Realization of an 3D ideal Weyl semimetal in $MnBi_{2-x}Sb_xTe_4$

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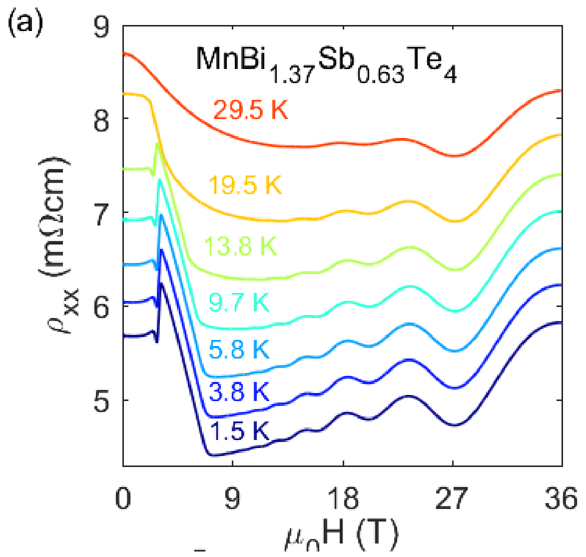
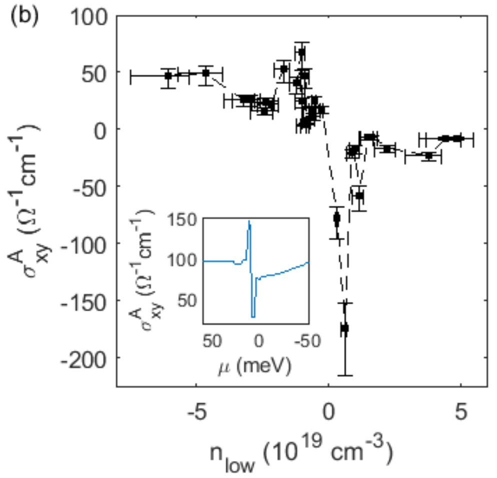
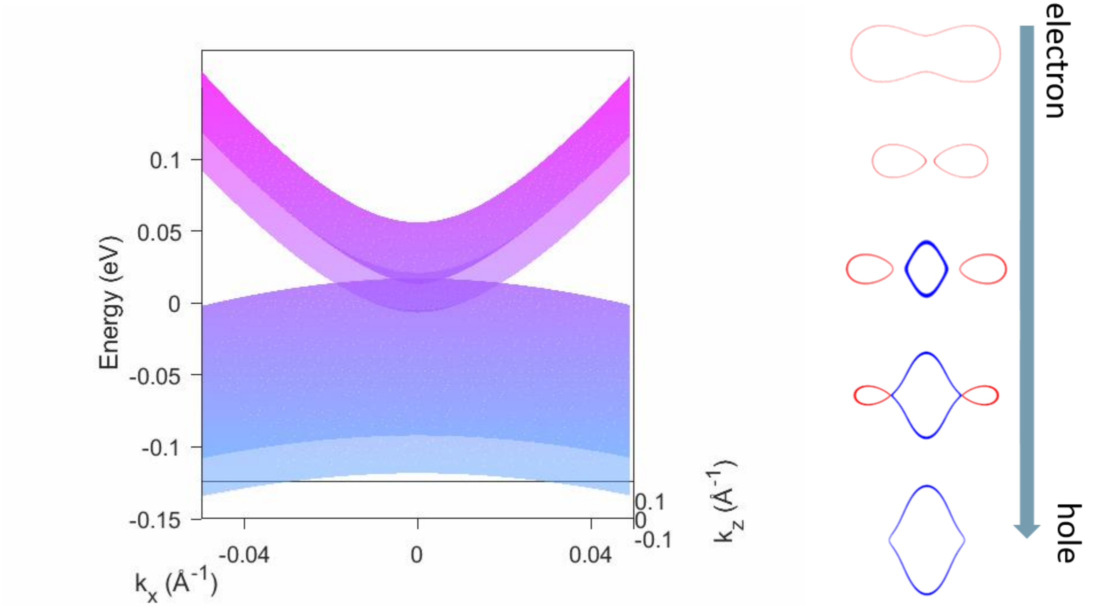
Department of Physics, University of Washington





Type-II Weyl Semimetal



Acknowledgements

UW Quantum materials group
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UW Theory
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Qianni Jiang
(Now GLAM Postdoc Fellow in Stanford)

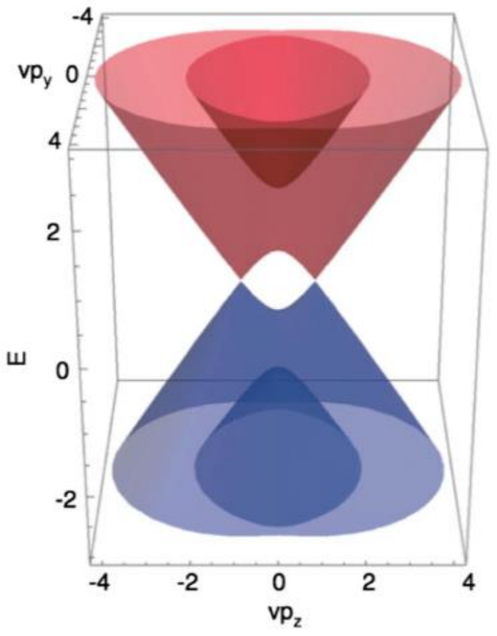
Pro-QM
Programmable Quantum Materials
DOE Energy Frontiers Research Center

GORDON AND BETTY MOORE FOUNDATION

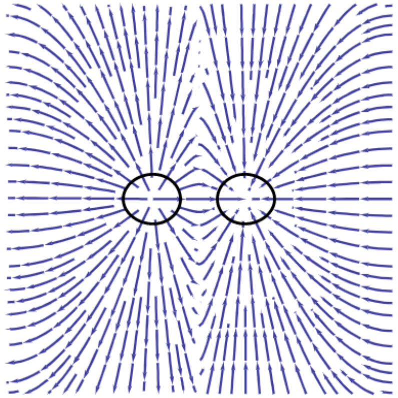
Background of Weyl Semimetals

Weyl Equation

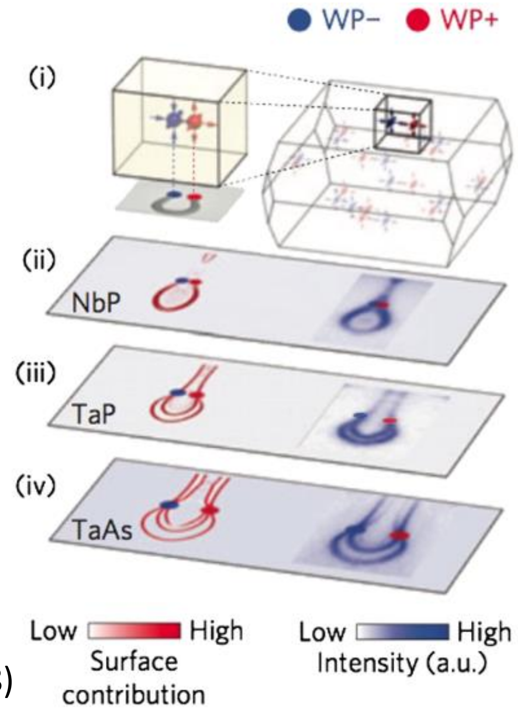
$$i\frac{\partial}{\partial t}\psi_{\pm} = \pm c\boldsymbol{p}\cdot\alpha\psi_{\pm}$$



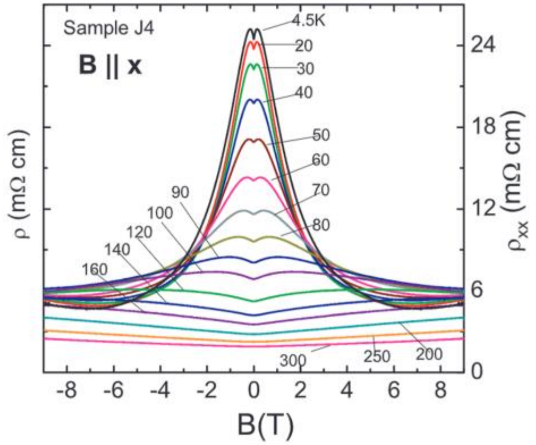
- Berry Flux



- Fermi Arc



- Chiral Anomaly



$$\frac{\partial}{\partial t}\rho_{\chi} + \nabla\cdot\mathbf{J}_{\chi} = -\chi\frac{e^3}{4\pi^2\hbar^2}\mathbf{E}\cdot\mathbf{B}$$

- **Intrinsic anomalous Hall**

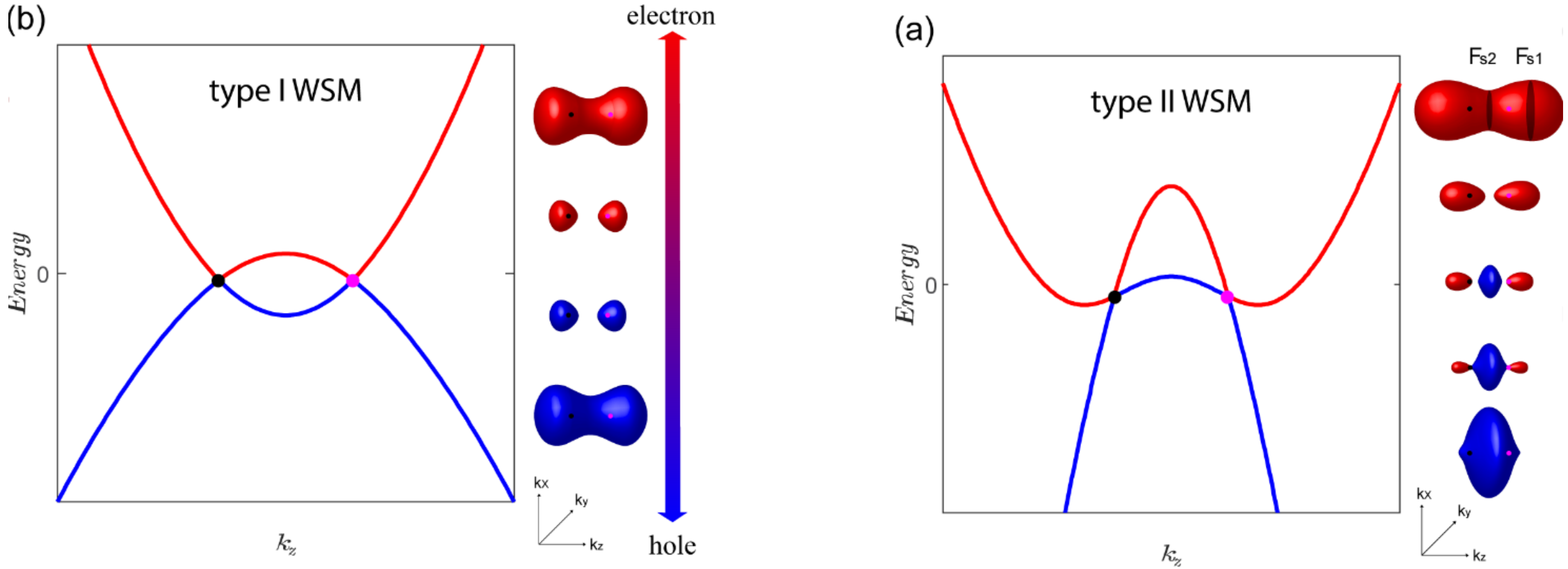
In an ideal Weyl semimetal:

$$\sigma_{xy}^{A} = \frac{e^2 Q}{2\pi^2\hbar} \qquad \text{Quantized}$$

Q : Weyl points separation

Z. Liu, et al. Nat. Mater. 15, 27 (2016)
J. Xiong et al. Science 350,413-416 (2015)
N.P. Armitage, et. al. Rev. Mod. Phys, 90(1), 015001 (2018)

Two types of Weyl Semimetals



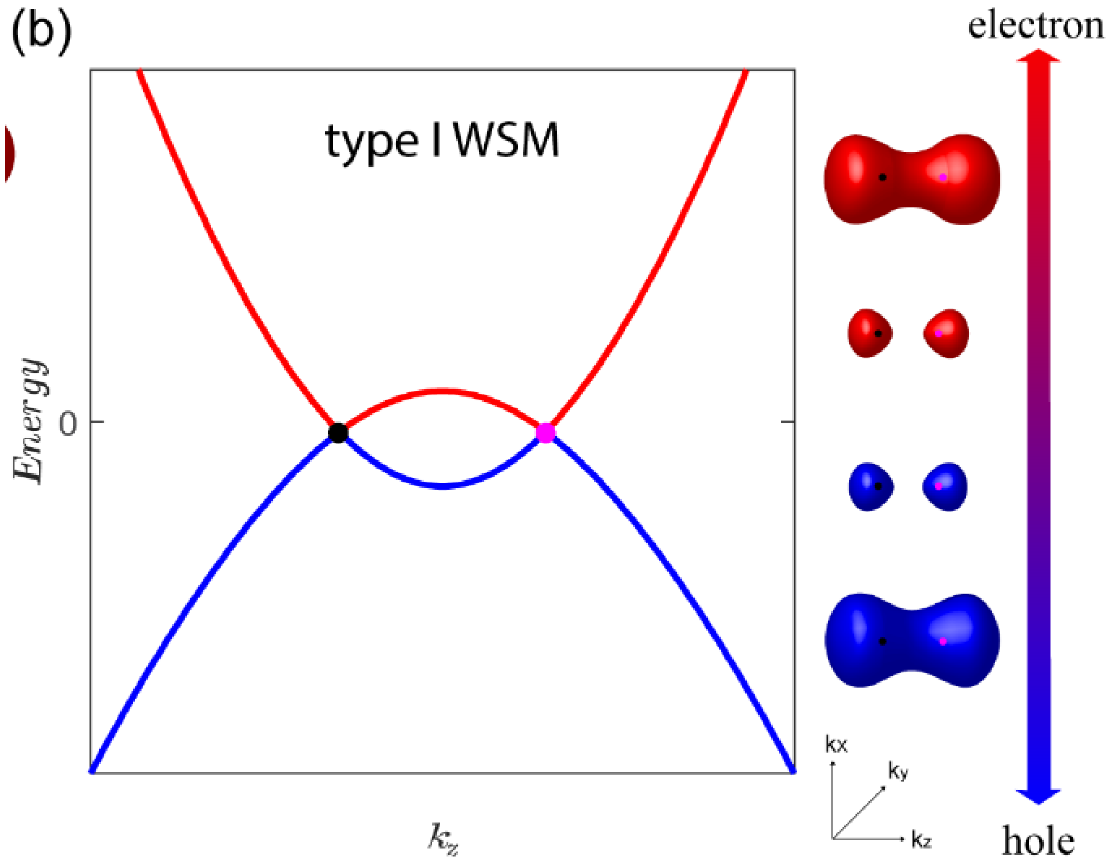
Z. Liu, et al. Nat. Mater. 15, 27 (2016)

J. Xiong et al. Science 350,413-416 (2015)

N.P. Armitage, et. al. Rev. Mod. Phys, 90(1), 015001 (2018)

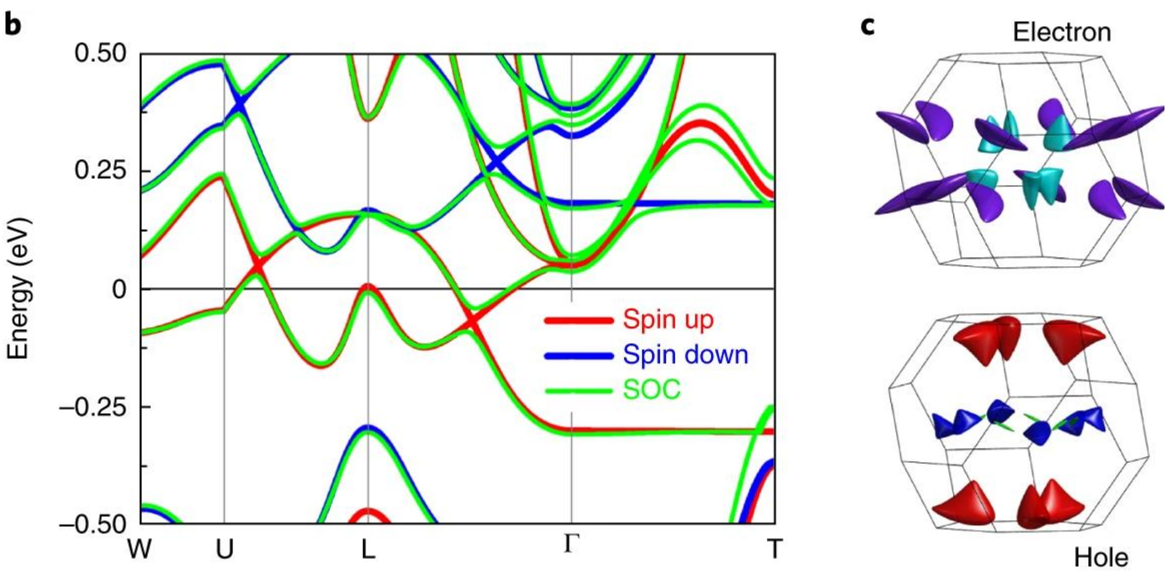
The need for an ideal Weyl semimetal

WSM to the theorists



WSM in reality

$Co_3Sn_2S_2$ FM WSM



Liu, E., Sun, Y., Kumar, N. *et al.* Giant anomalous Hall effect in a ferromagnetic kagome-lattice semimetal. *Nature Phys* **14**, 1125–1131 (2018).

The need for an ideal Weyl semimetal

PRL **107,** 127205 (2011) PHYSICAL REVIEW LETTERS week ending 16 SEPTEMBER 2011

Weyl Semimetal in a Topological Insulator Multilayer

A. A. Burkov[1,2] and Leon Balents[2]

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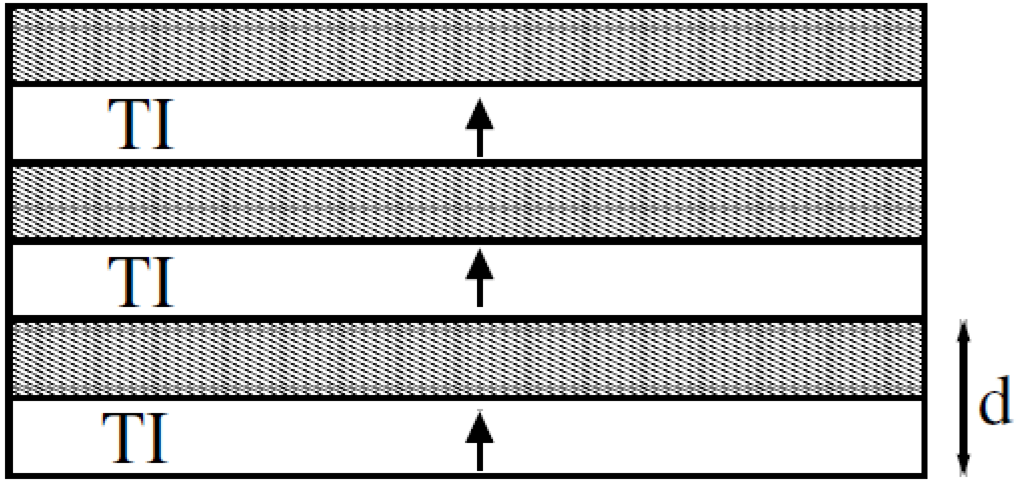
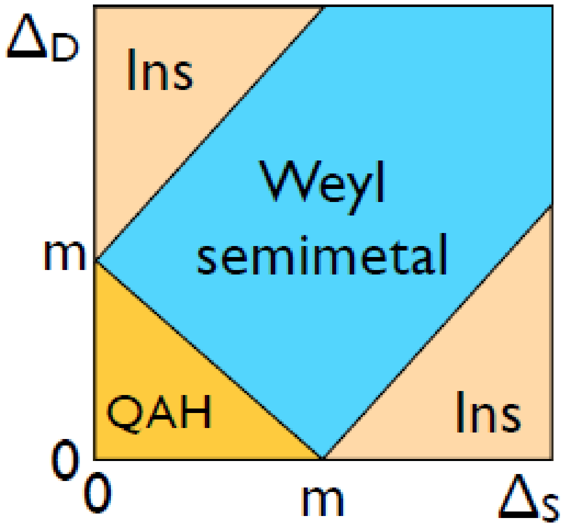
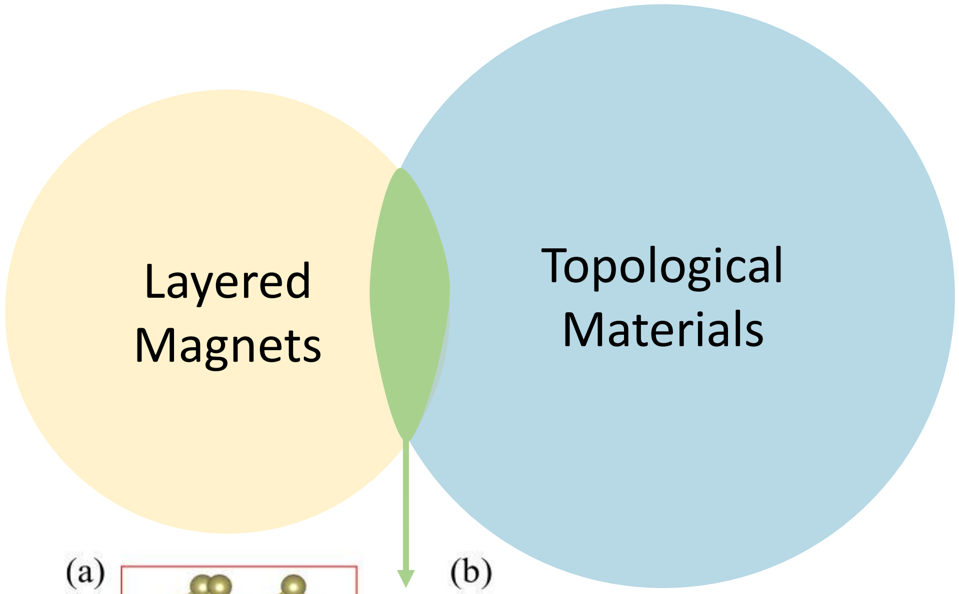
[2]*Kavli Institute for Theoretical Physics, University of California, Santa Barbara, California 93106, USA*

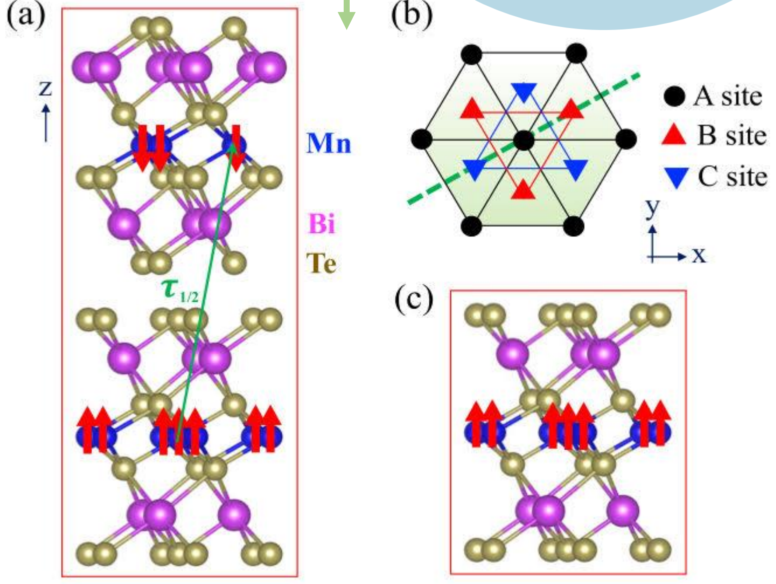
(Received 27 May 2011; published 16 September 2011)

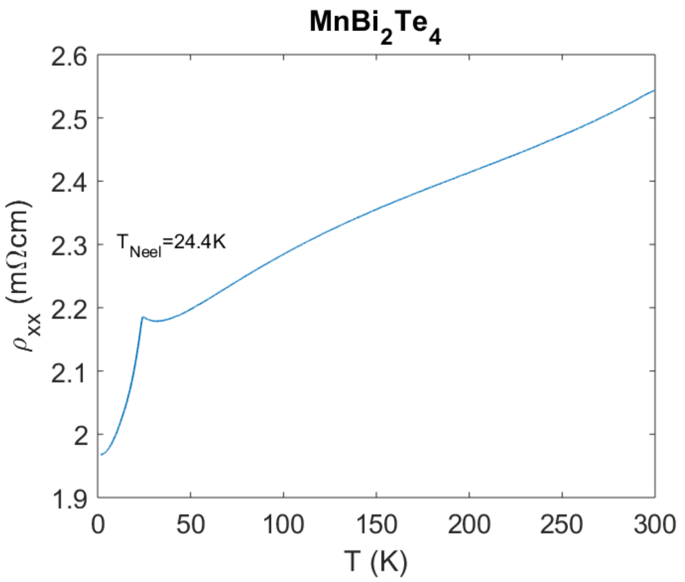


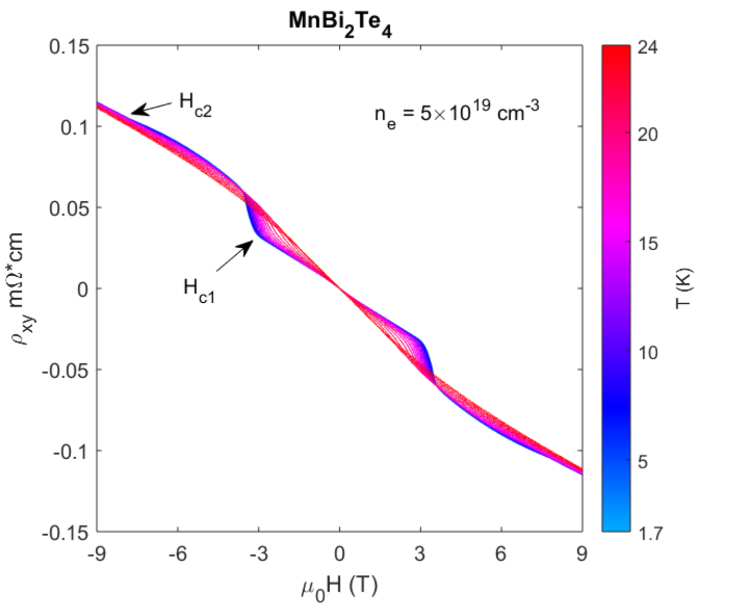


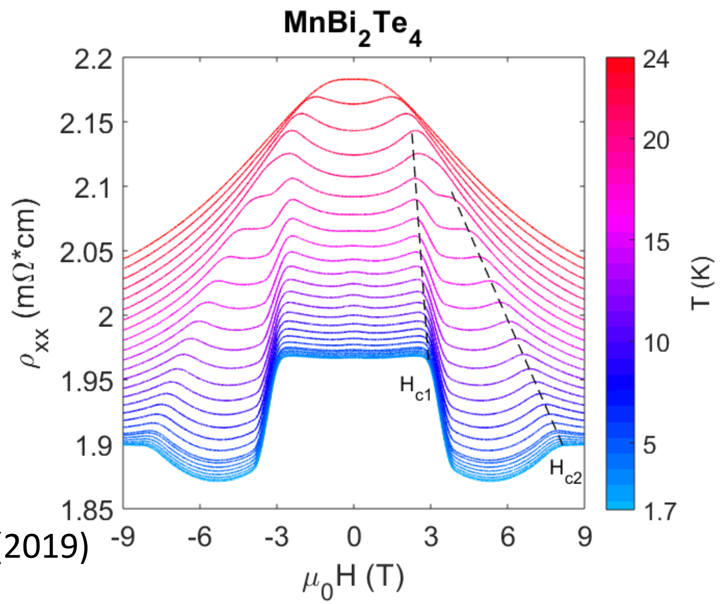
Background of $MnBi_2Te_4$

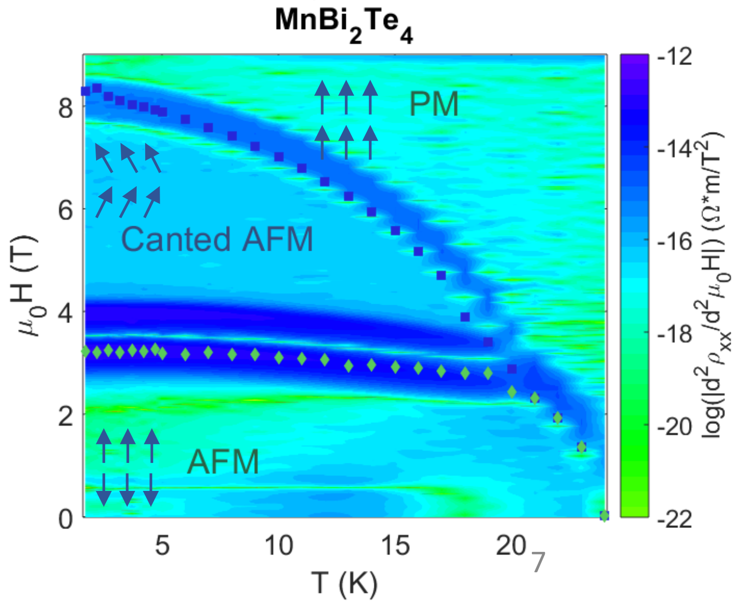






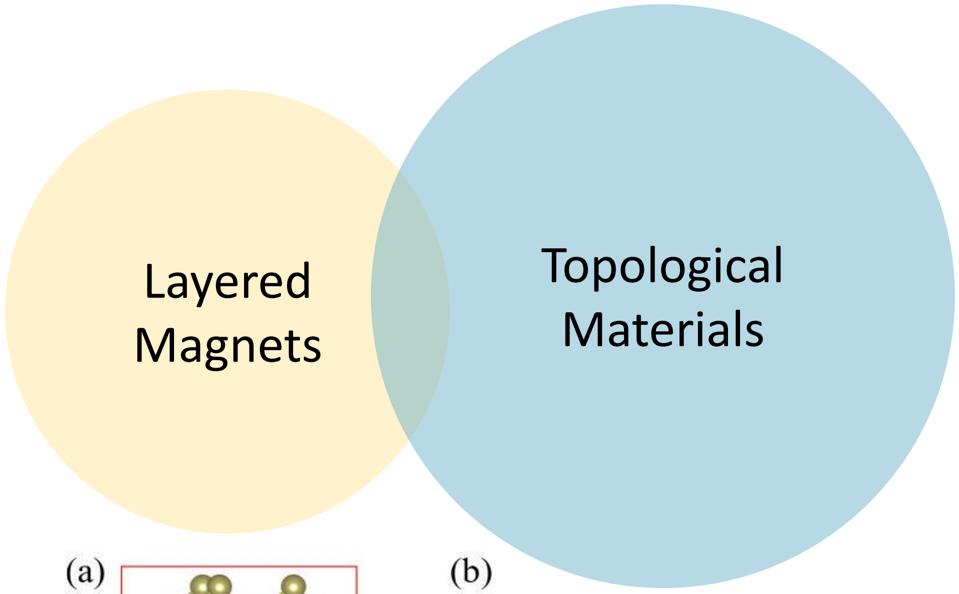


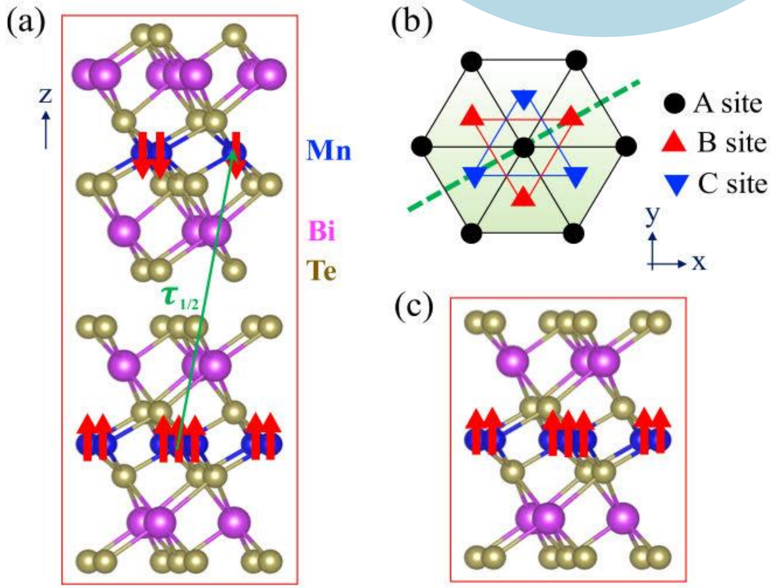




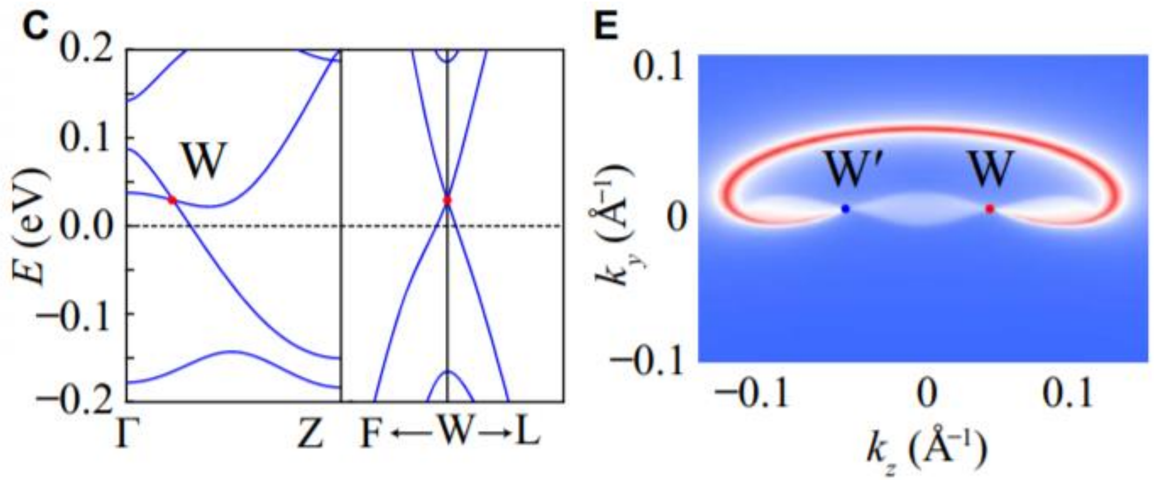
Chinese Phys. Lett. **36** 076801 (2019)
Chem. Mater. 31, 8, 2795–2806 (2019)
Phys. Rev. Materials 3, 064202 (2019)
Phys. Rev. B 99, 155125 (2019)

$MnBi_2Te_4$ as a natural superlattice of FMIs and TIs



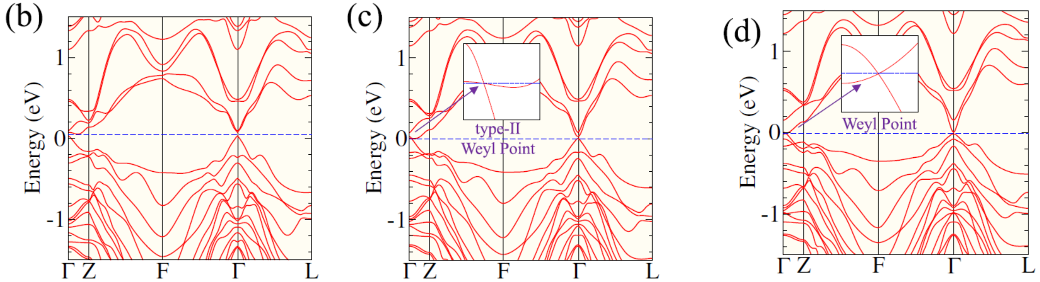


type-II Weyl



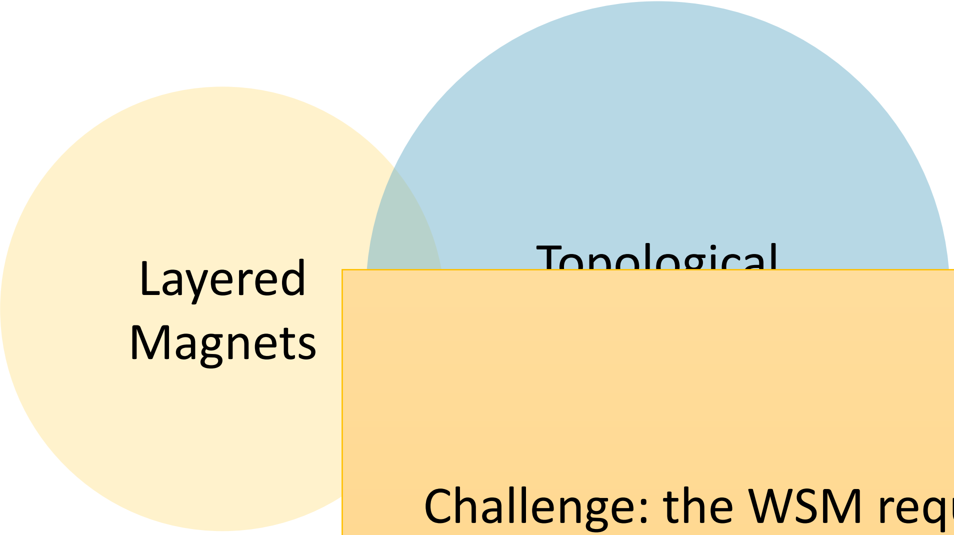
(Li J., et al., Sci. Adv. 2019;5: eaaw5685)

Trivial semiconductor | type-II Weyl | type-I Weyl

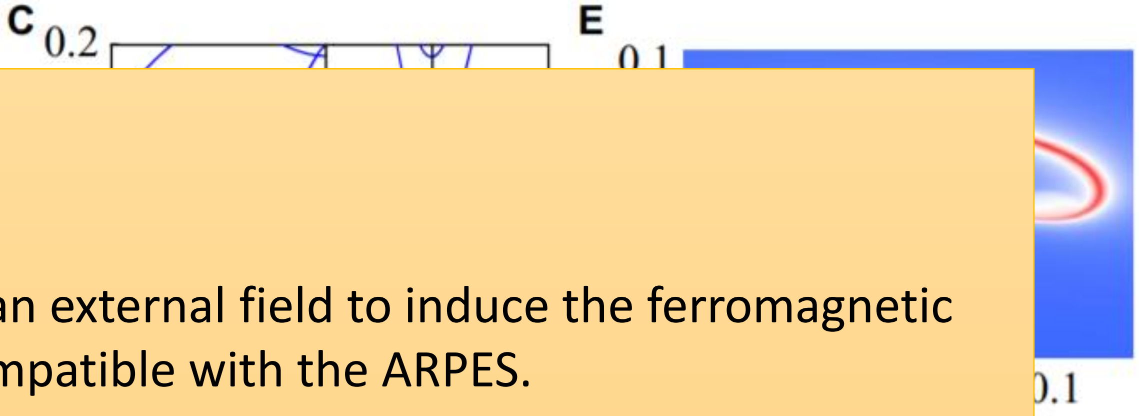


(Zhang D., et al, PRL 122.20 (2019): 206401)

$MnBi_2Te_4$ as a natural superlattice of FMIs and TIs

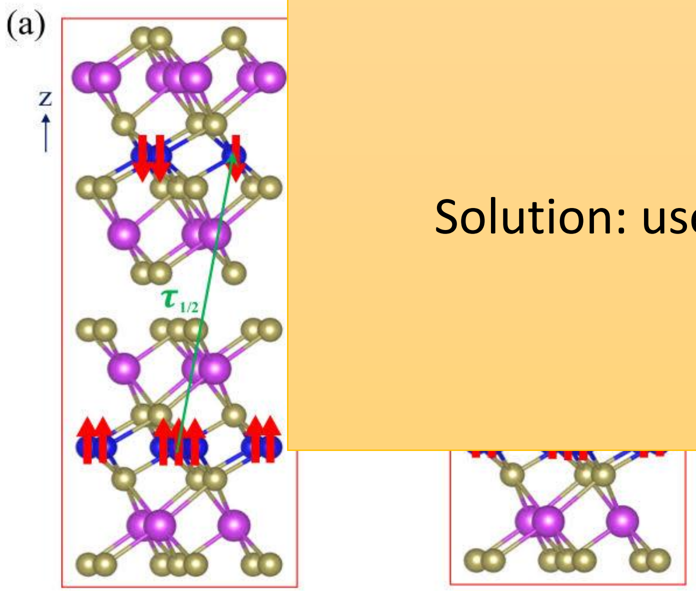


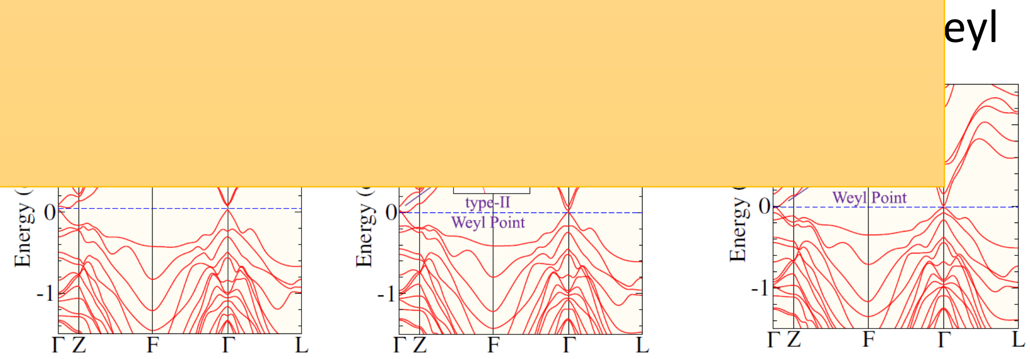
type-II Weyl



Challenge: the WSM requires an external field to induce the ferromagnetic state, incompatible with the ARPES.

Solution: use quantum oscillations to probe the electronic structure!

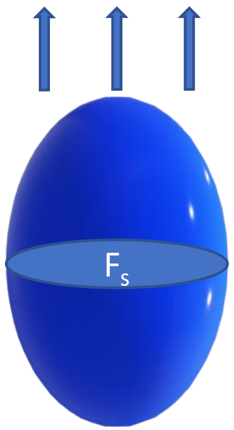




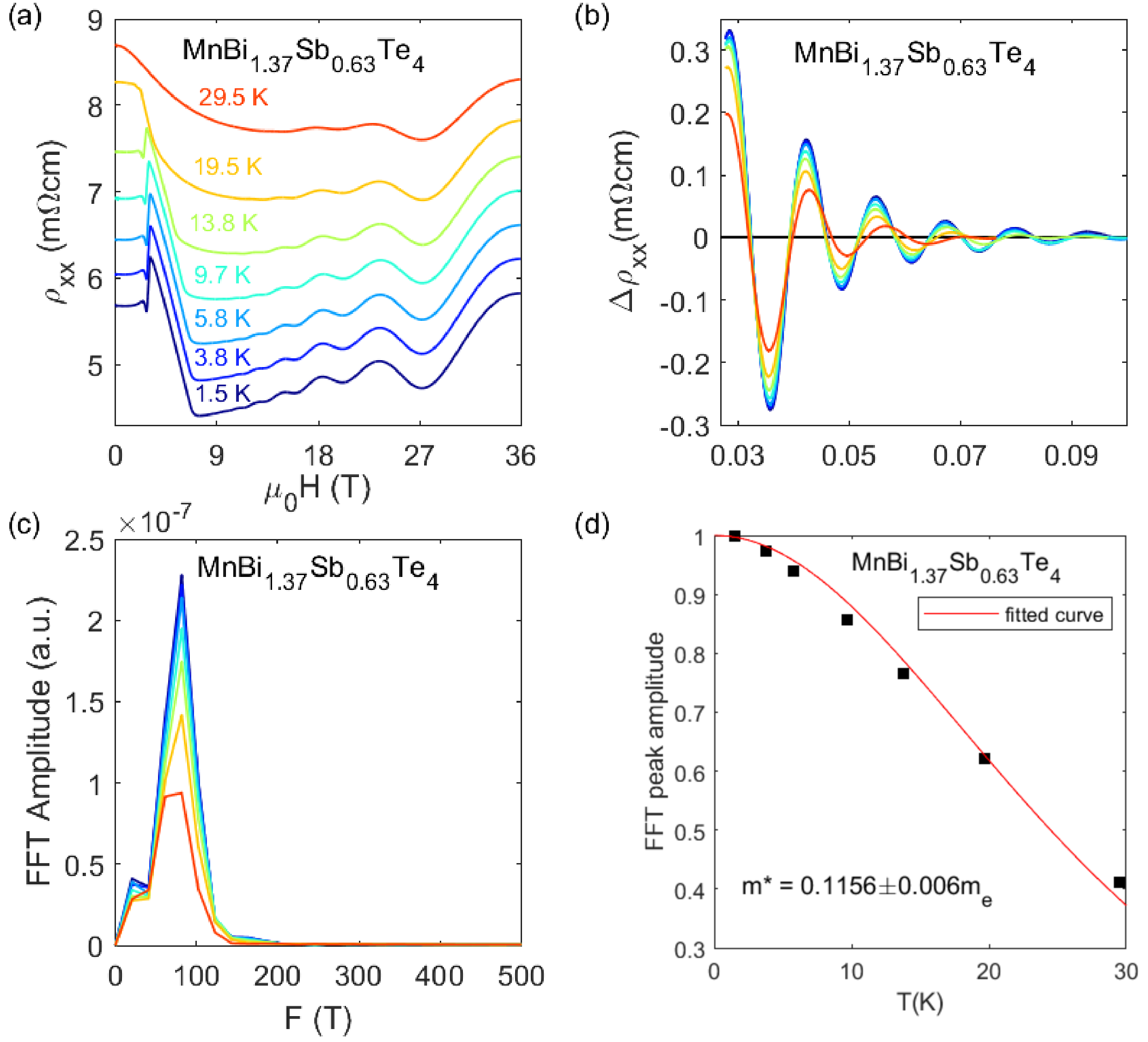
(Zhang D., et al, PRL 122.20 (2019): 206401)

Shubnikov-de Haas Oscillations of $MnBi_{2-x}Sb_xTe_4$

$\mu_0 H \parallel [001]$



$$\Delta\rho_{xx} \propto R_T R_D cos2\pi(\frac{F}{B} + \emptyset)$$



Dingle damping factor:

$$R_D = \exp(-\frac{\alpha T_D m^*}{B})$$

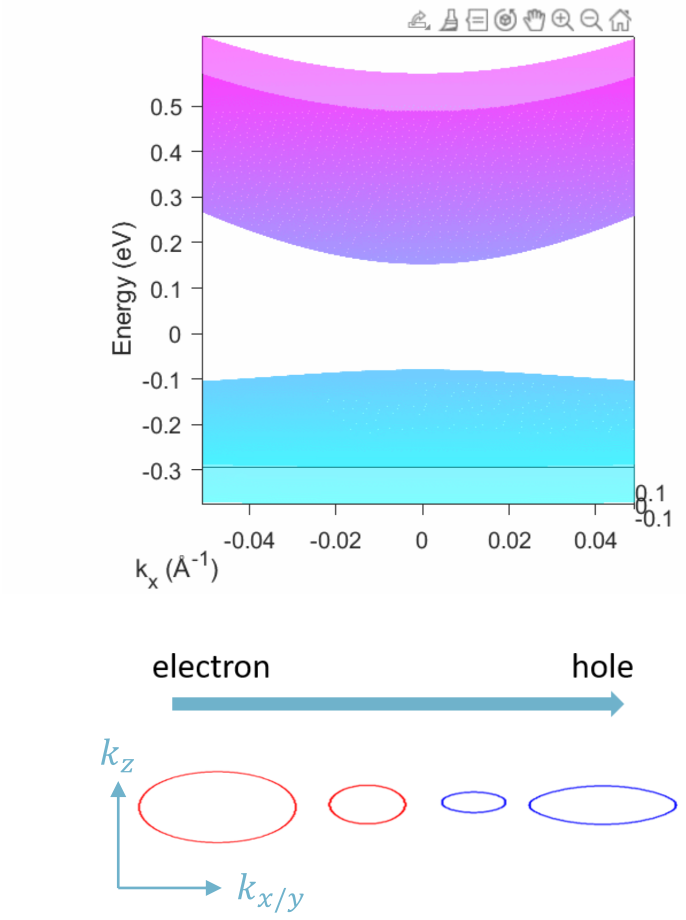
Thermal damping factor:

$$R_T = \frac{\alpha T m^*}{B sinh(\alpha T\, m^*/B)}$$

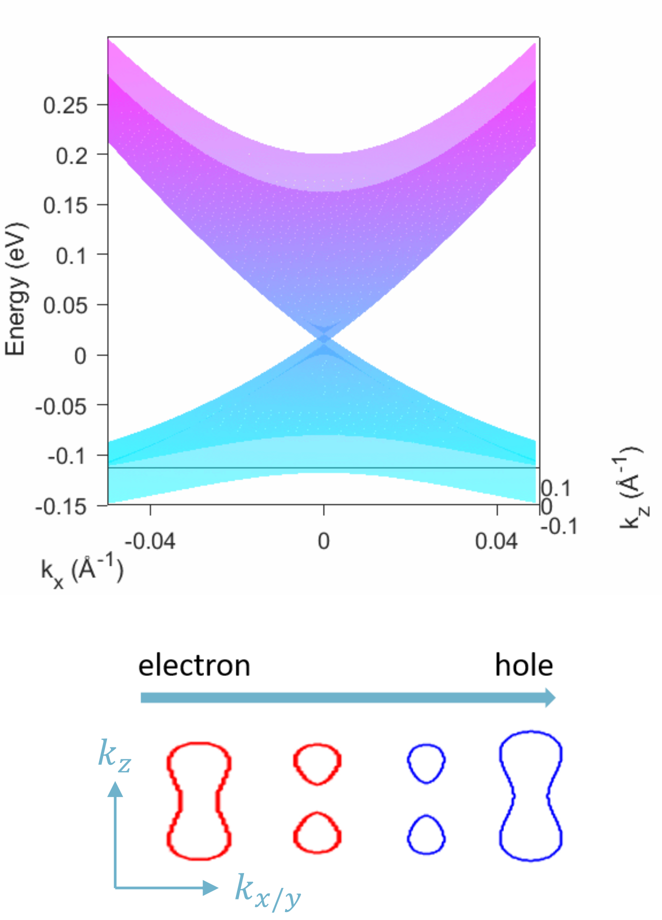
Fermi surface evolution of Weyl Semimetals

Q: How to distinguish a normal semiconductor, an ideal type-I WSM and an ideal type-II WSM in this case?

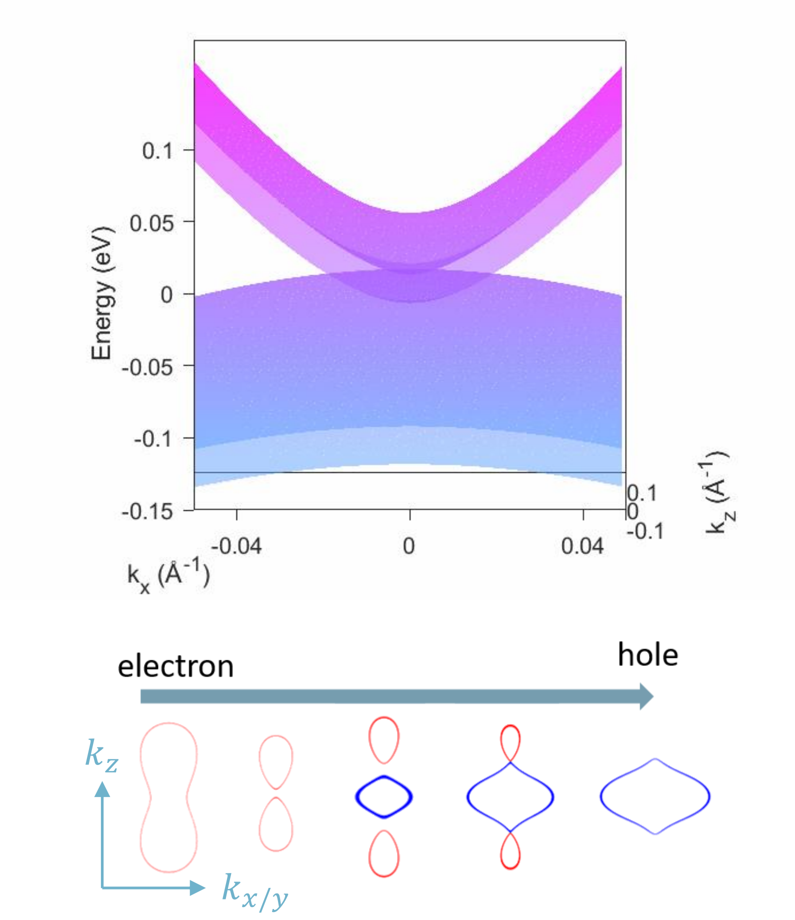
Normal Semiconductor



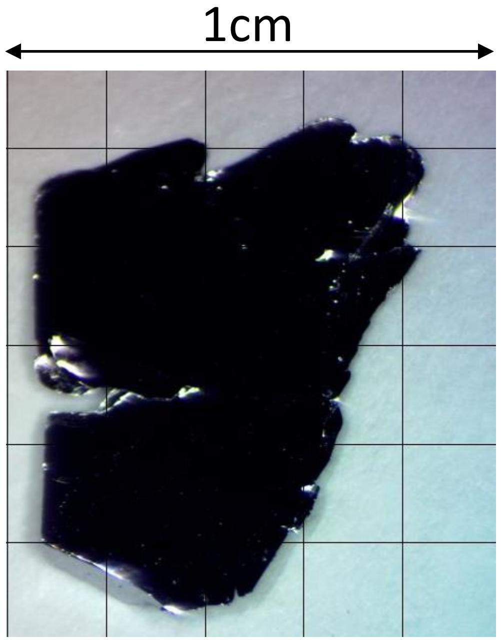
Type-I Weyl Semimetal



Type-II Weyl Semimetal

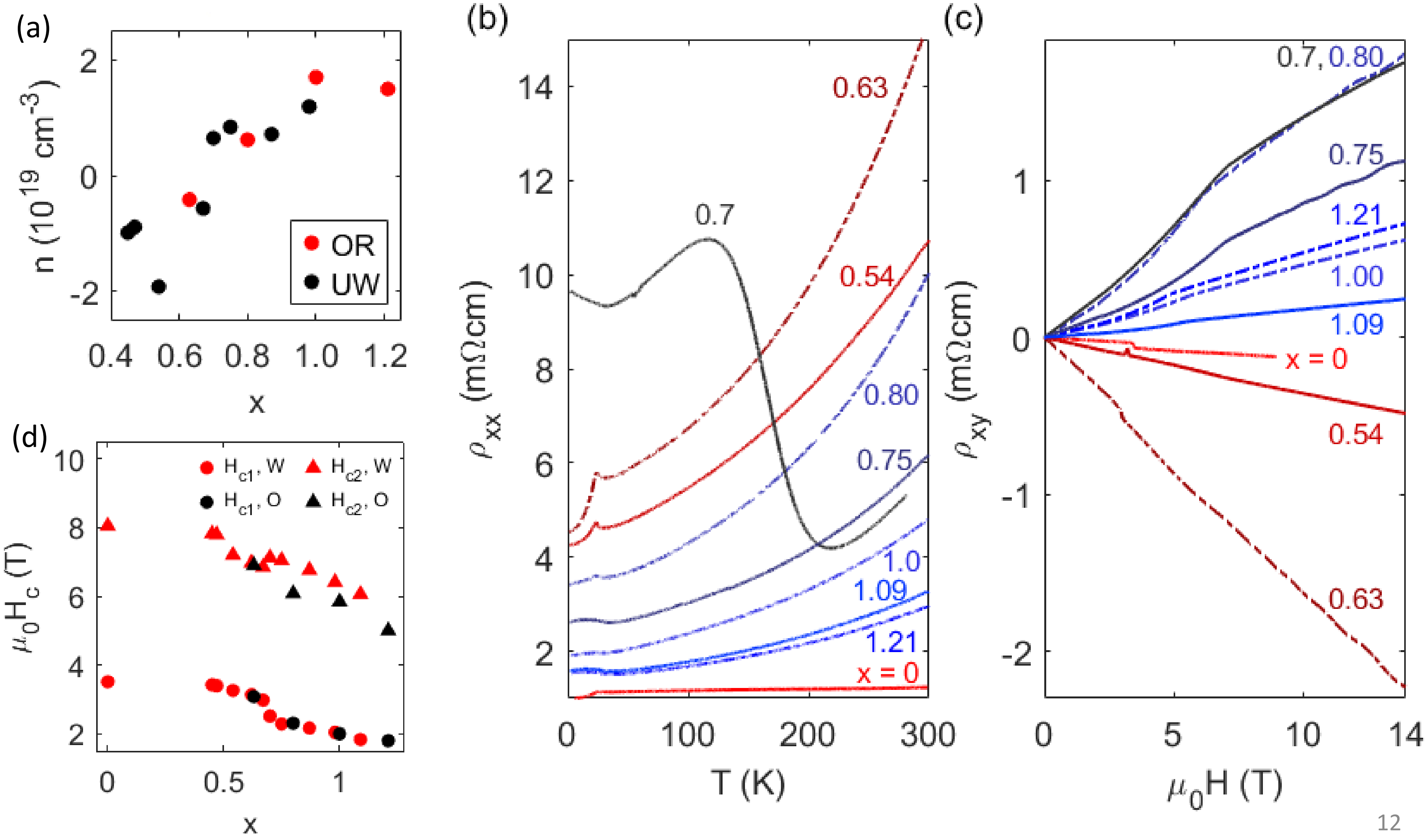


Transport Properties of $MnBi_{2-x}Sb_xTe_4$



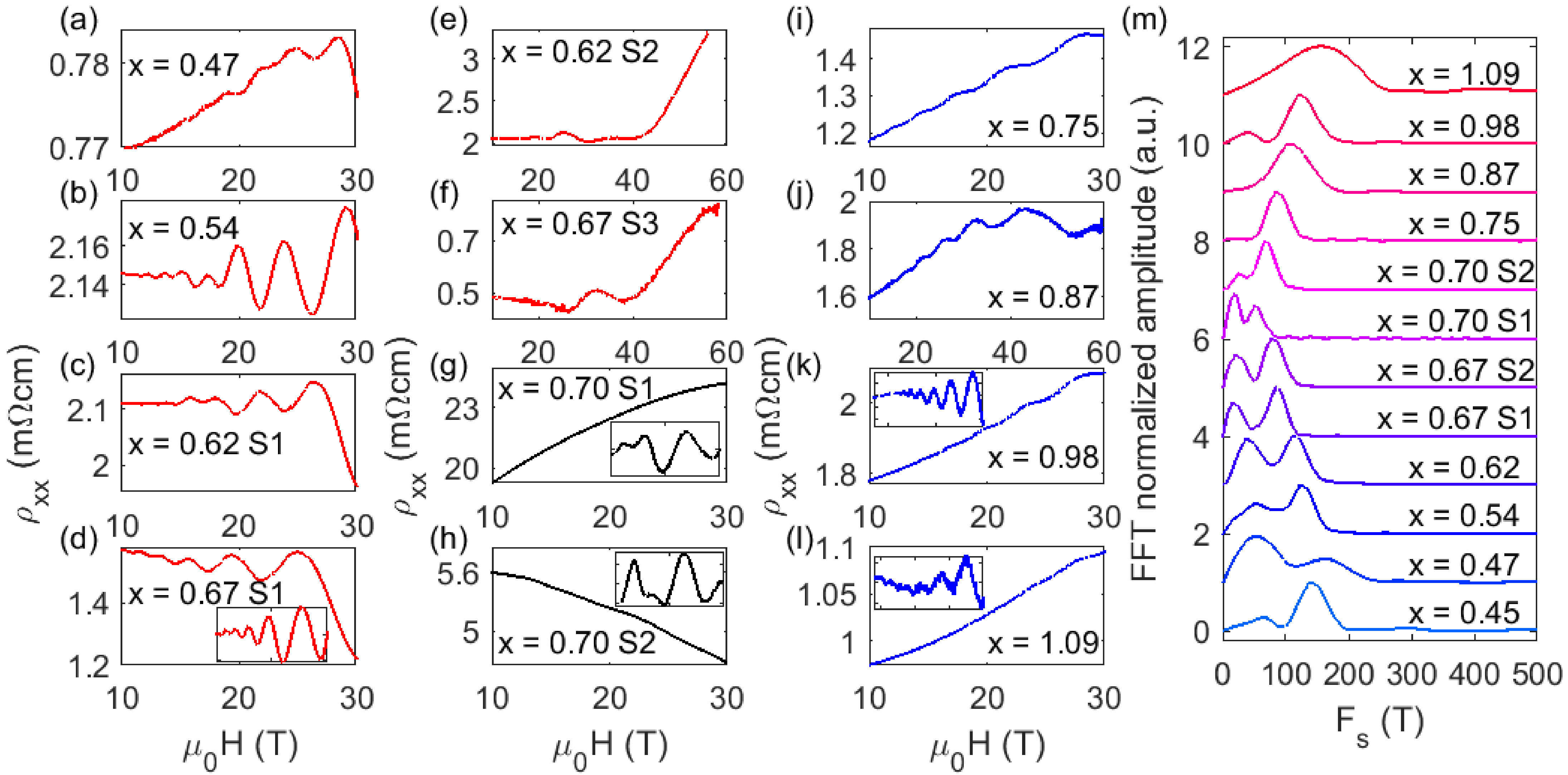
Single crystal of $MnBi_{2-x}Sb_xTe_4$

charge neutral point x ~ 0.7



Q. Jiang & J-H Chu, et al, PRB 103, 205111 (2021)

SdH Oscillations under a 31T DC Field



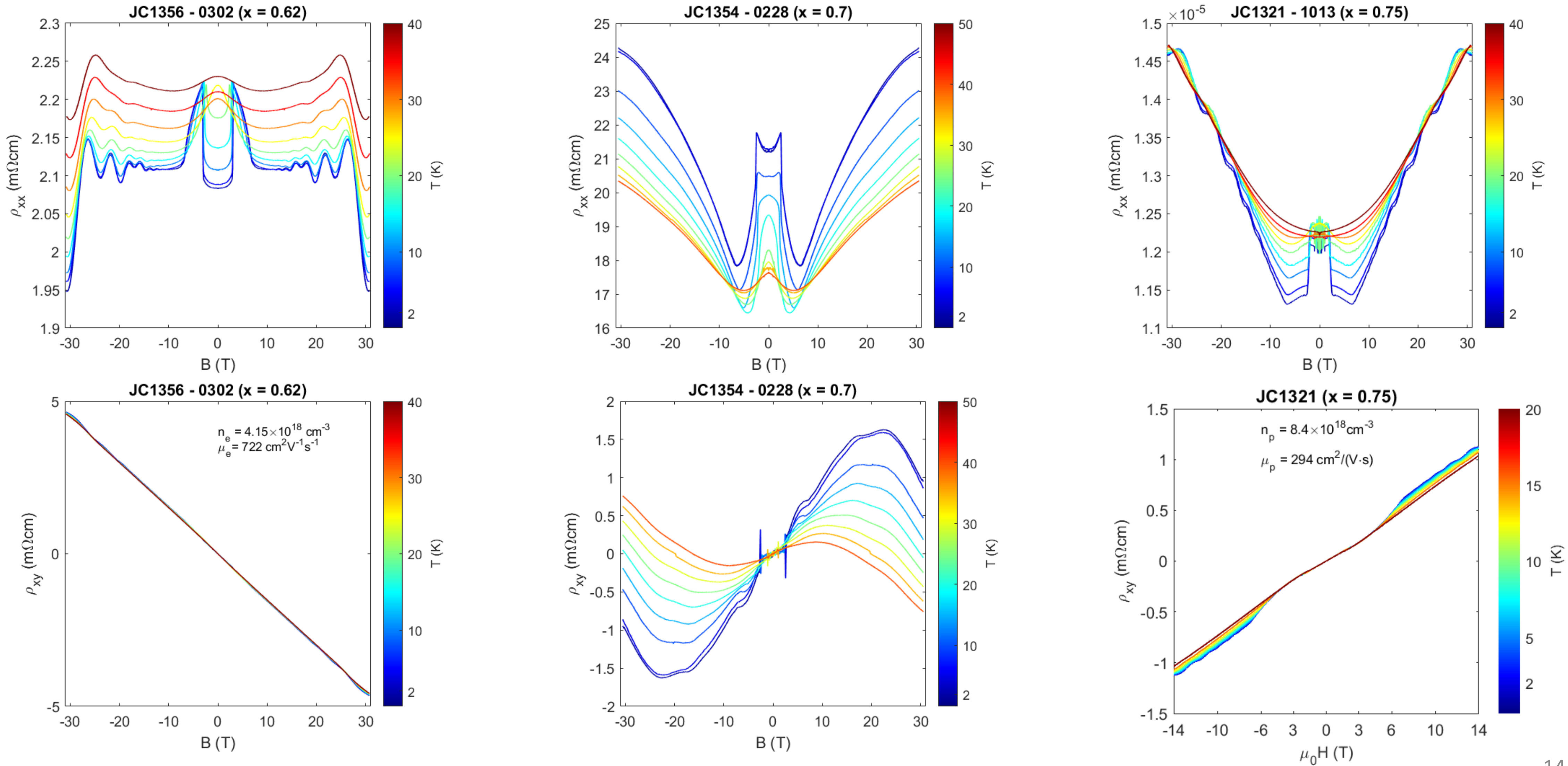
Heavily hole doped

charge neutrality

heavily Electron doped

SdH Oscillations under a 31T DC Field

$\mu_0 H \parallel [001]$

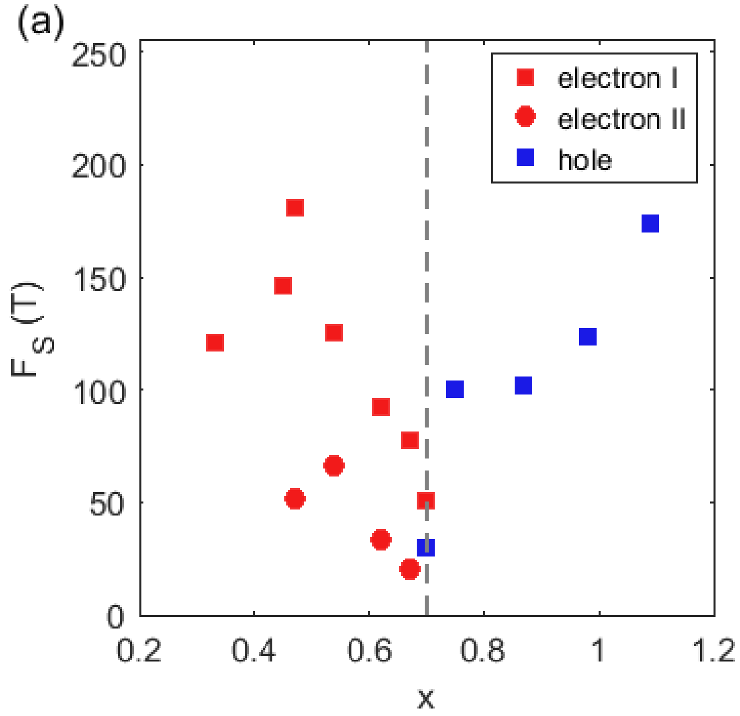


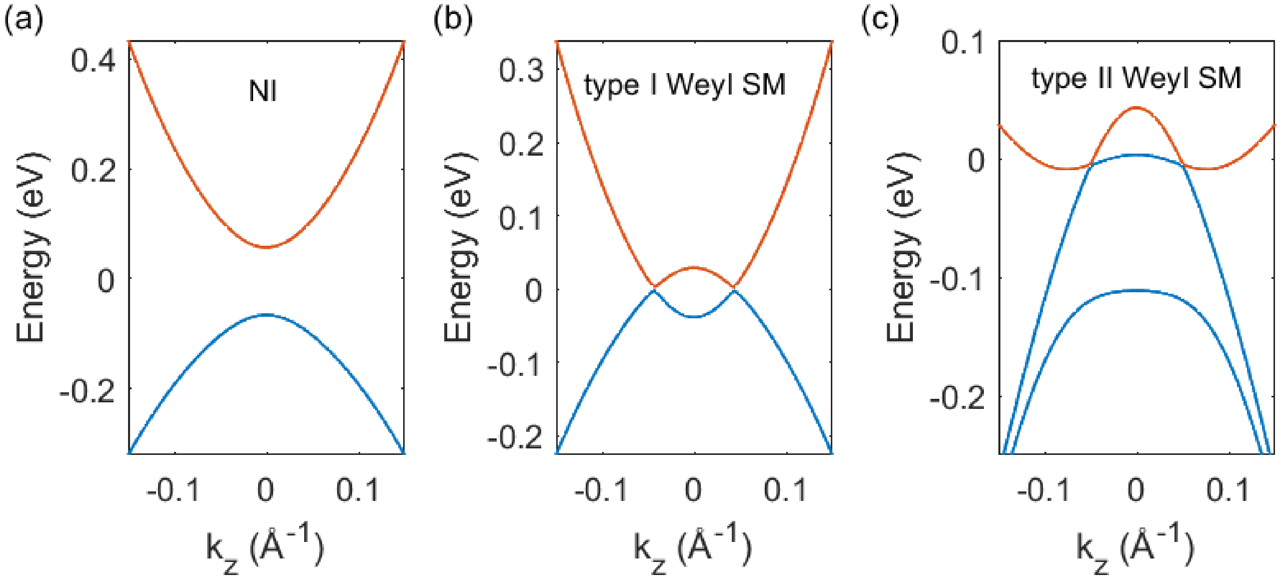
slightly electron-doped

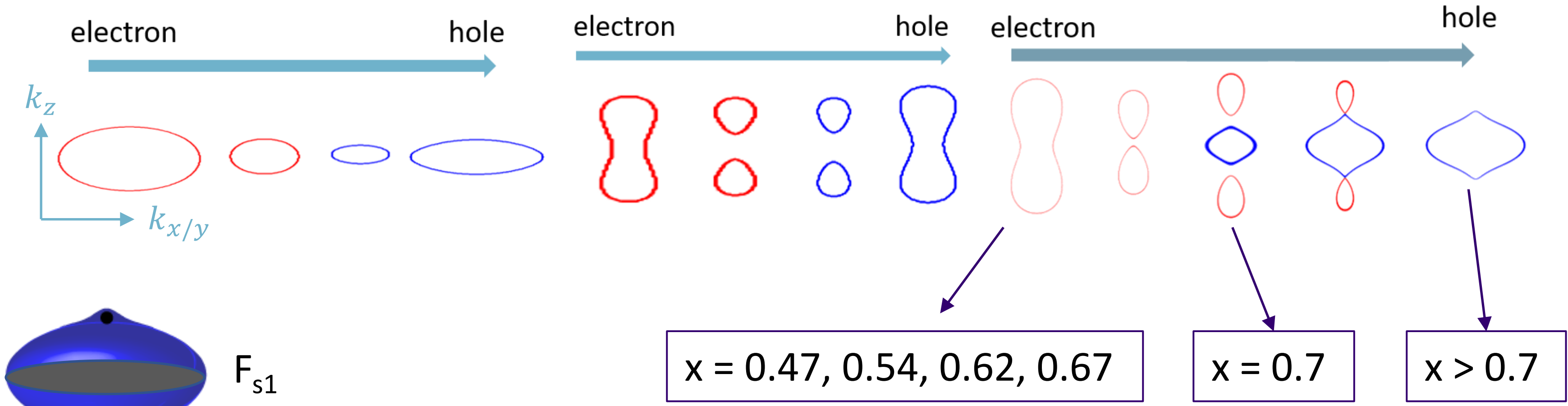
near charge neutral point

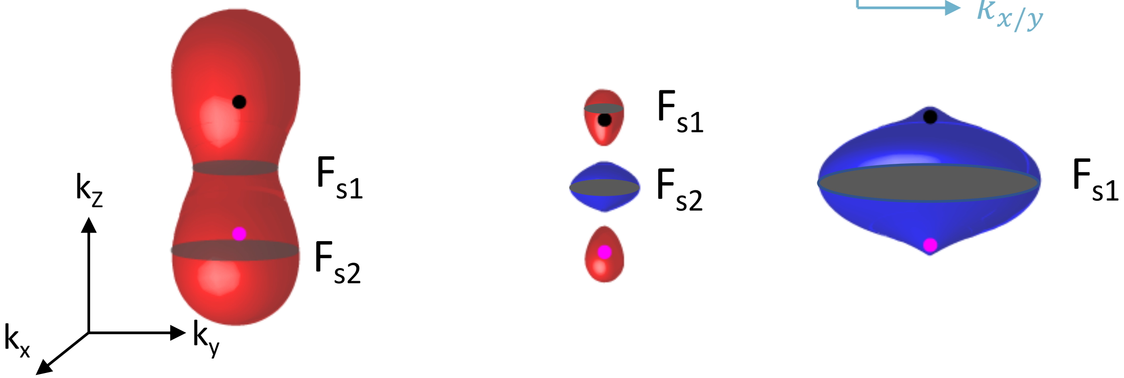
slightly hole-doped

Evolution of Fermi Pockets

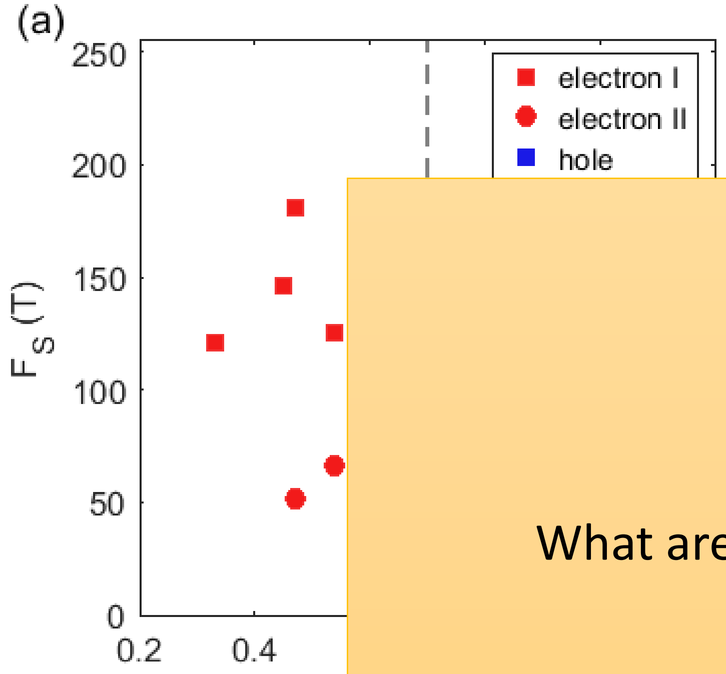


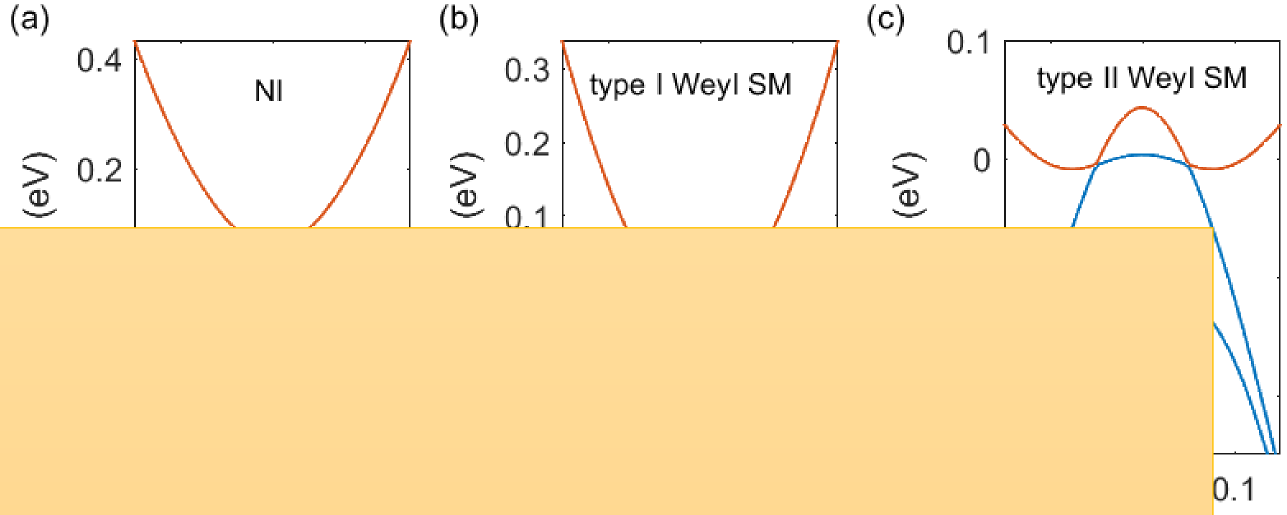




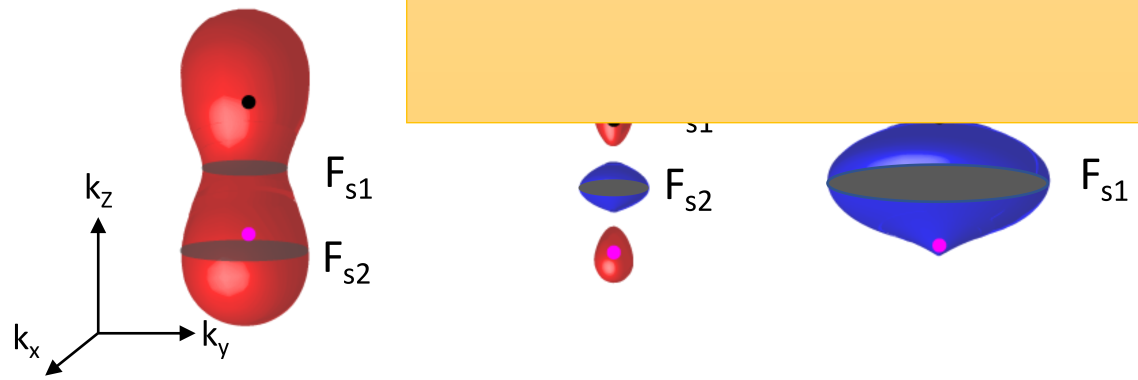


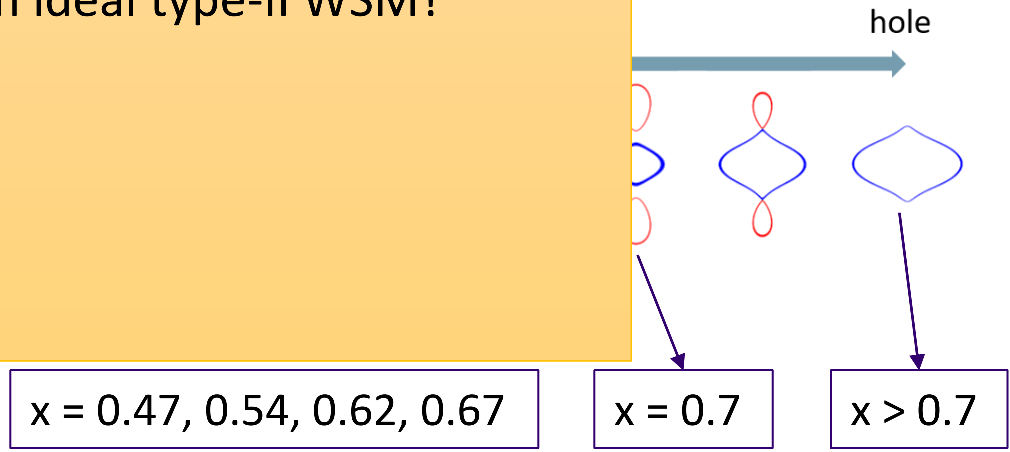
Evolution of Fermi Pockets





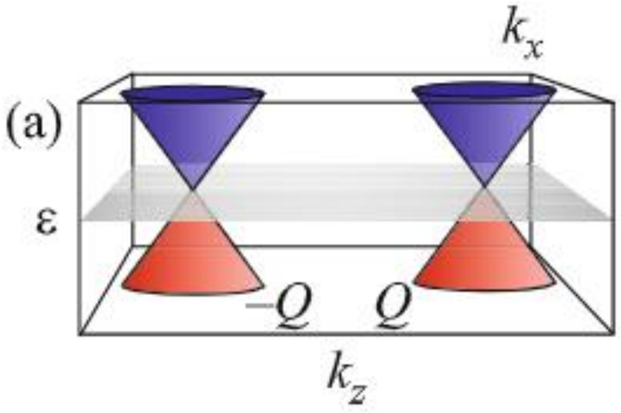
What are the observable consequences of an ideal type-II WSM?





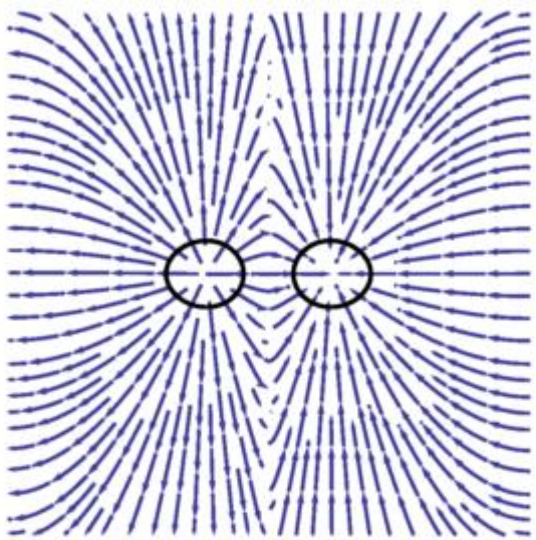
Anomalous Hall Conductivity of Ideal Weyl Semimetal

Type-I



$$\sigma_{xy} = \frac{e^2 Q}{2\pi^2 \hbar}$$

Q : Weyl points separation



Free carrier contribution:

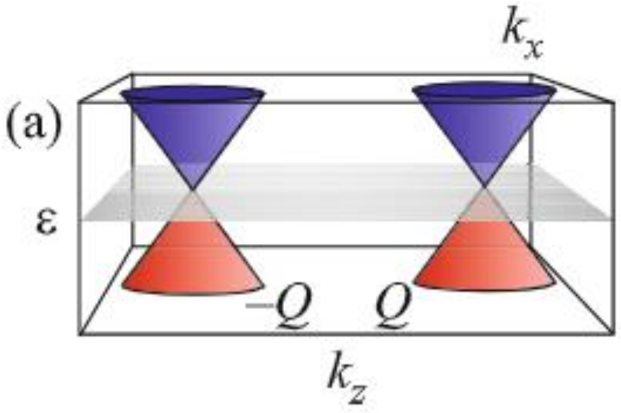
Integrate the z-component of Berry curvature over the occupied states

A. A. Burkov, Phys. Rev. Lett. **113**, 187202 (2014)

A. A. Zyuzin and R. P. Tiwari, JETP Letters, 2016, 103, 11, 717–722 (2016)

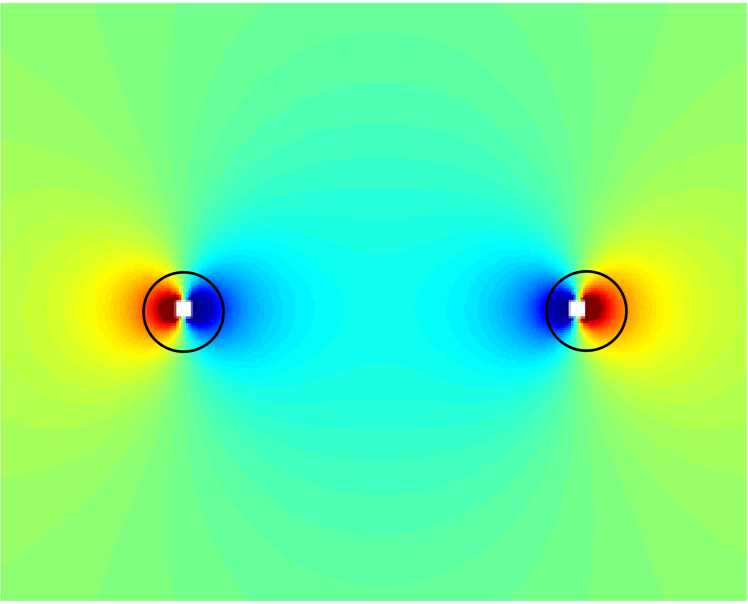
Anomalous Hall Conductivity of Ideal Weyl Semimetal

Type-I



$$\sigma_{xy} = \frac{e^2 Q}{2\pi^2 \hbar}$$

Q : Weyl points separation



Fermi Surface contribution:
Integrate the z-component of Berry curvature over the occupied states

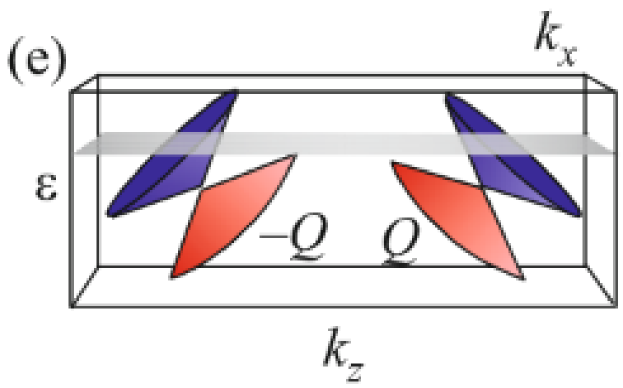
In type-I WSM the Fermi Surface contribution cancel!

A. A. Burkov, Phys. Rev. Lett. **113**, 187202 (2014)

A. A. Zyuzin and R. P. Tiwari, JETP Letters, 2016, 103, 11, 717–722 (2016)

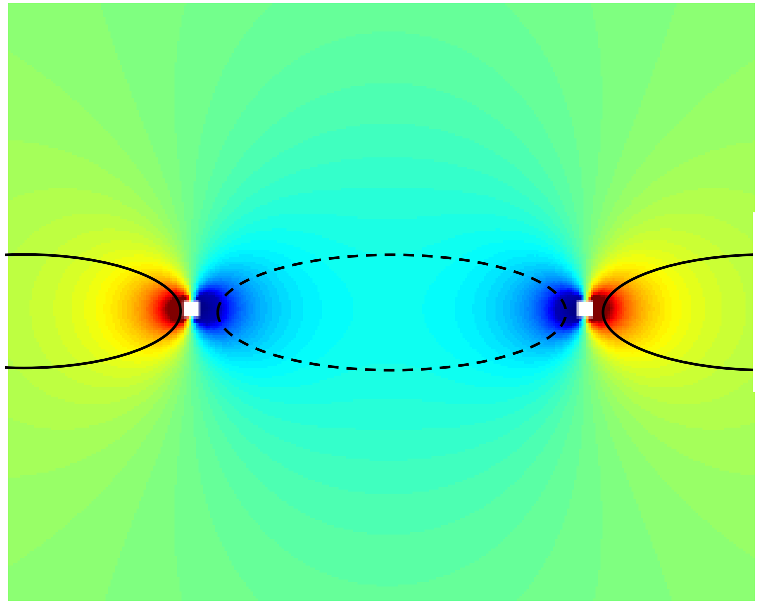
Anomalous Hall Conductivity of Ideal Weyl Semimetal

Type-II



$$\sigma_{xy} = \frac{e^2 Q}{2\pi^2 \hbar}$$

Q : Weyl points separation



Fermi Surface contribution:
Integrate the z-component of Berry curvature over the occupied states

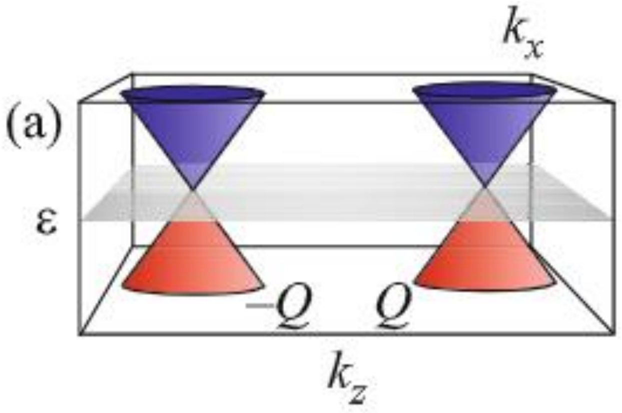
In type-II WSM the Fermi Surface contributions diverge!

A. A. Burkov, Phys. Rev. Lett. **113**, 187202 (2014)

A. A. Zyuzin and R. P. Tiwari, JETP Letters, 2016, 103, 11, 717–722 (2016)

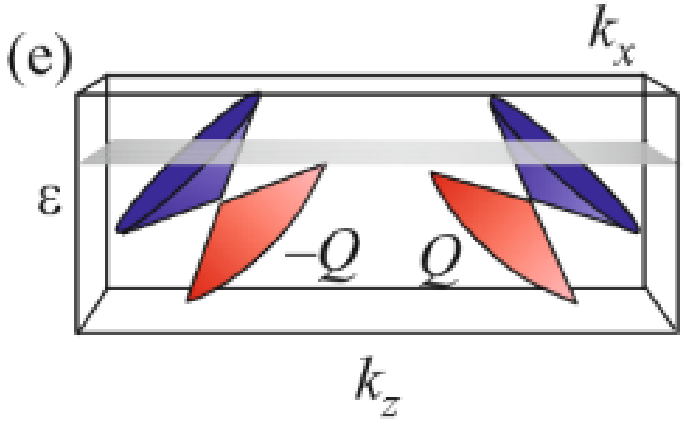
Intrinsic Anomalous Hall of Ideal Weyl Semimetal

Type-I

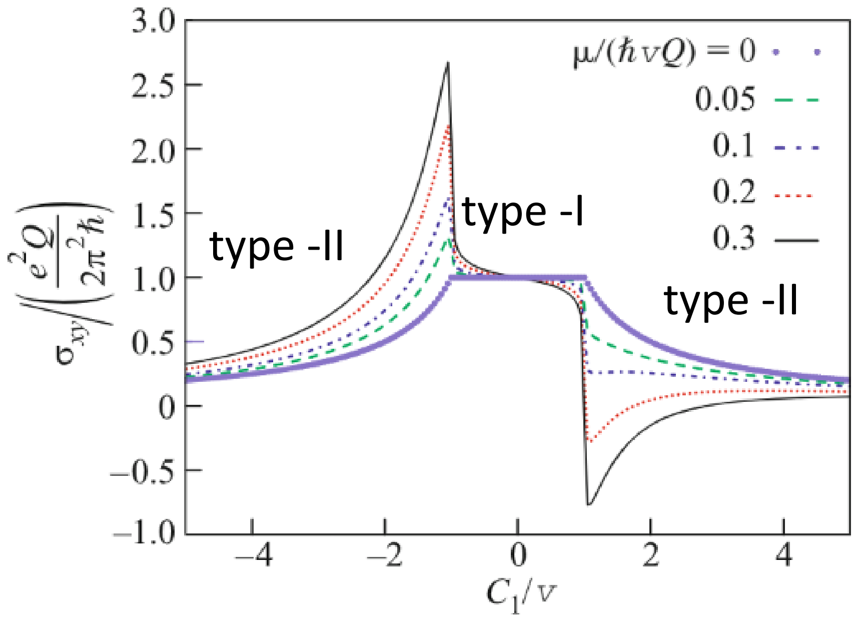


$$\sigma_{xy} = \frac{e^2 Q}{2\pi^2 \hbar}$$

Type-II



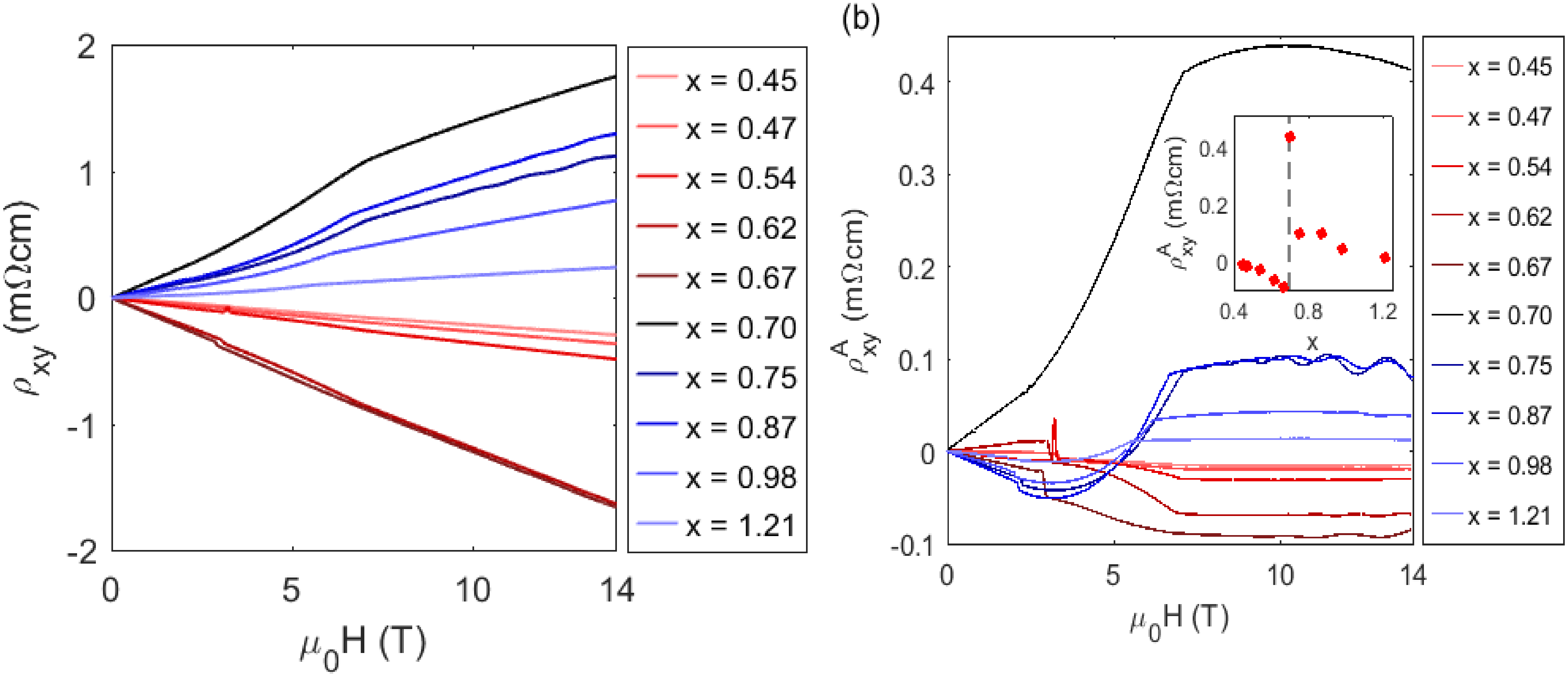
$$\sigma_{xy} = \frac{e^2}{2\pi^2\hbar}\left[Q + \frac{\mu}{4\hbar}\left(\frac{1}{C_2} - \frac{1}{C_1}\right)\left(\ln\left|\frac{2\hbar v\Lambda}{\mu}\right| - 1\right)\right]$$



A. A. Burkov, Phys. Rev. Lett. **113**, 187202 (2014)

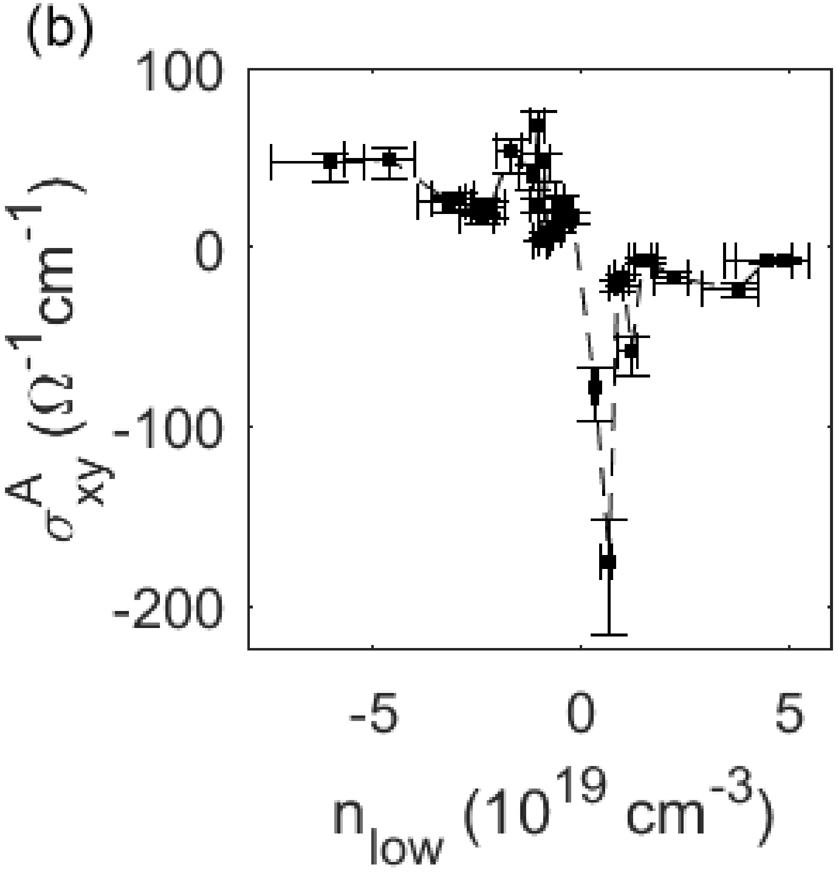
A. A. Zyuzin and R. P. Tiwari, JETP Letters, 2016, 103, 11, 717–722 (2016)

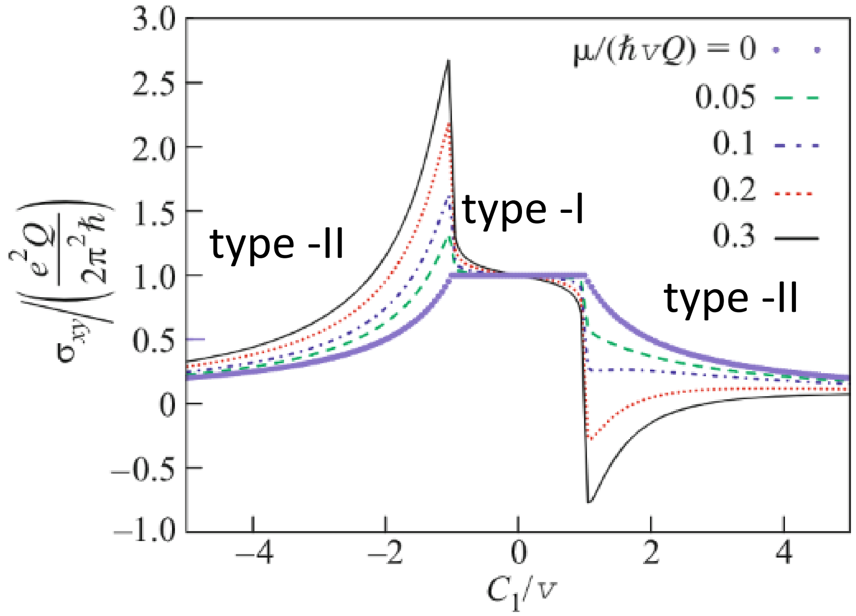
Anomalous Hall Effect in $MnBi_{2-x}Sb_xTe_4$



$$\rho_{xy}^A = \rho_{xy} - R_H \mu_0 H$$

Anomalous Hall Conductivity of $MnBi_{2-x}Sb_xTe_4$

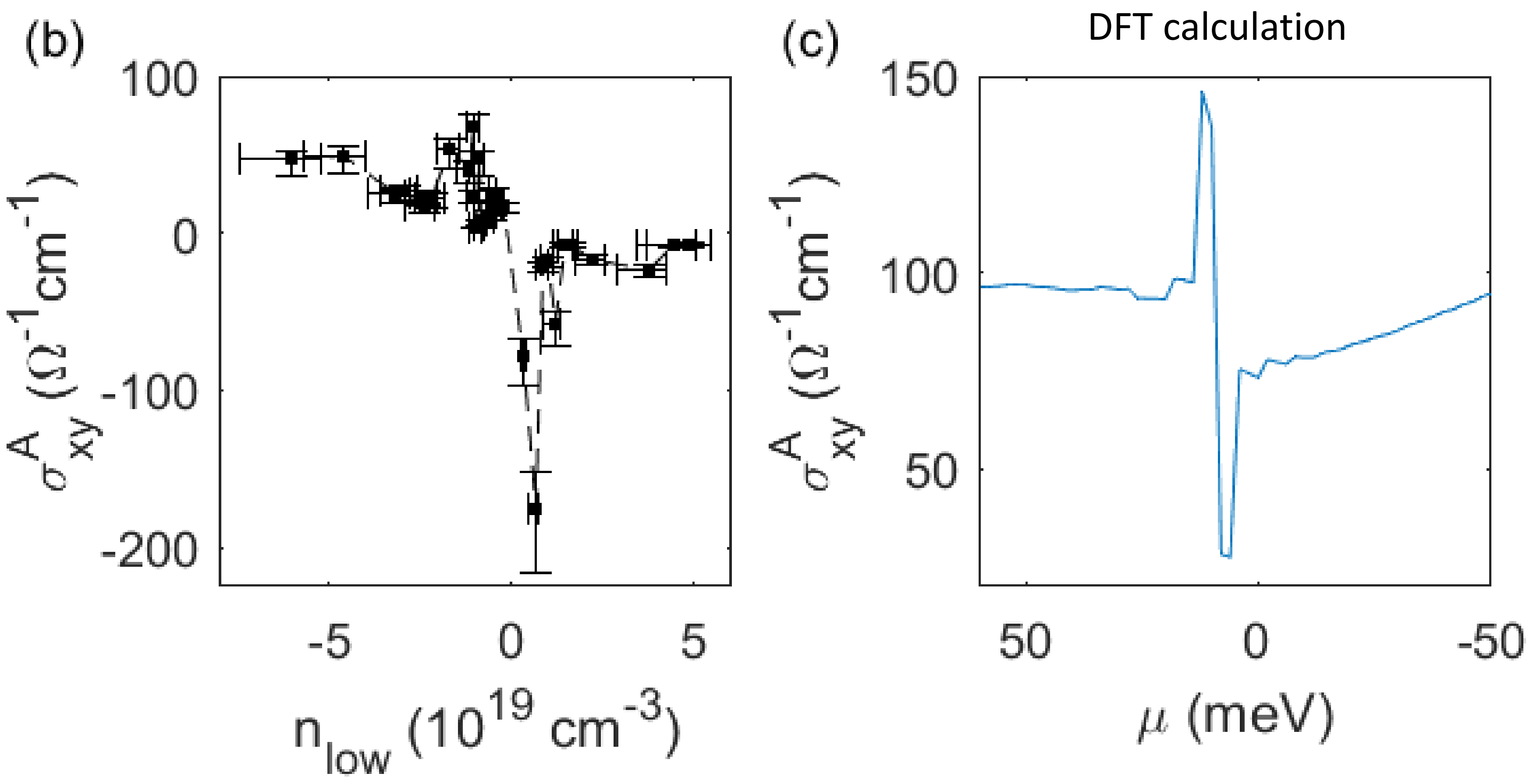




A. A. Zyuzin and R. P. Tiwari, JETP Letters, 2016, 103, 11, 717–722 (2016)

The evolution of anomalous Hall conductivity matches with the ideal type-II WSM case.

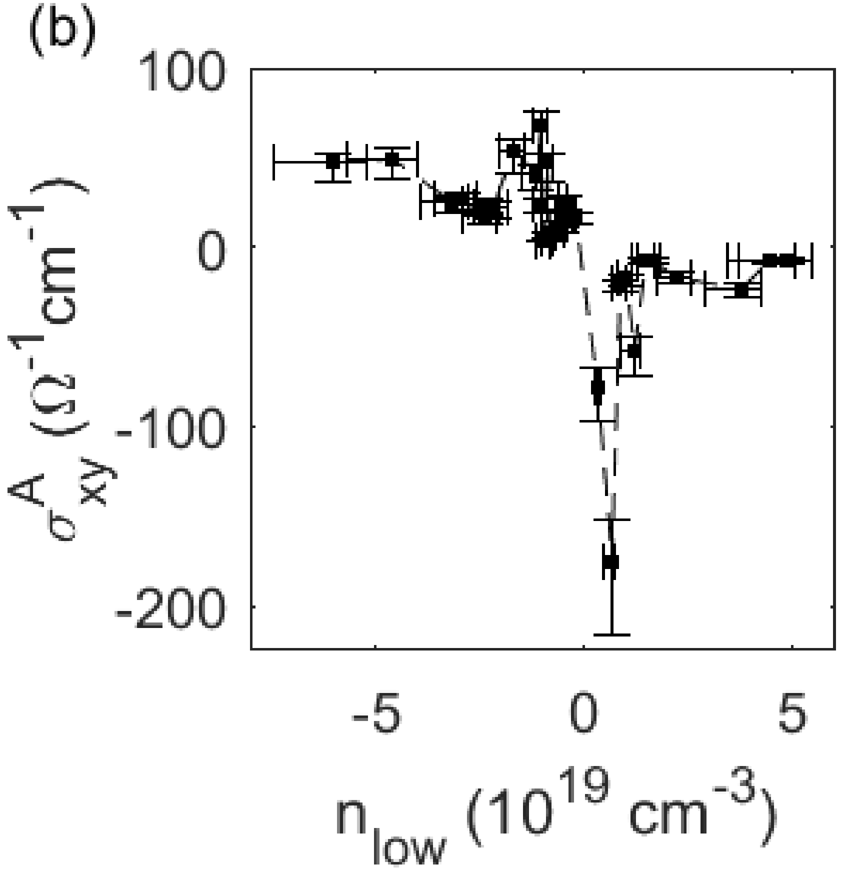
Anomalous Hall Conductivity of $MnBi_{2-x}Sb_xTe_4$

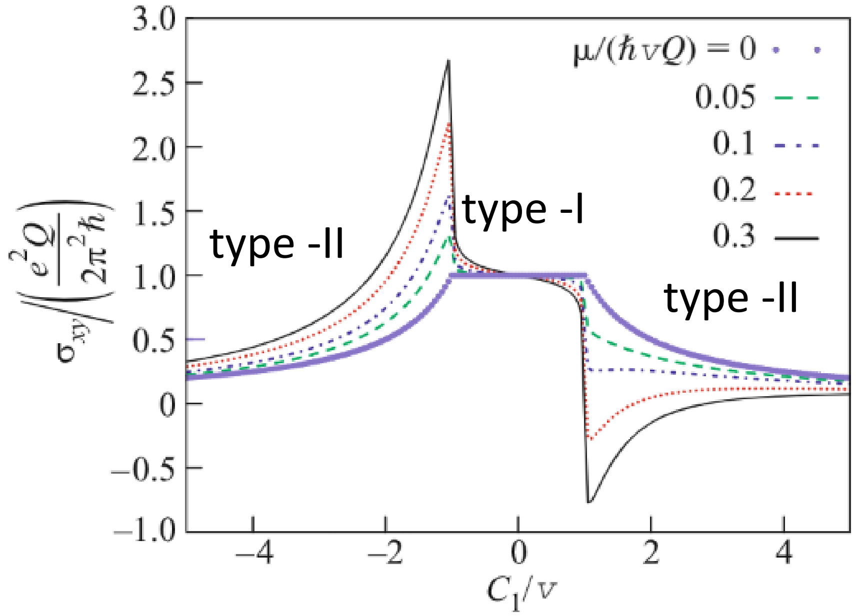


The evolution of anomalous Hall conductivity matches with the ideal type-II WSM case.

Q Jiang, J. Palmstrom, J. Singleton, J-H Chu et. al. arXiv:2306.08339 (2023)

Anomalous Hall Conductivity of $MnBi_{2-x}Sb_xTe_4$



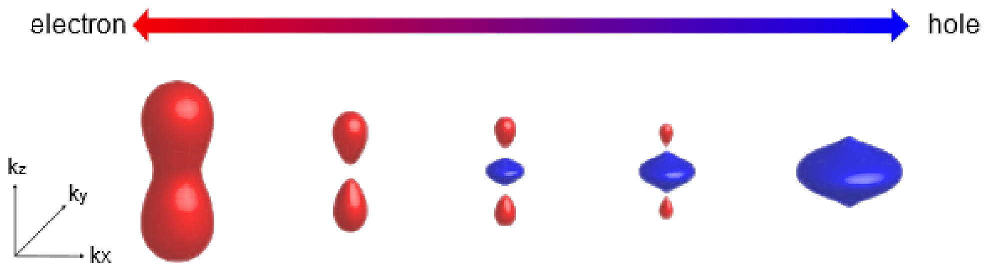


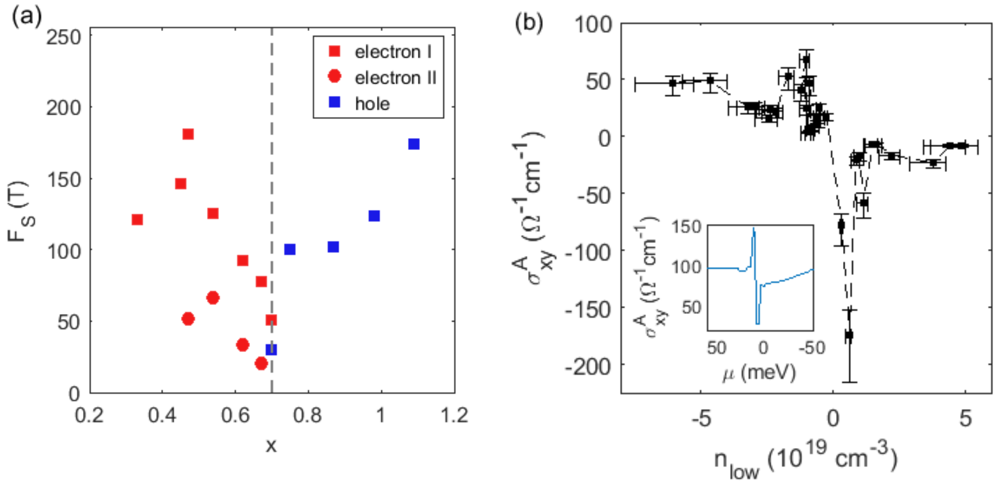
A. A. Zyuzin and R. P. Tiwari, JETP Letters, 2016, 103, 11, 717–722 (2016)

The evolution of anomalous Hall conductivity matches with the ideal type-II WSM case.

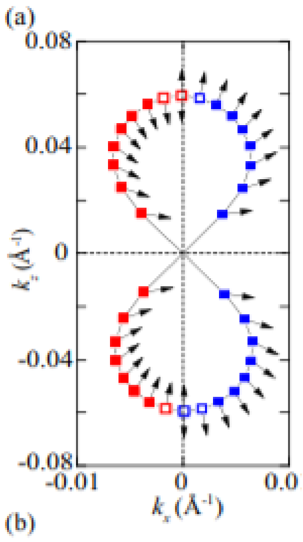
Summary

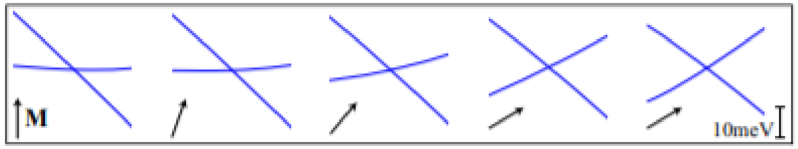
- An ideal type-II Weyl semimetal phase in Field-induced FM $MnBi_{2-x}Sb_xTe_4$

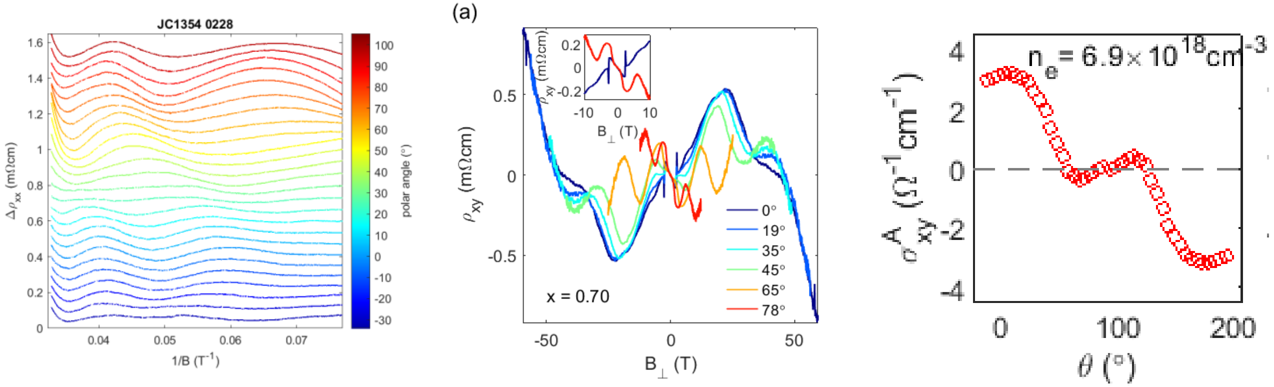




- Evidence of a type-II to type-I WSM transition by rotating the magnetic field







Q Jiang, J. Palmstrom, J. Singleton, J-H Chu et. al. arXiv:2306.08339 (2023)

Thank you!