Observation of the surface states in topological (Kondo) insulator Sm(Yb)B_6 and BiTeCl

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Acknowledgement

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Discussions and theory support:

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G. M. Zhang **(Tsing Hua University)**

Outline

- ARPES study on the surface states of SmB6 and YbB6
- STM study on the surface states of BiTeCl

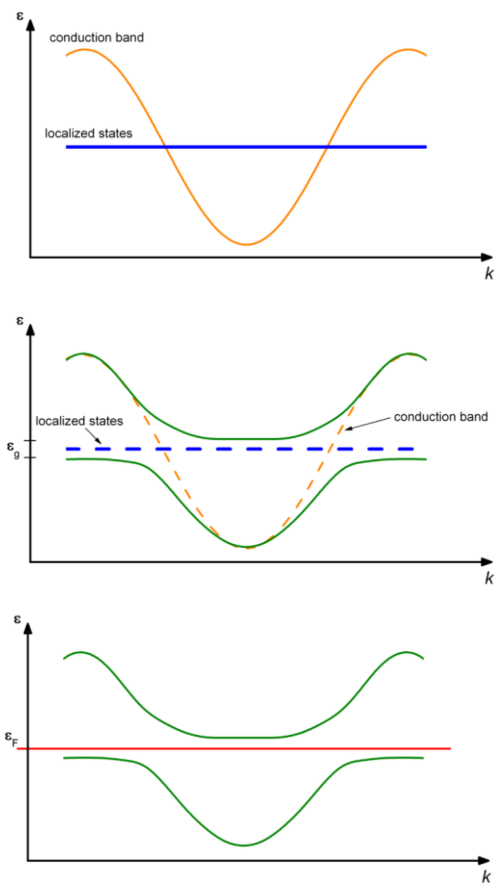
SmB$_6$ – a “mystery” Kondo insulator?

4f–5d hybridization

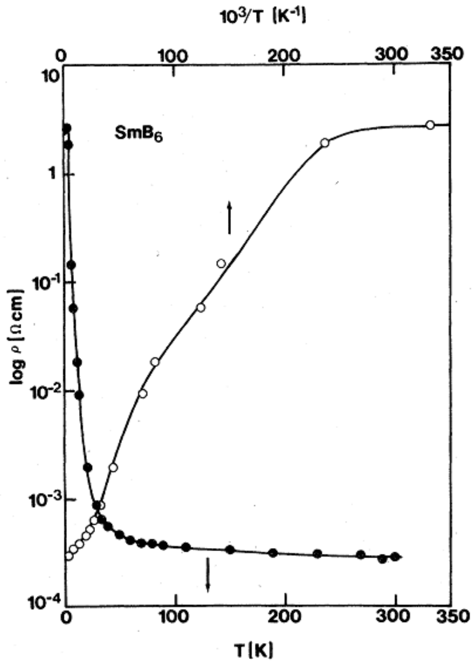
Saturated resistivity

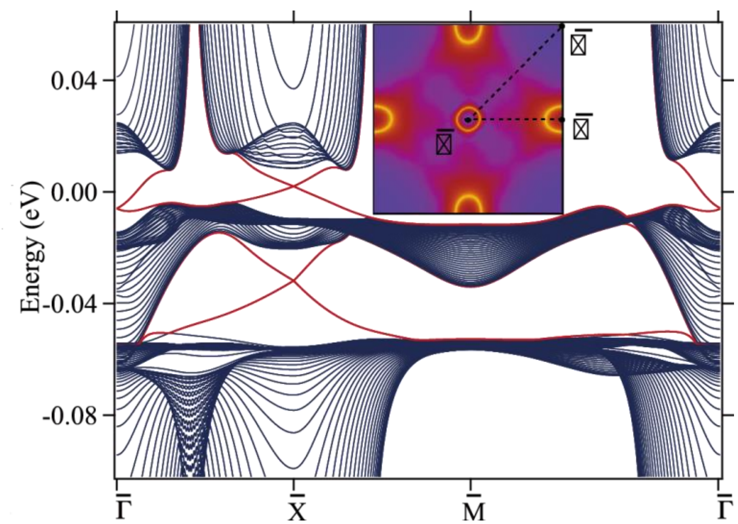
Topological Kondo insulator

High T



Low T



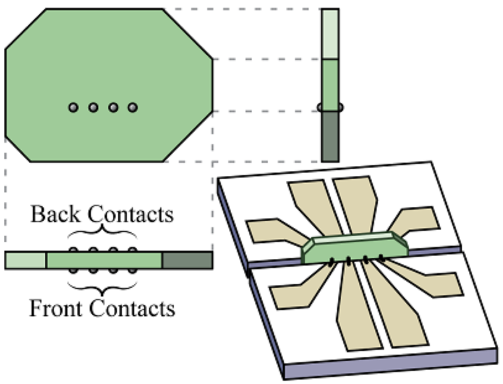


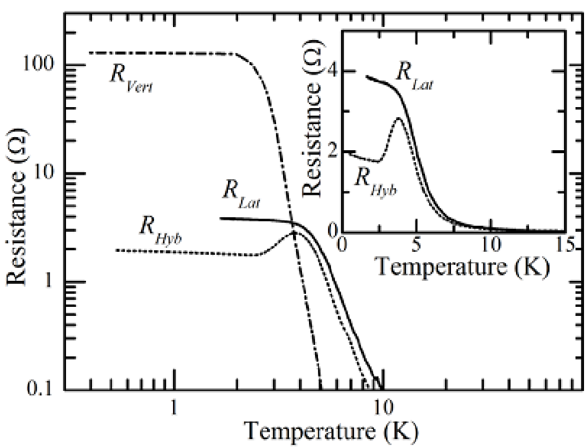
Origin of the “in-gap” states?

J. Allen et al, PRB 20, 4807 (1979).
X. Dai et al, PRL110, 096401 (2013).

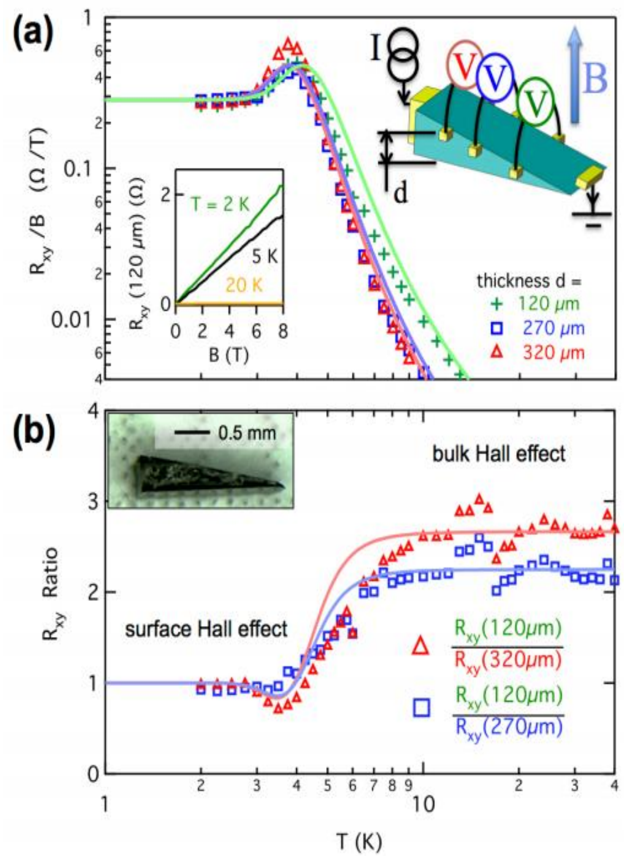
SmB_6 – recent experiment evidence of TKI

Surface conductivity at low T

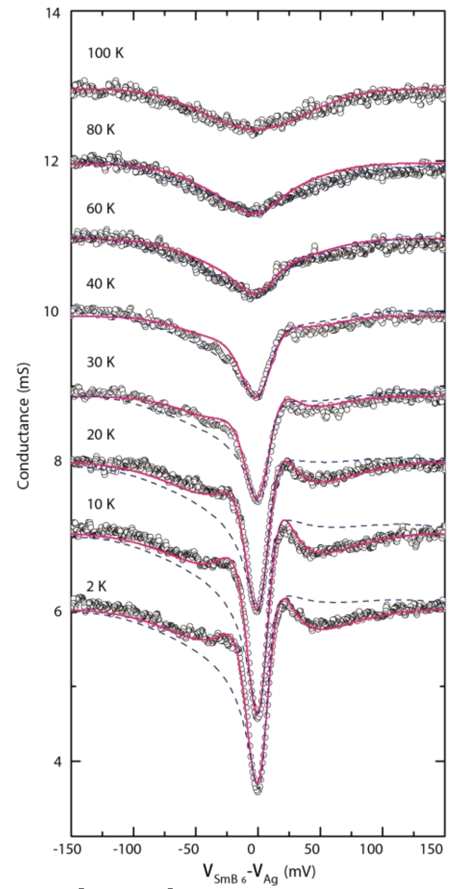




Surface hall effect



Point contact



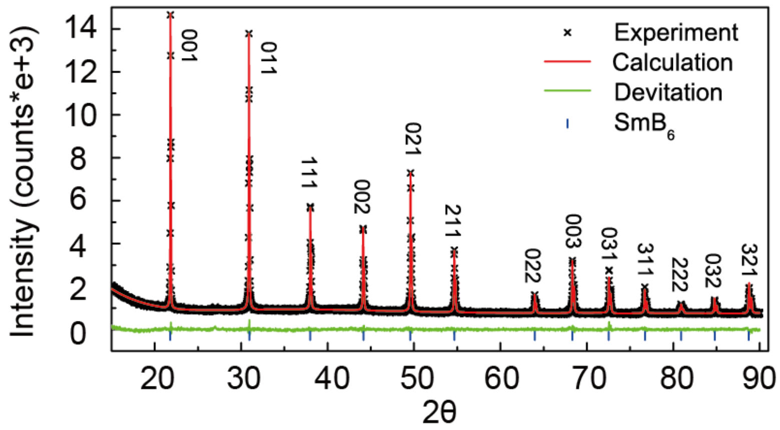
D. J. Kim, et al, Scientific Reports 3, 3150 (2013)

S. Wolgast, et al, Phys. Rev. B 88, 180405 (2013)

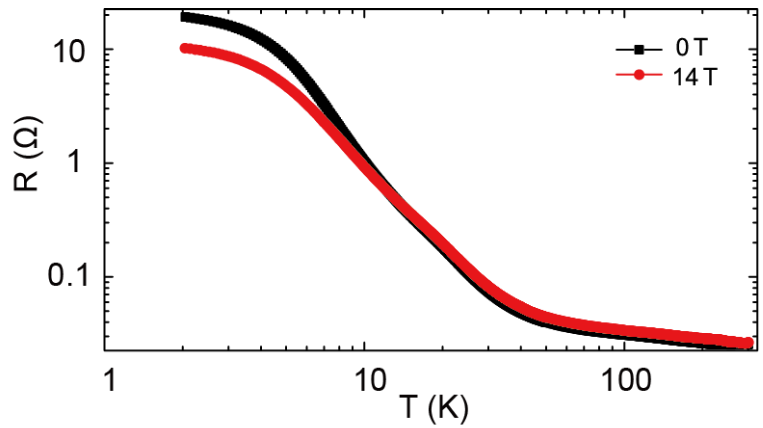
X. Zhang, et al, Phys. Rev. X 3, 011011 (2013)

Sample characterization

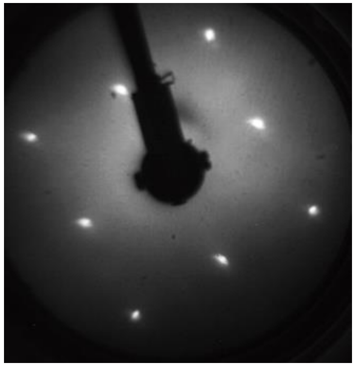
X-Ray Diffraction

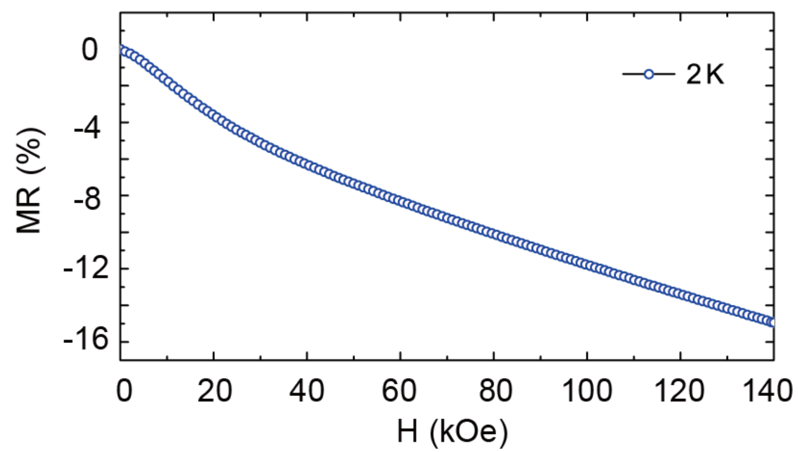


Magnetoresistance vs. T



LEED pattern

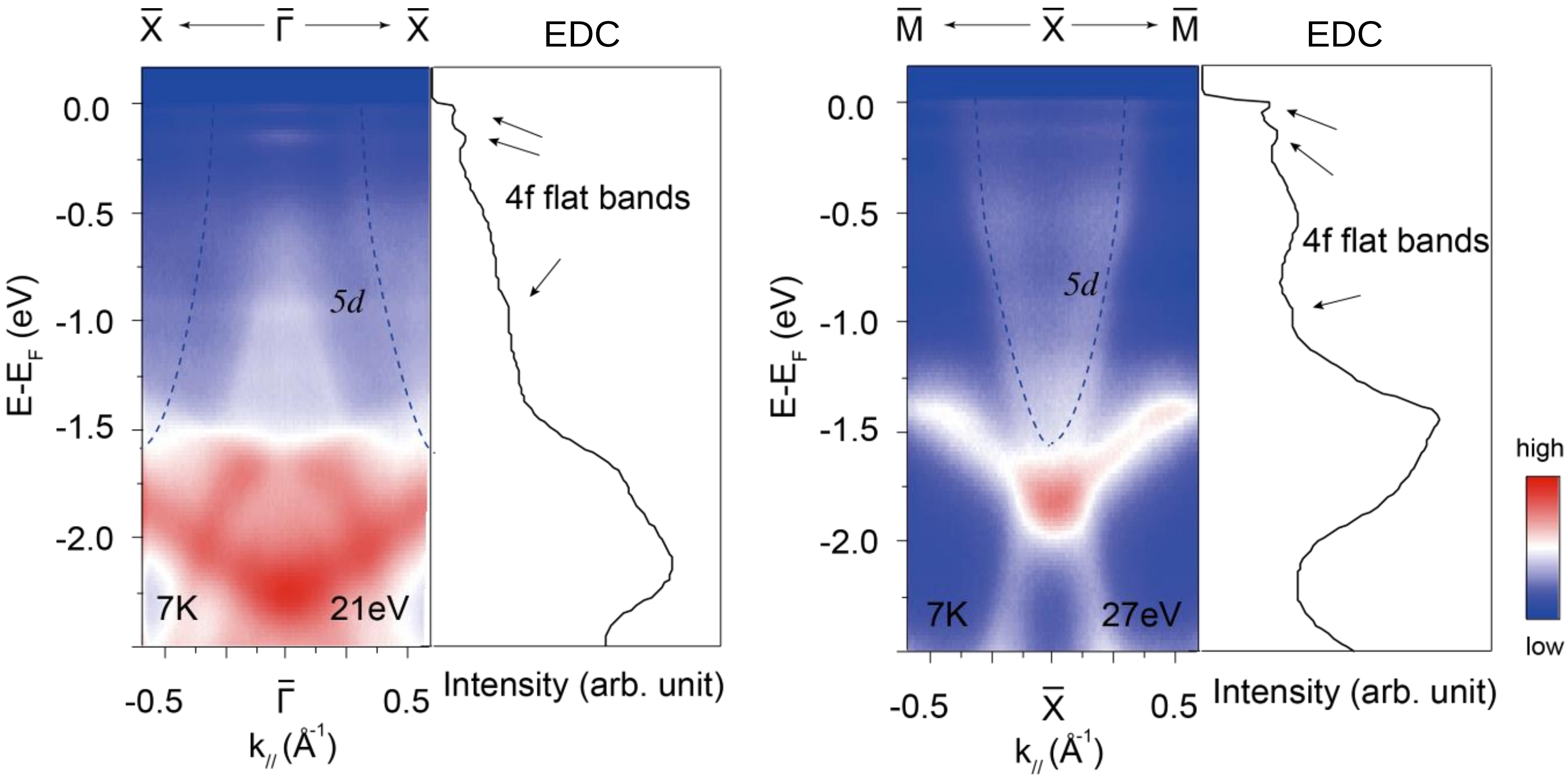




(100) face 1x1

Negative magnetoresistance in low temperature!

ARPES: Valence band structure

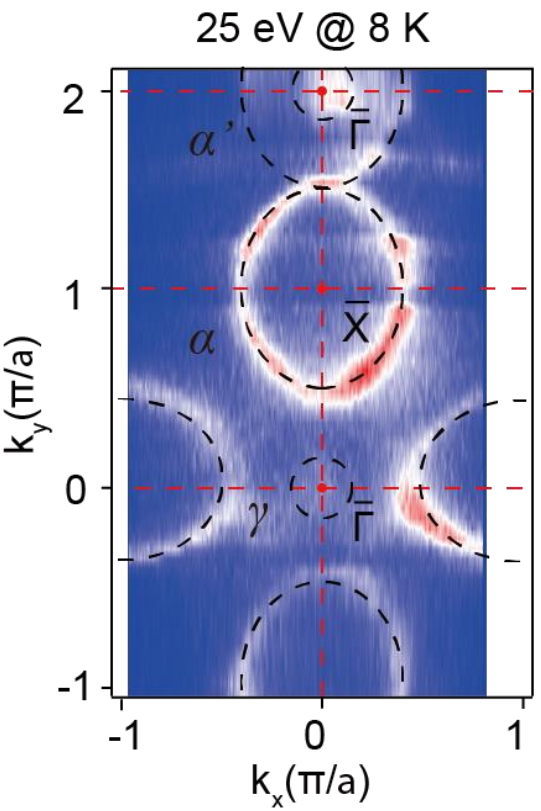


Localized 4f band located at -18 meV, -150 meV and -950 meV.

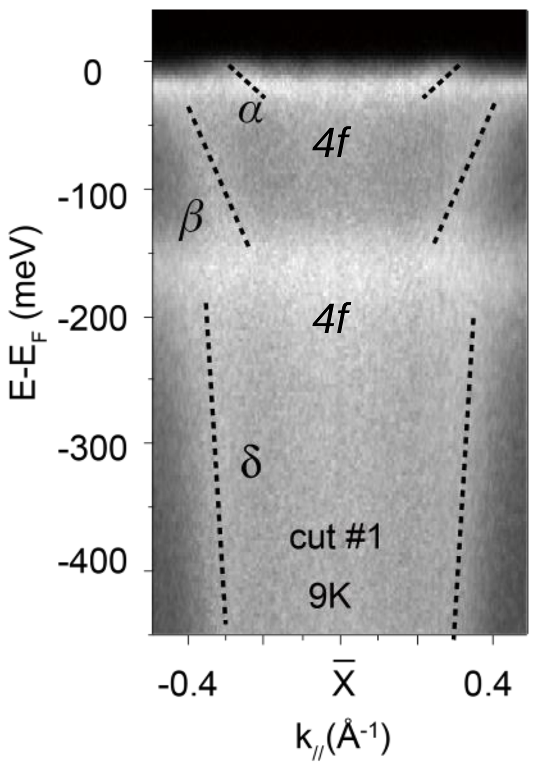
A parabolic 5d band around X point.

In-gap states: α

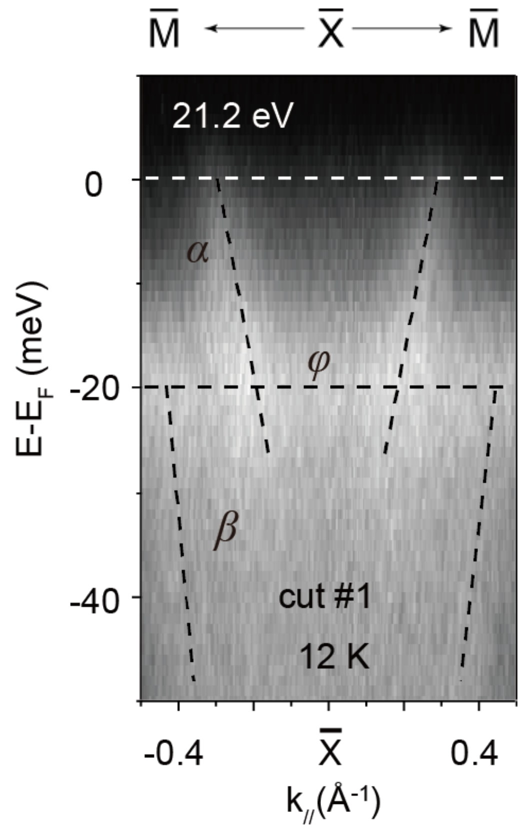
Fermi surface mapping



Cut along X

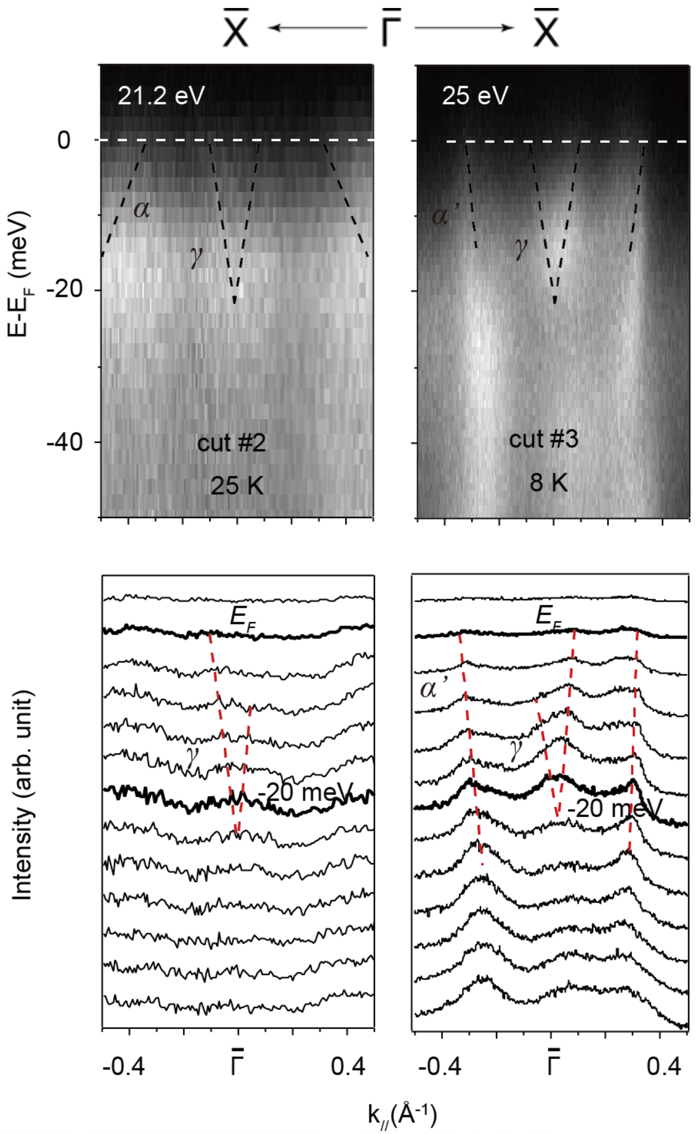


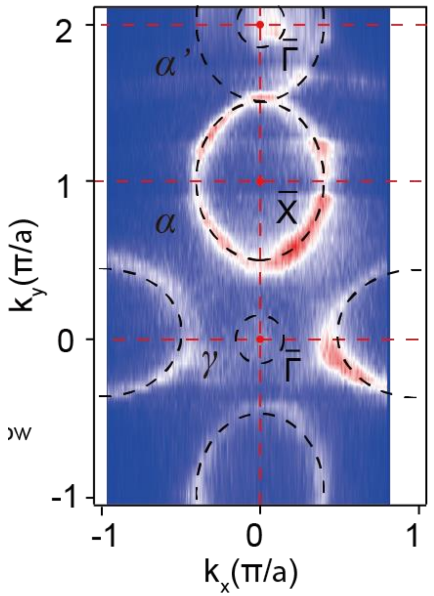
Cut along X, α band



β and δ bands should be originated from 5d band after hybridization.

In-gap states: γ





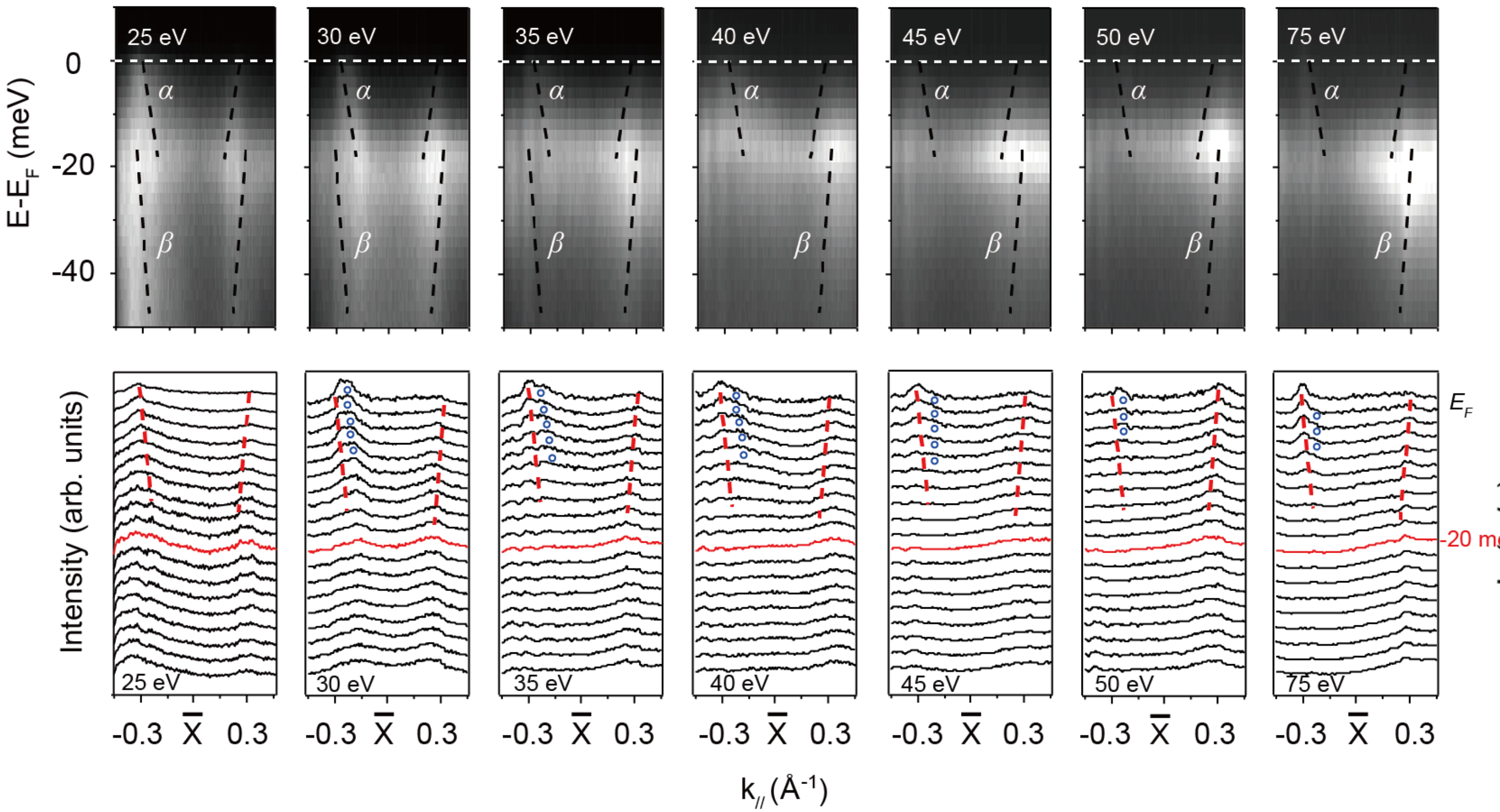
Surface states??

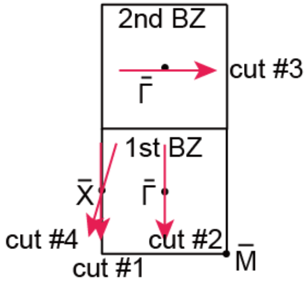
γ bands more observable in 2nd BZ.

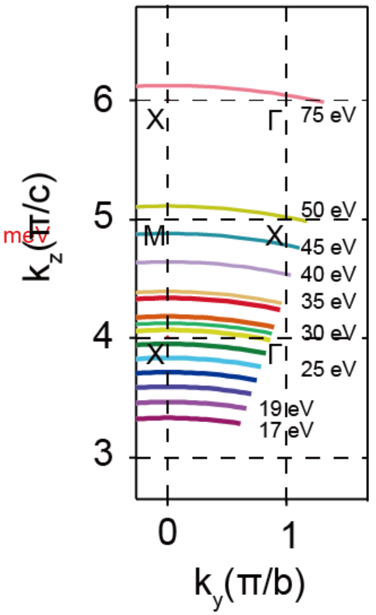
Linear dispersion of γ bands.

kz dependence of α band

α band along cut #4





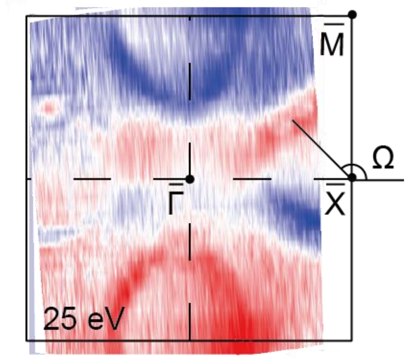


Negligible kz dependence for α band.

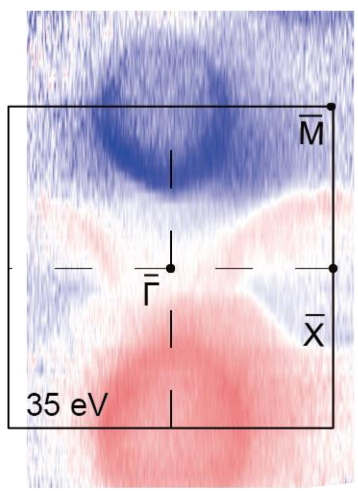
Surface States!

ARPES: Circular Dichroism

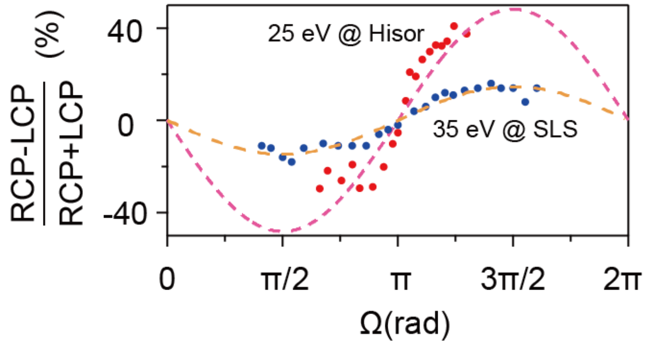
(RCP-LCP)/(RCP+LCP)

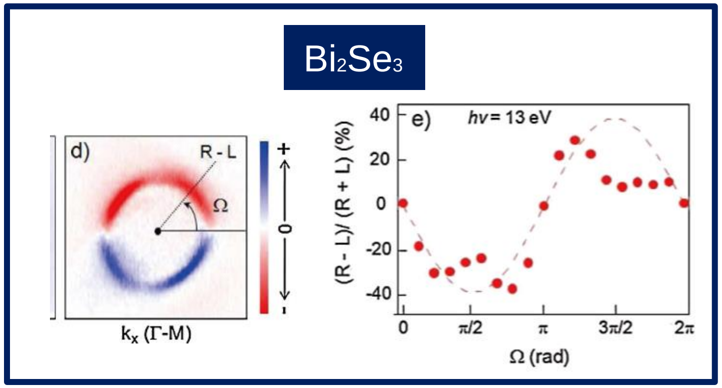


(RCP-LCP)/(RCP+LCP)

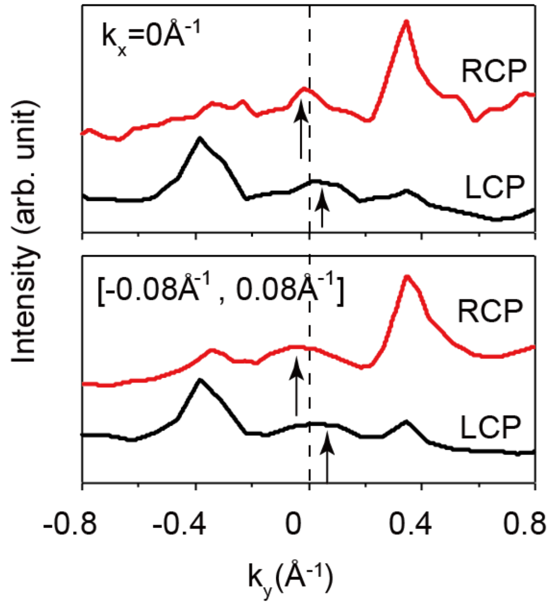


α band





γ band



Possible topological origin!

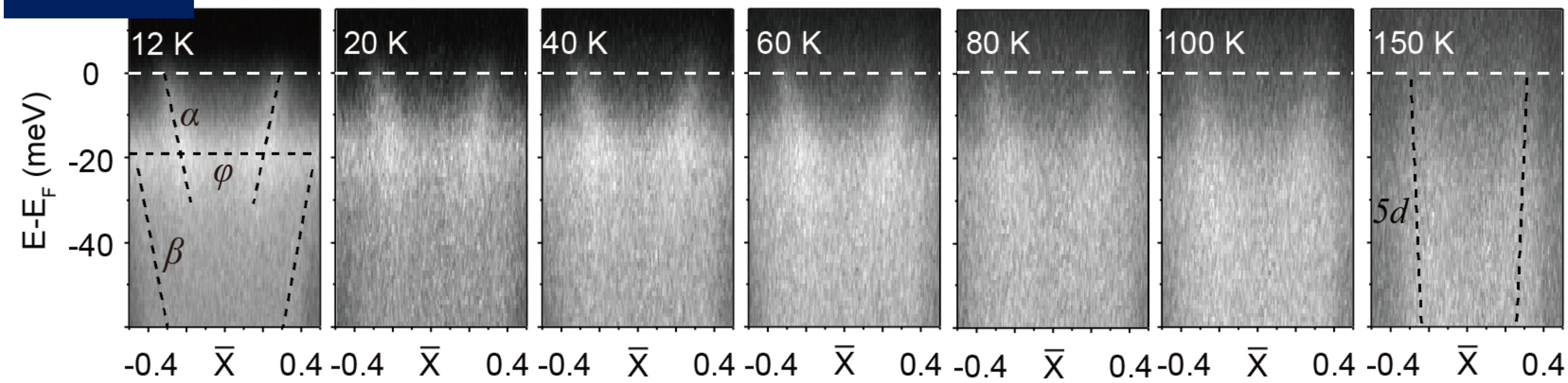
Chirality of orbital angular momentum in α band.

Intensity inversion between RCP and LCP data in γ band.

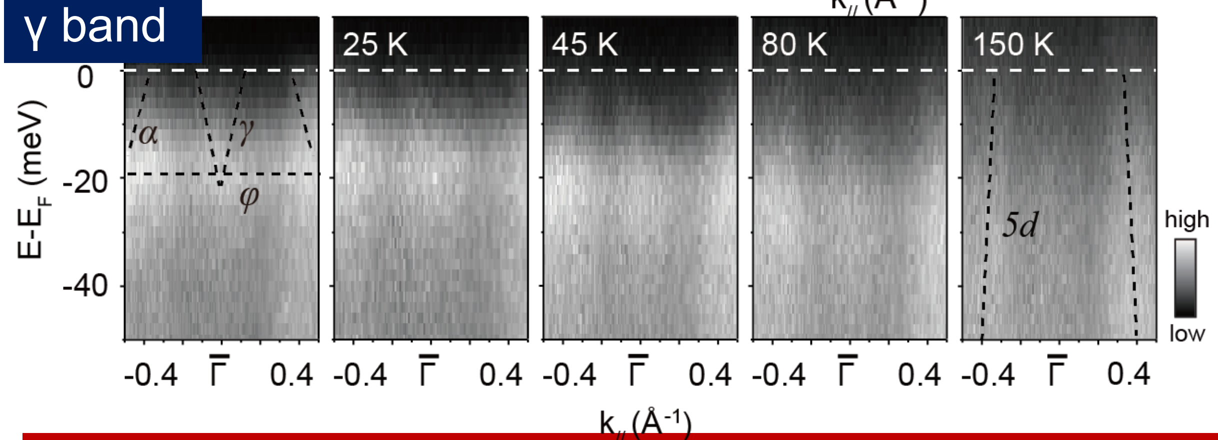
Park et al, Phys. Rev. Lett. 108, 0468 (2012)

ARPES: T dependence of α band

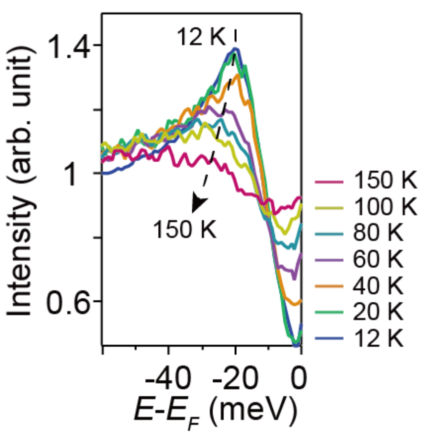
α band



γ band

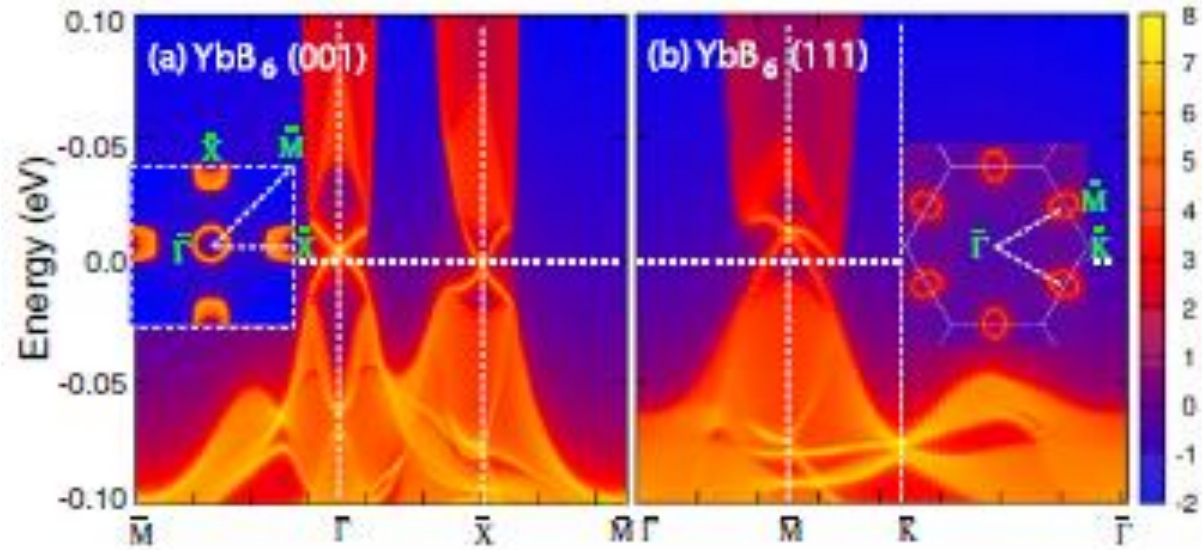


Integrated EDC near E_F



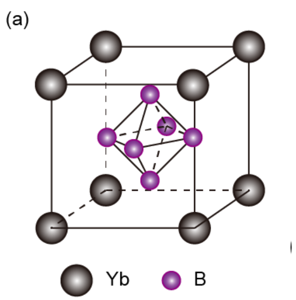
α and β bands vanish or merge into one 5d band at high temperatures.

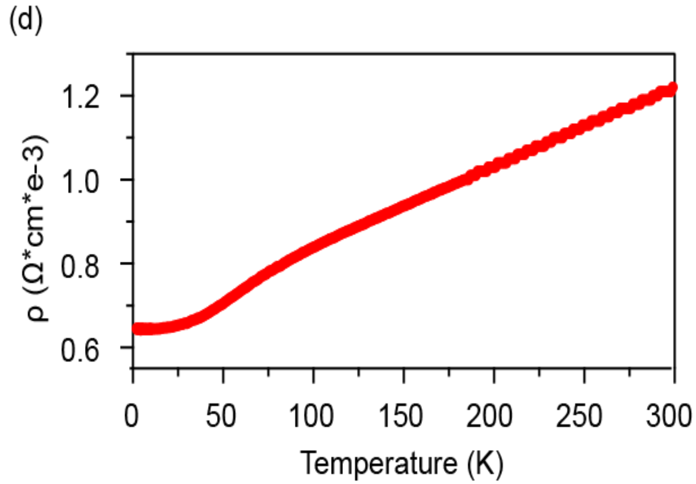
Possible TI candidate :YbB_6



Larger band gap than SmB6

31 meV vs 10 meV

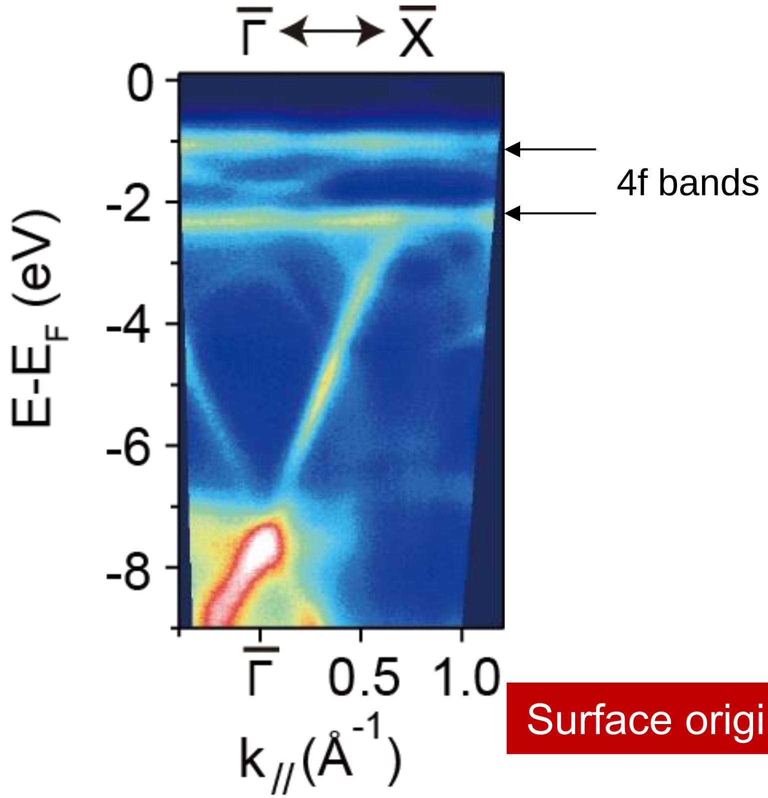




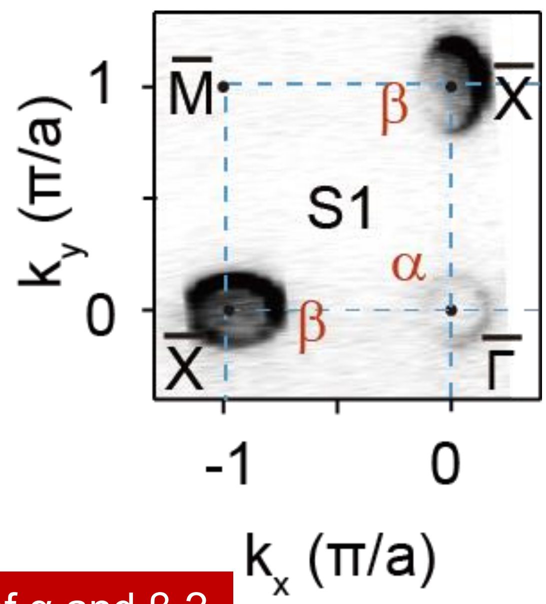
Metallic behavior in resistivity!

Topological insulator?

ARPES: Valence band structure



Fermi surface mapping

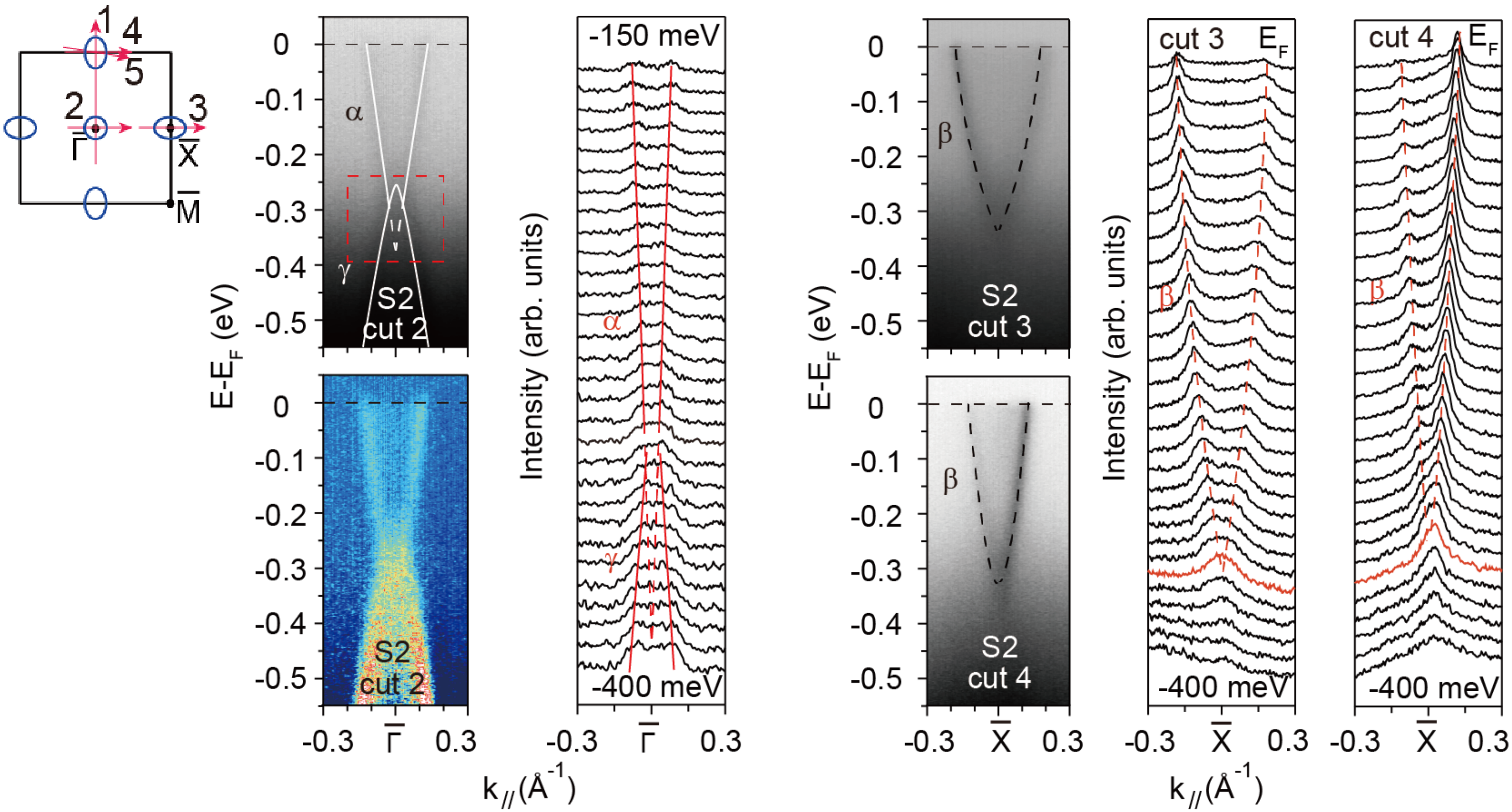


Surface origin of α and β ?

Non-dispersive Yb 4f bands are located at around 1 eV and 2.3 eV below Fermi energy.

An elliptical Fermi pocket located around X and a circular Fermi pocket around Γ are clearly observed.

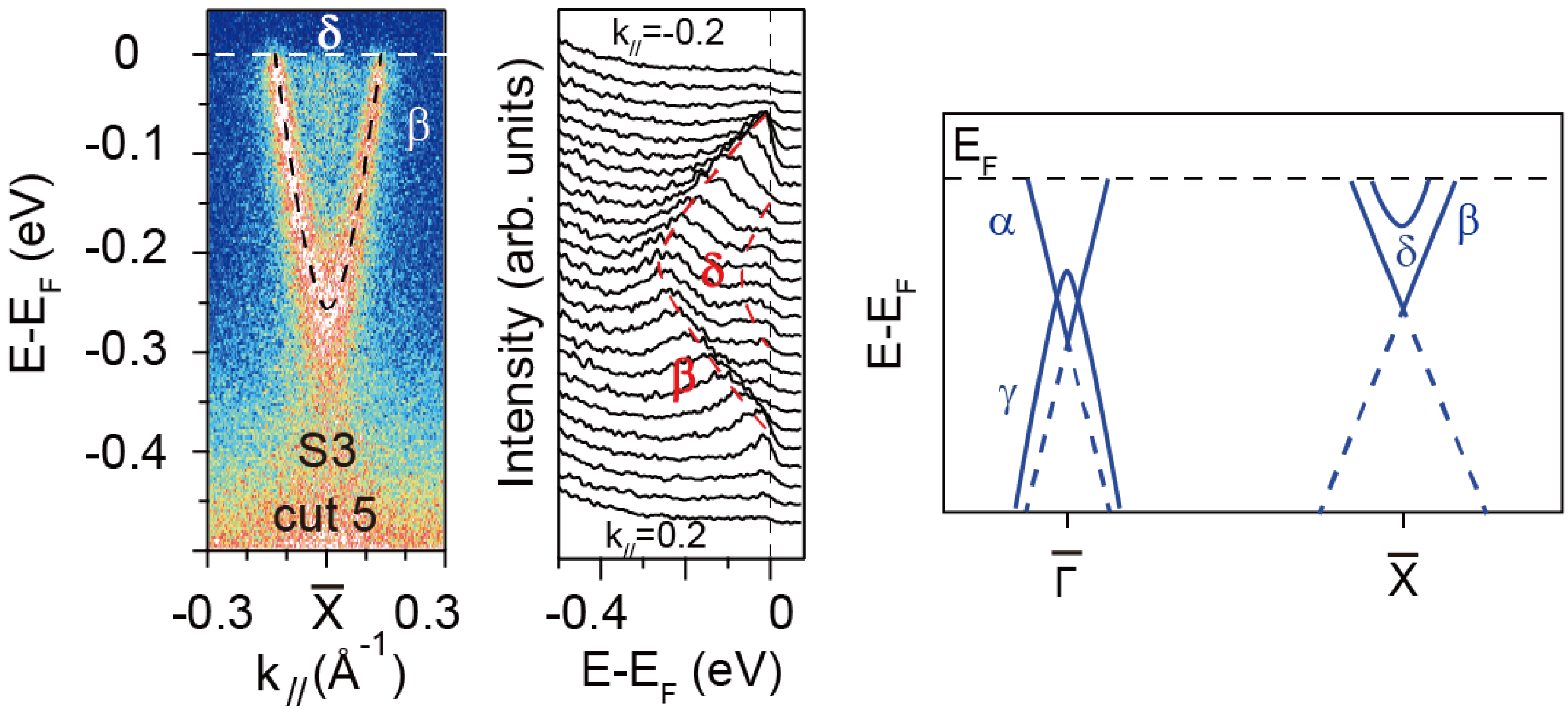
Near E_F dispersive states



Both the α band around Γ and β band around X show almost linear dispersion.

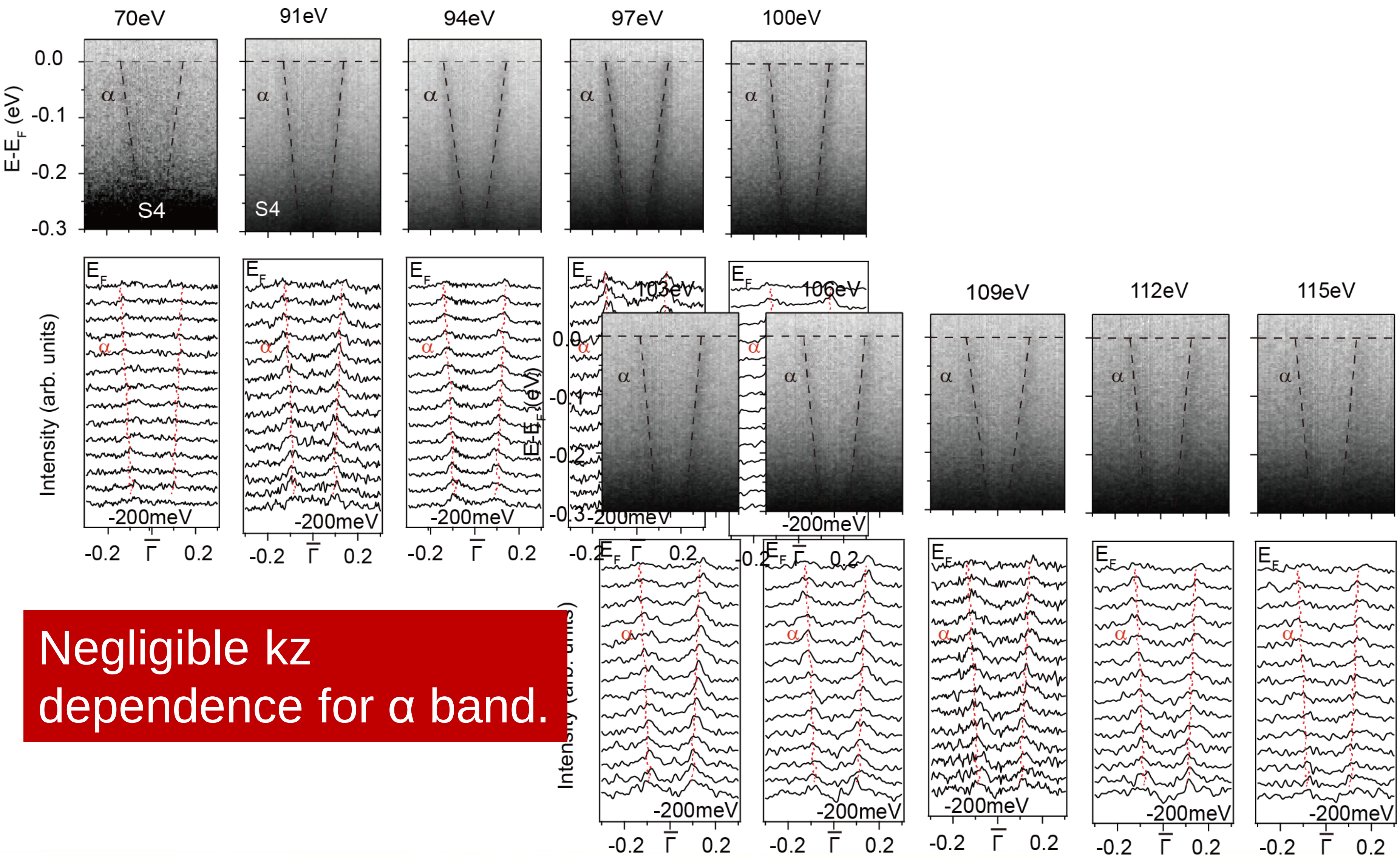
The band top of the γ band overlaps with the band bottom of α band in some energy range.

Near E_F dispersive states



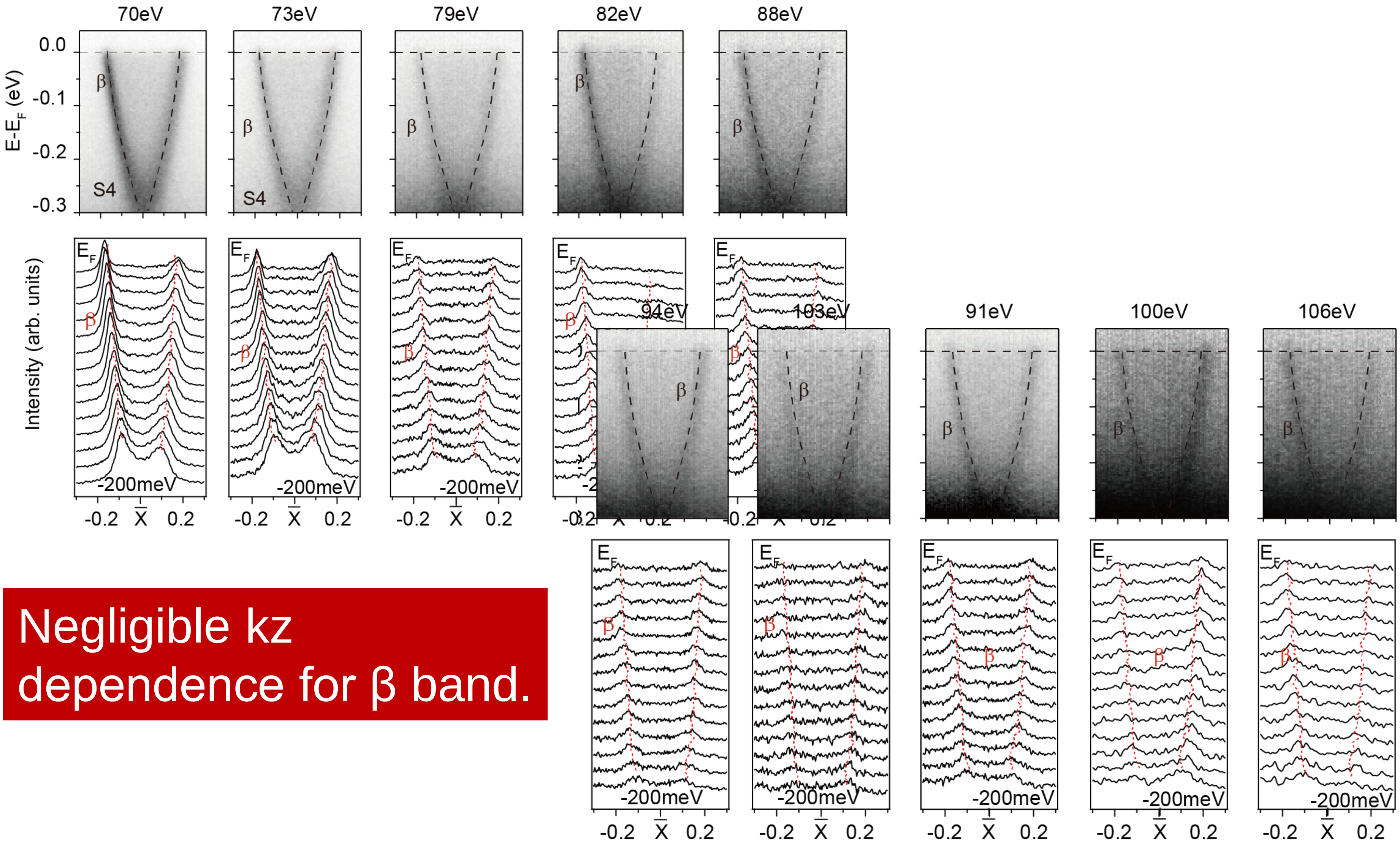
Bulk conduction δ band has been observed around the X point.

kz dependence of α



Negligible kz dependence for α band.

kz dependence of β



Negligible kz dependence for β band.

Summary

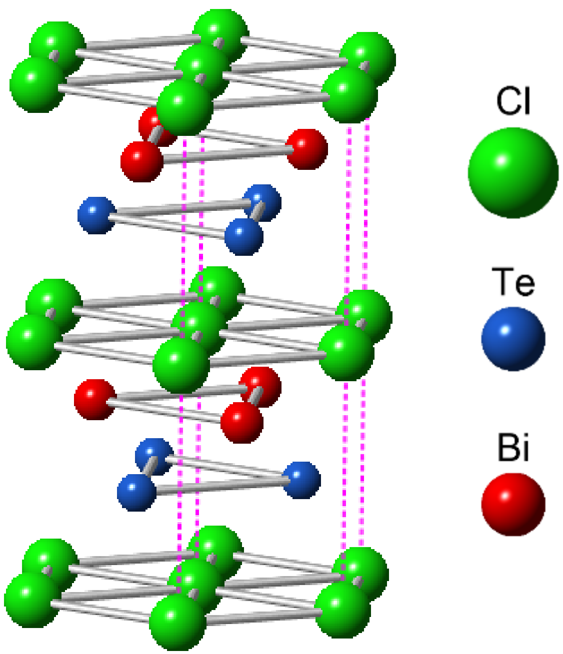
- SmB_6, identified almost linear dispersive states around Γ and X;
- Circular dichroism of the surface states indicate their possible topological origin;
- Temperature dependence data shows the hybridization of 4f-5d bands across the Kondo temperature.
- SmB_6 is likely a Topological Kondo Insulator.

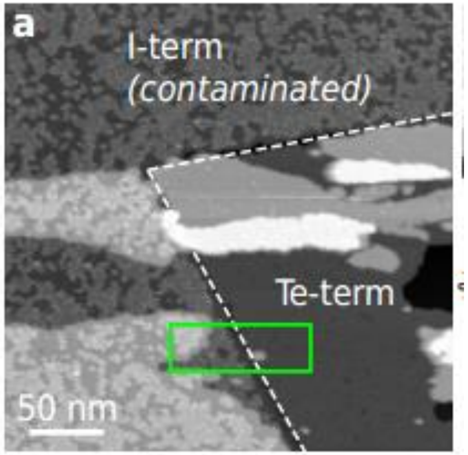
Outline

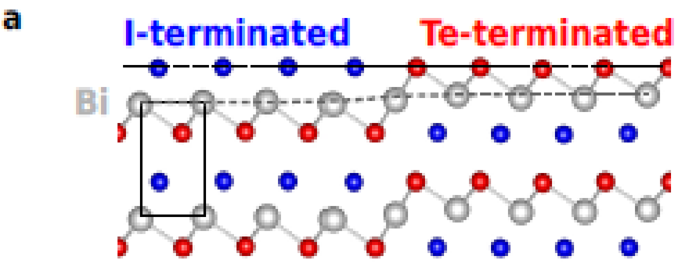
- ARPES study on the surface states of SmB6 and YbB6
- STM study on the surface states of BiTeCl

Structure of BiTeCl (Br, I)

BiTeCl (Br, I)



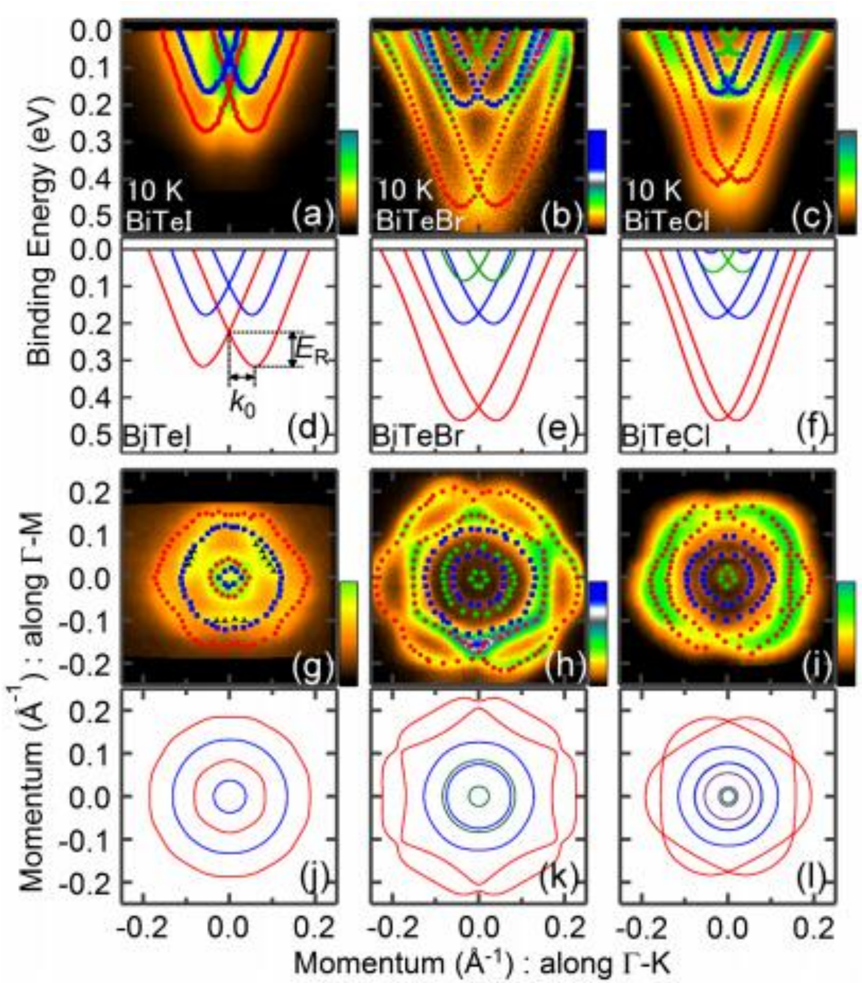


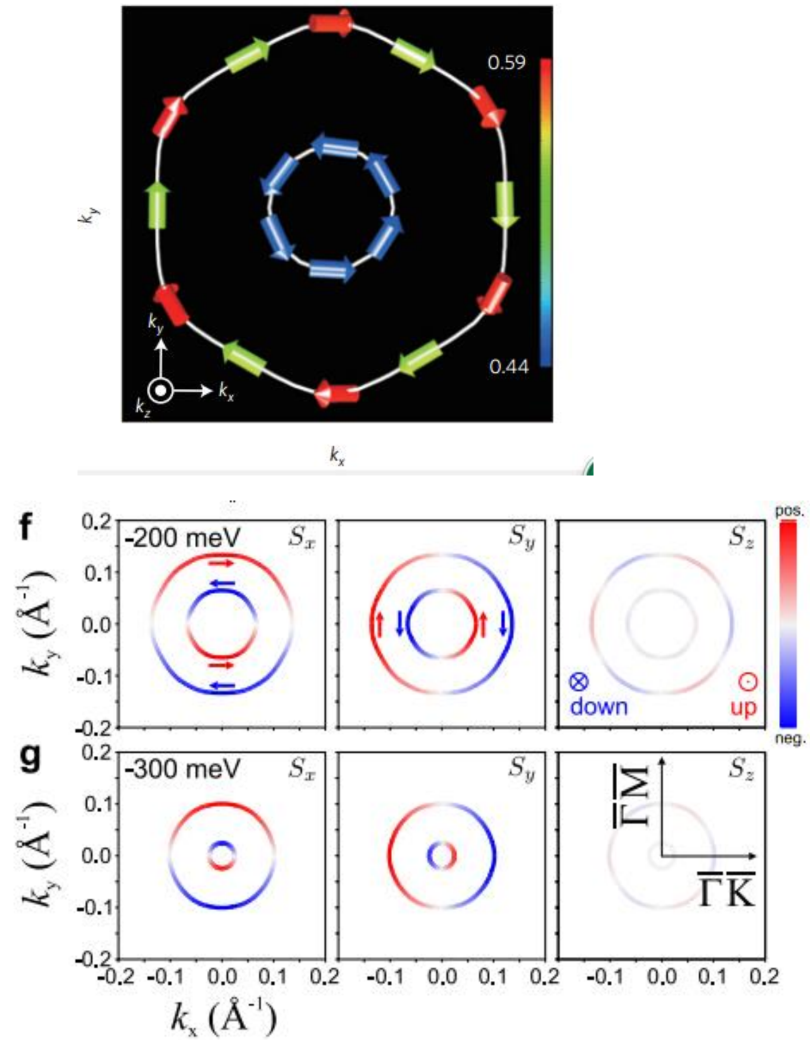


inversion-symmetry breaking

Polarized surface,
Rashba p-n junction

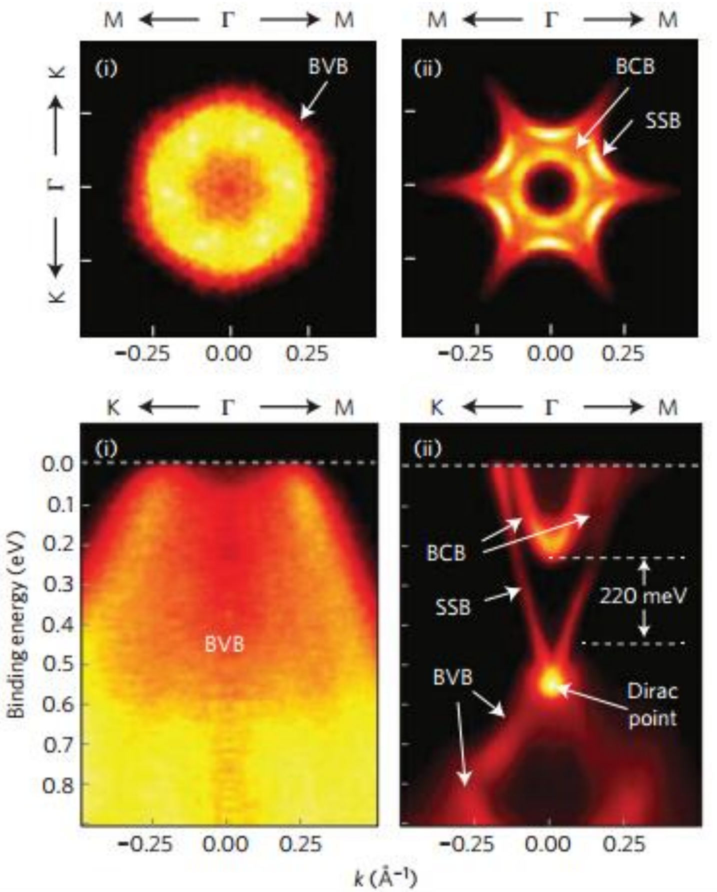
Giant Rashba-type splitting in BiTeCl (Br, I)

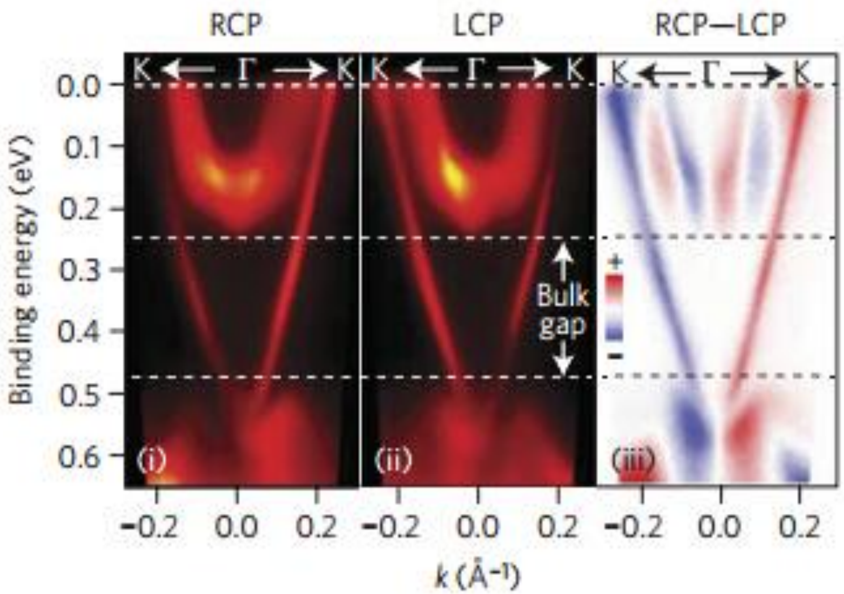




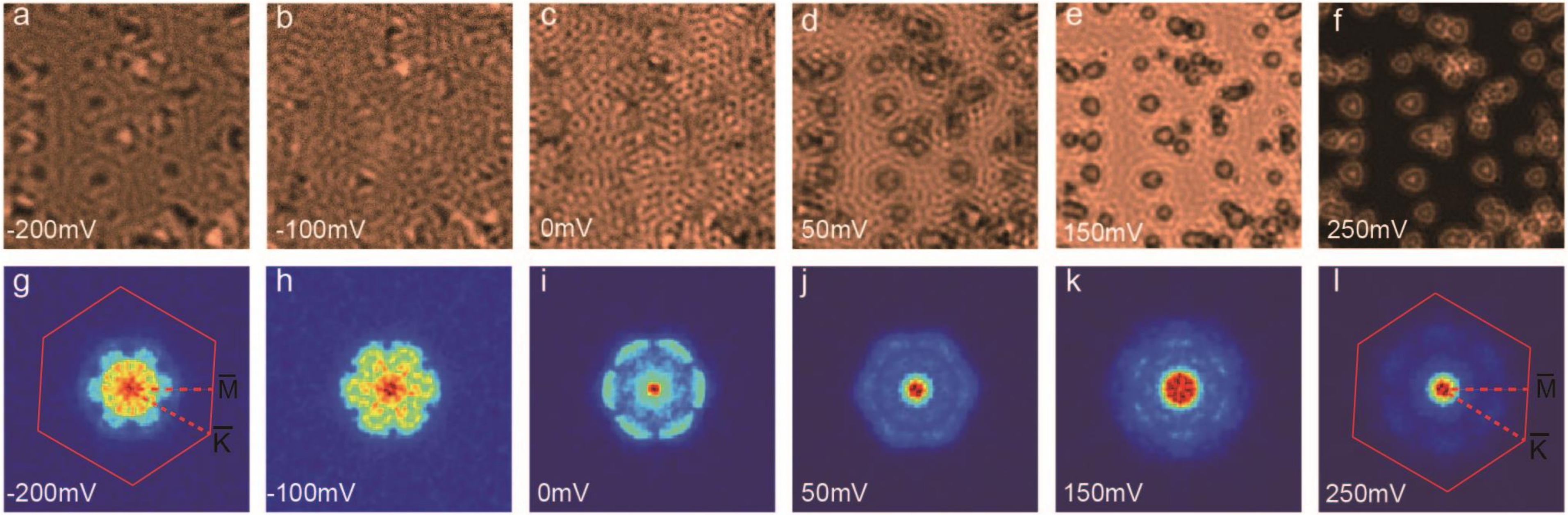
Possible topological surface states in BiTeCl

Y. L. Chen *et al.*, Nat. Phys. 9, 704 (2013)





Quasi - particle interference on BiTeCl

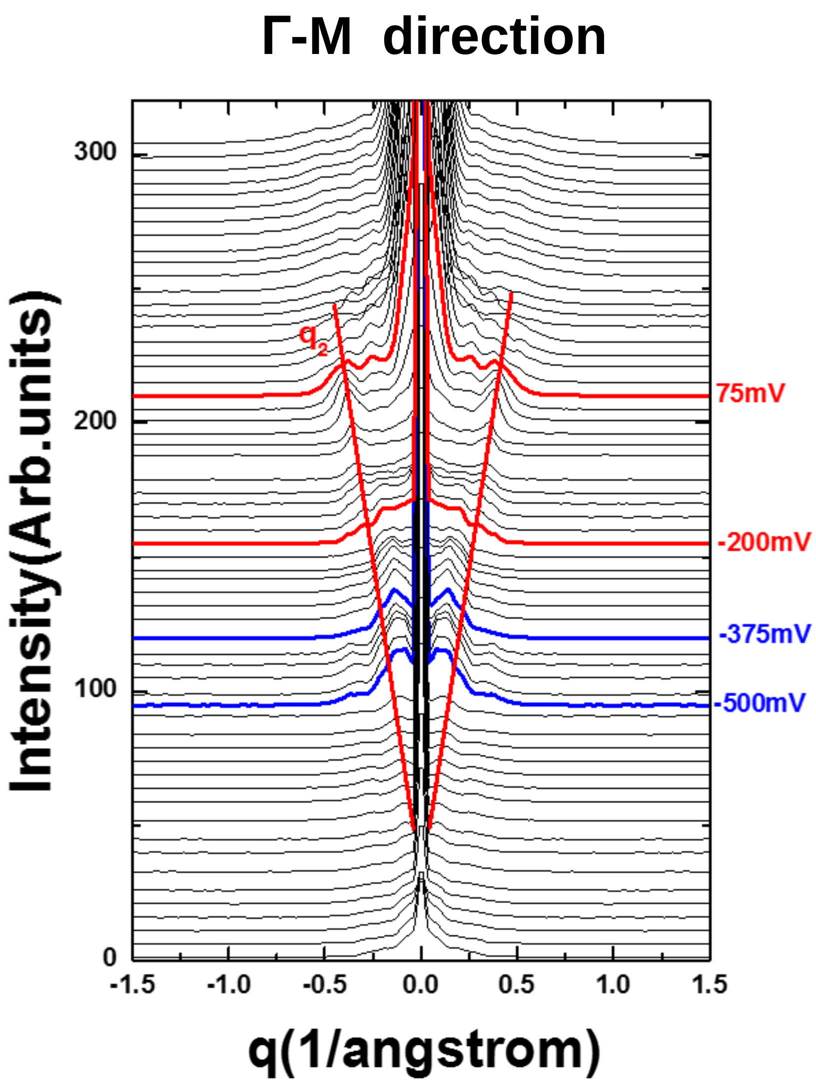


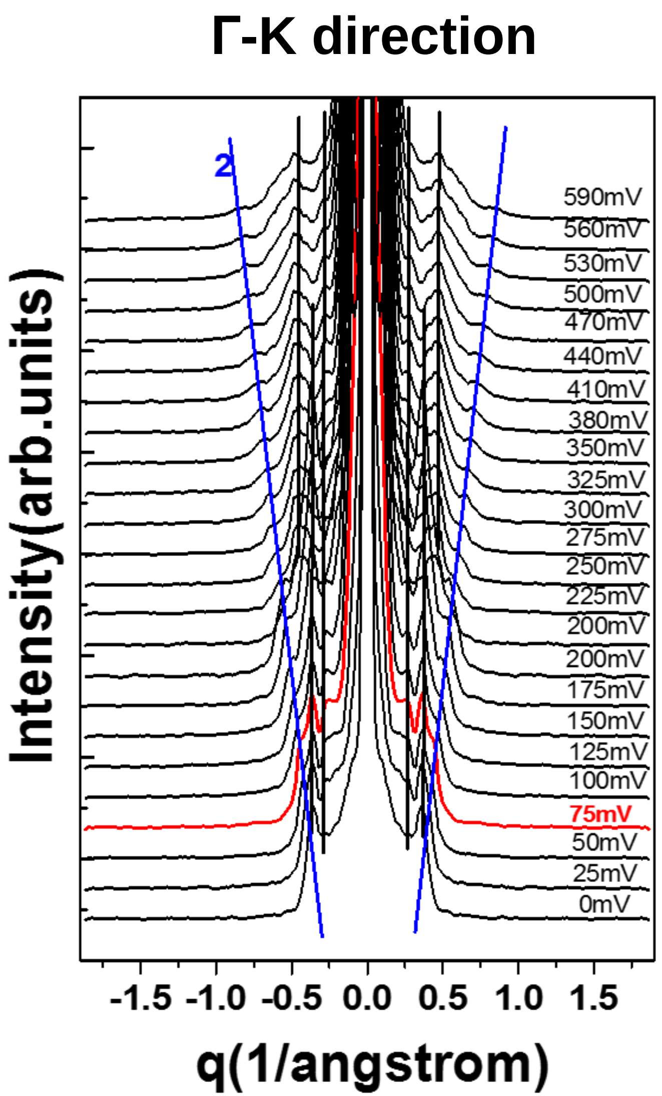
Scattering direction changes with energy!

-200mV---75mV: along Γ-M direction

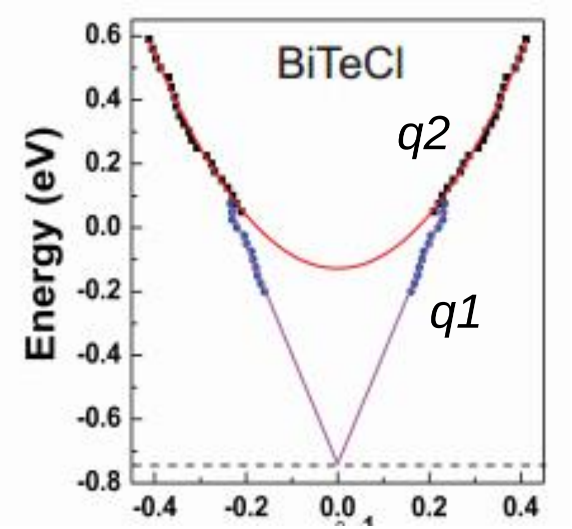
Above 75mV: along Γ-K direction

Dispersions of *q* vectors

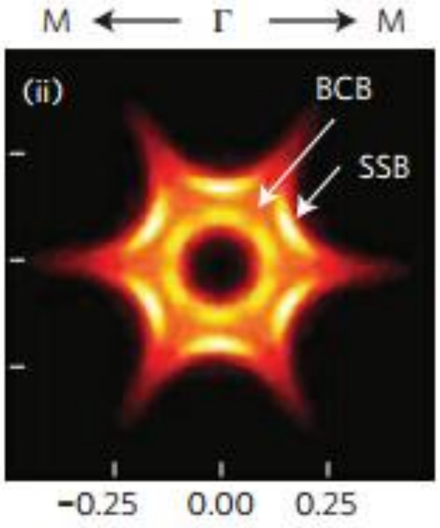




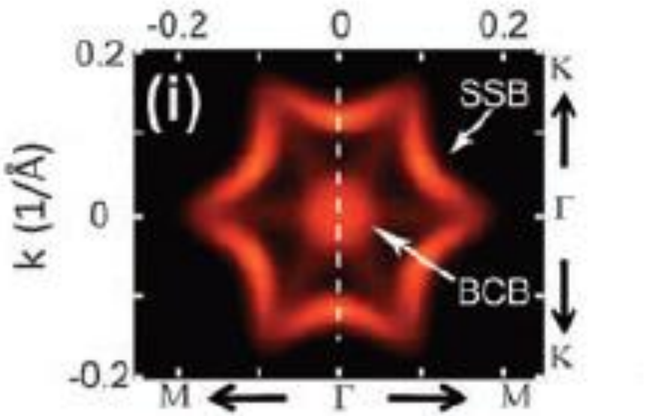
Origin of the two *q* vectors

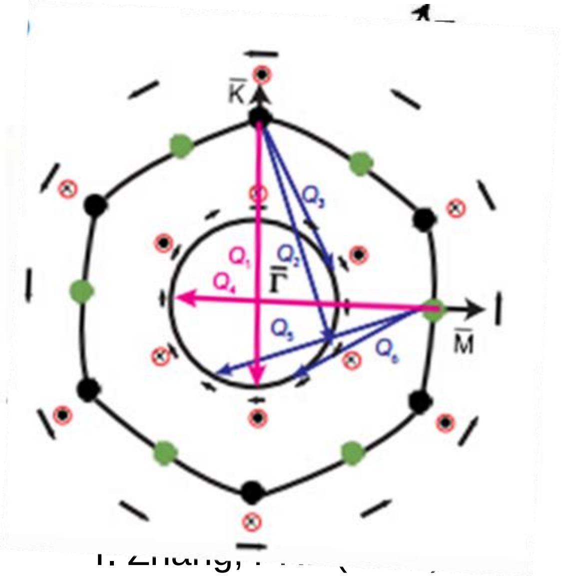


BiTeCl



Bi_2Te_3





q1 along direction is likely from topological surface states, like Bi_2Te_3, the back scattering is prohibit.

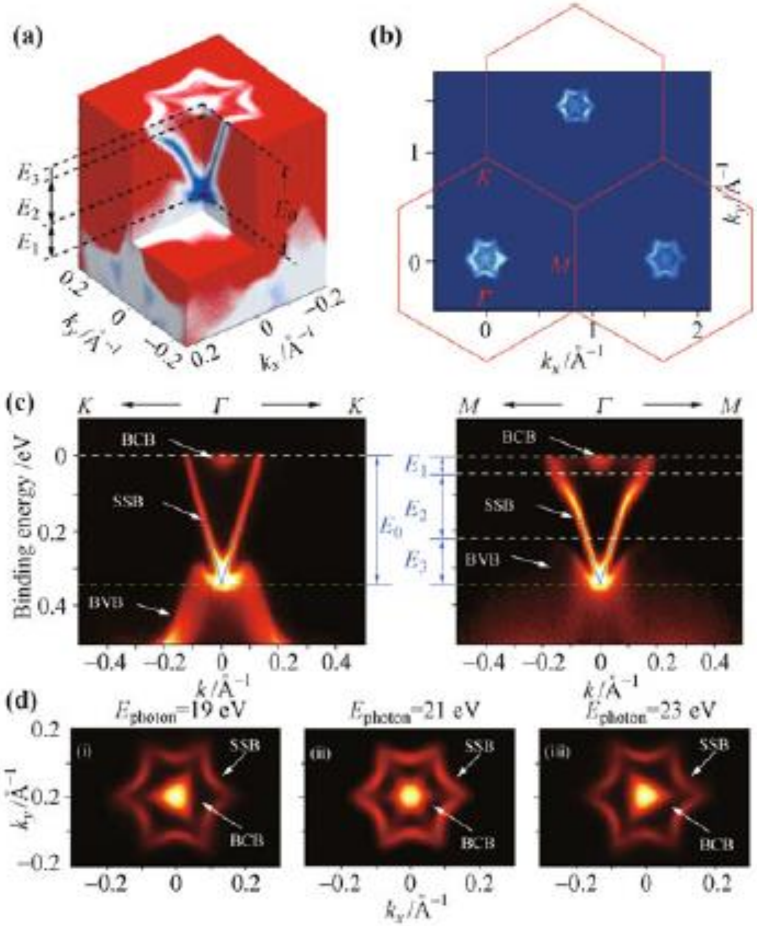
q2 could be a rashba like surface states, in which the back scattering is still possible

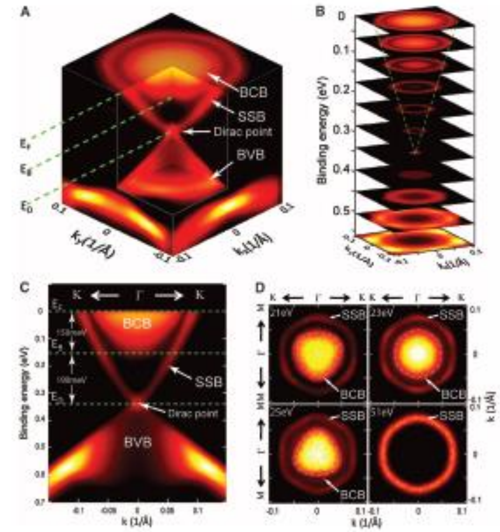
Summary

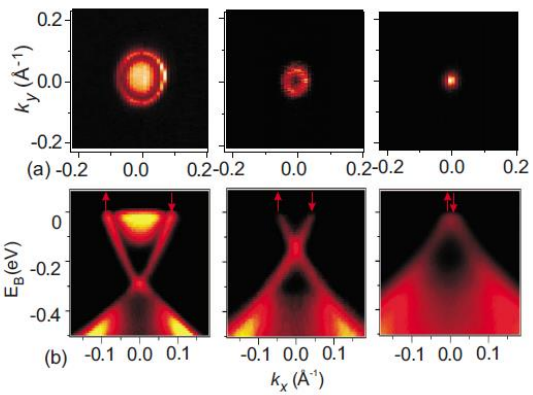
- Two branch of dispersive surface states are observed at BiTeCl surface.
- One of them is likely to be topological surface states without back scattering

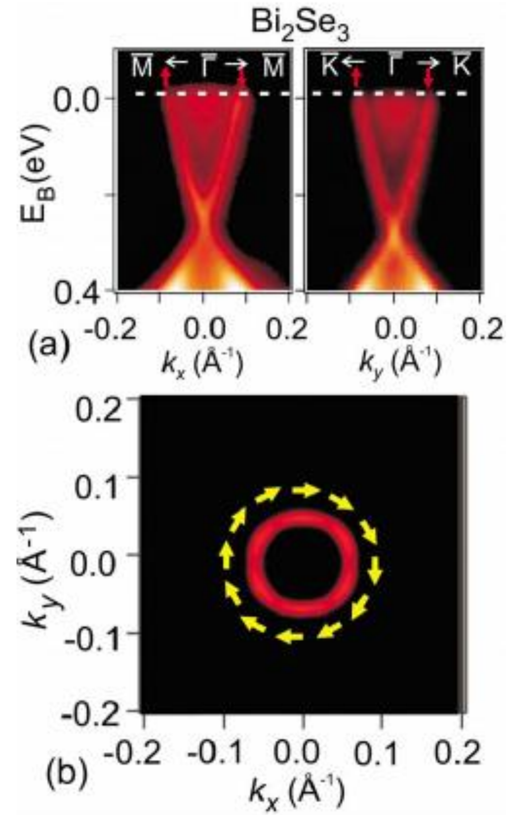

Thank you!

Angle-resolved photoemission spectroscopy







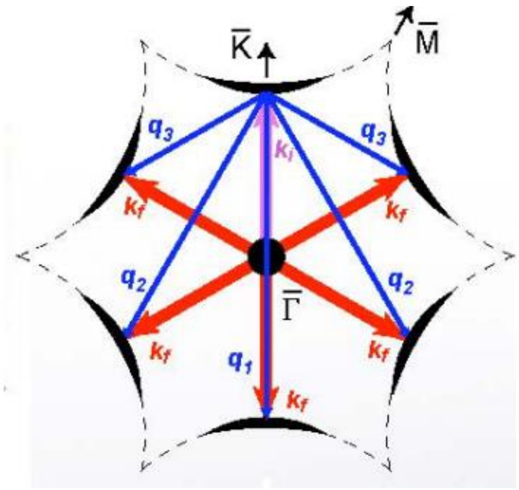


Y. L. Chen, et al, Science 325, 178 (2009)

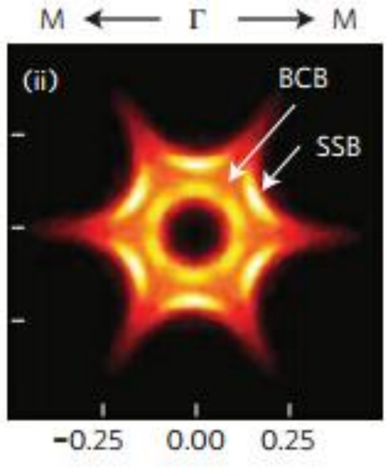
Y. L. Chen, et al, Science 329, 659 (2010) *D. Hsieh, et al, Nature 460, 1011 (2009)* *D. Hsieh, et al, Nature 460, 1011 (2009)*

Band structure

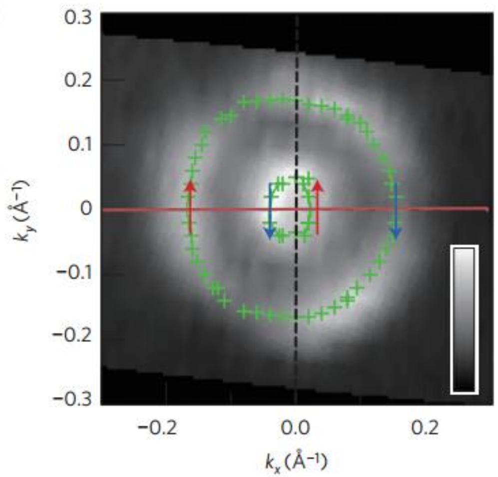
Bi_2Te_3



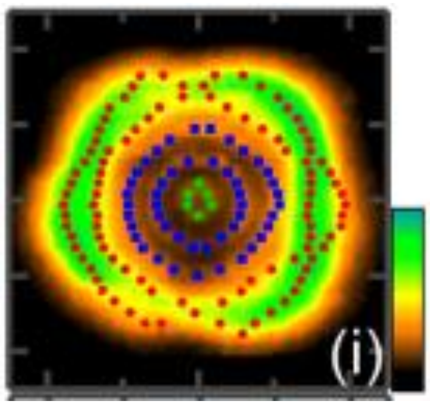
BiTeCl

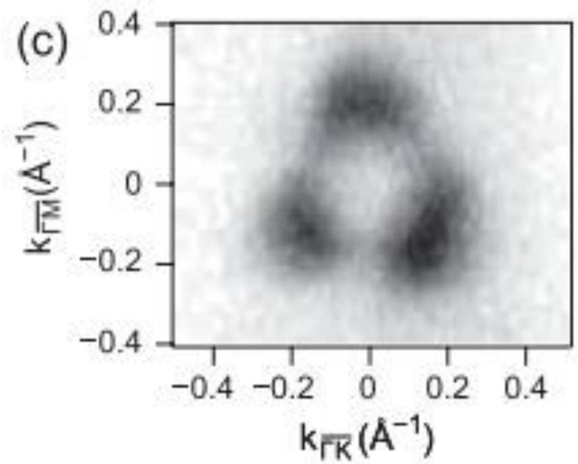


BiTeI

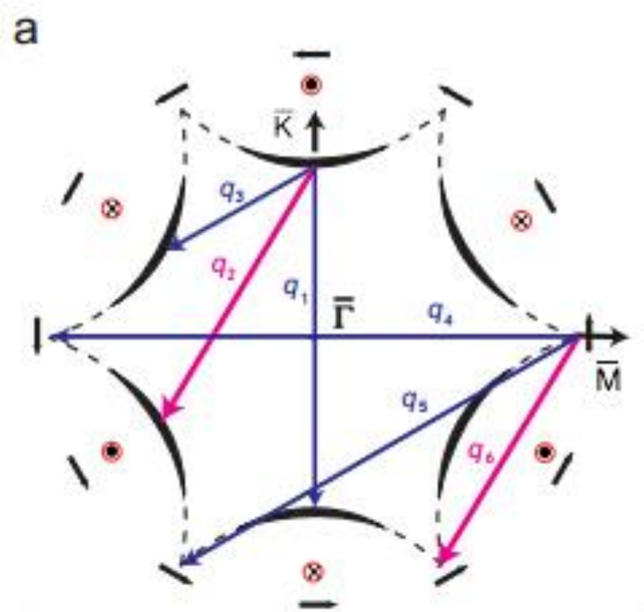


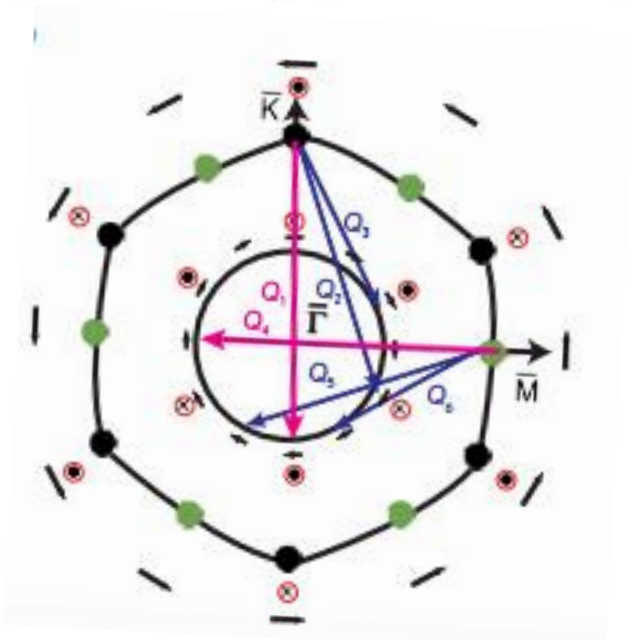
拓扑表面态是受到时间反演对称性保护的，在表面准粒子散射图像中，表现为非磁性杂质造成的背散射完全被压制。

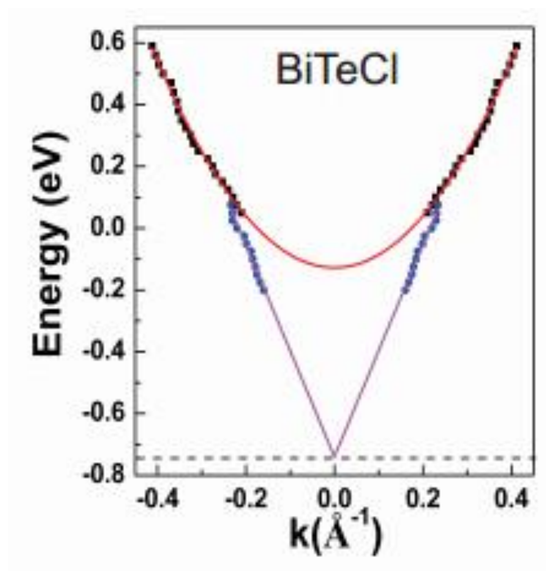


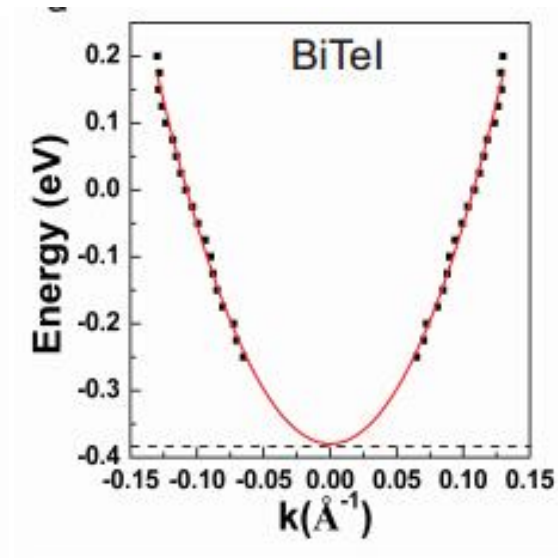


Conclusion I





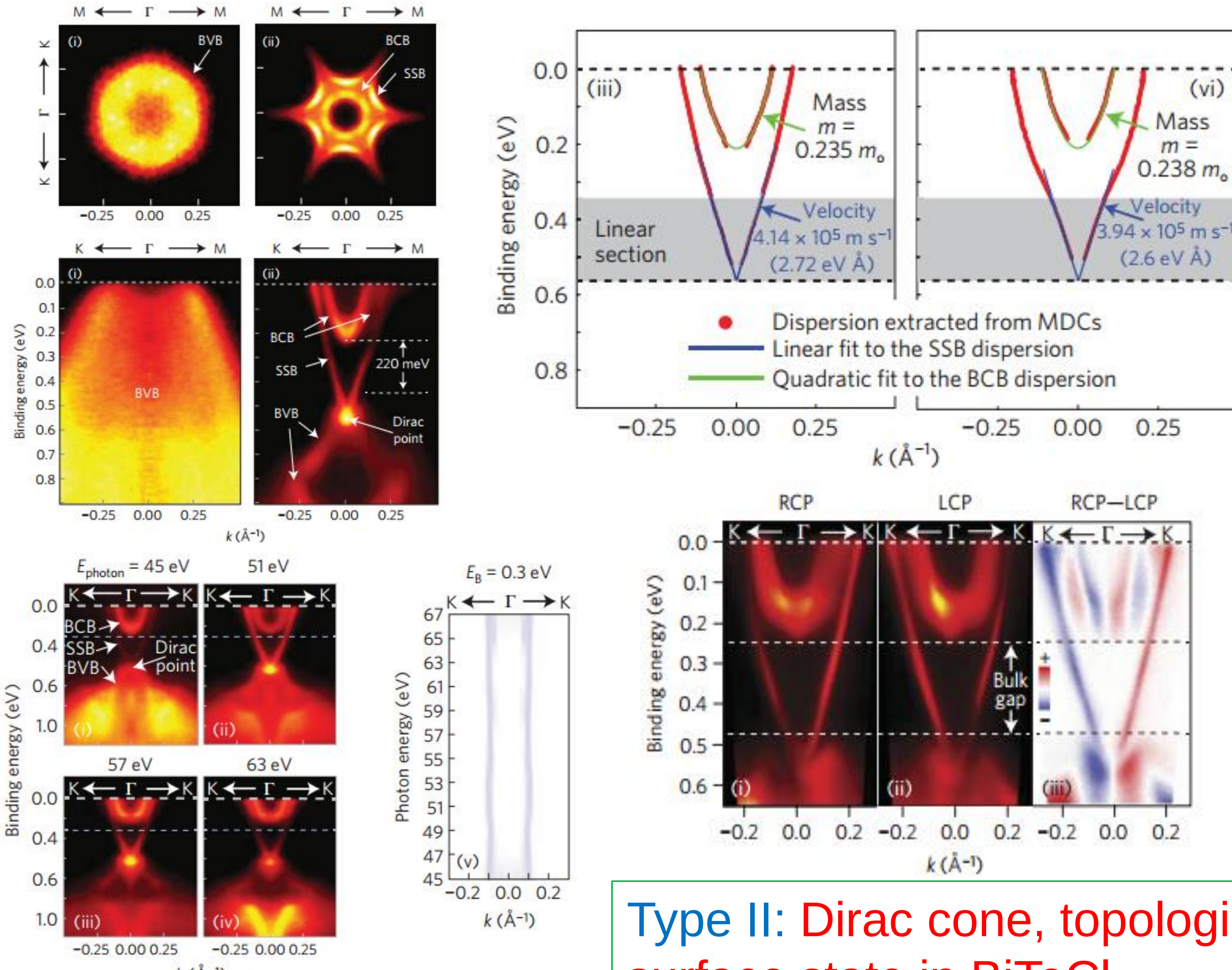




线性色散: q_2, Γ-M, Dirac cone
抛物线色散: Q_1, Γ-K, SCB

抛物线色散: Q_4, Γ-M, SCB

A single topological Dirac fermion in BiTeCl



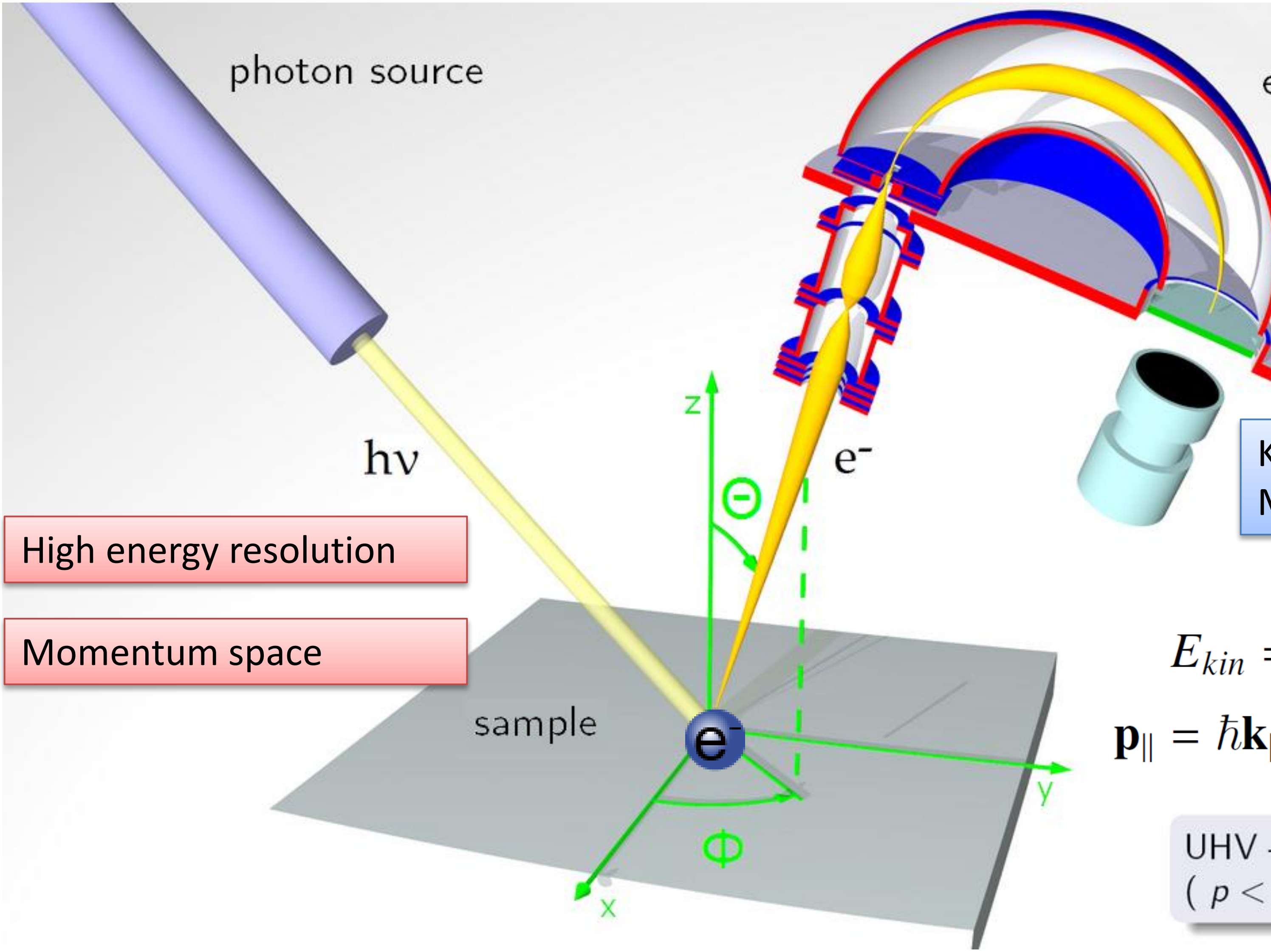
Y. L. Chen et al., Nat. phy. 9, 704 (2013)

Type II: Dirac cone, topological surface state in BiTeCl.

Summary of YbB_6

- Identified almost linear dispersive surface states around Γ and X;
- The total number of surface state is odd;
- Circular dichroism of the surface states indicate their possible topological origin;
- The bulk insulating gap might be around 100meV

- Unsolved issues
  - Two fold symmetry of circular dichroism in α band?



High energy resolution

Momentum space

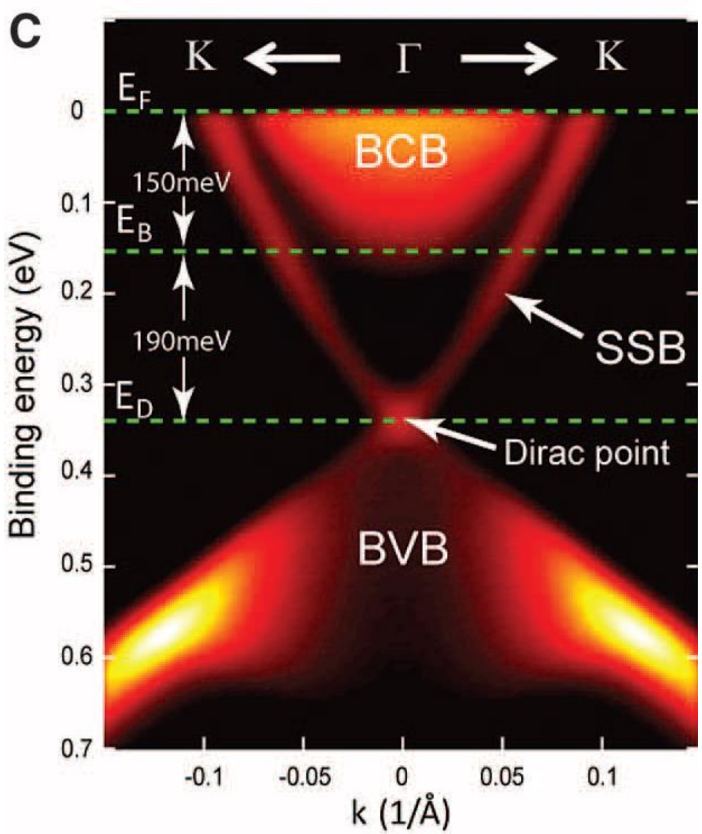
Kinetic Energy (E_{kin})
Momentum ($\mathbf{k}$)

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

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

UHV - Ultra High Vacuum
($p < 10^{-7}$ mbar)

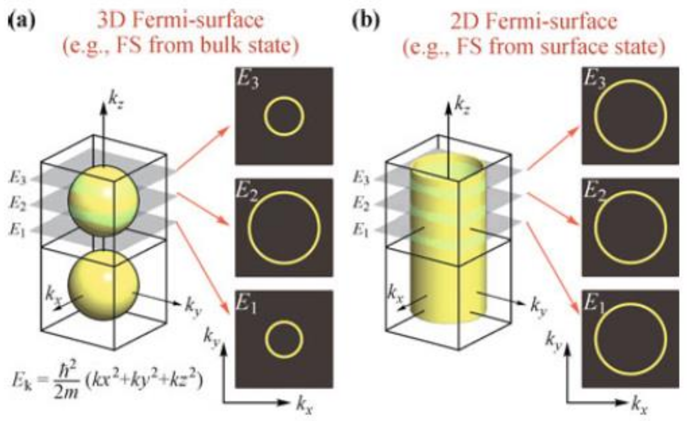
Spin polarized topological nontrivial surface states!



surface states

↓

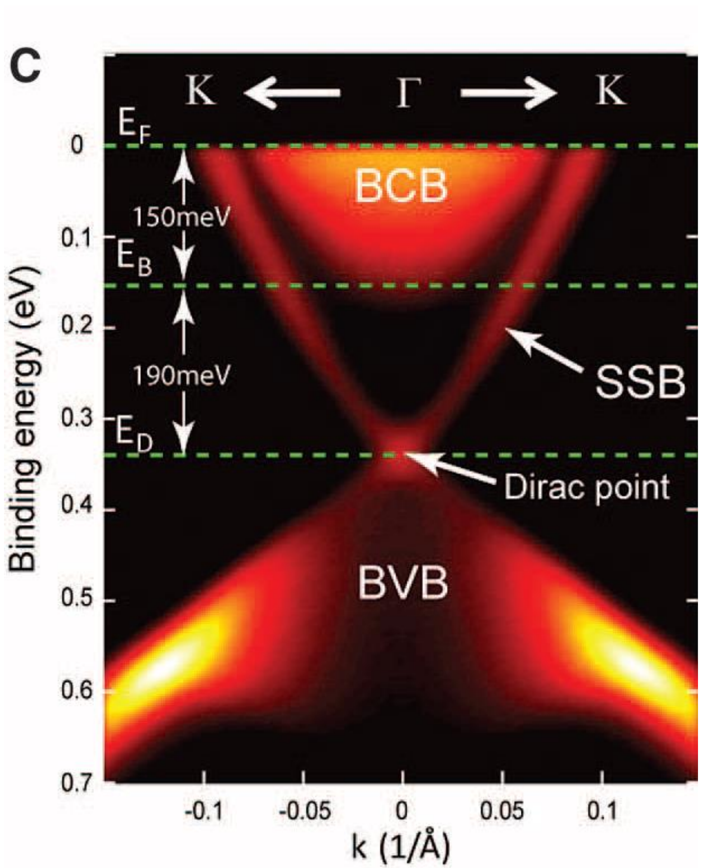
Photon energy dependent ARPES



Y. L. Chen, et al, Science 329, 659 (2010)

Y. L. Chen,Front. Phys., 2012, 7(2): 175–192

Spin polarized topological nontrivial surface states!

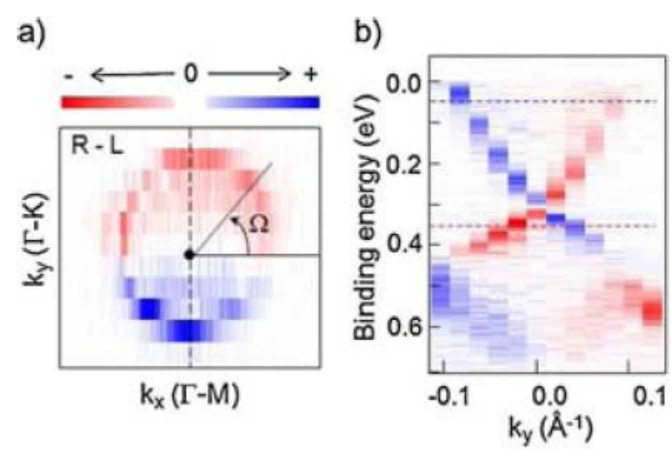


Y. L. Chen, et al, Science 329, 659 (2010)

Spin polarizaed

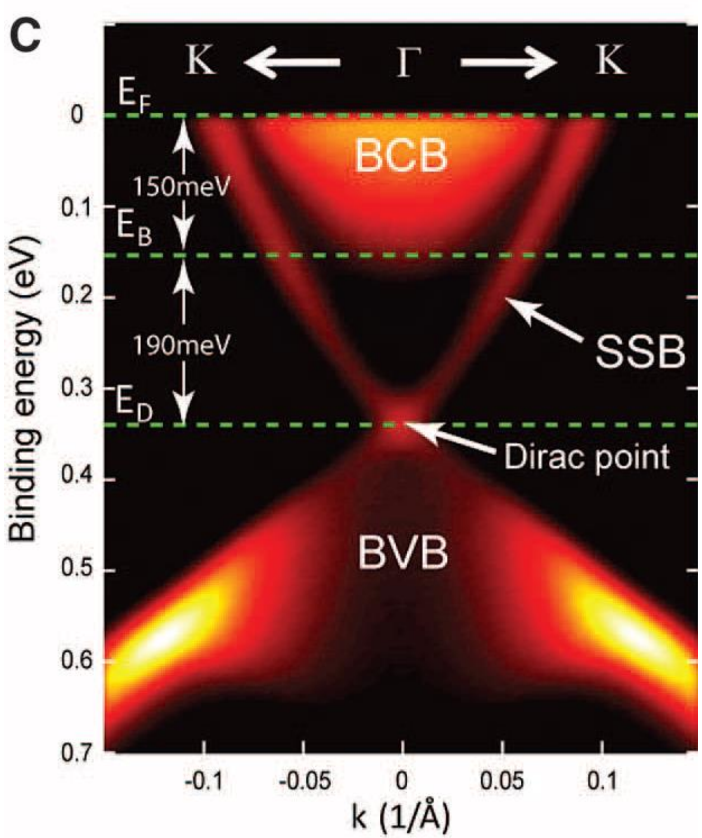
↓

Circular Dichroism ARPES



Park et al, Phys. Rev. Lett. 108, 0468 (2012)

Spin polarized topological nontrivial surface states!

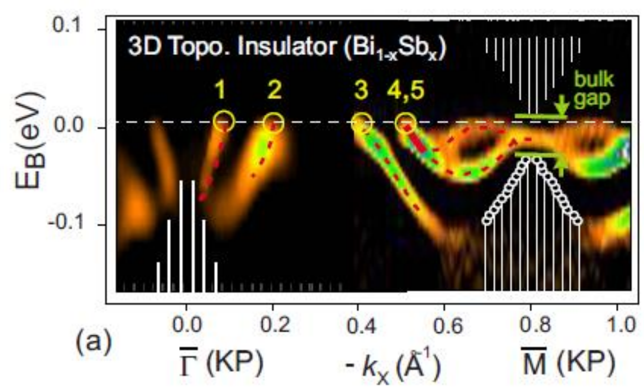


Y. L. Chen, et al, Science 329, 659 (2010)

topological nontrivial

↓

Odd number of Fermi pockets enclose the Kramers points!



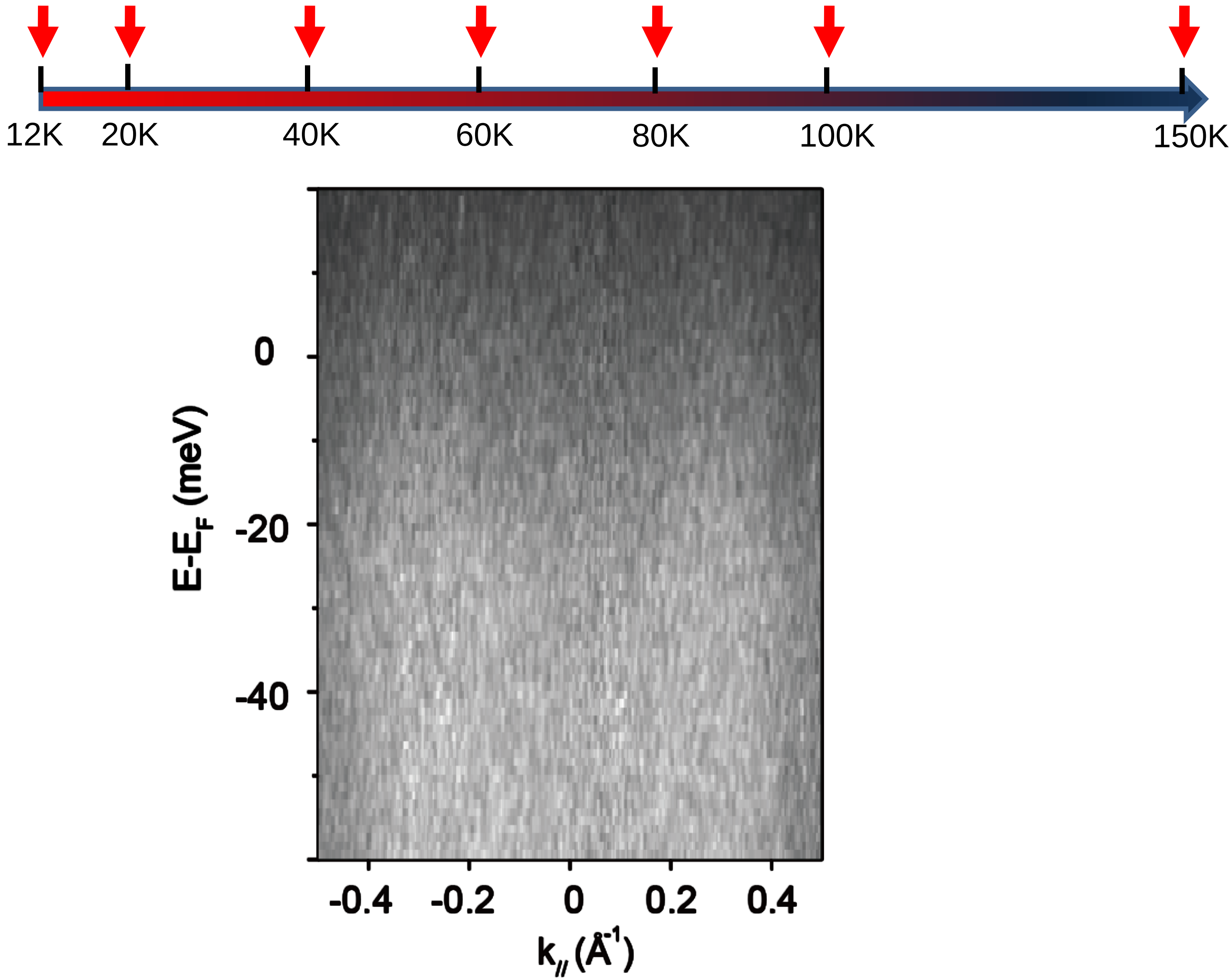
D. Hsieh, et al, Nature 452, 970 (2008)

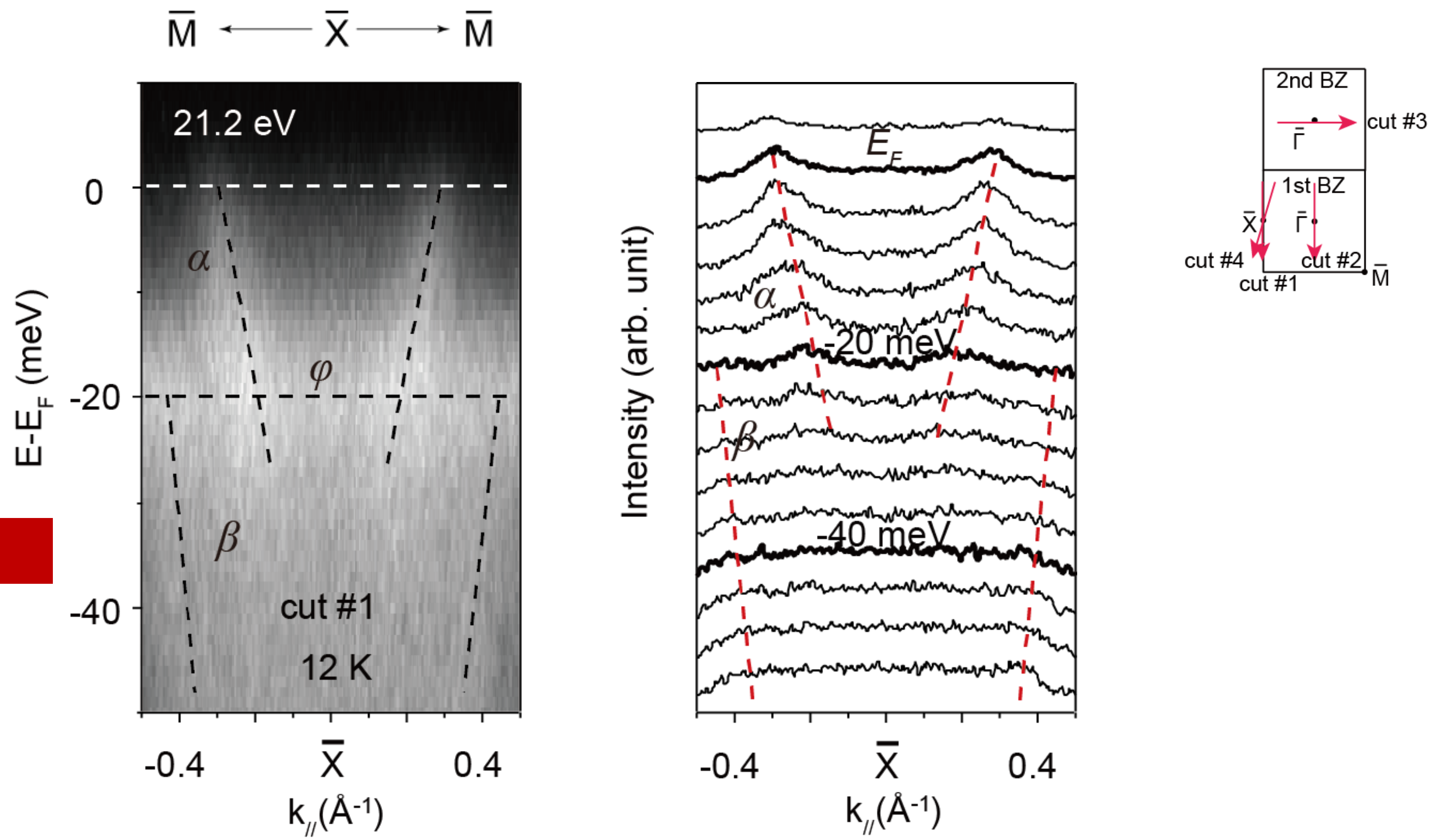
Both α and γ bands are likely to be topologically non-trivial!

The total number of surface state is odd!

↓

Topological Kondo Insulator


12K
20K
40K
60K
80K
100K
150K
E-E$_F$ (meV)
0
-20
-40
-0.4
-0.2
0
0.2
0.4
k$_{//}$ (Å^{-1})



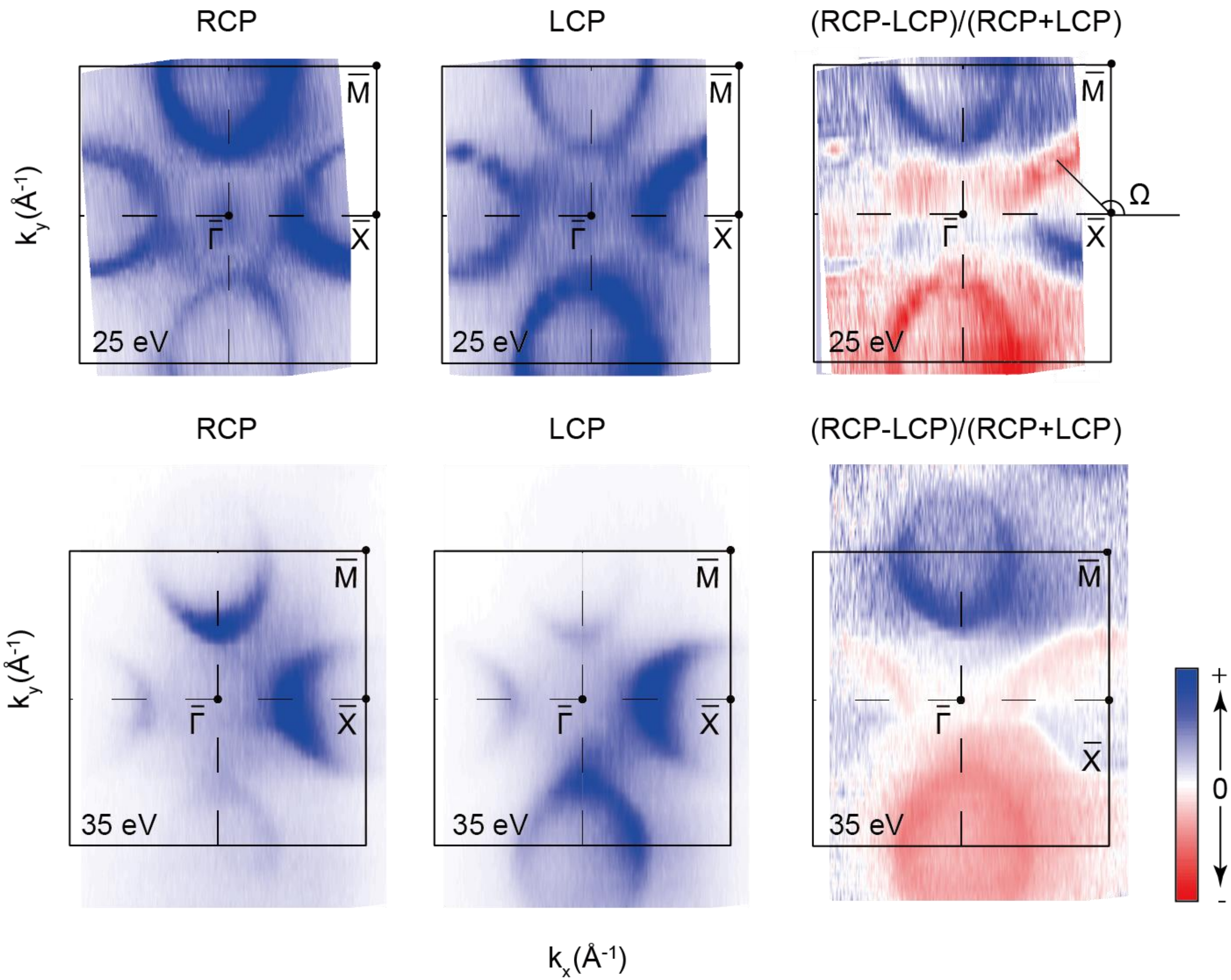
Surface states??

Linear dispersion of α bands.

α band goes straight through ϕ and coexists with β band.

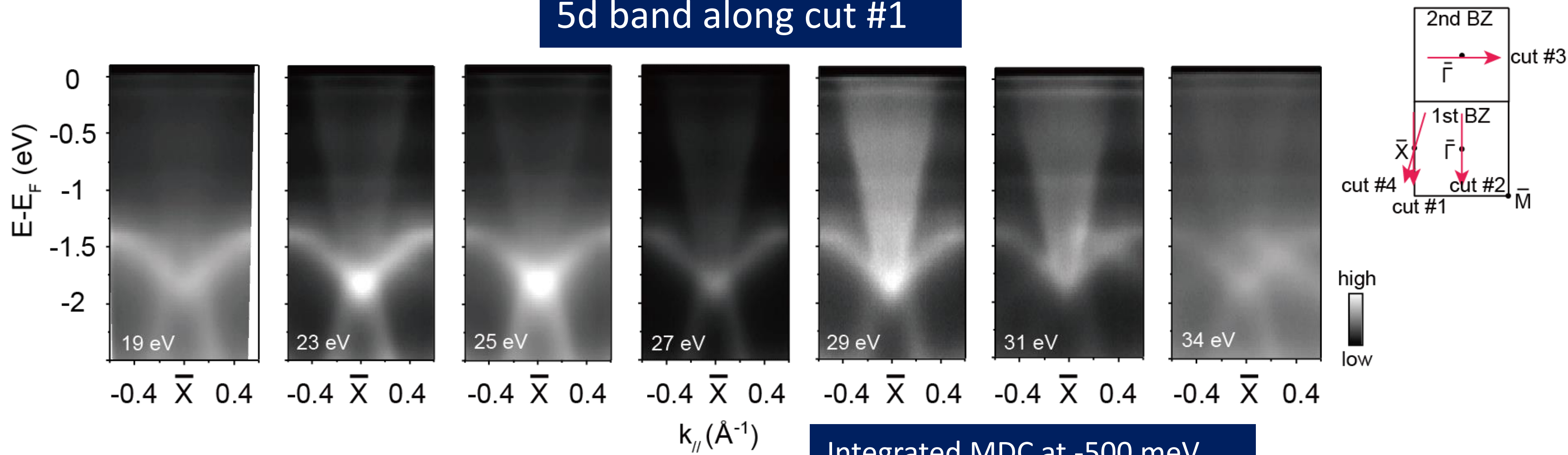
Sample 1 @ Hisor

Sample 2 @ SLS

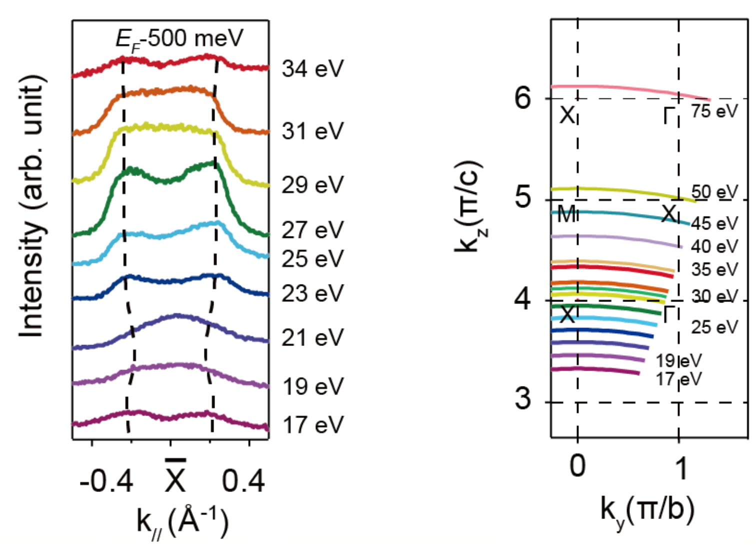


k_z dependence of 5d band

5d band along cut #1



Integrated MDC at -500 meV

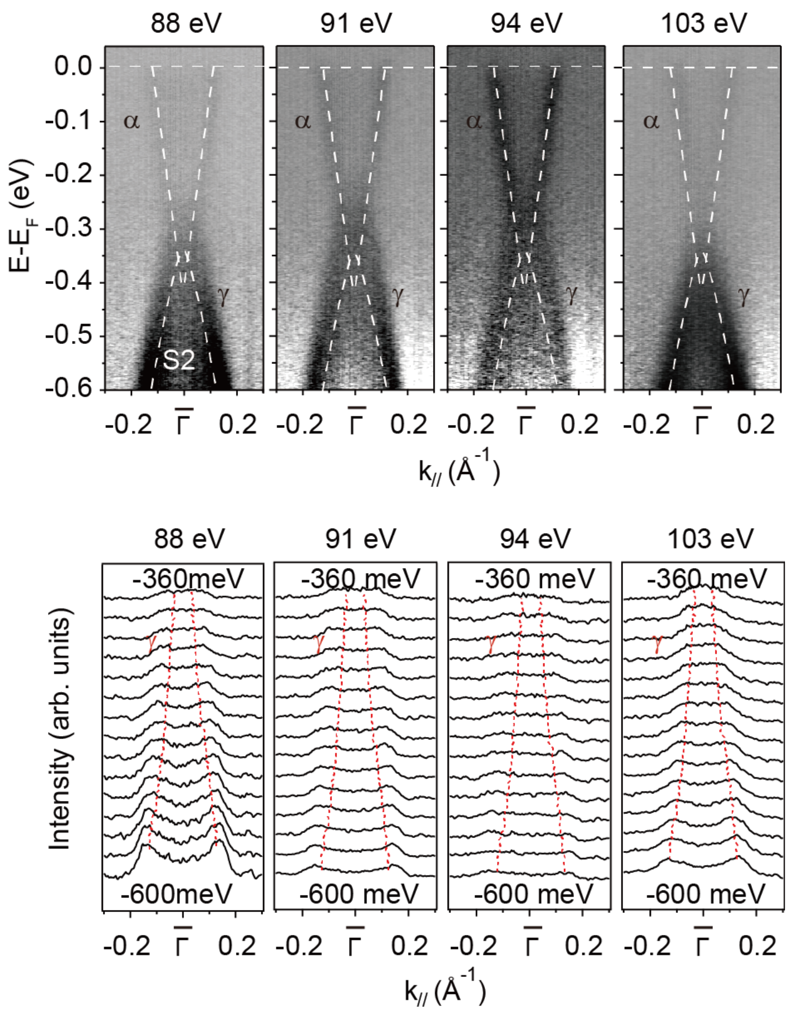


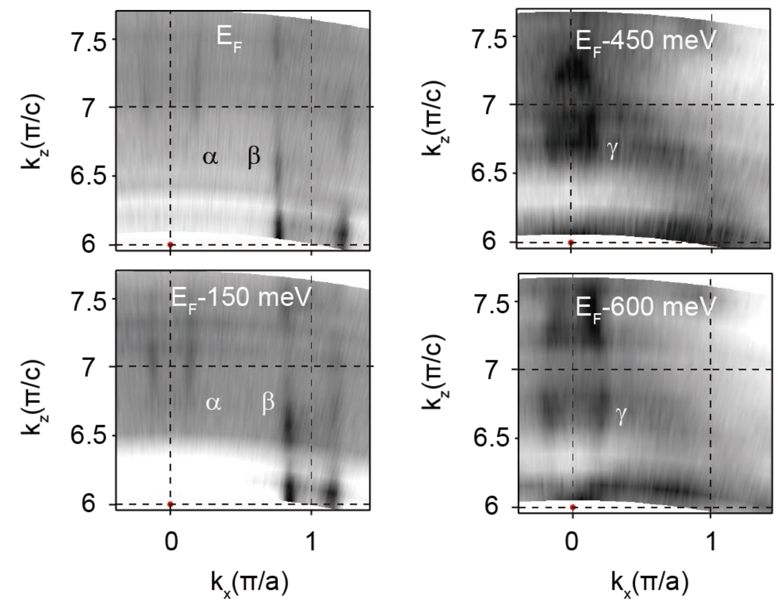
Poor k_z resolution to distinguish the strong k_z dispersion of the 5d band.

Surface States!

kz mapping

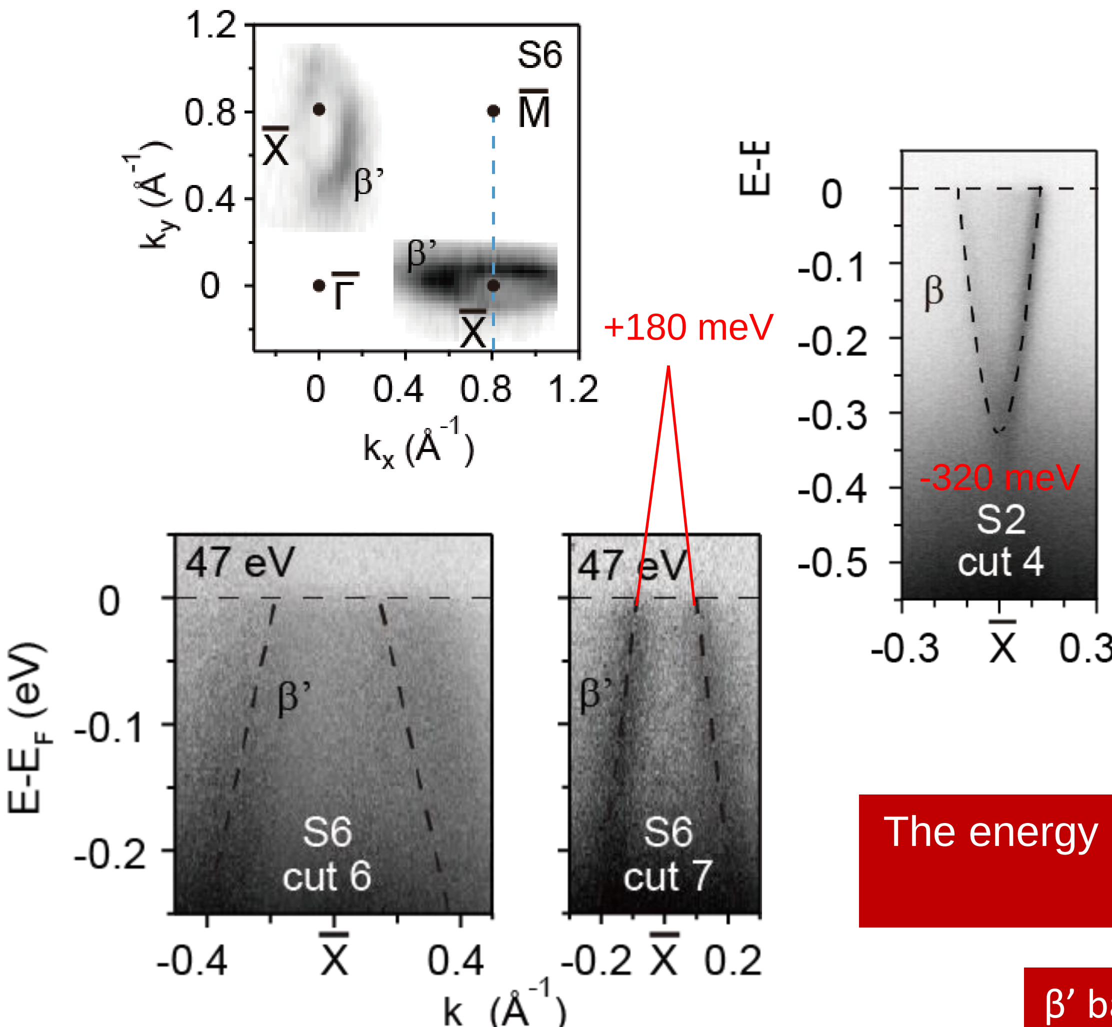
Odd FSs!

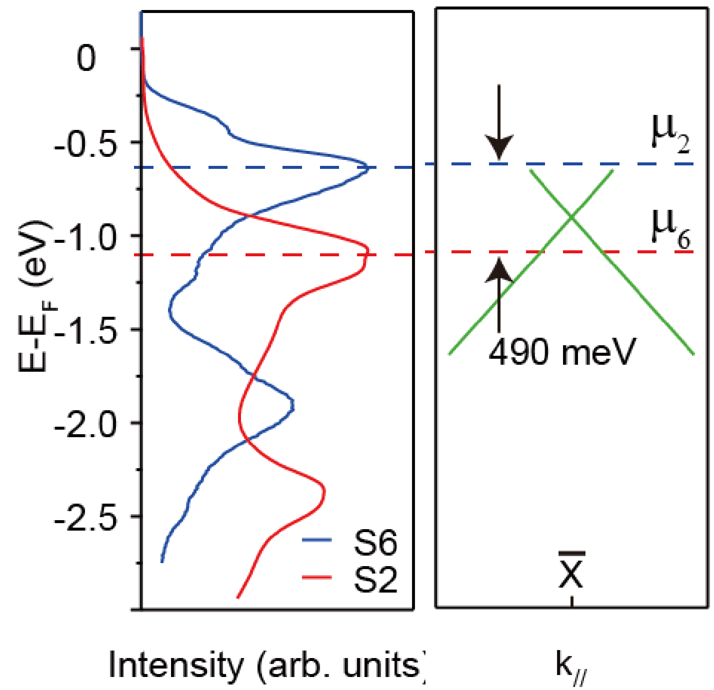




Obvious 2D nature of the α and β bands,
3D nature of γ band.

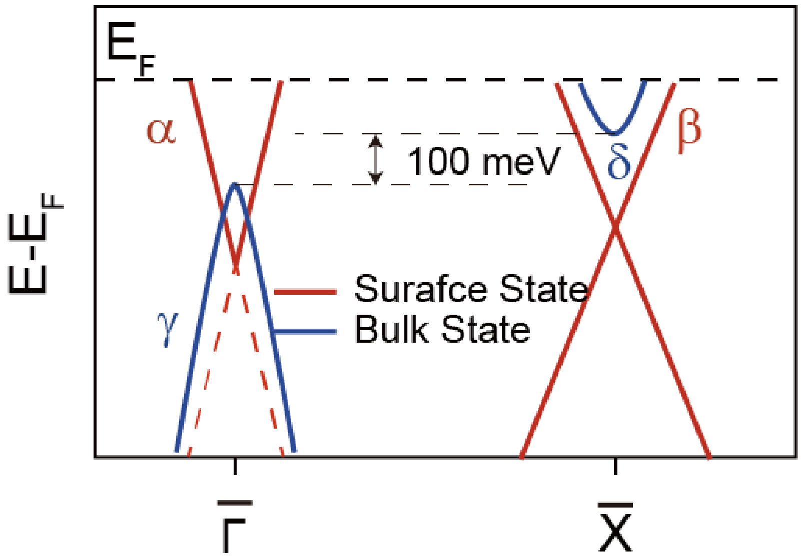
Bulk origin of γ band.



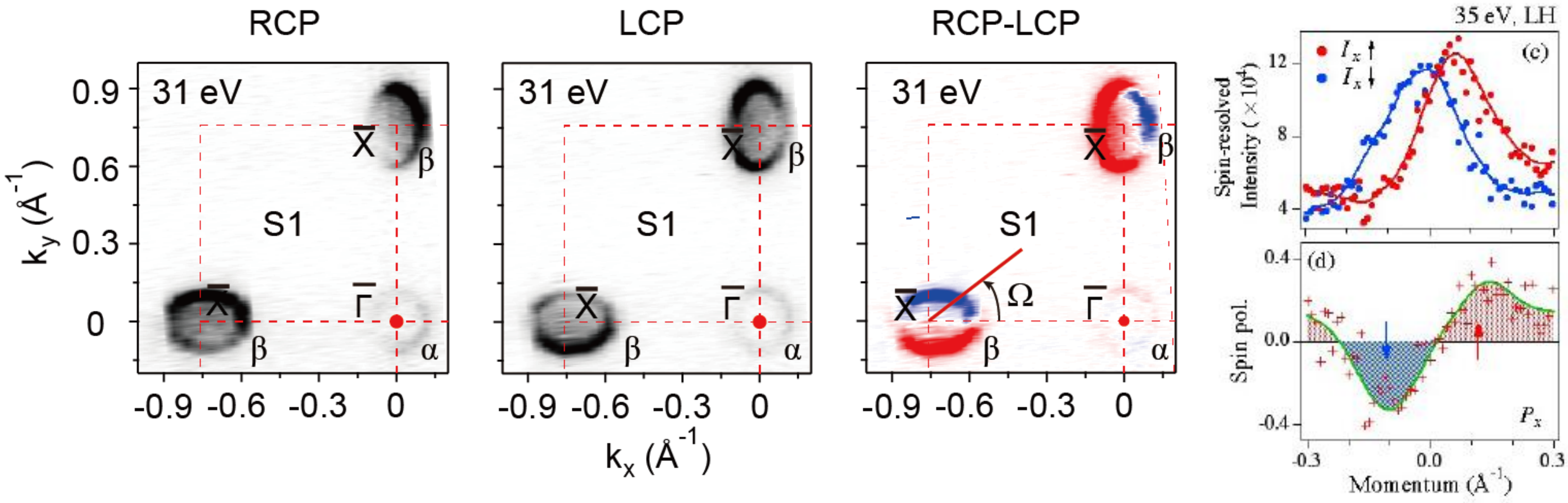


The energy position of the crossing point shifted about 500 meV.

β' band is the lower cone of β?

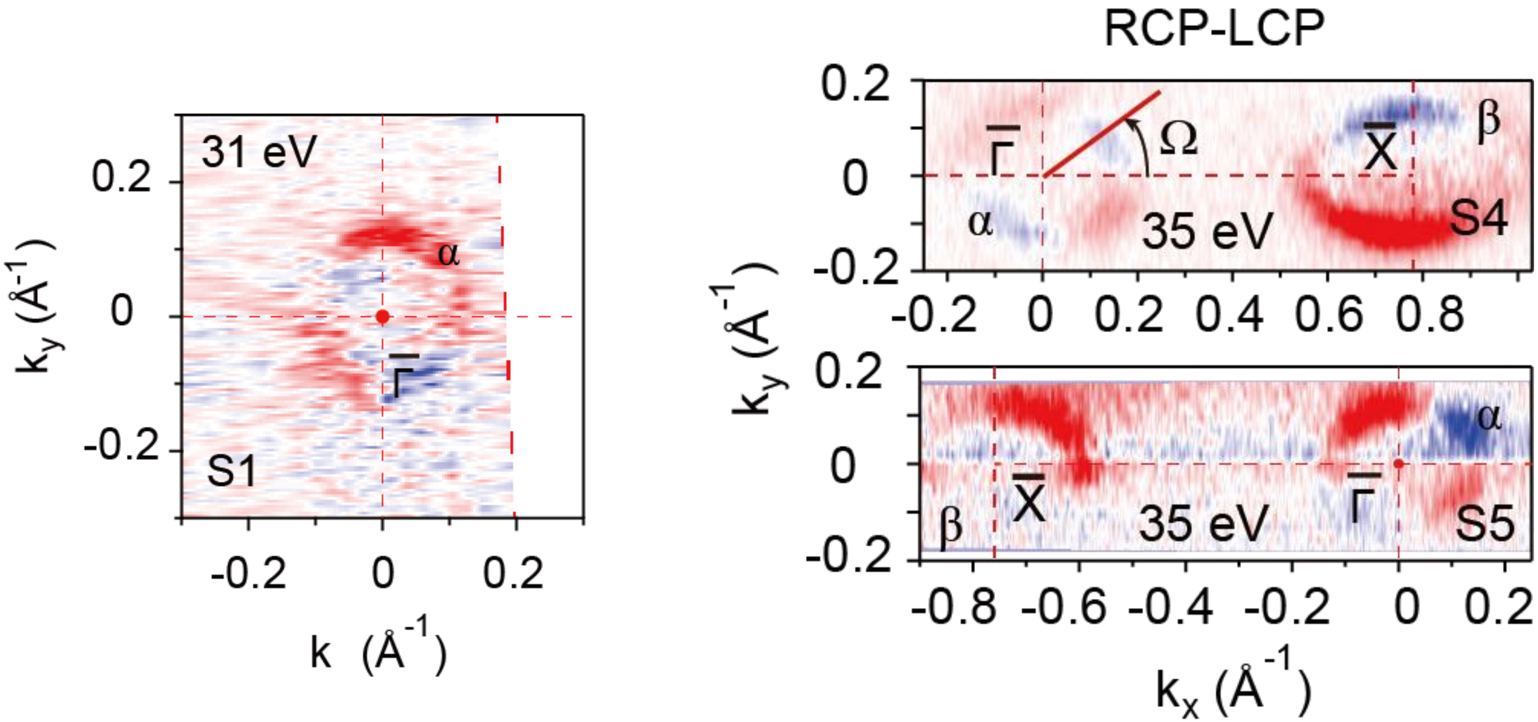


100 meV band gap!

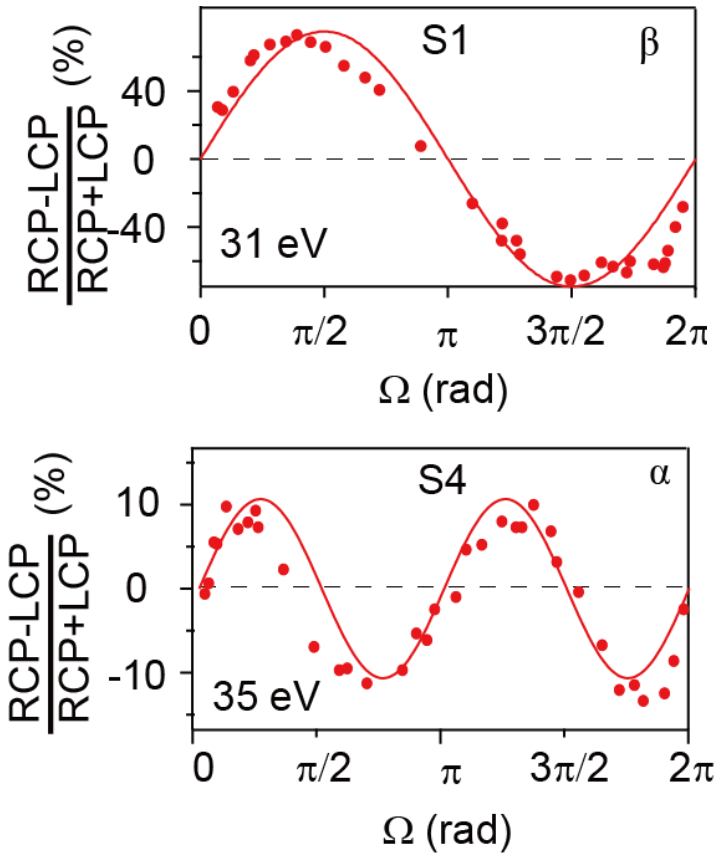


The CD of the β pocket shows an anti-symmetric pattern about the Γ-X axis in the surface BZ.

N. Xu, et al, arXiv: 1405.0165 (2014)

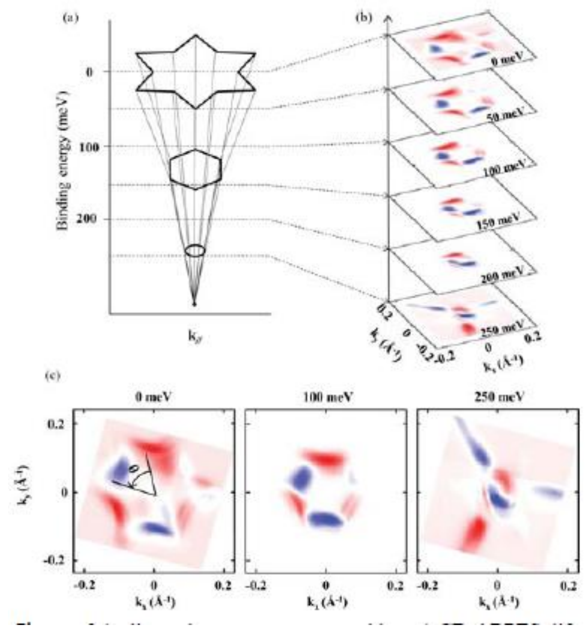


The CD of the α pocket shows a two-fold symmetry!



The CD both α and β can be well fitted by a sine function.

However, the period for β is 2π, while that for α is π.

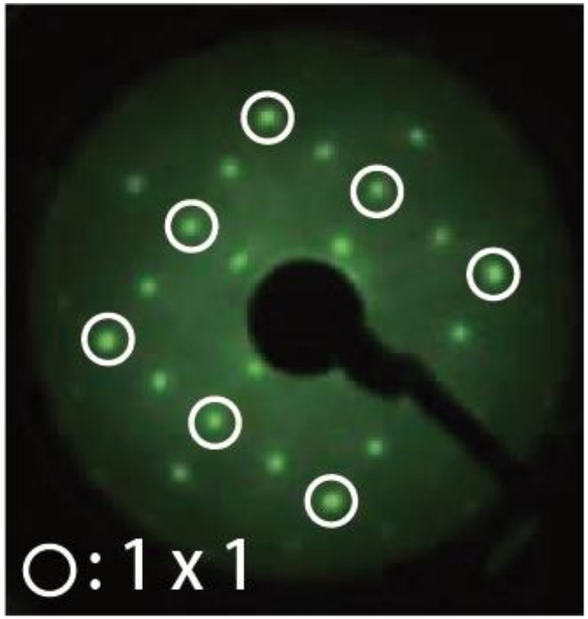


Chiral OAM!

W. Jung, et al, Phys. Rev. B 84, 245435 (2011).

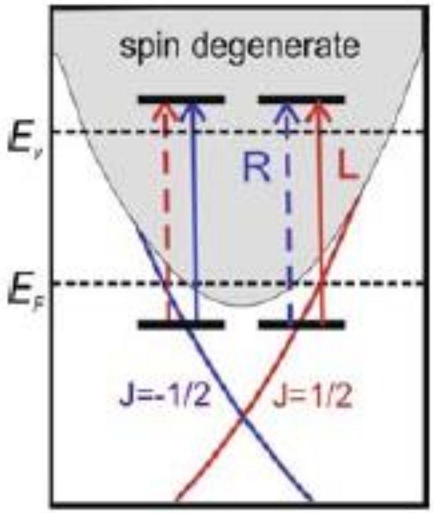
Surface reconstruction?

1x2 reconstruction



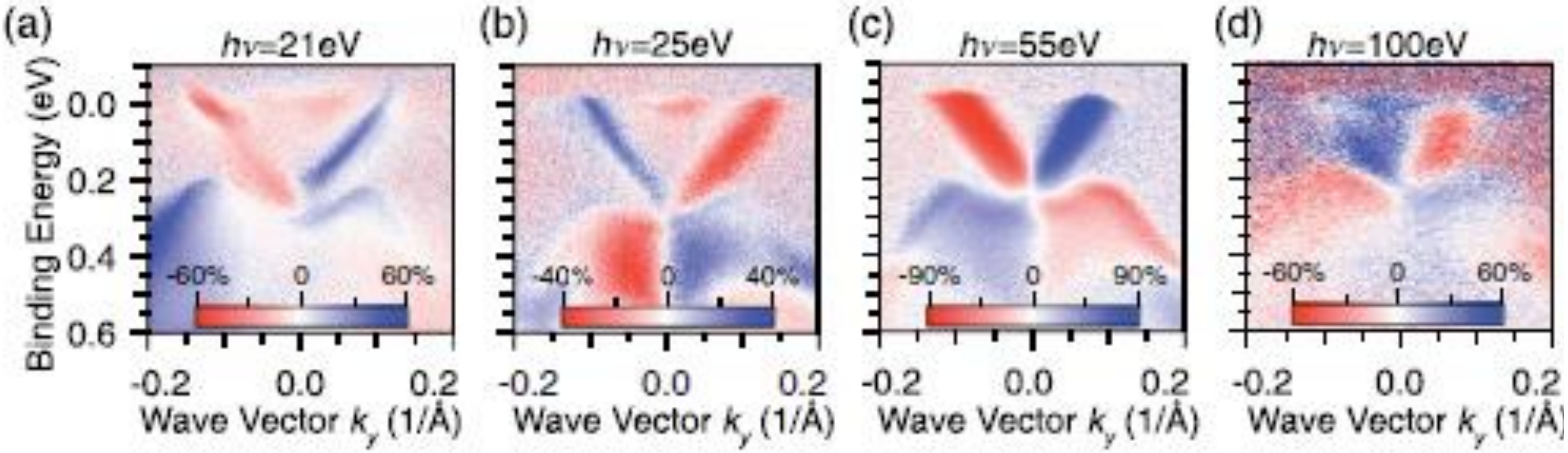
Shin-ichi Kimura et al, Phy. Rev. B 86, 075105 (2012)

Circular Dichroism ARPES



The spin polarization of the initial state and the helicity of light determines the matrix element and the intensity.

Circular Dichroism ARPES



S. R. Scholz, et al, Phy. Rev. Lett. 110, 286101 (2013)