School of Physics and Astronomy

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Faculty of Engineering and Physical Sciences

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A Dirac semimetal phase in topological insulator Sb_2Te_3

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EPSRC Engineering and Physical Sciences Research Council

NAME Nanoscale Advanced Materials Engineering

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Research Interests: Topological Materials Physics

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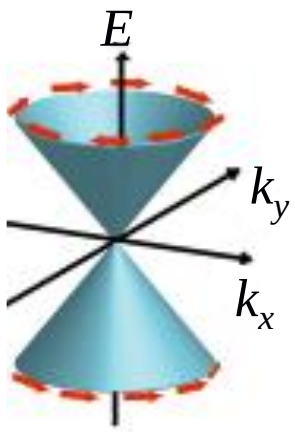
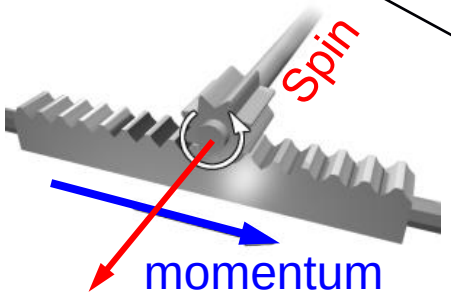
Metallic (gapless) edge/surface

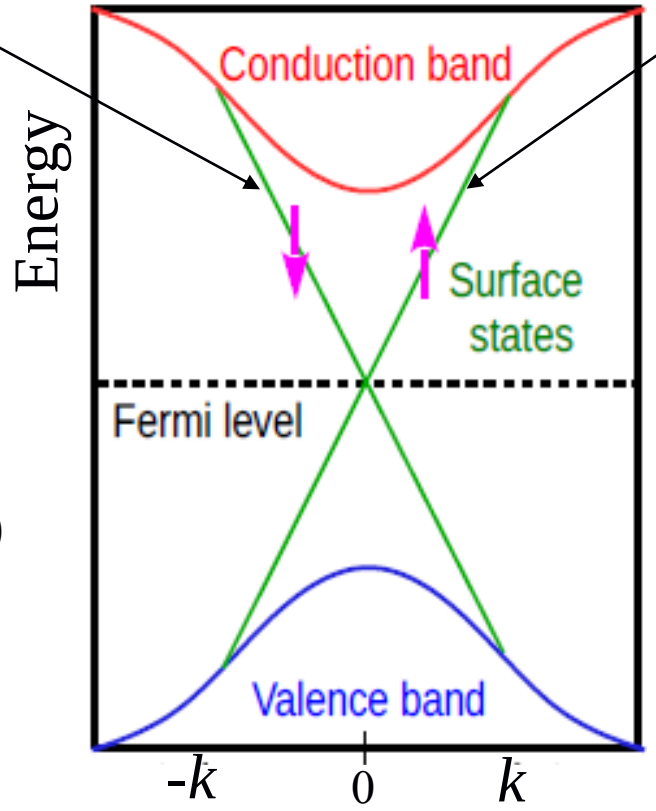
Topological insulators (TI)





Spin-momentum locking

Electronic band structure



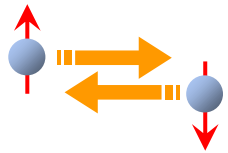
Fast response

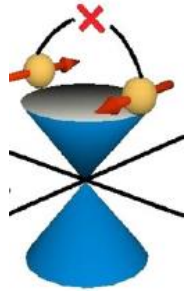
Massless Dirac fermions

(liner energy-momentum dispersion)

Energy saving

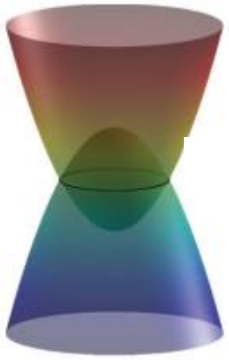
Pure Spin Current





Back scattering suppression

topological protection



Spin orbit interaction (SOI)

⇩

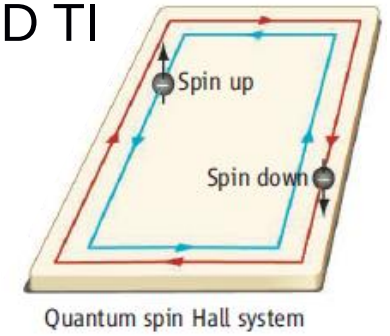
Band inversion

Kramers degeneracy

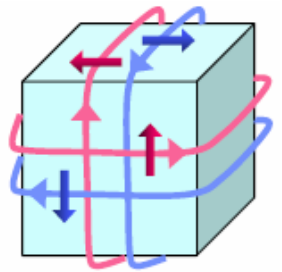
Presence of symmetries

e.g., Time/Spatial Reversal Symmetry

2D TI



3D TI



Nagaosa, Science (2007)

Research achievements

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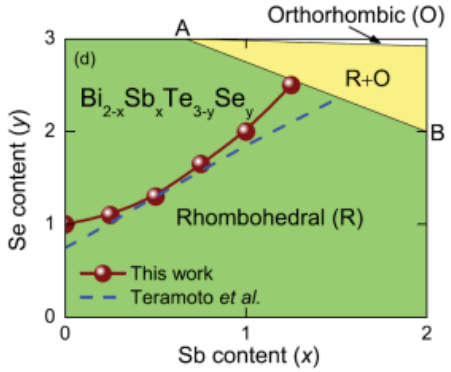
Bulk TI

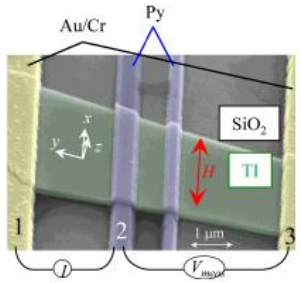
Surface-dominant transport



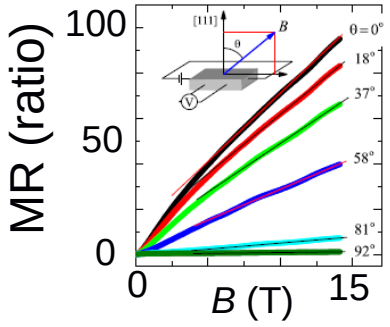
PRB **82** (2010) 241306(R)
PRL **107** (2011) 016801
PRB **84** (2011) 075316
PRB **84** (2011) 165311
PRB **85** (2012) 155301
PRB **86** (2012) 075306

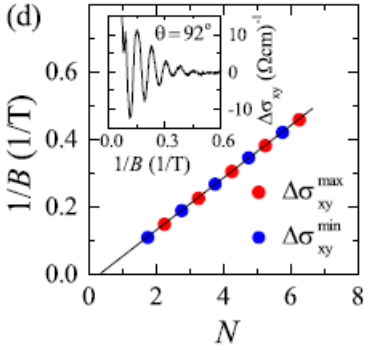
Spin-polarized current flow

Nano Lett. **14** (2014) 6226



Bulk TSM (Dirac semimetal)





TlBiSSe

PRB **91** (2015) 041203(R)

Superconducting TIs/TCIs

$Cu_xBi_2Se_3$

PRL **106** (2011) 127004
PRB **84** (2011) 054513
PRL **107** (2011) 217001
PRB **86** (2012) 180505(R)
PRB **90** (2014) 094503

$Sn_{1-x}In_xTe$

PRL **109** (2012) 217004
PRB **88** (2013) 140502(R)
Cryst. Growth Des. **15** (2015) 2748

$Cu_x(PbSe)_5(Bi_2Se_3)_6$

PRB **90** (2014) 220504(R)

Magnetic TI

Cr-$TlSbTe_3$

APL Mater. **3** (2015) 083302

Film TI

Bi_2Se_3

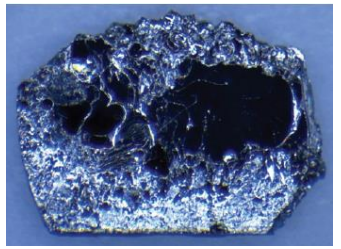
Adv. Mater. **24** (2012) 5581
PRL **109** (2012) 066803

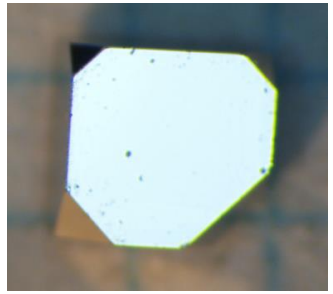
Bi_2Te_3/SnTe

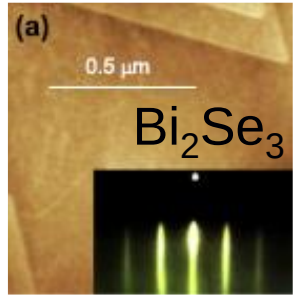
PRB **89** (2014) 121302

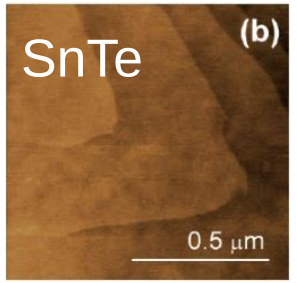
$(Bi,Sb)_2Te_3$

Nat. Commun. (2017) 1340
ACS Nano **9** (2015) 4050
APL **104** (2014) 161614









Material synthesis at Leeds: MBE thin film growth

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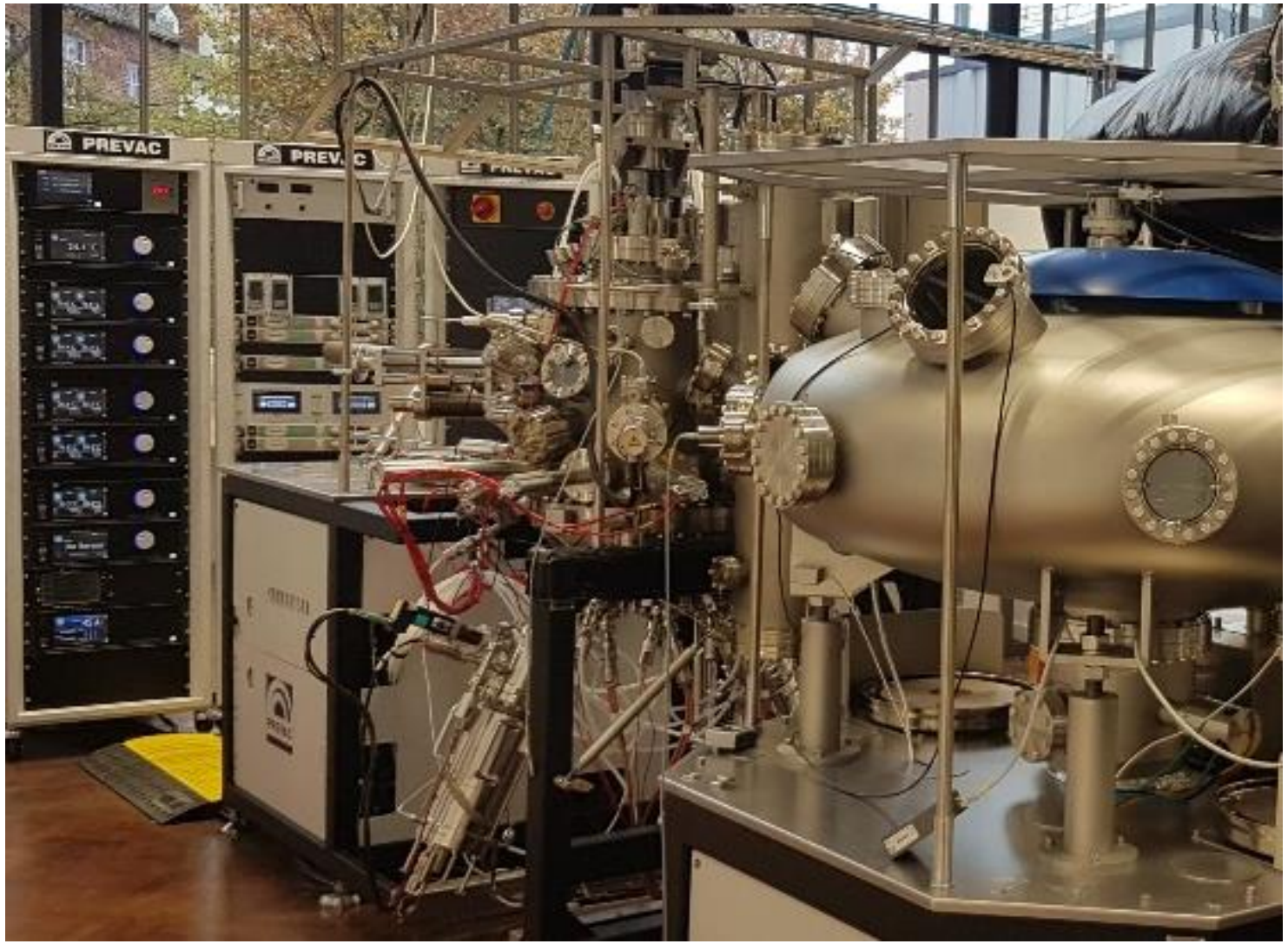

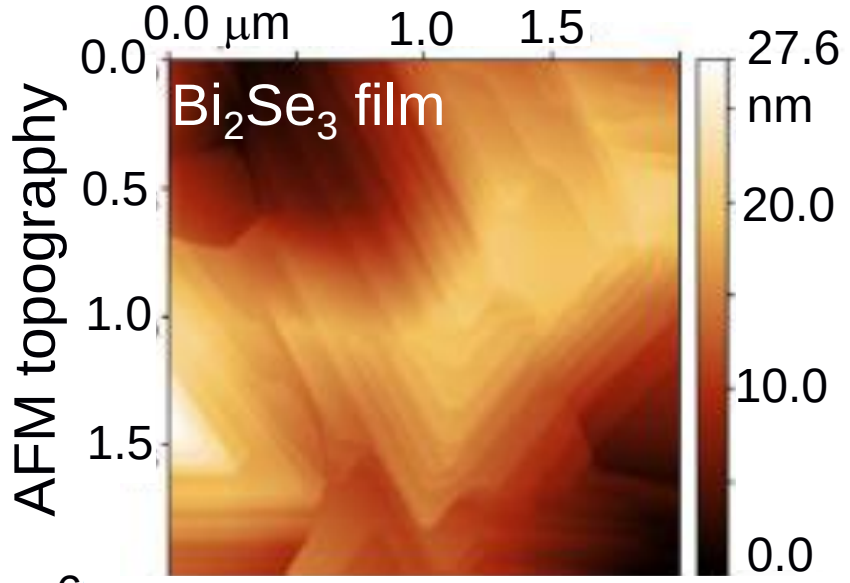

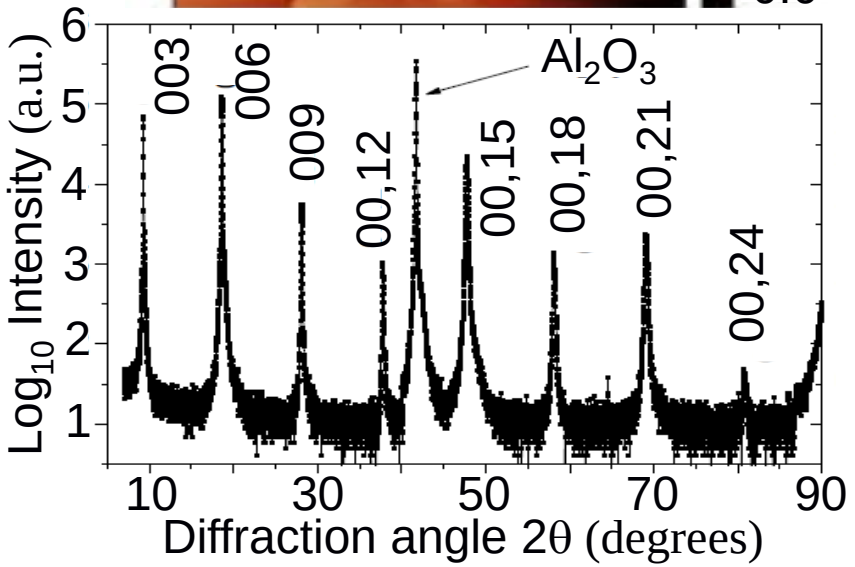

Material synthesis at Leeds: Single crystal/Physical vapour growth

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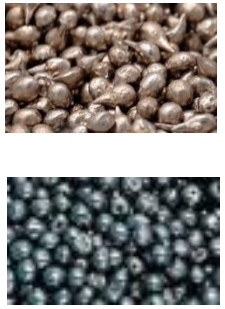
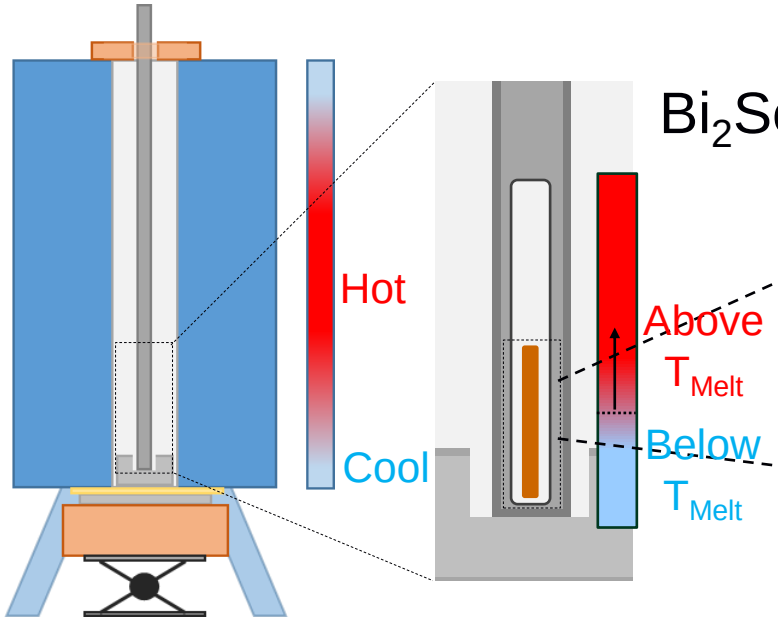
Source materials



Melt growth ($T \leq 1100^{o}C$)

polycrystalline sample

Single crystal growth

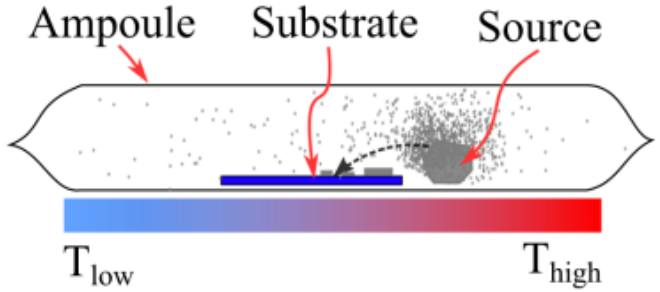


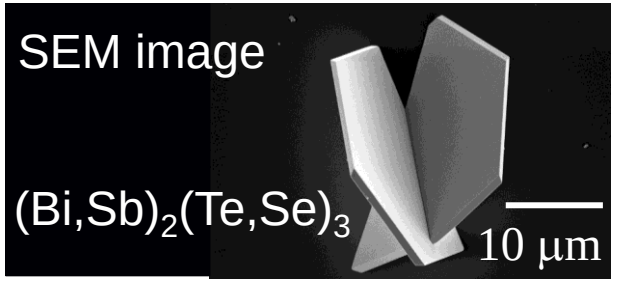
Naturally cleave planes (Van der Waals gap)

Bi_2Se_3 crystal

Doped-Sb_2Te_3 single crystal

Physical Vapour Transport crystal Growth (VTG)





Materials synthesis & Characterisation

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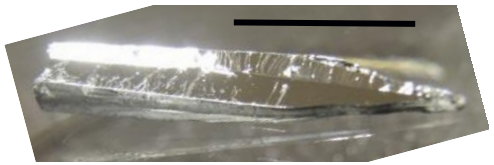
TMs

- **TIs** $(Bi_{1-x}Sb_x)_2Te_3$, Bi_2Te_3, Bi_2Se_3, Bi_2Te_2Se, $(Bi_{1-x}Sb_x)_2(Te_{1-y}Se_y)_3$, Sb_2Te_3
- **TCIs** SnTe, $Sn_{1-x}In_xTe$, $(Pb_{1-x}Sn_x)Te$, $(Pb_{1-x}Sn_x)Se$
- **TSMs** GeTe

Synthesis methods

Bi_2Se_3 1 cm

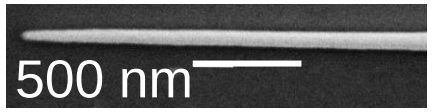


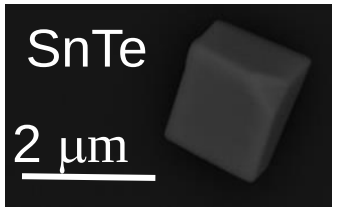
Single crystal

Bulk (melt growth)

Small-structures (VTG)

SnTe



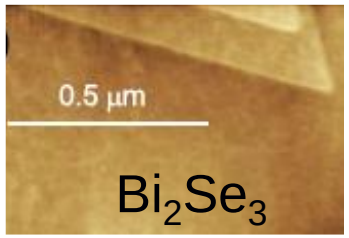


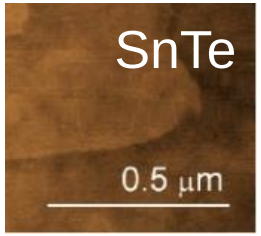
$Bi_{2-x}Sb_xTe_{3-y}Se_y$

200 μm

Epitaxial film

Thin/ultra-thin film (UHV-MBE)





Characterisation

Crystallinity: XRD

Morphology: XRR, AFM, SEM

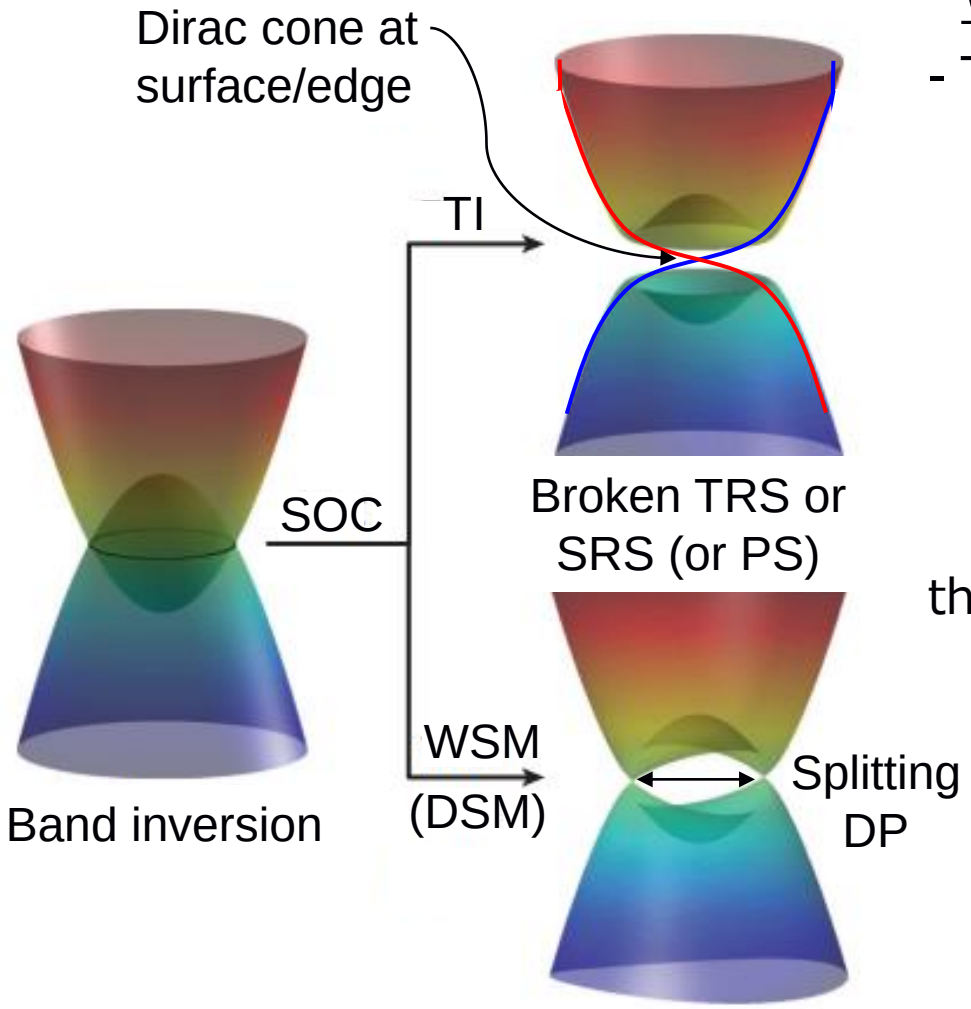
Electrodes fabrication: vacuum-cure Ag paint (bulk), lithography in clean room (film)

Magnetoelectric properties: transport, PC spectroscopy, SQUID, scanning Hall probe, MFM

More methods and more functional devices

Collaboration

Topological Semimetals

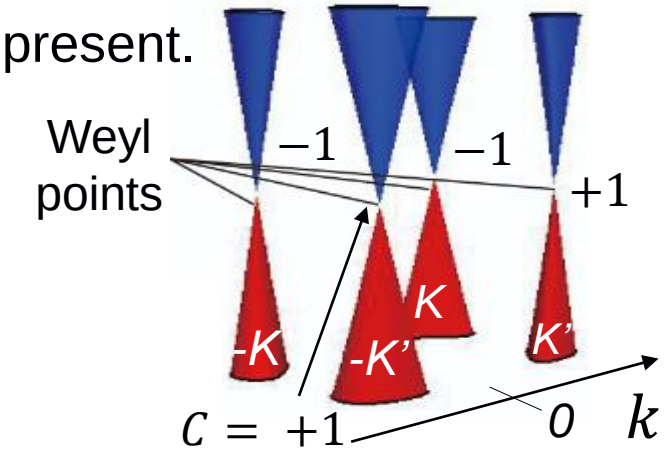


Weyl semimetals (WSM)

- Time Reversal Symmetry (TRS) is present.

Momentum transform: $k \rightarrow -k$

Spin transform: $\sigma \rightarrow -\sigma$



sing of Chern number *C*

⇕

Monopole (+1) or anti-monopole (-1)

the sum of the Chern numbers must be zero

(Nielsen-Ninomiya theorem)

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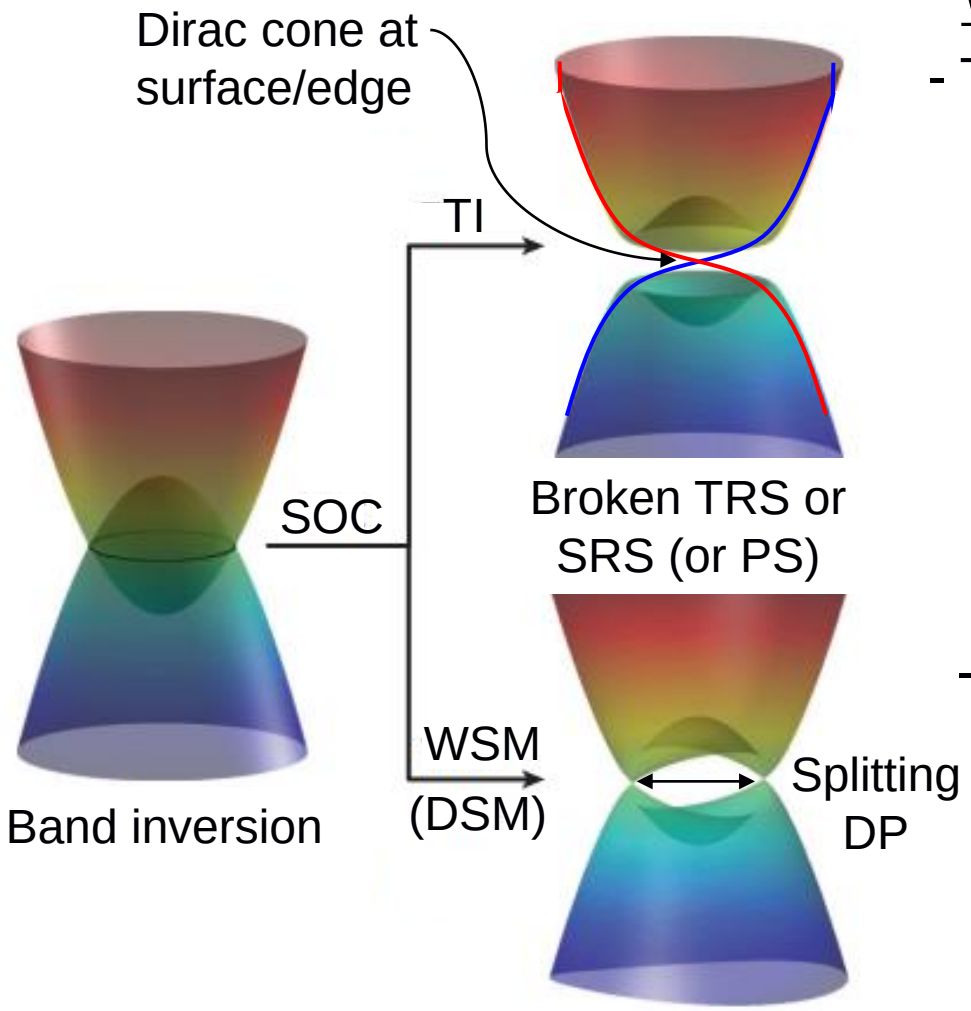
Topological Semimetals



Weyl semimetals (WSM)

- Time Reversal Symmetry (TRS) is present.

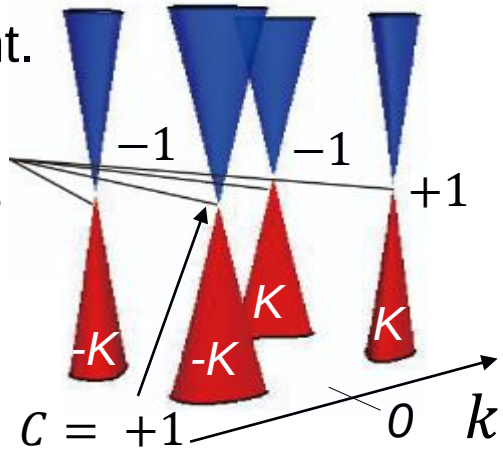
Momentum transform: $k \rightarrow -k$

Spin transform: $\sigma \rightarrow -\sigma$

sing of Chern number *C*

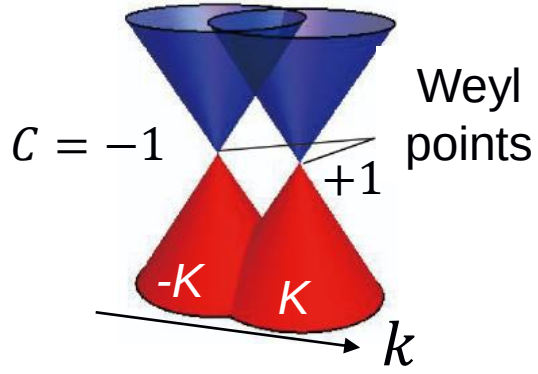
⇕

Monopole (+1) or anti-monopole (-1)



- Spatial Reversal Symmetry (SRS) or Parity symmetry (PS) is present.

Momentum transform: $k \rightarrow -k$



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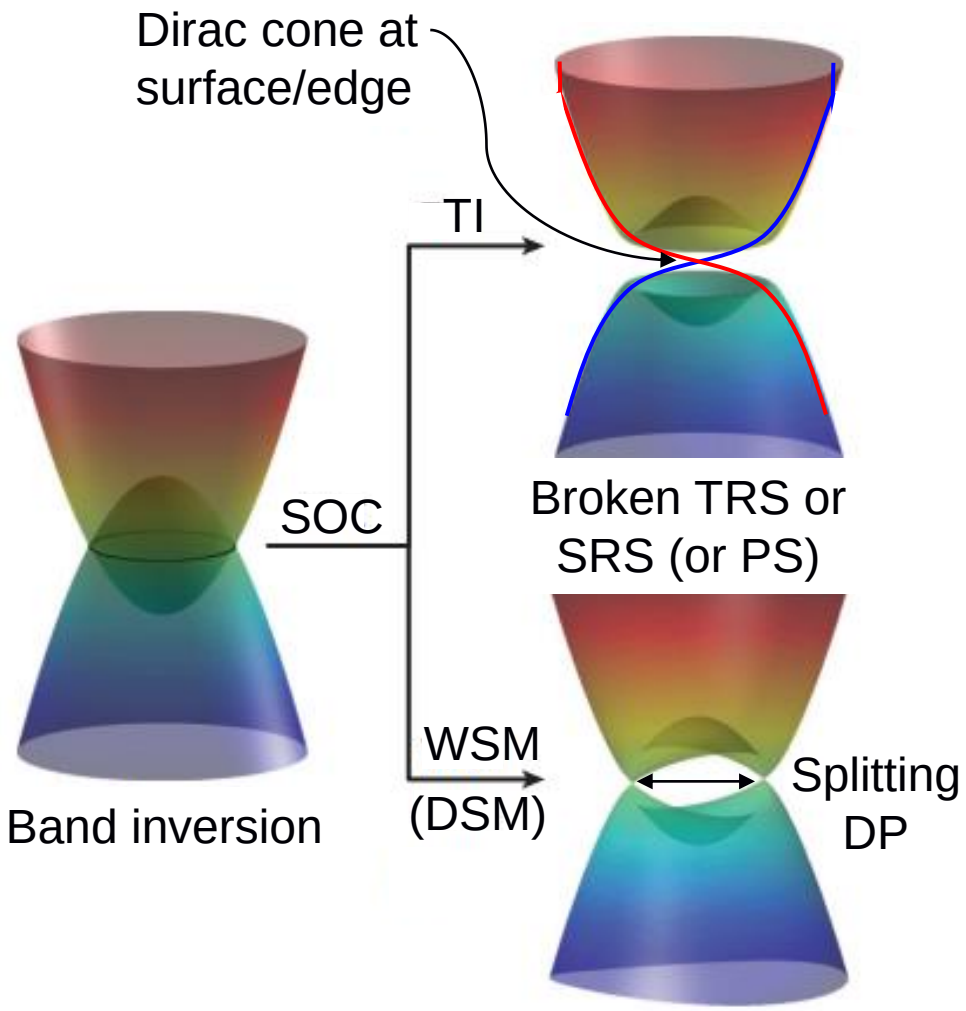
Topological Semimetals



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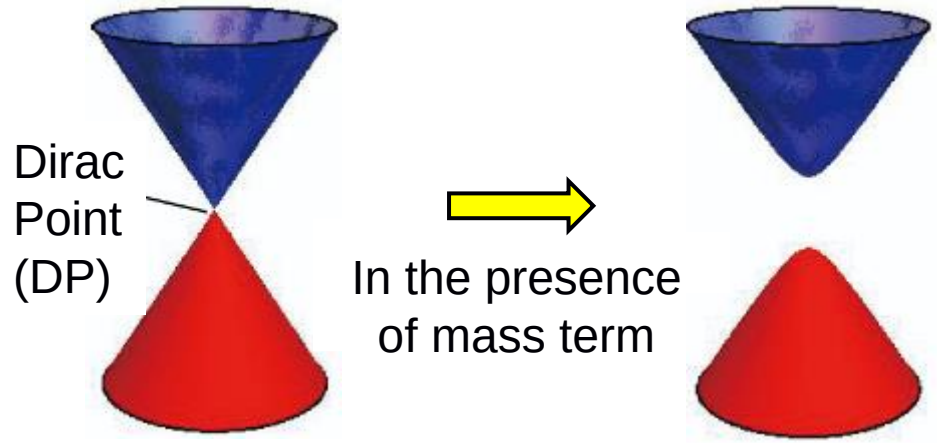
Dirac semimetals (DSM)

With TRS and SRS (PS)

NO topological protection for DPs or DNs



Factors for stabilising the DP(s)

- Single DP at the TRIM at the Brillouin zone boundary
- Nonsymmorphic crystal symmetry
  e.g. Bi_3Na (C_3 symmetry), Cd_3As_2 (C_4 symmetry)

Type-I/II Weyl/Dirac semimetals

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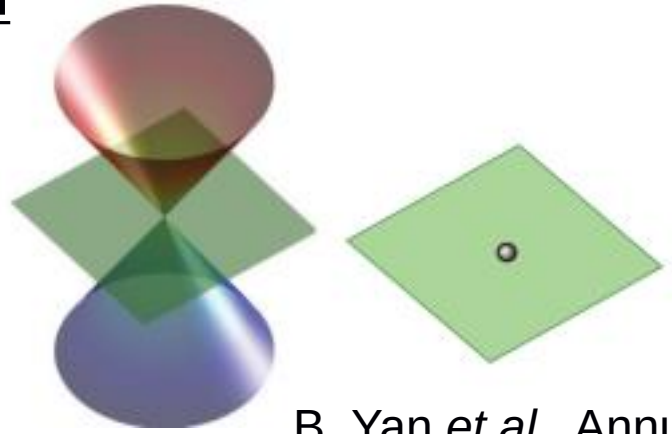
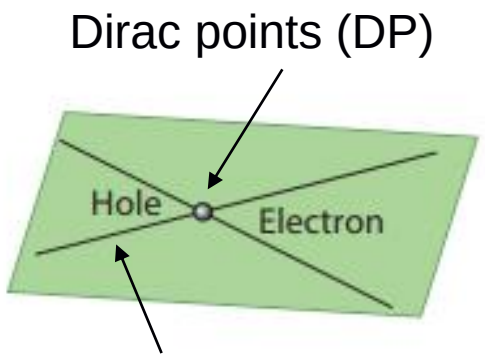
Type-I WSM



Type-II WSM



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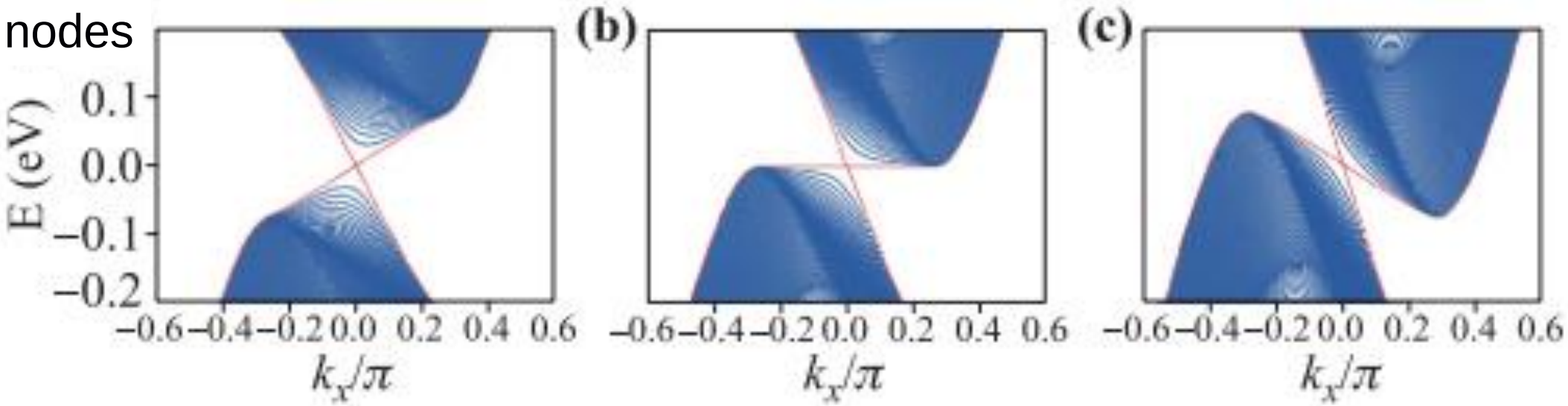
Dirac nodes



Si Li, et al., Front. Phys. 2020

Well-known TI, Sb2Te3

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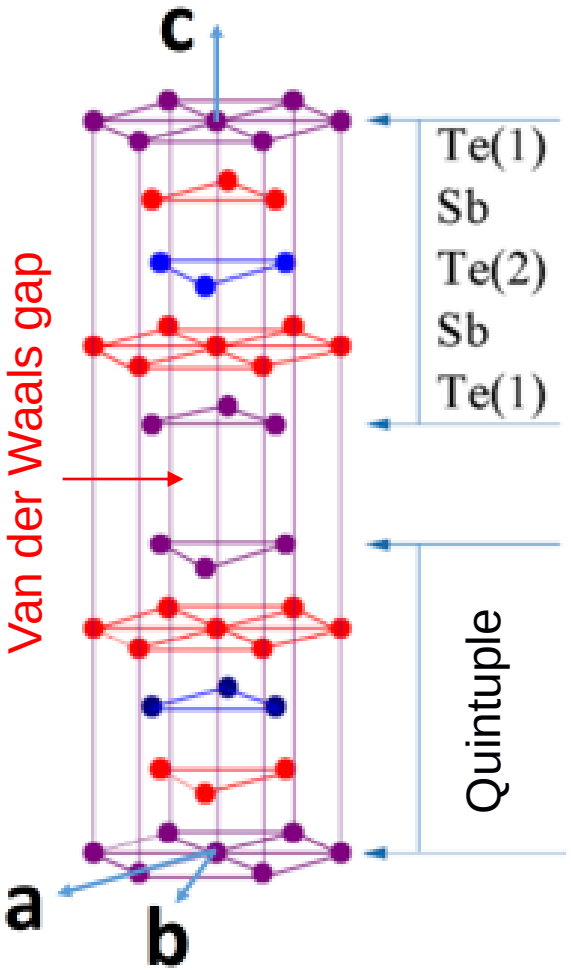
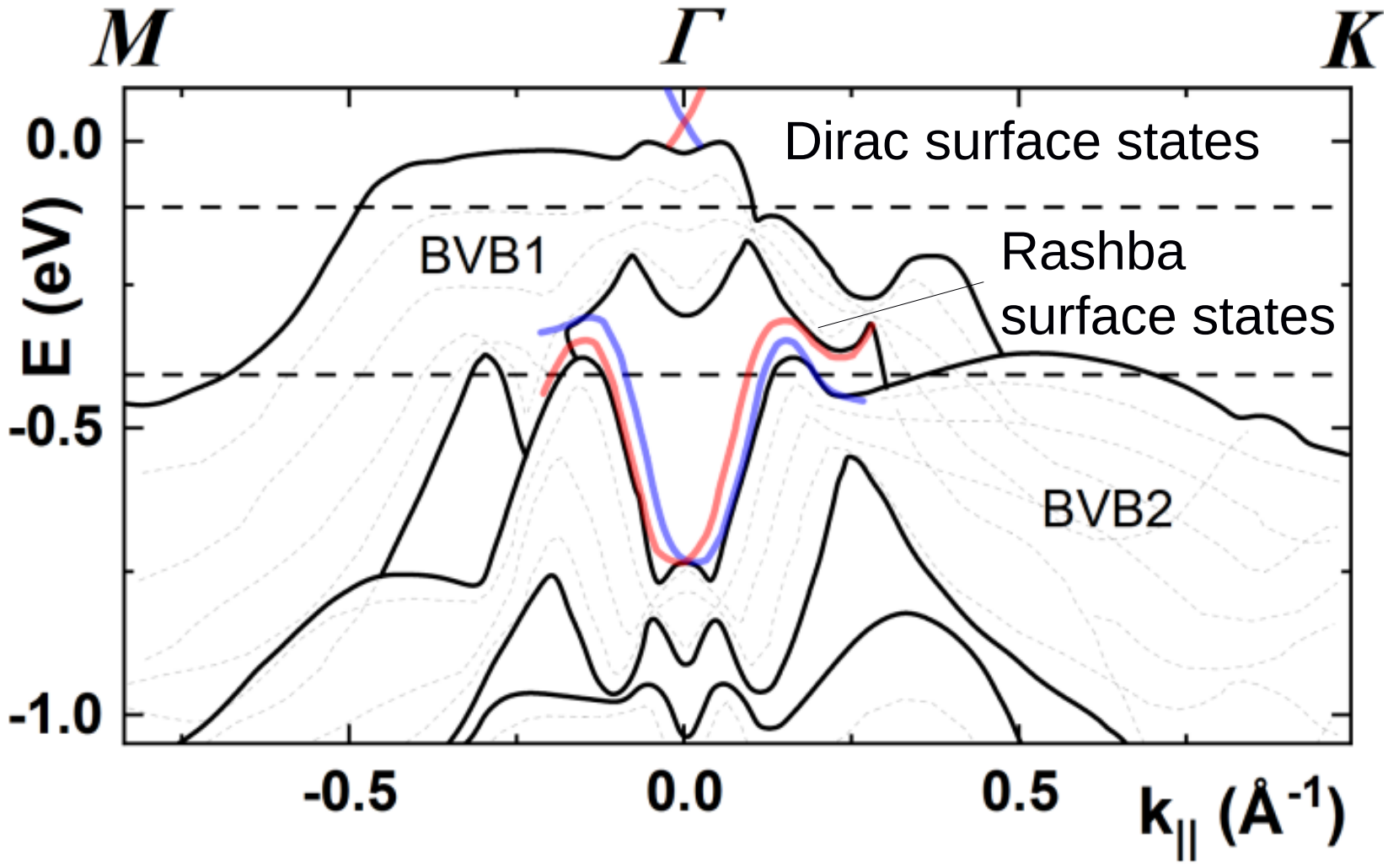
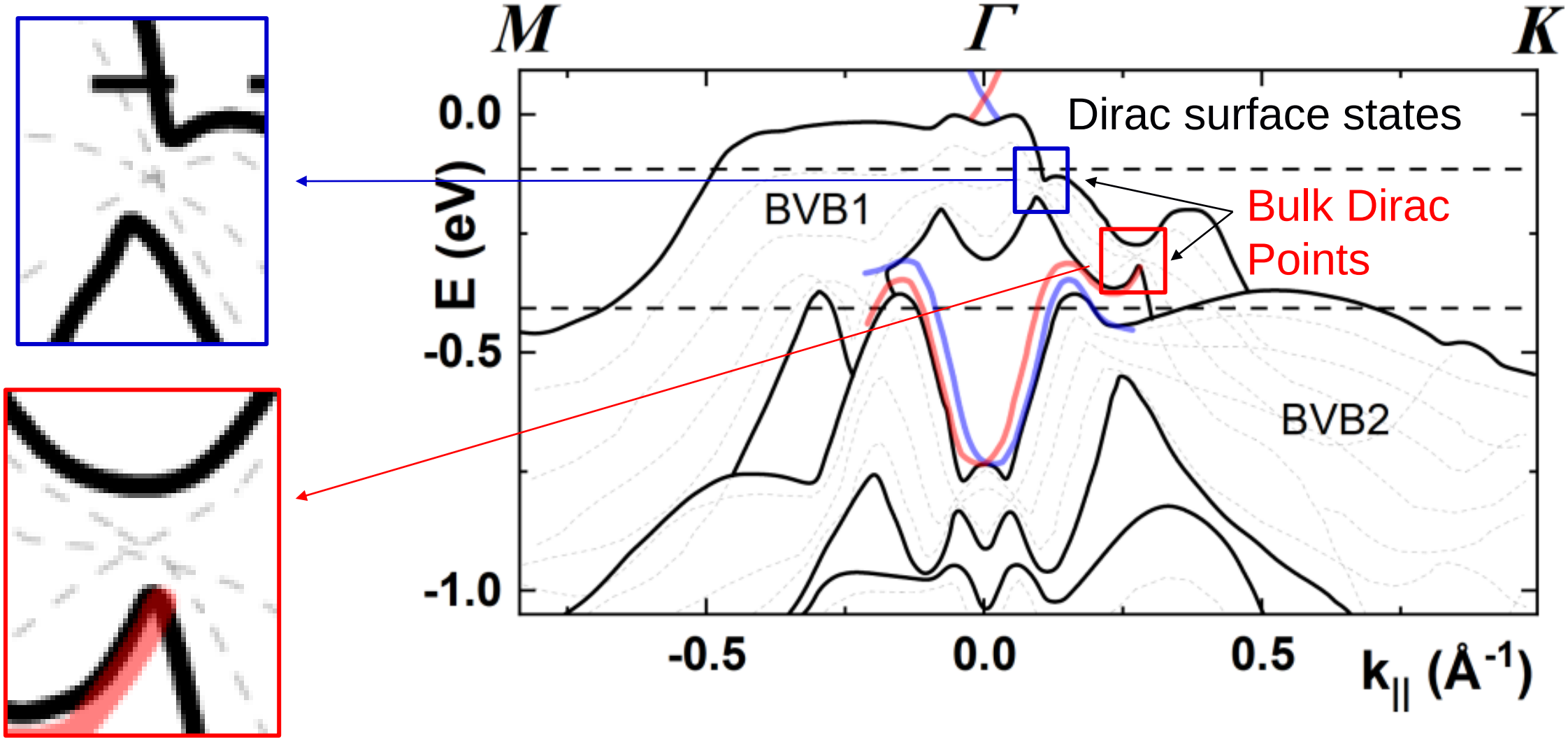
Crystal structure





Well-known TI, Sb2Te3



Type-I/II Weyl/Dirac semimetals

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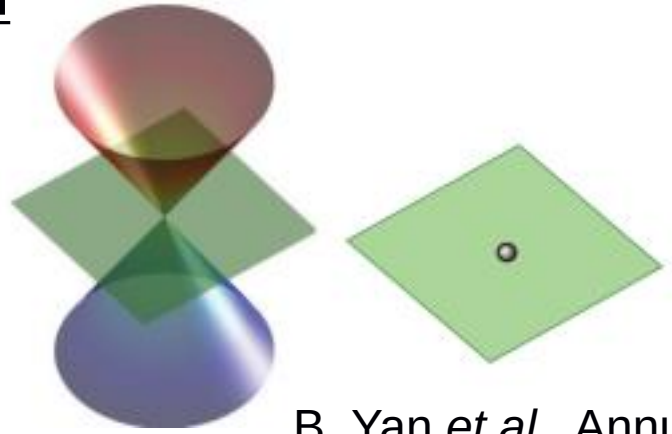
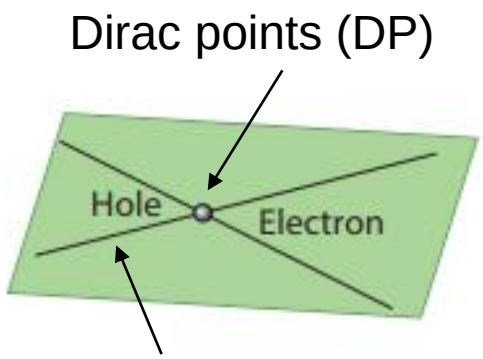
Type-I WSM



Type-II WSM



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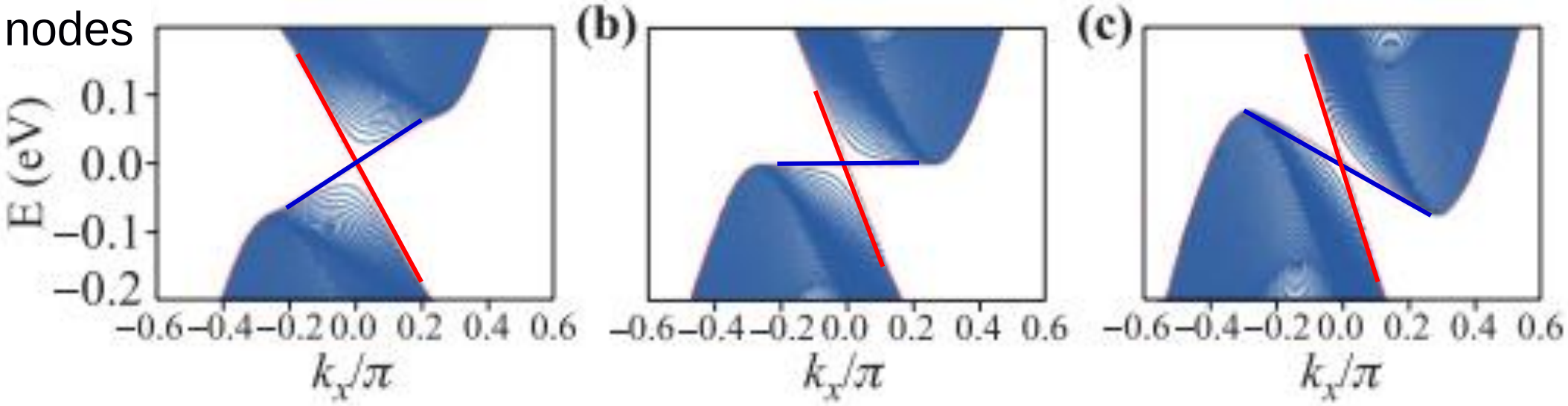
Dirac nodes



Si Li, et al., Front. Phys. 2020

Self-doping Sb_2Te_3

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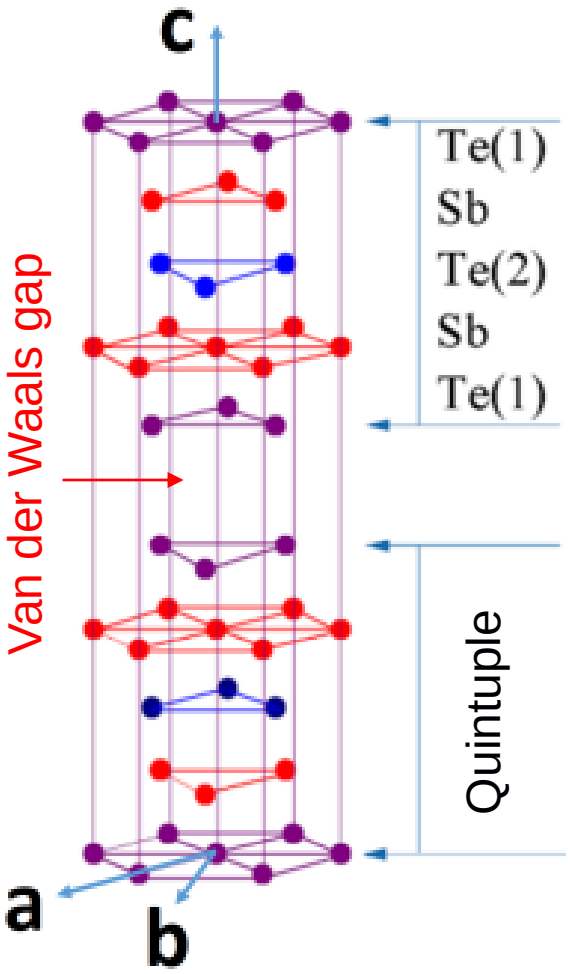
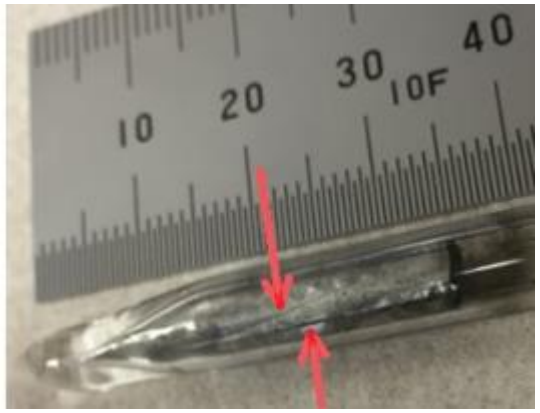
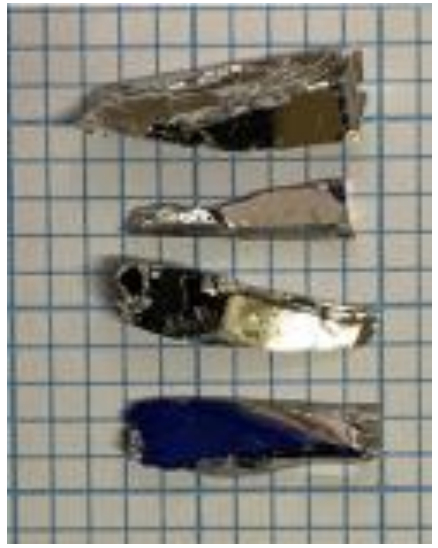
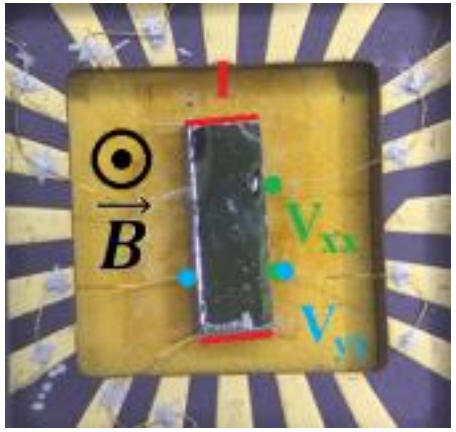
Crystal structure

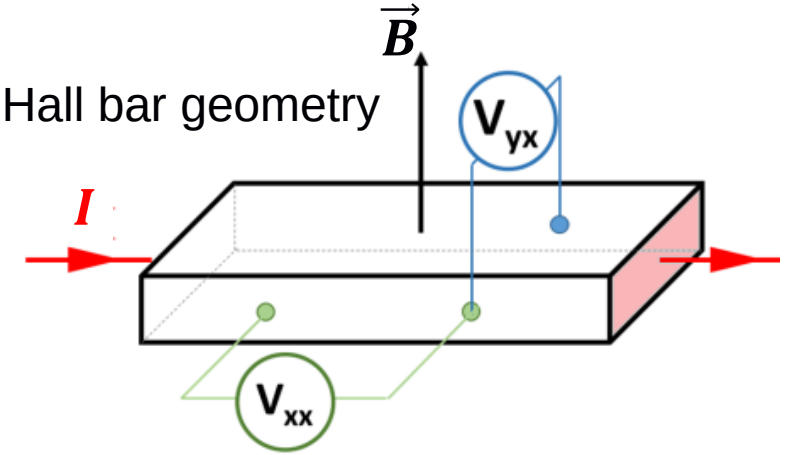


Tellurium-doped Sb_2Te_x ($x \geq 3$)









Shubnikov de Haas oscillations

Lifshitz-Kosevich form

$$\frac{\Delta\rho_{xx}}{\rho_{xx}} \propto \cos 2\pi\left(\frac{F}{B}-\frac{1}{2}+\beta\right)$$

The extremal Fermi surface cross sectional area (CSA)

$$= F\frac{2\pi e}{\hbar}$$

$$k_F = \sqrt{\mathrm{CSA}/\pi}$$

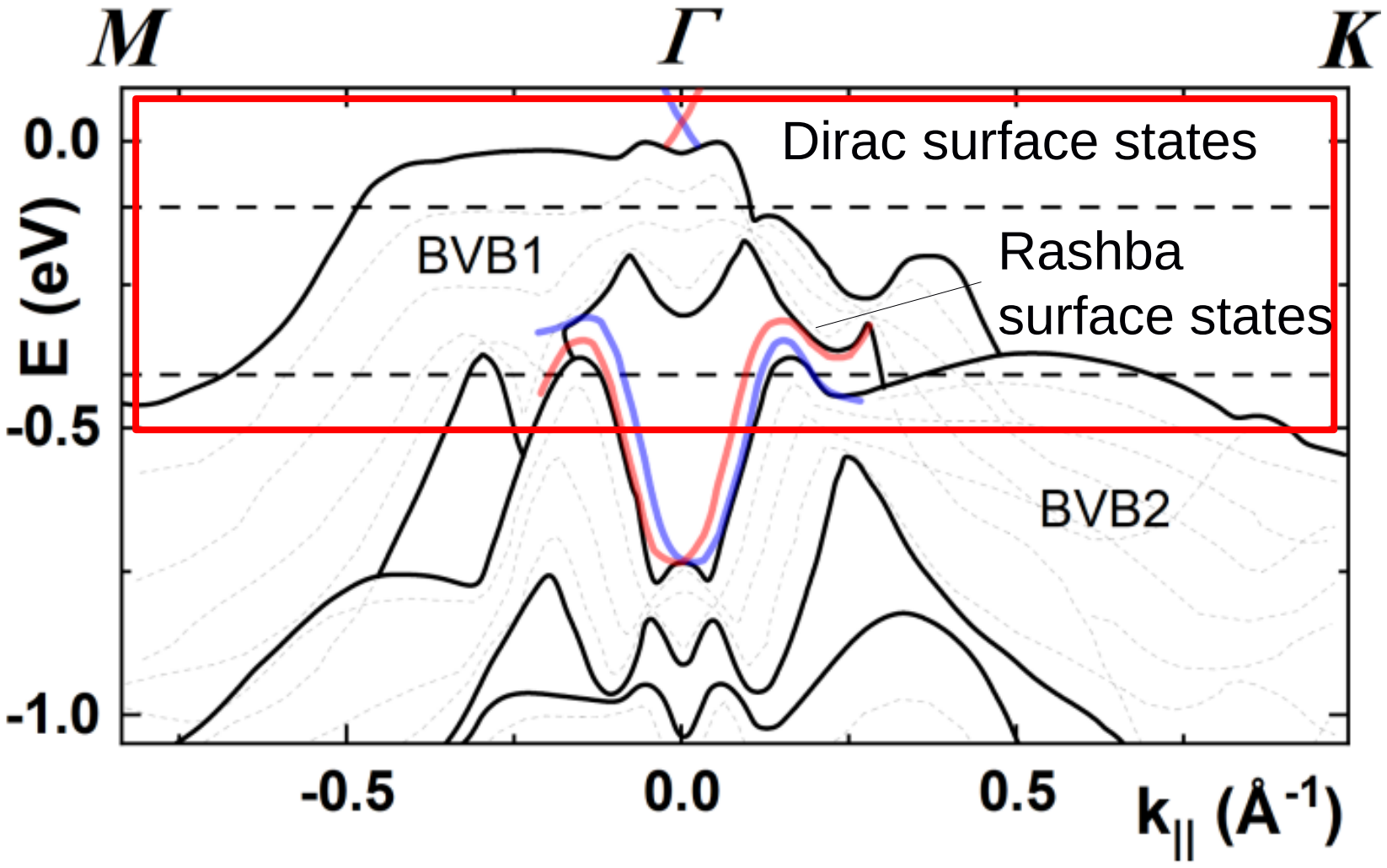
Landau lever fan diagram

If $\beta = \mp(0.5-\delta)$, e.g., $\delta \approx 1/8$

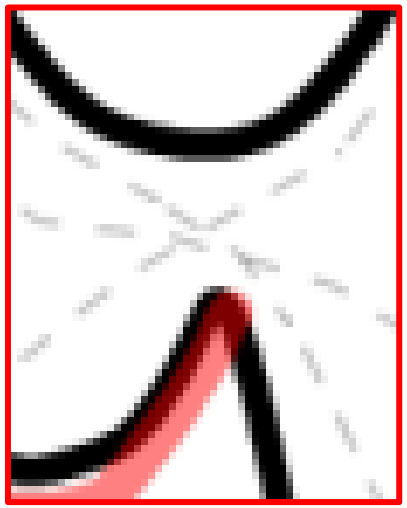
i.e., $\beta \approx \mp 0.375$, then, the system is **nontrivial**.

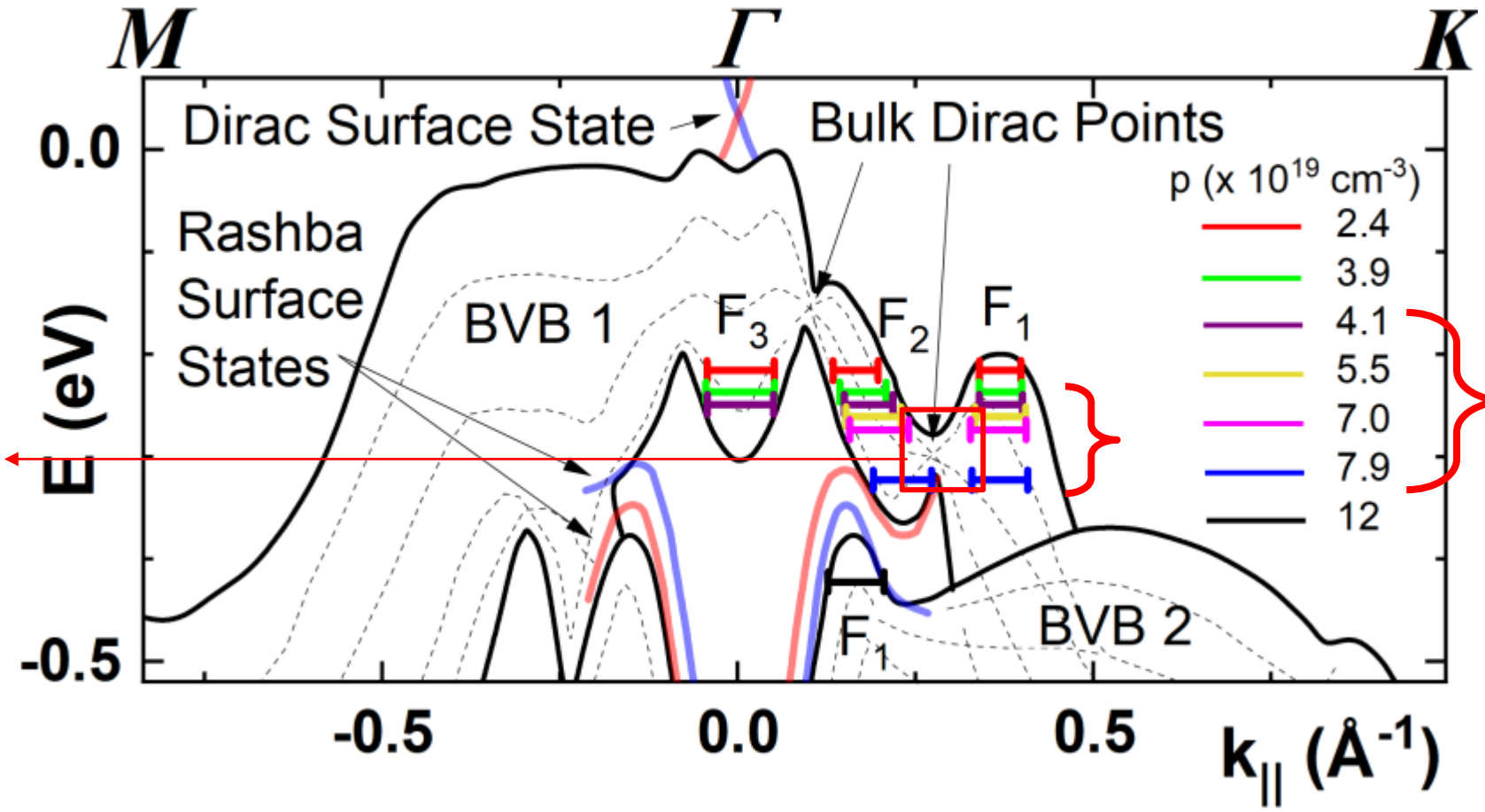
δ: band curvature correction

Band structure of Sb_2Te_3



Dirac semimetal phase of Sb_2Te_3





Nontrivial topology!

Bulk Dirac cones (NOT Dirac surface states) can present **nontrivial topology**!

Conclusions and Summary

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- We tuned the chemical potential of single crystal Sb_2Te_3 by Te doping
- Shubnikov de Haas oscillation for single crystal Sb_2Te_3 show beats in Quantum oscillations
- Observation of Dirac semimetal phase in TI, Sb_2Te_3
- Bulk Dirac cones can provide nontrivial topology
- We are happy to collaborate with you;

  we can provide topological materials thin films and single crystals.

Materials synthesis & Characterisation

HENRY ROYCE INSTITUTE

York TOHOKU KAISERSLAUTERN LEEDS Manchester spintec symposium

UNIVERSITY OF LEEDS

TMs
- **TIs** $(Bi_{1-x}Sb_x)_2Te_3$, Bi_2Te_3, Bi_2Se_3, Bi_2Te_2Se, $(Bi_{1-x}Sb_x)_2(Te_{1-y}Se_y)_3$, Sb_2Te_3
- **TCIs** SnTe, $Sn_{1-x}In_xTe$, $(Pb_{1-x}Sn_x)Te$, $(Pb_{1-x}Sn_x)Se$
- **TSMs** GeTe

Synthesis methods

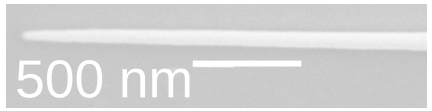
Bi_2Se_3 1 cm

Single crystal

Bulk (melt growth)

Small-structures (VTG)

SnTe

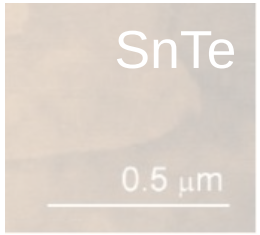


$Bi_{2-x}Sb_xTe_{3-y}Se_y$

Epitaxial film

Thin/ultra-thin film

(MBE, MOCVD)



Characterisation

Crystallinity: XRD

Morphology: XRR, AFM, SEM

Electrodes fabrication: vacuum-cure Ag paint (bulk), lithography in clean room (film)

Magnetoelectric properties: transport, PC spectroscopy, SQUID, scanning Hall probe, MFM

More methods and more functional devices

Collaboration

Thank you

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