

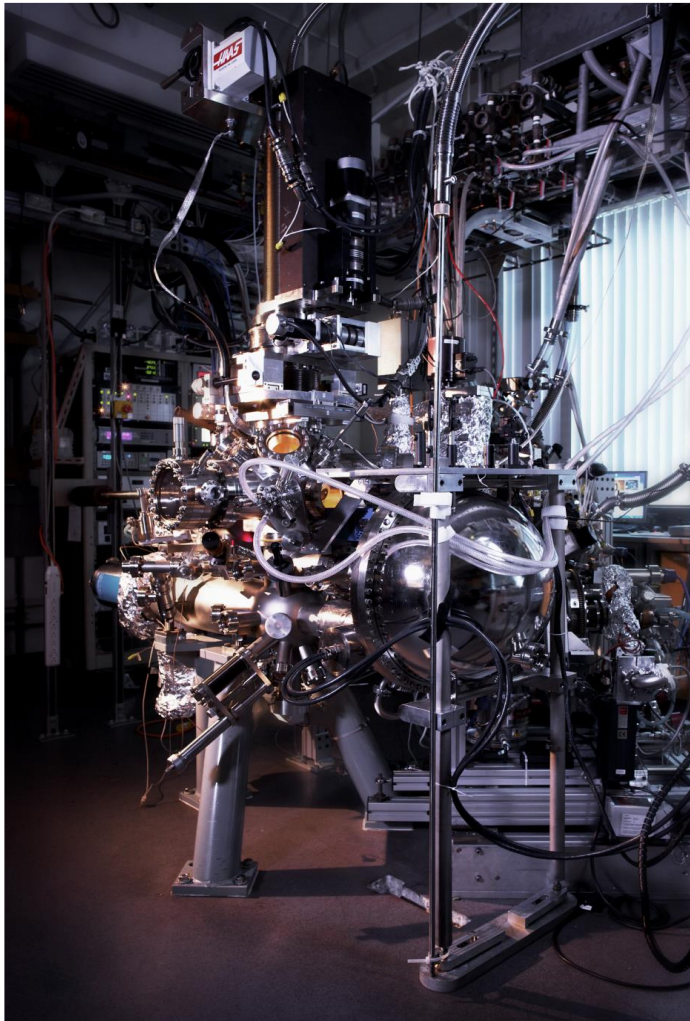


Spin-orbital textures in topological insulators

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Spin-Orbit Coupling & Relativistic Quantum Materials
Summer School

October 2015



Z.-H. Zhu, S. Zhdanovich, C.N. Veenstra,
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M.H. Haverkort, I.S. Elfimov, A. Damascelli

University of British Columbia

Bi_2Se_3 Samples

A. Ubaldini

University of Geneva

P. Syers, N.P. Butch, J. Paglione

University of Maryland

K. Kuroda

WASEDA University

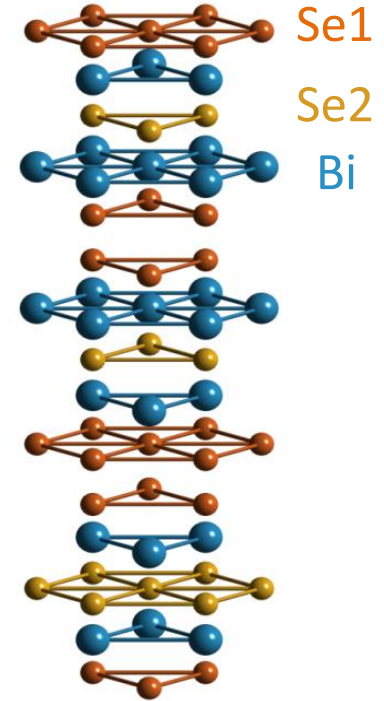
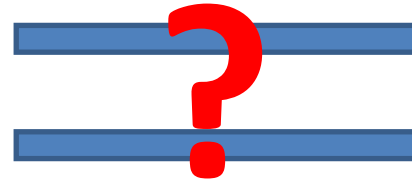
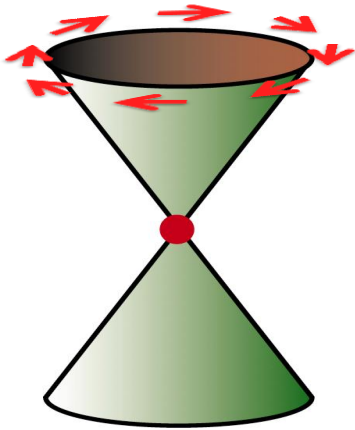
SR-ARPES

T. Okuda

HISOR

Outstanding question: spin polarization?

$$H_{\text{TSS}} = \zeta(\sigma_x k_y - \sigma_y k_x)$$

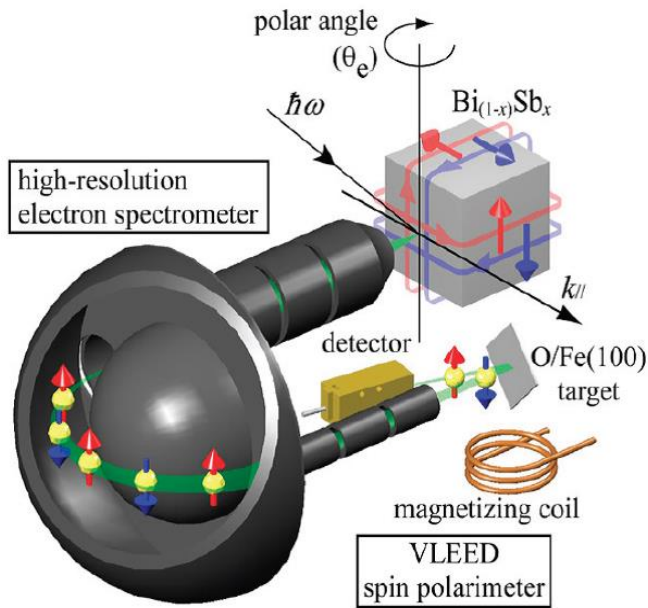


Chiral spin texture
100% polarization

Spin polarization in Bi_2Se_3 ?

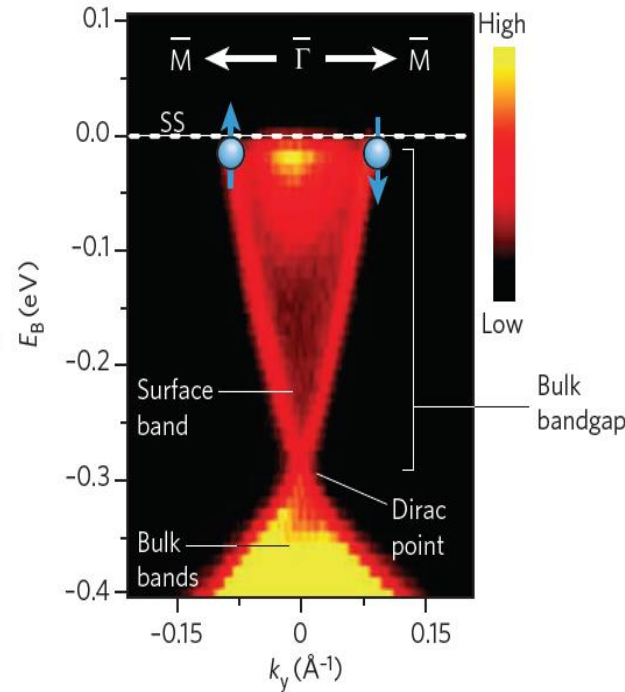
- orbital character of TSS
- how “thick” is the TSS

Outstanding question: spin polarization?

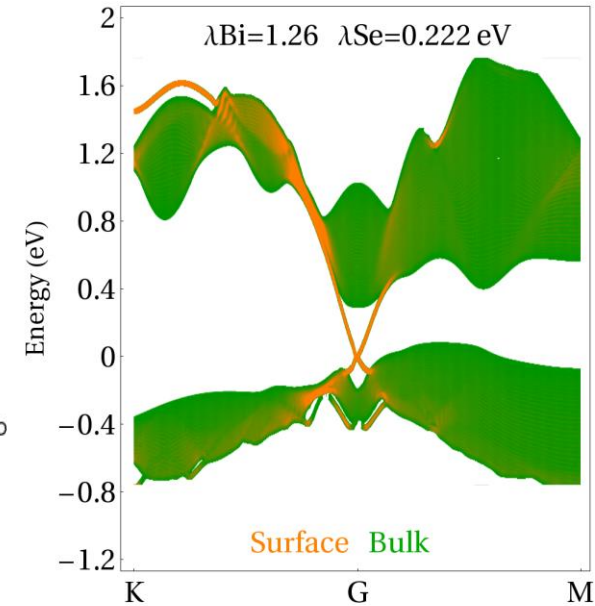


ARPES+Spin-polarimeter
surface and bulk

Akinori Nishide, et al (2010)



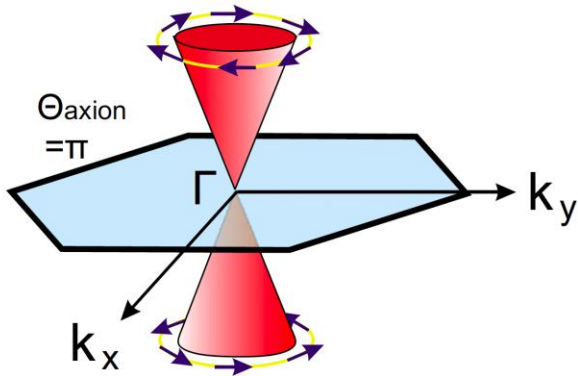
Y. Xia, D. Hsieh,
Hasan, Dil, et al. (2009)



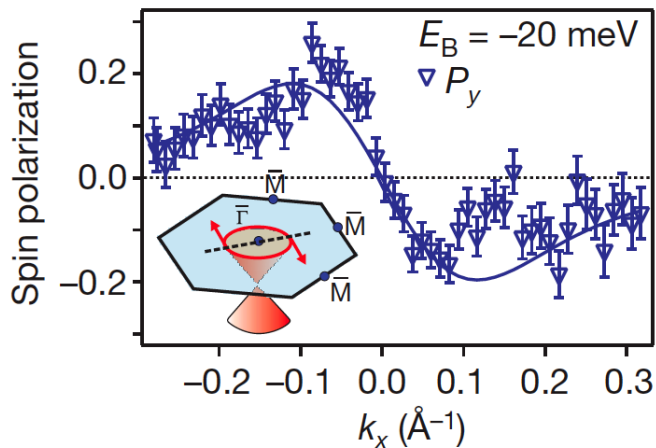
Z.-H. Zhu et al., (2013)

Outstanding question: spin polarization?

Topological Insulator



M. Hasan and C. Kane, *RMP* (2010)



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

Phenomenological model: **100%**

First principle calculations: **50-85%**

~50% Bi_2X_3 (X=Se,Te) Yazyev et al. *PRL* (2010)

~85% Bi_2Se_3 Zhao et al. *Nano Lett.* (2011)

Measured spin polarization range: **10-80%**

~30% $\text{Bi}_{1-x}\text{Sb}_x$ Hsieh et al. *Science* (2009)

~20% Bi_2Te_3 Hsieh et al. *Nature* (2009)

~10% Bi_2Se_3 Hirahara et al. *PRB* (2010)

~60% Bi_2Te_3 Souma et al. *PRL* (2011)

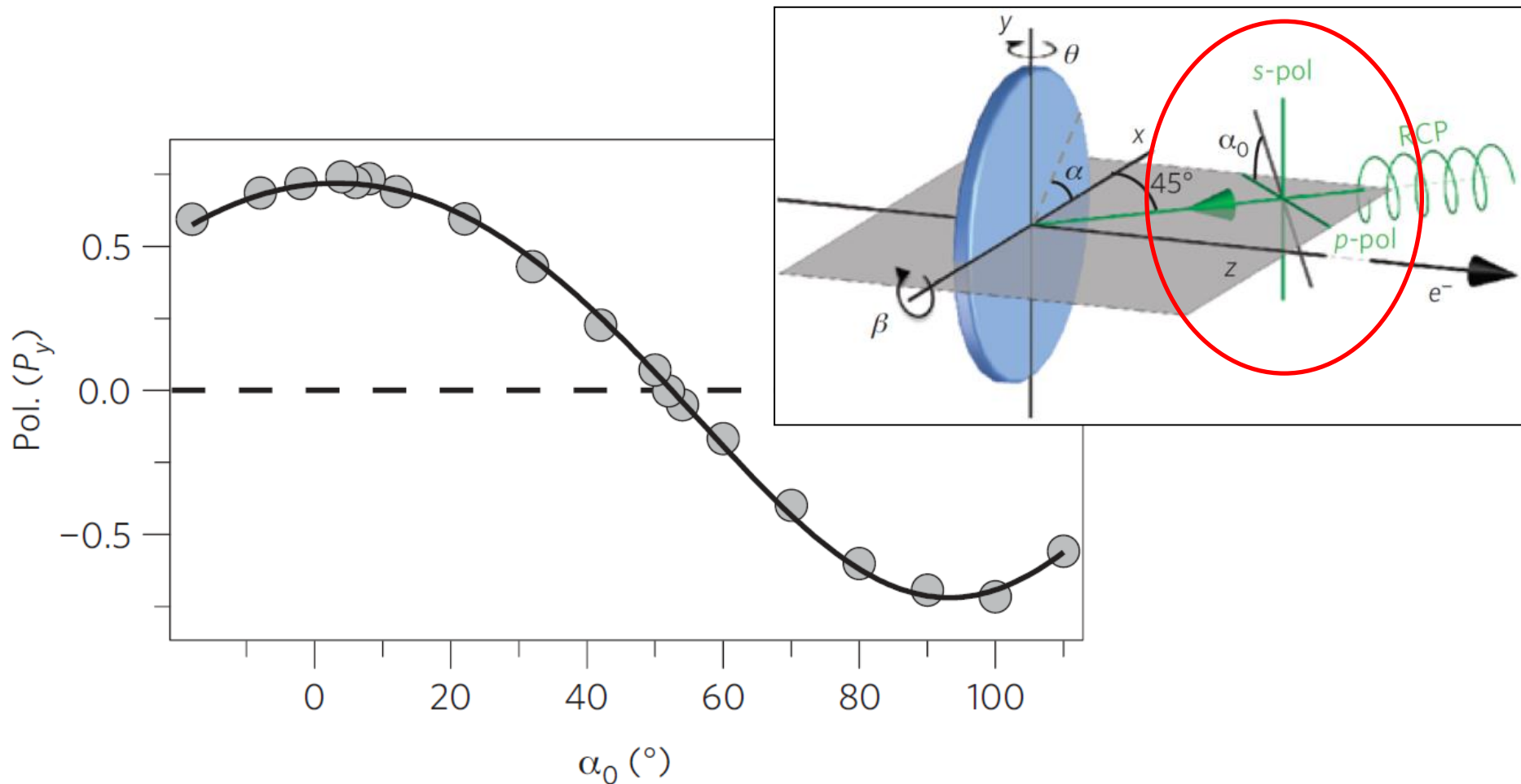
~75% Bi_2Se_3 Pan et al. *PRL* (2011)

~40% BiTlSe_2 Xu et al. *Science* (2011)

>80% Bi_2Se_3 Jozwiak et al. *PRB* (2011)



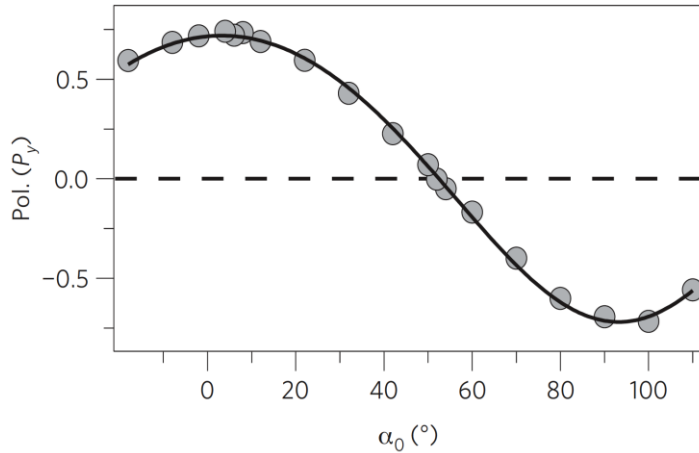
Photoelectron spin-flipping by light polarization?



Photoelectron spin rotates with light polarization:
Spin-dependent interaction with light?

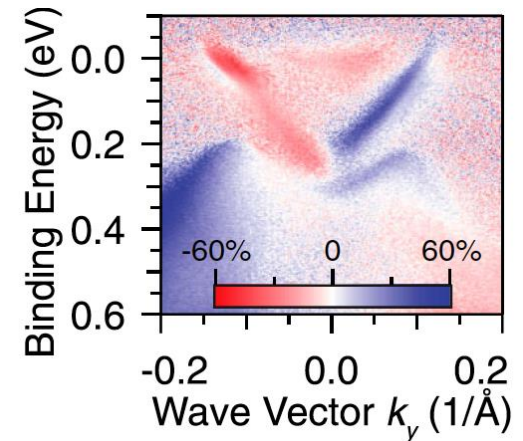
Outstanding questions: spin-orbital texture?

Photoelectron spin flipping



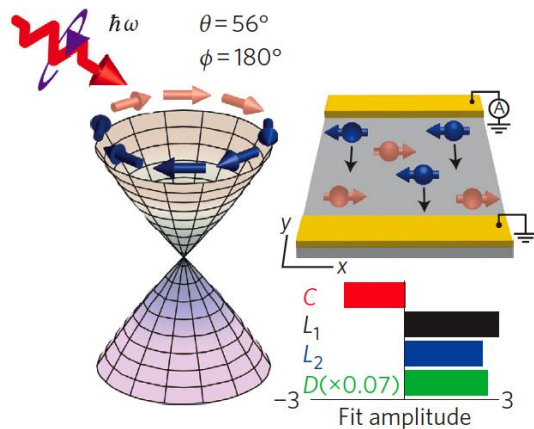
Jozwiak, et al., Nat. Phys. 9, 293 (2013)

Circular Dichroism reversal



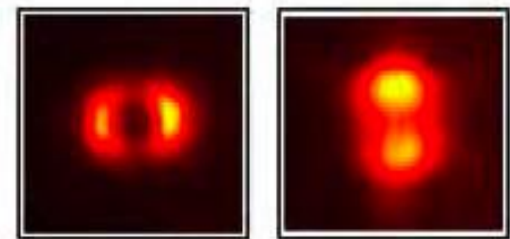
Scholz, et al. PRL 110, 216801 (2013)

Photocurrent



J.W. Mciver et al, Nature Nanotech 7, 96 (2011)

Orbital texture switching



Y. Cao, et al., Nature Phys. (2013)
& arXiv:1211.5998 (2012)

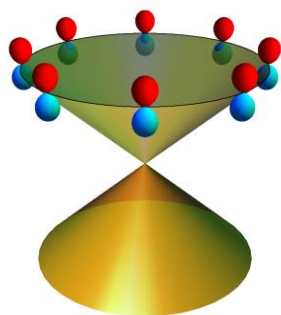
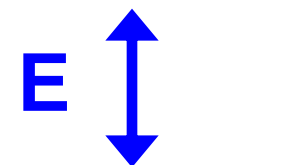
Theory:

H. J. Zhang, et al., arXiv: 1211.0762 (2012)

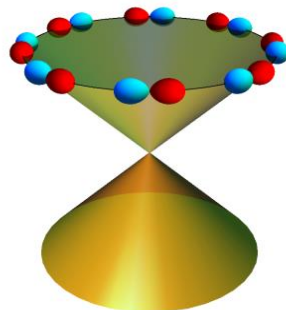
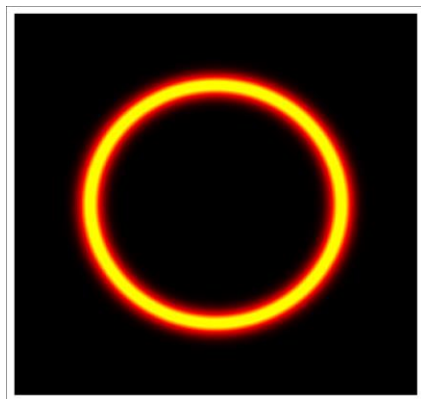
ARPES: Selection Rule for Linear Polarization

Bi, Se – p orbitals

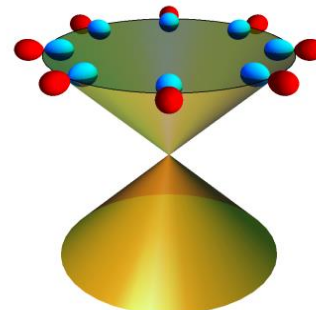
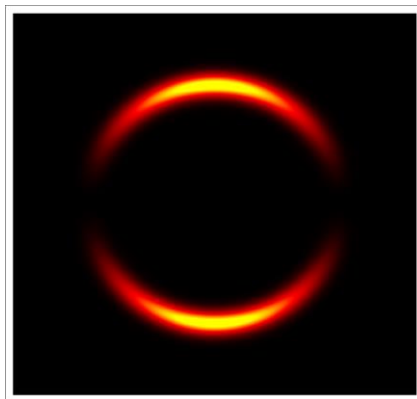
$$\langle \Psi_f | \mathbf{A} \cdot \mathbf{p} | \Psi_i \rangle$$



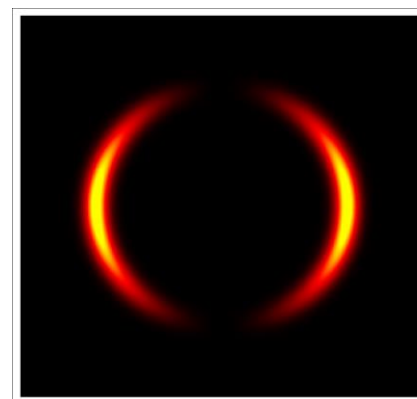
p_z



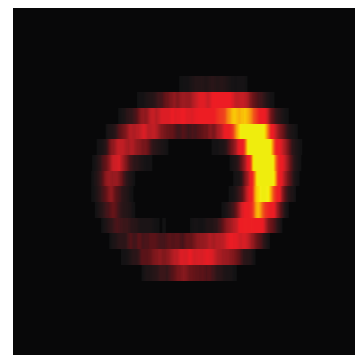
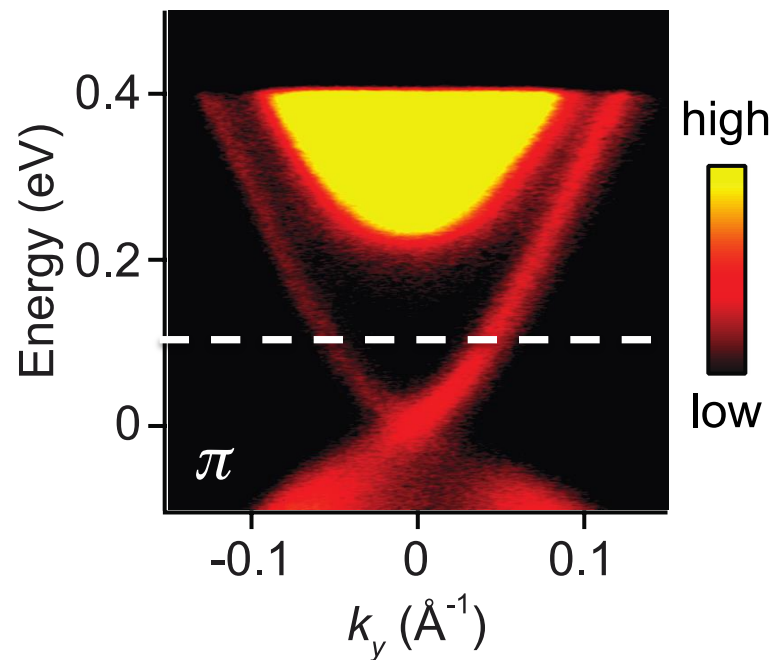
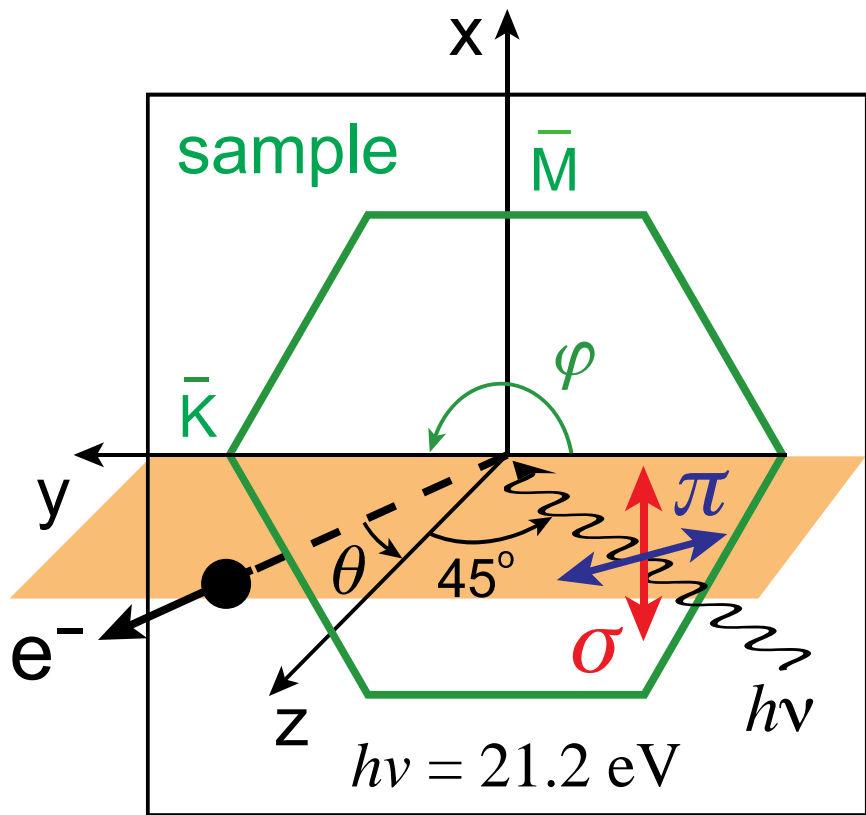
$p_{x,y}$



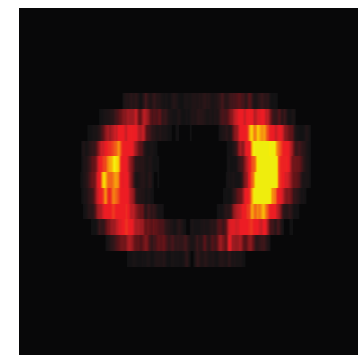
$p_{x,y}$



Linear-polarization dependent ARPES maps



$\pi - p_y$ and p_z

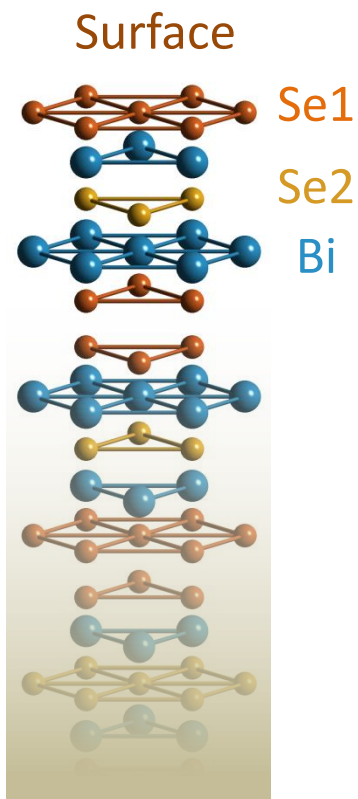


$\sigma - p_x$

$$I(\mathbf{k}) = I(-\mathbf{k})$$

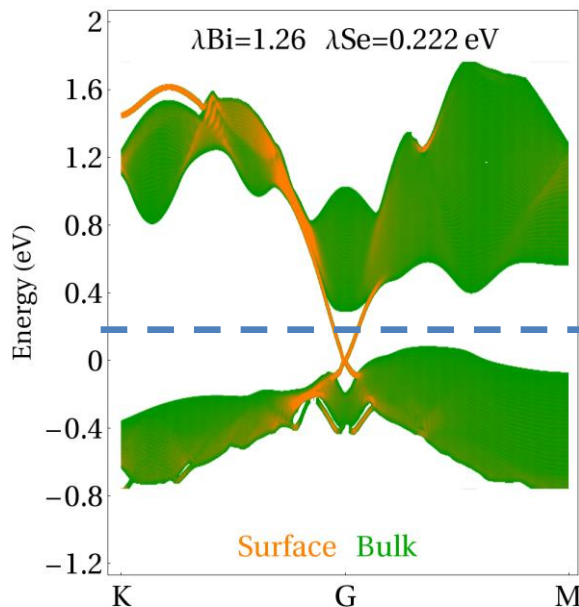


Topological surface state: finite extension into bulk



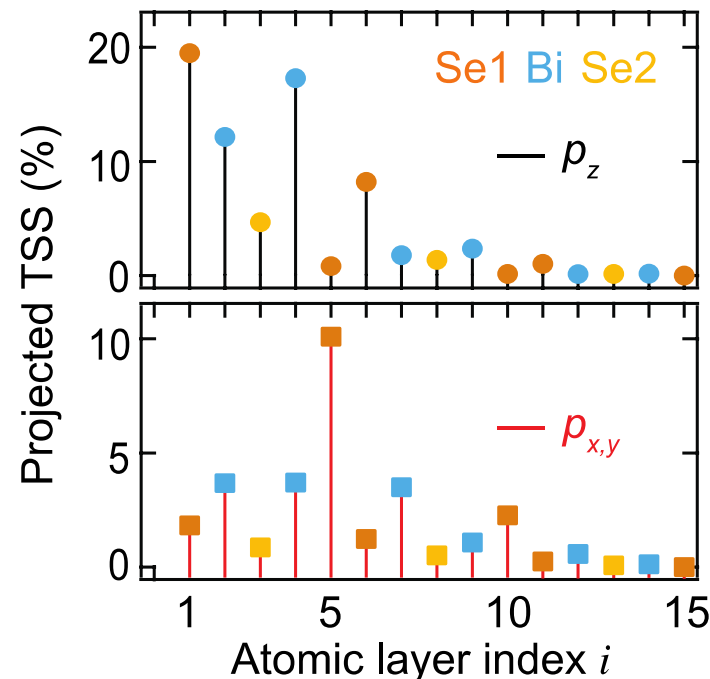
Bulk

250
layer
slab



$$\Psi_{\text{TSS}} = \sum_{i,\tau,\sigma} C_{i,\tau}^{\sigma} \psi_{i,\tau}$$

τ - $p_{x,y,z}$
 i - layer
 σ - spin



Spatial contributions to TSS

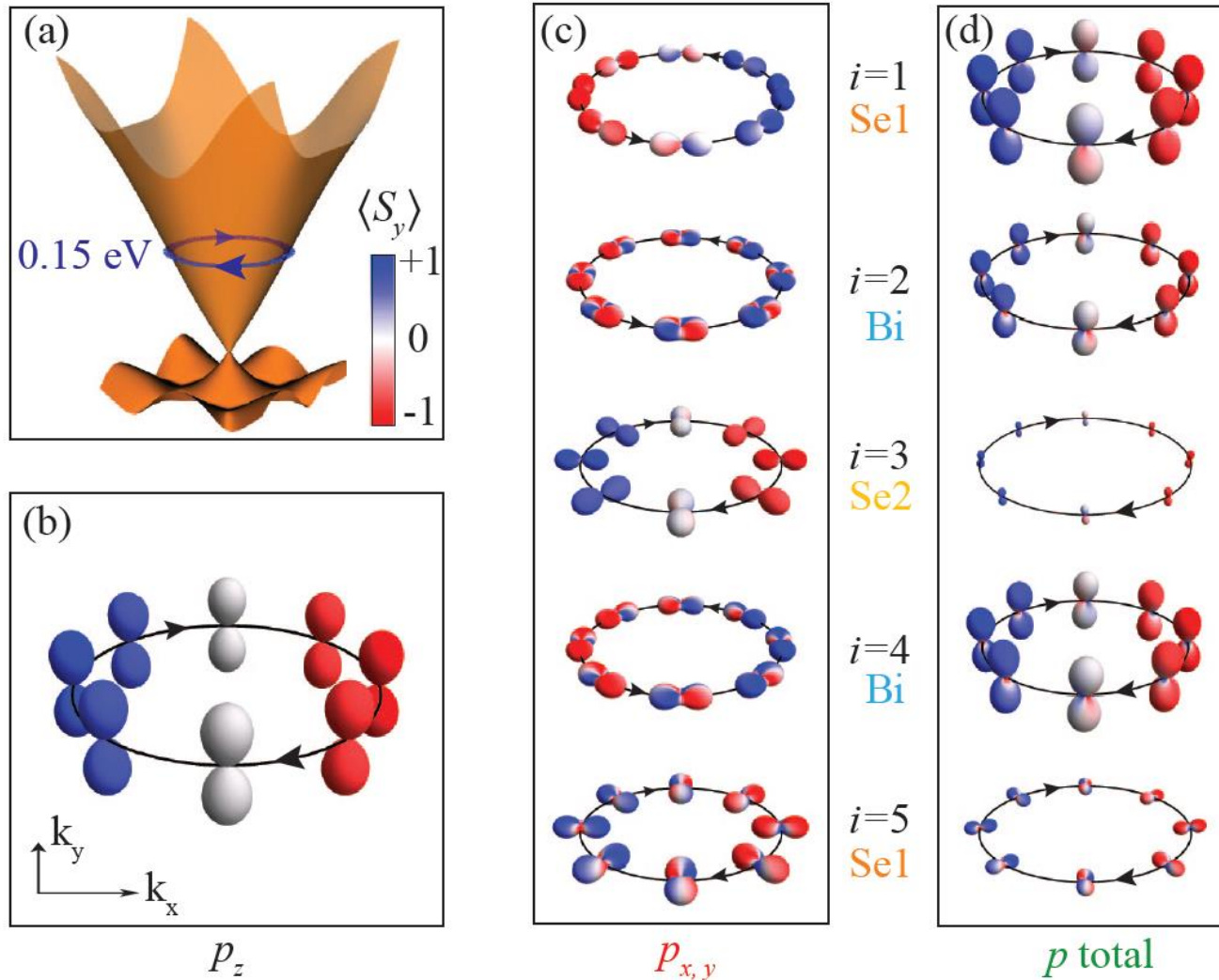
~75% from the 1st QL;

~25% from the 2nd QL.

Extends ~2nm deep into the bulk

Layer-dependent orbital weight

Layer-by-layer entangled spin-orbital texture



Entangled texture revealed by quantum interference in ARPES

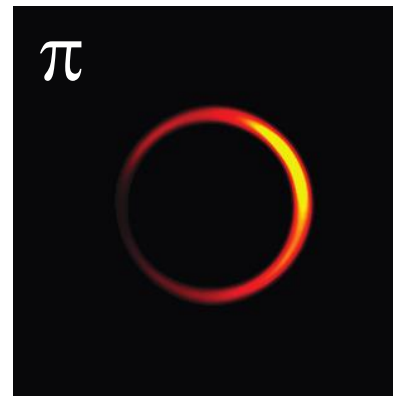
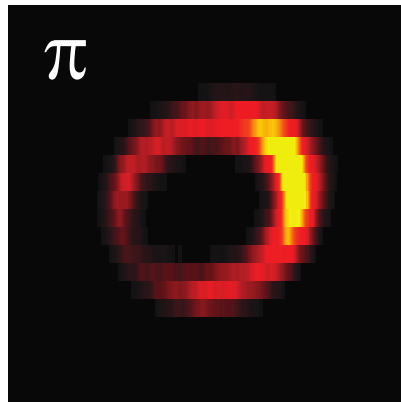
ARPES intensity

$$I \propto \langle \Psi_f | \mathbf{A} \cdot \mathbf{p} | \Psi_{\text{TSS}} \rangle$$

Initial state: $\Psi_{\text{TSS}} = \sum_{i,\sigma} \alpha_i \psi_{i,\mathbf{k}_{\parallel}}^{\sigma}$ from *ab initio* TB model

Final state: $\Psi_f = e^{i\mathbf{k} \cdot \mathbf{r}} \equiv e^{ik_z z} e^{i\mathbf{k}_{\parallel} \cdot \mathbf{r}_{\parallel}}$ Plane wave

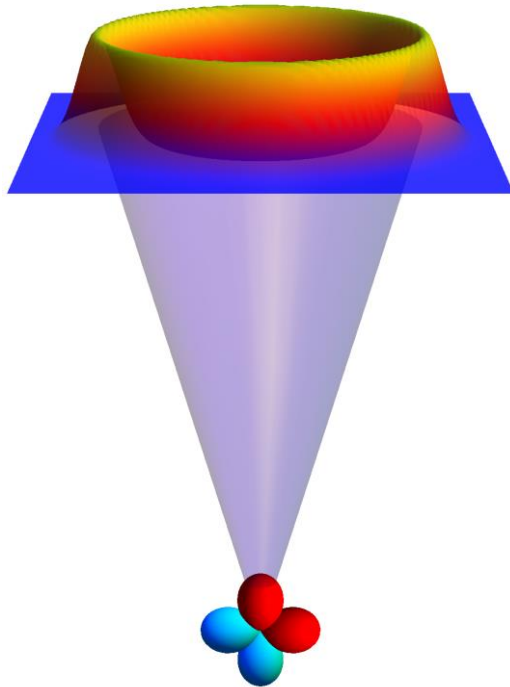
$$I \propto \sum_{\sigma} \left| \sum_i e^{-ik_z z} \langle e^{i\mathbf{k}_{\parallel} \cdot \mathbf{r}_{\parallel}} | \mathbf{A} \cdot \mathbf{p} | \alpha_i \psi_{i,\mathbf{k}_{\parallel}}^{\sigma} \rangle \right|^2$$



Asymmetric ARPES from a simple TSS model

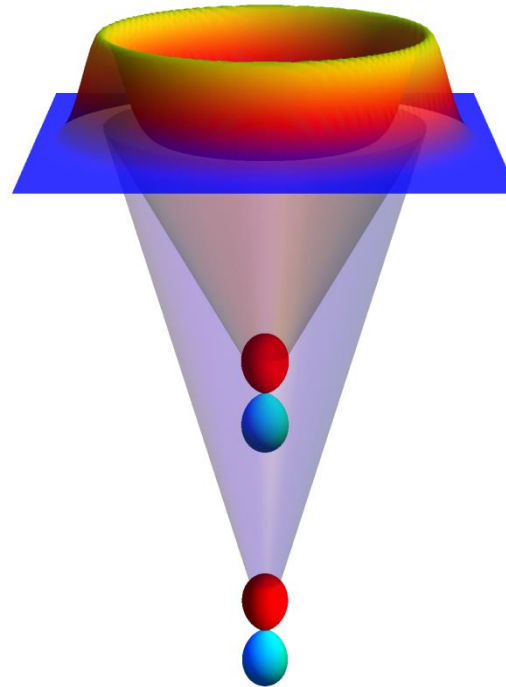
Quantum interference

1-layer system



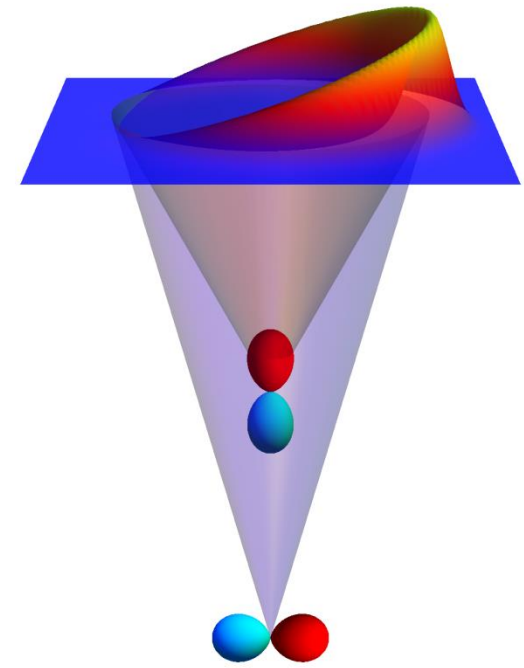
Multiple orbitals

2-layer system



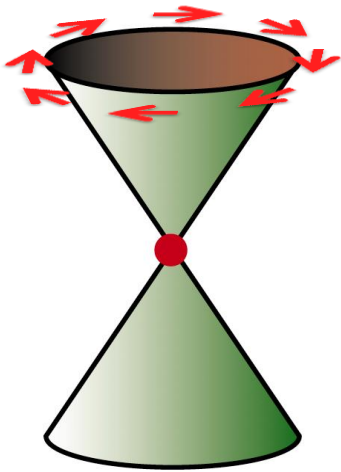
Single orbital

2-layer system



Multiple orbitals
Layer-by-layer dependence

Orbital-projected spin texture of TSS

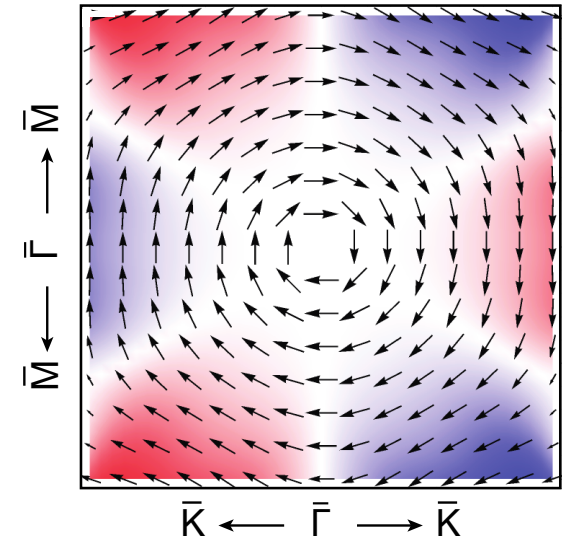


p_z

Model: **100%**

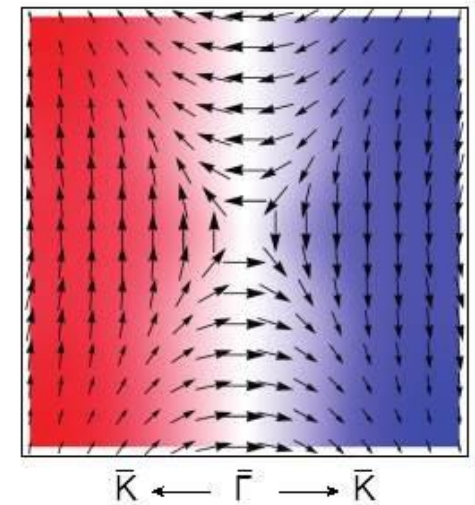
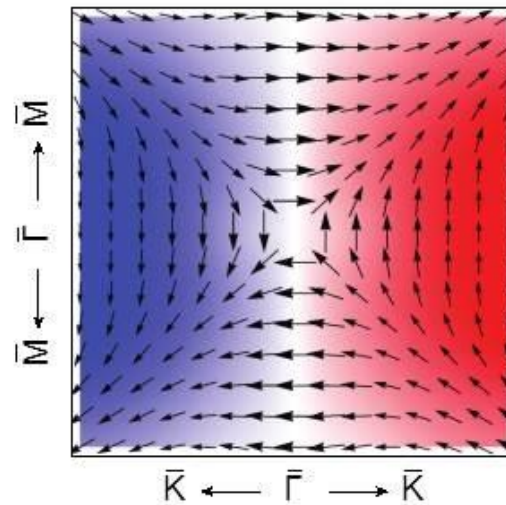
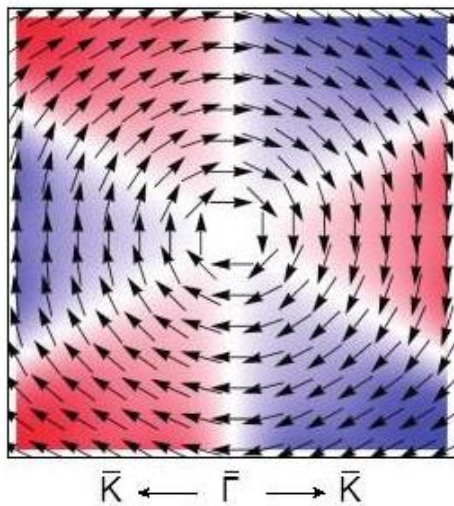
Spin-orbital entanglement

DFT: **< 75%**

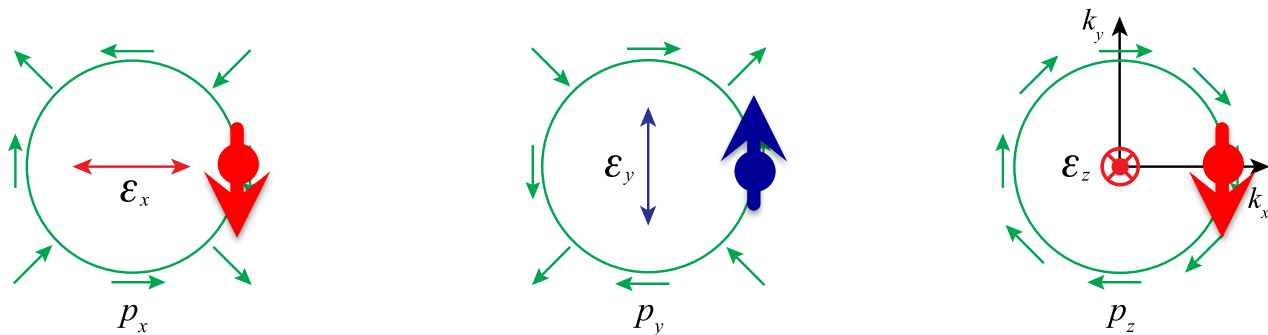


p_x

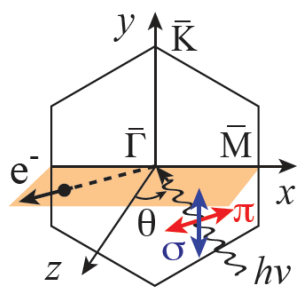
p_y



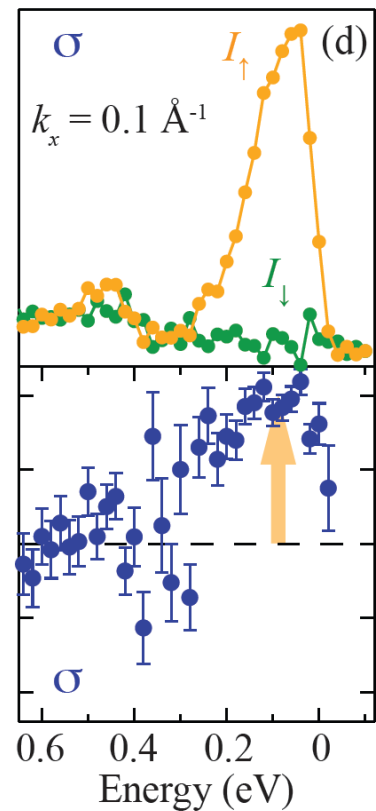
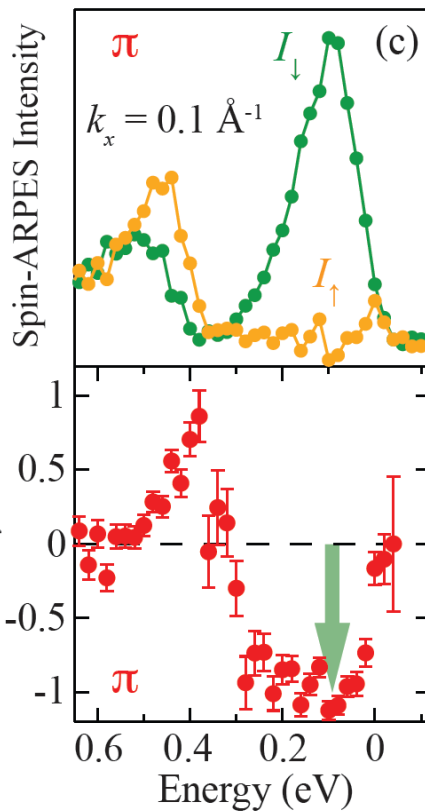
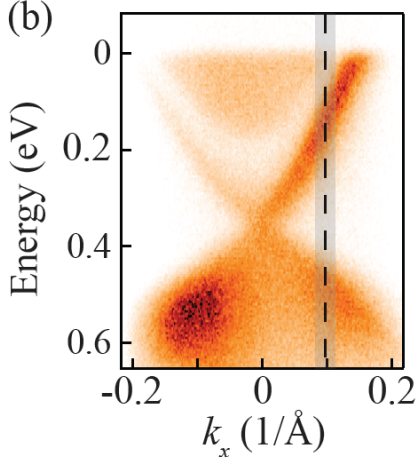
Spin-ARPES: orbital-coupled spin texture



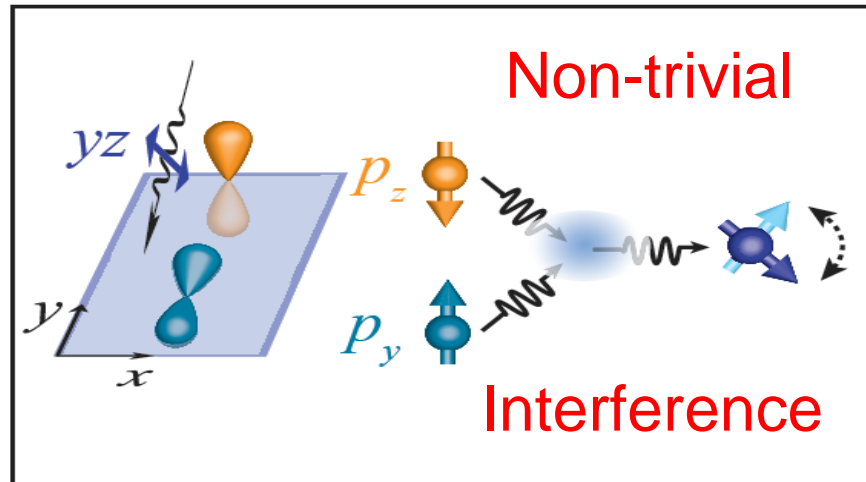
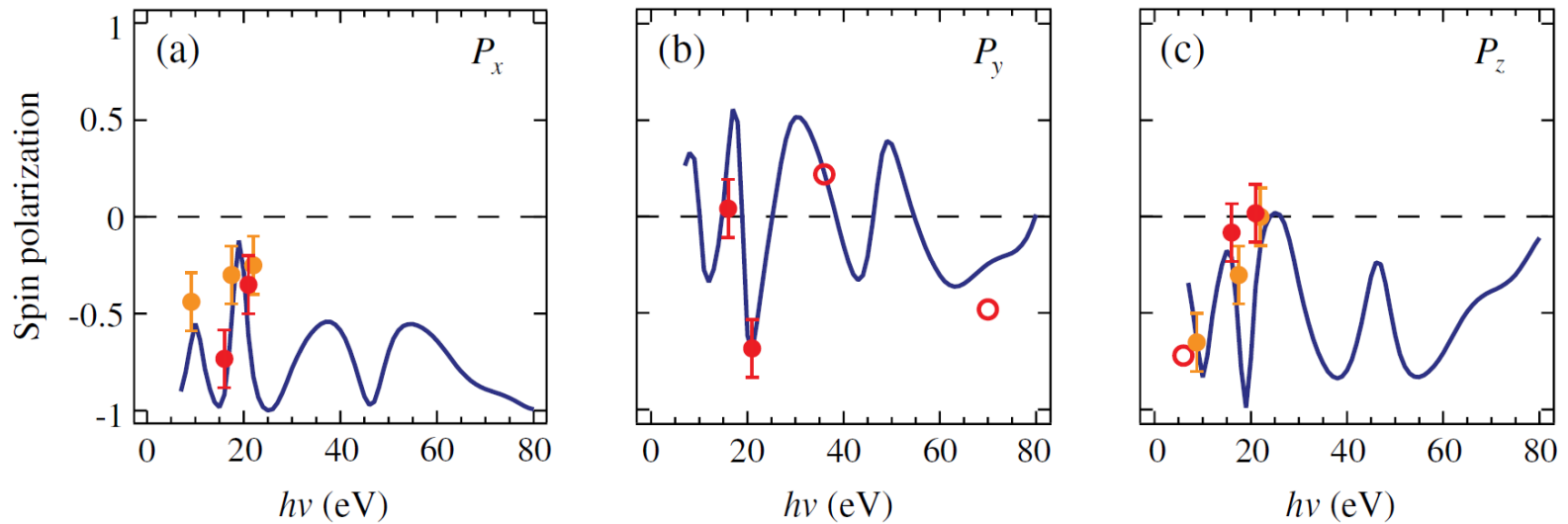
(a)



(b)



Manipulation of spin polarization by photon energy

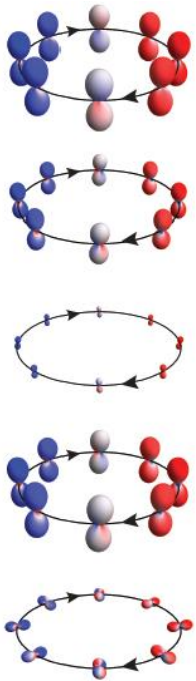


$$|\vec{P}| = 1$$

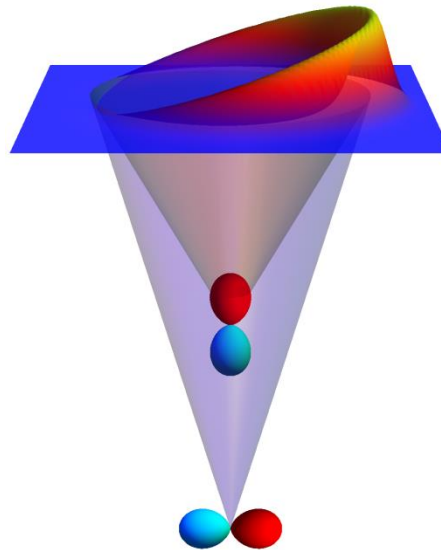
Optospintronics

Conclusions

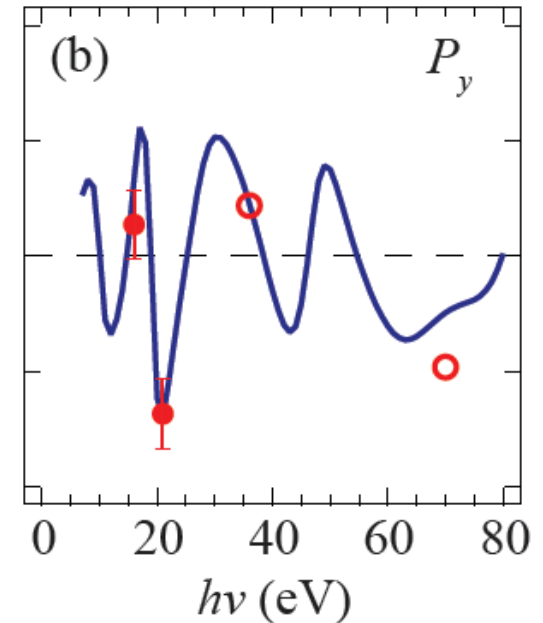
layer dependent spin-orbital entanglement



quantum interference effects in photoemission



$\pm 100\%$ spin polarization with linearly polarized light



Thank you