Topological Band and Correlated Insulators

Part 1

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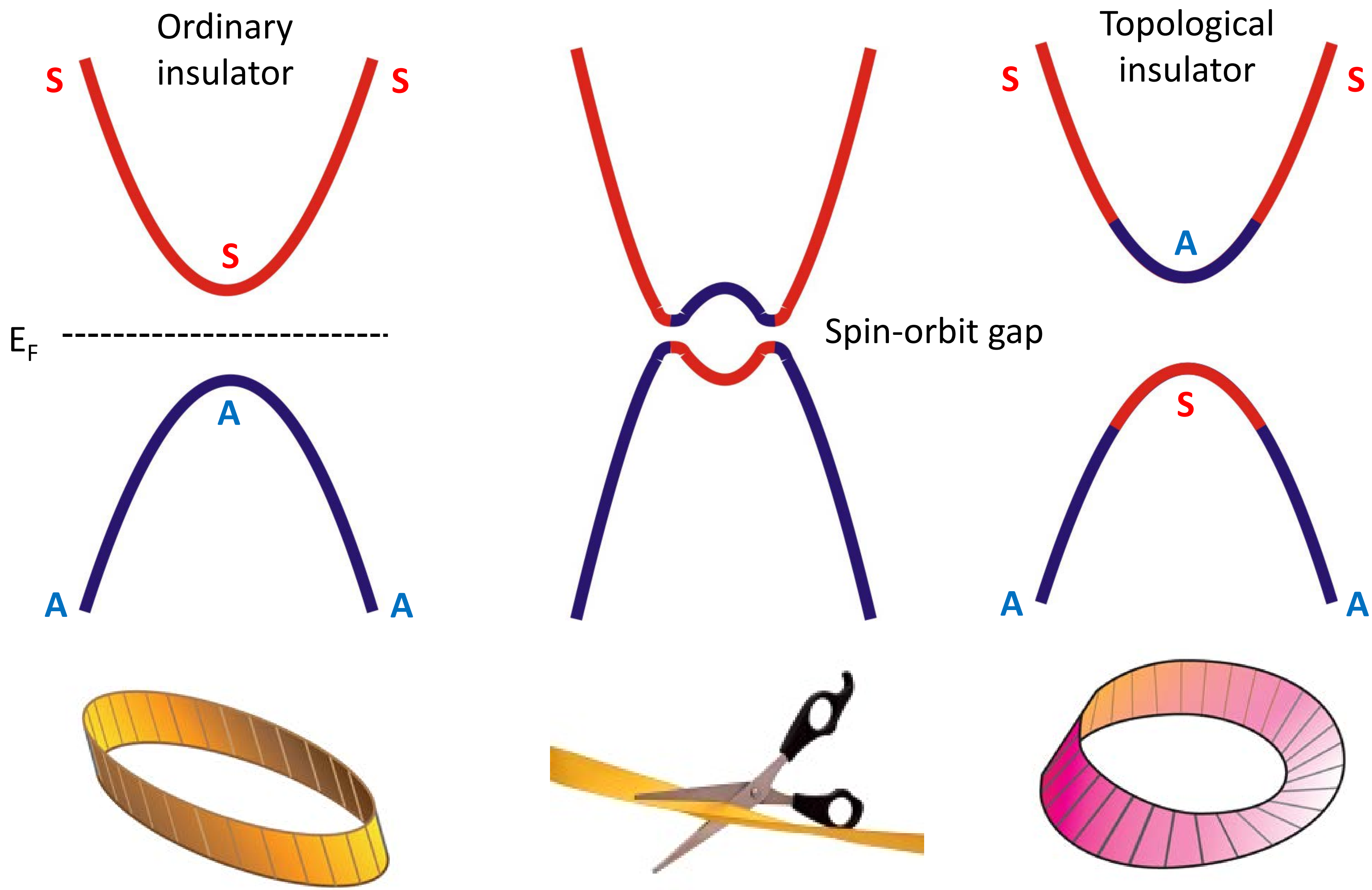
Outline

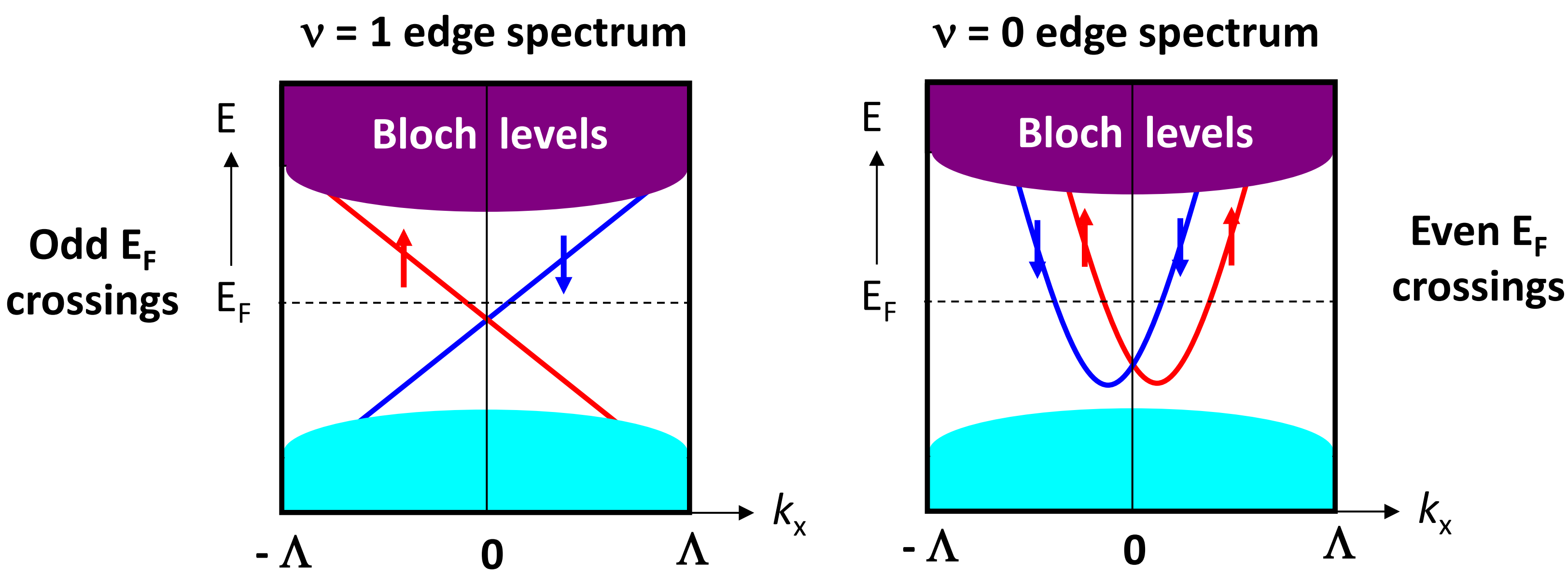
- The topological band insulator
- Angle-resolved photoemission spectroscopy (ARPES)
  - Working principles and current state-of-the-art
  - Application to 3D topological insulators

Bulk topological distinction



Kane & Mele PRL (2005) ; Bernevig, Hughes & Zhang Science (2007) ; Moore & Balents PRL (2007) ; Roy PRB (2009)

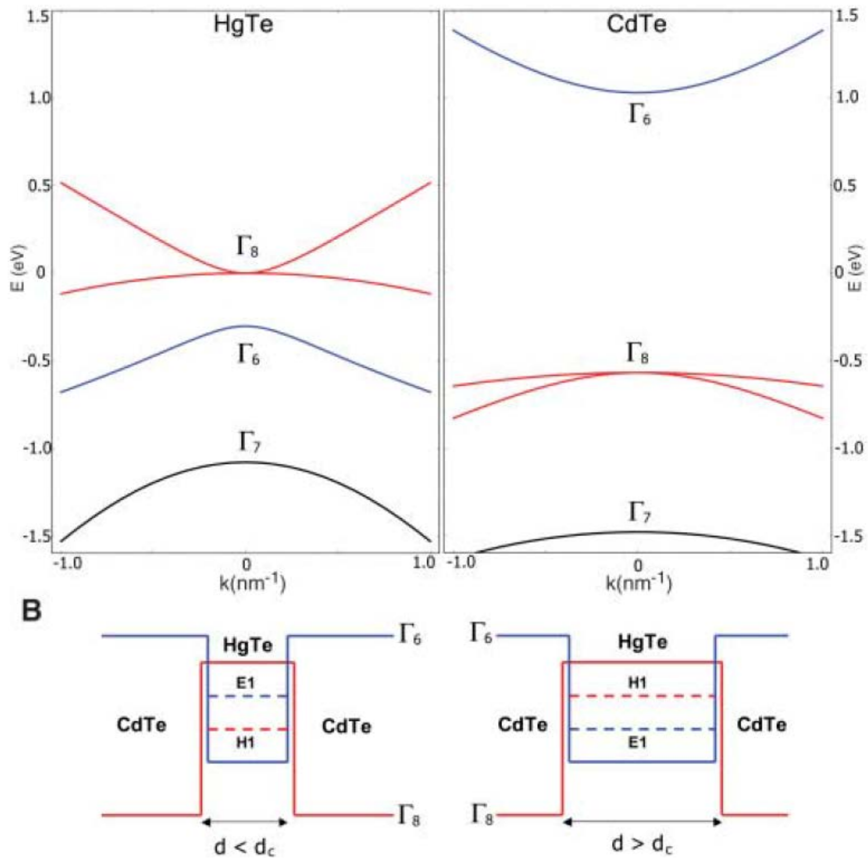
1D edge states of 2D topological insulators

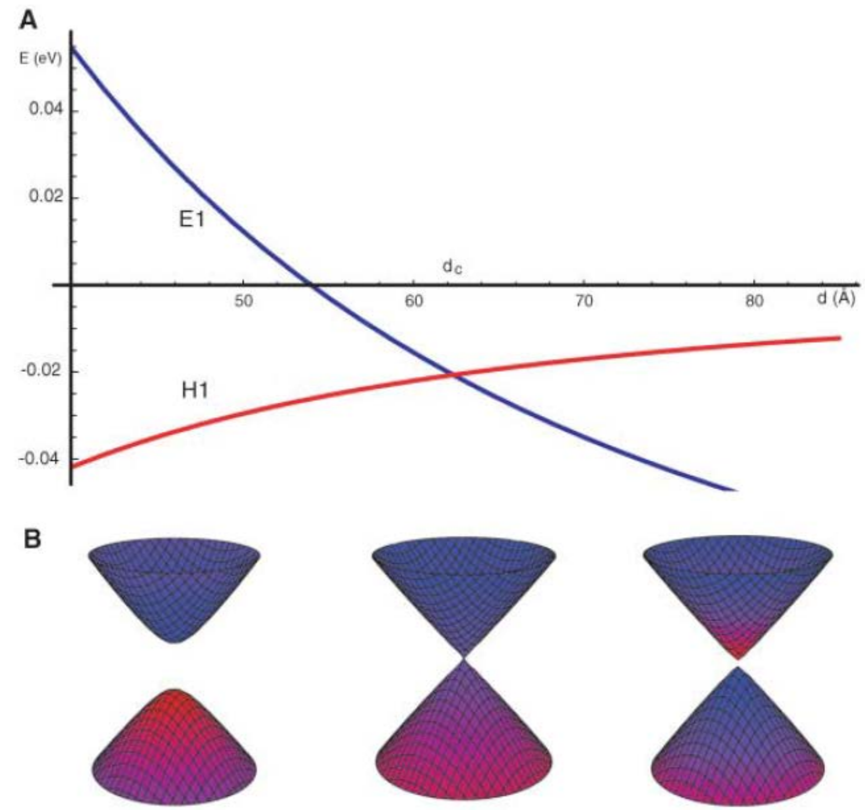


0, Λ are time reversal invariant. Satisfy Λ = -Λ mod **G**

- Topology determined by counting edge Fermi crossings between Λ's
- ν = 1 proposed in graphene but bulk gap too small

Realization of a 2D topological insulator in a quantum well

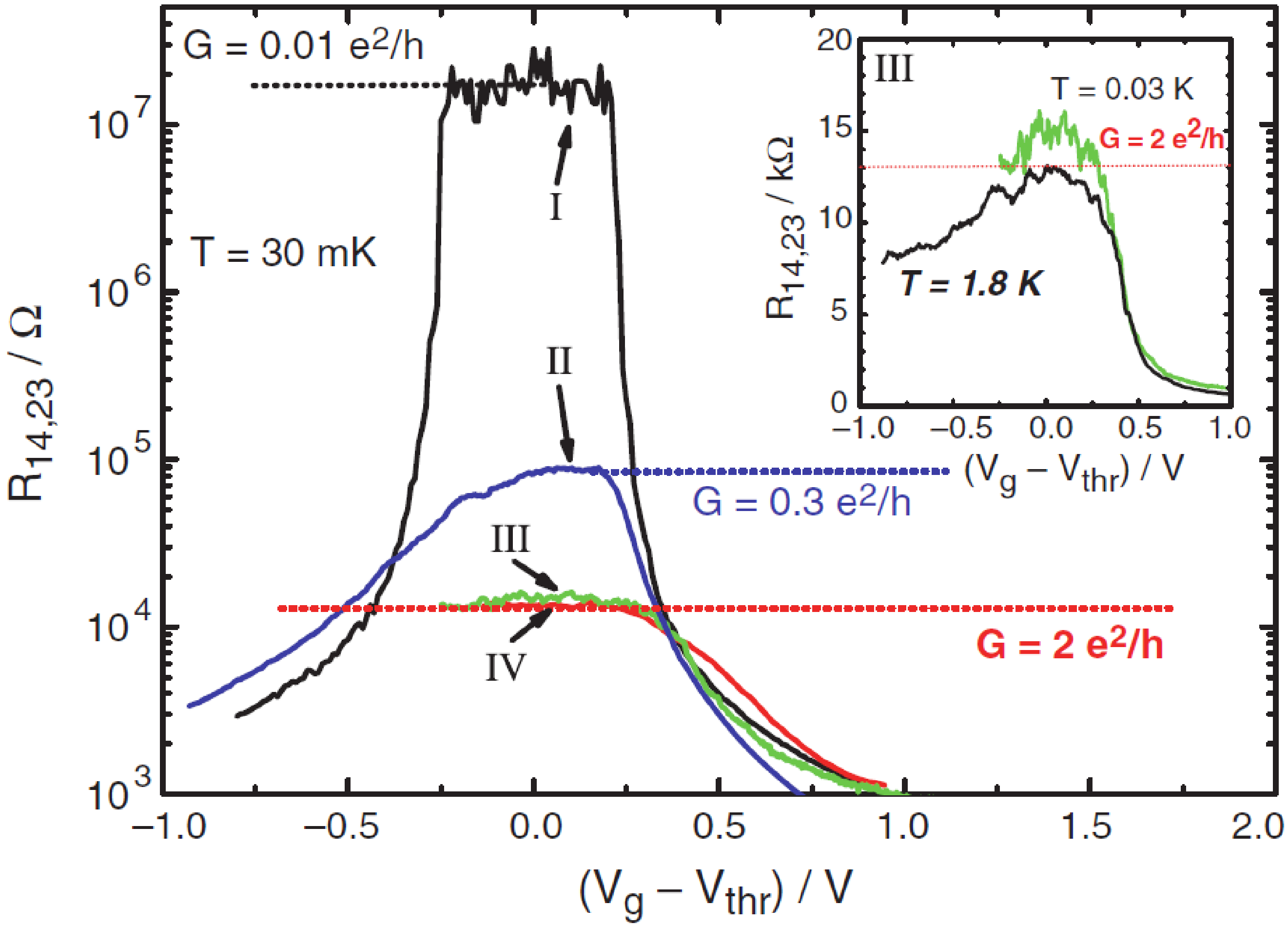




See also Joshua Folk talk

Bernevig et al., Science **314**, 1757 (2006)

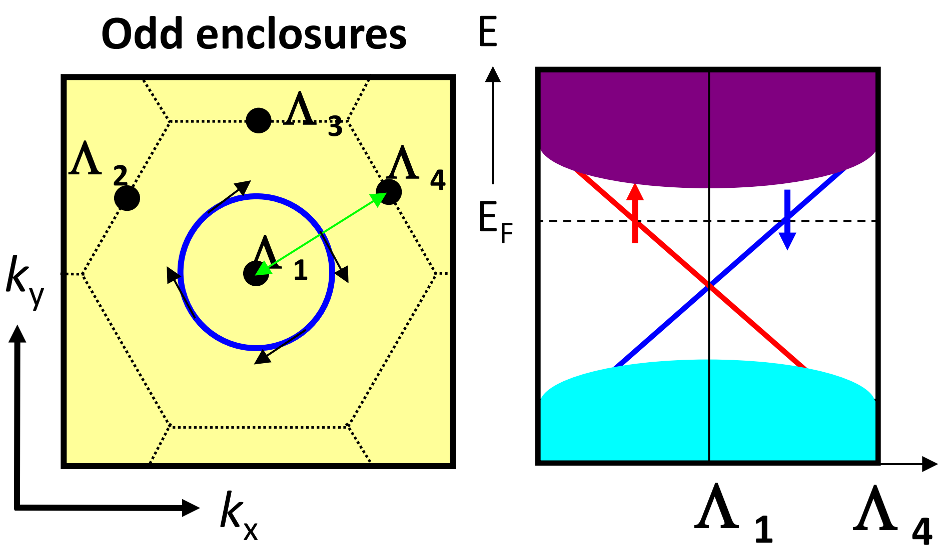
Experimental evidence for the 2D topological insulator



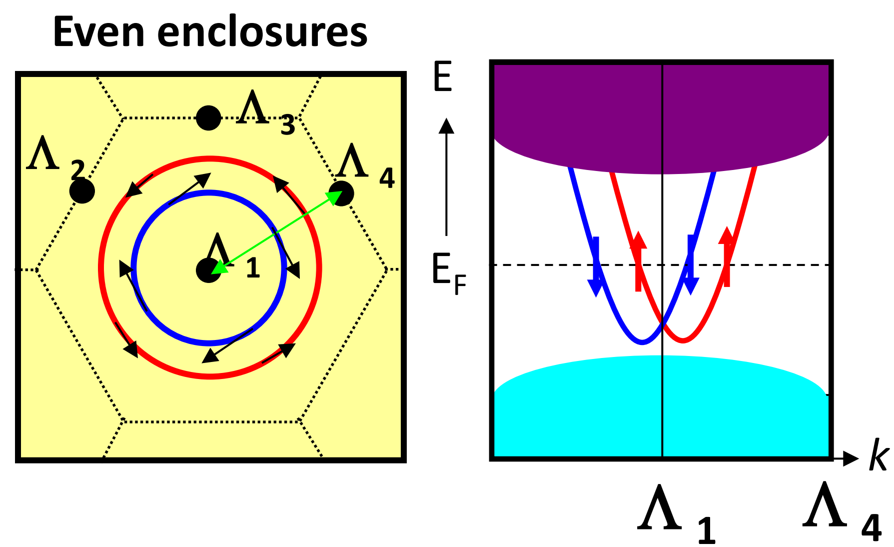
Konig et al., Science **318**, 766 (2007)

2D surface states of 3D topological insulators

$\nu_0 = 1$ surface spectrum



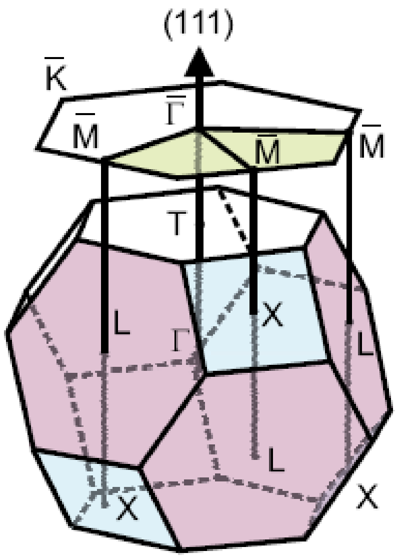
$\nu_0 = 0$ surface spectrum



Λ_i satisfy $\Lambda_i = -\Lambda_i \bmod \mathbf{G}$

Fu, Kane & Mele, PRL **98**, 106803 (2007)

$Bi_{1-x}Sb_x$ is predicted to be a 3D topological insulator



Fu & Kane, PRB **76**, 045302 (2007)

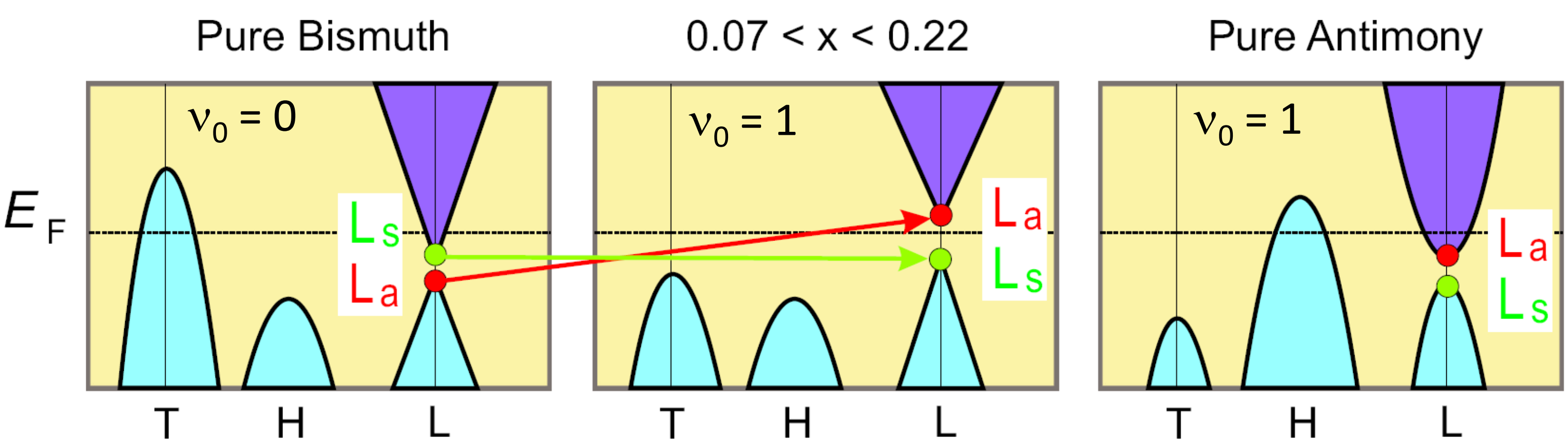
Parity eigenvalues

Bismuth

1Γ	Γ_6^+ Γ_6^- Γ_6^+ Γ_6^+ Γ_{45}^+	$-$
$3L$	L_s L_a L_s L_a L_a	$-$
$3X$	X_a X_s X_s X_a X_a	$-$
$1T$	T_6^- T_6^+ T_6^- T_6^+ T_{45}^-	$-$
	Z_2 class	$(0;000)$

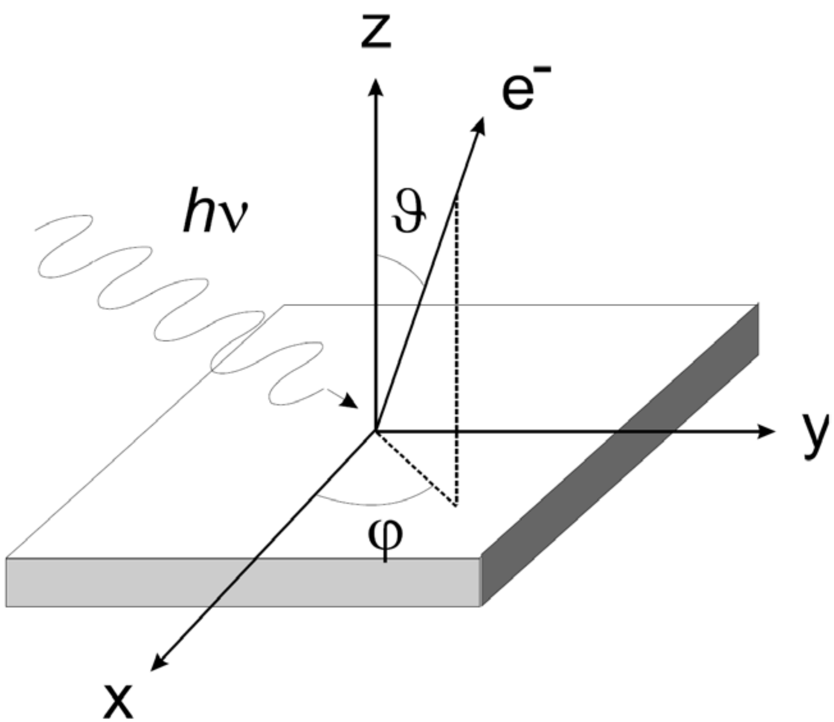
Antimony

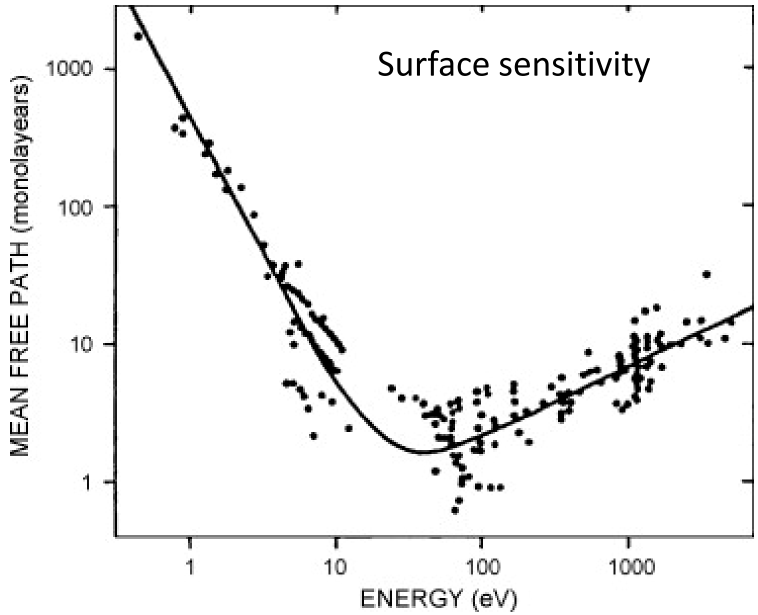
1Γ	Γ_6^+ Γ_6^- Γ_6^+ Γ_6^+ Γ_{45}^+	$-$
$3L$	L_s L_a L_s L_a L_s	$+$
$3X$	X_a X_s X_s X_a X_a	$-$
$1T$	T_6^- T_6^+ T_6^- T_6^+ T_{45}^-	$-$
	Z_2 class	$(1;111)$



For details see Marcel Franz talk

Basics of angle-resolved photoemission spectroscopy

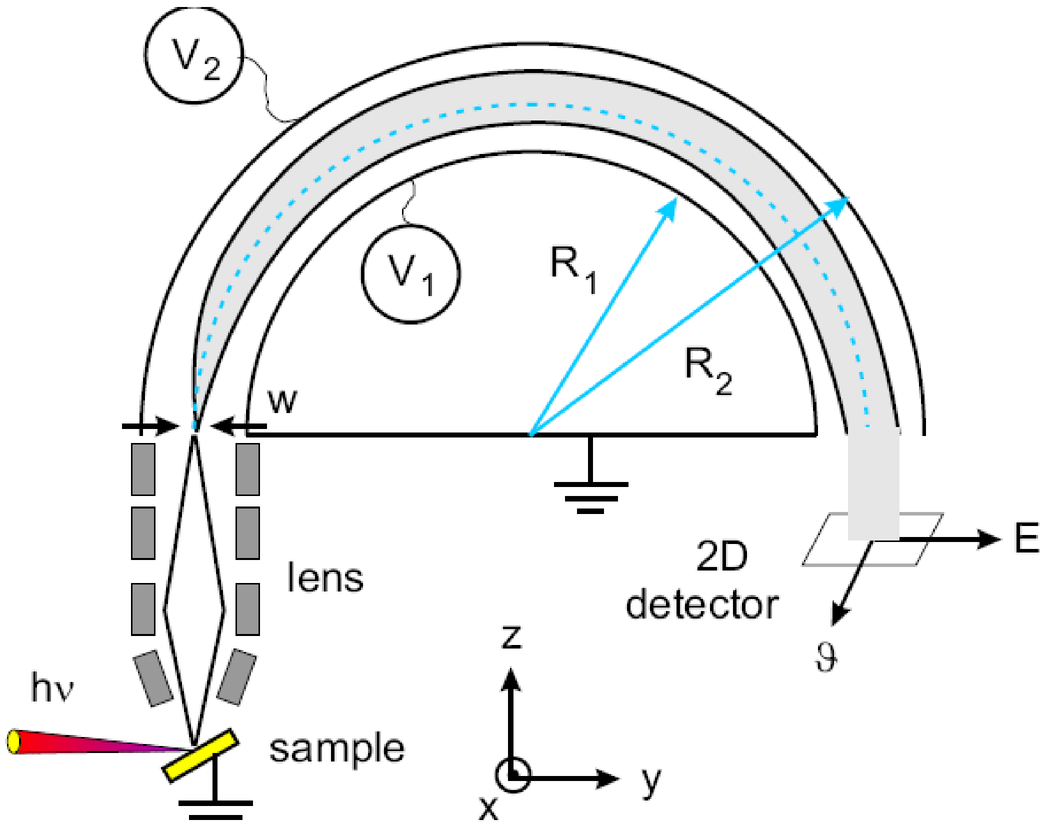


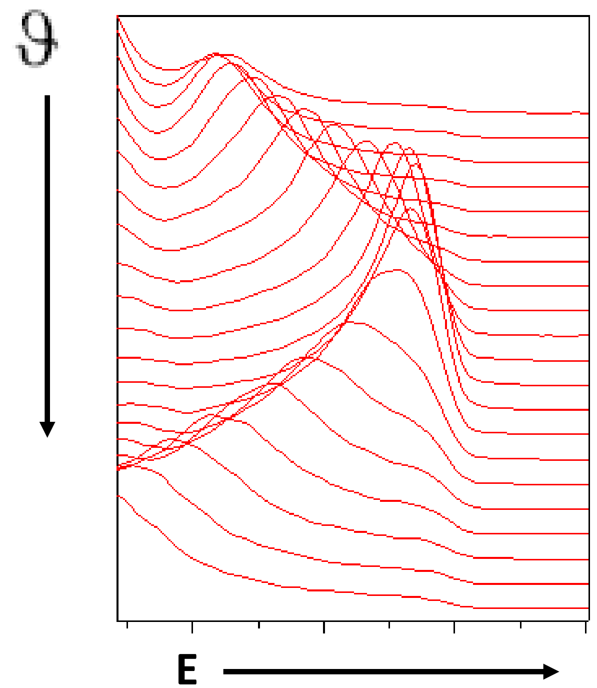


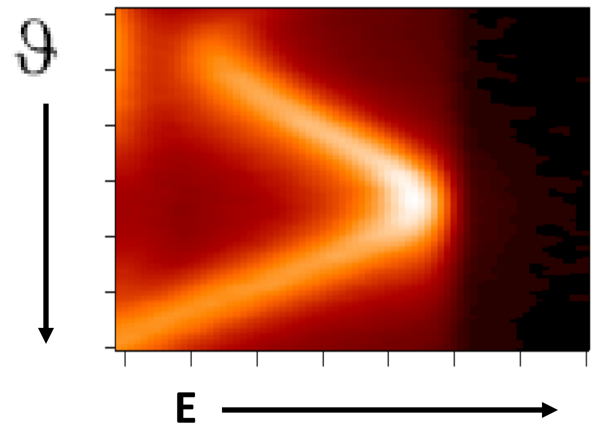
By measuring electron intensity as a function of E_{kin}, ϑ and φ, a momentum resolved energy spectrum is obtained.

See also Marco Grioni talk

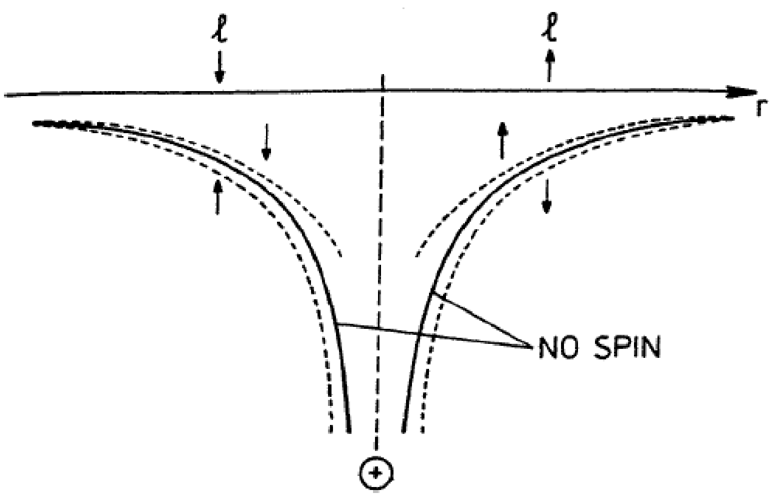
ARPES measurement technique







Basics of spin-resolved ARPES

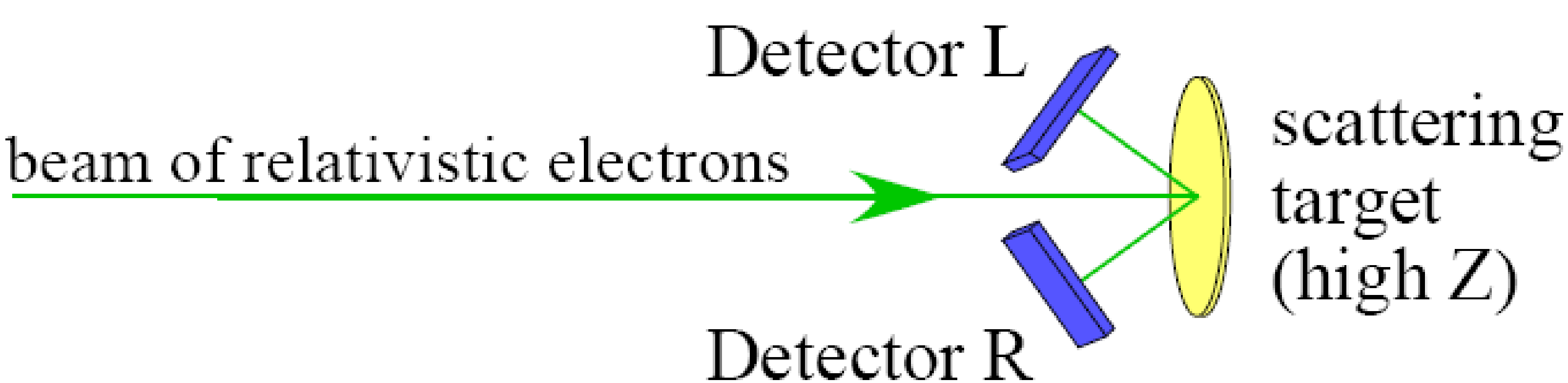


High Z atom

- Mott asymmetry left-right scattering of electron depending on its spin

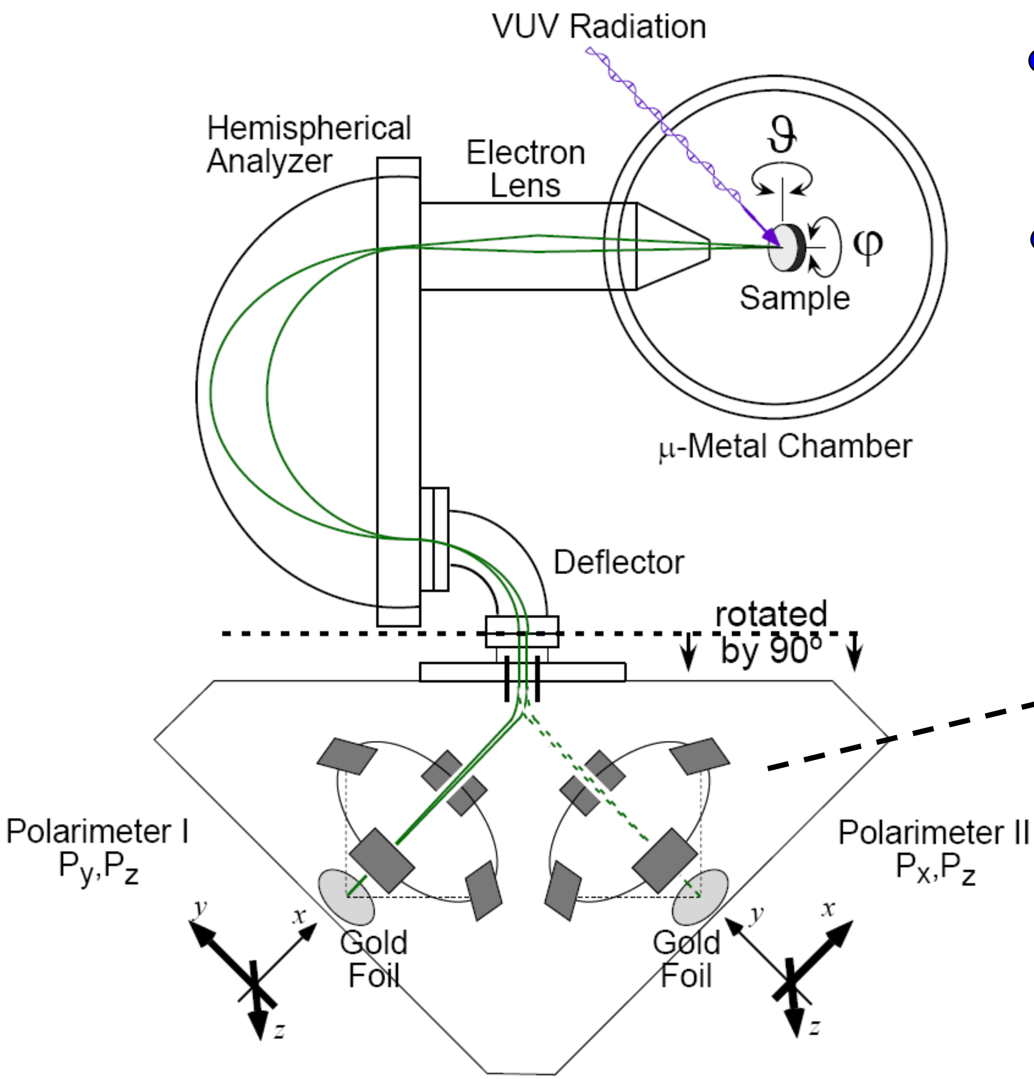
- Incident beam spin polarization given by

$$P \propto \frac{I_L - I_R}{I_L + I_R}$$



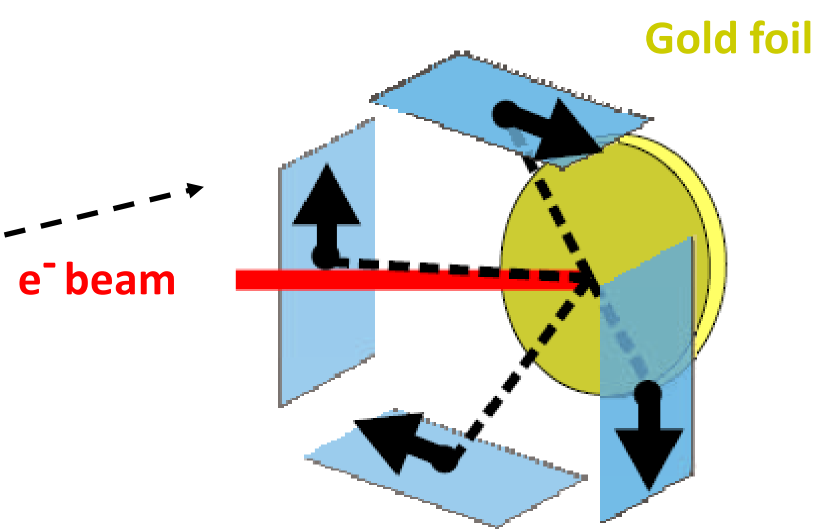
See also Marco Grioni talk

Double Mott detector configuration



M. Hoesch (PhD Thesis U. Zurich)

- Each Mott detector measures 2 orthogonal spin components
- Double Mott detector captures 4 (3 indep.) spin components



Common Light Sources for ARPES

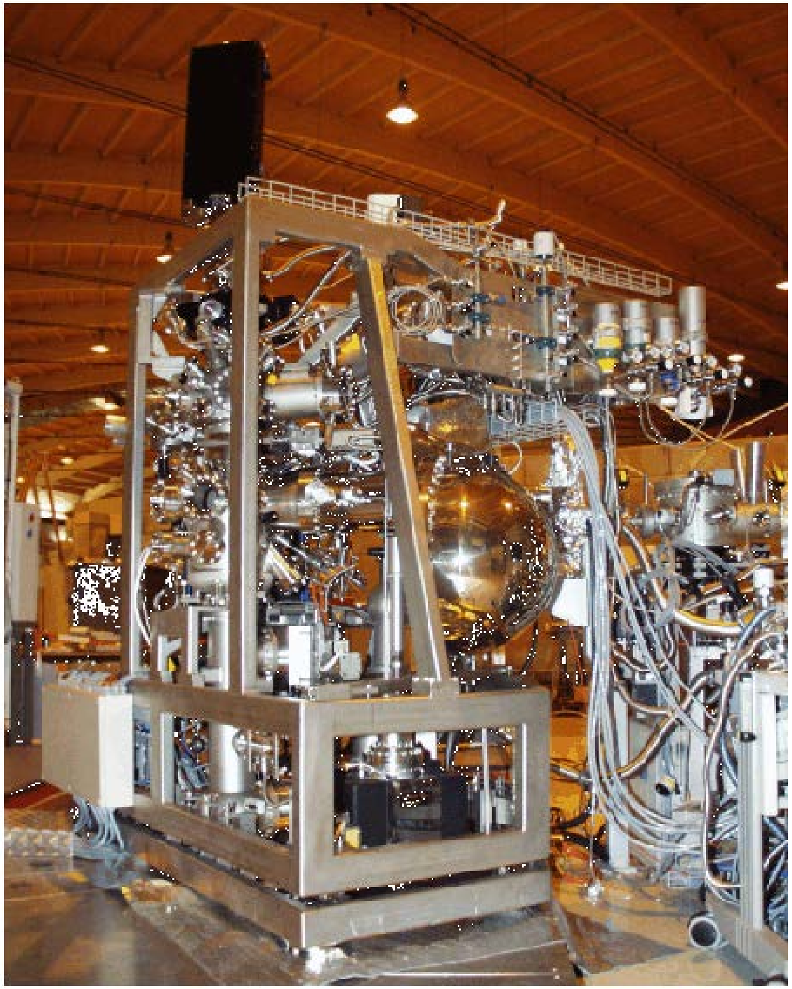
Synchrotron

Plasma Discharge

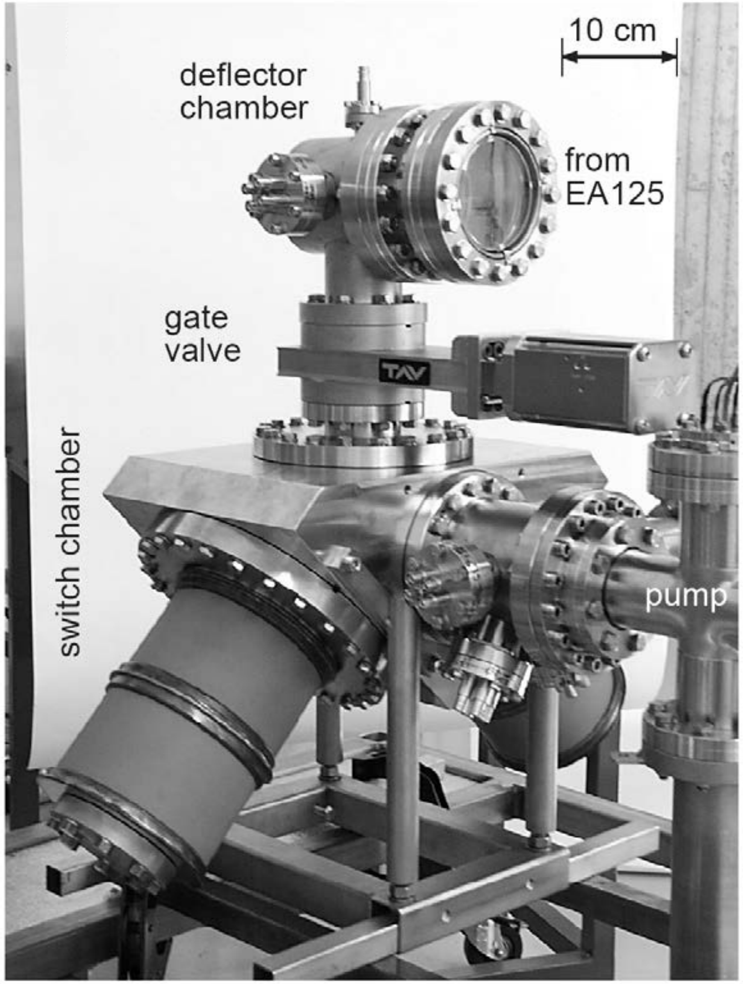
Lasers

Hemispherical and Spin-Resolved Detectors

Hemispherical analyzer

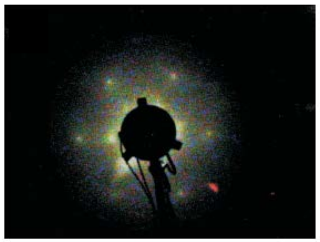


Double Mott detector

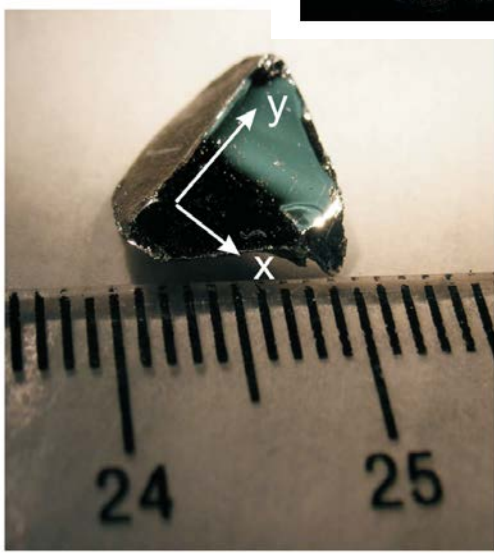


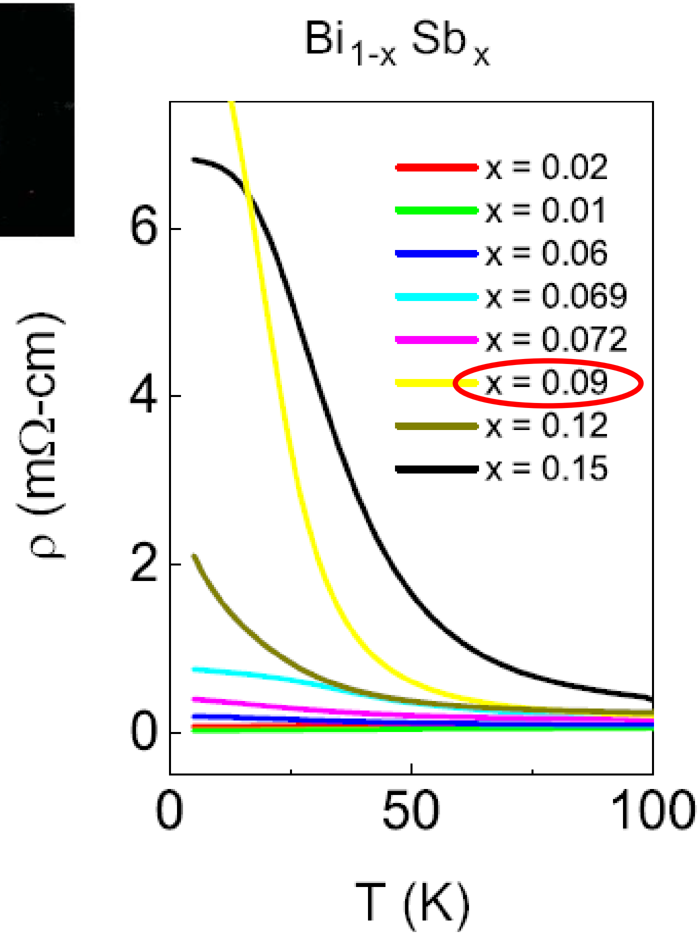
Sample characterization of $Bi_{1-x}Sb_x$

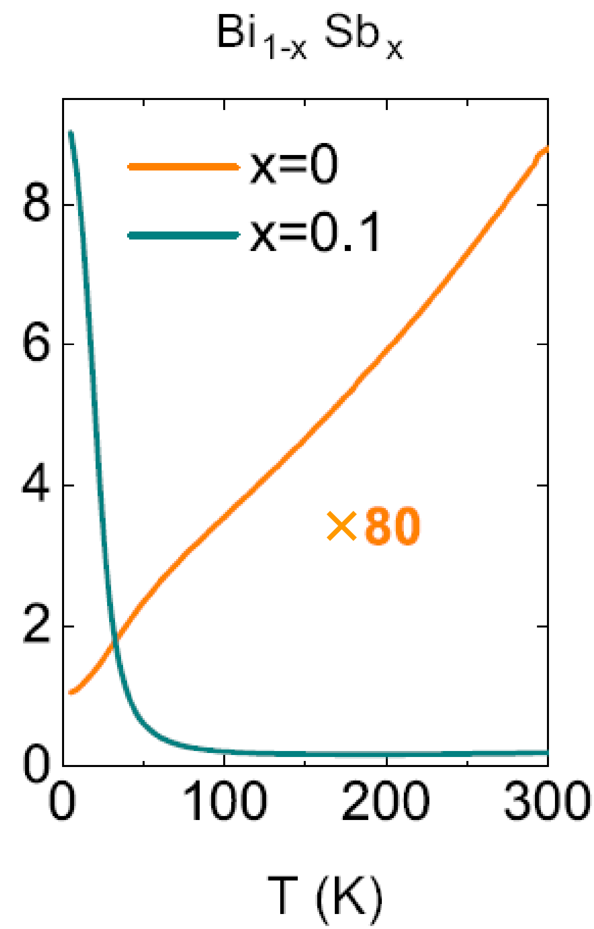
(111) surface LEED



High surface quality

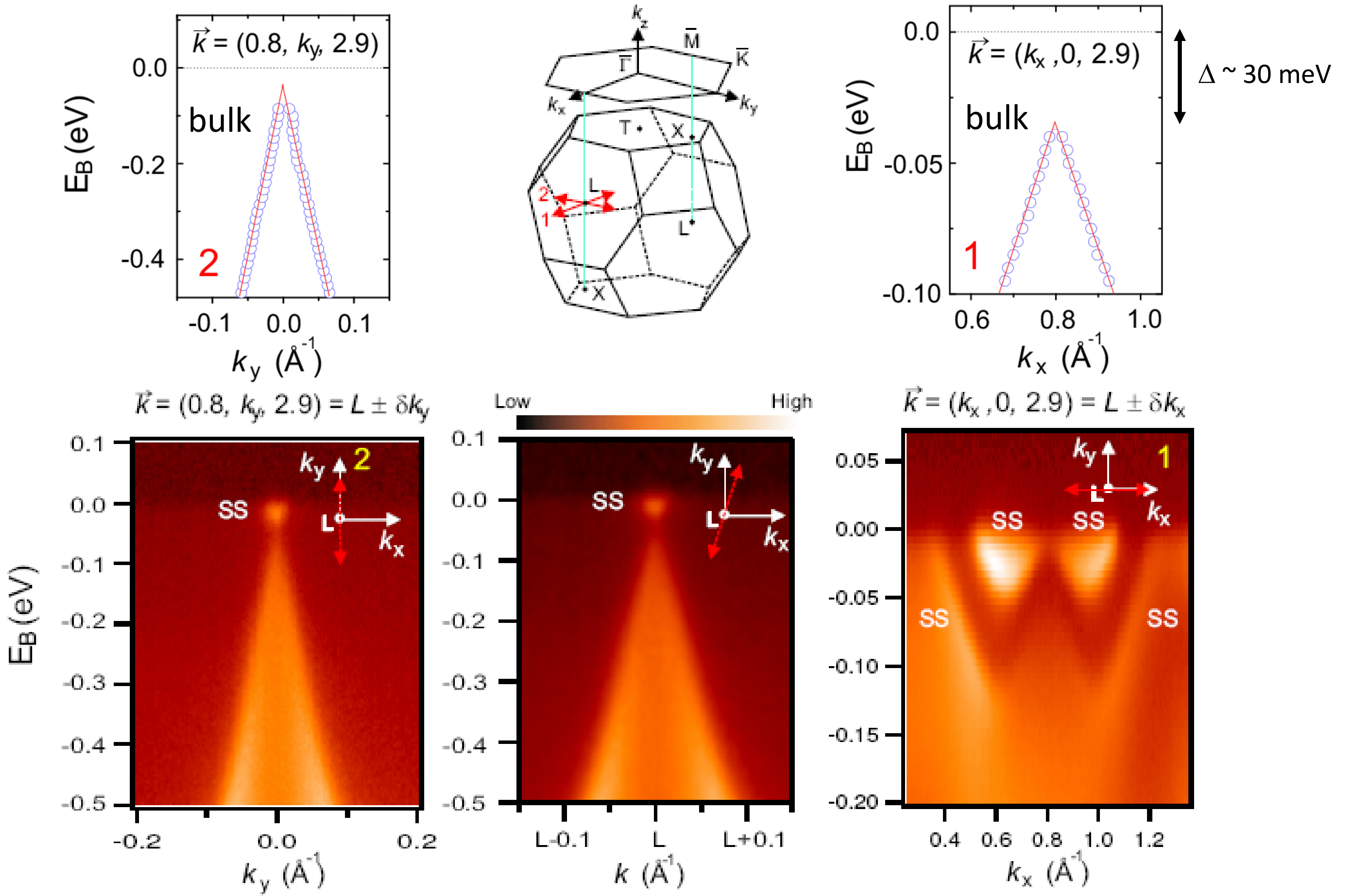






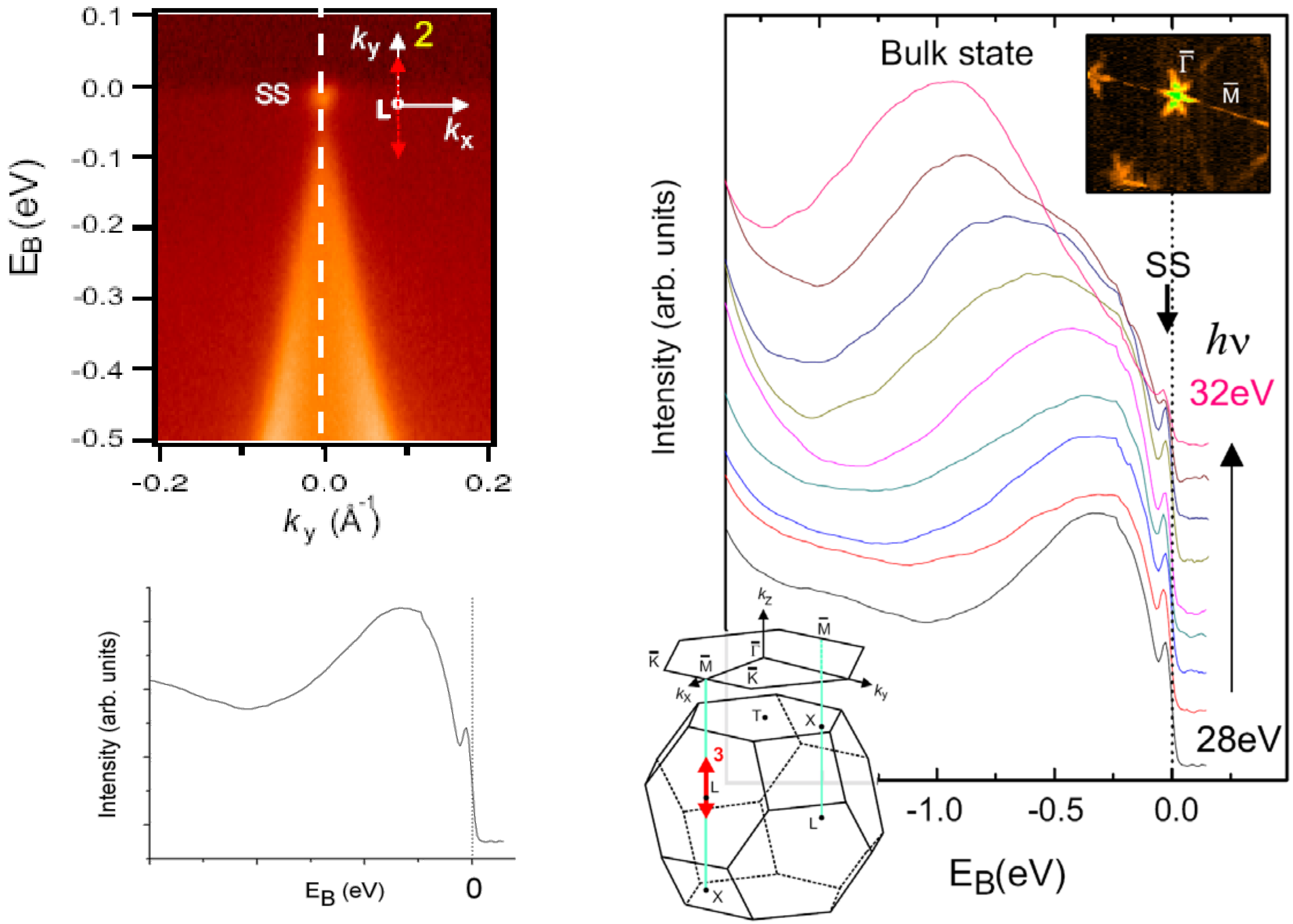
Hsieh et al., Nature **452**, 970 (2008)

Measuring bulk 3D Dirac fermions with ARPES



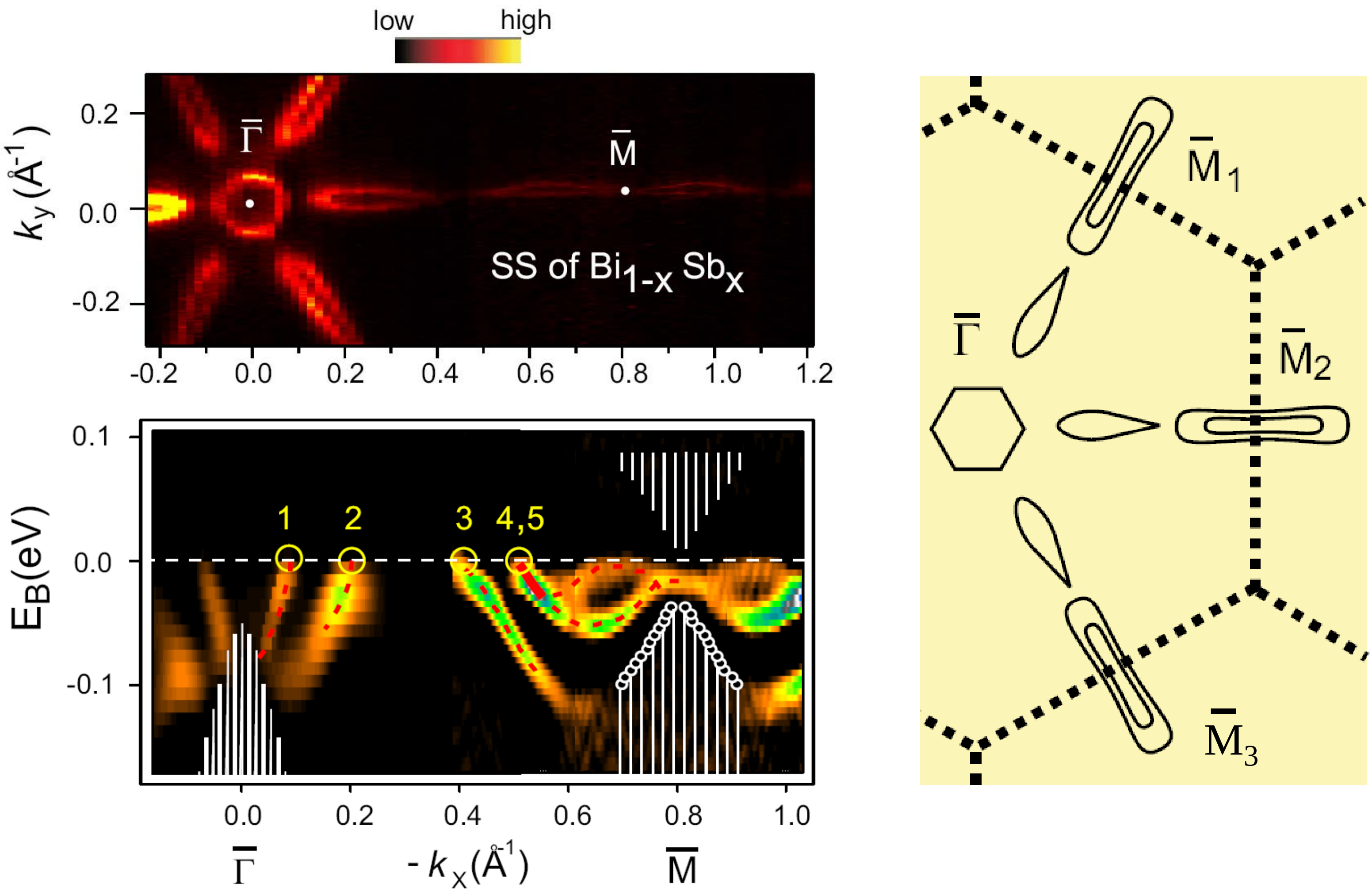
Hsieh et al., Nature **452**, 970 (2008)

Distinguishing bulk from surface states with ARPES



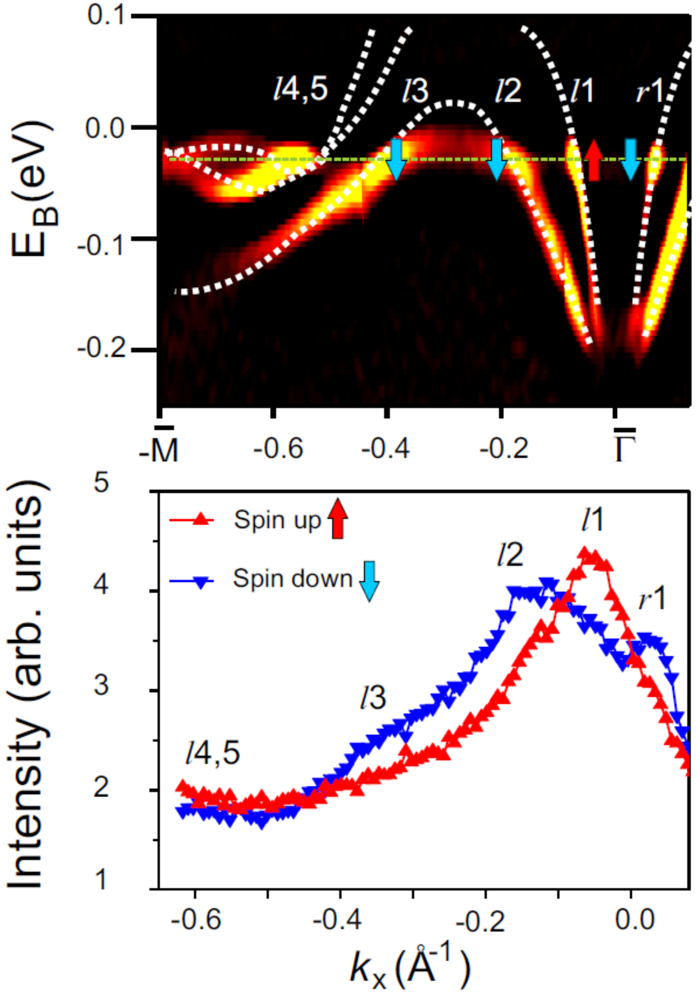
Hsieh et al., Nature **452**, 970 (2008)

Evidence for ν_0 = 1 gapless surface states on $Bi_{0.9}Sb_{0.1}(111)$

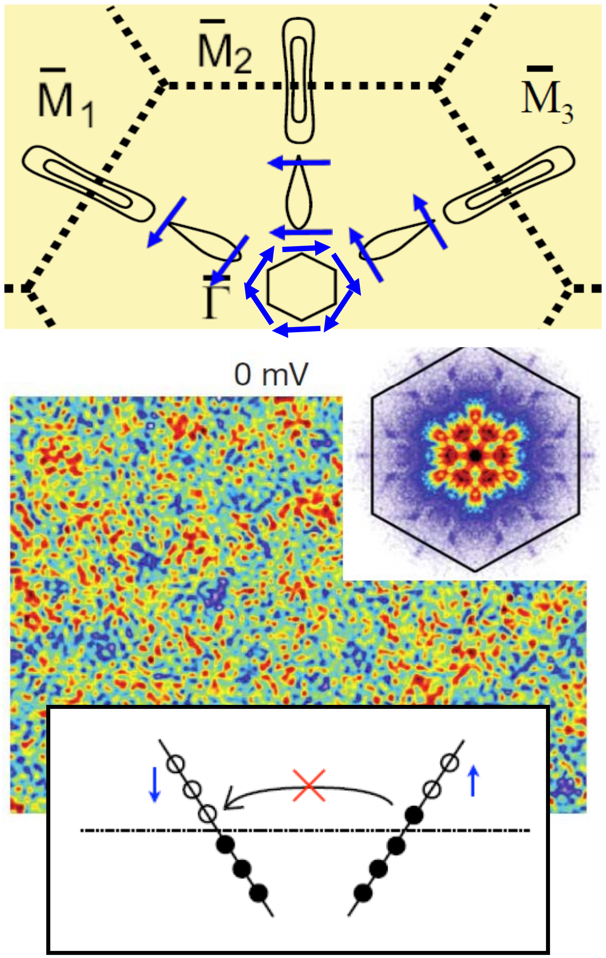


Hsieh et al., Nature **452**, 970 (2008)

Spin-texture of the $Bi_{1-x}Sb_x(111)$ Fermi surface



Spin-momentum locked texture describes π Berry's phase

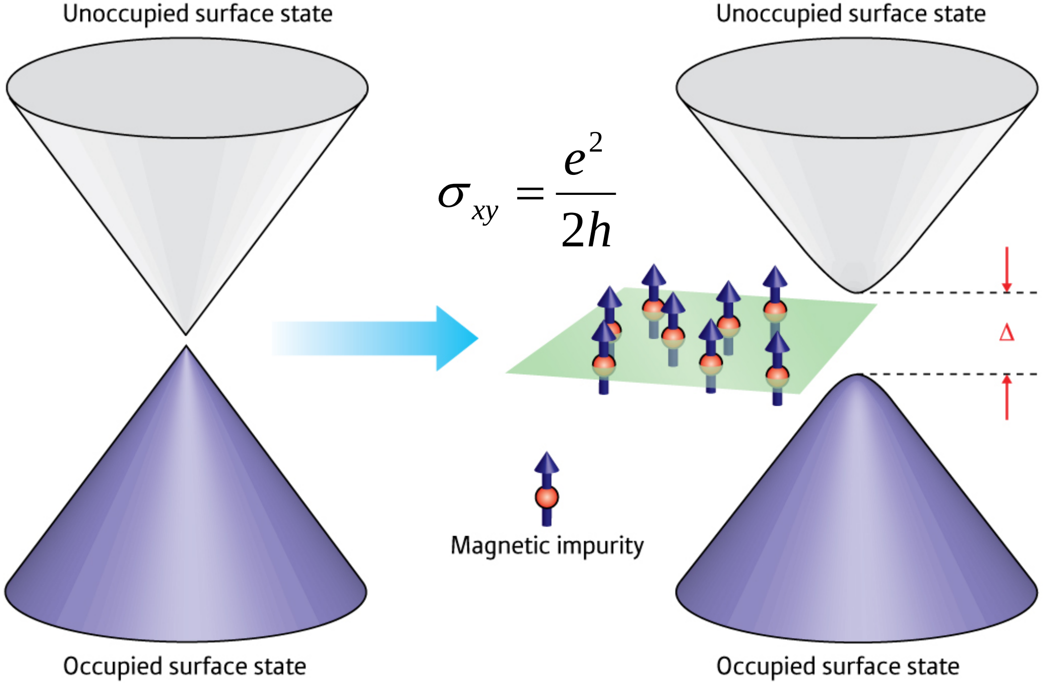


Hsieh et al., Science **323**, 919 (2009)

Roushan et al., Nature **460**, 1106 (2009)

Why the need to go beyond $Bi_{1-x}Sb_x$?

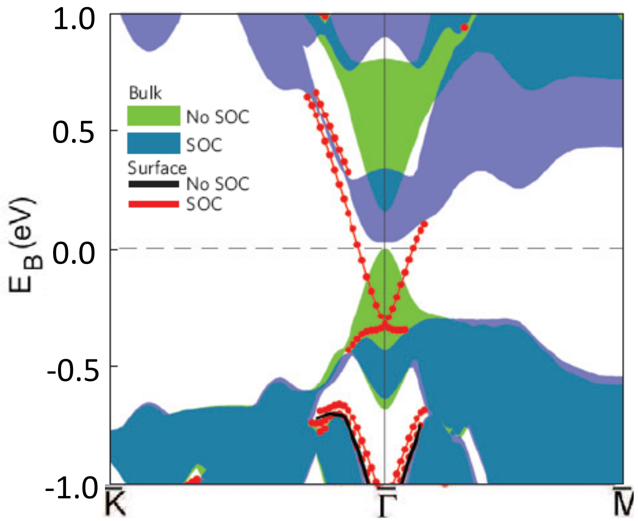
- $Bi_{1-x}Sb_x$ SS crosses E_F 5 times (4 trivial, 1 topological).
- Bulk gap is small (~ 50 meV).
- Disorder (random alloy).
- Cannot be tuned to Dirac neutrality point

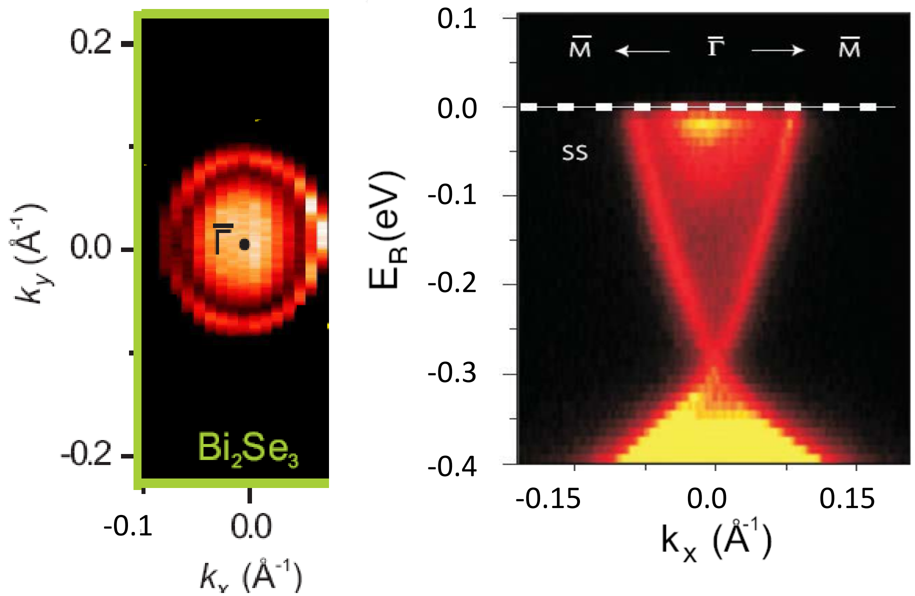


Fu & Kane, PRB **76**, 045302 (2007)

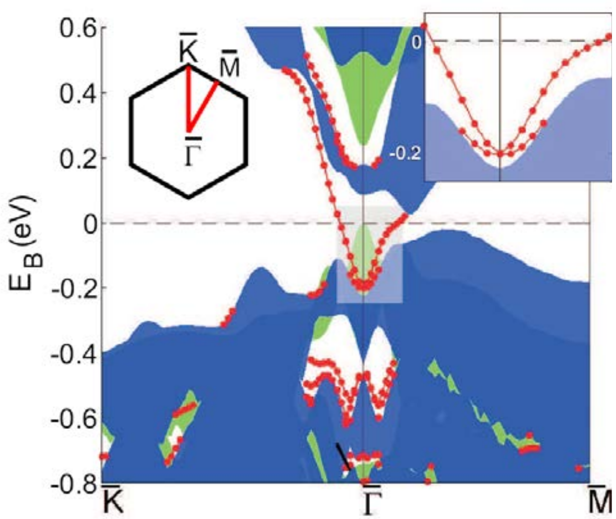
Qi, Hughes, Zhang, PRB **78**, 195424 (2008)

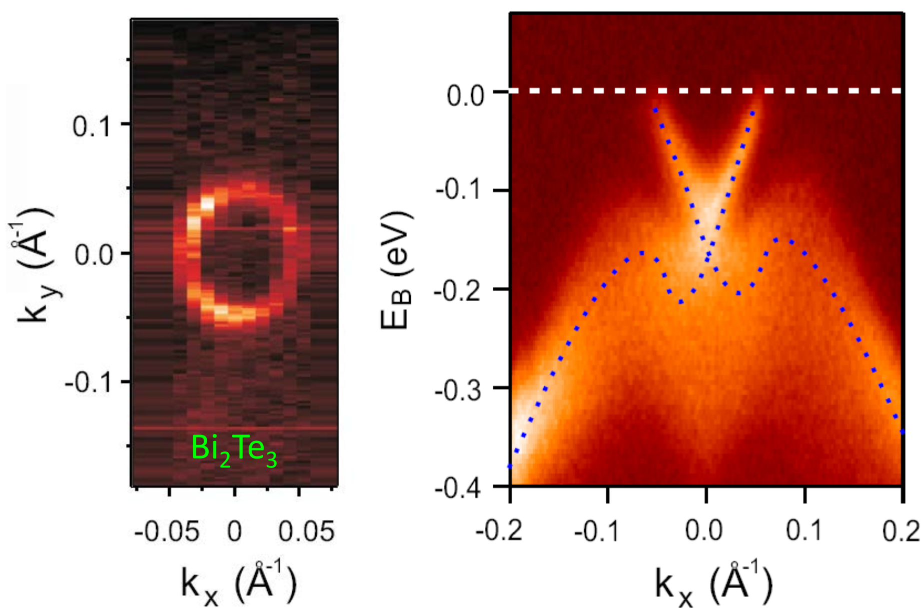
Single topological Dirac cone in Bi_2Se_3 and Bi_2Te_3





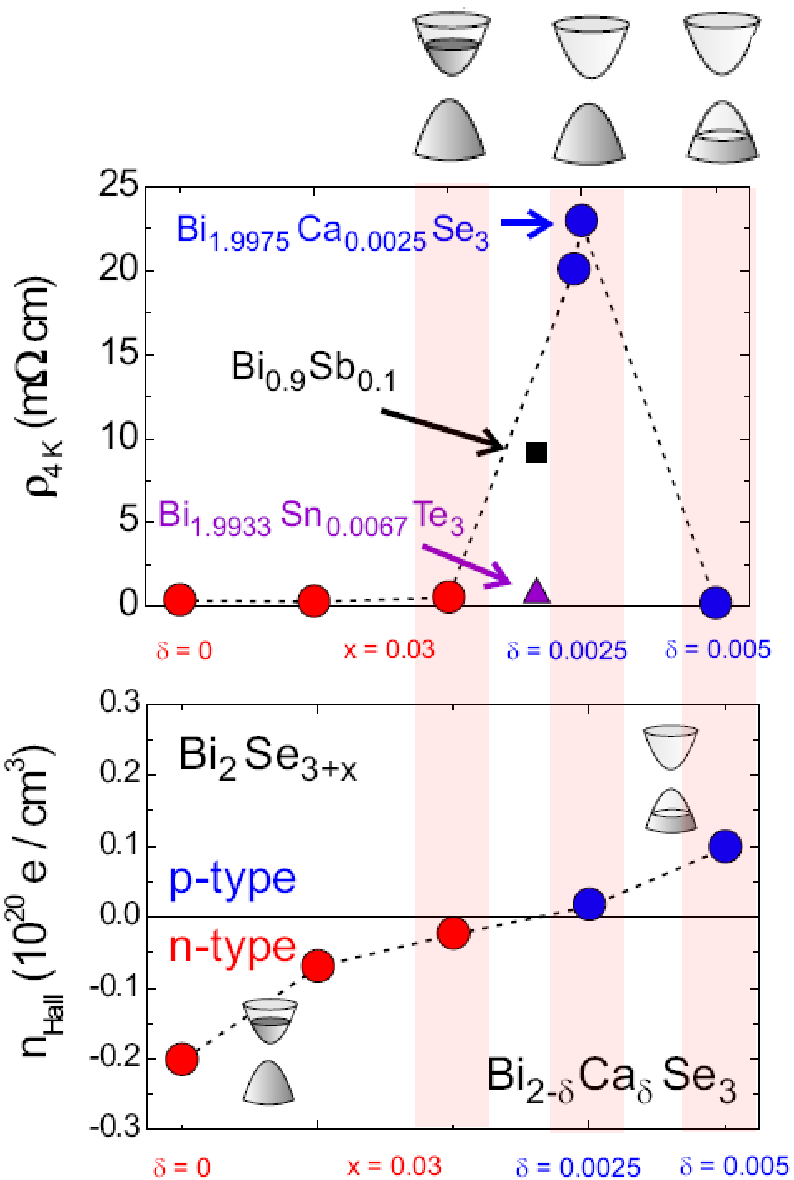
Xia, Qian, DH et al., Nature Physics **5**, 398 (2009)

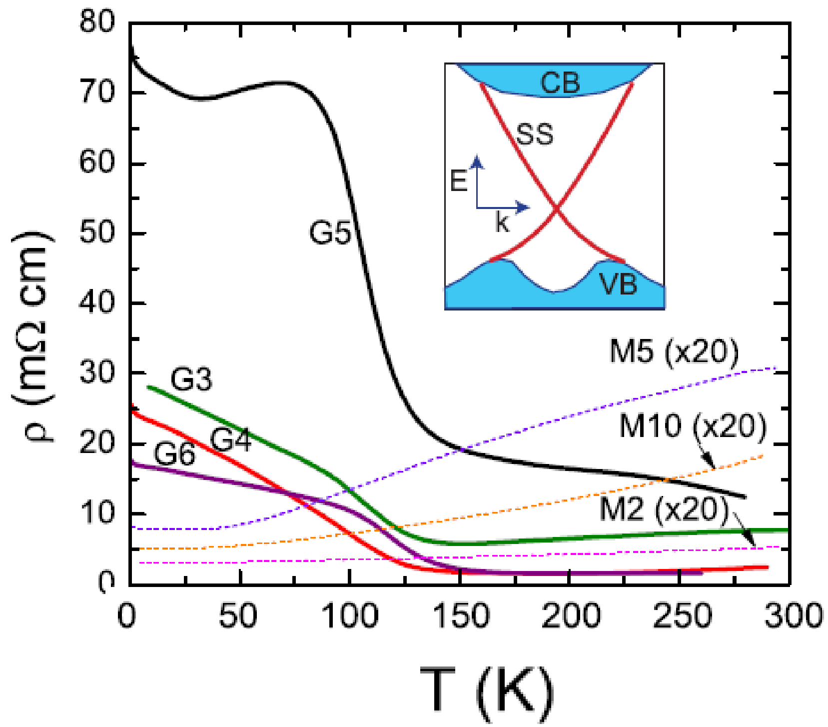




DH et al., PRL **103**, 146401 (2009)

Tuning to bulk insulator regime (transport signatures)

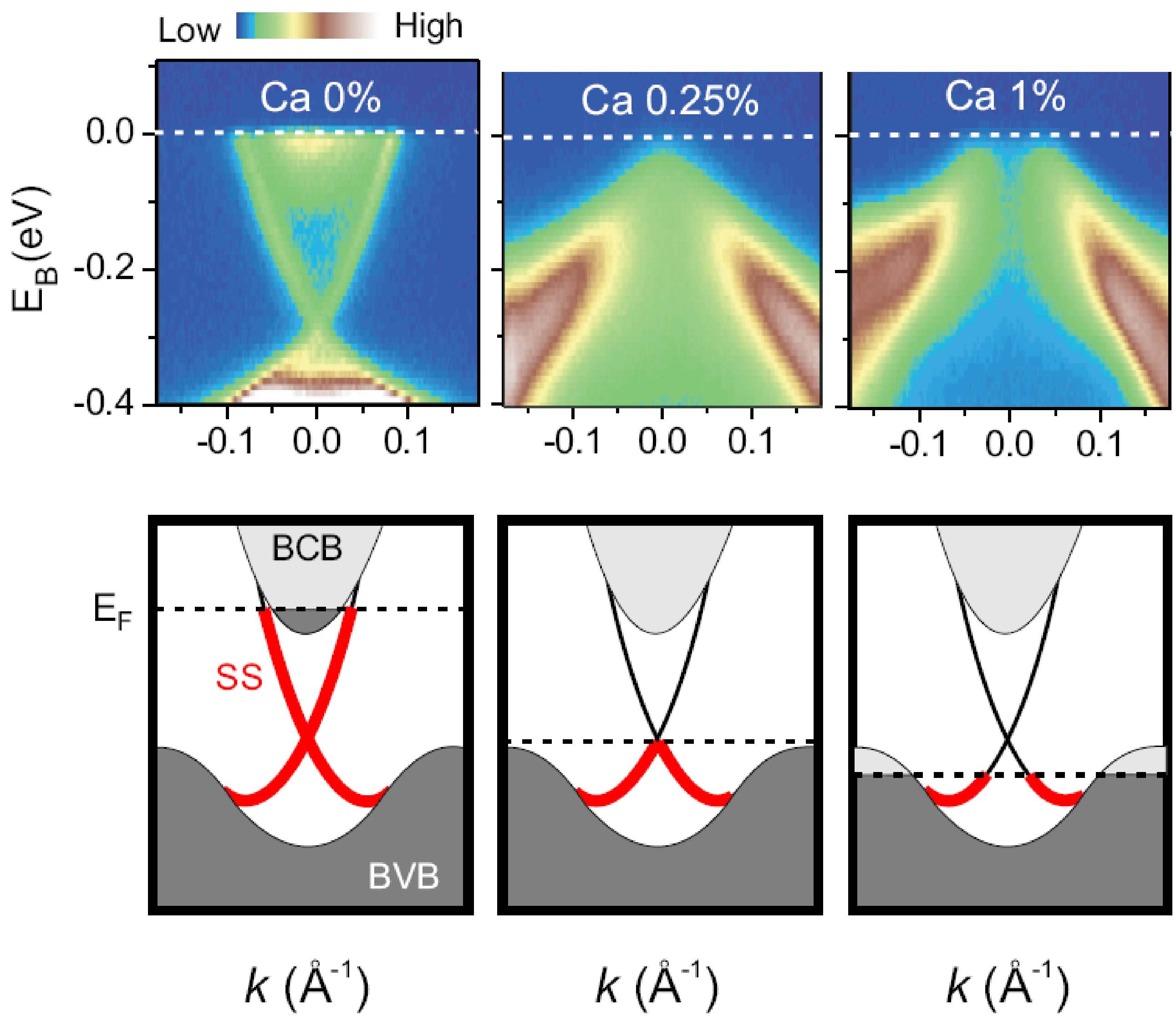




Hsieh et al., Nature **460**, 1101 (2009)

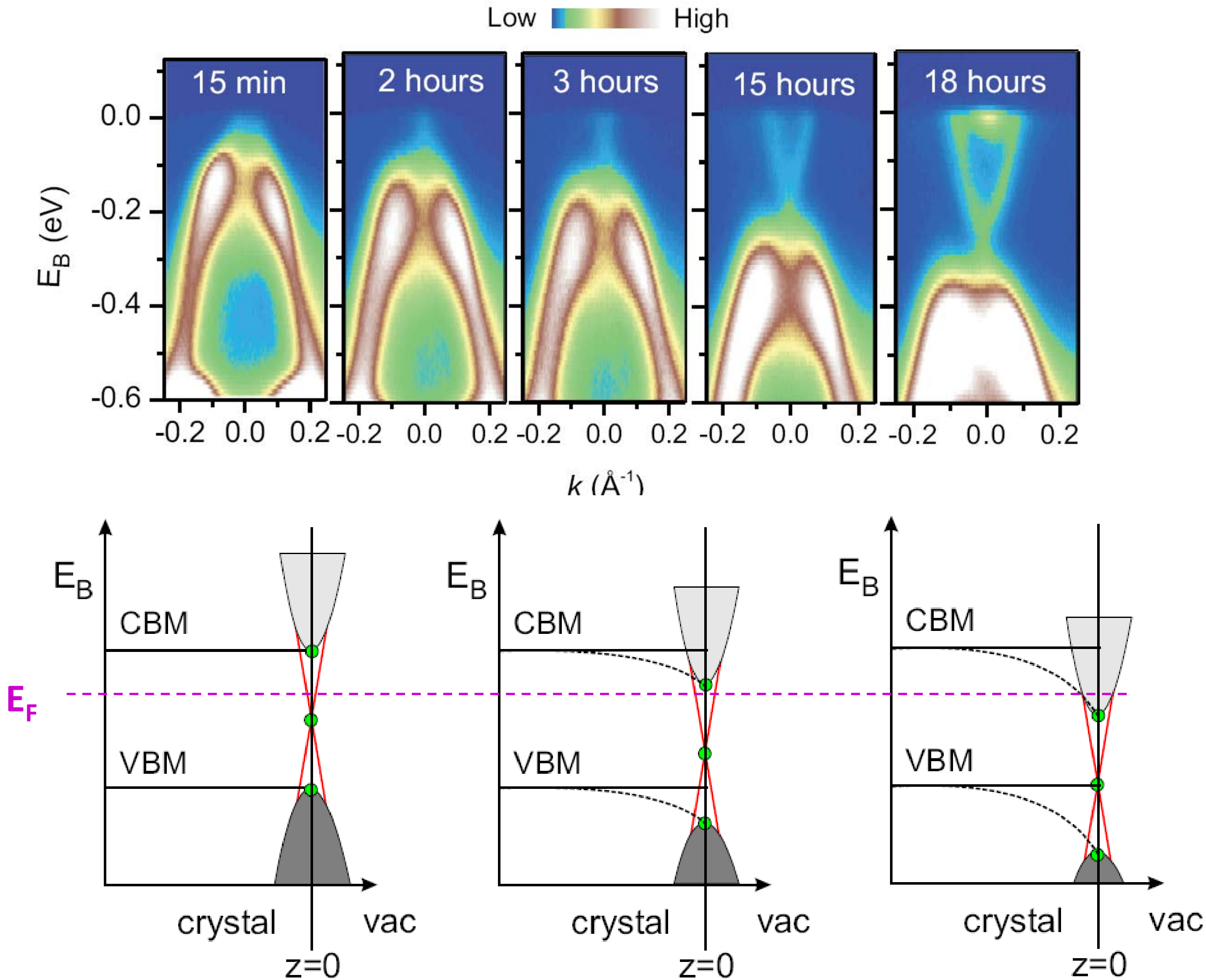
Checkelsky et al., PRL **103**, 246601 (2009)

Tuning to bulk insulator regime (ARPES signatures)



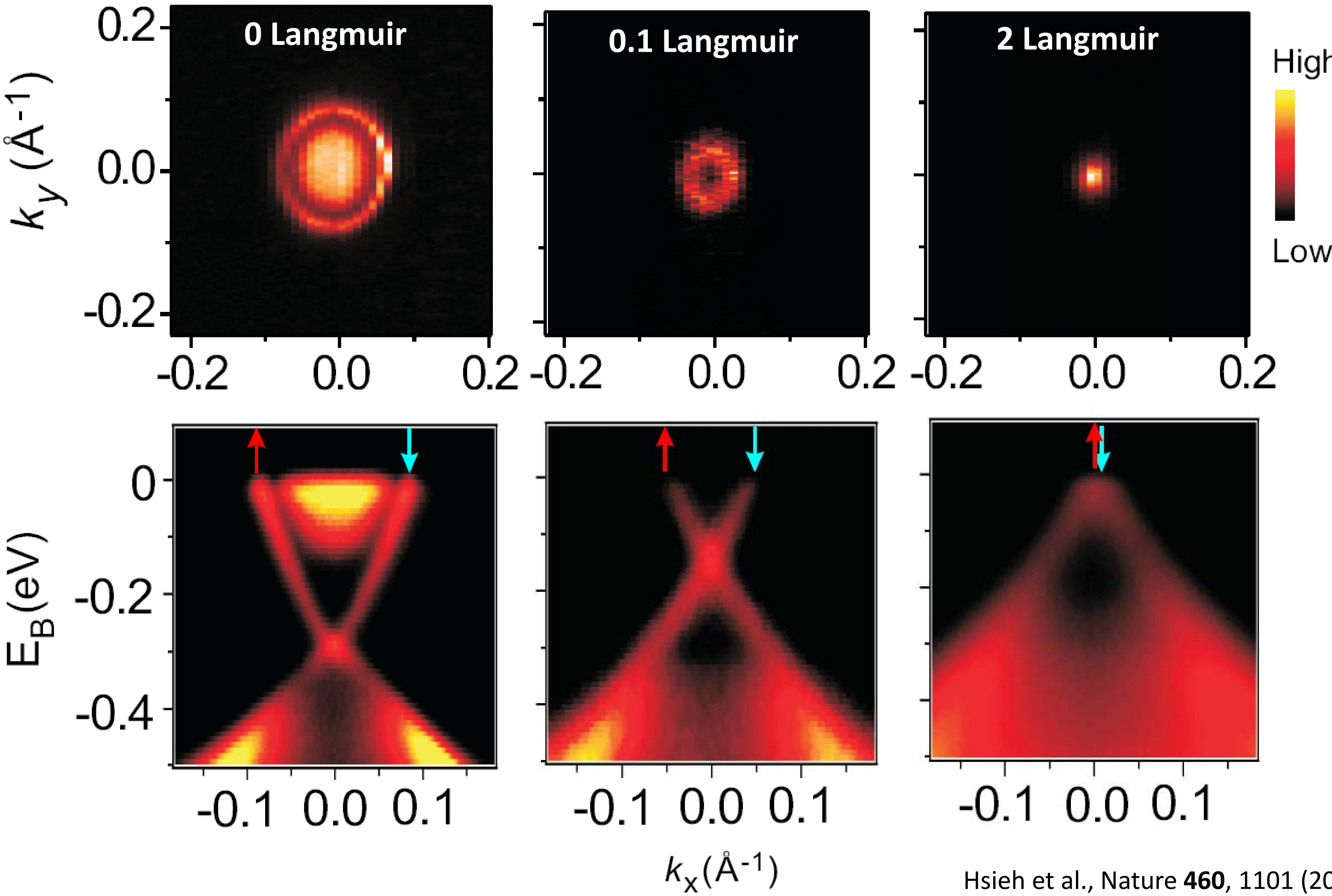
Hsieh et al., Nature **460**, 1101 (2009)

Time dependence of surface band bending



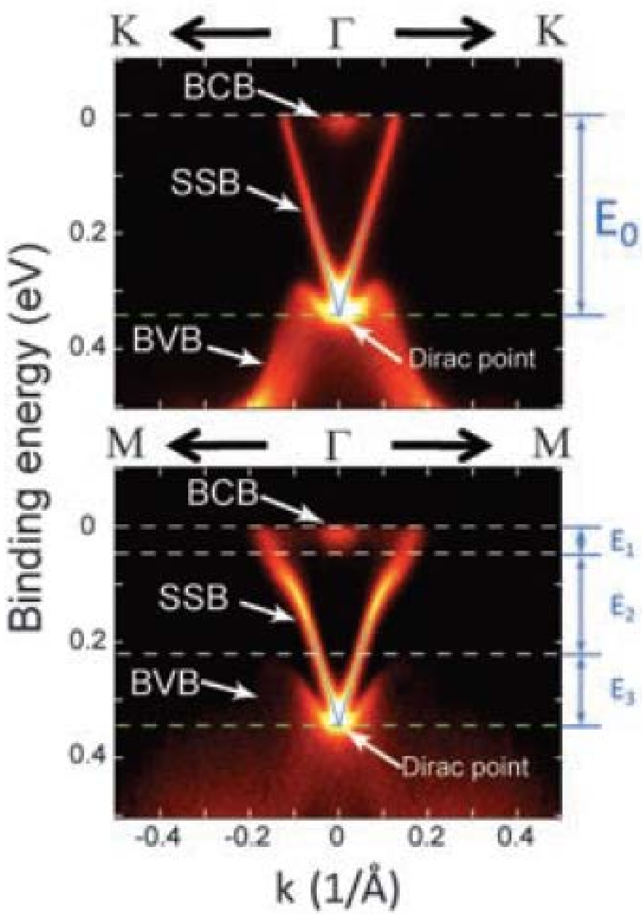
Hsieh et al., Nature **460**, 1101 (2009)

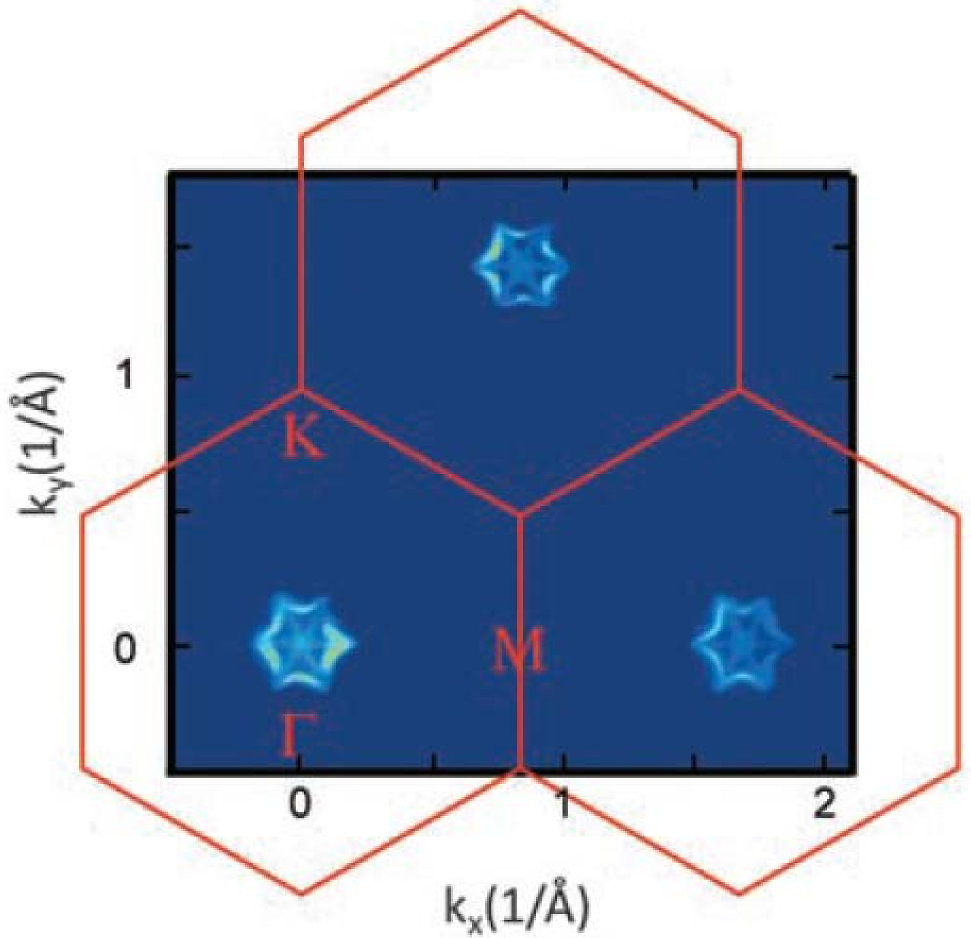
Depleting surface carriers via NO_2 adsorption



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

ARPES spectra of p-type Bi_2Te_3

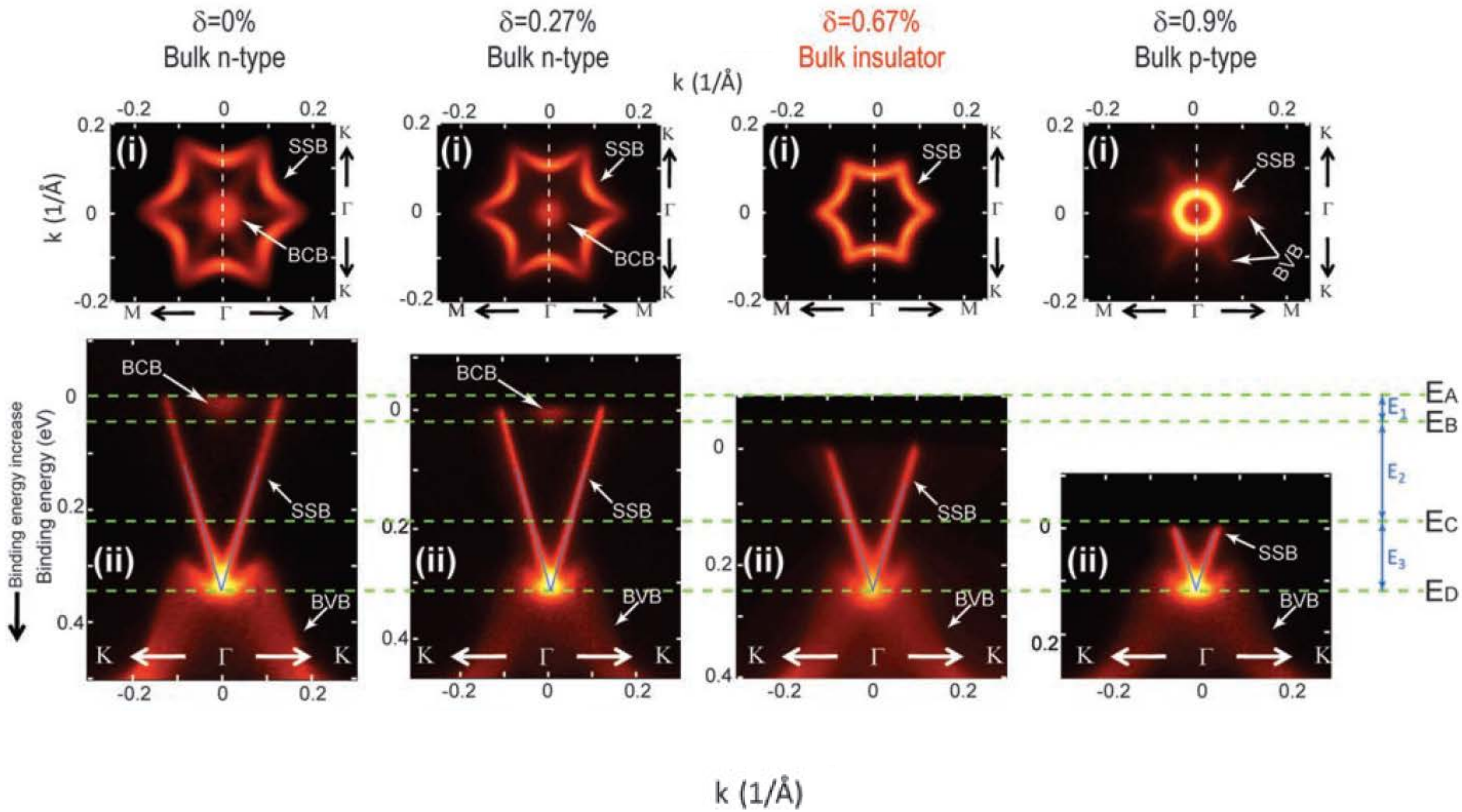




Chen et al., Science **325**, 178 (2009)

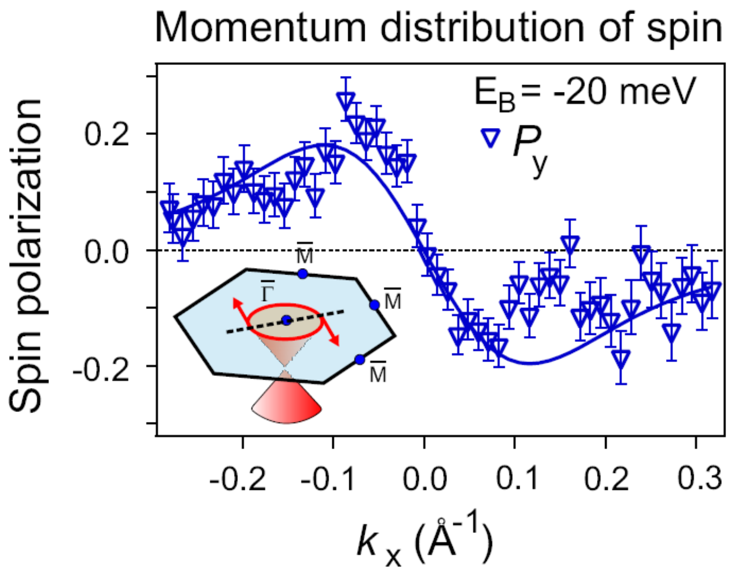
Hexagonal warped FS predicted by Fu, PRL **103**, 266801 (2009)

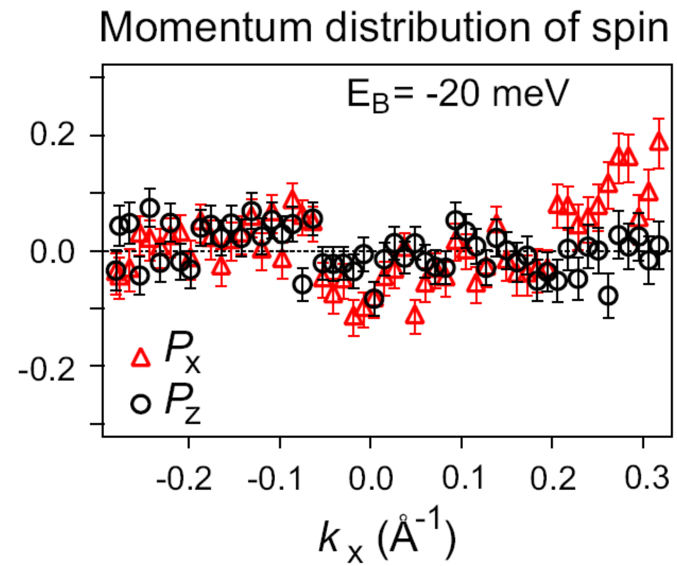
Reducing bulk carrier density via $(Bi_{1-\delta}Sn_{\delta})_2Te_3$

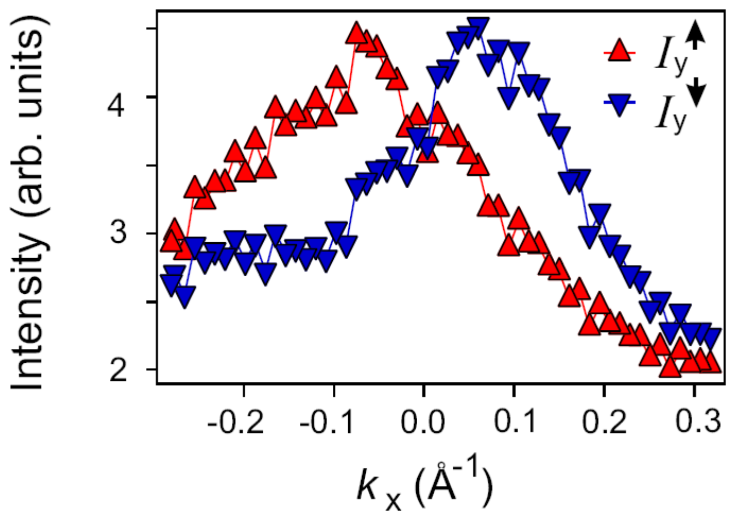


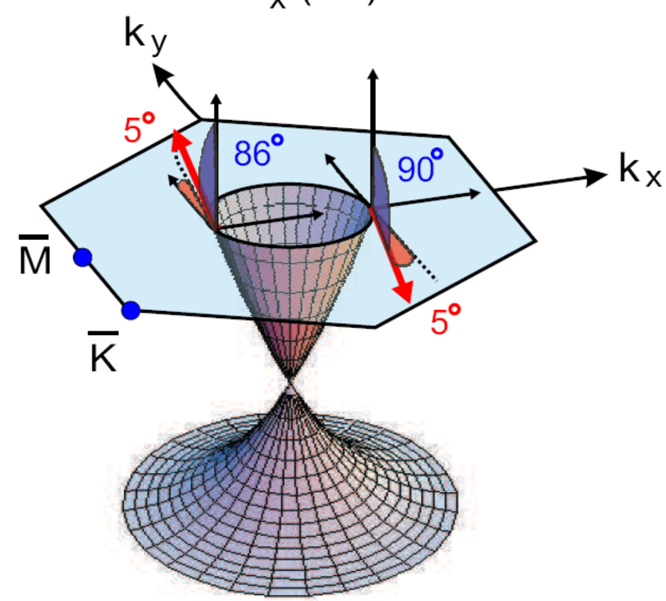
Chen et al., Science **325**, 178 (2009)

Spin-momentum locking in Bi_2X_3 series



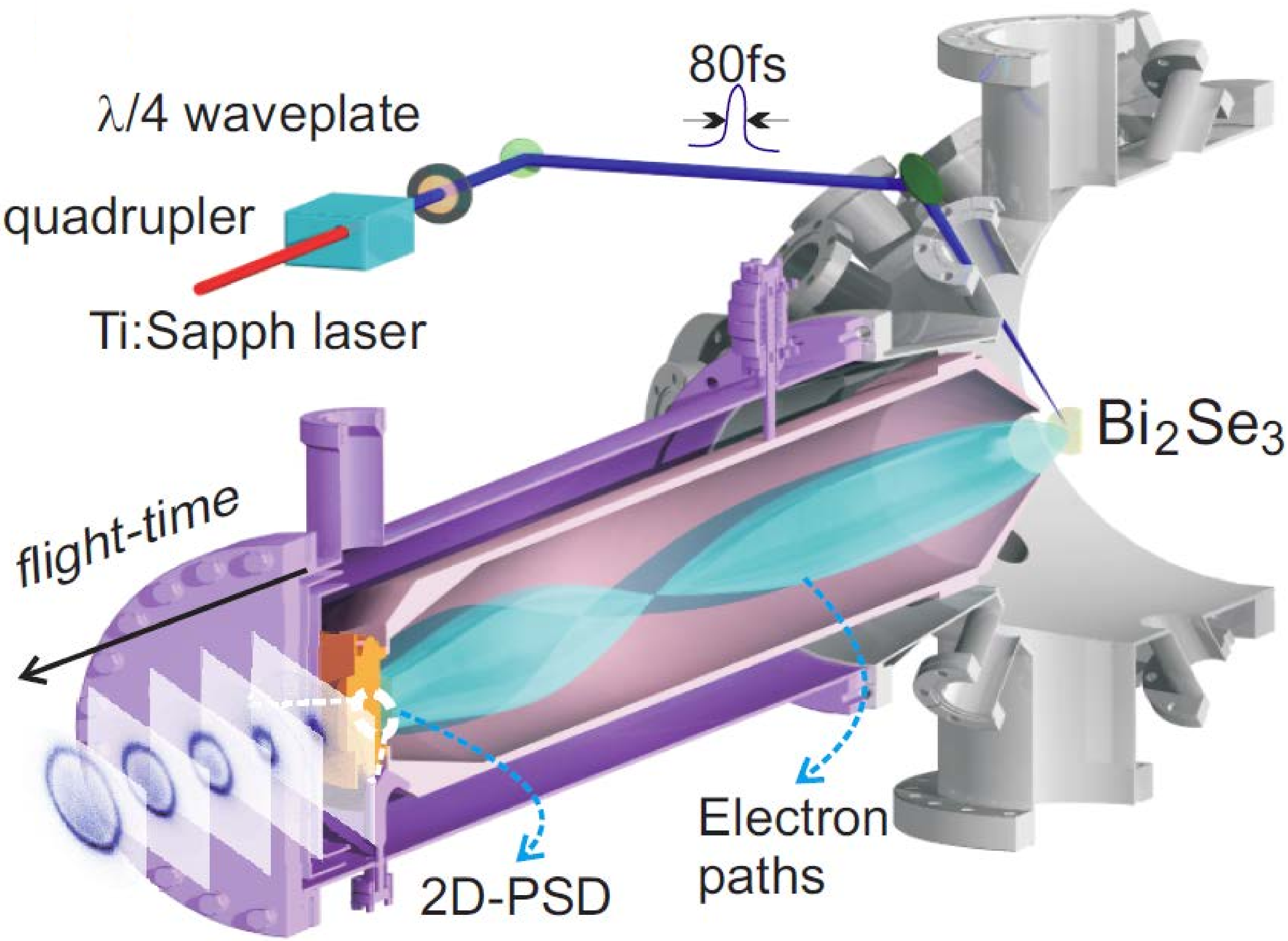






Hsieh et al., Nature **460**, 1101 (2009)

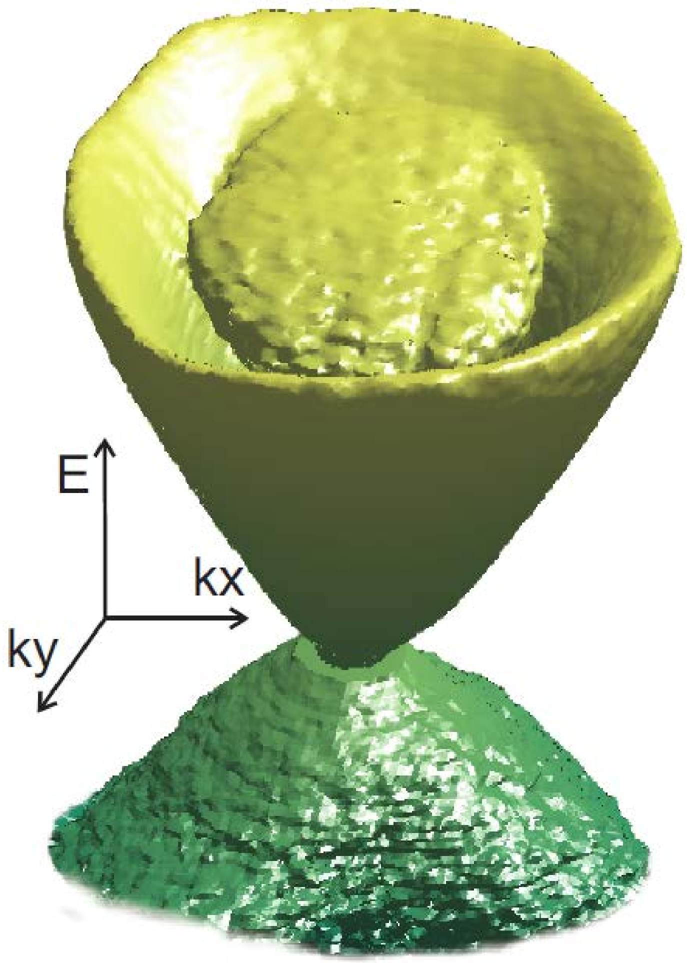
Time-of-flight based ARPES

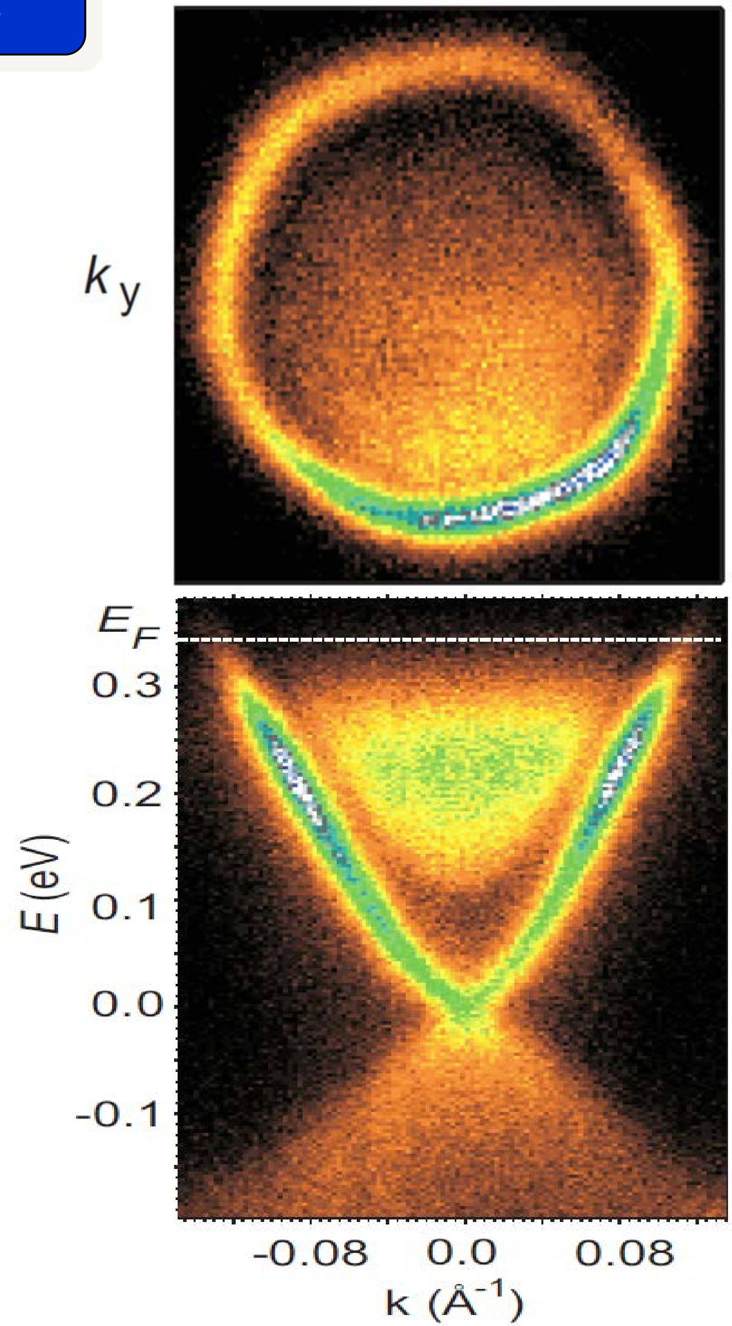


Collaboration with Prof. Nuh Gedik (MIT)

Simultaneous phase space mapping

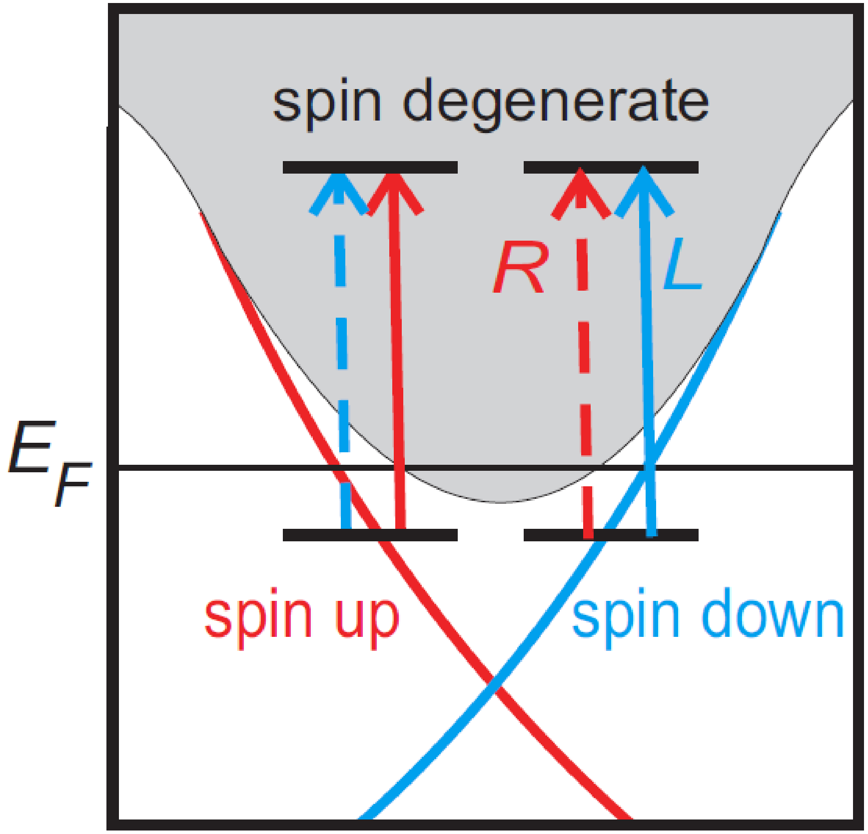
Resolved deformation features in Bi_2Se_3

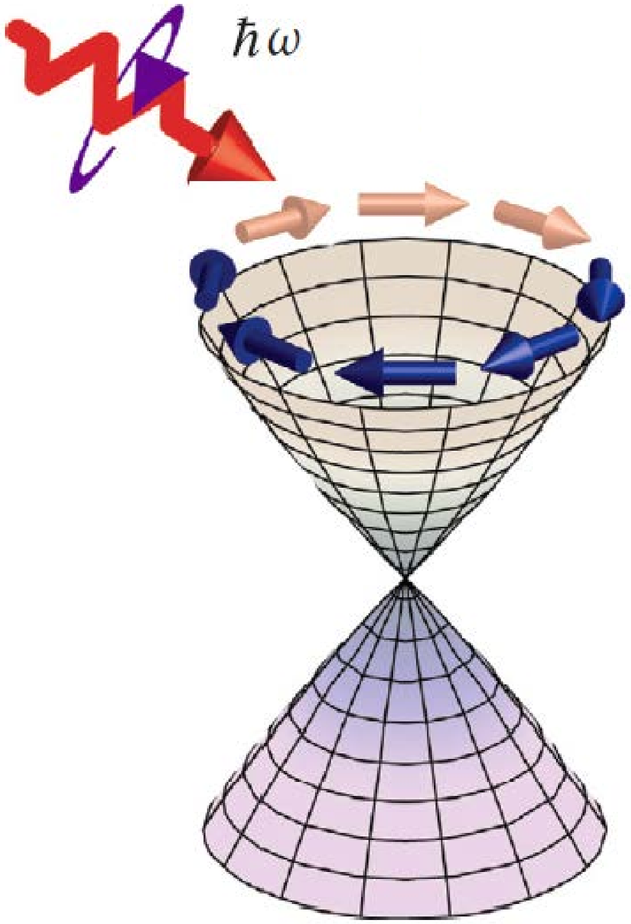




Y.H. Wang, D.H, et al., PRL 107, 207602 (2011)

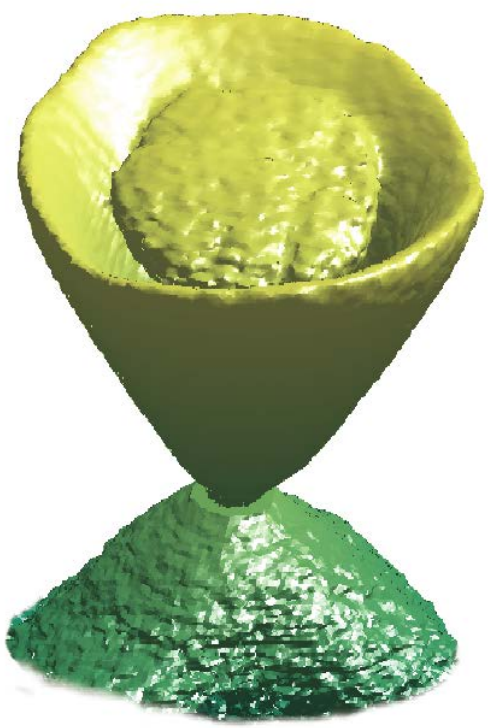
Spin dependent transition rates with circular light

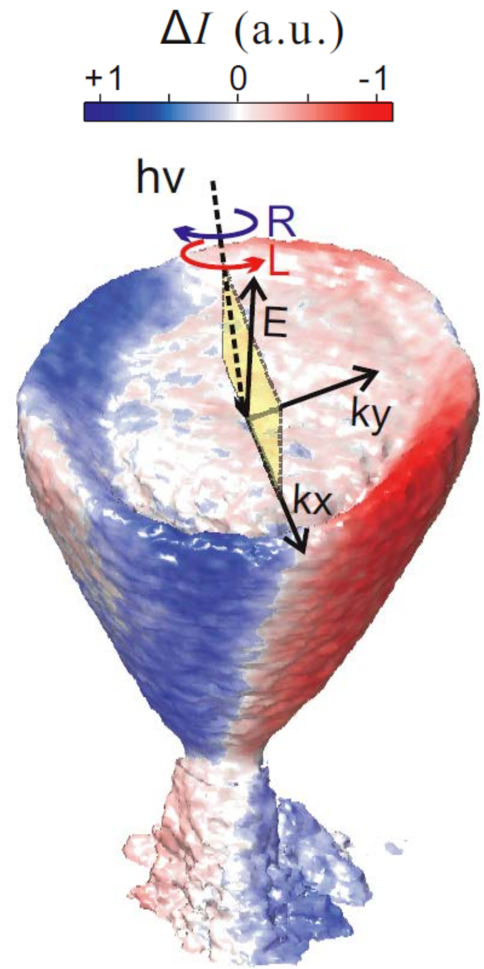


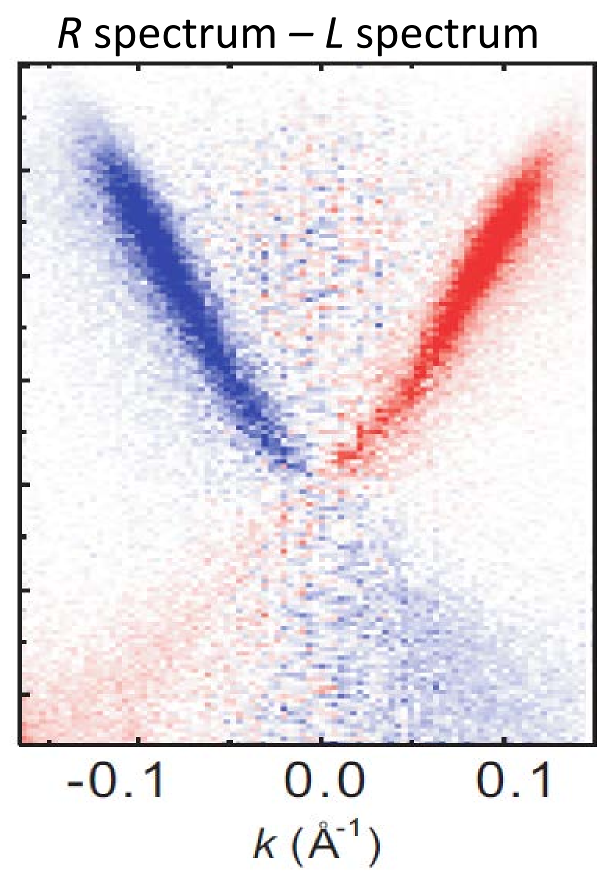


Y.H. Wang, D.H, et al., PRL 107, 207602 (2011)

Spin sensitivity with circular light



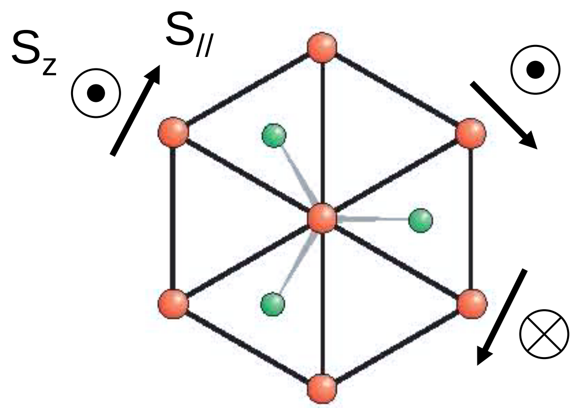




Y.H. Wang, D.H, et al., PRL 107, 207602 (2011)

3D vectorial spin analysis

$$\Delta I \equiv I_R - I_L = \alpha\langle S_x\rangle \mathrm{Re}\left(A_z^* A_y\right) + |\beta|\langle S_z\rangle \mathrm{Im}\left(A_x^* A_y\right)$$



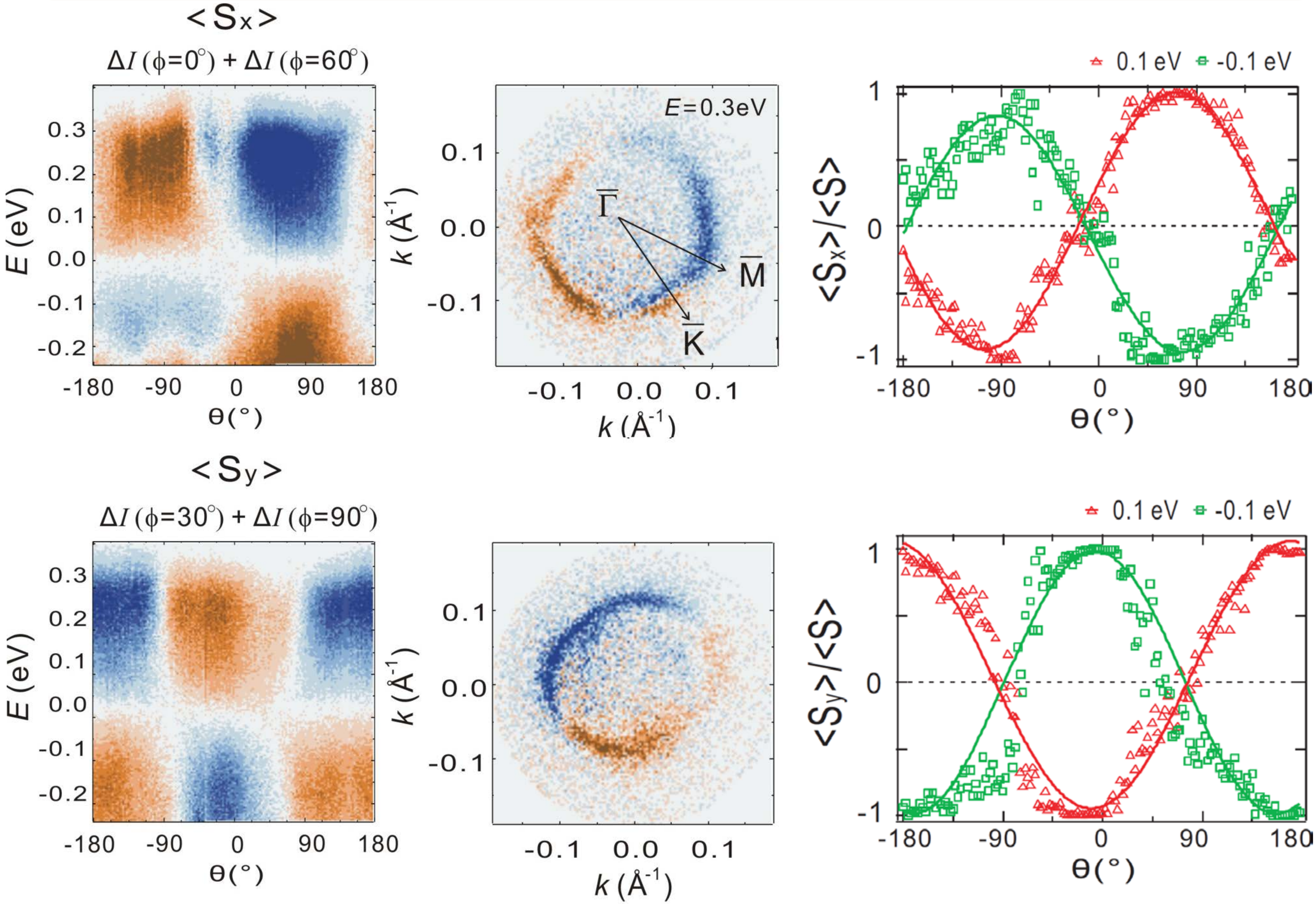
Time reversal symmetry + 3-fold rotational symmetry

Under 60 degree rotation $\langle S_x\rangle \rightarrow \langle S_x\rangle$ while $\langle S_z\rangle \rightarrow -\langle S_z\rangle$

$$\Delta I_{(60)} \equiv I_R - I_L = \alpha\langle S_x\rangle \mathrm{Re}\left(A_z^* A_y\right) - |\beta|\langle S_z\rangle \mathrm{Im}\left(A_x^* A_y\right)$$

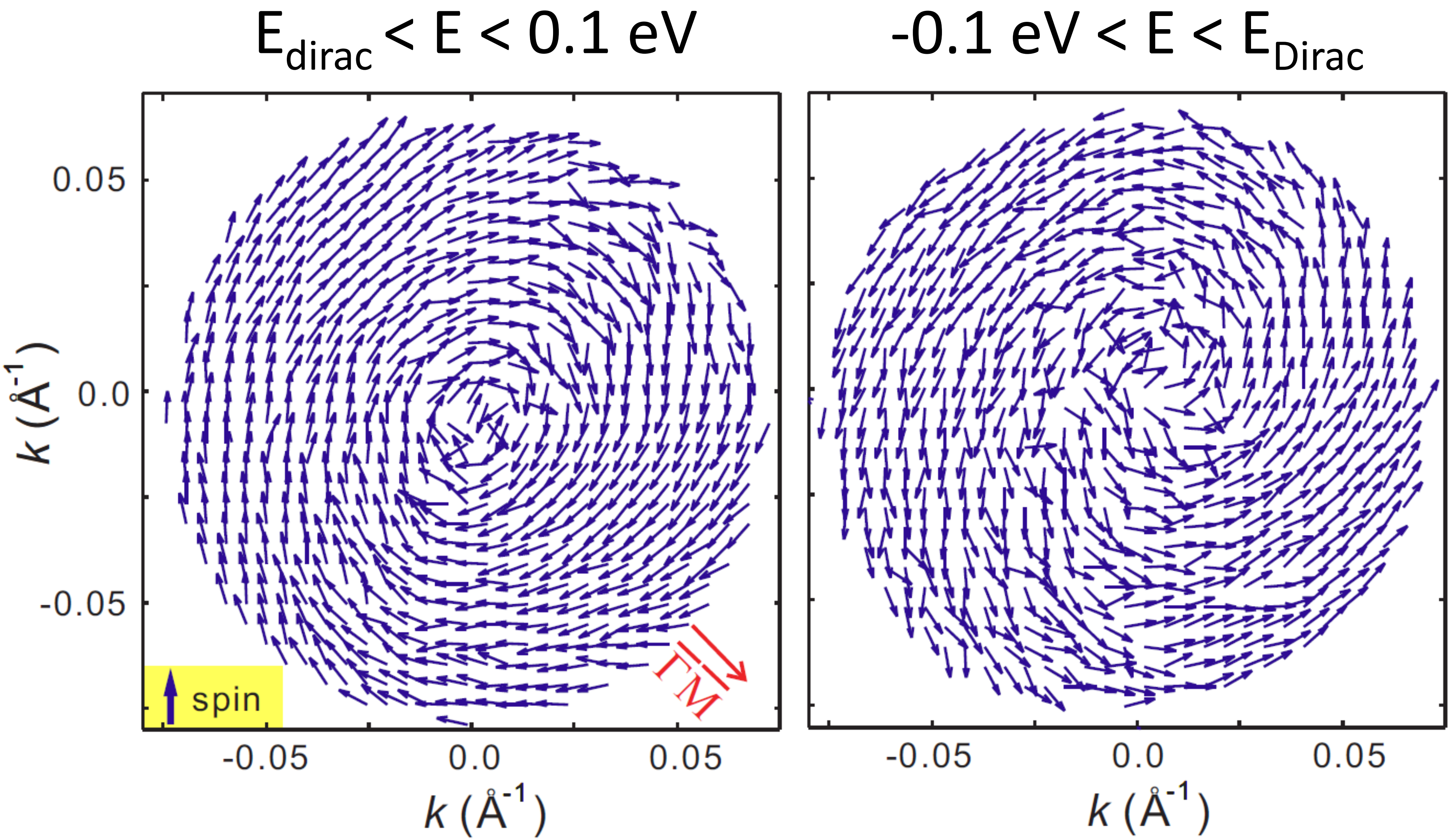
In collaboration with Liang Fu 2011

Spin sensitivity with circularly polarized light



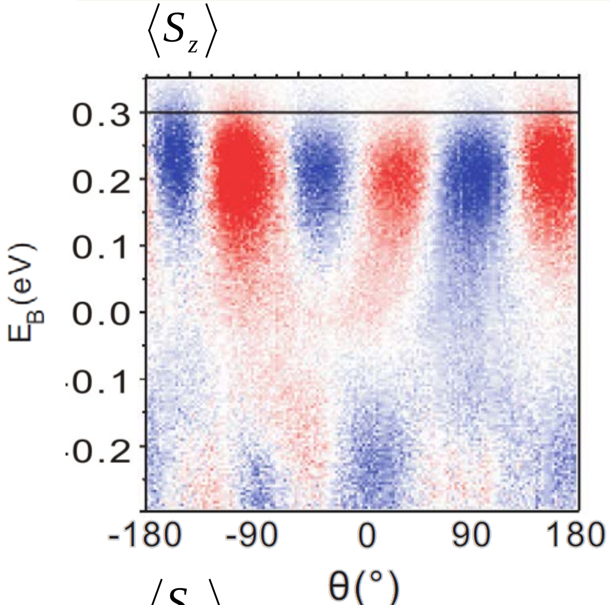
Y. Wang, D.H. et al., PRL 2011

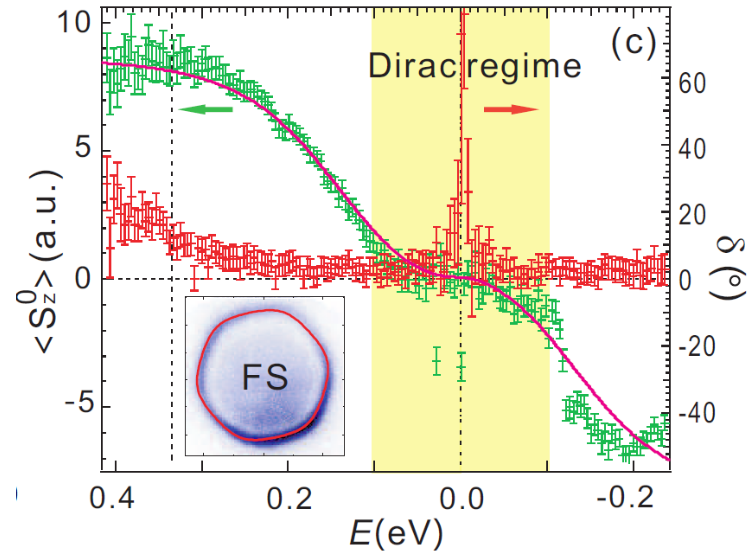
Spin texture of entire surface state simultaneously

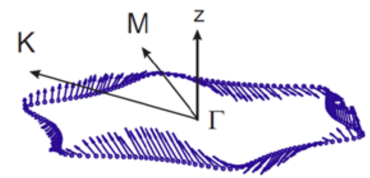


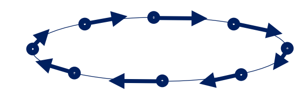
Y. Wang, D.H. et al., PRL 2011

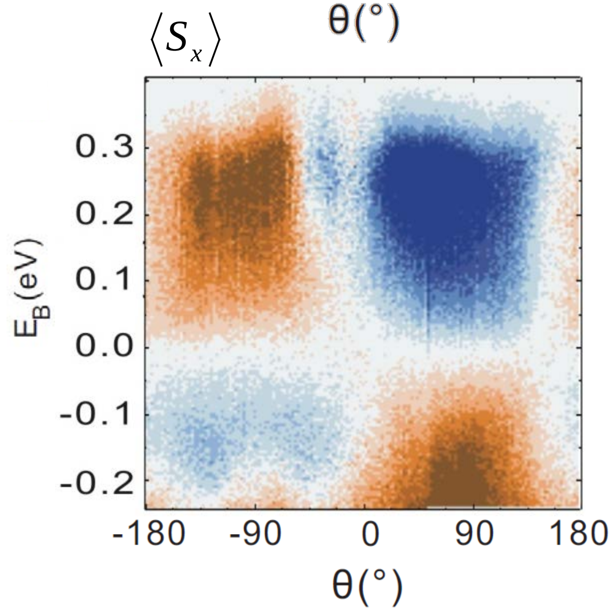
High energy: Deformed spin texture

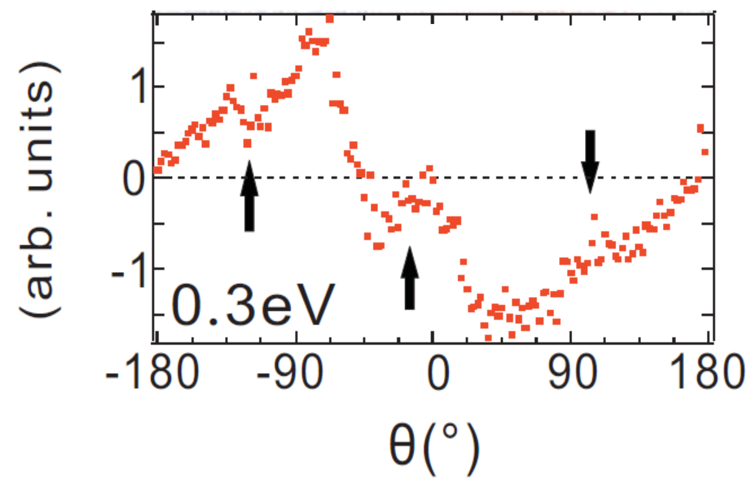


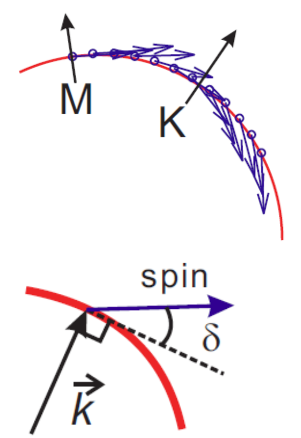






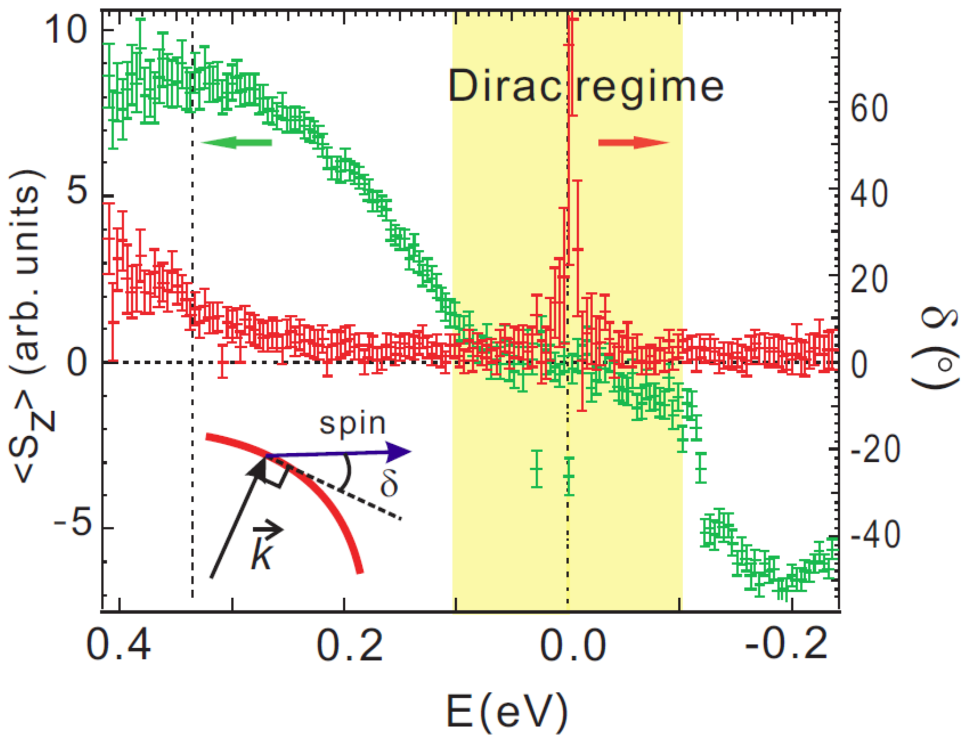




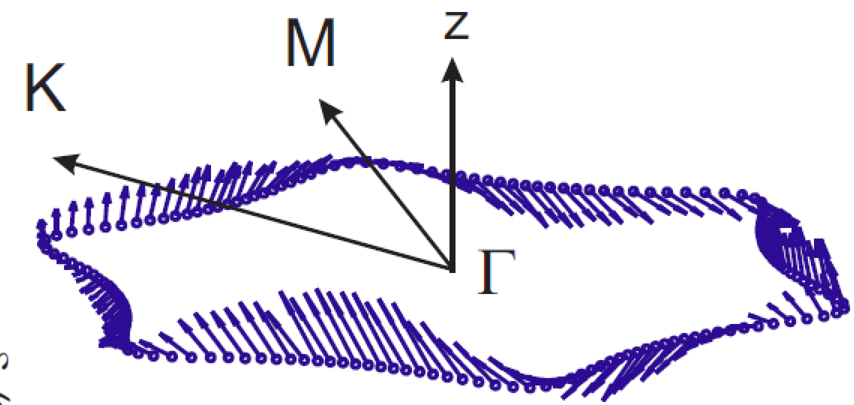


Y.H. Wang, D.H, et al., PRL 107, 207602 (2011)

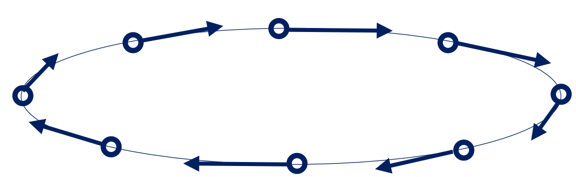
Hexagonally warped spin texture



High energy hexagonal deformed regime

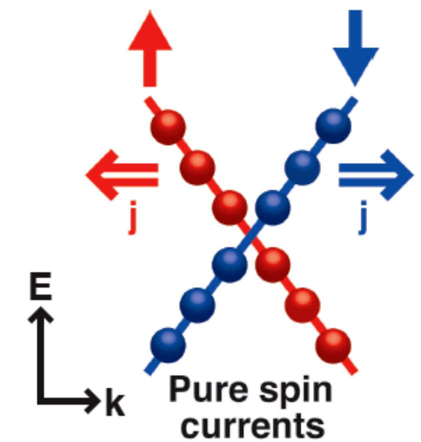


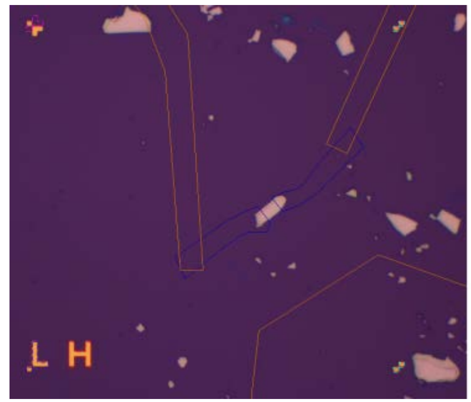
Low energy ideal planar regime

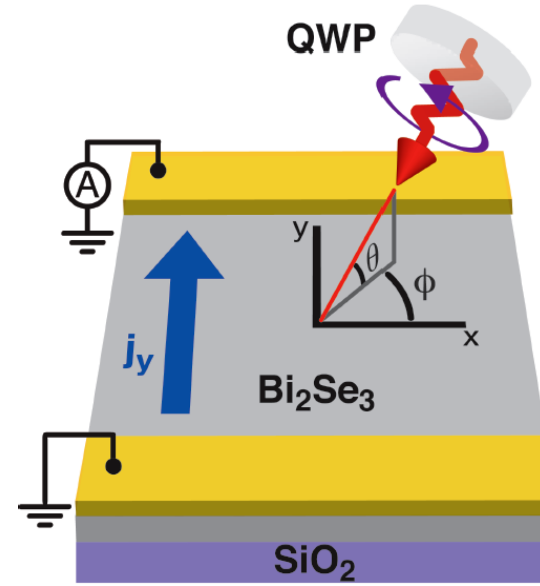


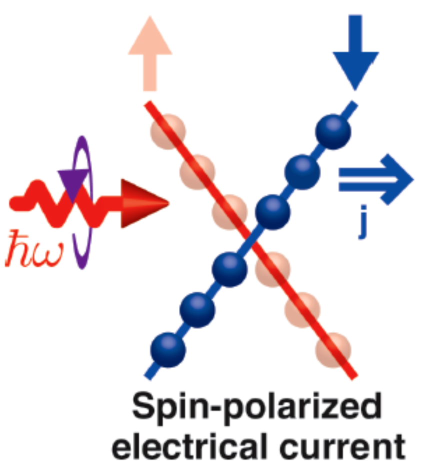
Y. Wang, D.H. et al., PRL 2011

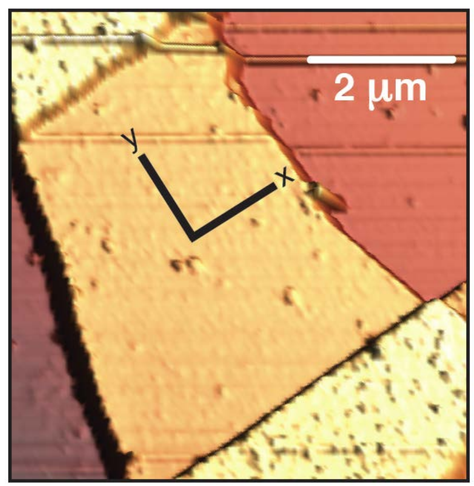
Spin currents driven by circular light

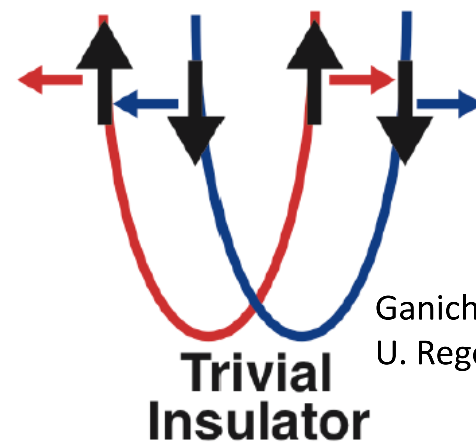












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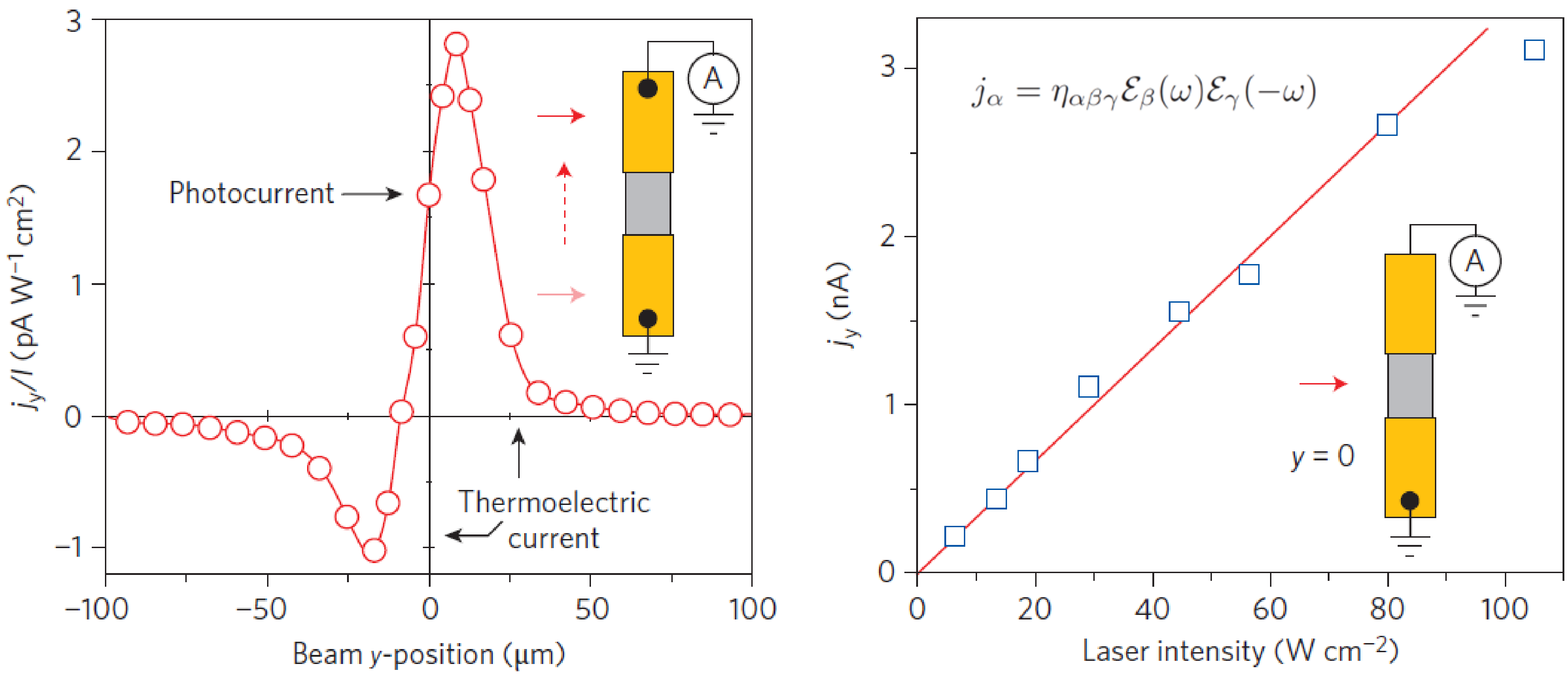
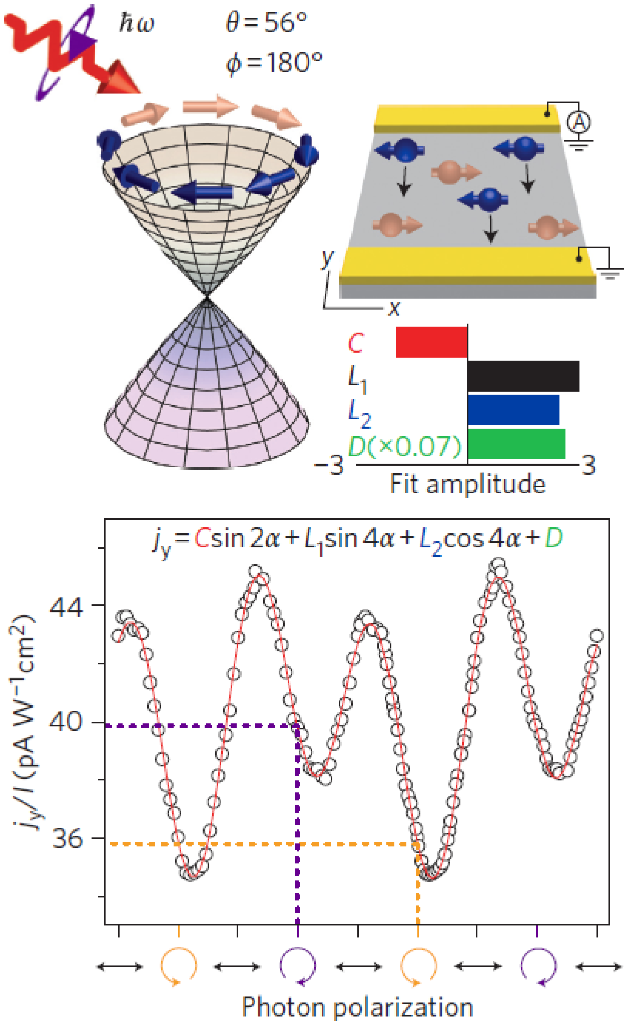
J.W. McIver, D.H., et al., Nature Nano., 7, 96 (2012)

Isolating the photo-galvanic contribution



J.W. McIver, D.H., et al., Nature Nano., 7, 96 (2012)

Photon helicity dependent currents observed in Bi_2Se_3



J.W. McIver, D.H., et al., Nature Nano., 7, 96 (2012)

End of Part 1