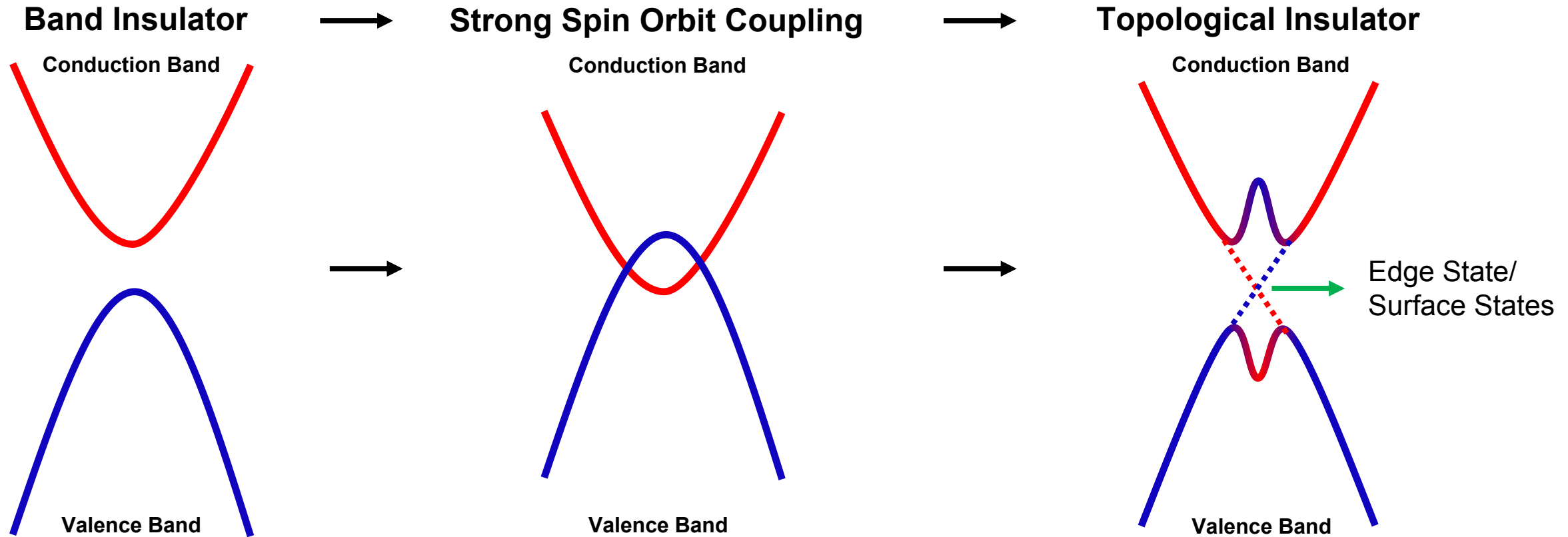


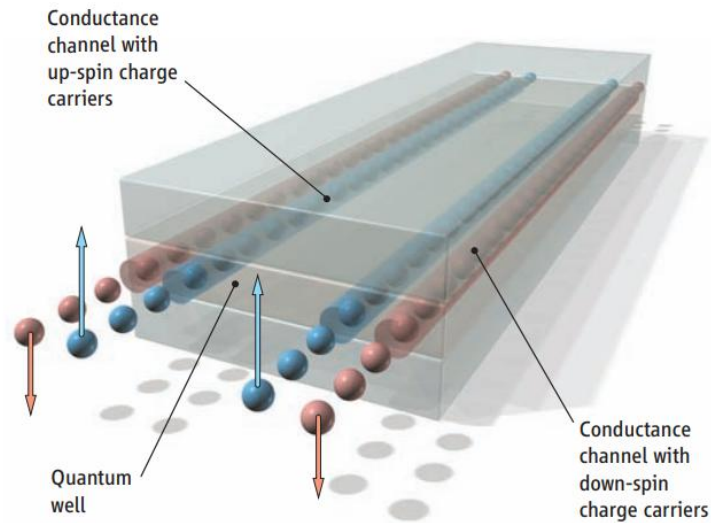
Topological Insulators(TI)



Hasan and Kane, *Rev. Mod. Phys.* **82**, 3045 (2010).
Qi and Zhang, *Rev. Mod. Phys.* **83**, 1057 (2011).

Theoretical Prediction and Realization of TI

2D TI (QSH insulator)



HgTe quantum wells

Bernevig et al., *Science* **314**, 1757 (2006).
König et al., *Science* **318**, 766 (2007).

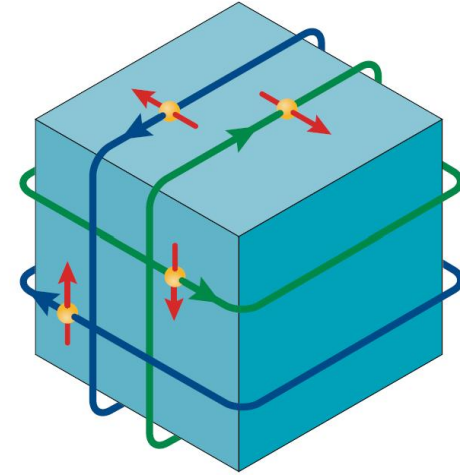
1T' monolayer WTe₂

Fei et al., *Nat. Phys.* **13**, 677 (2017).
Tang et al., *Nat. Phys.* **13**, 683 (2017).
Wu et al., *Science* **359**, 76 (2018).

InAs/GaSb quantum wells

Liu et al., *Phys. Rev. Lett.* **100**, 236601 (2008).
Knez et al., *Phys. Rev. Lett.* **107**, 136603 (2011).

3D TI



Bi_xSb_{1-x} alloys

Fu & Kane, *Phys. Rev. B* **76**, 045302 (2007).
Hsieh et al., *Nature* **452**, 970 (2008).

Bi₂Se₃ family

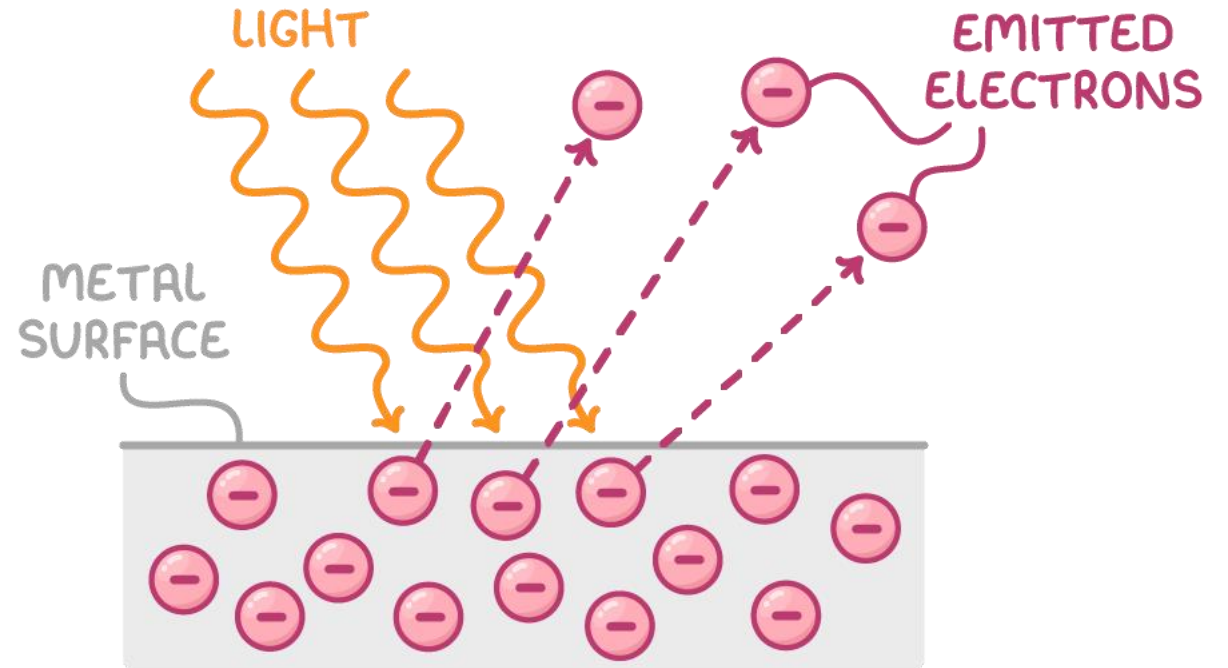
Zhang et al., *Nat. Phys.* **5**, 438 (2009).
Xia et al., *Nat. Phys.* **5**, 398 (2009).
Chen et al., *Science* **325**, 178 (2009).

Photoelectric Effect



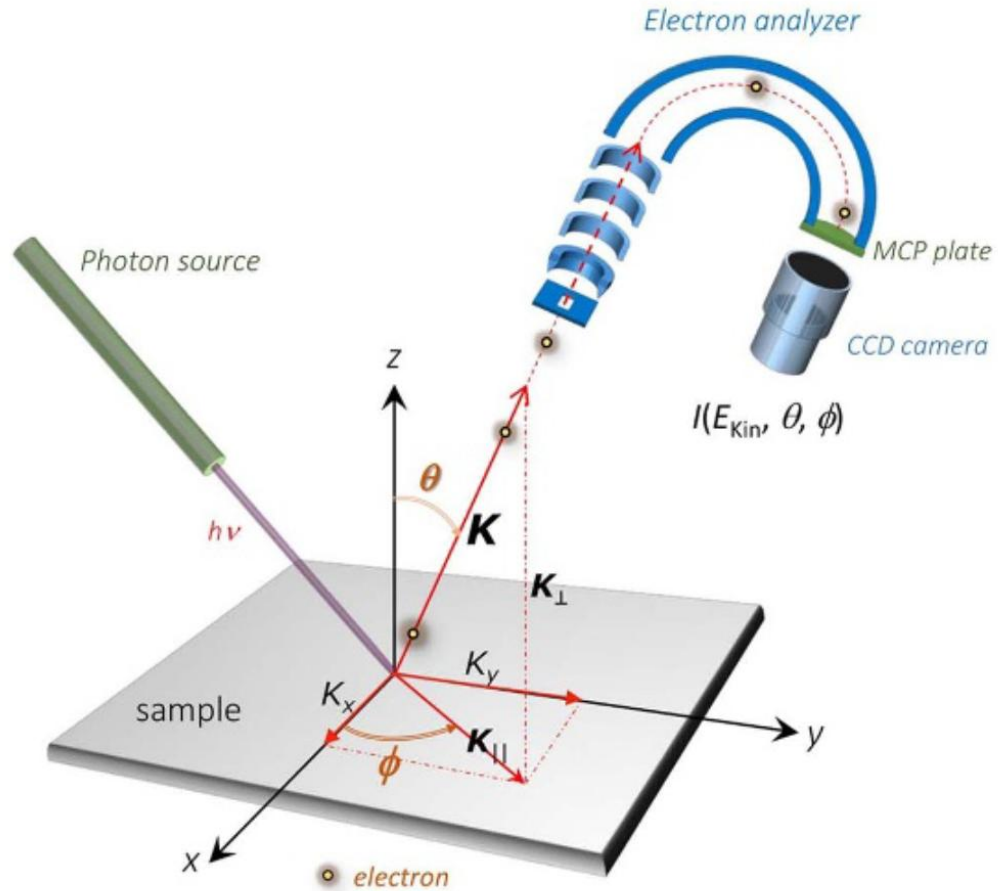
Heinrich Hertz Albert Einstein 

"for his services to Theoretical Physics,
and especially for his discovery of the law
of the photoelectric effect"



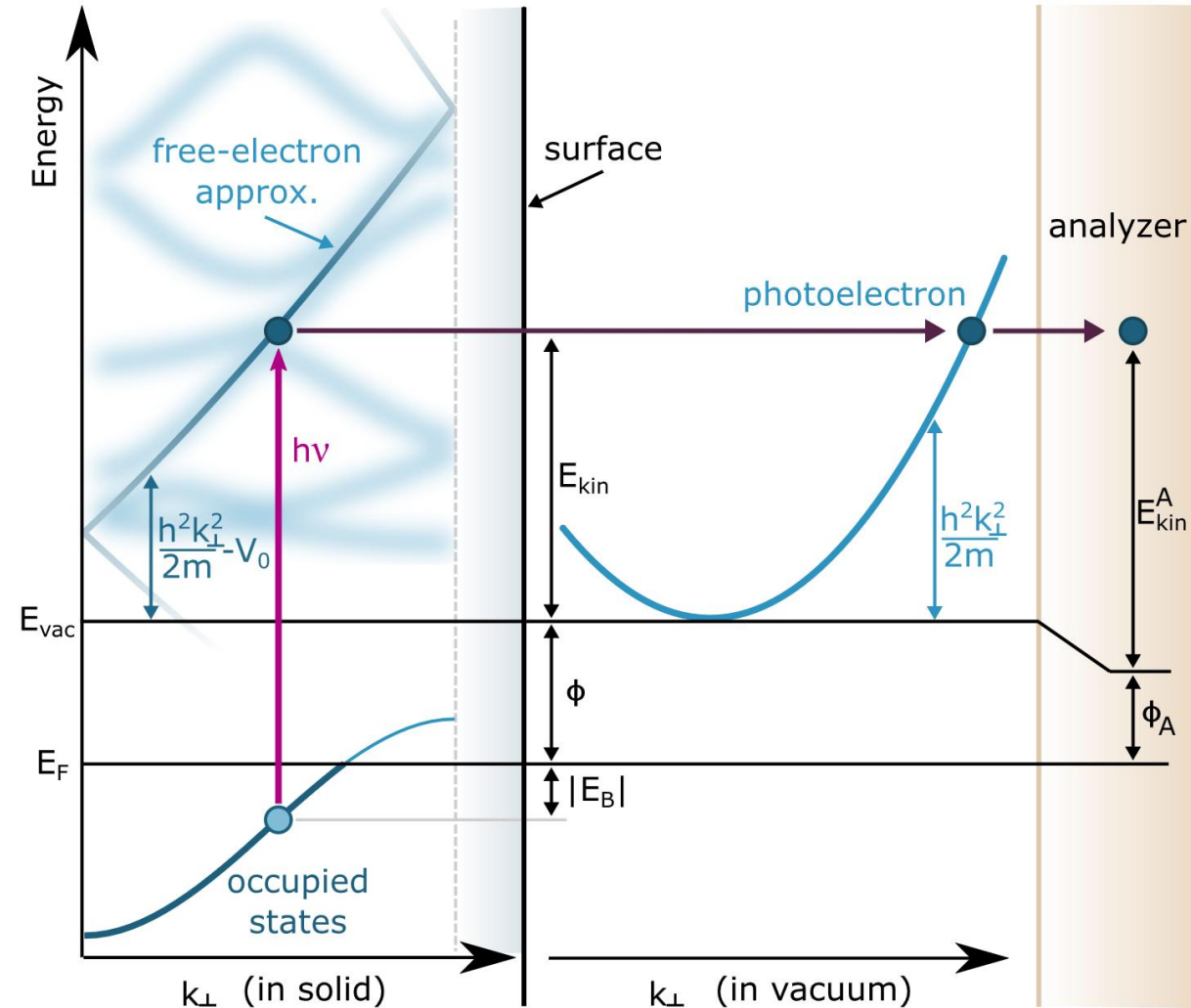
$$E_{kin} = hf - E_b - \Phi$$

Angle-resolved photoemission spectroscopy (ARPES)

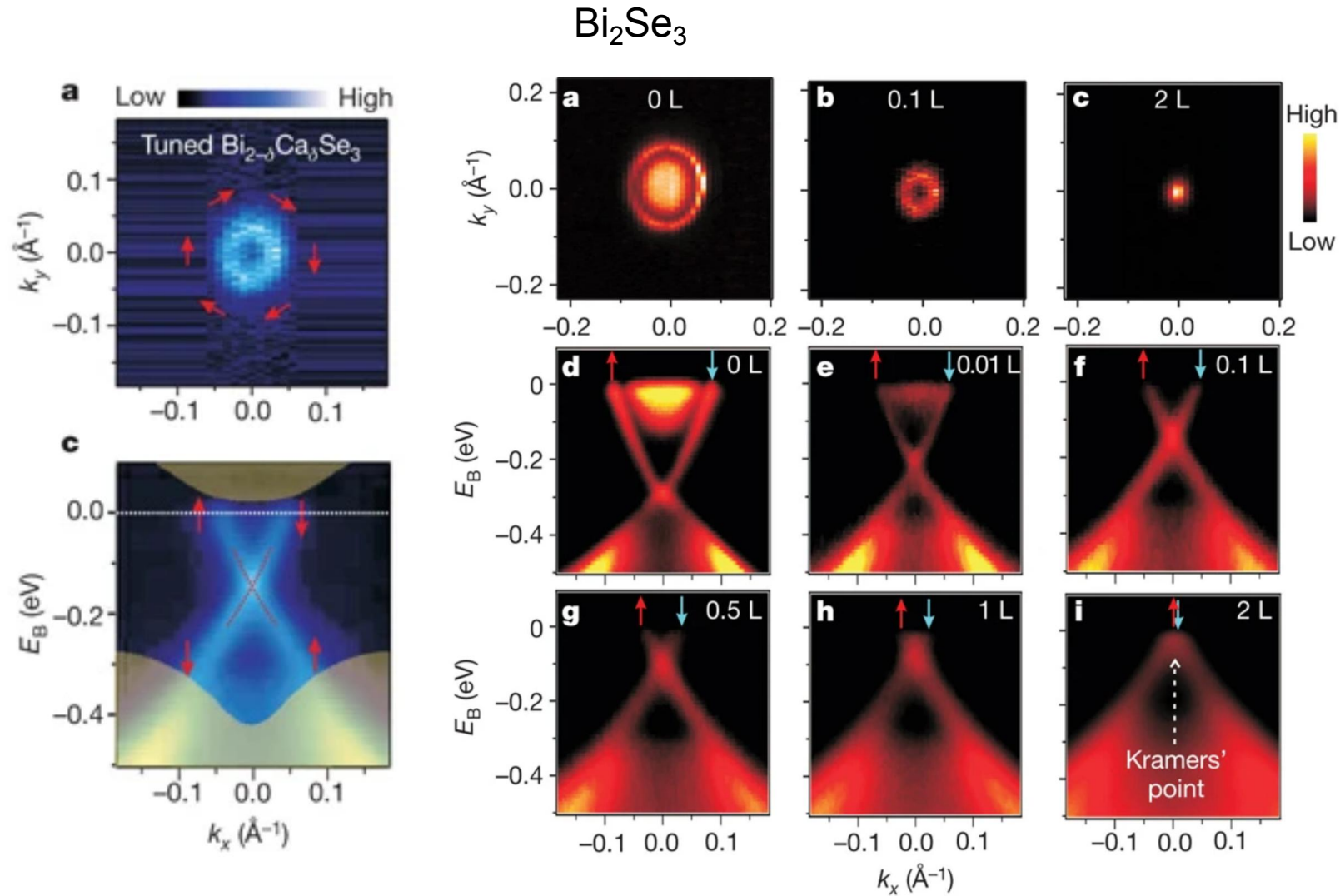


$$E_{kin} = h\nu - \phi - |E_B|$$

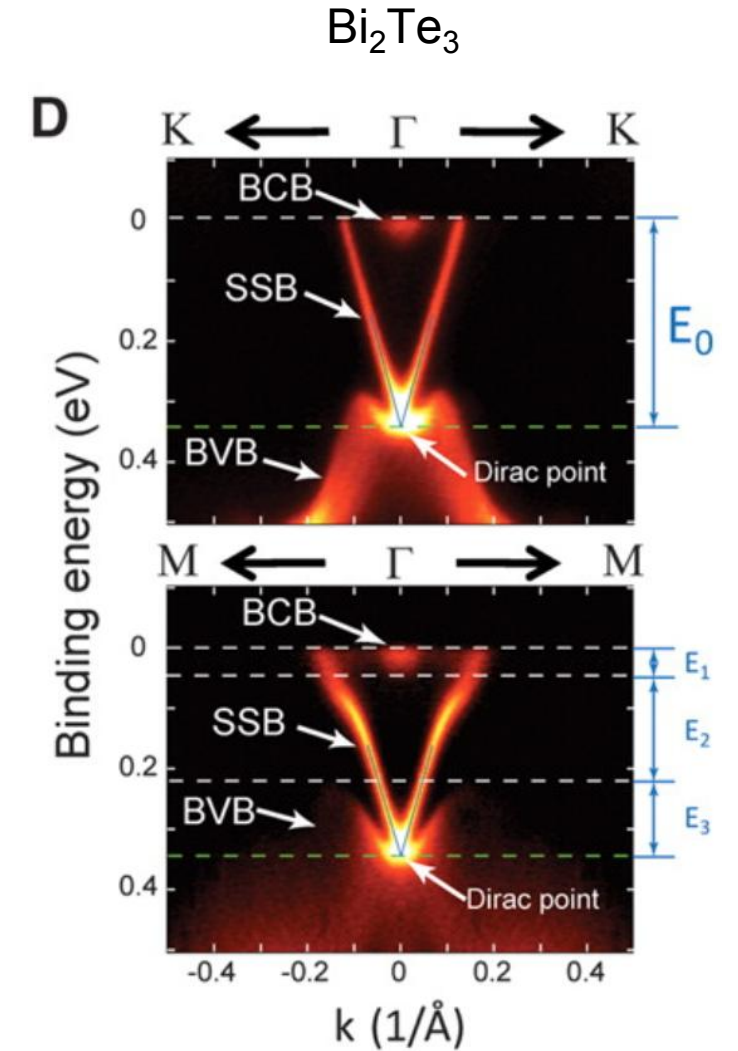
$$\mathbf{p}_\parallel = \hbar \mathbf{k}_\parallel = \sqrt{2m E_{kin}} \cdot \sin \vartheta$$



The Dirac SS in Bi_2Se_3 family



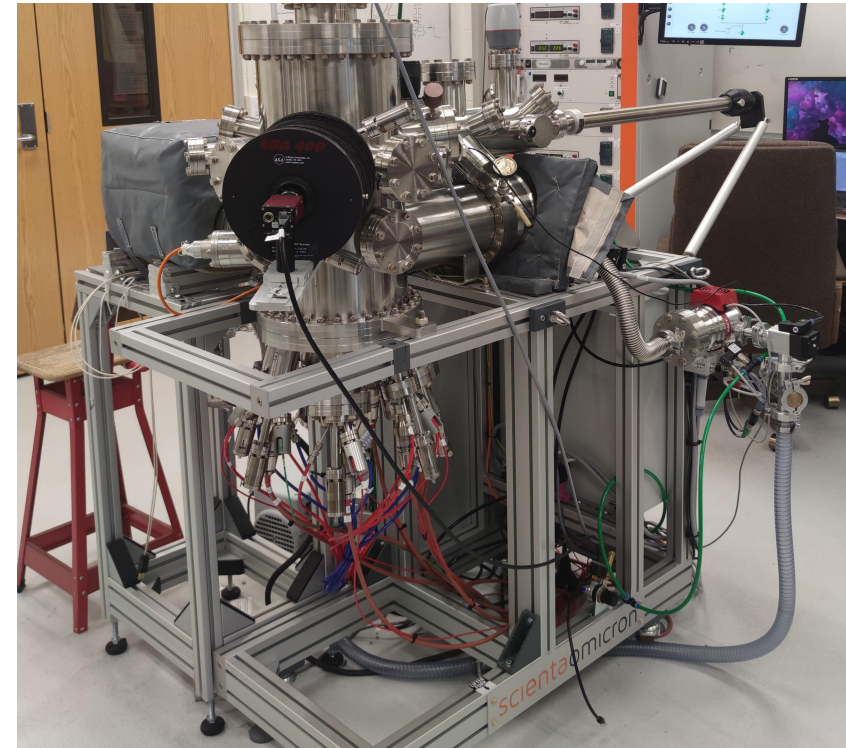
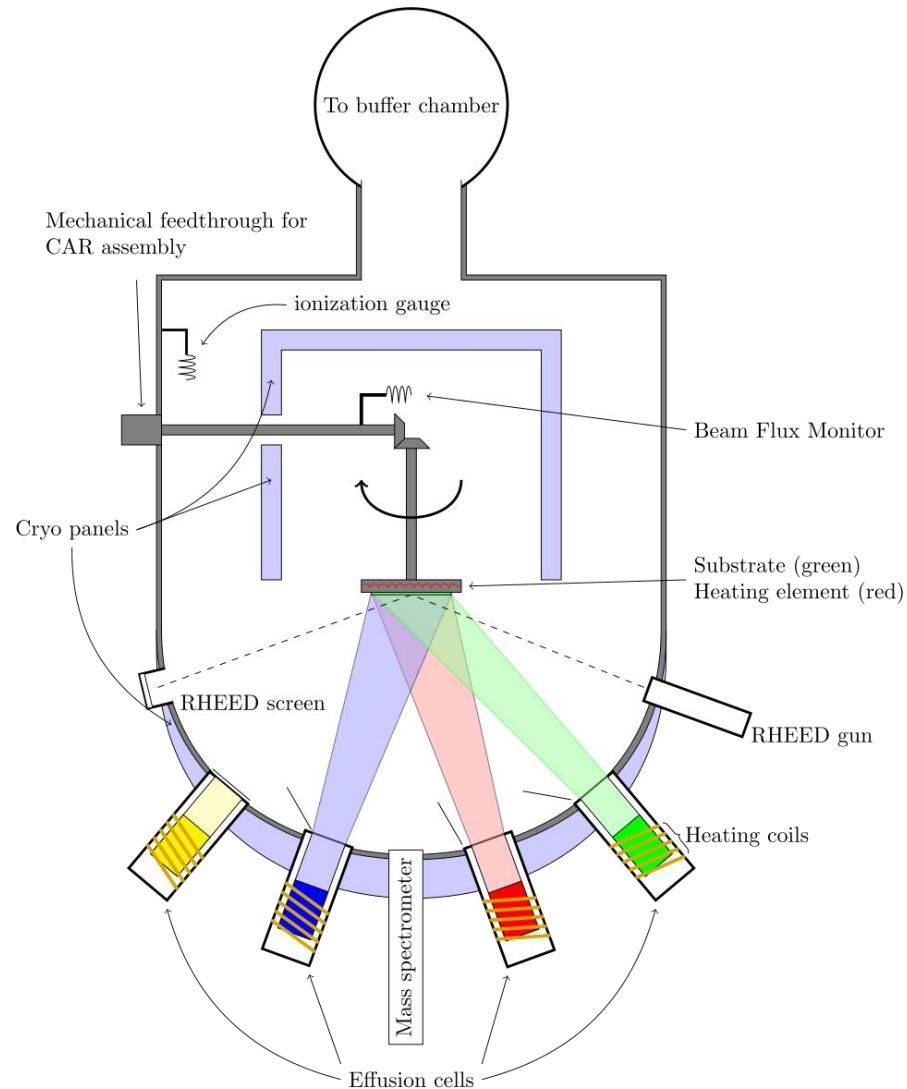
D. Hsieh et al., Nature 460, 1101 (2009)



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

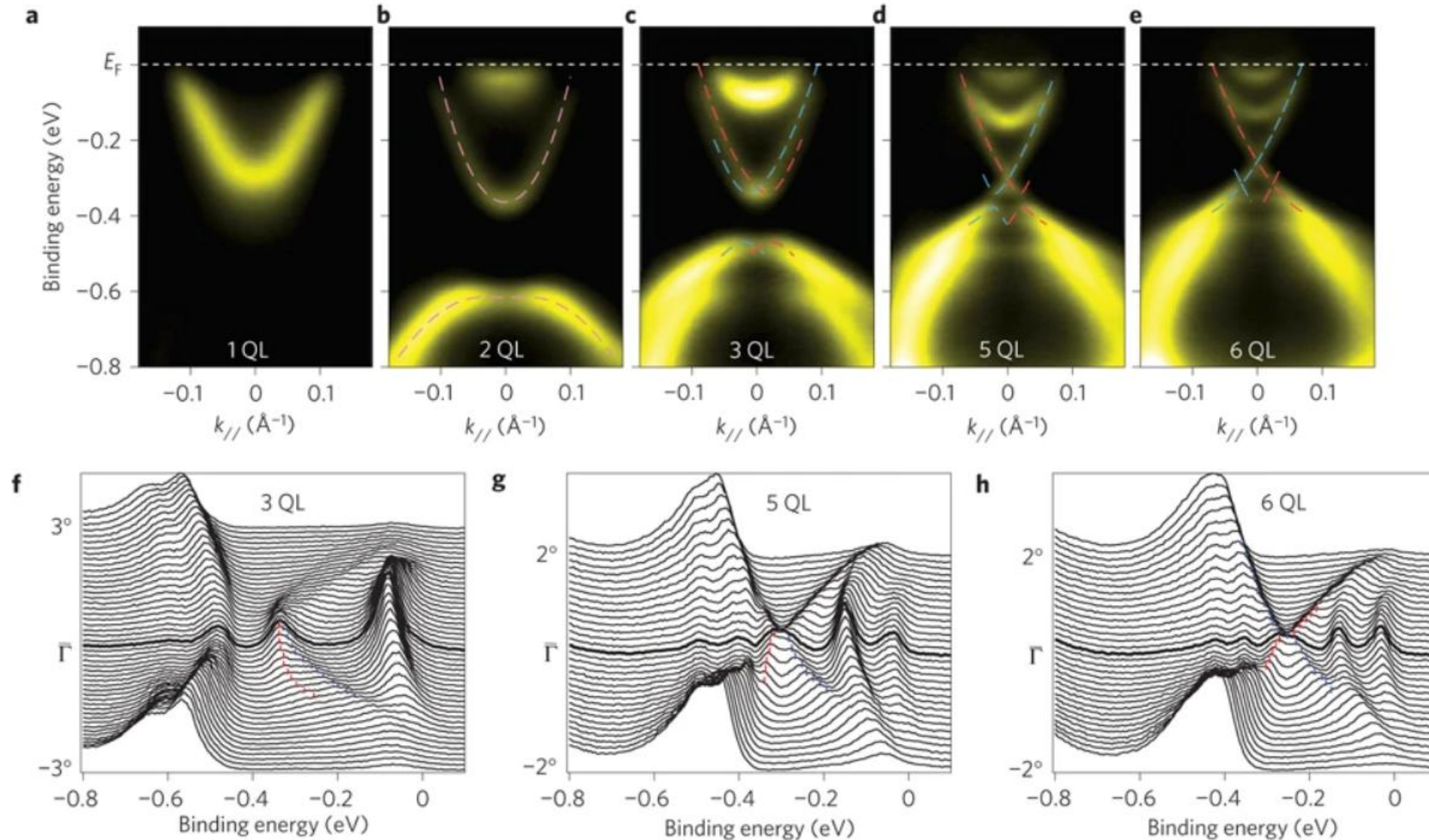
Dirac surface states of 3D TIs are observed in ARPES.

Molecular Beam Epitaxy (MBE)

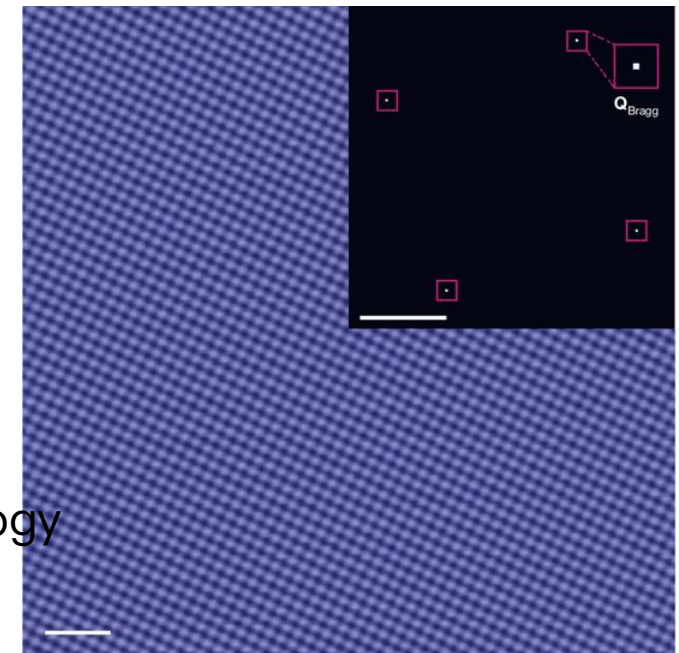
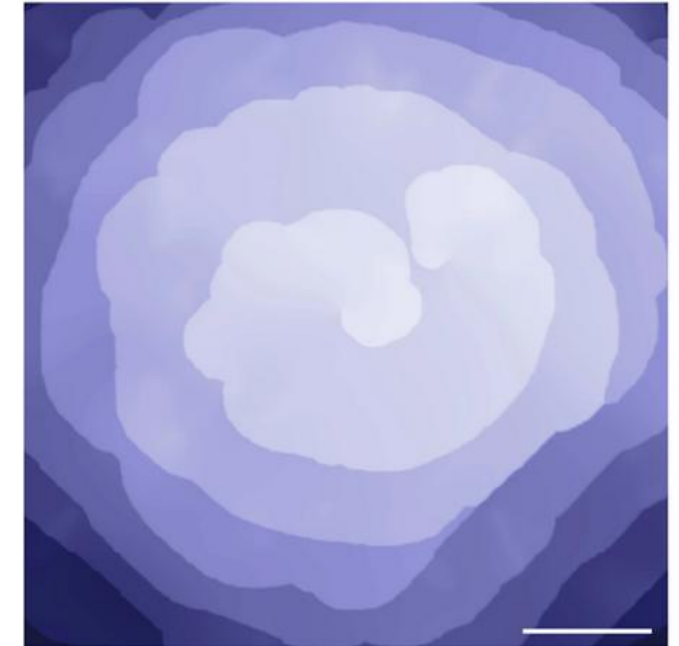
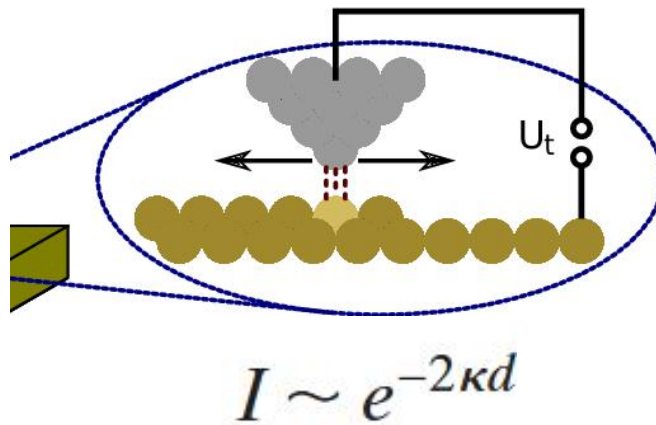
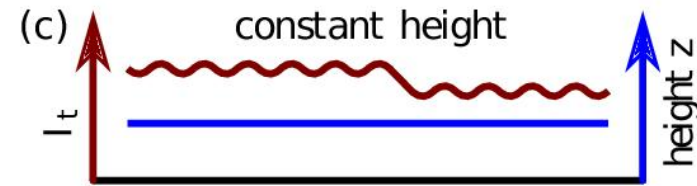
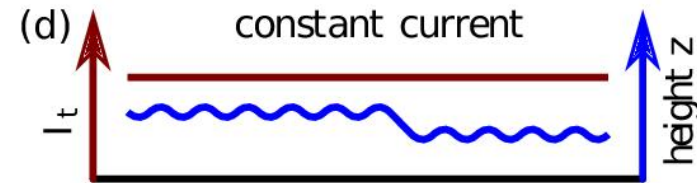
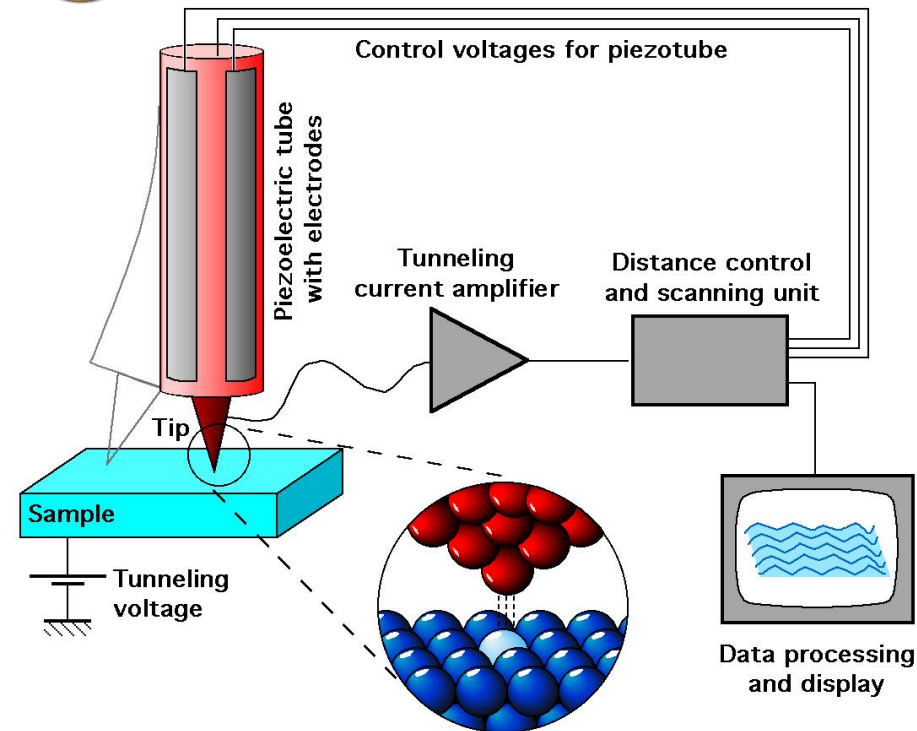


- Slow growth rate (0.2nm/min)
- Ultra-high vacuum (10^{-10} mbar)
- Thickness/interface engineering

Crossover from 2D to 3D of Bi_2Se_3

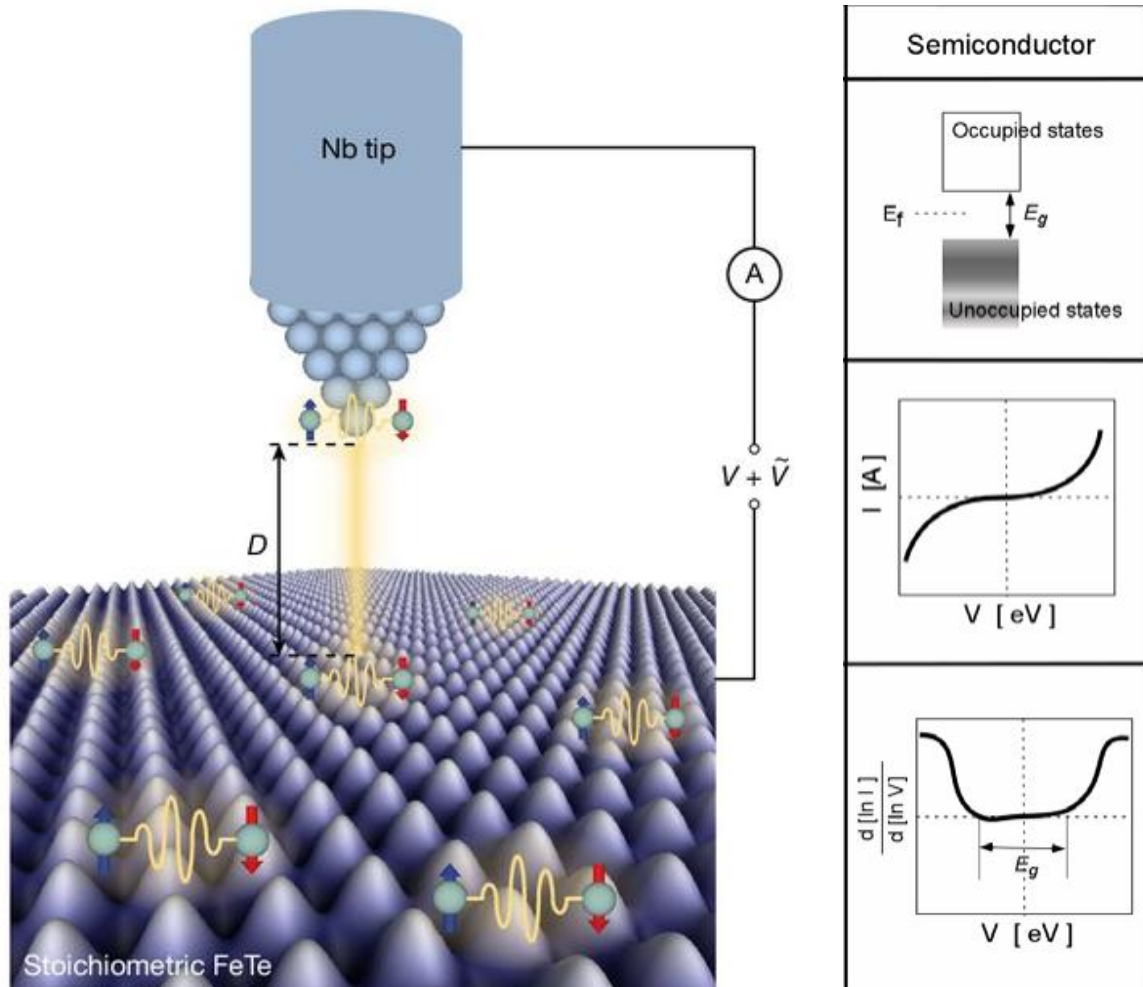


Scanning Tunneling Microscope



- Tunneling current depends on tip-sample distance.
- Fixing current → fixing tip-sample distance → Tip reads surface morphology

Scanning Tunneling Spectroscopy (STS)

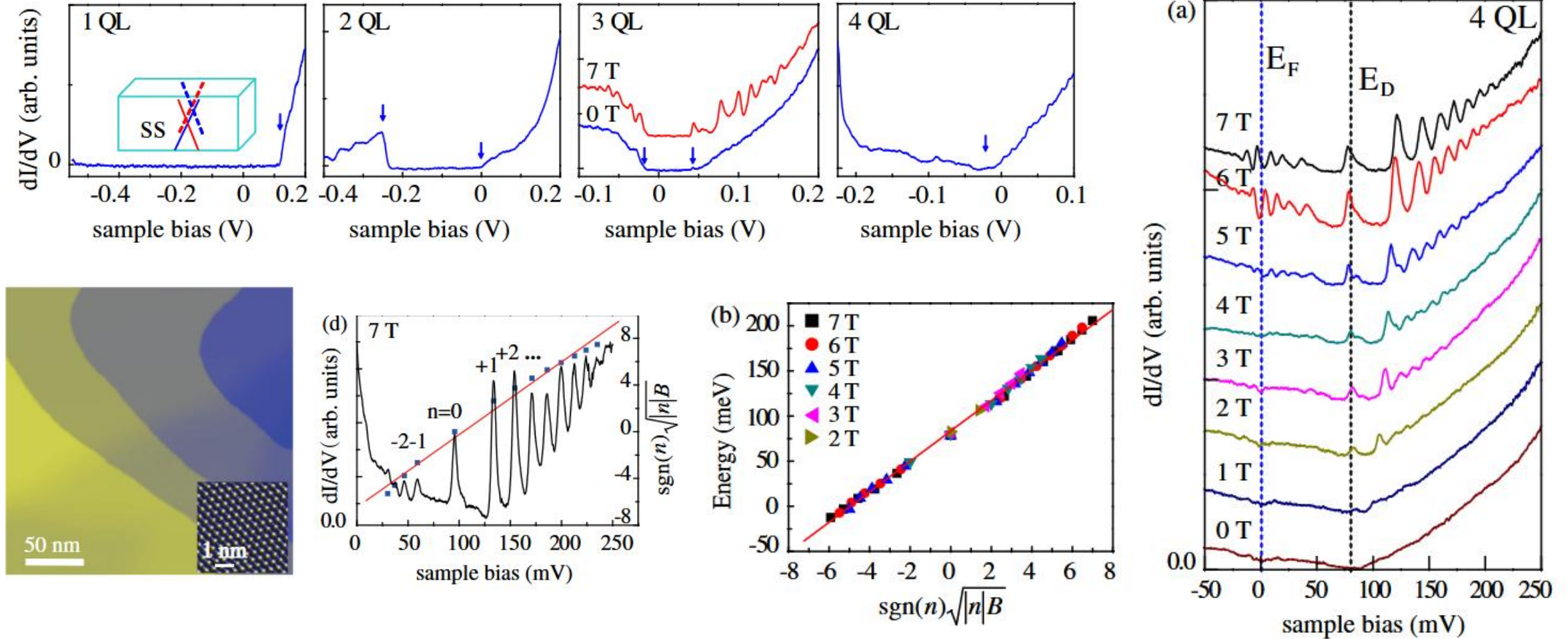


$$I_T \propto \int_0^{eV_B} \rho_T(eV - E) \rho_S(\vec{r}_T, E) T(z, eV, E) dE$$

$$\left. \frac{dI}{dV} \right|_{V_B} \propto \rho_S(eV) T(z, eV) + \int_0^{eV_B} \rho_S(E) \frac{\partial T(eV, E)}{\partial V} dE$$

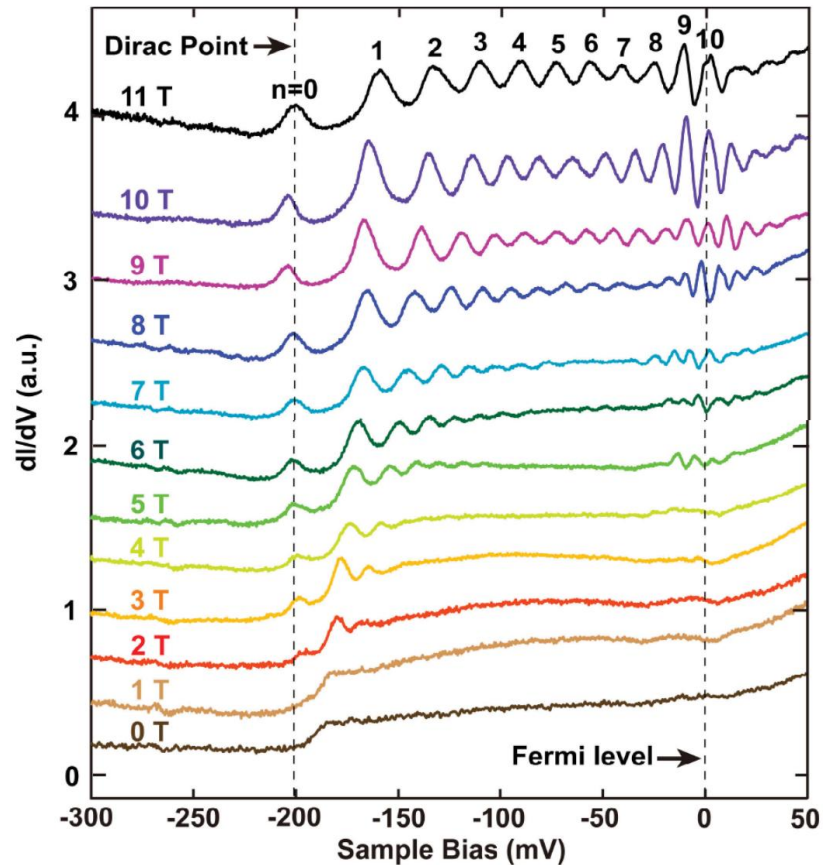
- I is continuously recorded with changing voltage bias.
- Differential conductance (dI/dV) resolves local density of states

Landau quantization in Sb_2Te_3

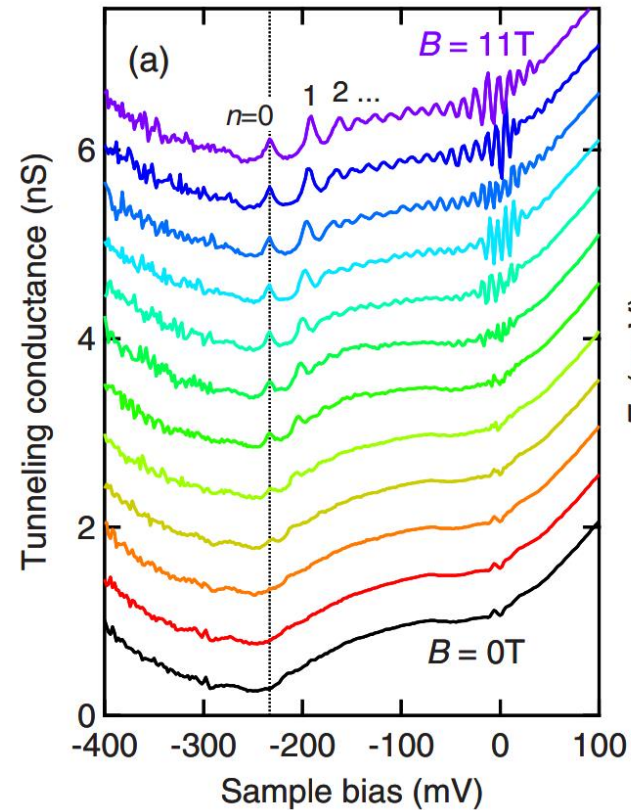


Landau levels are revealed in the STM/S measurements under high B field.

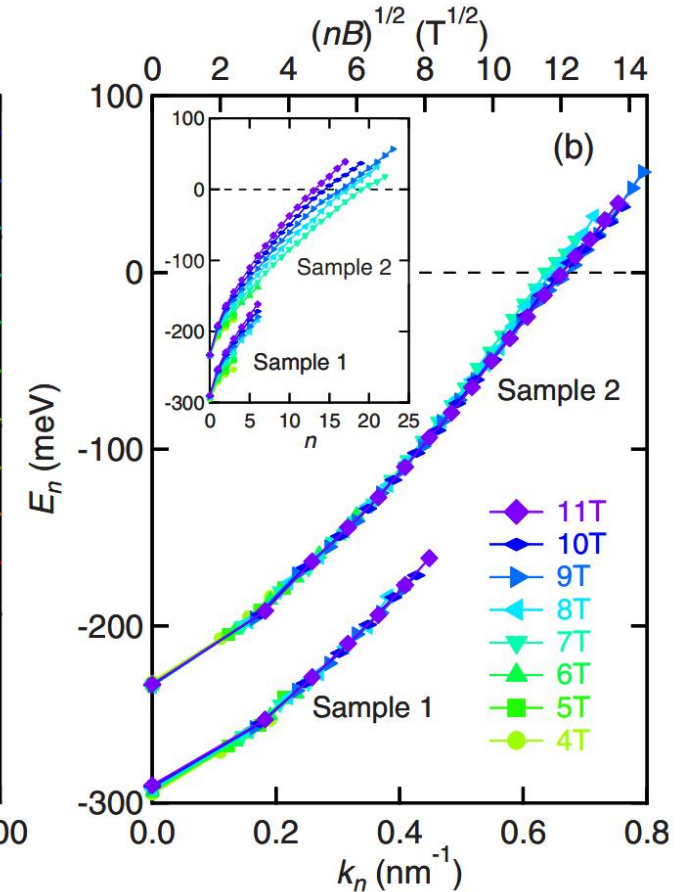
Landau quantization in Bi_2Se_3



Xue group
 Bi_2Se_3 film
PRL 105, 076801 (2010)



Sasagawa group
 Bi_2Se_3 crystal
PRB 82, 081305R 2010



Quantized Anomalous Hall Effect in Magnetic Topological Insulators

RUI YU, WEI ZHANG, HAI-JUN ZHANG, SHOU-CHENG ZHANG, XI DAI, AND ZHONG FANG

fewer

[Authors Info & Affiliations](#)

SCIENCE • 3 Jun 2010 • Vol 329, Issue 5987 • pp. 61-64 • DOI: 10.1126/science.1187485

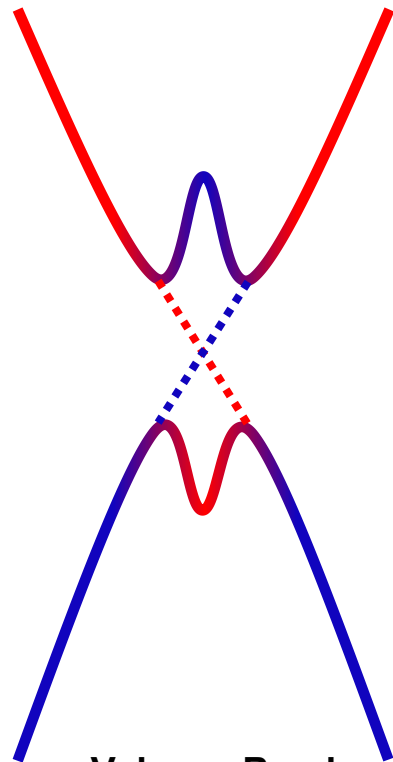
Conditions of QAH effect

(i) Inverted band structure

(ii) Ferromagnetic insulator

Topological Insulator

Conduction Band



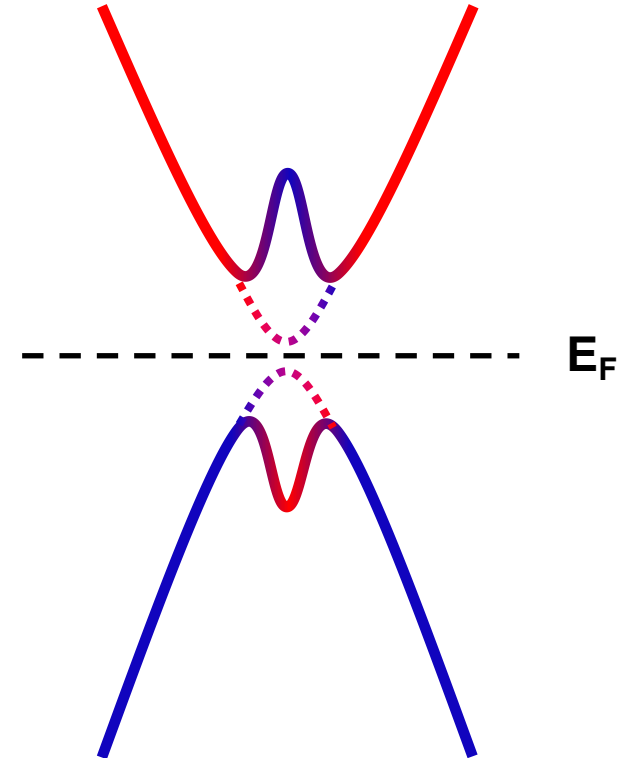
Valence Band

Inverted band structure

+ Ferromagnetic order



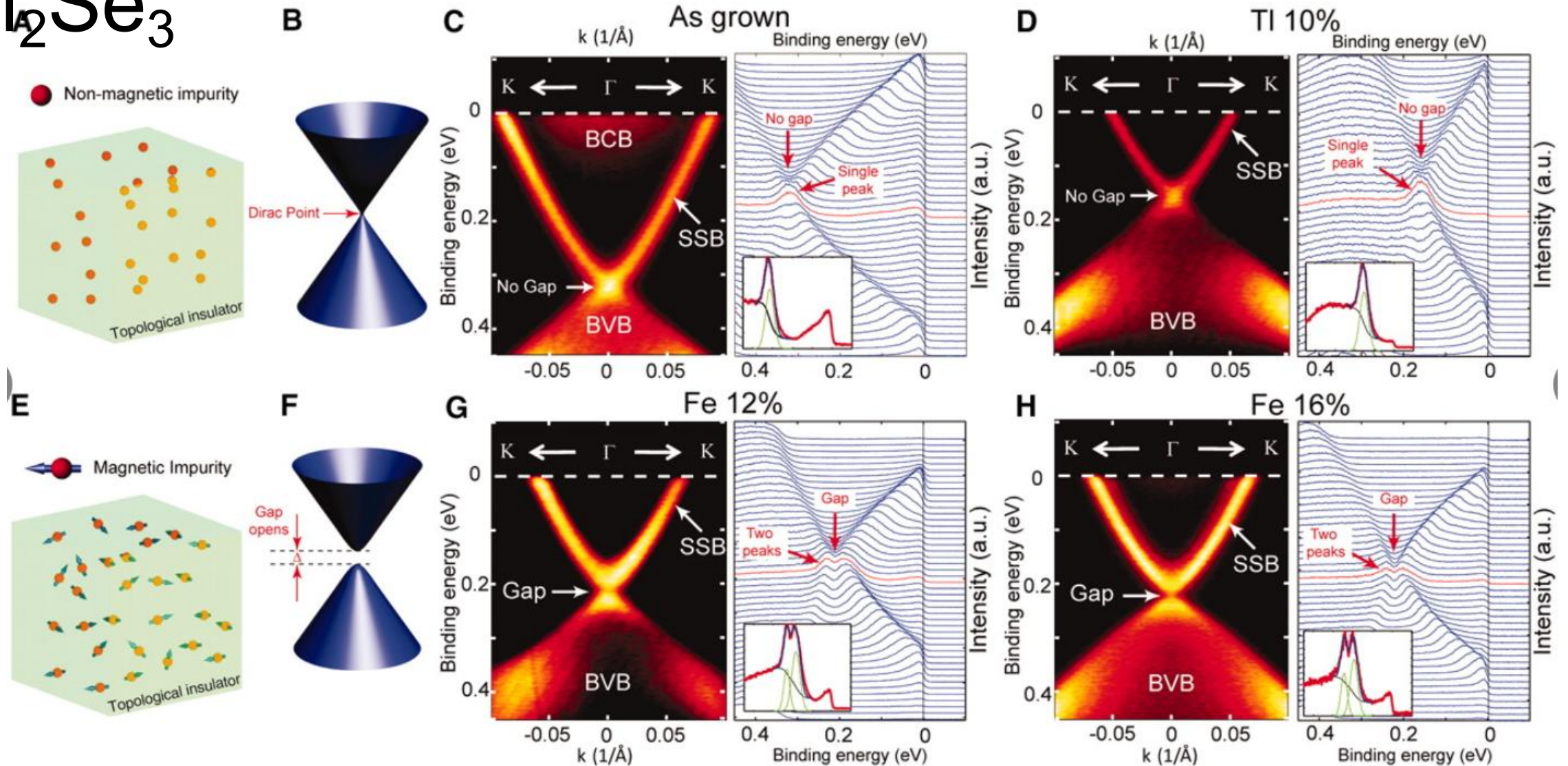
Conduction Band



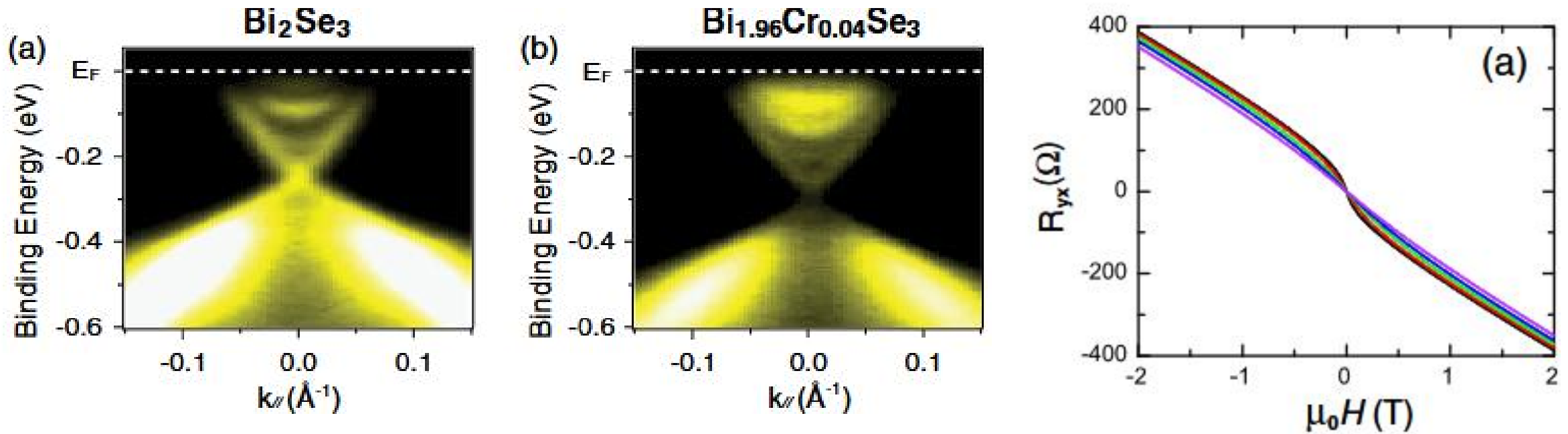
E_F

Valence Band

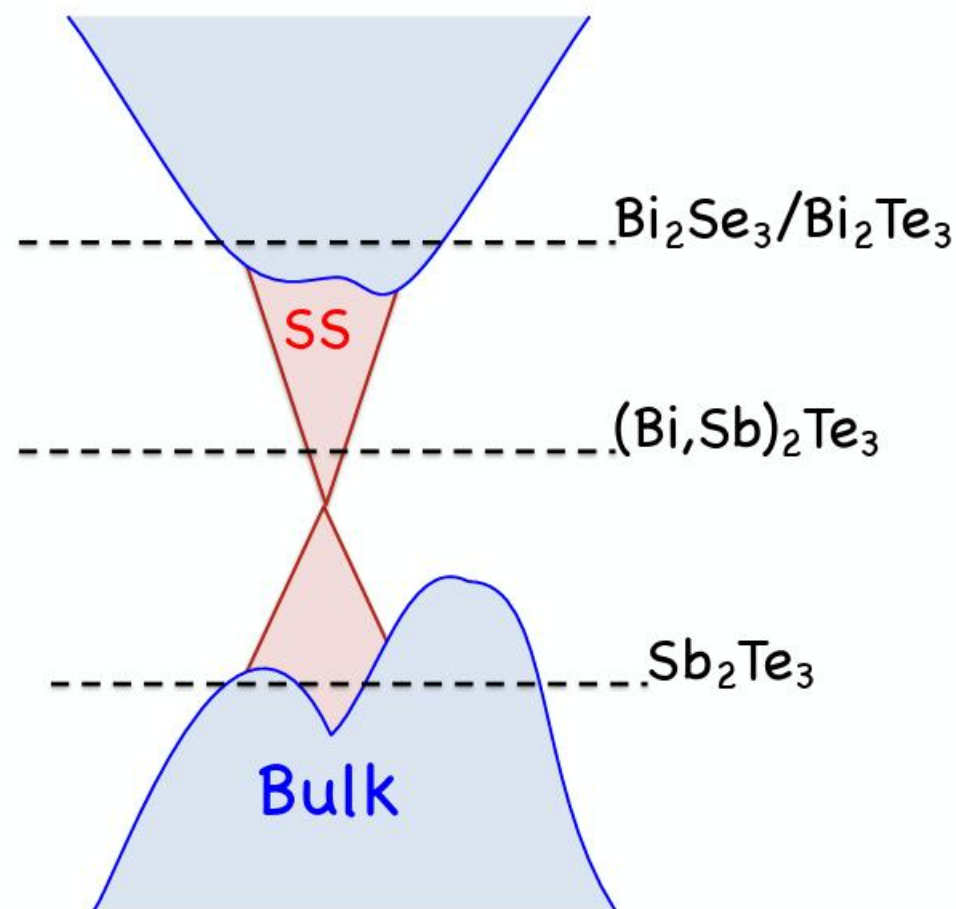
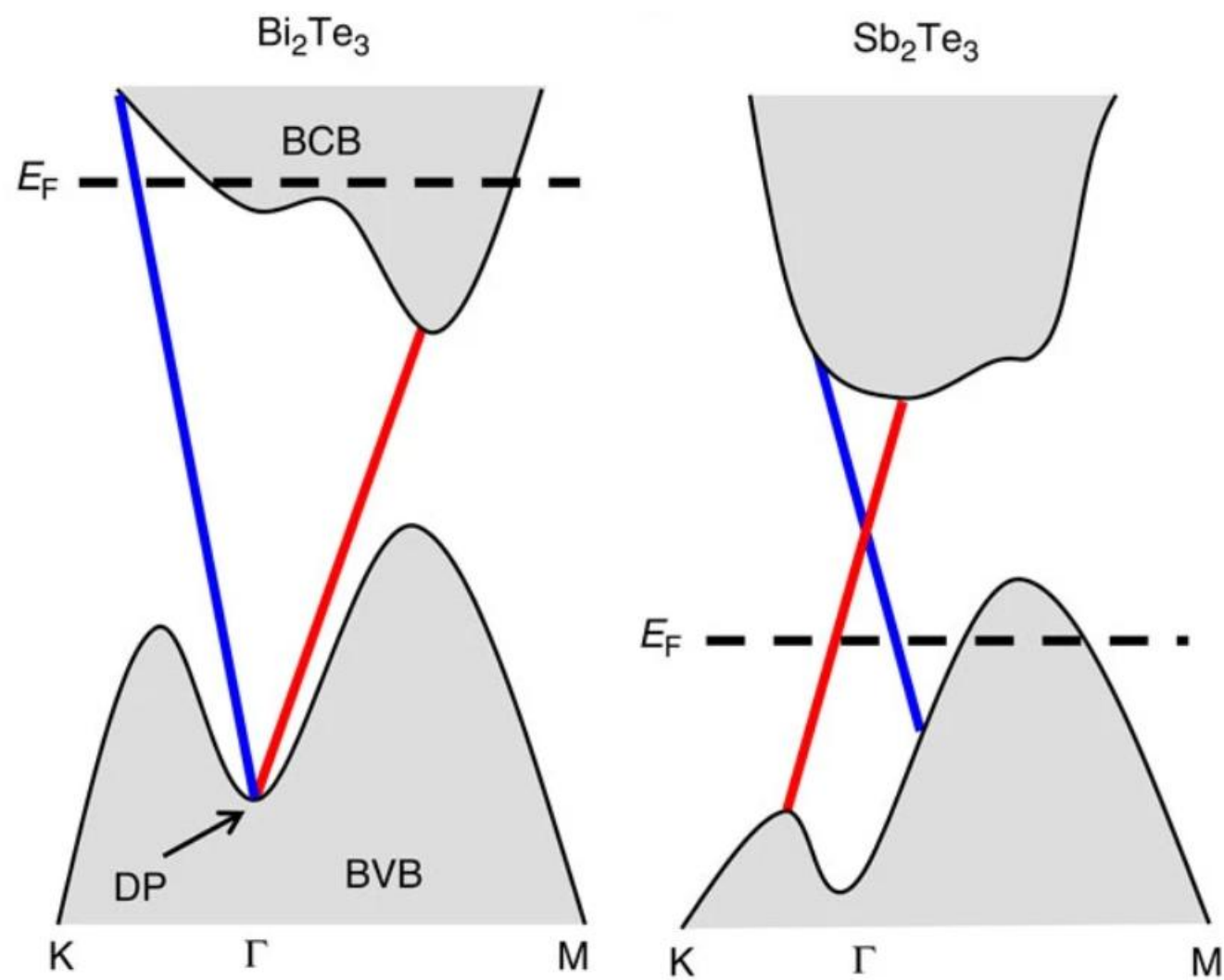
Magnetic exchange gap in Fe-doped Bi_2Se_3



Magnetic exchange gap in Cr-doped Bi_2Se_3



- Magnetic exchange gap observed in both Fe and Cr-doped Bi_2Se_3 .
- No long range FM order is observed.



Band engineering of $(\text{Bi}_{1-x}\text{Sb}_x)_2\text{Te}_3$

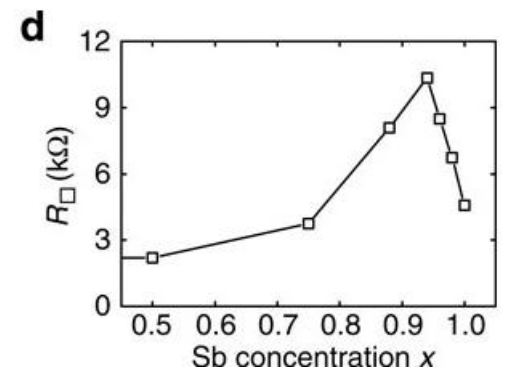
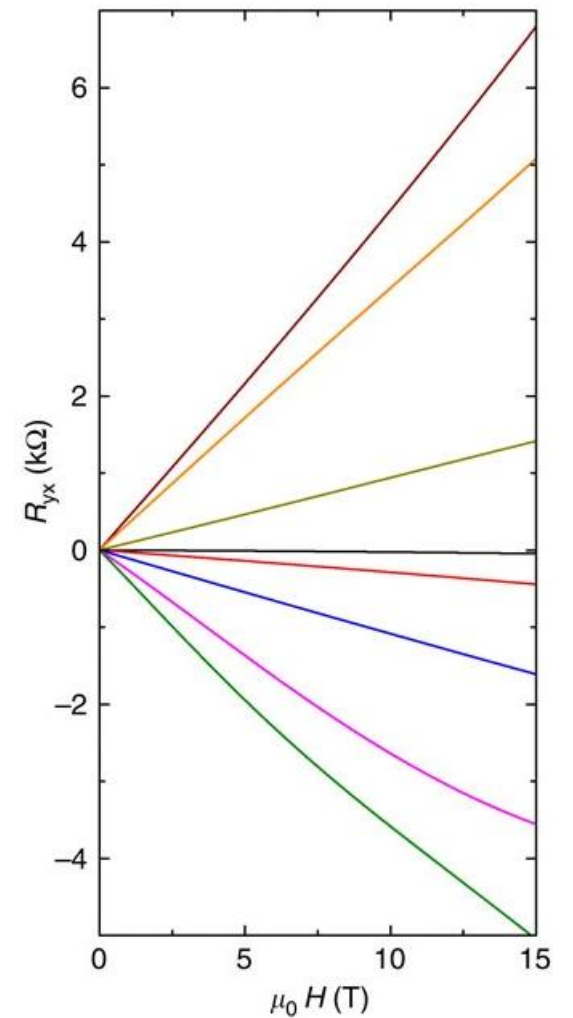
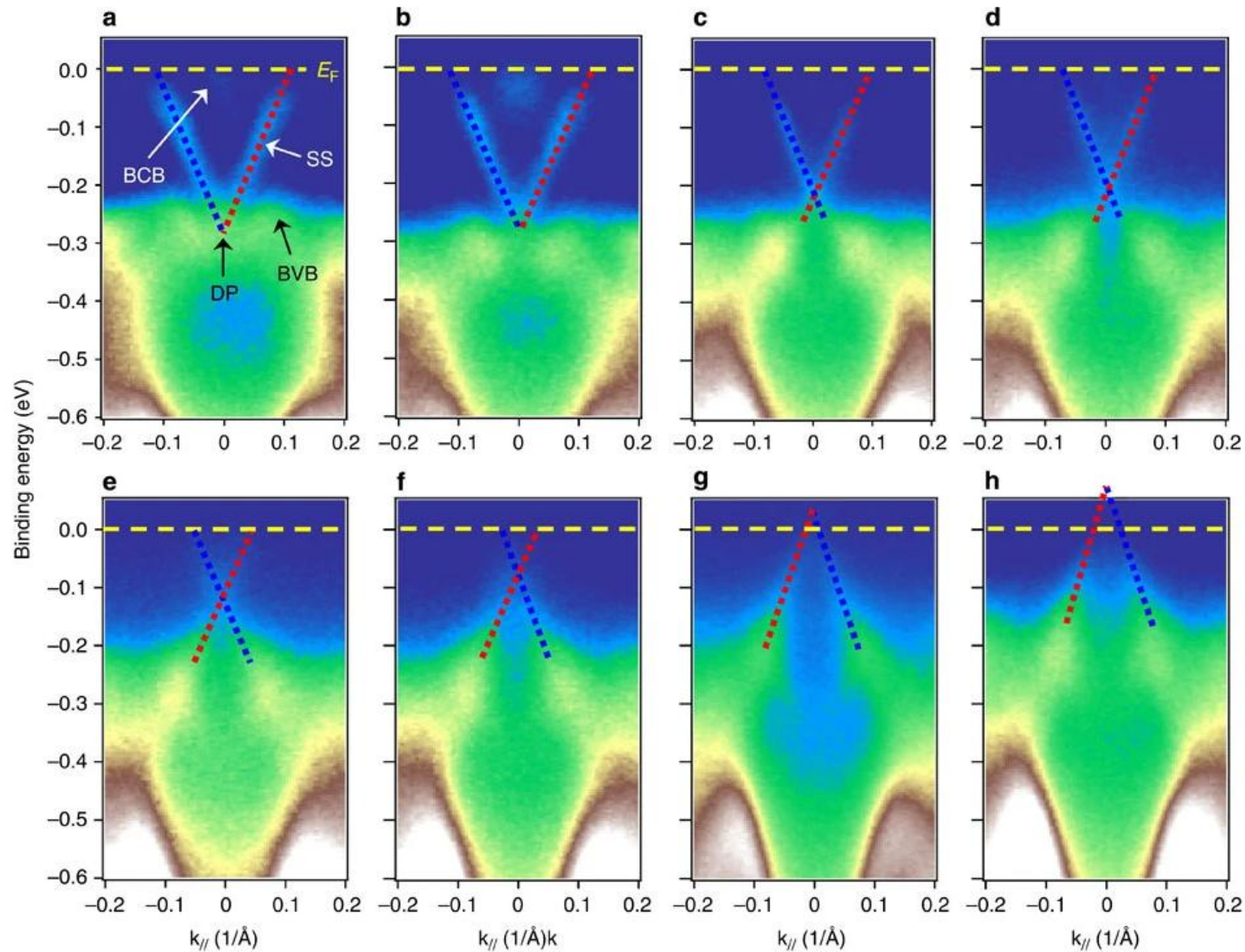
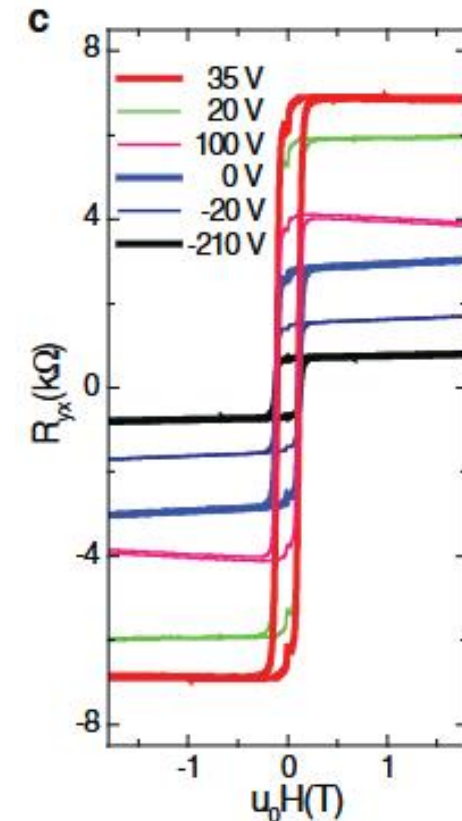
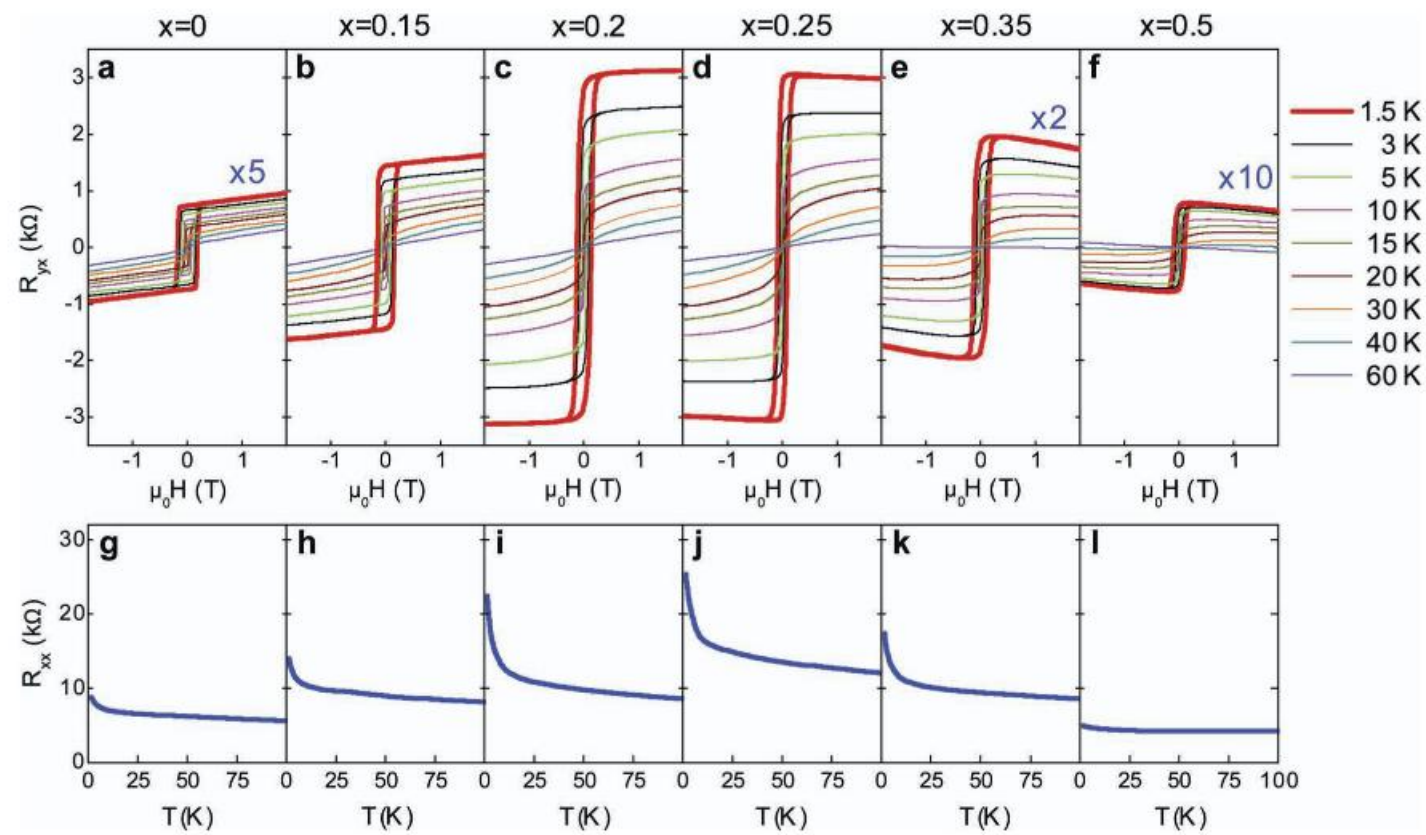


Figure 1 shows the measured band structures of $(\text{Bi}_{1-x}\text{Sb}_x)_2\text{Te}_3$ films with $x=0, 0.25, 0.62, 0.75, 0.88, 0.94, 0.96$ and 1.0 , respectively. The Dirac

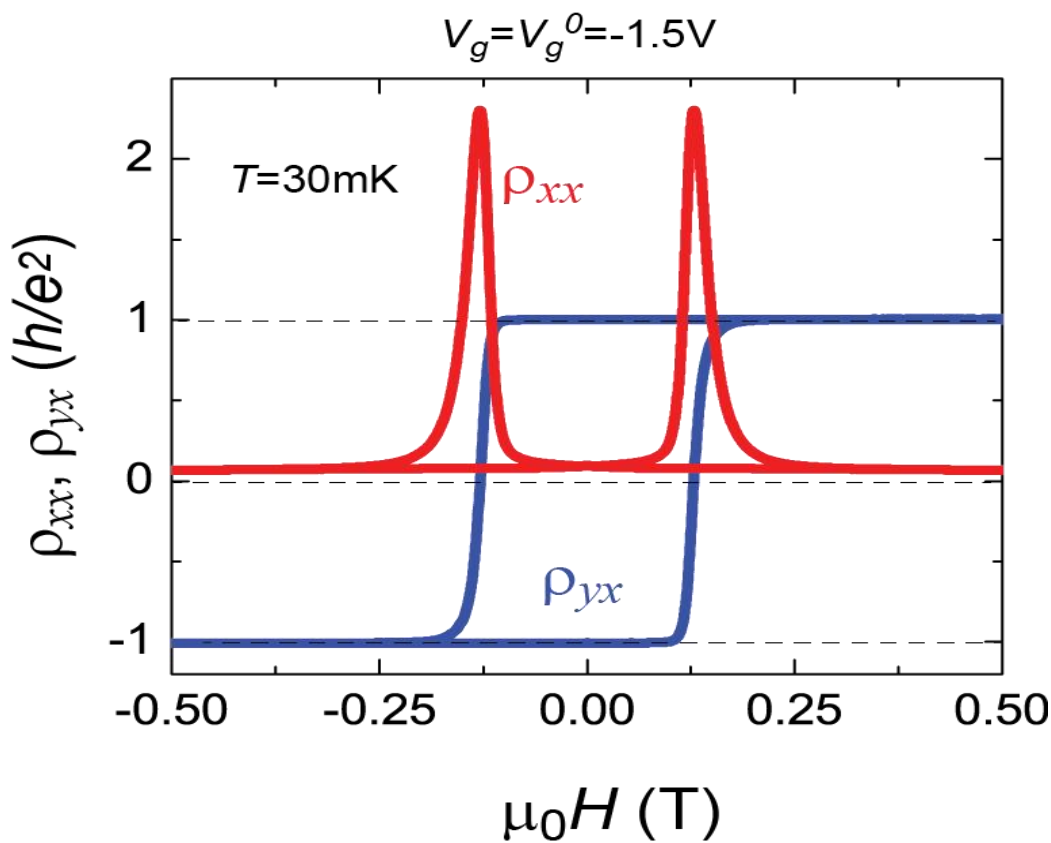
Long-range FM order and Giant AHE in Cr-doped $(\text{Bi}_{1-x}\text{Sb}_x)_2\text{Te}_3$



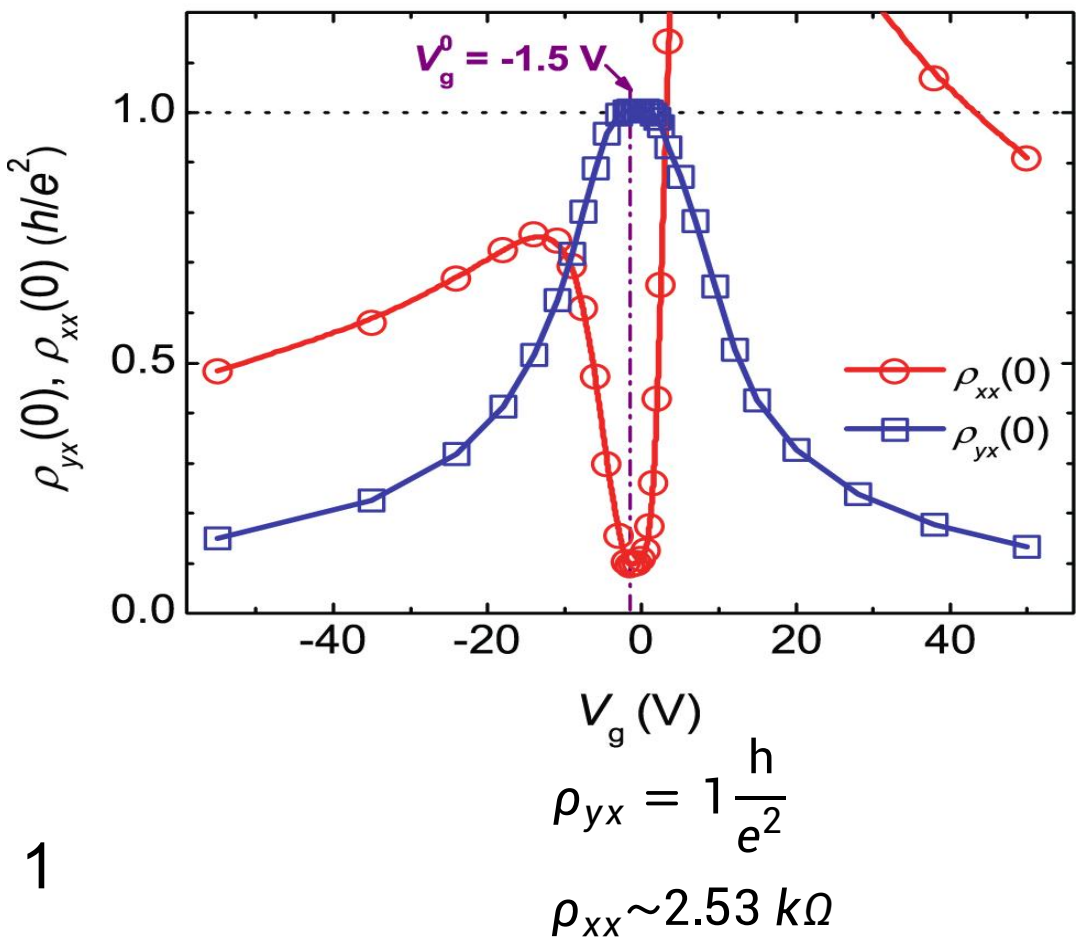
Long range FM order is achieved in Cr-doped $(\text{Bi}_{1-x}\text{Sb}_x)_2\text{Te}_3$.

QAH effect in Cr-doped TI films

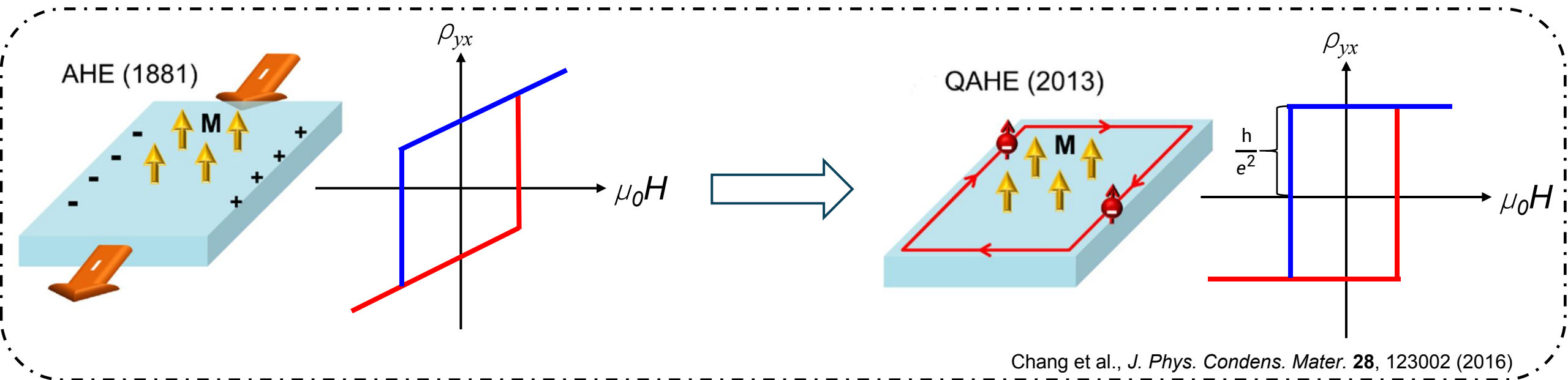
5QL Cr_{0.15} (Bi_{0.1}Sb_{0.9})_{1.85}Te₃ film



QAH effect with Chern number $C = 1$



From Anomalous Hall effect (AHE) to QAH effect



Intrinsic AHE: induced by energy band

$$\sigma_{xy} = \frac{e^2}{h} \sum_{\text{occupied}} \frac{1}{2\pi} \oint_{BZ} \Omega dk = \frac{e^2}{h} C$$

$$\oint_{BZ} \Omega dk = 2\pi C$$

$$\sigma_{xy} = \frac{e^2}{h} C$$

$$C \neq 0 \Rightarrow \text{QAHE}$$

