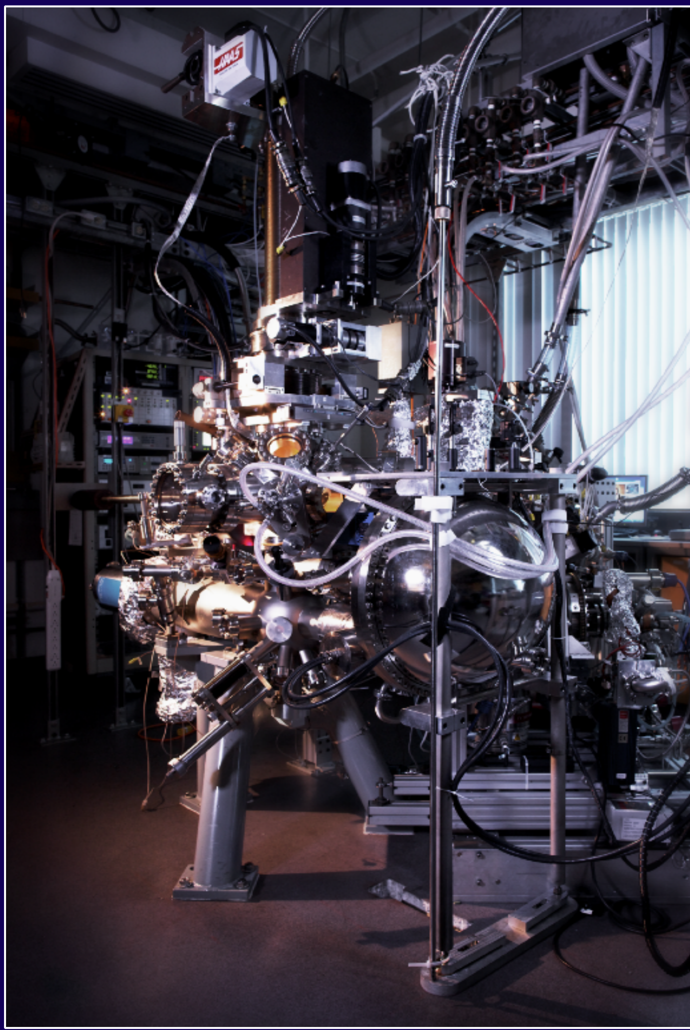
UNIVERSITY OF BRITISH COLUMBIA

Jason Zhihuai Zhu

ARPES study of the electronic structure of three-dimensional topological insulators

Andrea Damascelli's group



OUTLINE

3D topological insulator Bi_2Se_3

Angle-resolved photoemission spectroscopy

UBC ARPES group's work
- Surface instability control
- Entangled spin-orbital texture

Outline

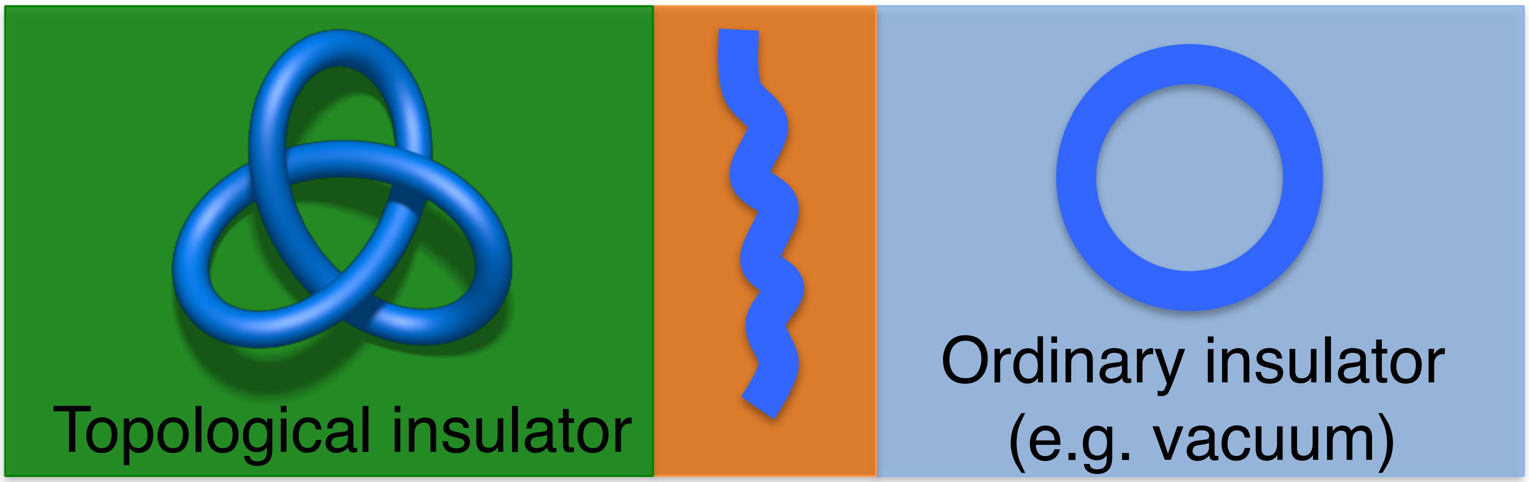
Introduction:

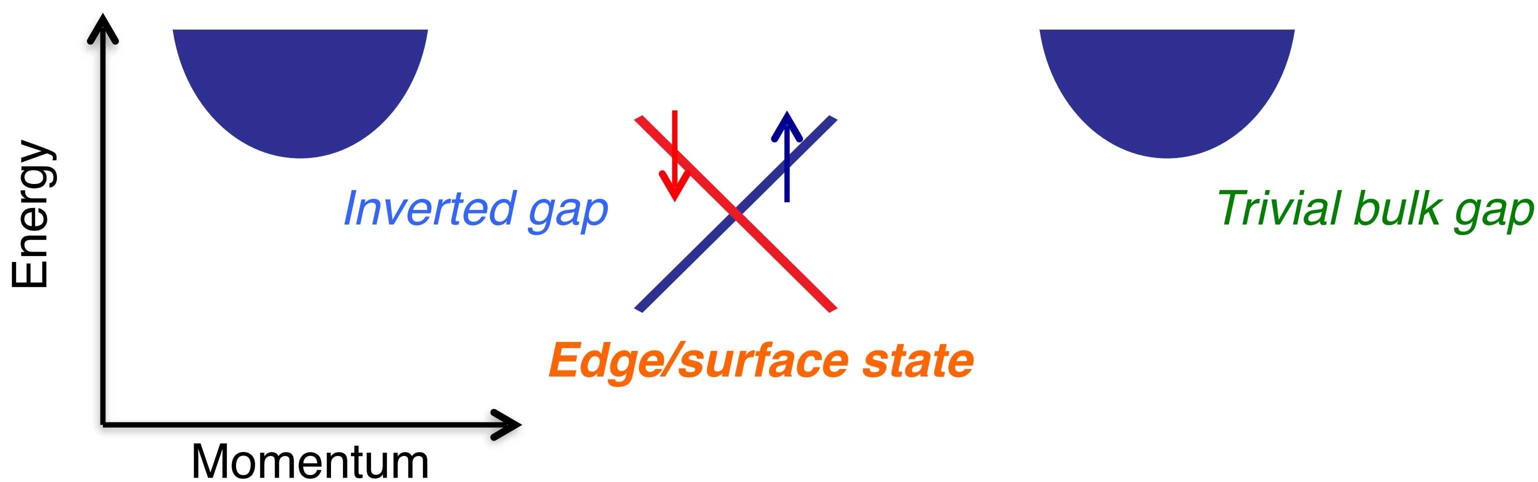
3D Topological Insulators

Why "Topological"

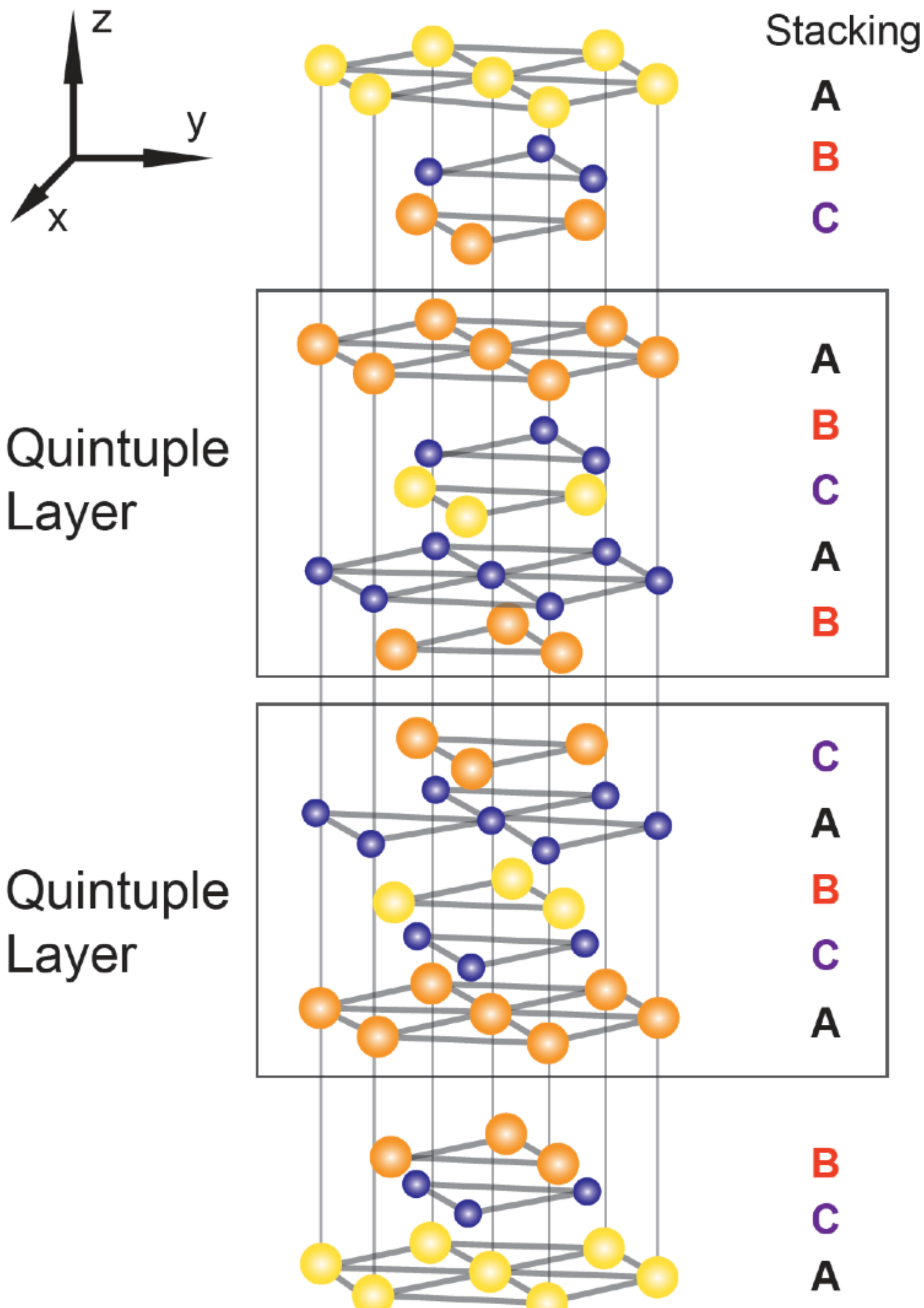
Topological invariant: quantity that does not change under continuous deformation

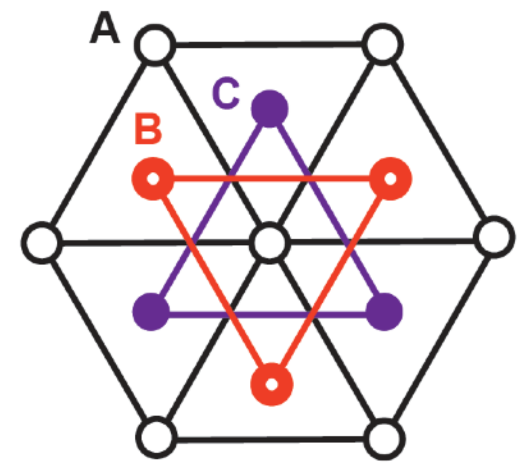
Joel E. Moore, Nature (2010)





Bi_2Se_3





Bi_2Se_3: crystal structure

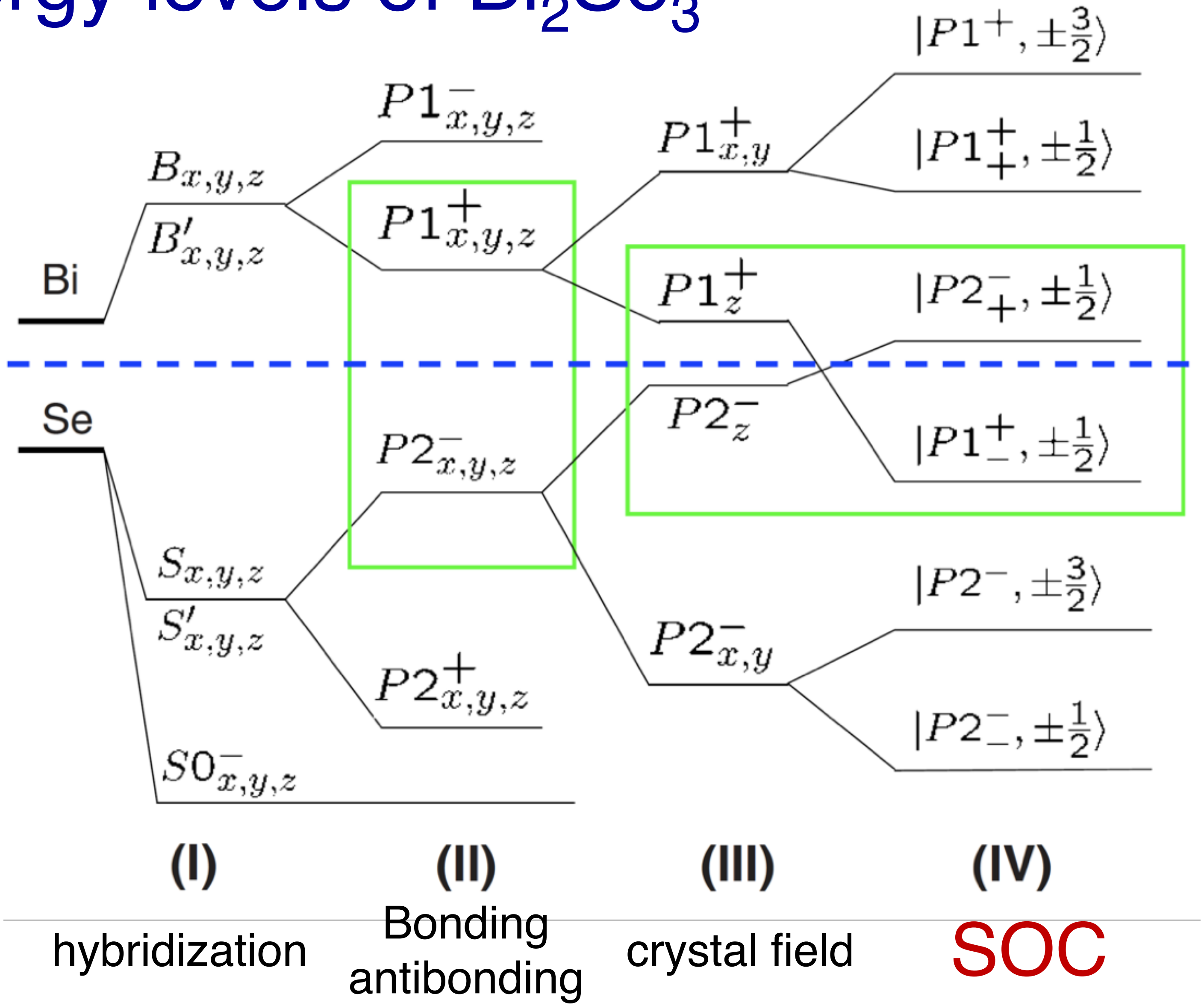
- Bi
- Se1
- Se2

Bi: $6s^2 6p^3$

Se: $4s^2 4p^4$

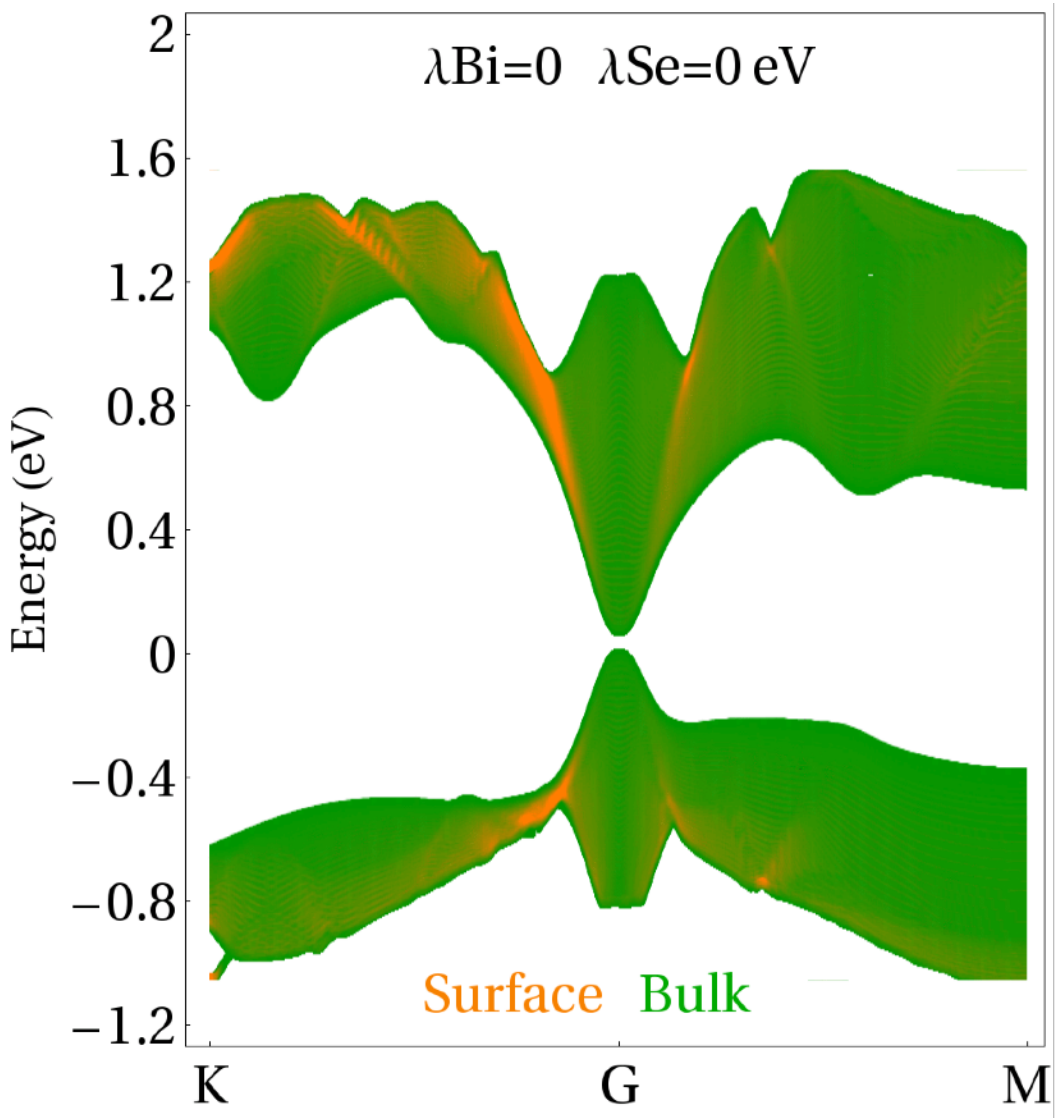
X.T. Zhu et al.,PRL 107. 186102 (201

Energy levels of Bi_2Se_3

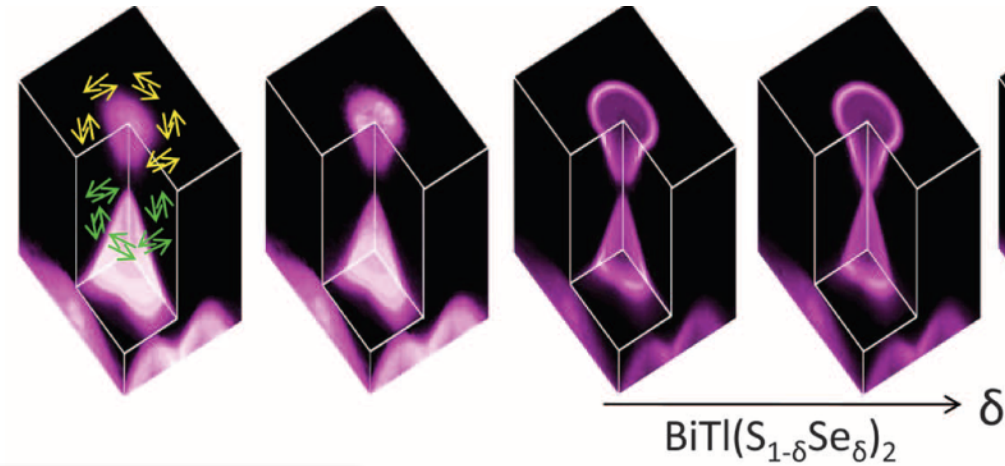


Liu et al, PRB **82**, 045122 (2010)

Trivial to Topological Insulator: Spin-orbit-driven Transition



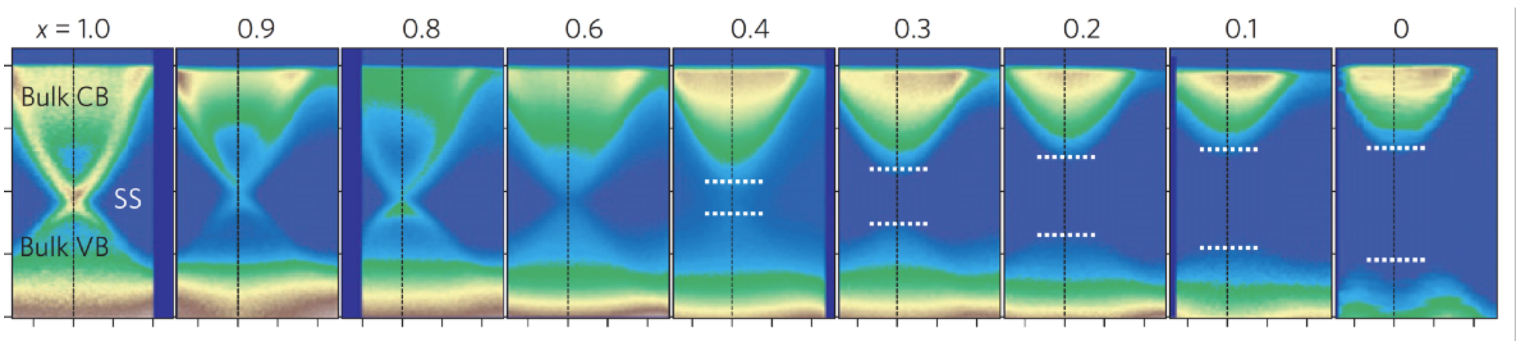
Trivial to non-trivial topological phase transition



S.Y. Xu, et al., Science (2011)

Modulate SOC

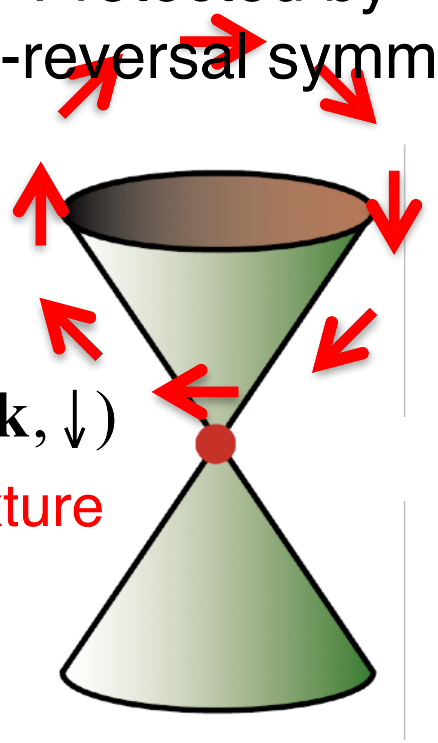
$BiTl(S_{1-x}Se_x)_2$



T. Sato, et al., Nat. Phys. (2011)

Robust Topological Surface Dirac Fermions

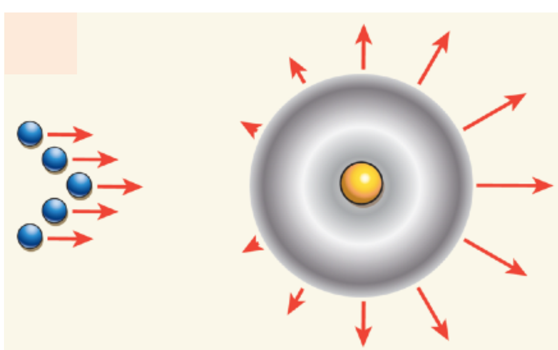
Protected by
time-reversal symmetry

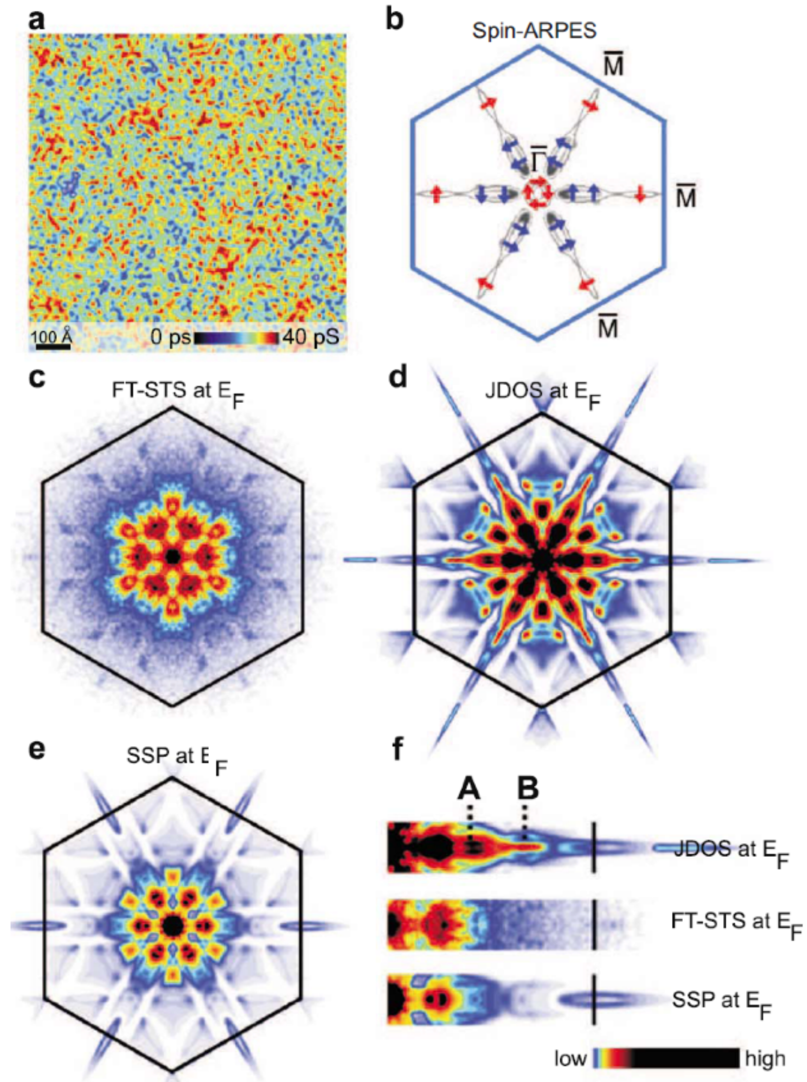


$$\Psi(\mathbf{k},\uparrow) = \Psi(-\mathbf{k},\downarrow)$$

Chiral spin texture

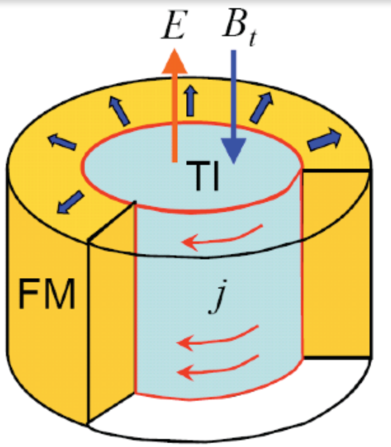
No backscattering





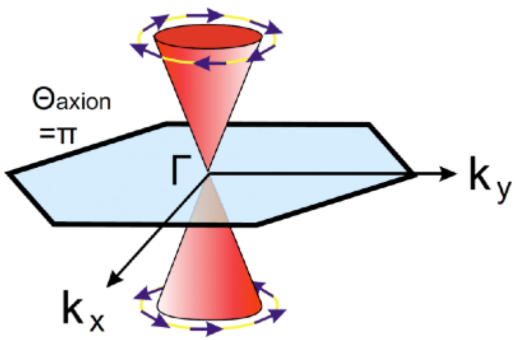
Roushan et al. Nature 2009

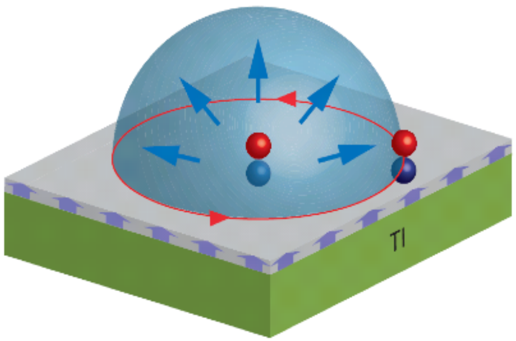
Application Potential



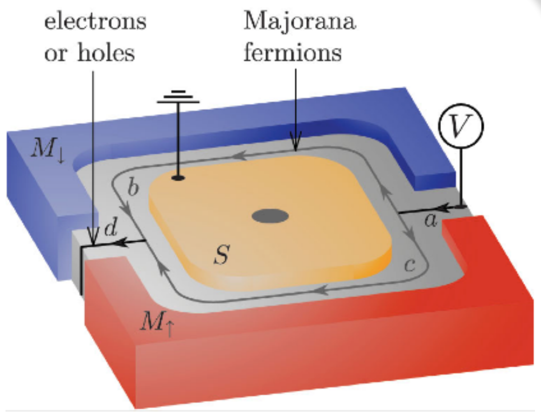
Magnetoelectric effect

Spintronics
:
TI + FM



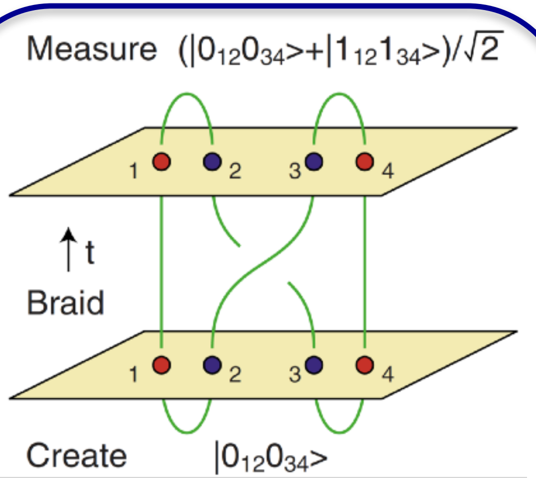


Magnetic monopole



Majorana fermions

Quantum computing:
TI + FM + SC



No-Abelian statistics

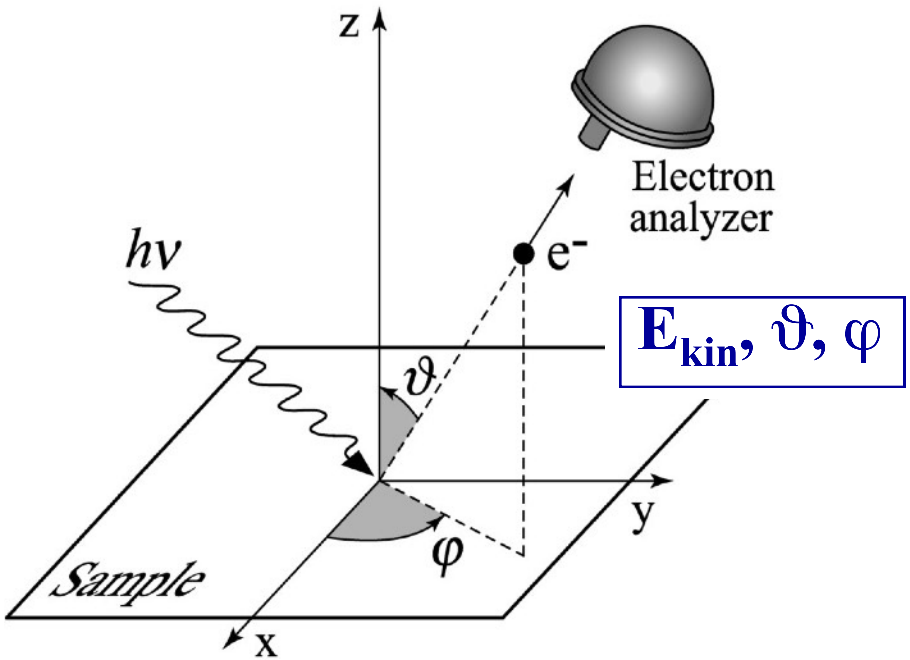
Hasan, *et. al.*, RMP (2010)
Qi, *et. al.*, RMP (2011)

Outline

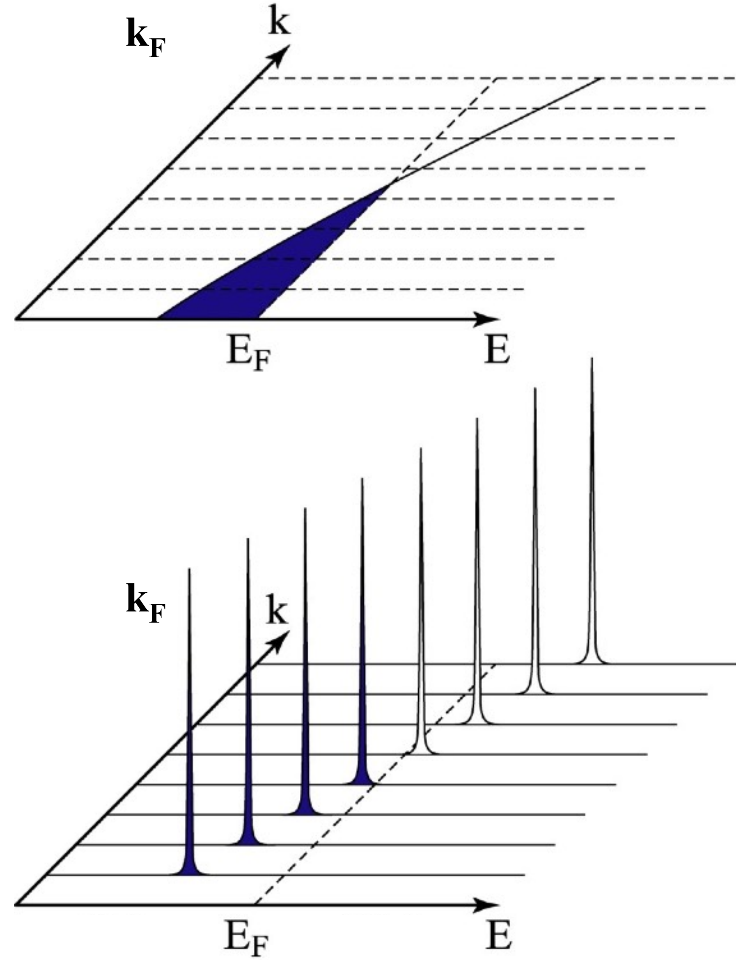
Introduction:

ARPES

Angle-Resolved Photoemission Spectroscopy



Electrons in Reciprocal Space



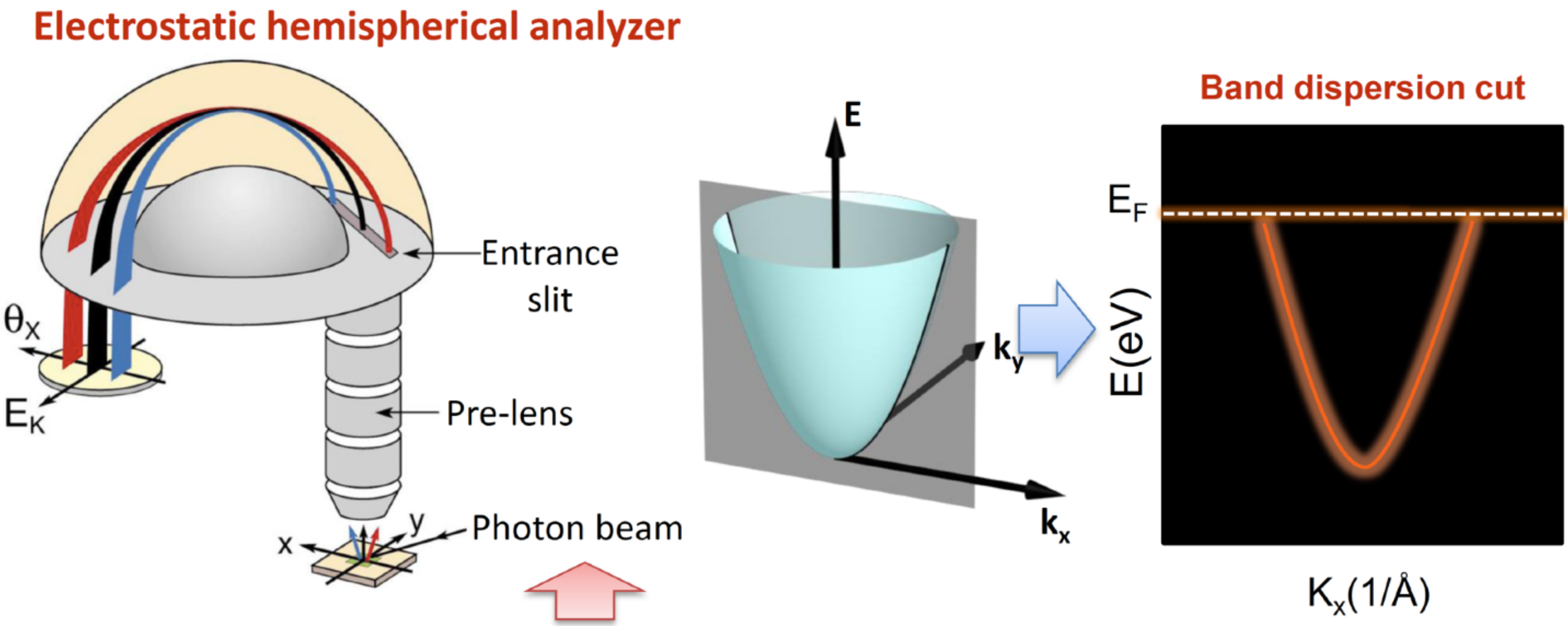
Energy Conservation

$$E_{kin} = h\nu - \phi - |E_B|$$

Momentum Conservation

$$\mathbf{p}_{||} = \hbar \mathbf{k}_{||} = \sqrt{2mE_{kin}} \cdot \sin\vartheta$$

Angle-Resolved Photoemission Spectroscopy



X-ray tube

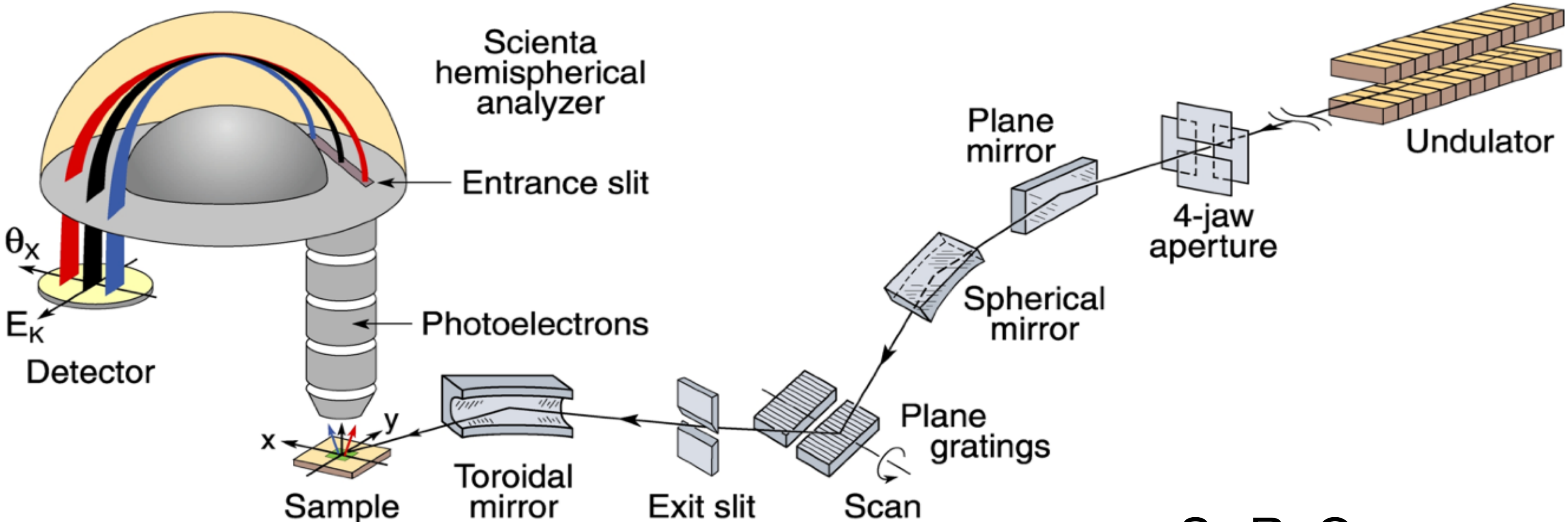
Gas discharge lamp

Laser

Synchrotron

Courtesy of Y.L. Chen

Angle-Resolved Photoemission Spectroscopy

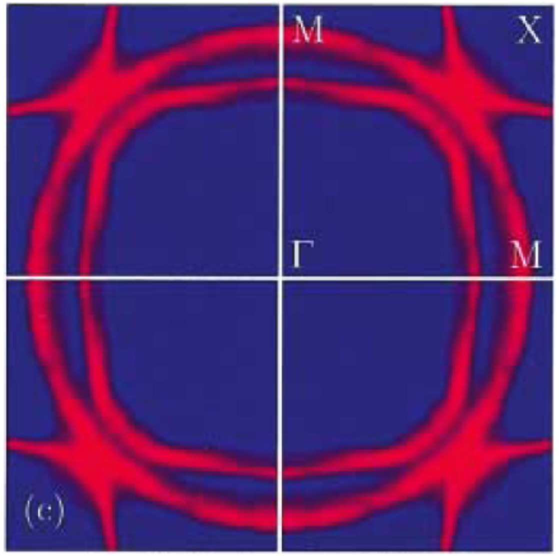


Parallel multi-angle recording

- Improved energy resolution
- Improved momentum resolution
- Improved data-acquisition efficiency

	ΔE (meV)	$\Delta\theta$
past	20-40	2°
now	1-10	0.2°

Sr_2RuO_4



A. Damascelli *et al.*, PRL **85**, 5194 (2000)

ARPES ON COMPLEX SYSTEMS

- **High energy resolution**

  $\Delta E < 1 meV$
- **High angular precision**

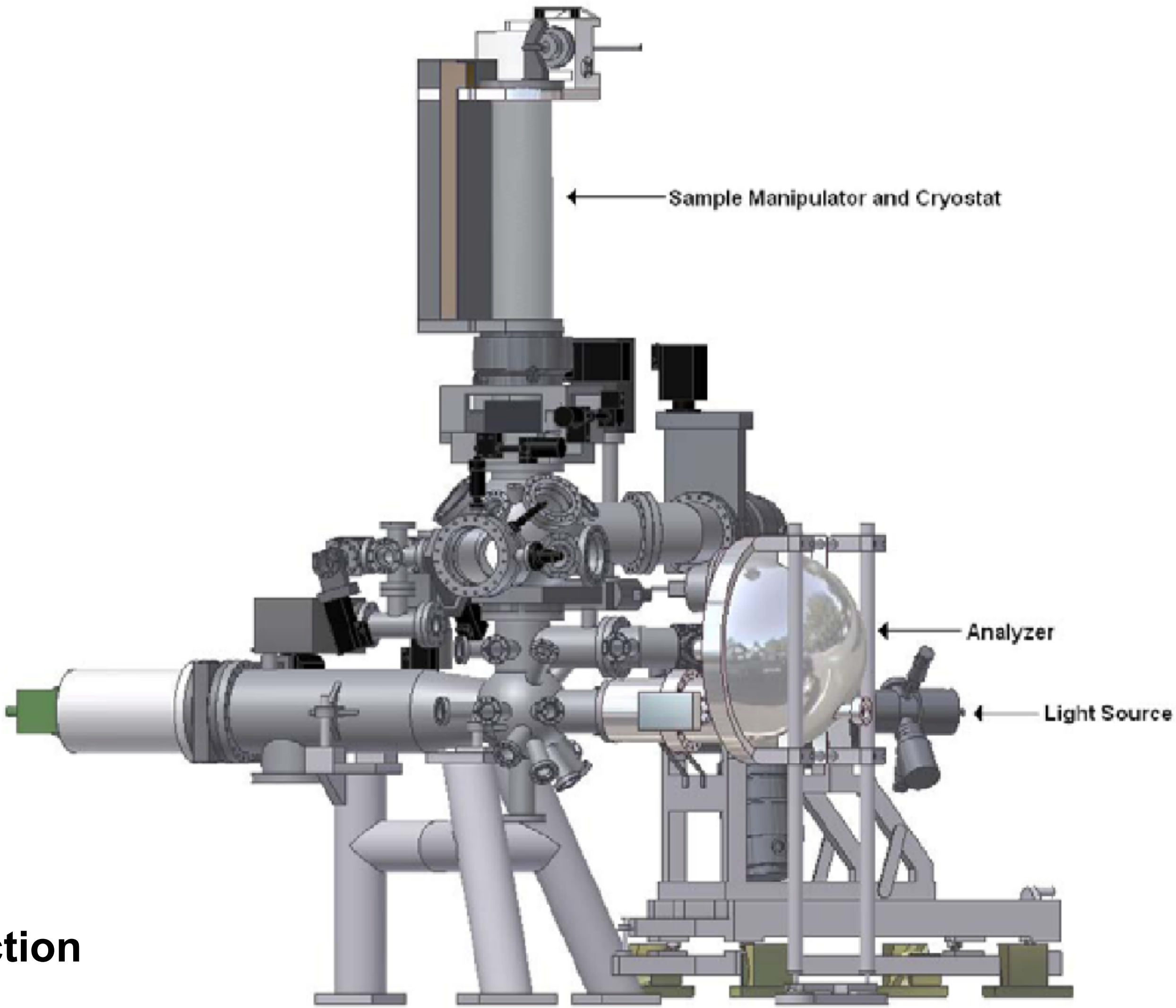
  $\pm$ 0.05º
- **Low base temperature**

  ~ 2 K
- **Photon energies**

  H_2, He, Ne
- **Polarization control**

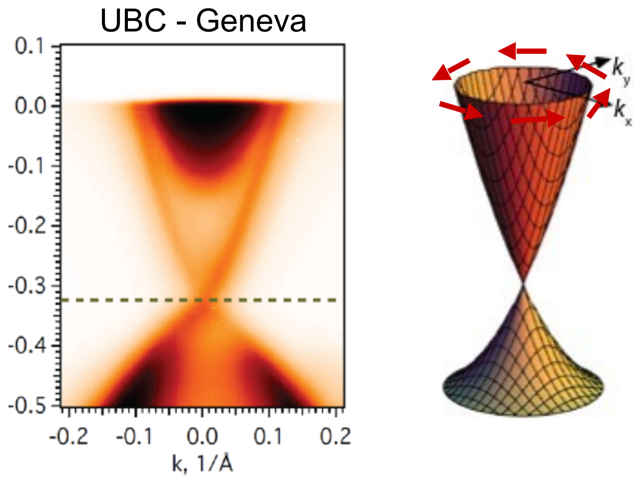
  linear
- **Ultra-high vacuum**

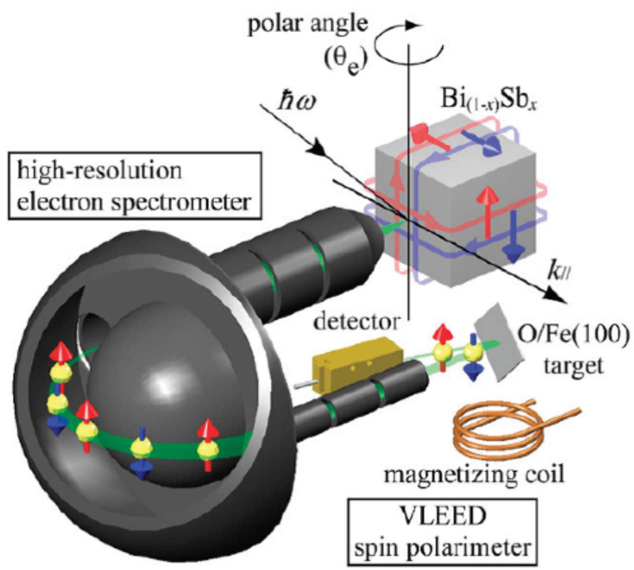
  ~ 10^{-11} torr
- **Surface / Thin films**
- **Low Energy Electron Diffraction**



New Developments: ARPES + Spin + Time

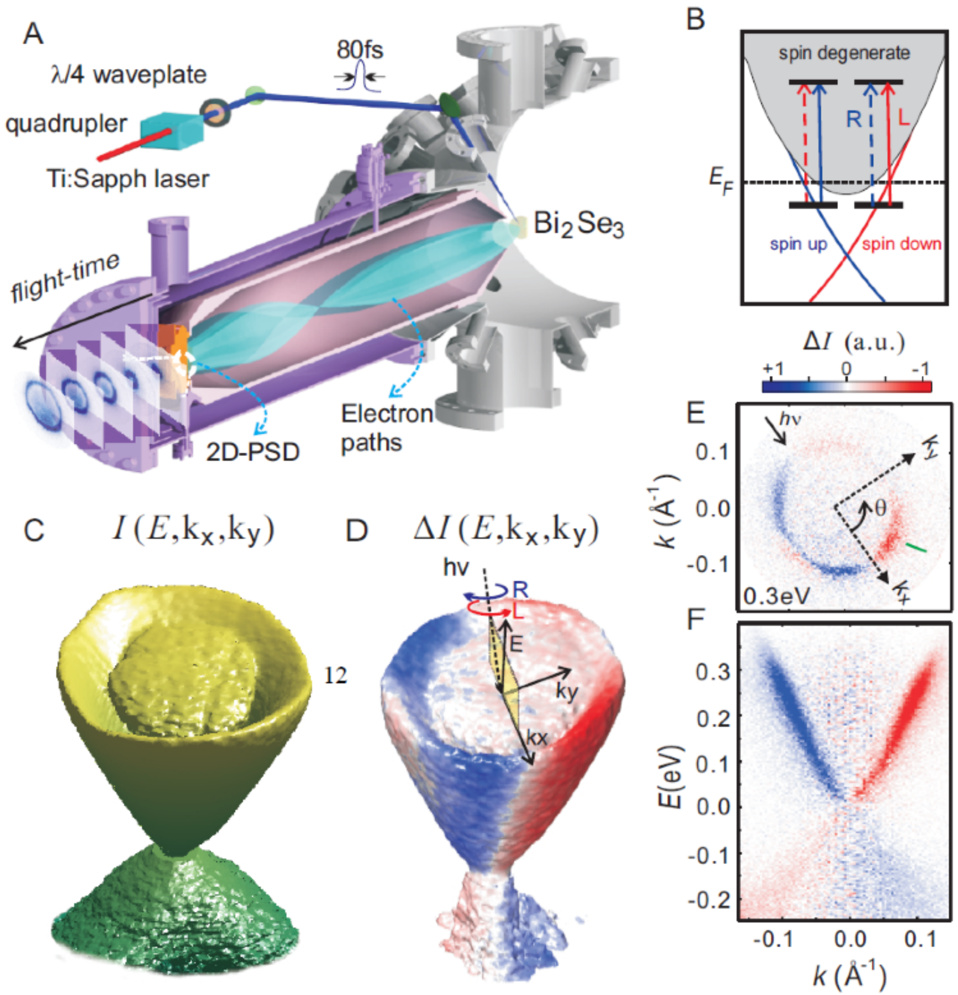
ARPES+Spin polarimeter





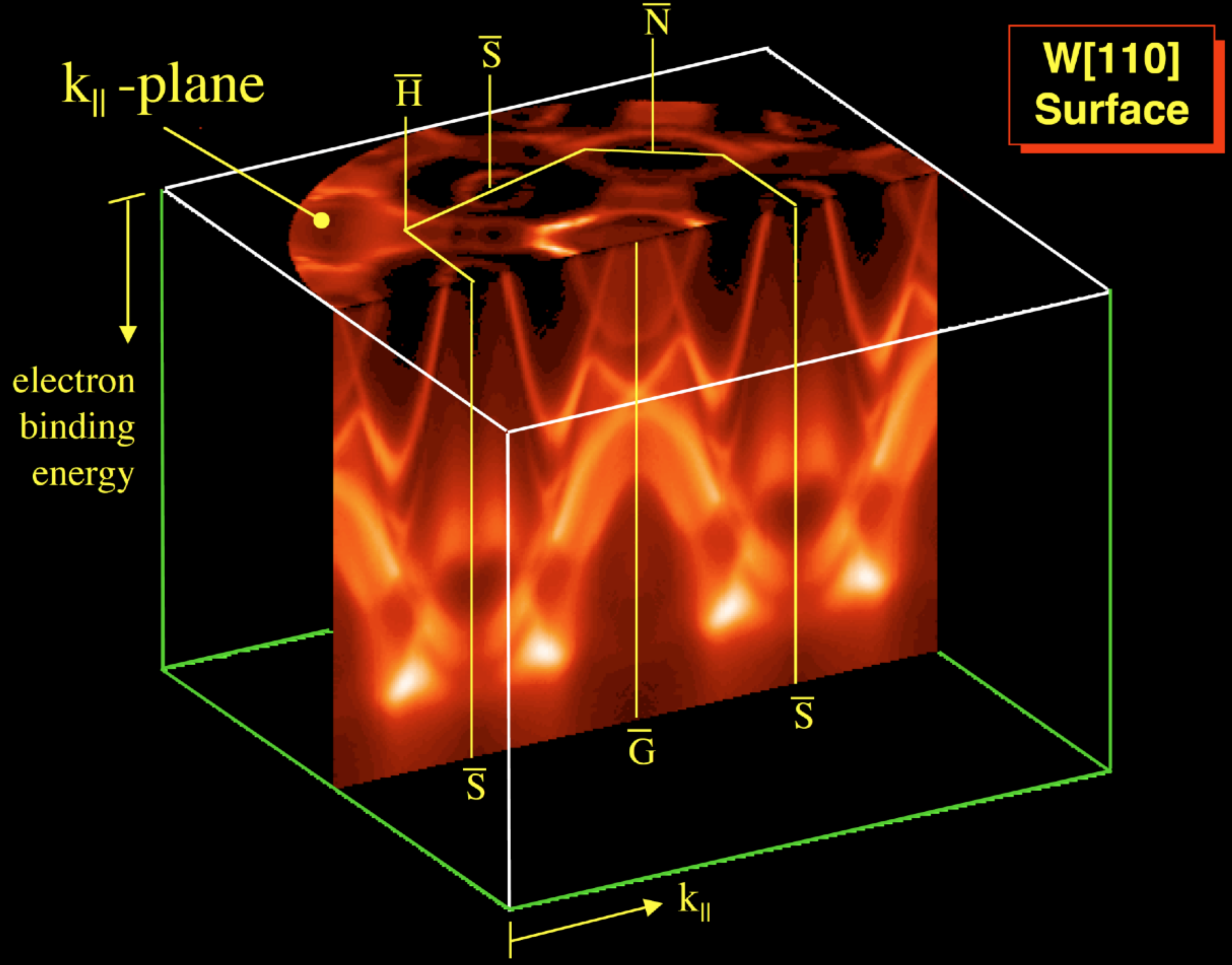
Nishide et a., New J. Phys. 12, 065011 (2010)

ARPES+Time of Fight



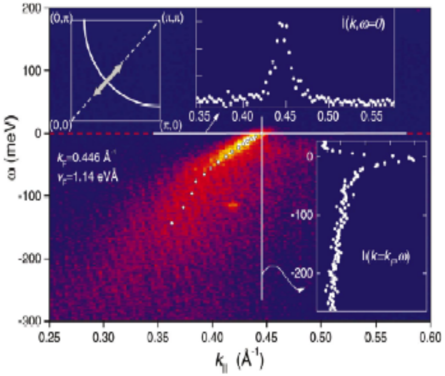
Wang et al., PRL 107, 207602 (2011)

Band Mapping and Fermi Contours



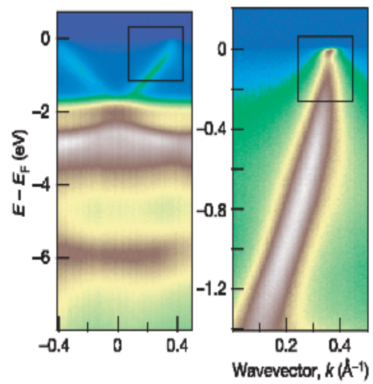
ARPES: Widespread Impact in Complex Materials

HTSC's



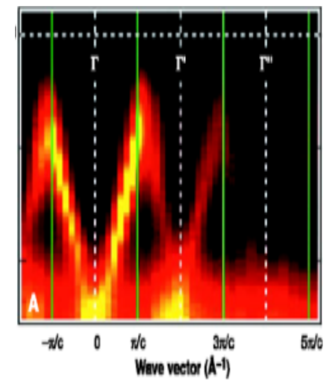
Science 1999

CMR's



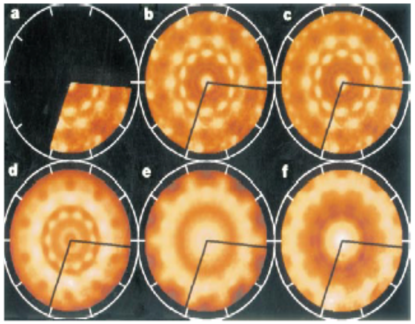
Nature 2005

CDW's



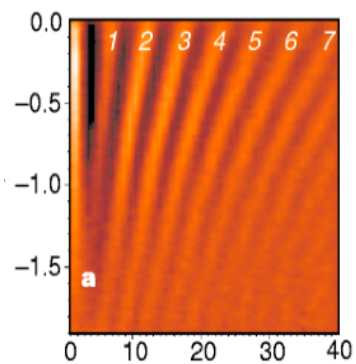
Science 2000

Quasicrystals



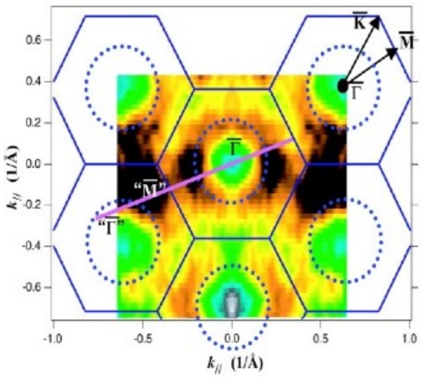
Nature 2000

Quantum Wells



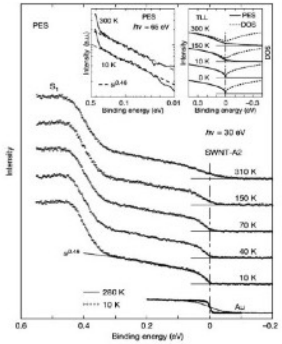
Nature 1999

C_{60}



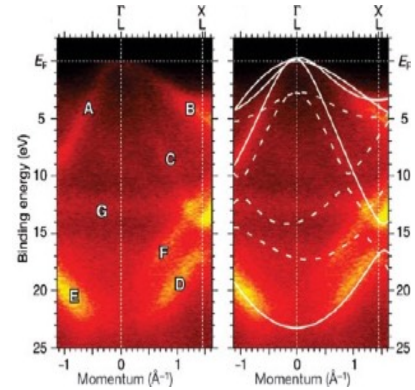
Science 2003

Nanotubes



Nature 2003

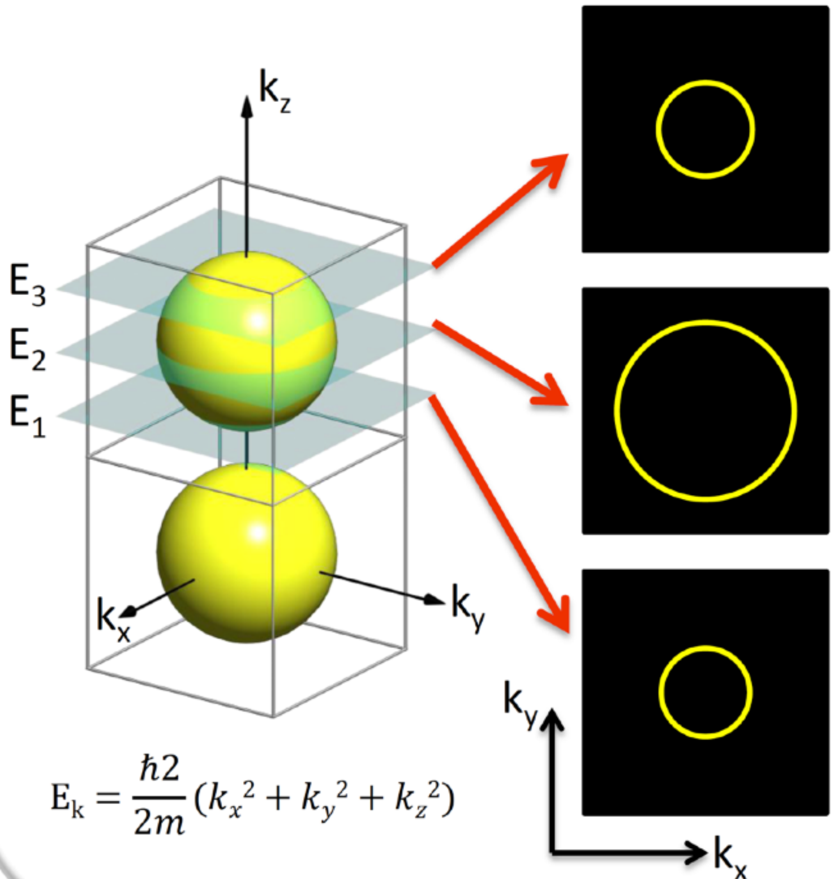
Diamond



Nature 2005

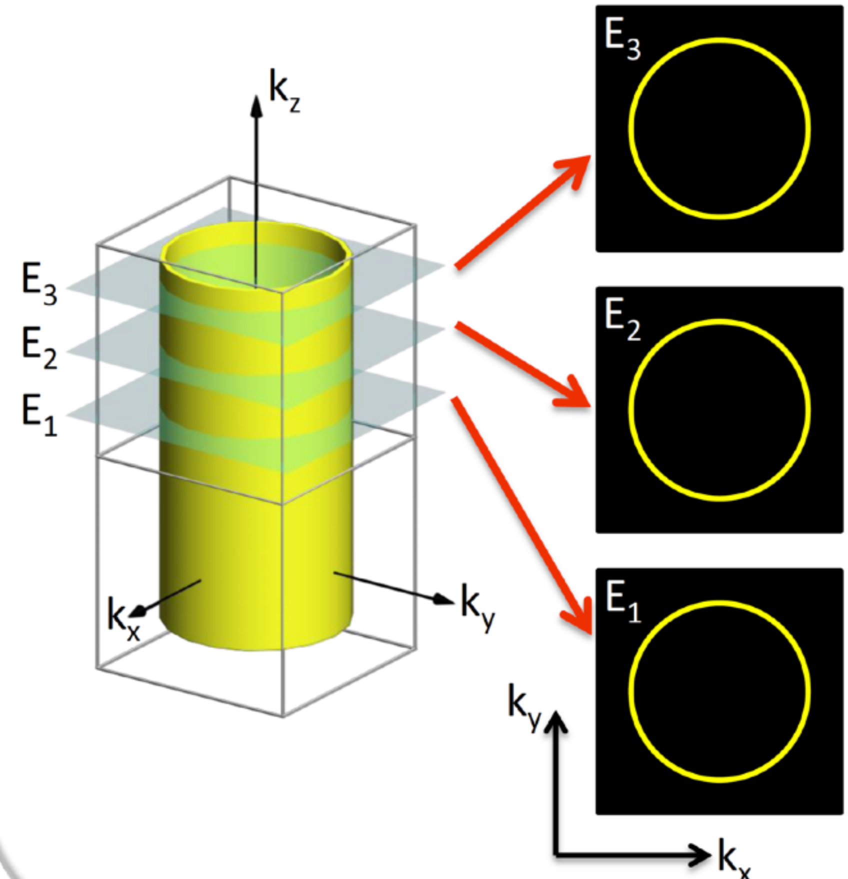
How to discriminate bulk & surface?

3D FS
(e.g. FS from bulk state)



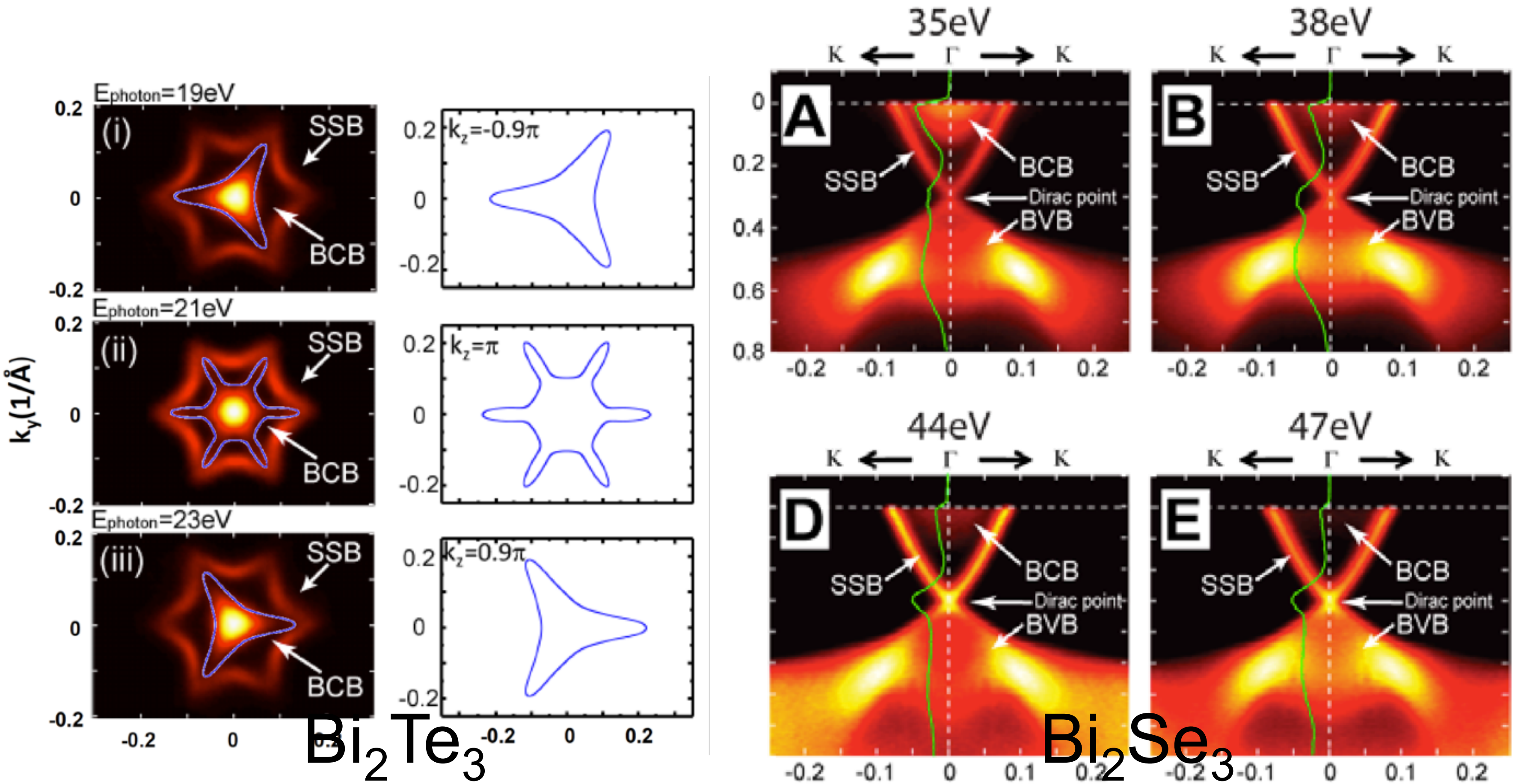
$$E_k = \frac{\hbar 2}{2m}(k_x{}^2 + k_y{}^2 + k_z{}^2)$$

2D FS
(e.g. FS from surface state)



Courtesy of Y.L. Chen

How to discriminate bulk & surface?



Bi_2Te_3

Bi_2Se_3

Y.L. Chen et al., Science (2009)

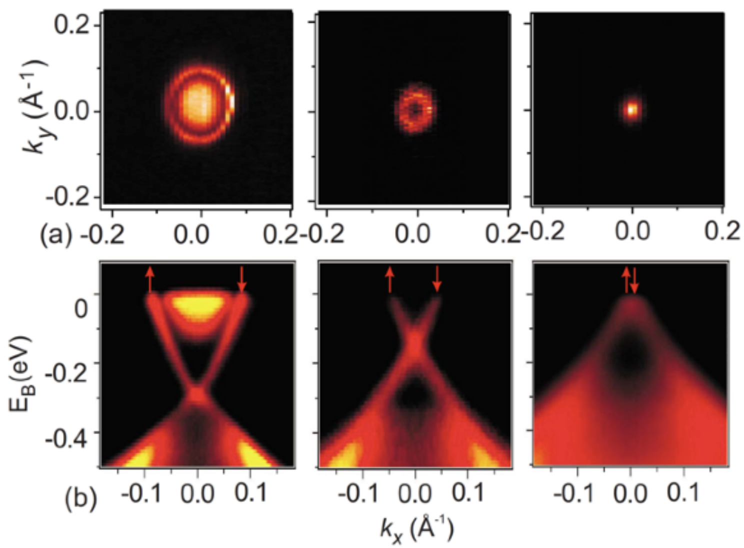
Outline

ARPES:

3D topological insulators

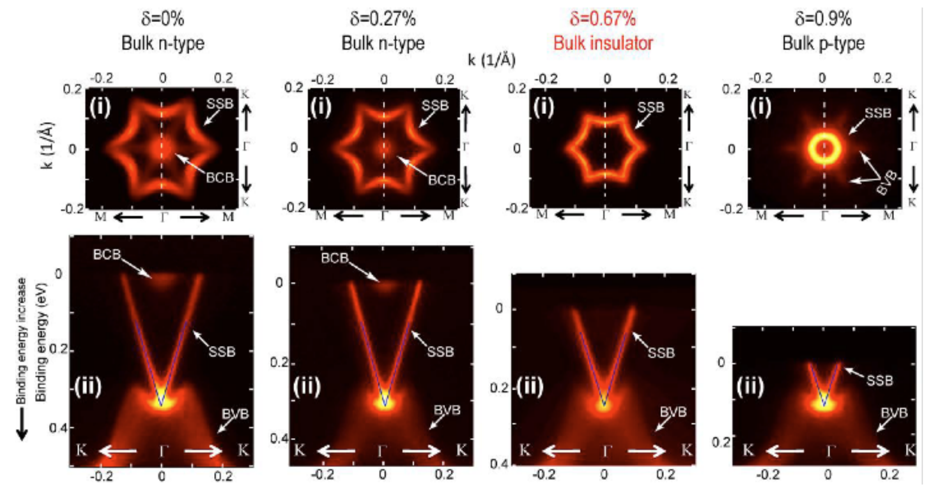
ARPES on 3D TIs since 2009

Bi_2Se_3

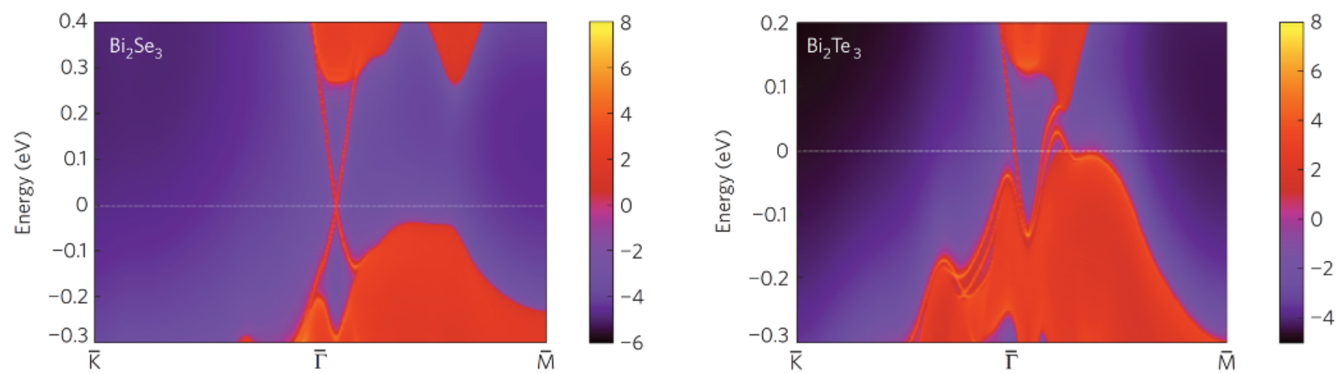


D. Hsieh, et al., Nature (2009)

Bi_2Te_3



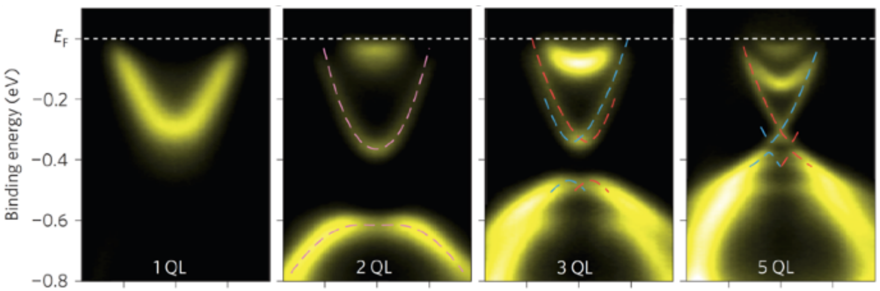
Y.L.Chen, et al., Science (2009)



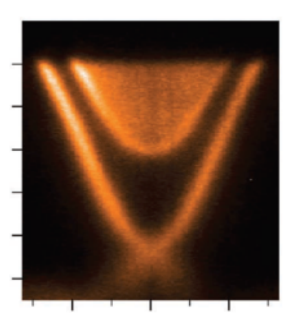
Theory: H.J. Zhang, et al., Nat. Phys. (2009)

ARPES on 3D TIs: MBE, 2DEG, warp, new materials……

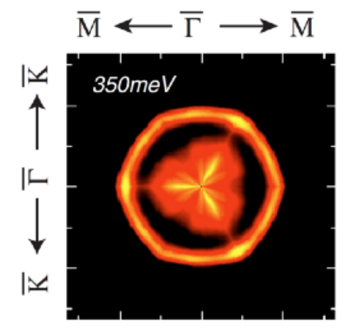
Bi_2Se_3: MBE thin film



2DEG

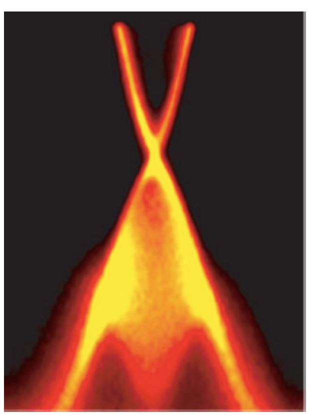


Bi_2Se_3: Warped DC

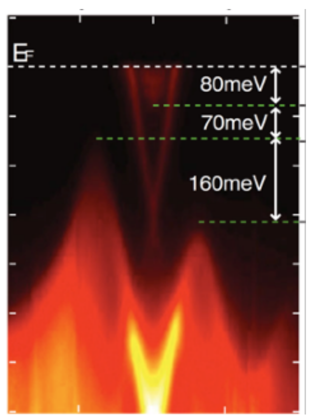


Y. Zhang, et al., Nat. Phys. (2010) M. Bianchi, et al., Nat. Comm. (2010) K. Kuroda, et al., RPL (2010)

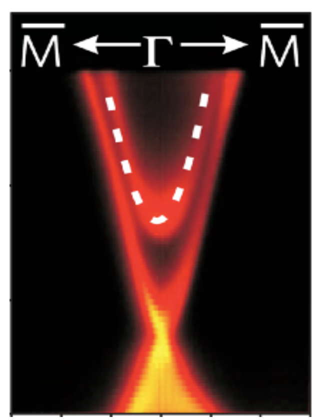
$TlBiSe_2$



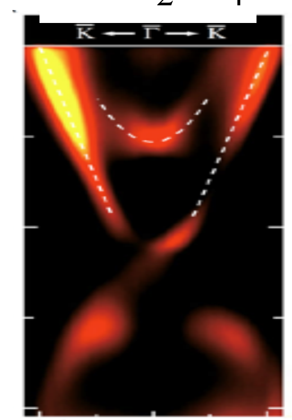
$TlBiTe_2$



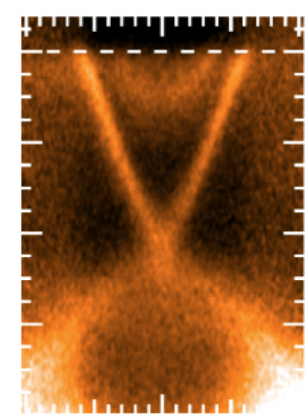
$Cu_{0.12}Bi_2Se_3$



$PbBi_2Te_4$



$BiTe_2Se$



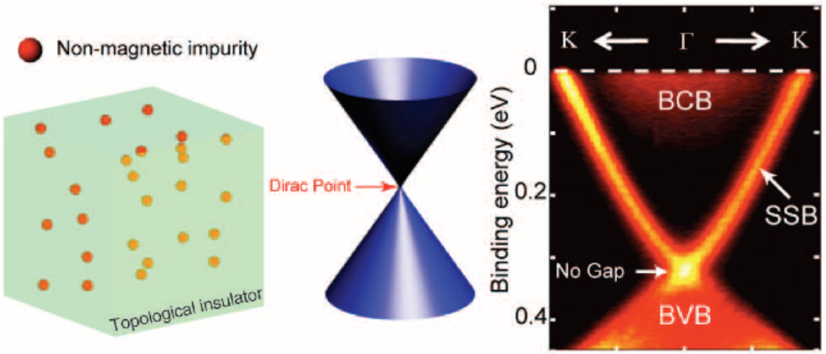
K. Kuroda, et al., RPL (2010)
T. Sato, et al., RPL (2010)
Y.L. Chen, et al., RPL (2010)

L. Wary, et al., Nat. Phys. (2010)

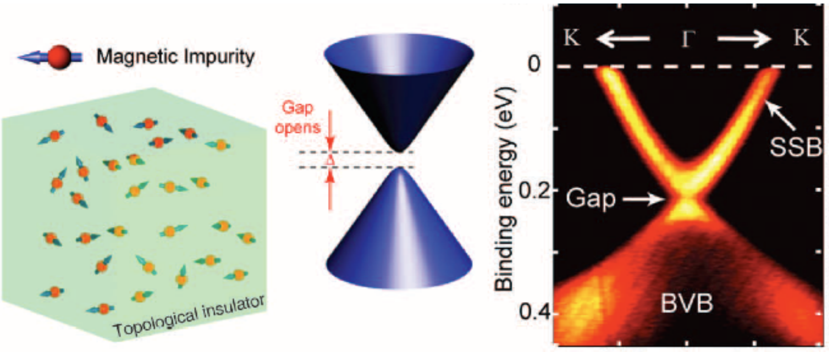
K. Kuroda, et al., RPL (2012)
K. Miyamoto, et al., RPL (2012)
M. Neupane, et al., RPB (2012)
T. Arakane, et al., Nat. Comm. (2012)

Broken time-reversal symmetry: magnetic impurities

Bi_2Se_3

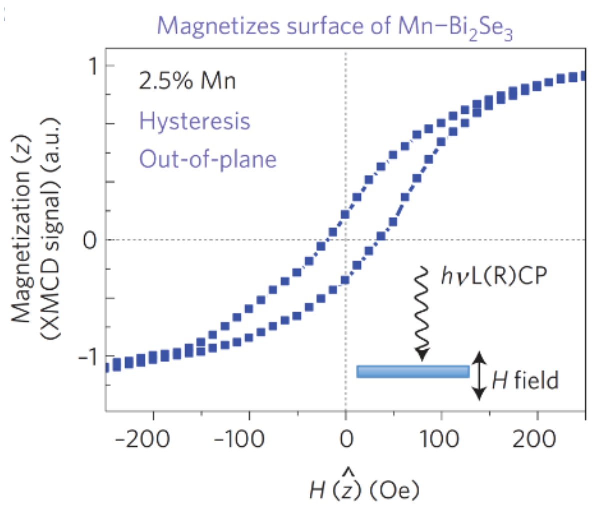


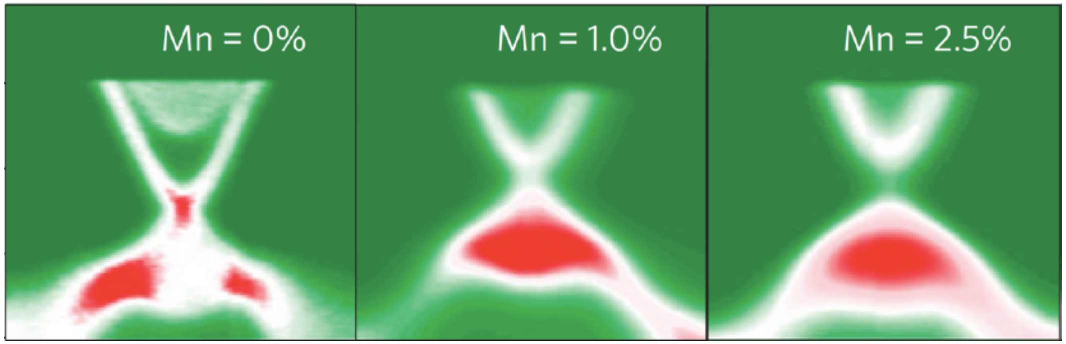
$(Bi_{0.88}Fe_{0.12})_2Se_{3.7}$

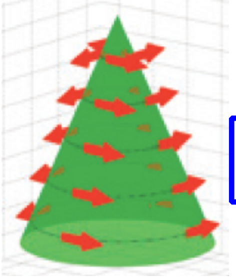


Y.L. Chen, et al., Science (2010)

MEB thin film: Mn-Bi_2Se_3



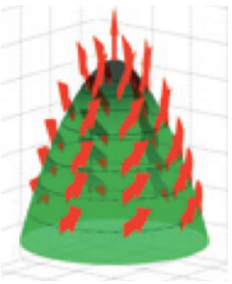




Spin texture of DC

Chiral

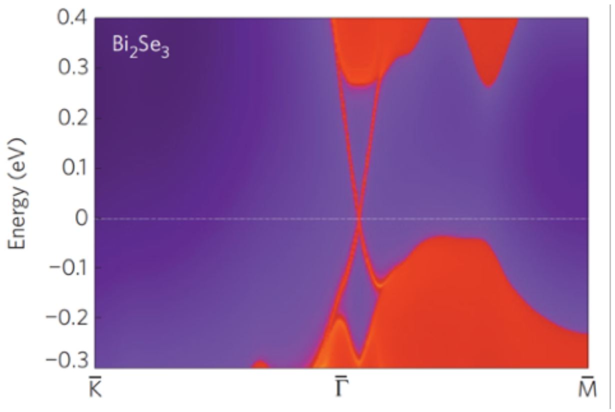
Hedgehog



S.Y. Xu, et al., Nat. Phys. (2012)

Impurities at the surface of Bi_2Se_3

Zhang *et al.*, Nat. phys. **5**, 438 (2009)

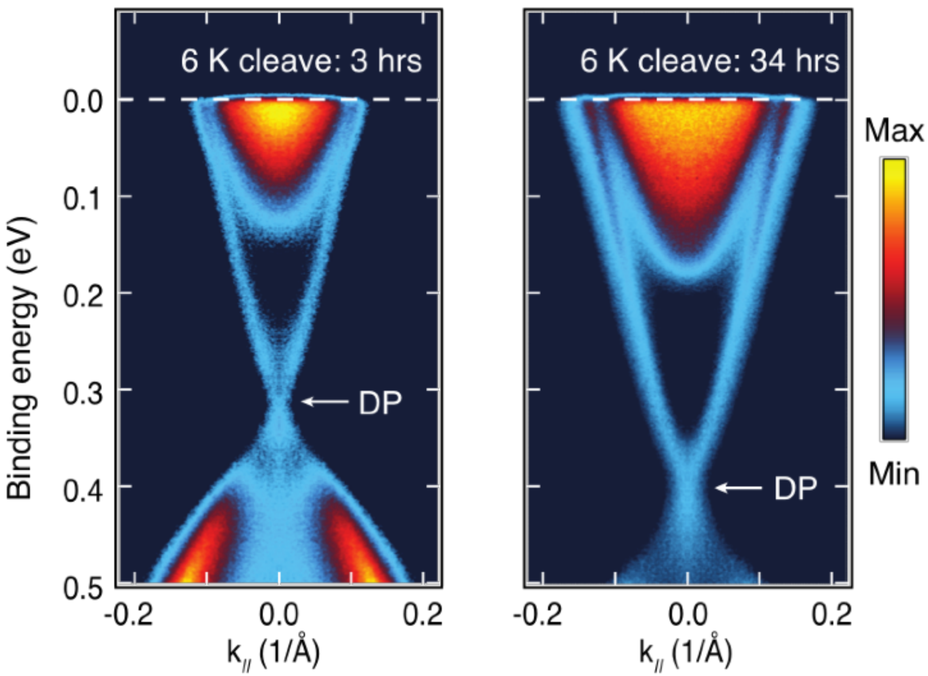


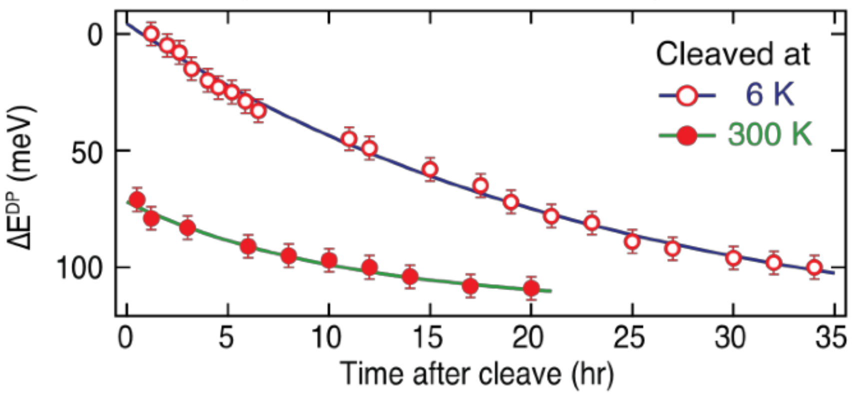
Problems on the materials:

- N-type bulk.
- Instability of the as-cleaved sample surface in UHV.
- Parabolic continuum of states: $K_{//}$ is not a good quantum number.

Can we overcome these problems?

Dirac point (DP) moving with time



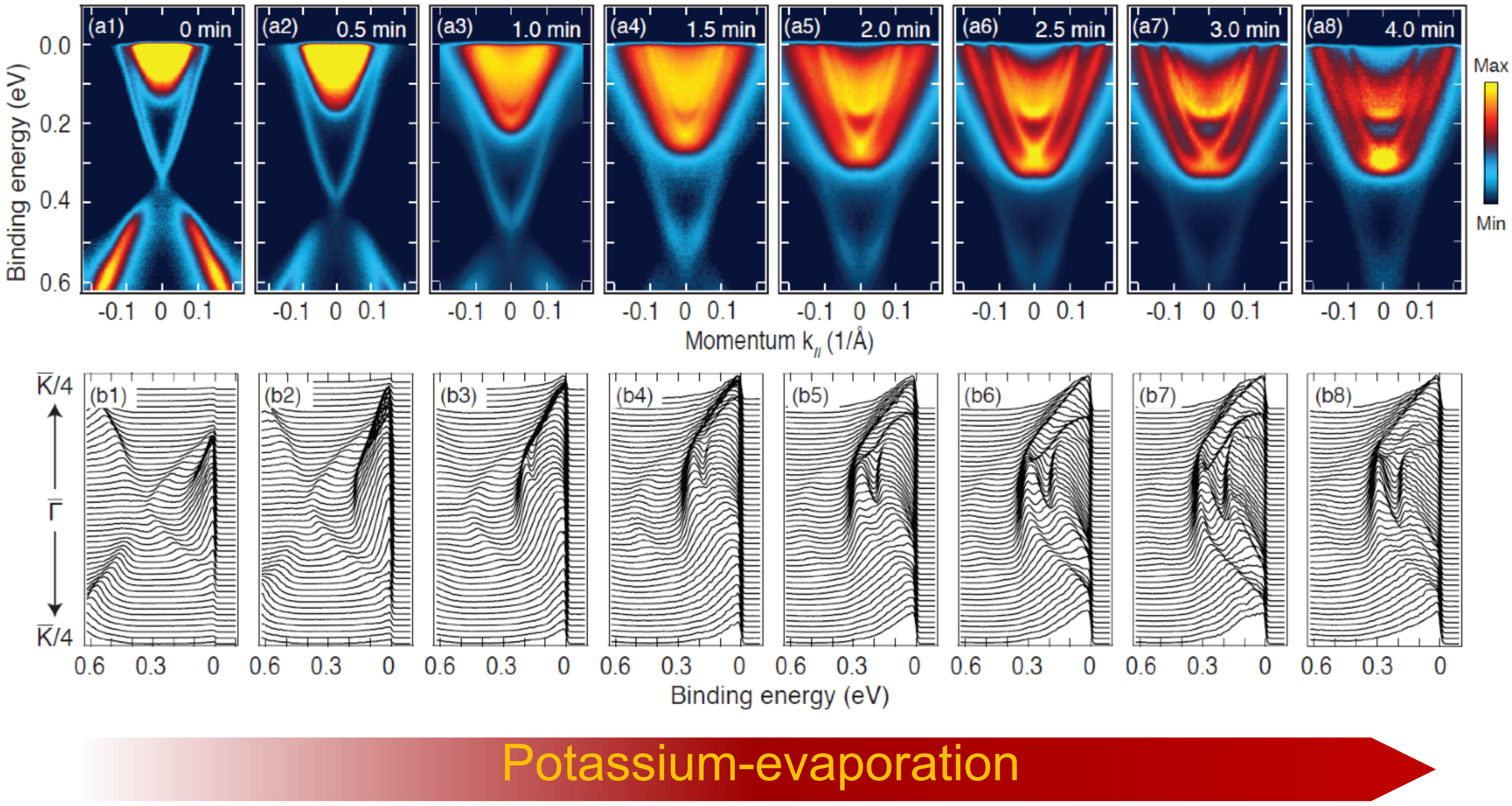


Z.-H. Zhu *et al.*, Phys. Rev. Lett. **107**, 186405 (2011)

K-deposited Bi_2Se_3: Spin-splitting control

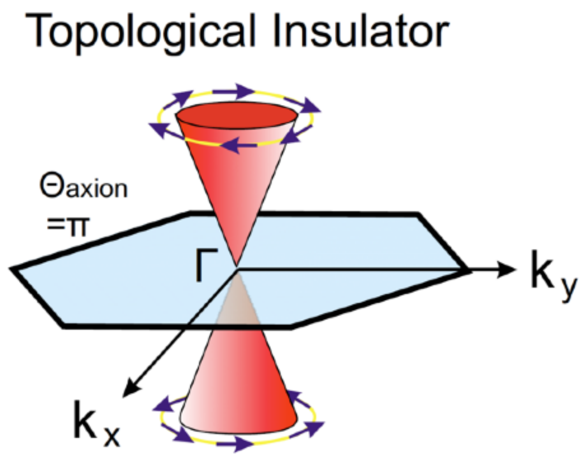
K-evaporation induces Rashba states

$$E^{\pm}(k_{\parallel}) = E_{\bar{\Gamma}} + \frac{\hbar^2 k_{\parallel}^2}{2m^\star} \pm \alpha_R k_{\parallel}$$

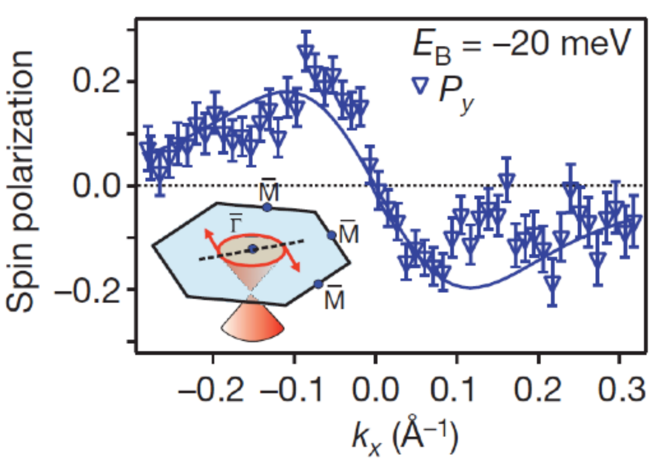


Z.H. Zhu et al., PRL **107**, 186405 (2011)

Spin texture of topological surface state



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) O.V. Yazyev et al. *PRL* (2010)

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

Measured spin polarization range: 10-80%

~30% $Bi_{1-x}Sb_x$ D. Hsieh et al. *Science* (2009)

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

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

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

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

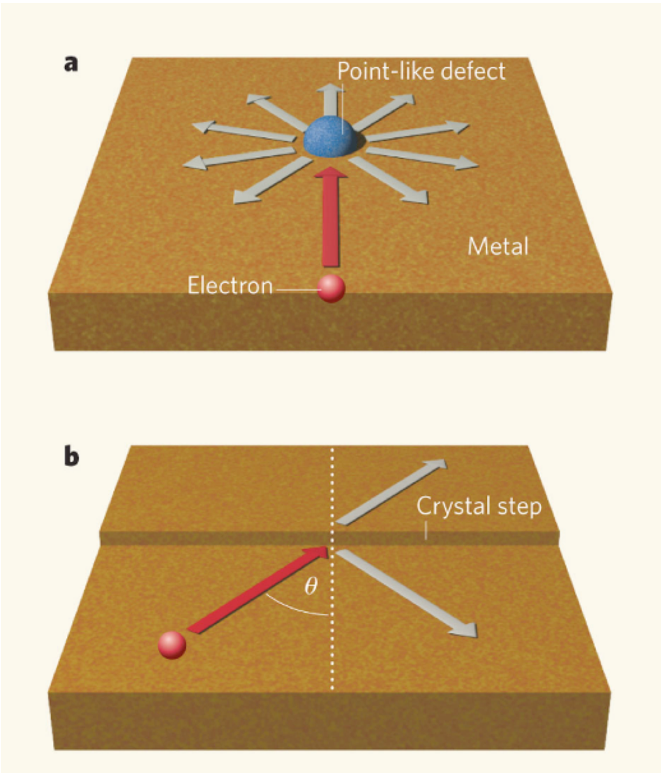
~40% $BiTlSe_2$ S.-Y. Xu et al. Science (2011)

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

?

Absence of backscattering

Simple idea:



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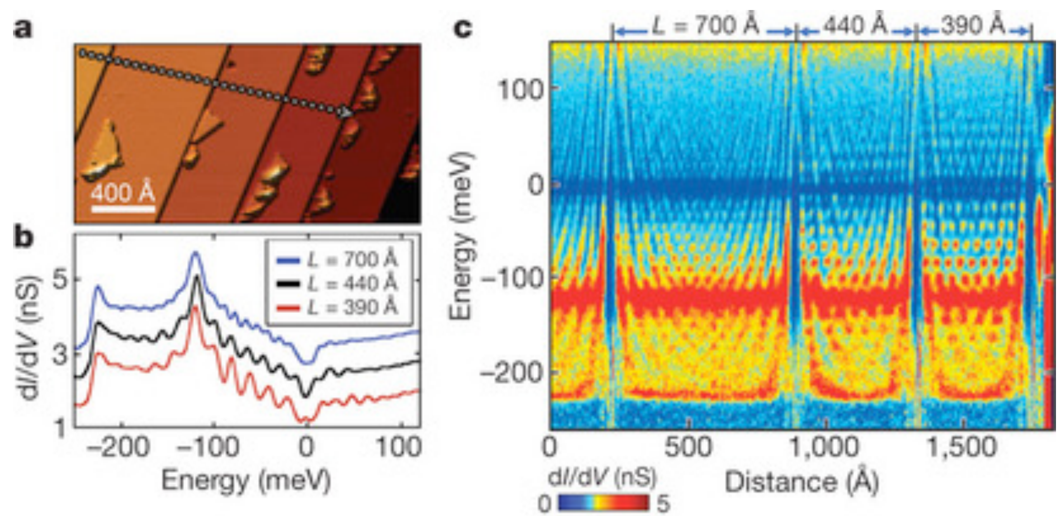
LETTERS

Transmission of topological surface states through surface barriers

Jungpil Seo[1], Pedram Roushan[1], Haim Beidenkopf[1], Y. S. Hor[2], R. J. Cava[2] & Ali Yazdani[1]



Periodic table of topological materials

Existence or absence of topological phases depends on symmetry and dimensionality of the system.

$\mathcal{T}$ symmetry Θ, particle-hole symmetry Ξ and chiral symmetry $\Pi = \Xi\Theta$

	Symmetry			d							
AZ	Θ	Ξ	Π	1	2	3	4	5	6	7	8
A	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
AIII	0	0	1	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0
AI	1	0	0	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
BDI	1	1	1	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$
D	0	1	0	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$
DIII	-1	1	1	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$	0
AII	-1	0	0	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$\mathbb{Z}$
CII	-1	-1	1	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0
C	0	-1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
CI	1	-1	1	0	0	$\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0

Chern insulators
Polyacetylene
Topological insulators
Topological insulators

Ryu, S., A. Schnyder, A. Furusaki, A. W. W. Ludwig, 2010, New J. Phys. **12**, 065010.

Kitaev, A., 2009, AIP Conf. Proc. **1134**, 22.