Spin Hall Effect in Topological Semimetals

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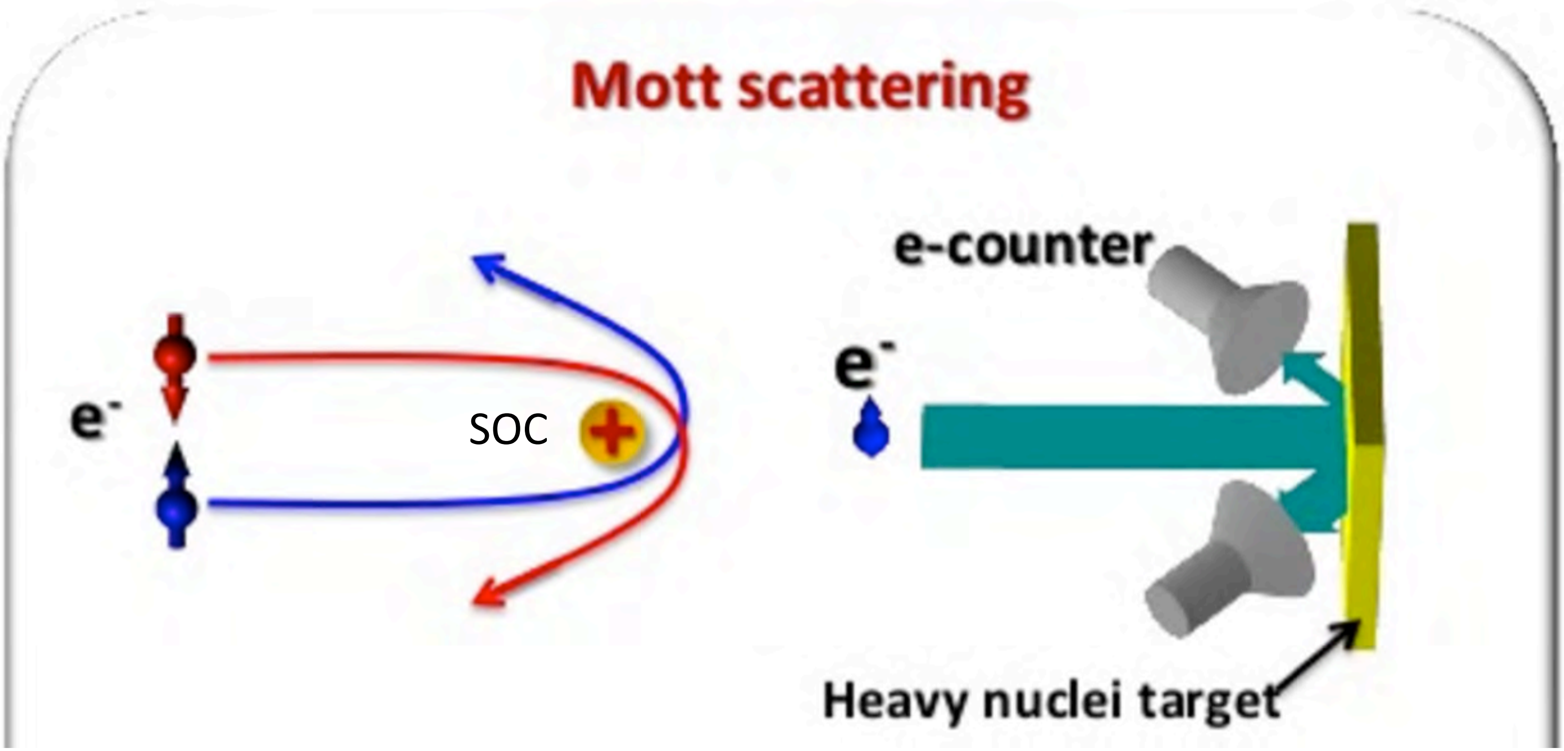
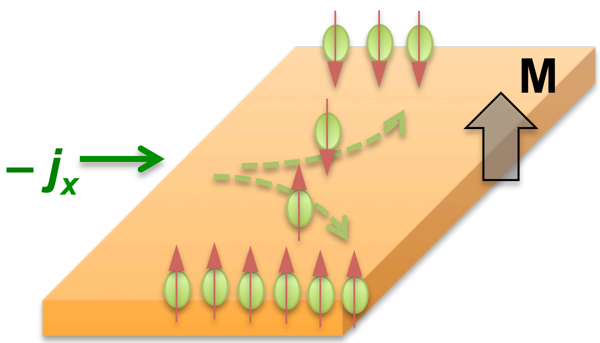


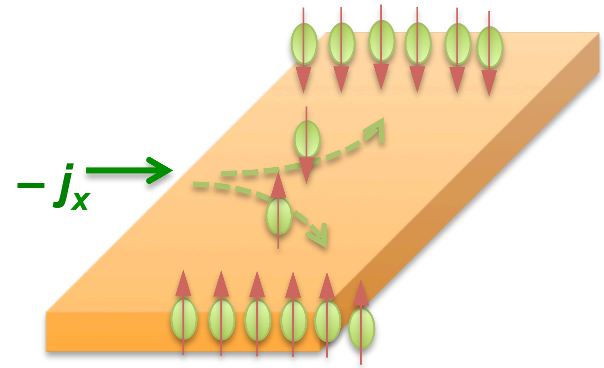
Mott scattering
e-
SOC
e-counter
e-
Heavy nuclei target

Anomalous Hall effect



$$j^{AHE} = j^{\uparrow} - j^{\downarrow}$$

Spin Hall Effect

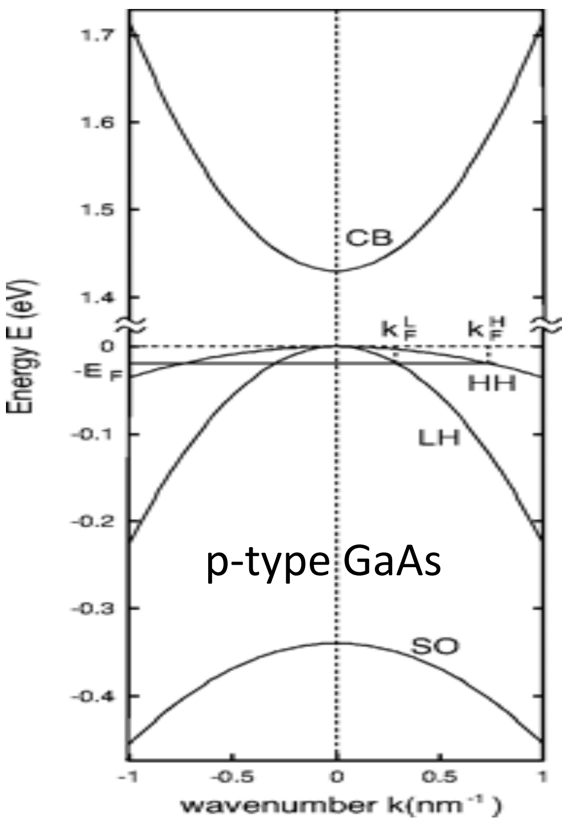


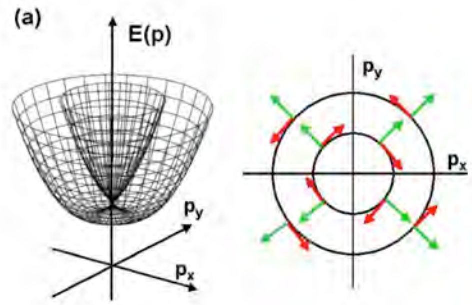
$$j^{SHE} = j^{\uparrow} + j^{\downarrow} \qquad \frac{\hbar/2}{e}$$

> The spin Hall effect:
> an external electric field induces a transverse spin current

An extrinsic effect, due to impurities in the presence of spin-orbit coupling (SOC).

Intrinsic Spin Hall Effect





SHE due to the band structure of the material

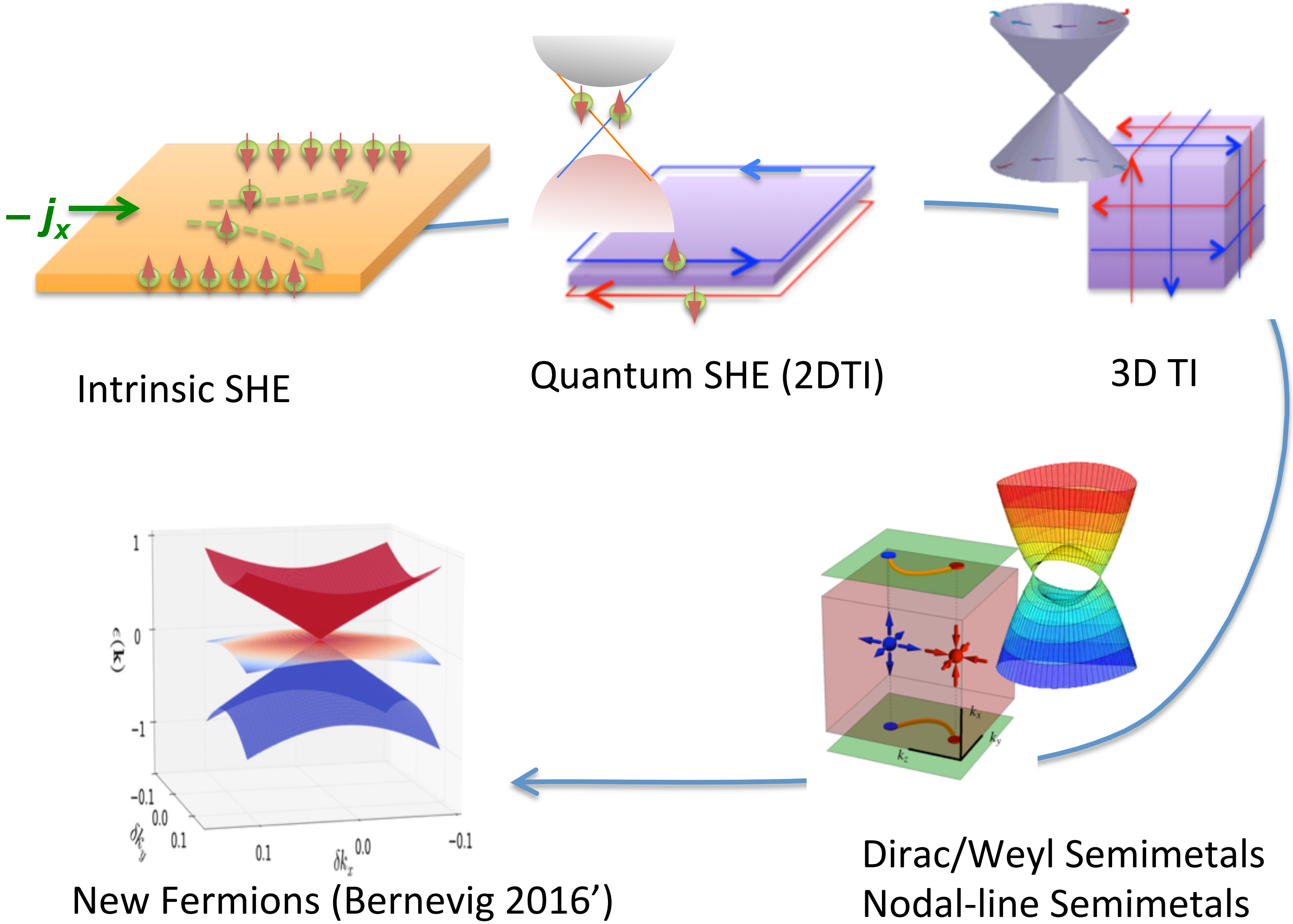
$$\sigma_{xy} = -\frac{e^2}{2\pi h} \sum_n \int_{BZ} d^2k \; n_F(\epsilon_n(\boldsymbol{k})) B_{nz}(\boldsymbol{k}),$$

Berry curvature
A fictitious magnetic field

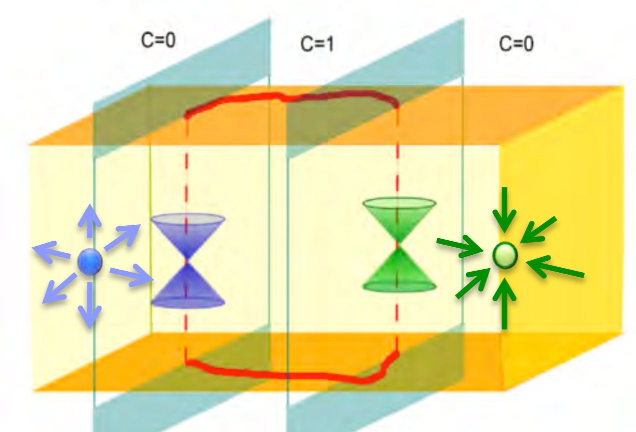
SHE metals -- > SHE insulators

Murakami, N. Nagaosa, and S. C. Zhang, Science 301, 1348 (2003).
J. Sinova, D. Culcer, Q. Niu, N. A. Sinitsyn, T. Jungwirth, and A. H. MacDonald, Phys. Rev. Lett. 92, 126603 (2004).

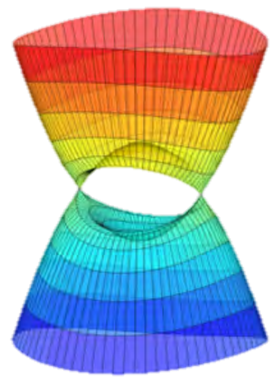
Spin Hall Effect and other topological states

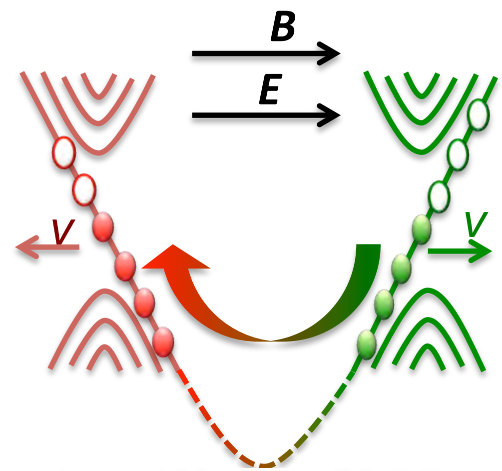


Weyl Semimetals



$$H = \pm \sigma \cdot p$$

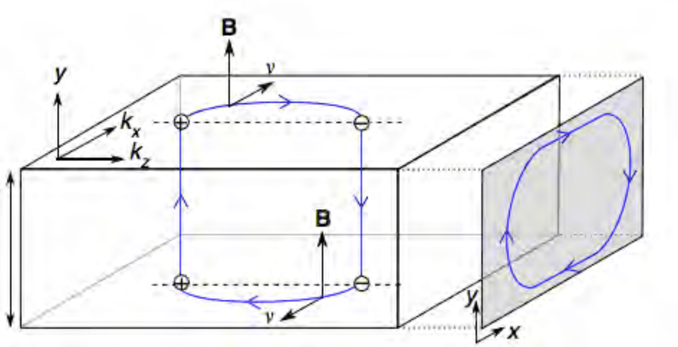




$$\frac{\partial Q_\chi^{3D}}{\partial t} = g\frac{\partial Q_\chi^{1D}}{\partial t} = -V\frac{e^3}{4\pi^2\hbar^2}\boldsymbol{E}\cdot\boldsymbol{B}$$

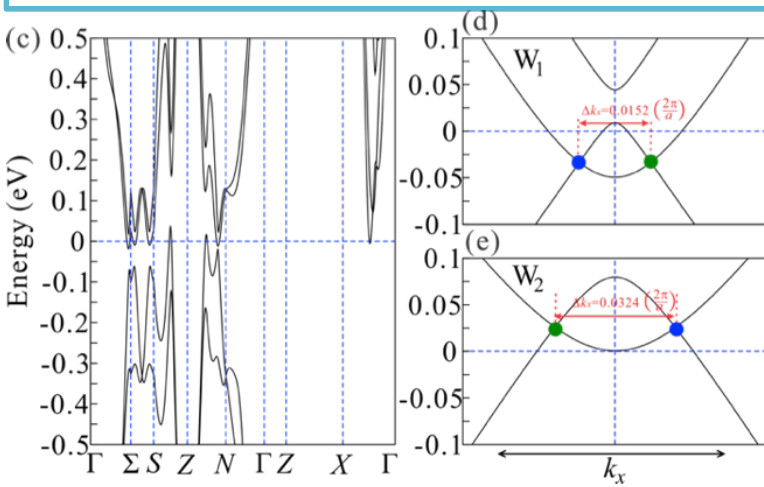
Fermi arcs

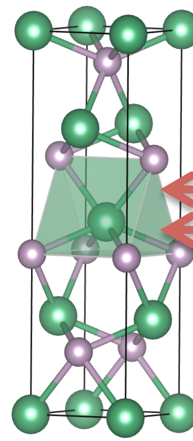
Chiral anomaly

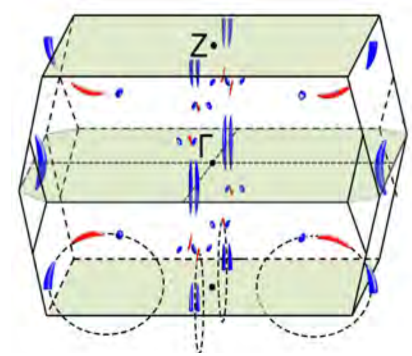


- **Bulk, 3D analogue of graphene**
- **Surface, Fermi arcs**

Reality in materials: bulk

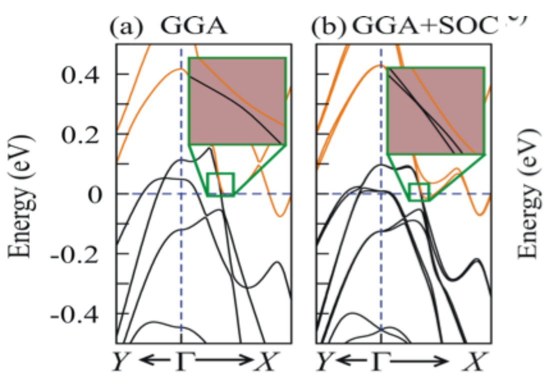


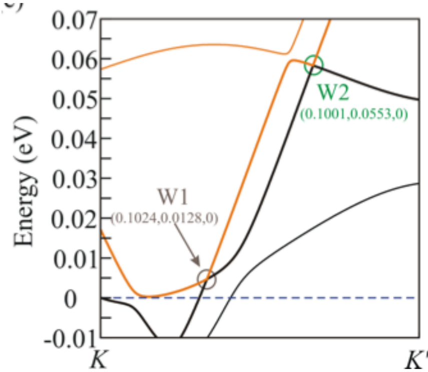


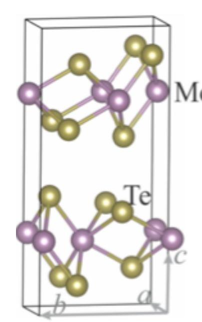


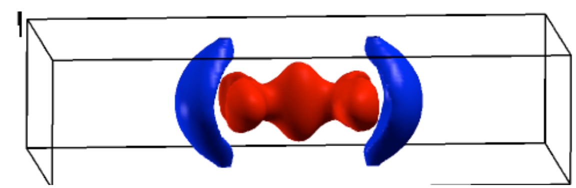
Weng, H. *et al.* *Phys. Rev. X* **5,** 011029 (2015).
Huang, S.-M. *et al. Nature Commun.* **6,** 7373 (2015).

F. Arnold et al., Nature Commun. 7, 11615 (2016).
C. Shekhar et al. Nature Physics 11, 645 (2015).









WTe2, MoTe2
ZrSiS

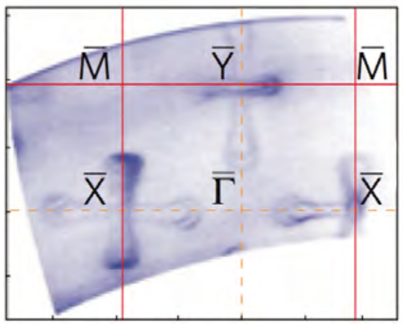
A. A. Soluyanov et al. Nature 527, 495 (2015).
Y. Sun et al. PRB 92, 161107(R) (2015).
L. M. Schoop et al. Nature Comm. 7, 11696 (2016).
M. N. Ali et al. Nature 514, 205 (2014).

Very bulk conductive

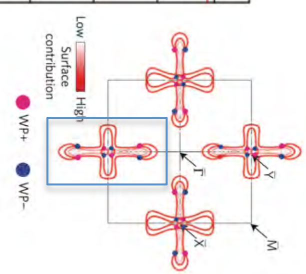
- High mobility
- Large MR

Reality in materials: Fermi arcs

TaAs



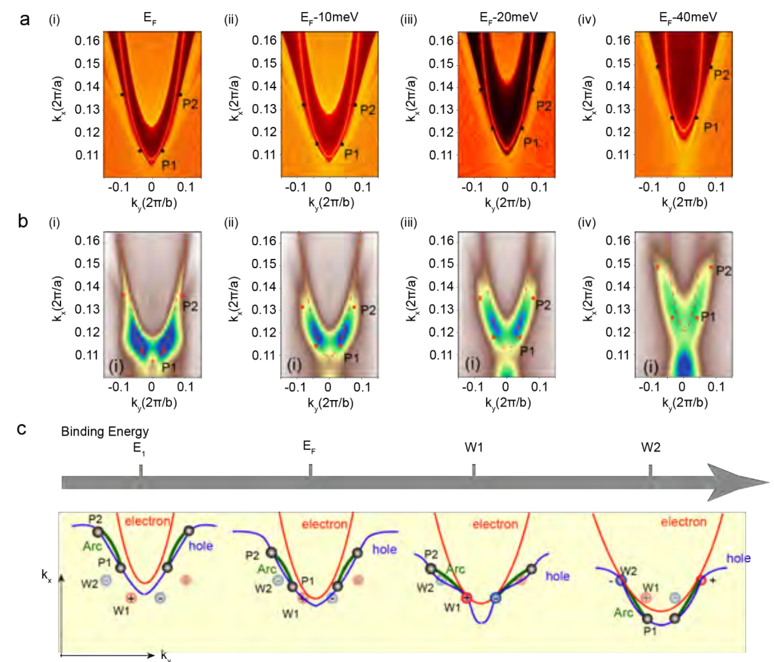
ARPES



Calculation

L.X. Yang et al. Nature Physics 11, 728–732 (2015)
B. Q. Lv *et al.*, *Phys. Rev. X* 5, 031013 (2015).
S.-Y. Xu *et al.*, *Science* 349, 613 (2015).

MoTe2



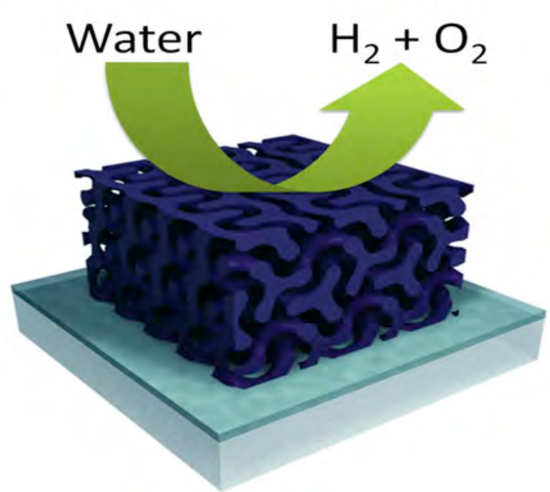
Jiang et al. 2016. arXiv:1604.00139

- Bulk bands
- Trivial surface states

Topological states for catalysis

Topological chemistry

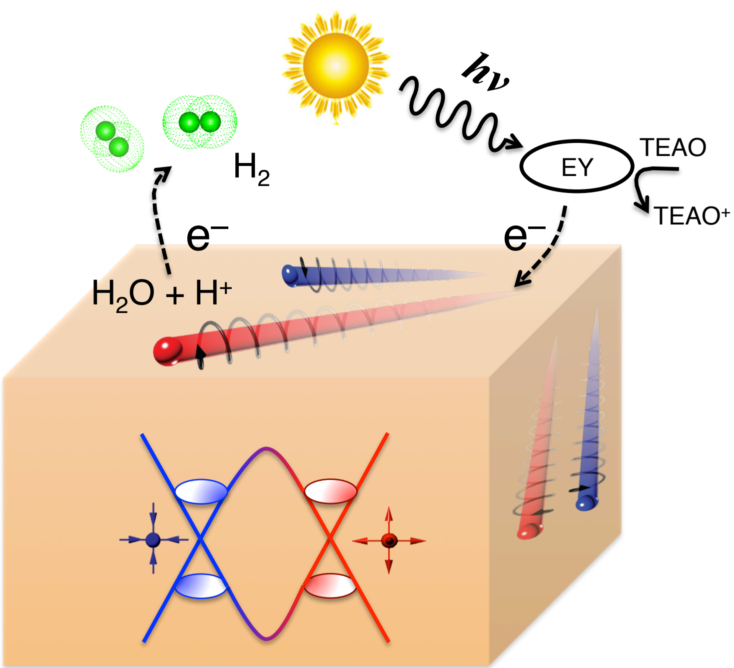
- Impact of topological states in the surface-related process e.g. catalysis
- Discovery of topological states on Au, Pt and Pd. [Nat. Comm. 6, 10167(2015)]
- Design of new catalysts from topological insulators and semimetals

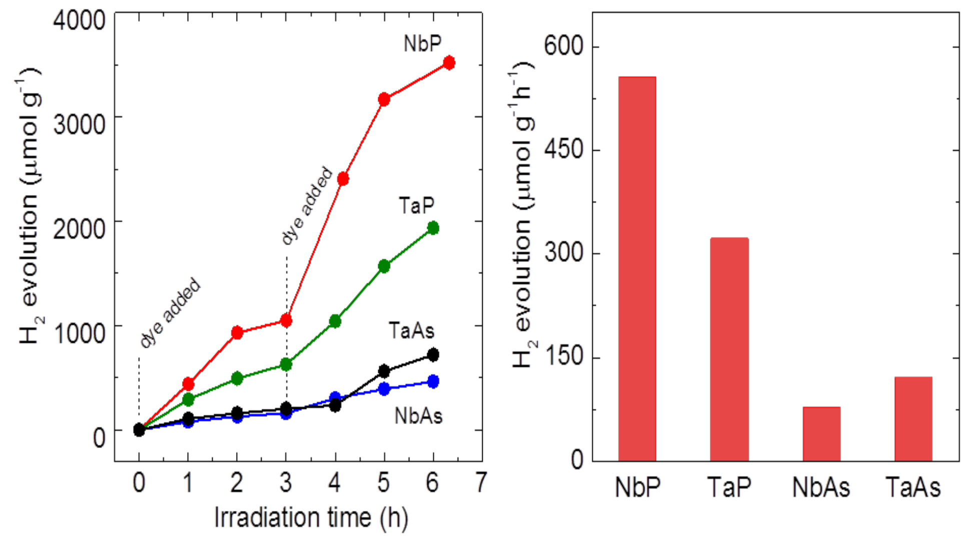


Topological states for catalysis

Proof of the principles: Solar hydrogen evolution catalyzed by WSMs

$H_2O \rightarrow H_2$





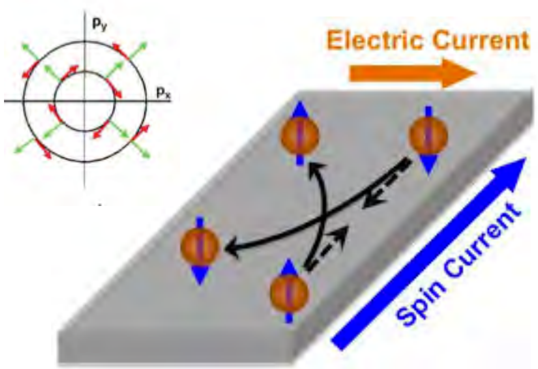
Rajamathi et al. submitted.

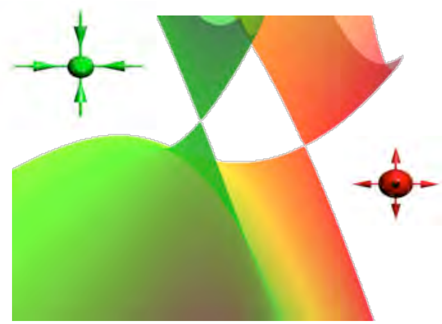
Comparable to MoS_2 in the photocatalytic HER.

- Stable surface states
- Surface-bulk-surface tunneling
- Highly mobile electrons

WSMs/DSMs for Spintronics

Spin Hall Effect for room temperature devices
(talks of Hyunsoo Yang & Timothy Phung)



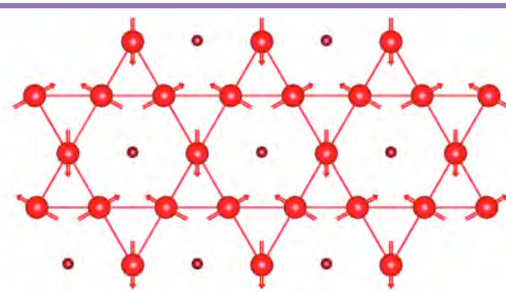


$$\sigma_{xy}^{z} = \frac{e}{\hbar}\sum_{\mathbf{k}}\Omega^{z}(\mathbf{k}) = \frac{e}{\hbar}\sum_{\mathbf{k}}\sum_{n} f_{\mathbf{k}n}\Omega_{n}^{z}(\mathbf{k}),$$

$$\Omega_{n}^{z}(\mathbf{k}) = \sum_{n'\neq n}\frac{2\mathrm{Im}\left[\langle\mathbf{k}n|j_{x}^{z}|\mathbf{k}n'\rangle\langle\mathbf{k}n'|v_{y}|\mathbf{k}n\rangle\right]}{(\epsilon_{\mathbf{k}n}-\epsilon_{\mathbf{k}n'})^{2}},$$

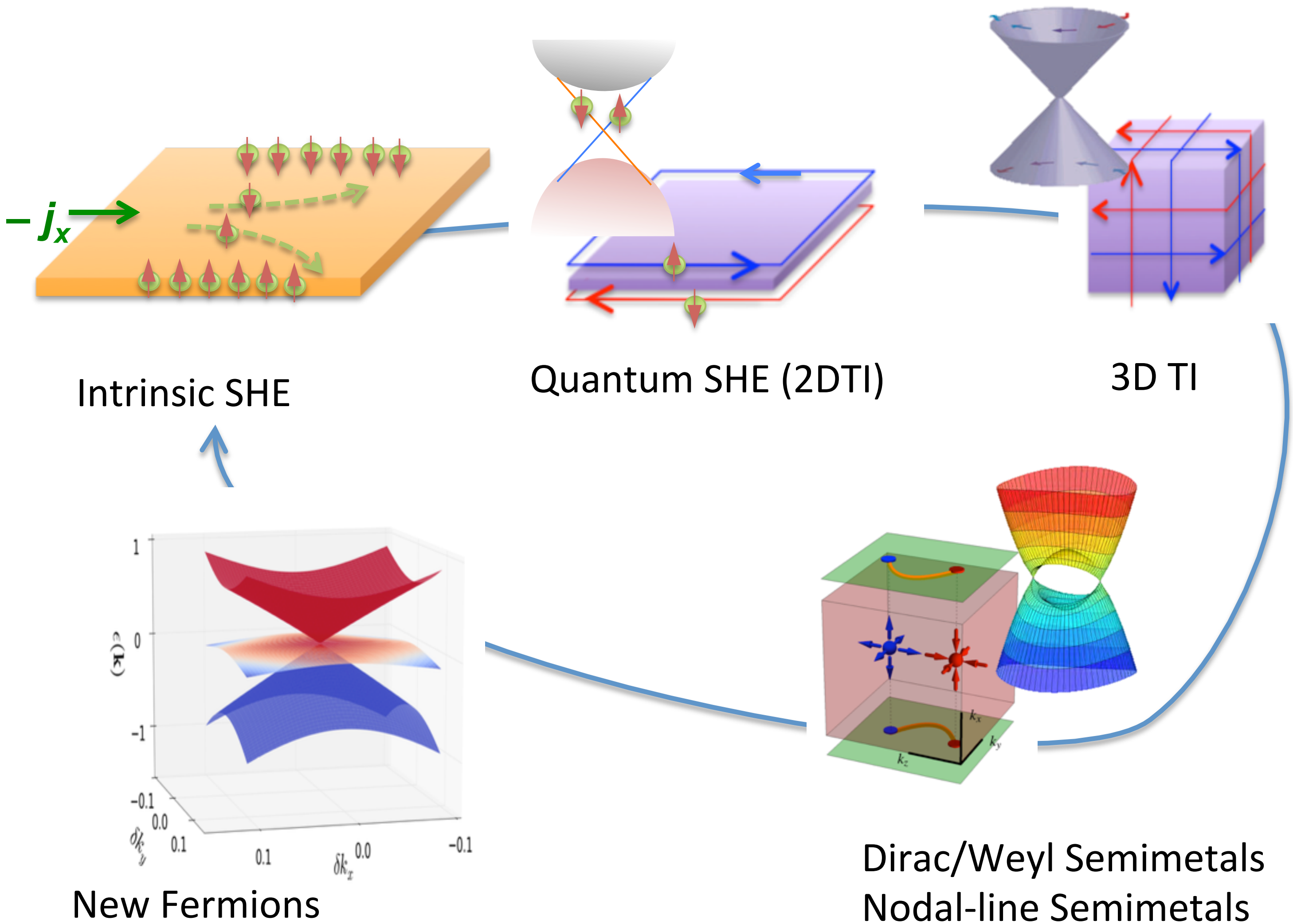
Spin Hall Effect

Monopoles of Berry curvature in a WSM e.g. TaAs, WTe_2, $MoTe_2$

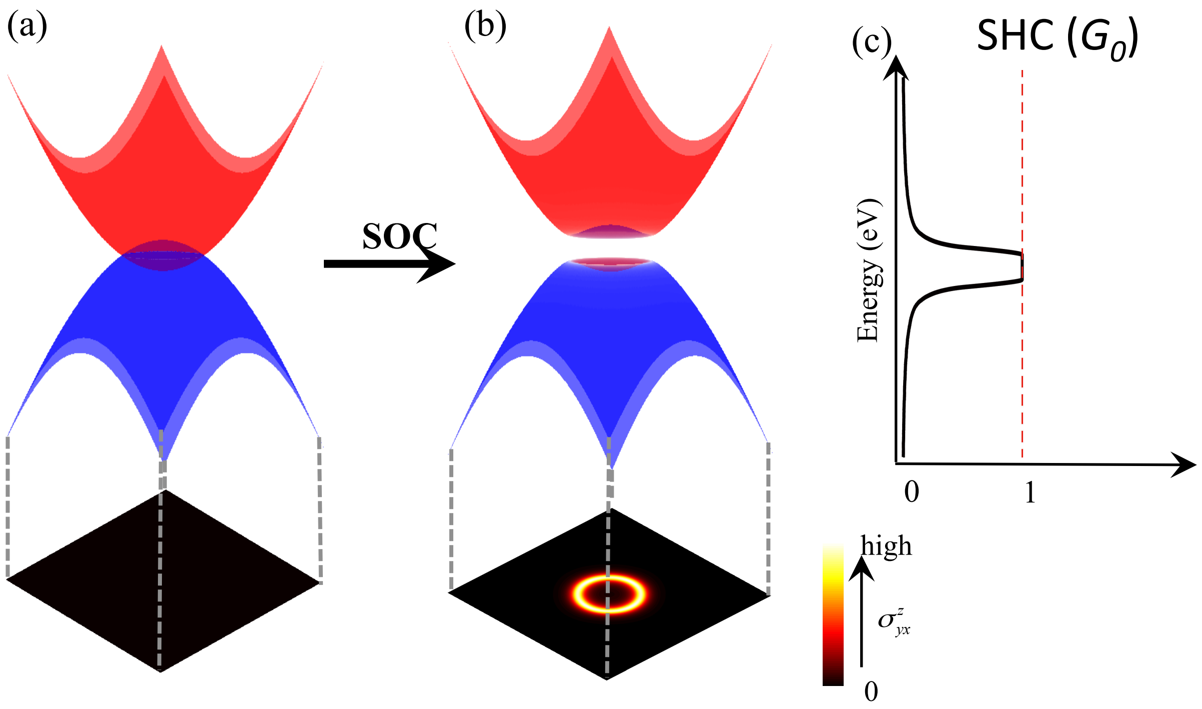


Noncollinear AFM
Mn_3X (X=Ir, Ge, Sn)

Spin Hall Effect and other topological states



Spin Hall Effect

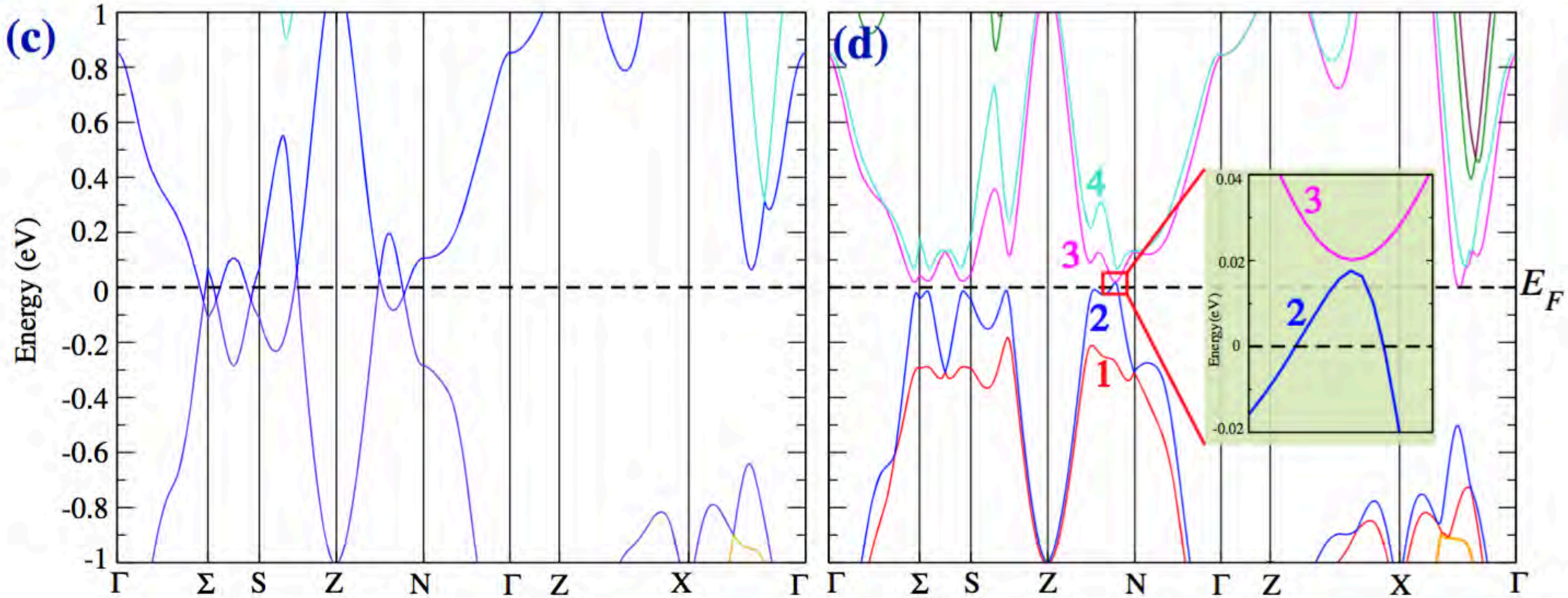


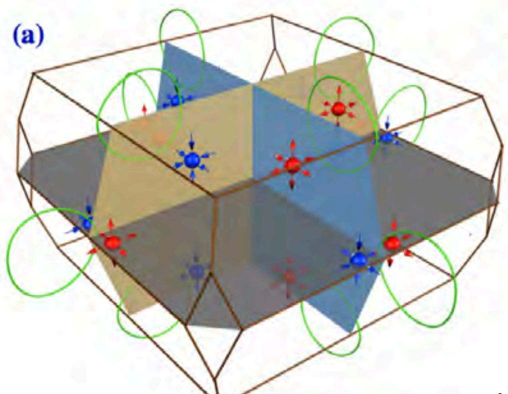
QSHE in a toy model that preserves Sz.

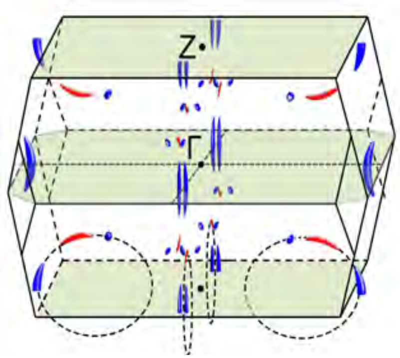
$$\Omega^z_n(\mathbf{k}) = \sum_{n' \neq n} \frac{2\mathrm{Im}[\langle \mathbf{k}n | j^z_x | \mathbf{k}n' \rangle \langle \mathbf{k}n' | v_y | \mathbf{k}n \rangle]}{(\epsilon_{\mathbf{k}n} - \epsilon_{\mathbf{k}n'})^2},$$

$$j^z_x = (s_z v_x + v_x s_z)/2$$

Band structure of TaAs-type WSMs



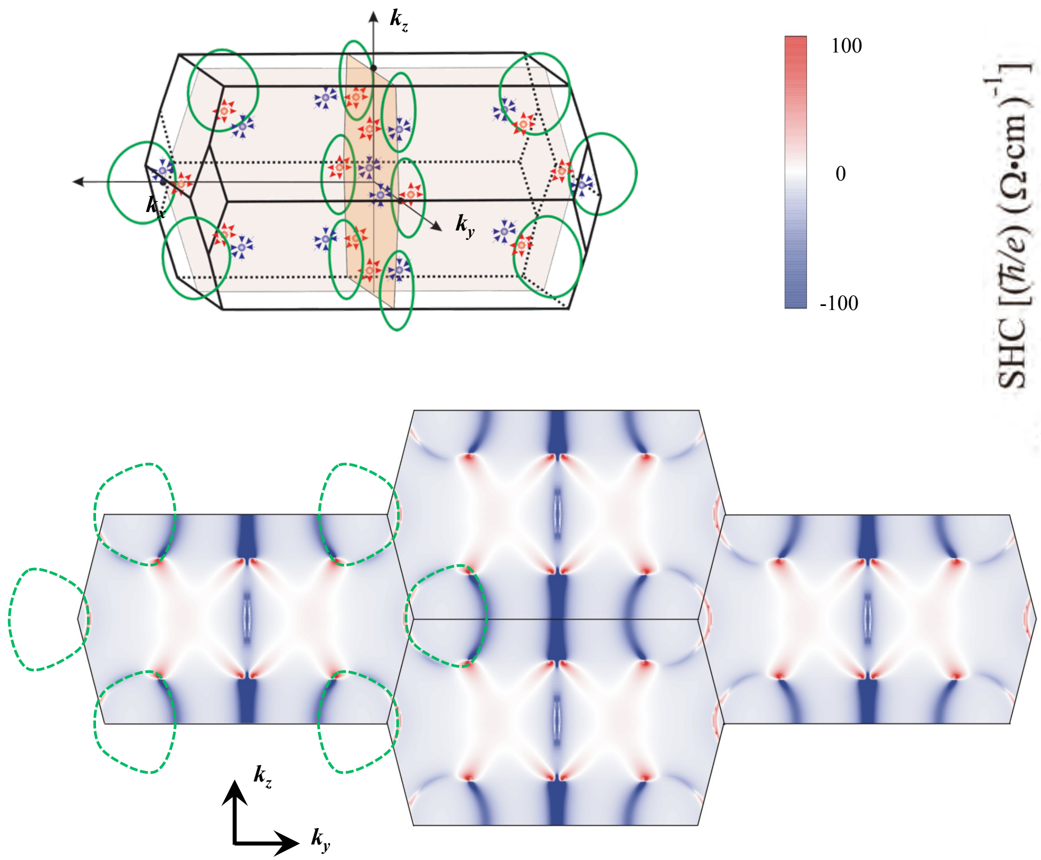


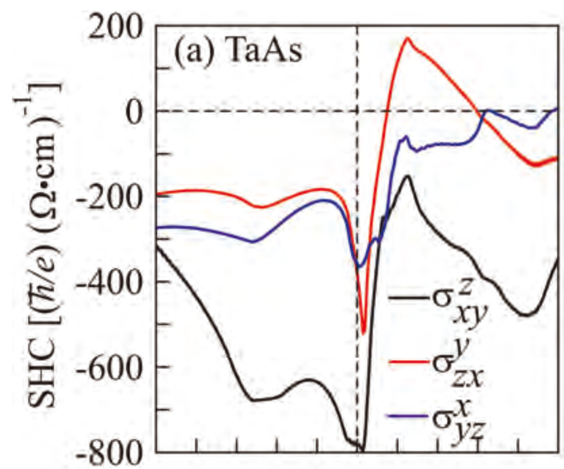


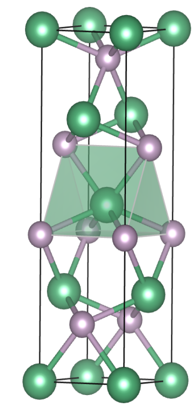
- Full of band crossing due to SOC
- Bulk carriers are not necessarily negative

Weng, H. *et al.* *Phys. Rev. X* **5,** 011029 (2015).

Spin Hall Conductivity







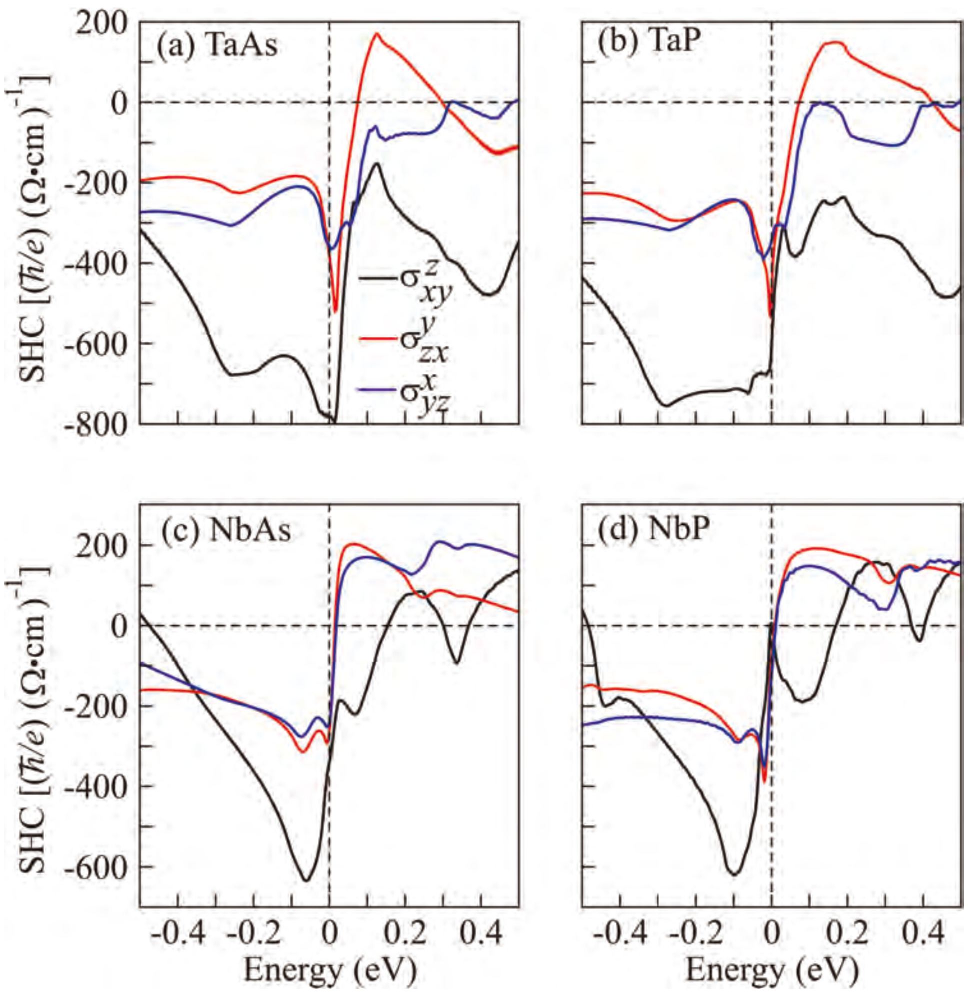
Anisotropic

σ^z_{xy} ~ 800 (TaAs)

~ 2000 (Pt)

Spin Hall Angle $\sigma^{Spin}/\sigma^{charge}$

Spin Hall Conductivity



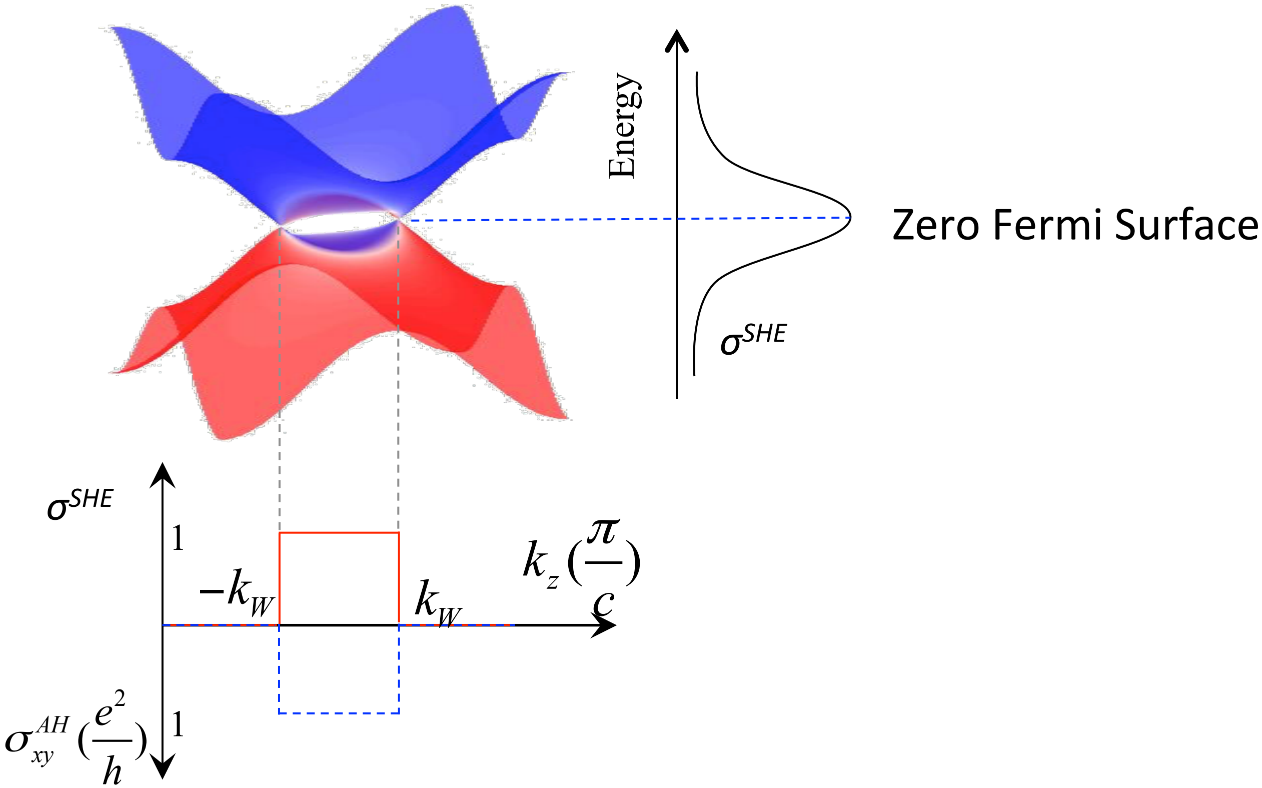
E_F at zero

	TaAs	TaP	NbAs	NbP
σ^z_{xy}	−762	−537	−326	7
σ^y_{zx}	−363	−457	−320	−83
σ^x_{yz}	−364	−346	−272	−135

Peaks of SHC are not Weyl points

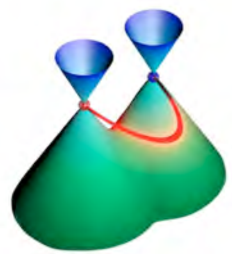
Y Sun, Y Zhang, C Felser, B Yan
arXiv:1604.07167 (2016)

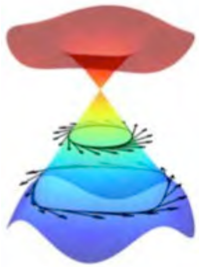
How does Weyl play?



Weyl band structure

Topological SMs vs TIs





Bulk 3D Weyl cones + Surface Fermi arcs

Bulk conductive

No chemical potential problem

Surface Dirac cones

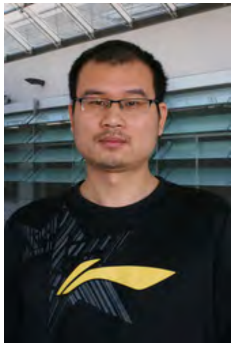
Bulk conductive --- weak SHE

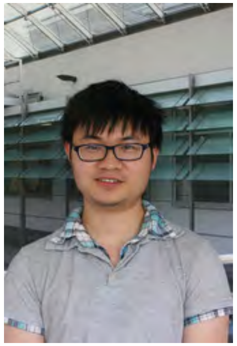
Bulk insulating --- non-conducting

Materials:
TaAs, WTe_2, $MoTe_2$ ZrSiS .....

Acknowledgement

Postdocs: Yan Sun
PhDs: Yang Zhang, Hao Yang





Collaborators

- Claudia Felser (MPI Dresden)
- Stuart Parkin (MPI Halle)
- Yulin Chen (Oxford)
- Haim Beidenkopf (Weizmann Institute)

Fruitful discussions

- Leslie Schoop (MPI Stuttgart)
- Andrei Bernevig (Princeton)
- Jairo Sinova (Mainz)

Thank you for your attendance!