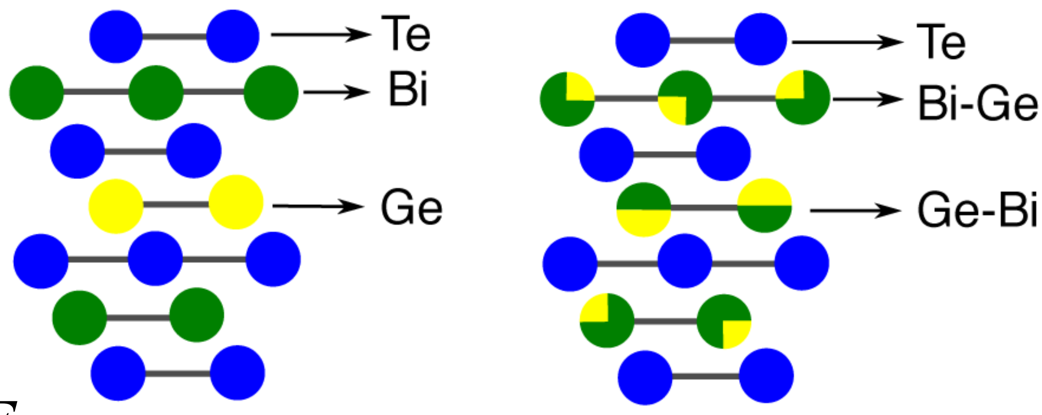


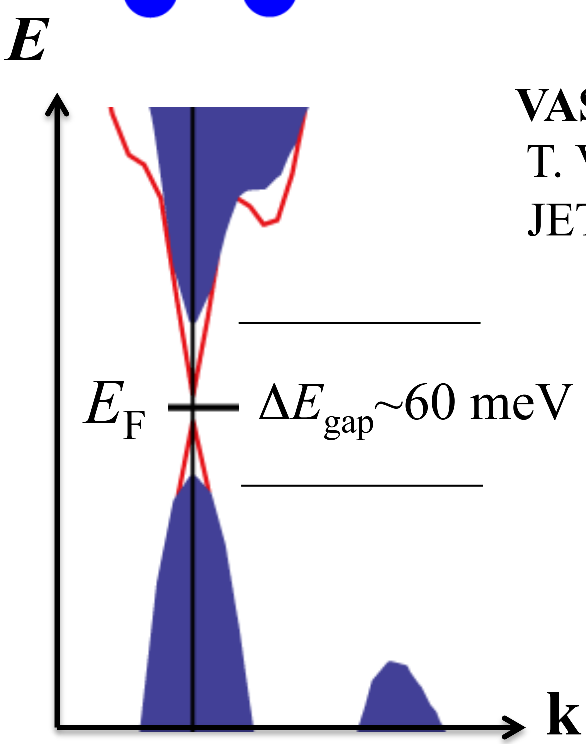
Both upper and lower TSSs available !

Atomic disorder effect in $GeBi_2Te_4$

Atomic disorder in real crystal.

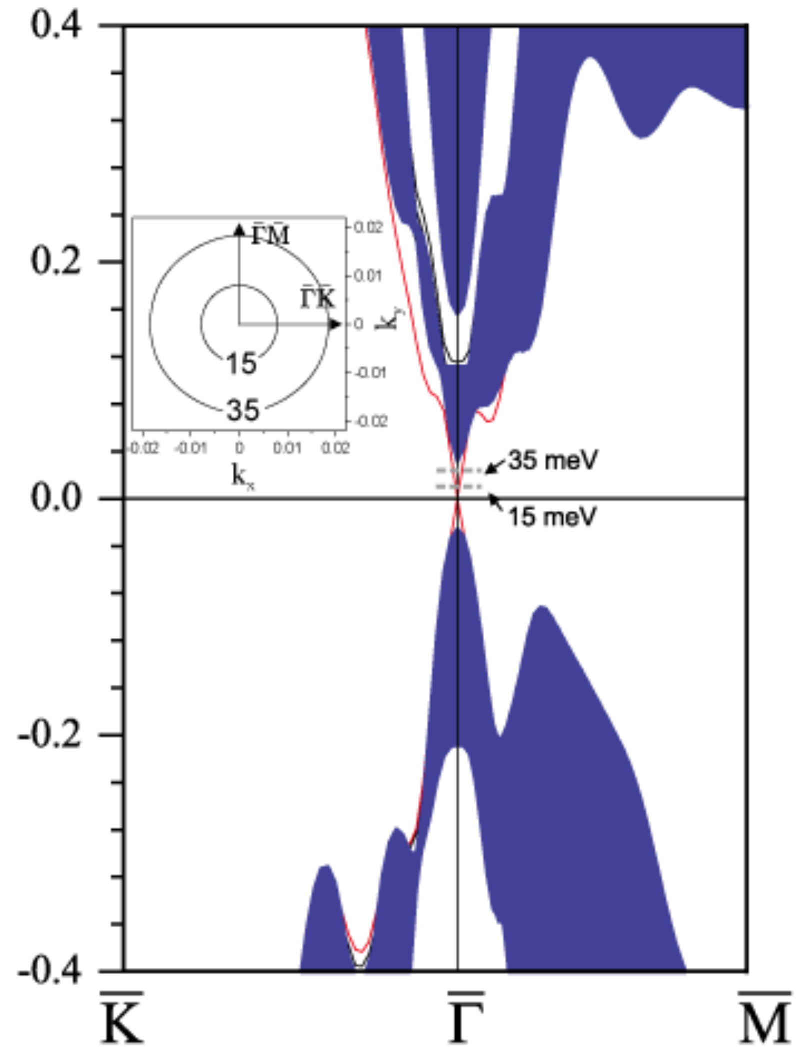
O. G. Karpinsky *et al*., J. Alloys Compd. (1998).





VASP&FLEUR:
T. V. Menshchikova *et al*.,
JETP Lett. (2011).

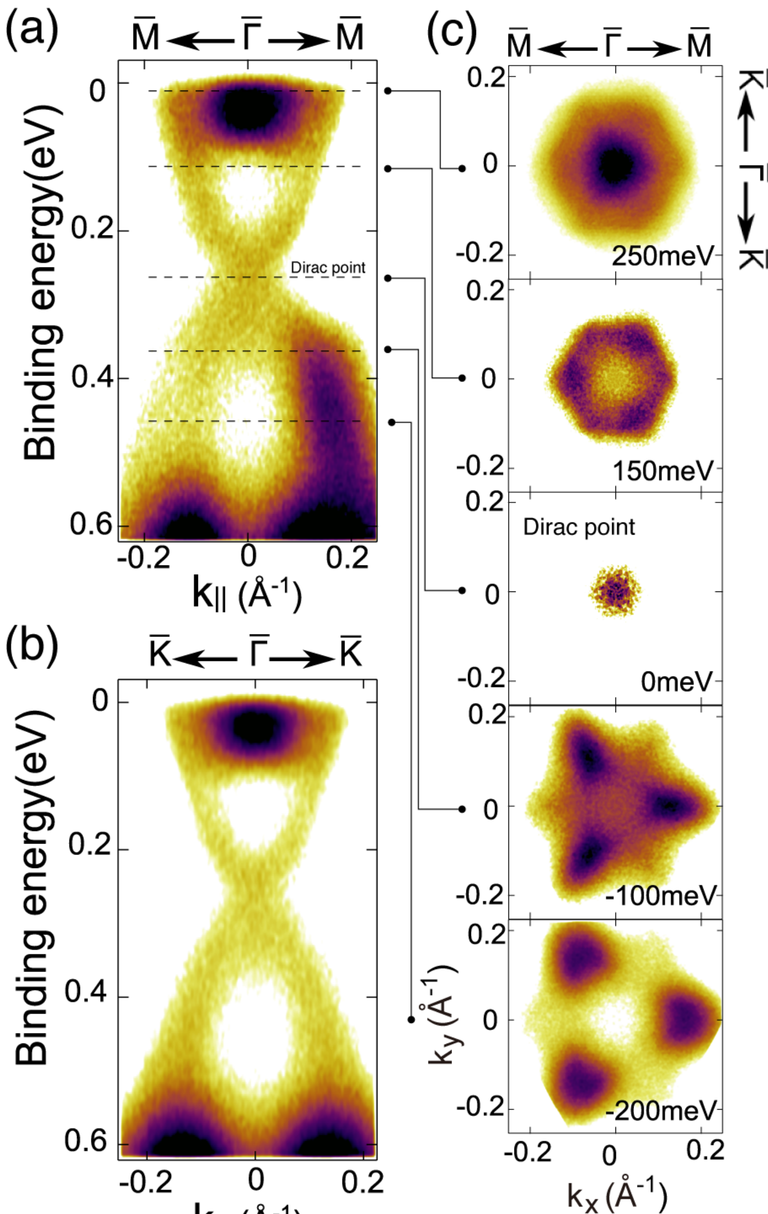
Well isolated TSS
but with small ΔE
is predicted for ideal
crystal structure.

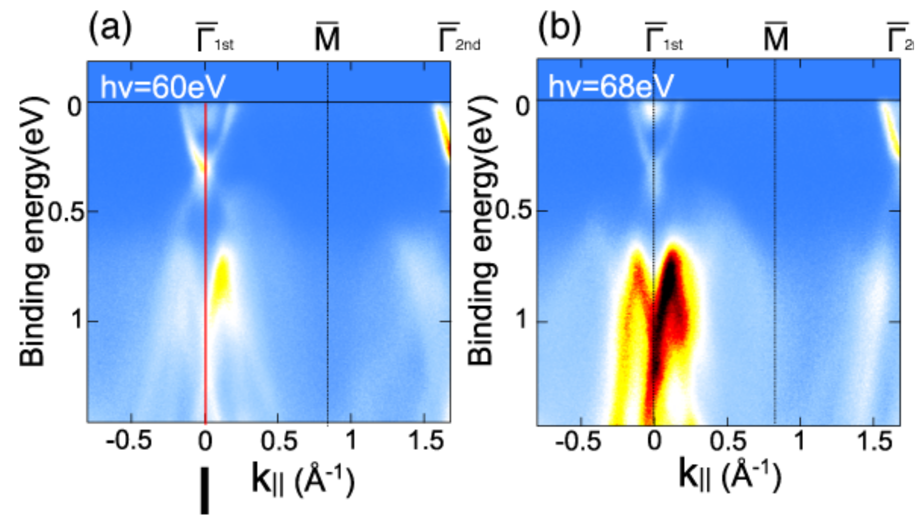


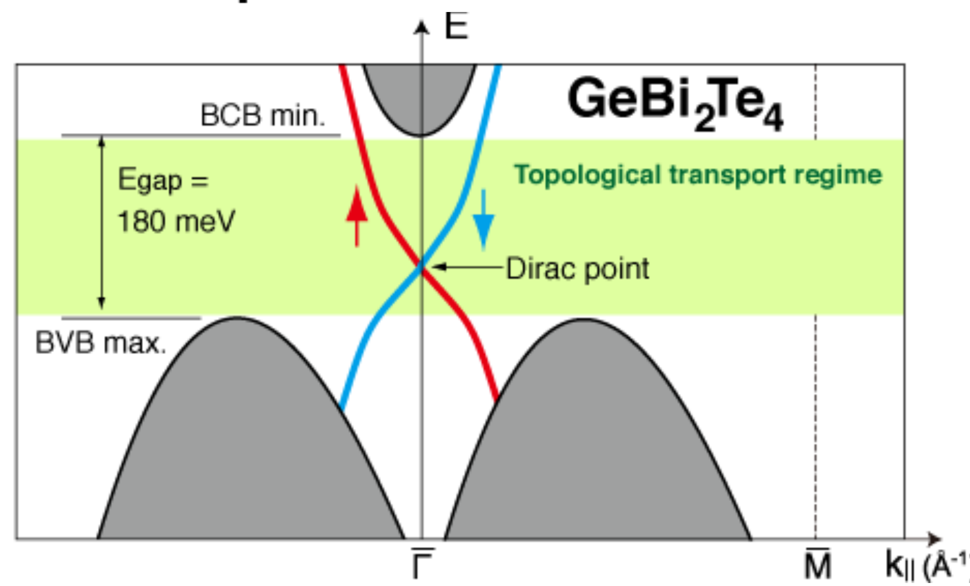
Disorder effect on ΔE, spin pol. of TSS?

New topological insulator $GeBi_2Te_4$

BL-1, 9B



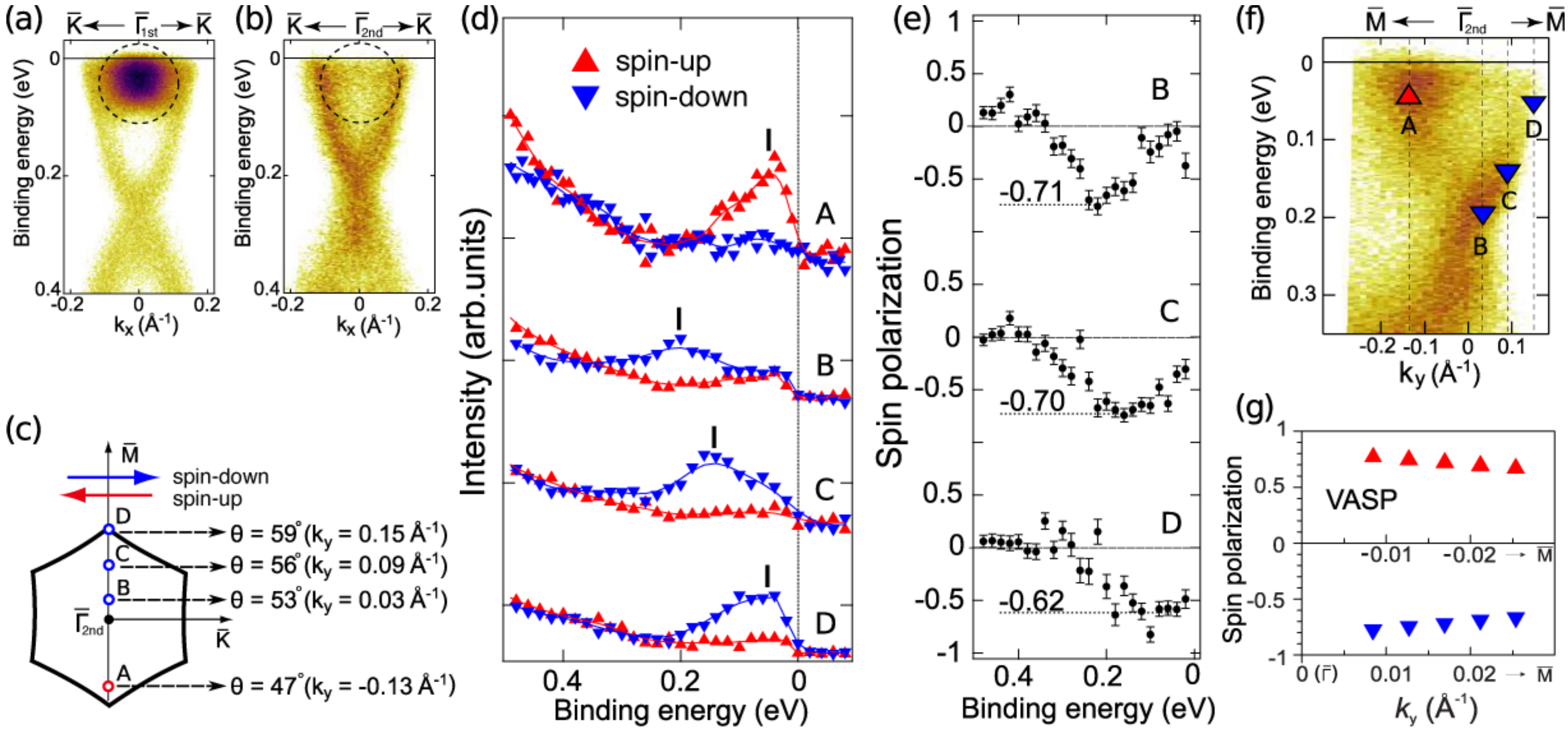




K. Okamoto and AK et al.,
Phys. Rev. B 86, 195304 (2012).

Spin resolved ARPES for $GeBi_2Te_4$

BL-9B



Please see, K. Okamoto and AK et al., Phys. Rev. B 86, 195304 (2012).

Highly spin polarized topological SS near the Dirac point even in the presence of atomic disorder

Summary

ESPRESSO

New spin resolved spectrometer based on VLEED

- Suitable for topological ins. study.
- 100 times higher efficiency than Mott.
- Best energy and angular resolutions:

$\Delta E = 7.5$ meV
$\Delta\theta = \pm 0.19°$

$TlBiSe_2$: K. Kuroda et al., submitted.

Bi_2Te_2Se : K. Miyamoto et al., Phys. Rev. Lett. 109, 166802 (2012).

$GeBi_2Te_4$: K. Okamoto et al., Phys. Rev. B 86, 195304 (2012).

Remarks on the first principles cal.

✔ Correct description of energy gap and its k-space location.

✔ Realistic situation like disorder effect is required.

✔ Prediction of a new TI with a sufficient energy gap ~1 eV.

Promises to promote a practical use of TI in spintronics !

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Taichi Okuda and Akio Kimura

"Spin- and Angle-Resolved Photoemission of Strongly Spin-Orbit Coupled Systems"

J. Phys. Soc. Jpn. 82, 021002 (2013).

Special Topics: Frontier of Condensed Matter Physics using Synchrotron Radiation

Thank you very much for your attention !