High-efficiency spin-resolved ARPES of a topological insulator with the spin-TOF analyzer

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Advanced Light Source

Materials Science Division

LBNL

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BERKELEY LAB Lawrence Berkeley National Laboratory

ALS

2011 ADVANCED LIGHT SOURCE USER MEETING

OCTOBER 3-5, 2011 | Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY Office of Science

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Experiment

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Sebastien Lounis (UCB)
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Z.-X. Shen (Stanford)
Jonathan Sobota (Stanford)
James Lee (Stanford)

Sample synthesis

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Costel Rotundu (UC/LBNL)

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Theory

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Beamline / Experiment Support

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Yi-De Chuang (ALS BL4.0.3)

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Tech. / Fab. Support

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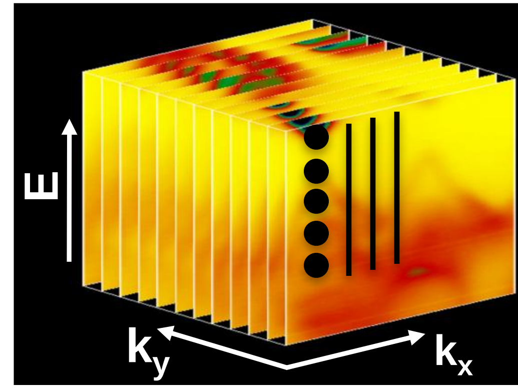
Scott DiMaggio (ALS)
Adrian Williams (ALS)
Kyle McCombs (ALS)
Monroe Thomas (ALS)

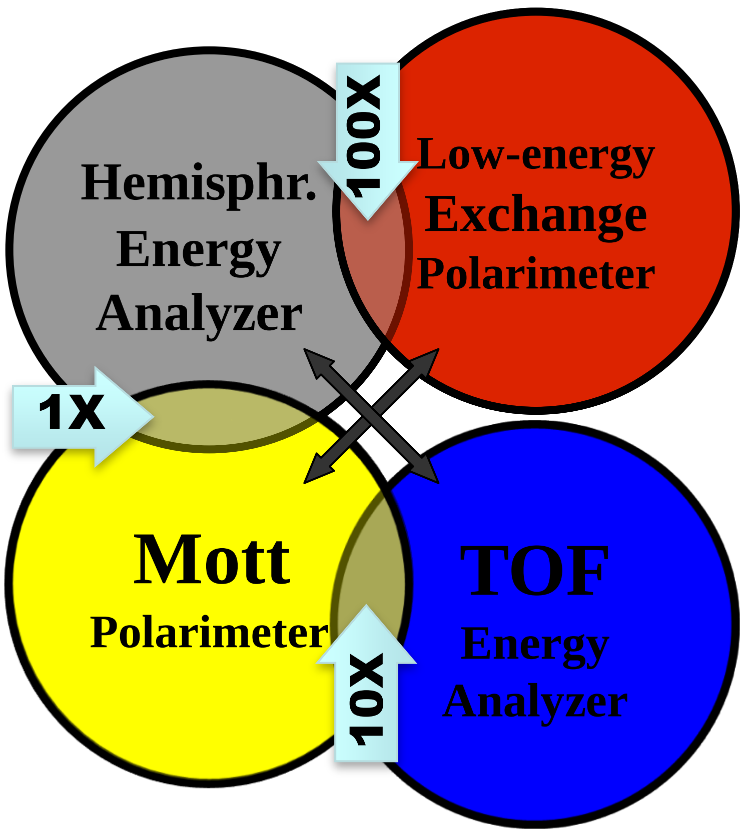
Spin resolution & efficiency



"Standard" ARPES : high speed 2D data acquisition

Efficiency ⟷ resolution, scope

Spin analysis: (1) low efficiency (FOMs ~ 10^{-4})
(2) "single" channel



Hemispherical **E**nergy **A**nalyzer
+ Mott scattering polarimeter

D.-J. Huang, *et al*., Rev. Sci. Instrum. (1993) (U. Texas)
A.V. Fedorov, *et al.,* J. El. Spectr. Rel. Phen. (1998) (BNL)
G. Ghiringhelli, *et al*., Rev. Sci. Instrum. (1999) (ESRF)
M. Hoesch, *et al*., J. El. Spectr. Rel. Phen. (2002) (SLS)

Hemispherical **E**nergy **A**nalyzer
+ **L**ow **E**nergy E**x**change scattering polarimeter

F.U. Hillebrecht, *et al.,* Rev. Sci. Instrum. (2002) (Düsseldorf)
R. Bertacco, *et al*., Rev. Sci. Instrum. (2002) (Milan)
T. Okuda, *et al*., Rev. Sci. Instrum. (2008) (SRL, Tokyo)
A. Winkelmann, *et al*., Rev. Sci. Instrum. (2008) (Max-Planck)

Time-**o**f-**F**light Analyzer
+ Mott scattering polarimeter

N. Müller, *et al*., J. El. Spectr. Rel. Phen. (1995) (BESSY)
G. Snell, *et al.*, Rev. Sci. Instrum. (2000) (U. W. Mich., ALS)
L. Moreschini, *et al*., Rev. Sci. Instrum. (2008) (ESRF)
C.M. Cacho, *et al*., Rev. Sci. Instrum. (2009) (Trieste)

Spin resolution & efficiency

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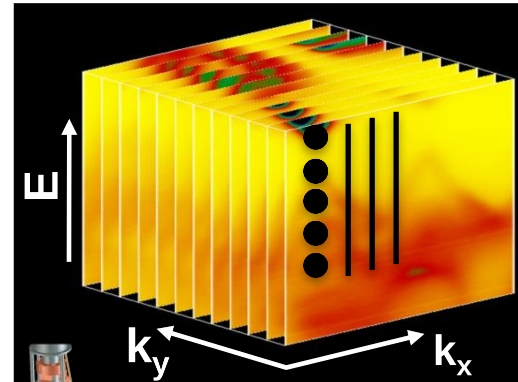
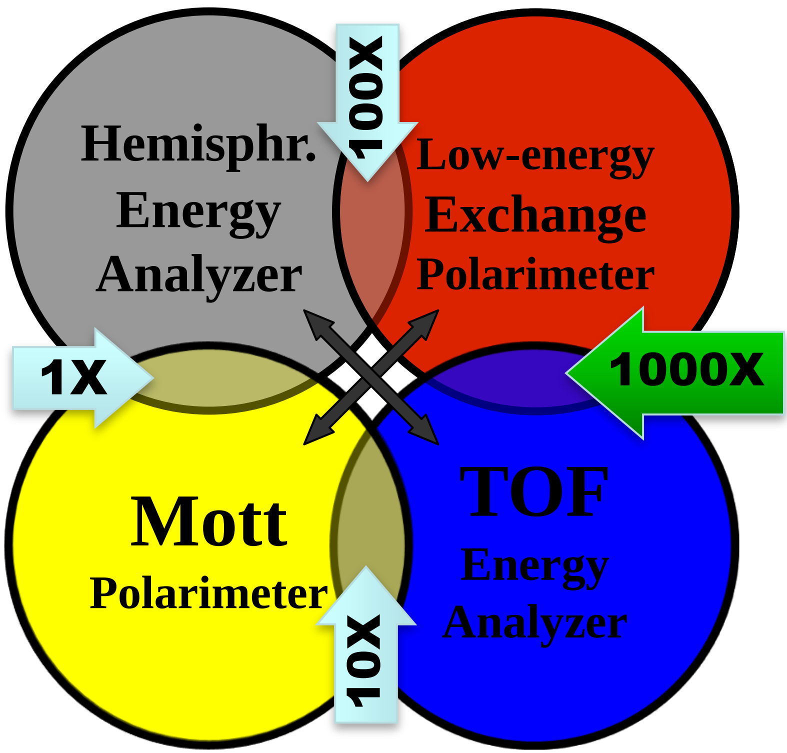
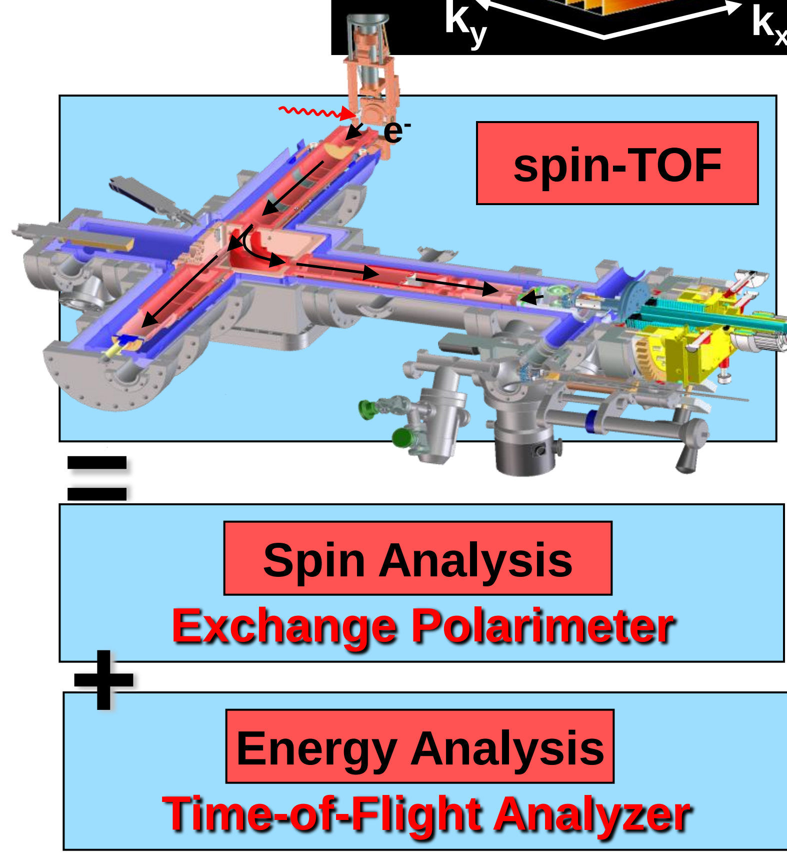




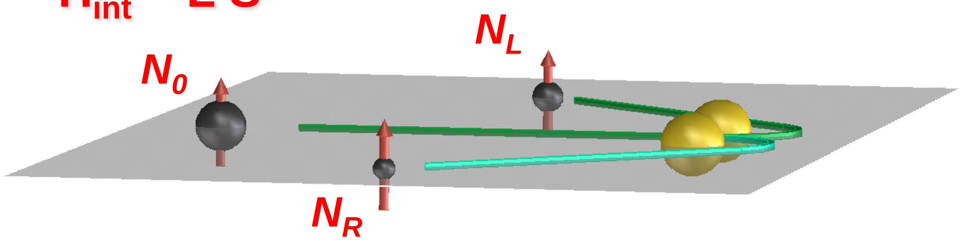


C. Jozwiak, *et al.*, Rev. Sci. Instrum. **81**, 053904 (2010), *patent pending*

Spin polarimeter efficiency

Mott polarimetry

$H_{int} \sim L \cdot S$



Requires: ≥ 20 keV → $N \ll N_0$

$S_{eff} \sim 0.20$ $N/N_0 \sim 0.002$ $FOM \sim 1 \times 10^{-4}$

resolving power: Sherman function

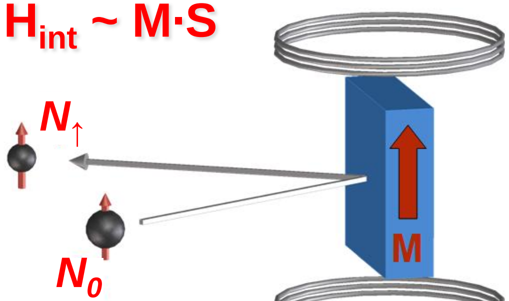
$$S_{\text{eff}} = \frac{1}{P}\frac{N_L - N_R}{N_R + N_L} \qquad P = \frac{1}{S_{\text{eff}}}\frac{N_L - N_R}{N_R + N_L}$$

Overall performance: figure of merit

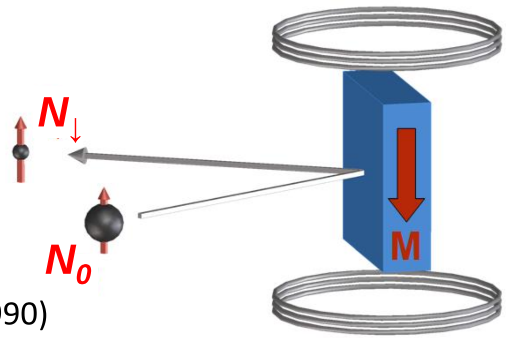
$$FOM = S_{\text{eff}}^2 \frac{N_L + N_R}{N_0}$$

Exchange polarimetry

$H_{int} \sim M \cdot S$



~10 eV



Target system:
50 ML Co/W(110)

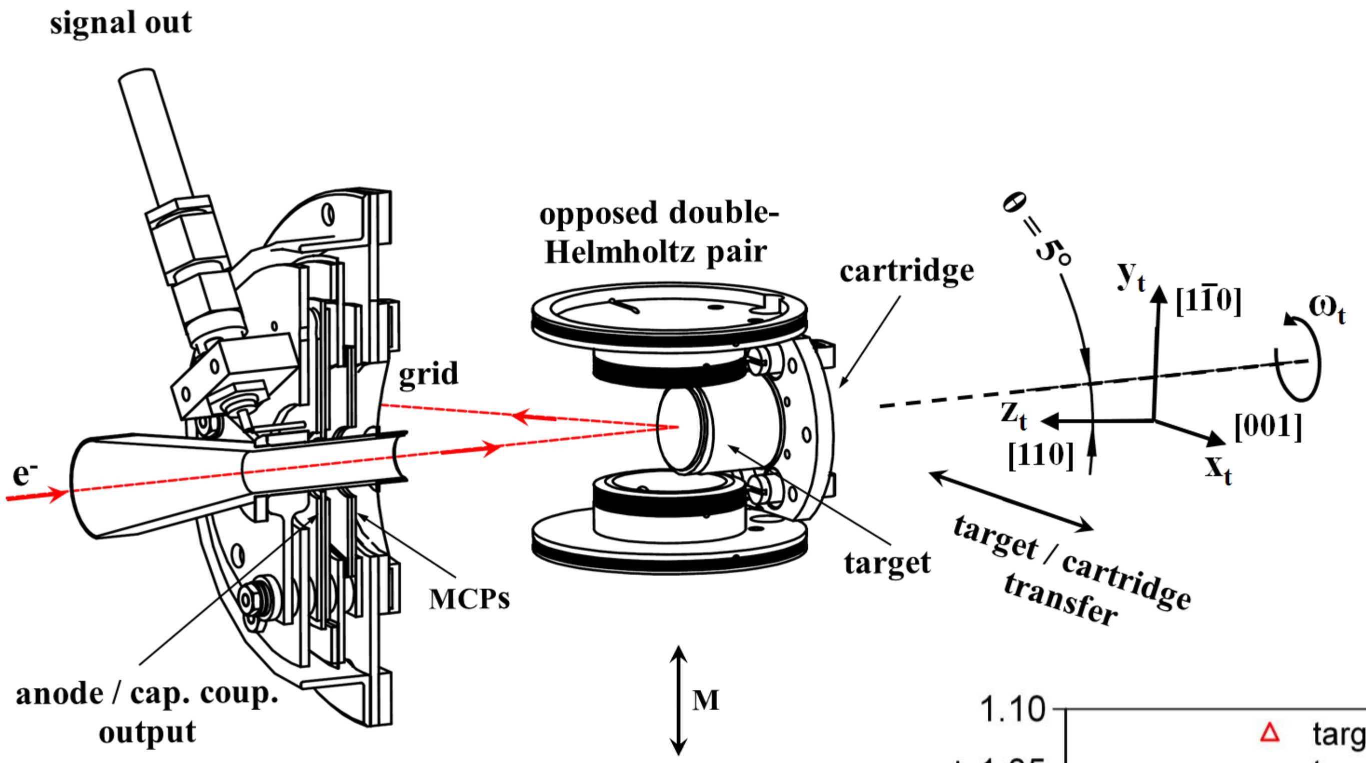
$S_{eff} \sim 0.12 \rightarrow 0.25$

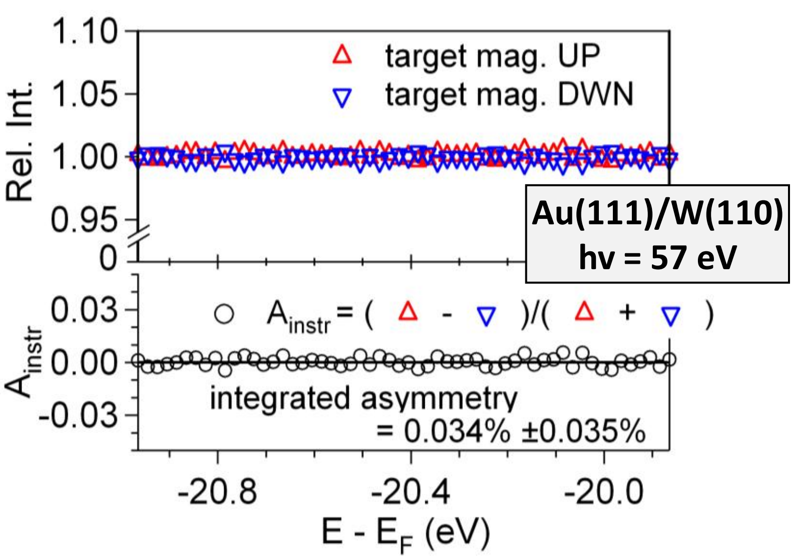
$N/N_0 \sim 0.065$

$FOM \sim 1 \times 10^{-3} \rightarrow 4 \times 10^{-3}$

R.J. Celotta, *et al.*, PRL **43**, 728 (1979)
D. Tillmann, *et al.*, Z. Phys. B **77**, 1 (1989)
M. Hammond, *et al.*, Vacuum **41**, 500 (1990)
F.U. Hillebrecht, *et al.*, PRL **65**, 2450 (1990)

Polarimeter design





Key Features:

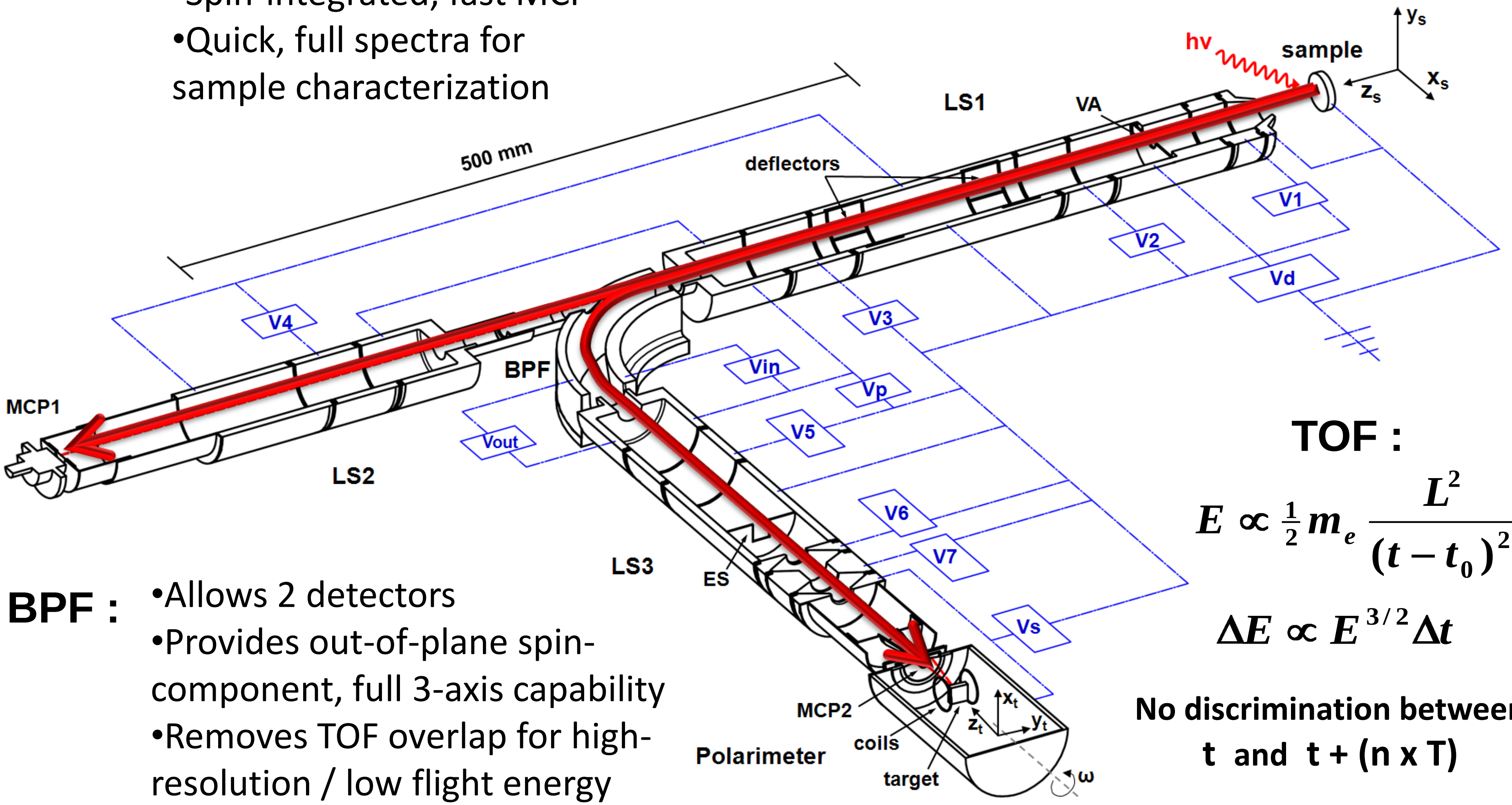
- High-speed detection - $\Delta t < 200$ ps
- Minimal scattering angle, θ
- Versatile, isolated target prep chamber
- Rotatable polarization axis
- Ultra-low false instrumental asymmetry

Full TOF lens system

2 modes of operation:

"M1" :
- Straight path
- Spin-integrated, fast MCP
- Quick, full spectra for sample characterization

"M2" :
- Spin polarimeter
- High-res, detailed spin-resolution
- 90° spherical bandpass filter (BPF)



BPF :
- Allows 2 detectors
- Provides out-of-plane spin-component, full 3-axis capability
- Removes TOF overlap for high-resolution / low flight energy

TOF :

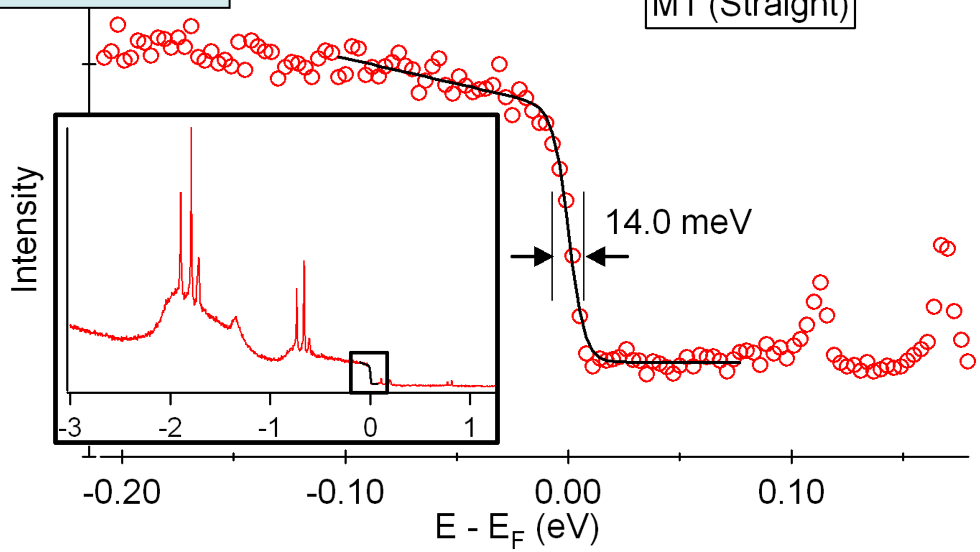
$$E \propto \tfrac{1}{2} m_e \frac{L^2}{(t - t_0)^2}$$

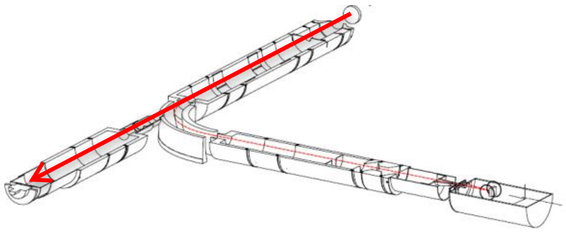
$$\Delta E \propto E^{3/2} \Delta t$$

No discrimination between t and t + (n x T)

Energy resolution performance: M1 and M2

W(110)
hv = 28 eV





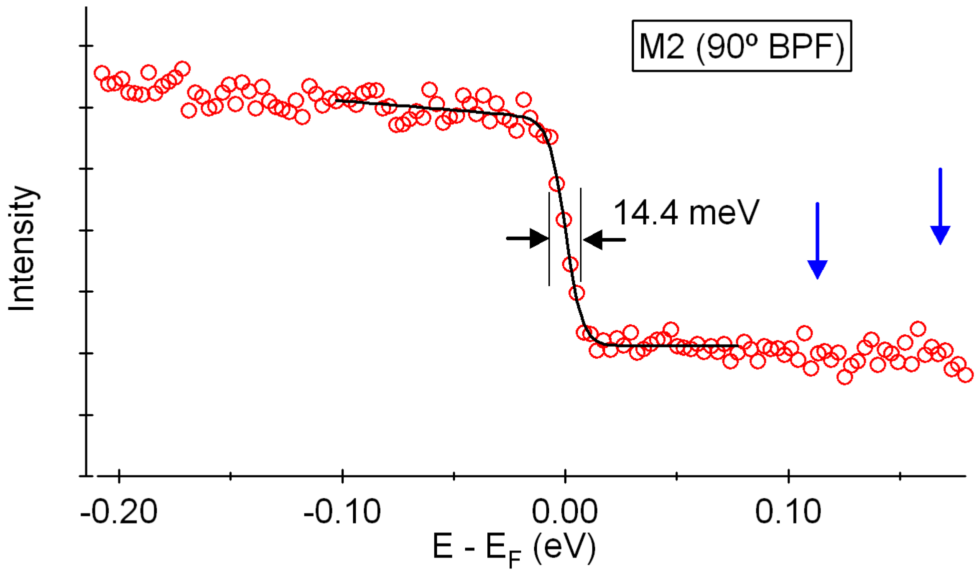
$\Delta E_{tot.} \sim 14$ meV

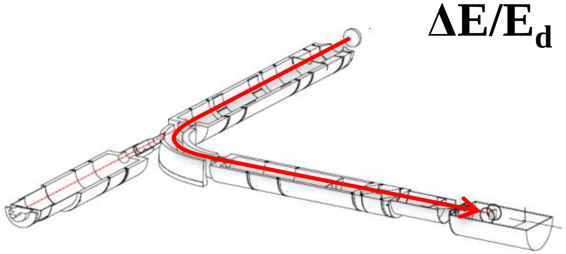
$\Delta E_{hv} \sim 10$ meV

$\Delta E_{4kT} \sim 4$ meV

$\Delta E_{TOF} \sim$ 9 meV

$\Delta E/E_d > 1000$





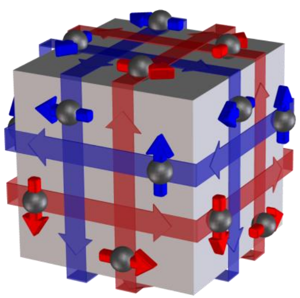
Low drift energy = high resolution

BPF = no overlap

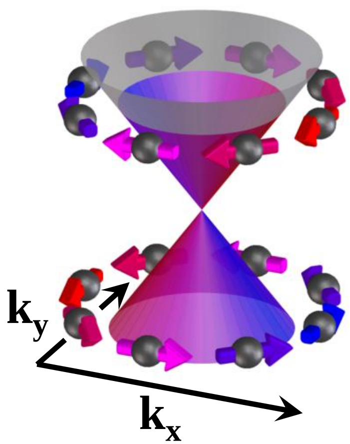
hv rep. rates over 10 MHz

Spin texture of topological insulators

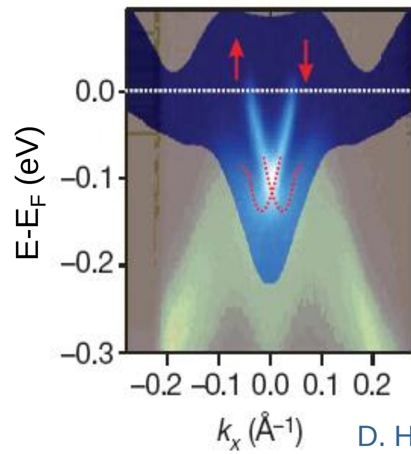
real-space

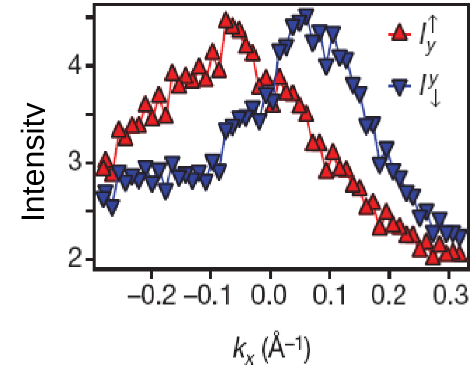


k-space



Bi_2Te_3





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

First measured spin polarizations < **20%**

~10% ($Bi_{1-x}Sb_x$) D. Hsieh, et al. *Science* (2009)
~20% (Bi_2Te_3) D. Hsieh, et al. *Nature* (2009)

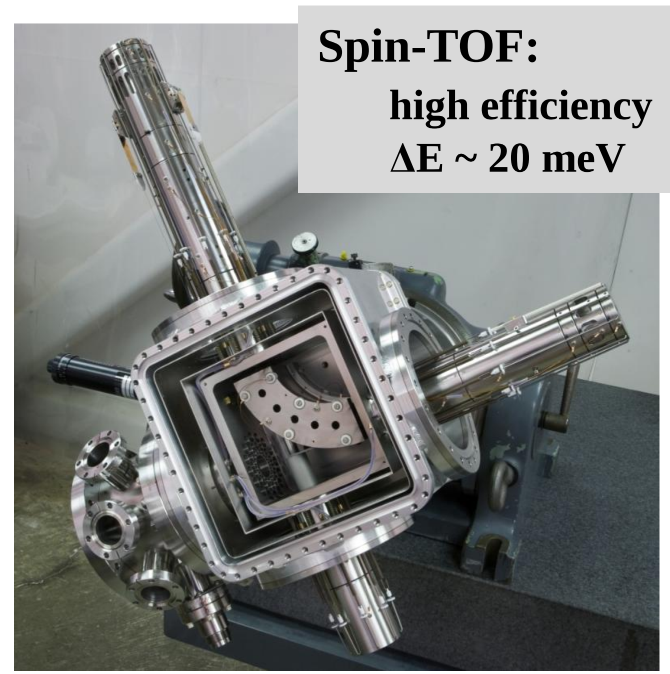
Experimental literature range ~ **10 – 75%**

~10% (Bi_2Se_3 thin film) T. Hirahara, et al. *PRB* (2010)
~60% (Bi_2Te_3) S. Souma, et al. *PRL* (2011)
~60% (Bi_2Te_3) S.-Y. Xu, et al. *arxiv:1101.3985* (2011)
~75% (Bi_2Se_3) Z.-H. Pan, et al. *PRL* (2011)

First principals calcs ~ **50%**

O. Yazyez, et al. *PRL* (2010)

Full understanding, characterization necessary for device development

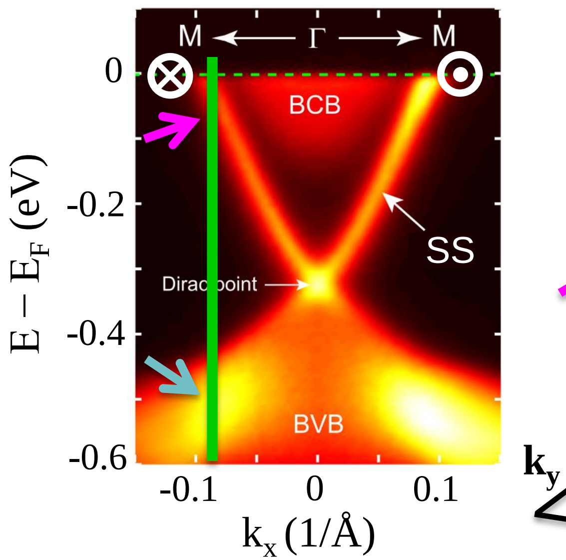


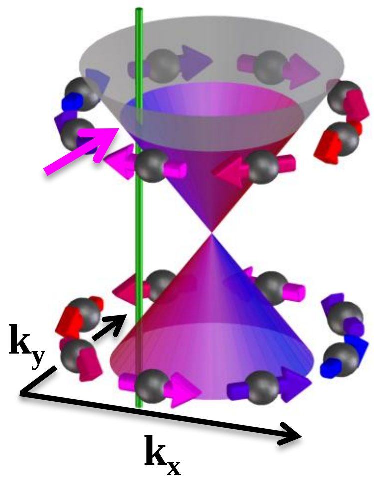
C. Jozwiak *et al.*, *RSI* **81**, 053904 (2010)

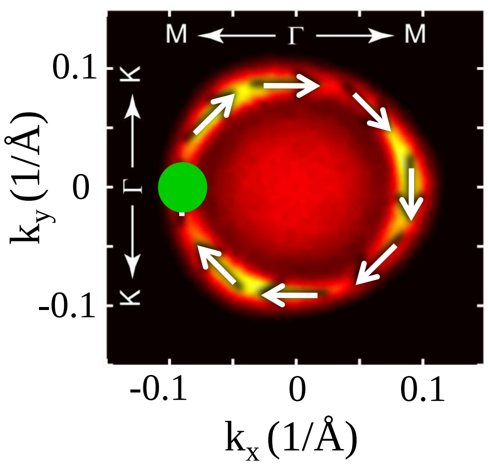
Spin-ARPES of Bi_2Se_3

High-Res ARPES

BL10 (HERS) hv = 36 eV

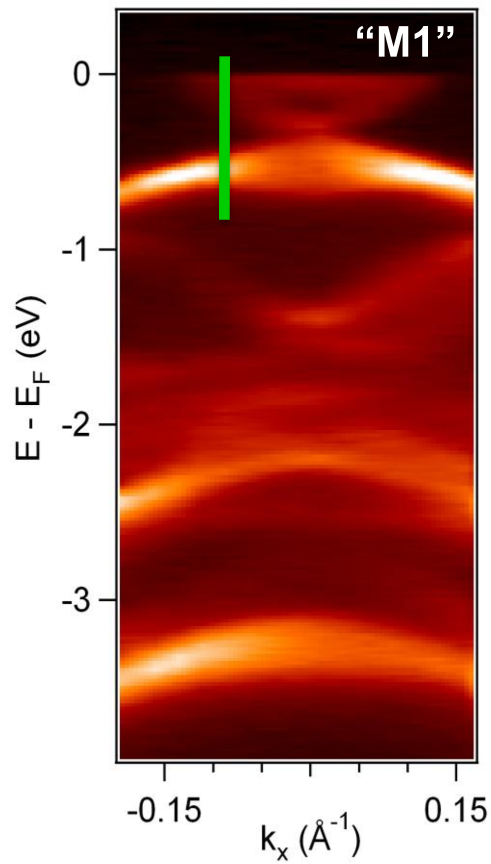






Spin-resolved ARPES

BL12.0.1 (spin-TOF) hv = 36 eV, p-pol



C. Jozwiak *et al.*, in press, PRB

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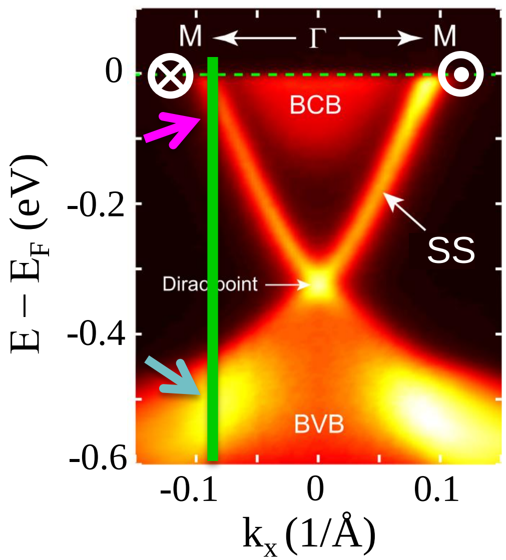

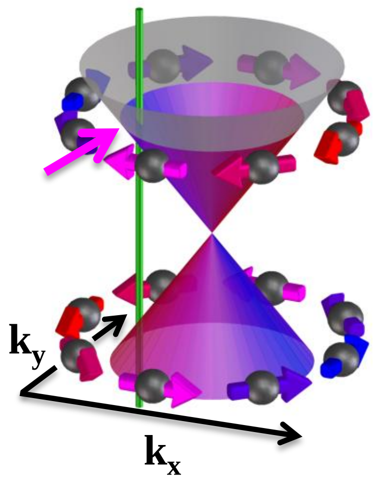

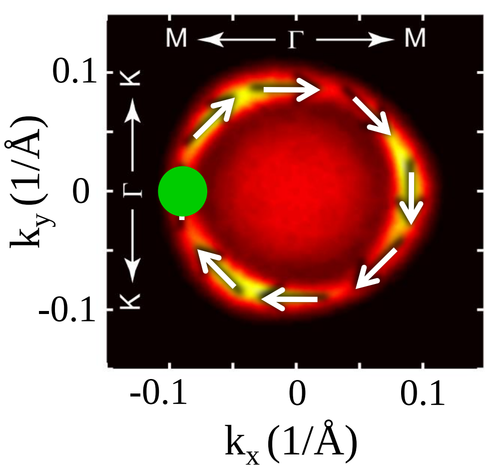

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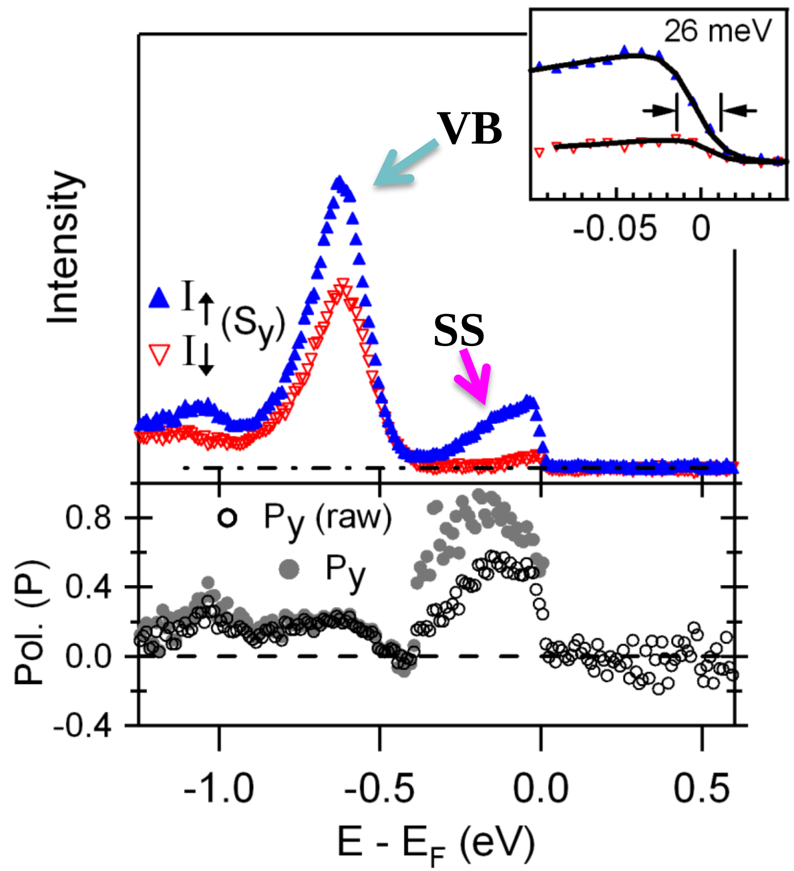

SS: **P ~ 80%**

VB: **P ~ 20%**

C. Jozwiak *et al.*, in press, PRB

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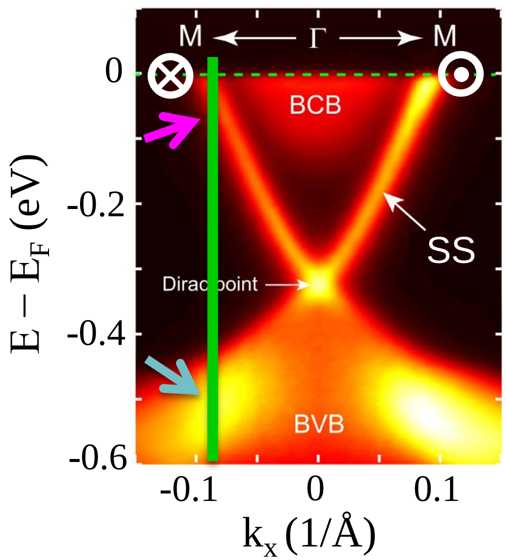

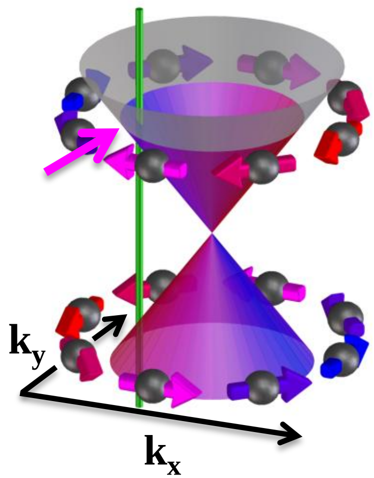

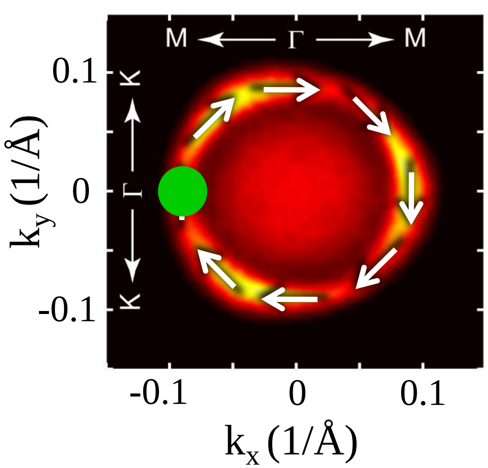

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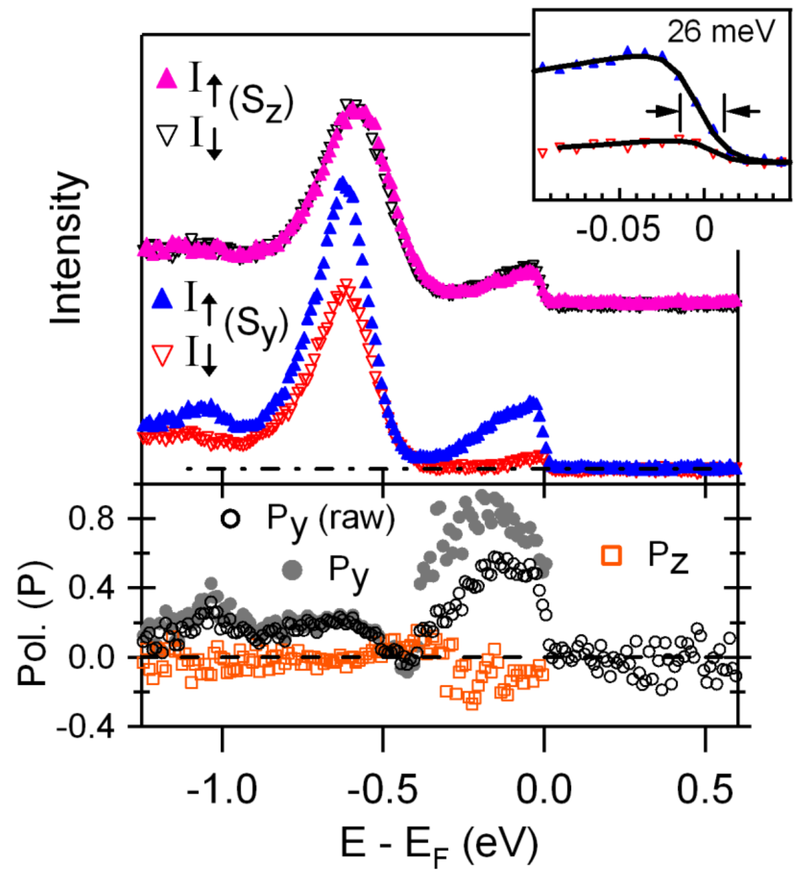

SS: **P ~ 80%**

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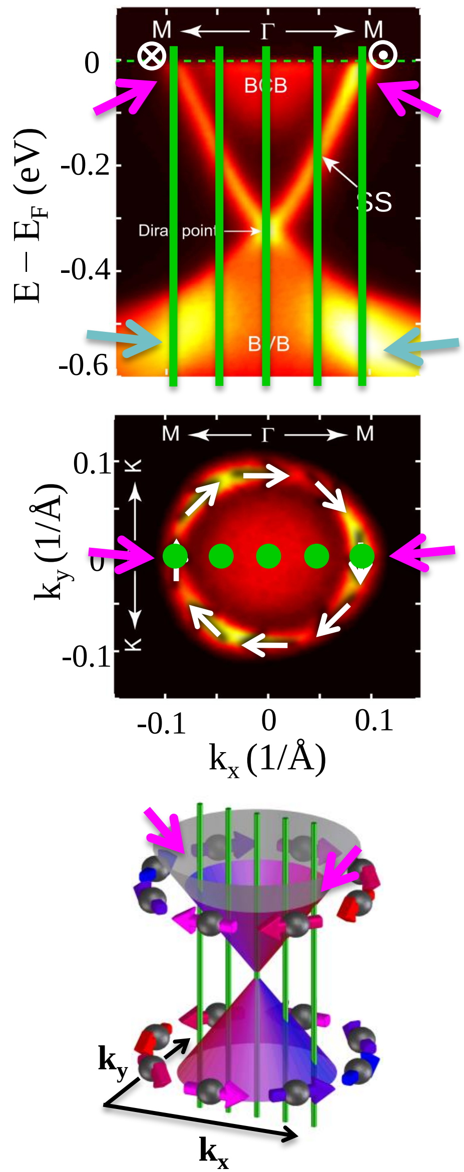
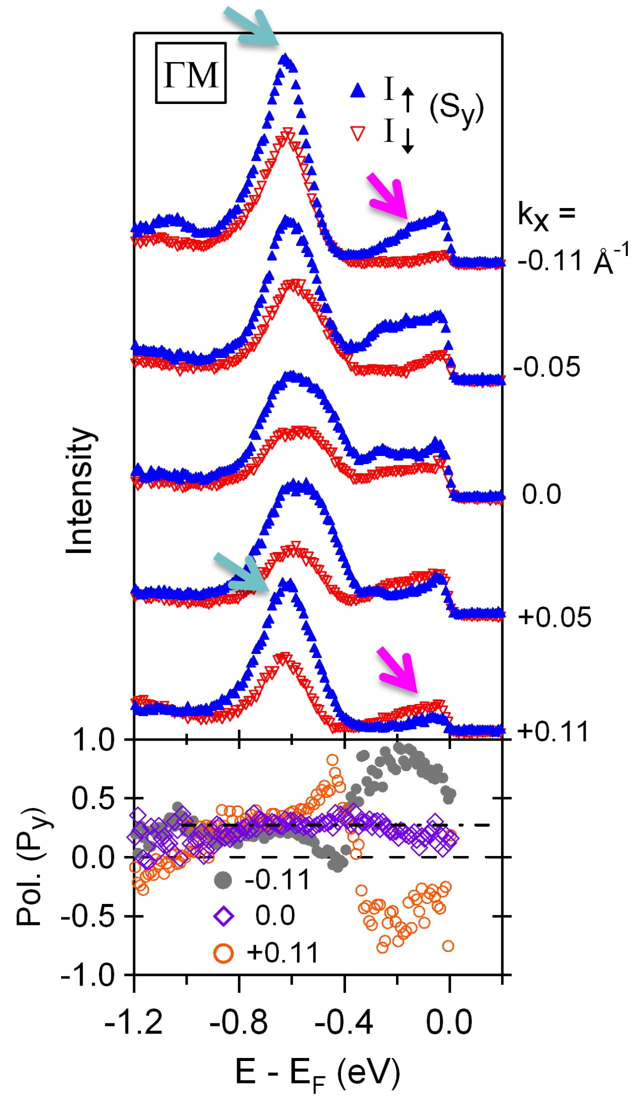
C. Jozwiak *et al.*, in press, PRB

Spin polarization **k**-dependence





SS

- P dependent on **k**
- **P(k) = -P(-k)**

(Time-reversal symmetry)

BB

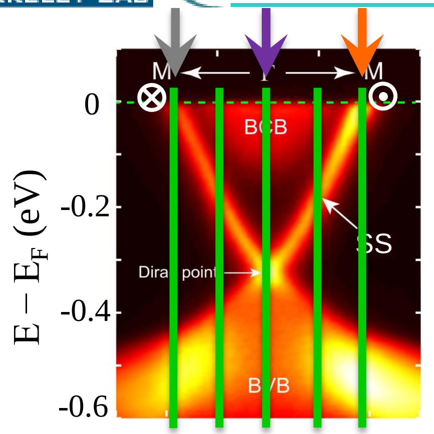
- P independent of **k**
- **P(k) ≠ -P(-k)**

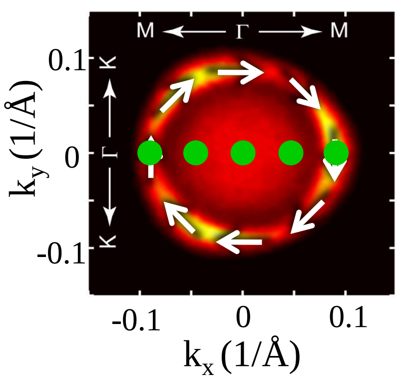
Photoelectron polarization components:

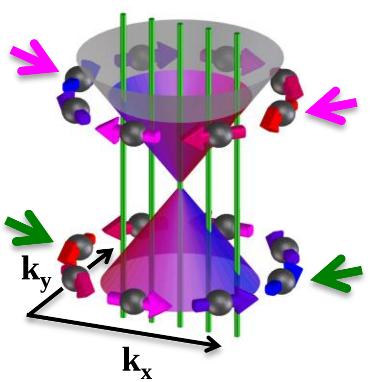
1) **k-dependent**
   Topological physics
2) **k-independent**
   Bulk bands

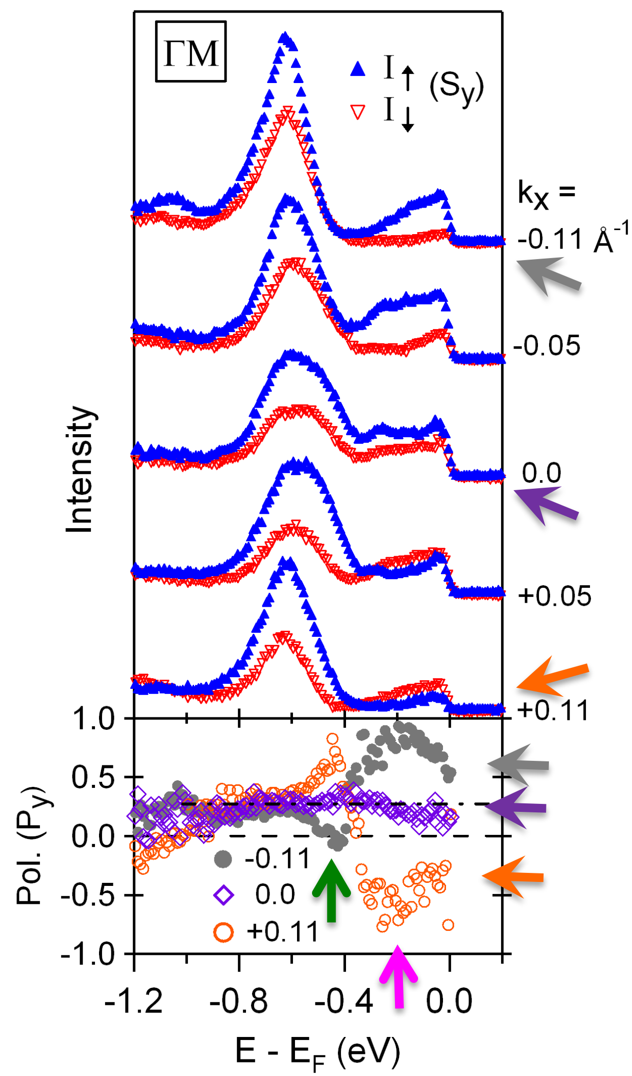
C. Jozwiak *et al.*, in press, PRB

Spin polarization **k**-dependence









C. Jozwiak *et al.*, in press, PRB

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(Time-reversal symmetry)

- Reversed helicity below Dirac point

($BiTlSe_2$) S.-Y. Xu *Science* (2011)

BB

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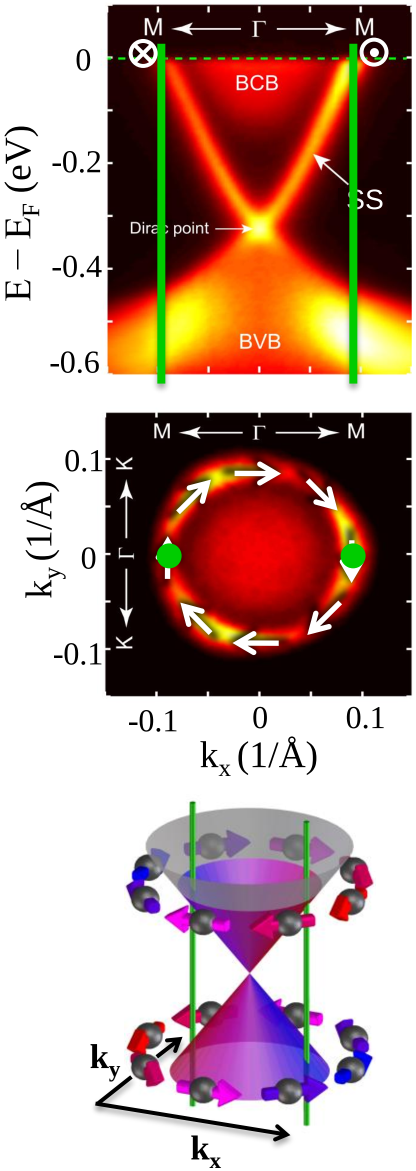
Spin polarization at room temp.



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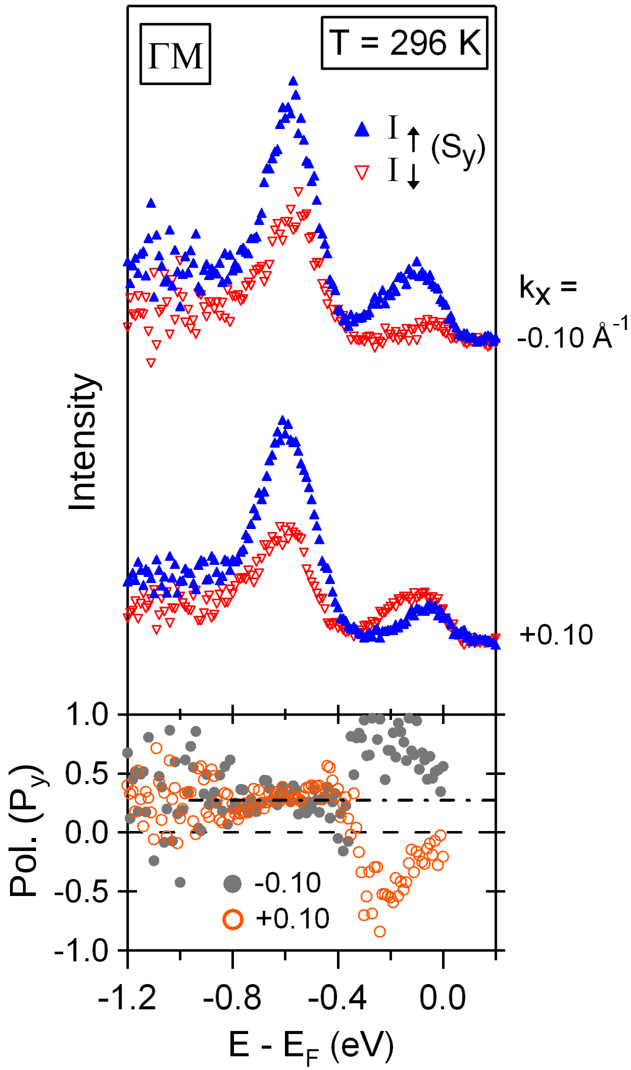

SS

- P dependent on **k**
- **P(k) = -P(-k)**

(Time-reversal symmetry)

- Reversed helicity below Dirac point
- P persists at room T

BB

- P independent of **k**
- **P(k) ≠ -P(-k)**
- P persists at room T

Photoelectron polarization components:

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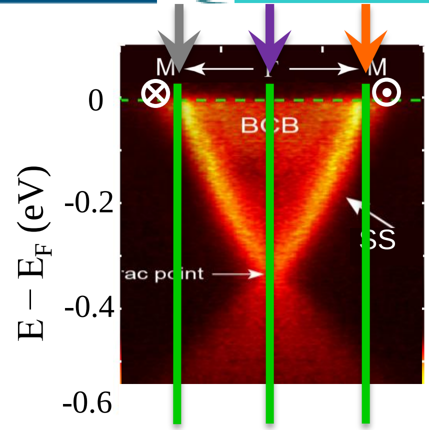
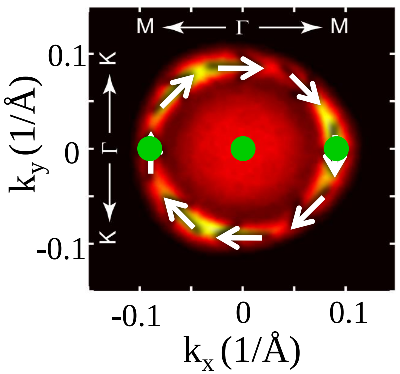
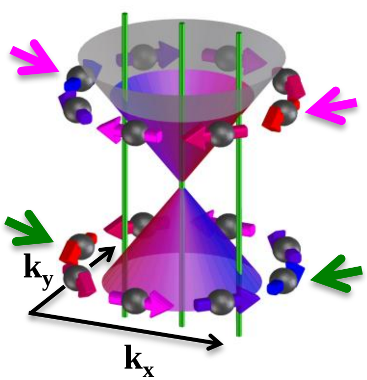
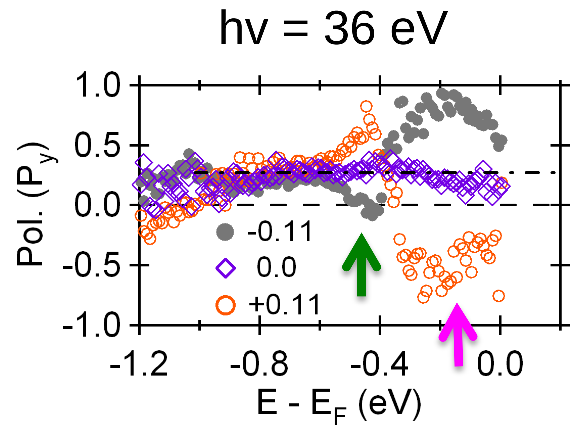
   Topological physics
2) **k-independent**
   Bulk bands

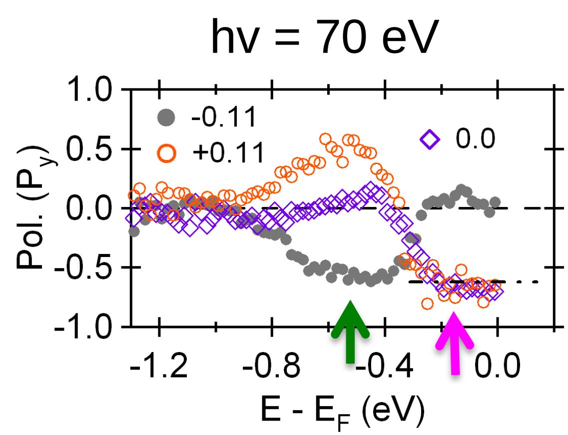
Spin polarization **hv**-dependence











C. Jozwiak *et al.*, in press, PRB

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- Reversed helicity below Dirac point
- P persists at room T

BB

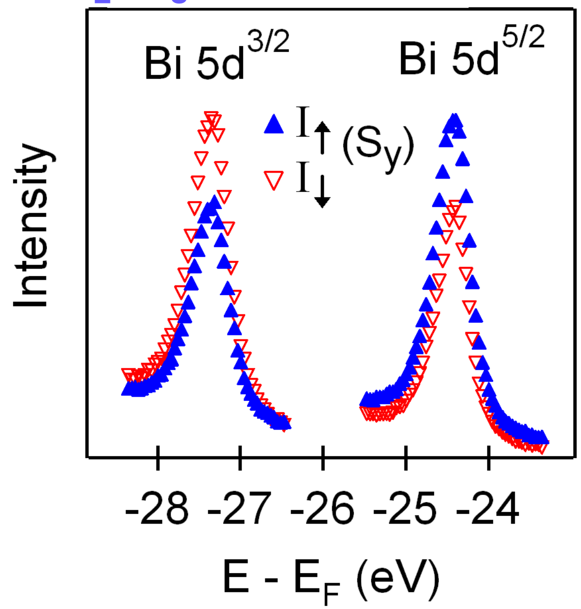
- P independent of **k**
- **P(k) ≠ -P(-k)**
- P persists at room T
- P dependent on hv

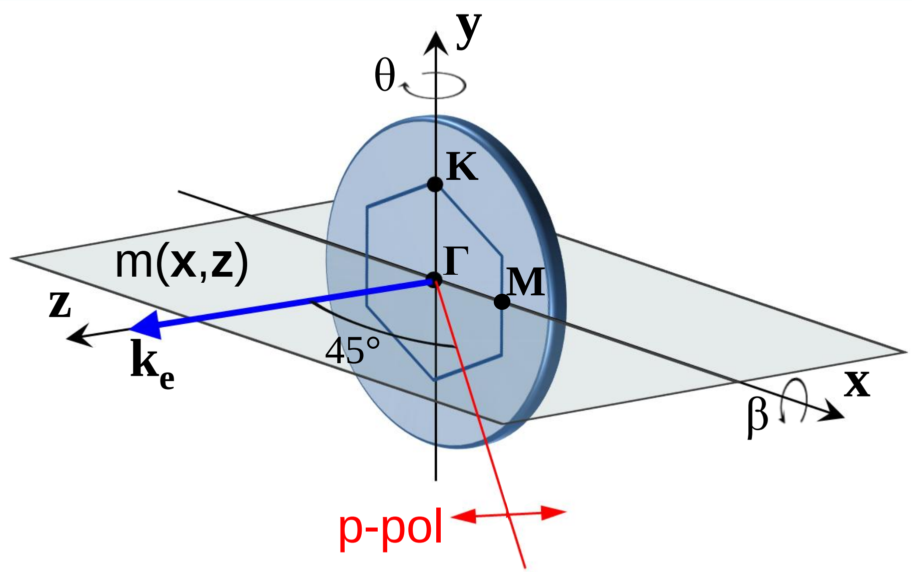
Photoelectron polarization components:

1) **k-dependent**
   Topological physics
2) **k-independent**
   Bulk bands

Spin-orbit induced photoelectron polarization

Bi_2Se_3





Atomic case: Cherepkov, *J Phys B* (1979)

$$\vec{P} = \frac{2\xi(\hat{k}_e \cdot \hat{\varepsilon})(\hat{k}_e \times \hat{\varepsilon})}{1 + 0.5\beta\left(3(\hat{k}_e \cdot \hat{\varepsilon})^2 - 1\right)}$$

ξ : due to interference of ℓ-1 and ℓ+1 phase shifts

Dependent on: geometry, photon energy and polarization

C. Jozwiak *et al.*, in press, PRB

Atoms:

Theory:

C.M. Lee, *PRA* **10**, 1598 (1974)
Cherepkov, *J Phys B* **12**, 1279 (1979)

Experiment:

(Xe) Heinzmann, *PRL* **42**, 1603 (1979)
(Xe) Schonhense, *PRL* **44**, 640 (1980)

Solid, core:

Experiment:

(Cu 3p) Roth, *PRL* **73**, 1963 (1994)
(W 4f) Rose, *PRB* **53**, 1630 (1996)
(Pt 4d,f) Yu, *PRB* **77**, 193409 (2008)

Solid, VB:

Theory:

Tamura, *SSC* **79**, 989 (1991)
Tamura, *EPL* **16**, 695 (1991)

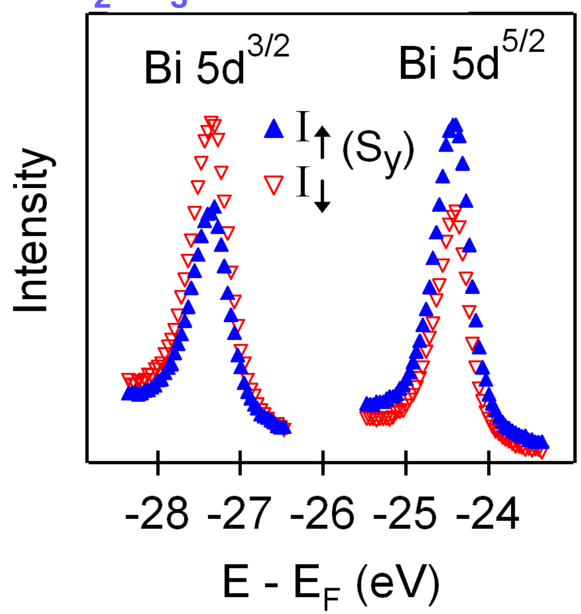
Experiment (Pt, Au):

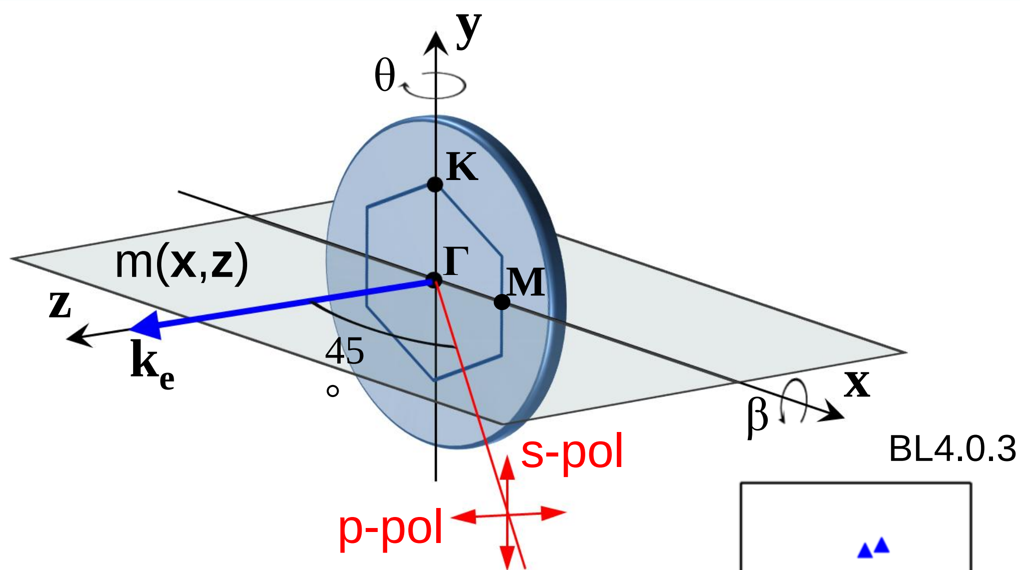
Schmiedeskamp, *APA* **53**, 418 (1991)
Irmer, *PRB* **45**, 3849 (1992)
Johnson, *Rep. Prog. Phys.* **60**, 1217 (1997)

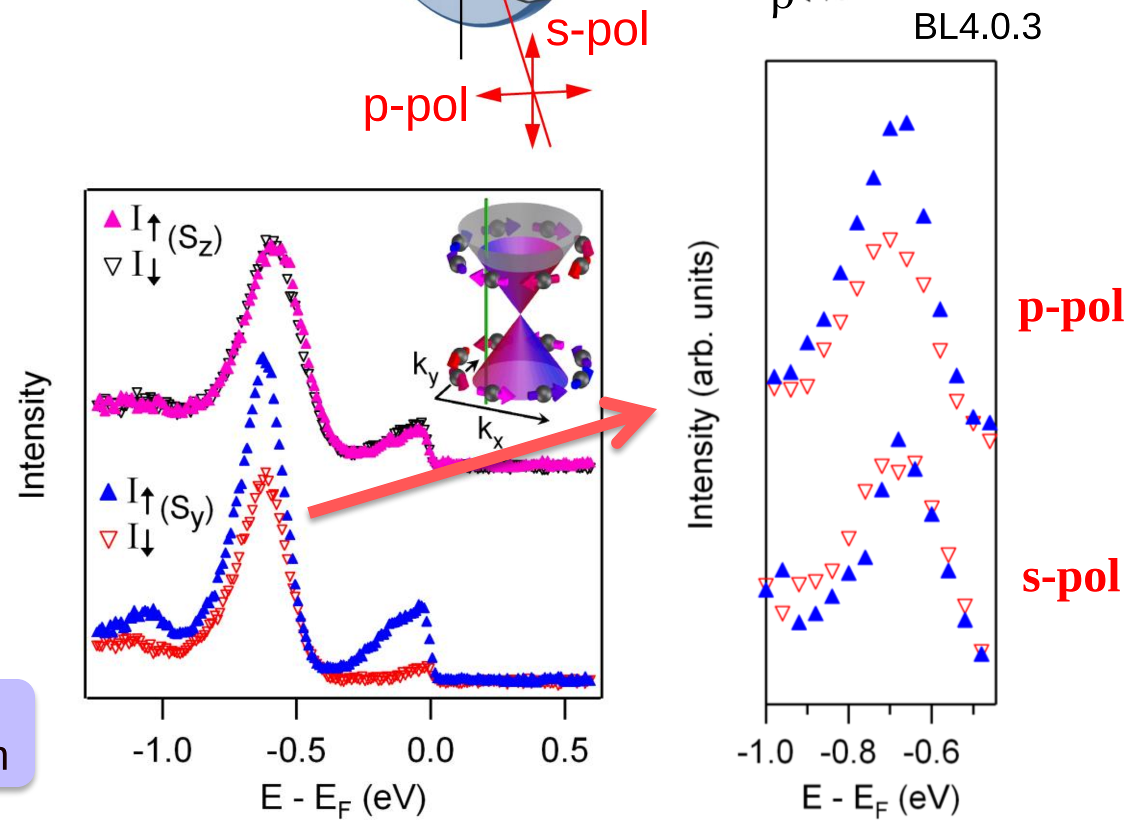
Relativistic one-step model calc.

Spin-orbit induced photoelectron polarization

Bi_2Se_3







Atomic case: Cherepkov, *J Phys B* (1979)

$$\vec{P} = \frac{2\xi(\hat{k}_e \cdot \hat{\varepsilon})(\hat{k}_e \times \hat{\varepsilon})}{1 + 0.5\beta\left(3(\hat{k}_e \cdot \hat{\varepsilon})^2 - 1\right)}$$

ξ : due to interference of ℓ-1 and ℓ+1 phase shifts

Dependent on: geometry, photon energy and polarization

C. Jozwiak *et al.*, in press, PRB

Conclusions

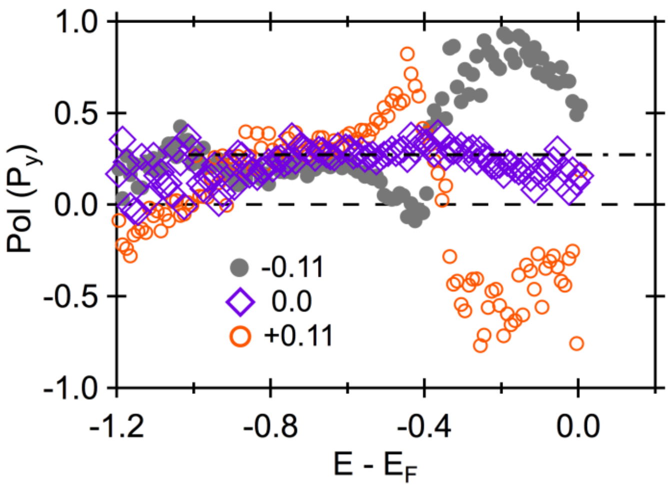
Efficient spin-resolved spectrometer by combining low-energy exchange scattering and TOF techniques

Thorough spin-ARPES study of 3D topological insulator, Bi_2Se_3

- Photoelectron polarization has 2 components

(1) **k**-dependent (P(k) = -P(-k))

- Topological spin texture
- High P ~ 80%
- Persists at room temperature
- Reversed helicity below Dirac point



(2) **k**-independent

- Also spin-orbit induced
- Dependent on geometry, photon energy and polarization (i.e. not just spin polarization of initial state)

- Photoelectron polarization ≠ initial state polarization

(Au) Henk, *PRB* **68**, 165416 (2003)
(graphene) Kuemmeth, *PRB* **80**, 241409(R) (2009)