Simultaneous vectorial spin mapping of a topological insulator using circular dichroism in time of flight photoemission

Nuh Gedik

Acknowledgements

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Experiment:

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Dillon Gardner, Young Lee (MIT)

Theory

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David Hsieh

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DOE

CMSE
MIT Center for Materials Science and Engineering

ARO

Outline of talk

Massachusetts Institute of Technology

- Introduction to topological insulators (TIs)

- Direct visualization of spins in TIs with laser based ARPES
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  - Coupling to the spins with light
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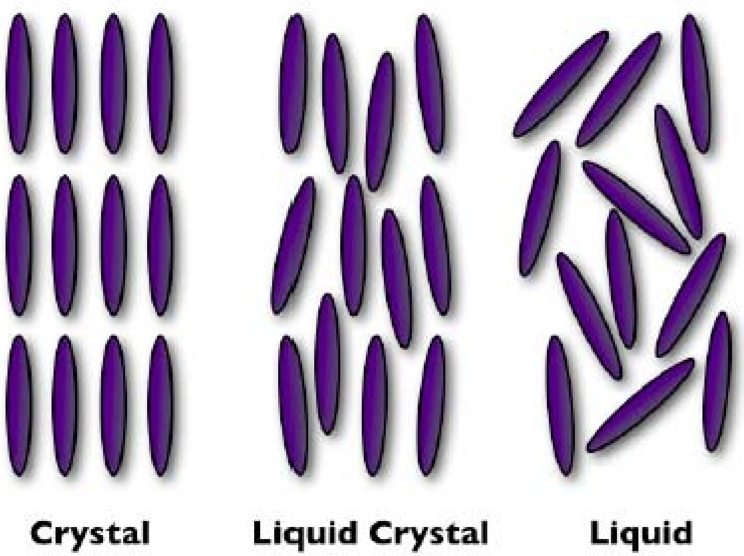
- Conclusion & Outlook

Ordered phases in condensed matter physics

Classify phases by symmetry



Landau

“a particular symmetry property exists or does not exist”

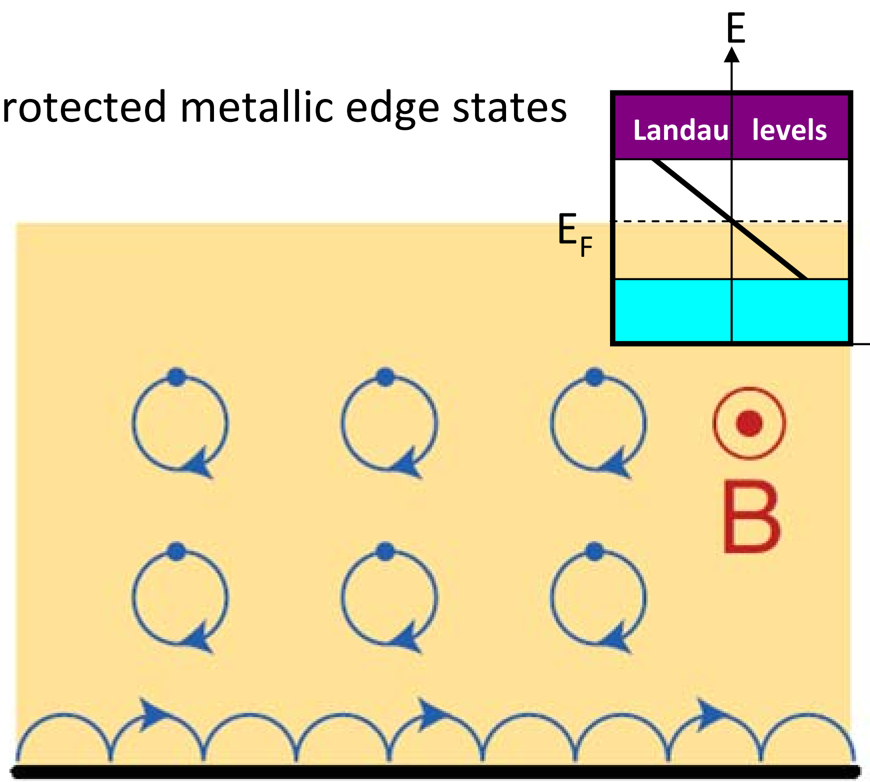
Order identified by a **spontaneously broken symmetry** :

liquid crystals, magnets, superconductors

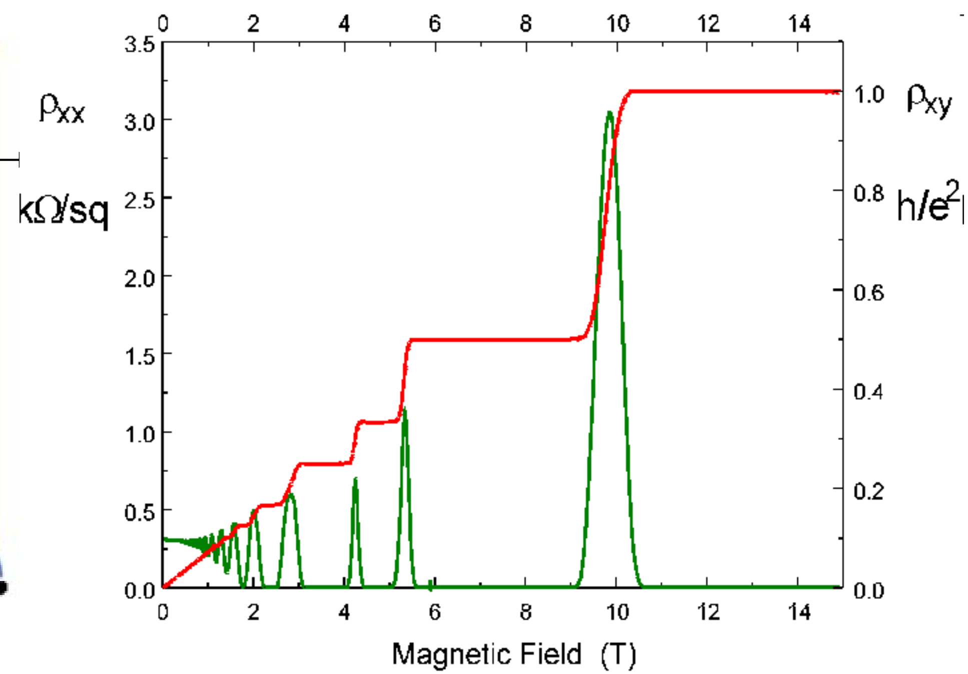
2D Quantum Hall Insulator

The *first* ordered phase beyond symmetry breaking (*1980 von Klitzing*)
Topological order induced by magnetic field

Protected metallic edge states



K. von Klitzing (Nobel Prize 1985)

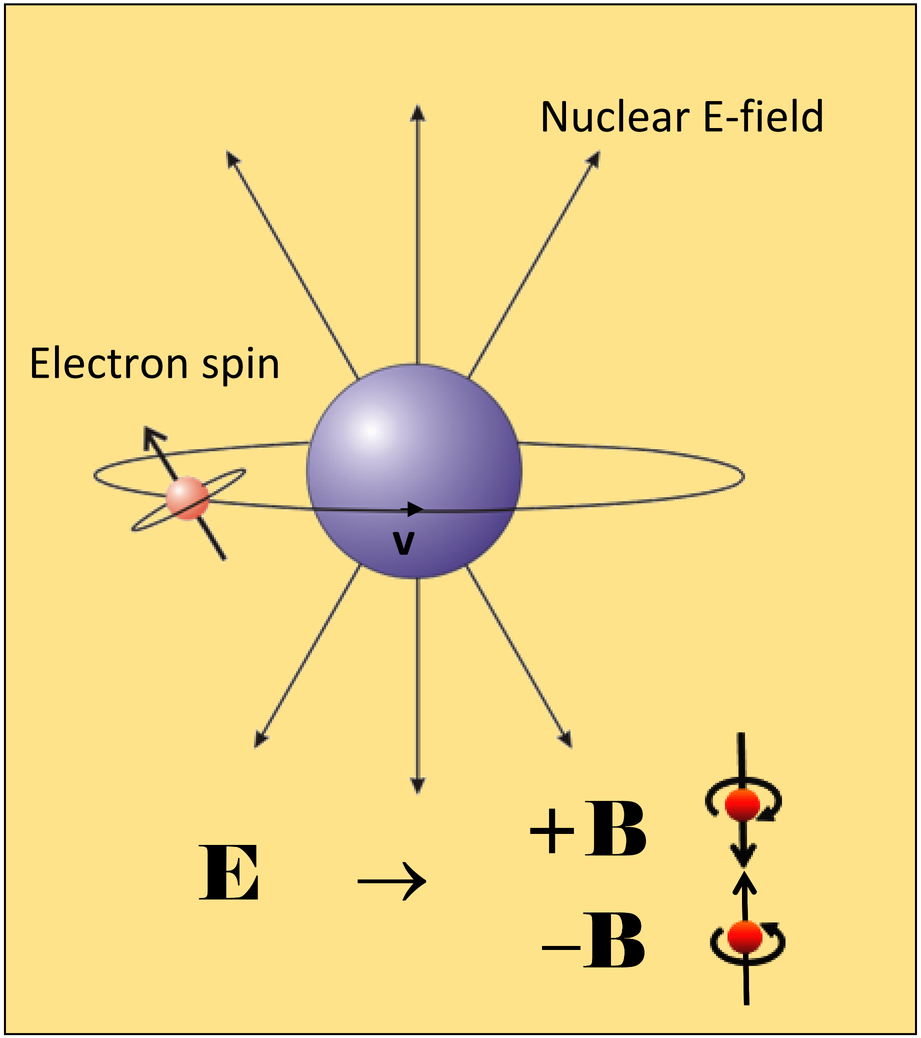


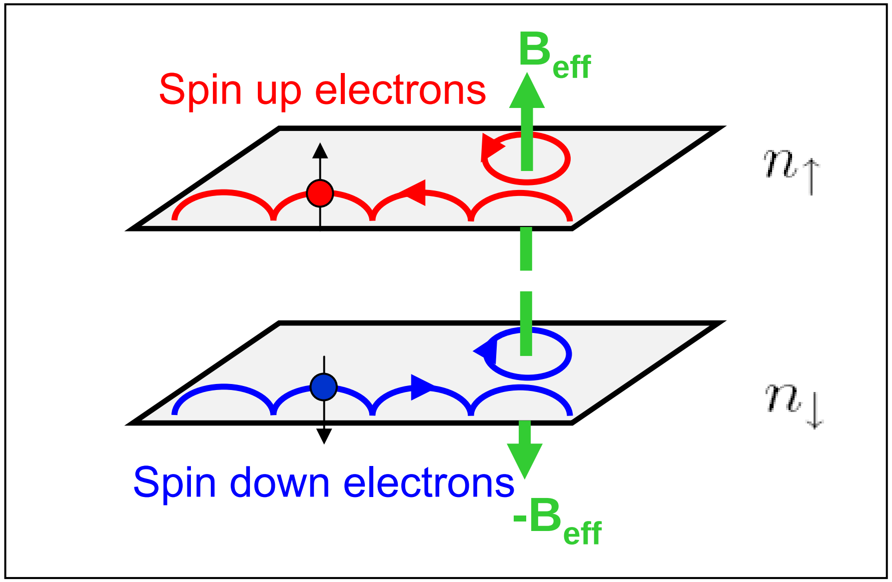
Hall Conductance $\sigma_{xy} = n\, e^2/h$

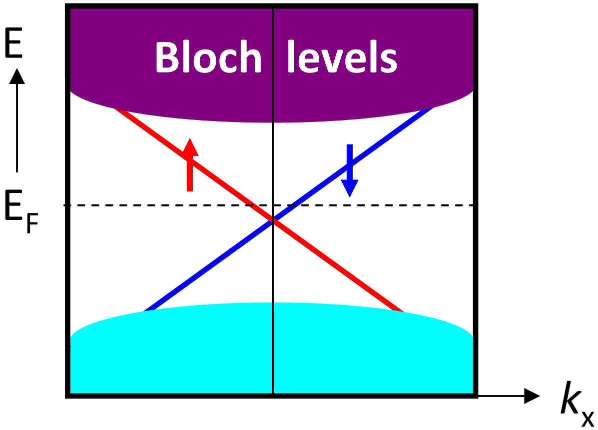
n is PRECISELY an integer even in dirty materials!!!

Topological order in 2D with NO magnetic field

Topological order induced by spin-orbit coupling , *zero magnetic field*



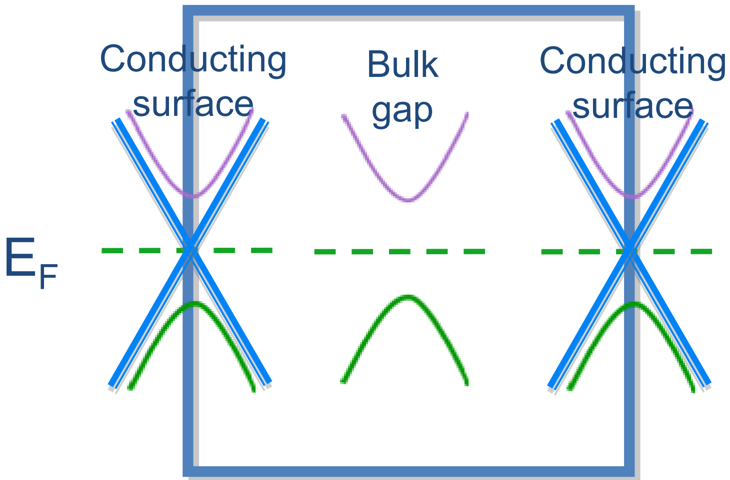




Kane & Mele (2005)

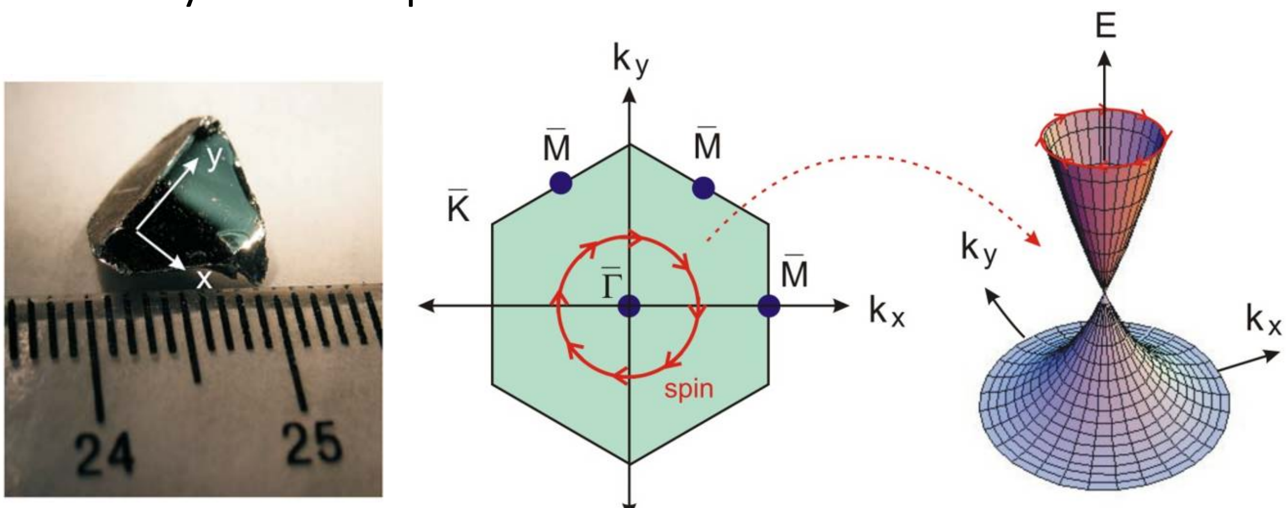
3D Topological Insulator

First genuinely 3D topological phase, *zero magnetic field*



A gapless metallic surface state appears at the surface of a topological insulator!

Crystals have protected metallic 2D surface states

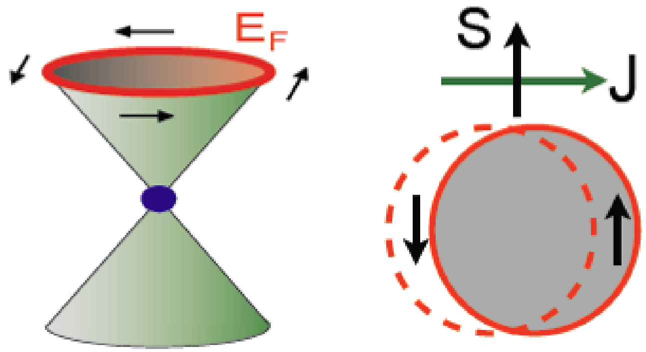


Unique properties of ideal 2D helical Dirac cones

Charge current ∝ Magnetization

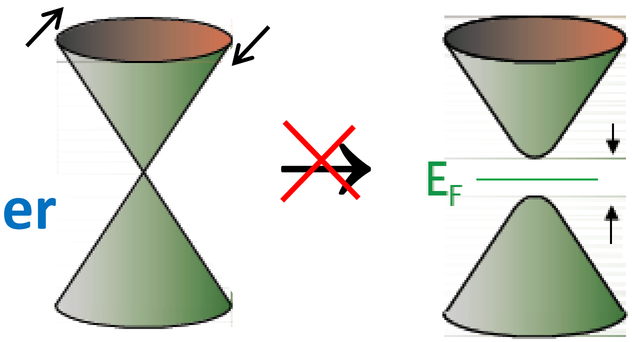
$\vec{j} = v_F \vec{S} \times \hat{z}$ (*Raghu et al, 2009*)

Potential new functionalities for spintronic and opto-electronic devices



Absence of backscattering

High mobility ~ 10,000 $cm^2/V \cdot s$ (*Qu et al, 2010*)
Potential for robust and low power electronics



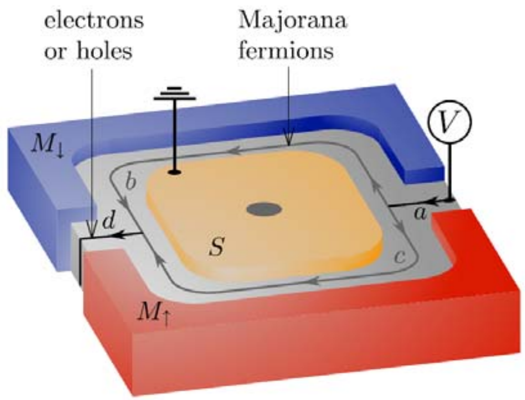
Immunity against non-magnetic disorder

Surface states are protected by time reversal symmetry and protected against non-magnetic disorder

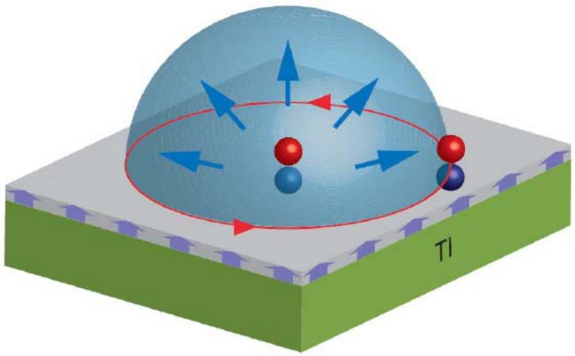
Hasan and Kane Rev.Mod.Phys.82:3045,2010

3D Topological insulators : Playground for new physics

Majorana fermions
Topological quantum computing

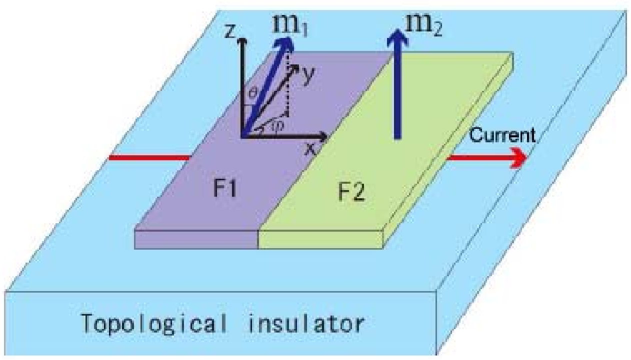


Axion electrodynamics



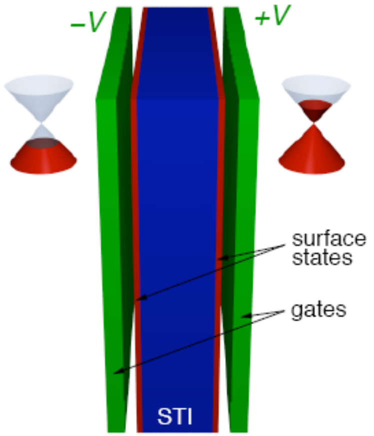
Qi et al, Science 323, 1184 (2009)

Low power spintronics



Phys. Rev. B 81, 121401(R) (2010)

Topological Bose condensate



B. Seradjeh et al PRL 2009

Massachusetts Institute of Technology

Probing and control of Spin-momentum locking in real materials

- Dispersion relation is not ideal Dirac cone in real materials
- The response of the spin structure against deviations in the band structure
- Optical manipulation of spin-momentum locking

Dynamical properties of surface states

- So far mostly equilibrium properties have been studied
- Responses to external stimuli such as light or magnetic field etc…

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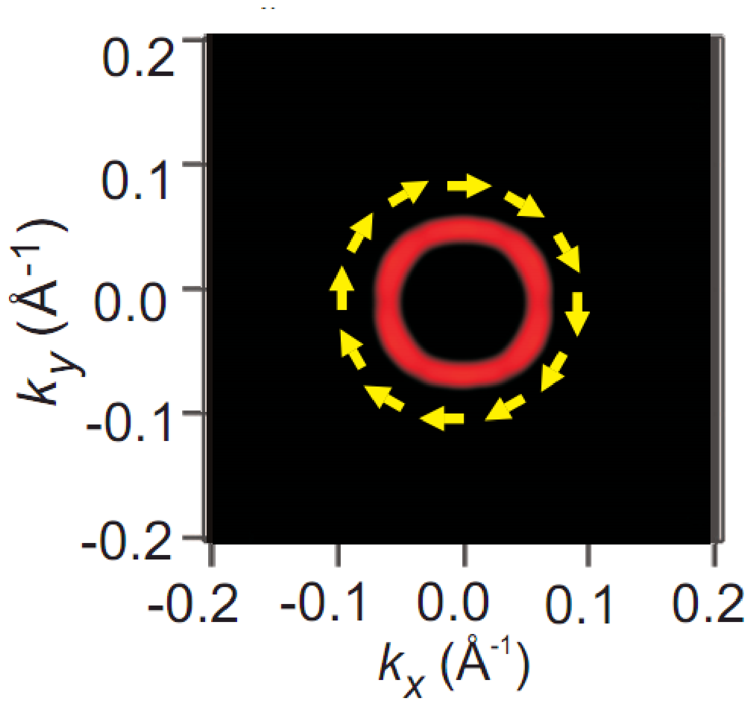
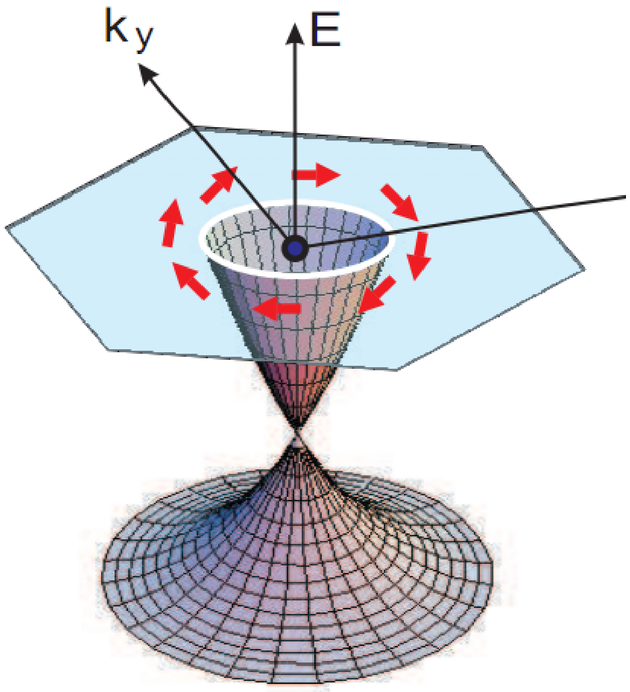
Ideal Dirac description of Topological Insulators





$$H(\vec{k}) = \hbar v_F \left(\vec{k} \times \vec{S}\right) \cdot \hat{z}$$

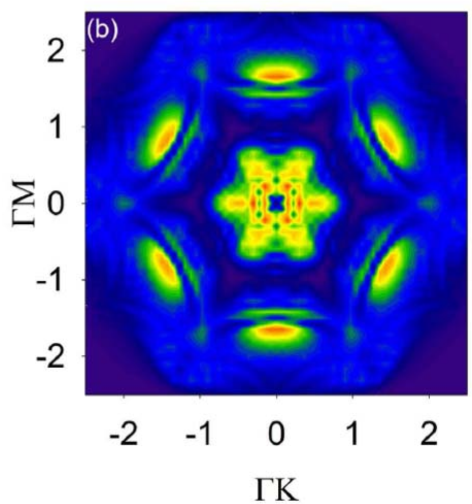
Hasan and Kane Rev.Mod.Phys.82:3045,2010

In reality surfaces are not ideal Dirac cones

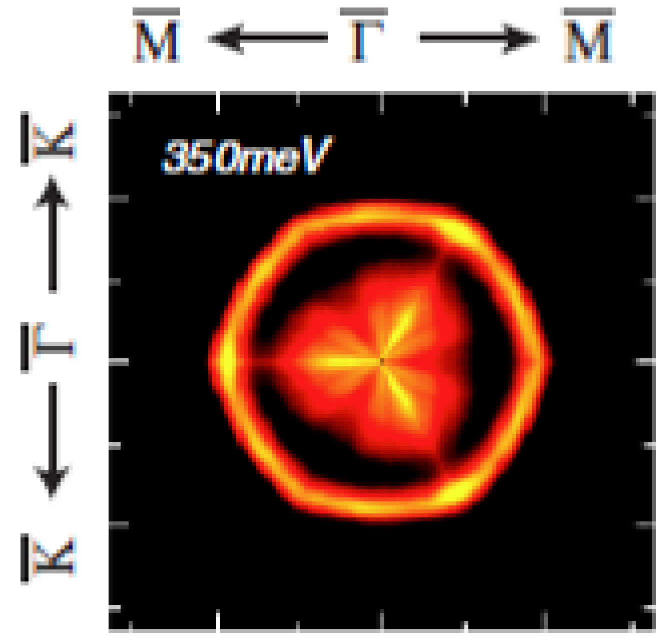
To know how charge current and magnetization couple in real materials
Need to understand spin texture over *all phase space*

Fu (2010)

Lee et al. (2010)



Bi_2Se_3



Kuroda et al (2010)

$$H = v(k_x s_y - k_y s_x) + \lambda(k_+^3 + k_-^3)s_z$$

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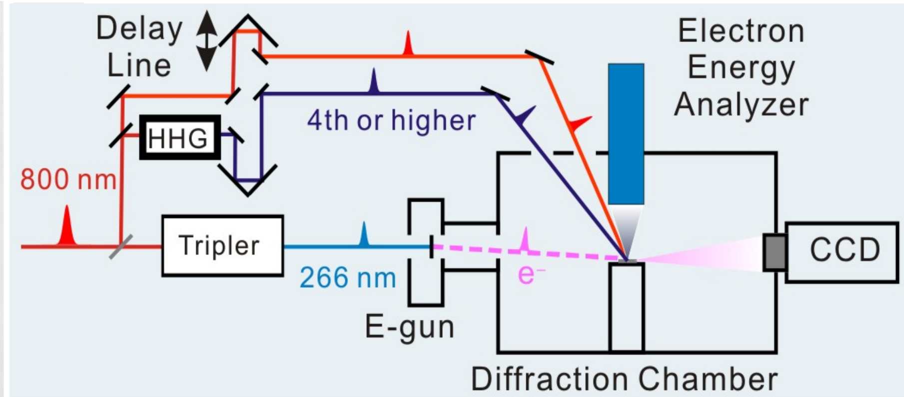
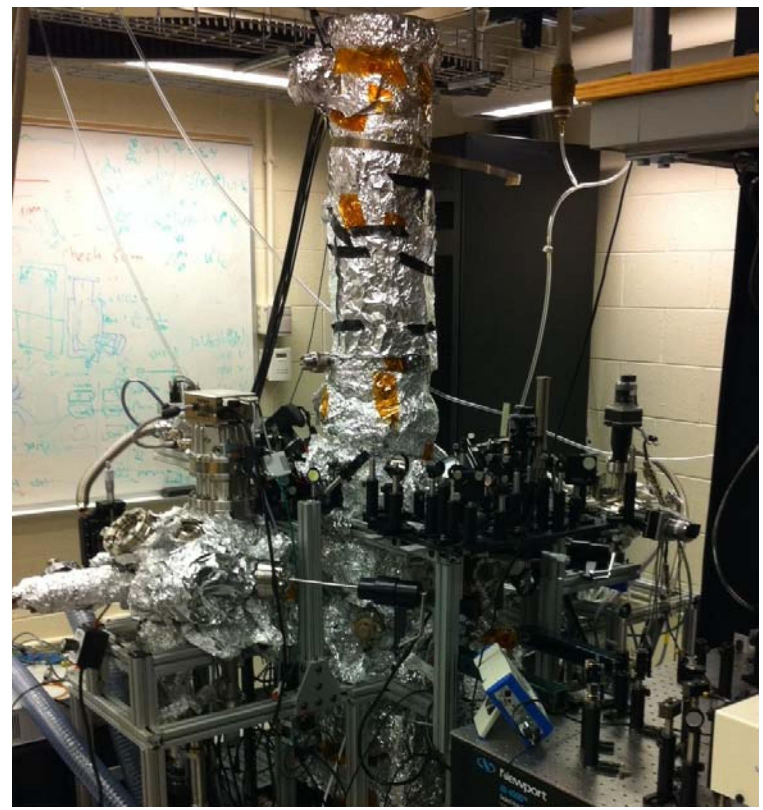
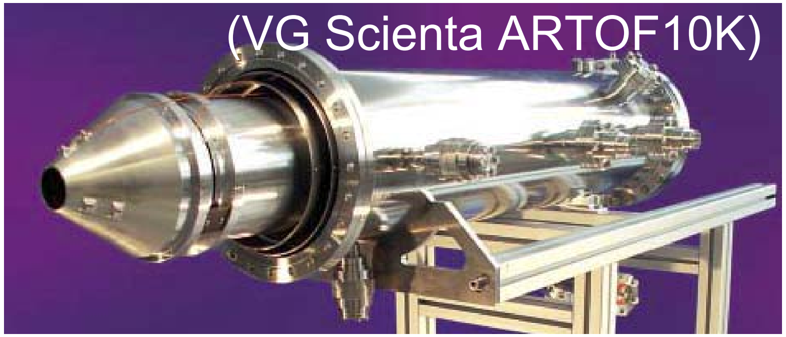
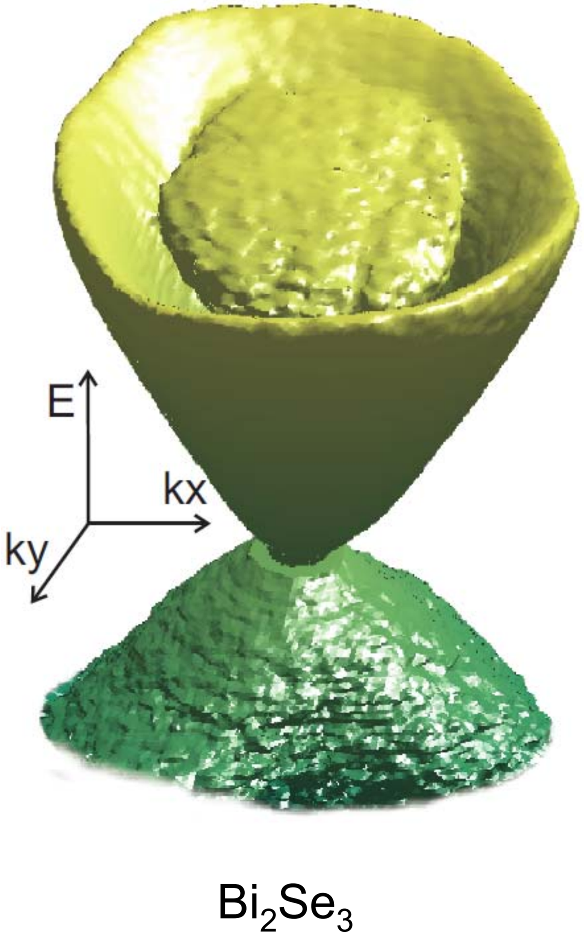
Angle resolved time-of-flight laser ARPES at MIT

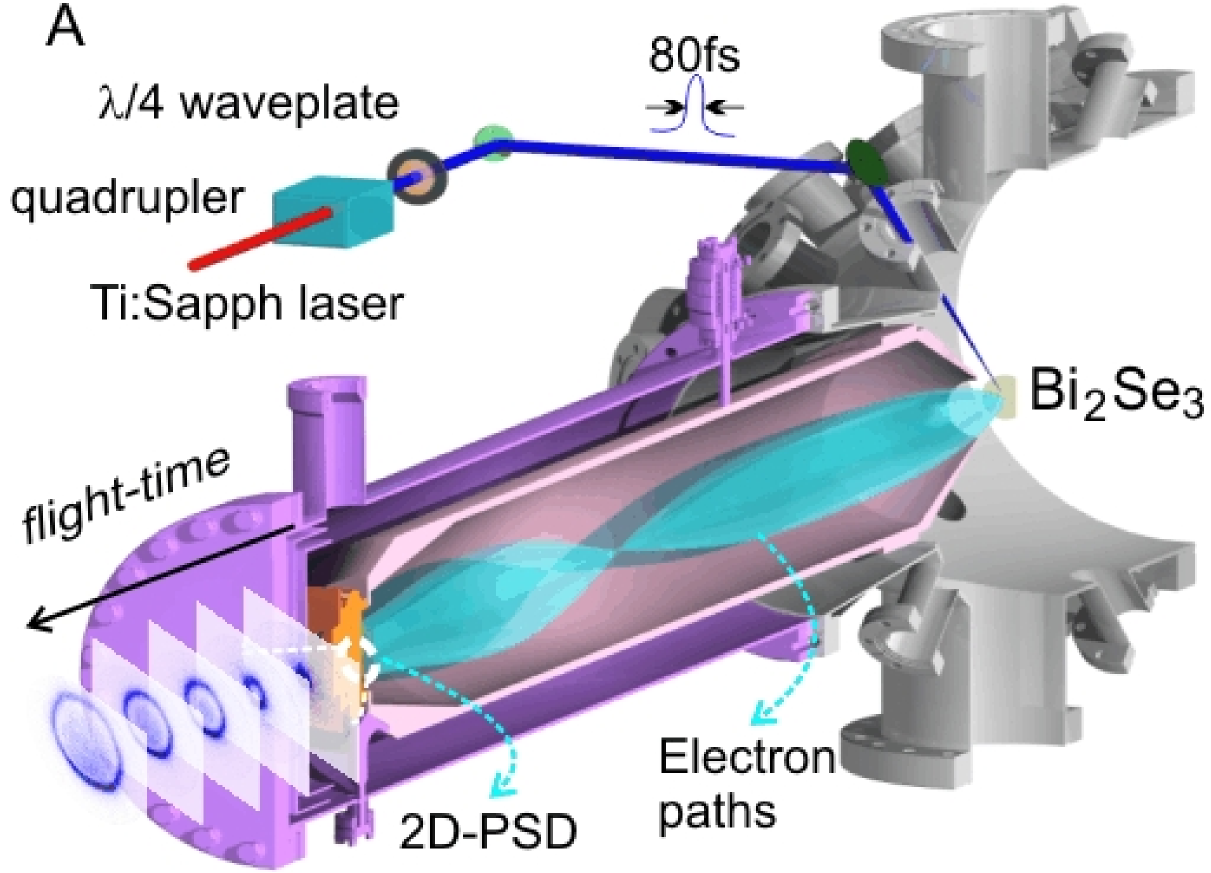




Probing Tis with angle resolved time-of-flight laser ARPES

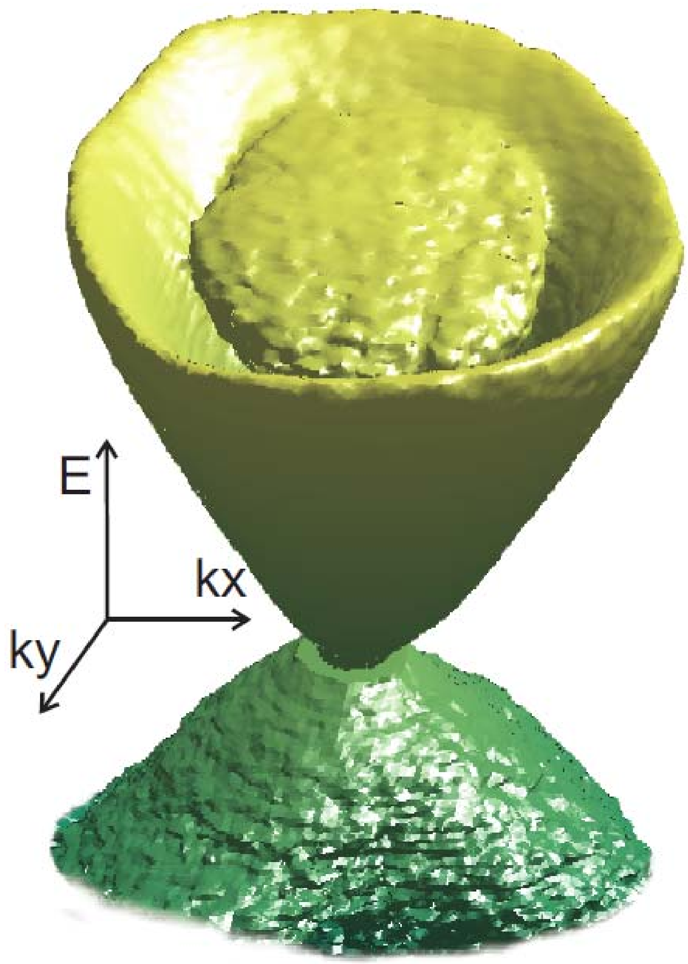


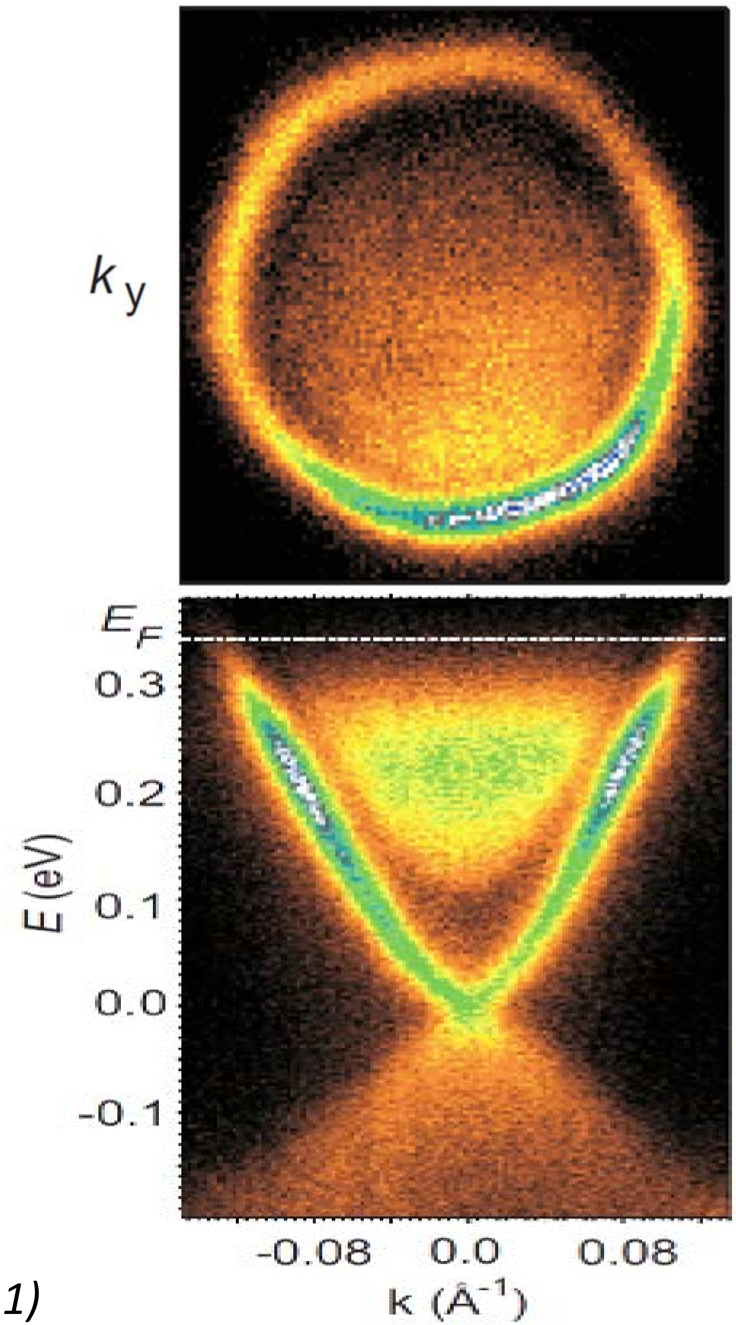




Simultaneous phase space mapping

Resolved deformation features in Bi_2Se_3





Wang et al arXiv:1101.5636 (accepted PRL 2011)

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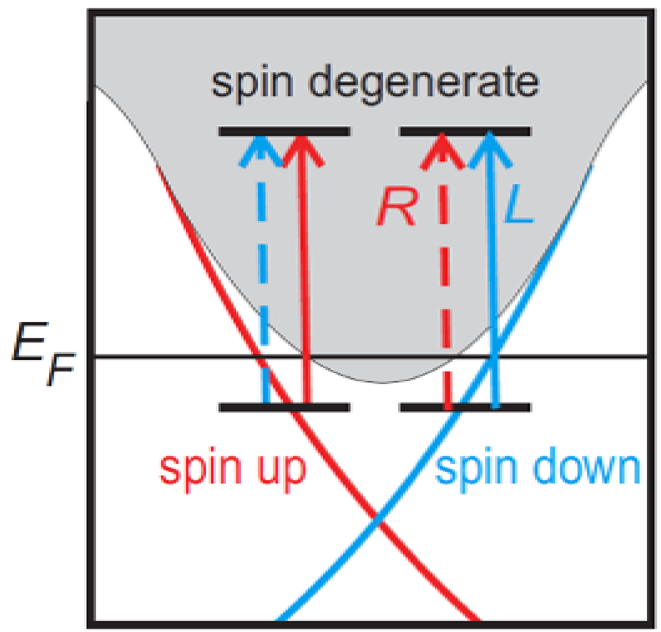
Coupling to the spin with light

Optical (UV) excitation into high energy spin-degenerate bulk states

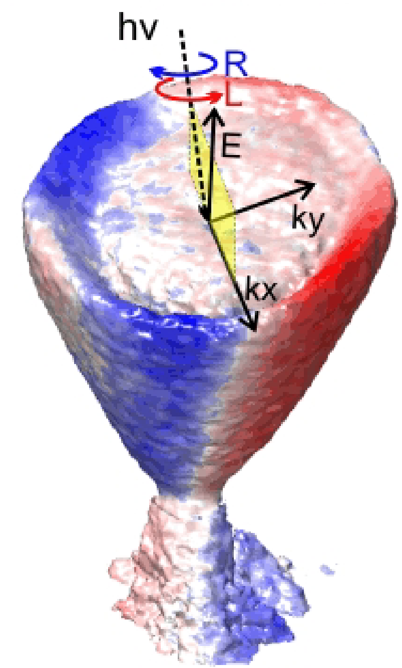
Transition probability sensitive to angle between angular momentum of circularly polarized photon and spin

$I(E, k_x, k_y)$

Linear



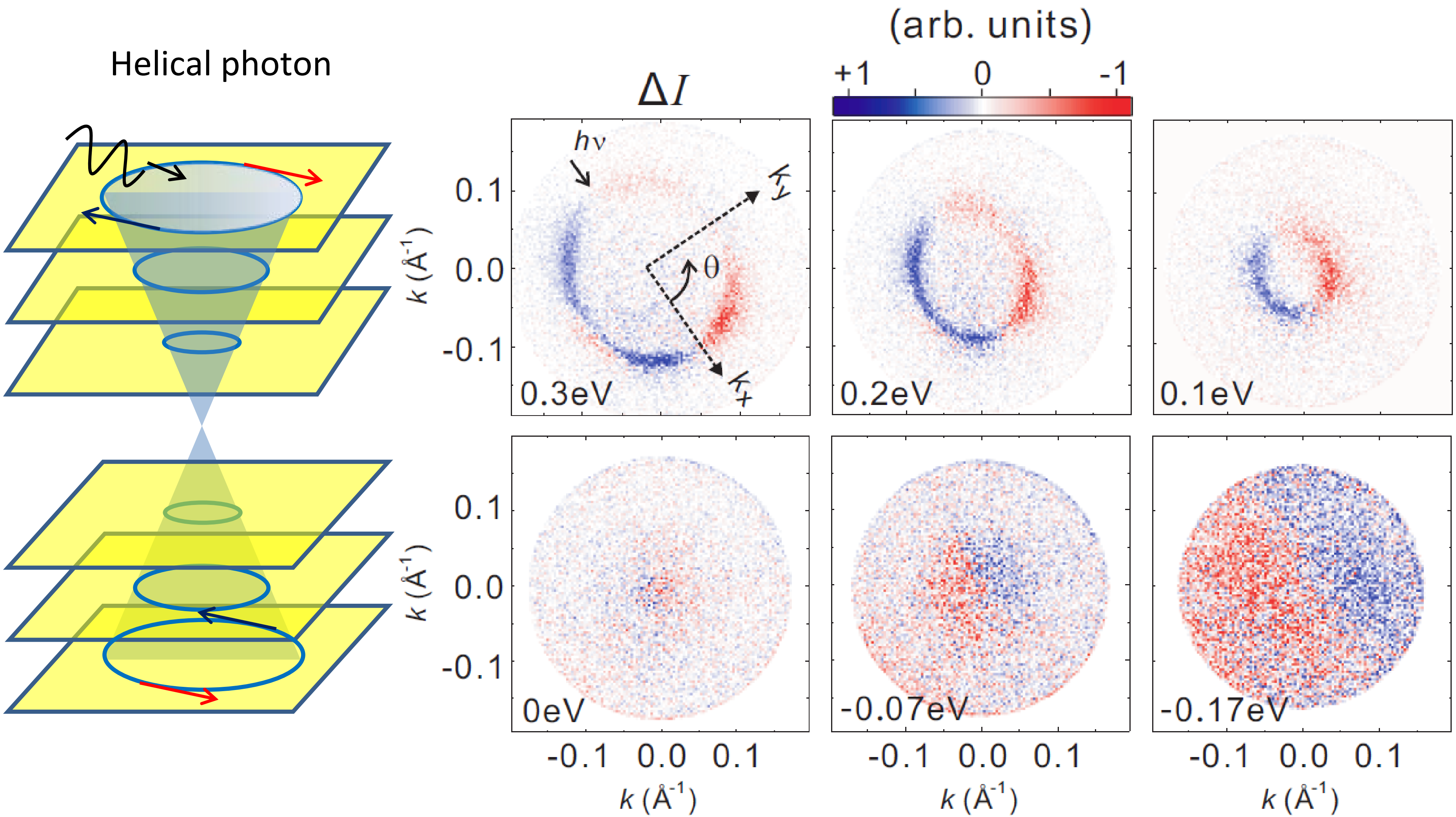
$\Delta I(E, k_x, k_y)$



(R) – (L)

Wang et al arXiv:1101.5636 (accepted PRL 2011)

Simultaneous spin mapping over Dirac cone



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3D vectorial spin analysis

ARPES matrix elements for transitions from helical surface states to bulk final states are derived from a spin-orbit Hamiltonian

$$H = \frac{\vec{P}^2}{2m} + U(\vec{r}) + \frac{\hbar}{4m^2c^2}(\vec{P} \times \vec{\nabla} V) \cdot \vec{s}$$

$$H(\vec{A}) = H - \frac{e\vec{P} \cdot \vec{A}}{m} - \frac{\hbar e}{4m^2c^2}(\vec{A} \times \vec{\nabla} V) \cdot \vec{s} + o(A^2)$$

Difference of *R* and *L* ARPES spectra at different sample angles allow

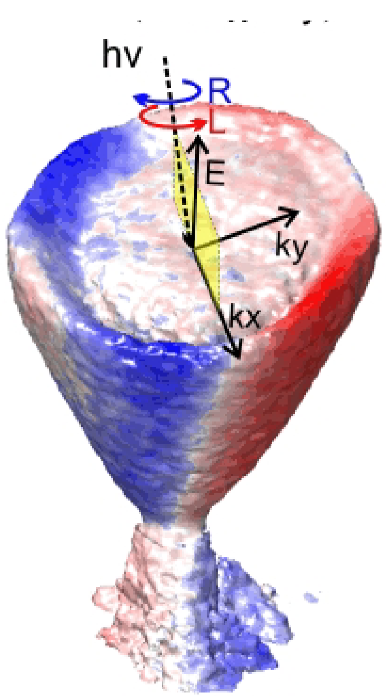
Independent measurement of $\langle S_x \rangle \langle S_y \rangle \langle S_z \rangle$ over entire phase space

Wang et al arXiv:1101.5636 (accepted PRL 2011)

3D vectorial spin analysis

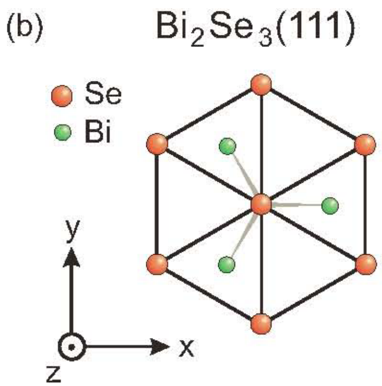
Massachusetts Institute of Technology

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



How to disentangle <S_x> and <S_z>?

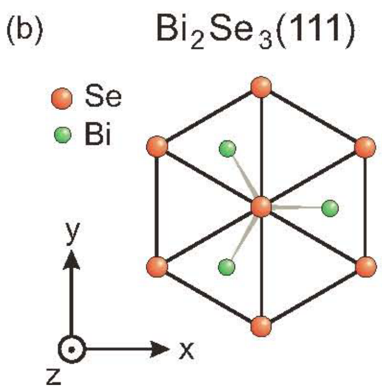
Use the symmetry properties…

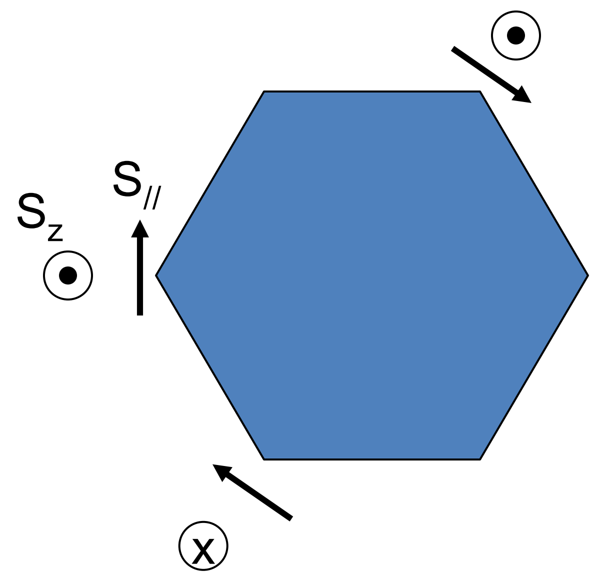


Wang et al arXiv:1101.5636 (accepted PRL 2011)

3D vectorial spin analysis

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





3 fold rotational symmetry

Time reversal symmetry

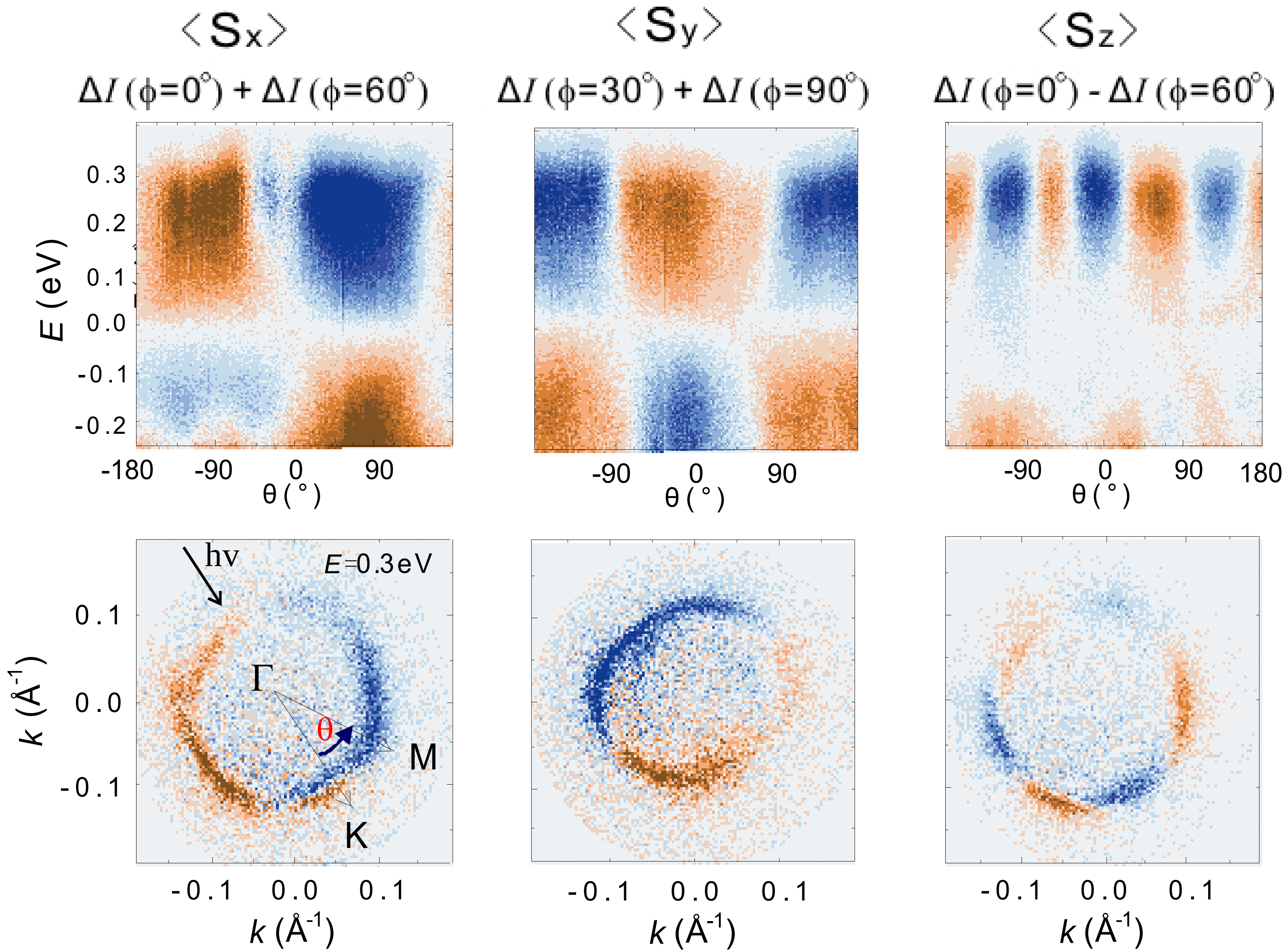
Under 60 degree rotation $<S_x> \rightarrow <S_x>$ while $<S_z> \rightarrow <S_z>$

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

Wang et al arXiv:1101.5636 (accepted PRL 2011)

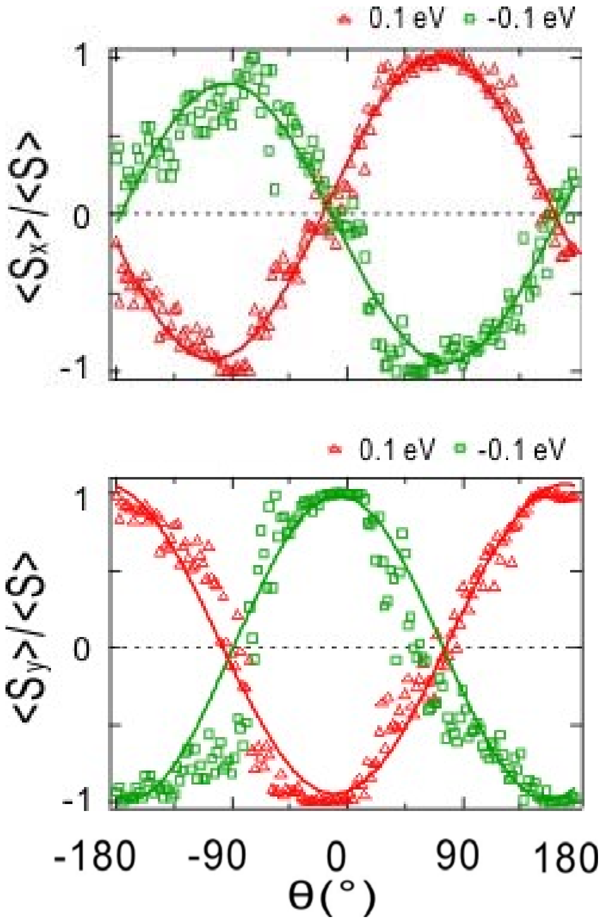
3D vectorial spin analysis

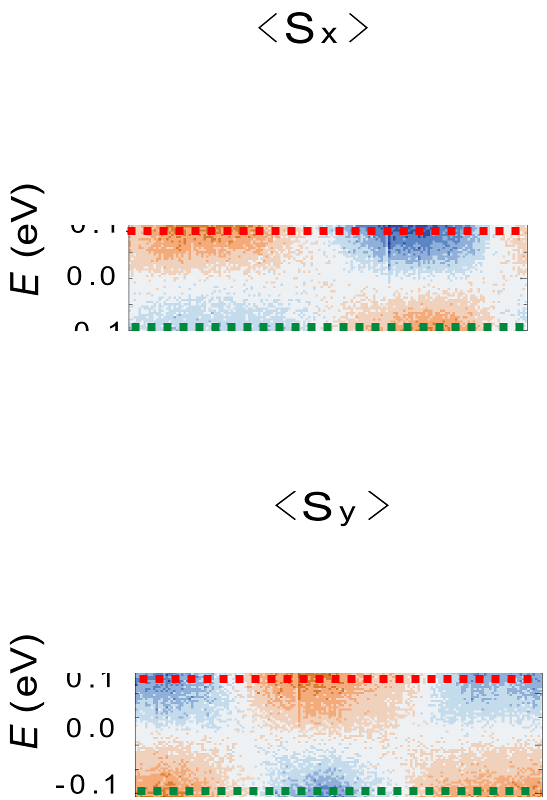
Massachusetts Institute of Technology

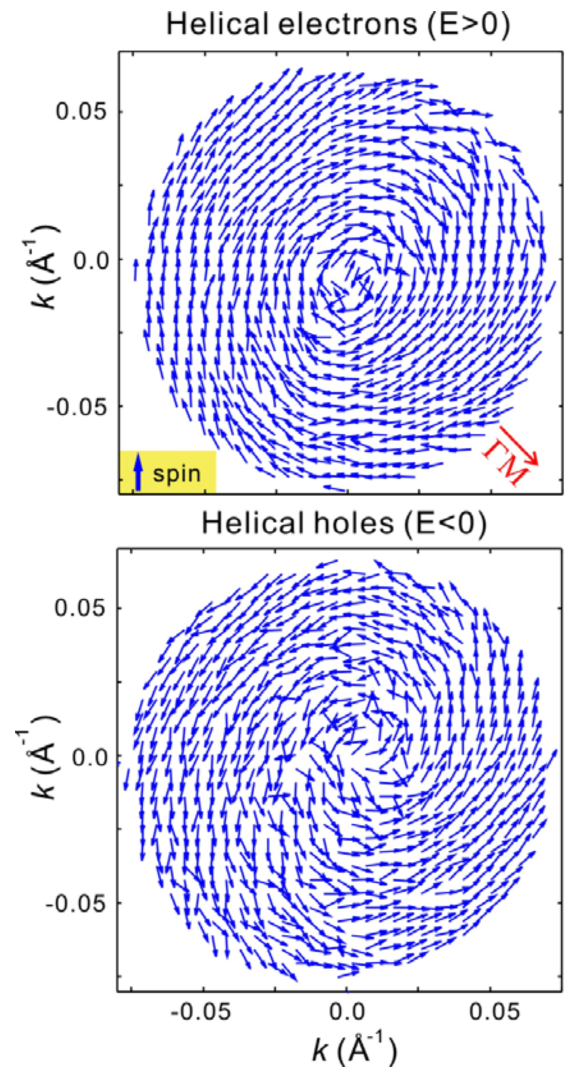


Wang et al arXiv:1101.5636 (Submitted 2011)

Spin texture in the Dirac limit

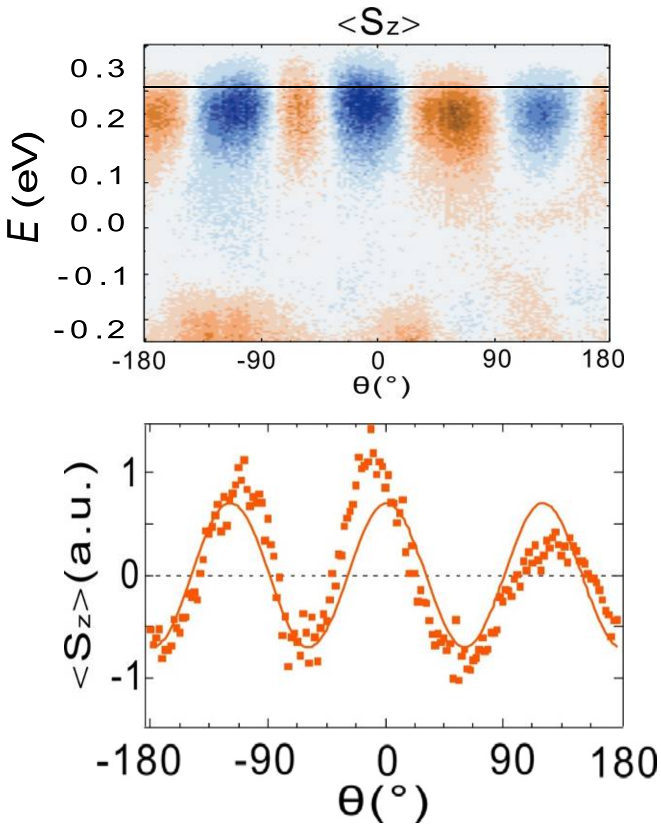


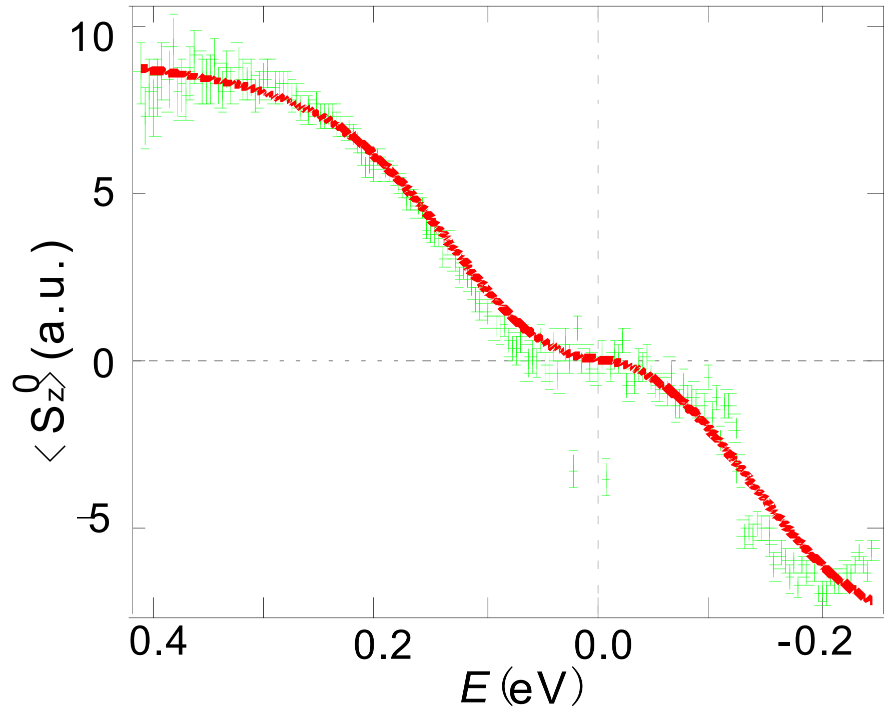




Wang et al arXiv:1101.5636 (accepted PRL 2011)

S_z energy dependence





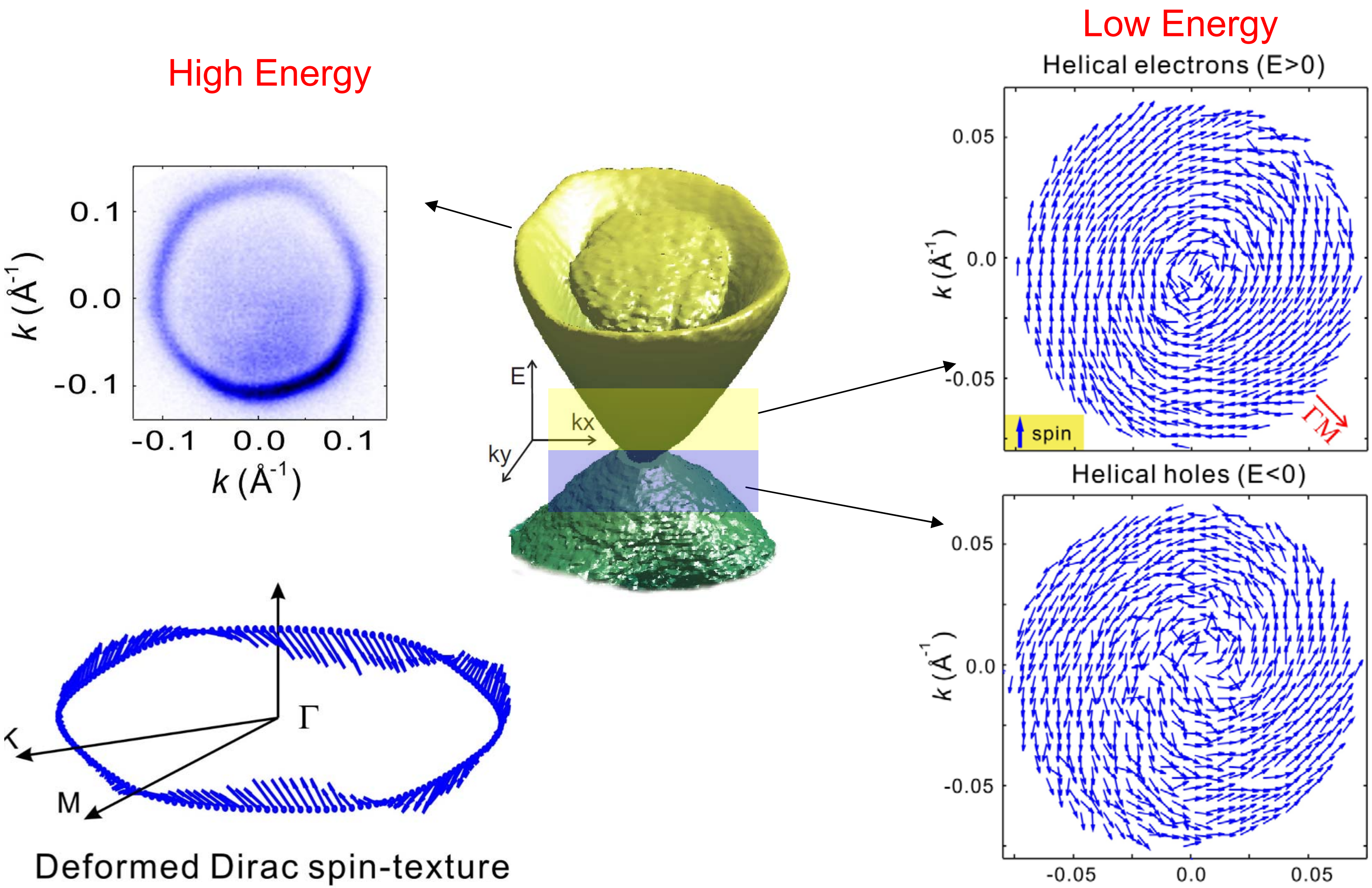
Fit to k•p theory

$$\left\langle S_z^0(E)\right\rangle = 1/\sqrt{1+[k(E)a]^{-4}}$$

Fu, PRL, 2010

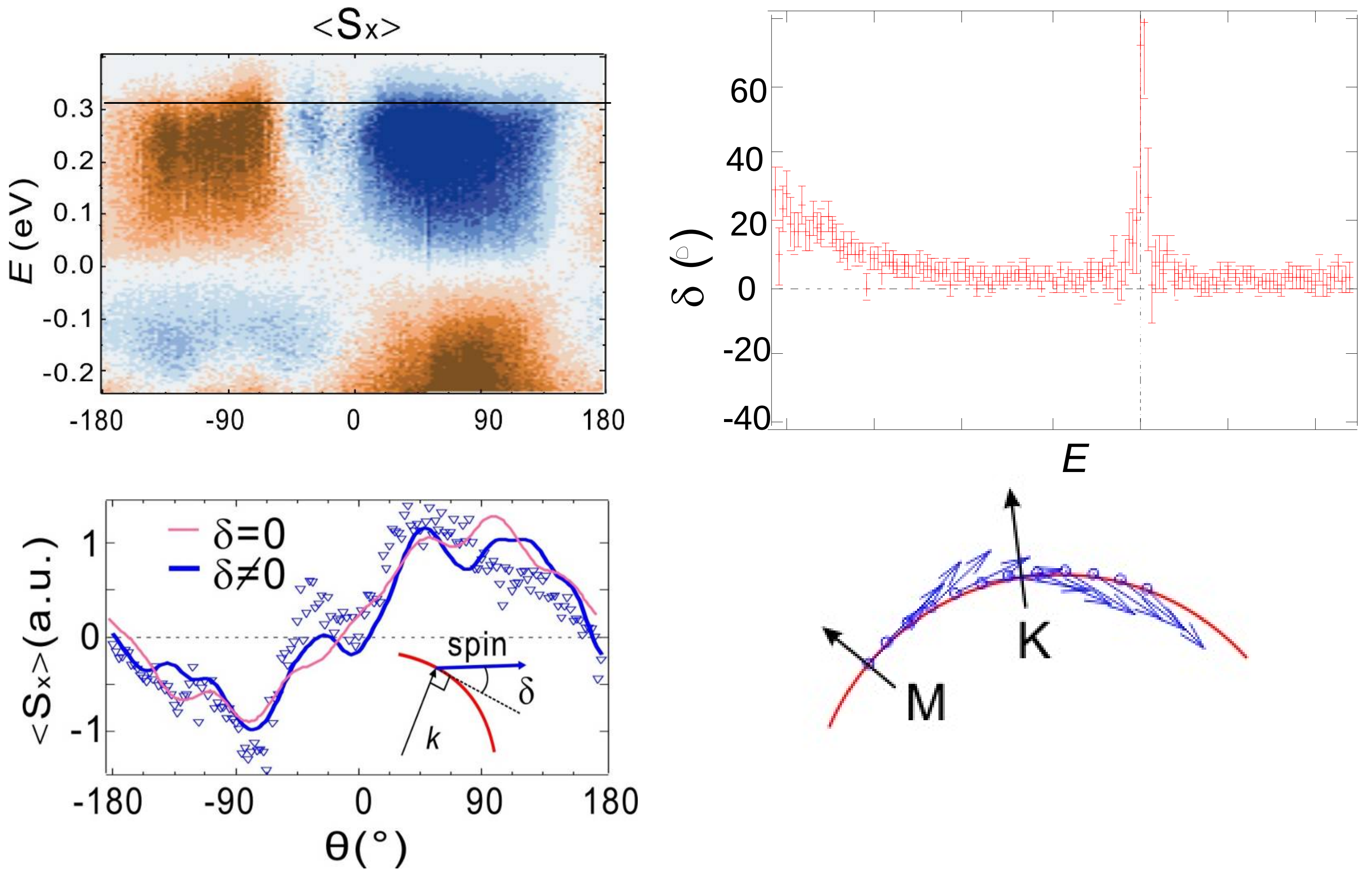
Wang et al arXiv:1101.5636 (accepted PRL 2011)

3D Spin texture in topological insulators



Wang et al arXiv:1101.5636 (accepted PRL 2011)

Unexpected in-plane spin canting



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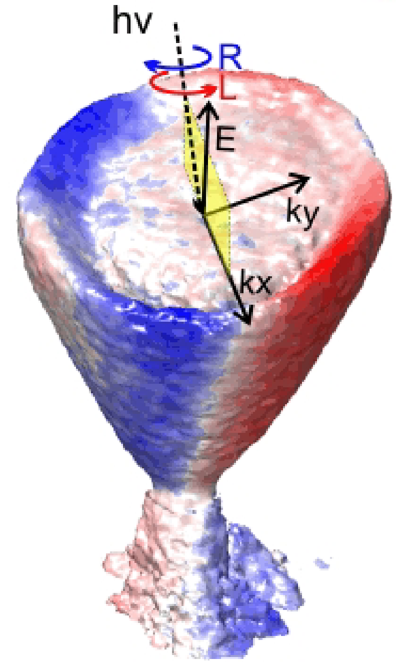
Summary

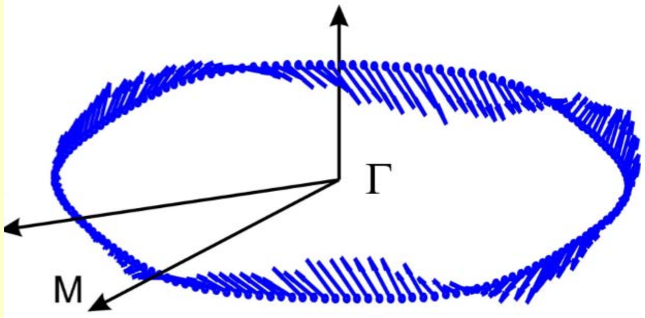
- 3D band mapping with time of flight ARPES

- Achieved simultaneous vectorial spin mapping in TIs by using circularly polarized light

- Directly observed ideal helical spin texture at low energies and deviations from ideal behavior at high energies

- Revealed S_z and canting of the in-plane spins in Bi_2Se_3





Deformed Dirac spin-texture